CORFU 2012

Summer Institute
"Particles and the Universe"

Probing Dark Matter with Monojets in ATLAS at the LHC

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Outline

- Dark Matter at Colliders
  - Why look at colliders?
  - Effective field theory description of SM particle - WIMP interaction
- Monojet Analysis
  - What to look for and how?
  - Backgrounds
  - Results
- Interpretation of results
  - Limits on WIMP production
  - Limits on WIMP-nucleon cross-sections
  - Limits on WIMP annihilation cross-sections

Dark Matter at Colliders

- Evidence for Dark Matter: mass determined by light emission ≠ mass determined by motion ⇒ **Dark 'Mass'**
- **Baryonic Dark Matter?** Non-luminous gas, MACHOs (black holes, neutron stars, ...)
  - Total amount inferred from Big Bang nucleosynthesis and CMB
    - Much smaller than the total amount of DM!
- **Hot Dark Matter?** Neutrinos
  - Thermally produced ultrarelativistic particles (m<keV):
    - large free-streaming length prevents early formation of small structures like galaxies!
- **Non-baryonic cold Dark Matter**!
  - Light: axions, sterile neutrinos, … created through phase transition or mixing
  - Massive: weakly Interacting massive particles (**WIMP**) (10 GeV-1 TeV)
    - Created thermally in early universe: SUSY LSP, KK states, …

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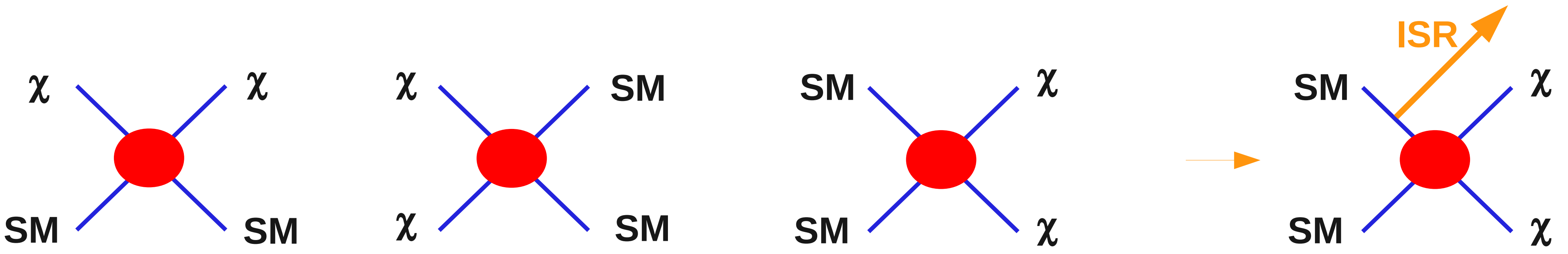
In reach of LHC!

Dark Matter at Colliders

- Different experimental approaches for WIMP DM searches:



direct | **indirect** | **collider: invisible** → **visible**

hadronic recoil:
deep underground, cryogenic

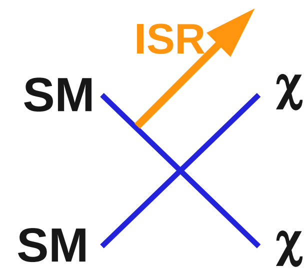
cosmic rays:
ground-based or space observatories

missing transverse energy in particle collisions → **Monojets**
Monophotons

- Colliders provide an independent and complementary approach!
- Assumption about SM-DM interaction needed: To predict signals, to interpret results, to compare collider limits to (in)direct detection experiments

Dark Matter at Colliders

- Model-independent approach *(T.Tait, et al., arXiv:1008.1783v2)*
  - χ is only new particle in LHC reach, SM-χ mediator very heavy
    → Effective field theory approach: **Contact interaction!**
    Coupling set by m(χ) and cut-off scale M_*
  - χ is Dirac Fermion (conclusions for Majorana Fermions also possible)



→ 14 operators possible – pick characteristic set

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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

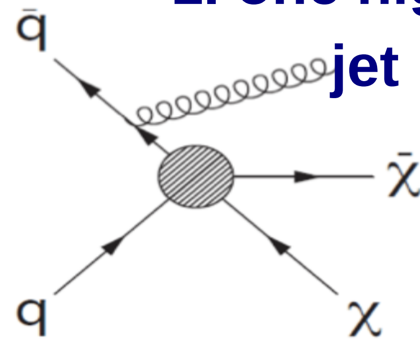
What are we looking for?

1. leading jet p_T > 120 GeV, $|\eta|$ < 2

2. missing E_T (MET) > 120 GeV, $|\Delta\varphi$ (jet$_2$, MET)$|$ > 0.5 (suppress back-to-back di-jet events)

3. $\leq$ 2 jets with p_T > 30 GeV and $|\eta|$ < 4.5, no leptons

1. one high-p_T jet



2. large missing E_T

3. nothing else!

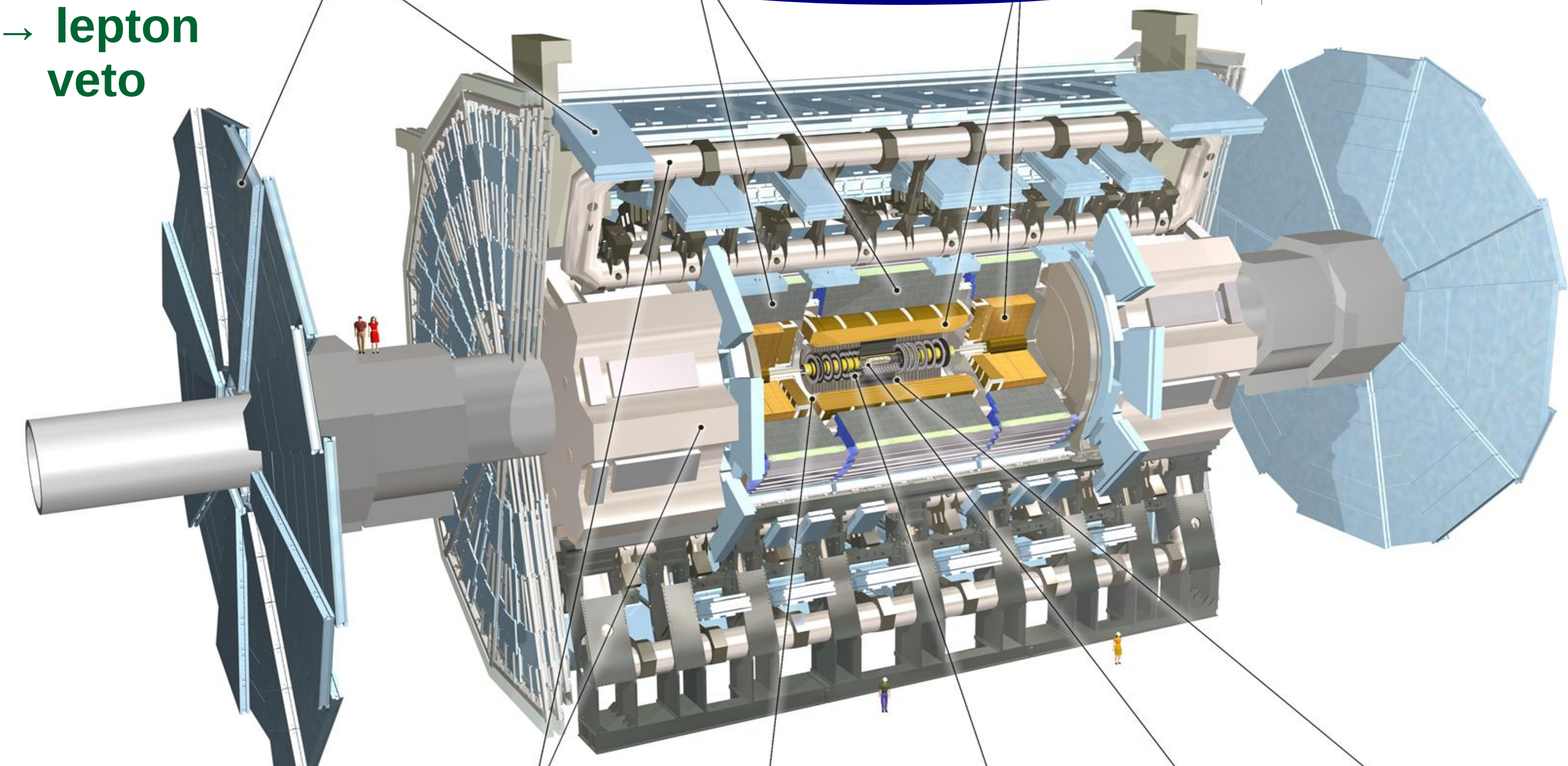
- Further: data quality, primary vertex with ≥ 2 associated tracks
- MET trigger used (70 GeV)

- Define 4 Signal Regions (SR): p_T, MET > 120, 220, 350, 450 GeV

Monojet Analysis in ATLAS

Muon system → lepton veto

Calorimeters → MET, jets



Inner detector → vertexing

Backgrounds

- **Irreducible:**
  - pp → Z → $\nu\nu$ + jets
- **Electroweak:**
  - pp → W → lν + jets,
  - pp → Z/γ → ll + jets
  - Very large cross-section, but small MET

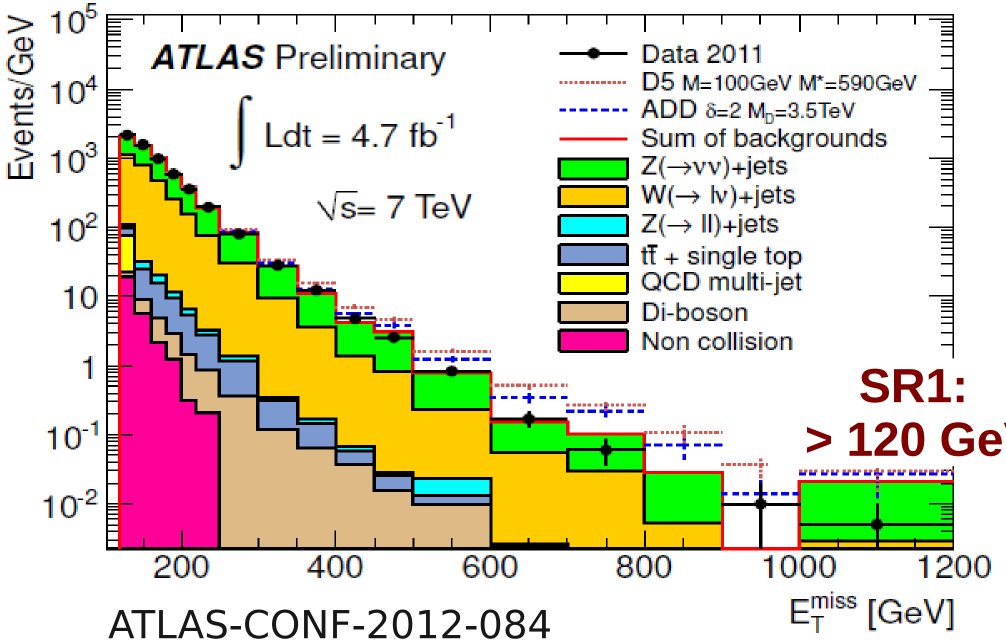
Data-driven: Control Regions (CR)

$$N_{\mathrm{SR}}^{\mathrm{predicted}} = (N_{\mathrm{CR}}^{\mathrm{Data}} - N_{\mathrm{Bkg}}) \cdot C \cdot \frac{N_{\mathrm{SR}}^{\mathrm{MC}}}{N_{\mathrm{jet/E_T^{miss}}}^{\mathrm{MC}}}$$

SR	$Z \to \nu\bar{\nu}$+jets	$W \to \tau\nu$+jets $W \to \mu\nu$+jets	$W \to e\nu$+jets	$Z \to \tau^+\tau^-$+jets $Z \to \mu^+\mu^-$+jets
CR	$W \to e\nu$+jets $W \to \mu\nu$+jets $Z \to e^+e^-$+jets $Z \to \mu^+\mu^-$+jets	$W \to \mu\nu$+jets	$W \to e\nu$+jets	$Z \to \mu^+\mu^-$+jets

- **QCD multijets:**
  - Estimated from di-, tri-jet events in data
- **Dibosons:**
  - Leptons, MET from W decay
  - Estimated from MC
- **Non-collision background:** noise, cosmic rays, beam-induced fake jets
  - Estimated from data
- **(Double) top:**
  - Leptons, large MET, many jets
  - Estimated from MC

Results



SR1: > 120 GeV

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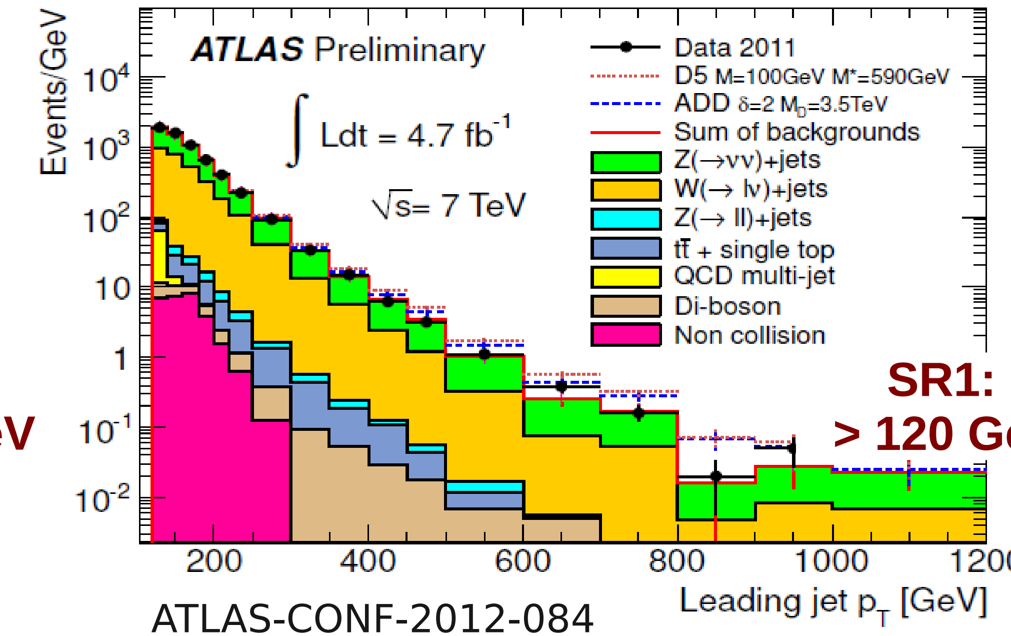

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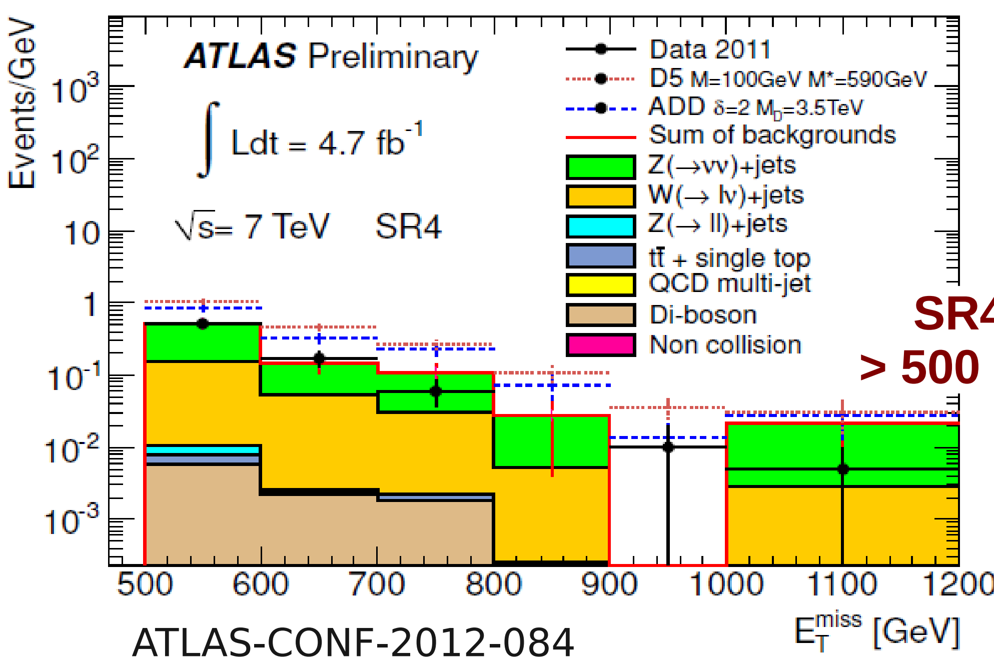

SR4: > 500 GeV

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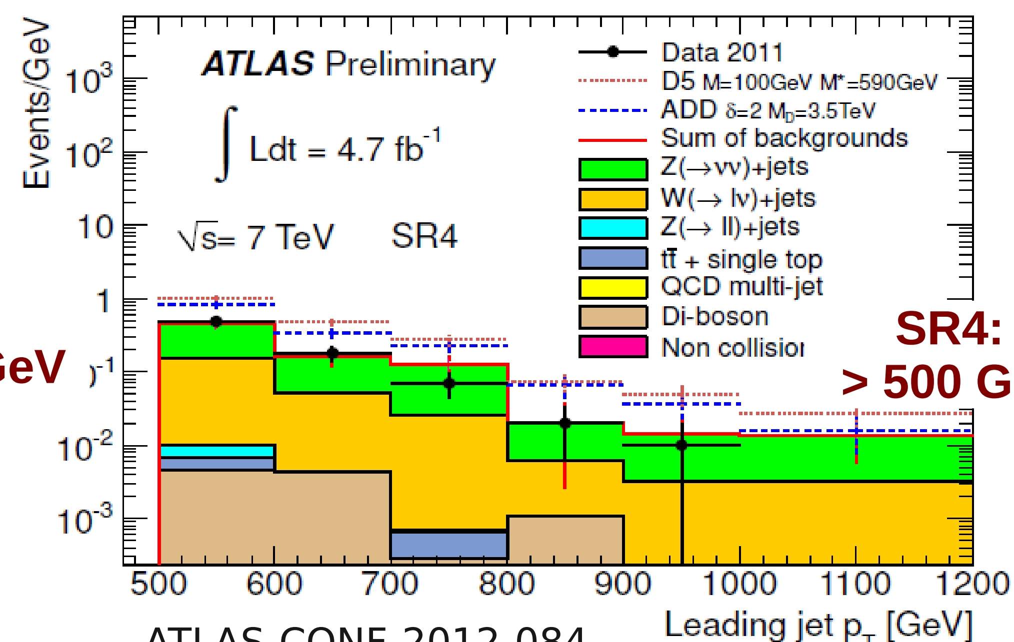

SR4: > 500 GeV

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Results – in Numbers

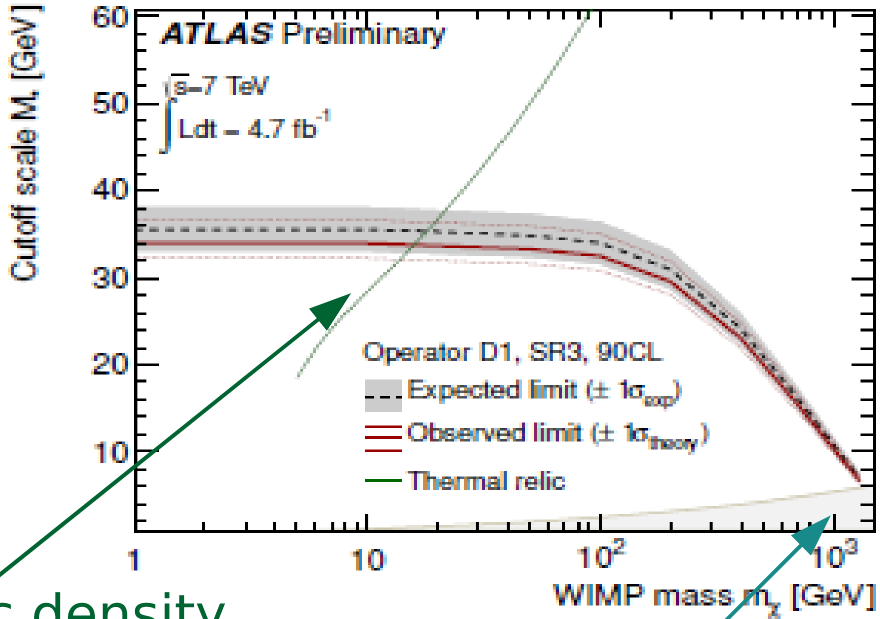
	SR1	SR2	SR3	SR4
$Z \to \nu\bar{\nu}$+jets	63000 ± 2100	5300 ± 280	500 ± 40	58 ± 9
$W \to \tau\nu$+jets	31400 ± 1000	1853 ± 81	133 ± 13	13 ± 3
$W \to e\nu$+jets	14600 ± 500	679 ± 43	40 ± 8	5 ± 2
$W \to \mu\nu$+jets	11100 ± 600	704 ± 60	55 ± 6	6 ± 1
$t\bar{t}$ + single t	1240 ± 250	57 ± 12	4 ± 1	-
Multijets	1100 ± 900	64 ± 64	8 ± 9	-
Non-coll. Background	575 ± 83	25 ± 13	-	-
$Z/\gamma^* \to \tau\tau$+jets	421 ± 25	15 ± 2	2 ± 1	-
Di-bosons	302 ± 61	29 ± 5	5 ± 1	1 ± 1
$Z/\gamma^* \to \mu\mu$+jets	204 ± 19	8 ± 4	-	-
Total Background	124000 ± 4000	8800 ± 400	748 ± 60	83 ± 14
Events in Data (4.7fb^{-1})	124703	8631	785	77

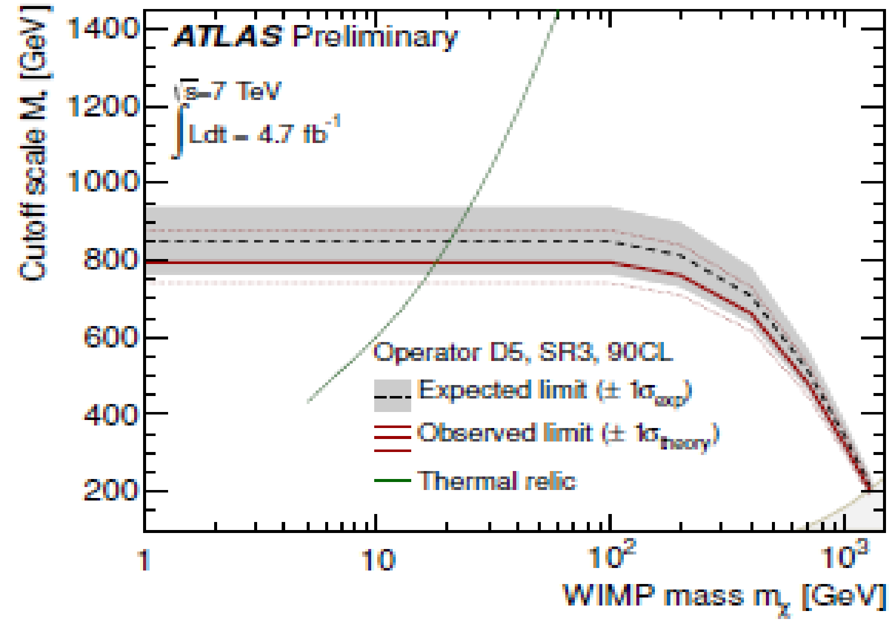
- Observed number of events agrees well with SM expectation

→ **Set 90% and 95% confidence level upper limits on the visible cross section (σ×A×ε) of new physics:**

$\sigma_{\text{vis}}^{\text{obs}}$ at 90% [pb]	1.63	0.13	0.026	0.006
$\sigma_{\text{vis}}^{\text{exp}}$ at 90% [pb]	1.54	0.15	0.020	0.006
$\sigma_{\text{vis}}^{\text{obs}}$ at 95% [pb]	1.92	0.16	0.030	0.007
$\sigma_{\text{vis}}^{\text{exp}}$ at 95% [pb]	1.82	0.17	0.024	0.008

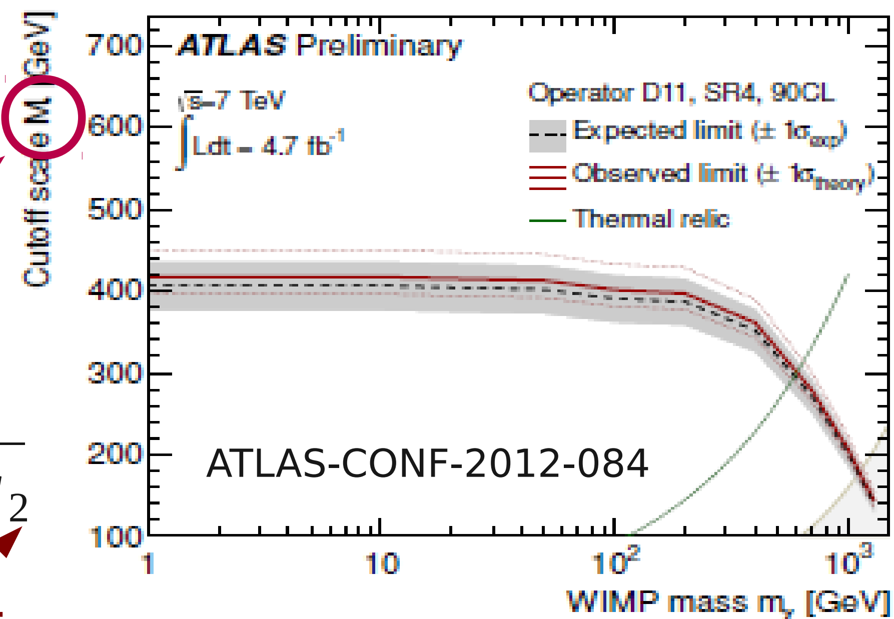
WIMP limits





Relic density (WMAP) WIMP annihilations only via given operator to light quarks only possible below line!

EFT breaks down

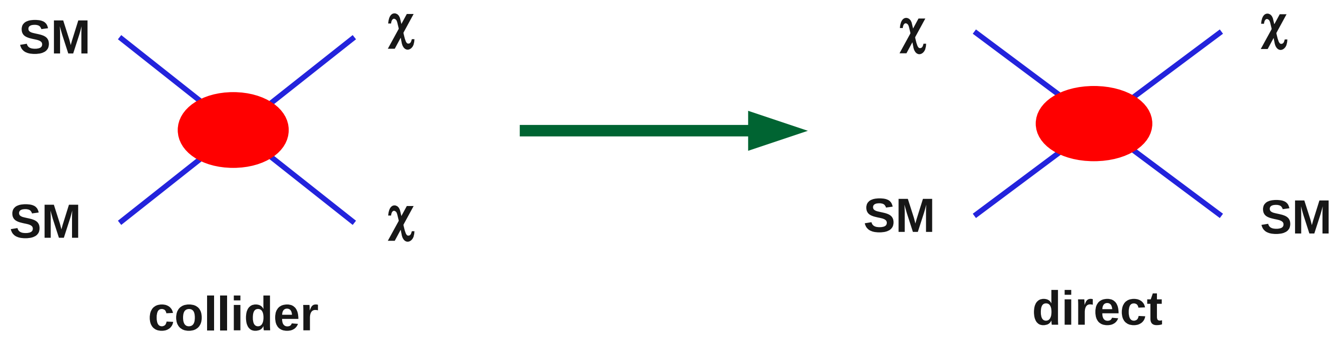


$$M_* \sim M / \sqrt{g_1 g_2}$$

Mediator mass **couplings**

WIMP-Nucleon limits

- LHC limits on visible cross-section → interpreted with specific m(χ) gives limit on M* → limit on WIMP-nucleon cross-section



$$\sigma_0^{D1} = 1.60 \times 10^{-37}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{20\text{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{D5,C3} = 1.38 \times 10^{-37}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{300\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{D8,D9} = 9.18 \times 10^{-40}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{300\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{D11} = 3.83 \times 10^{-41}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{100\text{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{C1,R1} = 2.56 \times 10^{-36}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{10\text{GeV}}{M_*}\right)^4,$$

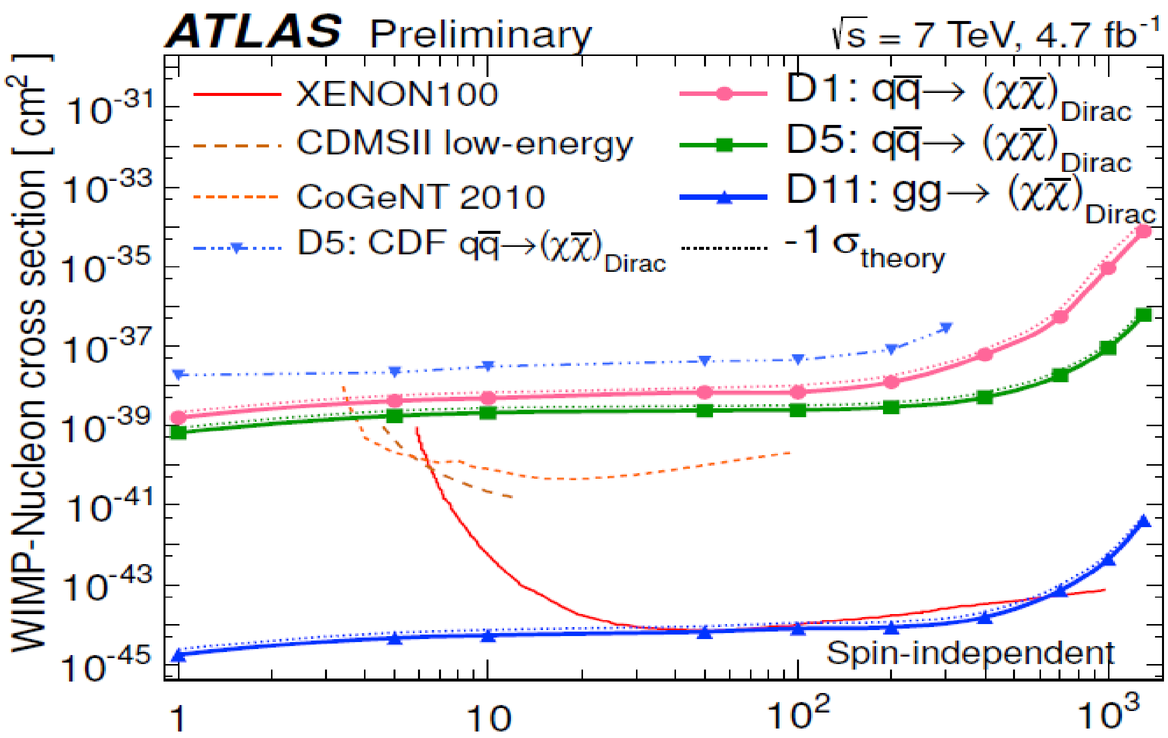
$$\sigma_0^{C5,R3} = 7.40 \times 10^{-39}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{60\text{GeV}}{M_*}\right)^4.$$

arXiv:1008.1783v2

WIMP–Nucleon limits

- Comparison with direct dark matter detection experiments
  - spin-dependent (SIMPLE, Picasso)
  - spin-independent (XENON100, CDMSII, CoGeNT)
- ATLAS limits competitive: especially strong for low m(χ)

→ complementary: different systematics!



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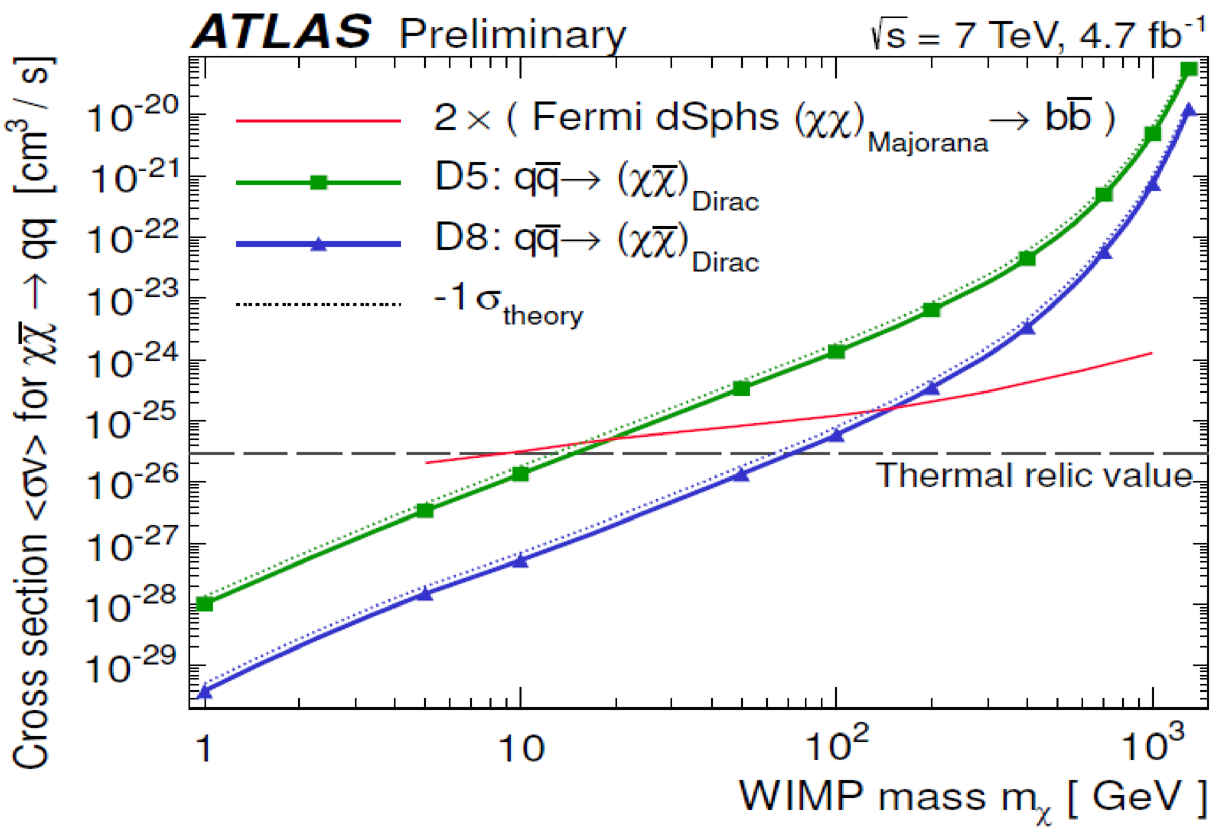
Relic abundance of WIMPs

- Limits on vector and axial-vector interactions can be translated into upper limits on WIMP annihilation cross-section to light quarks assuming the interactions are flavor-universal

  → compared to annihilations to $b\bar{b}$ from galactic high-energy gamma ray observations by FERMI LAT



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- Results are comparable
- For m(χ) < 10 GeV (D5) and m(χ) < 70 GeV (D8):
- ATLAS limits are **below** the values needed for WIMPs to make up CDM abundance in the early universe

  (assuming WIMPs annihilate exclusively via the particular operator)

Summary

- If dark matter in the universe consists out of WIMPs in reach of LHC energies, they can be pair-produced in collisons and probably detected through signatures of MET and an ISR jet
- A search for physics beyond Standard Model in events with such a monojet signature was carried out with 4.7 fb^{-1} of pp data.
- In each of the four signal regions, distinguished by MET and jet $p_{T,}$ data agree with the SM predictions and limits on the visible cross section of BSM signals are set
- Effective field theory is used to derive limits for WIMP pair production on a mass suppression scale M*
- Results are converted into WIMP-nucleon scattering and WIMP annihilation cross sections and compared to dedicated dark matter experiments
  - Results are competitive and complementary
- 8 TeV analysis is ongoing: will be optimized for WIMP searches, up to 6 times more data expected