Searches for Dark Matter at the ATLAS experiment

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On behalf of the ATLAS Collaboration

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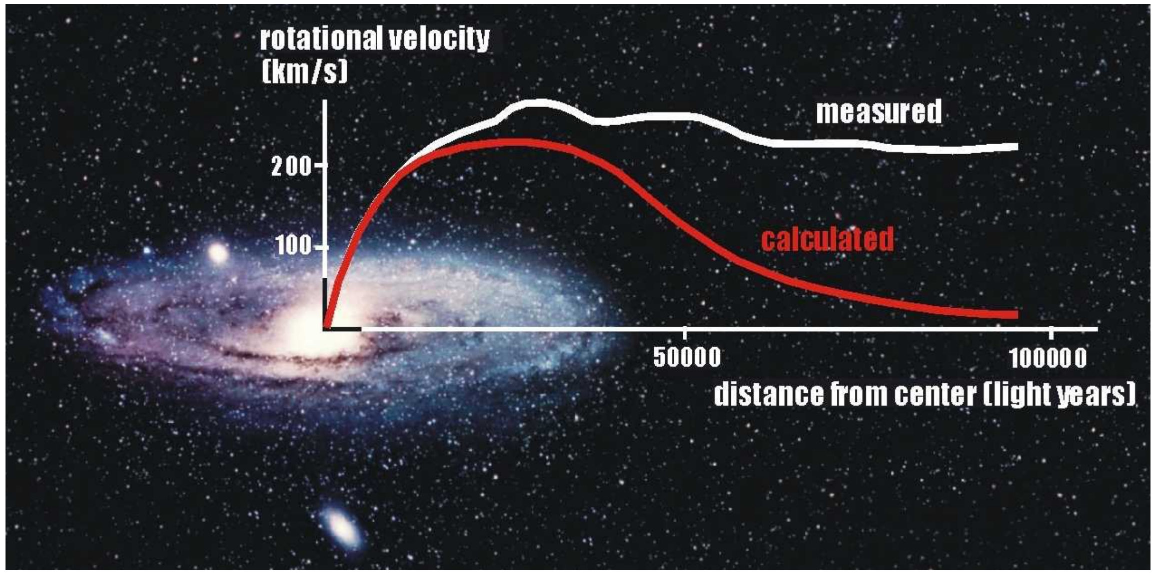
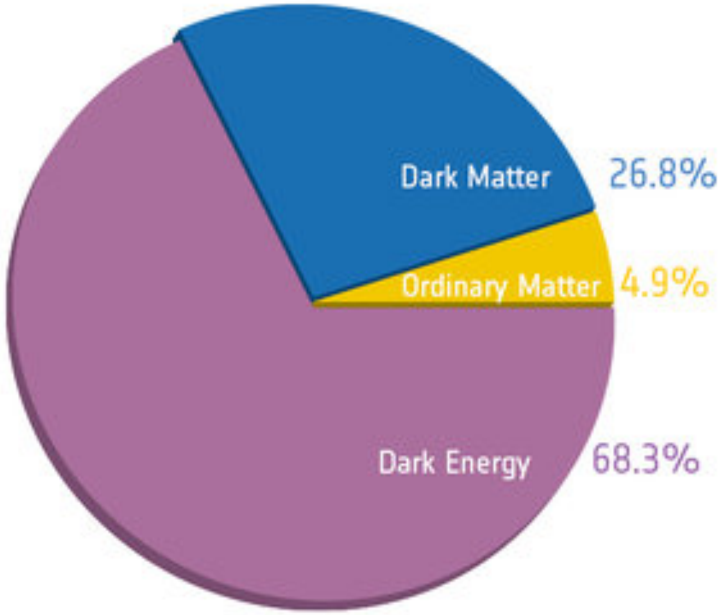
Dark matter

- Dark matter presence is confirmed by the study of galaxy rotation curves and from the study of the CMB anisotropies.



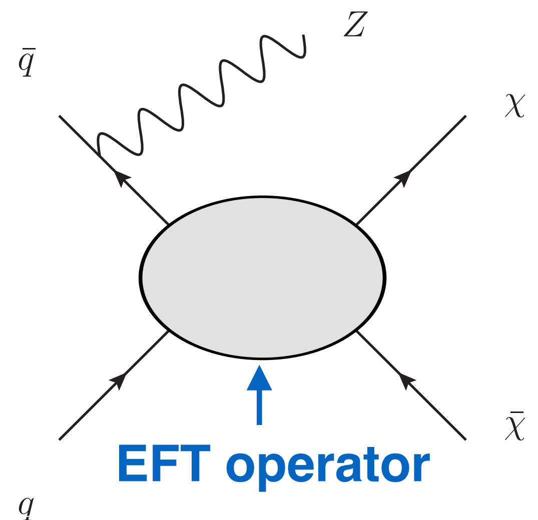
- Dark matter + dark energy form ~ 95 % of the Universe.



Weakly Interacting Particles (WIMPs) are the best candidates for dark matter particles

Models of dark matter production at colliders

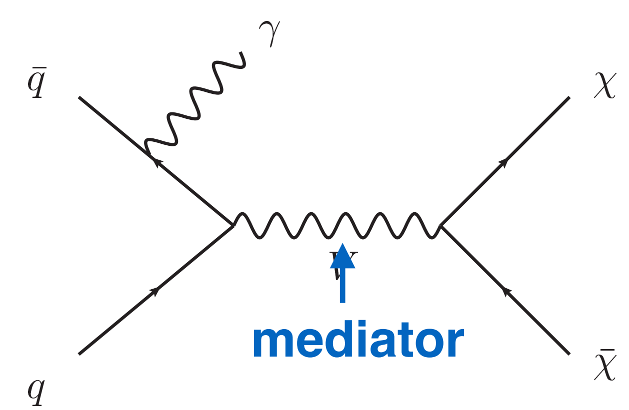
- **Effective field theories (EFT)** : Approximation of contact interaction through heavy mediator.
  - Results parametrised and a few parameters: scale of interaction M_* and WIMP's mass.
  - Poor approximation when interactions momentum transfer larger than intermediate state's mass.



Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Effective interactions coupling WIMPs to SM quarks and gluons

- **Simplified Models**: Reduce a complex model to a simple one with DM, using explicit mediators.
  - Additional parameters are need (mediator mass, couplings and decay width).
  - Searches more model-dependent, but models valid at all energies.



Dark Matter in ATLAS

- Dark Matter searches all rely on *high amount of transverse momentum imbalance* in the detector, indicating the presence of weakly interacting particles that escape undetected.

Search strategies based on looking for events with high E_T^{miss}

- $jet + E_T^{miss}$
- $\gamma + E_T^{miss}$
- $W^{\pm}/Z^0 + E_T^{miss}$ *(had, lep)*

Mono-X

- $t\bar{t} + E_T^{miss}$ *(0L,1L)*
- $b/b\bar{b} + E_T^{miss}$

Heavy flavor

- Results interpreted using Effective Field Theories (EFT) and with simplified models.

Mono-jet + E_T^{miss}

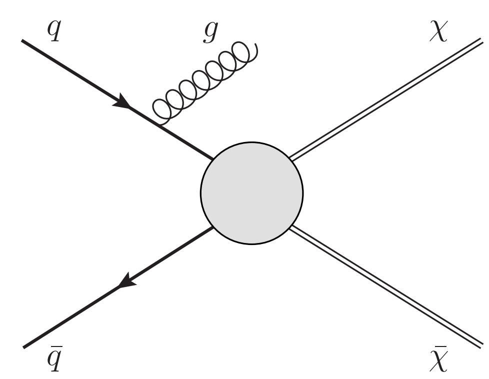
(arXiv:1502.01518v1[hep-ex])

- In most cases the most sensitive of the mono-X channels.

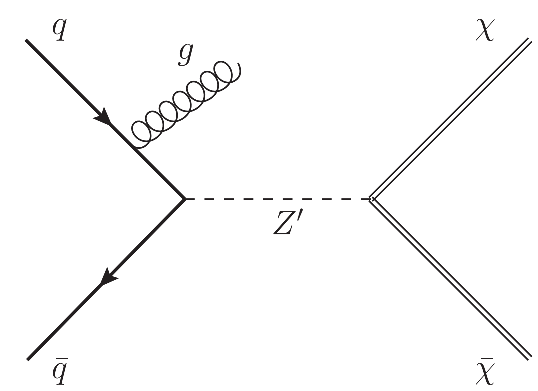
<u>Selection:</u>

- Event categorised in 9-E_T^{miss} bins : E_T^{miss}> 150, ..,700 GeV
- Leading-jet p_T: $p_T^{(j\text{-}lead)}$ > 120 GeV
- Jet recoils against *DM* pair: $p_T^{(j\text{-}lead)} > 0.5 \times E_T^{miss}$
- veto events with leptons and isolated tracks.
- $\Delta\phi(jet, E_T^{miss}) > 1.0$

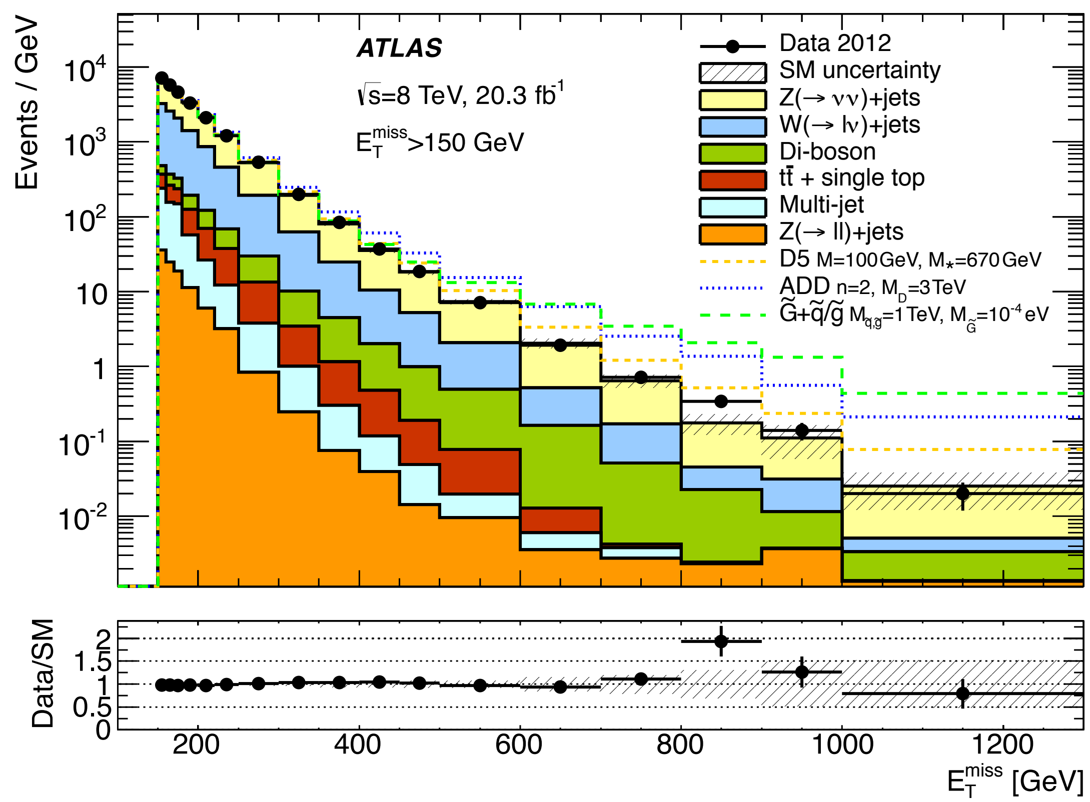
→ **Look in a region with high E_T^{miss}**

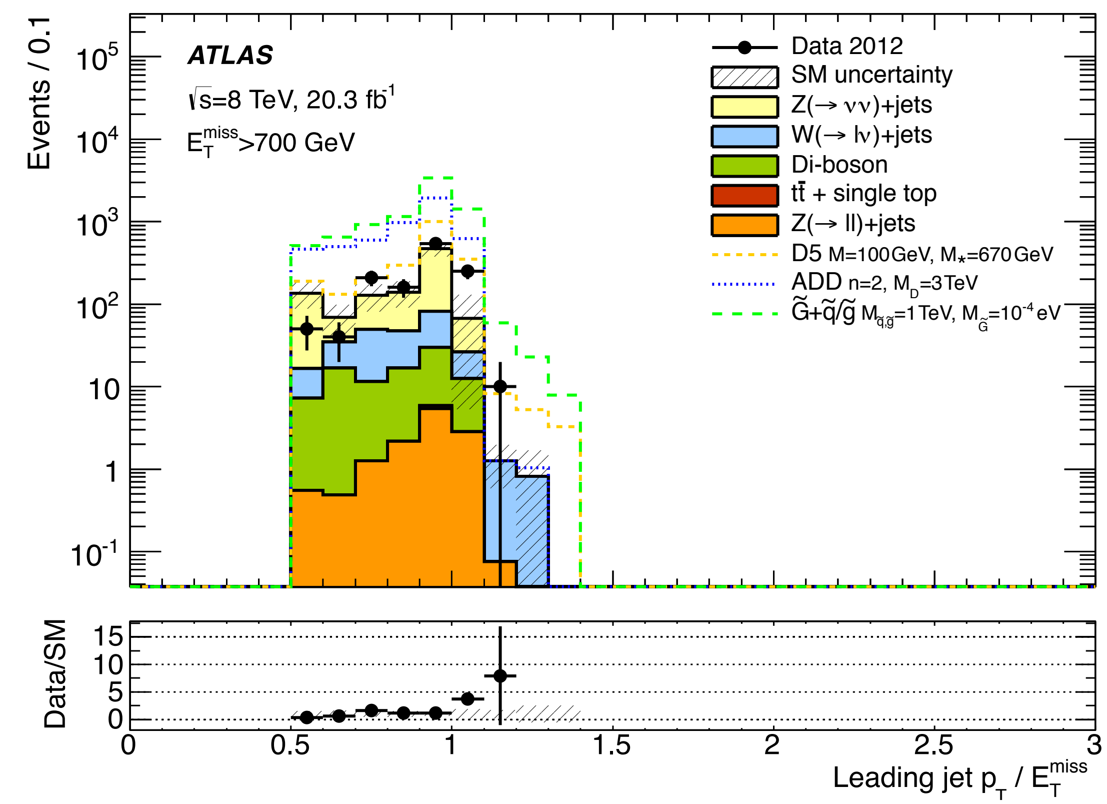


EFT



Simplified model

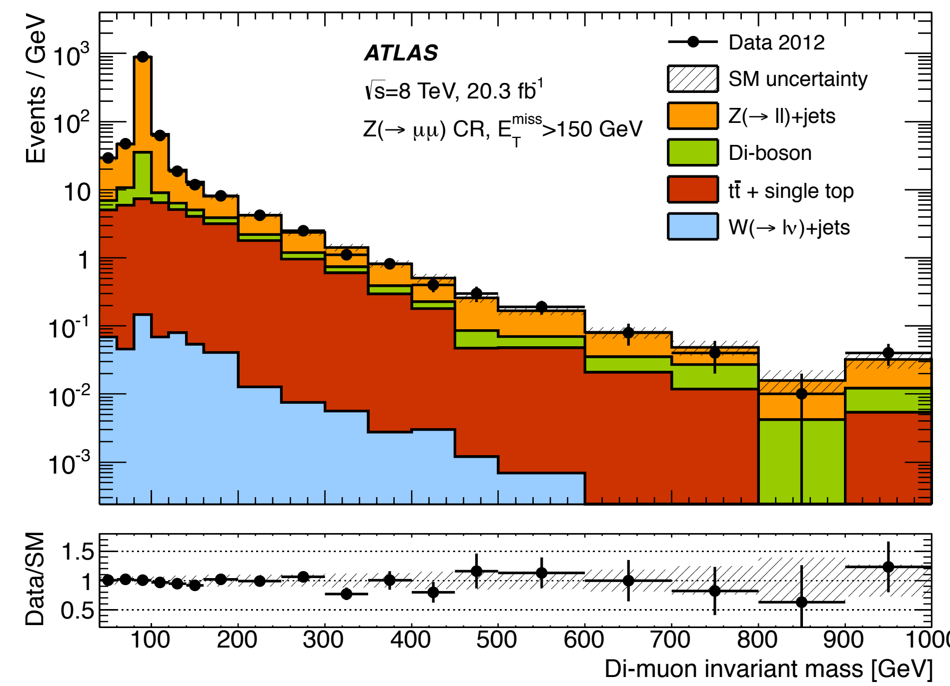


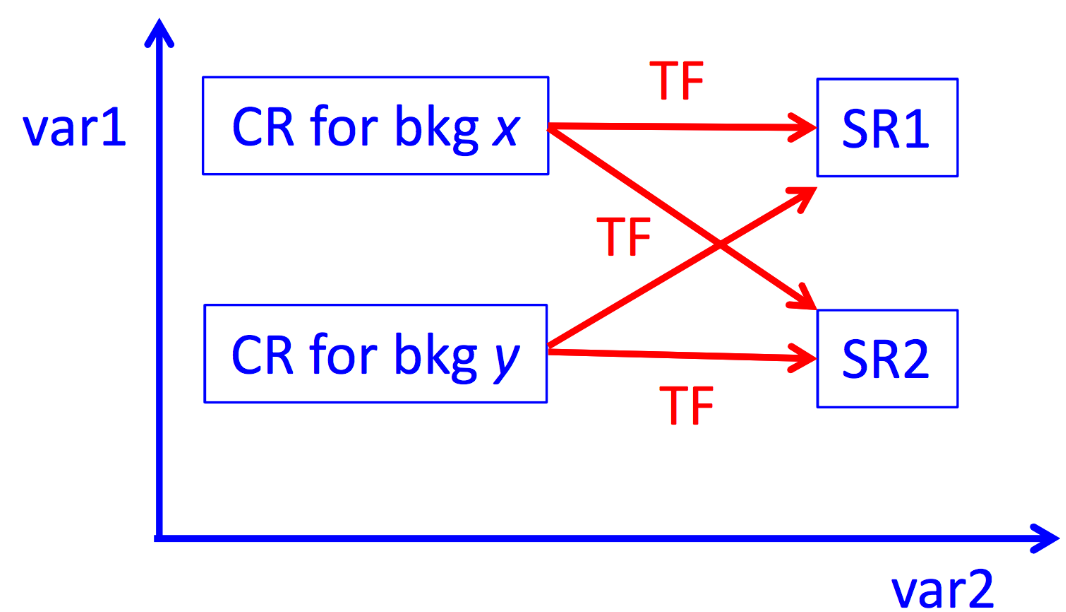


Mono-jet + E_T^{miss} : backgrounds (arXiv:1502.01518v1[hep-ex])

- Main background are EW processes with intrinsic E_T^{miss}, accompanied by jets.
- ***Z(νν)+jets*** : irreducible background.
- ***W(ℓν)+jets***: with unreconstructed or misidentified lepton.
- Both estimated from data using leptonic Z or W control regions (CRs).
- In this case, CRs are ***Z(ℓℓ)+jets*** and ***W(ℓν)+jets*** events with identified leptons.
- Event count from CR extrapolated to signal regions (SRs) using **transfer factors**.

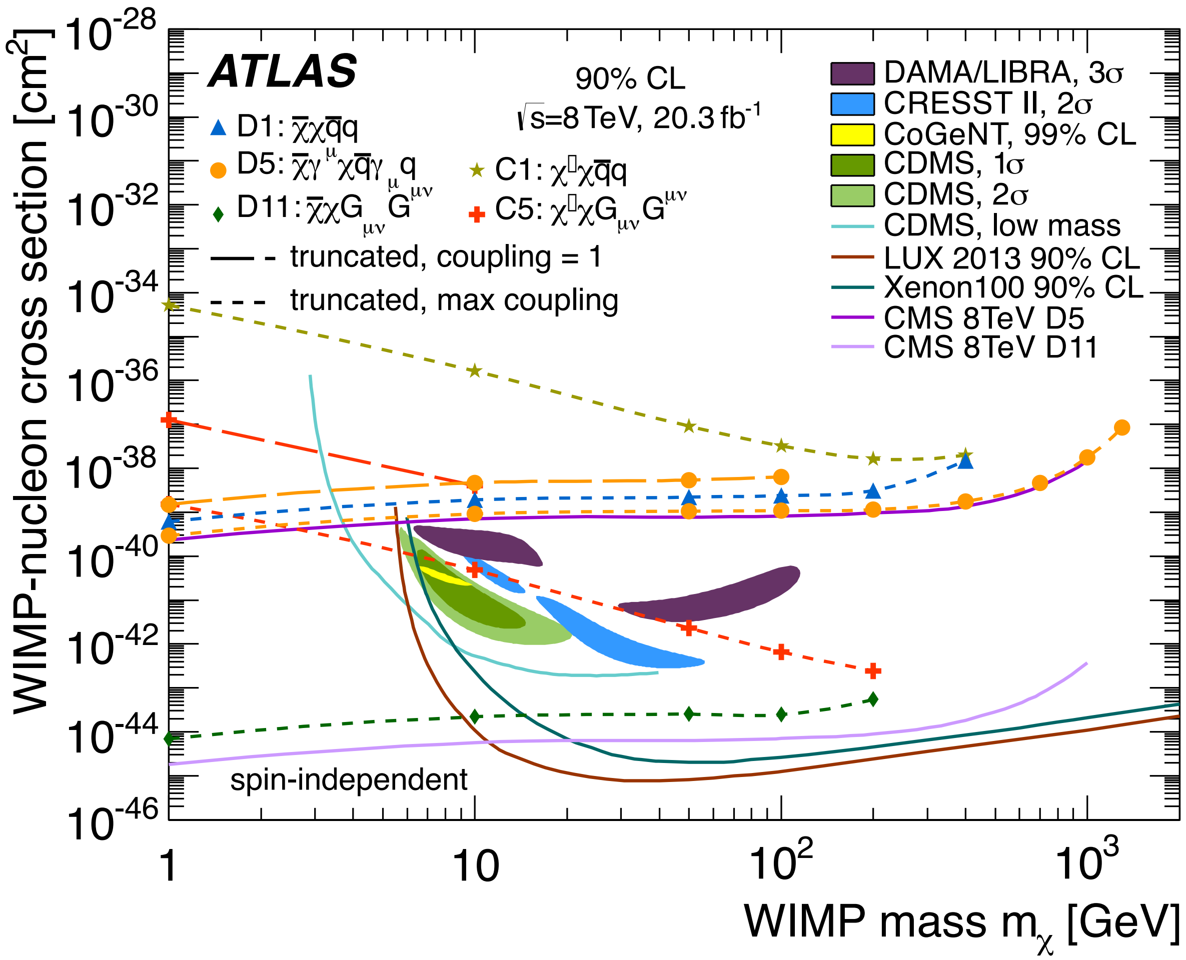
Z(ℓℓ)+jets control region

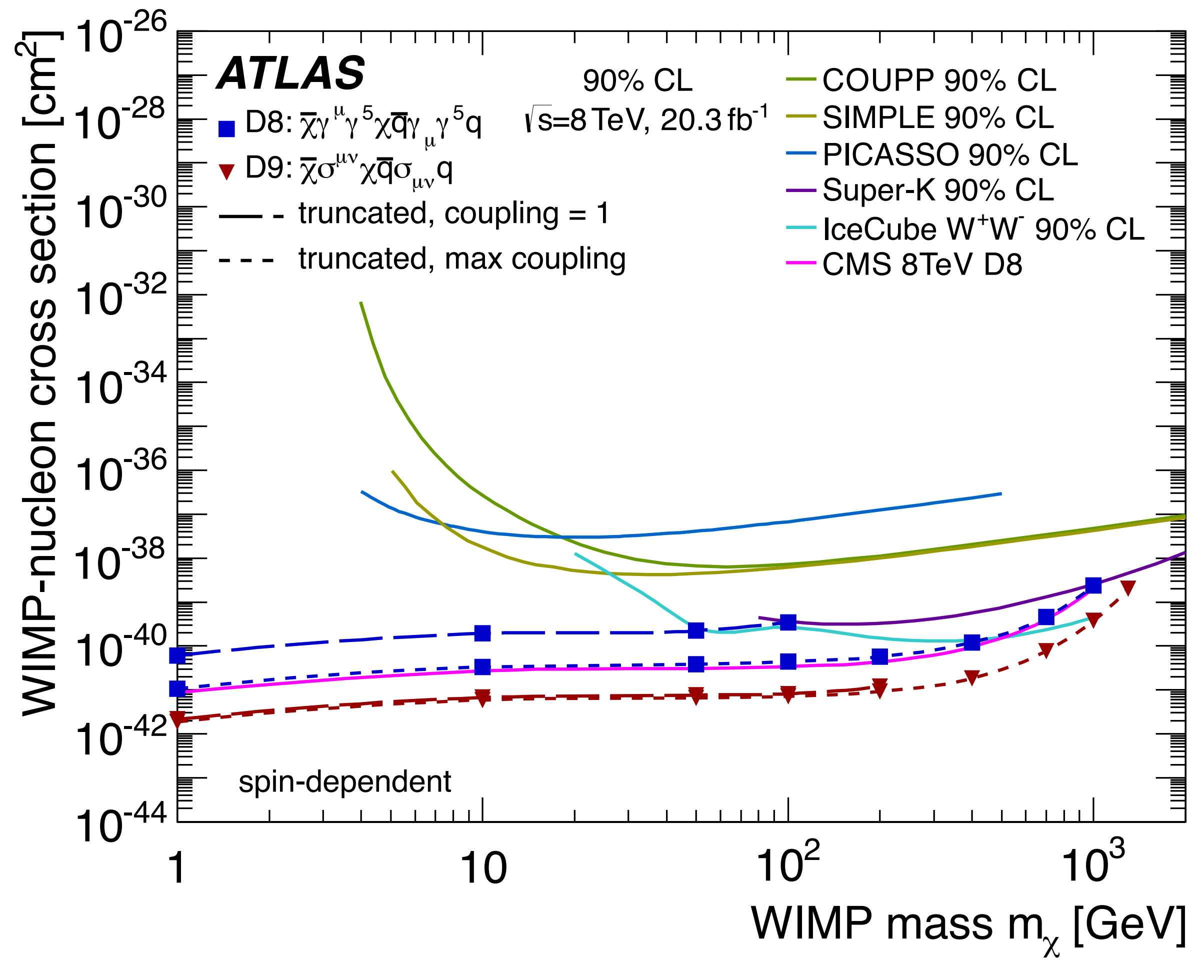




Mono-jet + E_T^{miss} : results

(arXiv:1502.01518v1[hep-ex])



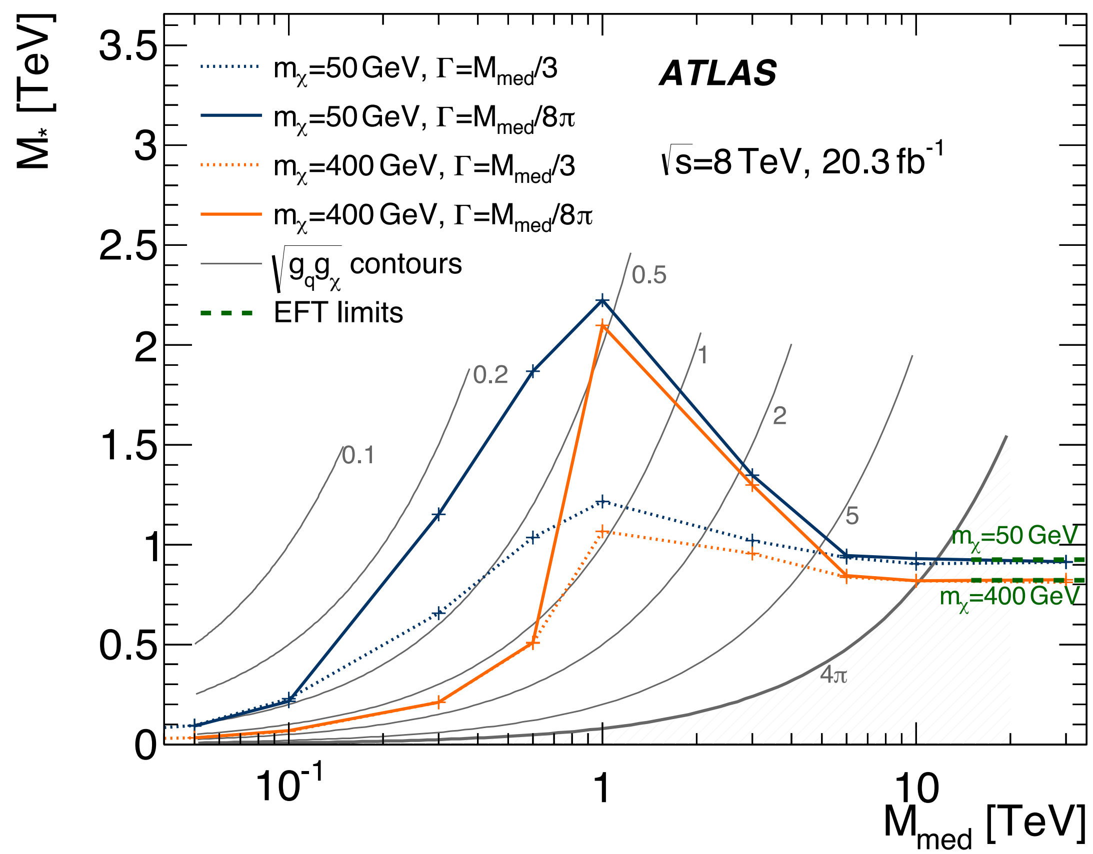


- ATLAS limits shown (by dashed lines) for several EFT operators.
- all measurement are consistent with SM.
- truncation procedure applied to ensure EFT validity
- Complementary of direct/indirect detection and colliders.
  - each experiment has its strength

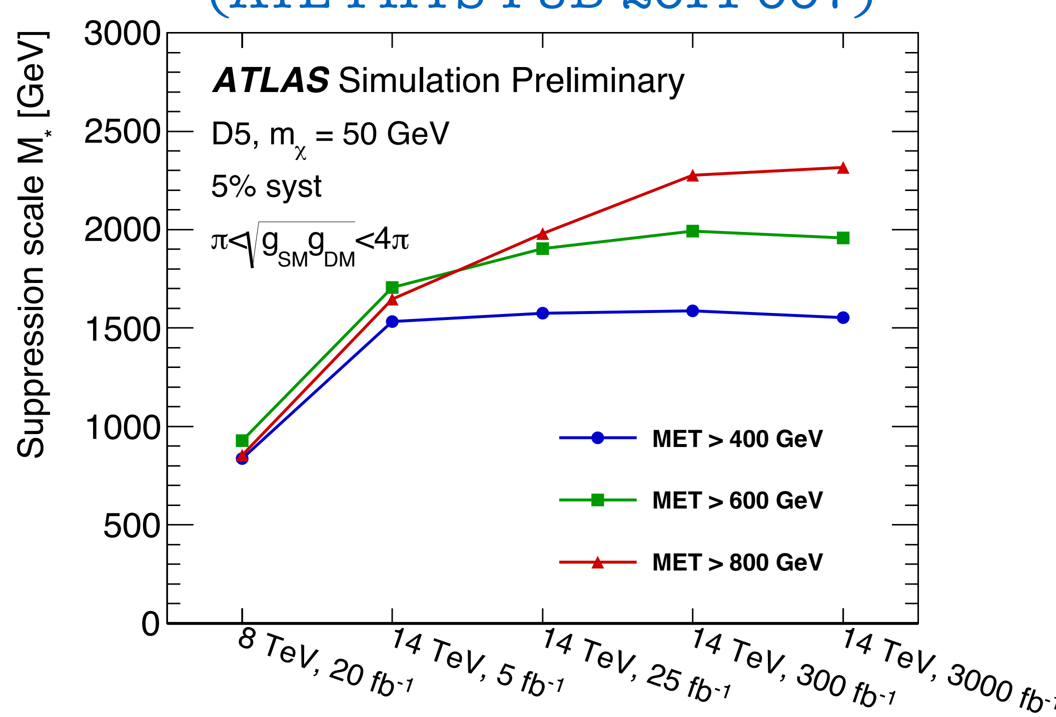
Mono-jet + E_T^{miss} : results

(arXiv:1502.01518v1[hep-ex])

- Simplified model(Z'-like mediator) results also available
  - more model parameters
  - complete description for physics at the LHC



(ATL-PHYS-PUB-2014-007)



- Improved sensitivity expected with first months of LHC run 2.
  - stronger focus on simplified models in run 2.

Mono-photon+ E_T^{miss}

(arXiv:1411.1559v2[hep-ex])

- Sensitive channel because of well-measured gamma and mostly EW backgrounds.

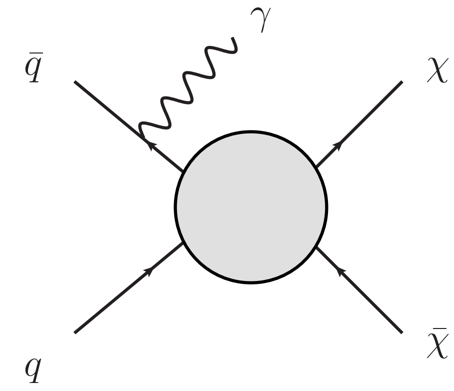
<u>Selection:</u>

- At leat 1-isolated photon ($p_T^{(\gamma)} > 125$ GeV)
- No leptons
- At most one jet.
- $\Delta\phi(\gamma, E_T^{miss}) > 0.4$
- $E_T^{miss} > 150$ GeV

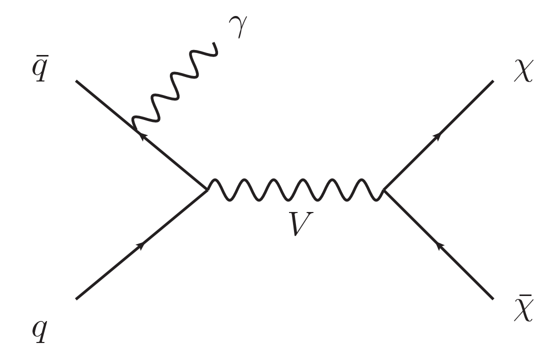
→ **Look in a region with high E_T^{miss}**

<u>Main background:</u>

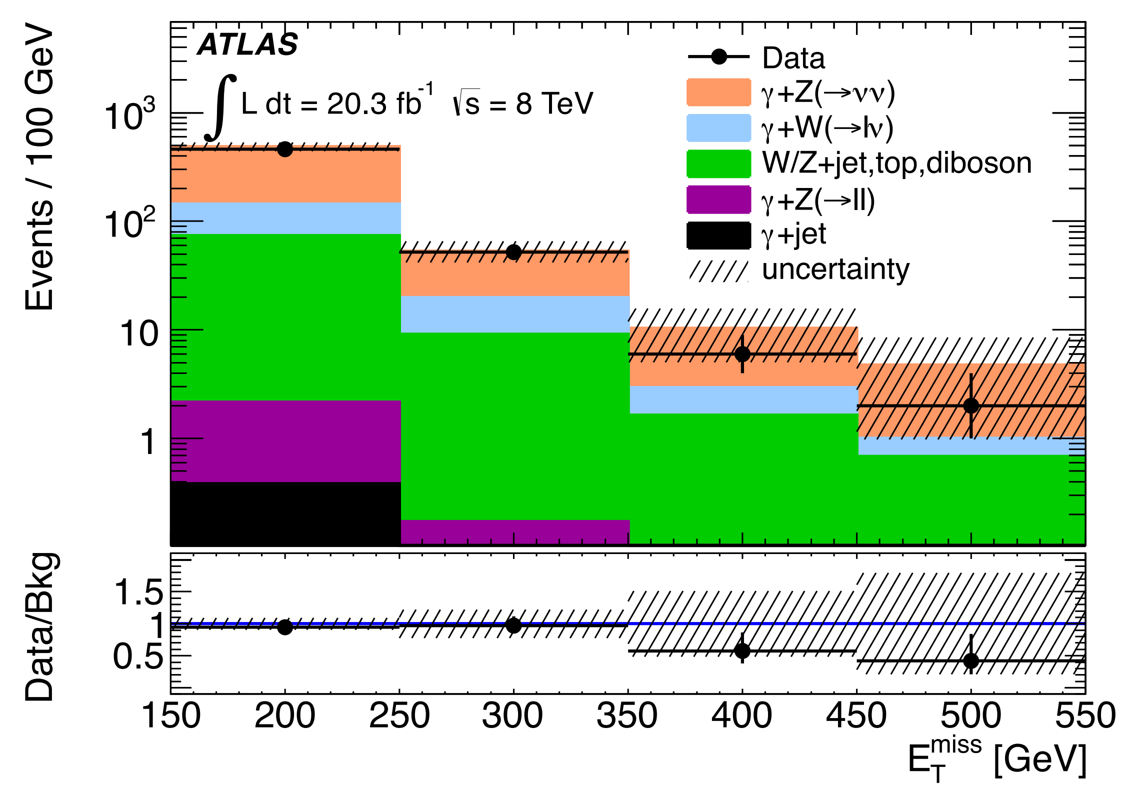
- ***Z(νν)+γ*** , ***W(ℓν)+γ*** : estimated in data control regions
- ***W/Z +jets***: estimated using data-driven jet—>γ misID factor



EFT



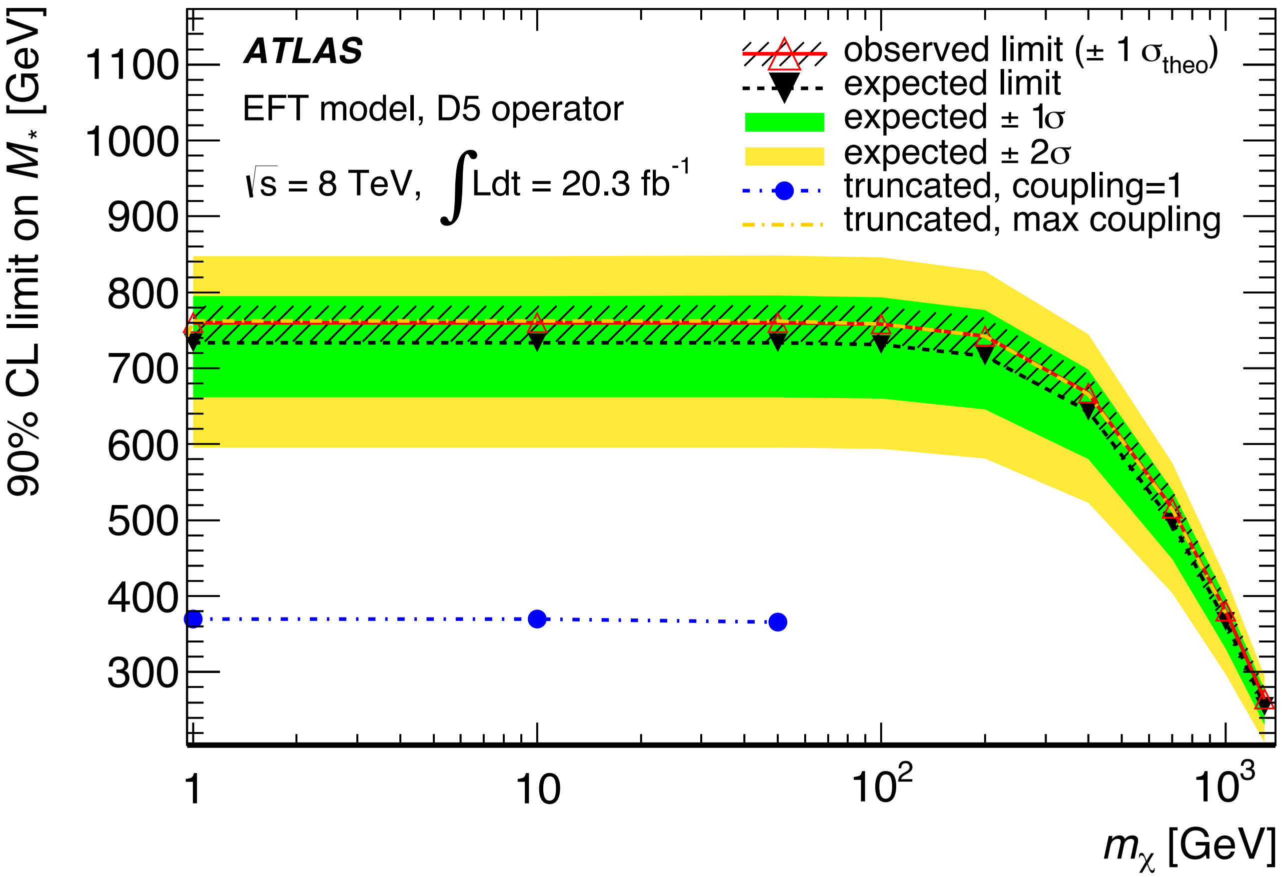
Simplified model

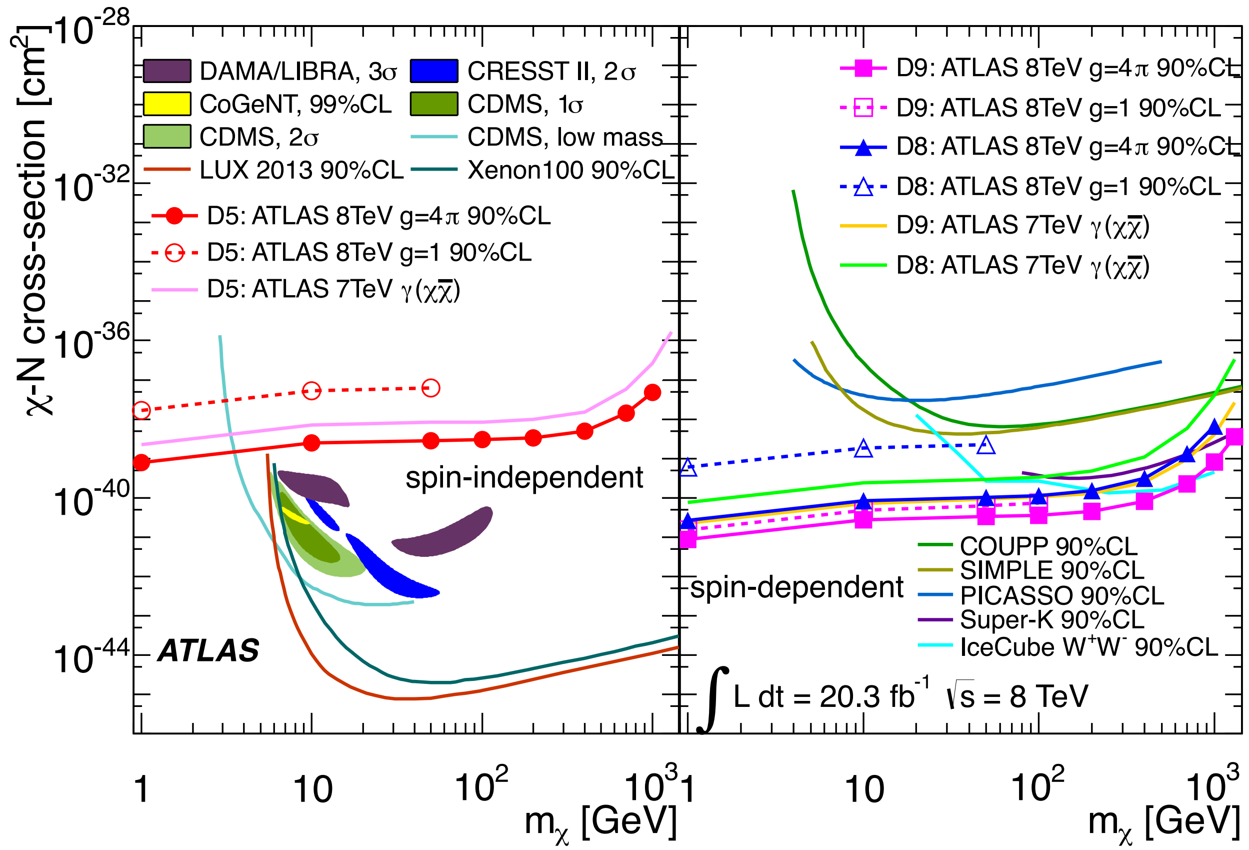


- No excess observed in signal region

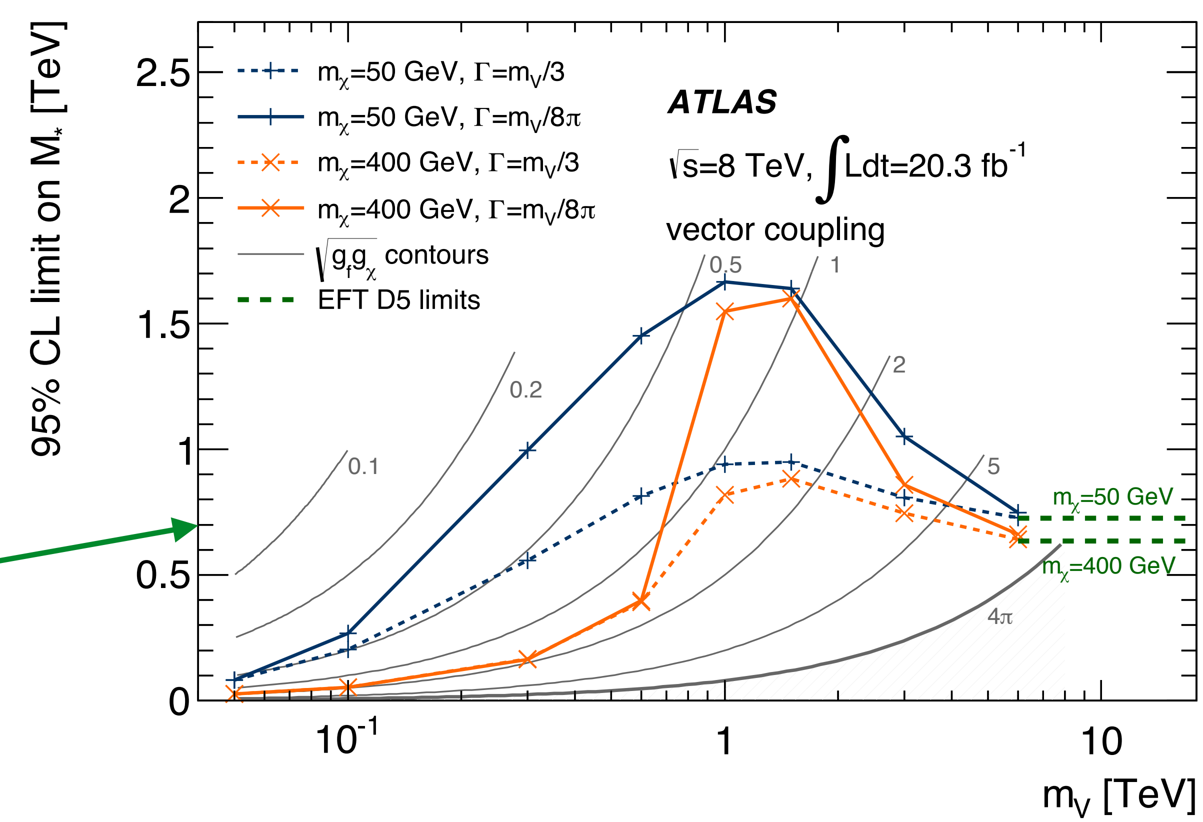
Mono-photon+ E_T^{miss} : results

(arXiv:1411.1559v2[hep-ex])



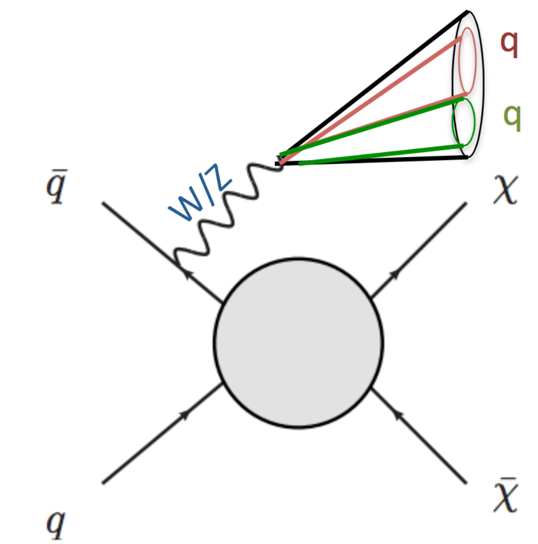


- all measurements are consistent with the SM.
- truncation procedure applied to ensure EFT validity.
- limits for three EFT operators (D5, D8 and D9)
- For very high mediator mass, limits should approach EFT (green dashed lines)



Mono-W/Z+ E_T^{miss} (hadronic)

(arXiv:1309.4017[hep-ex])



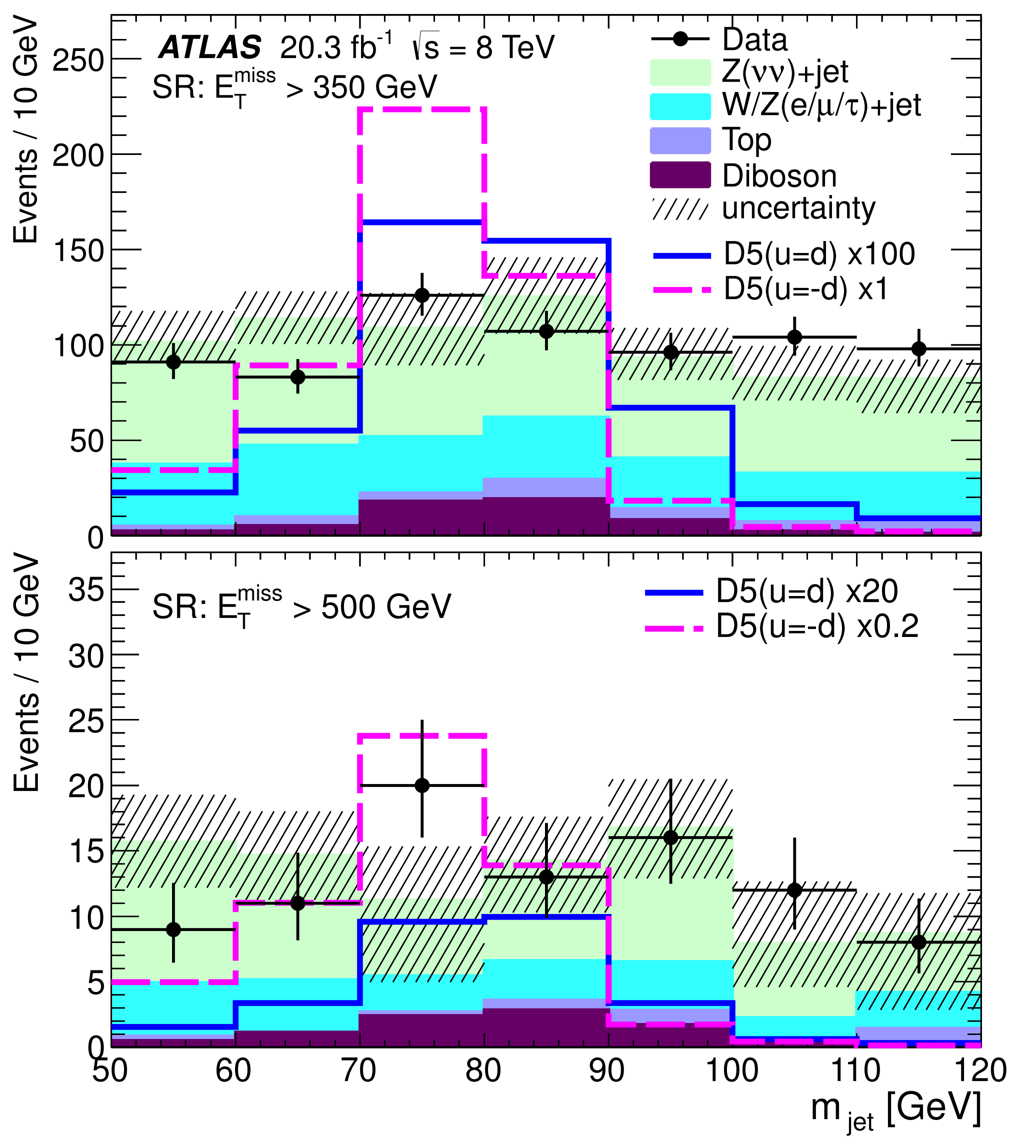
- 'Boosted' analysis : W/Z have large enough p_T that decay jets merge into a large-radius jet (*fat-jet*)

  Due to interference effects mono-W can be more sensitive

Selection:

- At least a large radius jet (*p_T >250 GeV*)
- *m_{jet} ∈[50,120] GeV*
- Lepton and photon vetoes
- overlap between narrow jet (p_T^{jet}>40GeV) and the fat-jet
- 2 signal regions with: *E_T^{miss}>350, 500 GeV*

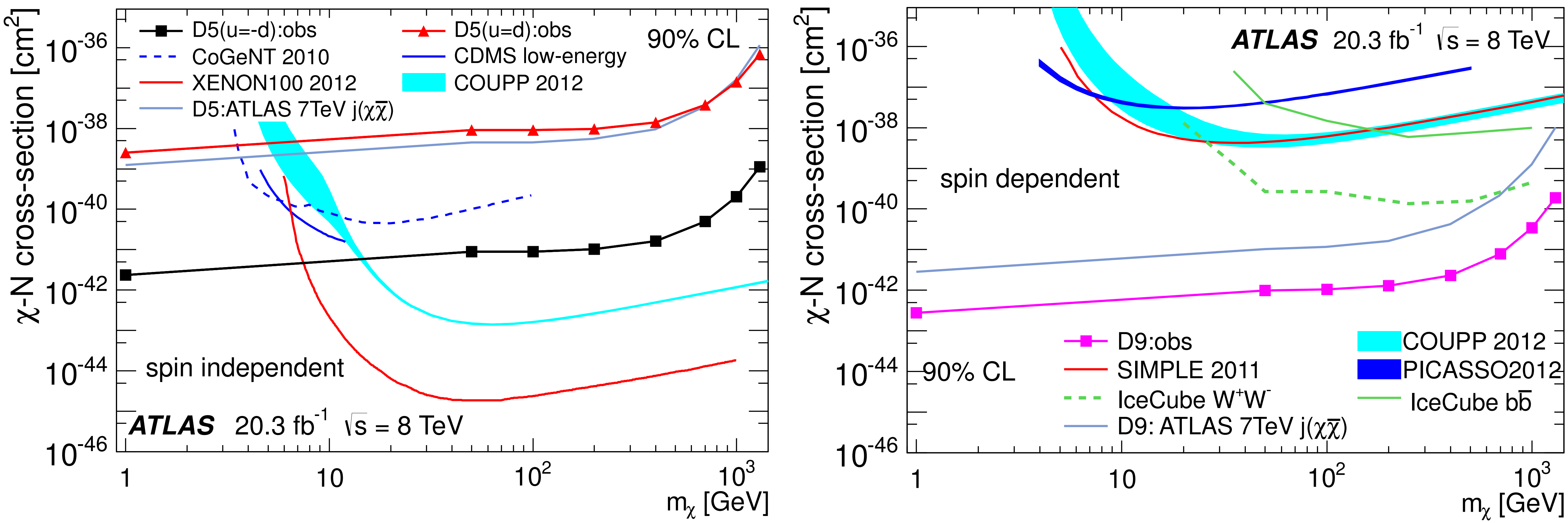
→ Look for an excess in the m_{jet} distribution



Main background:

- ***Z(νν)+jets*** , ***W(ℓν)+γ*** : estimated in data control regions
- ***W/Z(e/μ/τ)+jets***
- *Estimated from data control region*

Mono-W/Z+ E_T^{miss} (had.) : results (arXiv:1309.4017[hep-ex])



- When up-type and down-type couplings of *W* have opposite signs, ratio of mono-*W* >> rate of all other mono-boson production.

- limits for four EFT operators (C1, D1, D5, D9) .

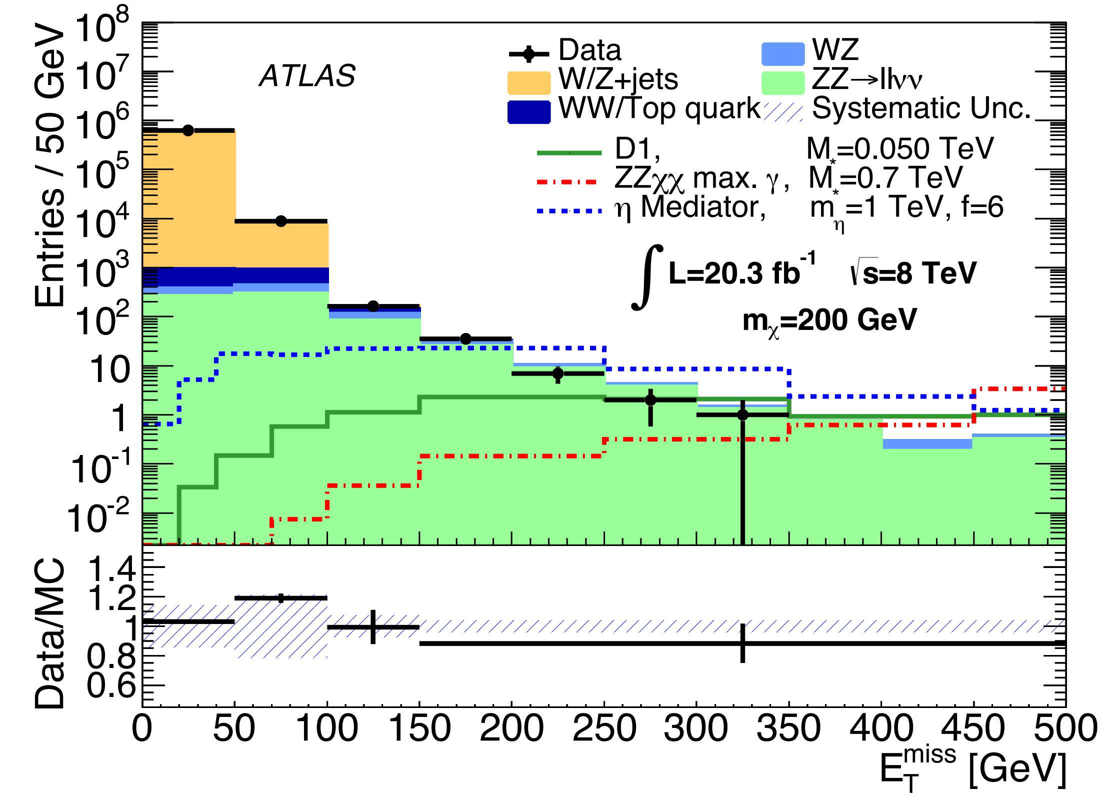
Mono-W/Z+ E_T^{miss} (lep.)

- Clean signatures with leptons at the final state.

$Z \rightarrow \ell^+\ell^-$ (arXiv:1404.0051v3[hep-ex])

- Two leptons with opposite charge *(ℓ=e, μ)*
- $m_{\ell\ell} \in [76, 106]$ GeV
- Jet and third lepton vetoes
- Main background: dibosons

→ **Search for an excess in events with high E_T^{miss}**

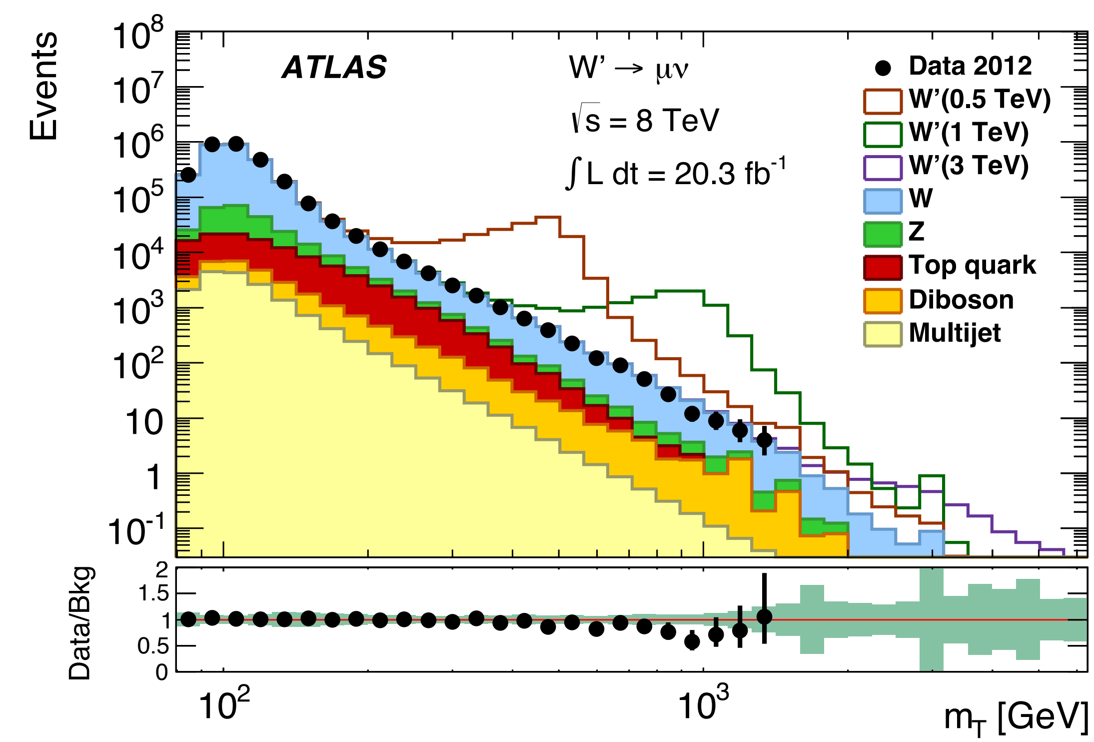


$W \rightarrow \ell\nu$ (arXiv:1407.7494v1[hep-ex])

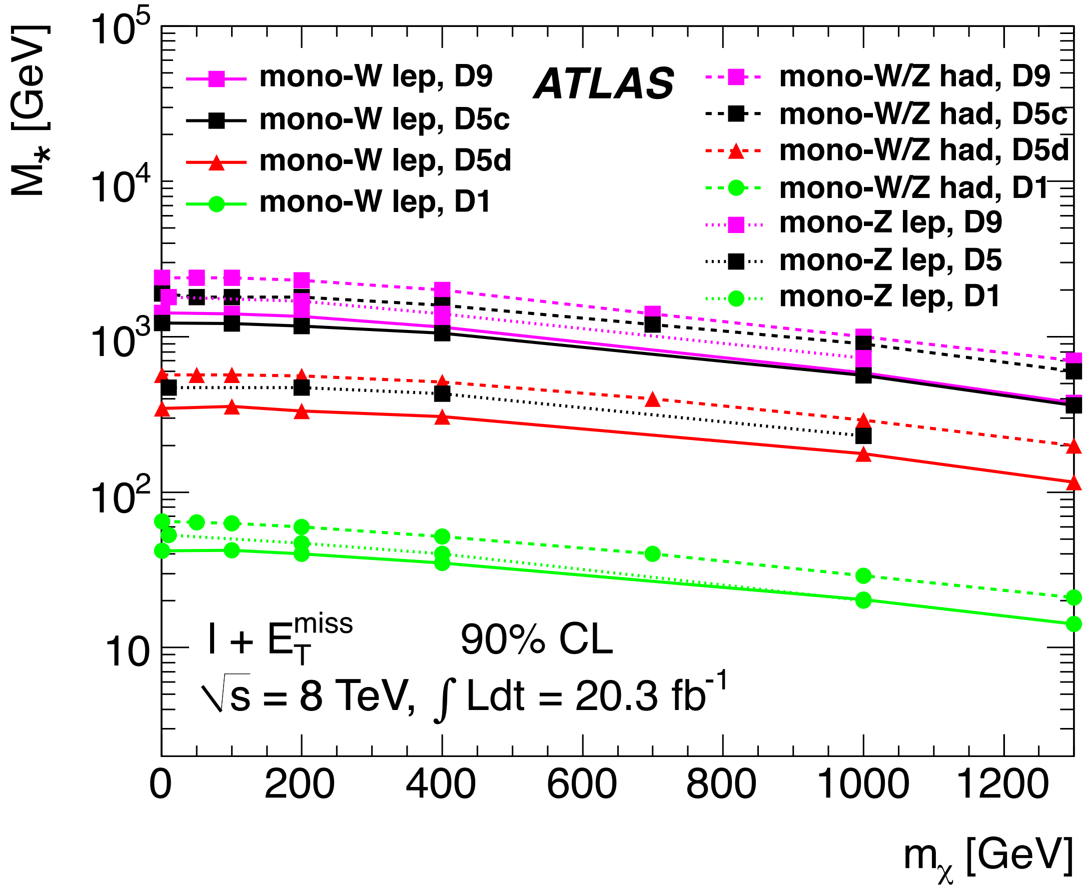
- One lepton (electron or muon).
- *e-channel : E_T>125 GeV and E_T^{miss}>125 GeV*
- *μ-channel : p_T>45 GeV and E_T^{miss}>45 GeV*
- Main background: *$W(\ell\nu)$ tail, $Z(\ell\ell)$ misidentified lepton, leptonic taus in $W(\tau\nu)$, $Z(\tau\tau)$*, dibosons

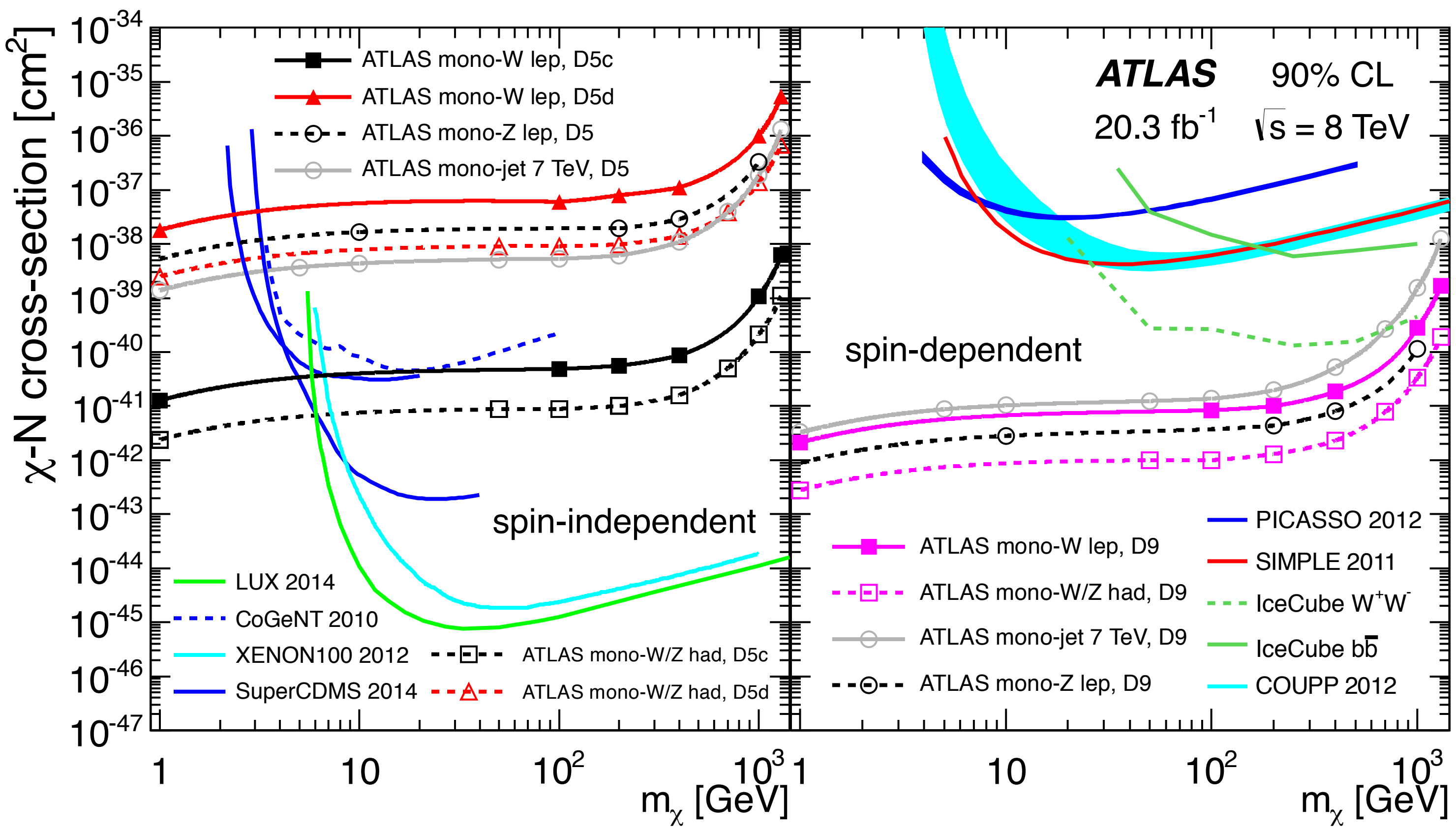
$$m_T = [2 p_T E_T^{miss} (1 - \cos\phi_{\ell\nu})]^{1/2}$$

→ **Look for an excess in events with high m_T**



Mono-W/Z+ E_T^{miss} (lep.) : results





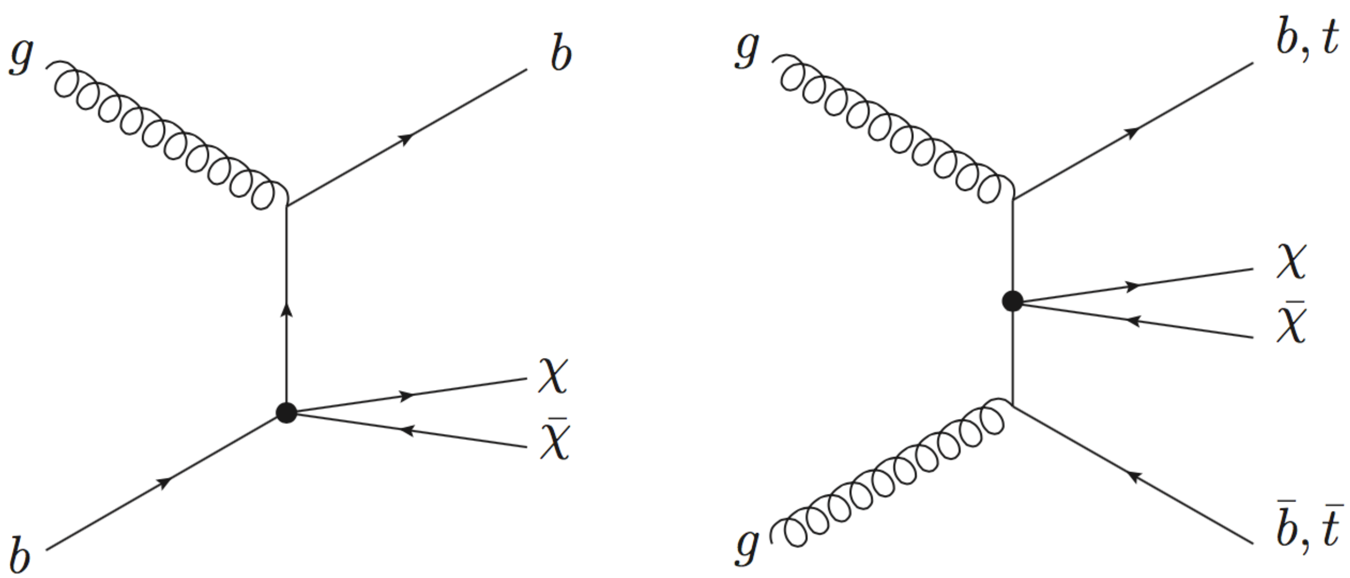
Stronger limits on M_* when W/Z decay hadronically

Heavy flavor+ E_T^{miss}

(arXiv:1410.4031v2[hep-ex])

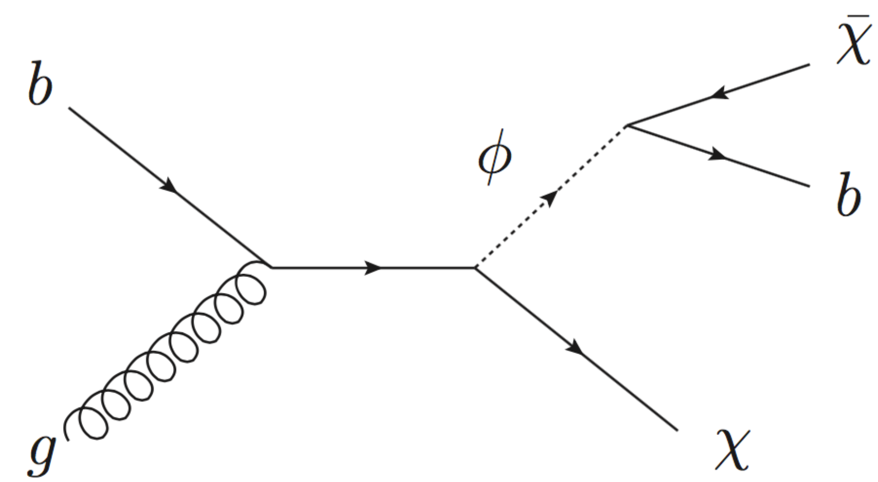
- Dark Matter search in final states with heavy flavour motivated on a variety of grounds.

EFT



In effective scalar-mediated interactions, DM couplings largest to massive quarks

Simplified model

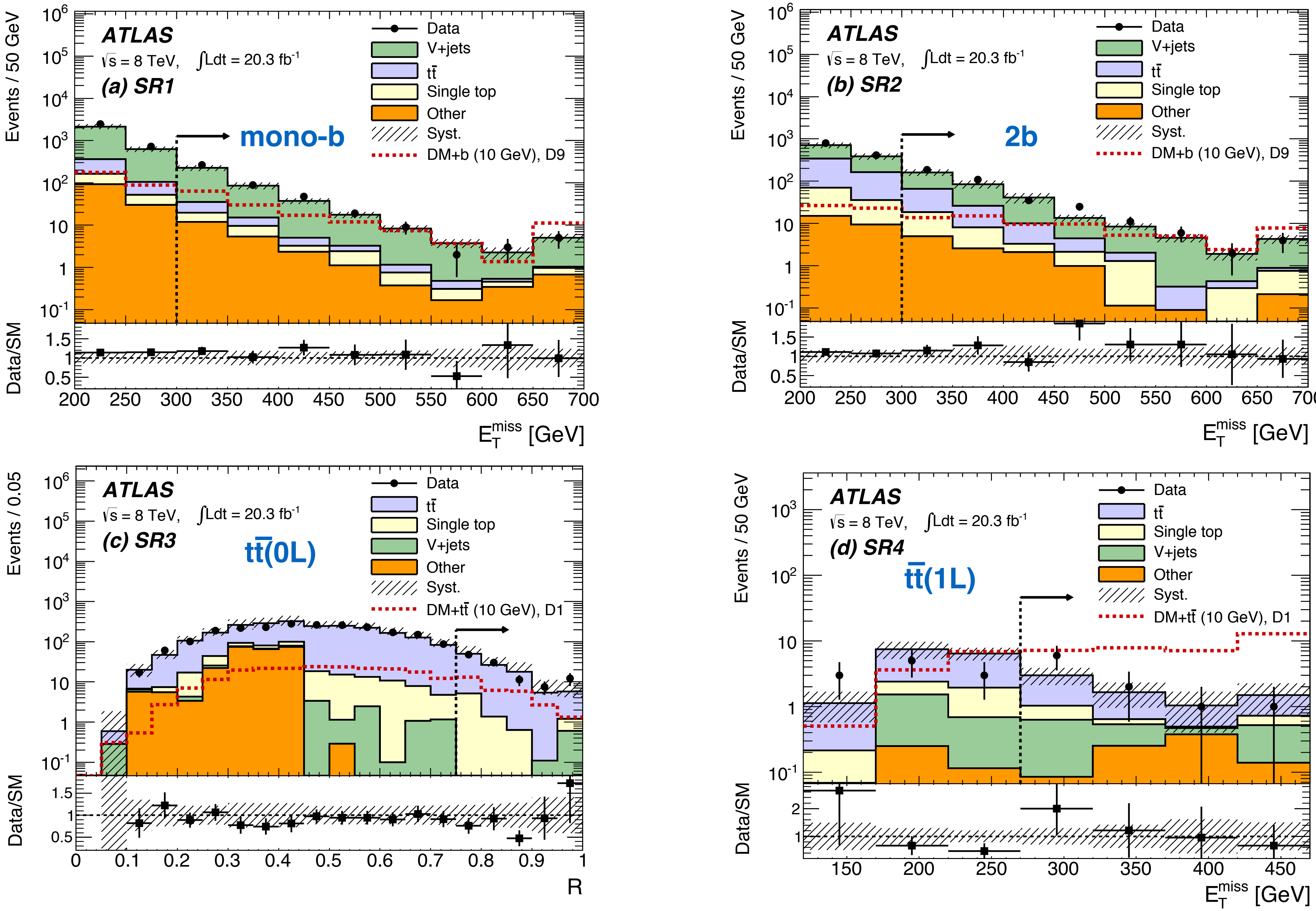


***b*-flavored DM(b-FDM) model, motivated by Fermi-LAT excess**

- Analysis uses 4 signal regions defined to target DM production with :
  - 1 or 2 *b* quarks
  - $t\bar{t}$ pair with all-hadronic or semi-leptonic decays
  - Large E_T^{miss}
- Selection in each region optimised wrt targeted final state and background

Heavy flavor+ E_T^{miss}

(arXiv:1410.4031v2[hep-ex])



- Data/SM comparisons in the different Signal Regions (SR). Good agreement.

- $t\bar{t}$(0L) uses a Razor variable (R) as discriminant .
(arXiv:1006.2727[hep-ex])

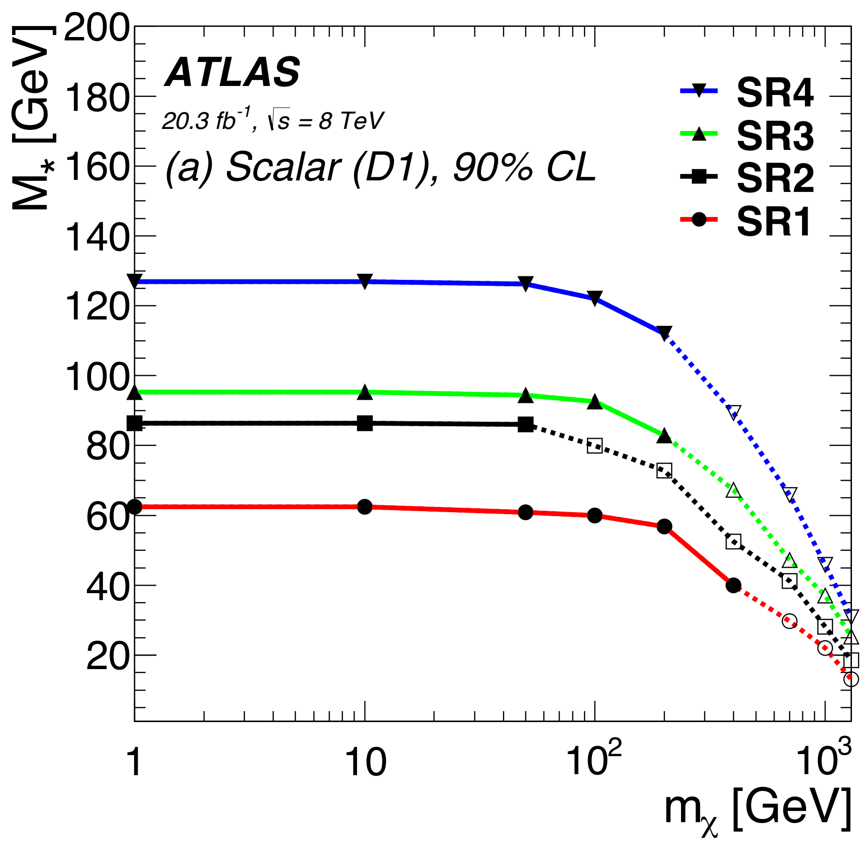
$$M_R \equiv \sqrt{(|\vec{p}_{J_1}| + |\vec{p}_{J_2}|)^2 - (p_z^{J_1} + p_z^{J_2})^2}$$

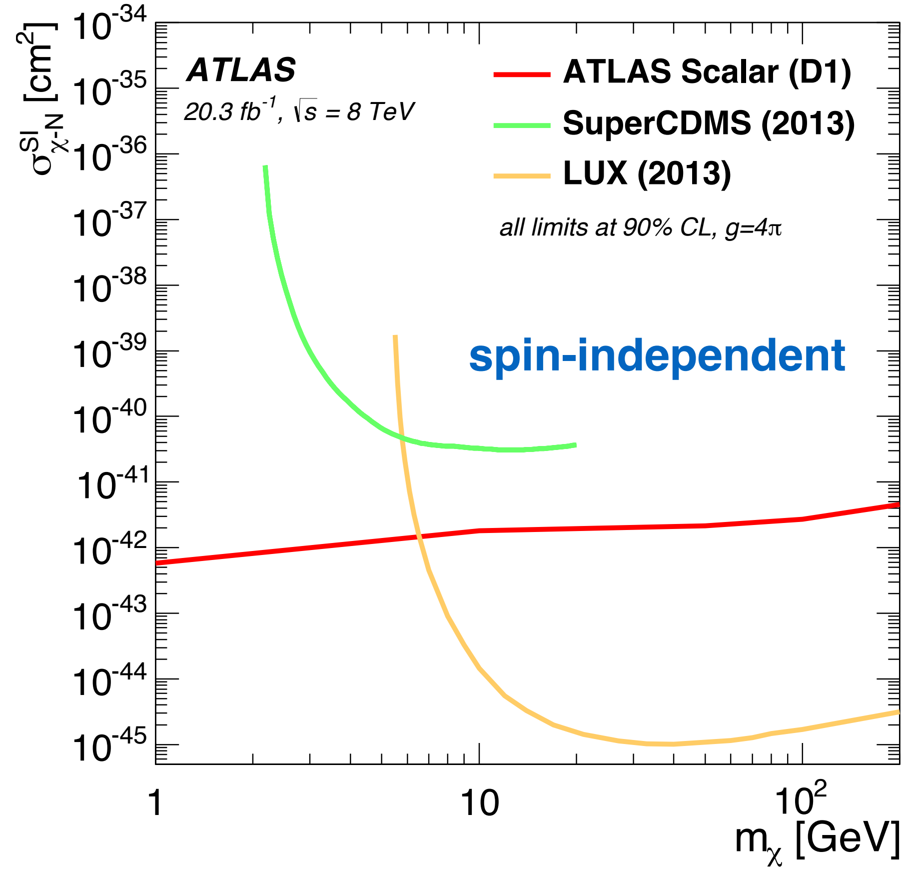
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{J_1} + p_T^{J_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{J_1} + \vec{p}_T^{J_2})}{2}}$$

$$R \equiv \frac{M_T^R}{M_R}$$

Heavy flavor+ E_T^{miss} : results

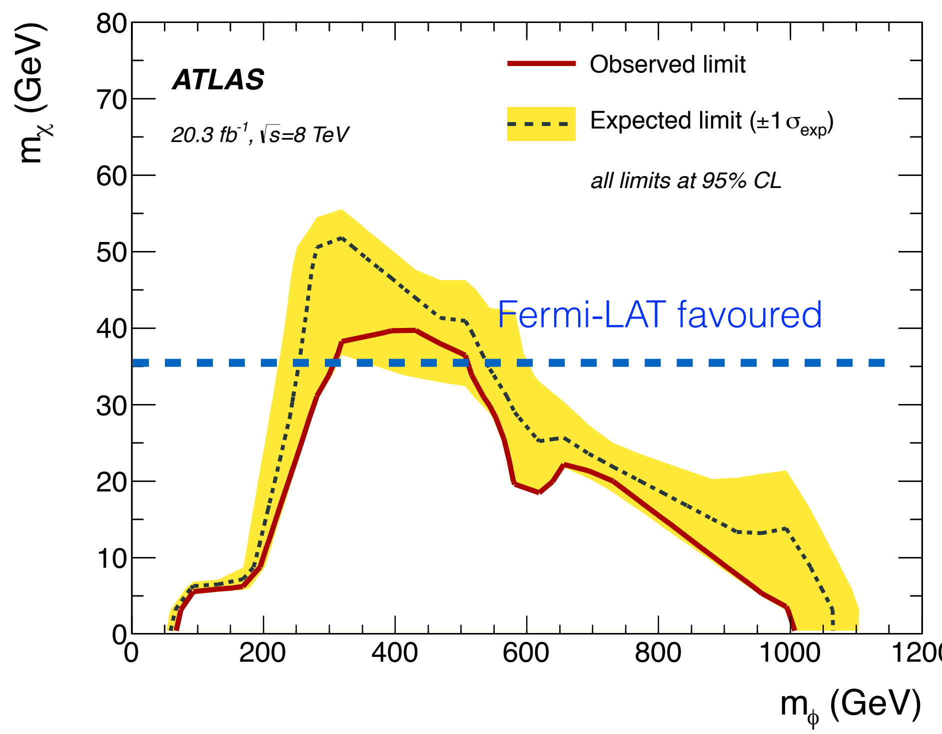
(arXiv:1410.4031v2[hep-ex])





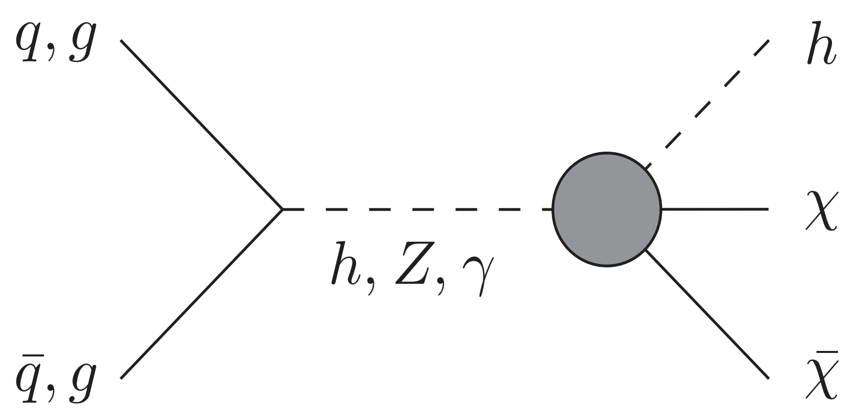
- limits for three EFT operators (C1, D1, D9).
  - D1 limits in top-quark SR better than in mono-jet, as scalar operators proportional to quark mass.

- Exclusion countour in *b*-FDM model :
  - Fermi-LAT interpretation suggests m_{DM} ~35GeV
  - For this m_{DM}, simplified model excludes mediator masses in range [~300, ~500] GeV

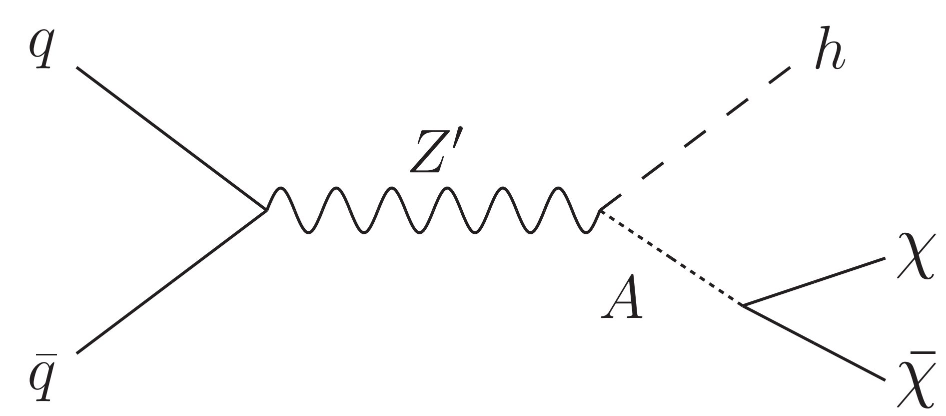


mono-H (into two b-quarks) + DM (to be submitted soon)

- Following Higgs discovery, mono-Higgs production in association with dark matter provides very interesting final states . Higgs not emitted from initial-state quarks, but from physics related to DM production.

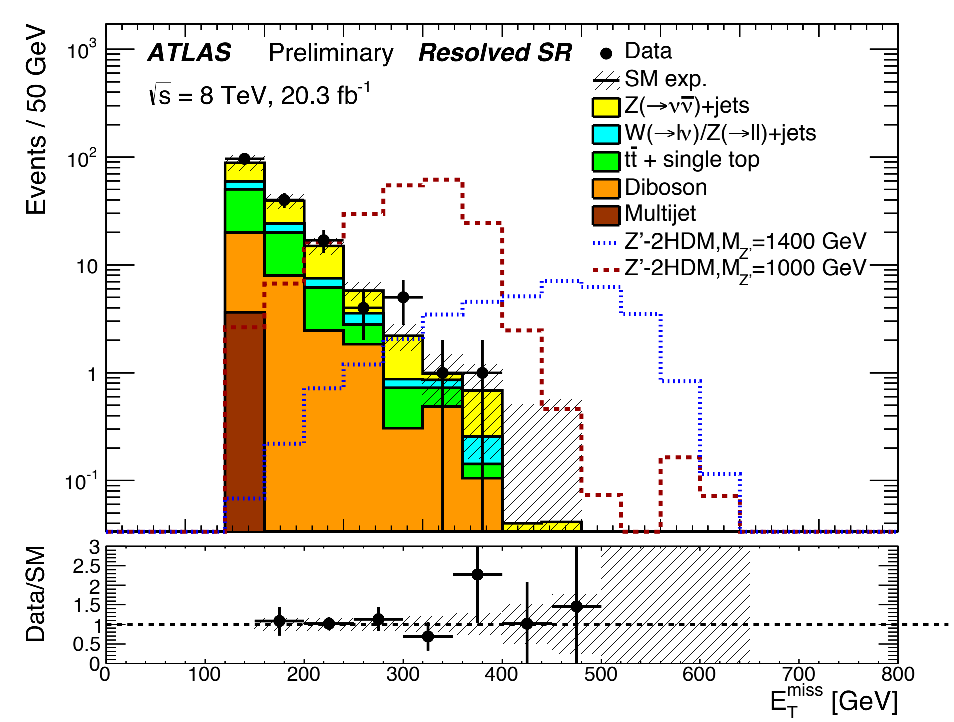


EFT contact operator



Z' mediator in 2HDM

- ***Higgs boson final states as a high-momentum bb system***
  - *$\Delta\phi_{min}(j_i, E_T^{miss}) > 1$.*
  - *Two signal regions have been considered :*
    - ***a pair of small radius jets (resolved)***
    - ***single large radius jet (boosted)***
  - *$m_{b1b2}/m_{Jet} \in [90,150]$ GeV*
  - Large cuts in *E_T^{miss} from 150 GeV to 400 GeV*



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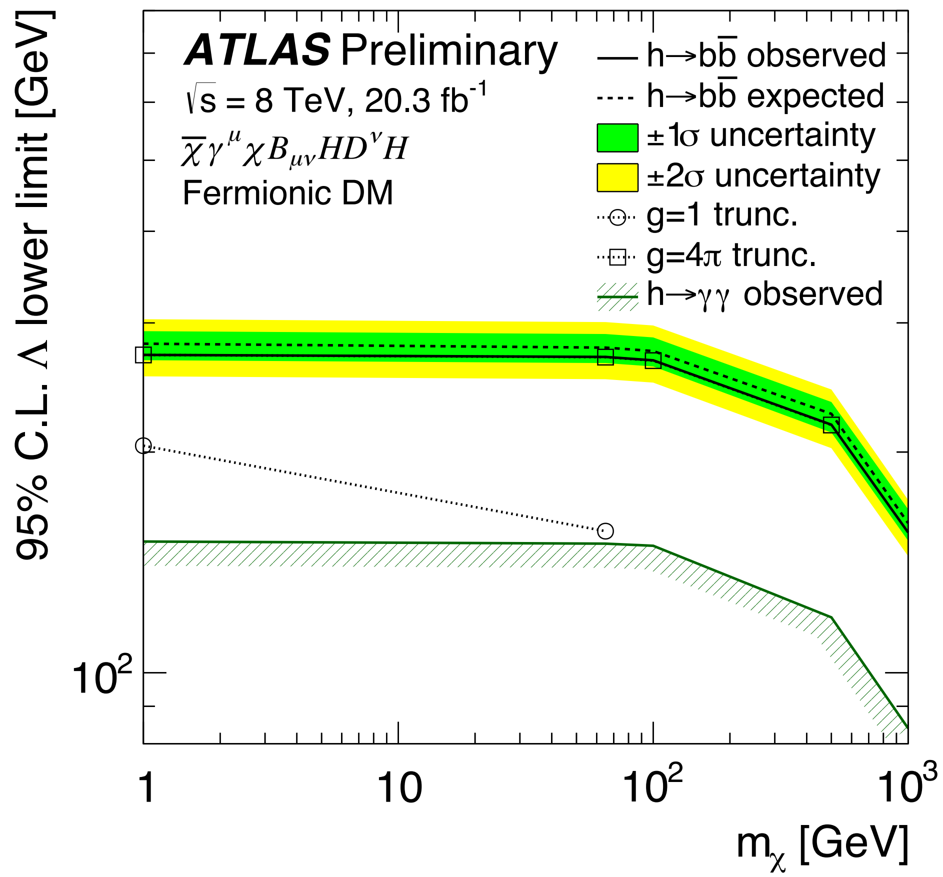
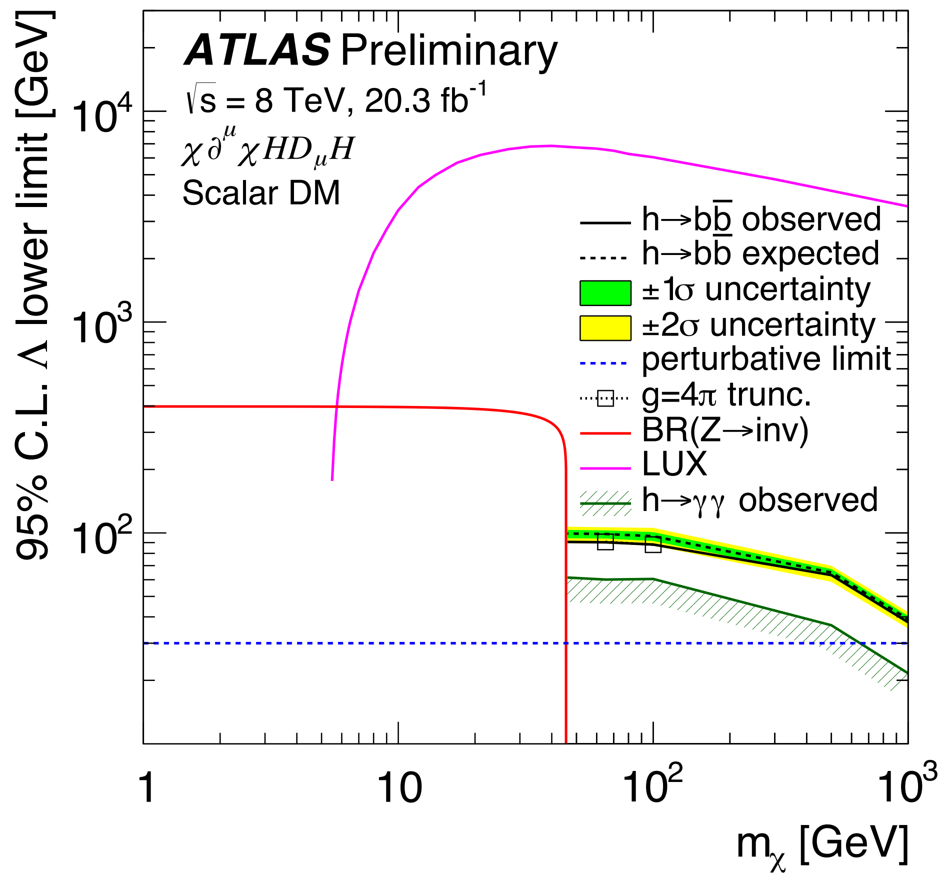
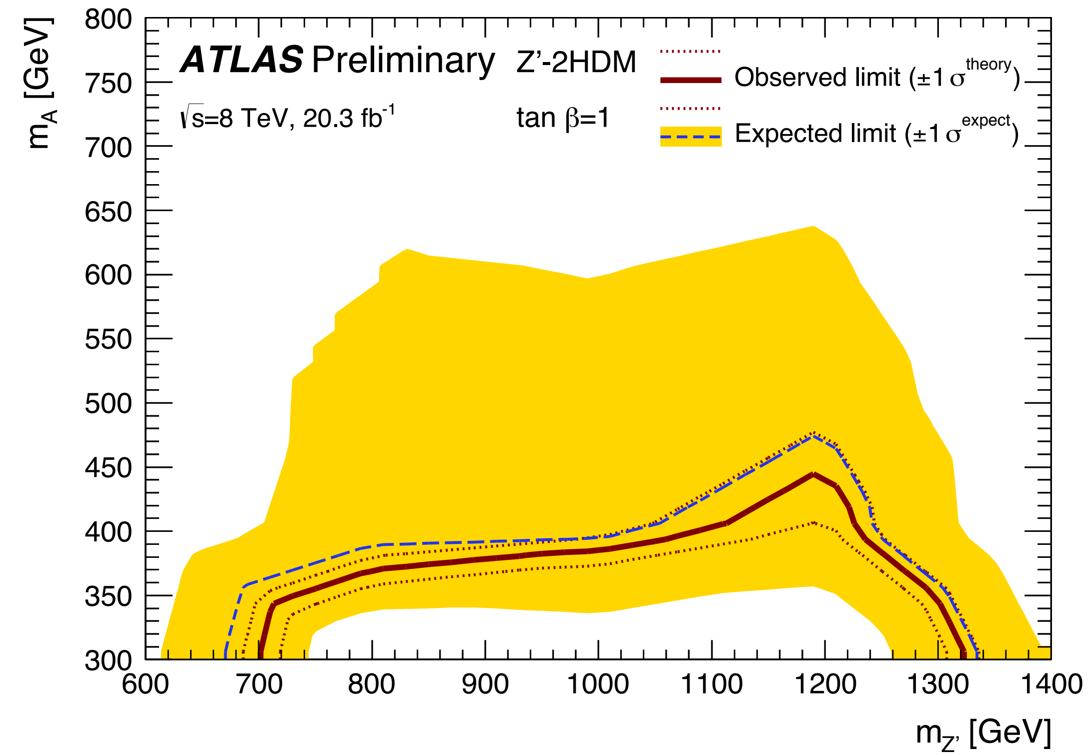




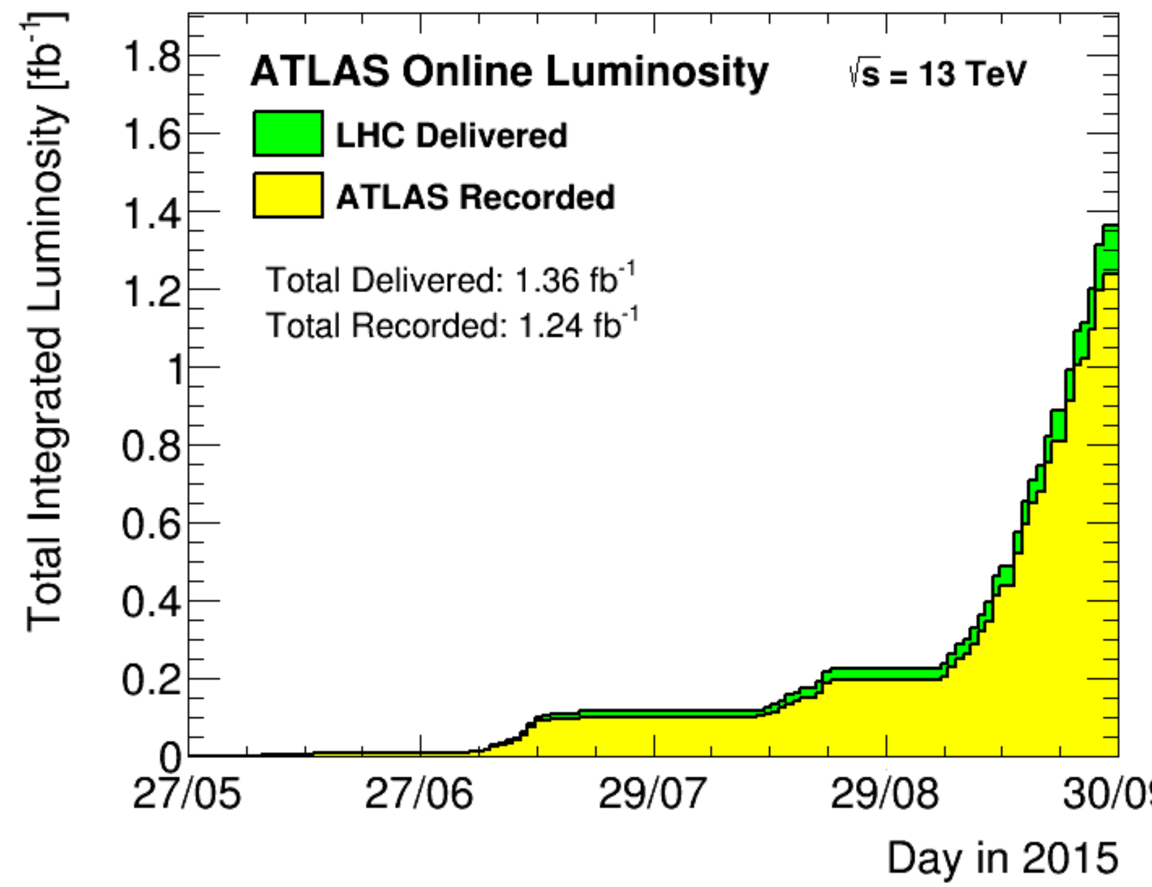
- Boosted SR is used to interpret 95% CL limits on the suppression scale Λ or coupling parameter λ for EFT models.

- Resolved SR sets 95% CL upper limits to exclude portions of parameter space of the *Z′-2HDM* model . Parameters spaces below the limit contours are excluded.



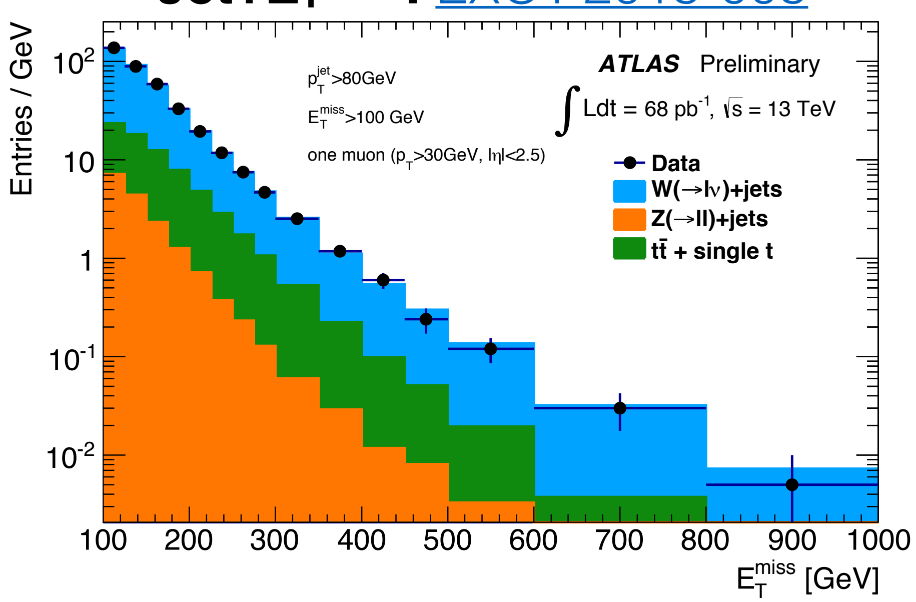
Toward LHC Run 2.

- Run 2 is underway
  - Benchmark models for dark matter search in Run2:
    - Trend is to move away from EFTs, focus in simplified models as much as possible



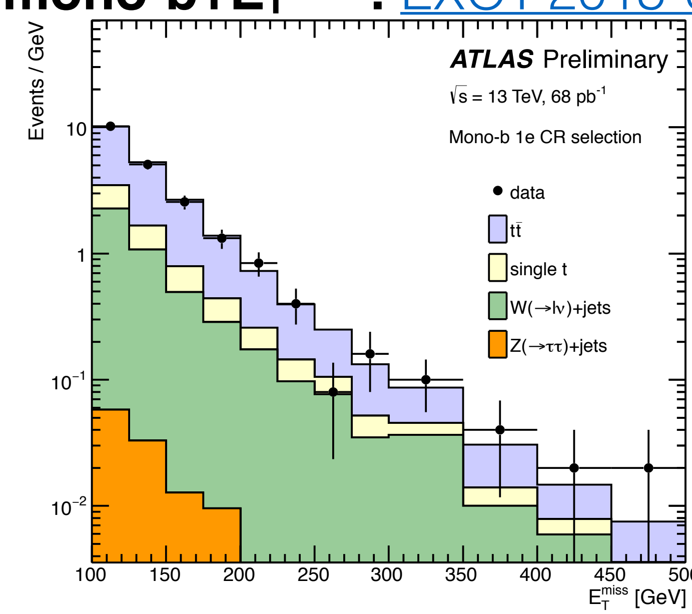
Early DM analysis plots from Run 2.

Jet+E_T^{miss}: EXOT-2015-005



- E_T^{miss} in $\boldsymbol{W\rightarrow\mu\nu}$ in control region.

mono-b+E_T^{miss}: EXOT-2015-007



- E_T^{miss} in ***1e*** control region.

- 68 pb^{-1} of data at 13 TeV.
- Prediction normalised to data.

Conclusions

- Broad variety of DM searches in ATLAS
- All data consistent with SM expectations
  - Significant regions of parameter space have been scanned.
  - Limits on New Physics using both EFT approach and simplified models.
- Excellent complementarity of ATLAS results and those from direct and indirect dark matter search experiments.
- Sensitivity increases significantly with 13 TeV.

Backup slides

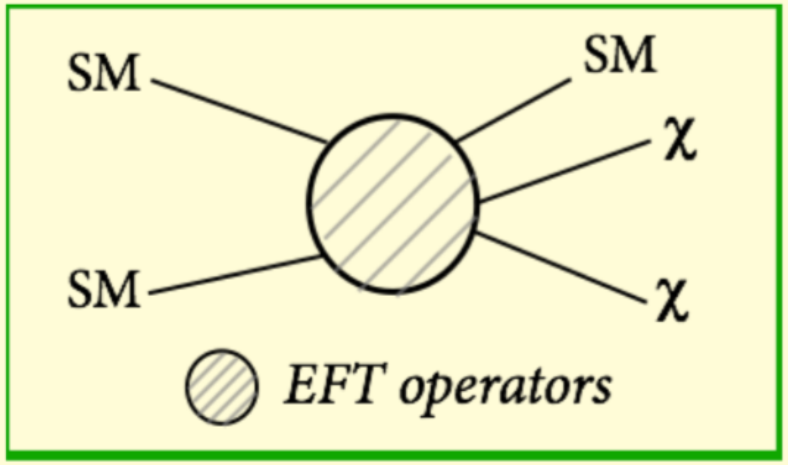
mono-H (into two b-quarks) + DM (to be submitted soon)

	Resolved	Boosted
$\Delta\phi_{\min}(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, j_i)$	> 1.0	> 1.0
Jet multiplicity	$2 \leq n_j \leq 3$	$n_J \geq 1$ $n_{j^{\mathrm{trk}}} \geq 2$
b-jet (60% eff.) p_{T}	$p_{\mathrm{T}}^{b_1} > 100$ GeV	-
b-jet multiplicity	$n_b \geq 2$ (60% eff.)	$n_{b^{\mathrm{trk}}} = 2$ (70% eff.)
Jet p_{T}	$p_{\mathrm{T}}^{b_2} > 60$ GeV when $n_j = 3$ $p_{\mathrm{T}}^{j_2} > 100$ GeV when $n_j = 3$	$p_{\mathrm{T}}^{J_1} > 350$ GeV
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	-	$< \pi/2$
Dijet separation	$\Delta R(j_1, j_2) < 1.5$	-
Invariant mass	90 GeV $\leq m_{b_1 b_2} \leq$ 150 GeV	90 GeV $\leq m_{J_1} \leq$ 150 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150, 200, 300, or 400 GeV	> 300 or 400 GeV

Effective Field Theories

$$L_{eff} = \sum_{quarks} G_\chi O(\chi, q) + G_\chi O(\chi, G).$$

$$G_\chi = \left(\frac{\sqrt{g_q g_\chi}}{M_\Psi}\right)^x \equiv \left(\frac{1}{M_*}\right)^x \rightarrow$$ **one parameter** (+ χ mass)



WIMP-DM (χ)	ID	interaction	Operator	G_χ
Dirac scalar	D1	quarks	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
Dirac vector	D5	quarks	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
Dirac axial-vector	D8	quarks	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
Dirac tensor	D9	quarks	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
Dirac scalar	D11	gluons	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
complex scalar	C1	quarks	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
complex scalar	C5	gluons	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$

Each **operator** can be classified in a systematic way. Different **signatures have different sensitivity to each operator**.

Effective Field Theories interpretations

Results are translated in terms of lower limits on M_*

$$M_*^{limit} = M_*^{gen} \left(\frac{\sigma_{th}}{\sigma_{excl}} \right)^{1/y}$$

(y depends on the operator)

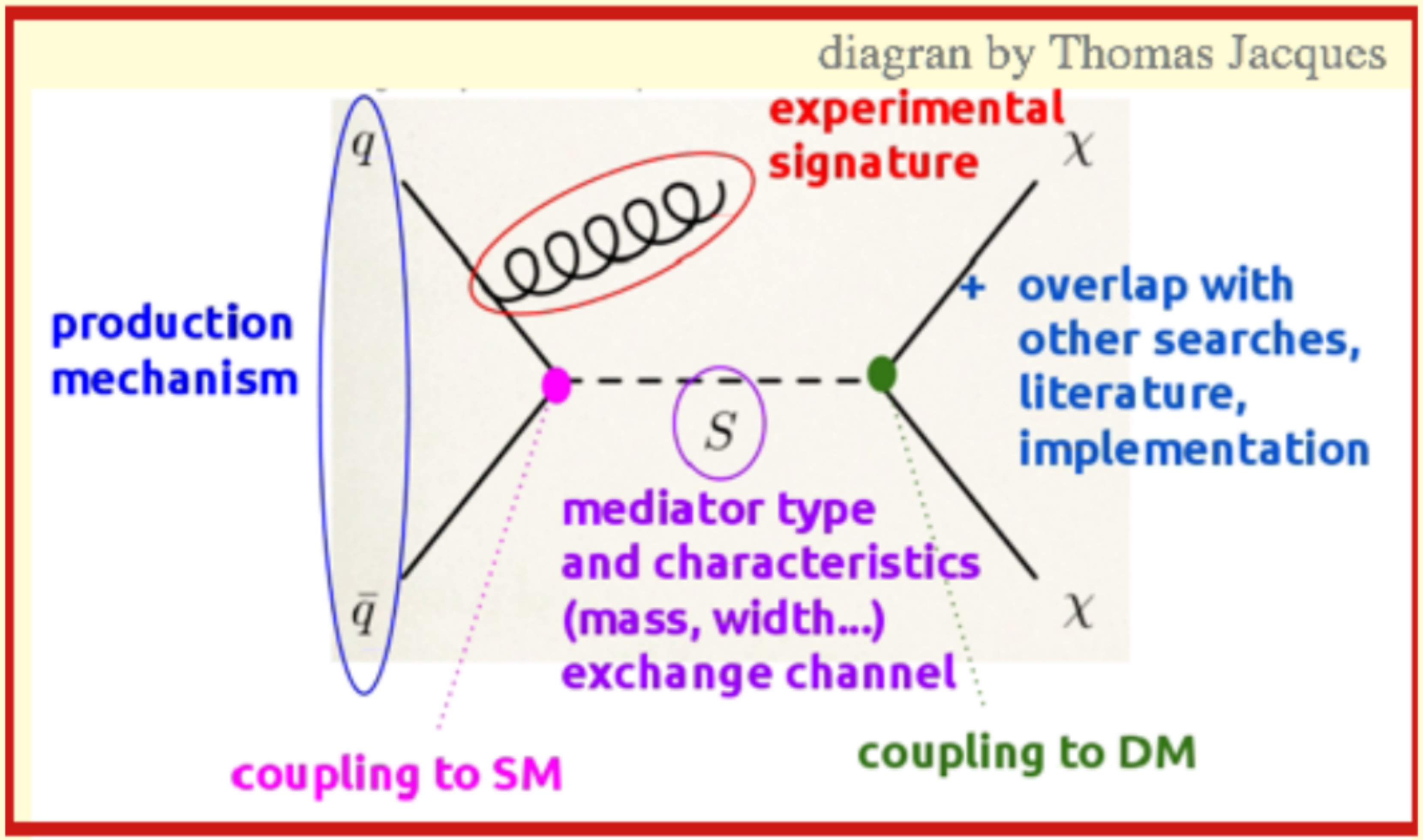
At the LHC energy, EFT assumption ($Q_{transf} << M_{med}$) might not hold. To verify this we need to assume something about the underlying physics

Different *truncation* strategies are used:

- assume simplest interaction structure and *correct* the cross section for only valid events ($Q_{transf} < f(g_q g_\chi, M_*)$)
- Evaluate the fraction of valid events R_{M_*} using an effective coupling $Q_{transf} < g_{eff} M_*$

Simplified models

- Reduce a complex model to a simple one with DM, a mediator between the SM and the Dark Sector, one interaction channel
- **Few free parameters:** m_{med}, m_{DM}, g_{SM}, g_{DM}, Γ_{med}
  + nature of mediator and DM and their interaction



- Simplified models can (also) be systematically classified
- They are always theoretically valid, although is up to the theorists to re-connect them back to the complete models

HF + DarkMatter

$$O_{D1} = \sum_{quarks} \frac{\mathbf{m_q}}{M_*^3} \bar{\chi}\chi\bar{q}q \qquad O_{C1} = \sum_{quarks} \frac{\mathbf{m_q}}{M_*^2} \chi^\dagger\chi\bar{q}q$$

- m_q motivated by MVF constraint, **enhanced coupling to top quark**
- investigation of bottom quark couplings interesting in case of only down-type interaction.