

DARK MATTER SEARCHES AT THE LHC

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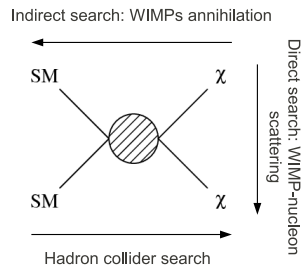
On behalf of the ATLAS and CMS Collaborations

*XLIXth Rencontres de Moriond
Electroweak Interactions and Unified Theories
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Dark Matter candidates at the LHC

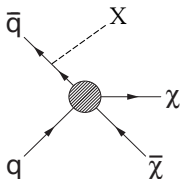
- Cosmological indications for “invisible”, Dark Matter (DM):
 - Rotation velocities of galaxies
 - Gravitational lensing
 - Cosmic microwave background (CMB)
- Search at hadron collider:
 - Could be produced as a WIMP
 - DM would be seen as missing energy
- Effective field theory (EFT):
 - Mediator too heavy to be generated directly
 - Contact interaction with suppression scale $M_\star \sim \frac{M}{\sqrt{g_\chi g_{SM}}}$, with g_χ and g_{SM} the couplings to Standard Model (SM) and DM, and M the mediator mass
- Simplified models:
 - Specified massive mediator
 - UV-complete (no validity issue)



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	$\frac{1}{4M_\star^2} \bar{\chi} \chi \alpha_s (G_{\mu\nu}^a)^2$

The mono-X signature

- Particle X can be radiated from the initial state (ISR), or be produced in association with invisible particle(s)

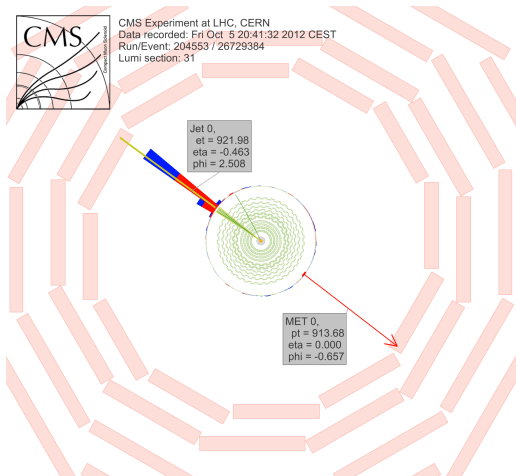


- X balances “missing energy” in transverse plane (\cancel{E}_T)
- X particles considered:

jet, W, Z, photon, top

- Mono-X topology allows for tagging production of new undetected particles

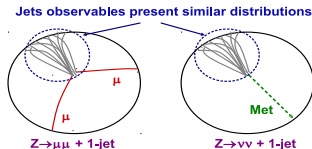
→ In the following, X always from ISR if not mentioned



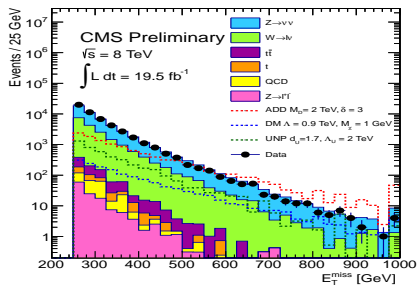
Search in the mono-jet final state [ATLAS, CMS]

- Preliminary results at $\sqrt{s} = 8$ TeV:
 CMS-PAS-EXO-12048 $\mathcal{L} = 20 \text{ fb}^{-1}$
 ATLAS-CONF-2012-147 $\mathcal{L} = 10.5 \text{ fb}^{-1}$
 ATLAS 7 TeV, 5 fb^{-1} : JHEP 04 (2013) 075
 CMS 7 TeV, 5 fb^{-1} : JHEP 09 (2012) 094
- Event selection:
 - Trigger: \cancel{E}_T [ATLAS] or $\cancel{E}_T + \text{jet}$ [CMS]
 - Central leading jet, at most 2 good jets
 - To suppress QCD multi-jet events:
 - ATLAS: $\Delta\phi(\cancel{E}_T, \text{jet}_2) > 0.5$
 - CMS: $\Delta\phi(\text{jet}_1, \text{jet}_2) < 2.5$
 - Veto on e and μ [ATLAS, CMS]
Explicit τ veto [CMS]
 - Inclusive signal regions (SR):
 - ATLAS: both lead jet p_T and $\cancel{E}_T > 120, 220, 350, 500$ GeV
 - CMS: lead jet $p_T > 110$ GeV and $\cancel{E}_T > 250$ to 550 GeV (step 50 GeV)

- Main background: $Z \rightarrow \nu\nu$
 - Estimate with W/Z [ATLAS] or Z [CMS] lepton data control regions (CR)

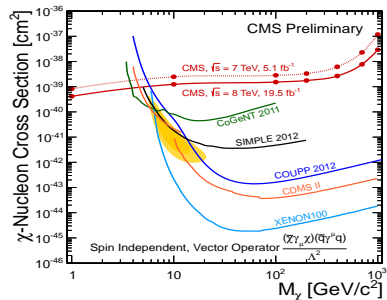
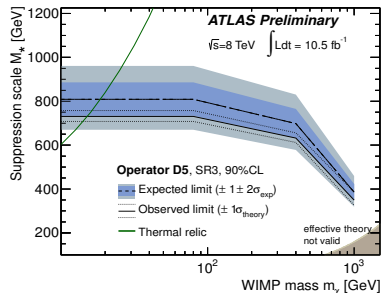


- Transfer CR to SR via simulation



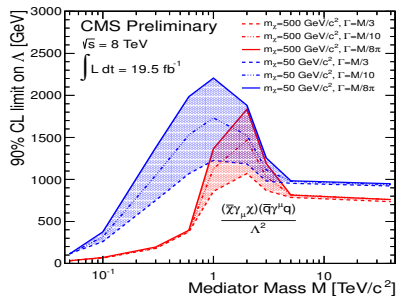
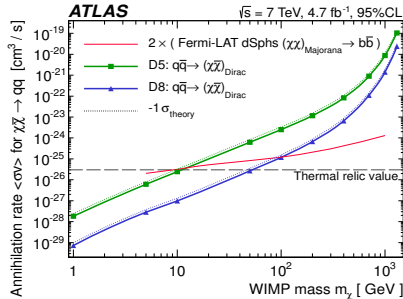
Search in the mono-jet final state [ATLAS, CMS]

- Total uncertainties on $Z \rightarrow \nu\nu$:
 - CMS: 4.5-15.6%
 - ATLAS: 3.3-20%
 - Main: low CR statistics at high \cancel{E}_T
- Limits:
 - Lower bound on EFT scale M_\star (Λ) extracted from limit on signal rate
 - Thermal relic density from WMAP compared to M_\star bounds
(If M_\star above relic line, results not consistent with WMAP, assuming one WIMP species produced via one given operator)
 - EFT scale bounds translated into $\sigma(\chi\text{-nucleon})$ upper limits
 - More in backup



Search in the **mono-jet** final state [ATLAS, CMS]

- Upper limit on DM annihilation:
 - Bounds on vector and axial-vector interactions translated into upper limits on $\sigma(\chi\chi \rightarrow qq)$ (light q)
 - Results compared to the annihilations to bb from Fermi LAT
 - Limits below relic value are not consistent with WMAP
- Lower bound on scale (Λ) of UV-complete simplified model:
 - Interactions via massive vector mediator (of mass M)
 - At high M , limits converge to those obtained assuming EFT
 - Width constrained from $M/8\pi$ to $M/3$



Search in the $\boxed{\text{mono-W}(\rightarrow \ell\nu)}$ final states [CMS]

- Preliminary result at $\sqrt{s} = 8 \text{ TeV}$:
CMS-PAS-EXO-13-004 $\mathcal{L} = 20 \text{ fb}^{-1}$

- Scenario:

- W radiated from u or d quark
- W leptonic decays

- e and μ channels combined

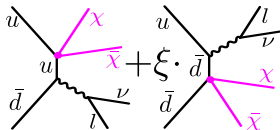
- Main observable: mass of (ℓ, \cancel{E}_T)

$$M_T = \sqrt{2 \cdot p_T^\ell \cdot \cancel{E}_T \cdot (1 - \cos \Delta\Phi_{\ell, \cancel{E}_T})}$$

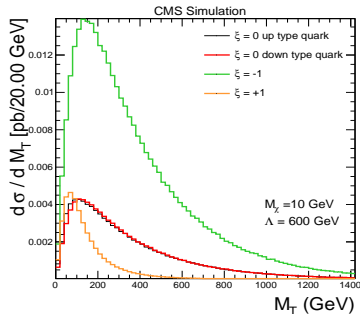
- Event selection:

- Based on CMS W' search [CMS-PAS-EXO-12-060]
- Trigger: single electron and single muon
- \cancel{E}_T balanced by lepton:
 $0.4 < p_T^\ell / \cancel{E}_T < 1.5$ and
 $\Delta\Phi(\ell, \cancel{E}_T) > 0.8\pi$

- DM production mode:

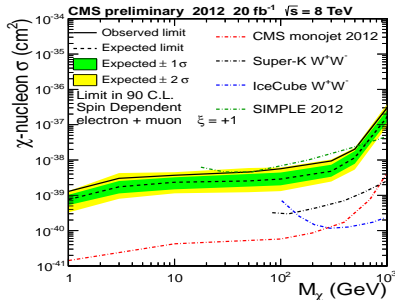
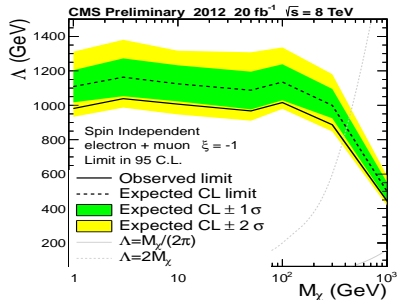
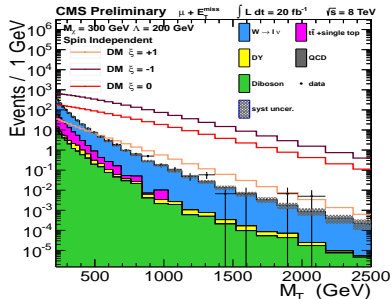


- Interference ξ between 2 processes
- $\xi = 1$ (-1): destructive (constructive)



Search in the $\text{mono-W}(\rightarrow \ell\nu)$ final states [CMS]

- Main background: $W \rightarrow \ell\nu$ (simulation, M_T -dependent NLO k-factors)
- Main uncertainty on background: lepton energy scale/resolution (1-10%)
- Lower bounds on EFT scale Λ derived using full M_T shape, and translated into $\sigma(\chi\text{-nucleon})$ upper limits (more in backup)



Search in the mono-W/Z($\rightarrow qq$) final state [ATLAS]

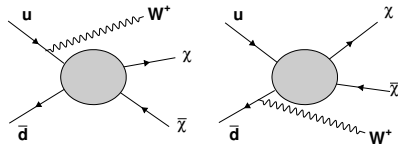
- Published: PRL 112, 041802 (2014)
 $\sqrt{s} = 8 \text{ TeV}$ $\mathcal{L} = 20 \text{ fb}^{-1}$

→ see P. Azzi's talk: "Boosted object searches"

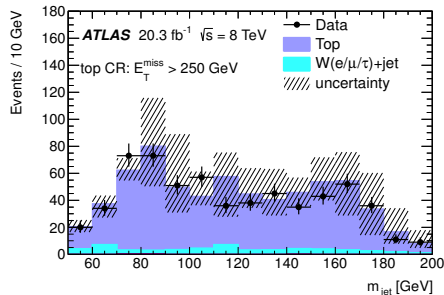
- Scenario:
 - W/Z radiated from u or d quark
 - W and Z hadronic decays
- W/Z decay reconstructed as single massive "fat" jet of mass m_{jet}
 (Cambridge-Aachen, $R = 1.2$)

Validation in top CR: includes W peak and tail due to b jet from top decay

- Event selection:
 - \cancel{E}_T trigger
 - ≥ 1 central fat jet with $p_T > 250 \text{ GeV}$ and $50 \text{ GeV} < m_{jet} < 120 \text{ GeV}$
 - ≤ 1 jet ($R = 0.4$) away from lead fat jet
 - Veto on electron, muon and photon
 - 2 SR: $\cancel{E}_T > 350 \text{ GeV}$ or 500 GeV

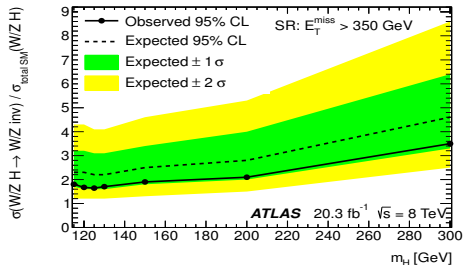
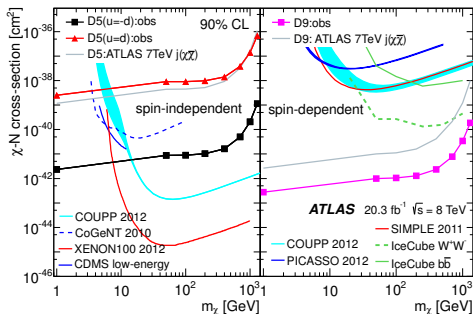


- Main backgrounds:
 - Z($\rightarrow \nu\nu$)+jets and W($\rightarrow \ell\nu$)+jets
 - Determined by extrapolating a data muon CR using simulation



Search in the $\text{mono-W/Z}(\rightarrow qq)$ final state [ATLAS]

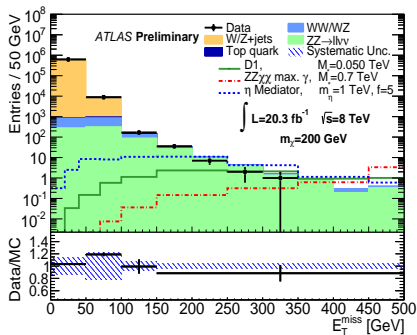
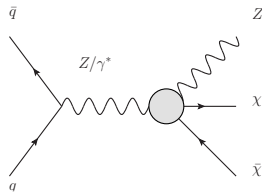
- Total background systematics:
 - Main: data CR statistics, fat jet and \cancel{E}_T calibration, theory
 - 5 to 13% (low to high \cancel{E}_T)
- EFT limits:
 - Upper limits on $\sigma(\chi\text{-nucleon})$ in D5 case with opposite sign u and d-quark couplings are improved by 3 orders of magnitude due to constructive interference ($\xi = -1$)
 - Lower bounds on scale in backup
- DM-SM interaction with Higgs:
 - Simple low mass mediator
 - $\sigma(\text{W/ZH}) \times \text{Br}(\text{H} \rightarrow \chi\chi)$ normalized to $\sigma_{SM}(\text{W/ZH})$ lower than 1.6 for $m_H = 125$ GeV



Search in the $\boxed{\text{mono-Z}(\rightarrow \ell\ell)}$ final state [ATLAS]

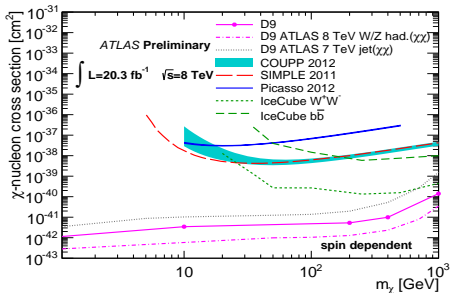
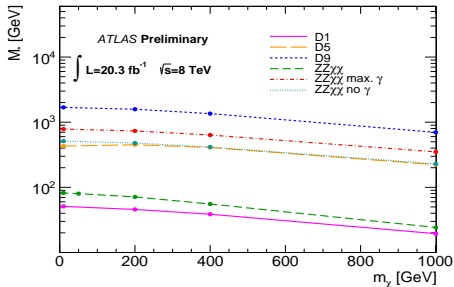
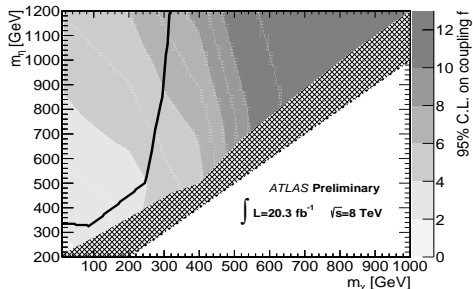
- Preliminary result: $\sqrt{s} = 8 \text{ TeV}$, $\mathcal{L} = 20 \text{ fb}^{-1}$
- 2 scenarios for DM pair production:
 - Z radiated from ISR
 - Z interacts directly with DM

Z/γ^* mixing is a theory parameter
- e and μ channels combined
- Main background: $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ (NLO simulation)
- Event selection:
 - Trigger: di-lepton or single lepton
 - 2 good leptons, $M_{\ell\ell}$ under Z-mass peak
 - No \cancel{E}_T from mismeasured jets: $\Delta\Phi(\cancel{E}_T, p_T^{\ell\ell}) > 2.5$, $|\eta^{\ell\ell}| < 2.5$, and $|p_T^{\ell\ell} - \cancel{E}_T|/p_T^{\ell\ell} < 0.5$
 - No 3^{rd} lepton and no jets
 - SR defined by $\cancel{E}_T > 150, 250, 350, 450 \text{ GeV}$



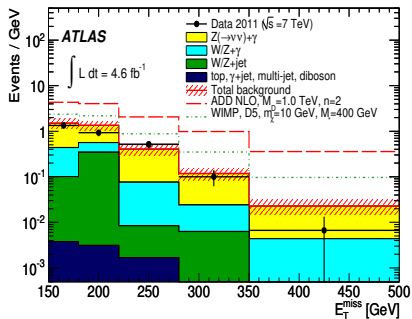
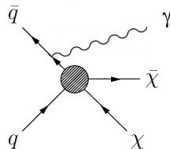
Search in the $\text{mono-Z}(\rightarrow \ell\ell)$ final state [ATLAS]

- Main background uncertainty: 17-99% (depending on SR, mainly due to theory)
- Case of scalar massive mediator (η) in UV-complete model:
 - Upper bounds on χ - η coupling (f)
 - Above black line, these are smaller than lower limit from relic abundance
- Below: limits on EFT scale and upper bounds on $\sigma(\chi$ -N)



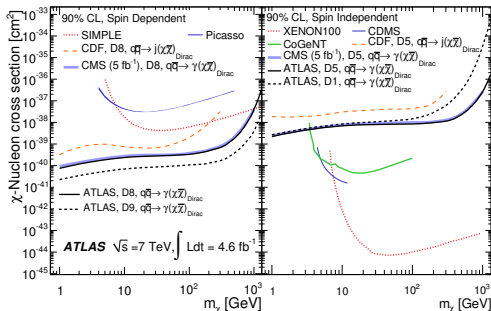
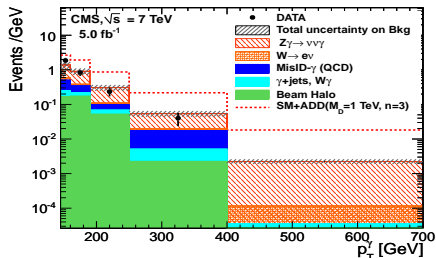
Search in the mono-photon final state [ATLAS, CMS]

- Published with $\mathcal{L} \sim 5 \text{ fb}^{-1}$ and $\sqrt{s} = 7 \text{ TeV}$:
PRL 110, 011802 (2013) [ATLAS]
PRL 108, 261803 (2012) [CMS]
- Main background: $Z(\rightarrow \nu\nu) + \gamma$
 - ATLAS: extrapolated from $\gamma + \mu + \cancel{E}_T$ CR
 - CMS: estimation from simulation (NLO)
- Event selection
 - Trigger: \cancel{E}_T [ATLAS], photon [CMS]
 - Central photon, $p_T > 150 \text{ GeV}$ [ATLAS]
 $p_T > 145 \text{ GeV}$ [CMS]
 - $\cancel{E}_T > 150 \text{ GeV}$ [ATLAS], 130 GeV [CMS]
 - Veto on electron and muons
 - ATLAS: allow up to one jet. Photon, jet and \cancel{E}_T well separated.
 - CMS: veto significant hadronic activity



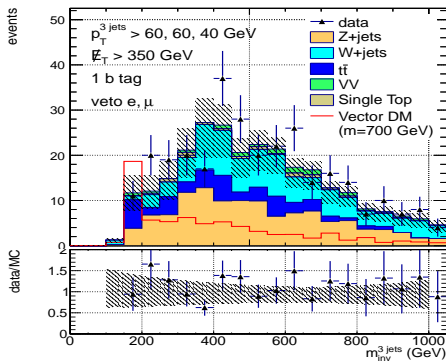
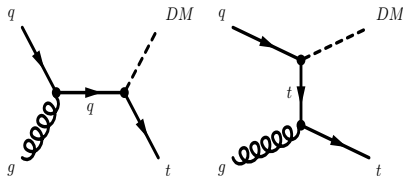
Search in the mono-photon final state [ATLAS, CMS]

- Systematics on background:
 - Total amounts to 15% [ATLAS] and 13% [CMS]
 - Main sources: \cancel{E}_T , jet and photon modelling, theory [CMS], and muon CR statistics [ATLAS]
- Limits on EFT scale obtained from simple counting experiment and translated into upper bounds on $\sigma(\chi\text{-}N)$
- ATLAS and CMS limits are similar
- D11 is not available (gg interaction)



Search in the **mono-top** final state [CMS]

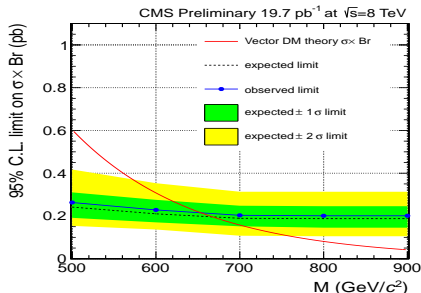
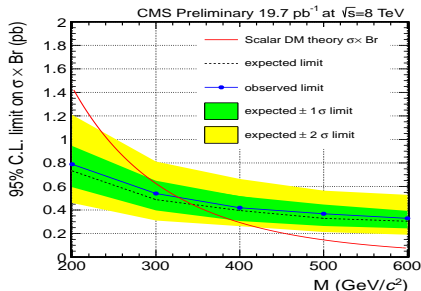
- Preliminary result at $\sqrt{s} = 8$ TeV:
CMS-PAS-B2G-12-022, $\mathcal{L} \sim 20 \text{ fb}^{-1}$
- Scenario:
 - top produced in association with DM (not from ISR)
 - top decays hadronically
 - FCNC considered
- Main backgrounds:
 - $Z(\rightarrow \nu\nu)+\text{jets}$ (from data CR)
 - $W(\rightarrow \ell\nu)+\text{jets}$ (from data CR)
 - $t\bar{t}$ (NNLO, top p_T reweighting)
- Event selection
 - SR trigger: \cancel{E}_T
 - Exactly 3 jets: $p_T > 60, 60, 40$ GeV, 1 b-tag, $m_{inv}^{3\text{jets}} < 250$ GeV
 - Veto on electron and muon
 - $\cancel{E}_T > 350$ GeV



Search in the mono-top final state [CMS]

- Systematics on background
 - Total: 57%
 - Main sources: $t\bar{t}$ theory and top p_T modeling, Z/W data CR statistics

- Limits:
 - Effective field theory for DM-SM interaction
 - Upper limits on $\sigma \times \text{BR}$ interpreted as lower bounds on DM candidate mass:
 - Scalar DM: 327 GeV
 - Vector DM: 655 GeV

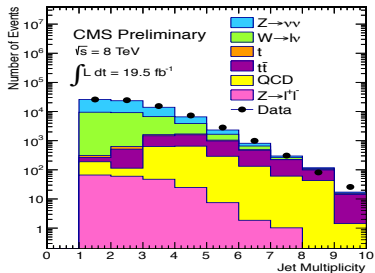
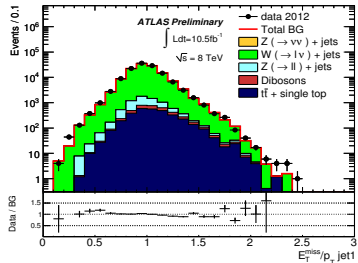
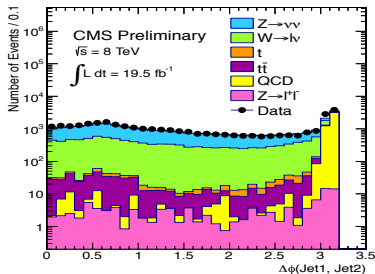
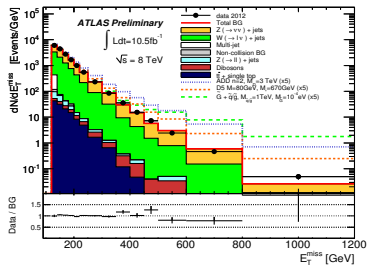


Conclusion

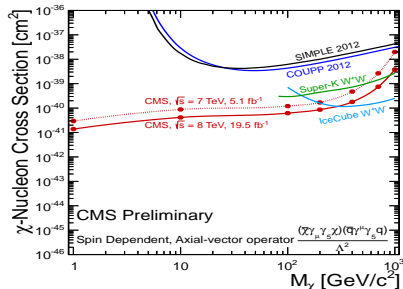
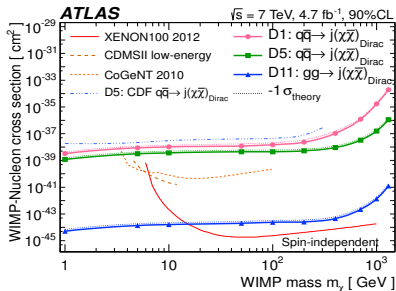
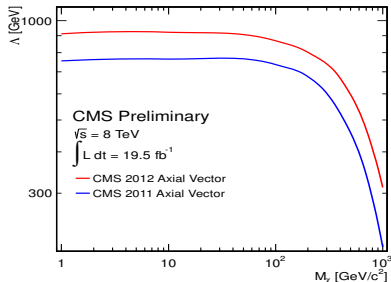
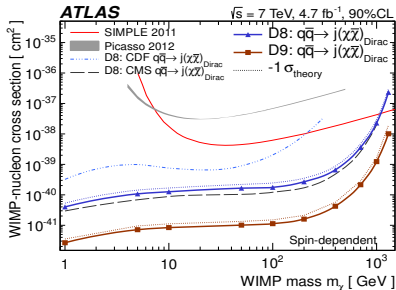
- The Mono-X searches involve a large scope of final states and are sensitive to Dark Matter production at the LHC
- Accurate “data-driven” techniques have been used for the determination of the main backgrounds
- No evidence of Dark Matter has been observed but limits have been set based on an effective field theory, and on UV-complete simplified models
- Dark Matter interpretation at the LHC is complementary to results of direct and indirect astroparticle experiments
- For more information:
 - ATLAS: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
 - CMS: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

BACKUP

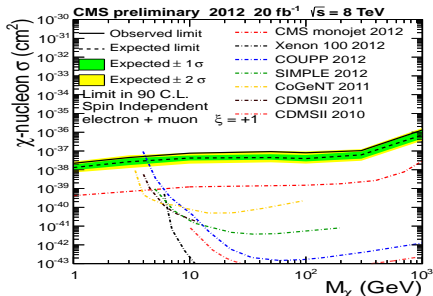
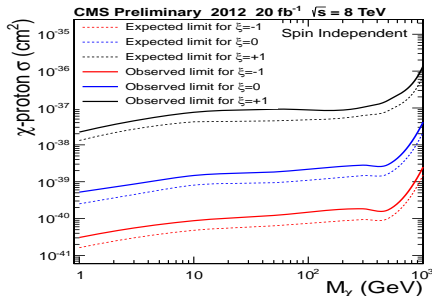
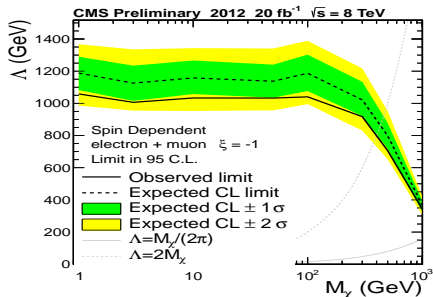
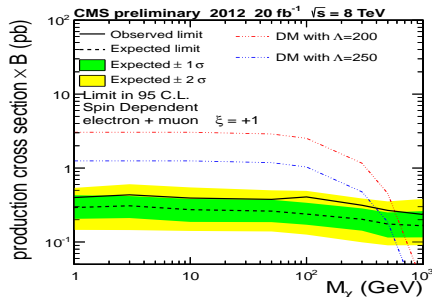
Mono-jet analyses: additional plots



Mono-jet analyses: additional plots



Mono-W($\rightarrow l\nu$) analysis: additional plots



Mono-W/Z($\rightarrow qq$) analysis: additional plots

