Dark Matter Searches at the LHC

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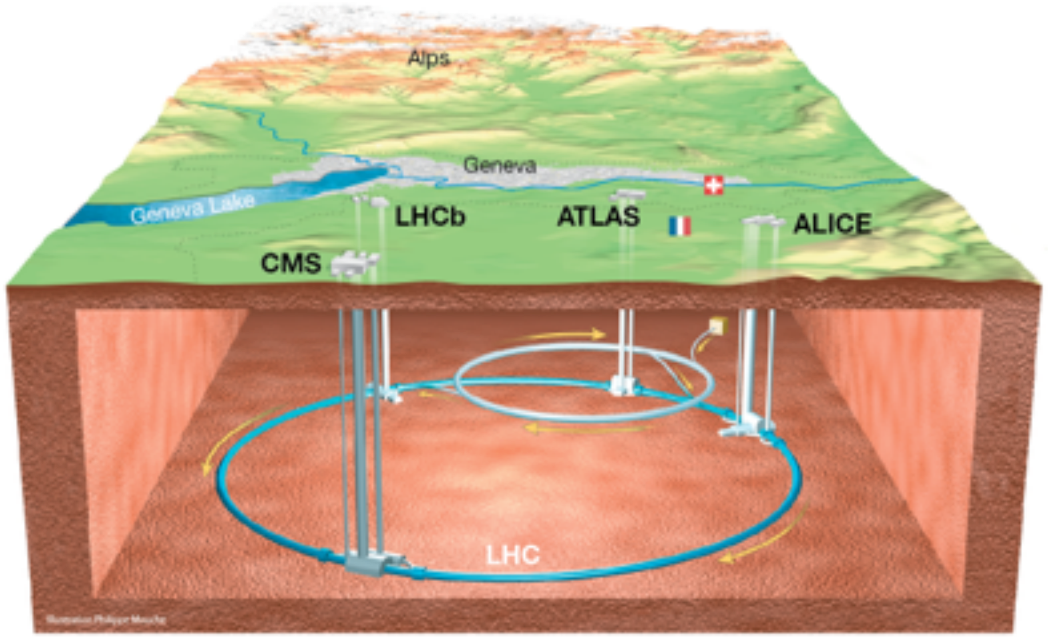
Large Hadron Collider

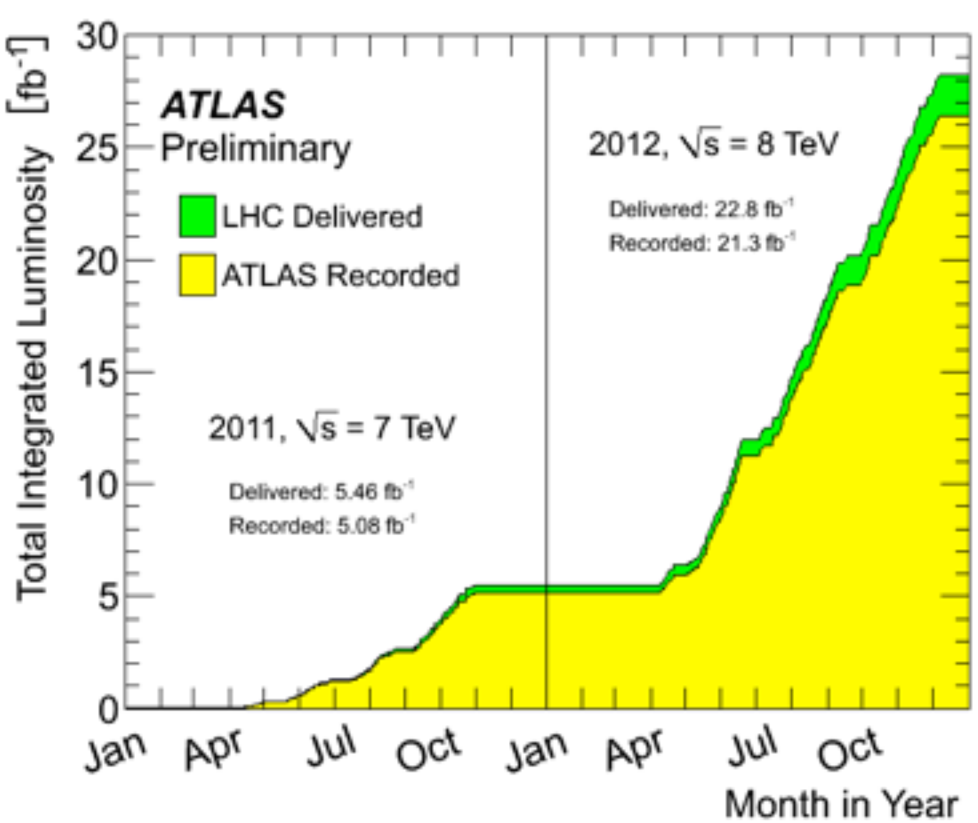
LHC collides protons with center-of-mass energies up to 14 TeV

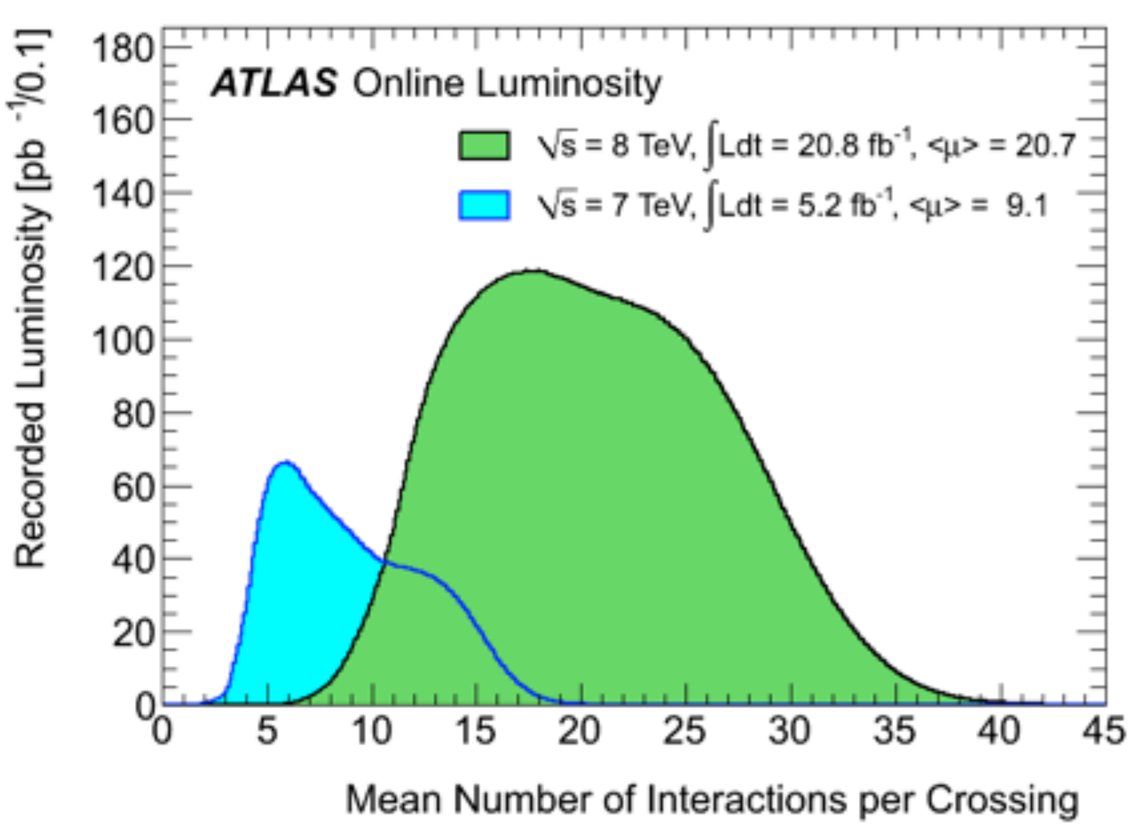
- Counter-circulating beams of >1000 bunches of ~10^{11} protons
- Bunches cross every 25 ns (or 50 ns) producing up to 40 p-p collisions



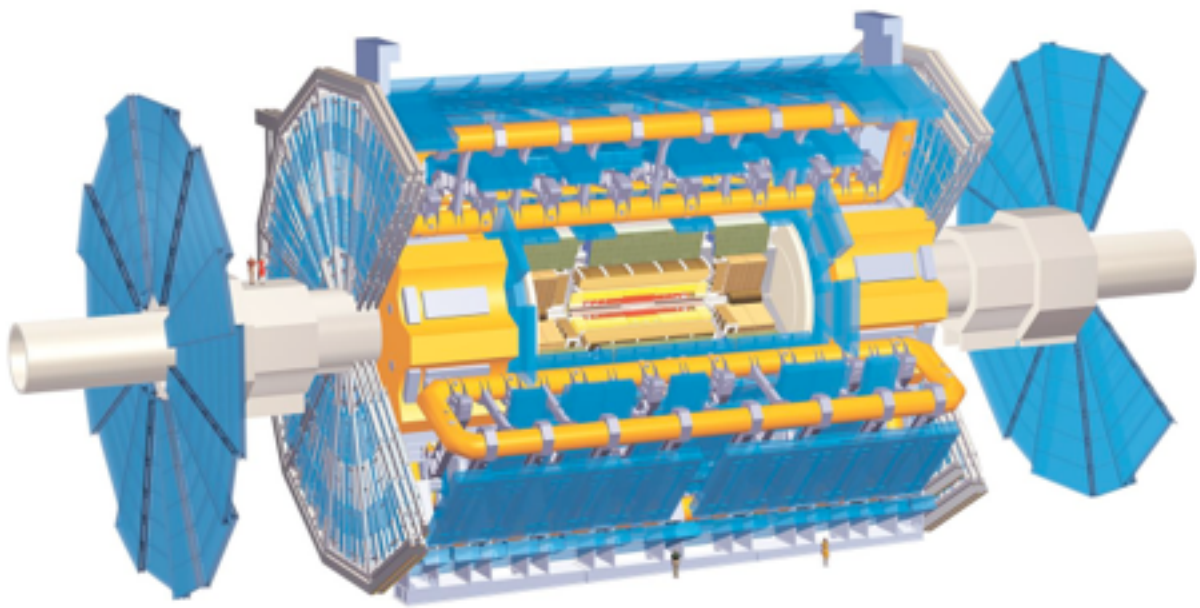
Run 1: 7 TeV (2010–11) and 8 TeV (2012)

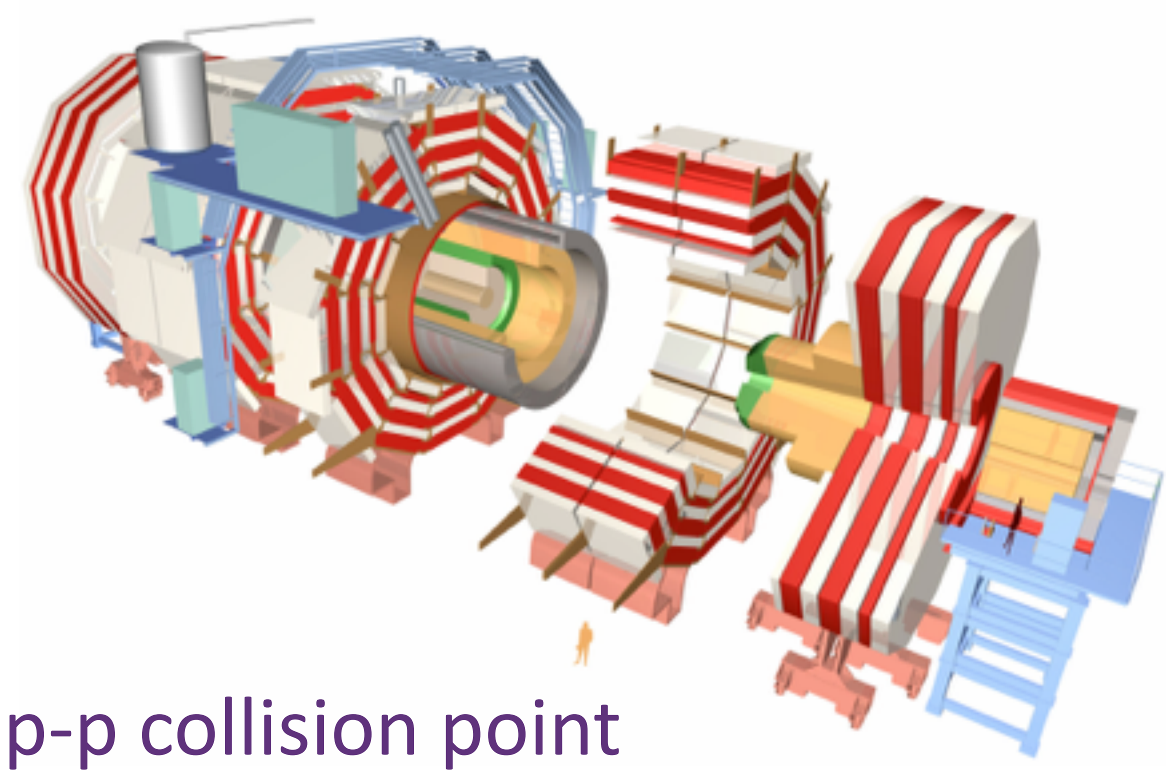
- All results presented today use 8 TeV data





ATLAS and CMS detectors



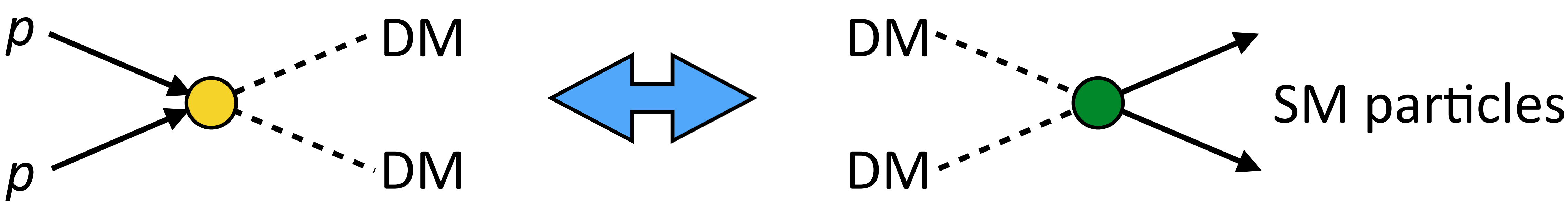


Each detector is built to surround a p-p collision point

- Near-4π coverage to detect all collision products (photons, leptons, hadrons) except for neutrinos and DM
- Energy/momentum measurement of all particles ➔ Inference of undetected particle(s) from momentum conservation in the transverse plane
  - p_T^X = transverse momentum of X (particle or group of particles)
  - MET = negative sum of p_T of all detected particles in an event
- All DM searches look for events with large values of MET

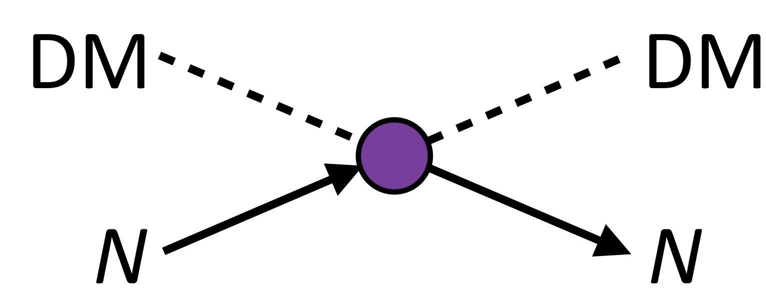
DM production at the LHC

LHC (hopefully) pair-produce DM particles in p-p collisions



Production cross-section $\sigma(pp \to \chi\bar{\chi})$ is related to the annihilation cross-section $\sigma(\chi\bar{\chi} \to \text{anything})$, but it's model-dependent

- Protons are made (mostly) of light quarks
- It also differs from the nucleon-DM elastic scattering cross-section measured by direct detection experiments



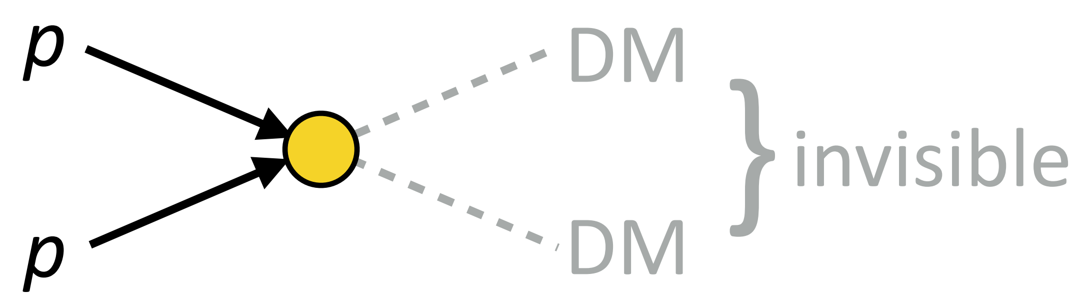
Interpretation gets complicated

- Pay attention to theory talks after the coffee break…

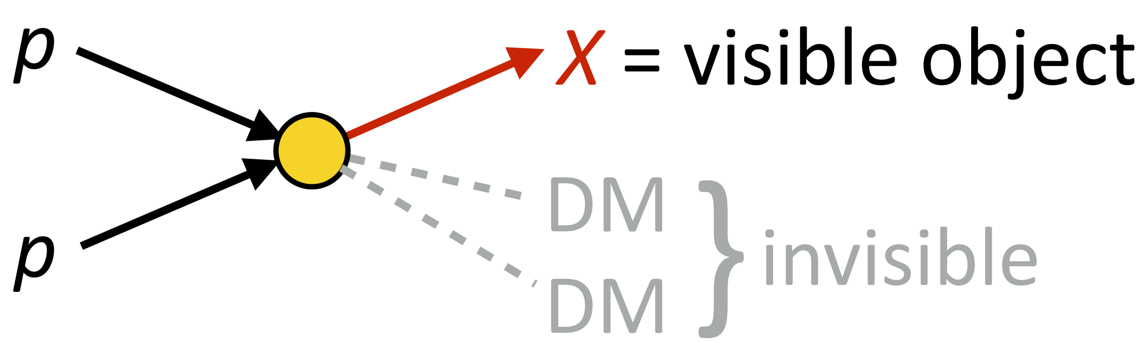
DM detection at the LHC

Experiments cannot see the final state with only DM particles

- How do we record and count such events?



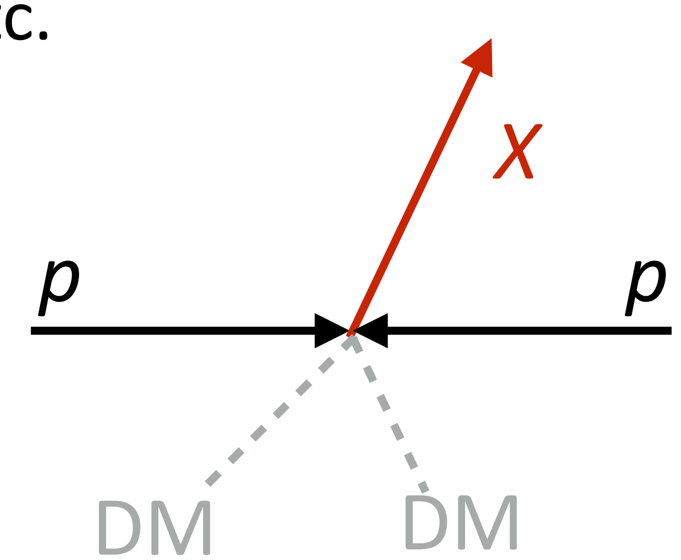
We need ≥1 extra particles produced with the DM particles



- We call it "mono-*X*" with *X* = jet, photon, Higgs, *W*, *Z*, etc.

Net momentum of the outgoing particles seems to violate momentum conservation → "MET"

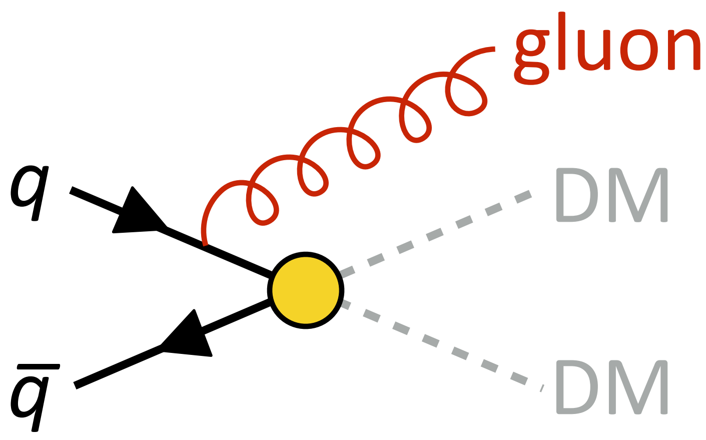
- Candidate events contain *X* + MET and little else



Where does "X" come from?

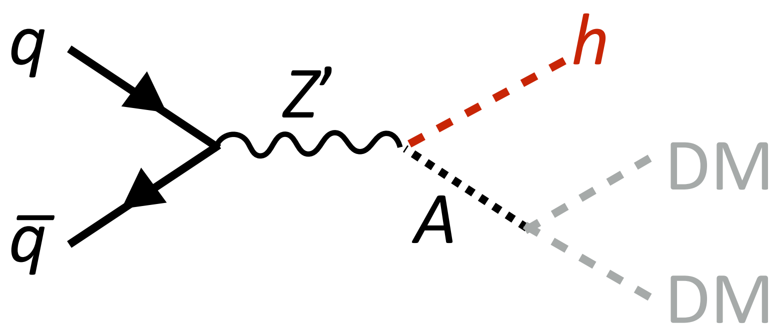
X may be radiated by the incoming quarks

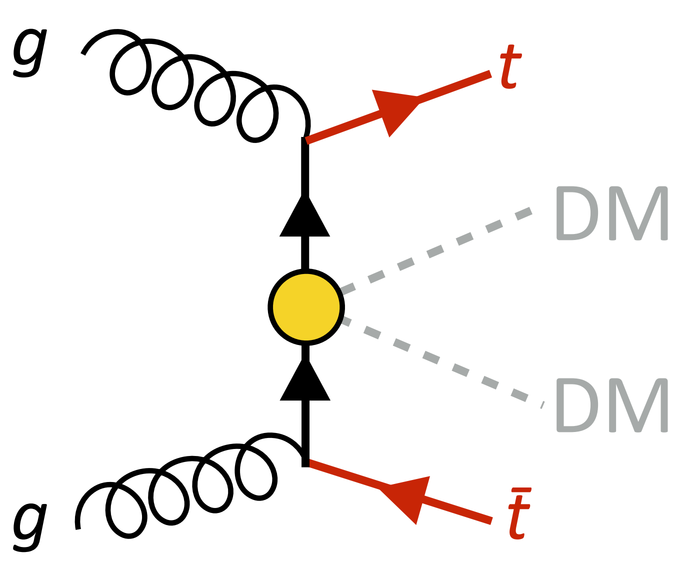
- X can be a gluon, photon, W or Z boson
- If $q\bar{q} \to \chi\bar{\chi}$ happens, $q\bar{q} \to \chi\bar{\chi} + (g/\gamma/W/Z)$ is guaranteed to happen



- If X = gluon, it turns into a "jet" and creates a "mono-jet" signature

X may be more closely connected to DM production, e.g.





- Cross-section depends on the exact model and the couplings
- May be large even if $q\bar{q} \to \chi\bar{\chi}$ is small

Mono-*X* results from Run 1

- All results use full statistics (~20 fb^{-1}) of 8 TeV collision data

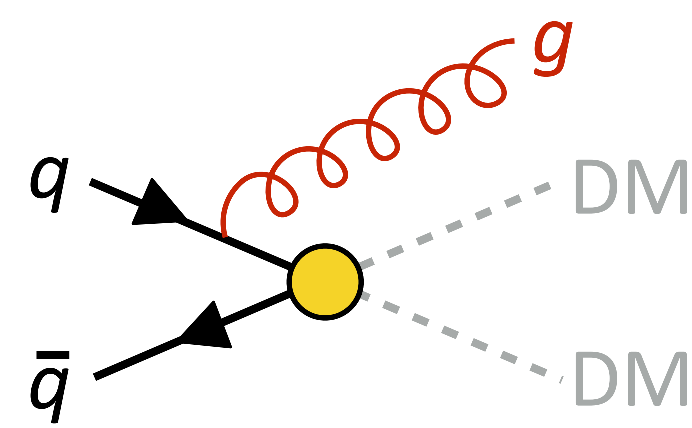
"*X*" in mono-*X*	Expt.	Reference	arXiv
jet	ATLAS	Eur. Phys. J. C 75 (2015) 299	1502.01518
	CMS	Eur. Phys. J. C 75 (2015) 235	1408.3583
≥2 jets	CMS	CMS-PAS-EXO-14-004	
photon	ATLAS	Phys. Rev. D 91 (2015) 012008	1411.1559
	CMS	submitted to Phys. Lett. B	1410.8812
W ($\rightarrow \ell\nu$)	ATLAS	JHEP 09 (2014) 037	1407.7494
	CMS	Phys. Rev. D 91 (2015) 092005	1408.2745
Z ($\rightarrow \ell\ell$)	ATLAS	Phys. Rev. D 90 (2014) 012004	1404.0051
	CMS	submitted to Phys. Rev. D	1511.09375
W or Z ($\rightarrow q\bar{q}$)	ATLAS	Phys. Rev. Lett. 112 (2014) 041802	1309.4017
	CMS	CMS-PAS-EXO-12-055	
$t\bar{t}$ (1 lepton)	CMS	JHEP 06 (2015) 121	1504.03198
$t\bar{t}$ (2 leptons)	CMS	CMS-PAS-B2G-13-004	
t or *b*-quark jet	ATLAS	Eur. Phys. J C75 (2015) 92	1410.4031
H ($\rightarrow \gamma\gamma$)	ATLAS	Phys. Rev. Lett. 115 (2015) 131801	1506.01081
H ($\rightarrow b\bar{b}$)	ATLAS	submitted to Phys. Rev. D	1510.06218

Mono-jet search

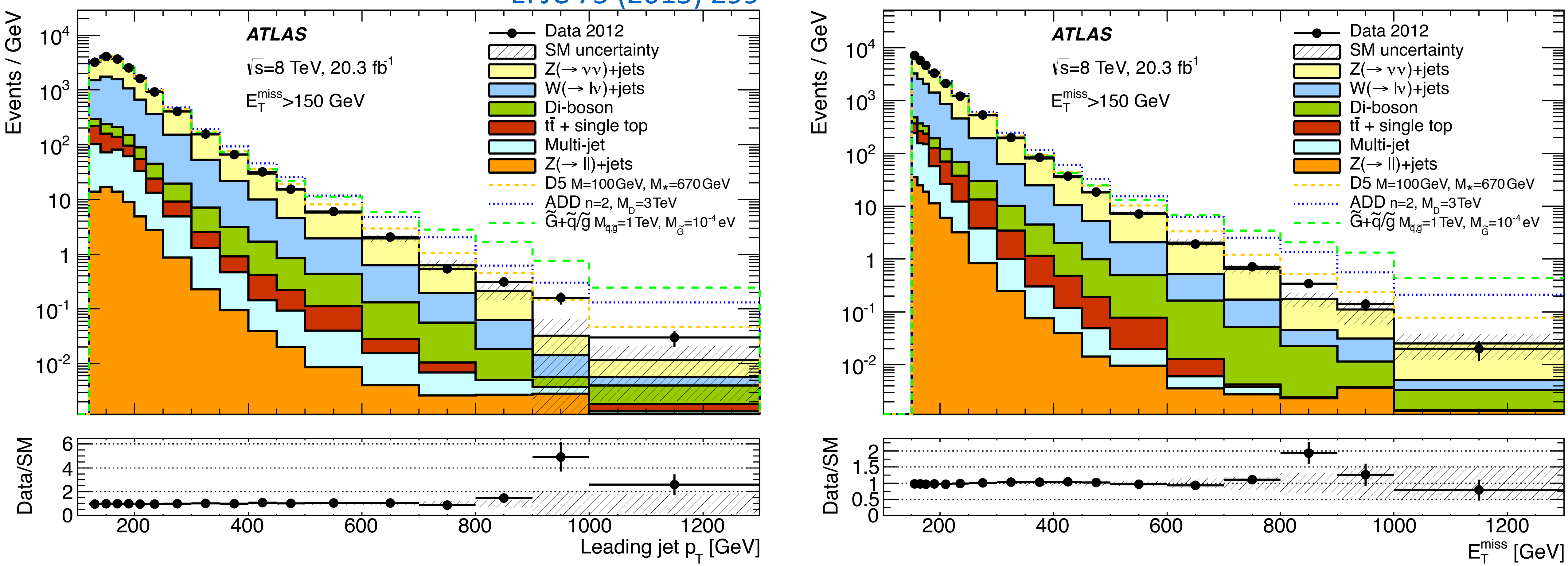
Mono-jet has the highest sensitivity to “generic” WIMP-like DM

ATLAS mono-jet search [EPJC 75:299]

- Select events with ≥1 jet with p_T^{jet} > 125 GeV and no leptons
- Require MET > 150 GeV and p_T^{jet}/MET > 0.5



EPJC 75 (2015) 299



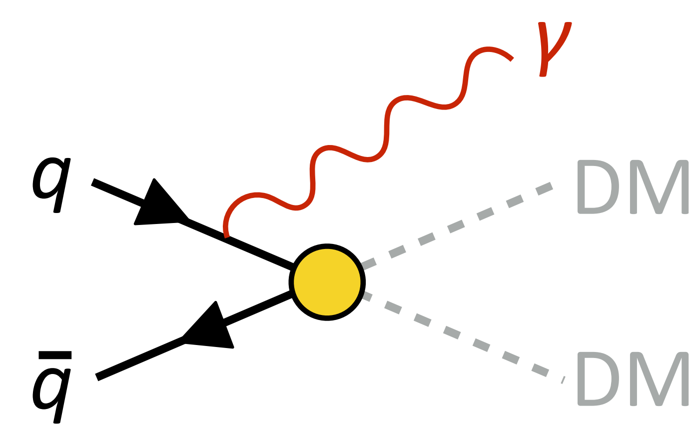
Mono-photon search

Mono-photon is similar to mono-jet

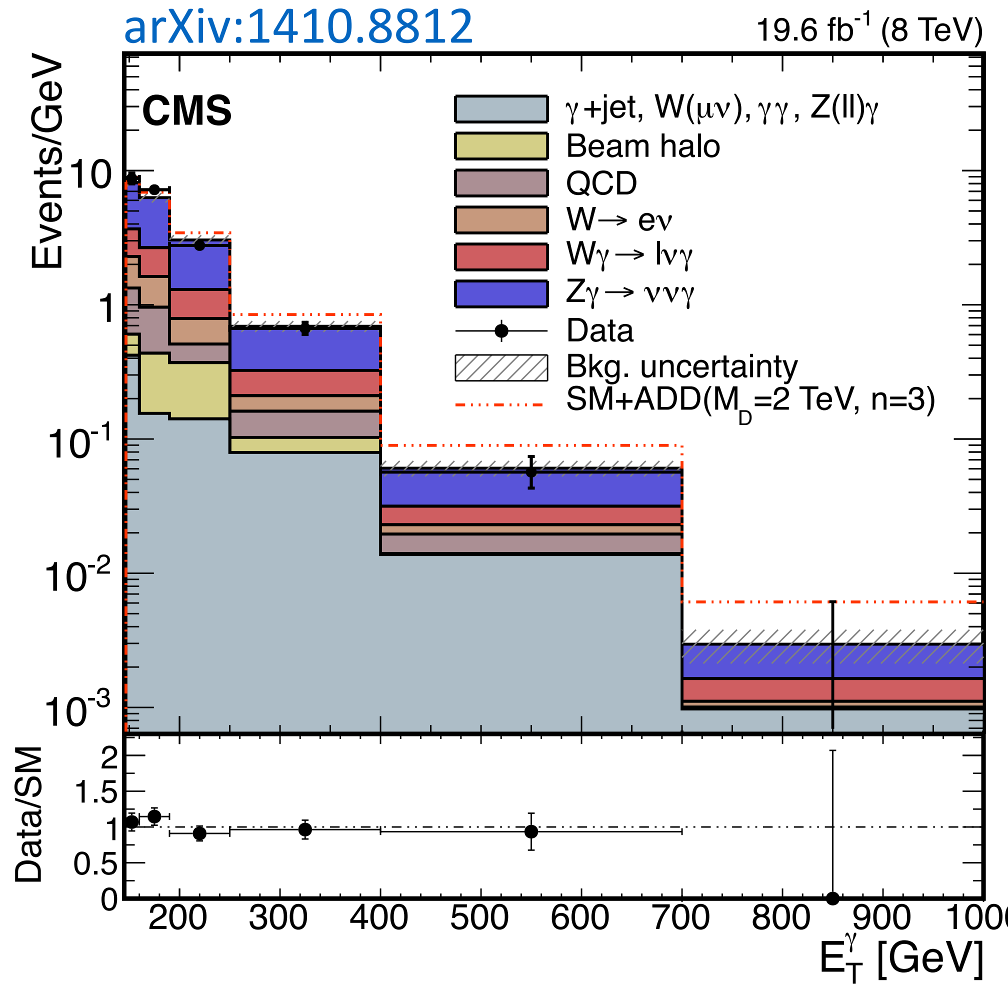
- Smaller signal cross-section, but smaller background

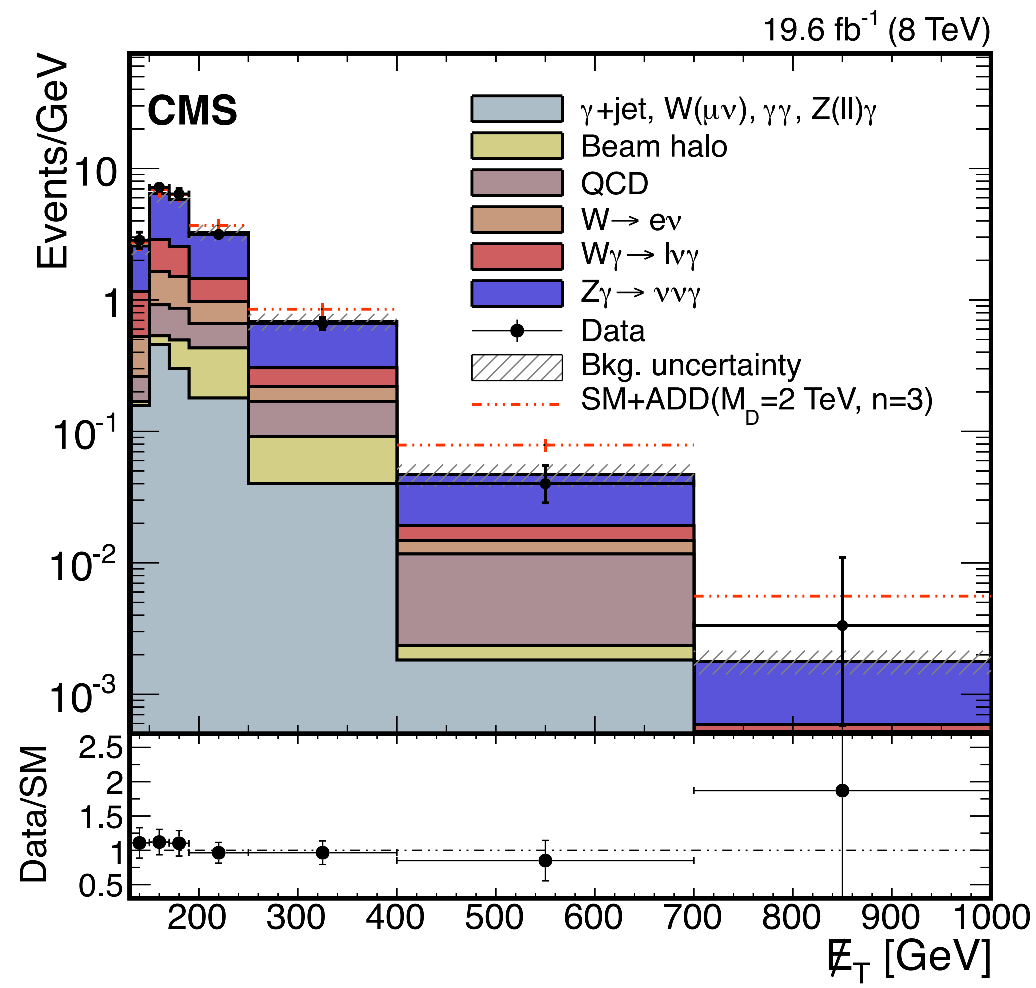
CMS mono-photon search [arXiv:1410.8812]

- One photon with $E_T^\gamma > 145$ GeV, and ≤1 jet
- Require MET > 140 GeV



arXiv:1410.8812

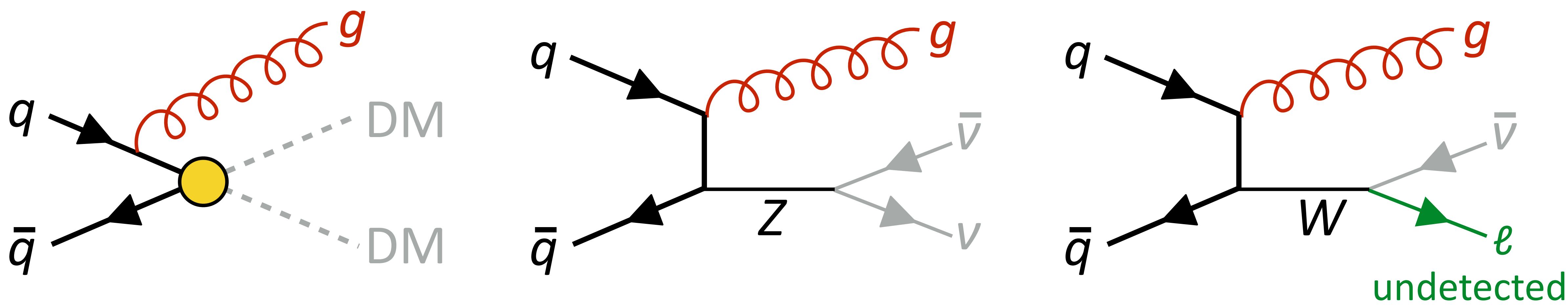




Background

Background in mono-jet/photon searches are dominated by

- Z ($\to \nu\bar{\nu}$) + jet/photon (irreducible)
- W ($\to \ell\nu$) + jet/photon where the lepton escaped detection



Estimate them using control samples in data

- Z ($\to \ell\ell$) and W ($\to \ell\nu$) + jet/photon where the leptons were detected
  - NB: BR($Z \to \ell\ell$) << BR($Z \to \nu\bar{\nu}$)
- Smaller background sources are estimated with simulation

Instrumental background has to be controlled, too

- e.g., beam-induced noise in the calorimeter that looks like a jet

Interpretation — EFT

LHC measures $\sigma(pp \to X + \mathrm{DM})$ in bins of MET

- How does it relate to the cosmic Dark Matter?

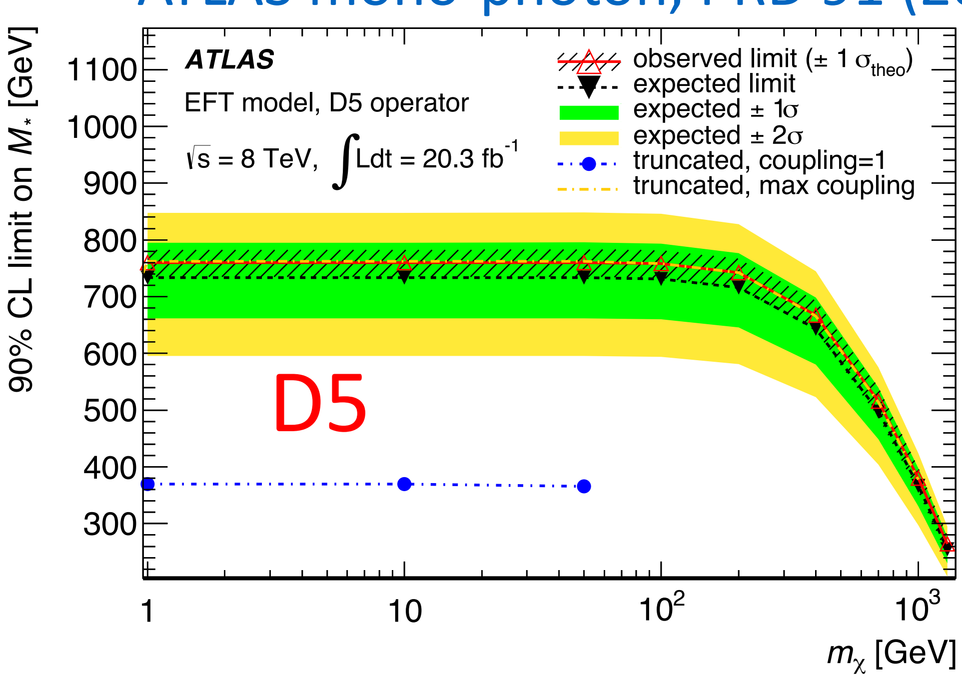
Interpretation requires theoretical assumptions

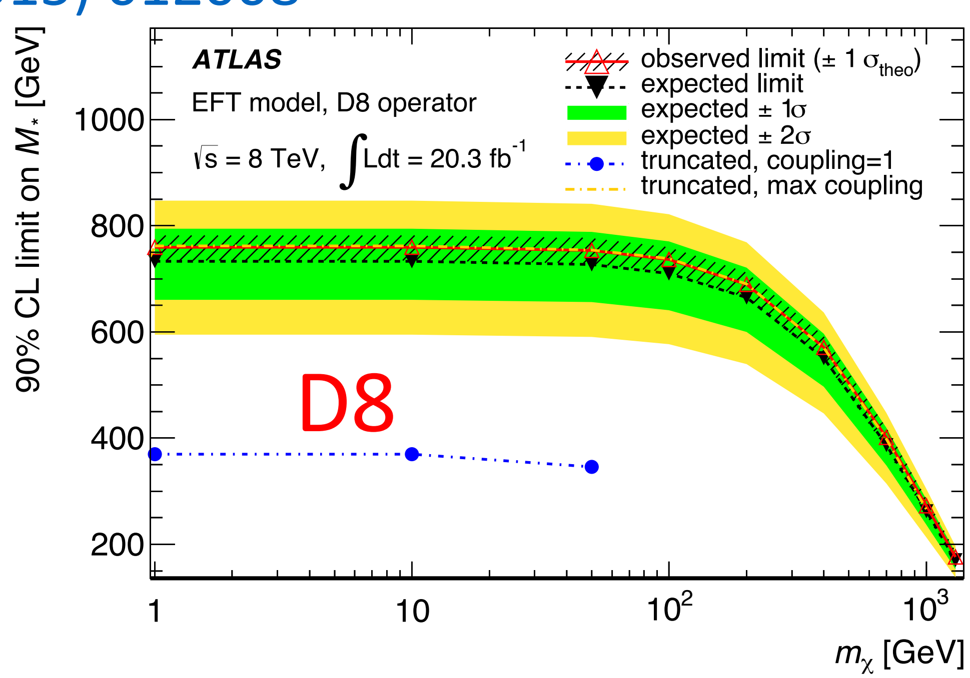
- What kind of DM (mass, spin, parity, interactions) is it?

Effective Field Theory (EFT) has been our benchmark

- Constrain the scale M_* as a function of the DM mass m_χ

ATLAS mono-photon, PRD 91 (2015) 012008





- NB: Validity of EFT is questionable at $M_* \lesssim 2m_\chi$

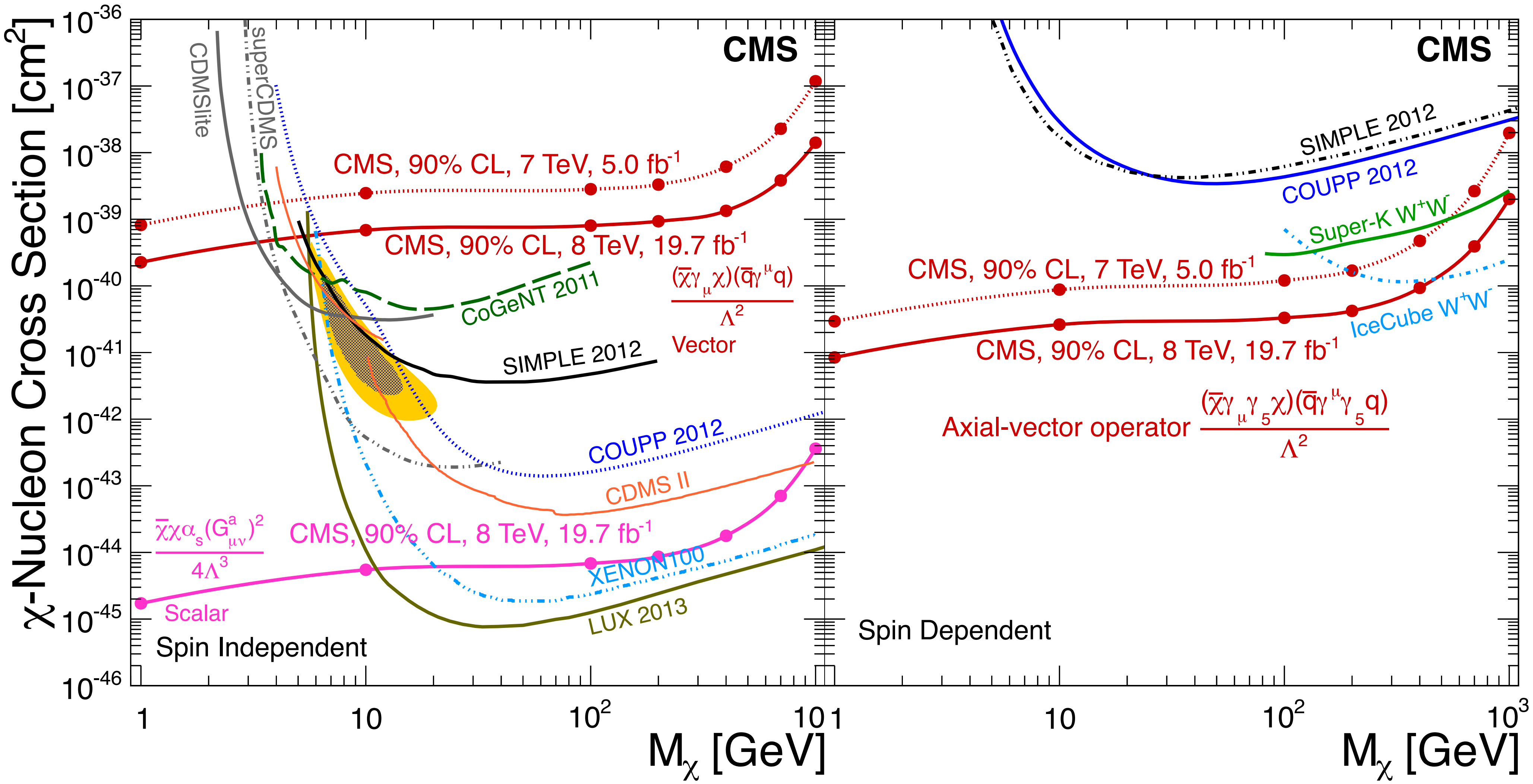
Goodman et al., PRD 82 (2010) 116010

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

LHC v.s. direct-detection

Caution: comparisons are strongly model-dependent

- Ex) EFT-based results from CMS mono-jet, EPJC 75 (2015) 235



- Limits for the vector (D5) and scalar (D11) operators differ by ~10^5
- LHC is more sensitive to light DM, and to spin-dependent interactions

Interpretation — Simplified model

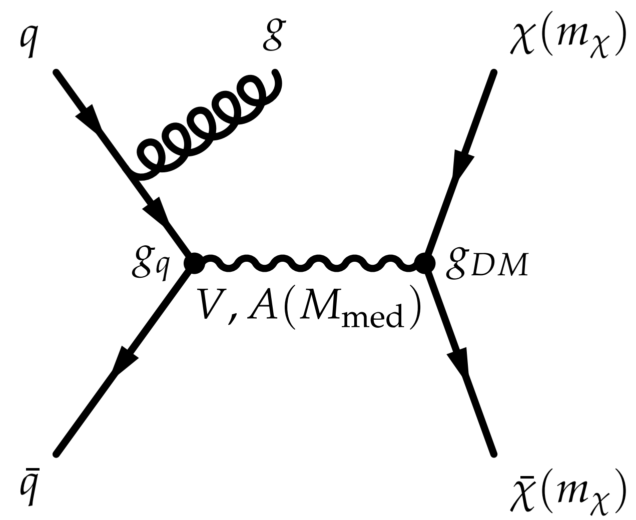
Validity of EFT has been a recurring question

- What if the mediator is light (a few 100 GeV)?

ATLAS/CMS DM Forum report [arXiv:1507.00966]

- Recommends simplified models for use in new measurements from the LHC
- Mono-jet results, for example, will be presented as a bound on the coupling ($g_q \cdot g_{\mathrm{DM}}$) on the M_{med}-v.s.-m_χ plane

Mono-jet example



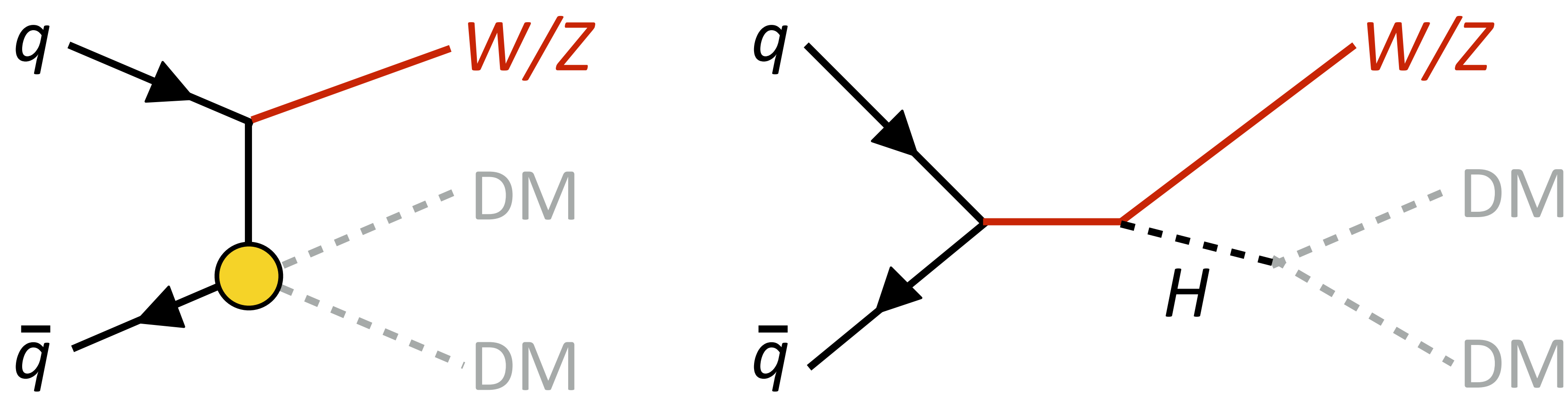
$$\mathcal{L}_{\mathrm{vector}} = g_{\mathrm{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\mathrm{axial-vector}} = g_{\mathrm{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$

Recent ATLAS/CMS papers report both EFT and simplified model results

Mono-W/Z

Mono-W/Z can be produced in the same way as mono-jet/photon, but other possibilities exist:



- "Higgs-strahlung" (right) probes Higgs-DM coupling, or invisible Higgs decays in general

ATLAS/CMS can detect W/Z in two ways

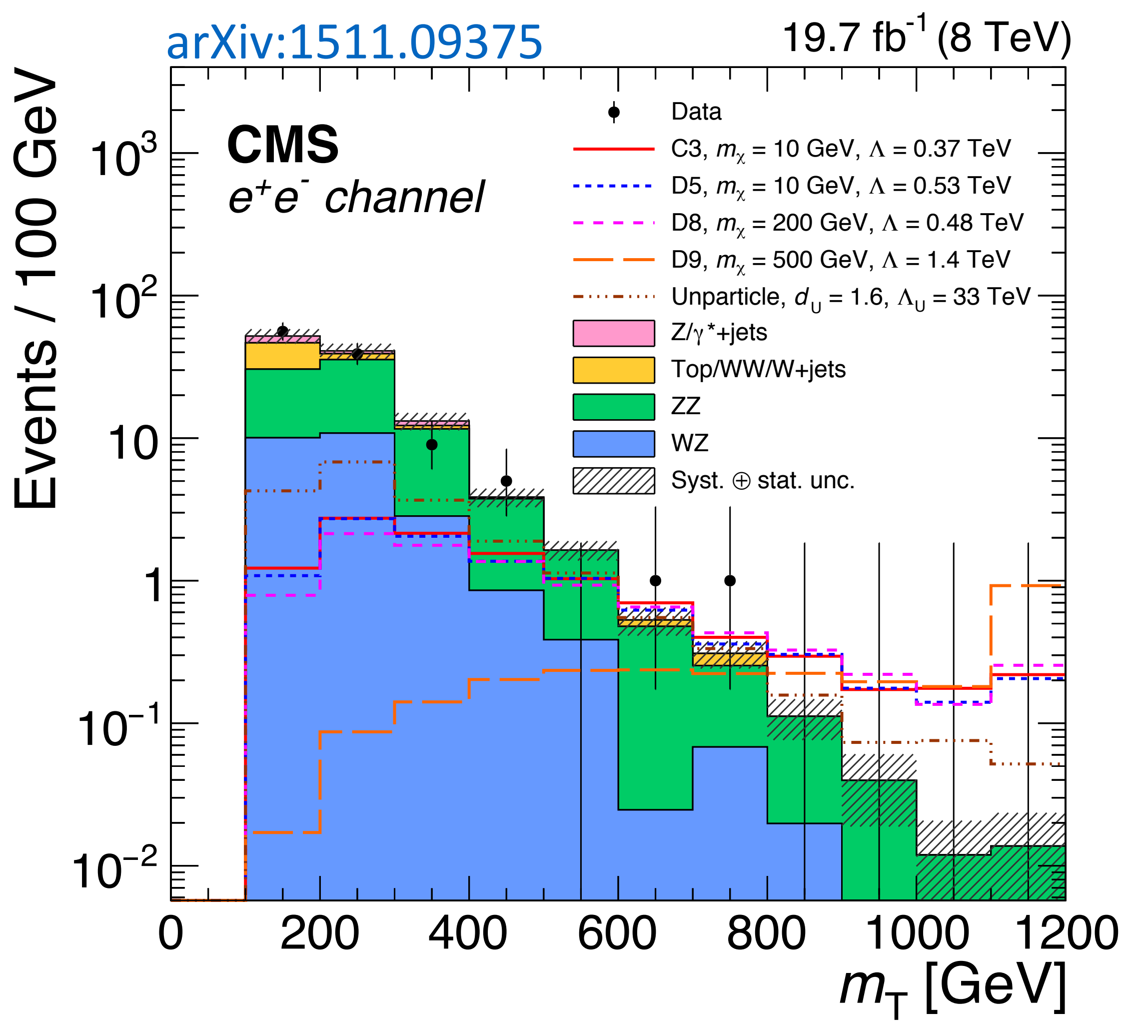
- Leptonic final states $W \to \ell\nu$ and $Z \to \ell\ell$
  - Small background. But small branching fractions
- Hadronic final states $W/Z \to q\bar{q}$ (2 jets)
  - Large branching fractions. But large background

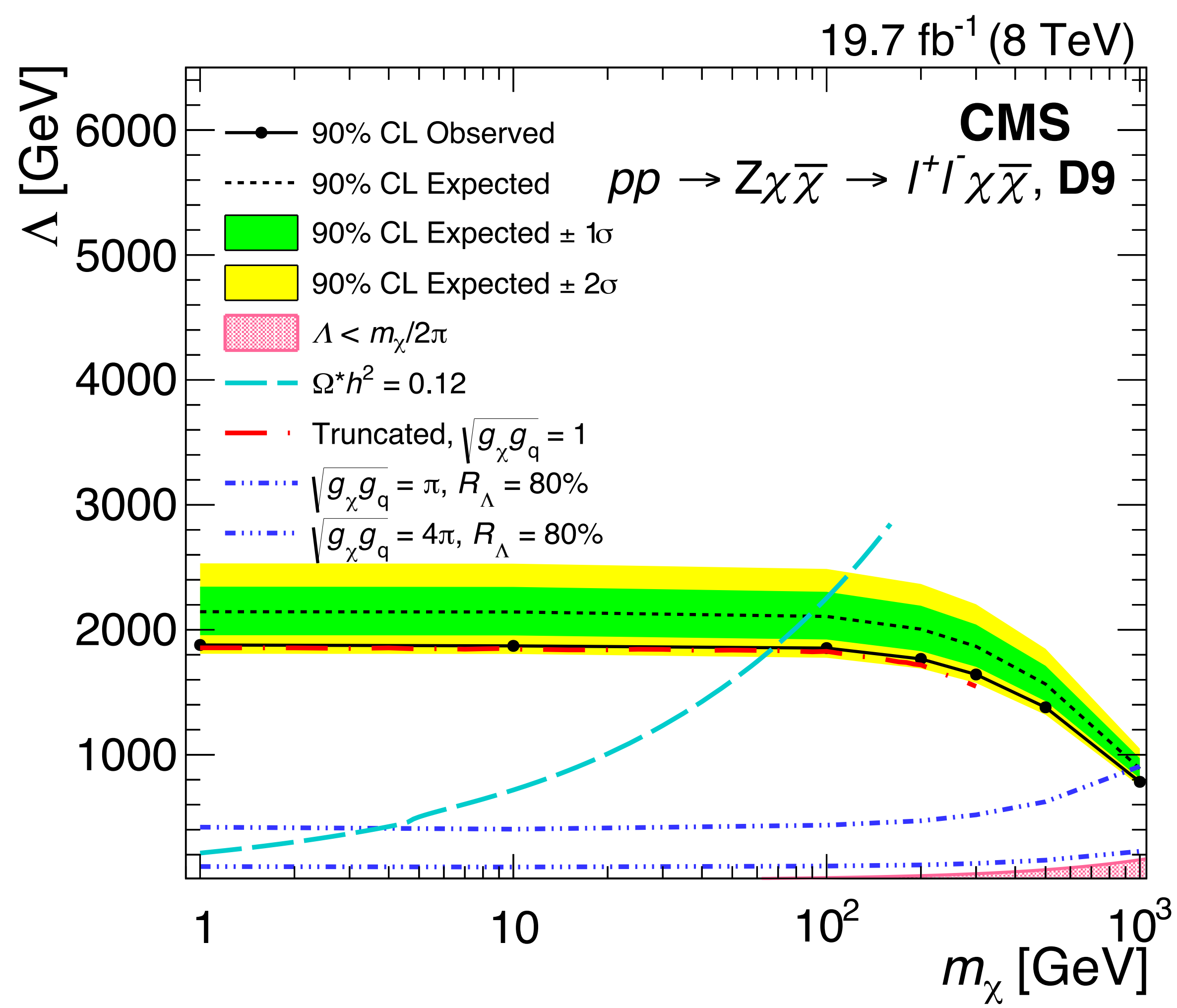
Leptonic mono-Z

CMS leptonic mono-Z [arXiv:1511.09375]

- $Z \to ee$ or $\mu\mu$ with $p_T^{\ell} > 20$ GeV, $|m_{\ell\ell} - m_Z| < 10$ GeV, and $p_T^{\ell\ell} > 50$ GeV
- MET > 80 GeV. MET is back-to-back and balanced with $p_T^{\ell\ell}$
- At most 1 jet and zero *b*-tagged jet (to suppress $t\bar{t}$ background)

arXiv:1511.09375



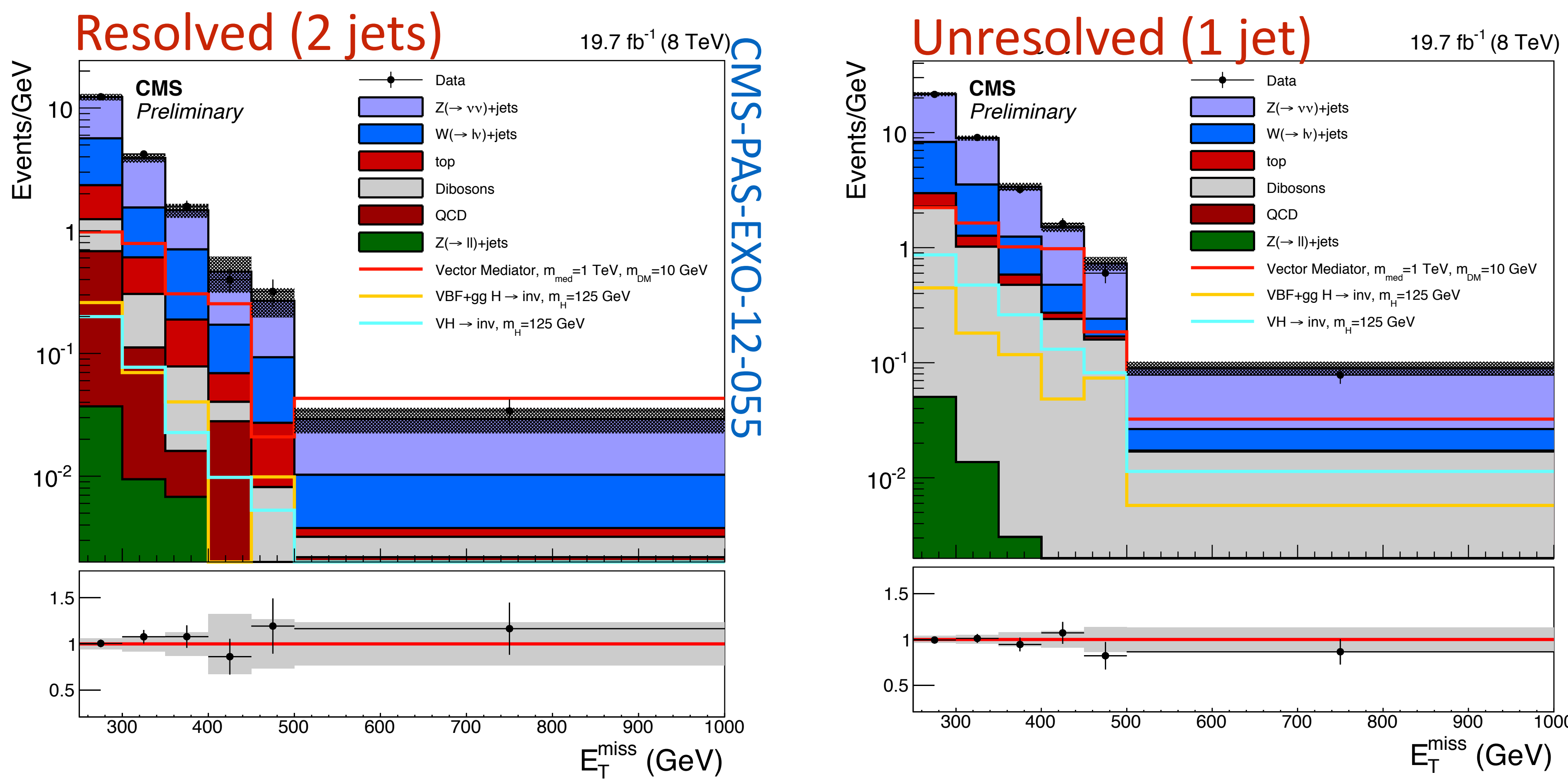


- Background is small, dominated by *WZ* and *ZZ* diboson production

Hadronic mono-*W/Z*

CMS hadronic mono-*W/Z* [CMS-PAS-EXO-12-055]

- Two jets may be detected as resolved (= 2 jets) or unresolved (= 1 jet) depending on the boost of the *W/Z*
  - Unresolved case requires analysis of sub-jet structure
- 60 < m_{jj} < 110 GeV, ≤1 extra jet, and MET > 250 GeV

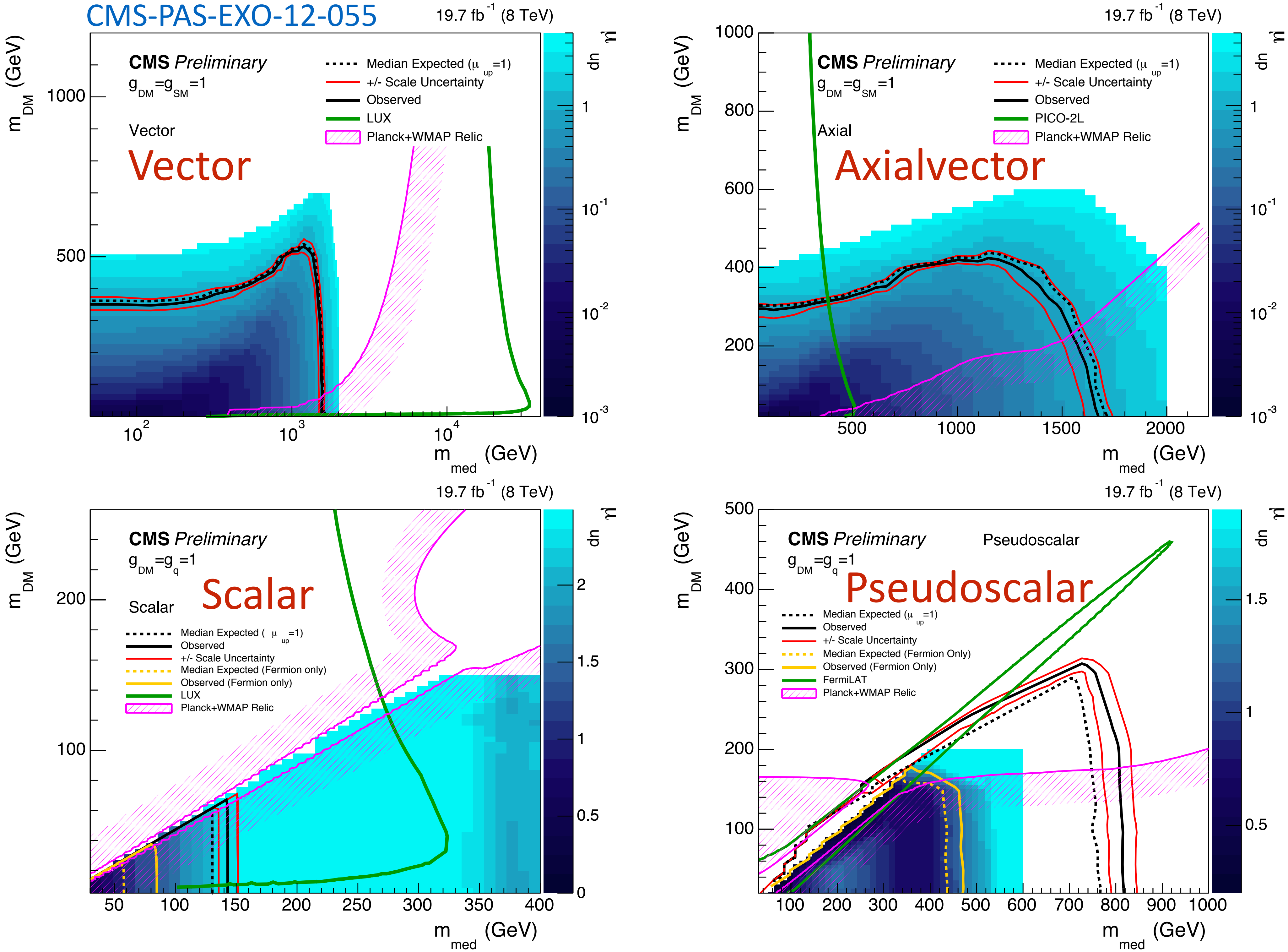


- Analysis also uses mono-jet events with p_T^{jet} > 150 GeV and MET > 200 GeV

Hadronic mono-W/Z

Simplified-model interpretation for different mediators

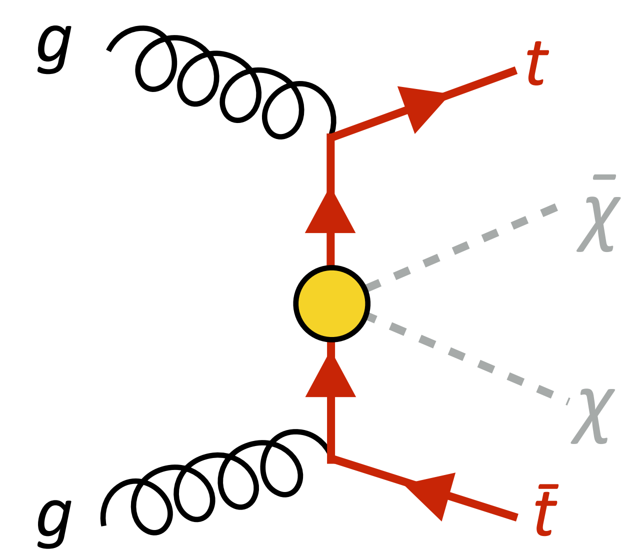
CMS-PAS-EXO-12-055



Mono(?)-$t\bar{t}$

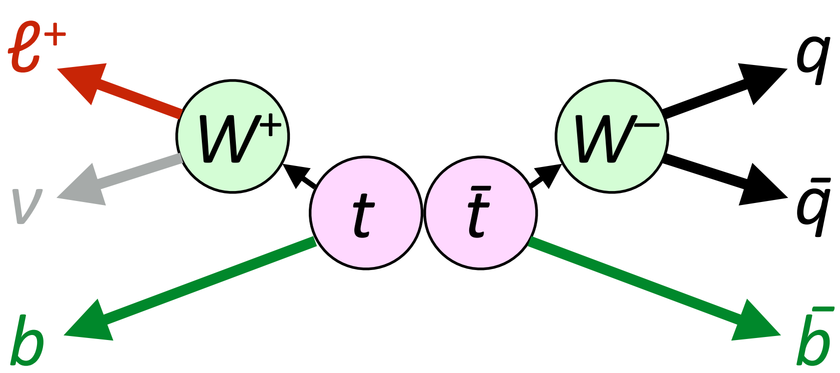
Scalar interaction (D1) between DM and quarks is $L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$

- Top quark is favored ➔ Search for MET + $t\bar{t}$ pair

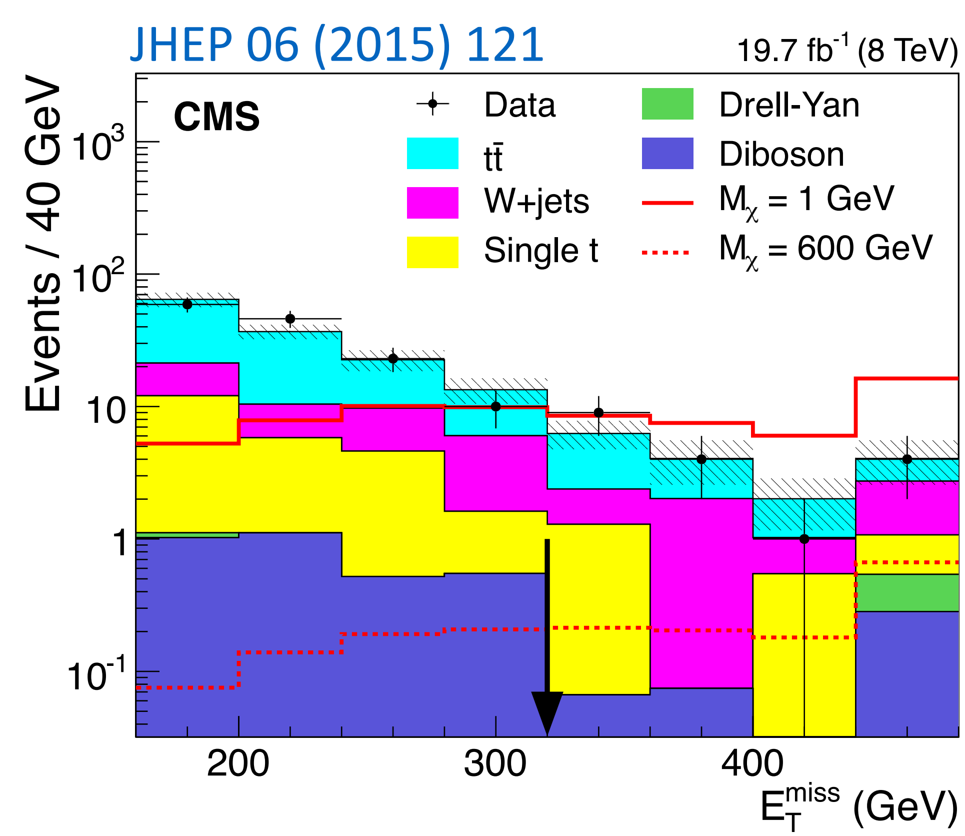


CMS $t\bar{t}$ + MET search [JHEP 06 (2015) 121]

- Reconstruct $t(\to\ell\nu b)\bar{t}(\to q\bar{q}\bar{b})$
- Require 1 lepton, ≥3 jets of which ≥1 is b-tagged



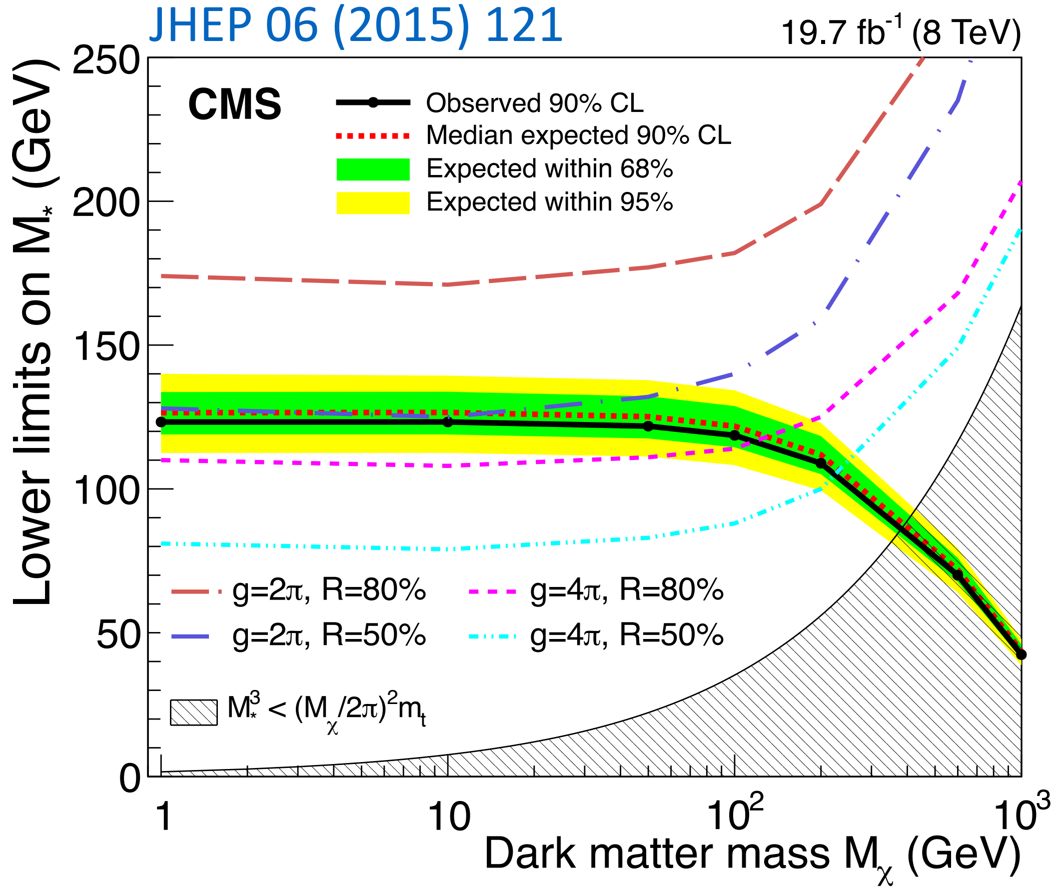
- MET > 320 GeV
- Additional kinematical cuts to reduce dominant background from SM $t\bar{t}$ events

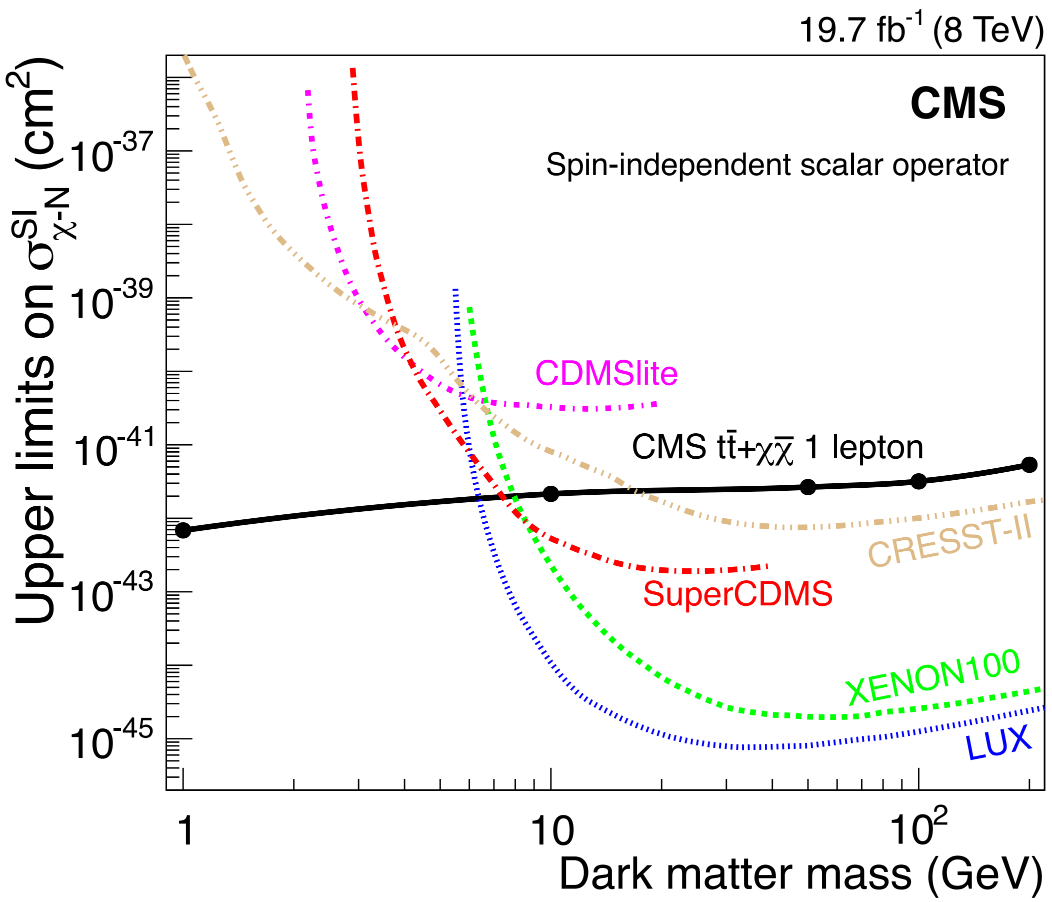


Mono(?)-$t\bar{t}$

Interpret the result in scalar EFT (D1) $L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$

JHEP 06 (2015) 121



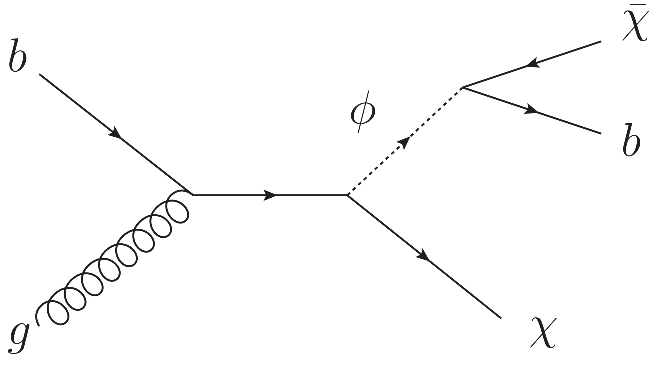


- c.f. Lower limit on D1 from mono-jet (ATLAS EPJC 75:299) is ~38 GeV

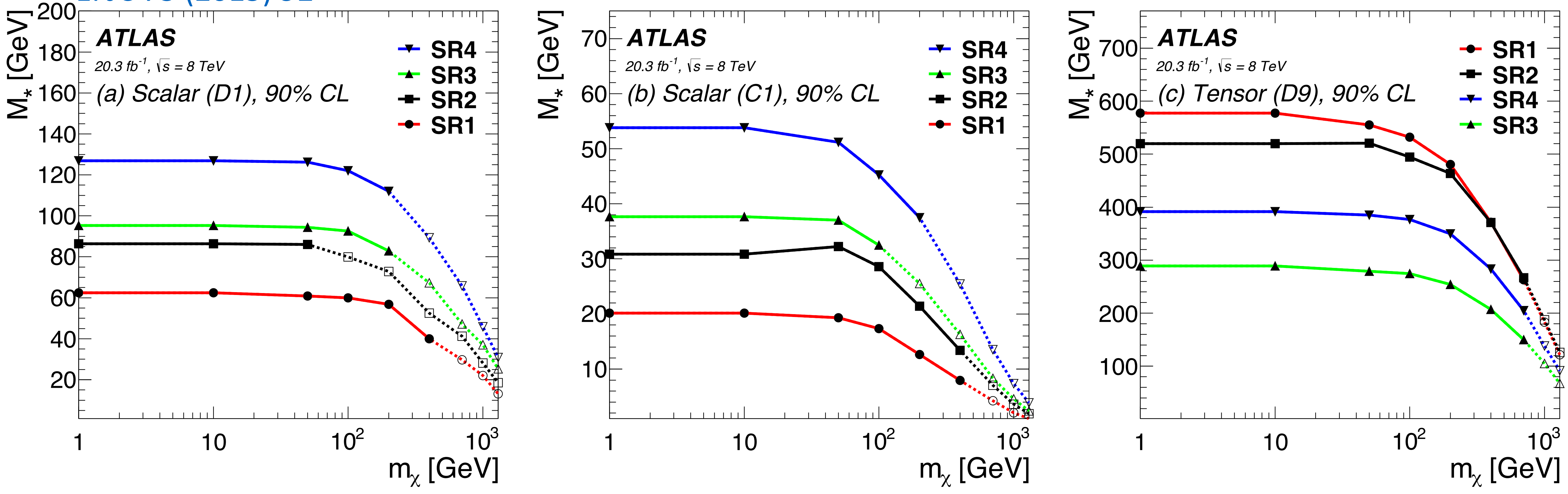
Mono(?)-$b/b\bar{b}/t\bar{t}$

ATLAS [EPJC 75 (2015) 92] searched more broadly for events with MET plus *b* or *t* quarks

- Four signal regions targeting 1, 2 *b*-quarks (SR1, 2) and $t\bar{t}$ decaying hadronically and semileptonically (SR3, 4)
- Additional sensitivity to scalar (D1, C1) and tensor (D9), as well as a bottom-flavored DM model (*b*-FDM)



EPJC 75 (2015) 92



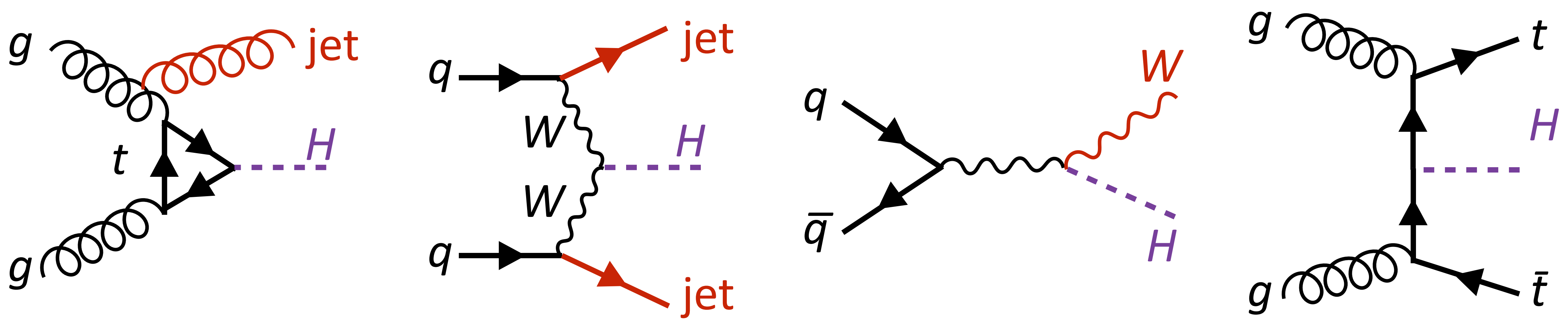
Higgs portal models

What if the Dark Matter couples only to the Higgs?

- Both $\sigma(pp \to \chi\bar{\chi})$ and $\sigma(N\chi \to N\chi)$ are strongly suppressed
  - Experimental constraint are very weak

One obvious test: invisible decay of Higgs → DM

- Similar to mono-X searches, look for events in which an invisible Higgs is produced with something else



- Combine all measurements to set upper limit on BR($H \to$ invisible)

Expt.	Reference	BR limit (95%)
ATLAS	arXiv:1509.00672, submitted to JHEP	< 23%
CMS	CMS-PAS-HIG-15-012	< 36%

Higgs portal models

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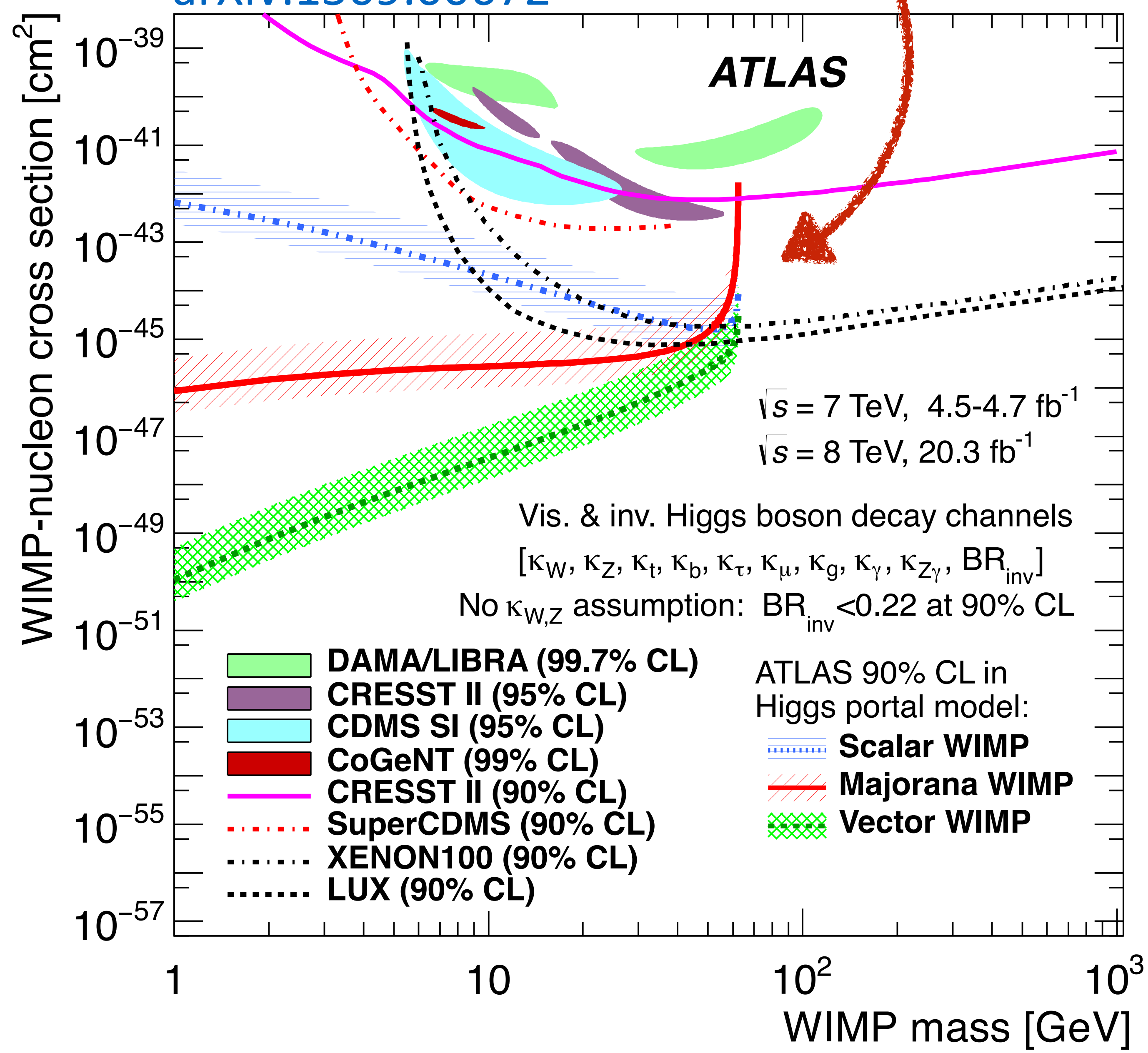
Translate from invisible Higgs decay to *N*-χ scattering cross-section

- Strong limit on Higgs Portal models for $m_\chi < m_H/2$
- NB: valid only if the DM does not interact with other SM particles

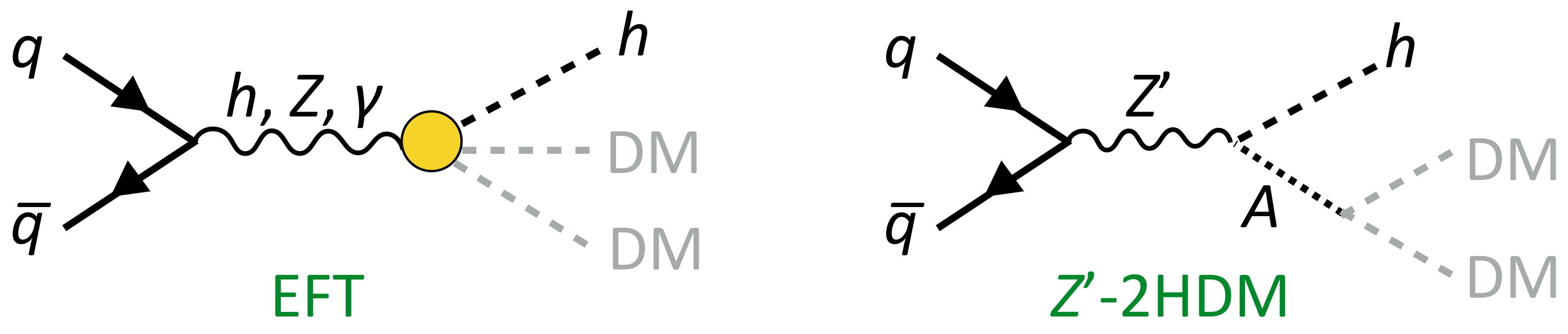
What if $m_\chi > m_H/2$?

arXiv:1509.00672



Mono-Higgs

Mono-Higgs is another probe to DM with special (or unique) couplings to the Higgs



The Higgs can be detected in several decay channels

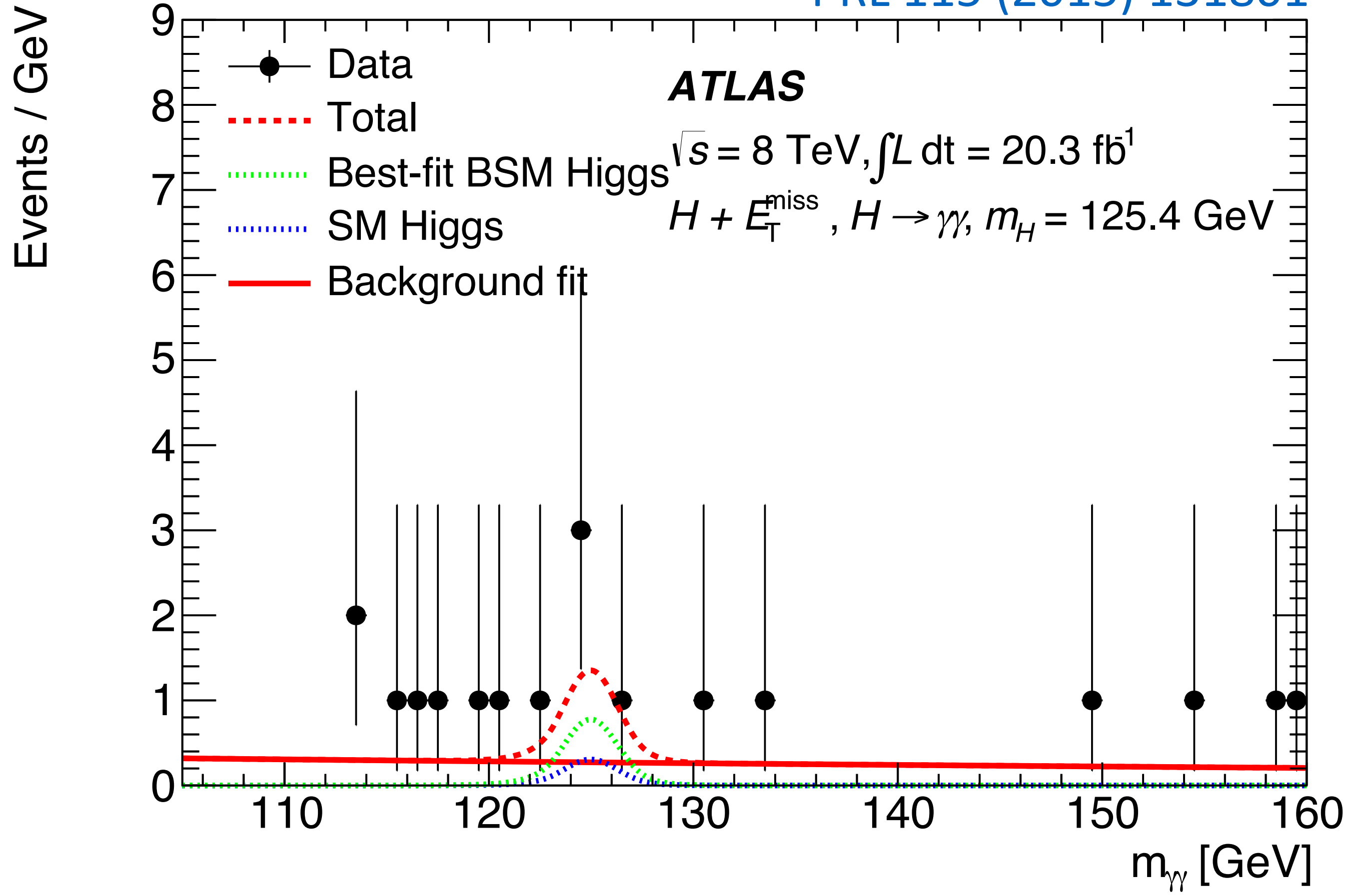
- $H \to \gamma\gamma$ has a small BR (0.23%), with small background
- $H \to b\bar{b}$ has a large BR (58%), with large background
- Other decays are too small to measure

Mono-Higgs → γγ

ATLAS mono-$H \to \gamma\gamma$ [PRL 115 (2015) 131801]

- Select events with 2 photons with $105 < m_{\gamma\gamma} < 160$ GeV
- Require MET > 90 GeV and $p_T^{\gamma\gamma} > 90$ GeV

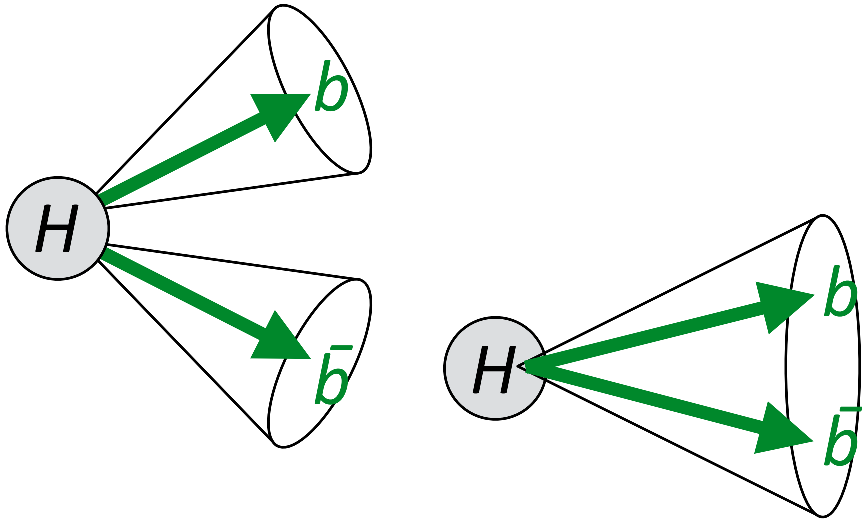
PRL 115 (2015) 131801



- Look for a peak at $m_{\gamma\gamma}$ = 125 GeV. Practically zero background
- Limited statistics makes $H \to \gamma\gamma$ less powerful than $H \to bb$ for now

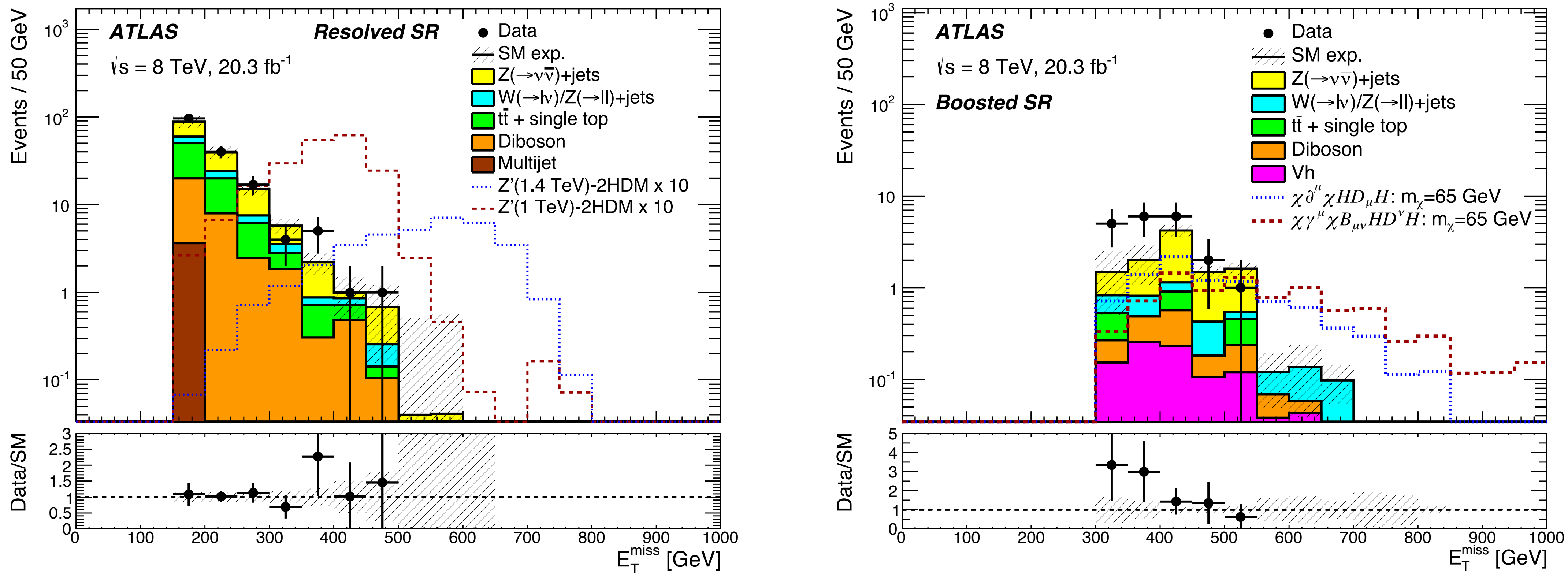
Mono-Higgs → $b\bar{b}$

ATLAS mono-$H \to b\bar{b}$ [arXiv:1510.06218]



- Two b-jets may be resolved or merged
- Resolved: 2 b-tagged jets with $p_T > 100/60$ GeV. $90 < m_{bb} < 150$ GeV. MET > 150 GeV
- Merged: 1 fat jet with $p_T > 350$ GeV that contains 2 b-tagged sub-jets. $90 < m_J < 150$ GeV. MET > 300 GeV

arXiv:1510.06218



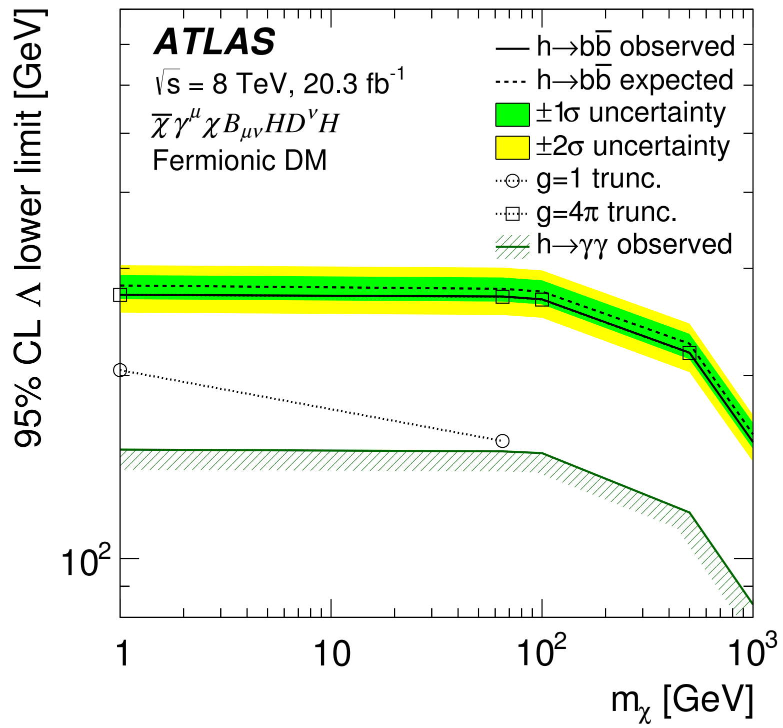
- Background is dominated by Z (→ $\nu\bar{\nu}$) + jets

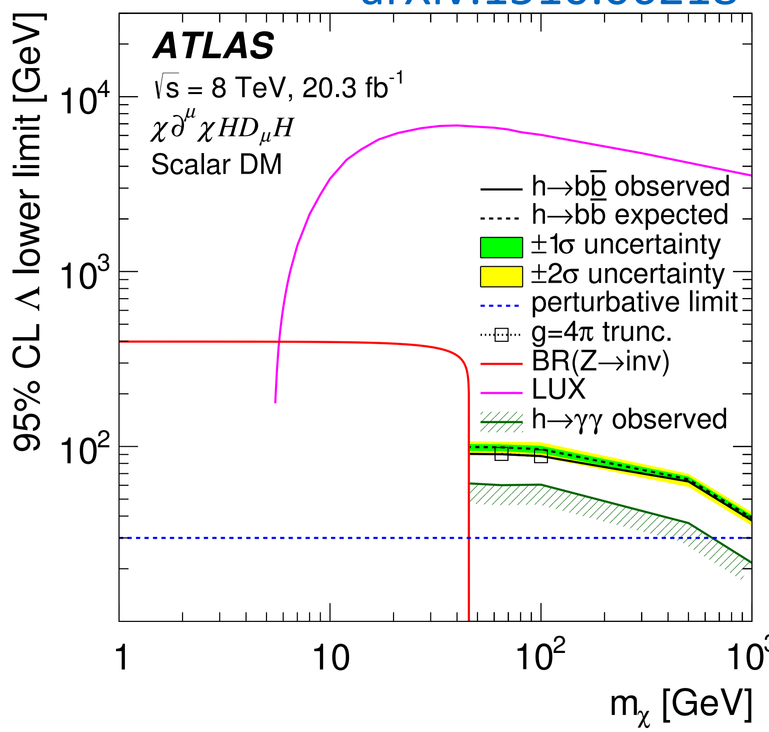
Mono-Higgs

ATLAS mono-$H \to b\bar{b}$ results interpreted

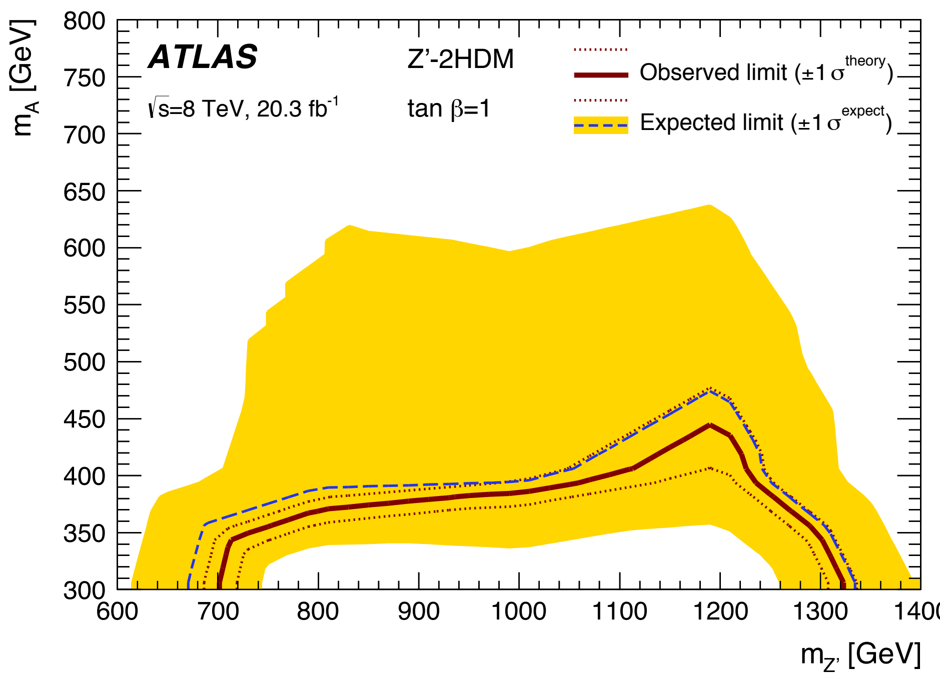
arXiv:1510.06218

- EFT scale limits for
  - $\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H$ (left)
  - $\frac{1}{\Lambda^2}\chi^\dagger\partial^\mu\chi H^\dagger D_\mu H$ (right)

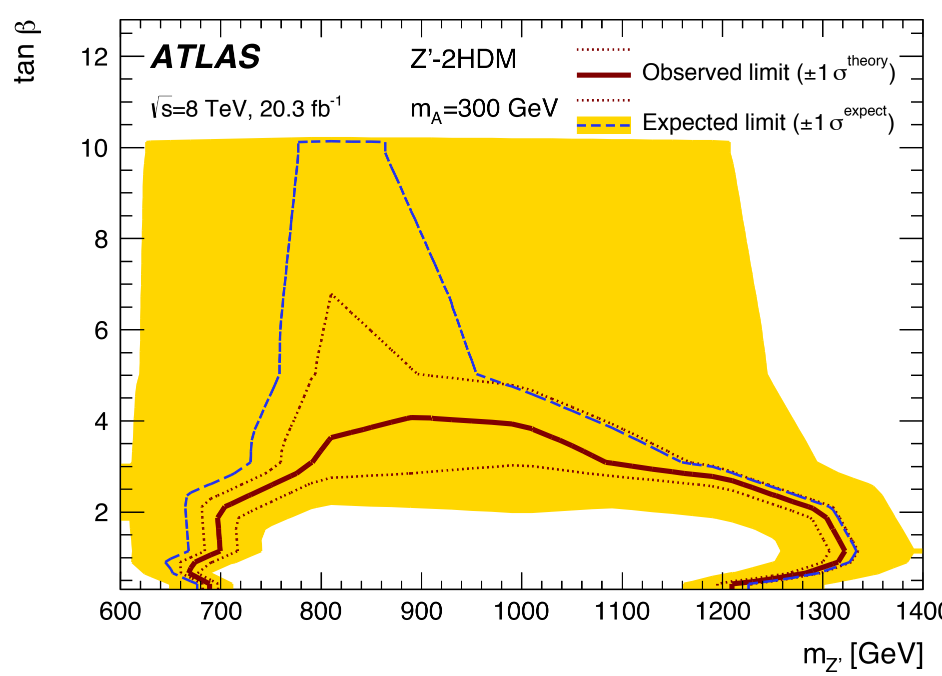




- Simplified Z' + 2HDM



(a) $m_{Z'} - m_A$

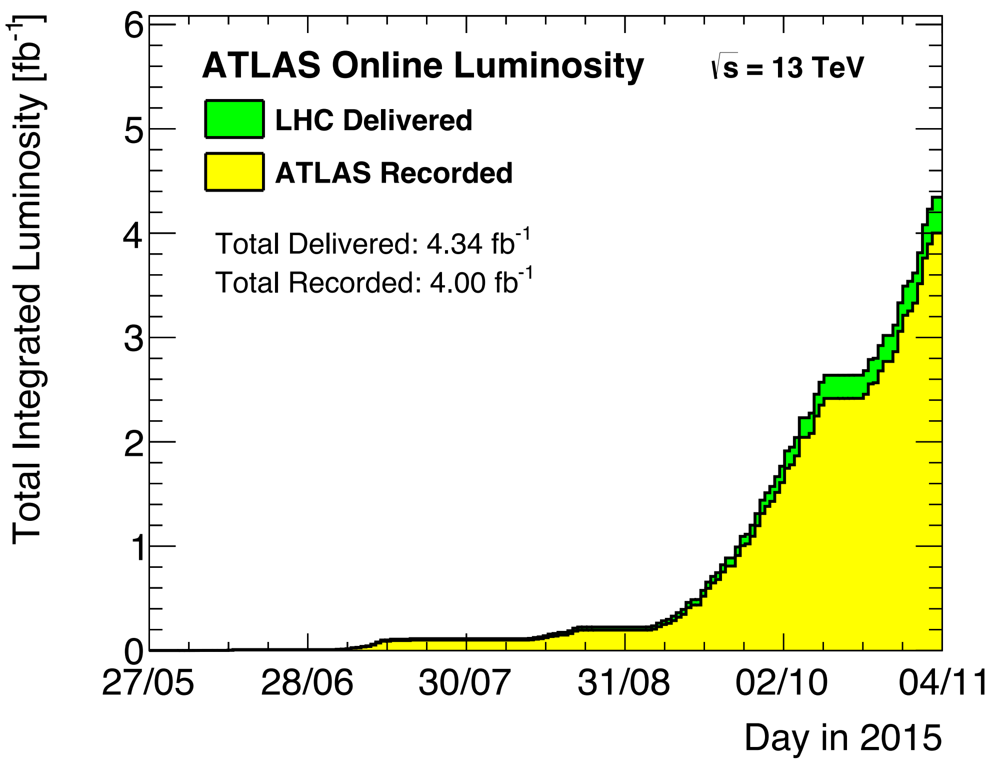


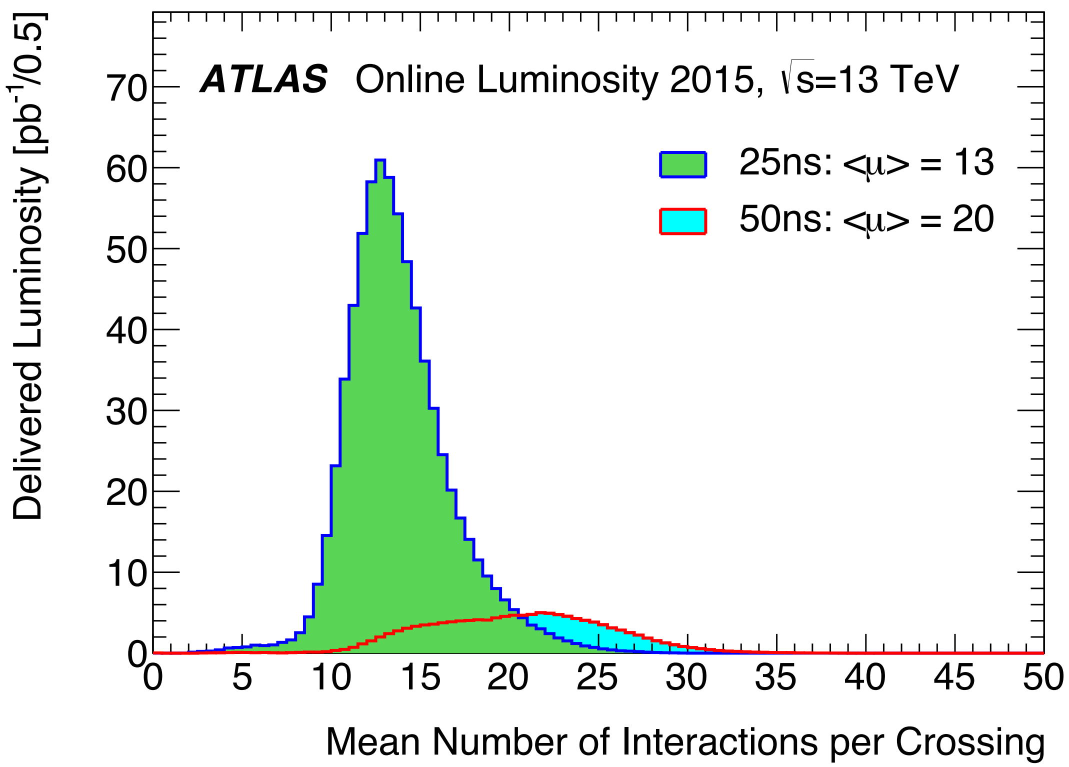
(b) $m_{Z'} - \tan\beta$

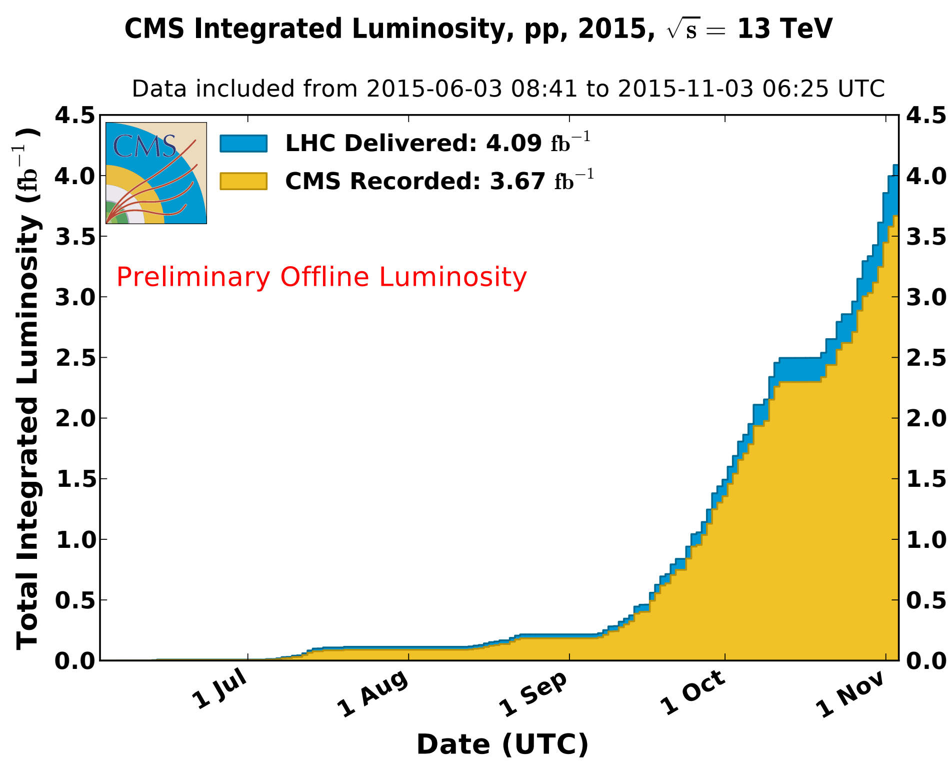
LHC Run 2

LHC re-started in June 2015 with 13 TeV

- About 4 fb^{-1}/experiment recorded in 2015
  - Will accumulate 100 fb^{-1} by 2018
- 8 TeV → 13 TeV increases parton luminosity
  - 2015 data can improve over Run 1
- LHC bunch spacing changed 50 ns → 25 ns
  - Reduced pile-up for the same luminosity







ATLAS mono-W/Z ($\to q\bar{q}$) in Run 2

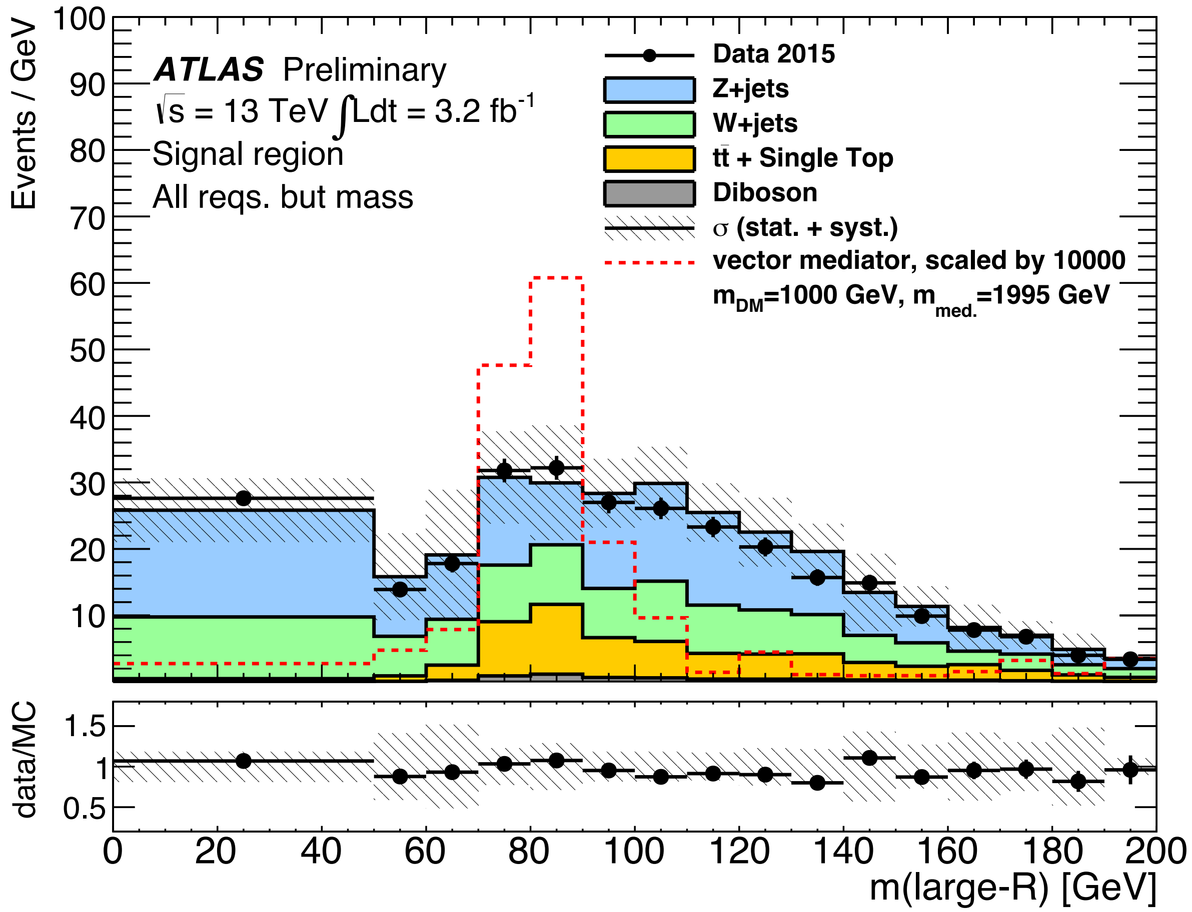
ATLAS-CONF-2015-080

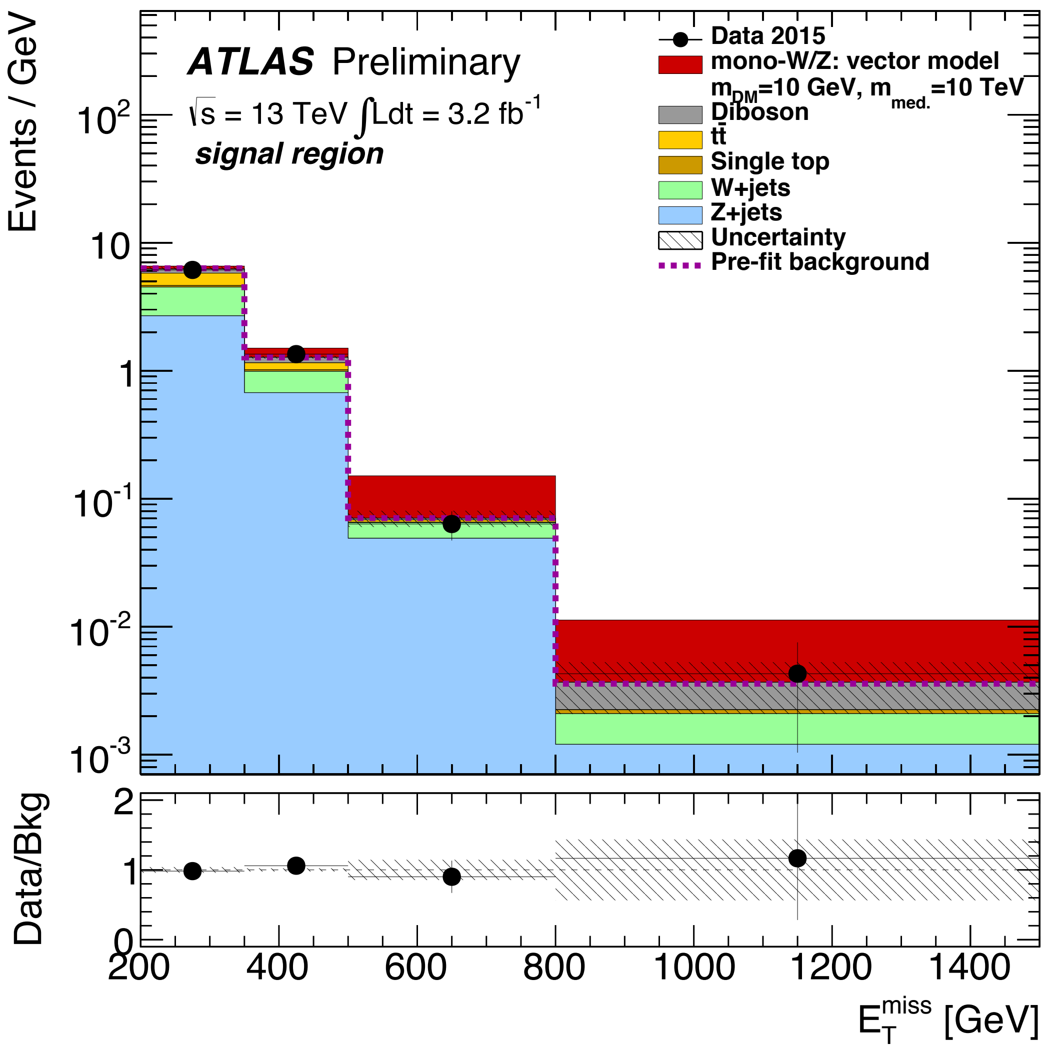
ATLAS has just released a Run 2 search for mono-W/Z

- 3.3 fb^{-1} of *p-p* collision data at 13 TeV
- Analysis is similar to the Run 1 search [PRL 112 (2014) 041802]

Select events with a fat jet (= boosted $W/Z \to q\bar{q}$) + MET

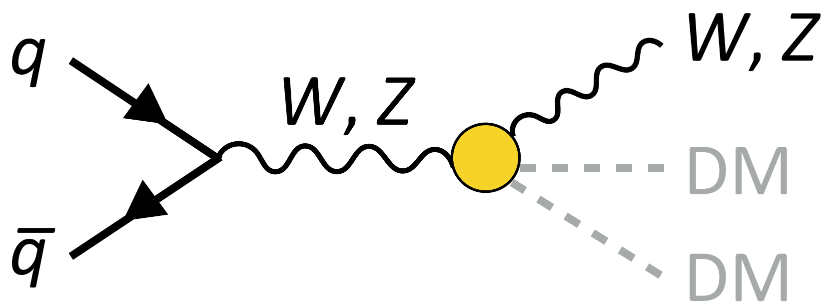
- The fat jet has p_T > 200 GeV and sub-jets consistent with $W/Z \to q\bar{q}$
- MET > 250 GeV. No leptons



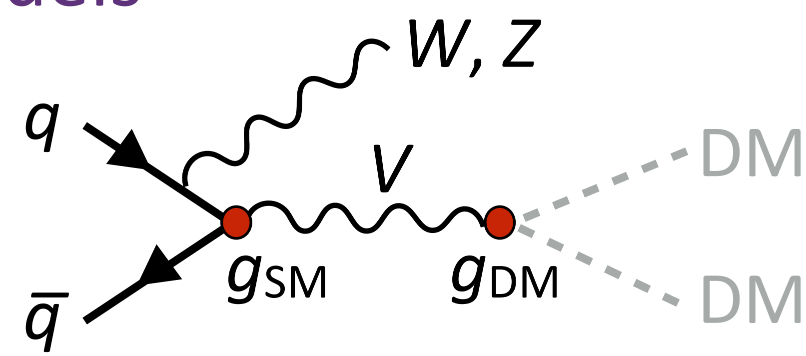


ATLAS mono-W/Z ($\rightarrow q\bar{q}$) in Run 2

Interpretation in EFT and simplified models

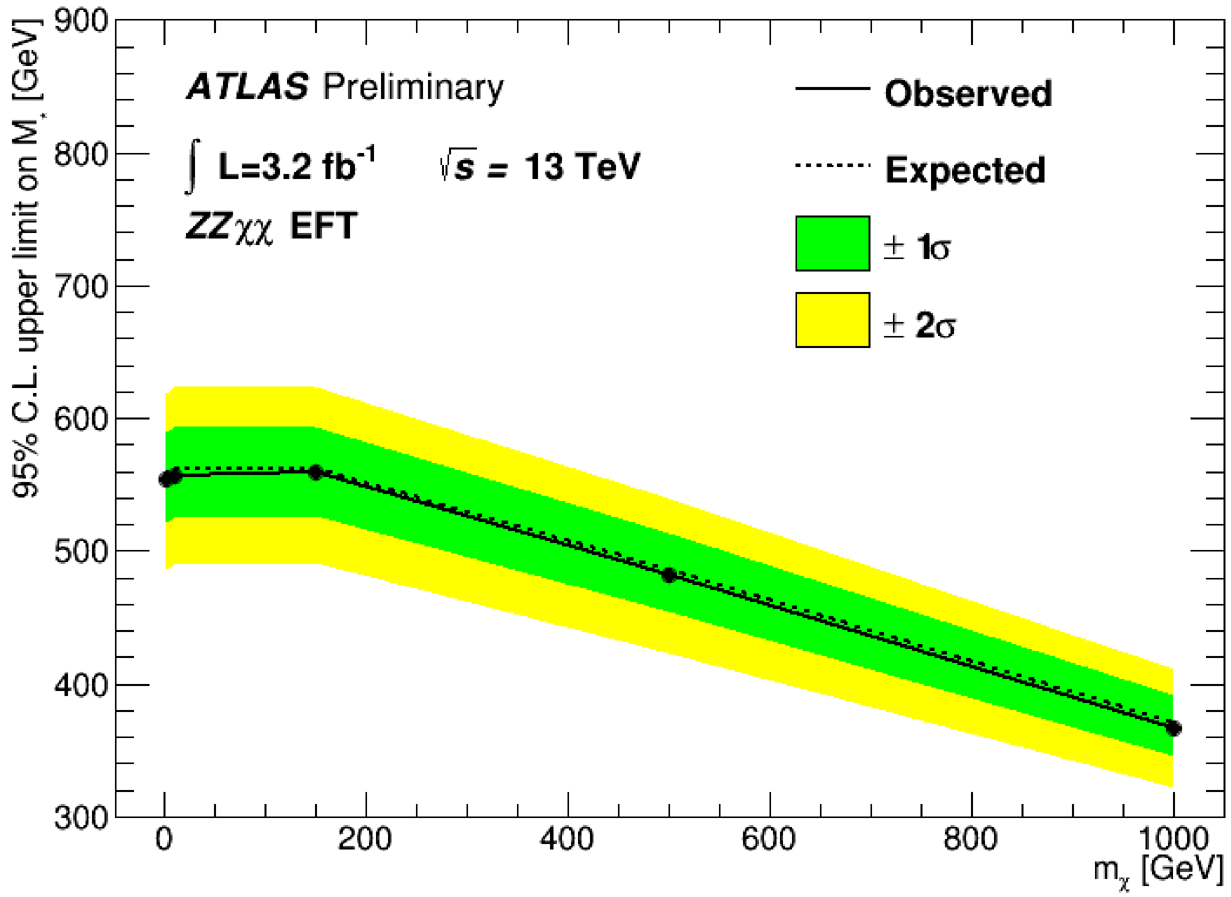


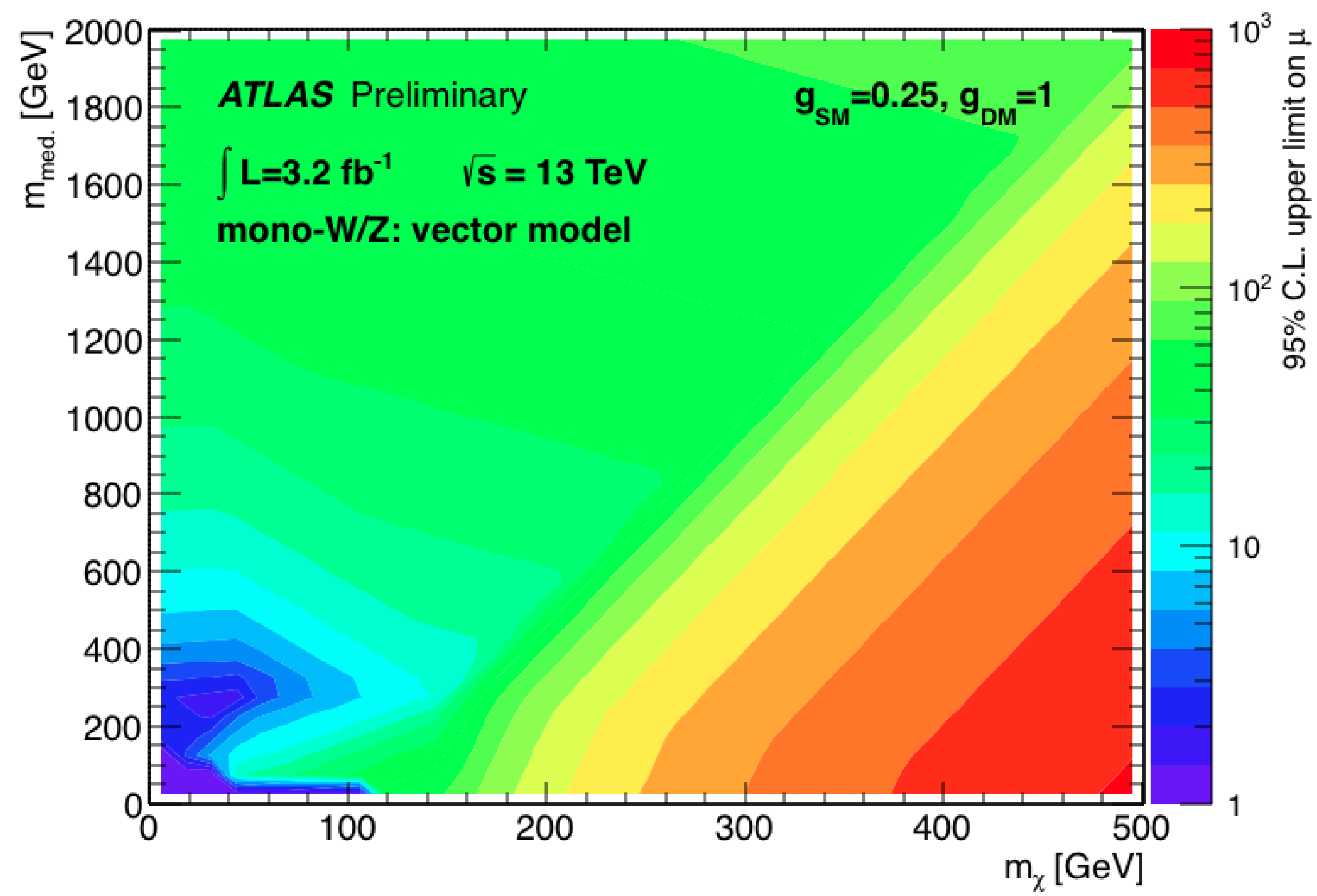
EFT



Simplified model

ATLAS-CONF-2015-080





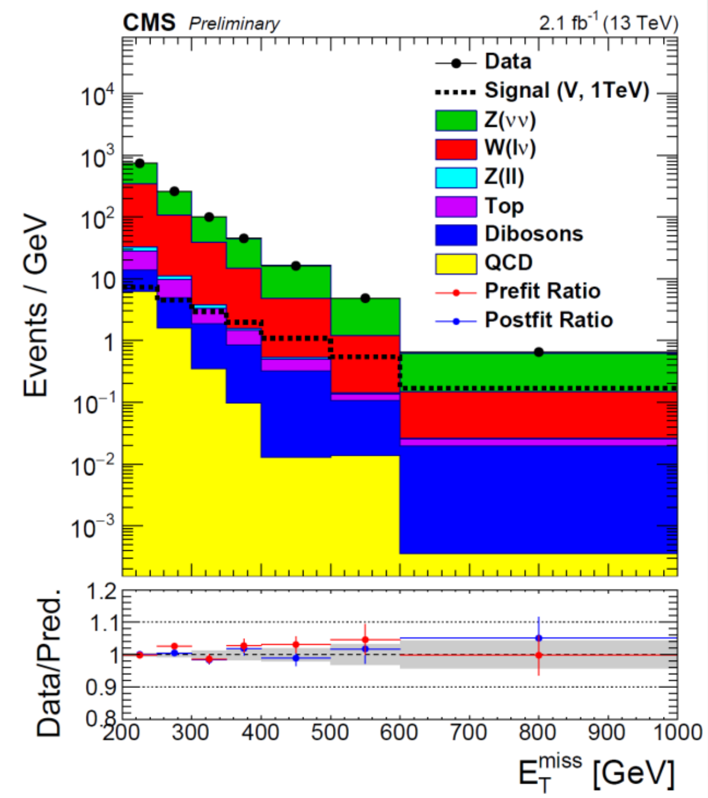
CMS mono-jet in Run 2

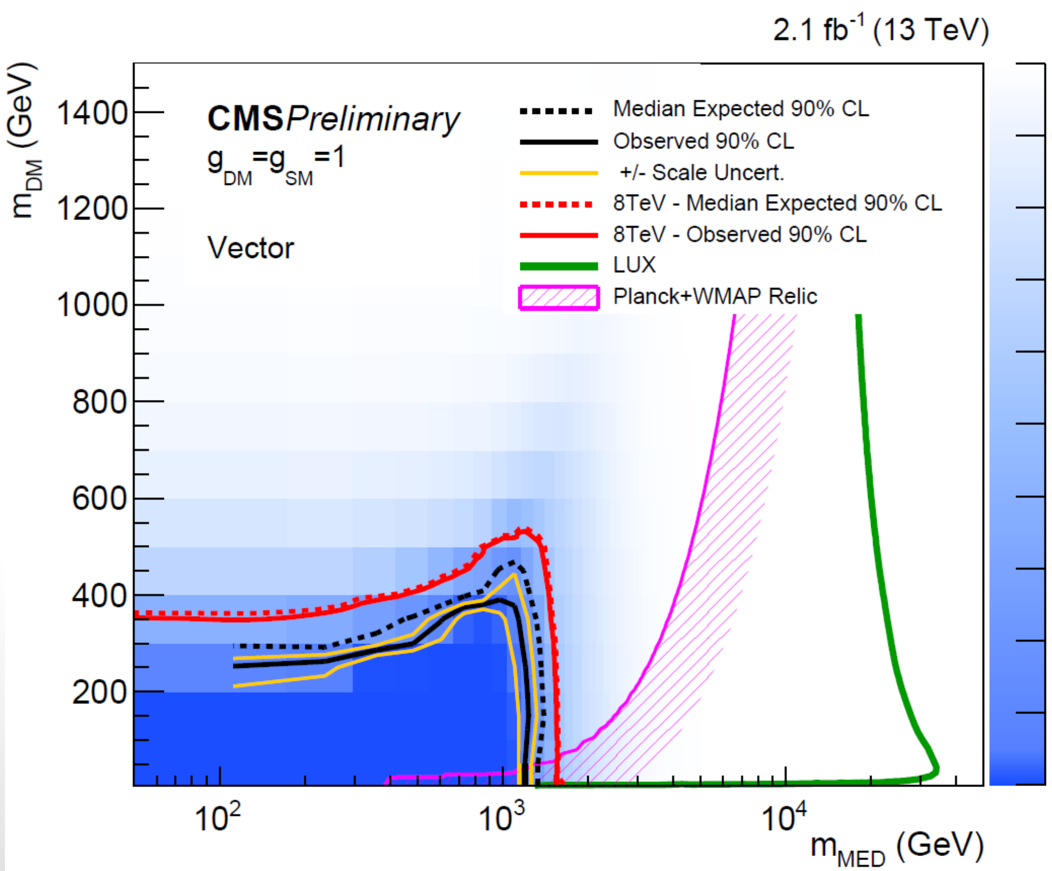
Slide by Jim Olsen

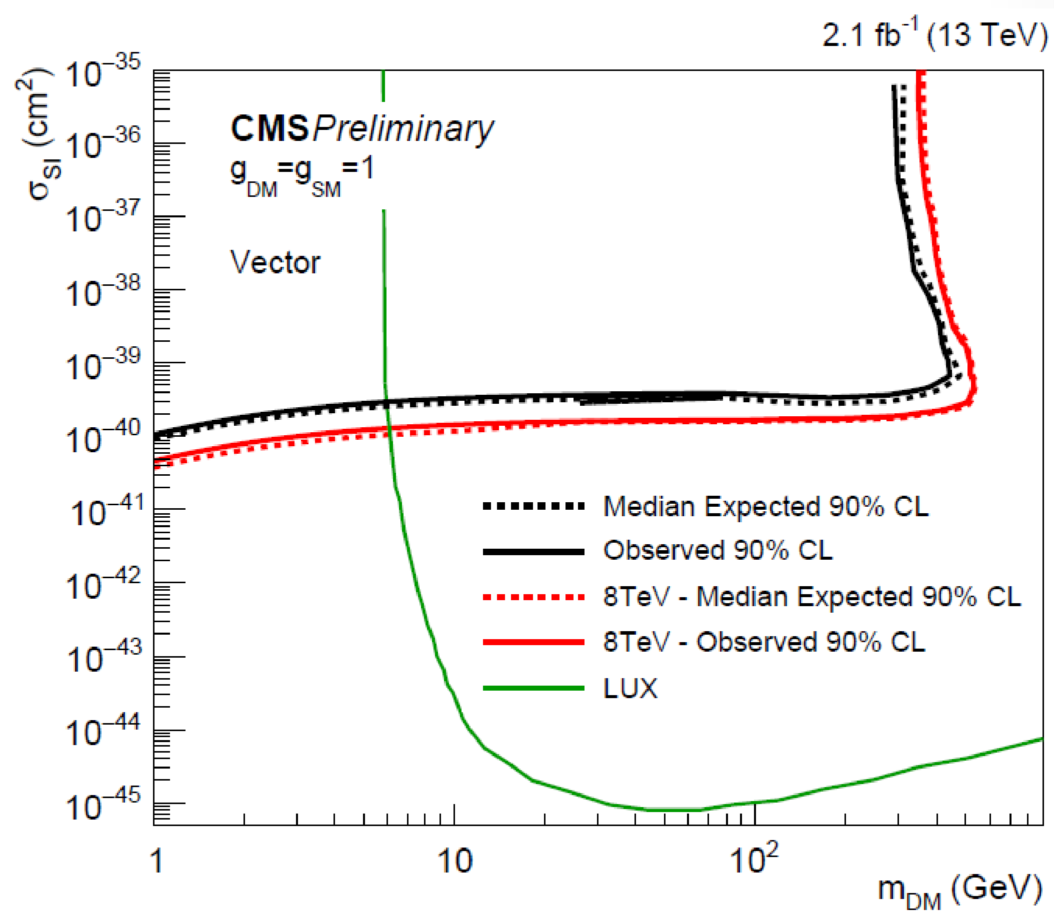
EXO-15-003

Search for dark matter

- Search for generic dark matter in **final states with jets and large missing transverse energy**
- Traditional monojet search extended to multijet final states, searching for DM pairs produced via a **vector mediator**
- Limits comparable to those set in Run 1







Summary

LHC hunts for Dark Matter in *pp* → *X* + invisible searches

- Mono-jet/photon/$W/Z/t\bar{t}$ searches cover a wide variety of DM interactions, for DM masses between 0 and several 100 GeV
  - Sensitive to light (as well as heavy) DM, spin-dependent (as well as spin-independent) interactions
  - Complementary to direct-detection experiments
- Higgs portal models are tested by invisible Higgs and mono-Higgs searches

Interpretation of results are often model-dependent

- Careful with plots that are valid only for particular forms of interaction
- Expect to see more simplified-model interpretations

LHC Run 2 has started with 13 TeV

- Results from 2015 data are coming out just now
- Next 3 years will vastly increase the data and improve our sensitivity