Mono-W/Z searches in ATLAS and CMS

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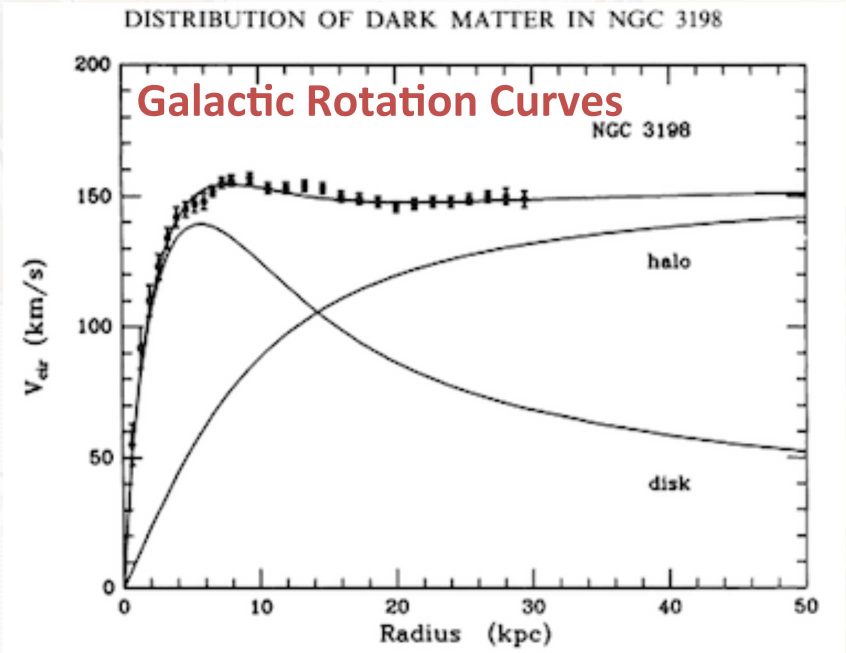
for the ATLAS and CMS collaborations

Dark Matter

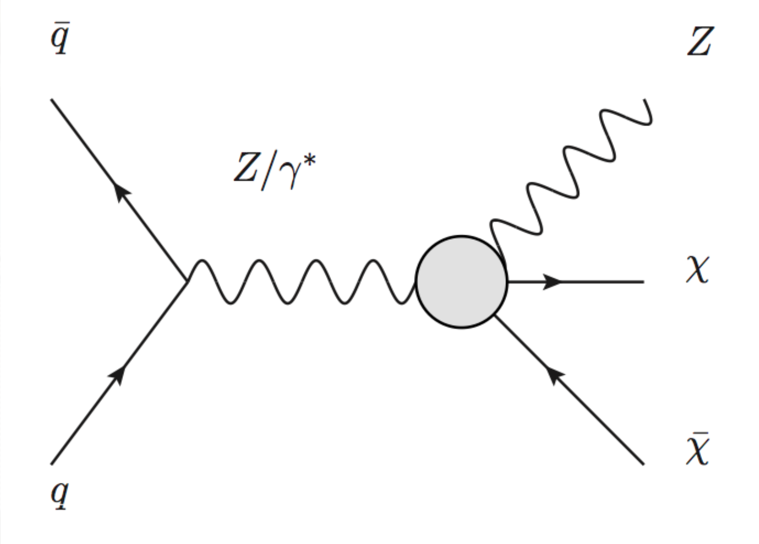
- After Higgs discovery, dark matter is the best motivated new physics search at the LHC
- Astrophysical observations have indicated the existence of a new type of matter, but never been directly observed
  - Galactic rotation curves
  - Orbits in galaxy clusters
  - Gravitational lensing
- Could be produced at the LHC: stable, weakly interacting, neutral particle



Astrophys. J. Part I, v295
1985, pp305-313

Outline

- Dark matter using W/Z+Missing Transverse Energy (MET):
  - Produced through qqχχ or ZZχχ interaction. Heavy particle mediates the interaction
  - For mono-W constructive and destructive interference in the qqχχ interaction is considered
- **mono-W/Z (ATLAS)**
  - **Leptonic decay – only mono-Z**
  - **Hadronic decay – mono-W/Z**
- **mono-W leptonic (CMS)**

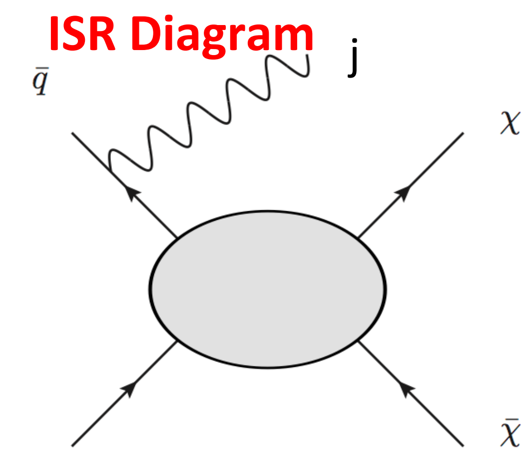


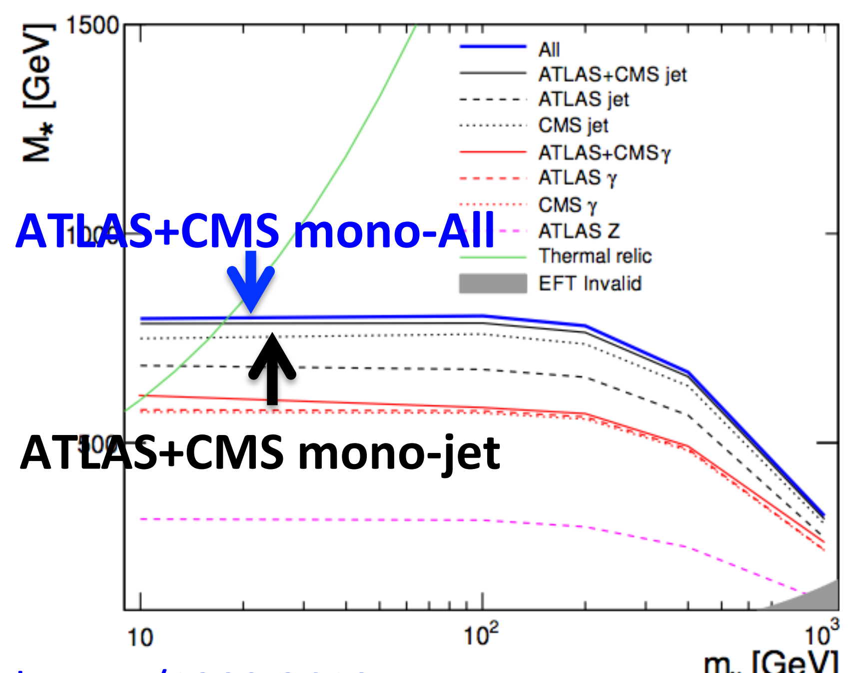
mono-Z leptonic

ATLAS: 1404.0051, PRD

Production of DM at colliders

- Need a visible particle in the final state
- qqχχ ISR EFT is very similar to direct detection
  - Visible particle is emitted as ISR from the quarks
- Strong ISR are dominant → mono-jet is the most sensitive to diagram
  - Mono-photon, mono-W/Z add only a small portion of sensitivity for this diagram
- But there are other diagrams

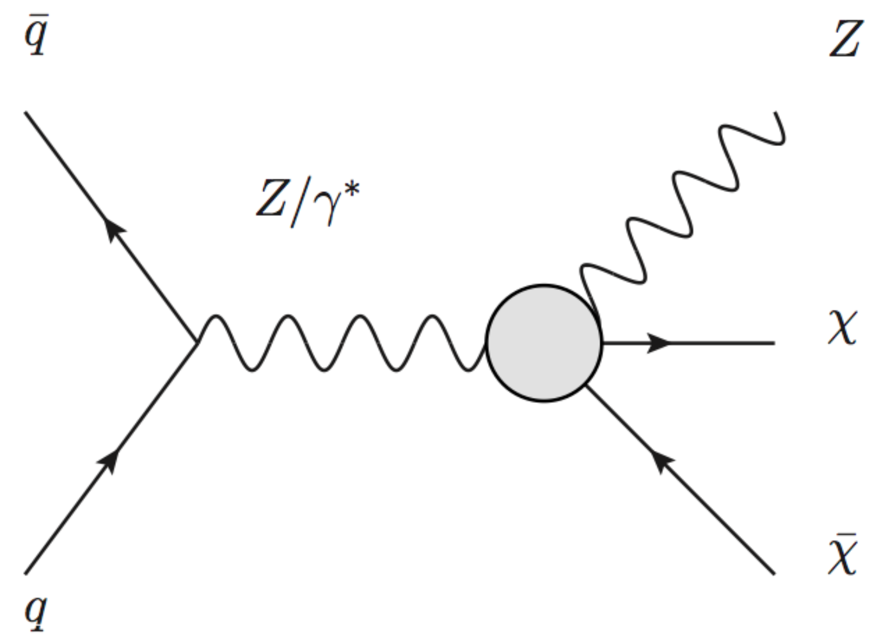




[hep-ex/1302.3619](hep-ex/1302.3619)

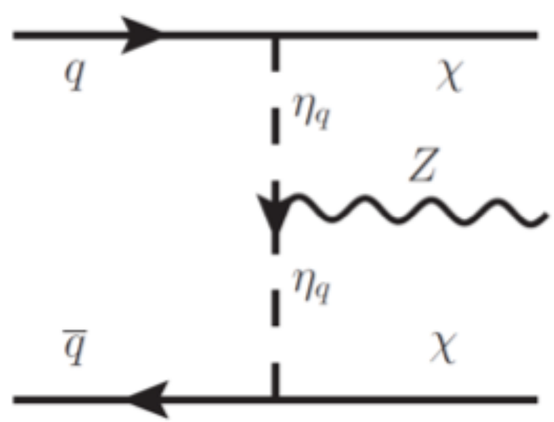
Production of DM in the mono-Z channel

- What if dark matter interacts primarily through electroweak bosons?
- mono-W/Z will be the most sensitive channels to dark matter
- First collider limits on this model
- Separate UV complete model:
  - Additional model with a scalar mediator η
- See Andrea de Simone and Thomas Jacques' talk for the limitations of EFTs



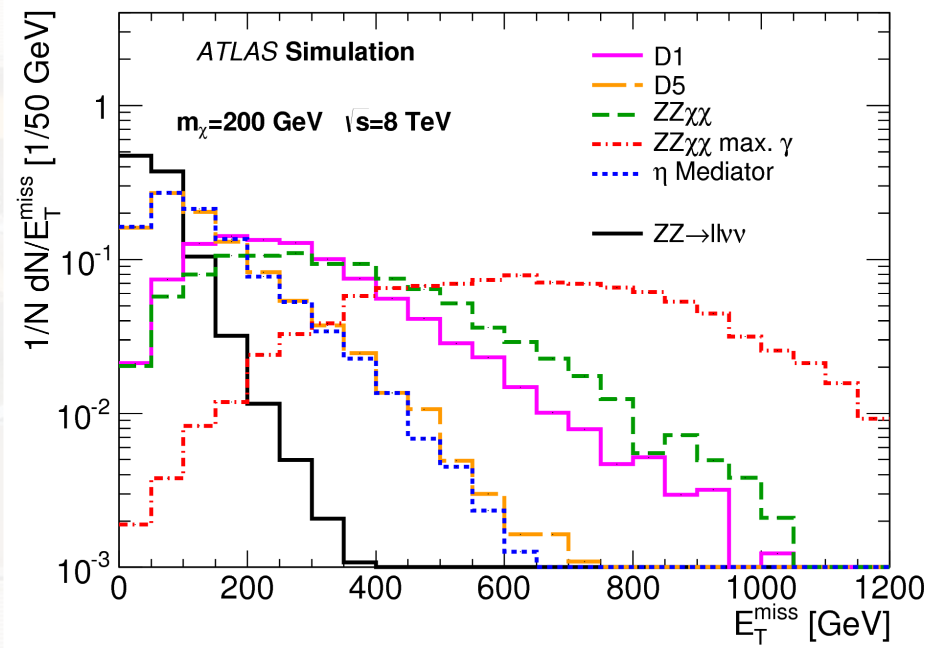
[hep-ex/1212.3352](hep-ex/1212.3352). L.Carpenter, AN, C.Shimmin, T.Tait, D.Whiteson

UV complete model



Signal Samples

- We have many types of signal samples which have different MET behavior.
- ISR EFT
  - D1: Scalar, spin-independent
  - D5: Vector in Lorentz sense, spin-independent
  - D9: Tensor, spin-dependent
- ZZχχ EFT (DM directly interacts with pairs of EWK bosons)
  - 5 dimensional
  - 7 dimension w/ maximal and minimal γ^* contribution
- UV complete: η mediator theory



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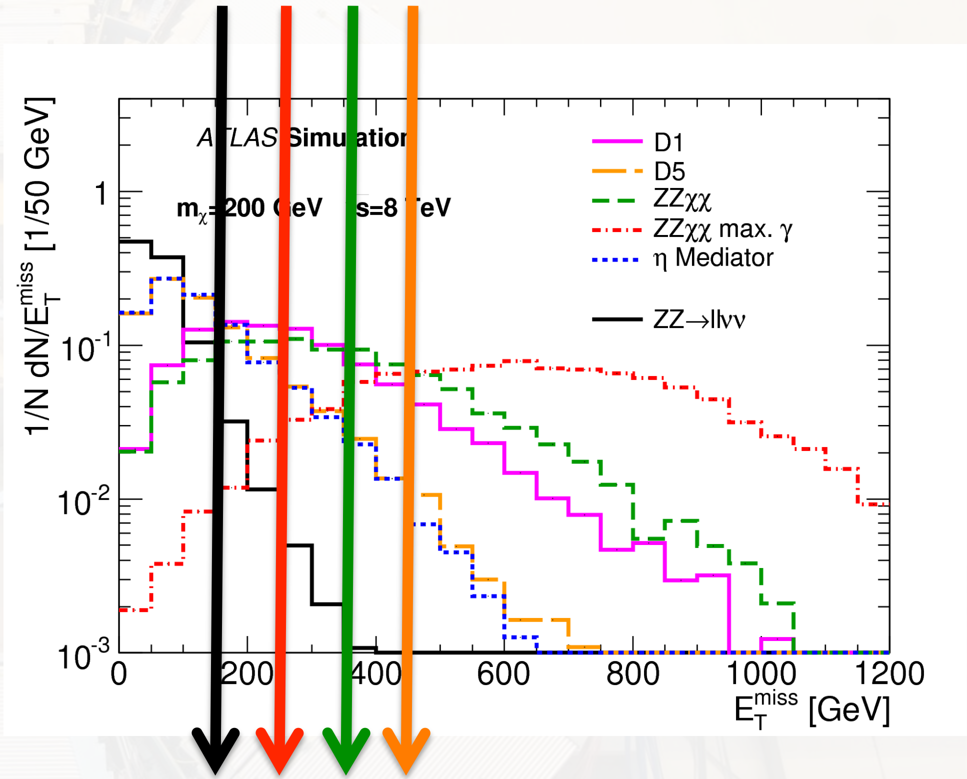
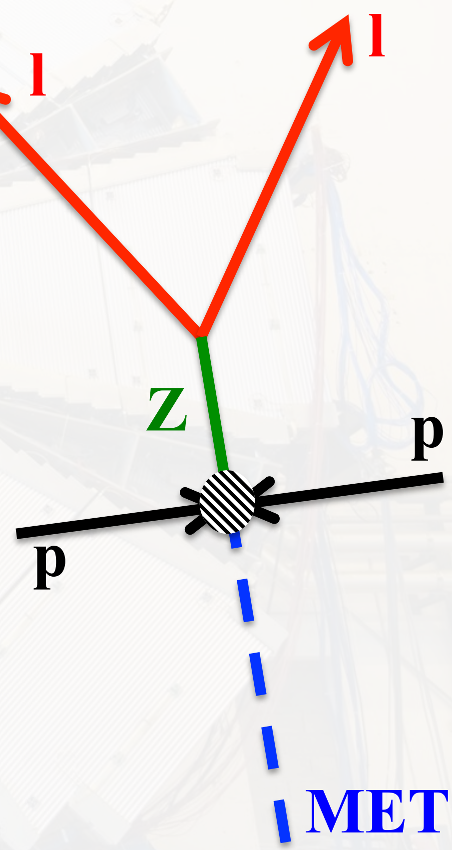


Four different signal regions with different MET thresholds

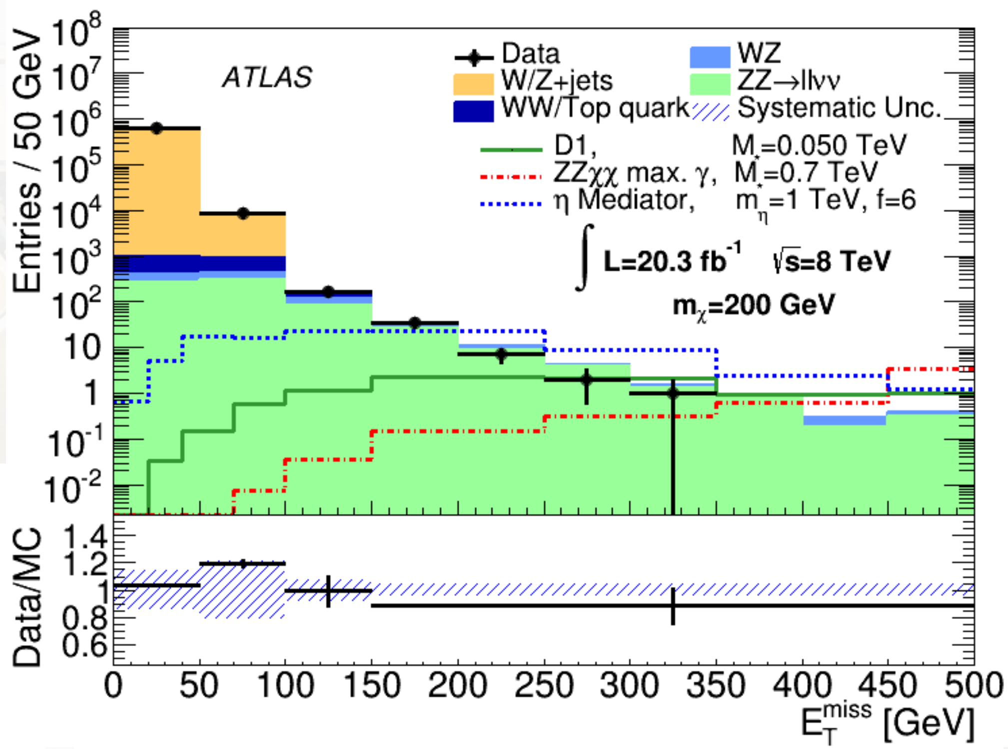
Analysis Strategy

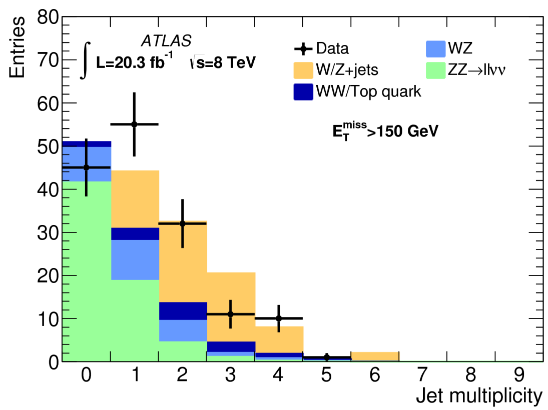
- dilepton + MET channel
  - 2 oppositely-charged same-flavor leptons
  - 15 GeV Z boson mass window (76-106 GeV)
- EFT operators have different MET shapes. Four signal regions
  - MET>150, 250, 350, and 450 GeV
- Reduce background
  - Jet veto
  - $\Delta\phi(Z,MET)>2.5$
  - $|MET-p_T^{ll}|/p_T^{ll} < 0.5$ (fractional p_T difference)
  - Veto events with an extra lepton
  - $|\eta^{ll}|<2.5$

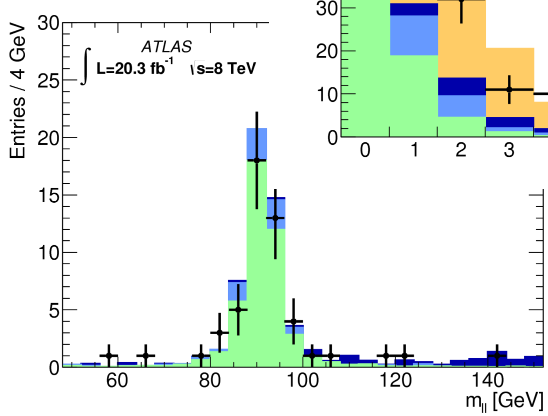


Kinematics

- 2012 data: 20.3fb^{-1}, observations are statistically consistent with background expectation
- 0 events in the highest MET signal region

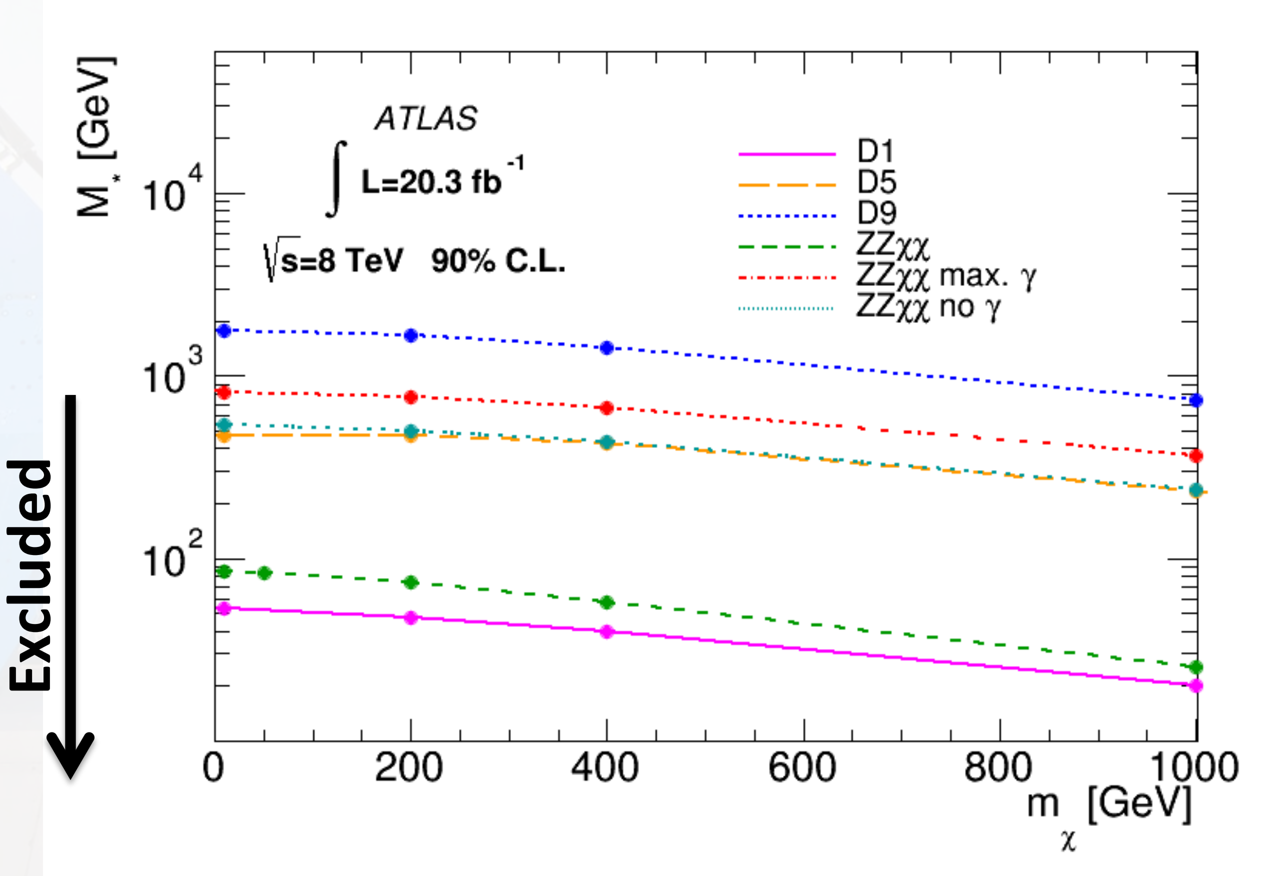






Process	E_T^{miss} threshold [GeV] 150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z+jets	0.1 ± 0.1	–	–	–
W+jets	0.5 ± 0.3	–	–	–
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0

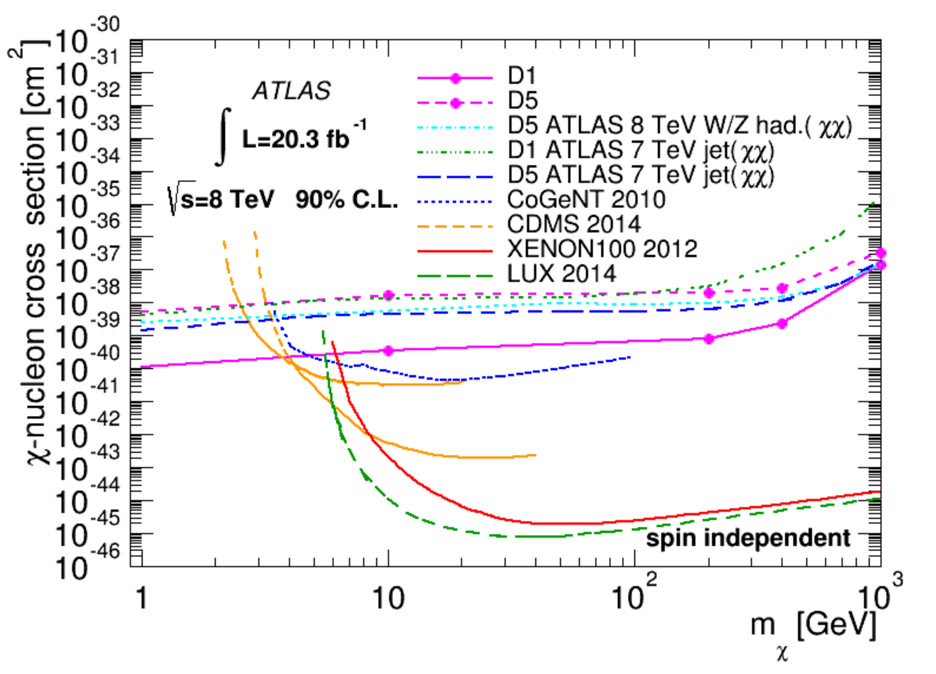
Collider limits

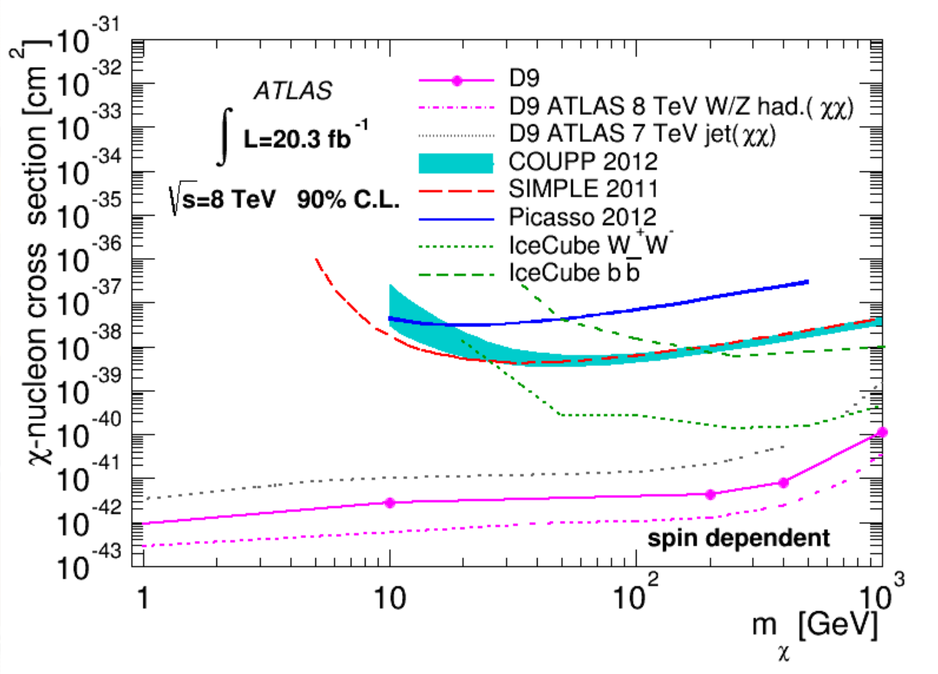


- $M^* \rightarrow$ inversely proportional to coupling
- Region below line excluded

- Limits range over an order of magnitude depending on the operator under consideration
  - Free parameters: m_χ, scale M*

Direct detection limits

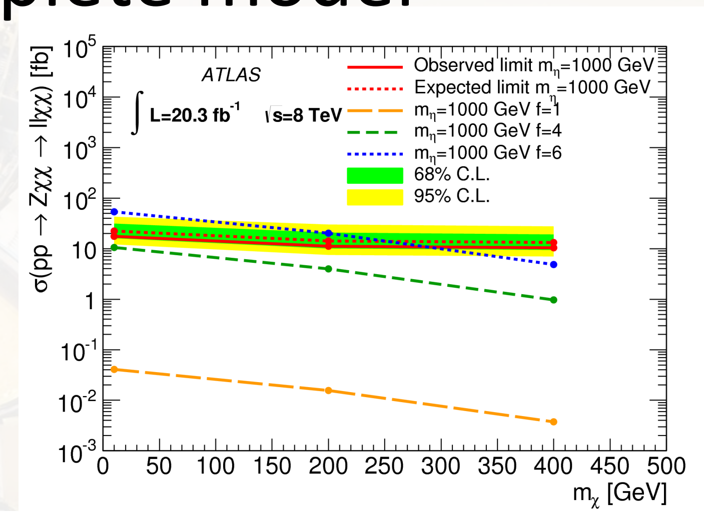


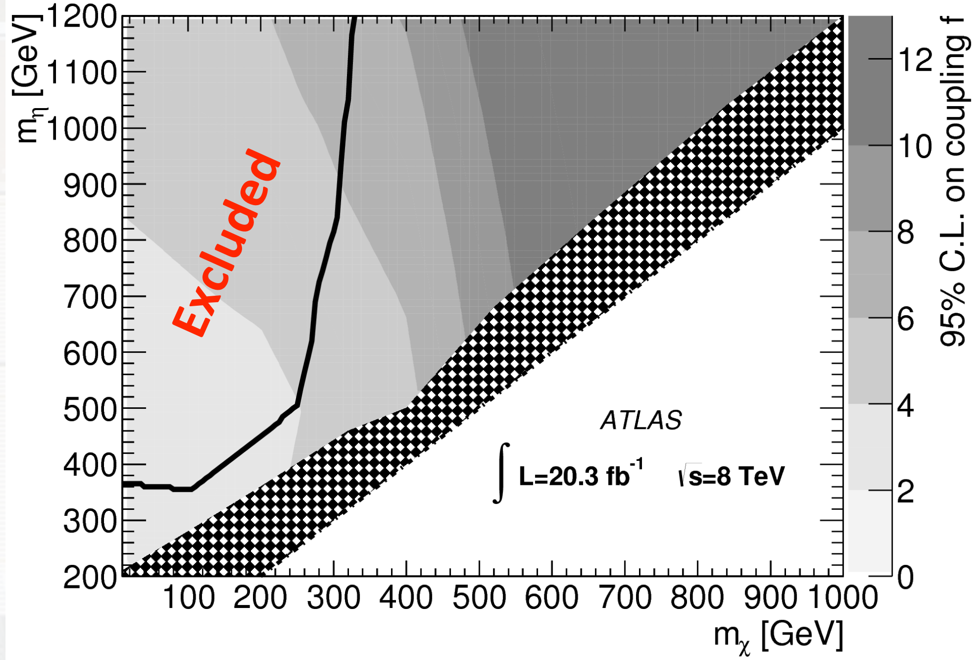


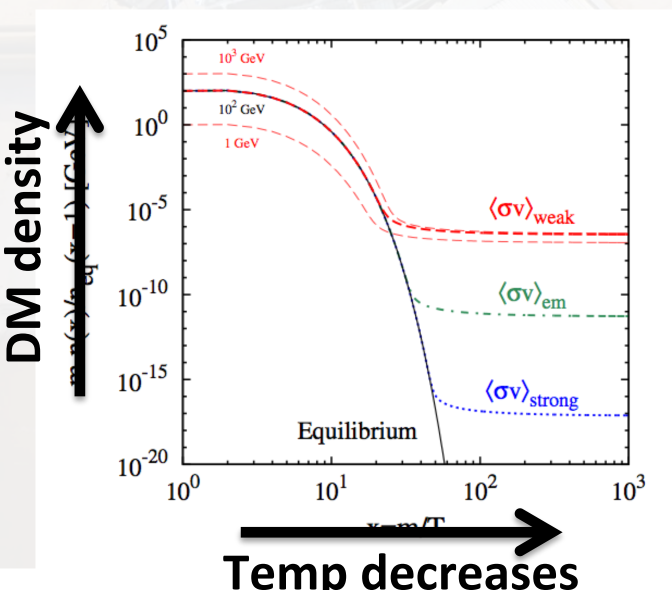
- Transform limits on the EFT scale, M*, into direct detection cross sections
- Complementary to the direct detection searches

Limits on UV complete model

- UV complete model has more parameters than the EFT
  - coupling, f
  - mass of mediator, η
  - mass of dark matter m_χ
- Compared *upper limit* from collider to *lower limit* from relic density
- Certain points have a *upper limit* higher than *lower limit* from relic density: excluded





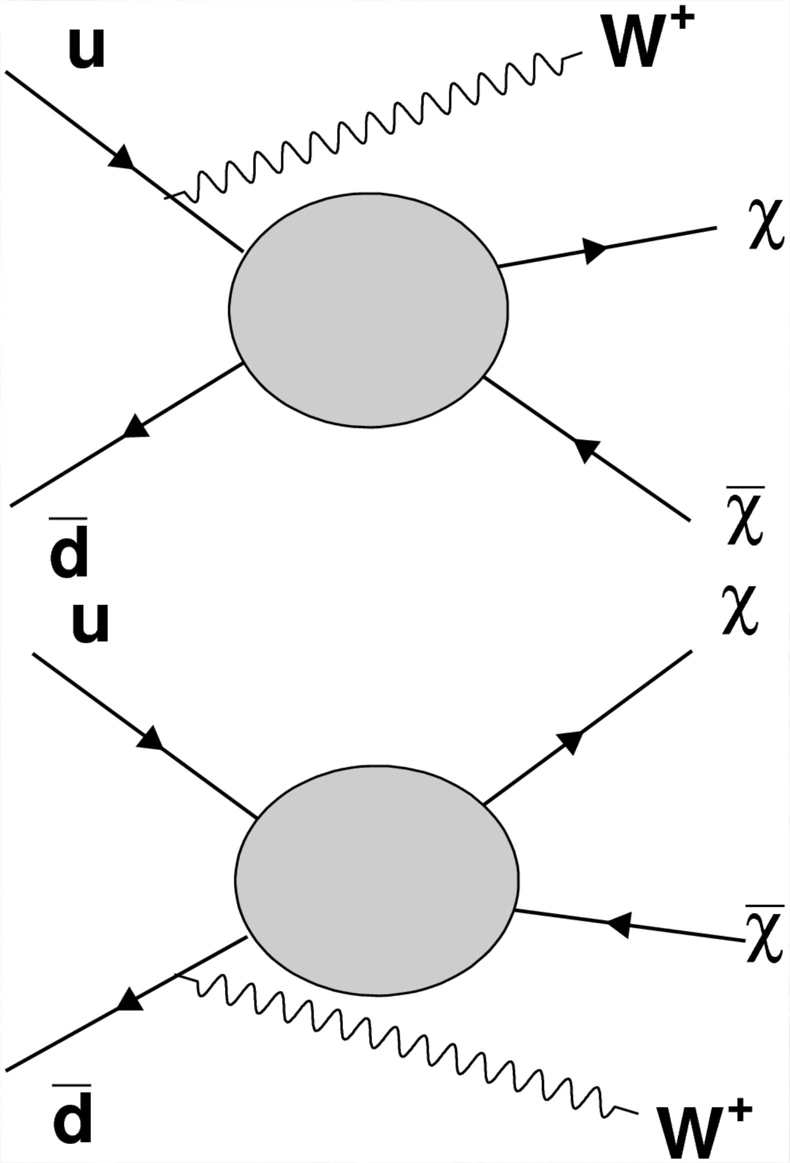


mono-W/Z hadronic

ATLAS: 1309.4017, PRL

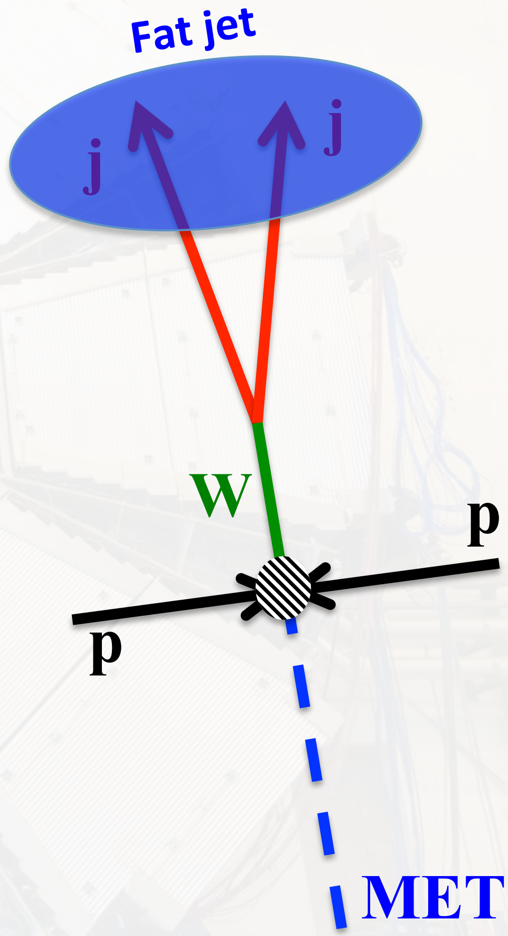
Production of DM in the Mono-W channel

- Mono-W is the dominant production mechanism of DM if the up and down couplings have opposite signs
  - Interfere constructively
  - C(u)=-C(d)
- Previous mono-X searches consider the couplings to be equal
  - C(u)=C(d)
- If DM is discovered at the LHC mono-W allows the opportunity to determine coupling to up- and down-quarks



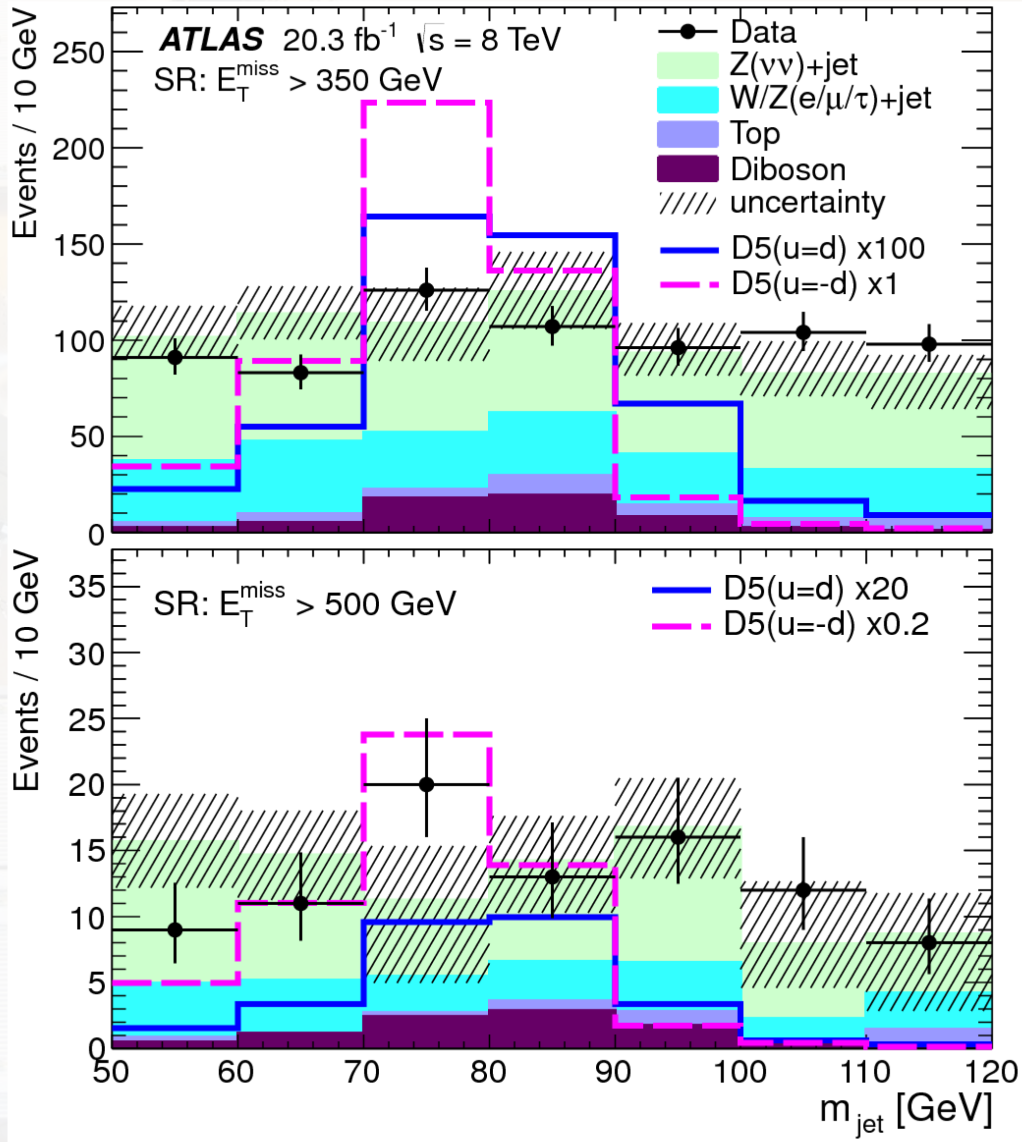
Mono-Fat-jet

- Fat-jet + MET channel
  - 1 large radius jet, r=1.2
  - p_T>250 GeV
  - 50 GeV<m_{jet}<120 GeV
- EFT operators have different MET shapes. Two signal regions
  - MET>350 and 500 GeV
- Reduce background
  - $\sqrt{y} = \min(p_{T1}, p_{T2})\Delta R/m_{\text{jet}}$ >0.4
  - Reject events with more than 1 narrow jet (r=0.4) with p_T>40 GeV and $|\eta|$<4.5
  - Reject events with any narrow jets with $\Delta\phi$(MET,jet)<0.4
  - Veto events with electrons, muons, or photons with p_T>10 GeV

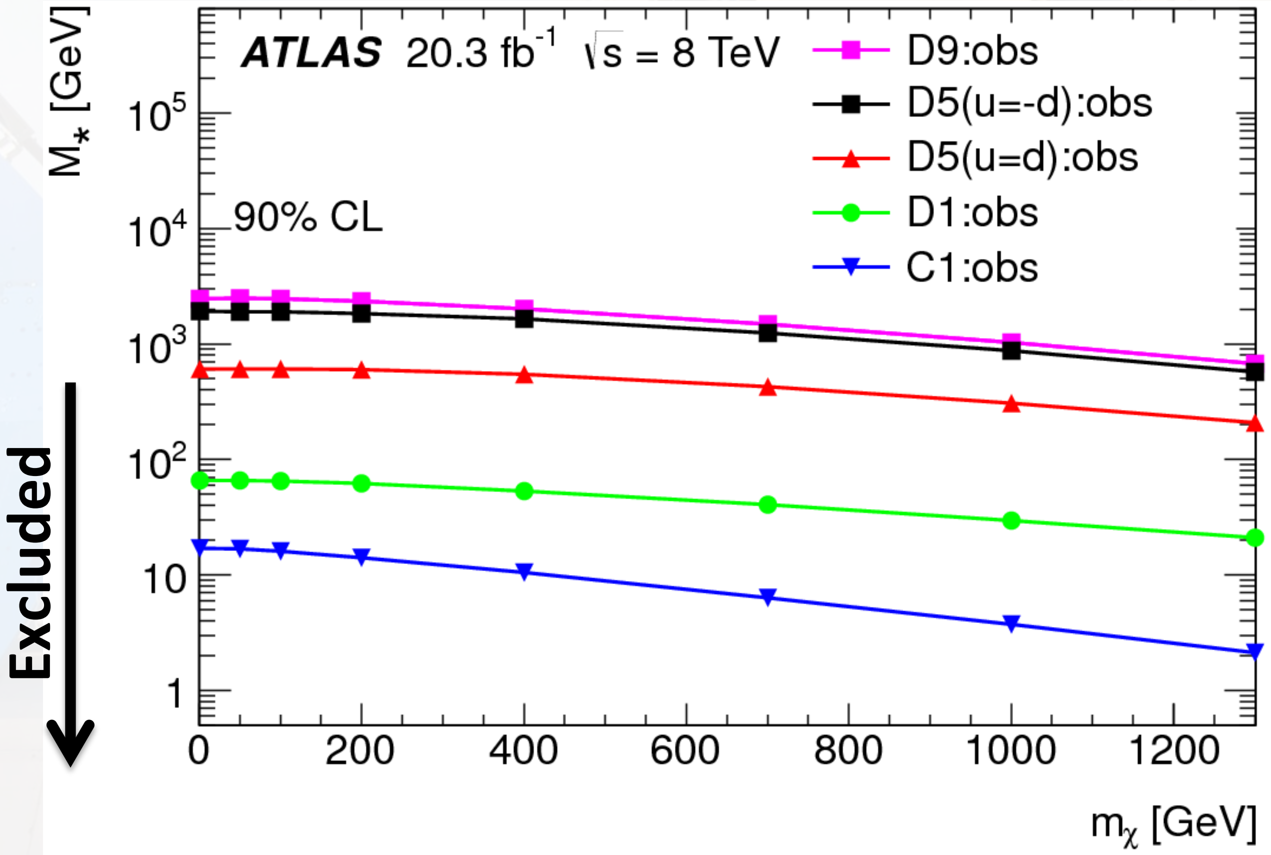


Kinematics

- Limits are set using predicted shape of the m_{jet} distribution
  - Upper distribution shows the MET>350 GeV signal region, bottom shows MET>500 GeV
  - M* = 1 TeV, and m_{χ}=1 GeV
- Data is in good agreement with predicted background



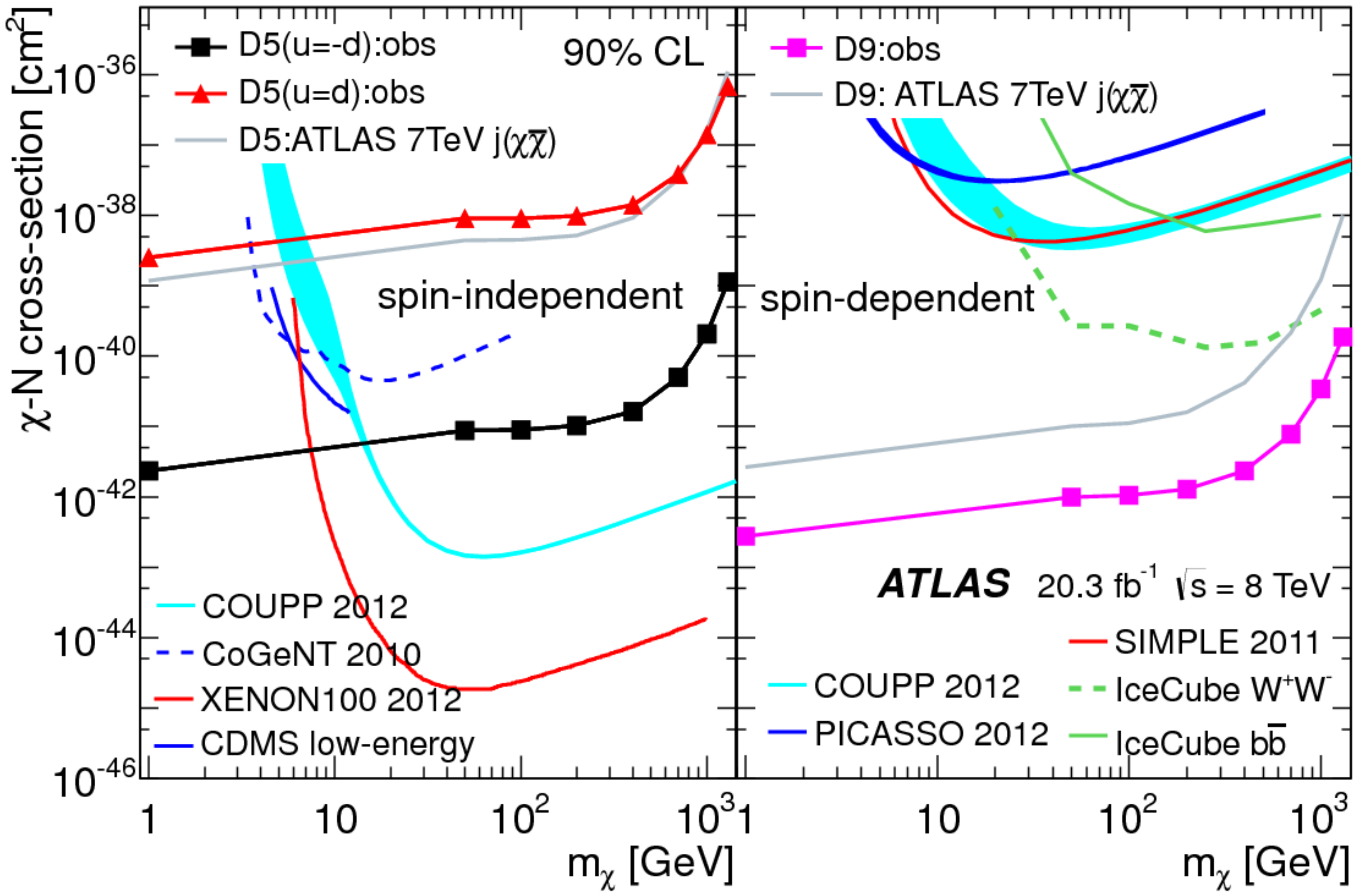
Collider limits



- M* → inversely proportional to coupling
- Region <u>below</u> line excluded

- Free parameters: m_χ, scale M*

Direct detection limits



- Transform limits on the EFT scale, M*, into direct detection cross sections
- Best limits from the LHC on dark matter so far

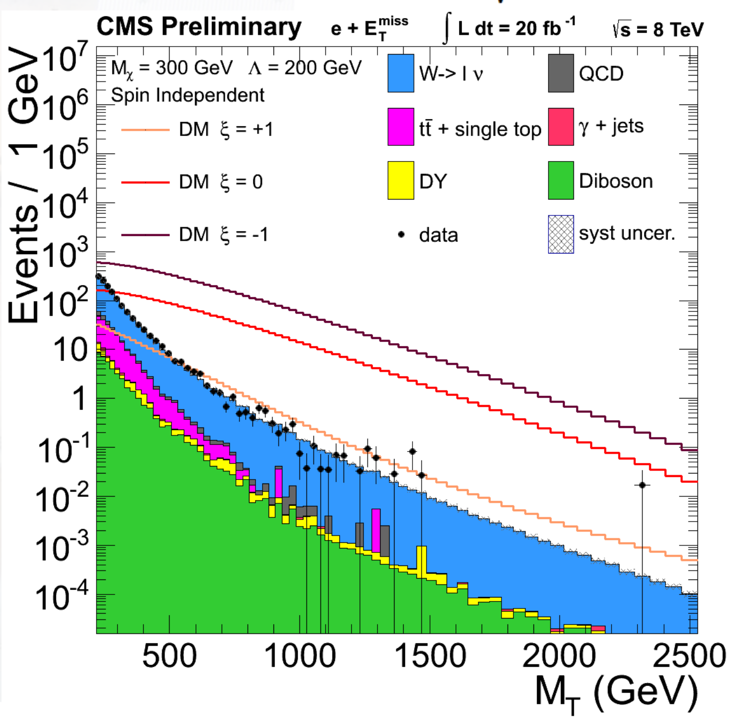
mono-W leptonic

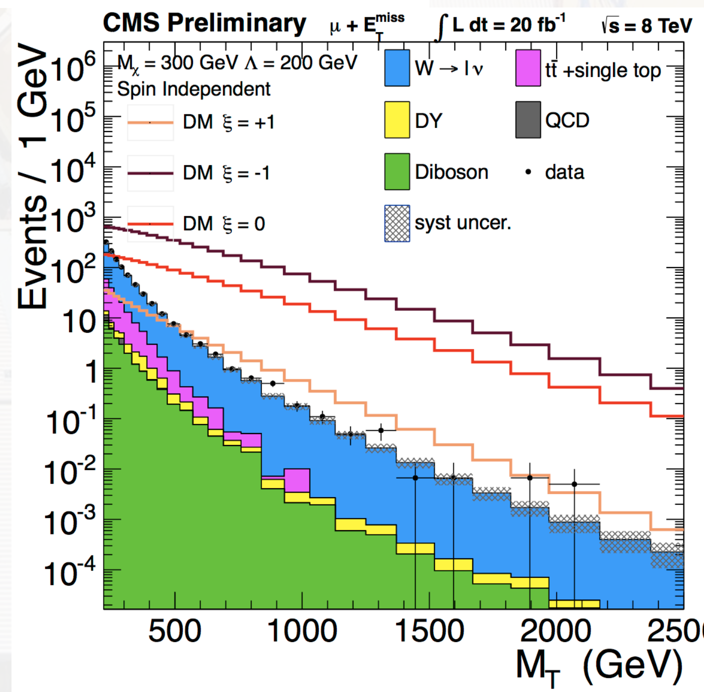
CMS: CMS-PAS-EXO-13-004

Analysis Strategy

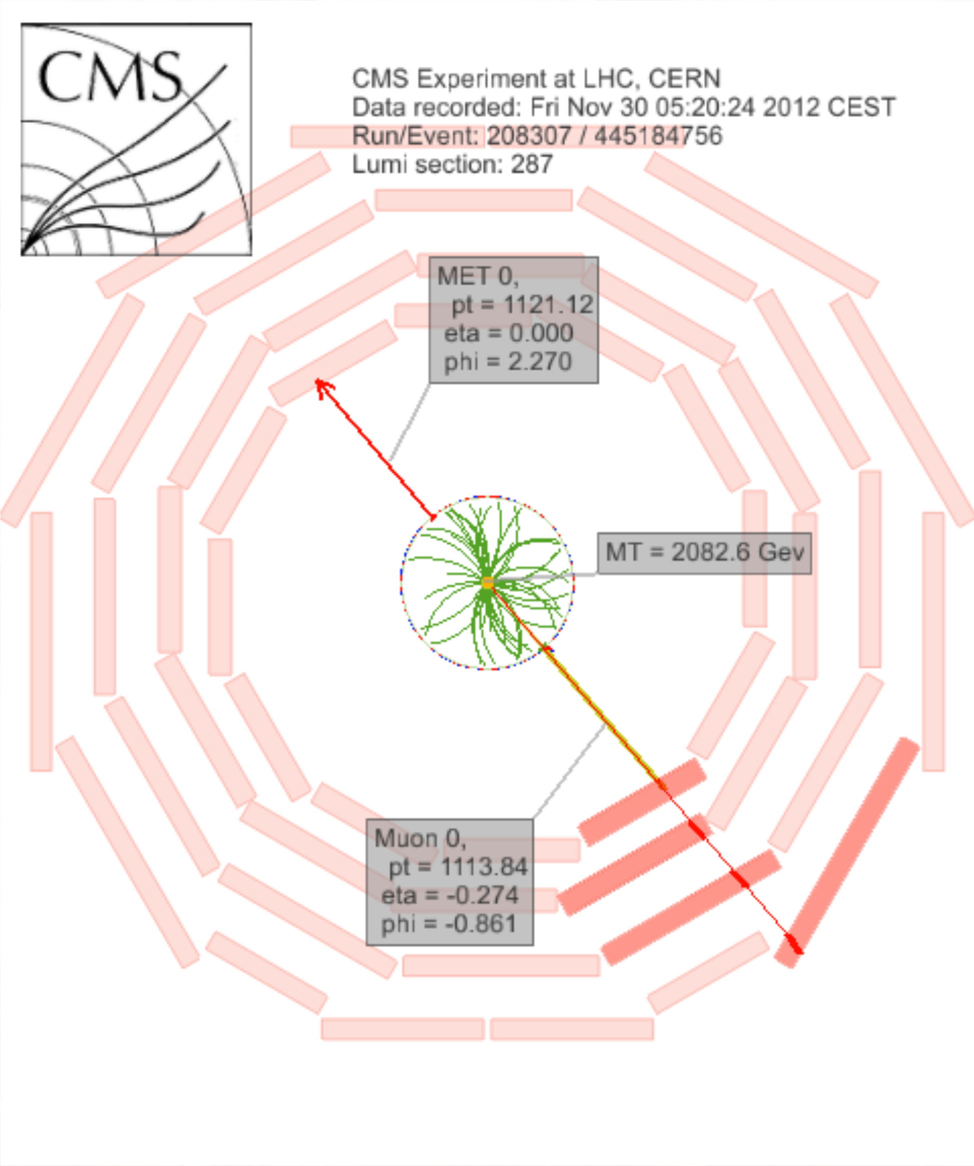
- One high-p_T lepton (>45 GeV for muons and >100 GeV for electrons)
- Ratio of lepton p_T to MET is between 0.4 and 1.5
- $\Delta\varphi$(lep., MET)>0.8π
- Excess in bins of M_T is used to set limit

$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

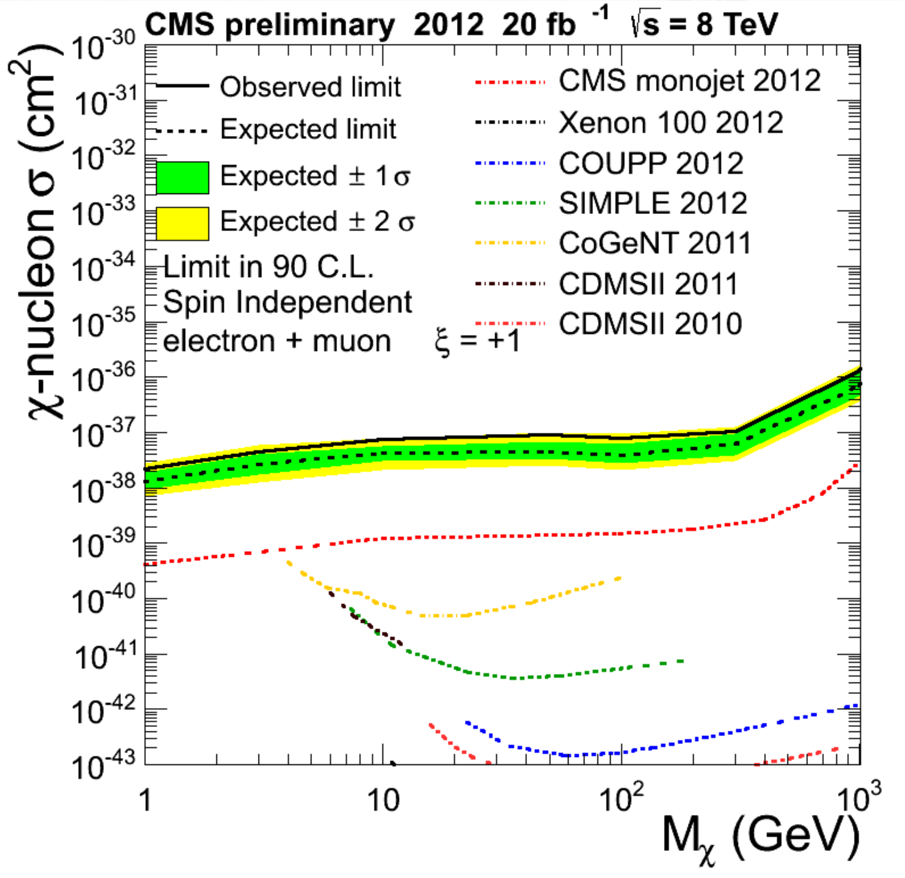


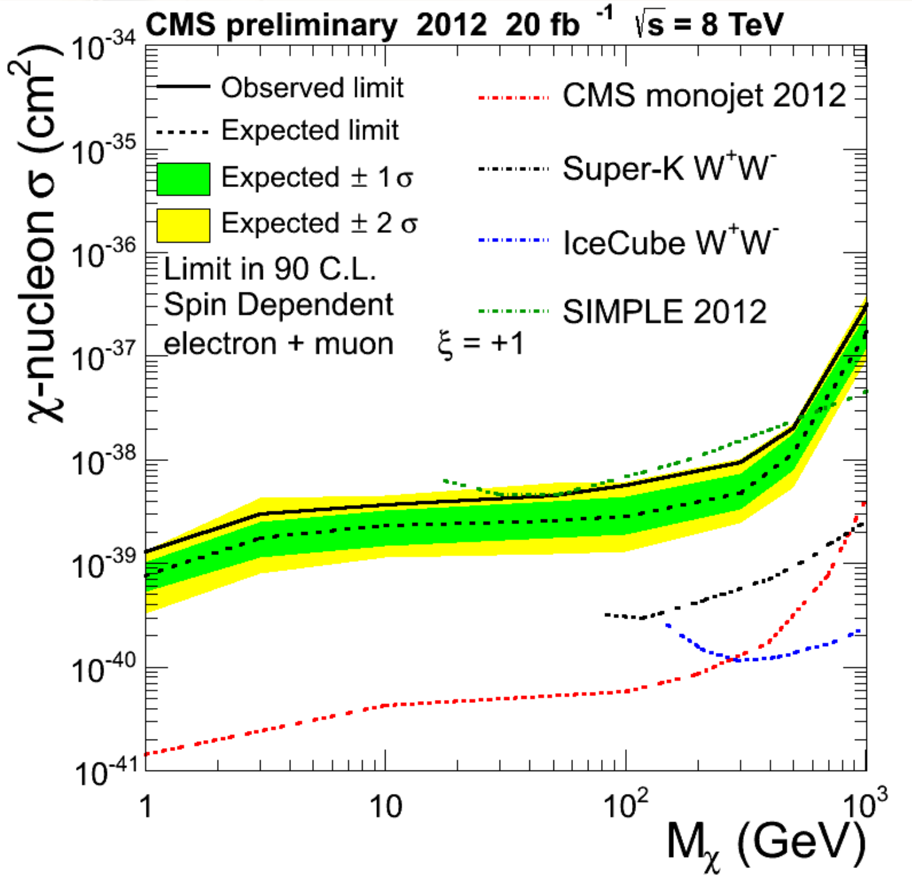


Event Display



Direct detection limits





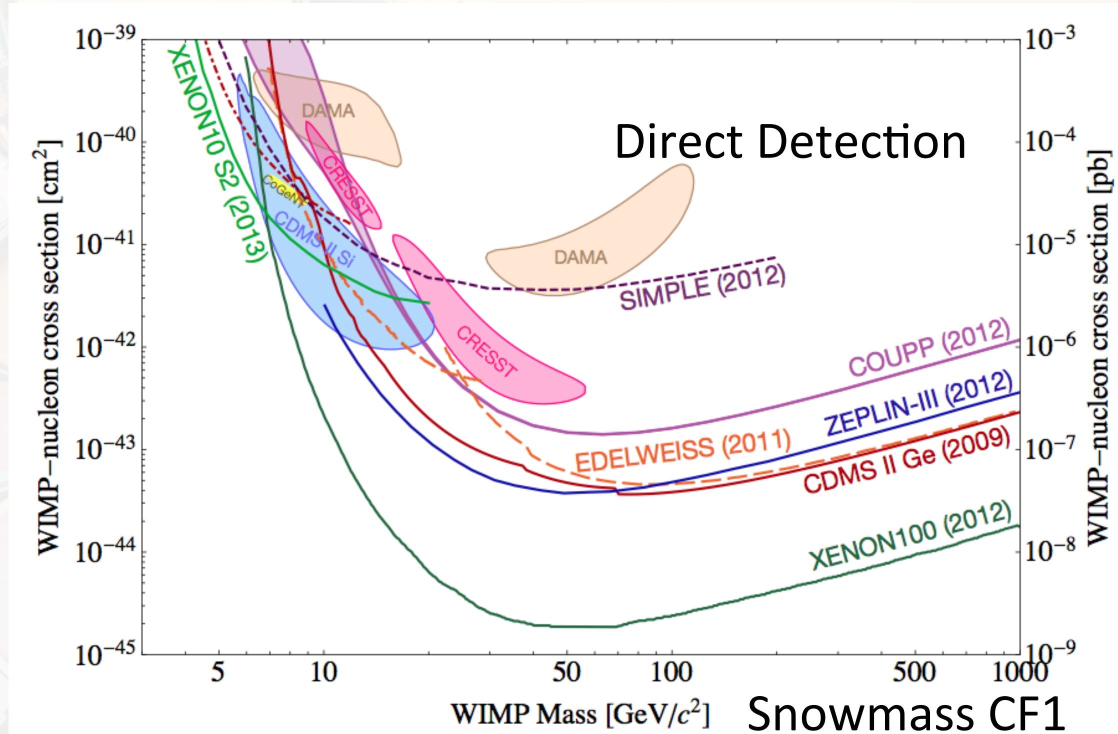
- Limits calculated using the M_T distribution compared to direct detection

Summary/Outlook

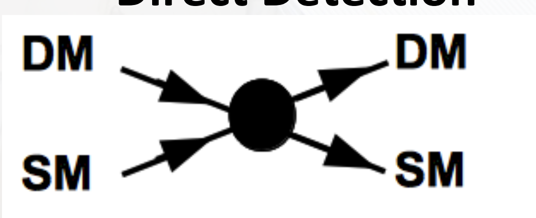
- Looking for new physics after Higgs
  - Dark matter most well-motivated search with colliders
- Looking for new physics in the high-MET range
  - Studied new kind of mono-Z EFT in the leptonic channel (ATLAS)
    - PRD: **1404.0051**
  - Studied new final state: mono-fat-jet, or mono-W/Z hadronic (ATLAS)
    - PRL: **1309.4017**
  - Studied mono-W in the leptonic channel (CMS)
    - Conference Note: **CMS-PAS-EXO-13-004**
    - ATLAS also has a conference note: **ATLAS-CONF-2014-017**
  - See Toyoko Orimoto's talk for more mono-EWK boson limits:
    - "Mono- and di-photon searches for new physics at the LHC"
- Set limits with 7 and 8 TeV data, preparing for 13 TeV!

Searches for dark matter

- Gravitational interactions provided first evidence for dark matter
- Search for weak interactions with ordinary matter
- Three types of searches
- **Collider searches**

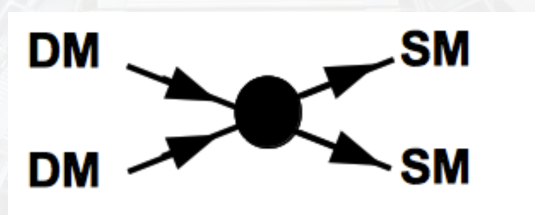


Direct Detection



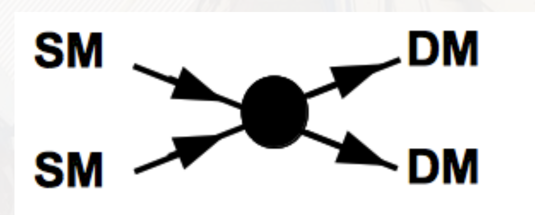
e.g. Xenon, LUX

Indirect Detection



e.g. IceCube

Collider



e.g. ATLAS, CMS

Lagrangians

$$\frac{1}{\Lambda_5^3}\bar{\chi}\chi(D_\mu H)^\dagger D^\mu H,$$

$$L = \frac{1}{\Lambda_7^3}\bar{\chi}\chi\sum_i k_i F_i^{\mu\nu}F^i_{\mu\nu},$$

$$\Gamma^{\text{Scalar}}(h\to\chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Scalar}}v^2}{64\pi m_h}\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

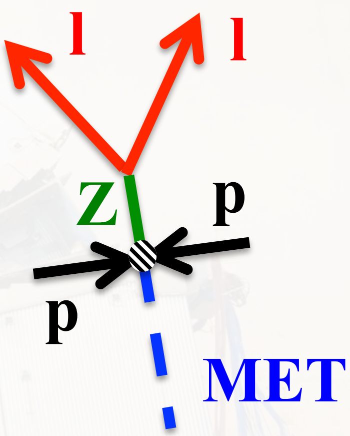
$$\Gamma^{\text{Vector}}(h\to\chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Vector}}v^2}{256\pi m_\chi^4 m_h}\left[m_h^4-4m_\chi^2m_h^2+12m_\chi^4\right]\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

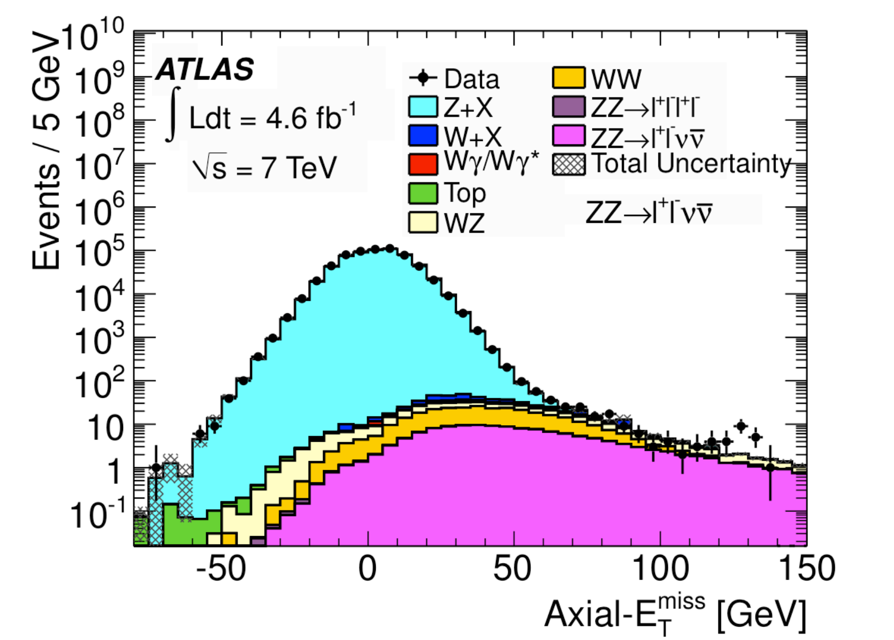
$$\Gamma^{\text{Majorana}}(h\to\chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Majorana}}v^2 m_h}{32\pi\Lambda^2}\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2}$$

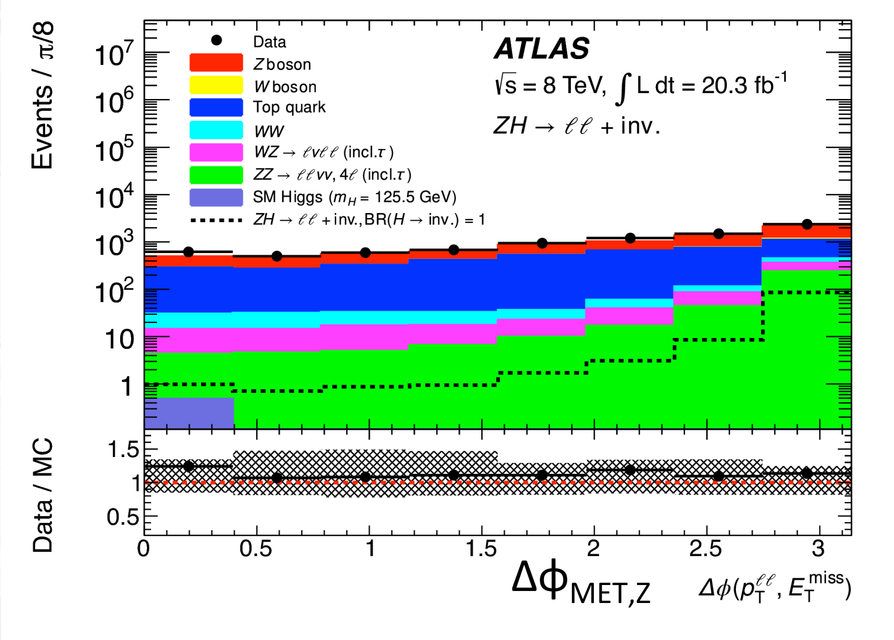
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Kinematics

- Most background comes from Z+jets with a mis-measured jet energy
- Studied axial-MET = -MET*cos($\Delta\phi_{MET,Z}$)
  - naturally combines the two
- But we cut on $\Delta\phi_{MET,Z}$ and MET separately - best distinguishing power

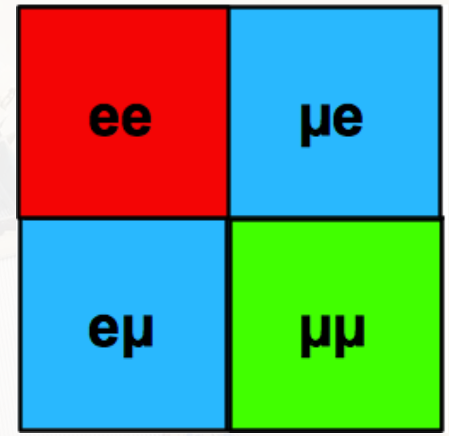






WW, tt, and Z→ττ backgrounds

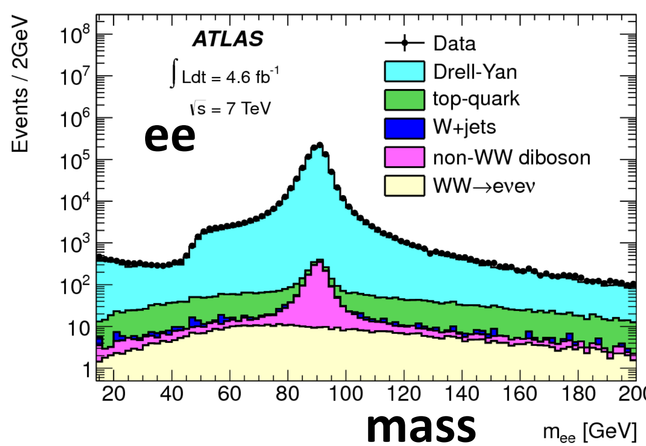
- *Data-driven* background estimate
  - Lower systematic uncertainty
- WW, tt, Wt, and Z→ττ backgrounds contribute to the ee and μμ signal regions **and** eμ region
  - ee:μμ:eμ as 1:1:2
- Correct for different lepton reconstruction efficiencies

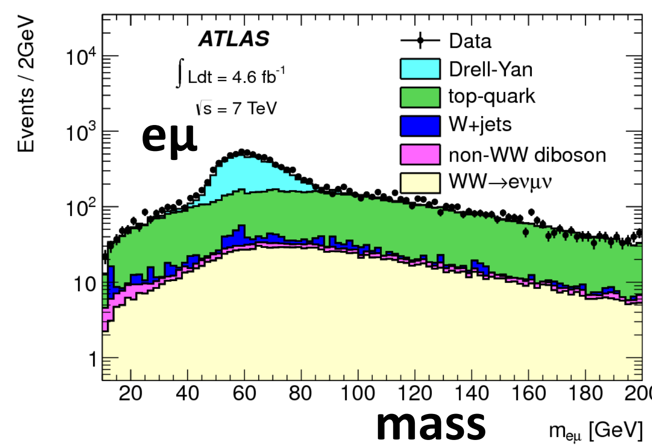


from WW cross section paper “Phys. Rev. D 87, 112001 (2013)”

$$N_{ee}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times k$$

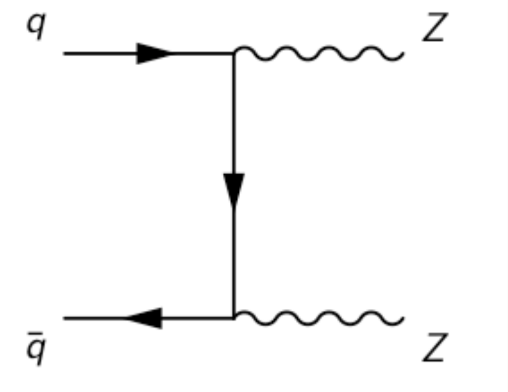
- k=ratio of avg. elec and muon reconstruction efficiency



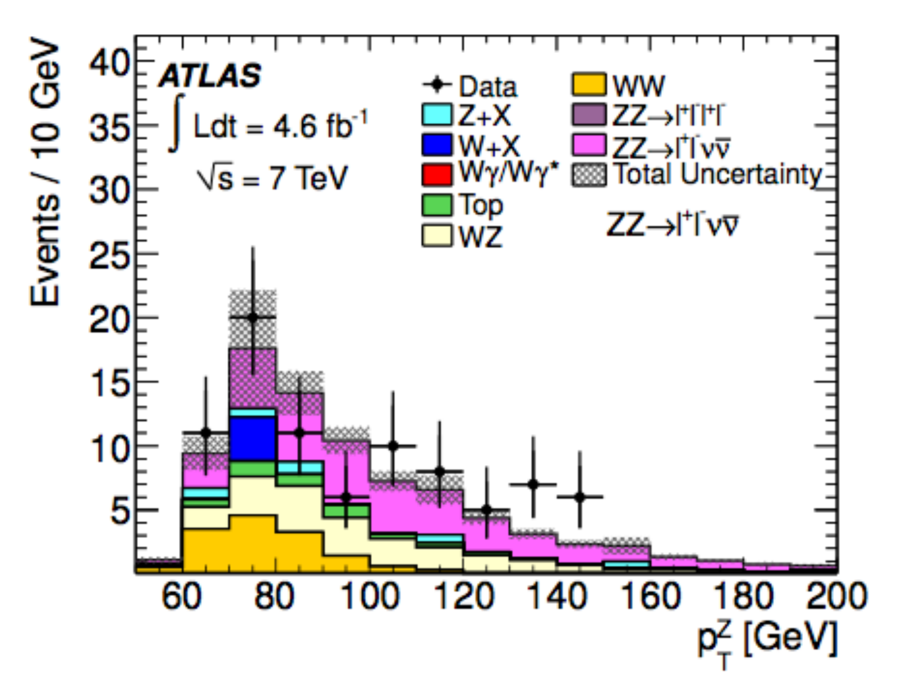


Backgrounds and Uncertainties

- Main background: ZZ production
  - other contributions: WZ, WW, Z+jets, top, fakes
- ZZ is main source of background uncertainty

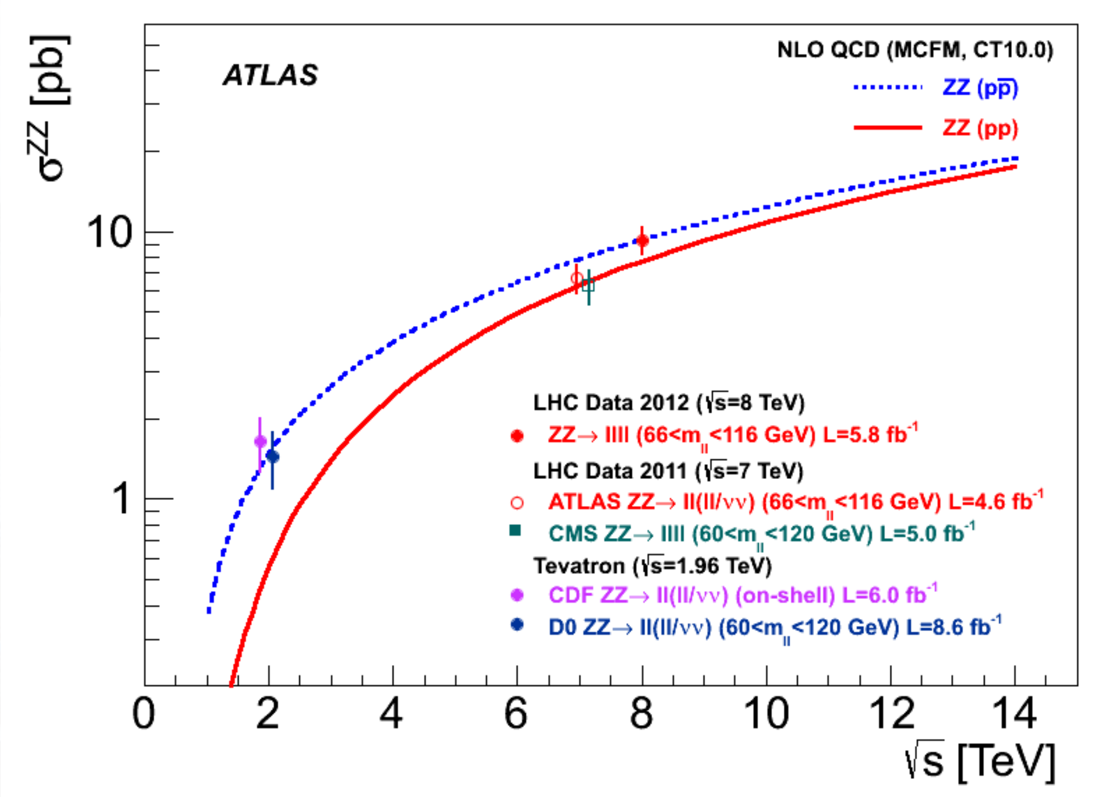


Uncertainty Source	E_T^{miss} threshold [GeV] 150	250	350	450
Statistical [%]	2	6	13	24
Experimental [%]	3	6	9	8
Theoretical [%]	35	35	35	35
Luminosity [%]	3	3	3	3
Total [%]	35	36	38	43



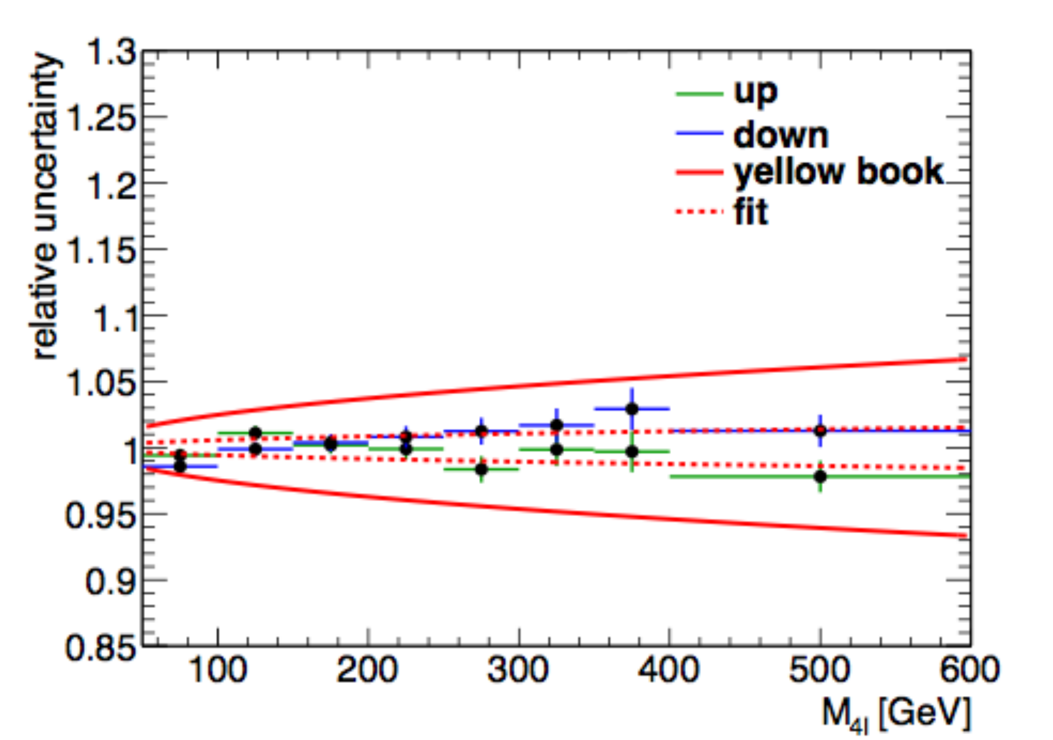
ZZ Cross Section Measurement

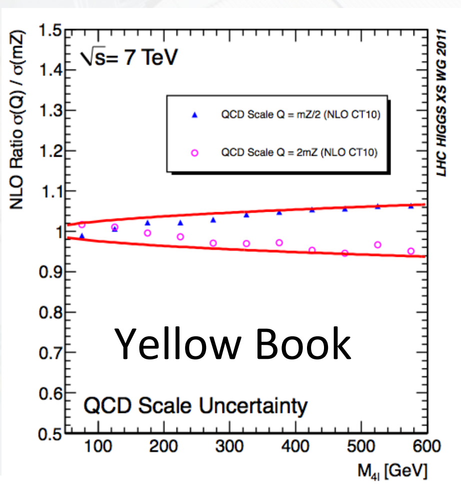
- ZZ cross section measurement at 7 TeV agrees with MC
  - Fiducial cross sections: $12.7^{+3.1}_{-2.9}\pm1.7\pm0.5$ fb measured vs. $12.5\pm0.1^{+1.0}_{-1.1}$ fb predicted
- ZZ→llvv background is estimated from MC
  - ZZ production checked in a 4 lepton control region



MC Theory systematics

- MC yellow book estimates ZZ background uncertainties using fixed scale llll decay channel
  - Parameterized fit for uncertainty
- Systematics are reduced for llνν
  - no γ* contribution
  - dynamic scale versus fixed scale

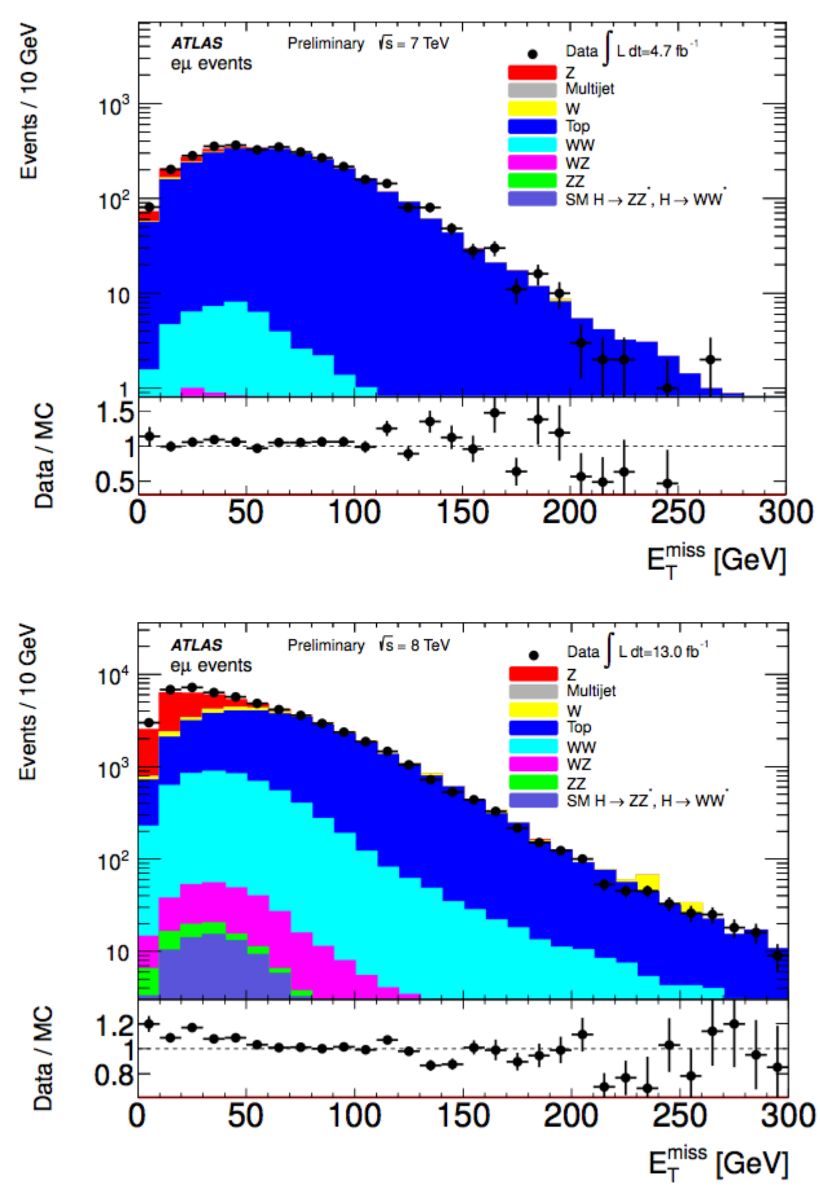




Additional systematics come from experimental uncertainty, difference in acceptance between Sherpa and PowhegBox, and PDF uncertainty for the D1 operator

WW, tt, and Z→ττ backgrounds

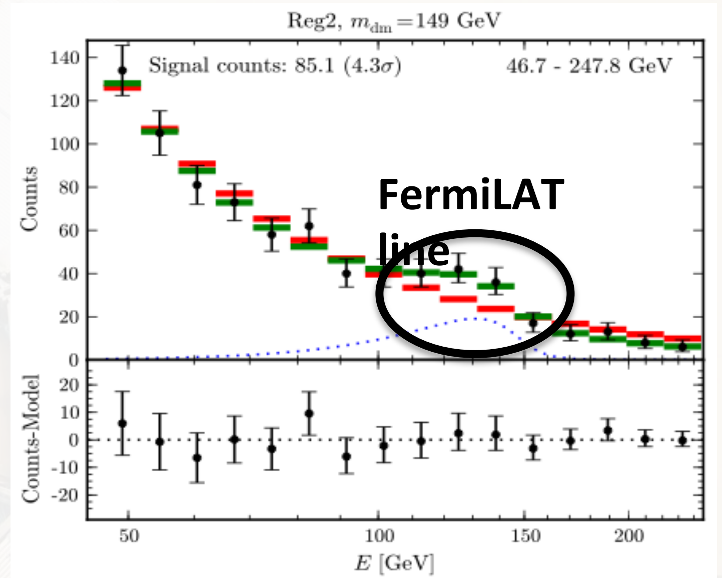
- Find eμ events satisfying analysis cuts
- Subtract non-WW, tt, Wt, and Z→ττ backgrounds to get $N_{e\mu}$
  - other diboson, W+jets
- Systematic uncertainties
  - Includes:
    - Statistical uncertainty, $N_{e\mu}$
    - Efficiency correction factor, k
    - Systematics on MC subtraction
  - ~75% for mono-Z
  - ~30% for ZH



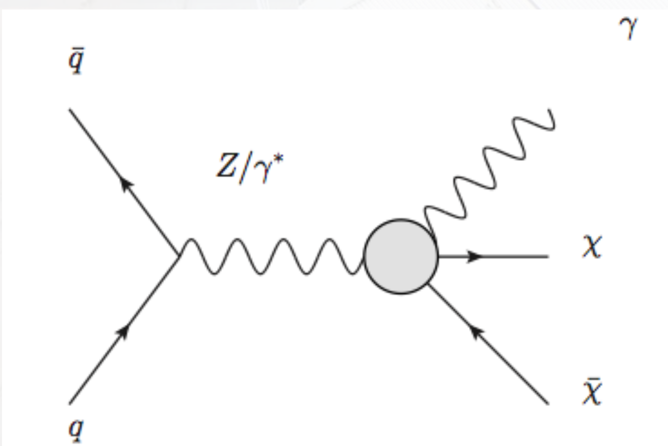
Aside: mono-γ

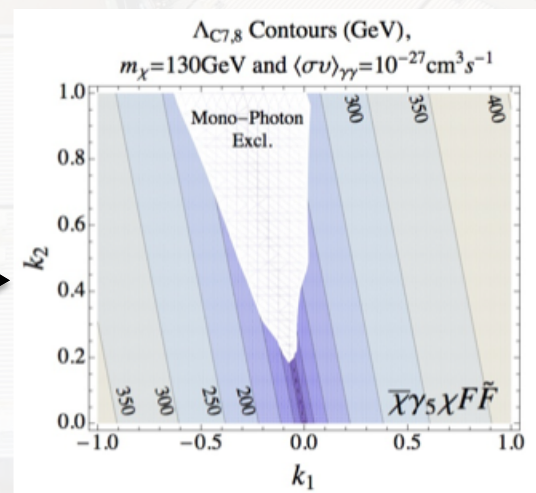
- Connection with the indirect detection bump from FermiLAT
  - Rule out region of phase space capable of producing the bump
- Reinterpret the 7 TeV mono-γ collider limits using the same s-channel diagram
- Operator models indirect production of dark matter with a photon and χ in the final state

FermiLAT Data



hep-ph/12031312. T.Bringmann et al.





hep-ph/1307.5064. <u>AN, L.Carpenter, R.Cotta, A.Johnstone, D.Whiteson</u>