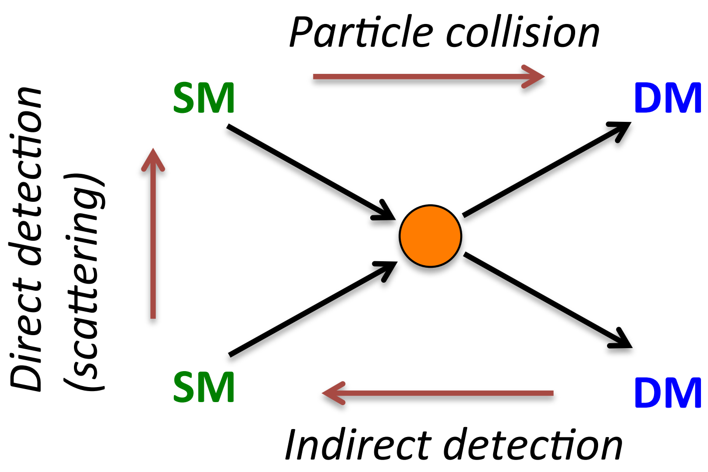
LHC Dark Matter Searches:
Results and Perspectives

HAP-Dark Matter, Karlsruhe 21-23 Sept 2015

Nicholas Wardle
On behalf of the ATLAS and CMS collaborations

Dark Matter Madness

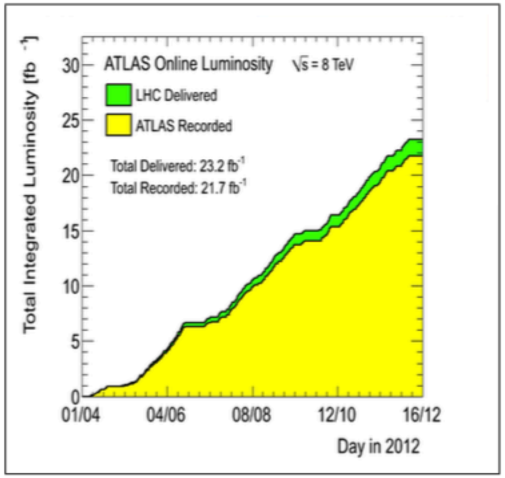
- Strong evidence of physics beyond the Standard Model
- We know very little about the nature of DM (gravitational interaction but what else?)
- If DM talks to SM particles (eg WIMPs) we can detect it via…

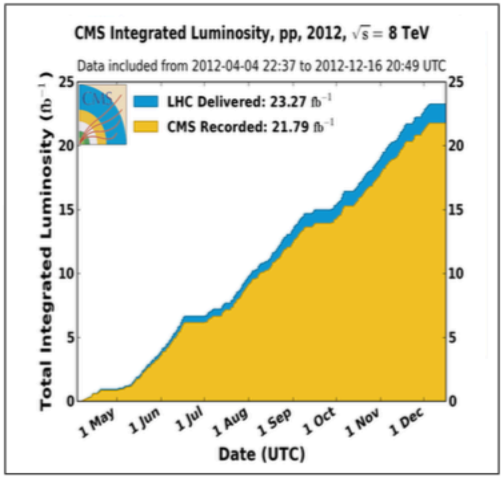


Increasing interest in dark matter (DM) searches at the LHC

- Complementary strategies to direct detection and spectral data
- High hopes to find evidence of DM production for **Run-2!**

The LHC @ CERN





Run-1 a huge success for the LHC!

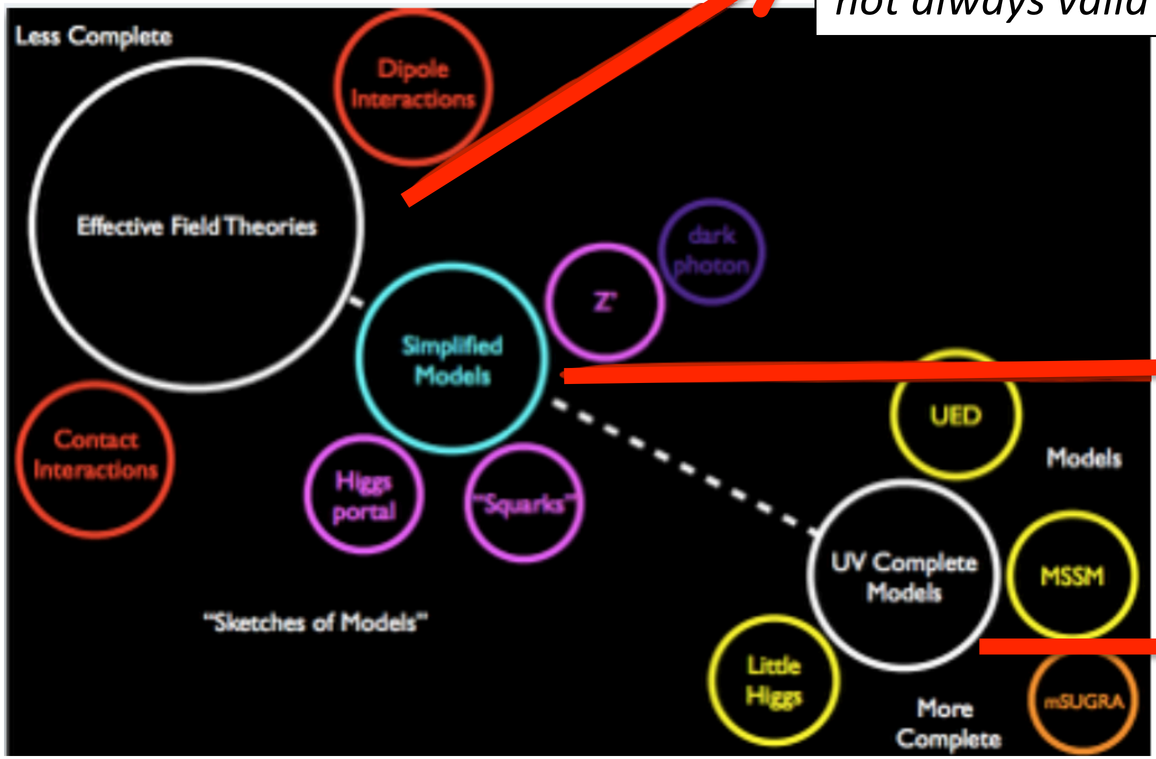
~20(5) fb-1 pp collisions per experiment collected at sqrt(s) = 8 (7) TeV

Interpretations of searches

Even a successful search at the LHC won't tell us…

- ✧ What is DM (fermion (dirac/majorana?)
- ✧ It's even the same as what's seen in galaxies (~stable for detector != stable)?
- ✧ Is any of these the right one

Tim Tait, DM@LHC 2013



Very few parameters, useful for comparison to direct detectors but not always valid

Fewer parameters to handle → captures relevant physics

Large parameter space in complete models

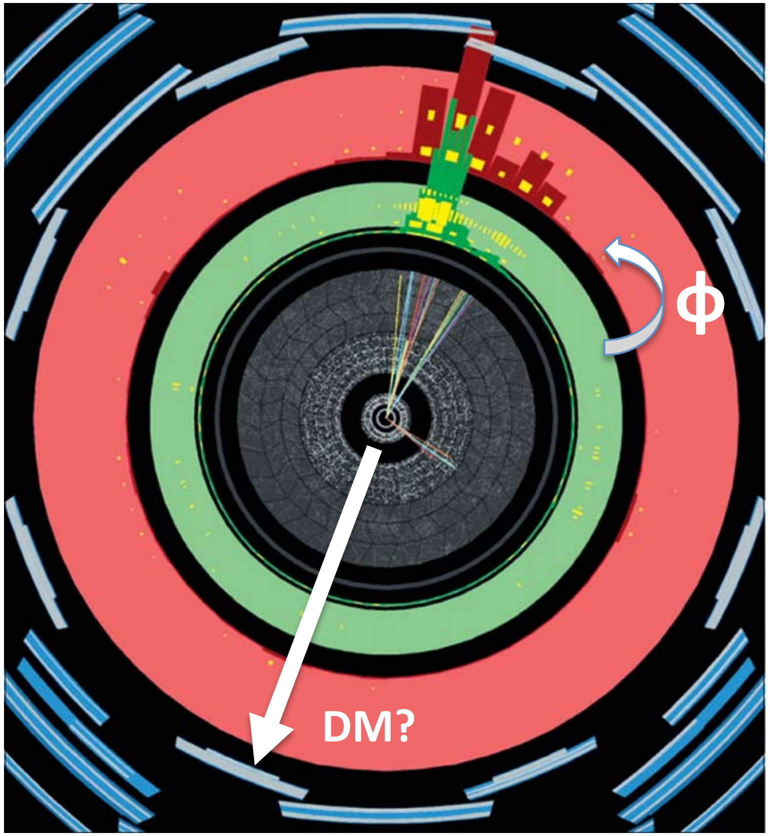
Mono-Mania

DM particles produced in p-p collisions escape the detector without interacting.

Search for an abundance of events with an imbalance of energy in the plane transverse to the beam line …

$$E_T^{miss} = | - \sum_n \vec{E}_T^n |$$

$$\vec{E}_T^n = E^n \cos\theta \cos\phi \cdot \hat{i} + E^n \cos\theta \sin\phi \cdot \hat{j}$$



Look for additional particles recoiling against DM particles.

Provides a rich assortment of **X +** **E_T^{miss}** searches at the LHC…

- Jet + **E_T^{miss}**
- W/Z (→leptons/jets) + **E_T^{miss}**
- γ + **E_T^{miss}**
- t/b + **E_T^{miss}**
- H + **E_T^{miss}**

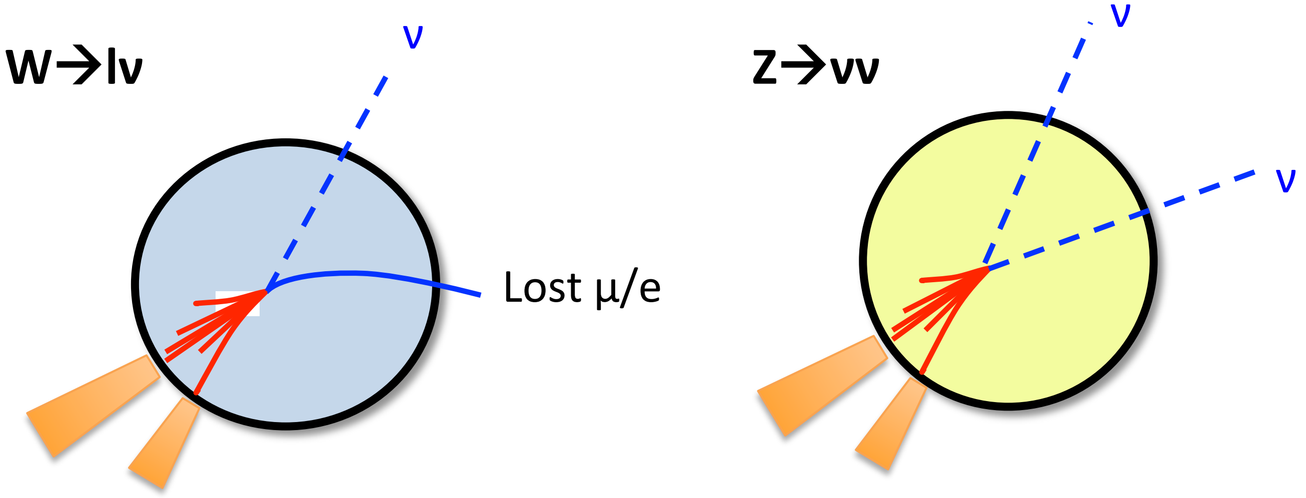
Of course, all RP-SUSY searches are DM searches but not the focus of this talk

Invisible Standard Model

Common enemies shared by many of the searches for DM

Neutrinos escape detection to mimic a DM signal!

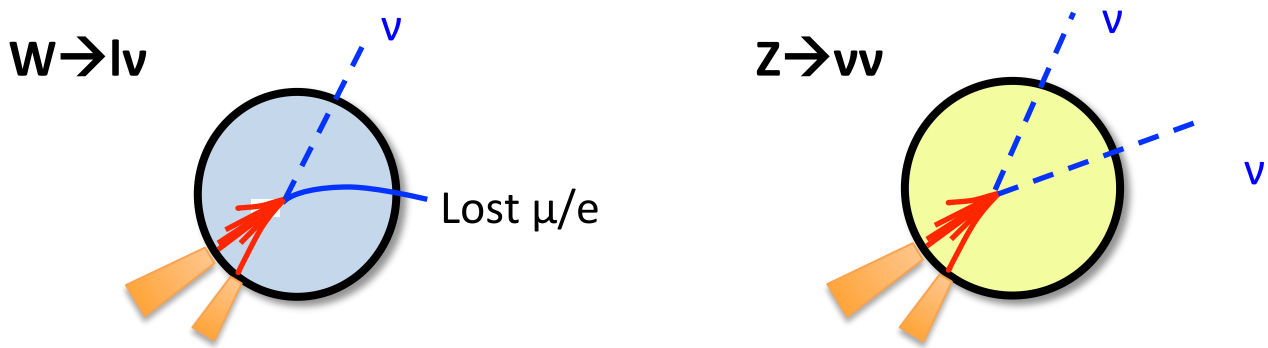
Most common are Z decays to neutrinos and leptonic W decays where the lepton falls outside of the acceptance or isn't reconstructed.

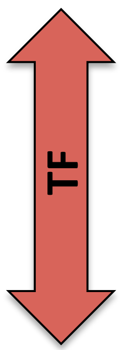


Relatively large cross-sections for these processes mean backgrounds are sizable compared to real signals.

Invisible Standard Model

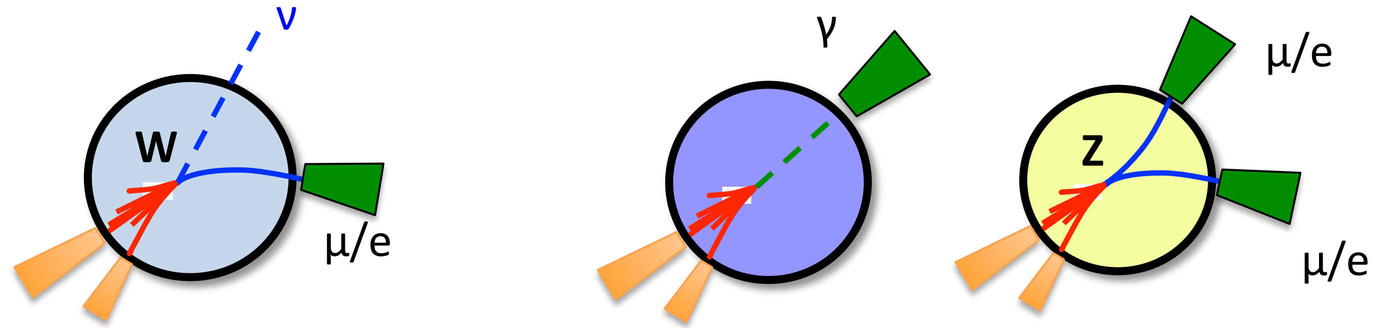
Signal Region





Extrapolate yields/shapes in well understood control regions CR) in data to constrain backgrounds in signal region (SR)
→ Transfer Factors (TF) taken from simulation/theory used for extrapolation: eg BR(Z→νν)/BR(Z→μμ)

Data Control Regions



In CRs, calculate "Fake" E_t^{miss} (recoil) → $|\vec{E}_T^{miss} + \sum \vec{p}_T^{ll/\gamma}|$

Invisible Standard Model

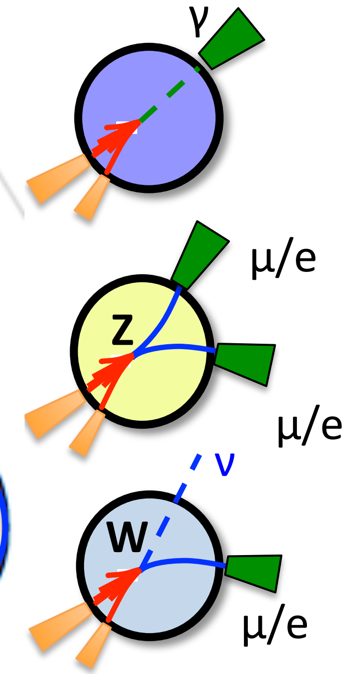
Compare the predictions with the data in the CRs → Maximize likelihood to obtain corrected prediction for backgrounds in signal regions

$$\mathcal{L}_c(\mu^{c,Z\to\nu\nu},\mu^{c,W\to l\nu},\theta,\phi) = \prod_i \text{Poisson}\left(d_i^{c,\gamma} \middle| B_i^{c,\gamma}(\phi) + \frac{\mu_i^{c,Z\to\nu\nu}}{R_i^{c,\gamma}(\theta)}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{c,Z} \middle| B_i^{c,Z}(\phi) + \frac{\mu_i^{c,Z\to\nu\nu}}{R_i^{c,Z}(\theta)}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{c,W} \middle| B_i^{c,W}(\phi) + \frac{\mu_i^{c,W\to l\nu}}{R_i^{c,W}(\theta)}\right)$$

Number of observed events

Expected 'other background' contamination in CR

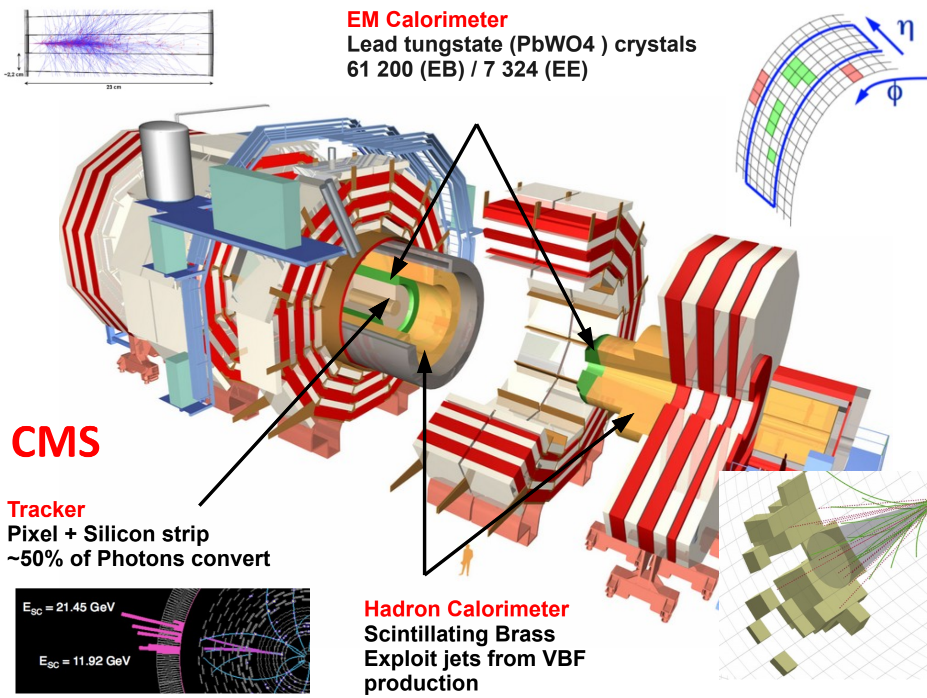
Expectation of number of Z/W/γ given TF (R)



Simultaneous likelihood used in several places instead of simple `count and scale approach'

The ATLAS and CMS Detectors

Dark Cameras



Hermetic design of ATLAS and CMS provides good coverage of interaction

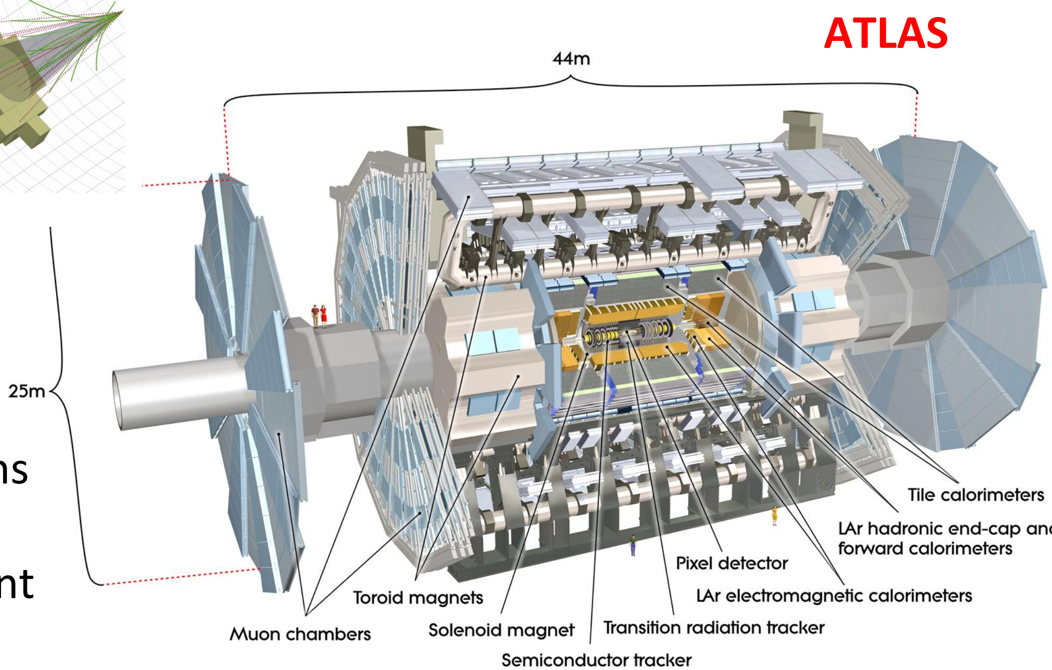
→ Several layers of detector targeting different final state particles

→ Vital for searches with missing energy

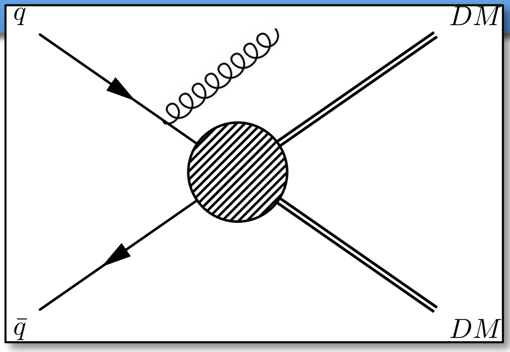
ATLAS/CMS triggers reduce 40 MHz (LHC)→ O(100) Hz

High multiplicity from multiple interactions (pile-up)

→ Need trigger which remain efficient within this restriction



Monojet

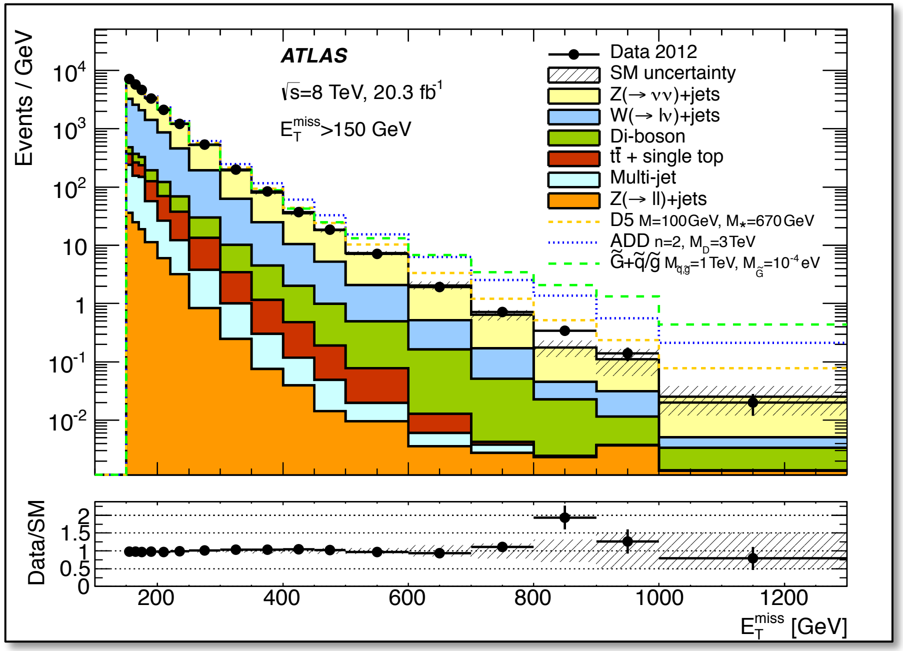


High-momentum jet, from initial state radiation (ISR), recoils against DM

- 1 central jet with high p_T > 110 GeV (CMS), > XXX GeV (ATLAS)
- Additional jets allowed only if $\Delta\phi(j,E_T^{miss})$ > 1.0 (ATLAS)
- 2nd jet allowed provided if $\Delta\phi(j_1,j_2)$ < 2.5 (CMS)
- Veto leptons, photons

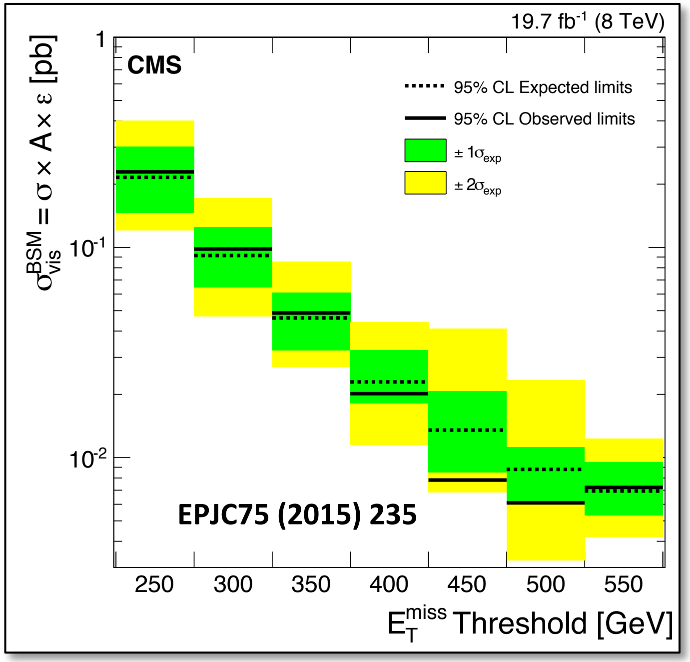
Dominant backgrounds from **Z(νν)+jets** and **W(lν)+jets** → Estimate the contributions with data using **Z→μμ/ee** and **W→μν/eν** events

EPJC (2015) 75:299



Define signal regions with increasing E_T^{miss} thresholds → Model independent cross-section limits

Upper limits with CLs



Di-jet (CMS Razor)

Additional jets produced in association with DM particles

- ✧ Additional information from second jet allows for good discrimination against SM backgrounds (W/Z/tt)
- ✧ Fit ''Razor-variable''

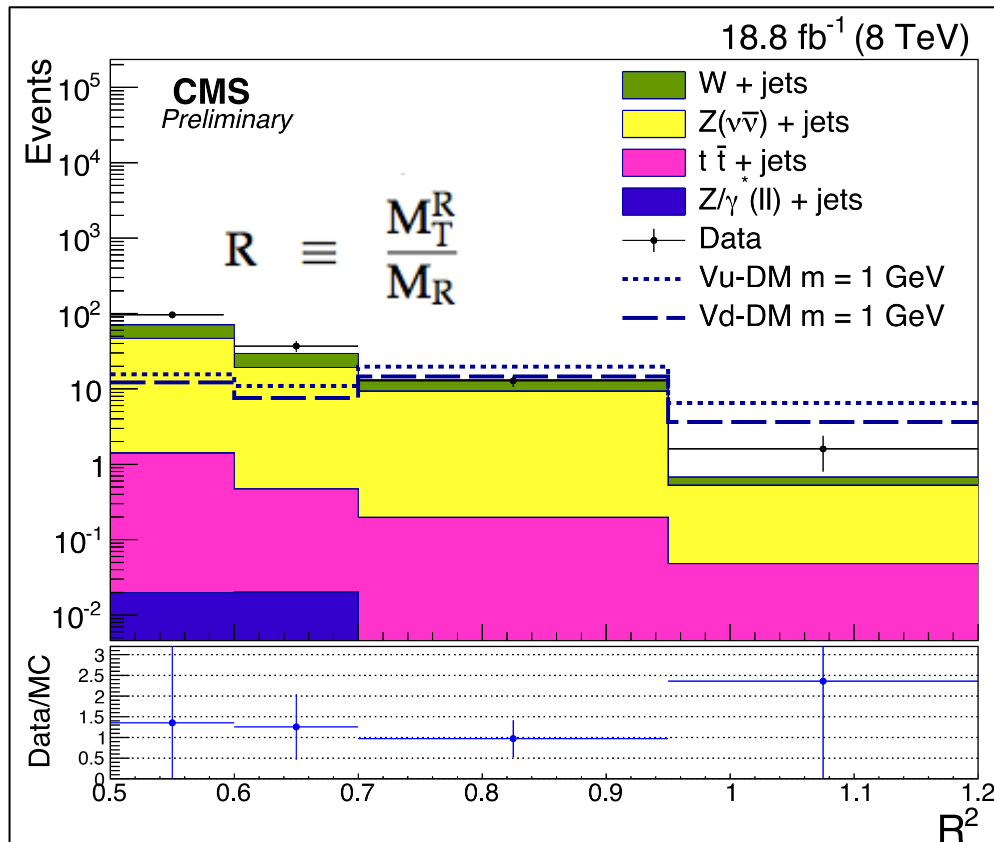
$$M_R \equiv \sqrt{(|\vec{p}_{J_1}| + |\vec{p}_{J_2}|)^2 - (p_z^{J_1} + p_z^{J_2})^2}$$

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

In 4x bins of $\mathbf{M_R}$

- ✧ bb and b tagged bins target scenario where DM preferentially couples to b-quarks [1]
- ✧ Backgrounds estimated from **μμ(b)+jj** or **μμ(b)+tt** control regions in data
- ✧ Complementary search to Monojet

CMS-PAS-EXO-14-004

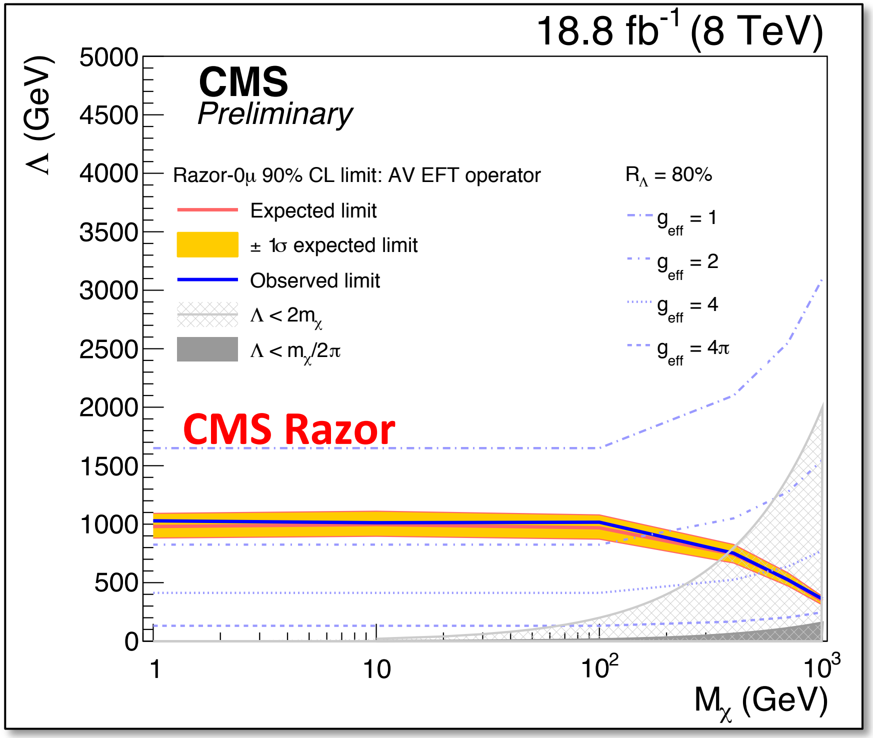


[1] Phys.Lett.B697:412-428,2011

Interpretations

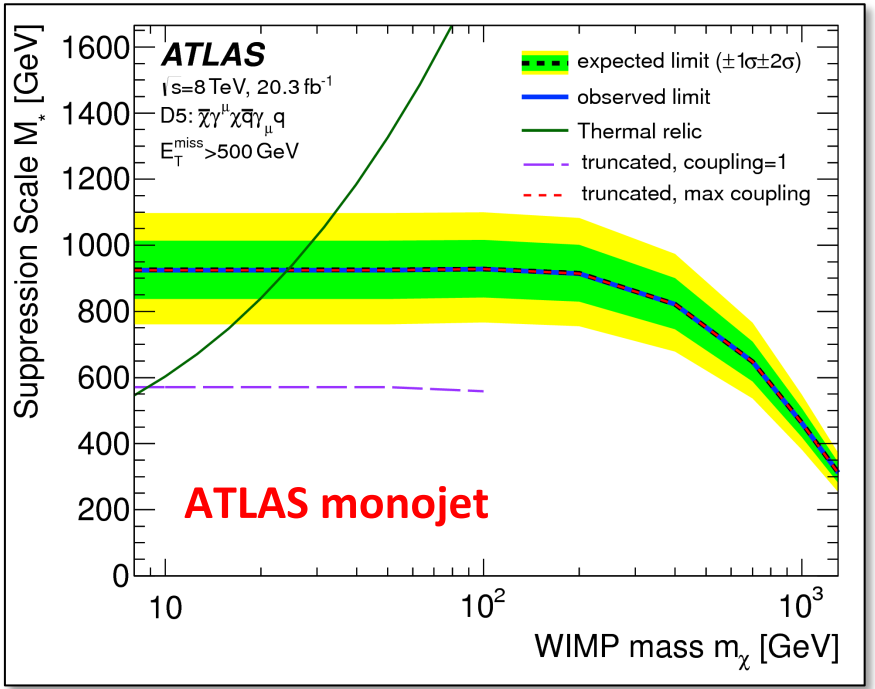
Set limits in low-energy effective field theory

- Consider various operators
- Set (lower) limits on contact interaction cut-off scale $\Lambda \approx M/\sqrt{g_q g_\chi}$
- Compare limits for different coupling scenarios truncating or requiring 80% threshold on number of EFT valid events

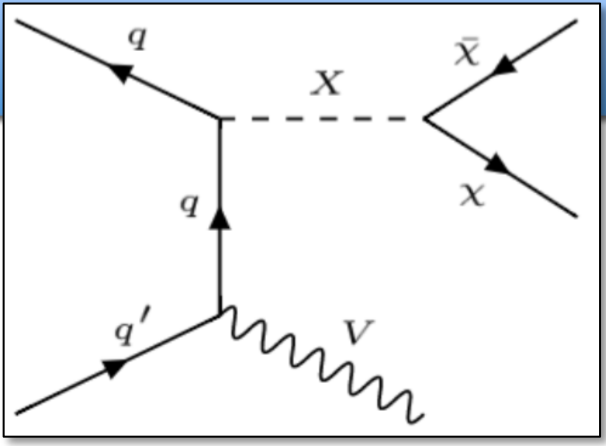


$$\hat{\mathcal{O}}_V = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma_\mu\chi\right)\left(\bar{q}\gamma_\mu q\right)$$ → Vector operator

$\Lambda =$



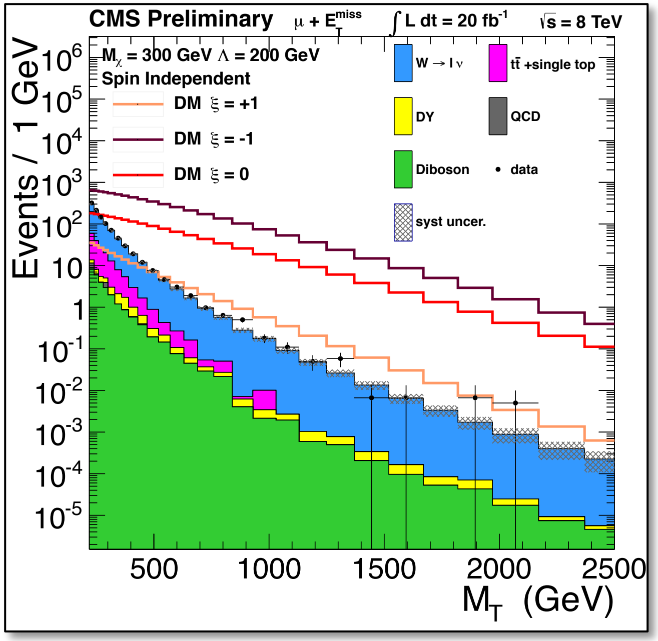
Mono-V (leptonic)



Associated production of DM with a W or Z (V) boson

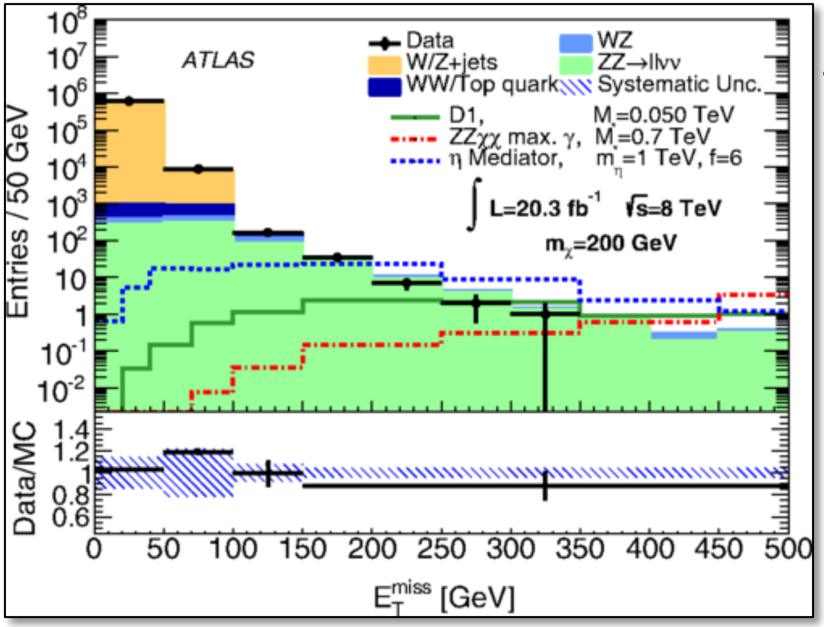
Smaller production cross-section but also lower backgrounds than jets final state.

Phys. Rev. D 91, 092005



Z(ll) + E_T^{miss}

- ✧ Look for 2 opposite-charge, same-flavor leptons
- ✧ Invariant mass consistent with Z boson $|m_{ll}-m_Z|< 10$ GeV (CMS), $76 < m_{ll} < 106$ GeV (ATLAS)
- ✧ Look for excess in E_T^{miss} (ATLAS) /m_T (CMS) spectrum



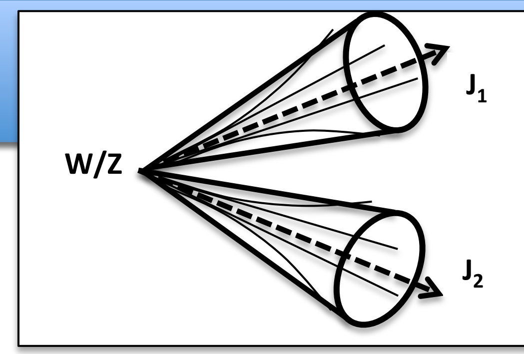
Phys. Rev. D 90, 012004

W(lν) + E_T^{miss}

- ✧ 1 isolated, high-p_T lepton
- ✧ Backgrounds from W/Z production decays with lepton out of acceptance.
- ✧ Discrimination from transverse mass variable

$$M_T = \sqrt{2p_T^l E_T^{miss}(1 - cos\Delta\phi)}$$

Mono-V (Hadronic)



Low p_T W or Z bosons decay to well separated jets (fully reconstructed)

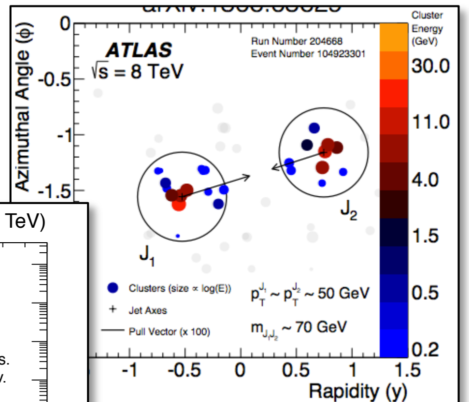
Look at mass and pT of the dijet system to distinguish backgrounds.

Exploit jet/di-jet properties:

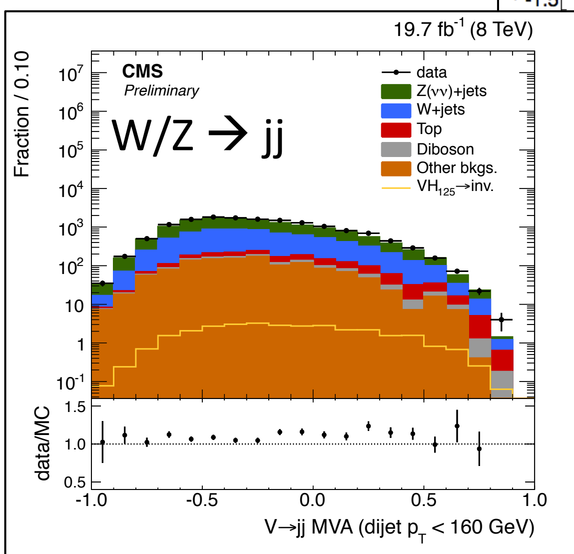
- ✧ Quark-gluon likelihood discriminator
- ✧ Jet-pull (color flow between jets) [1]
- ✧ "Mass-drop" [2]

Use photon CR with photon as 'fake' E_t^{miss} to dramatically reduce statistical uncertainty on **Z(νν)+jets** backgrounds

Combine into multivariate discriminator (CMS)

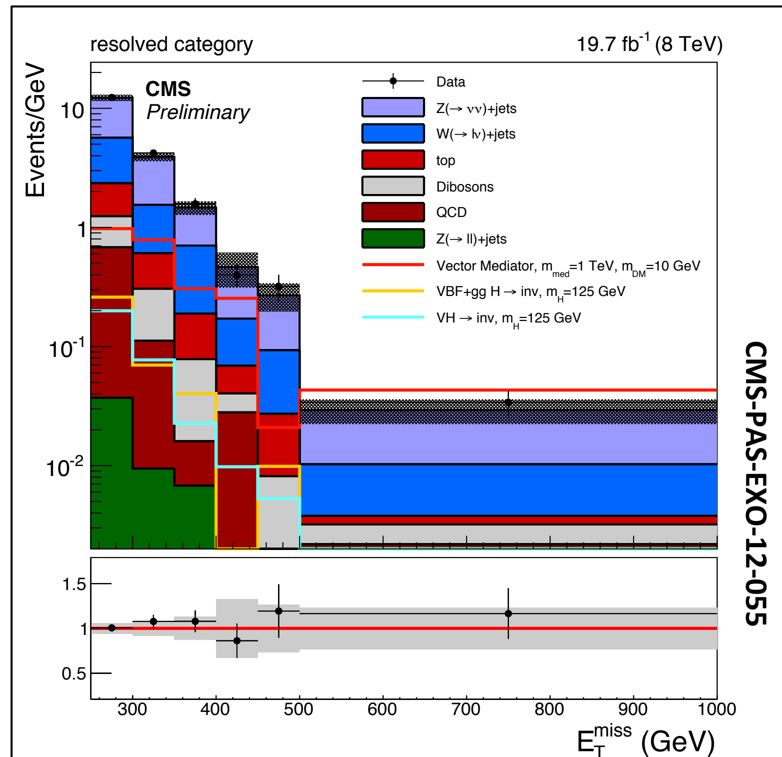


arXiv:1506.05629

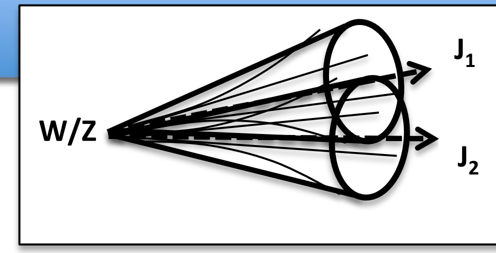


[1] arXiv:1001.5027

[2] PRL.114.041802



Mono-V (Hadronic)

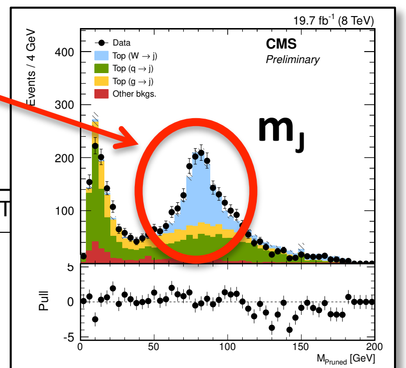


Boosted (high p_T) vector bosons decaying to jets will form a single "fat"-jet

Jet substructure techniques to identify V-bosons:

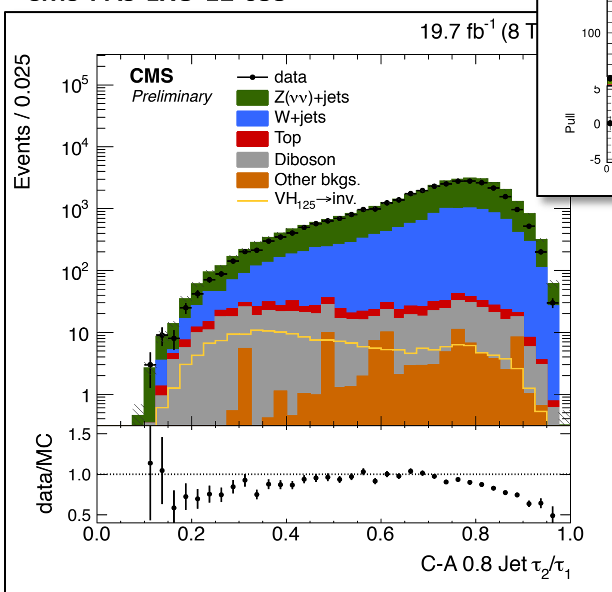
- ✧ Look for high-p_T fat jet with $\mathbf{m_J}$ close to m_W or m_Z
- ✧ N-subjettiness **(τ_N)** (likelihood for N-daughter hypotheses, CMS) or **momentum balance** (ATLAS) of lead jets to tag as having originated from a W or Z boson.
- ✧ Cut in (CMS) or fit to (ATLAS) the $\mathbf{m_J}$ spectrum.
- ✧ Use (di)-lepton and photon CR to determine W(l) and Z(νν) bkgs

W mass peak!

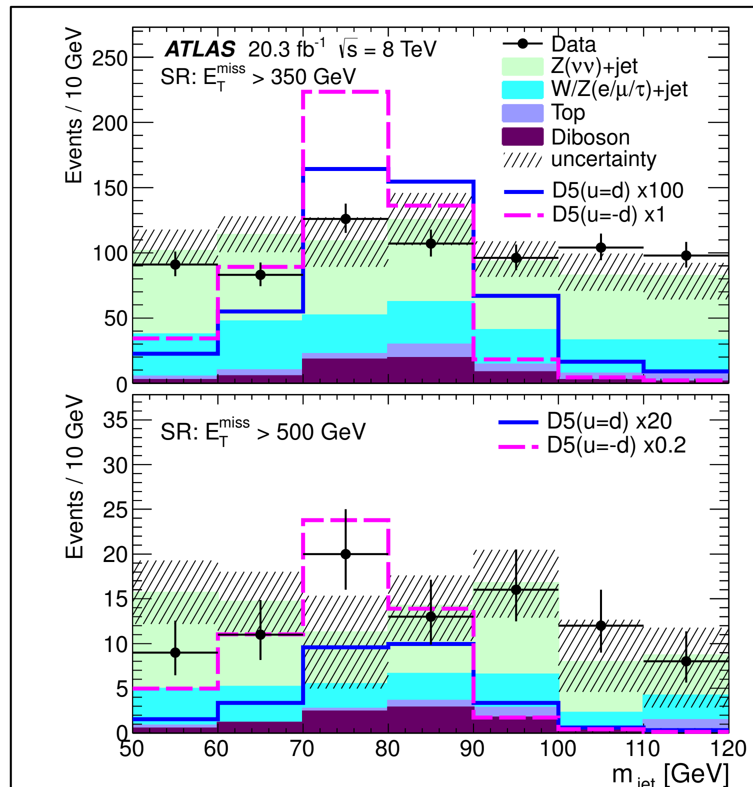


CMS-PAS-JME-14-002

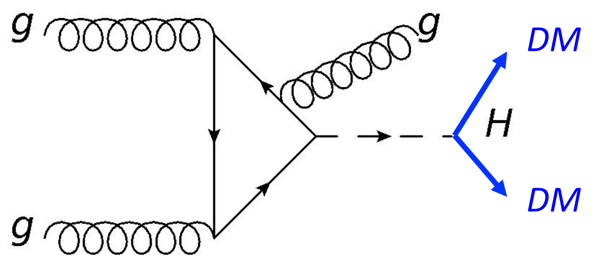
CMS-PAS-EXO-12-055



PRL 112, 041802 (2014)

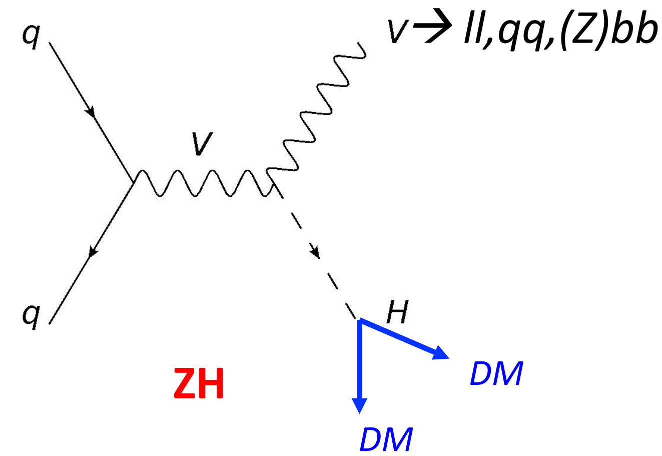


If DM is massive then **DM** ←→ **SM** mediated via the **Higgs boson** (Higgs portal Models*)



Gluon-fusion

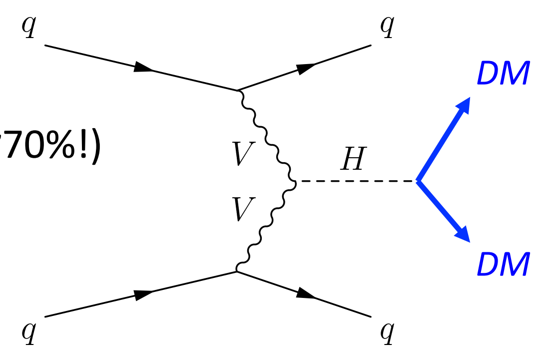
Dominant production but low acceptance after kinematic selection: >0 jets, large E_T^{miss} as in monojet search



ZH

Small x-section but very clean signature
- ✧ Look for pair of charged leptons / b-quarks consistent with Z decay
- ✧ V(had)+E_T^{miss} also targets this mode

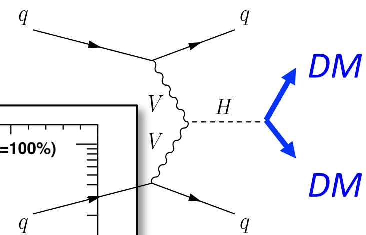
Smaller x-section (~10x less than ggF) but Large S/B ratio (~70%!)
- ✧ Search for two jets with large η-separation and large invariant mass
- ✧ Robust counting analyses in E_T^{miss} / m_{jj} tails



VBF

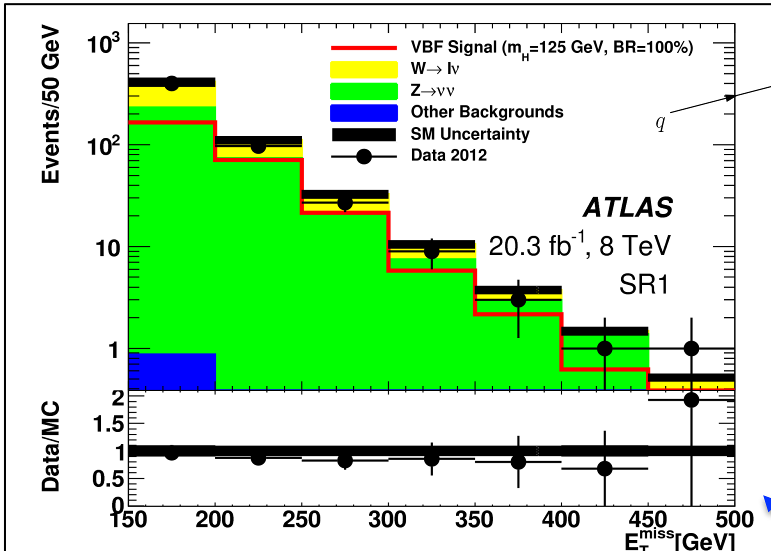
H → Invisibles

Dedicated Higgs targeted analyses from ATLAS and CMS…



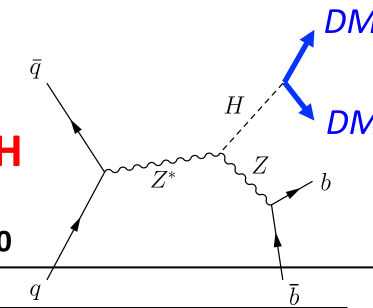
VBF

arXiv:1508.07869 (sub JHEP)

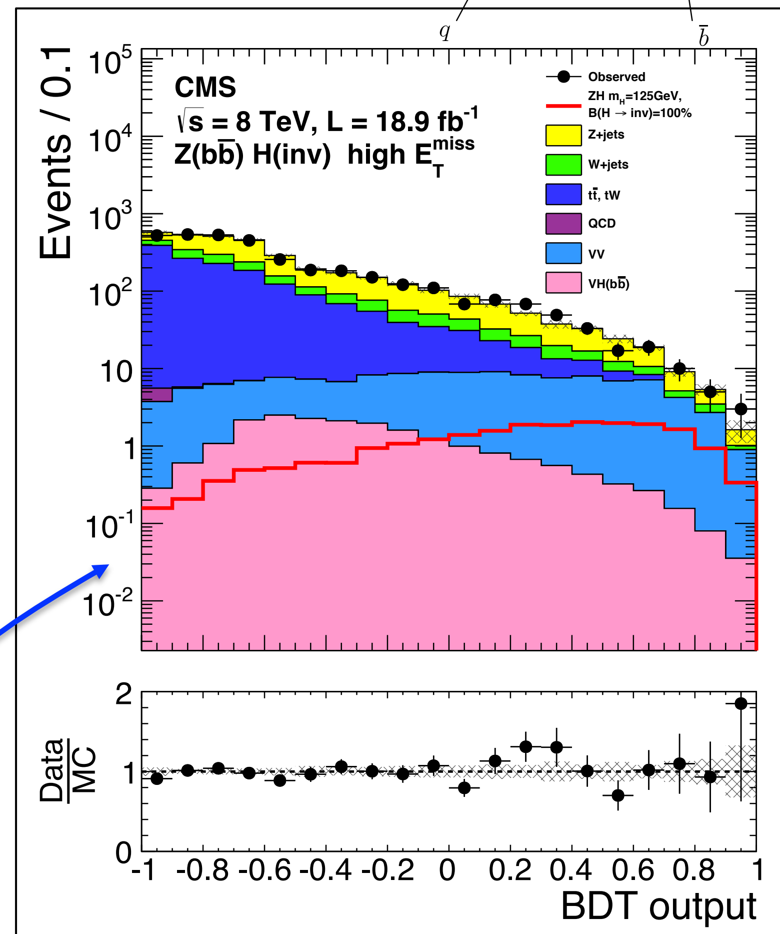


Multiple signal regions in ATLAS VBF defined in E_T^{miss} and m_{jj}

Z(bb)H



Eur. Phys. J. C 74 (2014) 2980



Fit dedicated BDT distribution in three E_T^{miss} regions in CMS (b-jet kinematics, secondary vertex information and color flow between b-jets)

H → Invisibles

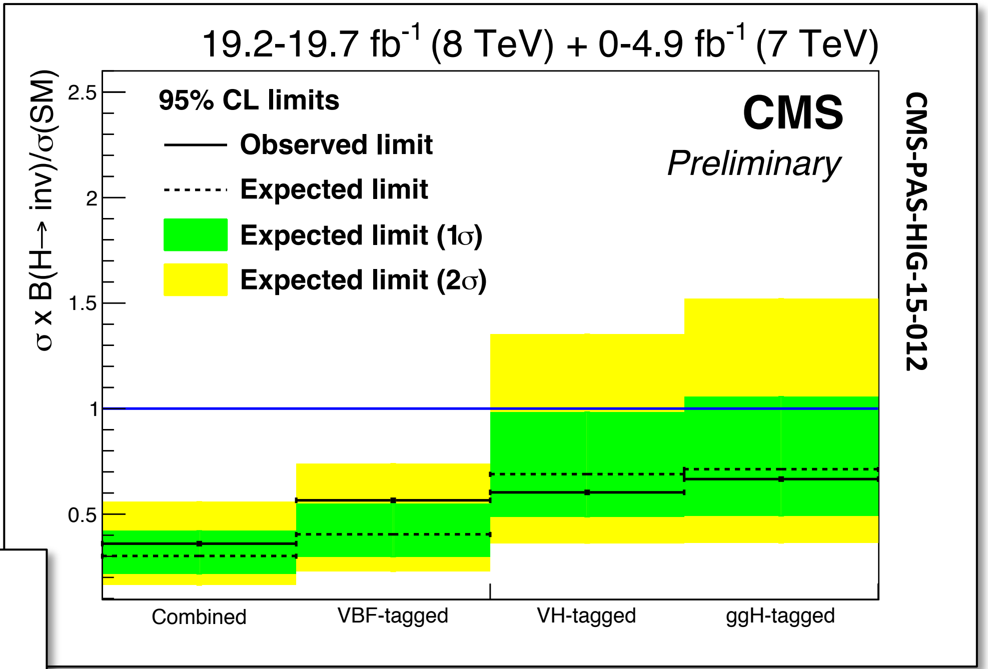
Combine several searches and interpret as limits on decay

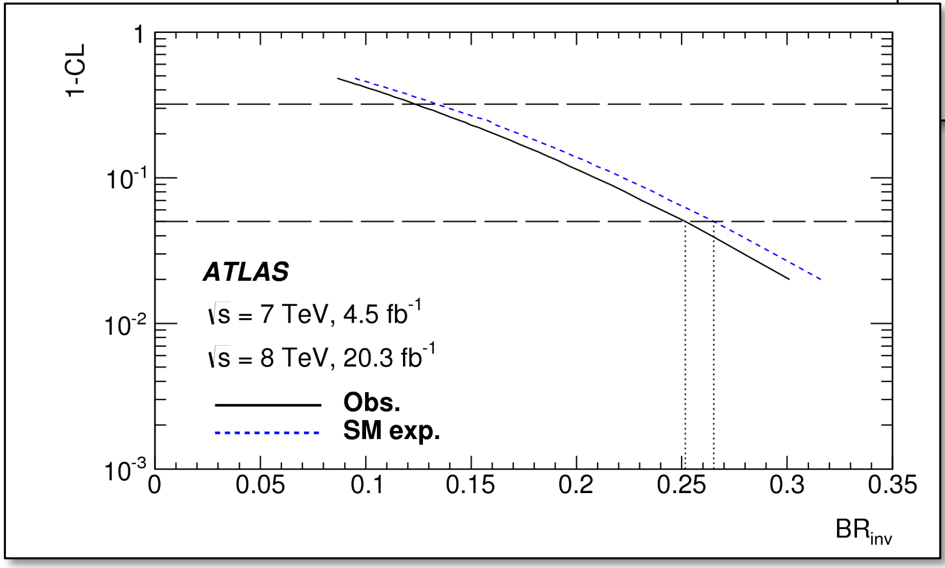
CMS combines (updated) monojet*, V(had) +Z(bb)+Z(ll)+(updated) VBF searches

Combined upper limit

BR(H→invisibles) < 36% (30%) obs (exp)

** With 'VBF-veto' to remove overlapping events*





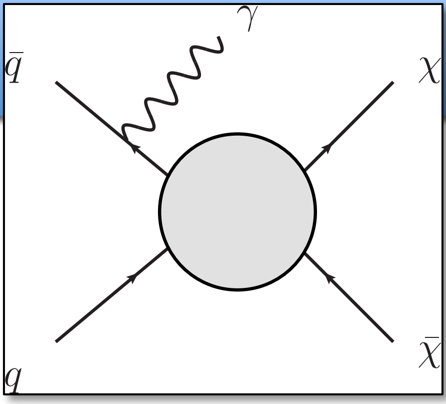
arxiv:1509.00672 (sub. JHEP)

ATLAS combines V(had)H+Z(ll)+VBF searches:

BR(H→invisibles) < 25% (27%) obs (exp)

**ATLAS use LLR but CLs gives identical result*

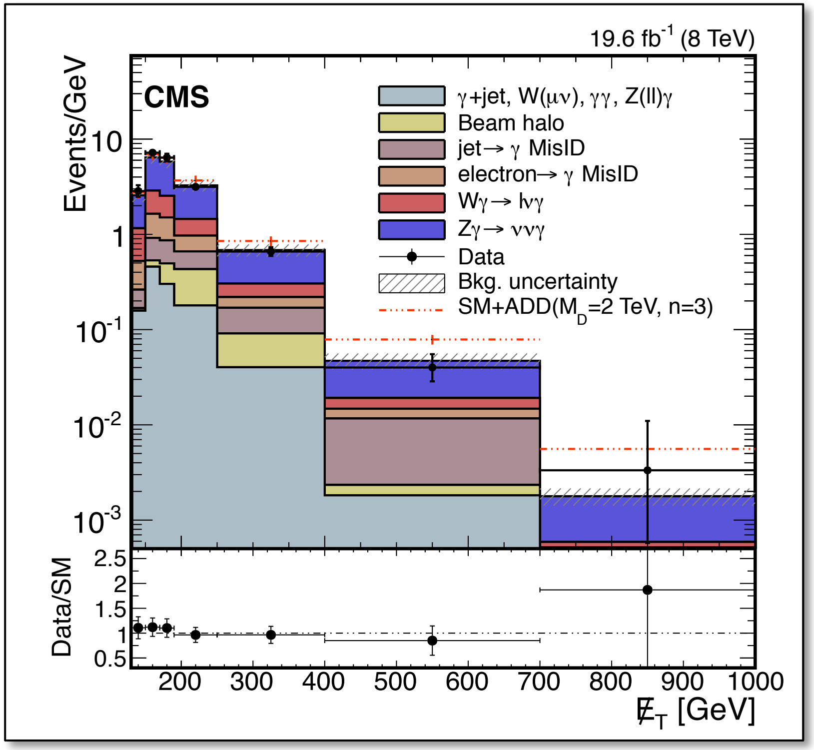
Mono-photon



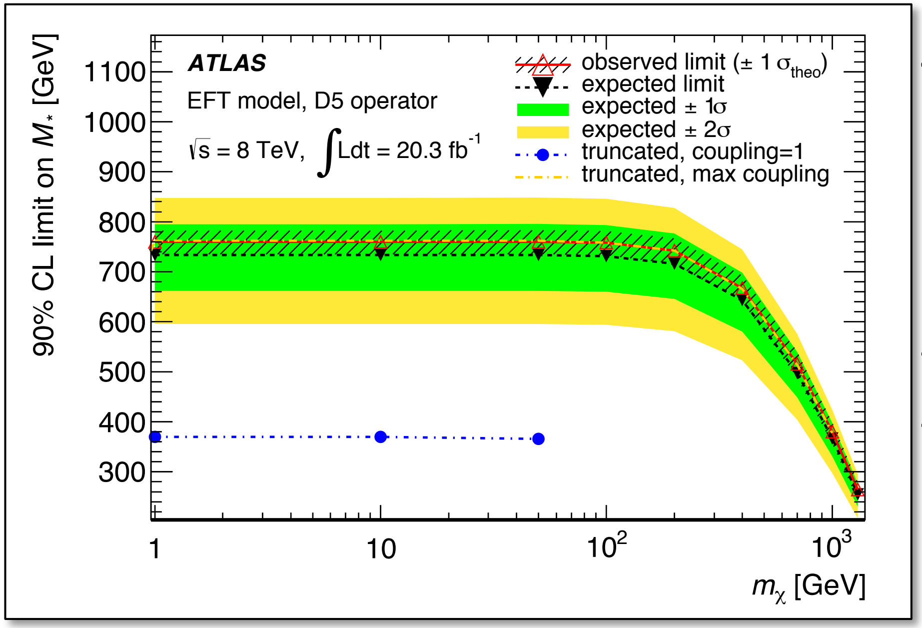
Typically smaller cross-sections but high-E_T photon easy to trigger
→ Lower E_T^{miss} thresholds accessible

Select events with,
- One high energy, isolated photon, E_T>145/125 GeV (CMS/ATLAS)
- E_T^{miss} > 150 /140 GeV (ATLAS/CMS)
- Reject events with overlapping photon and E_T^{miss} ($\Delta\phi(\gamma,\mathbf{E_T}^{miss})$<0.4/2 ATLAS/CMS
- Largest backgrounds from Wγ/Zγ estimated from lepton CR
- γ+jet background from MC validated with events inverting Δϕ (ATLAS) or correct using data-MC scale-factors (CMS)

CMS-PAS-EXO-12-047 (Sub PLB)

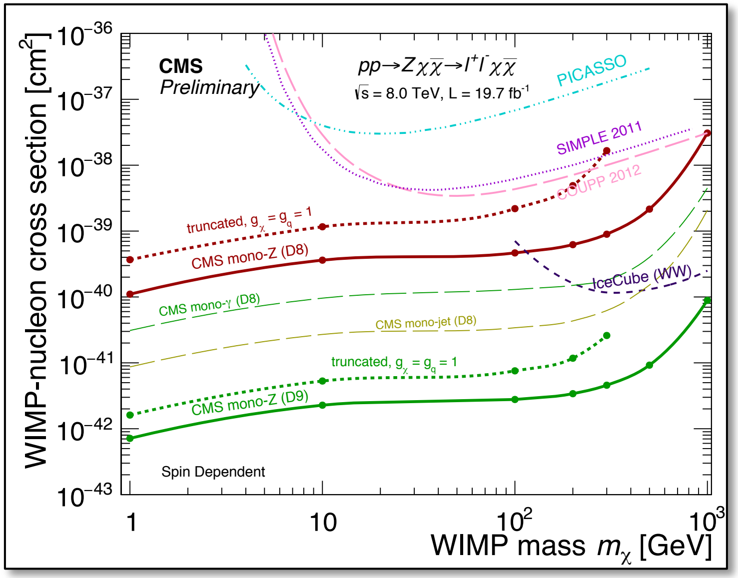


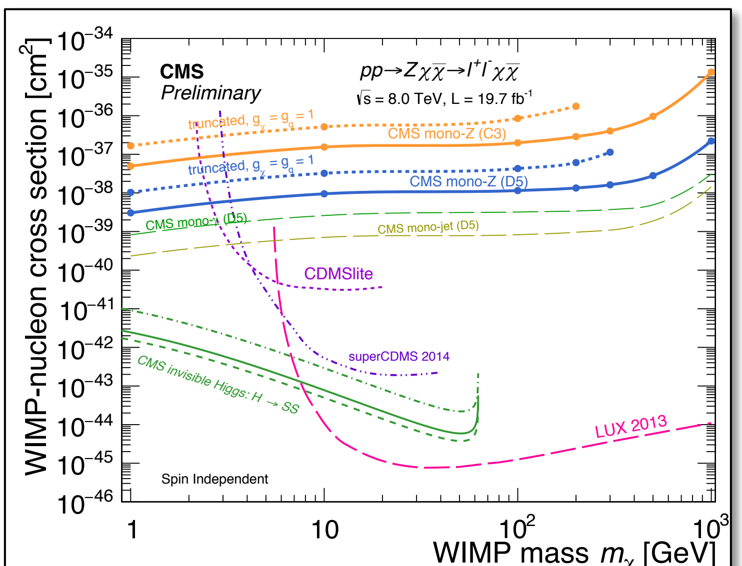
Limits on M(Λ) for vector operator*



Phys. Rev. D 91, 012008 (2015)

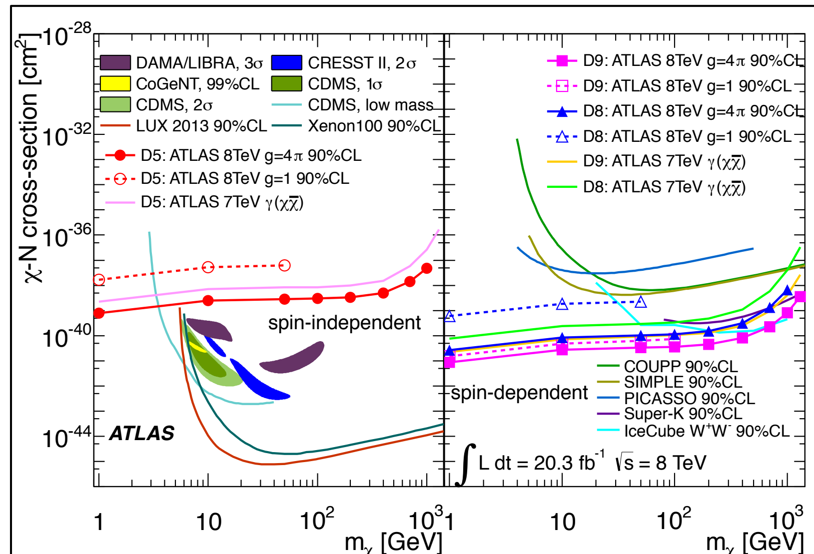
Comparisons to Direct Detectors

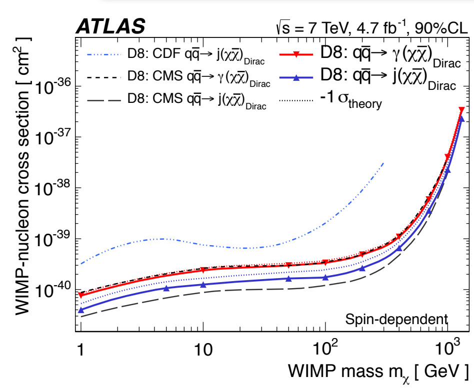


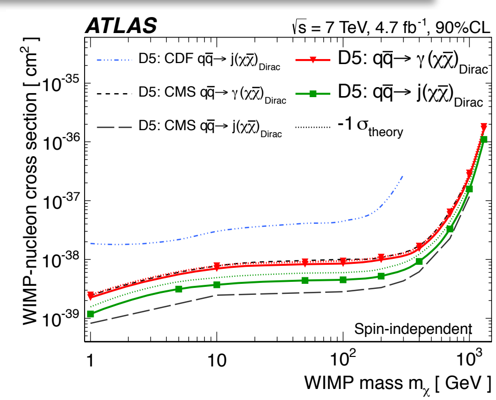


Translate EFT limits into upper limits on spin-dependent and spin-independent χ-N cross-sections

→ Complementary to DD searches



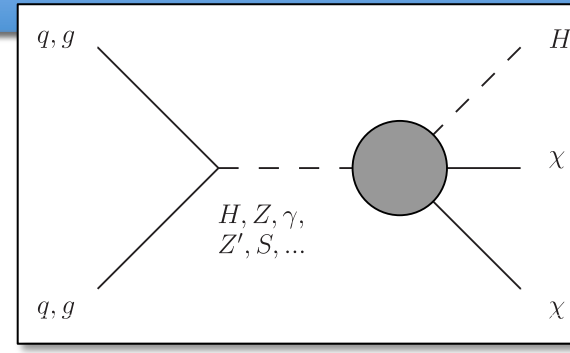




Mono-Higgs

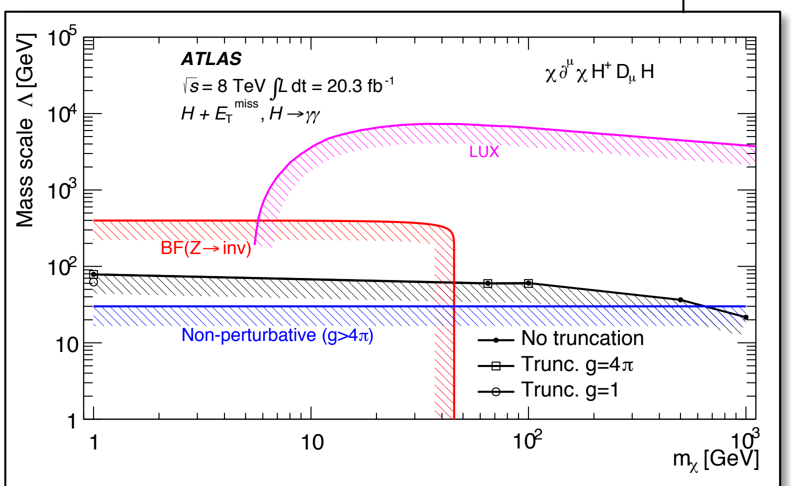
ATLAS H+E_T^{miss} with H→γγ

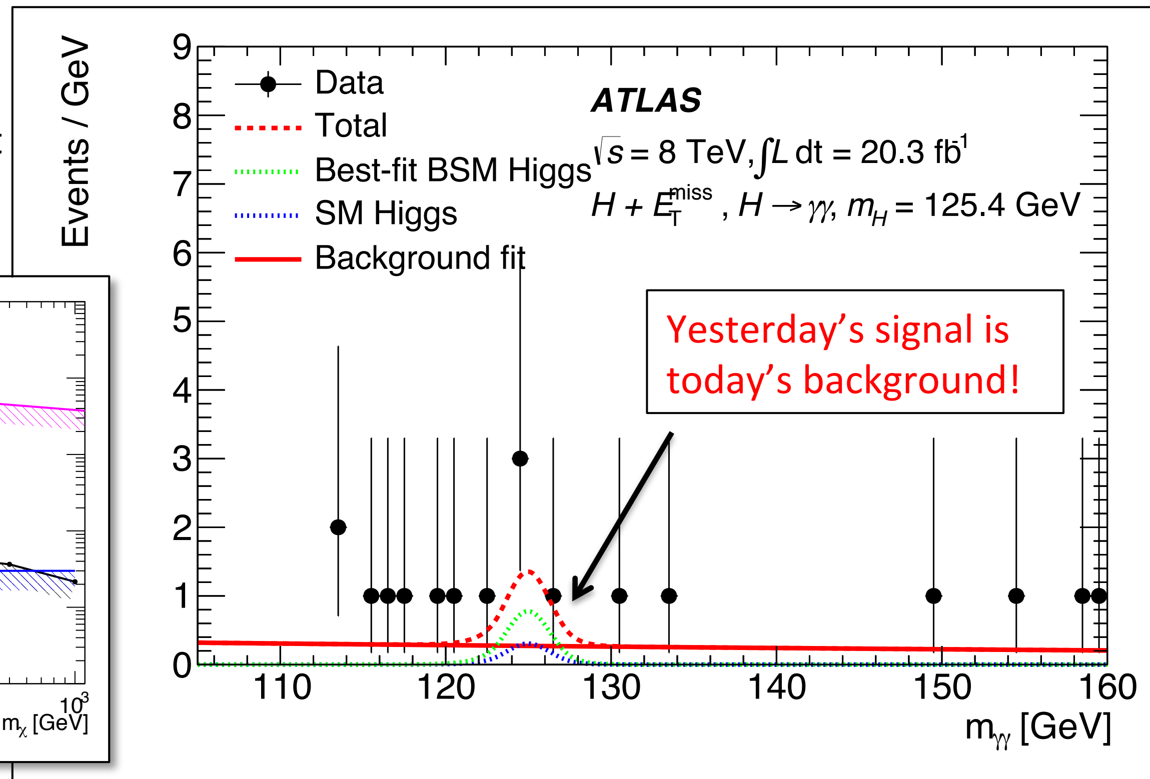
- Look for di-photon pair with photon $p_T/m_{\gamma\gamma}$> 0.35,0.25 GeV
- E_T^{miss} > 90 GeV
- Unbinned fit to diphoton invariant mass → bump hunt
- Peaking backgrounds from SM **Z(→νν)H** and **W(→lν)H**
- Wγγ, Zγγ, γγ non-resonant backgrounds estimated from $m_{\gamma\gamma}$ sidebands

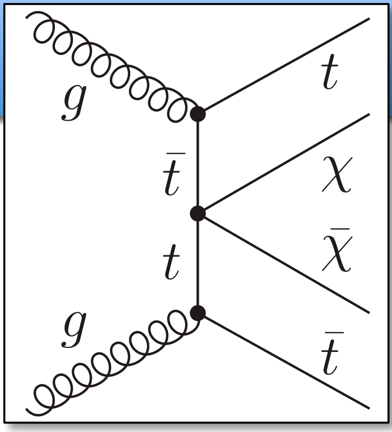


arXiv:1506.01081 (Acc PRL)

EFT interpretations compared to direct detection and Z constraints (LEP)







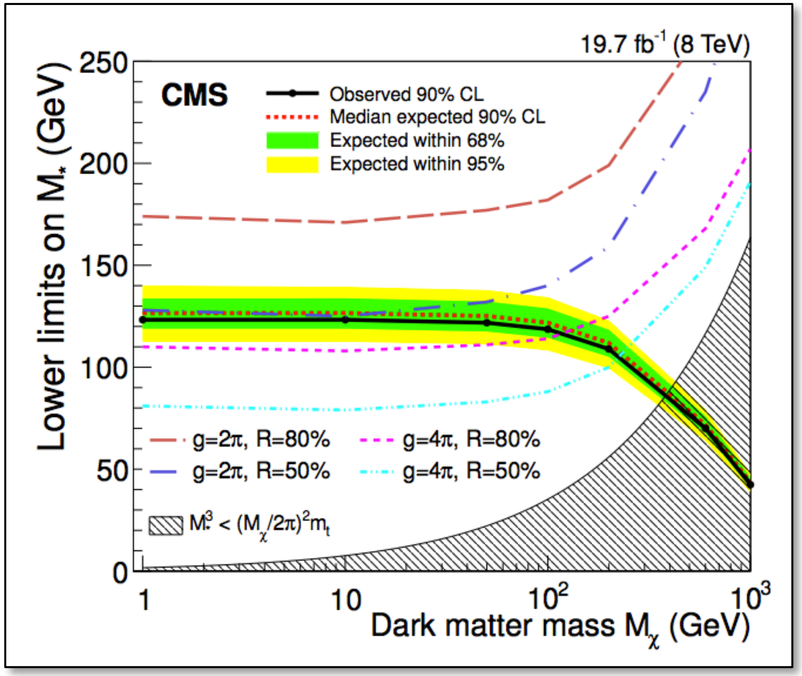
Scalar interactions with DM favor heavy-flavor quarks

- Top-quark and bottom-quark coupling enhanced (~m_q)
- Searches for top-quark pairs recoiling against the DM particles

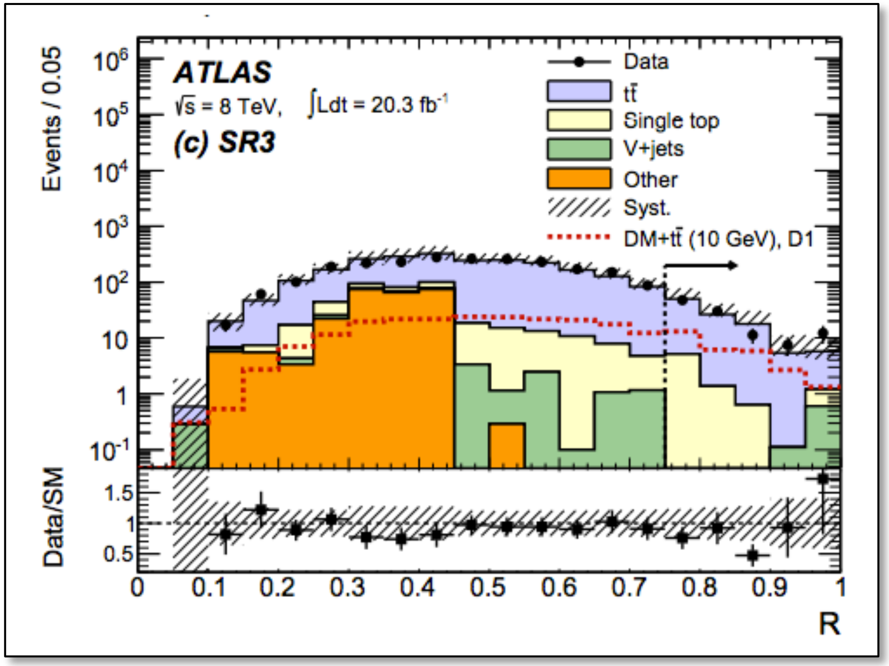
→ **tt+E_T^{miss}**

- One lepton + at least 1 b-tagged jet (CMS) or semi-leptonic / all hadronic + b-tags (ATLAS)
- E_T^{miss} > 320/300 or 200 GeV (CMS/ATLAS) ,
- m_T >160 GeV or R (razor) > 0.75 to remove W and tt backgrounds
- Normalize tt background from data CR

JHEP 06 (2015) 121

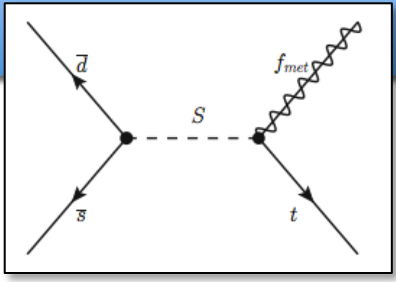


Eur. Phys. J. C (2015) 75:92

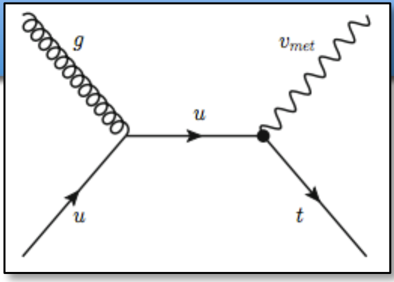


Heavy Flavor

Several BSM models predict single top + E_T^{miss}
→ Consider resonant and non-resonant production modes



Resonant

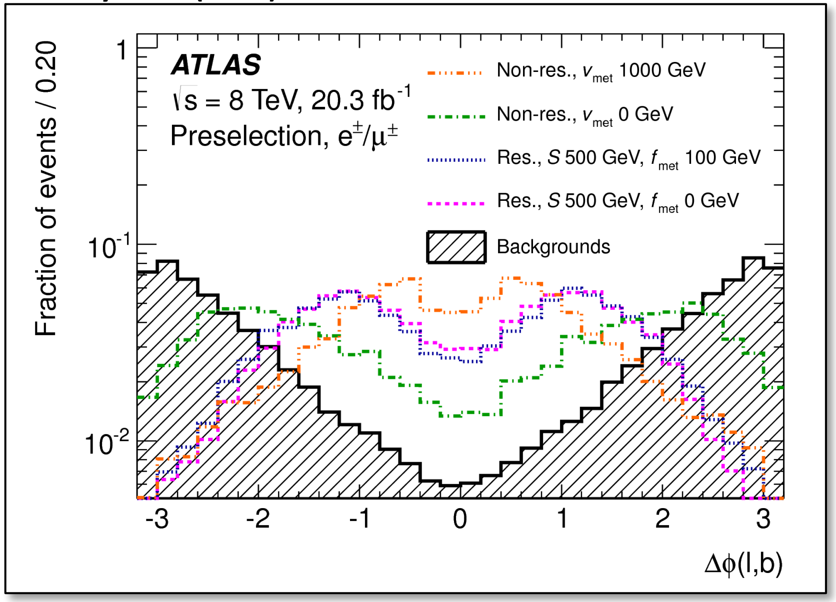


Non-resonant

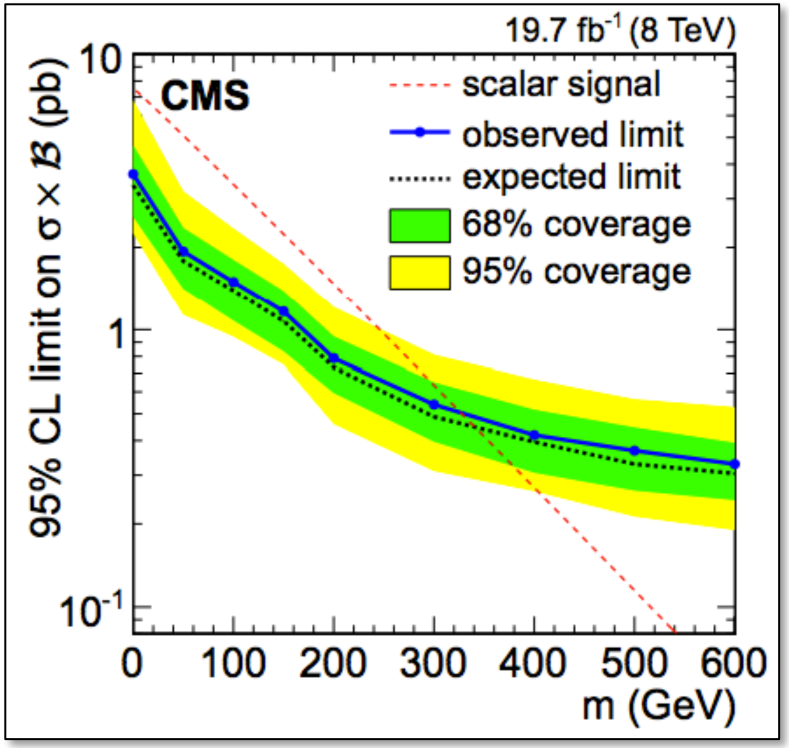
Leptonic (ATLAS) and hadronic (CMS) final states explored …

ATLAS: *two categories based on m_T and angle between lepton and b-jet.*

Eur. Phys. J. C (2015) 75:79



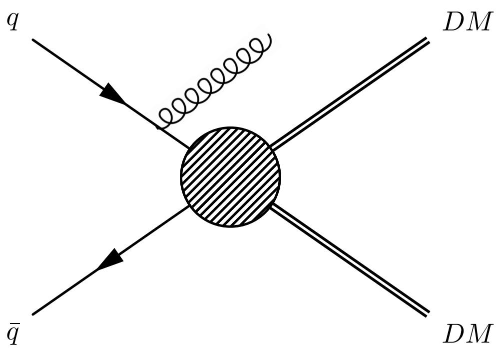
CMS: *Two categories defined with/without b-tagged jet*



Phys. Rev. Lett. 114, 101801 (2015)

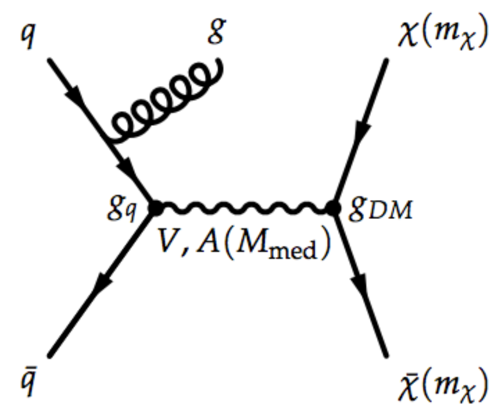
Moving on (LHC DM forum)

EFT interpretation useful as a benchmark for sensitivity and comparison to DD, However, validity break-down where LHC can reach mediator mass-scale



$$\sigma \propto 1/M^{*4}$$

Simplified models capture effects with direct access to mediator → overcome validity issues but more parameters to consider



$$\sigma \propto (g_{sm} g_{dm})^2 / M_{med}^4$$

Moving on (LHC DM forum)

arXiv.org > hep-ex > arXiv:1507.00966

Search or

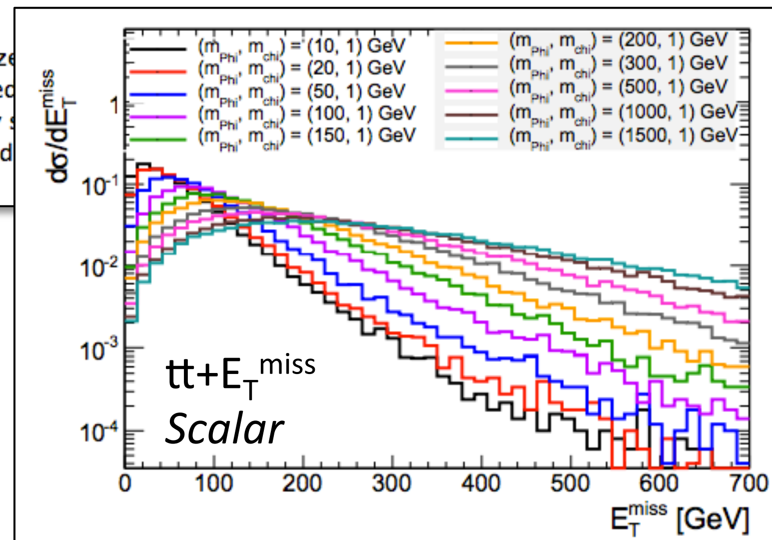
High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

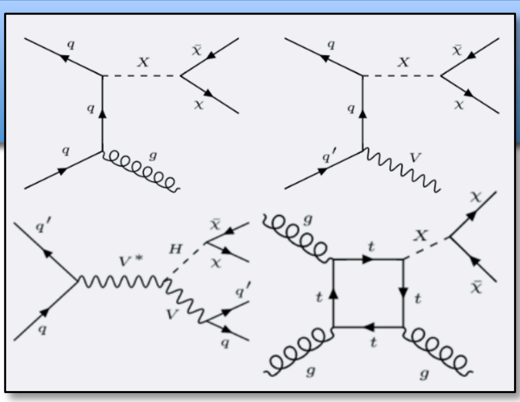
(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organize
experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified
searches. A prioritized, compact set of benchmark models is proposed, accompanied by
of generator implementations. This report also addresses how to apply the Effective Field
such interpretations.

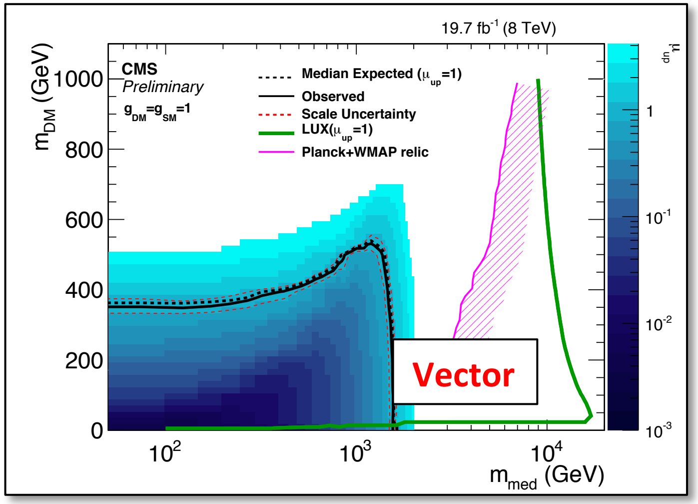


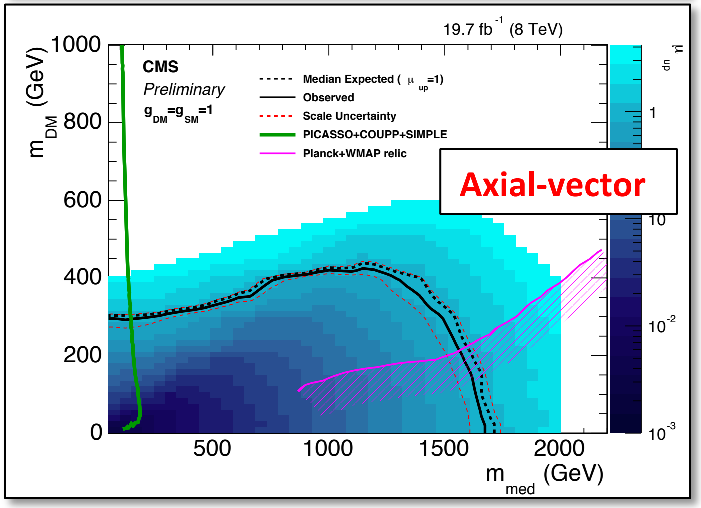
- ✧ Study of production cross-sections and kinematics of mediator models with different final states
- ✧ ATLAS + CMS + Theorists collaborate to produce agreed set of minimal benchmark simplified models to be considered in early Run-2 DM searches

CMS monojet + mono-V



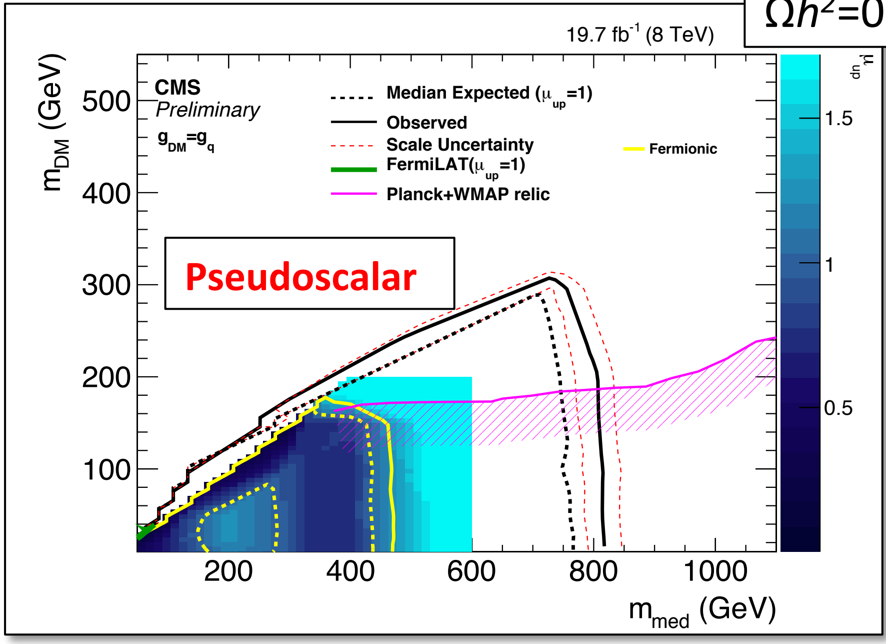
CMS 8TeV shape-analysis* simplified model interpretations





- ✧ Scan mediator and DM masses
- ✧ Fix couplings to $g_{SM}=g_{DM}=1$
- ✧ Mediator width (Γ) fixed under minimal width assumption (only SM and 1 DM candidate contribute)
- ✧ Compare to constraints from relic DM density

Ωh^2=0.12



*CMS-PAS-EXO-12-055 – monojet+mono-V(had)

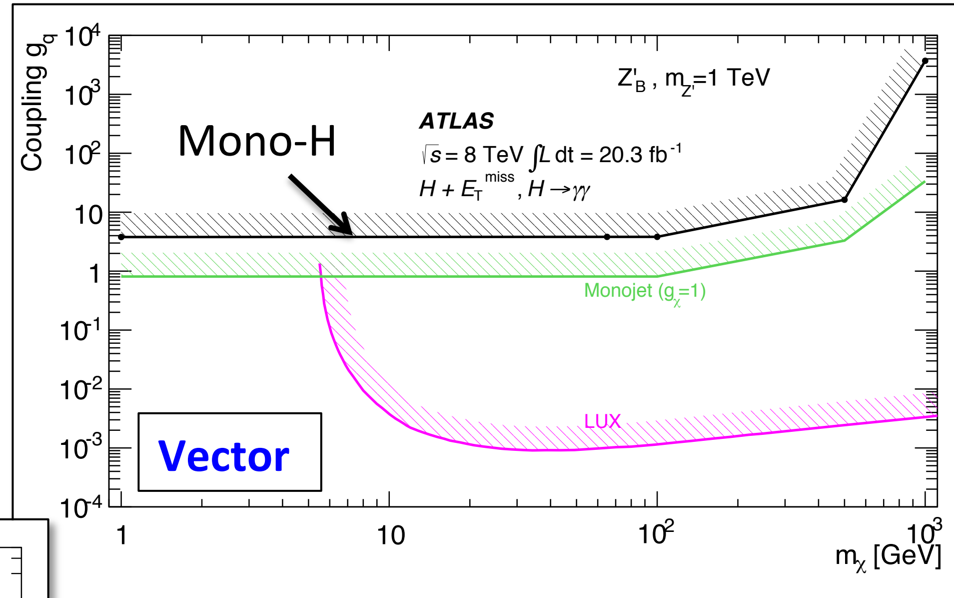
Mono-Higgs

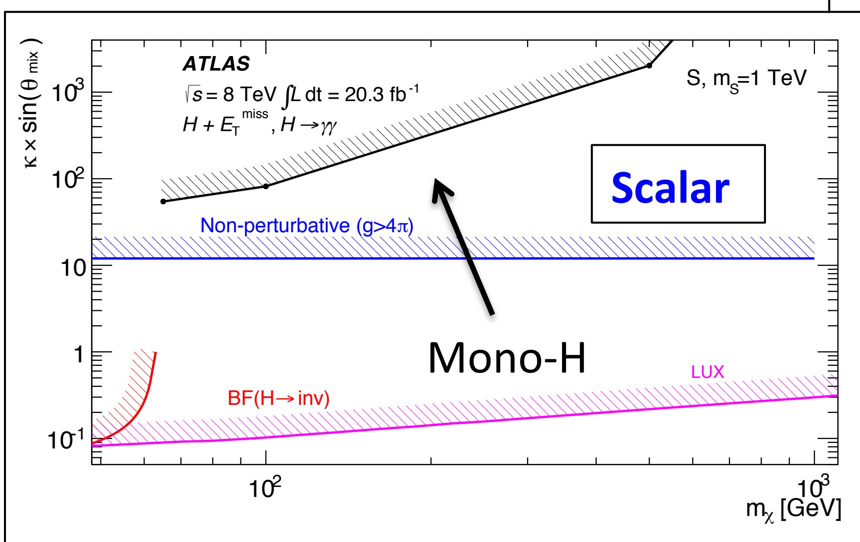
ATLAS analyses interpreted under simplified models…

Set limits on mediator coupling to SM assuming maximum coupling to DM for vector (Z') mediated model.

✧ Compare to ATLAS monojet limits

✧ Complementary to DD (LUX) search





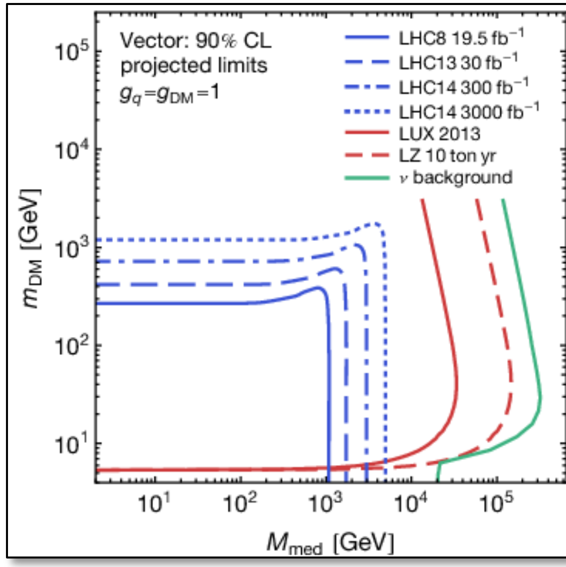
For the scalar mediator And k*sin(θ_{mix}) where θ_{mix} is the mixing ange between the scalar, **S**, and the Higgs boson.

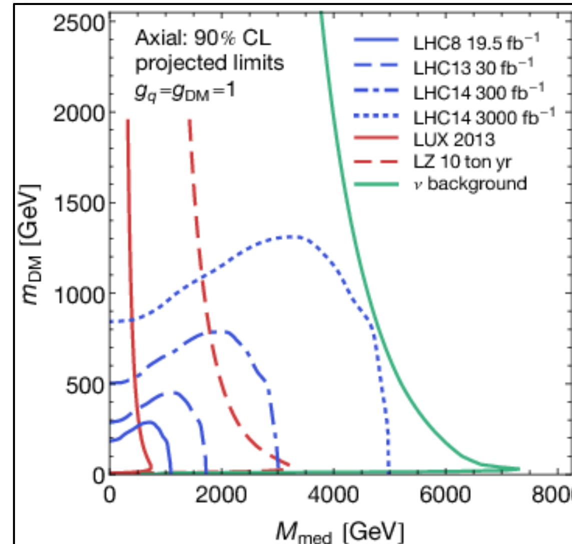
✧ Compare to constraints on BR(H→inv)

Prospects for Run-2 and Beyond

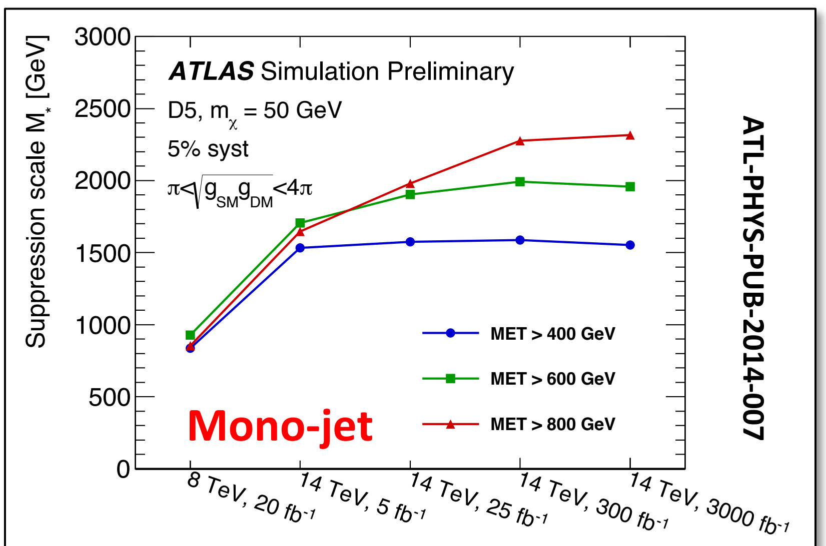
Projections from ATLAS and CMS monojet analyses

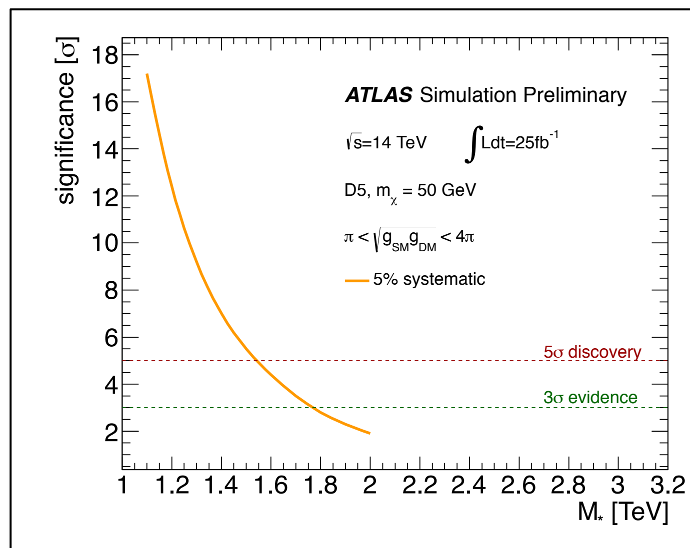
Expect to exceed Run-1 sensitivity with 5 fb^{-1} @ 13 TeV in these scenarios*





arXiv:1409.4075



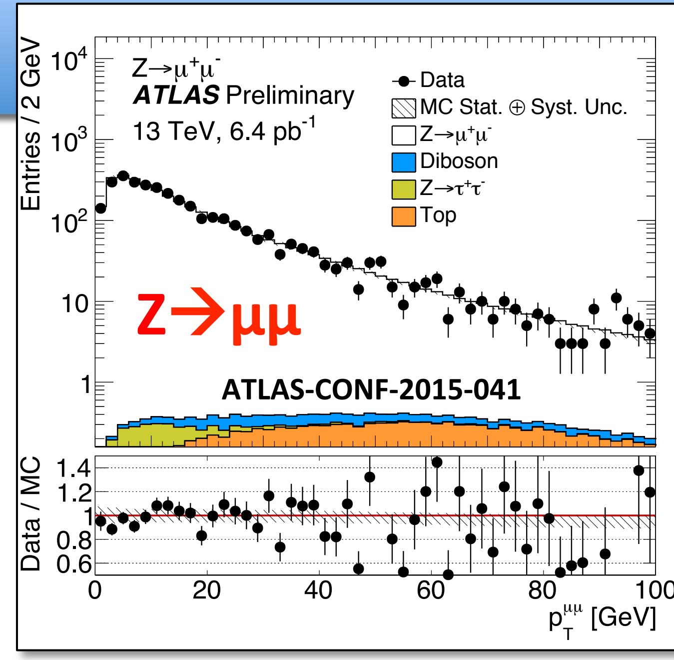


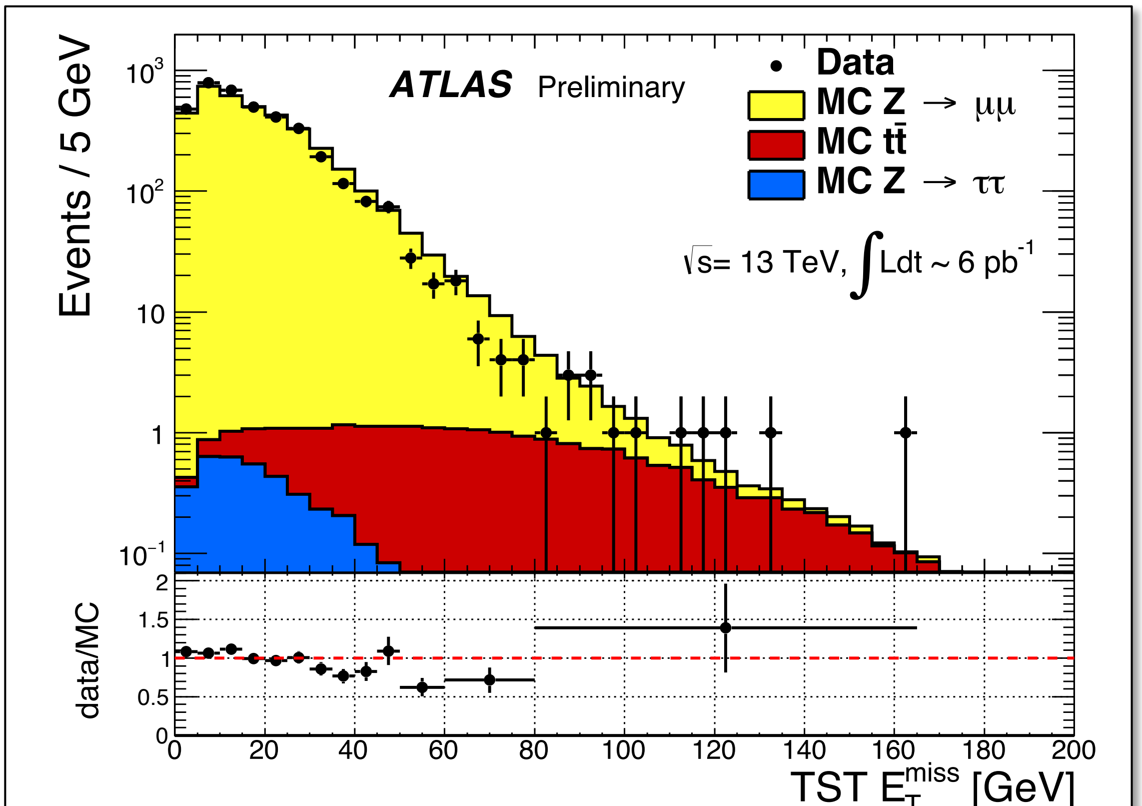
(*projections don't account for analysis improvements)

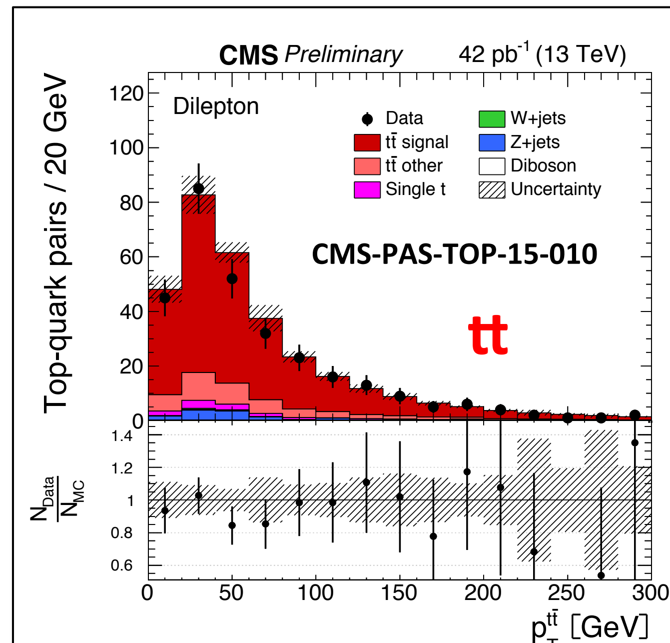
Run-2 has begun!

First collisions @ 13 TeV have been recorded!

- Commissioning E_T^{miss} and other variables looks promising
- Main backgrounds (Z/W/tt) are crucial to understand for DM searches.
- Differential cross-sections measurements of these processes help understand backgrounds in tails (eg pT, jet multiplicity..)





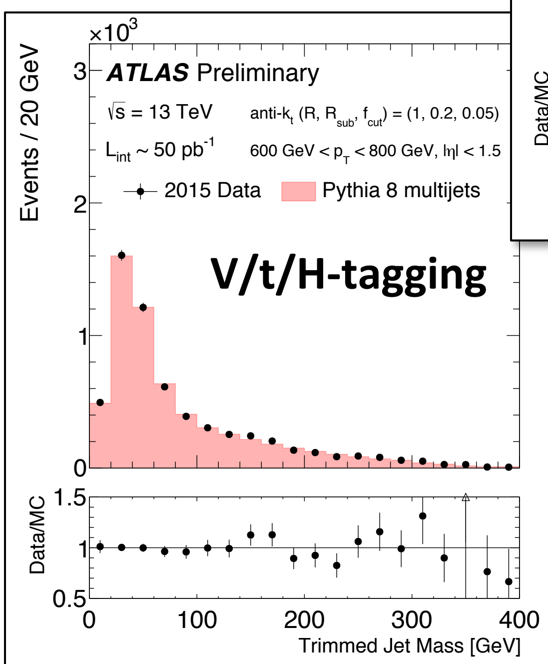


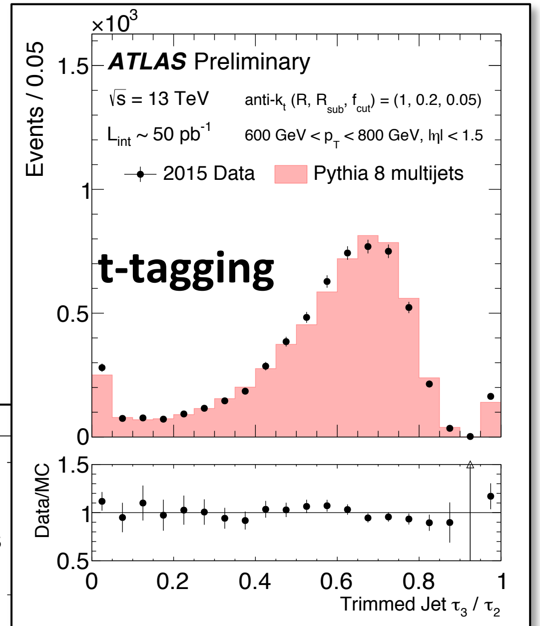
More boost objects at 13 TeV

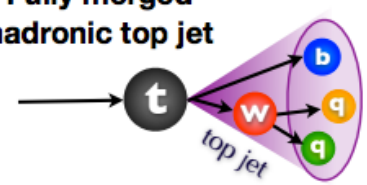
More energy in Run-2 means higher DM momentum

- Recoiling objects have higher Lorentz boost, hadronic decay products merge
- Jet-substructure Performance studies at higher COM energy vital for DM searches in boosted topoligies

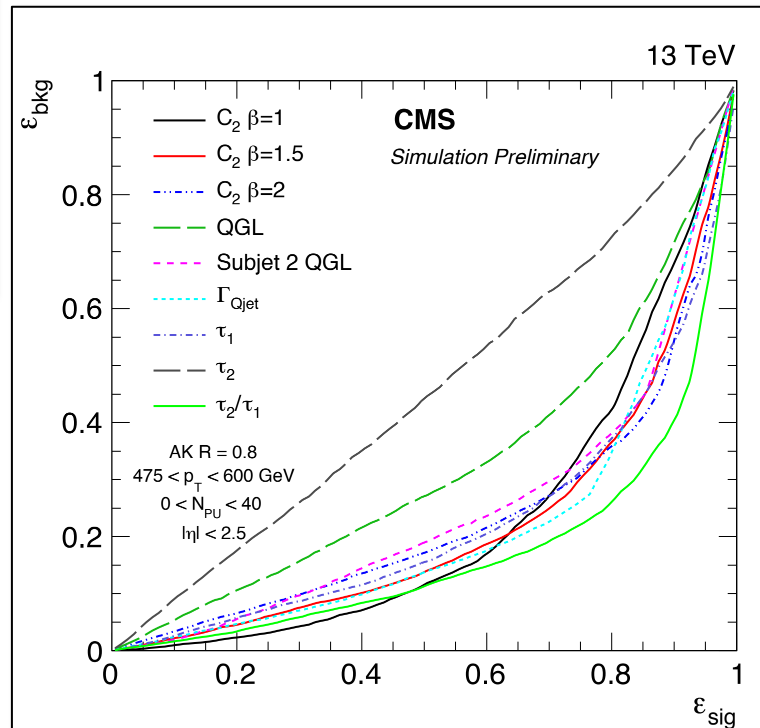
ATLAS-CONF-2015-035







Justin Pilot **BOOST 2015**



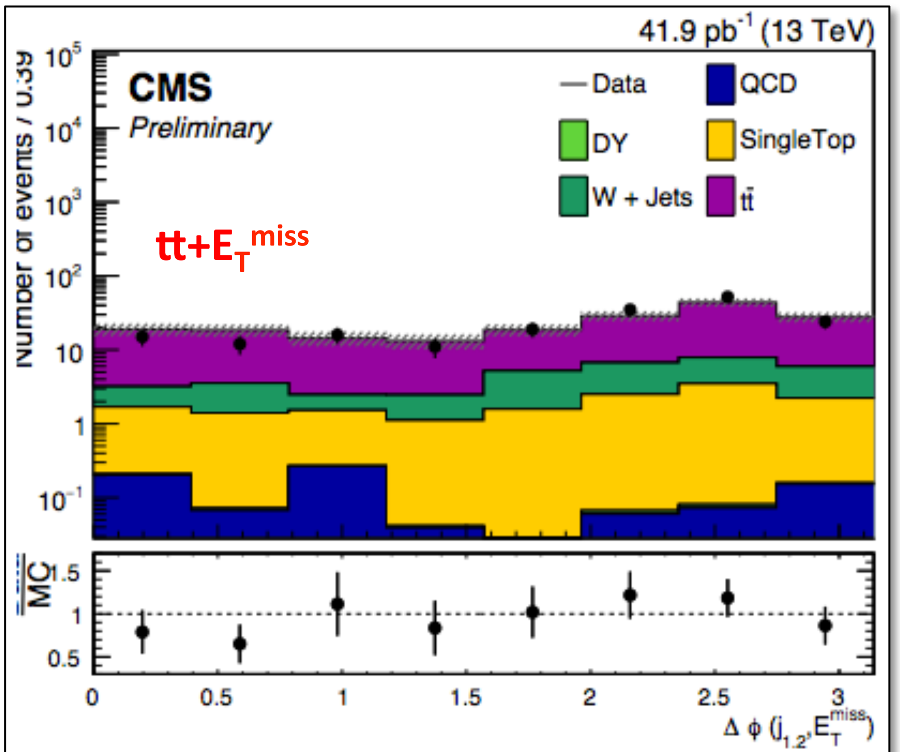
The search continues

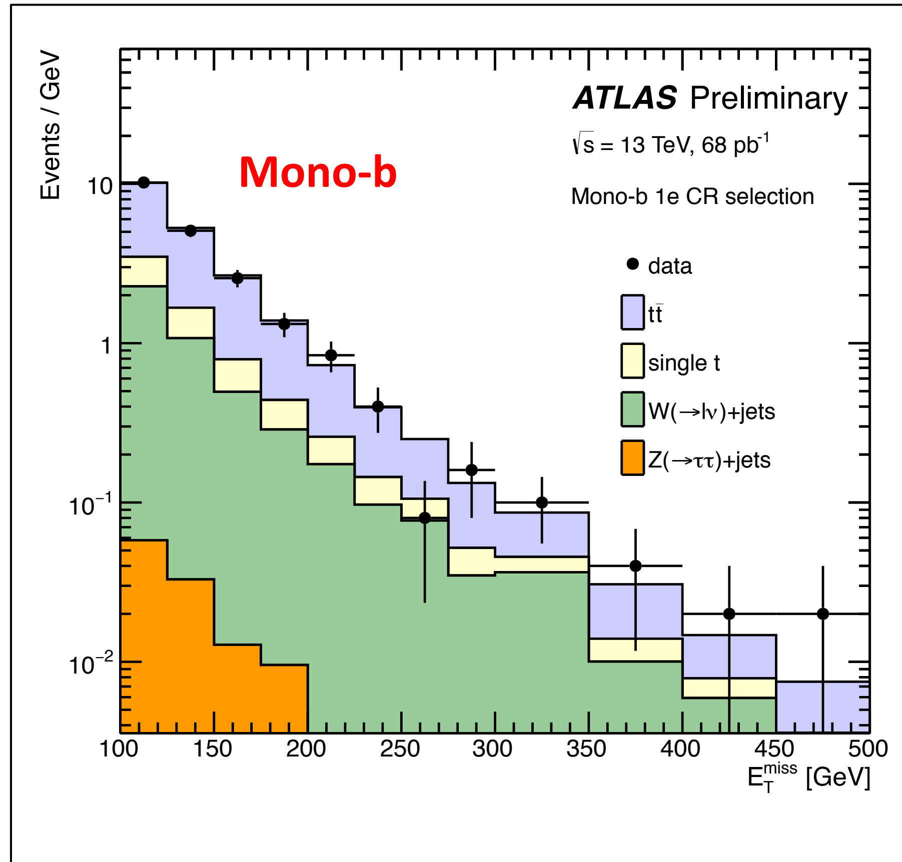
Heavy flavour + E_T^{miss} searches at 13 TeV are already progressing well

- ✧ Good agreement between simulation and the new data
- ✧ Can expect many more as the data comes

ATL-EXOT-2015-007

CMS-DP-2015-033





E_T^{miss} restricted at |η|<3 + response corrections

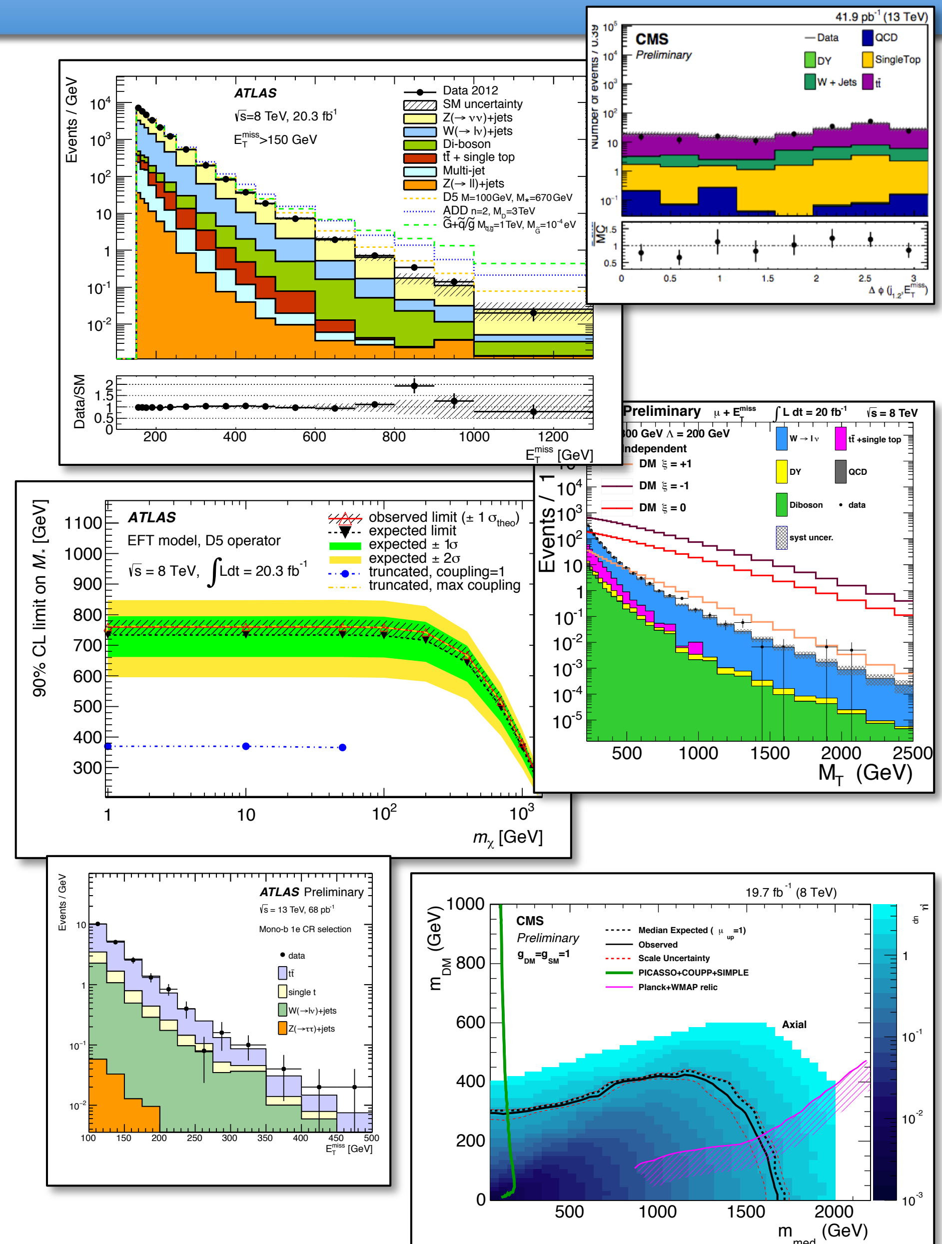
Summary

Wide variety of searches for DM at the LHC

- Mono-mania (X+E_T^{miss}) searches are simple yet powerful tools to look for DM production at ATLAS and CMS
- Interpretation of the data under EFT models
  → useful for comparing sensitivities between searches and direct detection
- Already looking to the use of simplified models to provide benchmarks suitable for the LHC

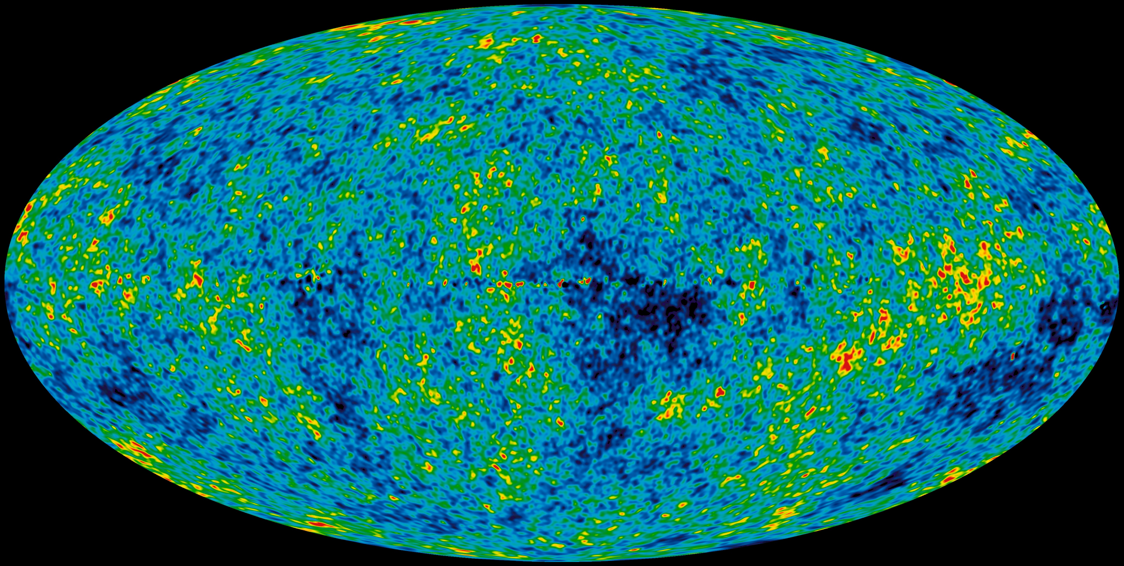
Run-2 is in progress!

- Data-taking and analyses are in full swing many expected to supersede Run-1 in the first year
- The all important **E_T^{miss}** looking good with the new data!
- More boost @ 13 TeV will require more use of sub-structure techniques
- DM is an exciting topic for Run-2 at the LHC, exciting times ahead!



Thank you!

Dark matter is out there

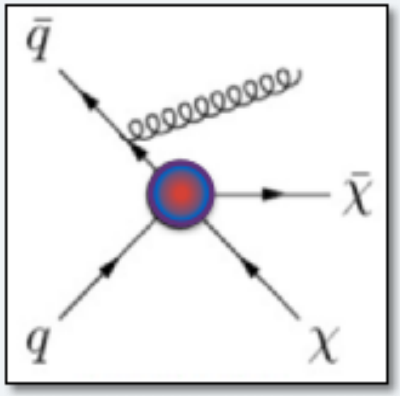


Let's hope we will find it in here!

BACKUP SLIDES

Effective operators describing DM-SM interaction (Effective Field Theory, EFT)

- Scalar/Vector (spin-independent, SI)
- Pseudo-scalar/Axial-vector (spin-dependent, SD)



Only 2 parameters

- Interaction scale $M^* = M_{med}/\sqrt{(g_\chi g_q)}$
- DM mass M_χ

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_*^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_*^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Validity issue for high transferred momentum, Q_{tr}: $Q_{tr}>M_{med}$

- Truncation techniques: account for the fraction of events not satisfying this assumption

A. de Cosa (LHCP 2015)

Monojet Selections

CMS

Selection highlights [CMS, EPJC75 (2015) 235]

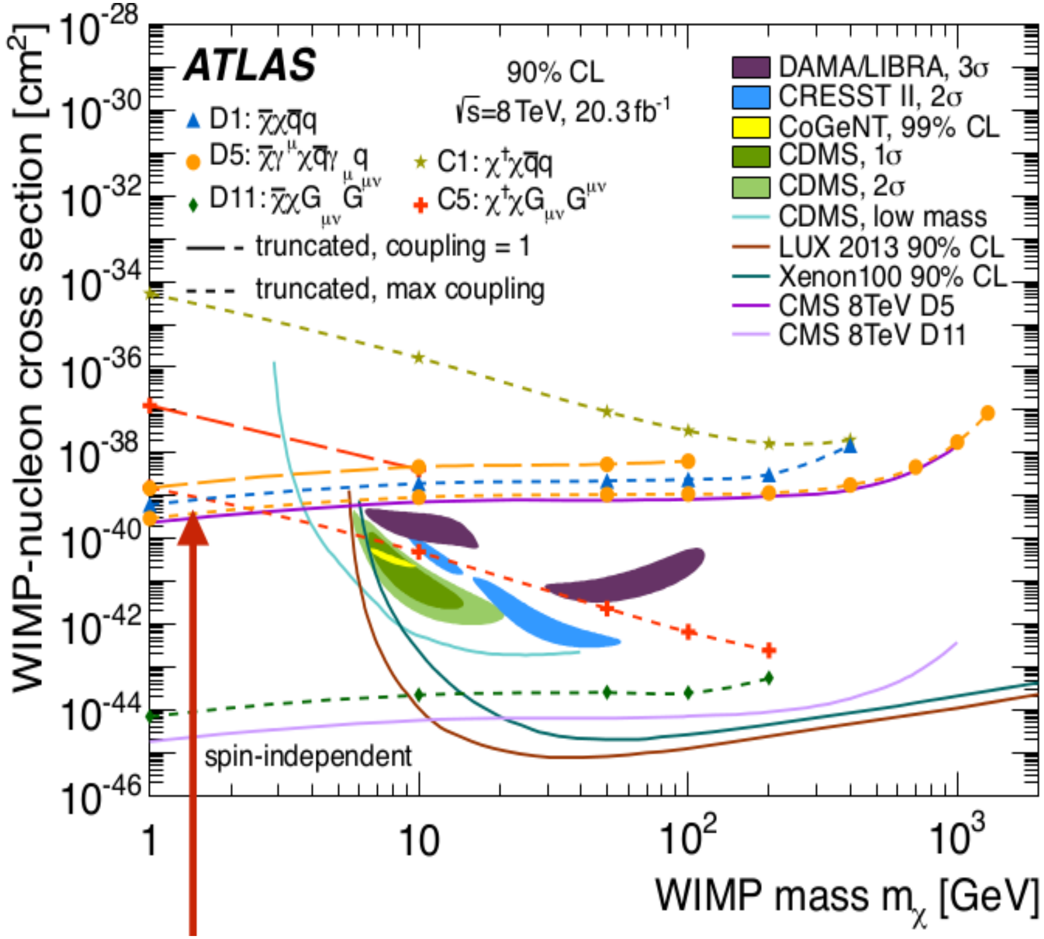
- Leading jet: p_T>110 GeV and $|\eta|$<2.4
- A second jet is allowed (to account for other jets from ISR)
  - p_T>30 GeV and $|\eta|$<4.5
  - must be close to the 1st jet: $\Delta\varphi(j_1, j_2)$<2.5
    - This requirement suppress dijet QCD events
- Event with more than 2 jets selected with same criteria as the trailing jet are discarded
  - This suppress ttbar and QCD multijet events
- Lepton veto (including hadronically decaying taus)
  - suppress W/Z production, dibosons, top-quark decays
  - Isolated leptons: $I(\Delta R=0.4)/pT < 0.2$
- Signal regions: 7 inclusive regions of E_T^{miss}
  - E_T^{miss} >250/300, 350, 400, 450, 500, 550 GeV

ATLAS

Selection highlights [ATLAS, EPJC (2015) 75:299]

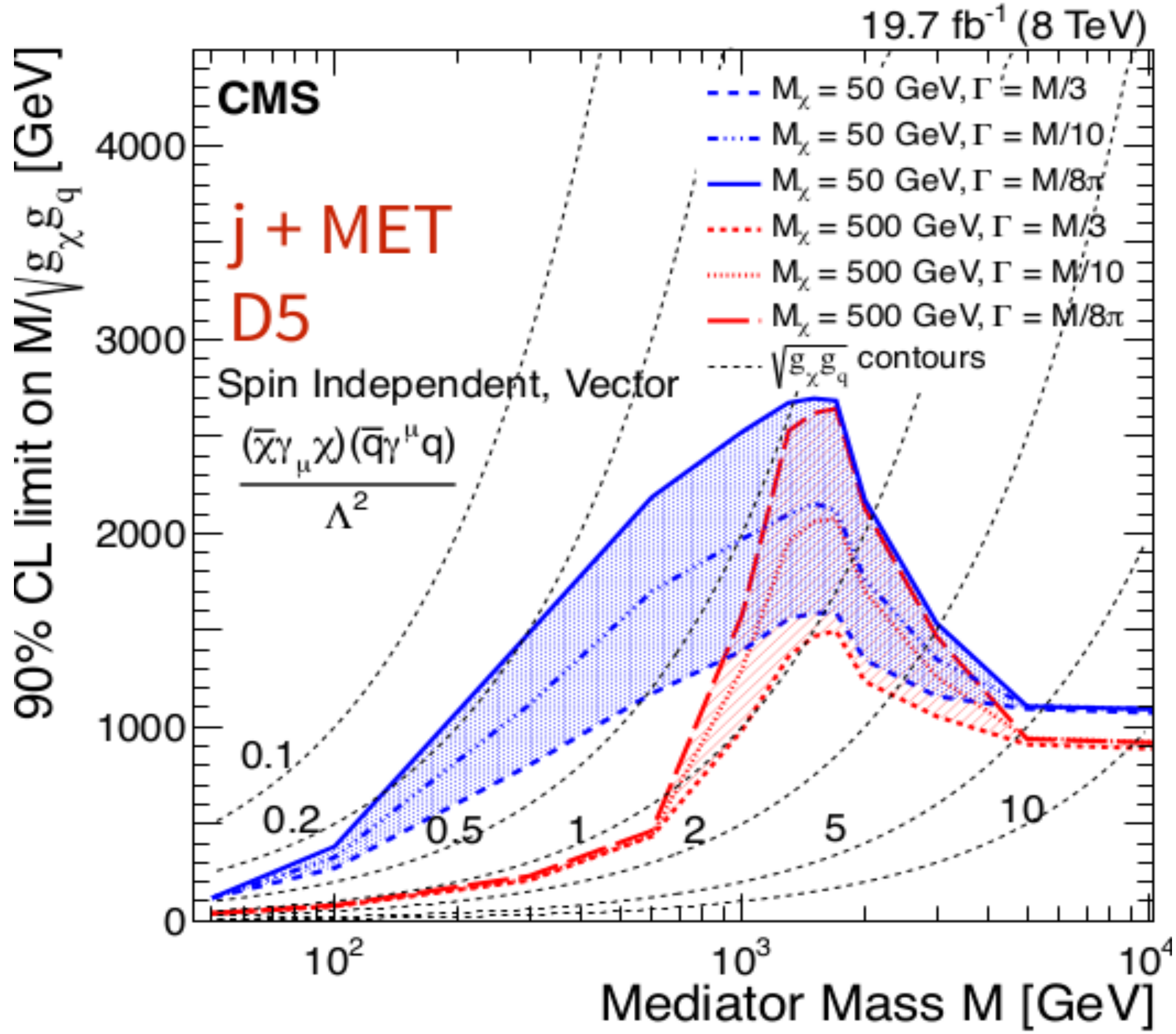
- At least one jet with p_T>30 GeV and $|\eta|$<4.5
- Leading jet with p_T>120 GeV and $|\eta|$<2.0
  - p_T/E_T^{miss}>0.5
  - $\Delta\varphi(j1, E_T^{miss})$>1.0
    - reduces multijet bkg
- Lepton veto (also on isolated tracks)
  - suppress W/Z production, dibosons, top-quark decays
  - Isolated leptons: $Iso(\Delta R=0.4)/p_T < 0.2$
- Signal regions: 8 inclusive regions of E_T^{miss}
  - E_T^{miss} >150,200, 250, 350, 400, 500, 600, 700 GeV

ATLAS monojet



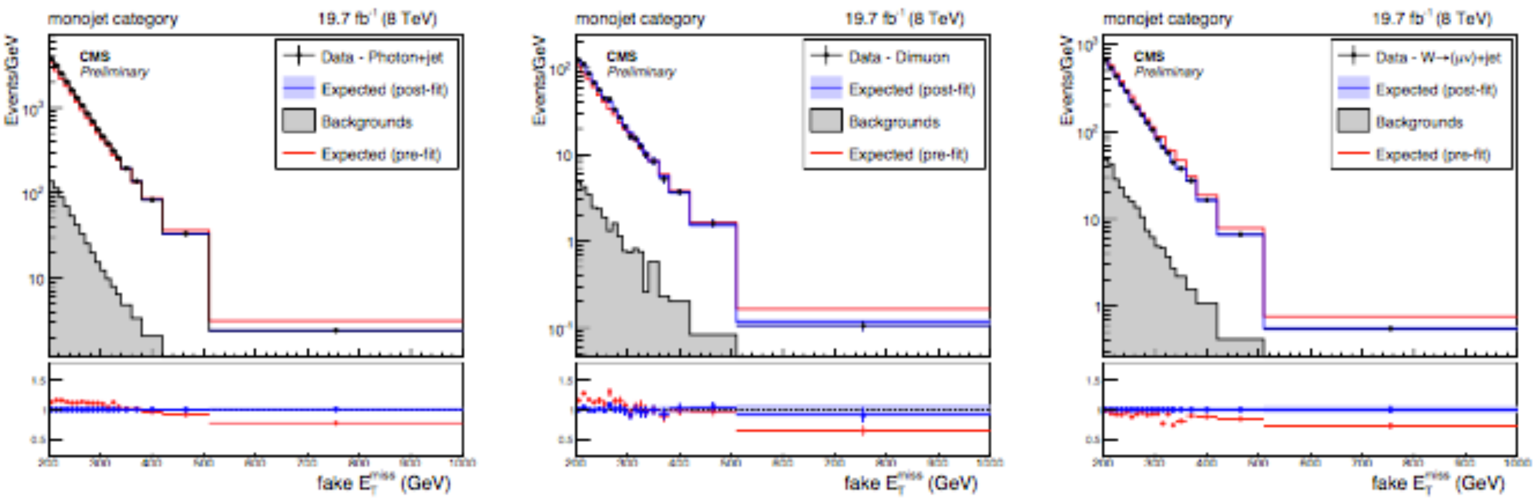
Similar to CMS EFT interpreted result

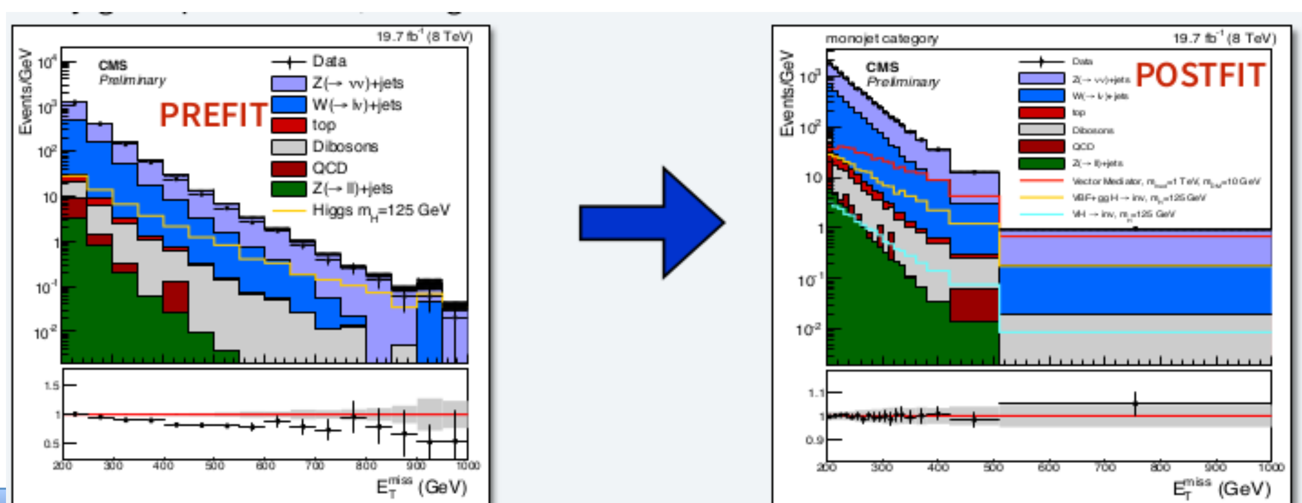
CMS monojet


19.7 fb^{-1} (8 TeV)
CMS
j + MET
D5
Spin Independent, Vector
$\frac{(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2}$
M_χ = 50 GeV, Γ = M/3
M_χ = 50 GeV, Γ = M/10
M_χ = 50 GeV, Γ = M/8π
M_χ = 500 GeV, Γ = M/3
M_χ = 500 GeV, Γ = M/10
M_χ = 500 GeV, Γ = M/8π
$\sqrt{g_\chi g_q}$ contours
0.1
0.2
0.5
1
2
5
10
90% CL limit on $M/\sqrt{g_\chi g_q}$ [GeV]
Mediator Mass M [GeV]
0
1000
2000
3000
4000
10^2
10^3
10^4

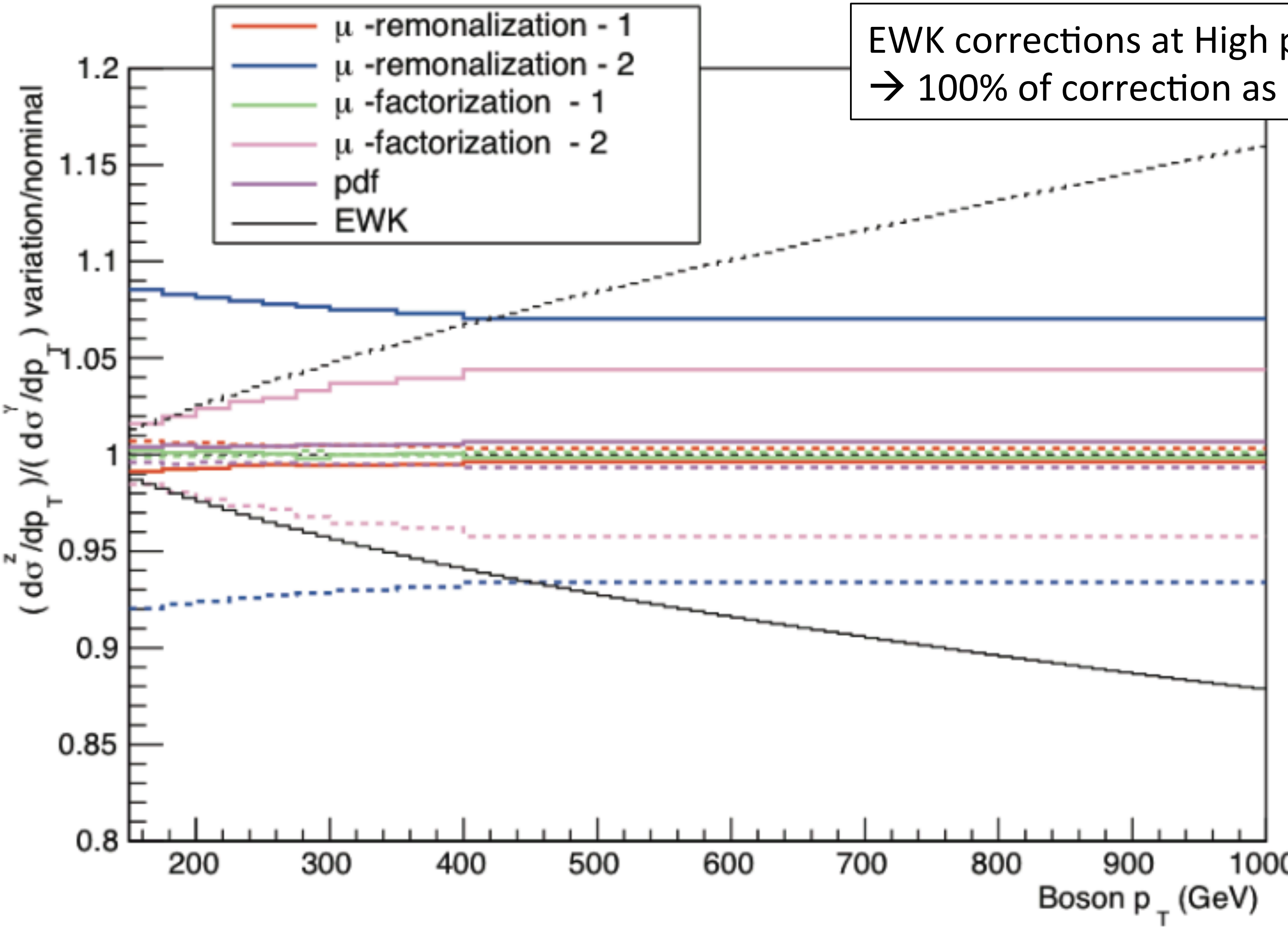
CMS Monojet+mono-V (EXO-12-055)

Simultaneous multi binned likelihood fit to 3 Control Regions (photon, muon, dimuon) (example, monojet category)





Corrects both shape and normalisation of V+jets backgrounds



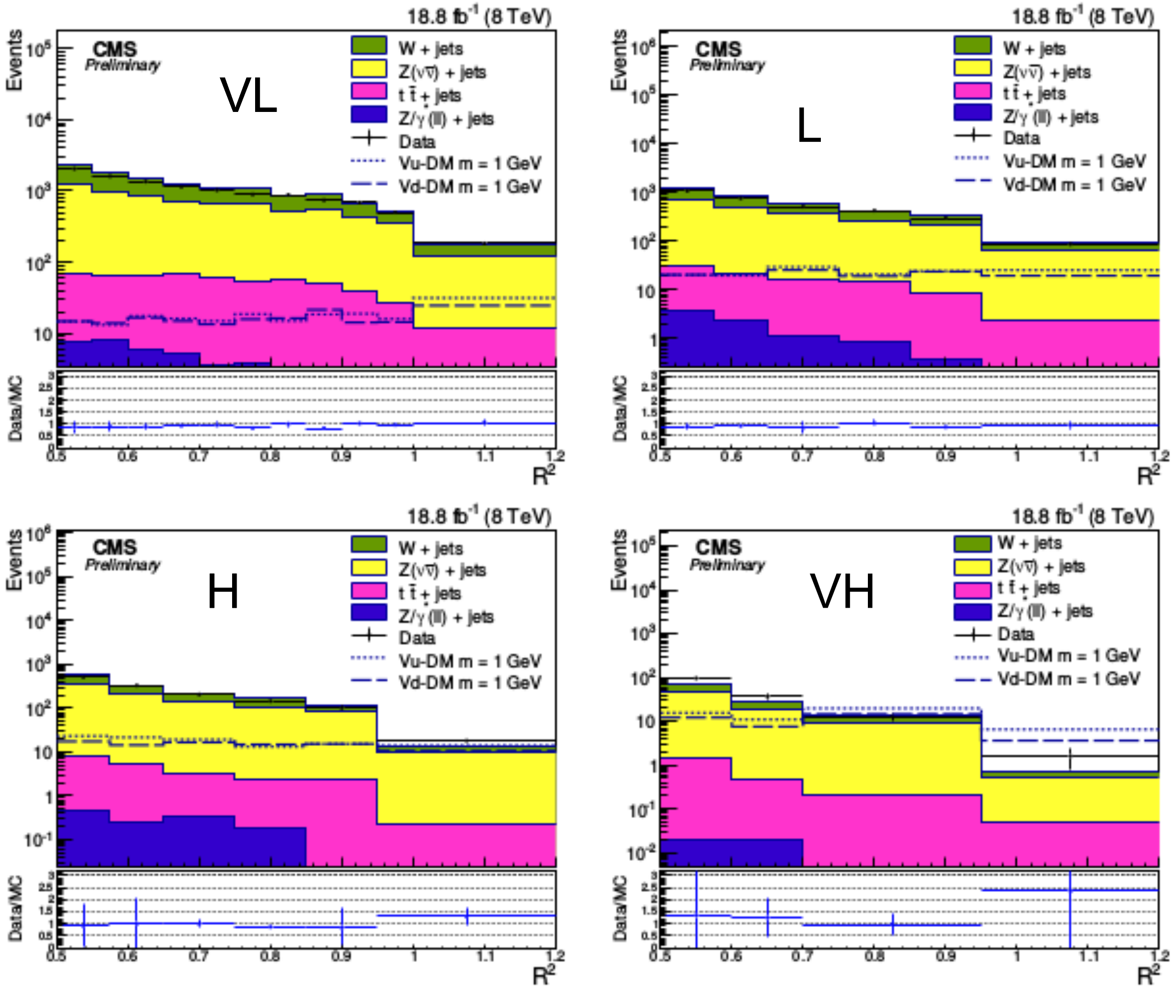
EWK corrections at High pT are large!
→ 100% of correction as uncertainty

CMS Razor

Categorise events based on MR variable

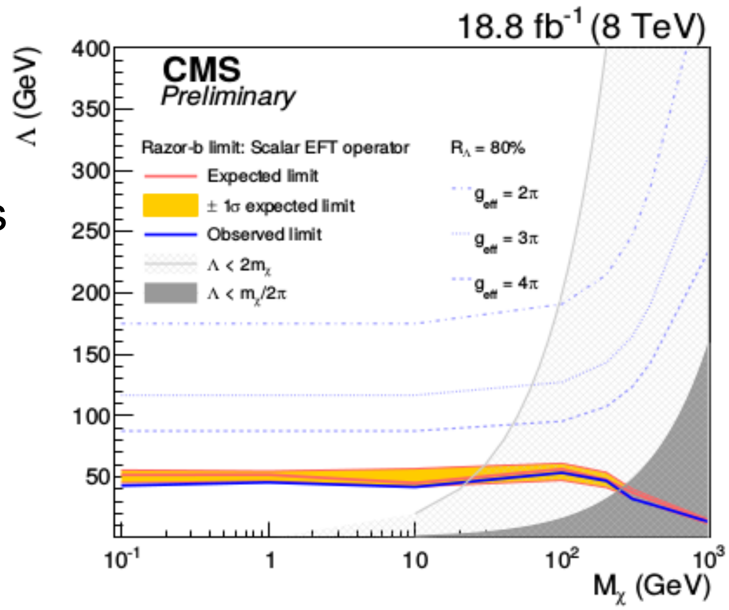
Table 2: Definition of the event categories based on the M_R value, the muon multiplicity, and the output of the CSV b-tagging algorithm. For all the samples, $R^2 > 0.5$ is required.

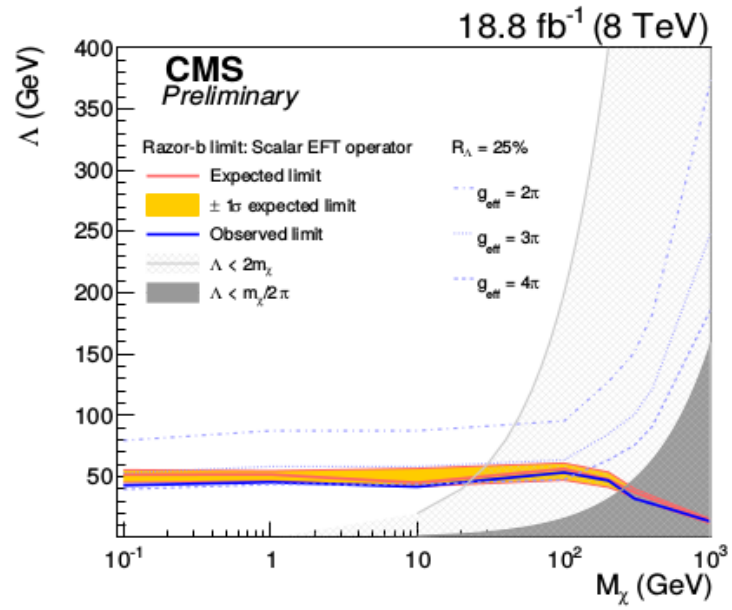
Sample	b-tagging selection	M_R selection
0μ, 1μ, and 2μ	no CSV loose jet	$200 < M_R \leq 300$ GeV (VL) $300 < M_R \leq 400$ GeV (L) $400 < M_R \leq 600$ GeV (H) $M_R > 600$ GeV (VH)
$0\mu bb$	≥ 2 CSV tight jets	$M_R > 200$ GeV
$0\mu b$	=1 CSV tight jets	
$1\mu b$	≥ 1 CSV tight jets	
$2\mu b$		
$Z(\mu\mu)b$	≥ 1 CSV loose jets	



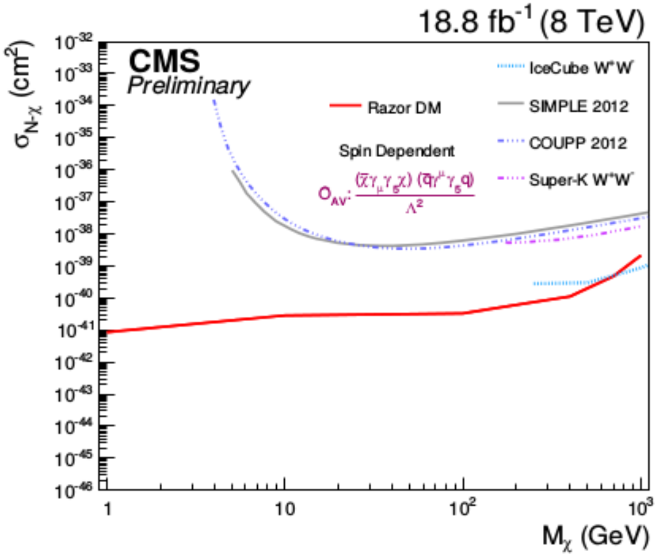
Events with >2 reconstructed jets are included by forming 2 "megajets" (sum jet 4-momenta) to calculate Razor variables

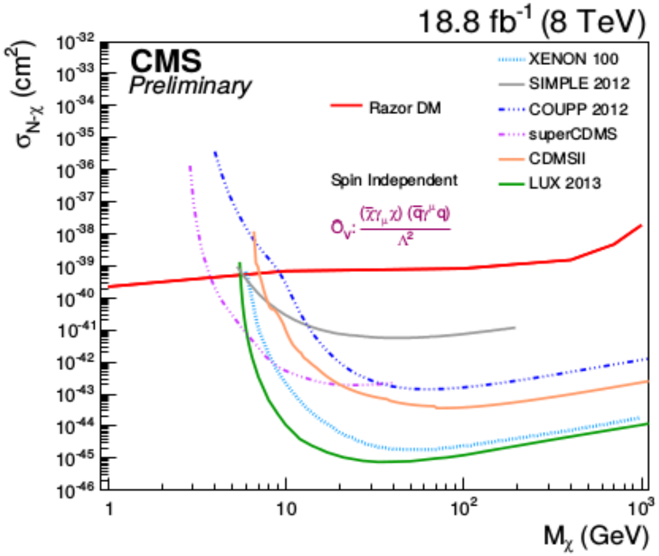
B-tagging brings sensitivity in scalar/pseudo-scalar models





V/A Comparison to Direct Detectors





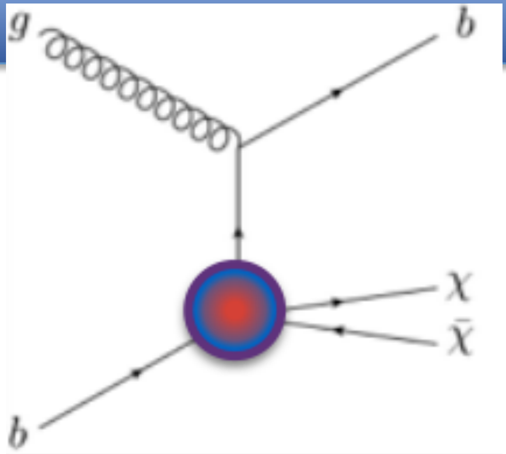
$$\sigma^{SD}_{N-\chi} = 0.33\frac{\mu^2}{\pi\Lambda^4_{LL}},$$

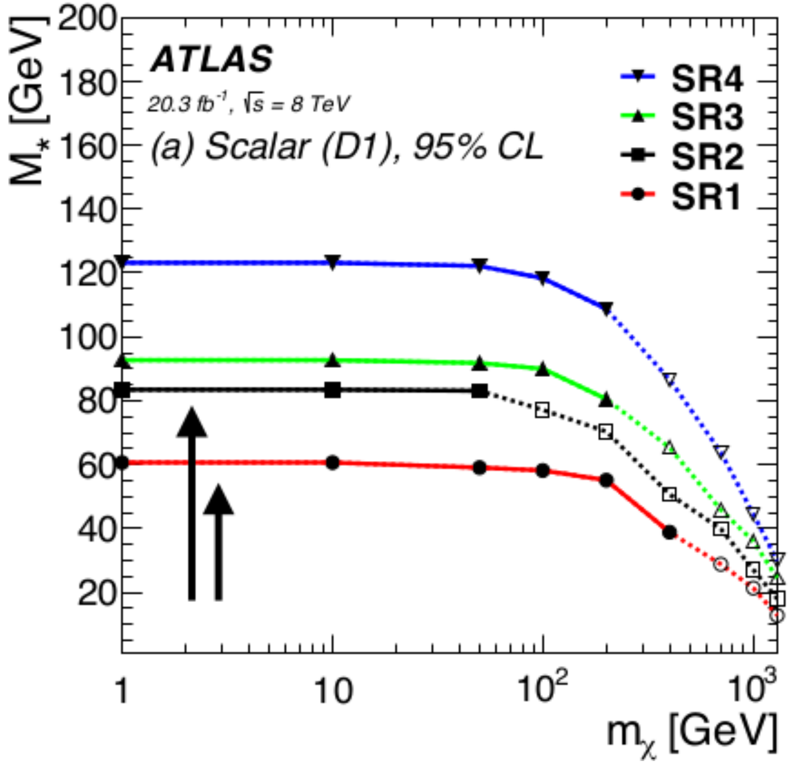
$$\sigma^{SI}_{N-\chi} = 9\frac{\mu^2}{\pi\Lambda^4},$$

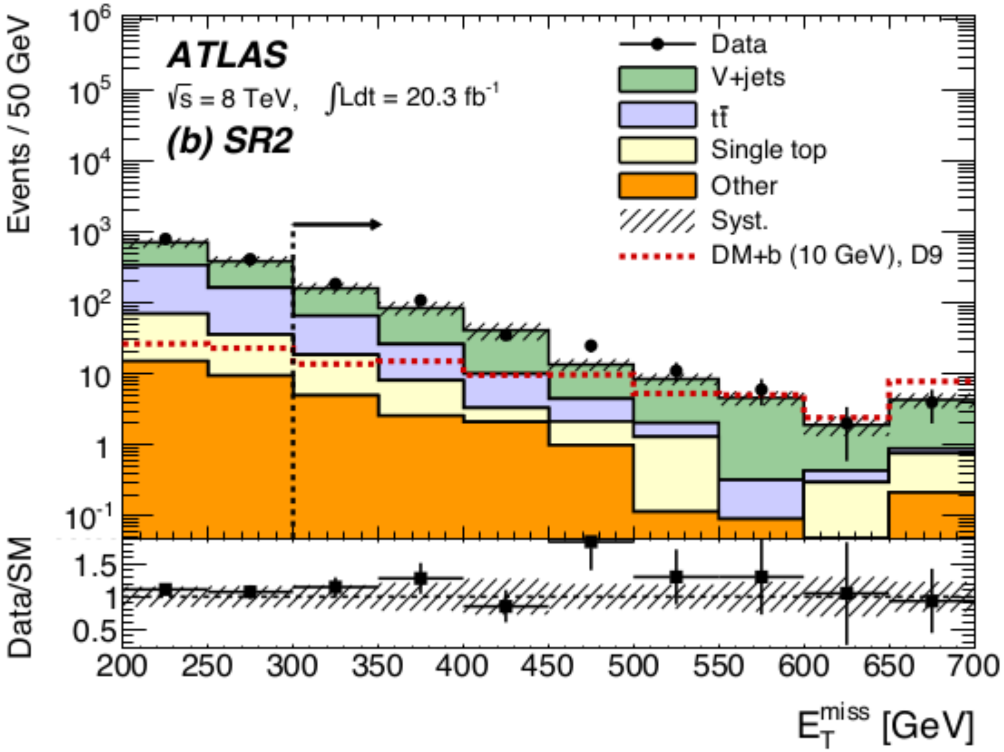
$$\mu = \frac{M_\chi M_p}{M_\chi + M_p},$$

ATLAS mono-b search

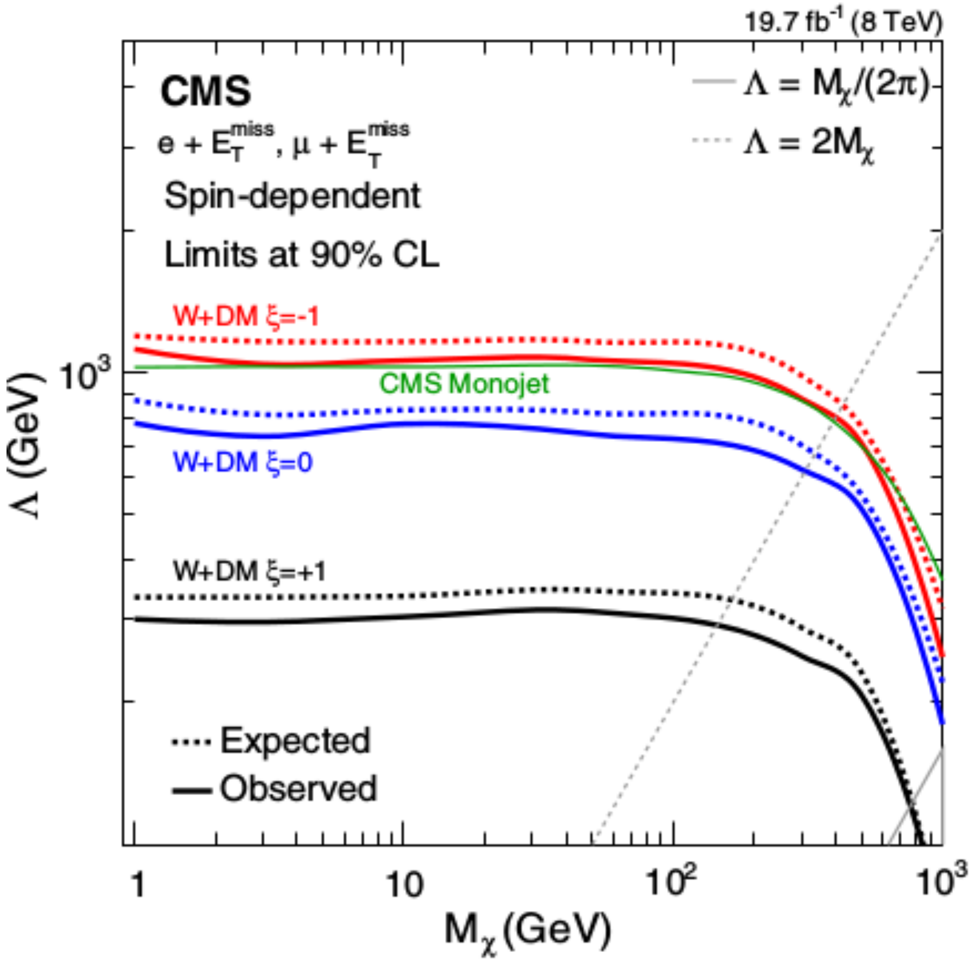
Single b-tagged category
→ search sensitive to b-FDM model



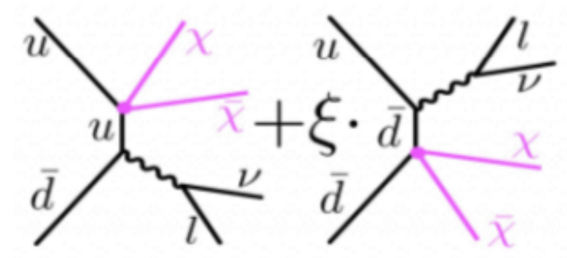




Comparison of mono-V analyses



Improved sensitivity in models interference in couplings to up/ down quarks



not particularly favoured model since potentially violates gauge invariance*

*arxiv.org/abs/1503.07874

Cross-section scaling 13 TeV/ 8 TeV(monojet)