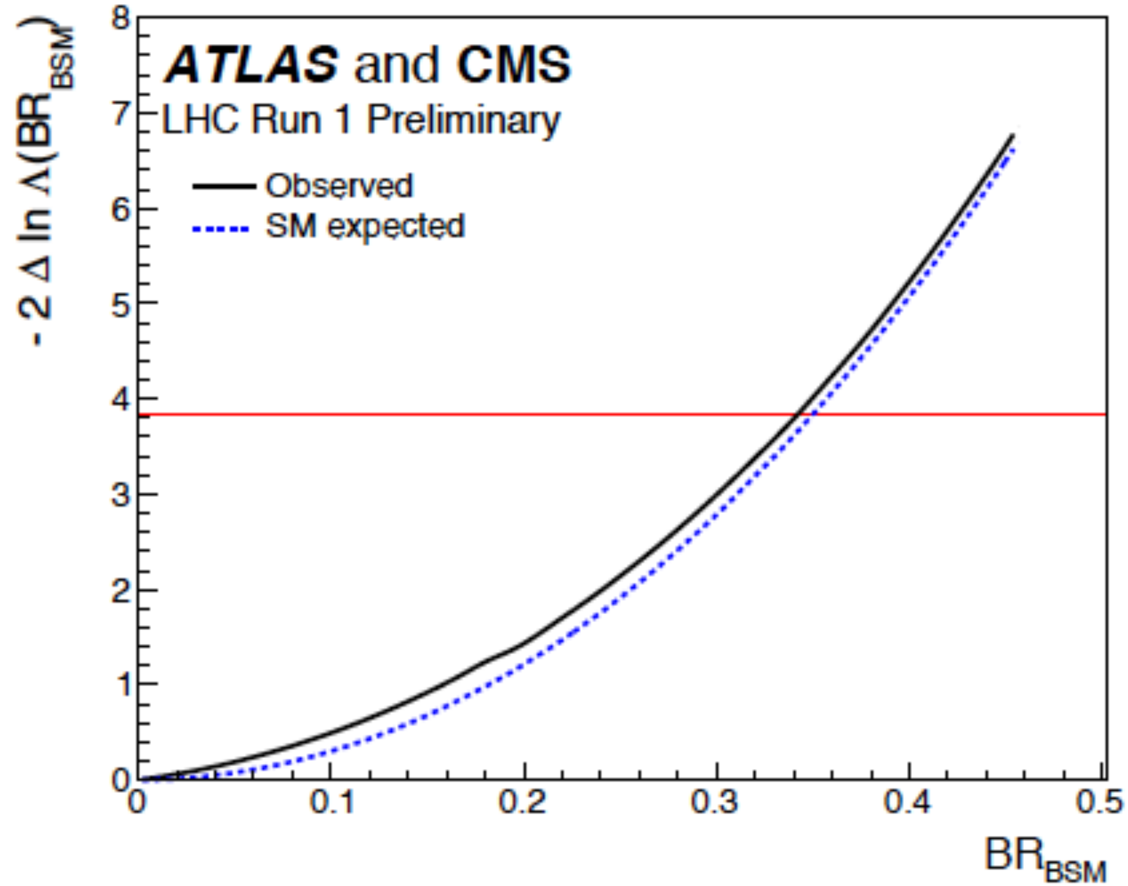
Search for Dark interactions at the LHC

Kétévi A. Assamagan
BNL

Outline

- Searches for dark interactions in the decays of h125
- Mono-X searches

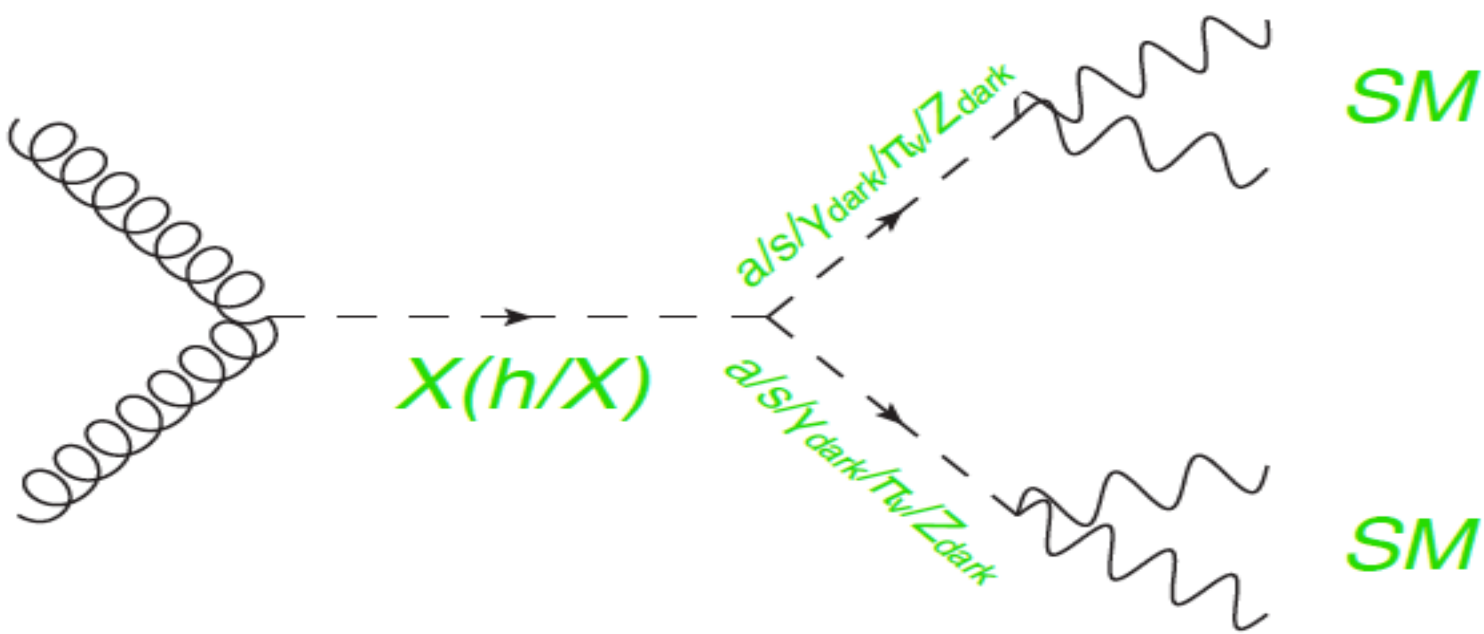
Searching for new physics in h125 decays



- BR (h125 → BSM) < 34% at 95% CL

Searching for dark interactions in h125 decays

- It could be h → WIMP (invisible/undetected)
- Or it could be



Prompt and non-prompt decays of the intermediate state

LHC Searches

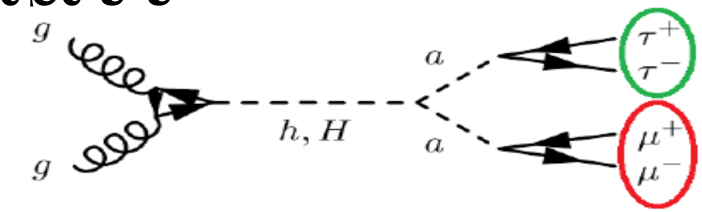
- H → aa → fermions
  - 4b
  - $2b2\tau$
  - $2b2\mu$
  - $2\mu2\tau$
  - 4τ
- H → aa → 4γ
- H → aa → 2b+Missing Energy
- H → Z (Zdark) Zdark → 4l
  - Zdark = Z_d
- H → invisible
- H → lepton-jets
- H → Long-lived particles → Displaced hadronic jets
- H → …
- Mono-X
- …

I will not address the theoretical framework. The earlier theory talks cover this. I will focus on published Run1 and Run2 searches

Run 1 searches

h → aa → μμττ

- Single μ and di-μ triggers used
- 2 signal regions, SRμ and SRe
- No significant excess in 3.7 < $m_{\mu\mu}$ (GeV) < 50
- Upper bound on h → aa production relative to the SM gg->h production

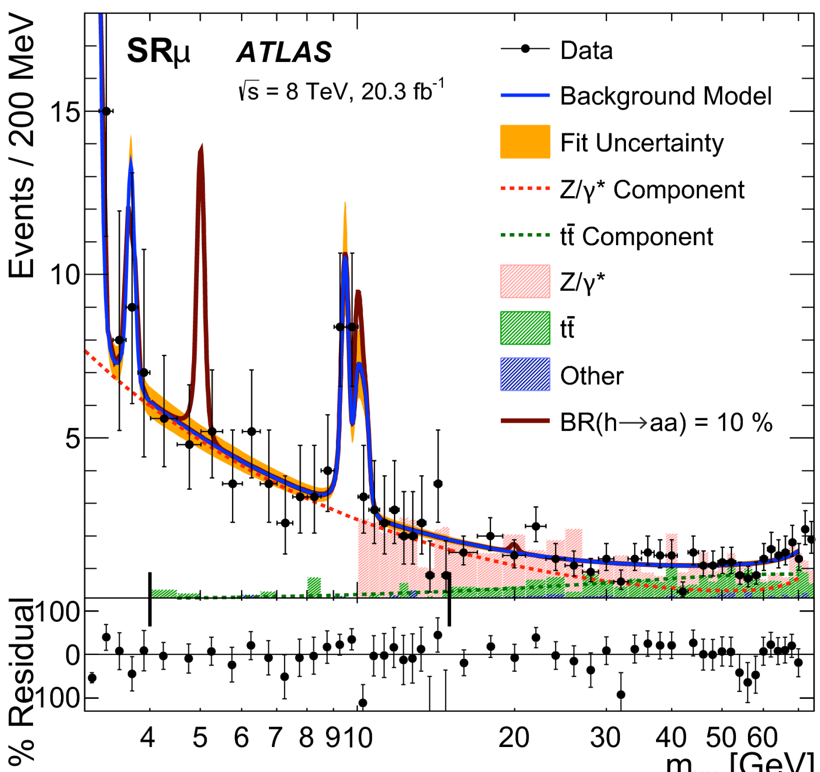


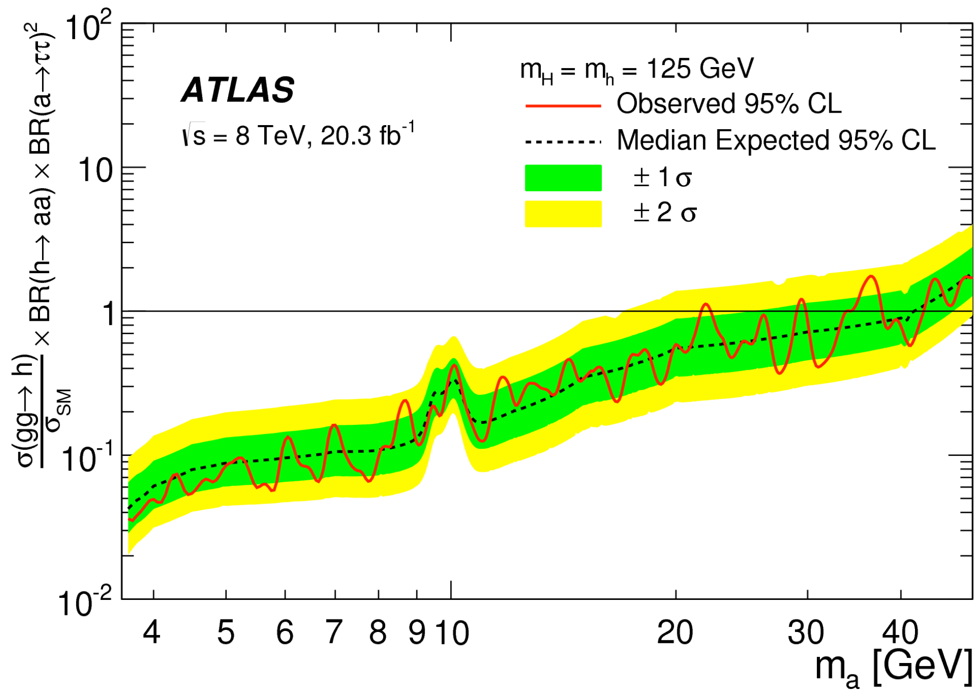
Pre-select $\mu^\pm\mu^\mp$ events

Signal Selection: $\mu^\pm\mu^\mp+\ell^\pm\mathrm{trk}^\mp$

Validation: $\mu^\pm\mu^\mp+\ell^\pm\mathrm{trk}^\pm$

Control: $\mu^\pm\mu^\mp+$(b-)jets

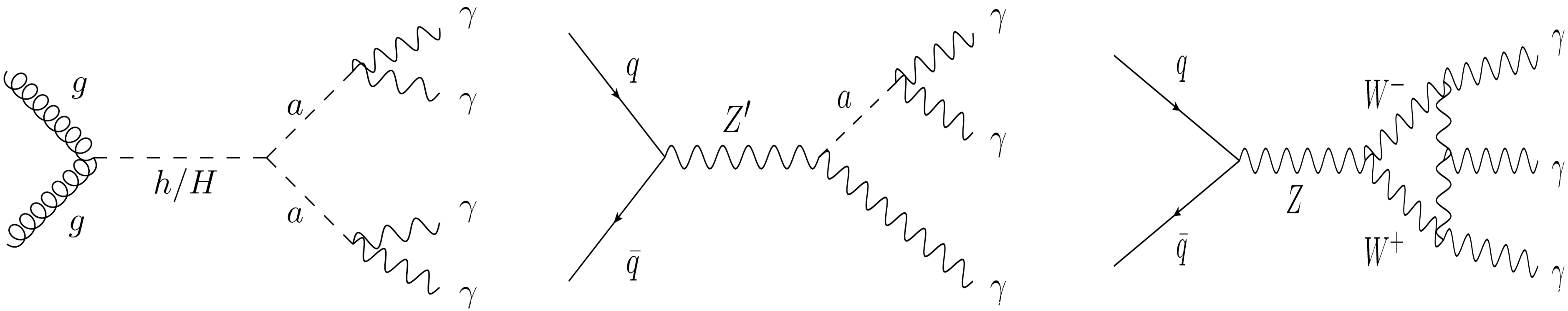




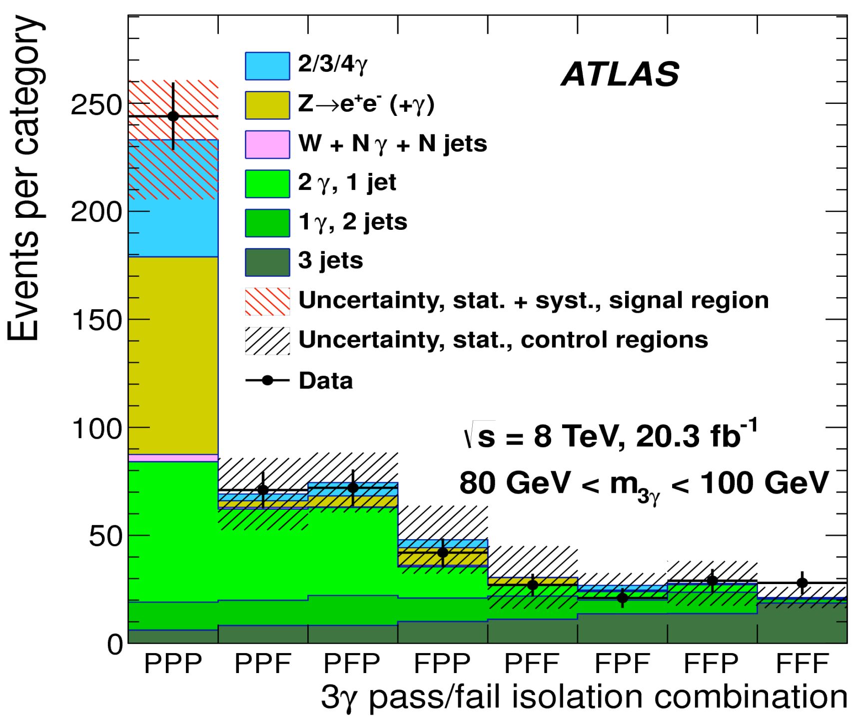
Phys. Rev. D92 (2015) 052002

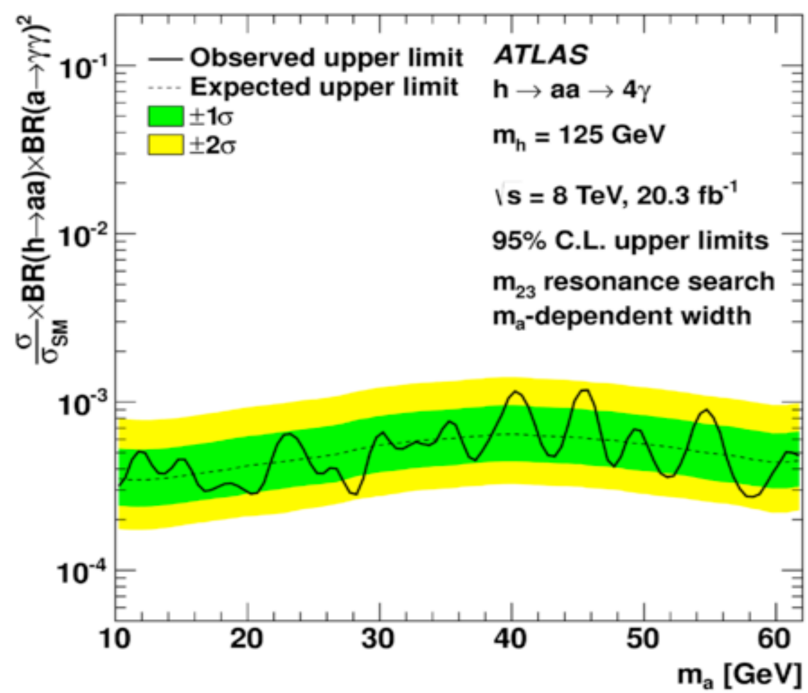
$h \rightarrow aa \rightarrow 4\gamma$

arXiv:1509.05051



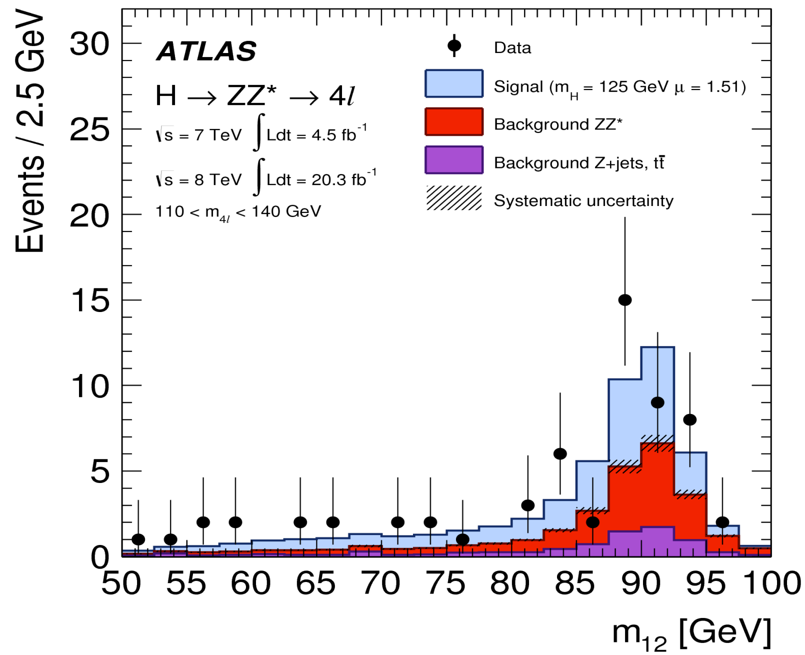
- No excess. Limits for SM $h \rightarrow 4\gamma$, $H \rightarrow 4\gamma$ and $Z' \rightarrow 3\gamma$

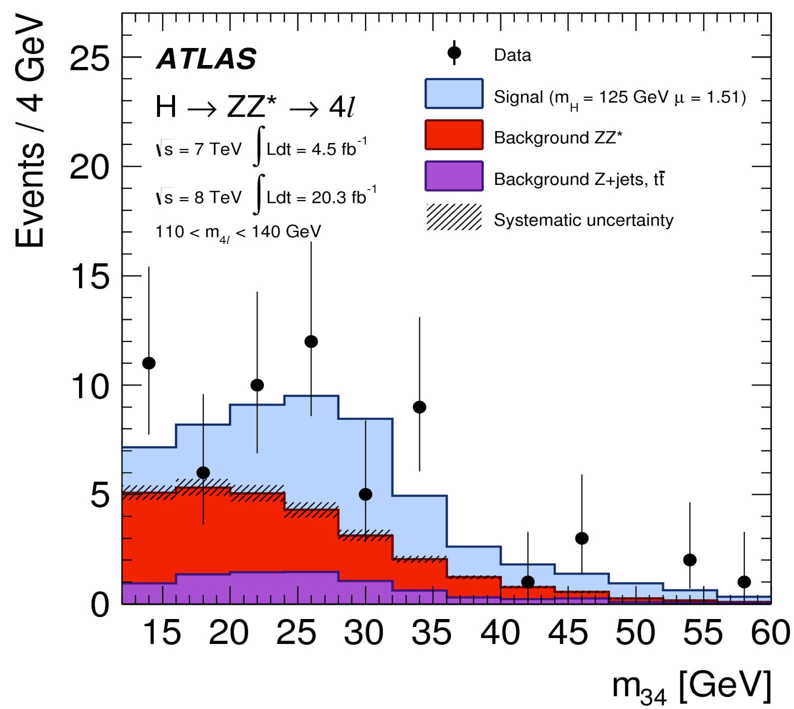




$H \rightarrow ZZ^* \rightarrow 4l$ (SM)

- $H \rightarrow ZZ^* \rightarrow 4l$ (l=e, or μ)
- Quadruplets of 4l, grouped into 2 pairs of Same Flavor Opposite Sign(SFOS) leptons
- 4l ordered with indices 1, 2, 3 and 4 such that m_{12} (first pair SFOS) and m_{34} (2^{nd} pair SFOS)
- m_{12}, leading pair, assumed to reconstruct the Z-boson
- m_{34}, sub-leading pair, assumed to reconstruct the Z^*
- Retain 1 unique quadruplet with the requirement of m_{12} closest to m_Z: $50 < m_{12} < 106$ GeV



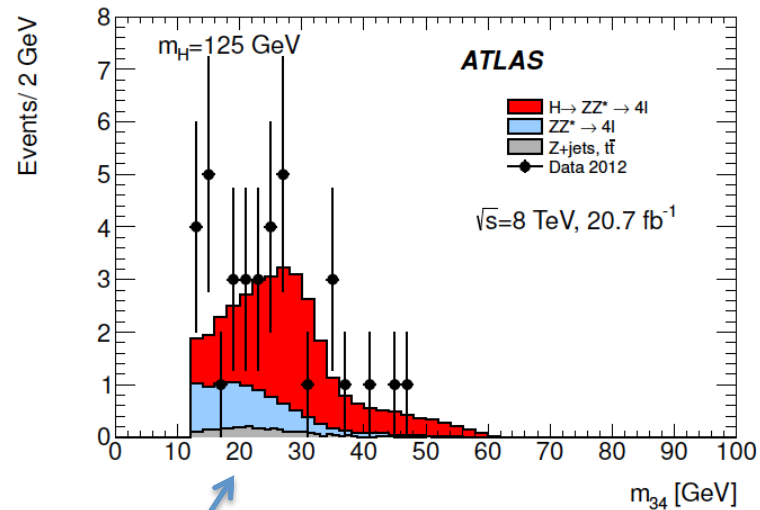


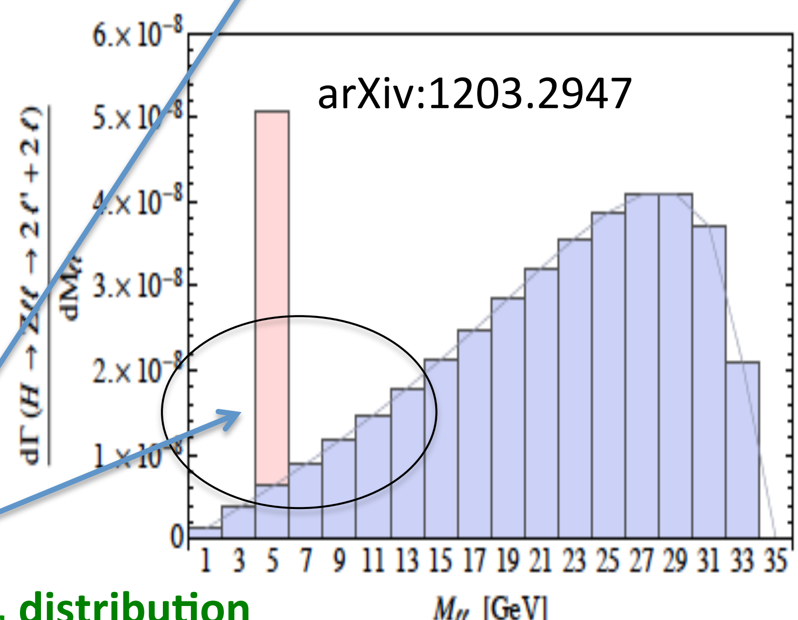
$H \rightarrow ZZ_d \rightarrow 4l$ – Run1

Phys. Rev. D 92 (2015) 092001

- Same as in the standard $H \rightarrow ZZ^*$ $\rightarrow 4l$ search until you get to the m_{34} distribution
- Z_d assumed to be narrow and on-shell
- **Take a model for the signal line shape $Z_d \rightarrow 2l$, smeared with detector resolution, and search for a narrow peak in the m_{34} distribution**
- $115 < m_{4l} < 130$ GeV
- Covers the range $m_{Zd} < m_H - m_Z$ ~35 GeV
- However, because of this requirement on m_{12}, $50 < m_{12} < 106$ GeV, the coverage in m_{Zd} can be extended to 55 GeV
- **No excess of events seen consistent with : $H \rightarrow ZZ_d \rightarrow 4l$**

  in $15 < m_{2l} < 55$ GeV



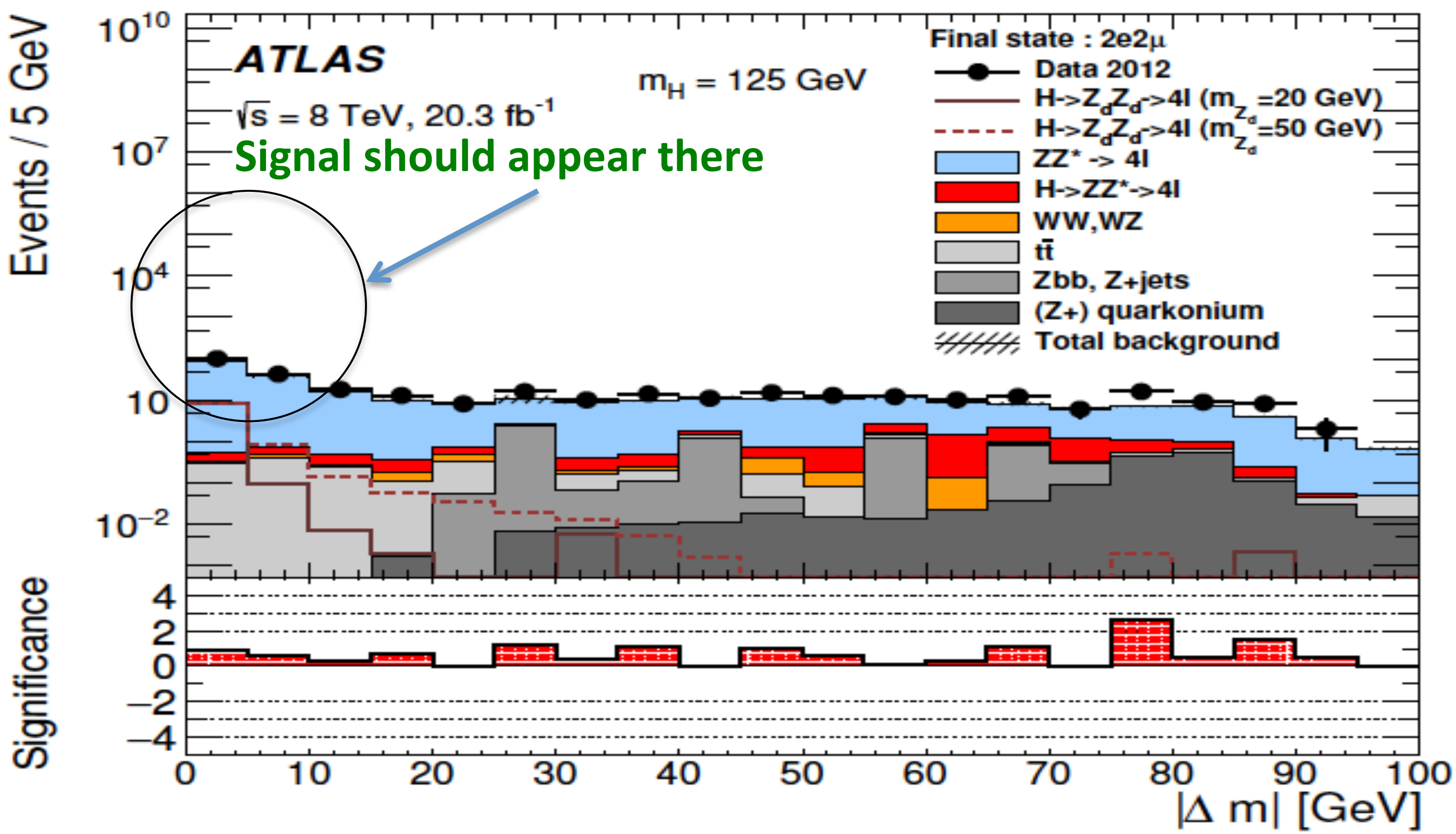


Signal should appear as a narrow peak in m_{34} distribution

$H \rightarrow Z_d Z_d \rightarrow 4l$ – Run1

- Start with the identification of 4leptons as in $H \rightarrow ZZ^* \rightarrow 4l$, and the formation of 4l quadruplets with SFOS
- Select the unique quadruplet by exploiting the mass difference **$\Delta m = |m_{12}-m_{34}|$ minimal**
- $115 < m_{4l} < 130$ GeV
- **Apply a Z-veto and J/Psi and Upsilon-Veto**

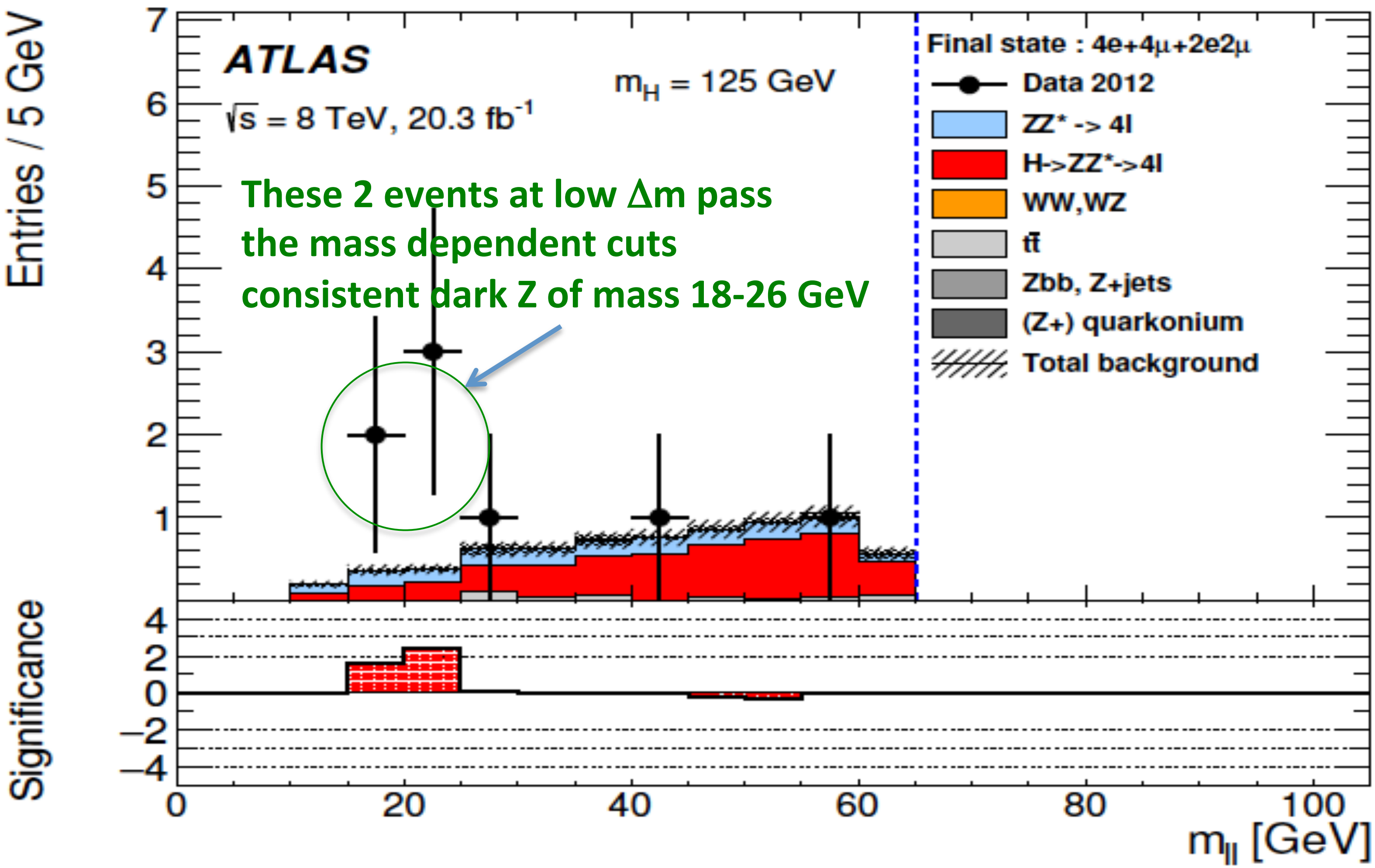
Phys. Rev. D 92 (2015) 092001



$H \rightarrow Z_d Z_d \rightarrow 4l$

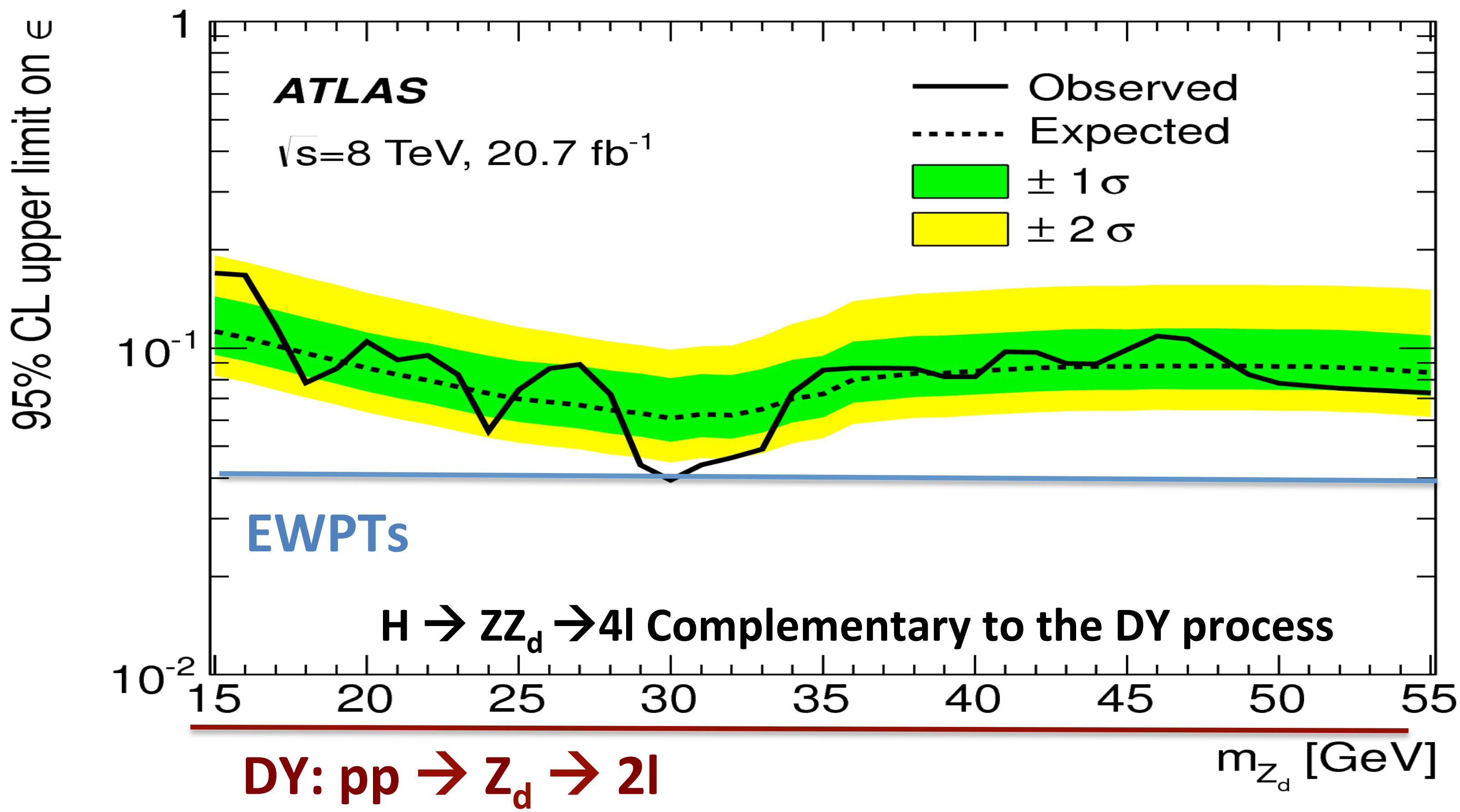
- No significant excess. $1.7\sigma(4e)$ and $1.7\sigma(4\mu)$. 0 event in $2e2\mu$

Loose Signal Region: $15 < m_{2l} < m_H/2$



ε from BR ($H \rightarrow ZZ_d \rightarrow 4l$) measurement

- Use the calculations of Curtin et al, arXiv: 1412.0018 to extract ε from the BR ($H \rightarrow ZZ_d \rightarrow 4l$). $\varepsilon \gg \kappa$



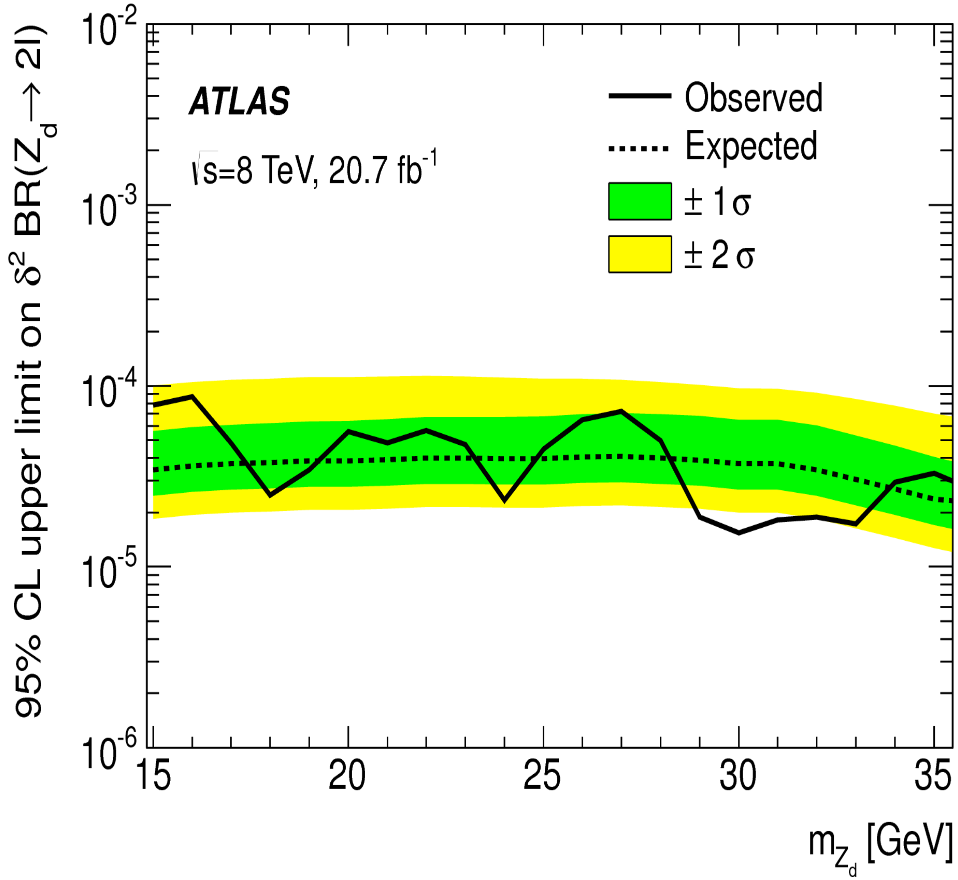
Upper bound on the Z-Z_d massing mixing parametr δ from BR ($H \rightarrow ZZ_d \rightarrow$ 4l) measurement

- One can show that in the limit of $m_{Zd}^2 \ll (m_H^2 - m_Z^2)$:

Davoudiasl et al, arXiv: 1304.4935, arXiv: 1203.2947

$$\frac{R_B}{(1-R_B)} \simeq \delta^2 \times \mathrm{BR}(Z_d \rightarrow 2\ell) \times \frac{\mathrm{BR}(Z^* \rightarrow 2\ell)}{\mathrm{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{\mathrm{SM}}},$$

$$f(m_{Z_d}) = \frac{1}{16\pi} \frac{(m_H^2 - m_Z^2)^3}{v^2 m_H^3}.$$

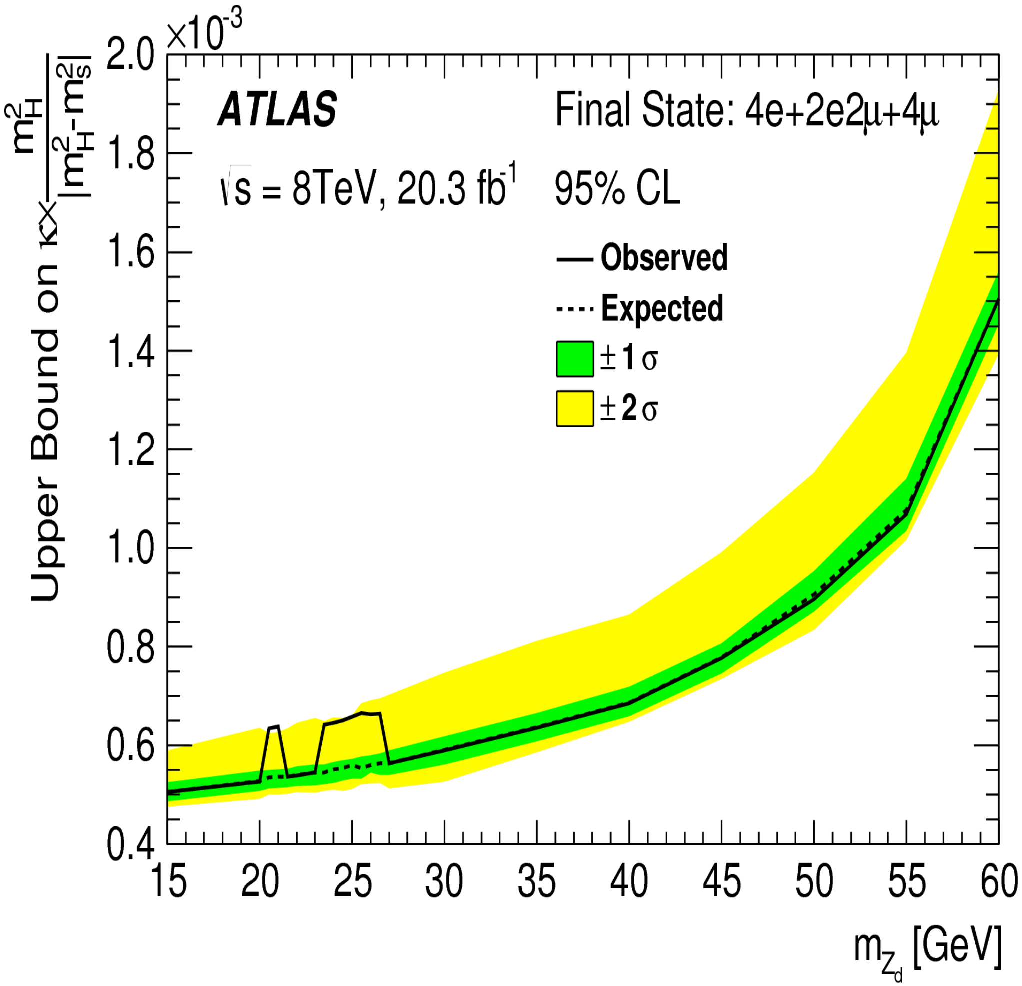


Upper bound on Higgs mixing parameter κ from $H \rightarrow Z_d Z_d \rightarrow 4l$

- From Curtin et al, arXiv: 1412.0018, one can show that κ relates to our measurement as follows:

$$\kappa^2 = \frac{\Gamma_{SM}}{f(m_{Z_d})} \frac{BR(H \to Z_d Z_d)}{1 - BR(H \to Z_d Z_d)},$$

$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1 - \frac{4m_{Z_d}^2}{m_H^2}} \times \frac{\left(m_H^2 + 2m_{Z_d}^2\right)^2 - 8\left(m_H^2 - m_{Z_d}^2\right) m_{Z_d}^2}{\left(m_H^2 - m_S^2\right)^2}.$$



$K \gg \varepsilon$

$m_S > m_H/2$

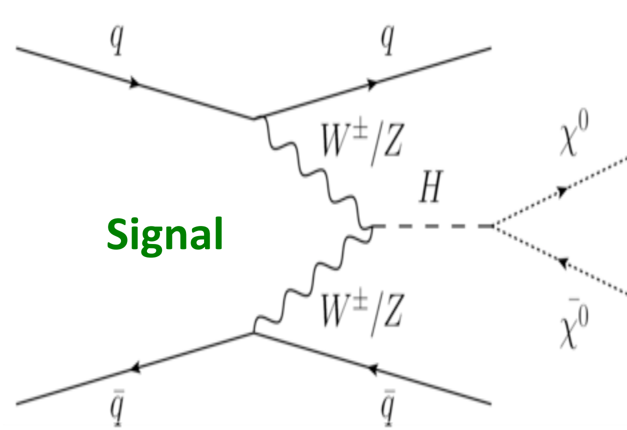
h → invisible

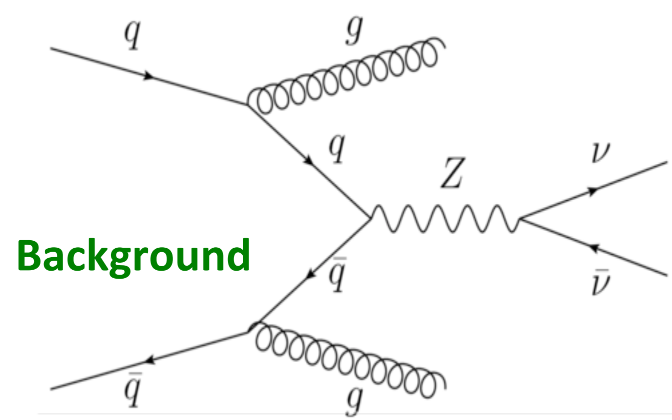
H → invisible Run 1 Results

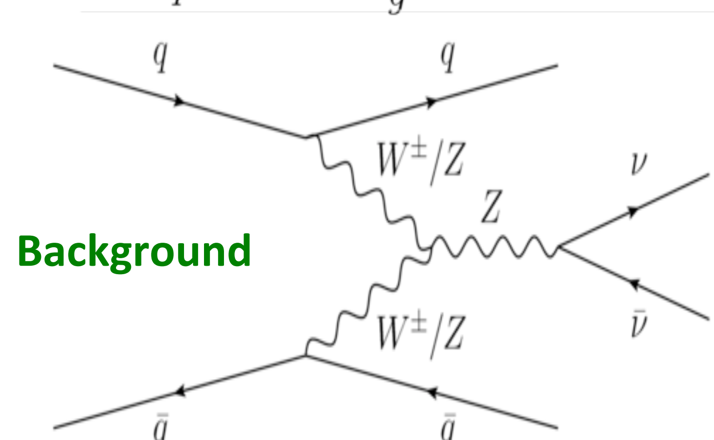
- **ZH, Z → ll (l=e, μ) and H → invisible**
  - Phys. Rev. Lett. 112, 201802 (2014)
  - Upper bound on BR (H → invisible): Obs (Exp) 0.75 (0.62)
- **VH, V → jj and H → invisible**
  - Eur. Phys. J. C75.7 (2015) 337, arXiv: 1504.04324 [hep-ex]
  - Upper bound on BR (H → invisible): Obs (Exp) 0.78 (0.86)
- **Monojet search with H → invisible interpretation**
  - Eur. Phys. J. C75 (2015) no. 7, 299, arXiv:1502.01518
  - Limit on σ x BR (H → invisible)
  - Not sensitive as BR (H → invisible) measurement
- **VBF H → invisible**
  - JHEP 01 (2016) 172, arXiv:1508.07869
  - Upper bound on BR (H → invisible): Obs (Exp) 0.29 (0.35)
  - Combination of two categories of searches
    - VBF combined results. Obs (Exp) 0.28 (0.31)
- **Grand combination of H → invisible measurements**
  - JHEP 11 (2015) 206, arXiv:1509.00672
  - Combination of Z(→ll), V(→jj), and VBF
  - Obs (Exp) 0.25 (0.27)

VBF H → invisible

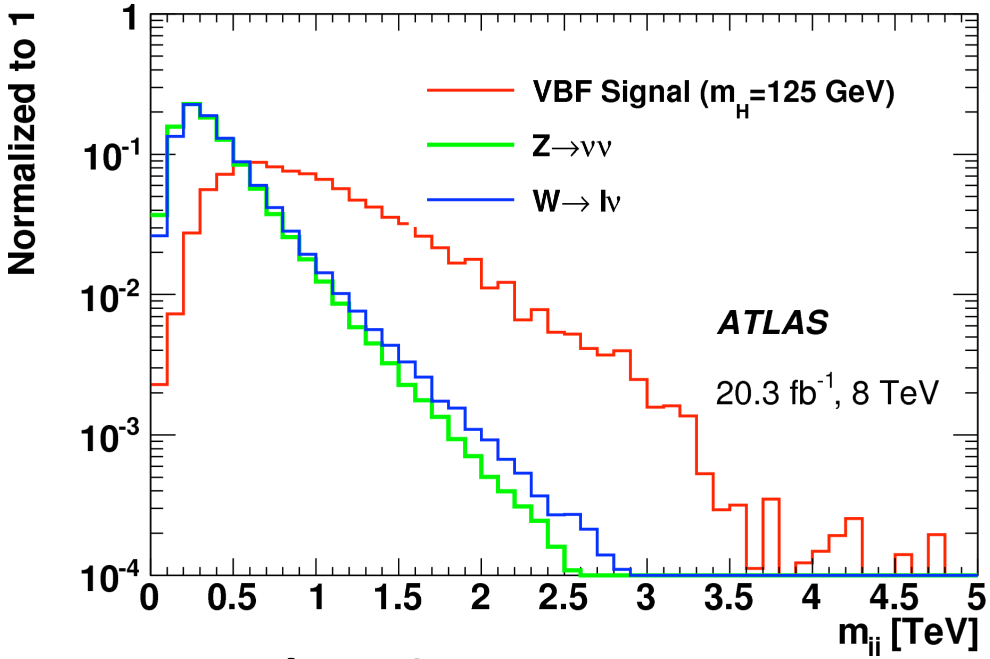
- **Two forward jets with large rapidity gap**
  - Minimal or no central jet activities
- **Higgs decaying to undetected particles (invisible)**
  - Thus expecting large missing energy (MET) associated to 2 jets with large rapidity gap
  - e.g. H → WIMPs
  - H → $\chi^0\chi^0$ where $m_{\chi 0} < m_H/2$
- **MET trigger used**
- **Signals**
  - VBF Higgs production
  - Also ggF+2jets (~20%).
  - Simulate H → invisible with H → ZZ → 4ν
- **Backgrounds**
  - Z+jets with Z → νν
  - W+jets with W → lν (undetected lepton)
  - Multijets
  - ttbar, single top and dibosons

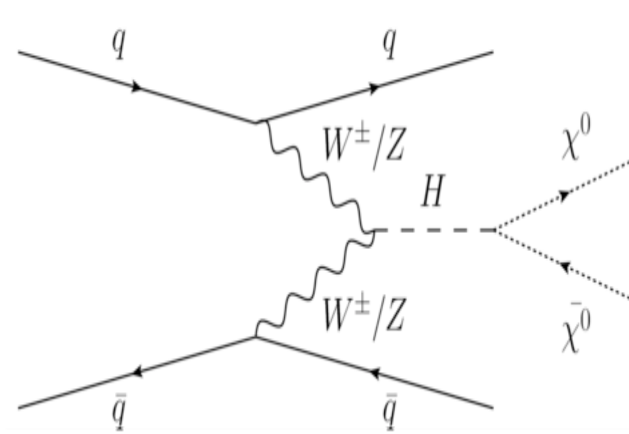






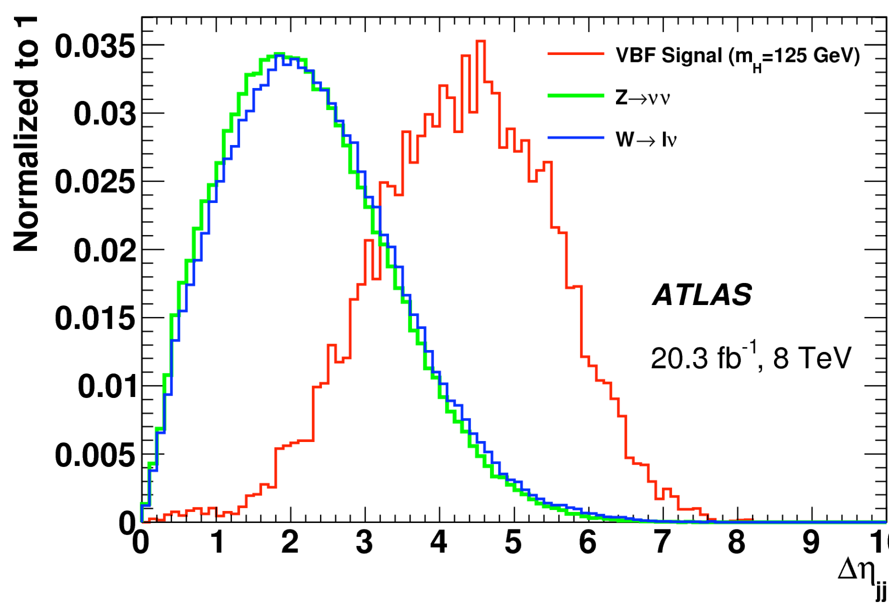
VBF H → invisible





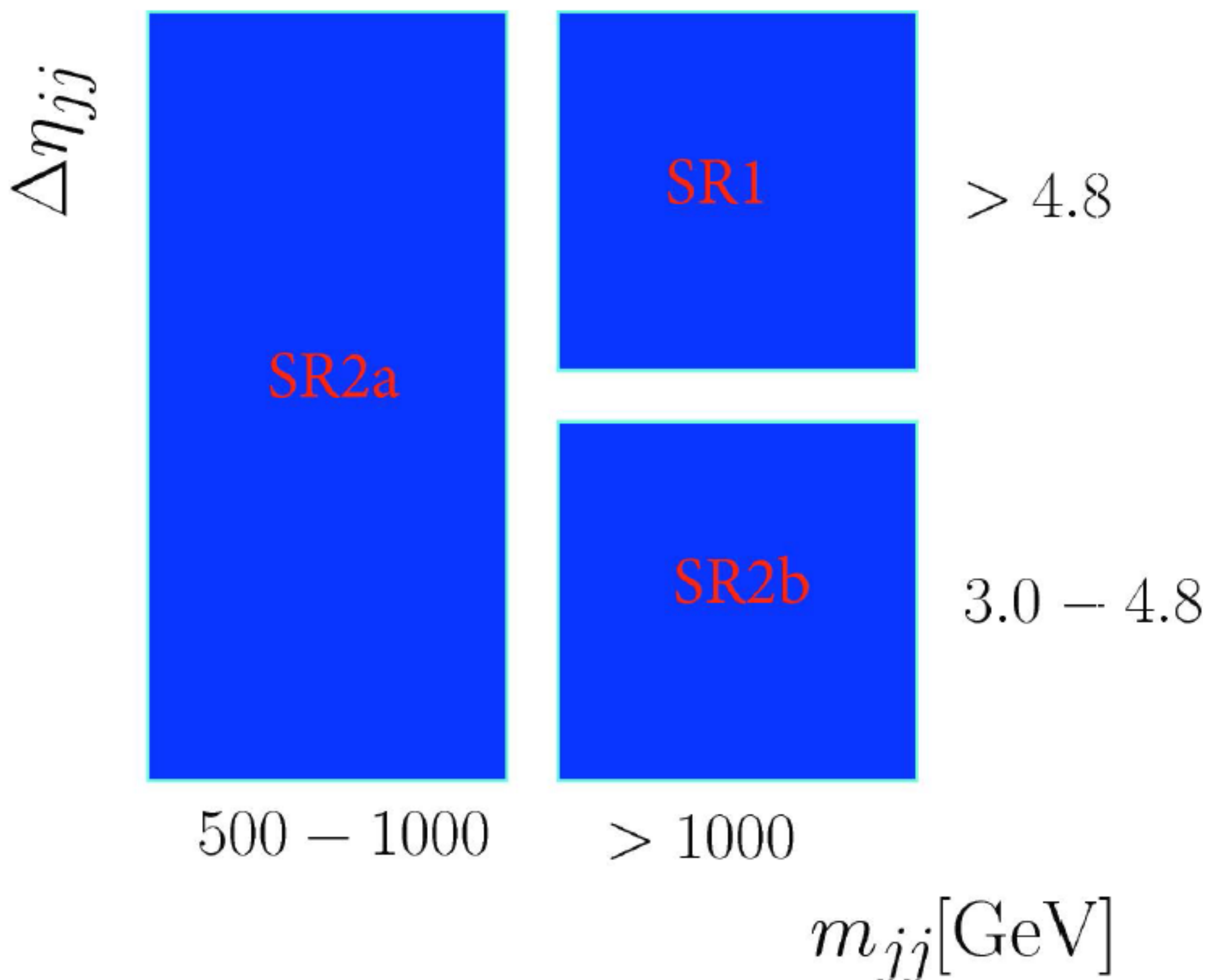
VBF Signal

- **VBF Topology & Characteristics**
  - 2 forward jet at high rapidity, large $\Delta\eta_{jj}$
  - High di-jet invariant mass
  - In the central region of the detector: low gluon radiation due to colorless W/Z exchange
    - Veto on central jets



VBF H → invisible

- Three categories of searches based on
  - The di-jet invariant mass m_{jj}
  - And the rapidity gap between the jets, $\Delta\eta_{jj}$



Most Sensitive: SR1

SR2 was meant as a complement to SR1 to improve sensitivity

VBF H → invisible

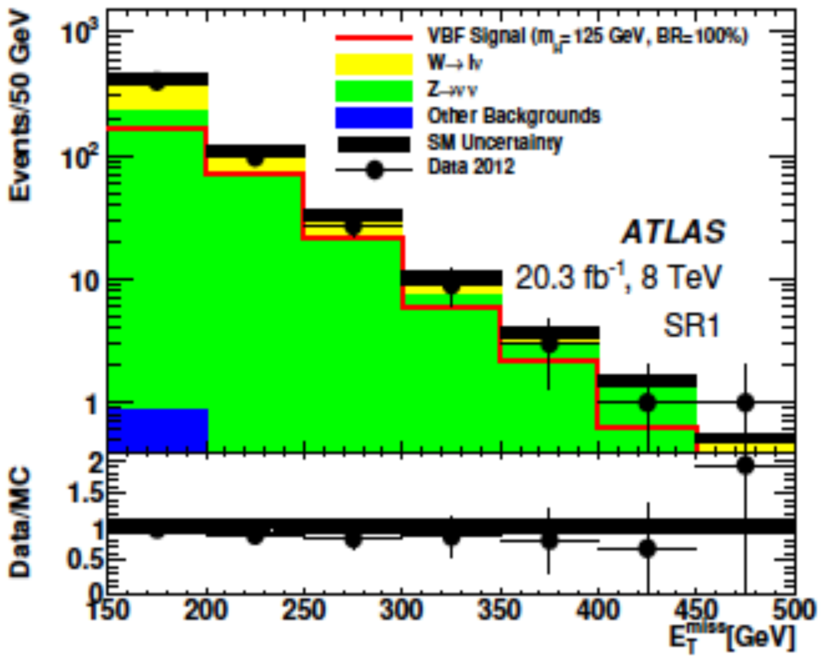
- **Z+jets with Z→νν background estimated from**
  - Z+jets with Z→ll data control regions (CR)
  - And W+jets with W → lν data control regions
- **W+jets with W→lν background estimated from**
  - W+jets with W→lν data control region
- **Multijet background estimated from**
  - Multijet enriched data control samples by reserving the requirements of $\Delta\phi_{jj}$ and $\Delta\phi_{j,MET}$
- **ttbar, single top and di-bosons estimated from**
  - Monte Carlo
- **Residual background contamination in the Z→ll CR**
  - subtracted using MC predictions
- **Multijet background in the W→lν CR subtracted by a fit to the transverse mass distribution**

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos(\Delta\phi_{\ell, E_{\mathrm{T}}^{\mathrm{miss}}})\right]}$$

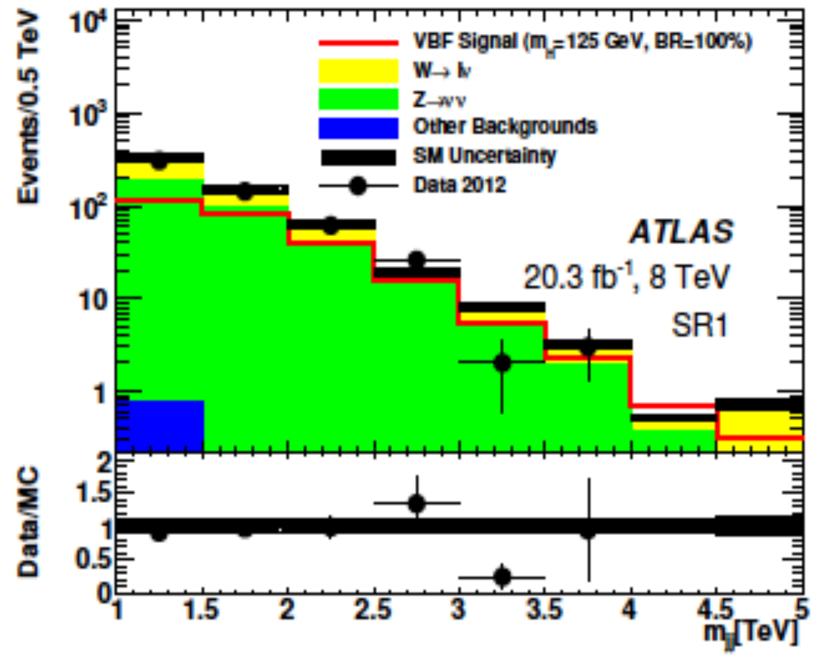
- **Unique estimates of Z→νν and W→lν background obtained from**
  - A simultaneous fit to the SR and the CRs

$$Z_{\mathrm{SR}} \sim (Z_{\mathrm{SR}}/Z_{\mathrm{CR}})^{\mathrm{MC}} \times Z_{\mathrm{CR}}^{\mathrm{data}},$$
$$Z_{\mathrm{SR}} \sim (Z_{\mathrm{SR}}/W_{\mathrm{CR}})^{\mathrm{MC}} \times W_{\mathrm{CR}}^{\mathrm{data}},$$
$$W_{\mathrm{SR}} \sim (W_{\mathrm{SR}}/W_{\mathrm{CR}})^{\mathrm{MC}} \times W_{\mathrm{CR}}^{\mathrm{data}}.$$

VBF H → invisible Results



(a) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution



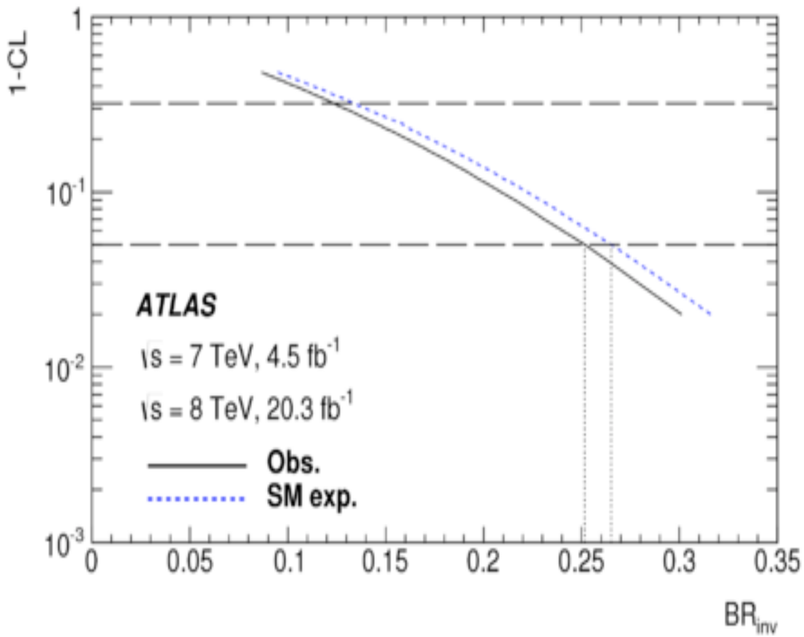
(b) m_{jj} distribution

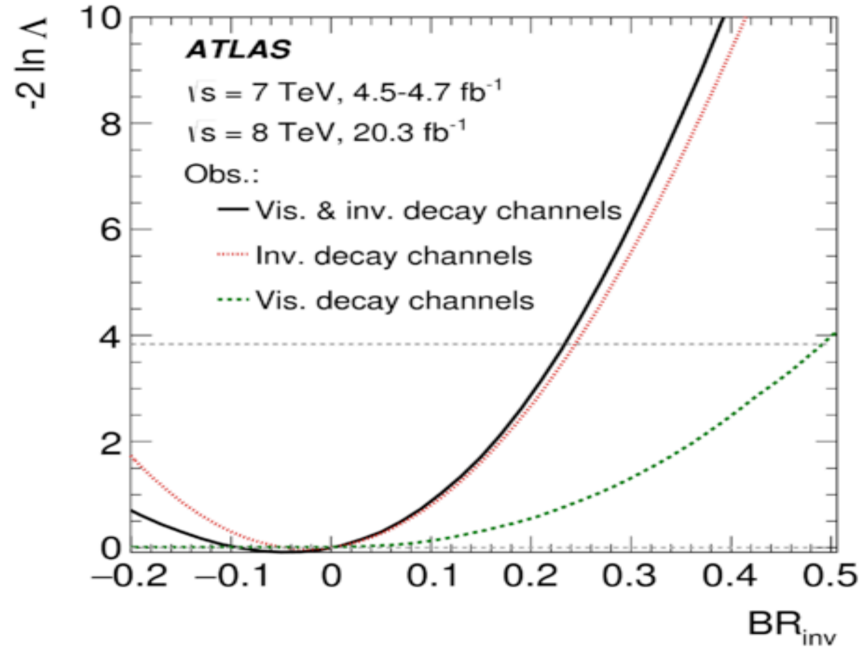
No excess

Post-fit distributions and estimates

Signal region Process	SR1	SR2a	SR2b
ggF signal	20± 15	58± 22	19± 8
VBF signal	286± 57	182± 19	105±15
$Z(\rightarrow \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\rightarrow \ell\nu)$+jets	235± 42	1010± 50	225±16
Multijet	2± 2	20± 20	4± 4
Other backgrounds	1±0.4	64± 9	19± 6
Total background	577± 62	2680±130	583±34
Data	539	2654	636

Combined H → invisible Results





Results	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
VBF h	0.28	0.16	0.21	0.31	0.41	0.56
$Z(\to \ell\ell)h$	0.75	0.33	0.45	0.62	0.86	1.19
$V(\to jj)h$	0.78	0.46	0.62	0.86	1.19	1.60
Combined Results	0.25	0.13	0.18	0.27	0.35	0.47

ATLAS VBF H → invisible: best direct search result at the LHC

Higgs Portal Dark Matter

- The upper bound on the BR (H → invisible) can be used to constrain WIMP-Nucleon scattering cross section and compare to Direct Dark Mark Matter Detection Experiments

$$\Gamma_H^{\mathrm{inv}} = \frac{\mathrm{BF}(H \to \mathrm{invisible})}{1 - \mathrm{BF}(H \to \mathrm{invisible})} \times \Gamma_H,$$

$$\Gamma_{H\to SS}^{\mathrm{inv}} = \frac{\lambda_{HSS}^2 v^2 \beta_S}{64\pi m_H},$$

$$\Gamma_{H\to VV}^{\mathrm{inv}} = \frac{\lambda_{HVV}^2 v^2 m_H^3 \beta_V}{256\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4}\right),$$

$$\Gamma_{H\to ff}^{\mathrm{inv}} = \frac{\lambda_{Hff}^2 v^2 m_H \beta_f^3}{32\pi\Lambda^2},$$

$$\sigma_{SN}^{\mathrm{SI}} = \frac{\lambda_{HSS}^2}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

$$\sigma_{VN}^{\mathrm{SI}} = \frac{\lambda_{HVV}^2}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_V + m_N)^2},$$

$$\sigma_{fN}^{\mathrm{SI}} = \frac{\lambda_{Hff}^2}{4\pi\Lambda^2 m_H^4}\frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},$$

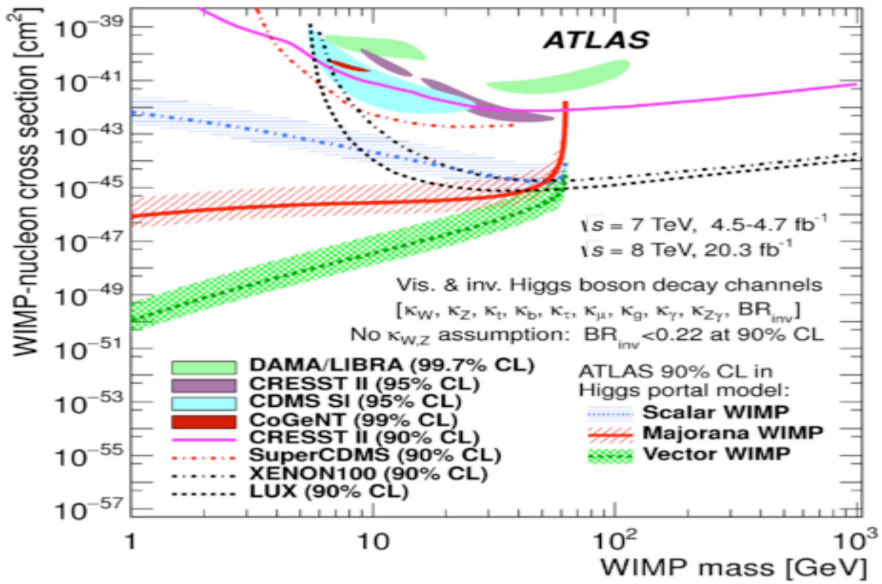
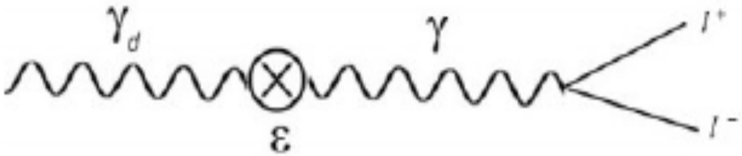


Table 11: Parameters in the Higgs-portal dark-matter model.

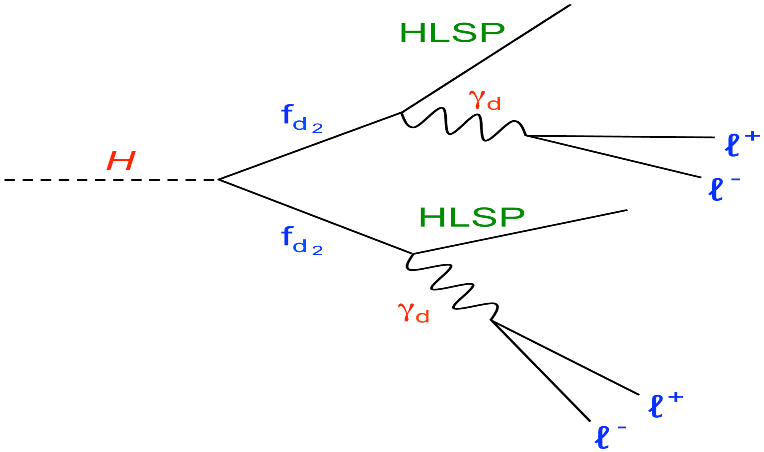
Vacuum expectation value	$v/\sqrt{2}$	174 GeV
Higgs boson mass	m_H	125 GeV
Higgs boson width	Γ_H	4.07 MeV
Nucleon mass	m_N	939 MeV
Higgs–nucleon coupling form factor	f_N	$0.33^{+0.30}_{-0.07}$

Lepton jets (LJ) and Long-Lived Particles (LLPs)

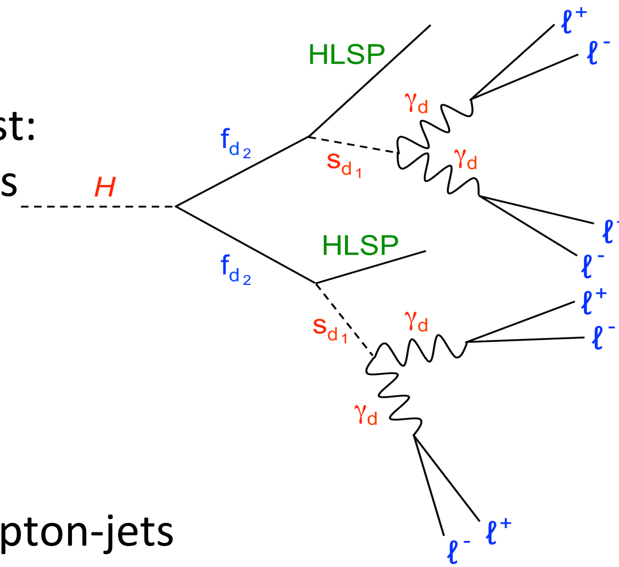
H → lepton-jets + X



Kinetic mixing ε between dark photon and SM photon
Signature: collimated pairs of leptons (lepton-jets)



Parameter of interest:
- Dark photon mass
- ε
- Dark photon cτ



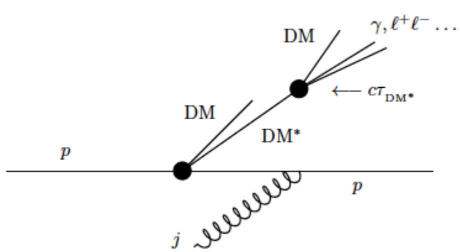
Prompt or displaced lepton-jets

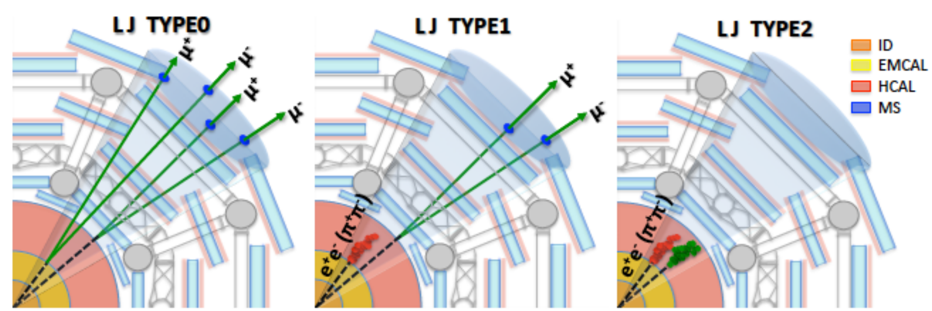
ATLAS, *JHEP11(2014)088*

Falkowski, Ruderman, Volanski and Zupan
http://arxiv.org/abs/1007.3496

FRVZ signal models with ggF Higgs production

Izaguirre, Krnjaic, Shuve
http://arxiv.org/abs/1508.03050

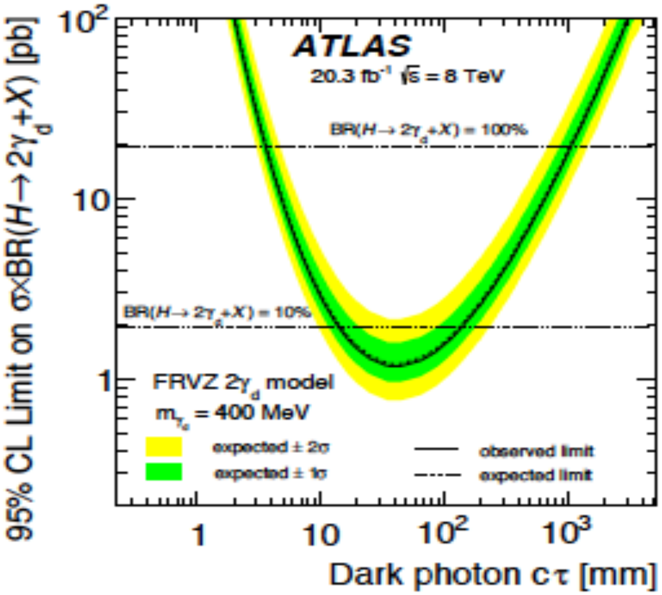


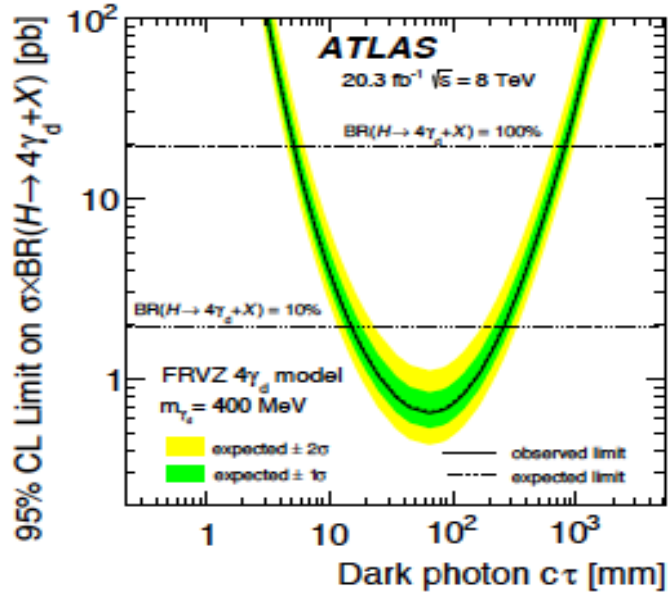


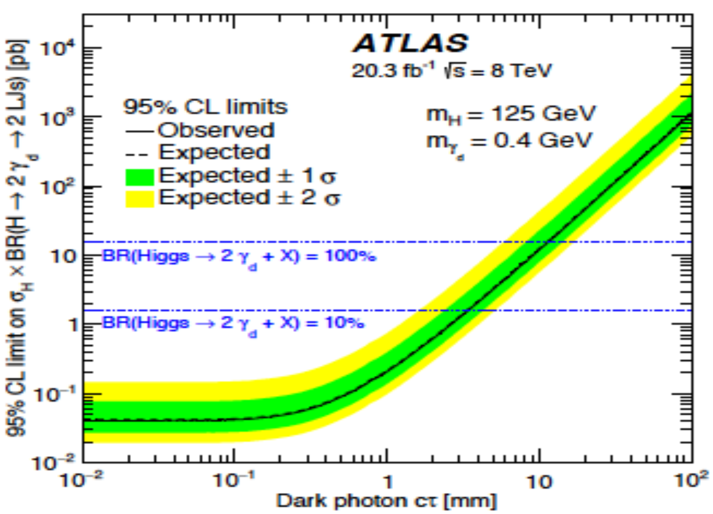
H → lepton-jets + X

- Run 1 exclusion limits

FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \to 2\gamma_d + X$	no limit
$H \to 4\gamma_d + X$	$52 \leq c\tau \leq 85$

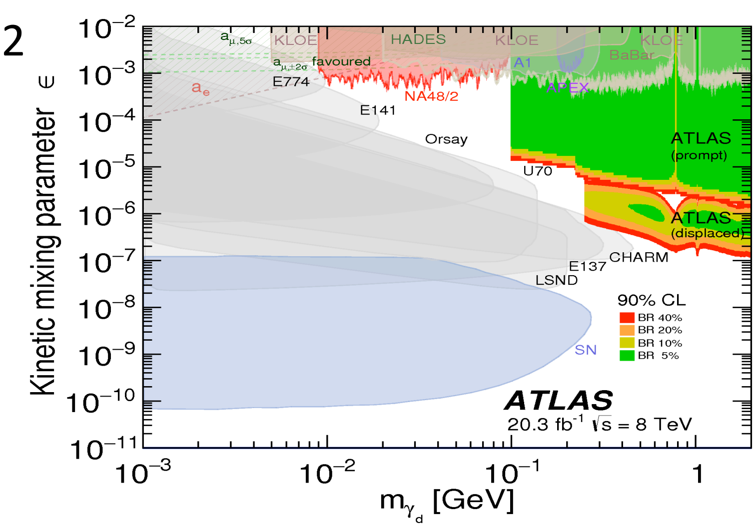






JHEP02(2016)062

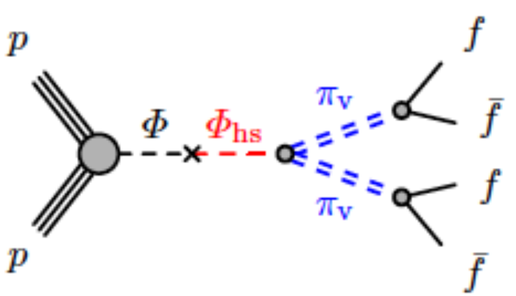
For BR=10%, cτ<3.2 excluded



Long-lived, weakly-interacting particles → displaced hadronic jets

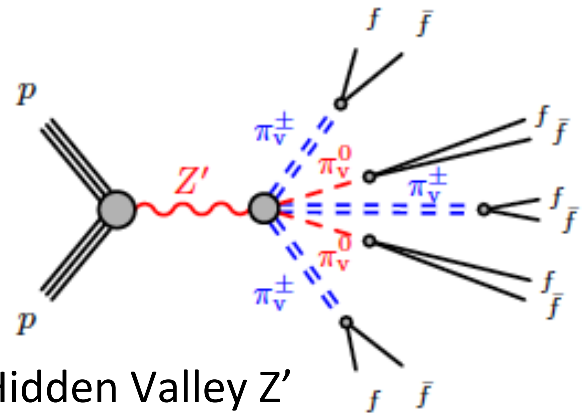
PRD 92, 012010 (2015)

- Benchmark models



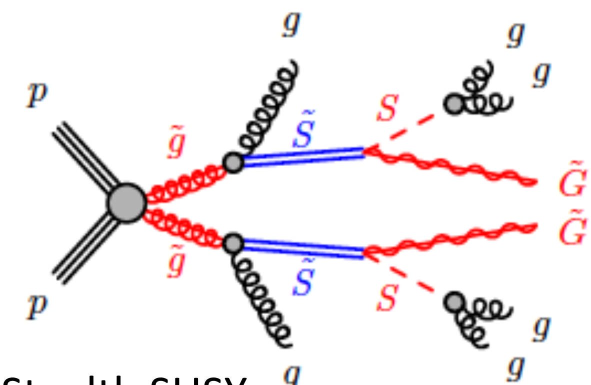
Higgs decays

(a)



Hidden Valley Z'

(b)

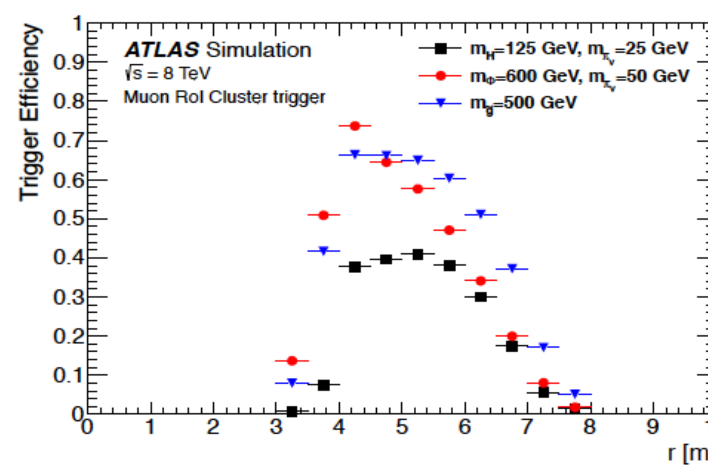


Stealth SUSY

LLPs decays to hadronic jets far from the IP
Search for displaced vertices in the ID and MS

Muon RoI Cluster Trigger to select hadronic decays in the outer radius of HCal to middle of MS

Single jet + Met Trigger also used for the Z' search



Long-lived, weakly-interacting particles → displaced hadronic jets

Limits of H → LLPs signal strength

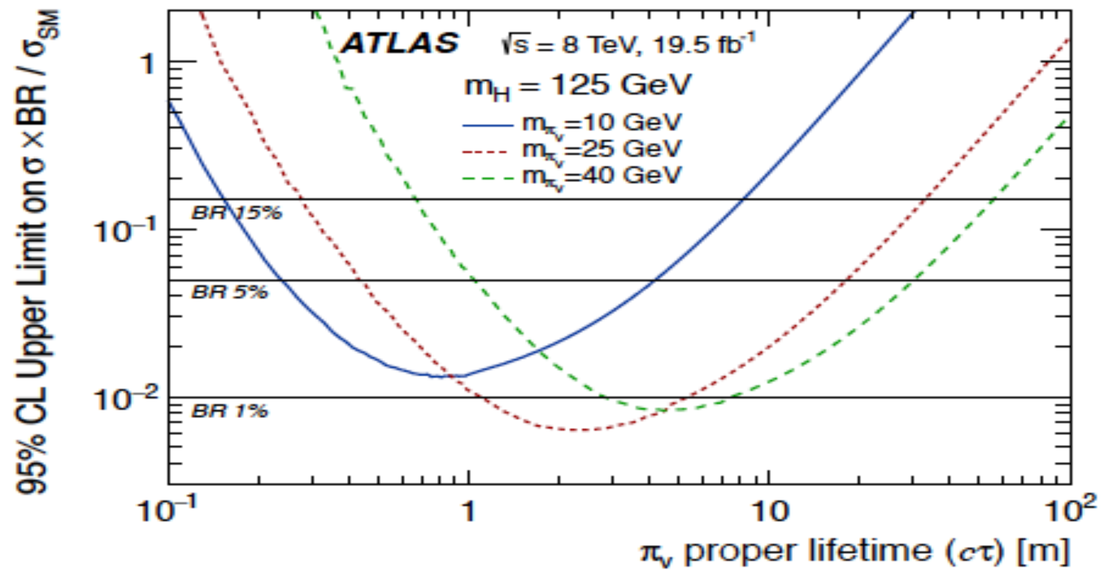


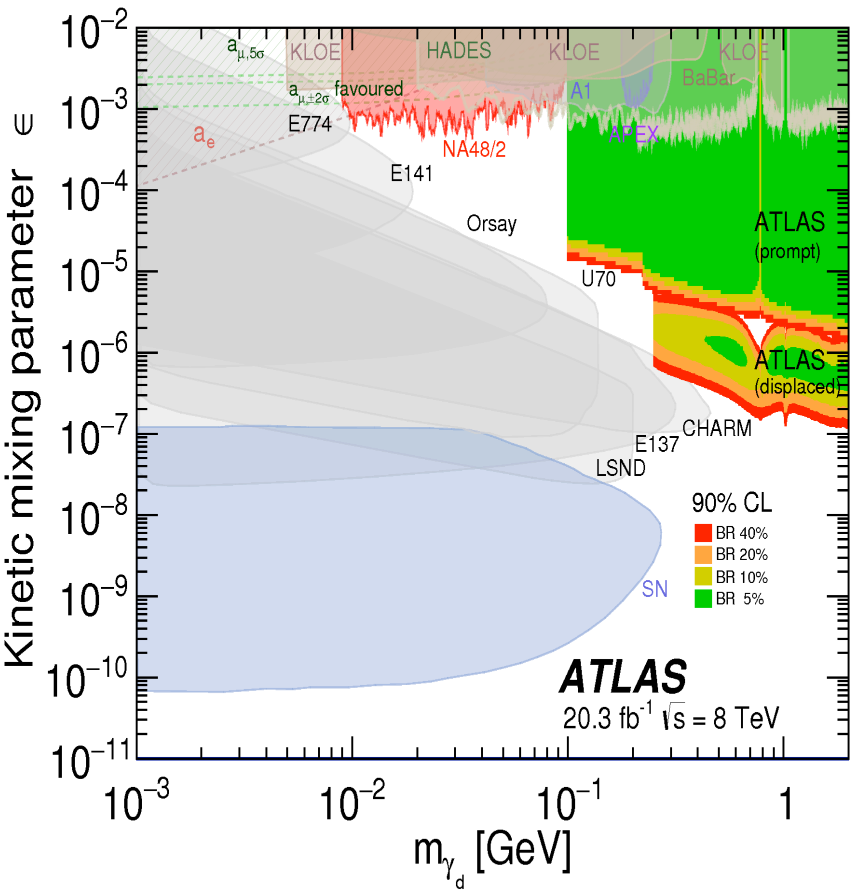
TABLE XI. Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30%, 15%, 5%, or 1% BR for m_H = 125 GeV.

m_{π_v} [GeV]	Excluded $c\tau$ range [m] 1% BR	5% BR	15% BR	30 % BR
10	no limit	0.24–4.2	0.16–8.1	0.12–11.8
25	1.10–5.35	0.43–18.1	0.28–32.8	0.22–46.7
40	2.82–7.45	1.04–30.4	0.68–55.5	0.52–79.2

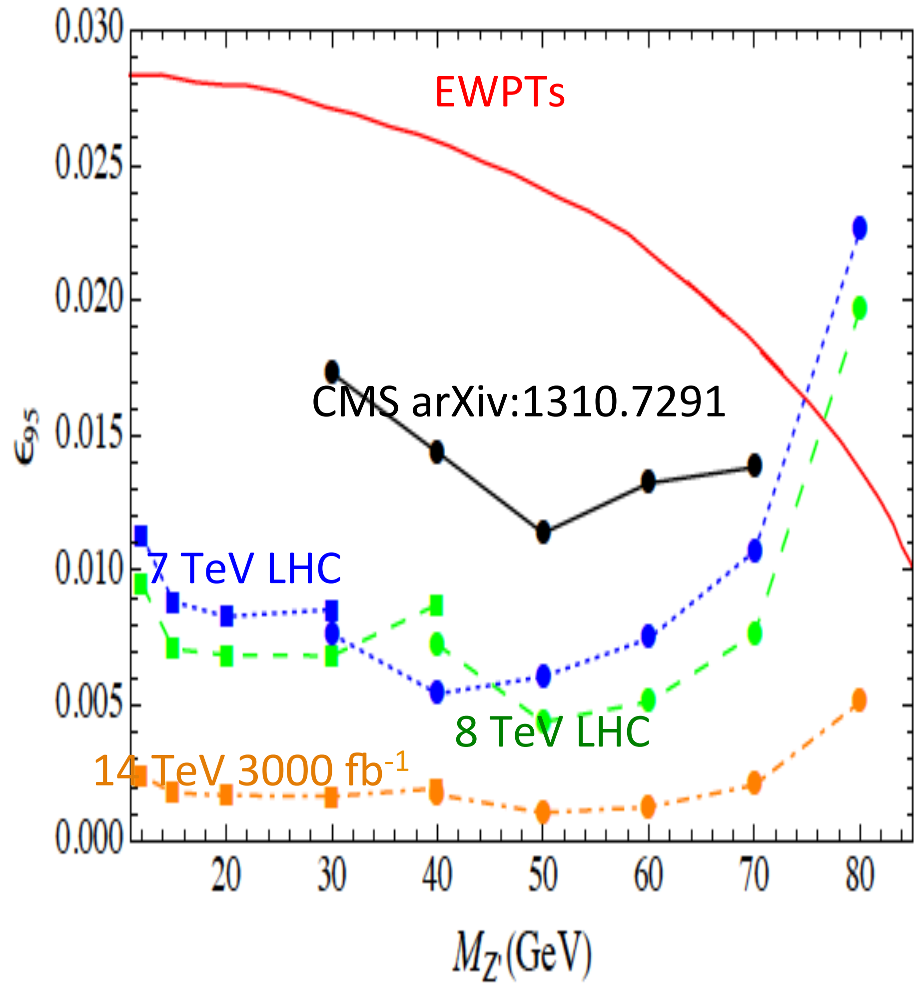
Significant range of cτ
Excluded for BR <=5%

Bounds on kinetic mixing parameter ε

JHEP02(2016)062



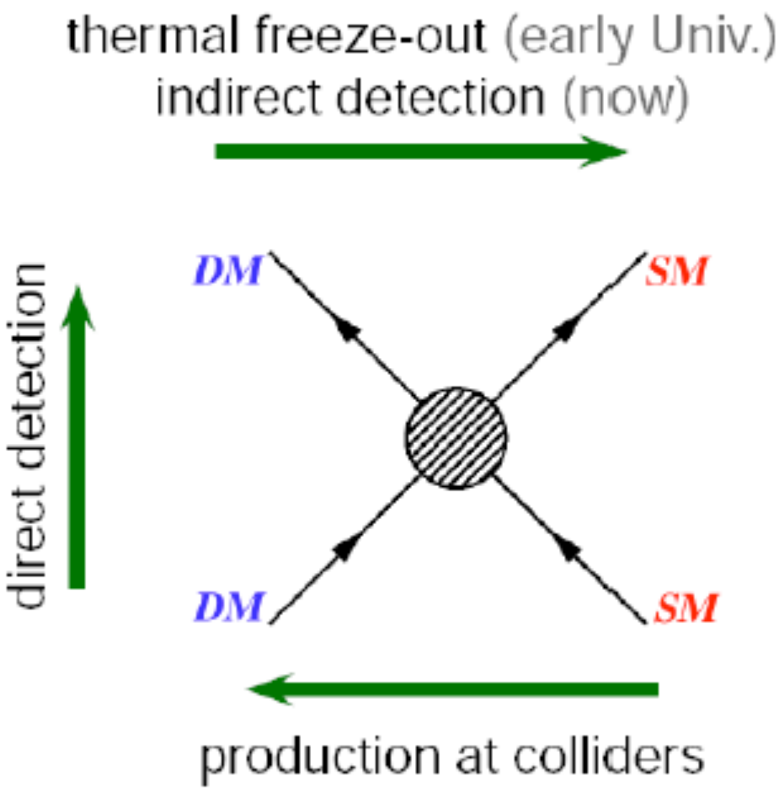
1408.1075v2

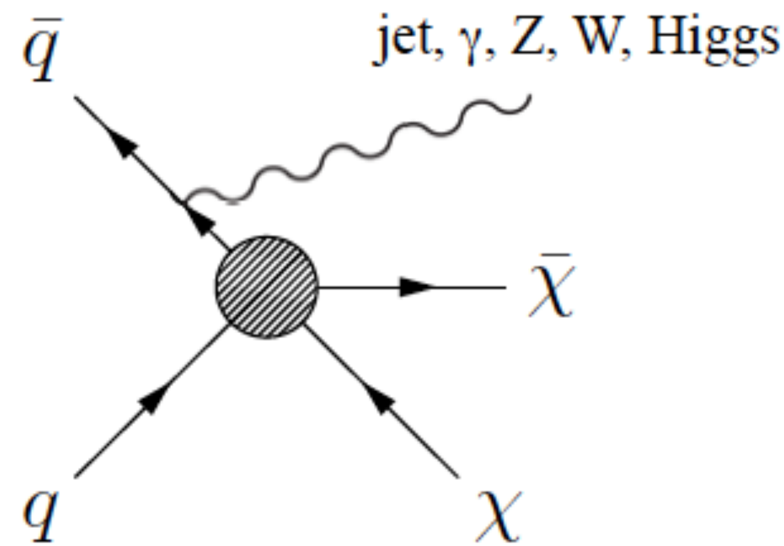


Mono-X

Dark Matter Searches at Colliders

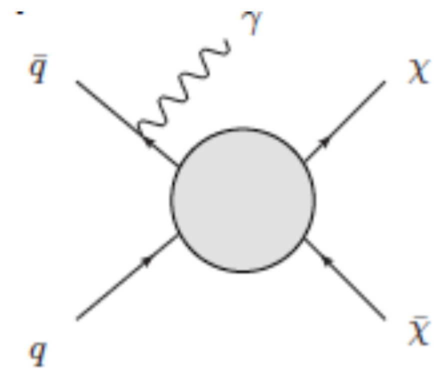
- Produce DM in proton-proton collisions
- Search for Mono-X events (X=jets, photon, W/Z, etc)
  - DM direct production in association with visible objects

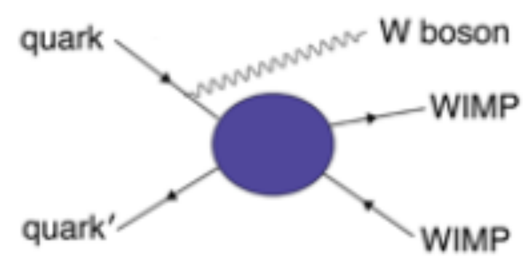




Effective Field Theories (EFT)

- **Broad coverage of models by integrating out the details**
- **Model parameters**
  - The suppression scale M*
  - The DM mass m_χ
- **DM couples to quarks and gluons**
  - SM particles in the initial state
  - Monojet searches
- **DM couples to bosons**
  - SM particle from the main interaction
  - Mono-photon/W/Z searches



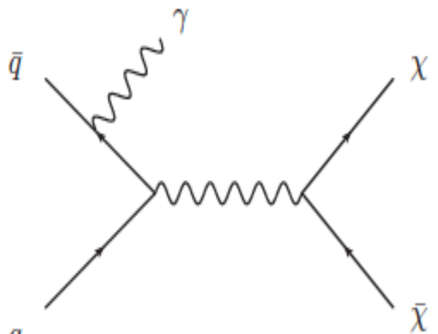


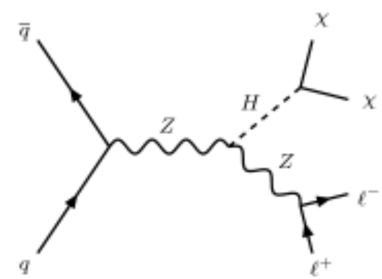
[J. Goodman et al. arXiv:1008.1783]
[Y. Bai et al. arXiv:1005.3797]
[P. Fox et al. arXiv:1109.4398]
[J. Feng et al arXiv:1102.4331]
and many others

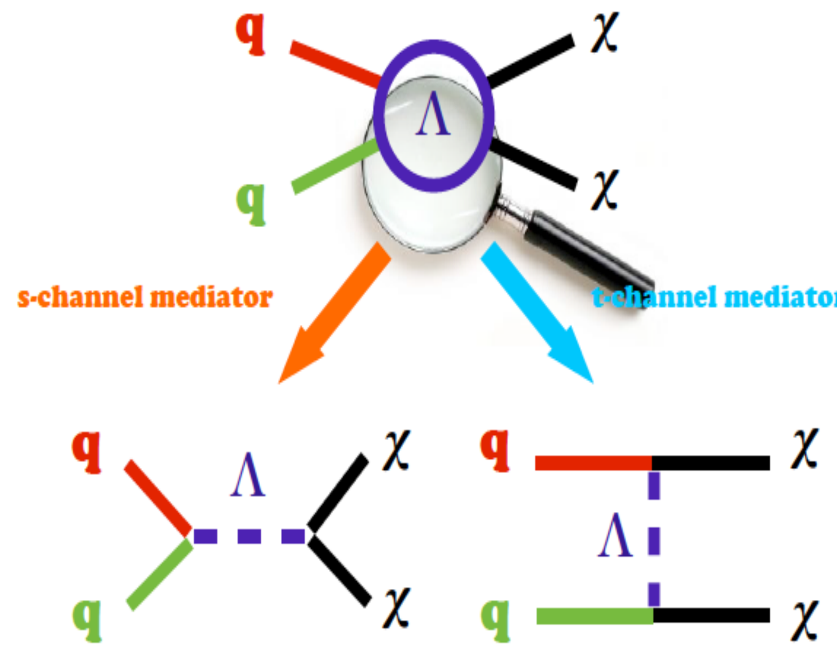
[A.J. Nelson et al. ArXiv:1307.5064]
[N. Lopez et al arXiv:1303.6734]

Simplified Models

- **Keep information in the intermediate state**
  - s-channel (Z' portal, Higgs-portal, etc)
  - t-channel (colored scalars, etc)







  - In the limit of heavy mediator mass, recover EFT

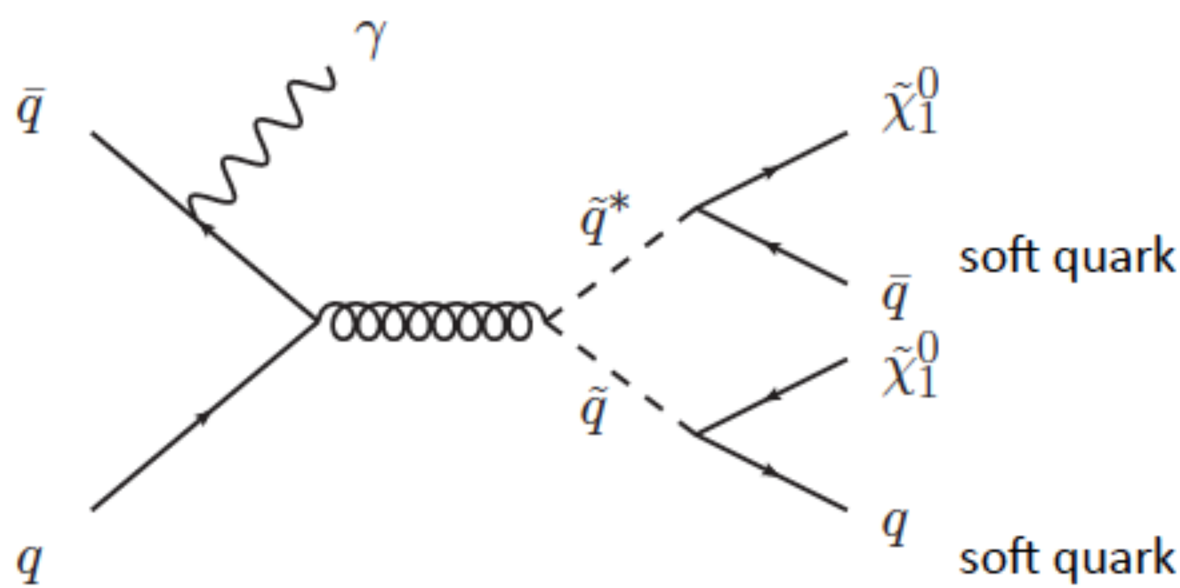
$$\frac{g_f^2 g_\chi^2}{(Q_{tr}^2 - m_V^2)^2} \xrightarrow{Q_{tr} << m_V} \frac{g_f^2 g_\chi^2}{m_V^4} = \frac{1}{M_*^4}$$

$$M_* = m_V / \sqrt{g_f g_\chi}$$

[J. Abdallah et al. arXiv:1409.2893]
[H. An et al. arXiv:1308.0592]

Supersymmetry

- **Compressed SUSY leads to mono-X signatures**
  - Squark-LSP mass splitting small
  - Jets too soft to be reconstructed
  - ISR SM particles

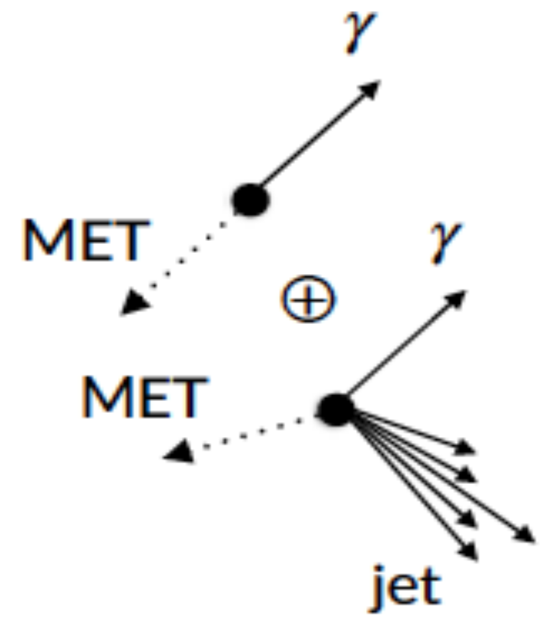


Mono-photon

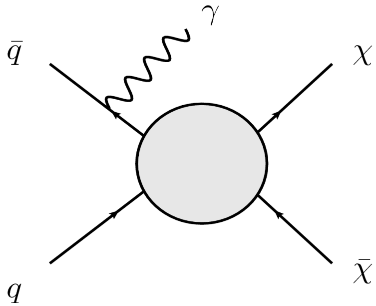
- **Signature:**
  - Missing transverse energy (MET) with a single isolated energetic photon

arXiv:1411.1559 [hep-ex]

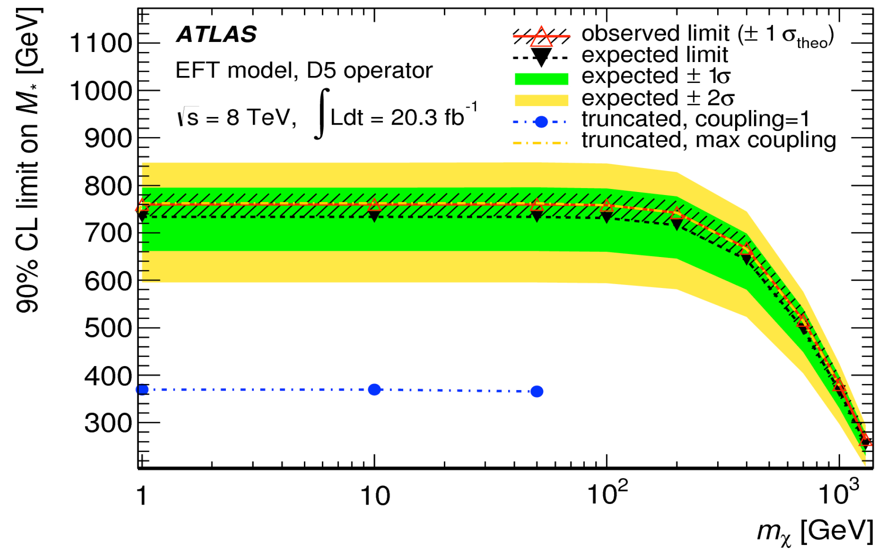
- **Signal region (SR) selection**
  - MET trigger with a threshold of 80 GeV
  - Calorimeter based MET > 150 GeV
    - Muons are treated as invisible particle
    - $Z(\mu\mu)+\gamma$ is similar to $Z(\nu\nu)+\gamma$ in the MET spectrum
  - Photon with E_T>150 GeV and $|\eta|$<2.37
    - Tight identification and isolated in the calorimeter
    - Away from the MET direction
  - Veto other objects
    - No more than 1 jet with p_T>30 GeV
    - No electron with p_T>7 GeV
    - No muon with p_T>6 GeV
  - Cut-and-count experiment

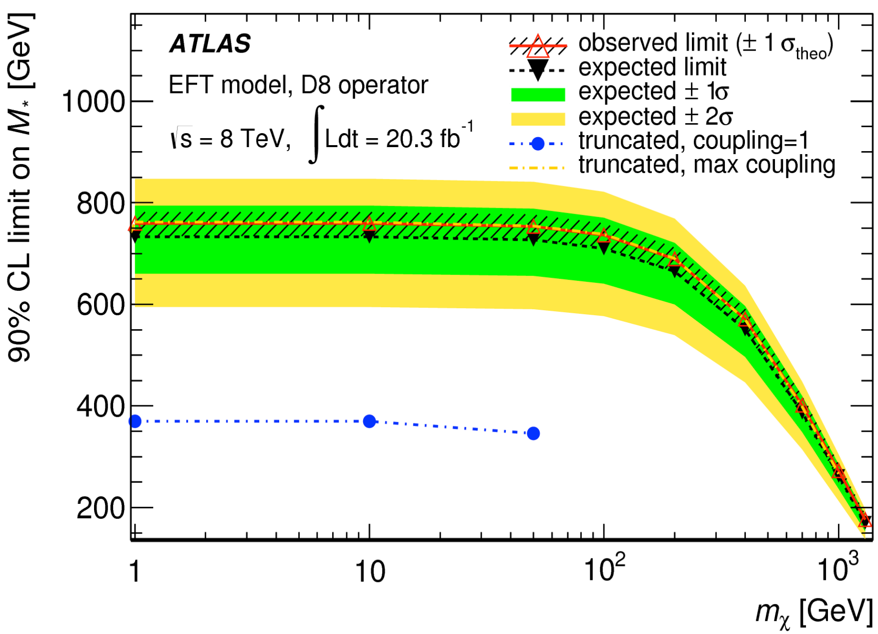


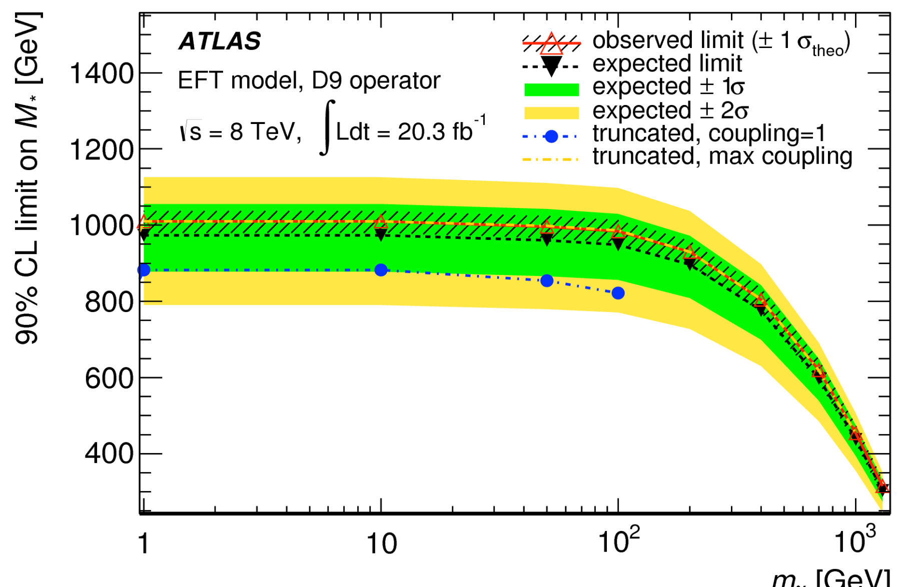
EFT Limit



- Convert the cross section limit into lower limit on M* from different DM mass m_χ
- Collider searches are sensitive to lower DM masses due to production energy limitation

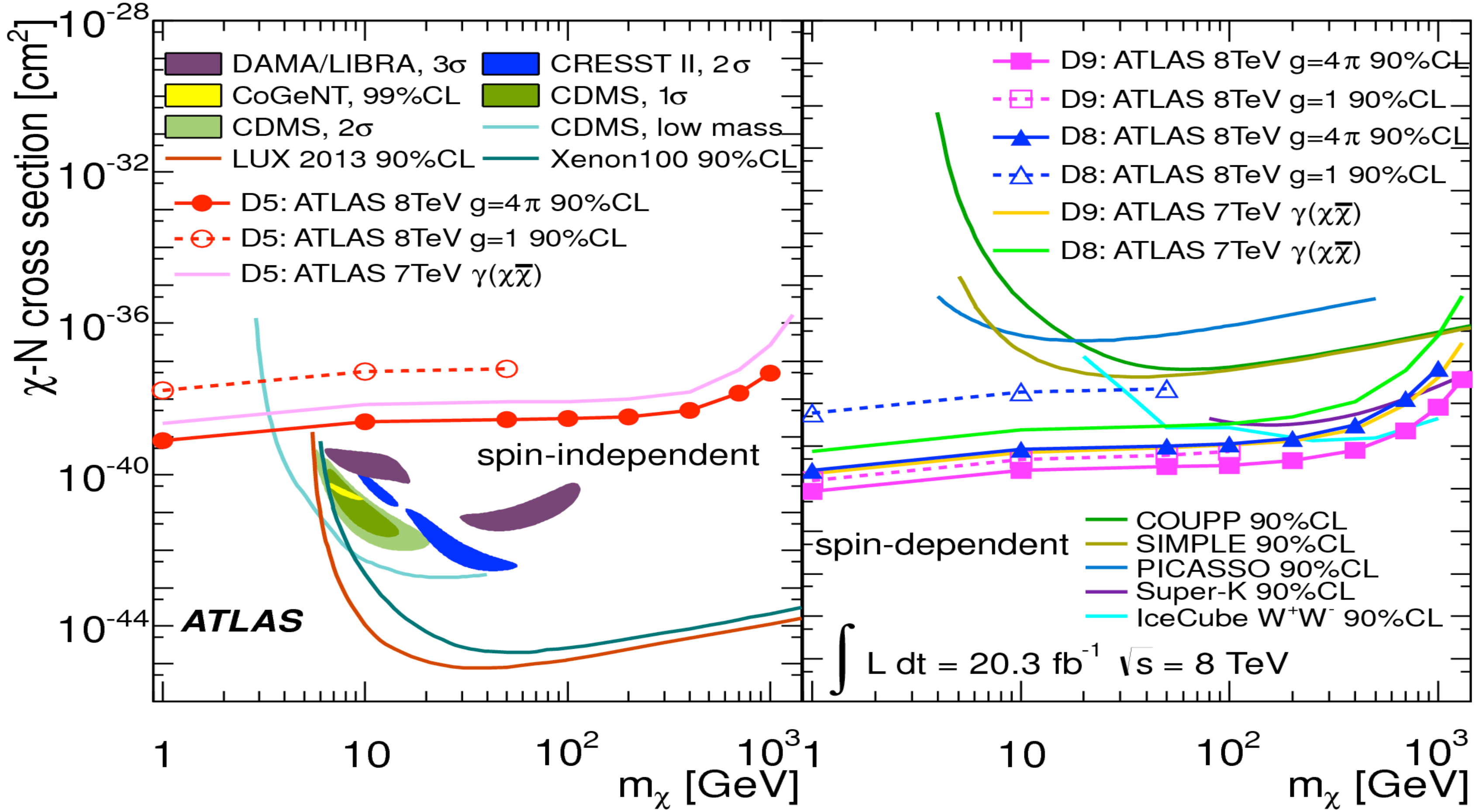






Constraints on Direct Detection

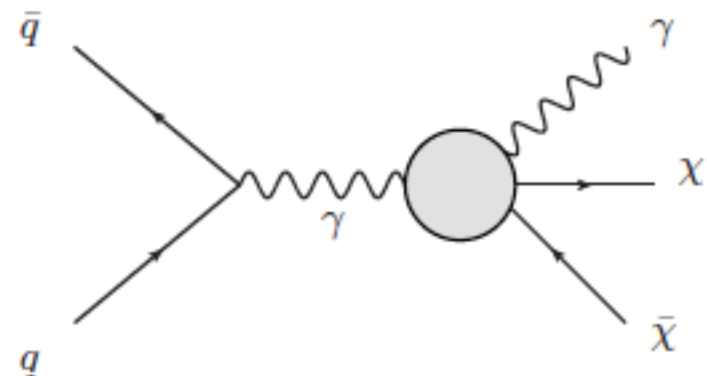
- To compare with direct detector experiments, we produce constraints on DM-nucleon scattering cross section



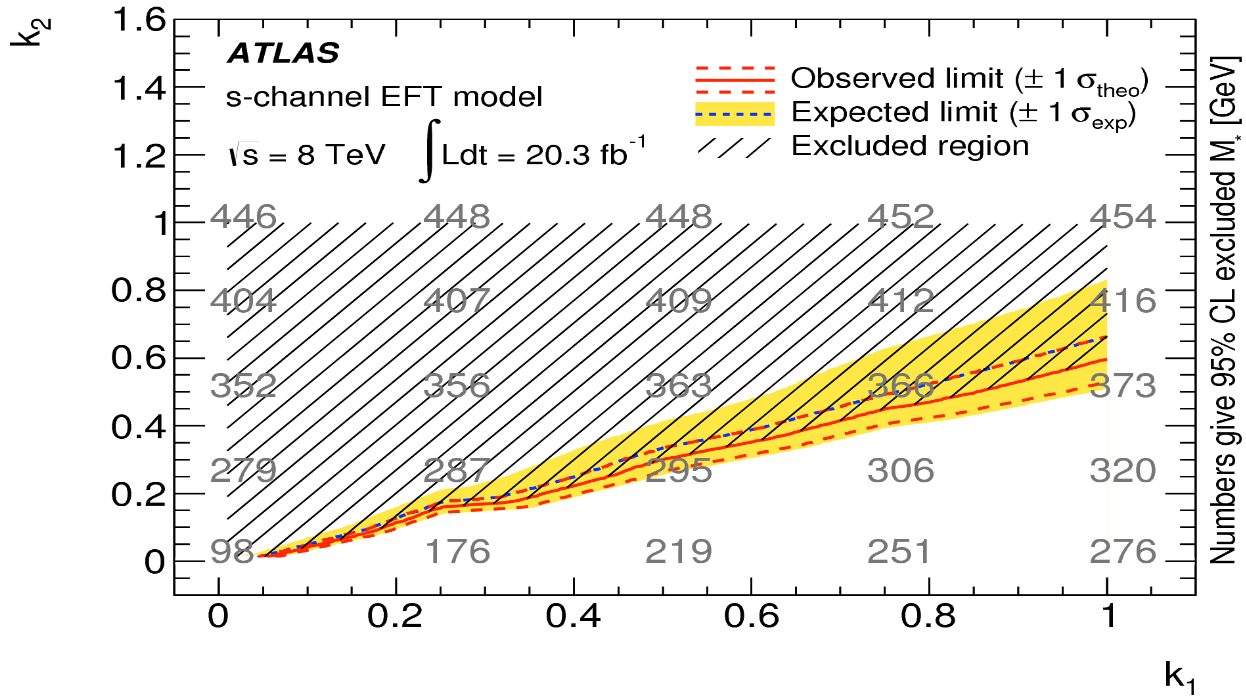
Complementary to astrophysical experiments

Constraint on Indirect Detection

- s-channel model with $\gamma\gamma\chi\chi$ EFT vertex
  - k1 and k2 control the relative couplings of the DM to various pairs of the electro-weak gauge bosons
- Constrain effectively the parameter space
  - Limit on the mass scale M* in (k1, k2) parameter space
- Good example to cross check astrophysical excess using collider experiments
  - Exclusion line drawn by considering the value of M* needed to generate the $\chi\chi \rightarrow \gamma\gamma$ annihilation rate consistent with the Fermi-LAT γ-ray line near 130 GeV

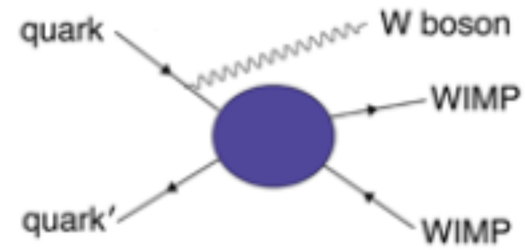


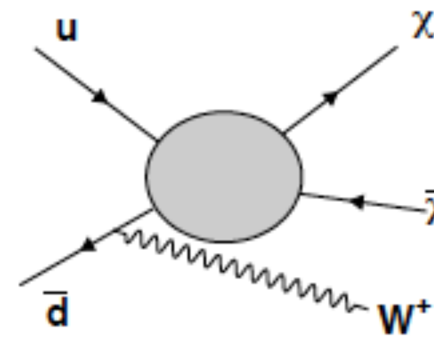
[A.J. Nelson et al. arXiv:1307.5064]

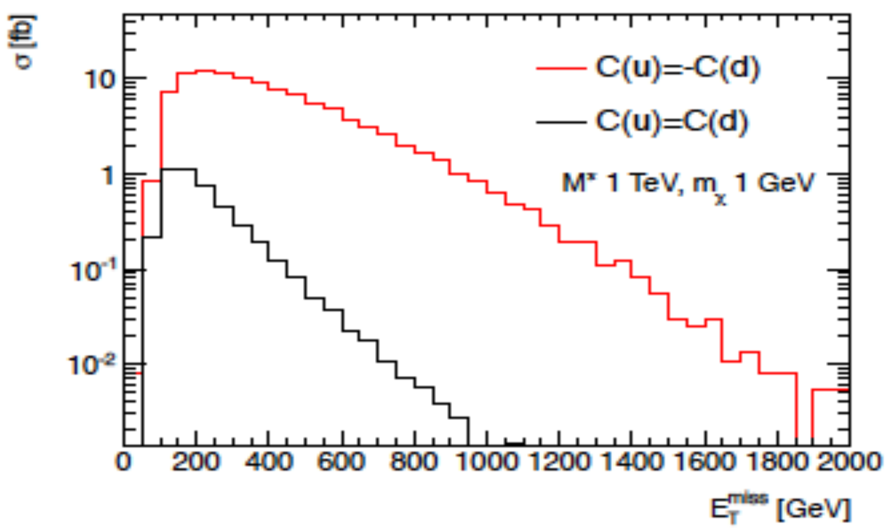


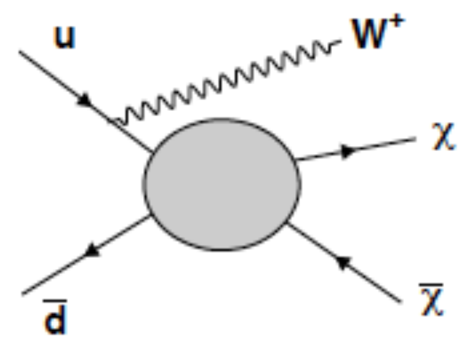
Mono-W and Mono-Z

- If the mediator coupling to “up” and “down” quarks are the same
  - Mono-jet dominate the mono-X sensitivity
- Mono-W
  - Constructive interference for vector and axial-vector operators
  - Large production rate and the W is strongly boosted
  - Mono-W has the best sensitivity







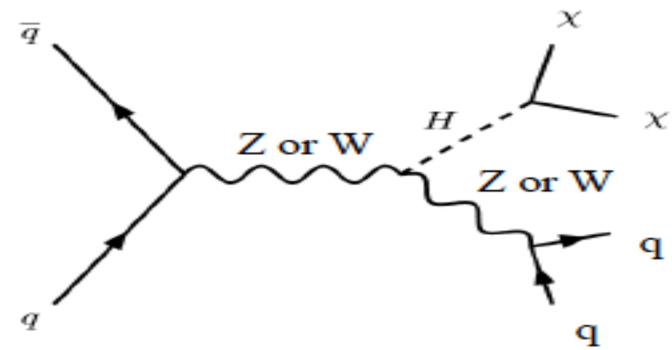


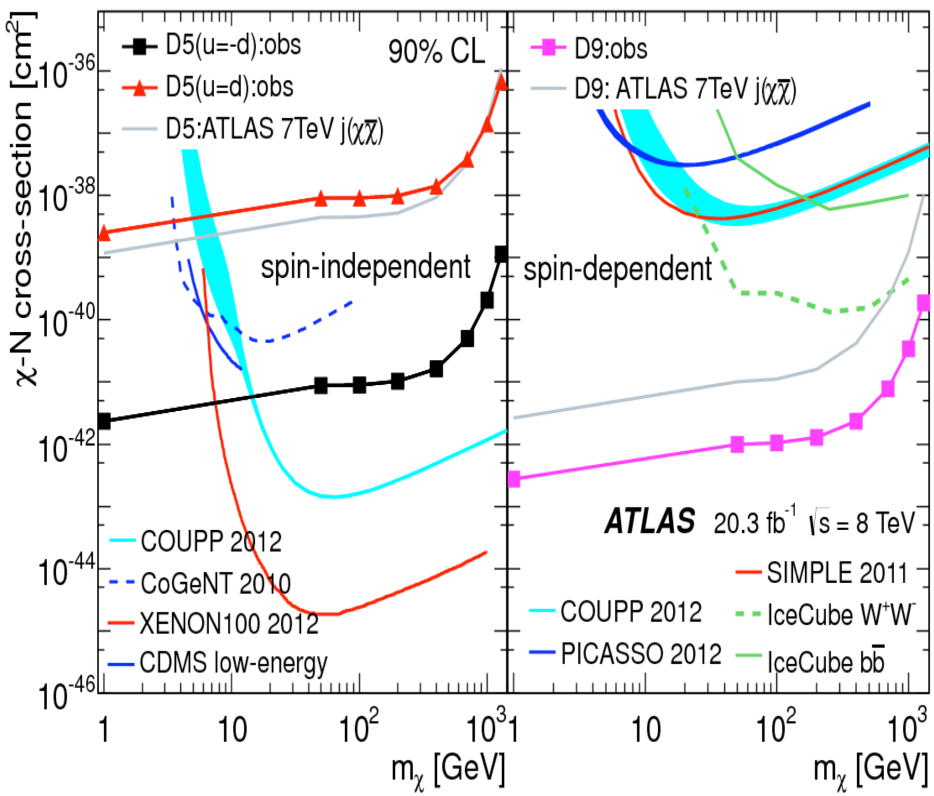
- Focus on hadronic decays
  - Better sensitivity than the leptonic decays
  - More challenging to reconstruct the hadronic W/Z

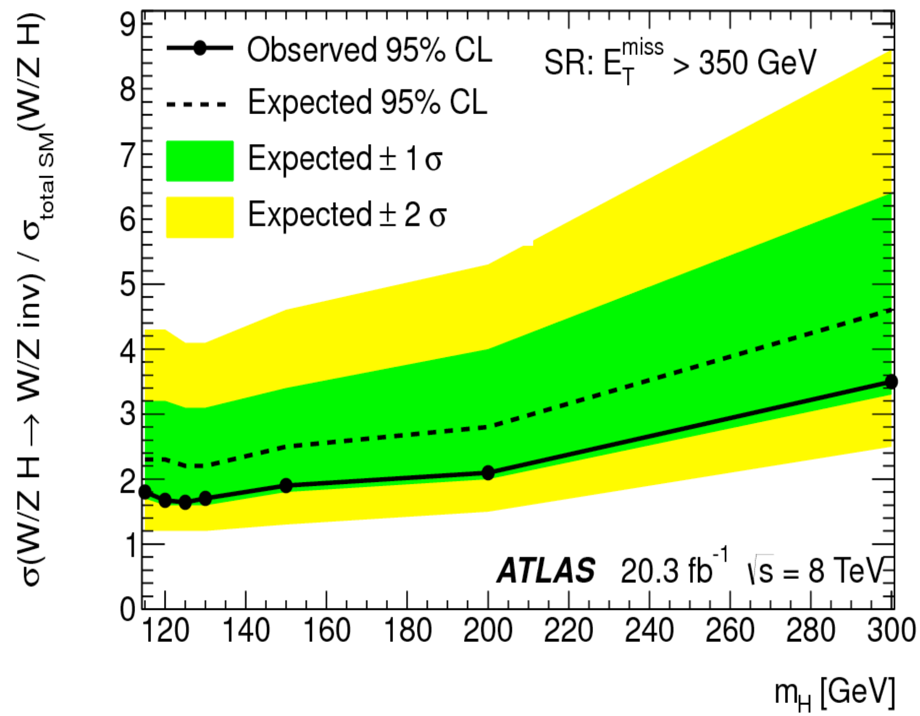
Mono-W: DM and Higgs portal DM

Phys. Rev. Lett. 112, 041802 (2014)

- Higgs decay to invisible
- VH production
  - Same signature
- Use mono-V(jj) to constraint V(jj)H
  - Not fully optimized for Higgs portal model

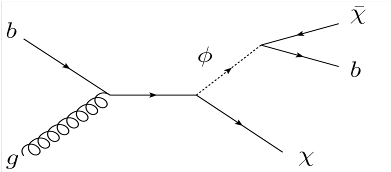






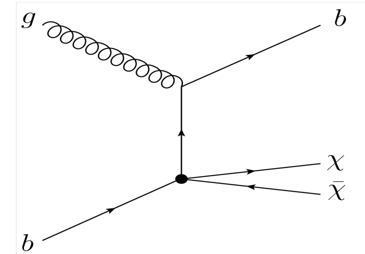
BR (H → invisible) < 1.6 @95% CL

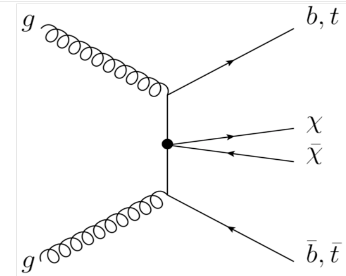
Search for DM in events with heavy quarks and MET

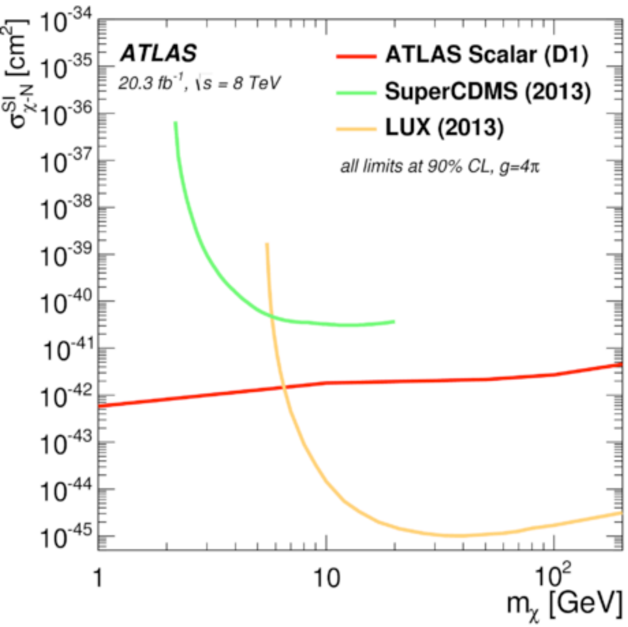


arXiv:1410.4031v1 [hep-ex]

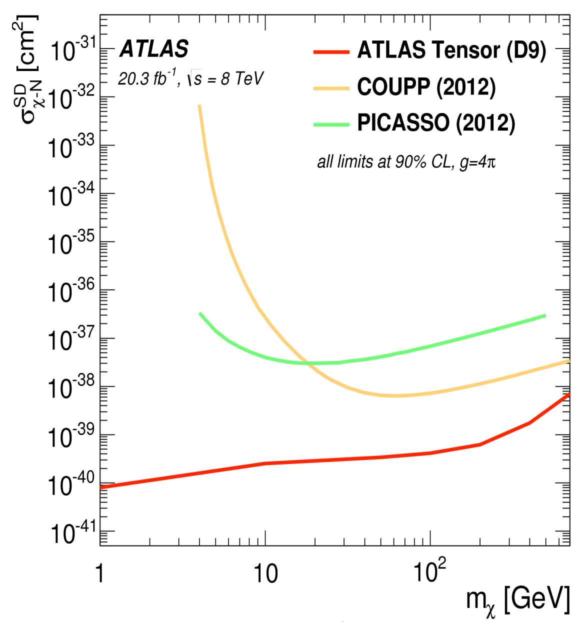
- **Search for events with at least 1 high p_T jet and large MET categorized into 4 signal regions (SR)**
  - SR1: DM with 1 b-jet
  - SR2: DM with 2 b-jets
  - SR3: DM with ttbar (both tops decay hadronically)
  - SR4 DM with ttbar (one top leptonically, other hadronically)



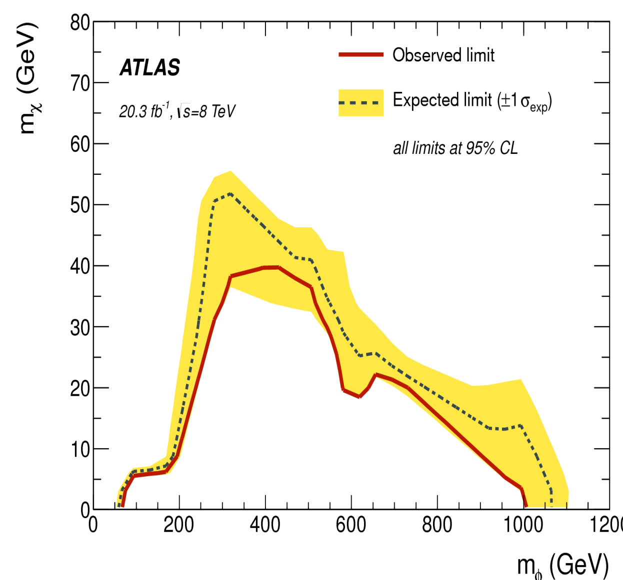




Spin-independent



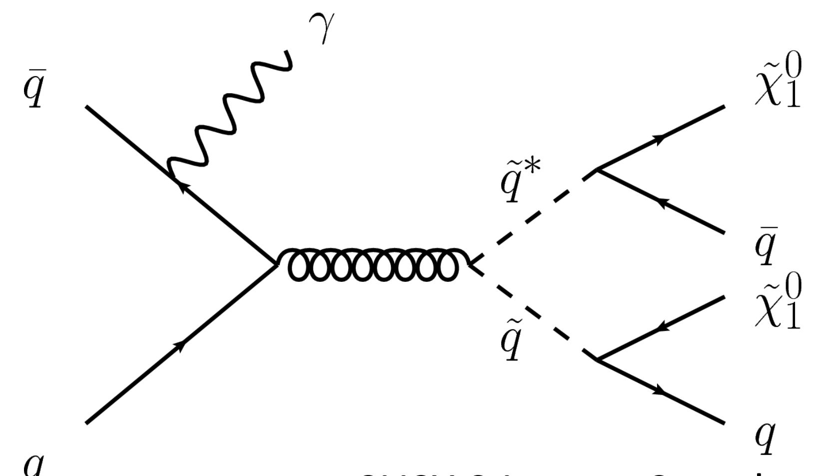
Spin Dependent

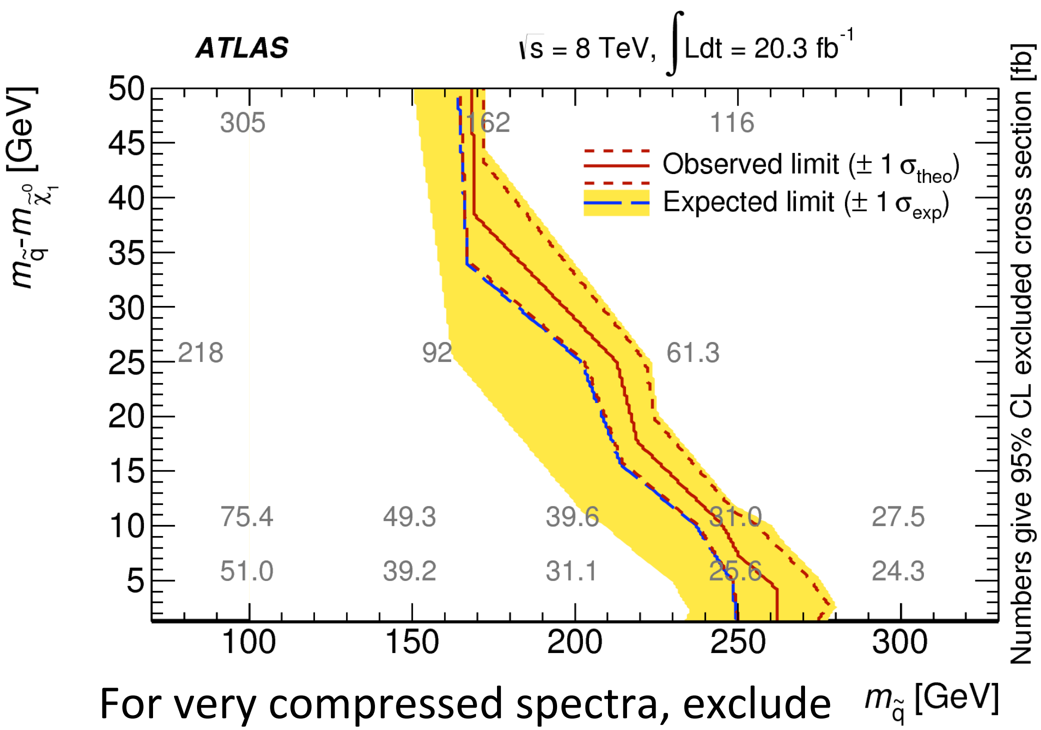


B-FDM

Compressed Supersymmetry (SUSY)

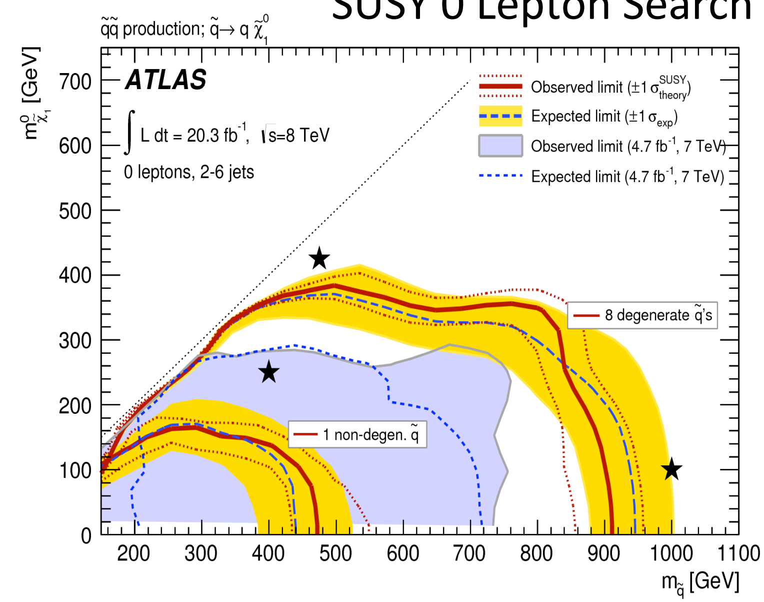
- Small mass splitting between squark and LSP
- Consider the first 2 generation squarks generation (degenerate)
- Quarks are too soft to be reconstructed as jets
- ISR photons give mono-photon signature
  - Complementary to SUSY 0-lepton search





For very compressed spectra, exclude squark mass up to 250 GeV

SUSY 0 Lepton Search



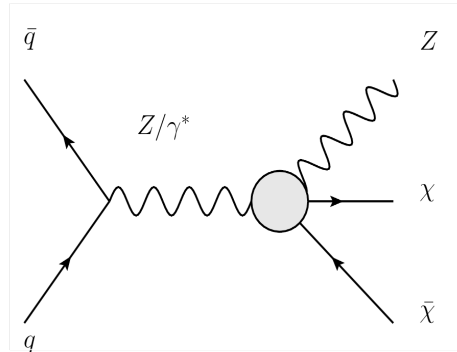
JHEP09(2014)176

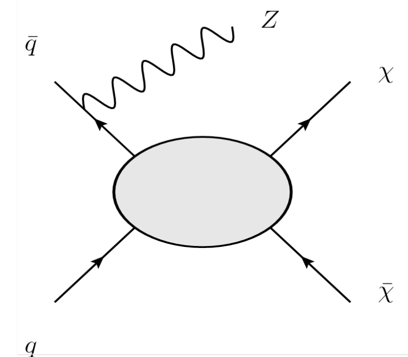
Complementary to SUSY 0L Search

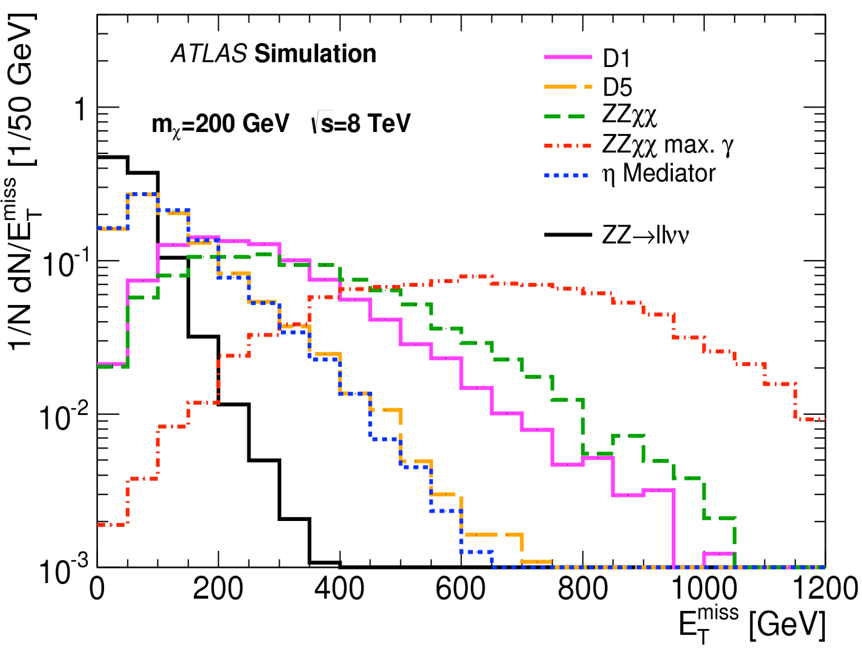
Search DM in Events with Z (→ll) and MET

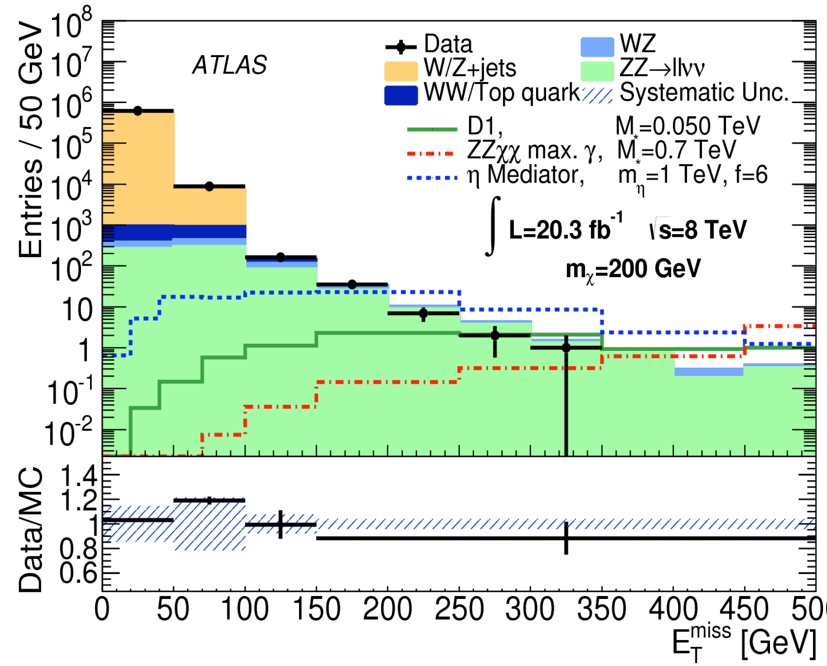
Phys. Rev. D. 90, 012004 (2014)

- Z → ll (l=e, μ)+MET
  - m_{ll} consistent with m_Z
- Dominant backgrounds
  - Z(ll)+νν and WW(lνlν)
- 4 different signal regions considered with different MET thresholds
  - 150, 250, 350 and 450 GeV





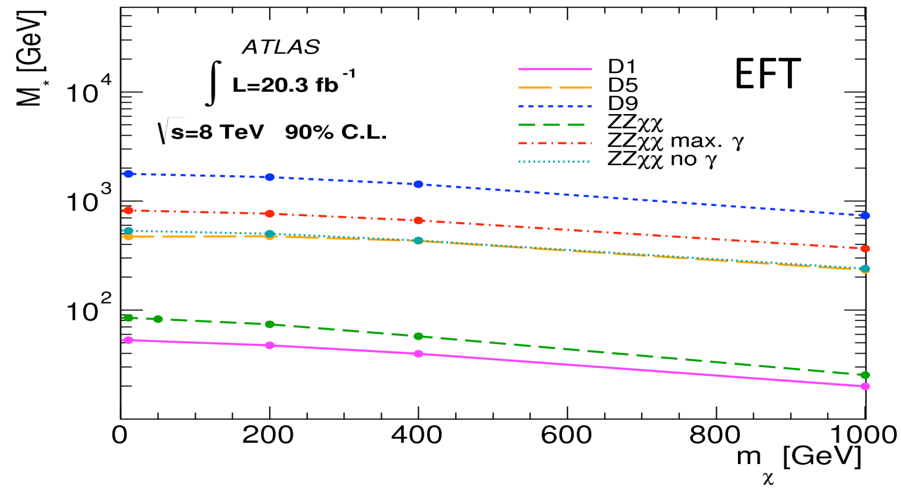


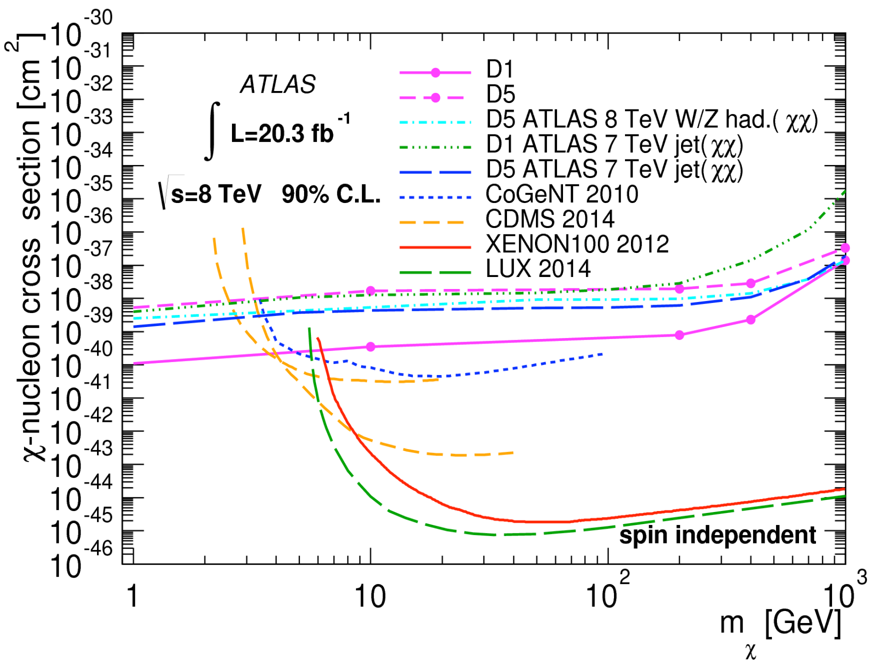


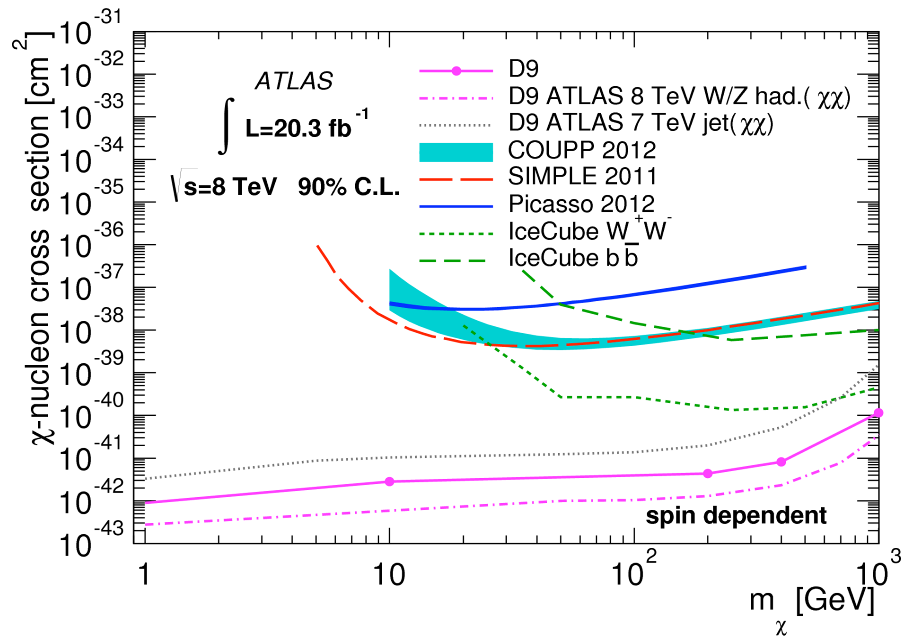
Search DM in Events with Z (→ll) and MET

	E_T^{miss} threshold [GeV]			
	150	250	350	450
	Fiducial cross section [fb]			
Expected Limits [fb]	3.0	0.73	0.36	0.27
Observed Limits [fb]	2.7	0.57	0.27	0.26

95% CL upper limit on fiducial cross-section

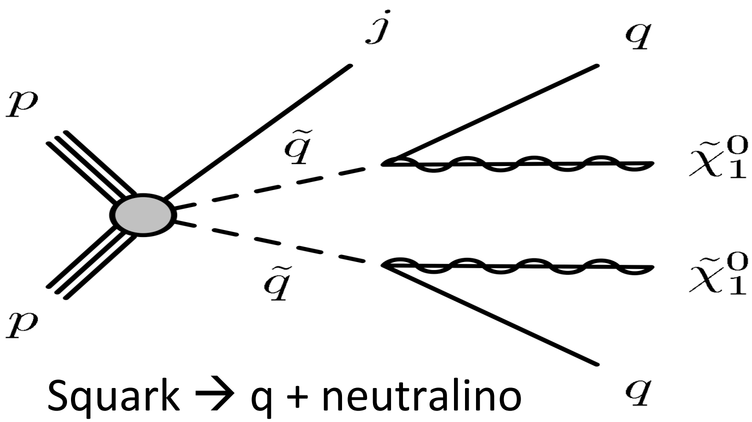




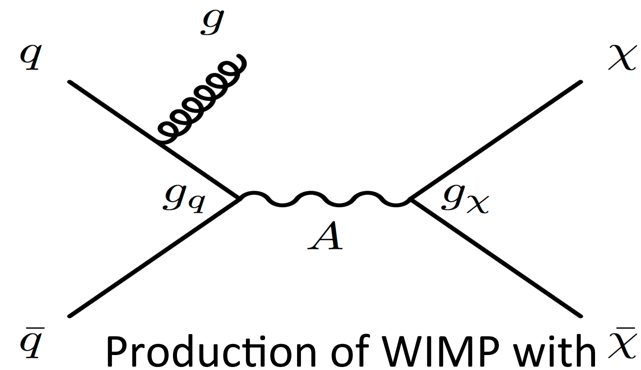


Run 2

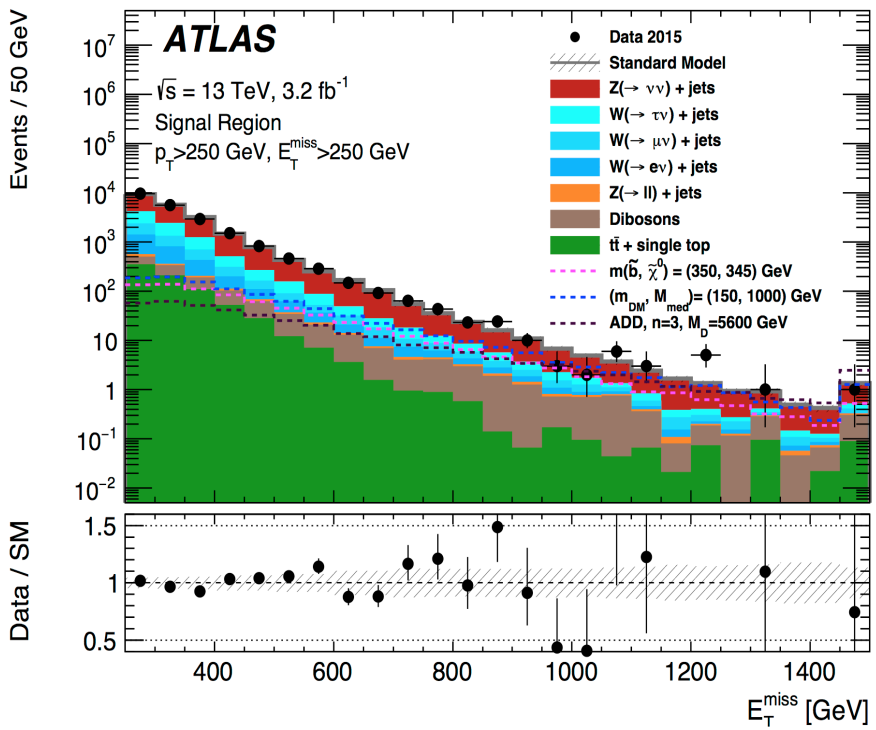
Run 2 mono-jet results

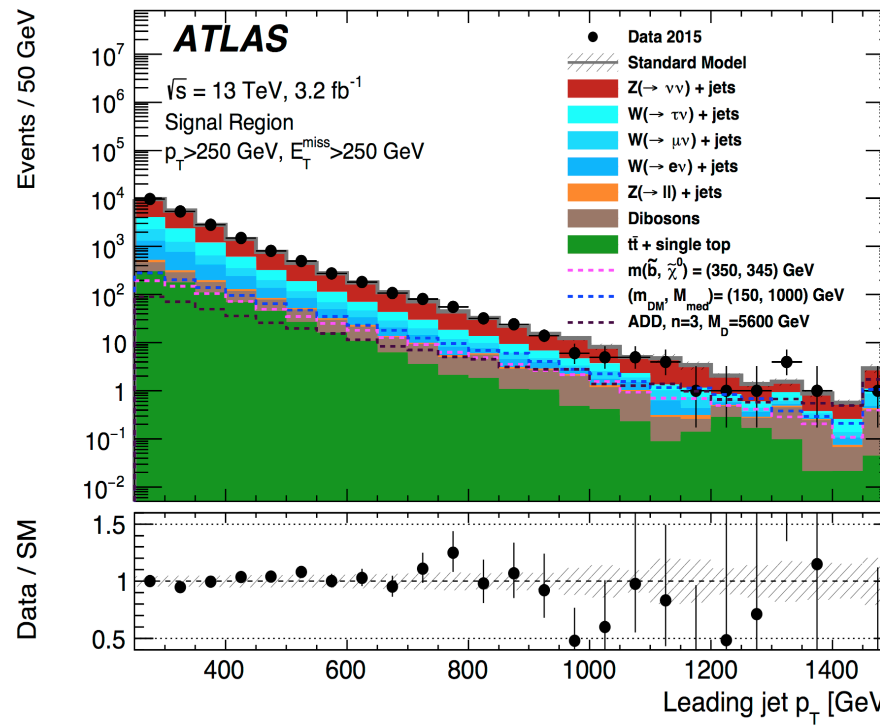


Squark → q + neutralino

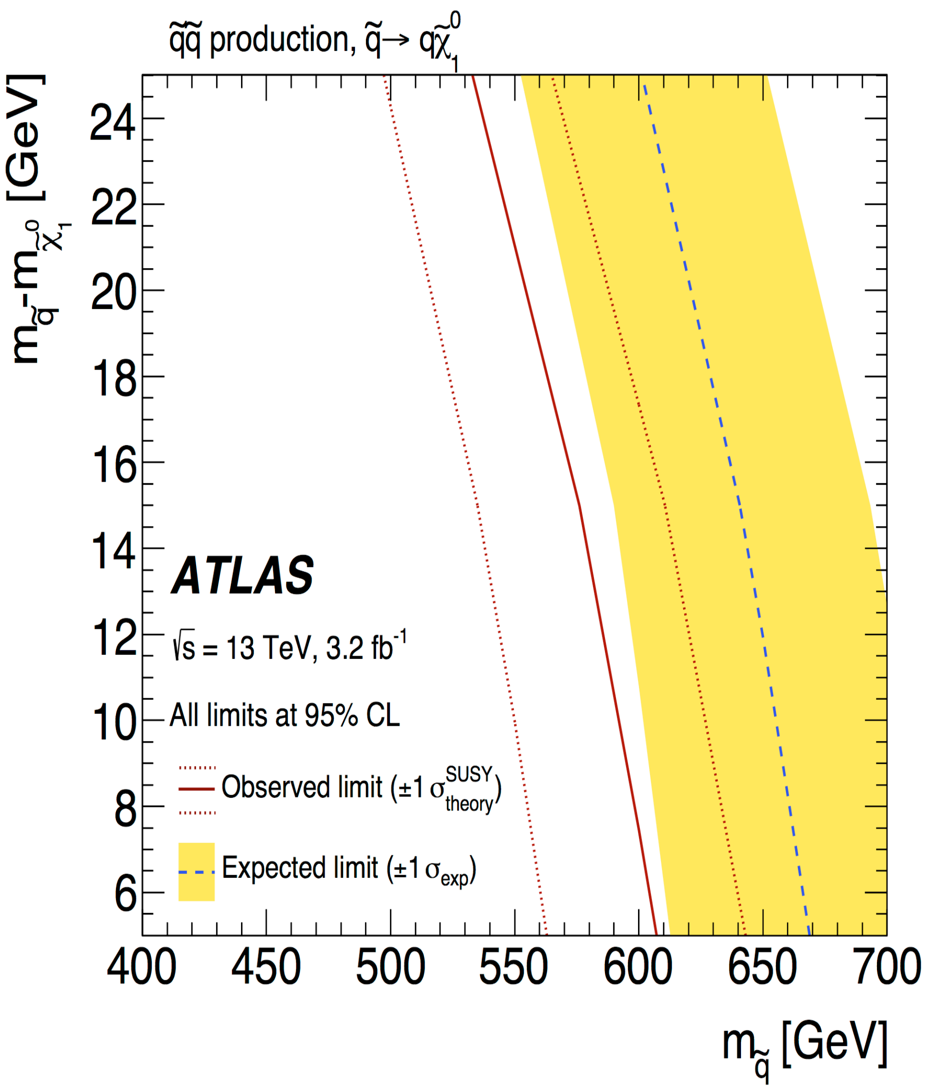


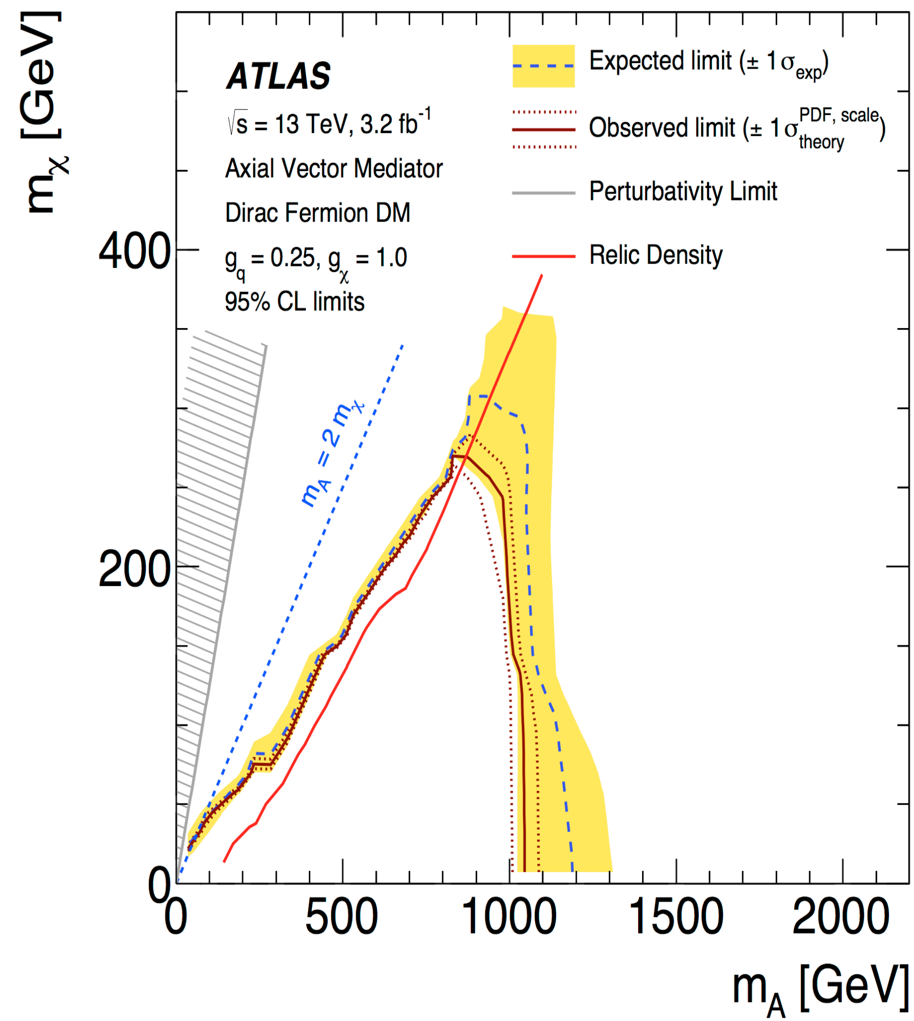
Production of WIMP with mediator A





Run 2 mono-jet results





Conclusions

- Many Run 1 searches for dark interactions at LHC
  - Dark vector bosons in H → 4l events
  - H → invisible particles
  - H → lepton-jets
  - H → LLPs
  - H → aa → fermions, photons
  - Mono-X
- No excess found
- Run 2 might yield exciting discoveries

- **Dark Interactions workshop at BNL 4-7 October 2016**
  - www.bnl.gov/di2016

EFT

- Example of DM χ interactions with SM particles where χ is assumed to a Dirac fermion. Λ parameterizes the coupling strength of scalar (D1), vector (D5), axial-vector (D8) and tensor (D9) interactions between χ and the SM particle

[L. carpenter et al. arXiv arXiv 1212.3352]

$$\Sigma_q \left\{ \frac{m_q}{\Lambda^3_{D1}} \bar{q} q \, \bar{\chi}\chi + \frac{1}{\Lambda^2_{D8}} \bar{q}\gamma^\mu\gamma_5 q \, \bar{\chi}\gamma_\mu\gamma_5\chi + \frac{1}{\Lambda^2_{D5}} \bar{q}\gamma^\mu q \, \bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2_{D9}} \bar{q}\sigma^{\mu\nu} q \, \bar{\chi}\sigma_{\mu\nu}\chi \right\}$$

Scalar

Vector

Axial-Vector

Tensor

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

[J. Goodman et al. arXiv 1008.1783v2]

D: WIMPS that are Dirac Fermions

C: WIMPS that are Complex Scalars

R: WIMPS that are real Scalars

We throw away events where the EFT is invalid because the momentum transfer surpasses the scale of the contact interaction