Search for dark matter in the mono-lepton channel at the LHC

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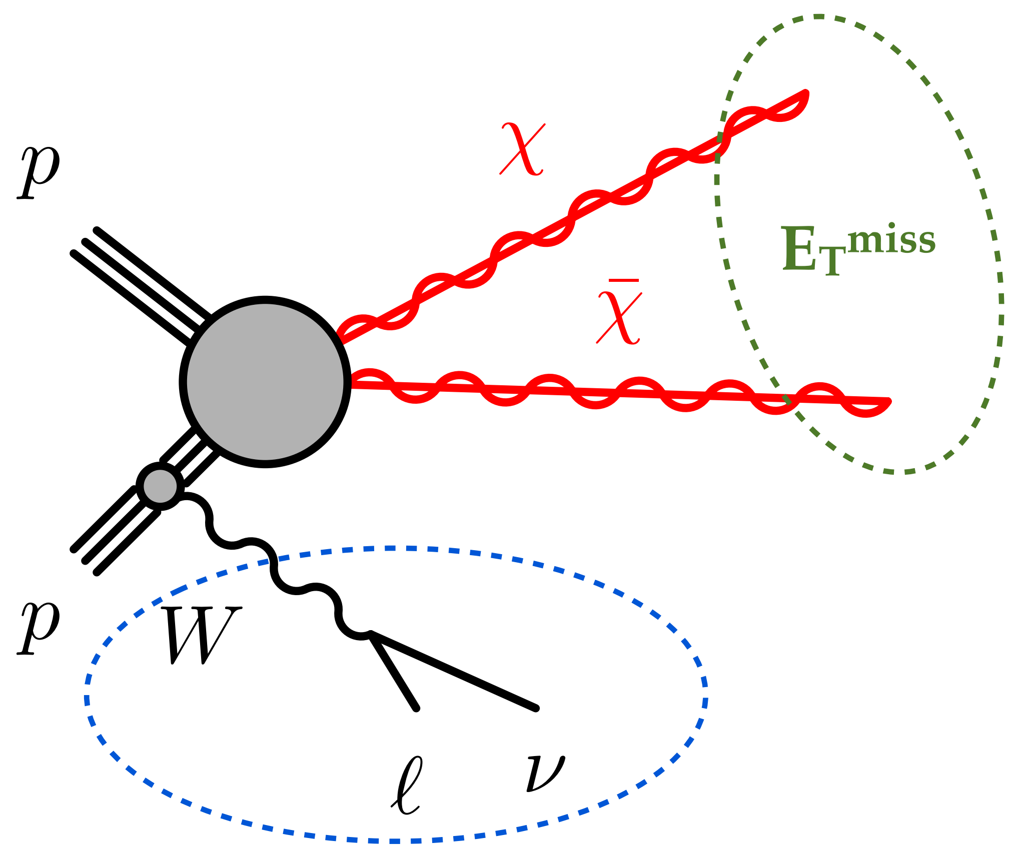
Dark Matter with Mono-lepton Signature

Direct pair-production



Leptonically decaying *W* recoiling against dark matter

Pros:

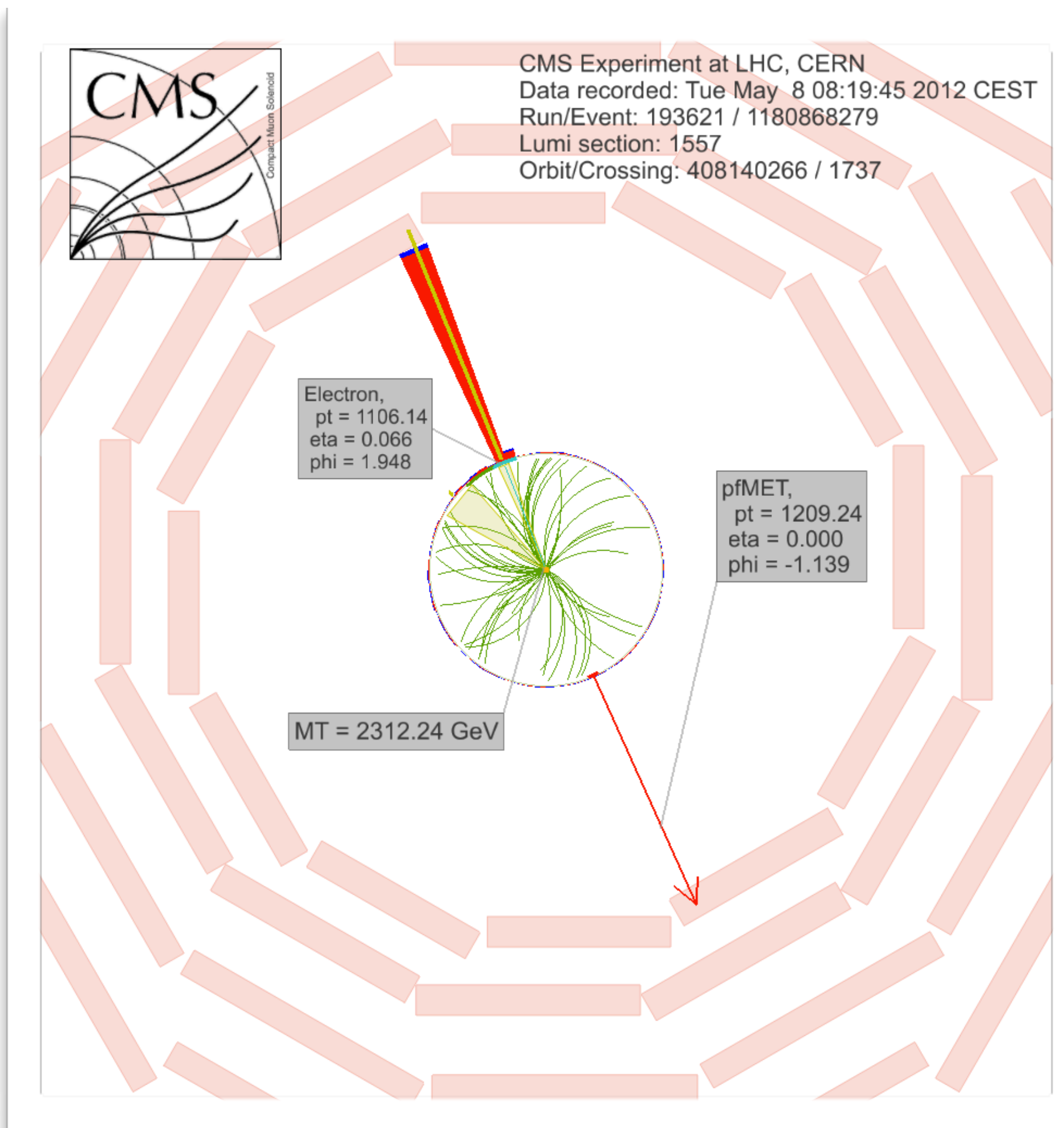
Lepton allows highly efficient triggering

Low and reasonably well understood SM background

Cons:

Overall lower expected σ×B compared to other modes (i.e. mono-jet)

Possible experimental signature : High p_T electron recoiling against missing transverse momentum (E_T^{miss})



Mono-*W* is favored over mono-jet if the couplings to up and down quarks have the same magnitudes but opposite signs (due to constructive interference)

The Effective Field Theory (EFT)

- Four fermion contact interaction w/ two incoming quarks & two fermionic DM particles
- Assuming weakly-interacting particles, various couplings are investigated:

ATLAS

- Three main operators of arxiv:1008.1783

$$\mathrm{D1}: \frac{m_q}{M_*^3}\bar{\chi}\chi \cdot \bar{q}q \qquad \mathrm{D9}: \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu}q$$

$$\mathrm{D5}: \frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\chi \cdot \bar{q}\gamma_{\mu}q$$

CMS

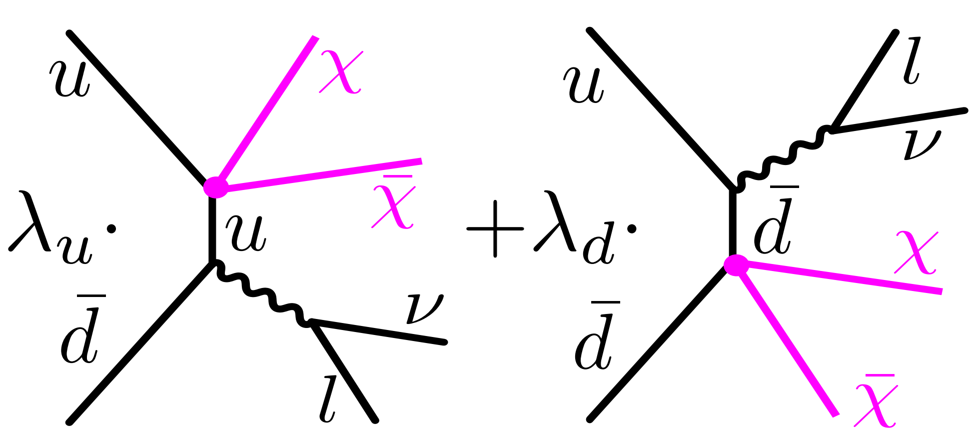
- Two main operators:

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma^5\chi \cdot \lambda_i\bar{q}_i\gamma_{\mu}\gamma^5 q_i \qquad (\equiv \mathrm{D8})$$

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi \cdot \lambda_i\bar{q}_i\gamma_{\mu}q_i \qquad (\equiv \mathrm{D5})$$

$$\Lambda = M_* = \frac{M_{\mathrm{messenger}}}{\sqrt{g_1 g_2}}$$

- χ is the spinor (Dirac fermion) including mass term m_χ
- Mass scale (Λ) is the scale of the effective interaction & $g_{1,2}$ are the coupling constants



- Relative sign of λ_u & λ_d determines the interference
  - $\xi = 0, \pm1$ ($= \lambda_u \lambda_d$ with $|\lambda| = 0$ or 1)
  - Most pronounced differences in (axial-)vector operators
    - ATLAS considers $\xi = \pm1$ for D5 (+1 : D5d and -1 : D5c)
    - CMS considers all three cases for both D5 and D8

On the Validity of the EFT

$$\Lambda = M_* = \frac{M_{\text{messenger}}}{\sqrt{g_1 g_2}}$$

One "messenger"

Two couplings

For the EFT to make sense the "messenger" should be sufficiently heavy

$$M_{\text{messenger}} > 2 \cdot m_\chi$$

In order to have a perturbative theory: $g_1 g_2 \leq (4\pi)^2$

resulting in: $\Lambda = M_* \geq \frac{m_\chi}{2\pi}$

or with a more stringent criterion: $g_1 g_2 = 1$

results in: $\Lambda = M_* \geq 2 m_\chi$

arxiv:1407.7494

arxiv:1408.2745

Search Strategies

- Select events with exactly one high p_T / E_T lepton (muon or electron)
  - **ATLAS** : E_T (p_T) > 125 (45) GeV in the e (μ)-channel
  - **CMS** : E_T (p_T) > 100 (45) GeV in the e (μ)-channel
  - Asymmetry between channels due to different trigger thresholds
  - Stringent additional requirements on the objects to ensure high quality
    - Isolation, certain detector signature, etc.

- Exploit p_T^{lepton} vs E_T^{miss} balance by requiring:
  - **ATLAS** : $E_T^{miss} > 125$ (45) GeV in the e (μ)-channel
  - **CMS** : $0.4 < p_T^{lepton} / E_T^{miss} < 1.5$ and $\Delta\phi(\text{lepton}, \boldsymbol{p}_T^{miss}) > 2.5$ (in both e/μ-channels)

- Use transverse mass, $m_T = [2 \cdot p_T^{lepton} \cdot E_T^{miss}(1-\cos\phi_{l\nu})]^{1/2}$, as the main discriminator:
  - **ATLAS** : Perform "single-bin counting experiment" using events with $m_T \geq m_{T,min}$
    - $m_{T,min}$ is optimized for each model separately for best expected sensitivity
    - Same thresholds are used in both e/μ-channels
  - **CMS** : Perform "multi-bin counting experiment" using events with $m_T > 220$ GeV
    - Takes advantage of full shape, converges to "single-bin counting" for low background
    - Same threshold of 220 GeV is used in both e/μ-channels

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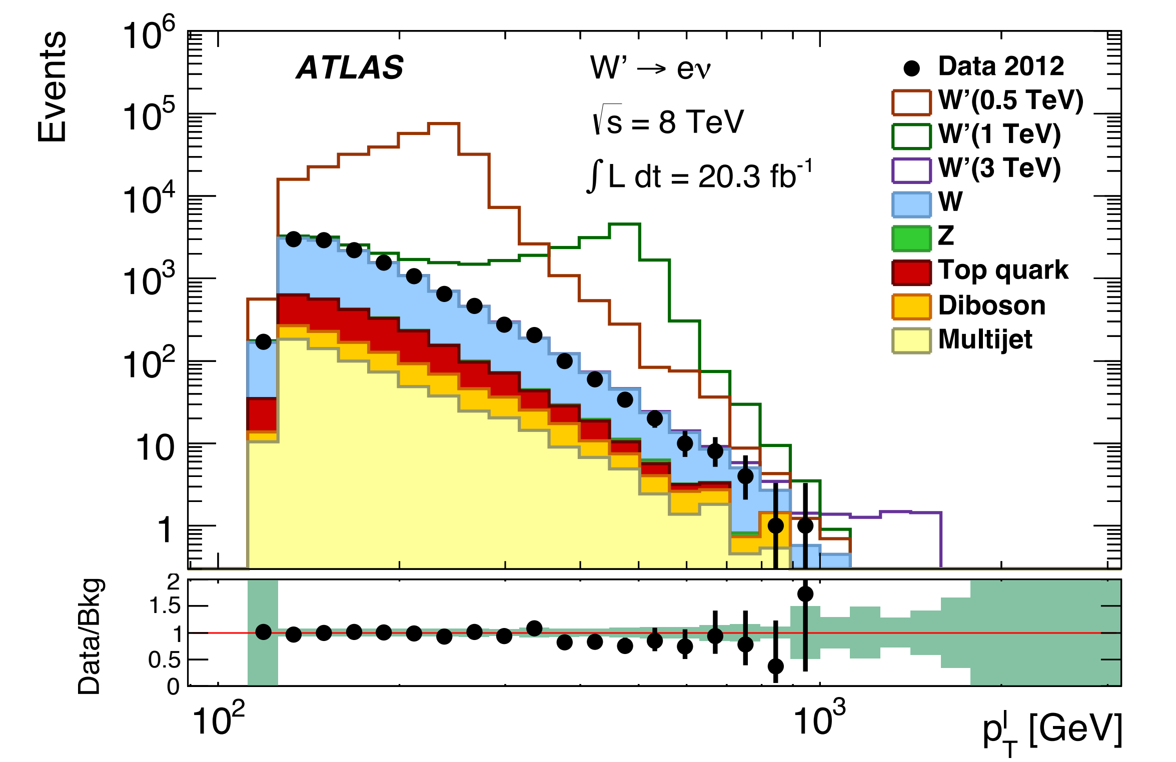
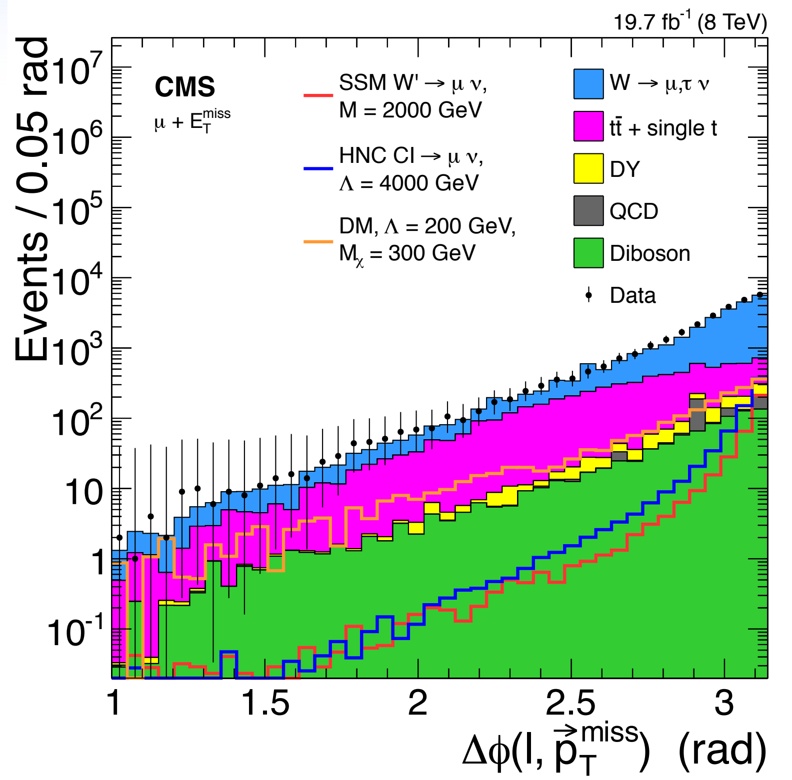
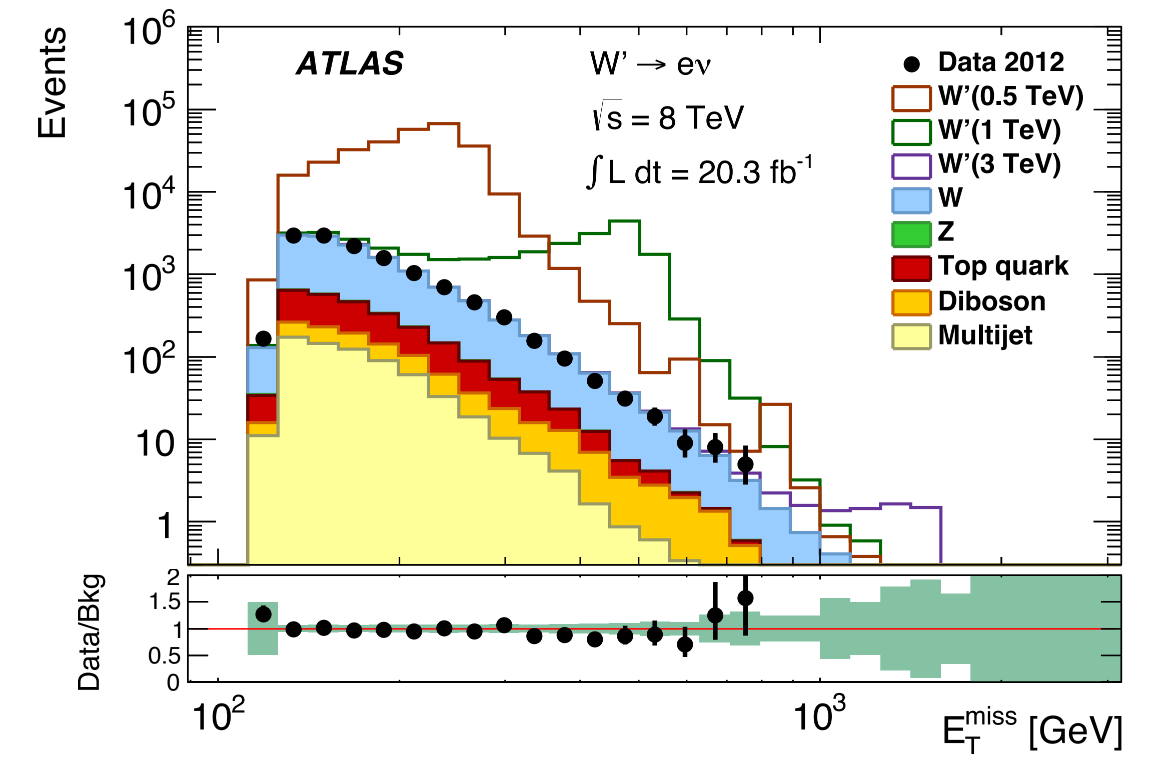
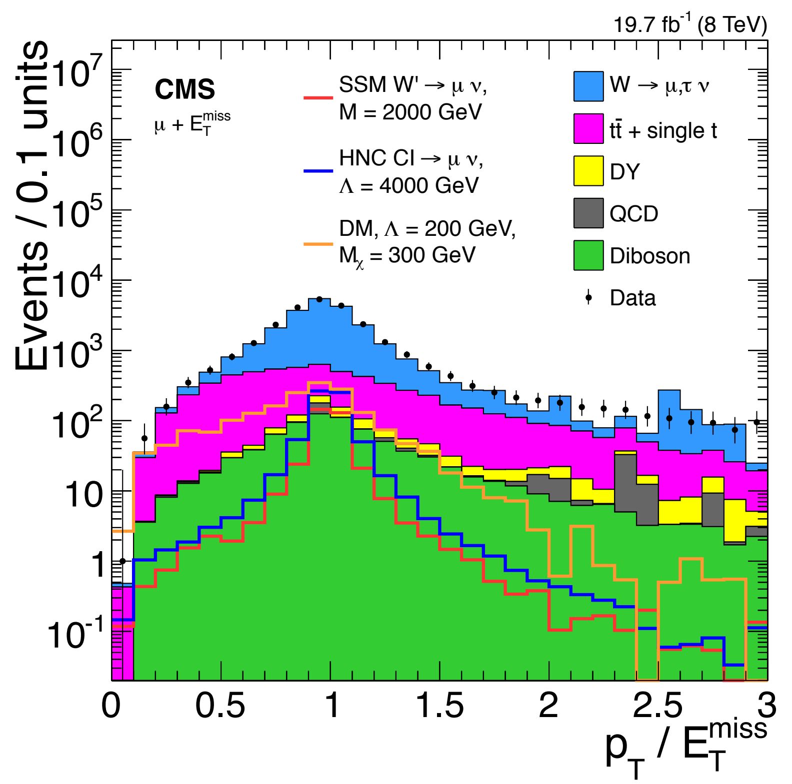
Event Kinematics









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Signal

- DM signal samples are generated using Madgraph5 @ LO at both ATLAS and CMS

ATLAS

m_χ [GeV]	DM production σB [pb] D1 $M_* = 10$ GeV	D5d $M_* = 100$ GeV	D5c $M_* = 1$ TeV	D9 $M_* = 1$ TeV
1	439	72.2	0.0608	0.0966
100	332	70.8	0.0575	0.0870
200	201	58.8	0.0488	0.0695
400	64.6	32.9	0.0279	0.0365
1000	1.60	2.37	0.00192	0.00227
1300	0.213	0.454	0.000351	0.000412

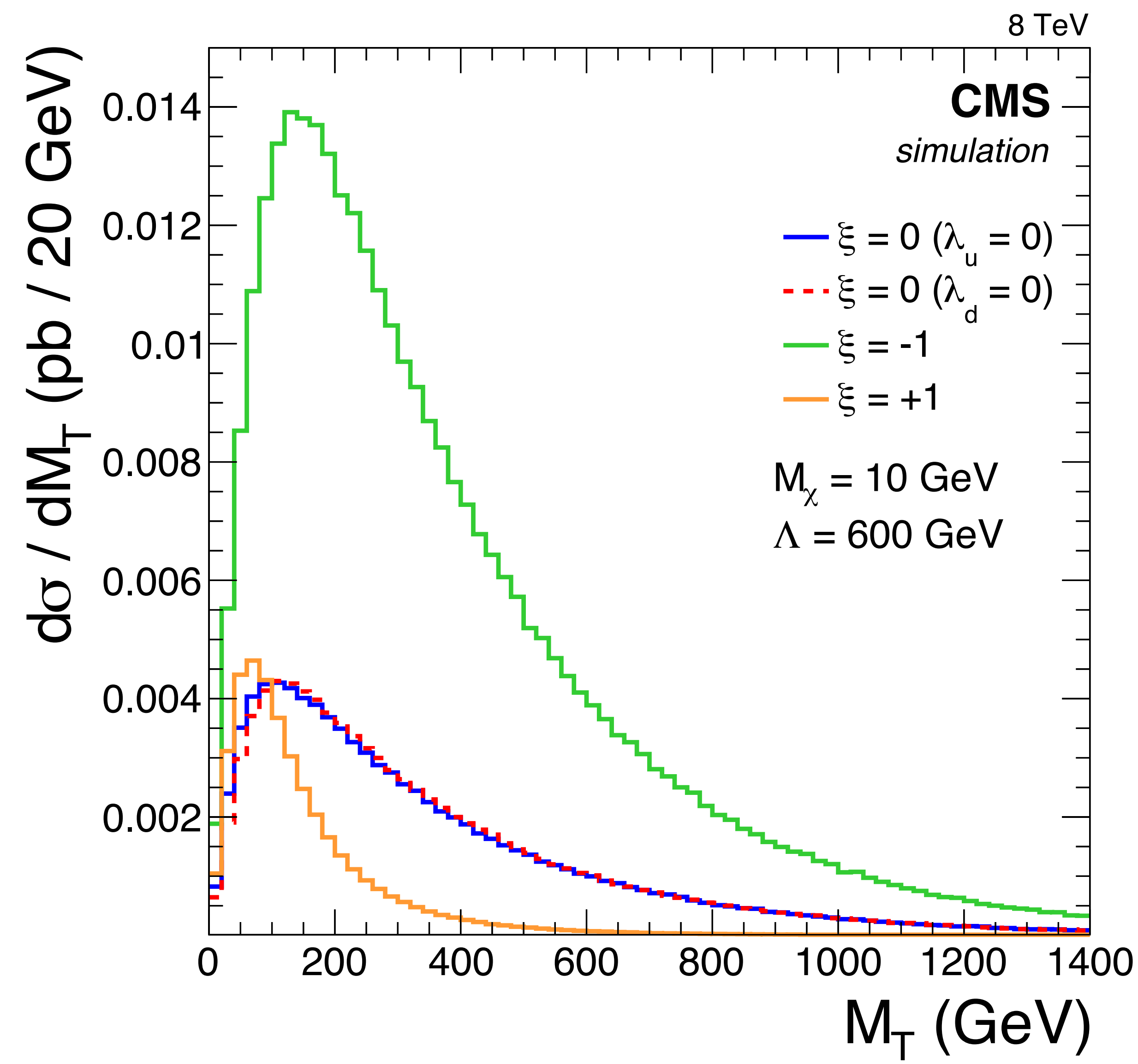
Typical production cross-sections (LO) for different operators

Values are given for the sum of three lepton flavors l = e, μ, τ

CMS

	Dark matter					
interference parameter ξ	1	0	-1	1	0	-1
Particle mass	$\sigma_{LO}\mathcal{B}$ (pb)			χ-proton cross section (pb)		
Spin-independent $\Lambda = 200$ GeV						
$M_\chi = 3$ GeV	3.1	7.4	26.5	3.6	1.6	0.4
$M_\chi = 100$ GeV	2.9	7.1	25.2	6.0	2.7	0.7
$M_\chi = 300$ GeV	1.9	4.8	17.2	6.1	2.7	0.7
$M_\chi = 500$ GeV	1.0	2.5	9.1	6.1	2.7	0.7
$M_\chi = 1000$ GeV	0.1	0.3	0.9	6.1	2.7	0.7
Spin-dependent $\Lambda = 200$ GeV						
$M_\chi = 3$ GeV	3.1	7.4	26.5	0.2	0.8	1.9
$M_\chi = 100$ GeV	2.5	6.4	22.8	0.3	1.4	3.2
$M_\chi = 300$ GeV	1.2	3.1	11.1	0.4	1.4	3.3
$M_\chi = 500$ GeV	0.5	1.2	4.3	0.4	1.4	3.3
$M_\chi = 1000$ GeV	0.03	0.1	0.2	0.4	1.4	3.3

Typical production cross-sections (LO) for different operators



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Backgrounds

ATLAS CMS

Process	Generator	Cross-section
$W \to l\nu$	Powheg	NNLO ($m_{l\nu}$ dependent)
	Pythia	NLO (m_T dependent)
$Z \to ll$	Powheg	NNLO (m_{ll} dependent)
	Powheg (e,μ) & Pythia (τ)	NLO
Top-quark pair Singe top-quark	Powheg & MC@NLO	NNLO
	MC@NLO & Powheg	NNLO
VV with *V*=*W*,*Z*	Sherpa	multi-leg LO
	Pythia	NLO
Multi-jet	Data-driven	N/A
	Data-driven (e) & Pythia (μ)	N/A & LO
γ+jet	Pythia (e-only)	LO

Systematics (ATLAS)

Summary of systematic uncertainties for $m_T > 1.5$ TeV
(except the luminosity uncertainty of 2.8%)
Typical systematics for the Sequential Standard Model W' with mass of 2 TeV

Source	ε_{sig} $e\nu$	ε_{sig} $\mu\nu$	N_{bkg} $e\nu$	N_{bkg} $\mu\nu$
$W' \to \ell\nu$				
Reconstruction and trigger efficiency	2.5%	4.1%	2.7%	4.1%
Lepton energy/momentum resolution	0.2%	1.4%	1.9%	18%
Lepton energy/momentum scale	1.2%	1.8%	3.5%	1.5%
E_T^{miss} scale and resolution	0.1%	0.1%	1.2%	0.5%
Beam energy	0.5%	0.5%	2.8%	2.1%
Multi-jet background	-	-	2.2%	3.4%
Monte Carlo statistics	0.9%	1.3%	8.5%	10%
Cross-section (shape/level)	2.9%	2.8%	18%	15%
Total	4.2%	5.6%	21%	27%

- Main contributions come from:
  - Lepton efficiency/scale and resolution and limited MC statistics (mainly for the background)
  - Cross-section (shape/level)
    - PDF choice, PDF+α_s variations, and scale variations

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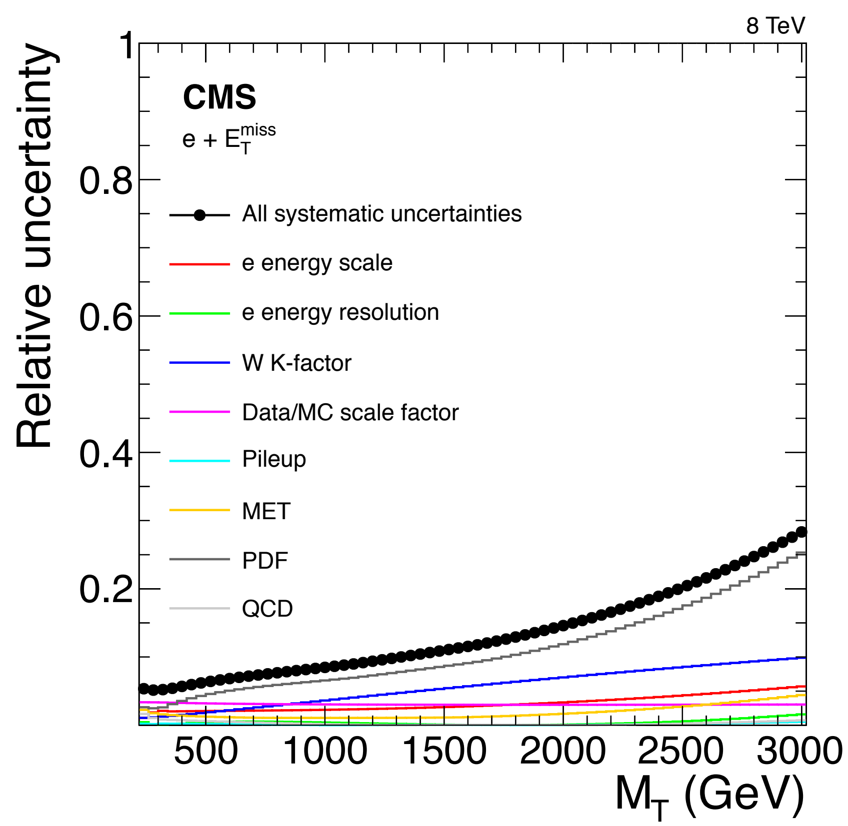
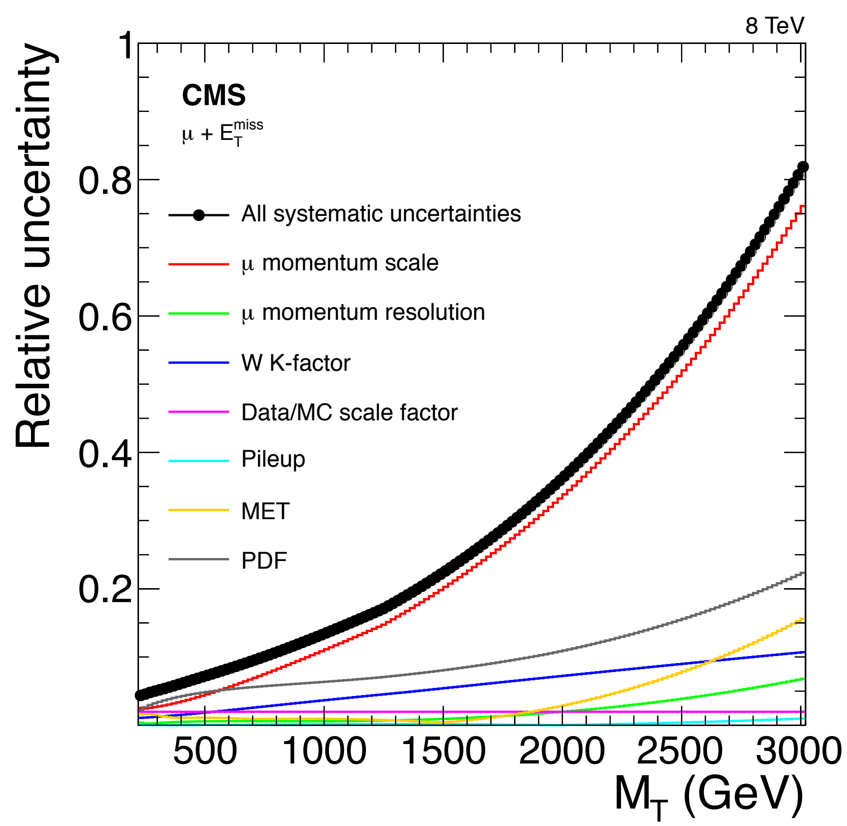
Systematics (CMS)

Summary of systematic uncertainties on the background
(except the luminosity uncertainty of 2.6%)





- Main contributions come from:
  - Lepton momentum scale (μ-channel)
  - PDF (PDF choice, PDF+α_s variations, and scale variations a la PDF4LHC)
  - W K-factor
    - Arises from additive vs multiplicative combination of QCD and EW higher-order corrections
    - Central value is the average of the two methods

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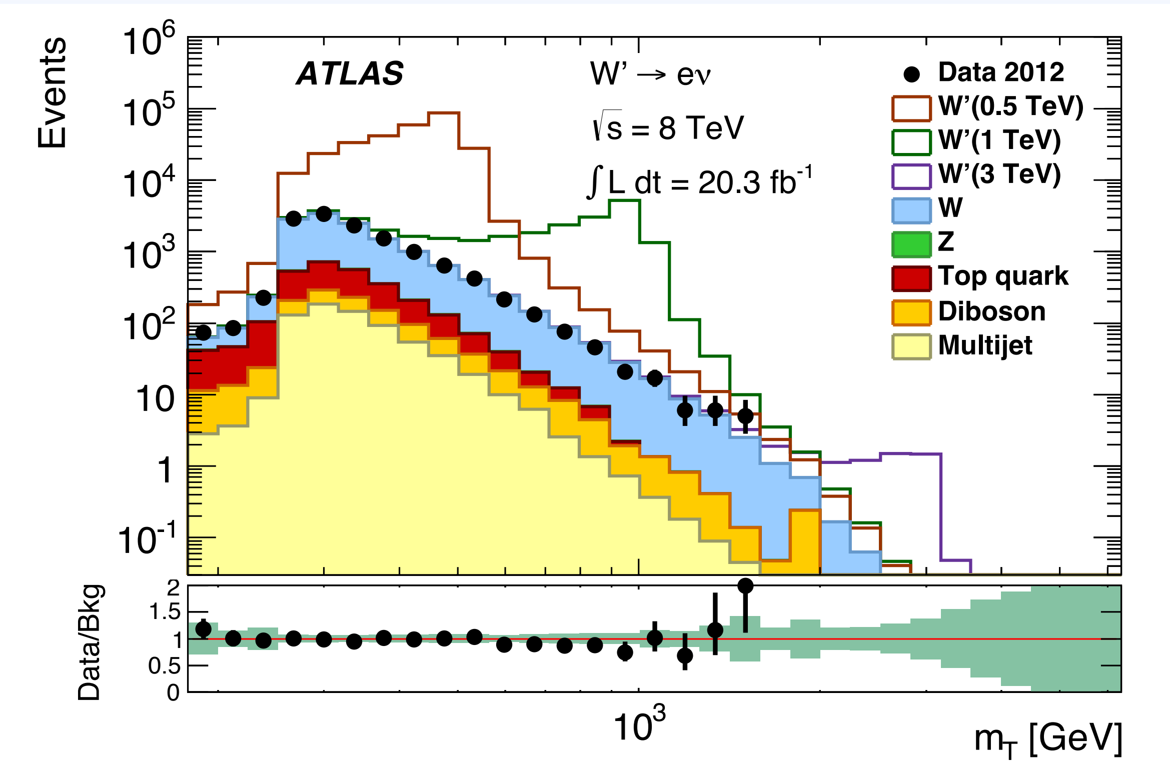
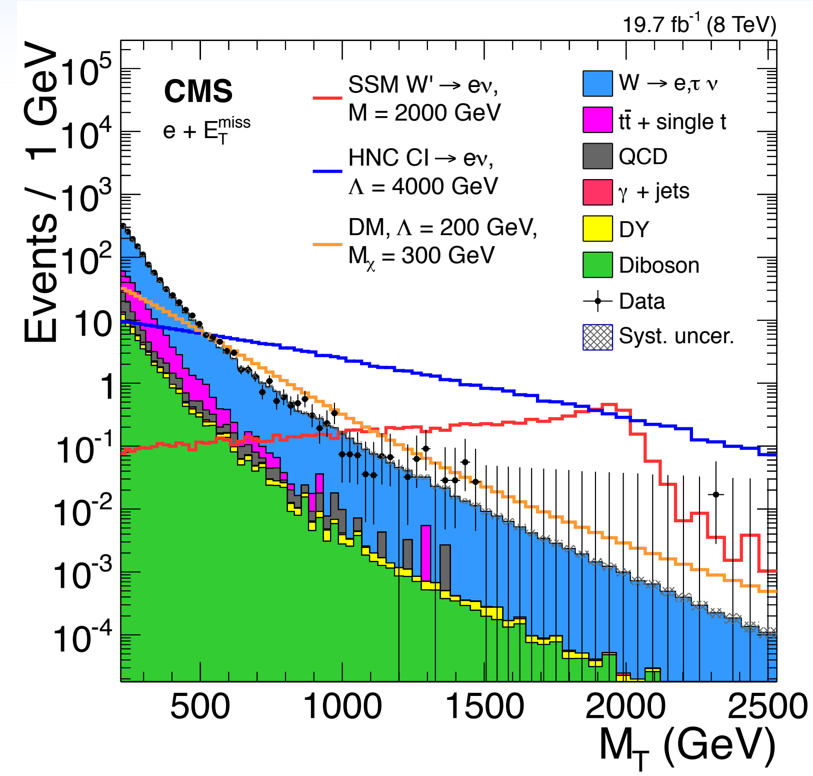
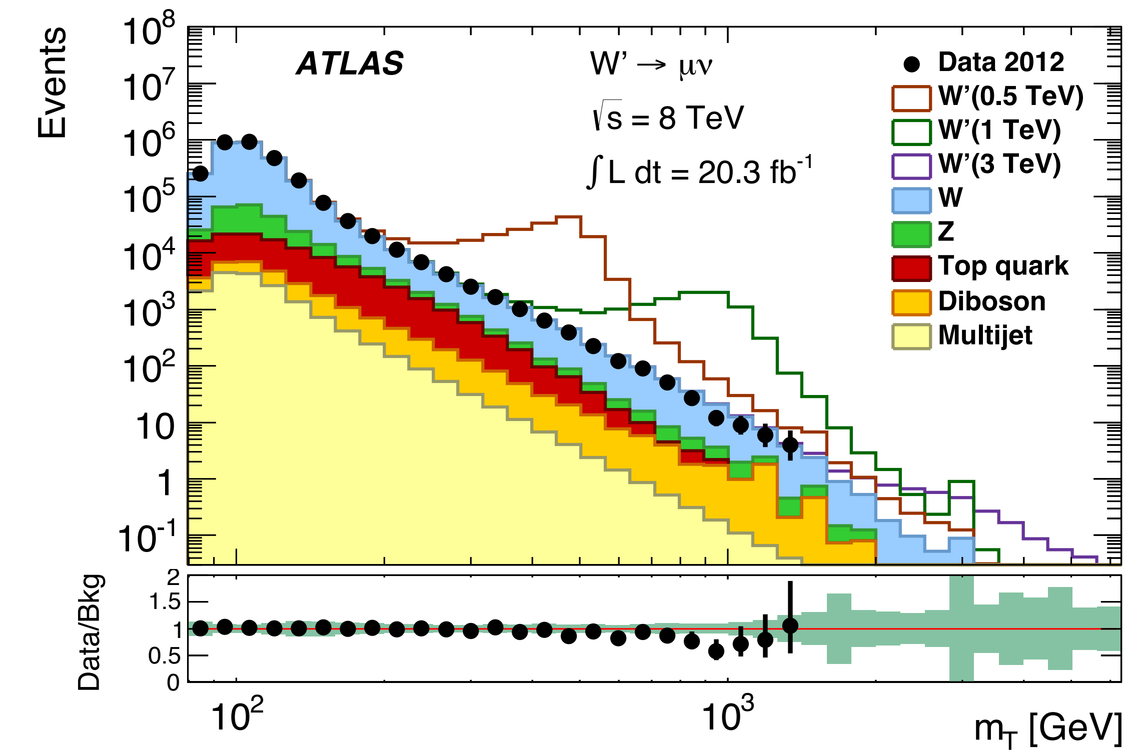
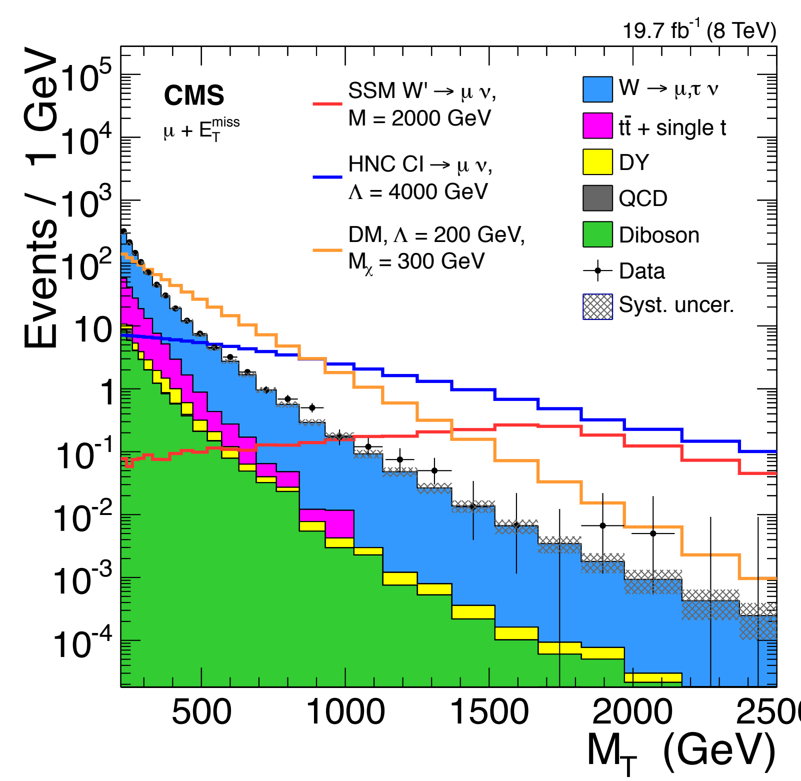
m_T Distributions









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Event Yields (ATLAS)

m_χ [GeV]	m_{Tmin} [GeV]	Channel	$\varepsilon_{\mathrm{sig}}$	N_{sig}		N_{bkg}	N_{obs}
D1 Operator							
1		$e\nu$	0.0294 ± 0.0044	87000 ± 13000			
		$\mu\nu$	0.0177 ± 0.0023	52500 ± 7000			
100		$e\nu$	0.0396 ± 0.0052	89000 ± 12000			
		$\mu\nu$	0.0252 ± 0.0033	56600 ± 7500			
200		$e\nu$	0.0484 ± 0.0057	65800 ± 7700			
	796	$\mu\nu$	0.0293 ± 0.0034	39900 ± 4600	$e\nu$	116 ± 15	101
400		$e\nu$	0.0709 ± 0.0071	30900 ± 3100	$\mu\nu$	84 ± 10	58
		$\mu\nu$	0.0398 ± 0.0041	17300 ± 1800			
1000		$e\nu$	0.0989 ± 0.0100	1070 ± 110			
		$\mu\nu$	0.0621 ± 0.0068	673 ± 73			
1300		$e\nu$	0.0964 ± 0.0095	138 ± 14			
		$\mu\nu$	0.0522 ± 0.0048	75.1 ± 6.9			
D5d Operator							
1		$e\nu$	0.0148 ± 0.0016	7230 ± 800			
		$\mu\nu$	0.0080 ± 0.0011	3890 ± 530			
100		$e\nu$	0.0158 ± 0.0018	7580 ± 850			
		$\mu\nu$	0.0096 ± 0.0012	4600 ± 580			
200		$e\nu$	0.0147 ± 0.0015	5850 ± 610			
	597	$\mu\nu$	0.0086 ± 0.0011	3420 ± 430	$e\nu$	456 ± 45	414
400		$e\nu$	0.0190 ± 0.0020	4220 ± 440	$\mu\nu$	305 ± 30	255
		$\mu\nu$	0.0113 ± 0.0013	2500 ± 300			
1000		$e\nu$	0.0281 ± 0.0025	450 ± 41			
		$\mu\nu$	0.0177 ± 0.0019	283 ± 30			
1300		$e\nu$	0.0291 ± 0.0028	89.3 ± 8.5			
		$\mu\nu$	0.0167 ± 0.0018	51.1 ± 5.4			

m_χ [GeV]	m_{Tmin} [GeV]	Channel	$\varepsilon_{\mathrm{sig}}$	N_{sig}		N_{bkg}	N_{obs}
D5c Operator							
1		$e\nu$	0.0737 ± 0.0047	30.3 ± 1.9			
		$\mu\nu$	0.0435 ± 0.0034	17.9 ± 1.4			
100		$e\nu$	0.0798 ± 0.0050	31.0 ± 1.9			
		$\mu\nu$	0.0437 ± 0.0034	17.0 ± 1.3			
200		$e\nu$	0.0762 ± 0.0049	25.1 ± 1.6			
	843	$\mu\nu$	0.0461 ± 0.0034	15.2 ± 1.1	$e\nu$	86 ± 12	79
400		$e\nu$	0.0857 ± 0.0055	16.2 ± 1.0	$\mu\nu$	65.5 ± 8.5	40
		$\mu\nu$	0.0532 ± 0.0040	10.0 ± 0.8			
1000		$e\nu$	0.0987 ± 0.0091	1.28 ± 0.12			
		$\mu\nu$	0.0636 ± 0.0057	0.824 ± 0.074			
1300		$e\nu$	0.1010 ± 0.0095	0.240 ± 0.023			
		$\mu\nu$	0.0589 ± 0.0057	0.140 ± 0.014			
D9 Operator							
1		$e\nu$	0.0851 ± 0.0053	55.5 ± 3.5			
		$\mu\nu$	0.0517 ± 0.0035	33.8 ± 2.3			
100		$e\nu$	0.0950 ± 0.0056	55.8 ± 3.3			
		$\mu\nu$	0.0529 ± 0.0038	31.1 ± 2.3			
200		$e\nu$	0.1040 ± 0.0062	48.9 ± 2.9			
	843	$\mu\nu$	0.0553 ± 0.0039	26.0 ± 1.8	$e\nu$	86 ± 12	79
400		$e\nu$	0.1030 ± 0.0067	25.5 ± 1.6	$\mu\nu$	65.5 ± 8.5	40
		$\mu\nu$	0.0578 ± 0.0042	14.3 ± 1.0			
1000		$e\nu$	0.1070 ± 0.0092	1.63 ± 0.14			
		$\mu\nu$	0.0615 ± 0.0055	0.944 ± 0.084			
1300		$e\nu$	0.1020 ± 0.0100	0.285 ± 0.029			
		$\mu\nu$	0.0573 ± 0.0056	0.160 ± 0.016			

- Three main signal regions are used
- No statistically significant difference between the expected background and observation
- Expected signal yields are also shown for a selected set of mass scales
    - 10 GeV for D1, 100 GeV for D5d and 1 TeV for D5c and D9

arxiv:1408.2745

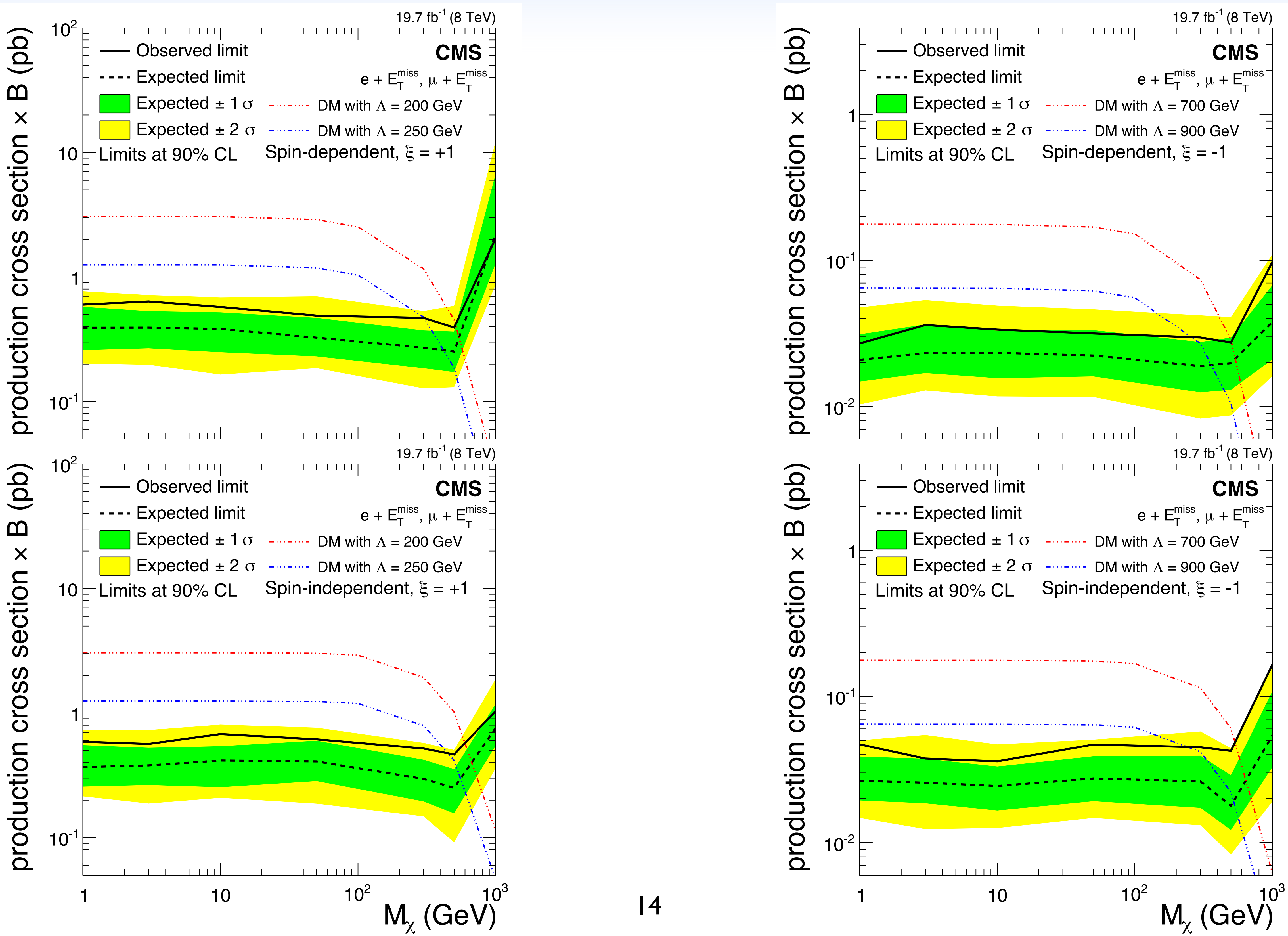
Event Yields (CMS)

		$M_T > 1.0$ TeV	$M_T > 1.5$ TeV	$M_T > 2.0$ TeV
Electron channel				
Data		24	1	1
SM Background		$26.0^{+2.5}_{-2.5}$	$2.02^{+0.26}_{-0.25}$	$0.207^{+0.036}_{-0.033}$
W′	$M_{W'} = 2.5$ TeV	$50.5^{+7.5}_{-7.5}$	$38.8^{+6.1}_{-6.1}$	$24.0^{+3.9}_{-3.9}$
	$M_{W'} = 3$ TeV	$10.3^{+2.1}_{-2.1}$	$7.8^{+1.9}_{-1.9}$	$5.8^{+1.5}_{-1.5}$
HNC-CI	$\Lambda = 4$ TeV	1120^{+110}_{-110}	368^{+47}_{-47}	105^{+19}_{-19}
	$\Lambda = 9$ TeV	$43.4^{+4.3}_{-4.3}$	$14.3^{+1.8}_{-1.8}$	$4.08^{+0.75}_{-0.75}$
DM vector-coupling, $M_\chi = 50$ GeV, $\Lambda = 300$	$\xi = +1$	$0.402^{+0.050}_{-0.050}$	$0.0346^{+0.0072}_{-0.0070}$	$0.0033^{+0.0010}_{-0.0010}$
	$\xi = 0$	$6.8^{+1.5}_{-1.5}$	$1.25^{+0.42}_{-0.42}$	$0.22^{+0.11}_{-0.11}$
	$\xi = -1$	$27.4^{+5.9}_{-5.9}$	$5.0^{+1.7}_{-1.7}$	$0.89^{+0.44}_{-0.43}$
Muon channel				
Data		35	3	1
SM Background		$26.1^{+4.4}_{-4.3}$	$2.35^{+0.70}_{-0.60}$	$0.33^{+0.16}_{-0.12}$
W′	$M_{W'} = 2.5$ TeV	$48.7^{+4.1}_{-4.1}$	$36.1^{+2.8}_{-3.1}$	$20.3^{+3.0}_{-3.4}$
	$M_{W'} = 3$ TeV	$9.88^{+0.99}_{-0.98}$	$7.33^{+0.64}_{-0.65}$	$5.00^{+0.16}_{-0.39}$
HNC-CI	$\Lambda = 9$ TeV	$42.4^{+3.8}_{-3.8}$	$13.8^{+2.0}_{-2.0}$	$4.47^{+0.90}_{-0.94}$
	$\Lambda = 4$ TeV	1091^{+97}_{-98}	356^{+50}_{-52}	115^{+23}_{-24}
DM vector-coupling, $M_\chi = 50$ GeV, $\Lambda = 300$	$\xi = +1$	$0.271^{+0.070}_{-0.067}$	$0.0151^{+0.0061}_{-0.0056}$	$0.00088^{+0.00051}_{-0.00043}$
	$\xi = 0$	$6.7^{+1.6}_{-1.6}$	$1.43^{+0.54}_{-0.51}$	$0.31^{+0.17}_{-0.15}$
	$\xi = -1$	$27.1^{+6.6}_{-6.5}$	$5.8^{+2.2}_{-2.1}$	$1.25^{+0.68}_{-0.60}$

- Yields are shown for a selection of M_T thresholds
- No statistically significant difference between the expected background and observation
- Expected signal yields are also shown for a selected mass scale and M_χ

arxiv:1408.2745

Limits on σB



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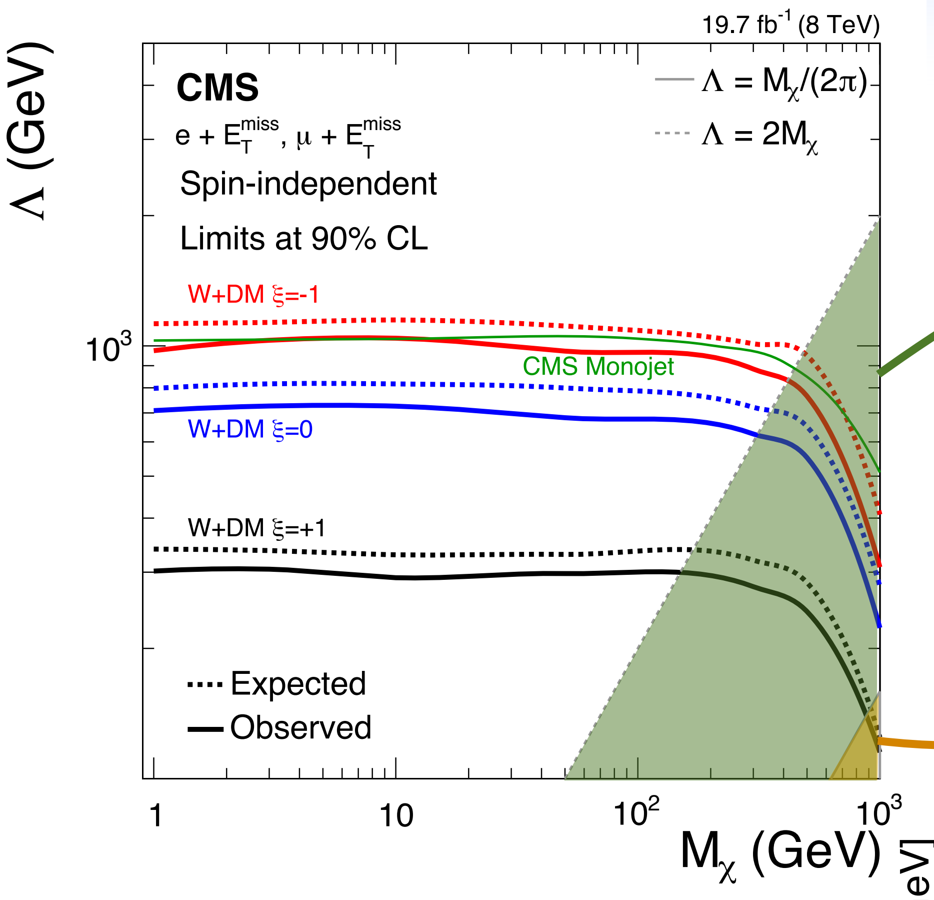
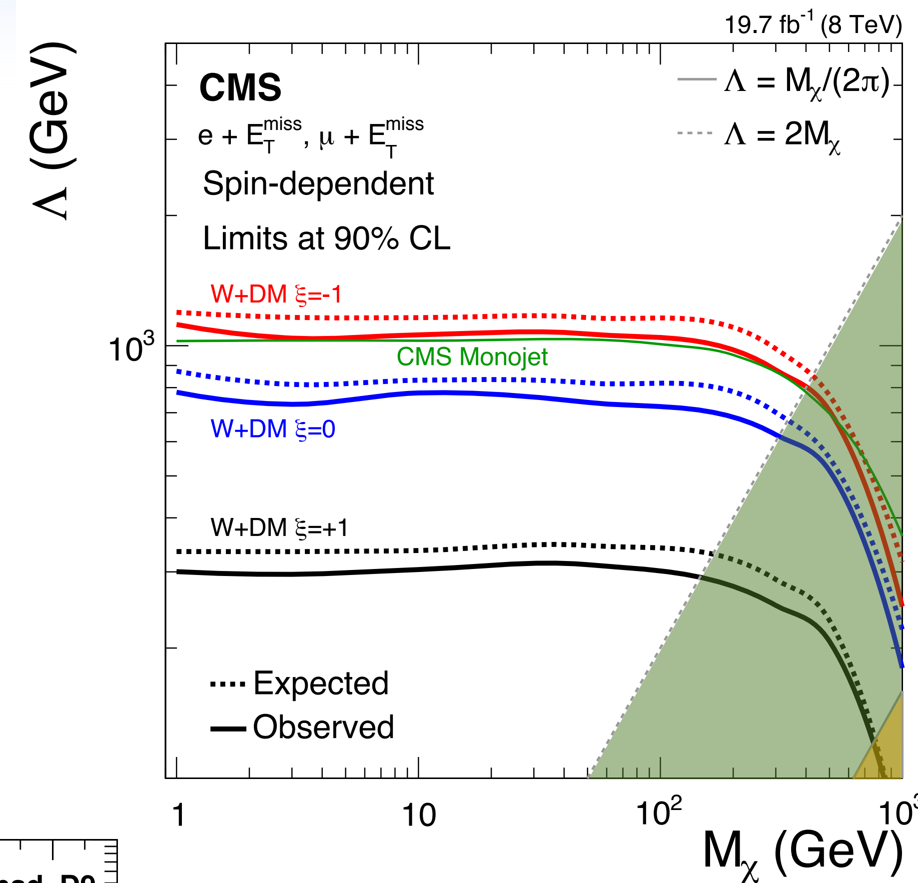
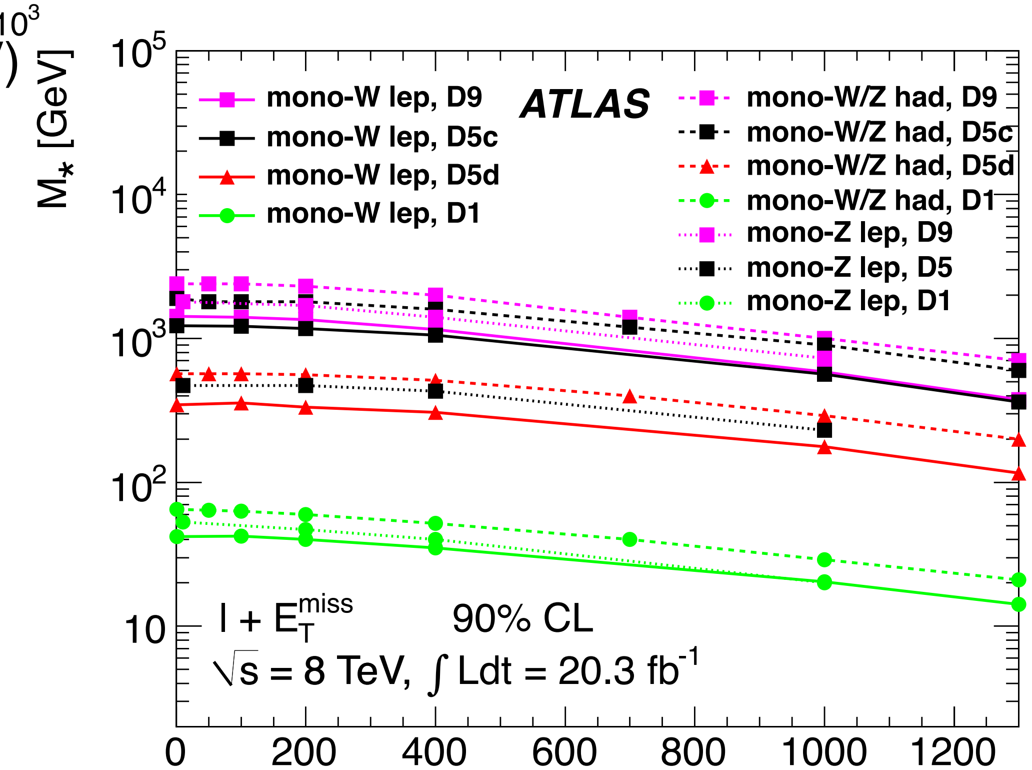
Limits on Λ



$\Lambda < 2M_\chi$

$\Lambda < M_\chi/(2\pi)$





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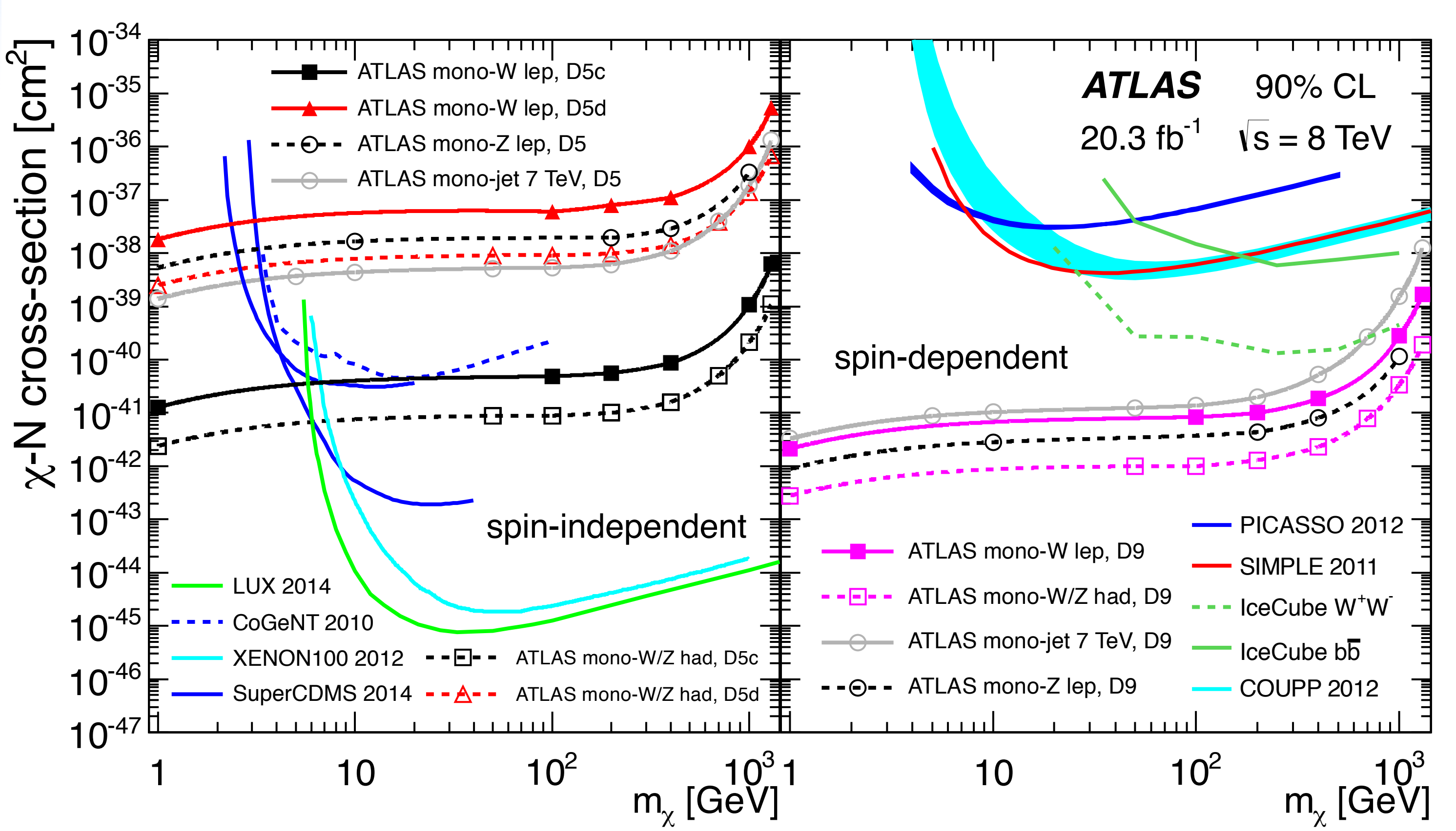
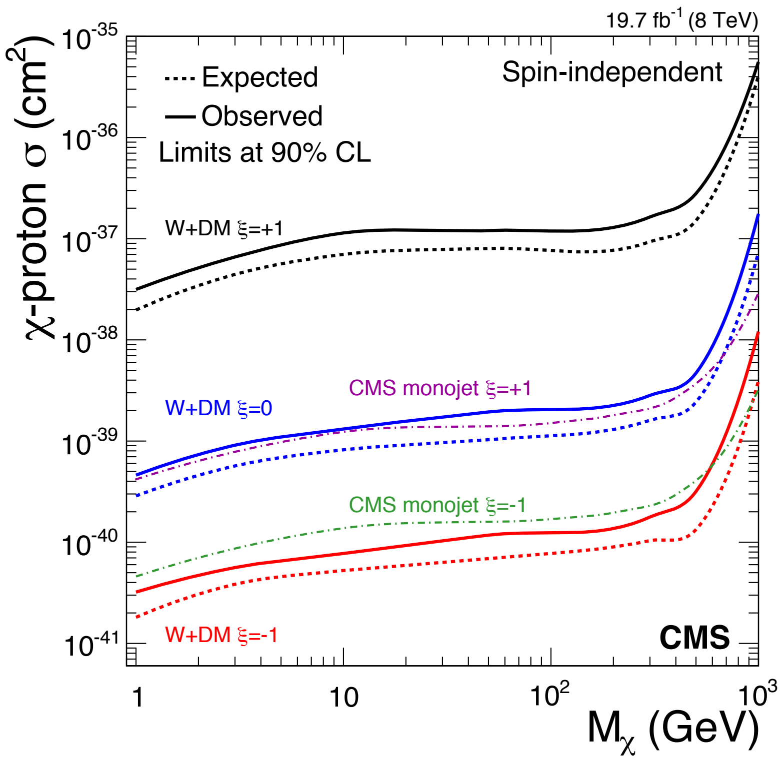
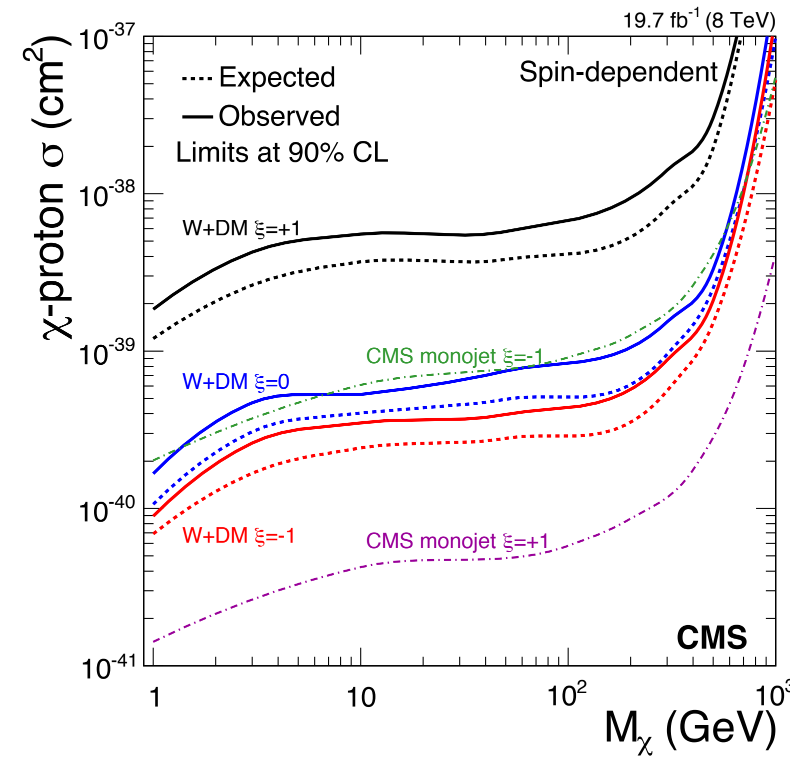
Limits on χ-N σ





- Strong limits at low m_χ compared to direct detection experiments
- Complementary to other collider searches (mono-*W*/*Z* hadronic and mono-*Z* leptonic)



Conclusions

- A summary of ATLAS and CMS searches for DM pair-prod. in mono-lepton final state

- Results are based on the latest 8 TeV *pp* collision data w/ $L_{int} \sim 20\ fb^{-1}$
  - ATLAS : JHEP **09** (2014) 037, http://arxiv.org/abs/1407.7494
  - CMS : Submitted to PRD, http://arxiv.org/abs/1408.2745

- No significant excess above Standard Model expectations is observed in either search

- Looking forward to the upcoming 13 TeV *pp* collision data to see a hint for new physics