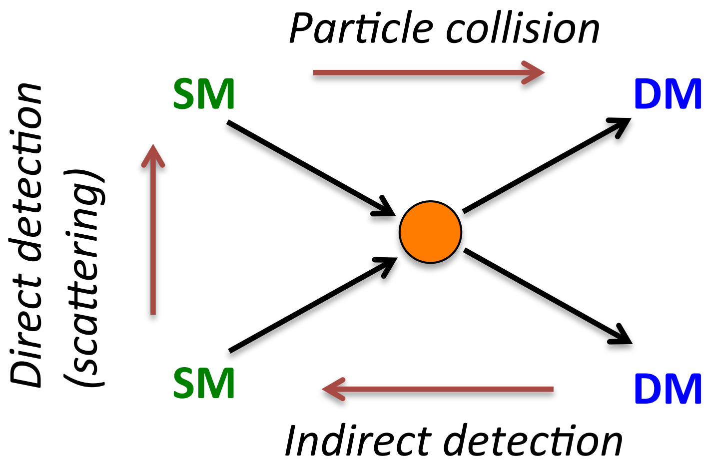
Summary of DM searches in CMS

LHC DM Working Group
10/12/2015

Nicholas Wardle

Dark Matter Madness

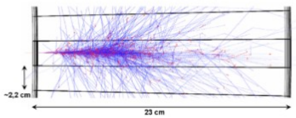
- ✧ Strong evidence of physics beyond the Standard Model
- ✧ We know very little about the nature of DM (gravitational interaction but what else?)
- ✧ If DM talks to SM particles (eg WIMPs) we can detect it via…



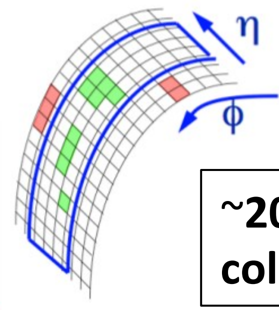
Increasing interest in dark matter (DM) searches at the LHC

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

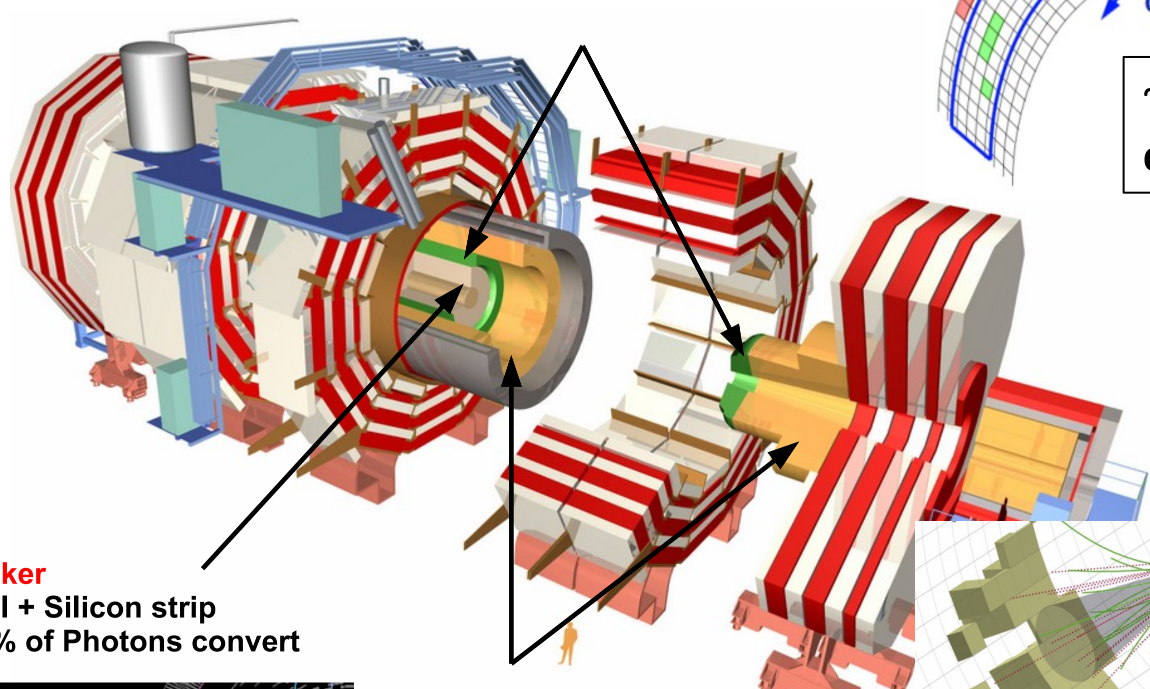
Run-1 a huge success for CMS and the LHC!

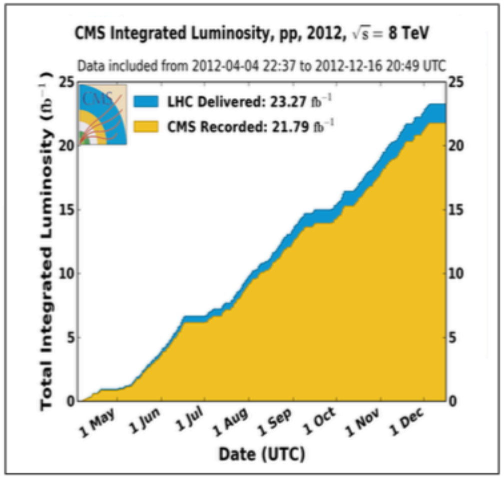


EM Calorimeter
Lead tungstate (PbWO4) crystals
61 200 (EB) / 7 324 (EE)

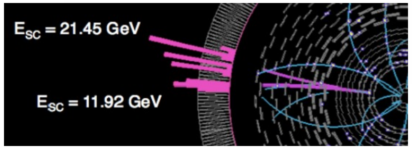


~20(5) fb-1 pp collisions collected at sqrt(s) = 8 (7) TeV

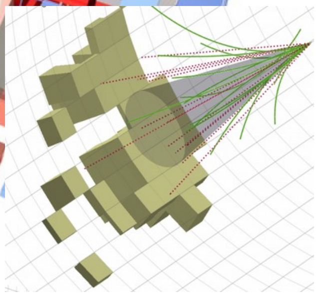




Tracker
Pixel + Silicon strip
~50% of Photons convert



Hadron Calorimeter
Scintillating Brass
Exploit jets from VBF production



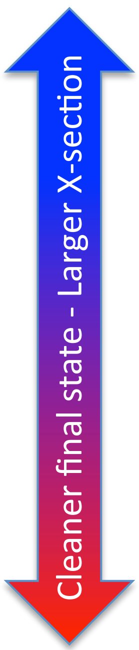
Mono-Mania (MET+X)

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

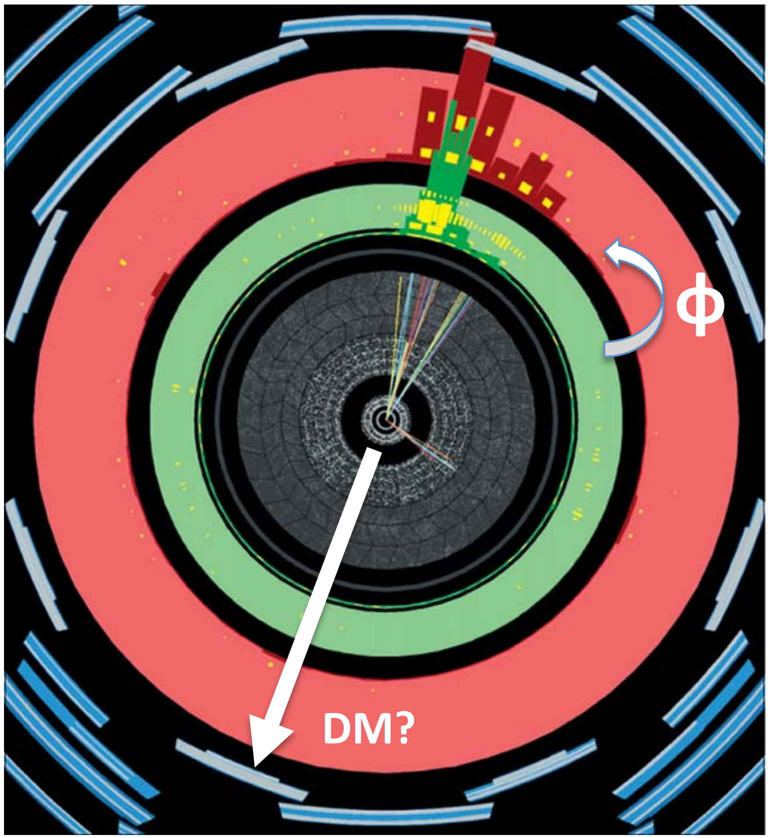
Search for an abundance of events with an imbalance of energy in the transverse plane

Look for additional particles recoiling against DM particles.

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

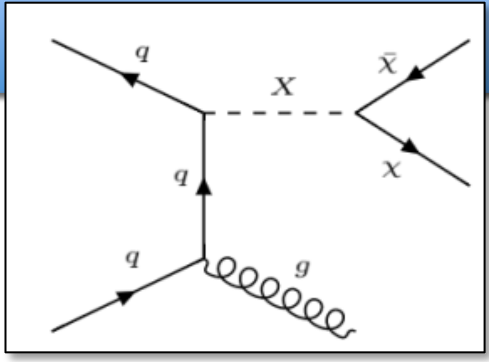


- ✧Jet + E_T^{miss}
- ✧W/Z (→lep/jet) + E_T^{miss}
- ✧t/b + E_T^{miss}
- ✧γ + E_t^{miss}
- ✧H + E_T^{miss}



**NB// also many SUSY searches cover DM but not covered here*

Monojet



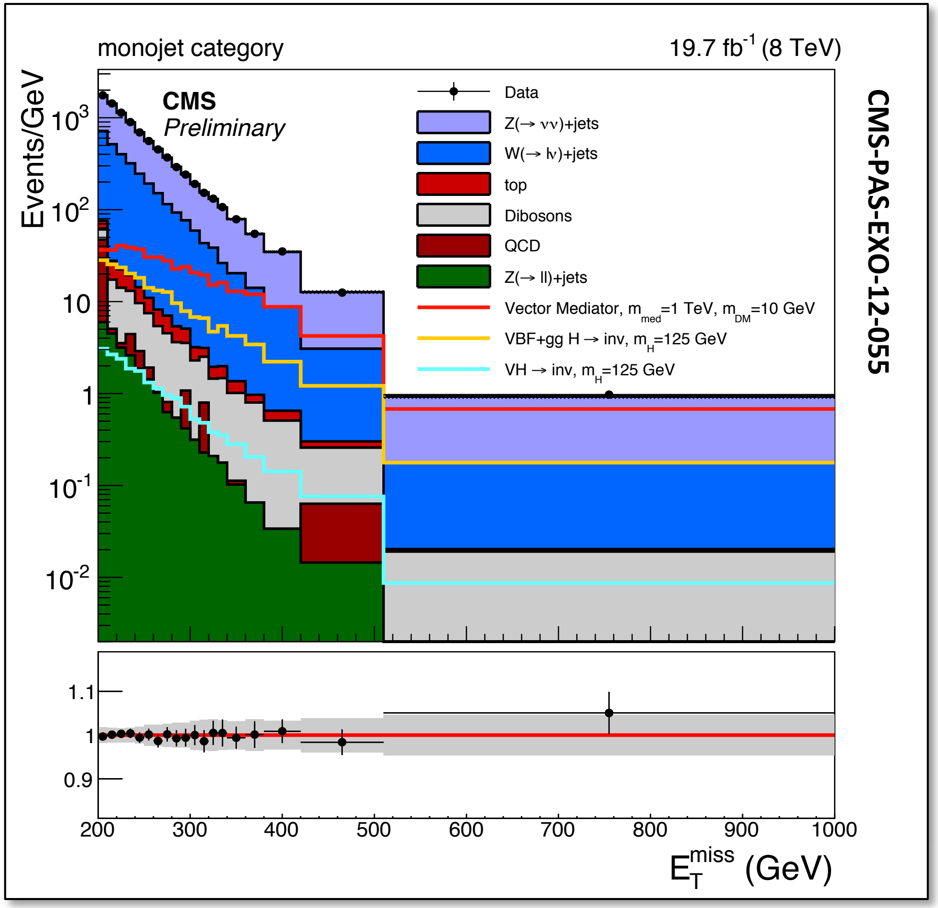
High-momentum jet, from initial state radiation (ISR), recoils against DM

- ✧ 1 central jet with high p_T > 150 GeV, $|\eta|<2$ with $\Delta\phi(j,E_T^{miss}) > 2$
- ✧ 2^{nd} jet allowed provided if $\Delta\phi(j_1,j_2) < 2$
- ✧ Veto leptons photons with p_T>10 GeV and taus with p_T>15 GeV

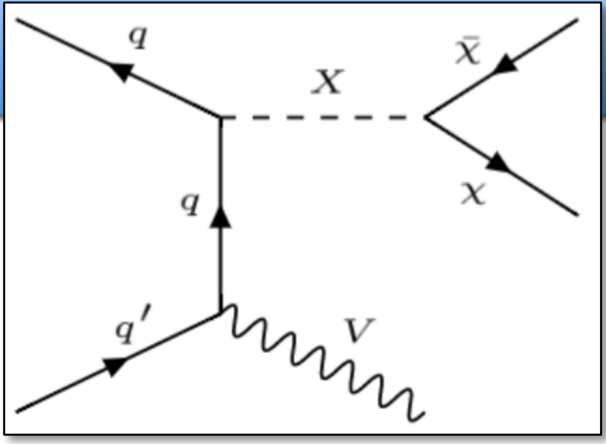
Signal extraction from fit using multiple bins in E_T^{miss}

Dominant backgrounds from Z(νν)+jets and **W(lν)+jets**

→ Estimate the contributions with data using Z→ll +jet, γ+jet and **W→lν +jet** events



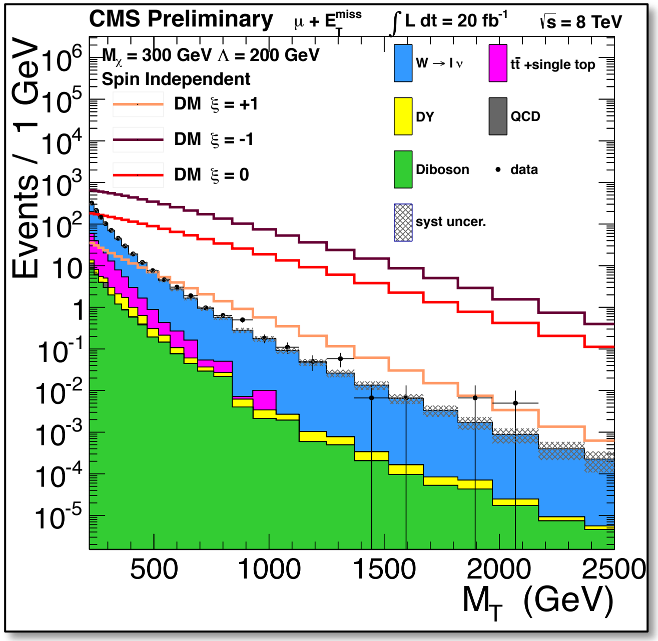
Mono-V (leptonic)



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

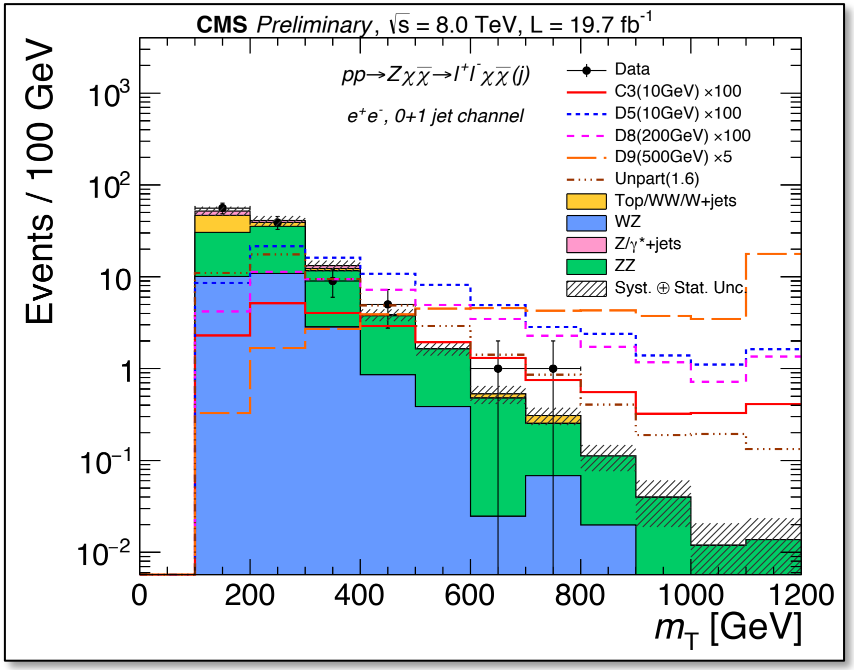


$W(l\nu) + E_T^{miss}$

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

$Z(ll) + E_T^{miss}$

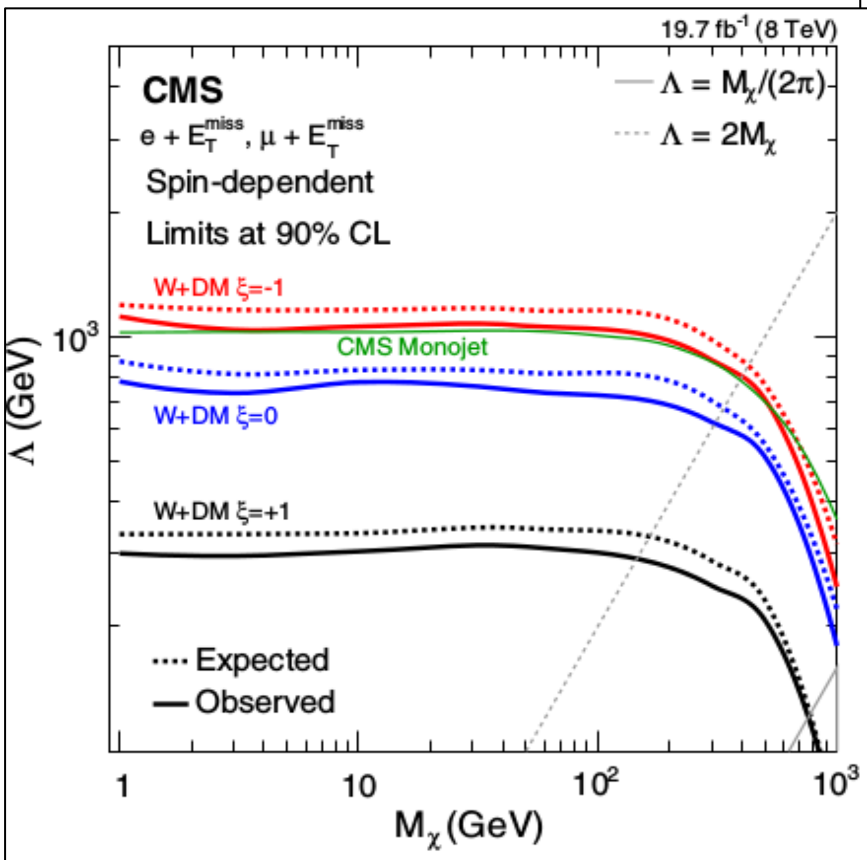
- Look for 2 opposite-charge, same-flavor leptons
- Invariant mass consistent with Z boson $|m_{ll}-m_Z| < 10$ GeV
- Look for excess in m_T spectrum

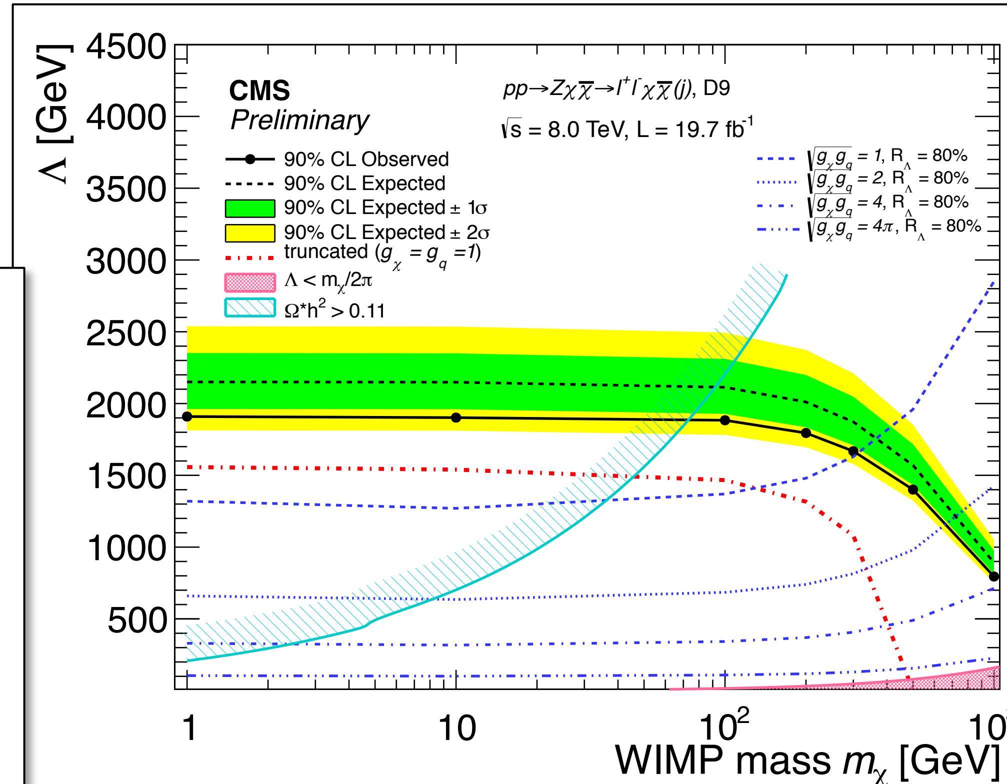


CMS-PAS-EXO-12-054

Mono-V (leptonic)

Interpret in terms of lower limit on new physics scale **(Λ)** as a function of **DM mass**

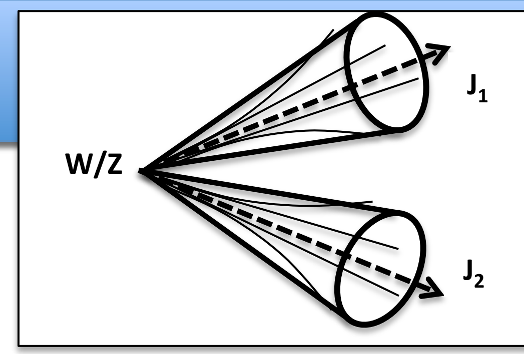




✧ Increased sensitivity to models with enhanced couplings to vector bosons

✧ Need to consider regions of Validity for EFT approach (eg via truncation)

Mono-V (Hadronic)



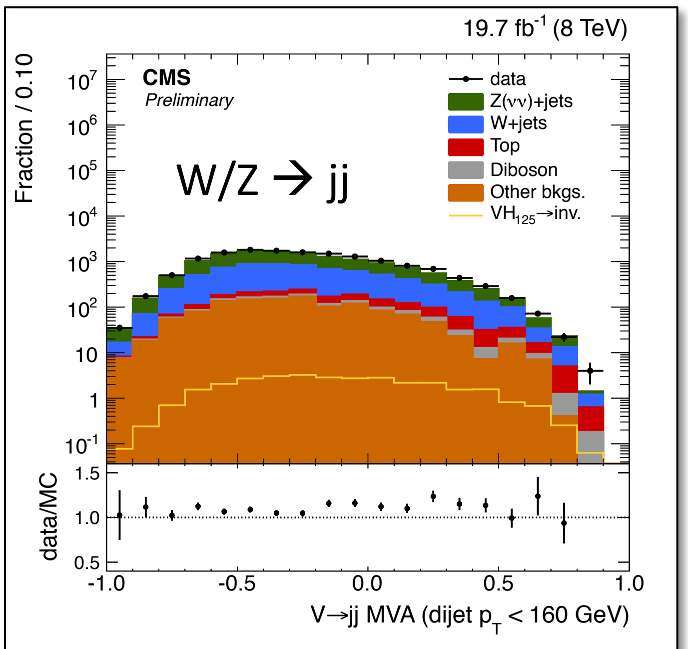
Low p_T W or Z bosons decay to well separated jets (fully reconstructed)

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]

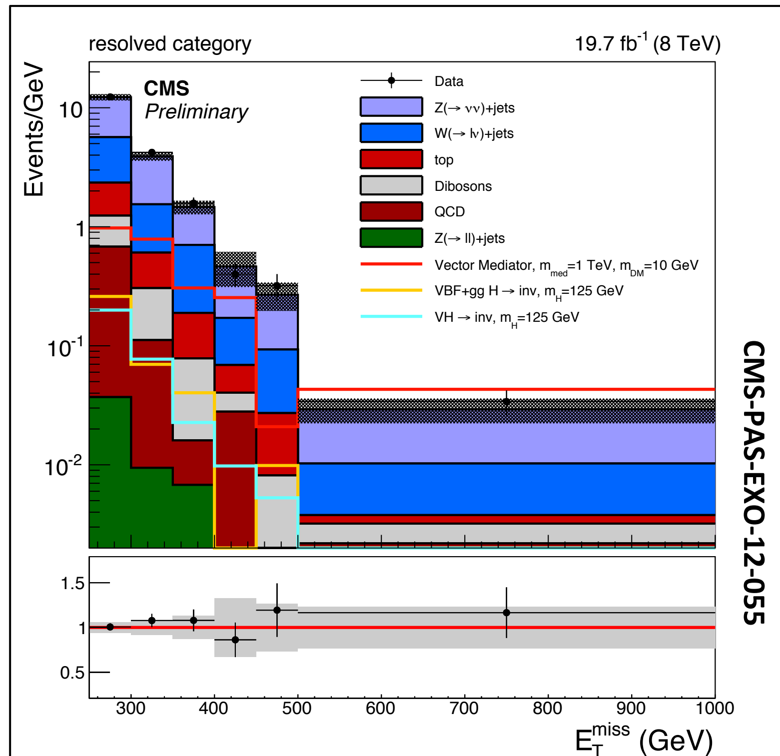
Combine into multivariate discriminator



[2] PRL.114.041802

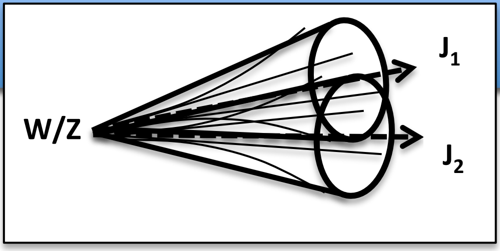
[1] arXiv:1001.5027

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



CMS-PAS-EXO-12-055

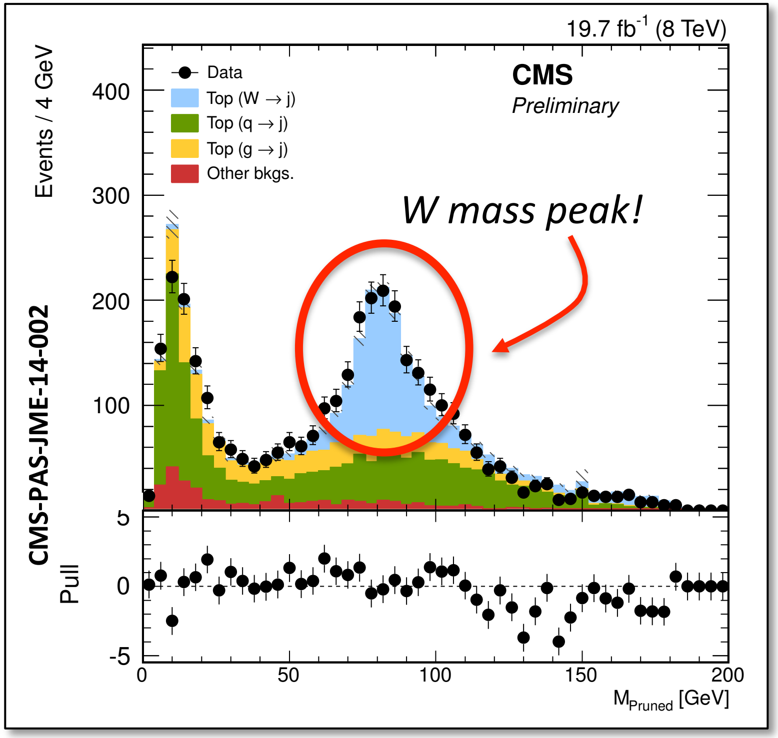
Mono-V (Hadronic)

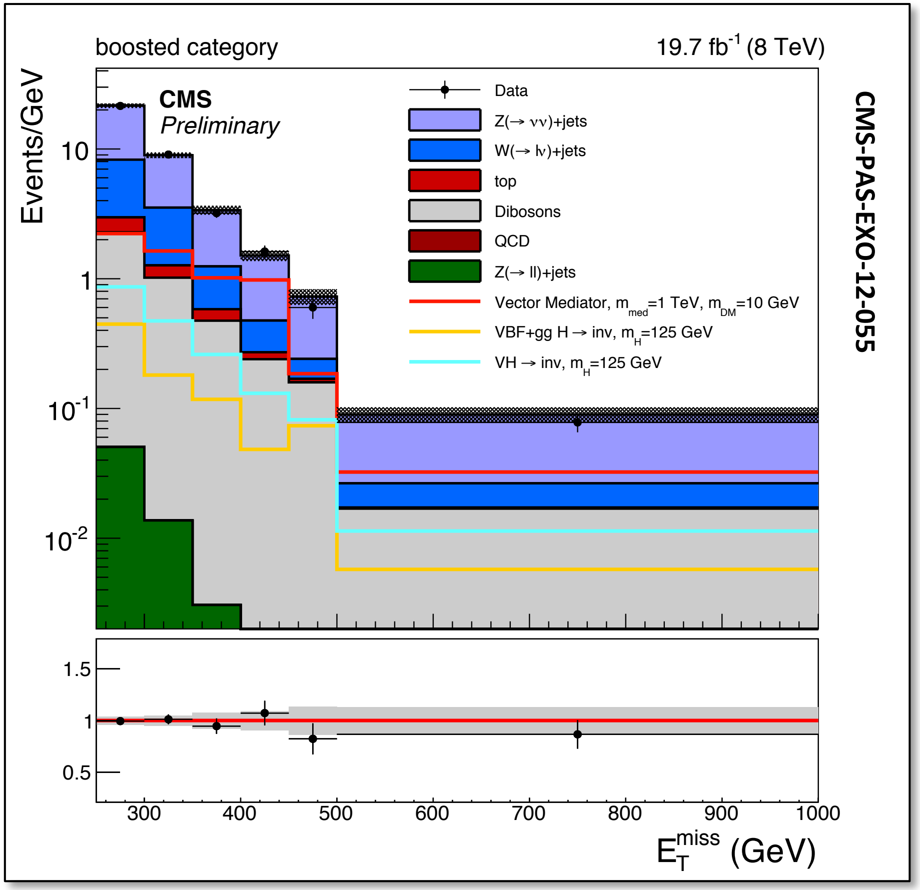


Boosted (high p_T) vector bosons decaying to jets will form a single "fat"-jet

Jet substructure techniques to identify V-bosons:

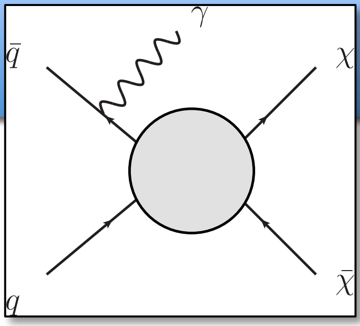
- Look for high-p_T fat jet with $\mathbf{m_J}$ close to m_W or m_Z
- N-subjettiness **(τ_N)** (likelihood for N-daughter hypotheses of lead jets to tag as having originated from a W or Z boson.
- Use (di)-lepton and photon CR to determine W(l) and Z(νν) bkgs





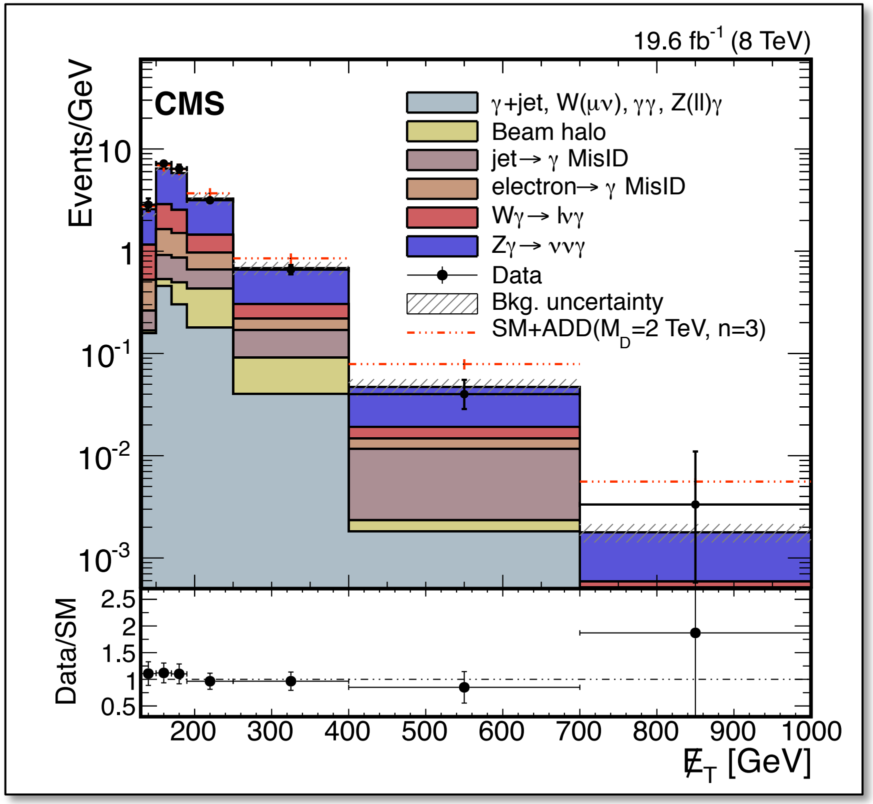
Mono-photon

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

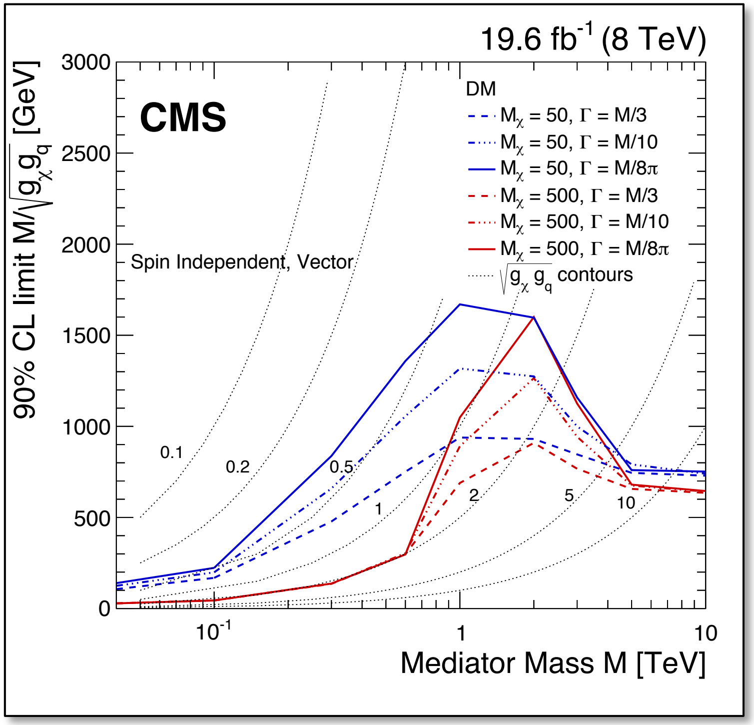


- One high energy, isolated photon, E_T>145
- E_T^{miss} > 140 GeV
- Reject events with overlapping photon and E_T^{miss} ($\Delta\phi(\gamma,E_T^{miss})$<2)

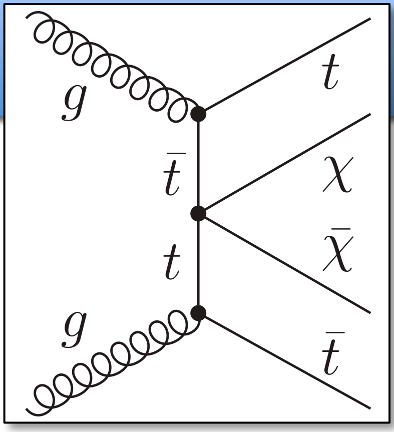
CMS-PAS-EXO-12-047 (Sub PLB)



- Largest backgrounds from Wγ/Zγ estimated from lepton CR
- γ+jet background from MC corrected using data-MC scale-factors



Heavy Flavor



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, E_T^{miss} > 320
- ✧ m_T >160 GeV to remove W and tt backgrounds
- ✧ Normalize tt background from data CR

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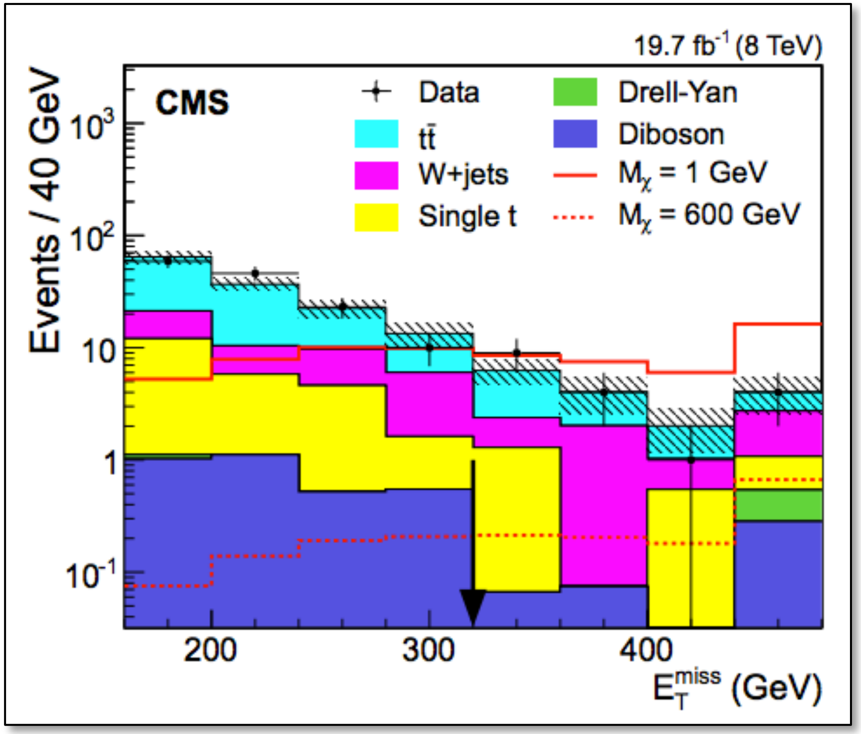
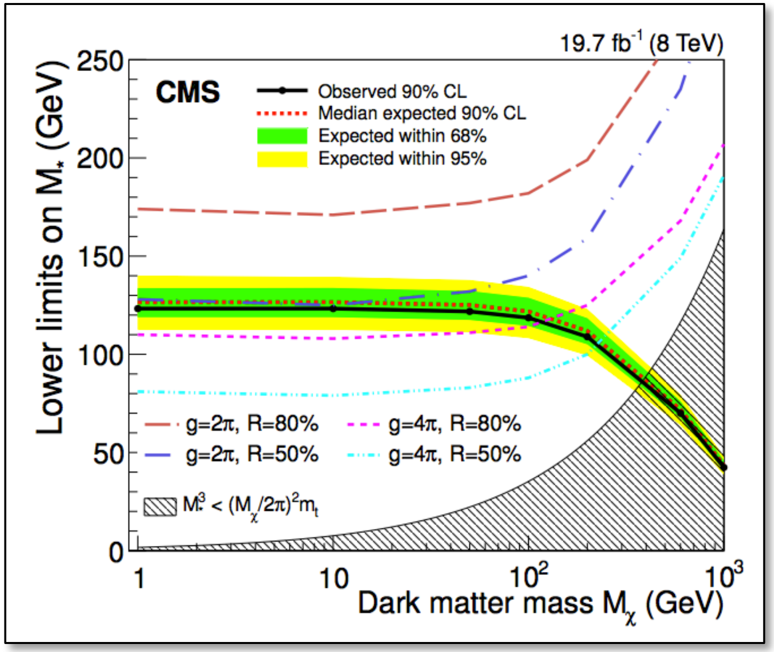




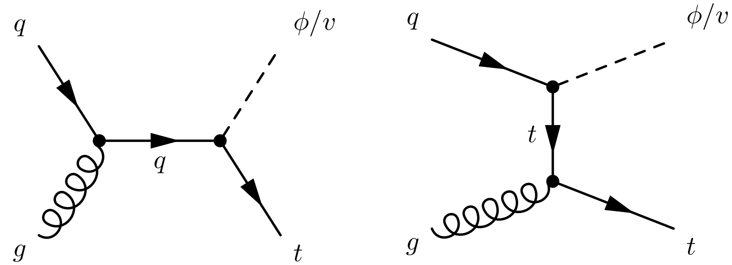
Heavy Flavor

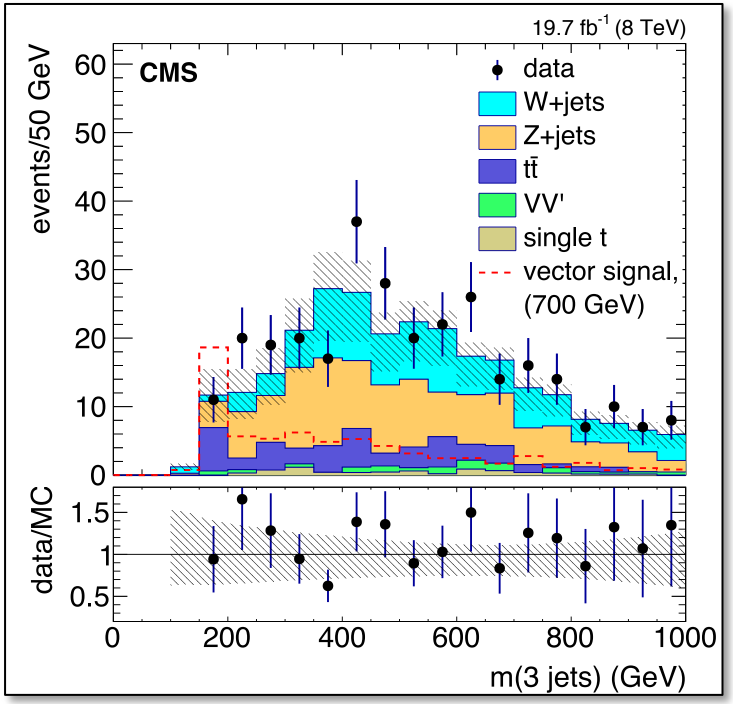
Several BSM models predict single top + E_T^{miss}

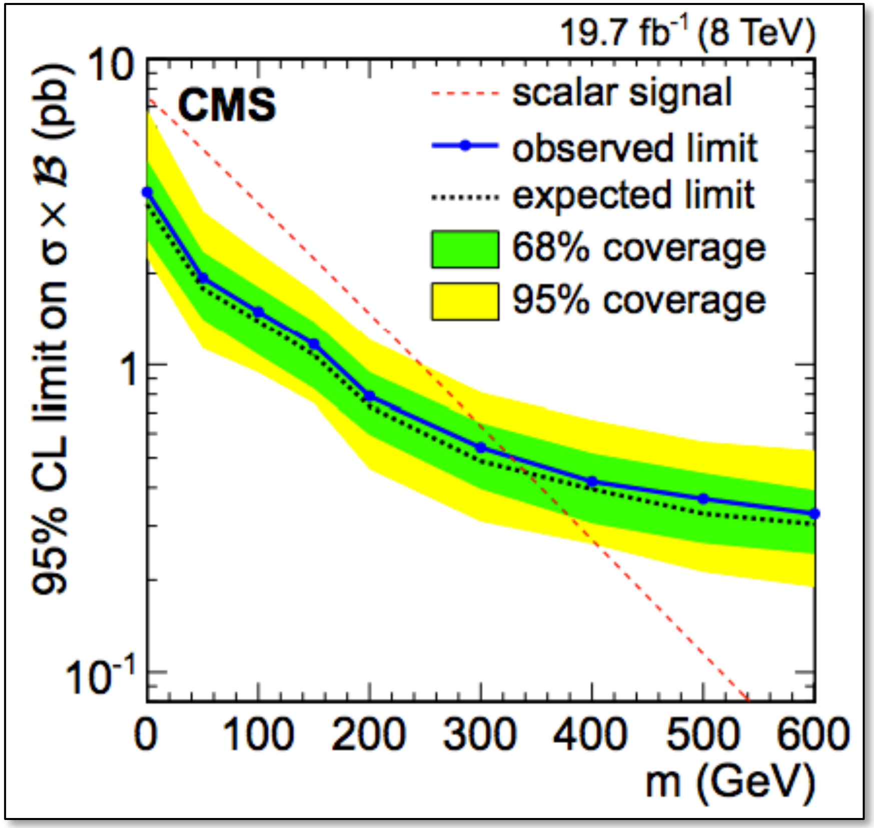
→ Consider resonant and non-resonant production modes

✧ Hadronic final states used for mono-top analysis, veto events with isolated leptons

✧ Cut on invariant mass of 3 jet (top) system < 250 GeV







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

Di-jet/bb + E_T^{miss}

Additional jets produced in association with DM particles

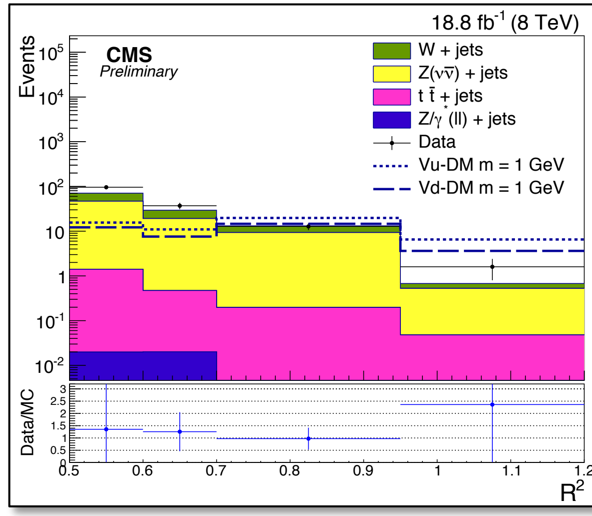
- ✧ Additional information from second jet allows for good discrimination against SM backgrounds (W/Z/tt)
- ✧ Fit ''Razor-variable"

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

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

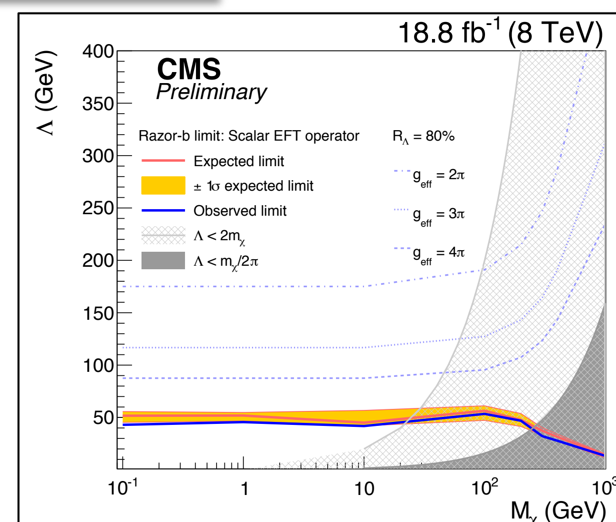
$$R \equiv \frac{M_T^R}{M_R}$$

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

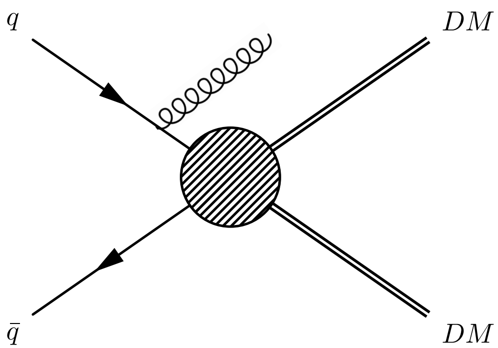
CMS-PAS-EXO-14-004



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

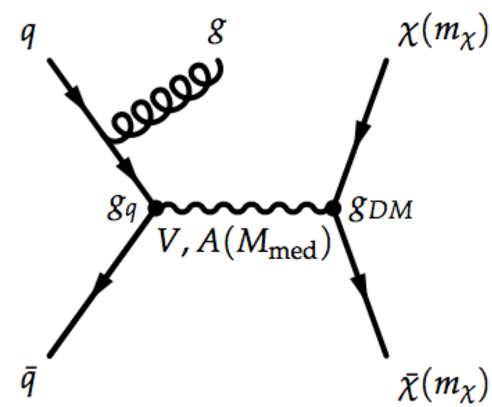
Moving on from EFT(LHC DM forum)

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



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

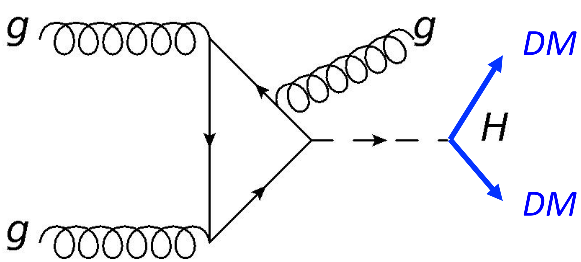
Simplified models capture effects with direct access to mediator → overcome validity issues but more parameters to consider



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

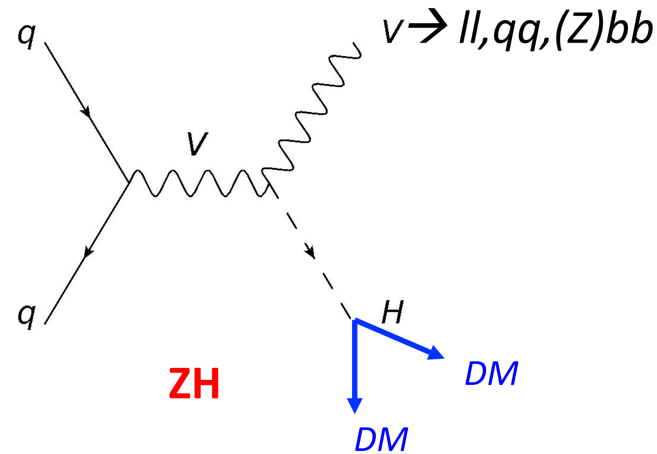
H → Invisibles (concrete scalar model)

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



Gluon-fusion

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



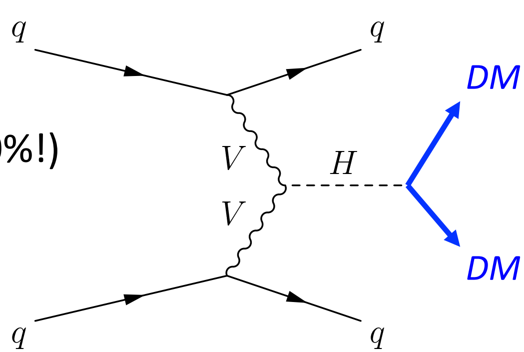
ZH

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

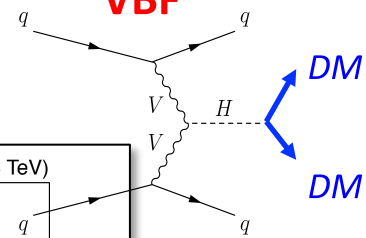


VBF

H → Invisibles

Dedicated Higgs analyses …

VBF



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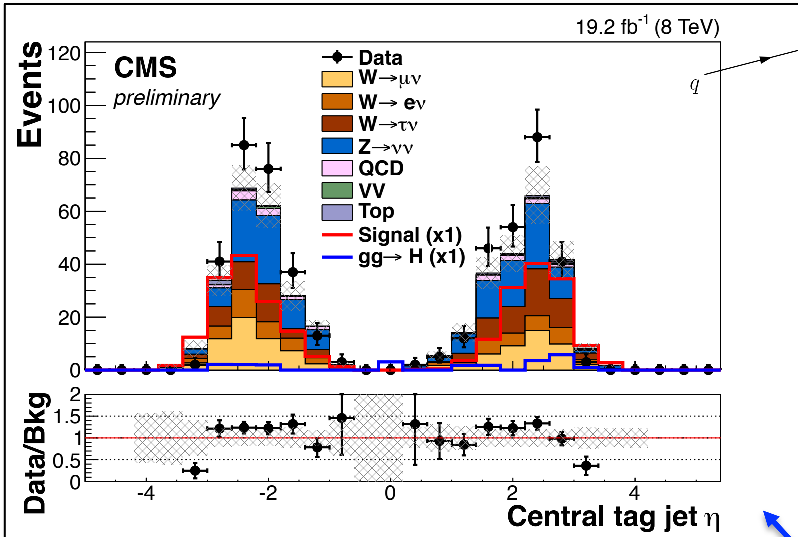
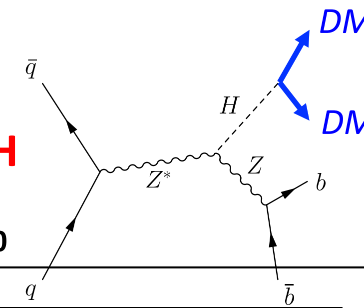


Z(bb)H



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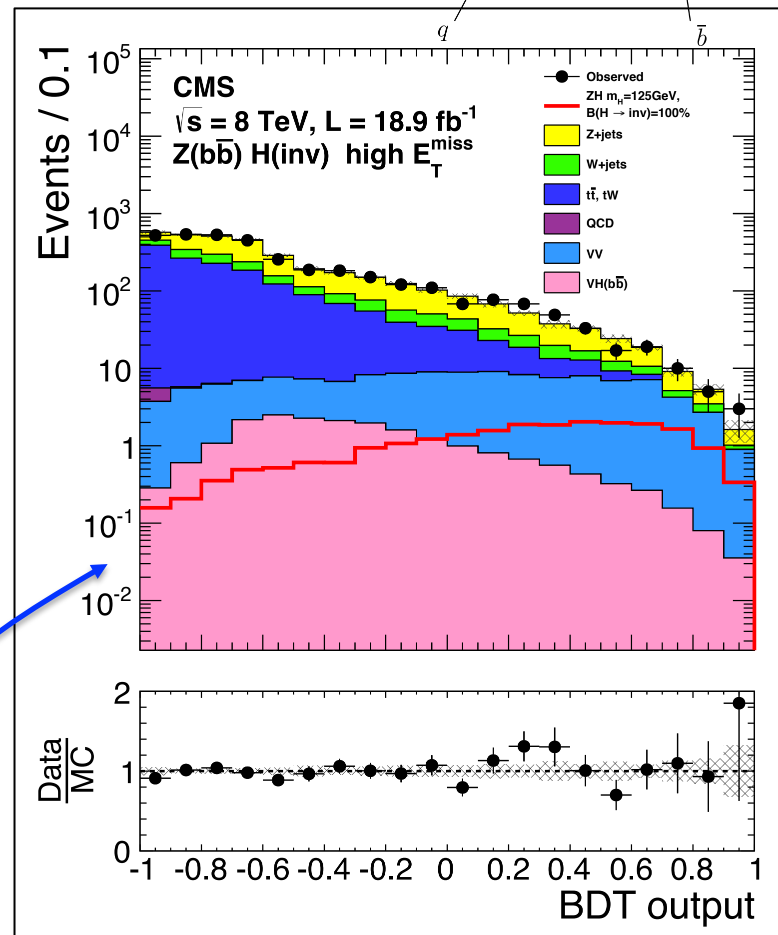


Select VBF-jet kinematics + $E_T^{miss} > 90$ GeV. W→μ,τ,e + ν and Z→μμ CR for bkg estimation. Uses Run-1 parked dataset

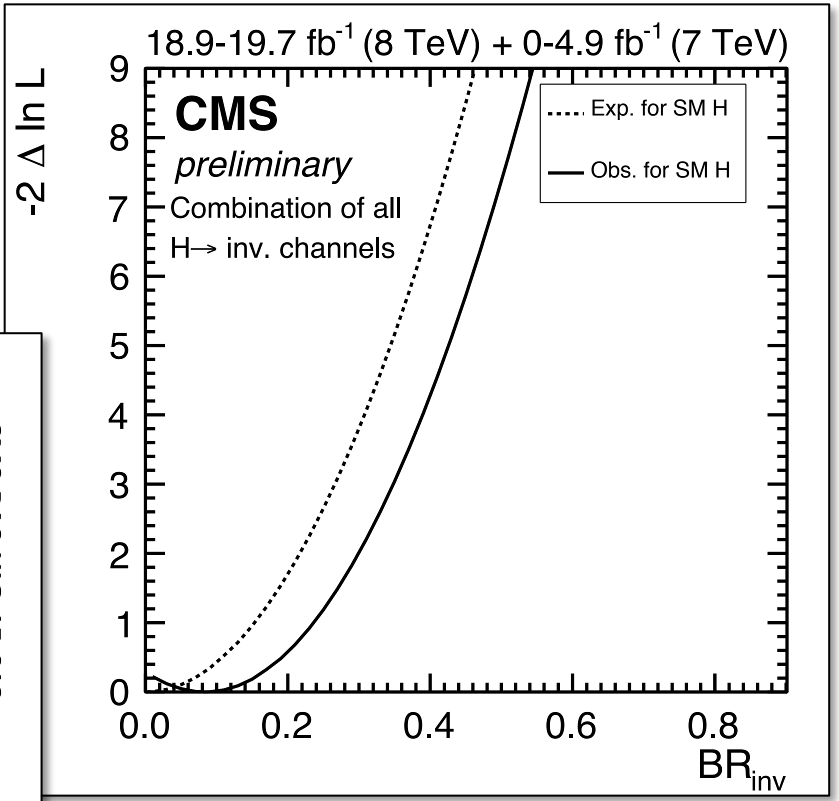
Fit BDT distribution in three E_T^{miss} regions in CMS (b-jet kinematics, secondary vertex information and color flow between b-jets)

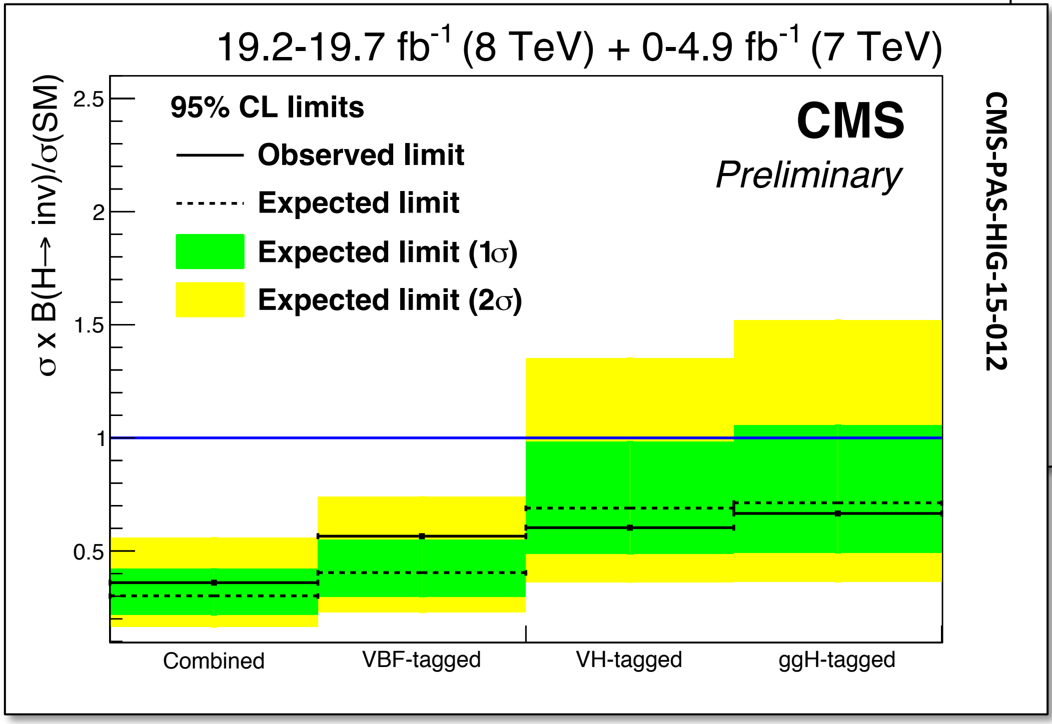
H → Invisibles

Combine several searches and interpret as limits on decay

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

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





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

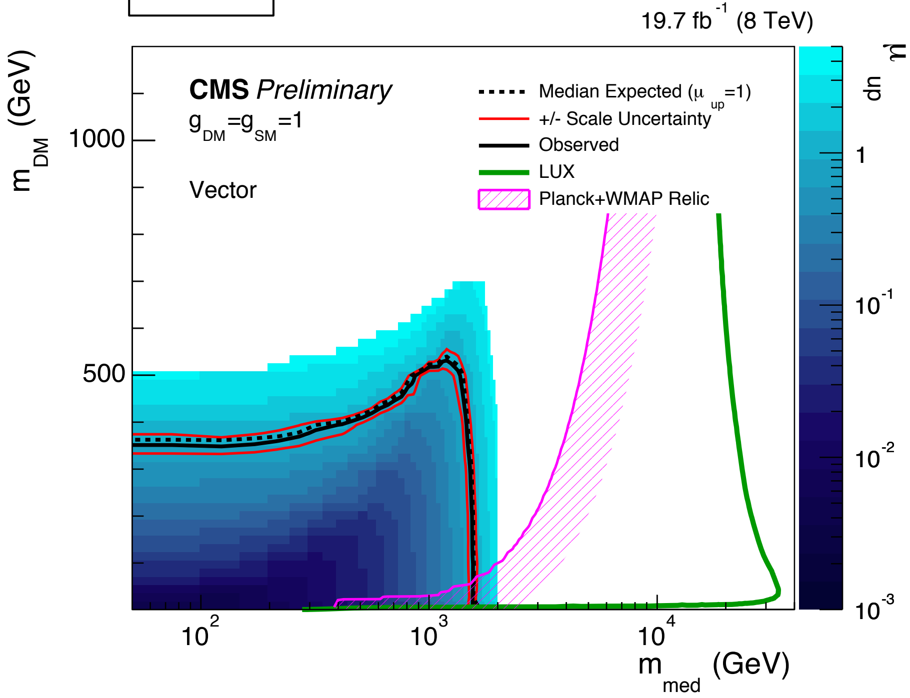
Simplified Model interpretation (CMS-PAS-EXO-12-055)

Combination of monojet + mono-V (hadronic) searches interpreted under simplified model

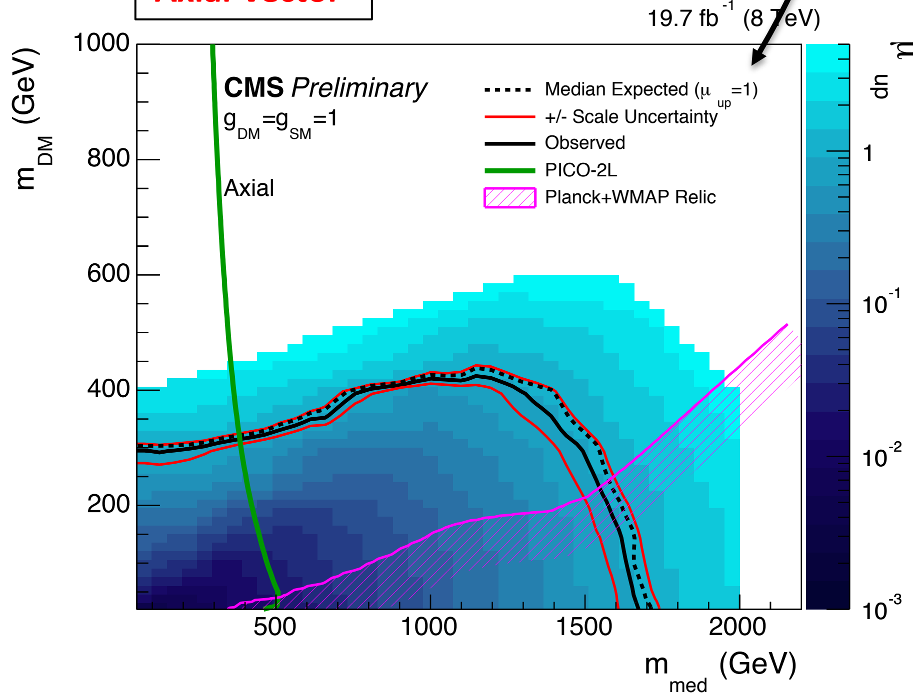
- ✧ Scan mediator and DM masses, Fixing couplings to 1
- ✧ Mediator width (Γ) determined under minimal width assumption (only SM and 1 fermonic DM particle contribute)
- ✧ Comparison to direct detection + Relic constraints (MadDM)

Good complementarity with Relic constraints and direct-detection in axial-vector case

Vector



Axial-vector

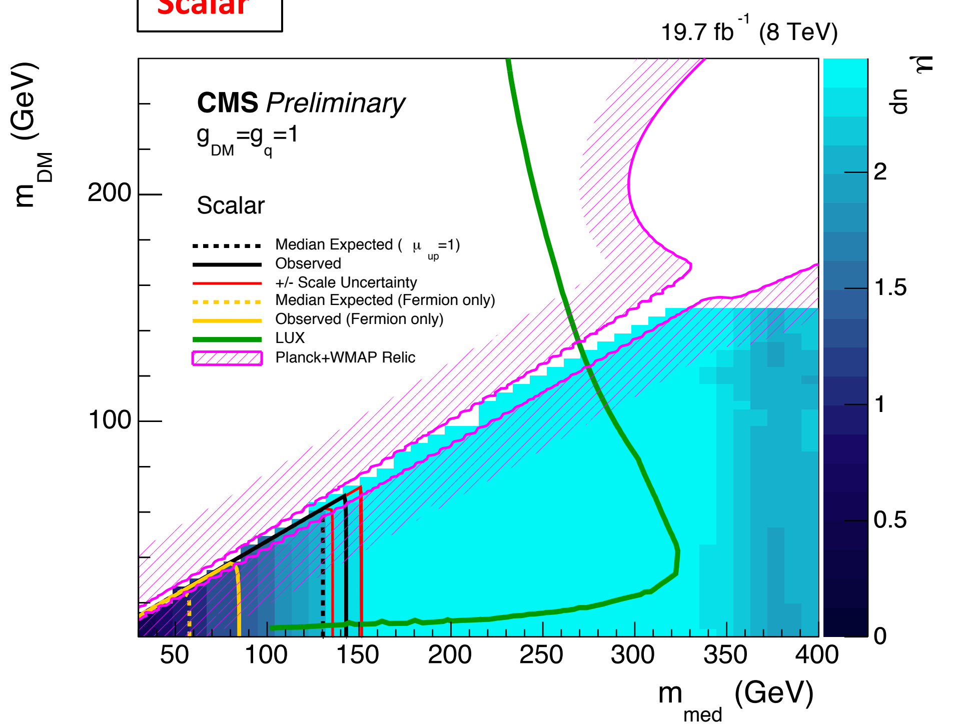


Simplified Model interpretation (CMS-PAS-EXO-12-055)

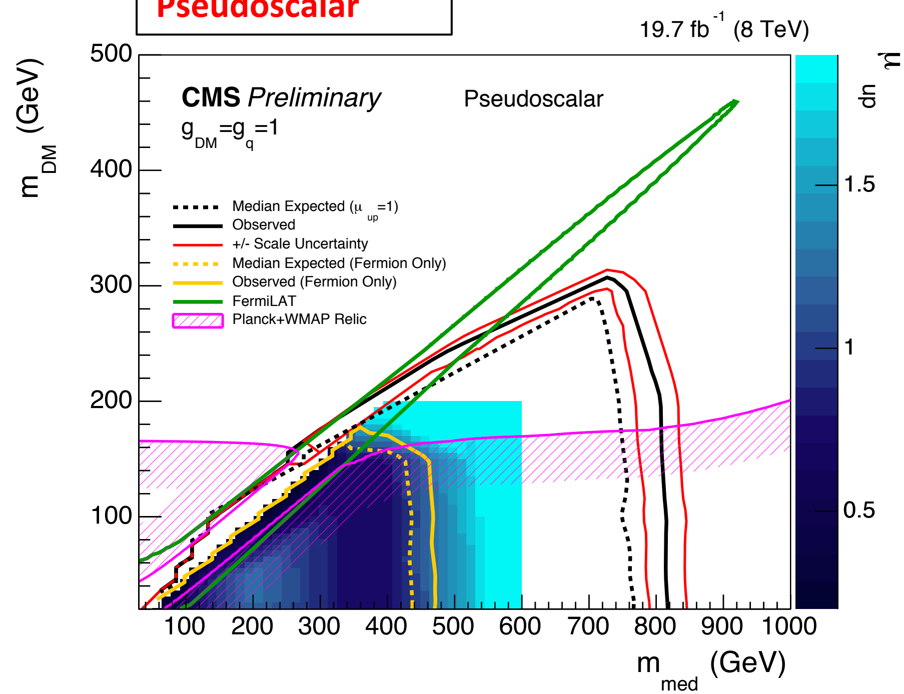
Scalar and pseudo-scalar case * assume Yukawa-couplings to SM $g_{SM} = g_q m_q / v$,

Fermion only scenario assumes no couplings to vector bosons (results in greatly reduced sensitivity for spin-0 mediators)

Scalar



Pseudoscalar



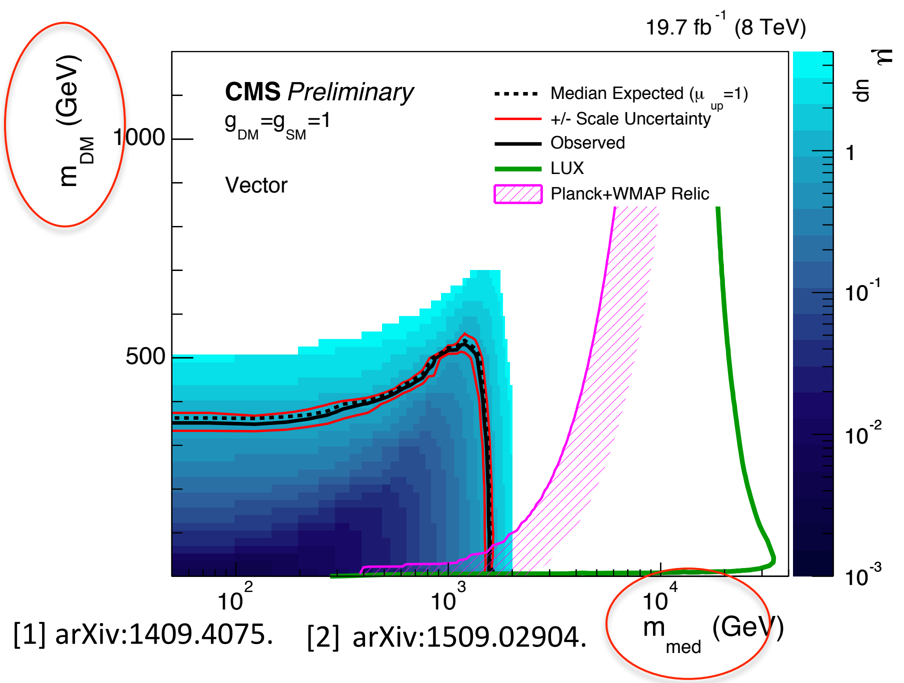
*mono-V topology signal generated with JHUgen

Simplified Model interpretation (CMS-PAS-EXO-12-055)

Comparison to direct-detection in terms of DM-nucleon scattering cross-section vs DM mass planes (comparison on the direct-detections own turf)

→ Re-interpretation of **exclusion contours** in m_{DM}-m_{MED} plane [1,2]

$$\sigma^0_{SI} = \frac{9 g^2_{DM} g^2_{SM} \mu^2_{n\chi} (m_{DM})}{\pi m^4_{med}}$$



$$\mu_{n\chi} = m_n m_{\mathrm{DM}} / (m_n + m_{\mathrm{DM}})$$

[1] arXiv:1409.4075. [2] arXiv:1509.02904.

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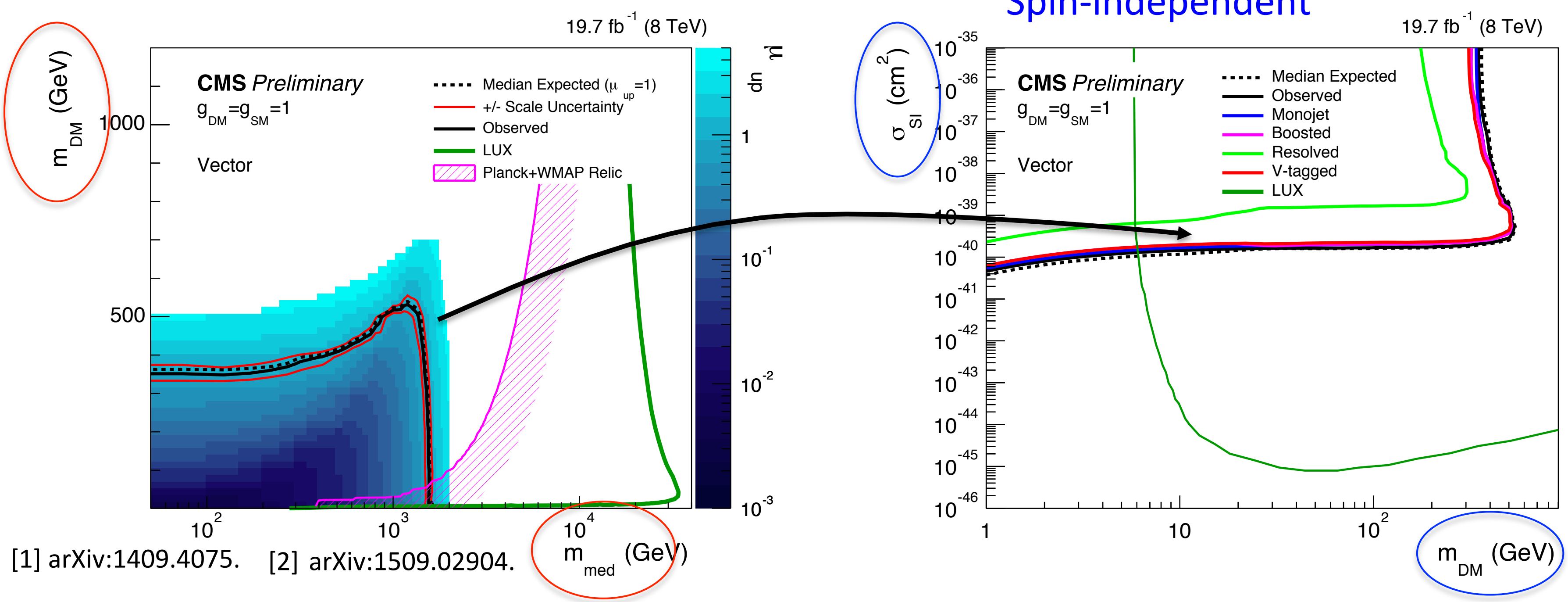
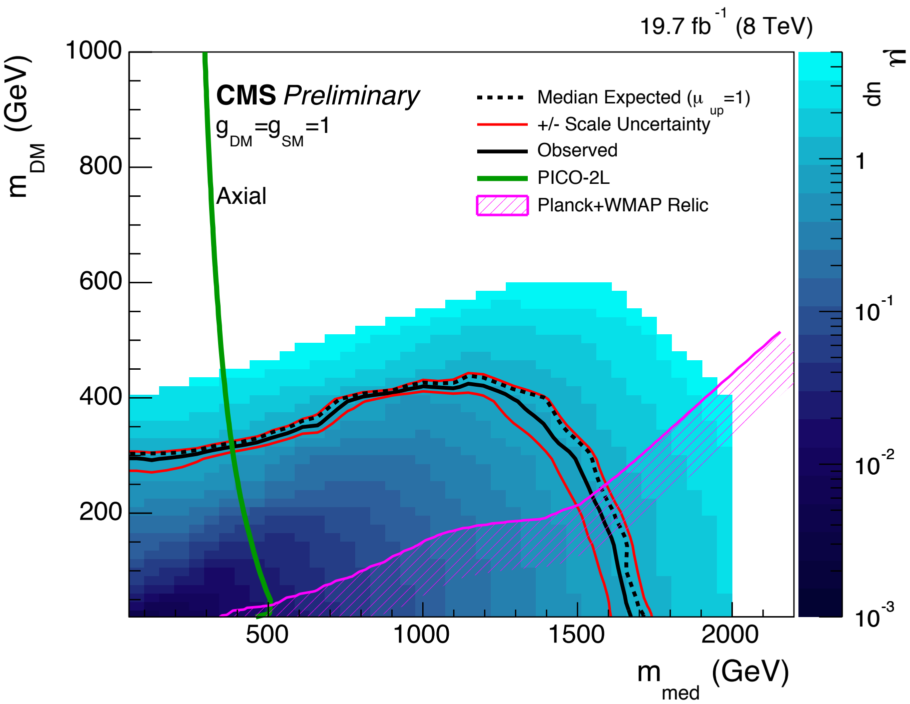
Spin-independent

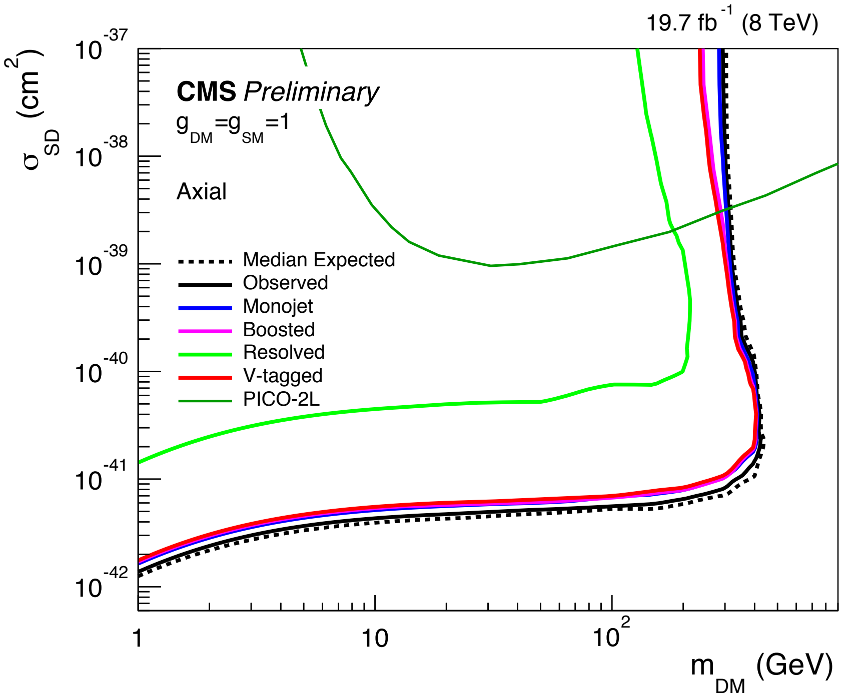


[1] arXiv:1409.4075. [2] arXiv:1509.02904.

Spin-dependent case

$$\sigma^0_{SD} = \frac{3g^2_{DM}g^2_{SM}(\Delta_u + \Delta_d + \Delta_s)\mu^2_{n\chi}(m_{DM})}{\pi m^4_{med}}$$





$\Delta_u = -0.42,\ \Delta_d = 0.85$ and $\Delta_s = -0.08$ **(JHEP 07 (2012) 009)**

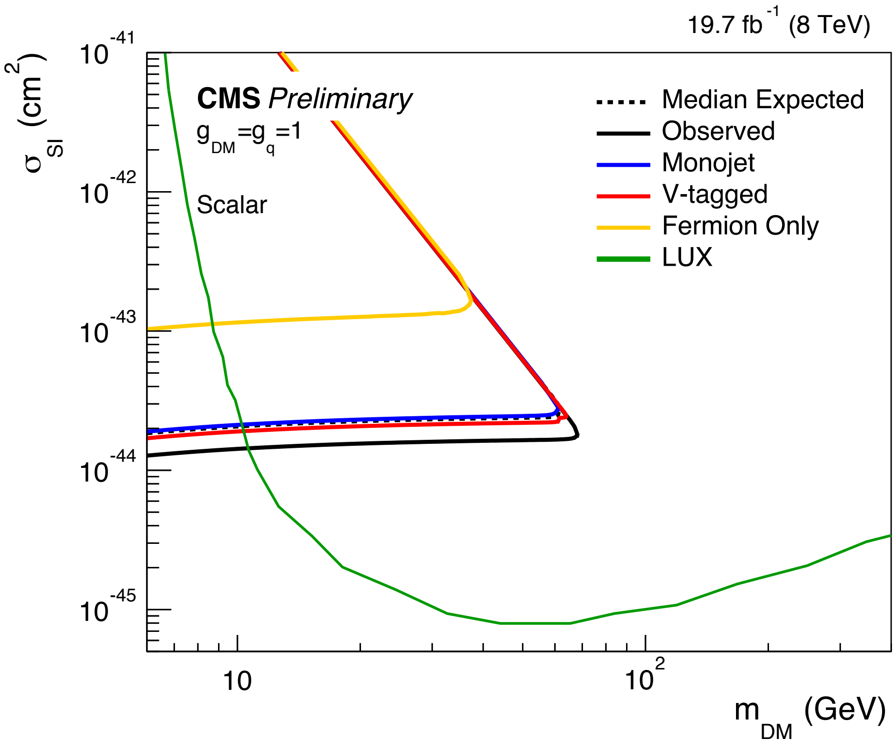
Simplified Model interpretation (CMS-PAS-EXO-12-055)

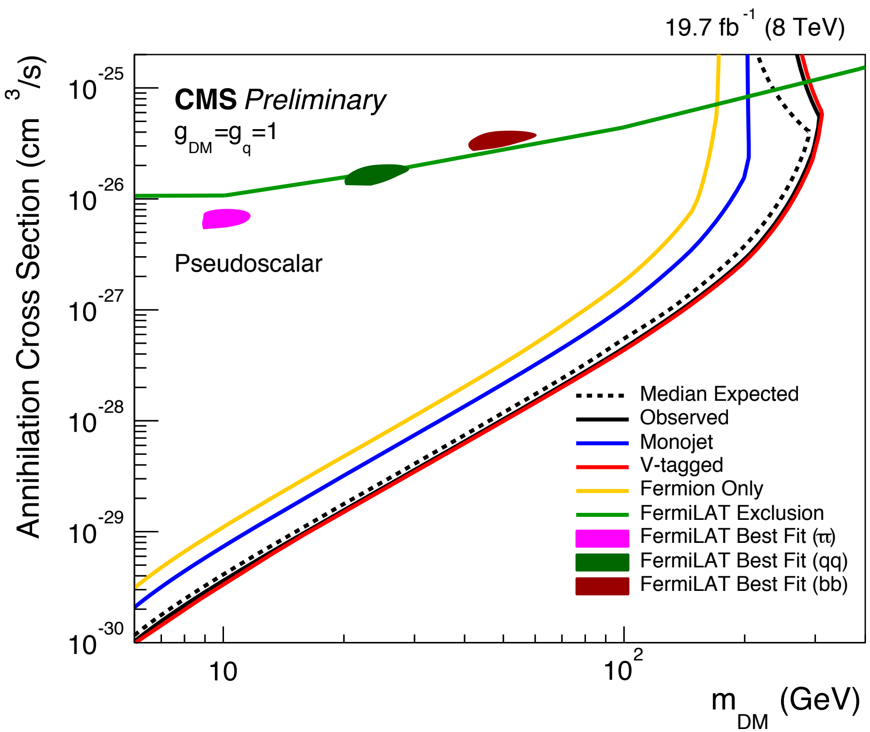
Spin-0 scenario interpretations assume only couplings to heavy quarks

→ limits the sensitivity in direct detection but avoids additional assumptions on light-quark couplings

DM-nucleon scattering velocity suppressed in pseudoscalar scenario

→ Compare sensitivity in terms of DM-annihilation cross-section (CMS limit assumes only bb mode is relevant)





Plans for Run 2 (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 organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of 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

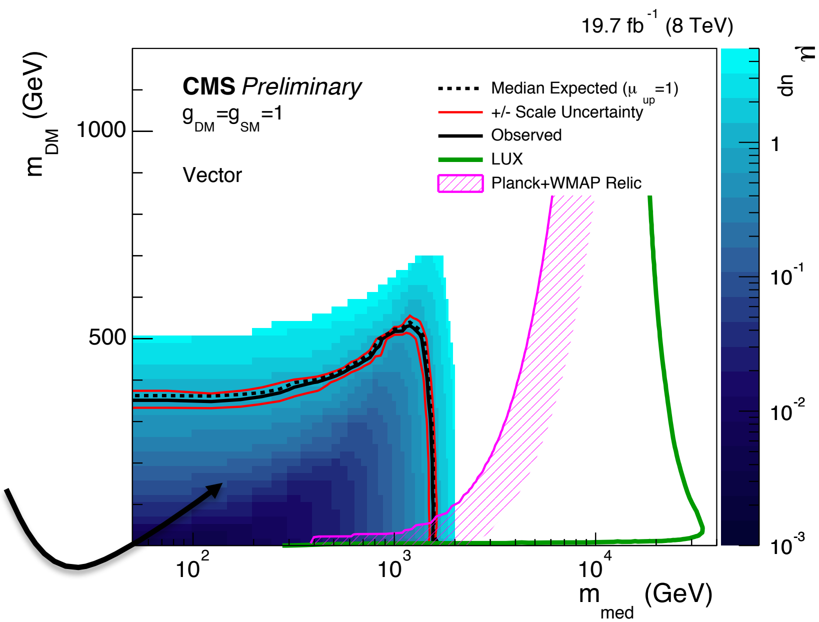
Plans for Run 2

LHC DM Forum recommendation of common grid of model points as benchmark for all DM searches (all final states) to cover variation in kinematics

m_{DM} (GeV)	m_{med} (GeV)									
1	10	20	50	100	200	300	500	1000	**2000**	5000
10	10	15	50	100						5000
50	10		50	95	200	300				5000
150	10				200	295	500			5000
500	10						500	995	**2000**	5000
1000	*10*							*1000*	***1995***	*5000*

How do we go from this…

…to this?



Plans for Run 2 (LHC DM forum)

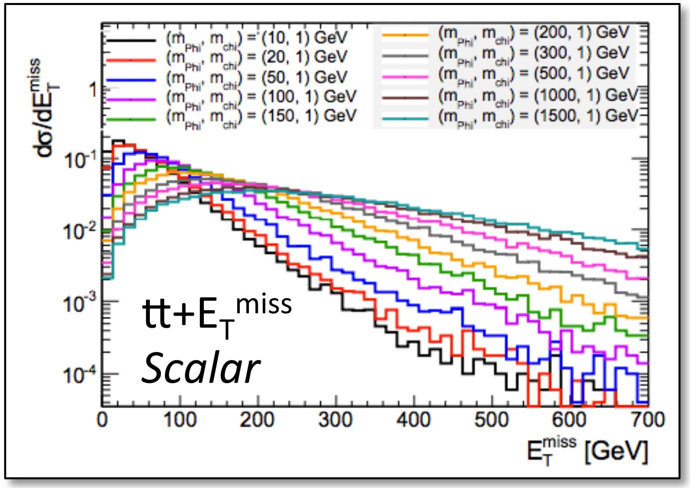
Need a finer grained sampling the parameter space with additional points to produce smooth contours.

→ The use of shape-based analyses, multiple observable requires a careful consideration of the appropriate distributions to interpolate

Example procedure

High statistics generator level samples (eg MG+PS) used to fill in the gaps.

→ *+ Fast sim of the detector?*



Use key analysis variables at generator level to reweight* full RECO samples at intermediate points.

→ *EG E_T^{miss} vs $\Delta\varphi(Z,E_T^{miss})$ for mono-Z*

Repeat for each mediator and for different coupling scenarios

→ *Different effects on kinematics for different analyses*

*Could investigate other interpolation schemes instead of "reweighting"

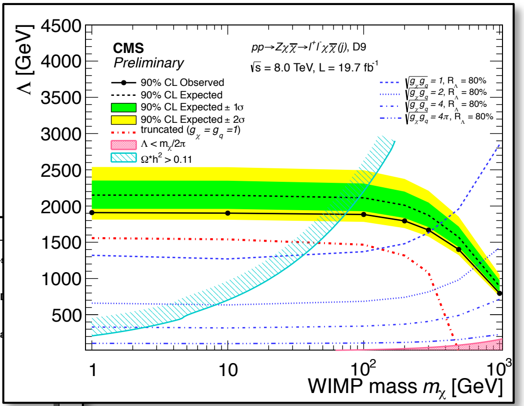
Summary

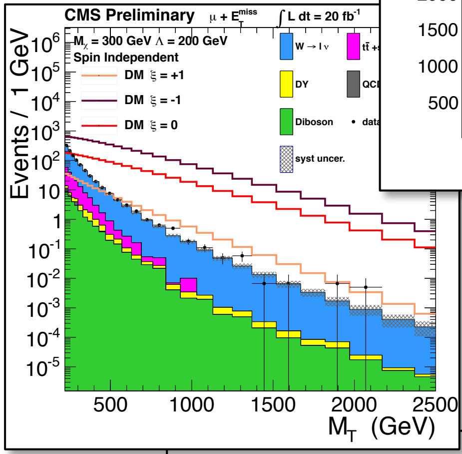
Wide variety of searches for DM at CMS in Run-1

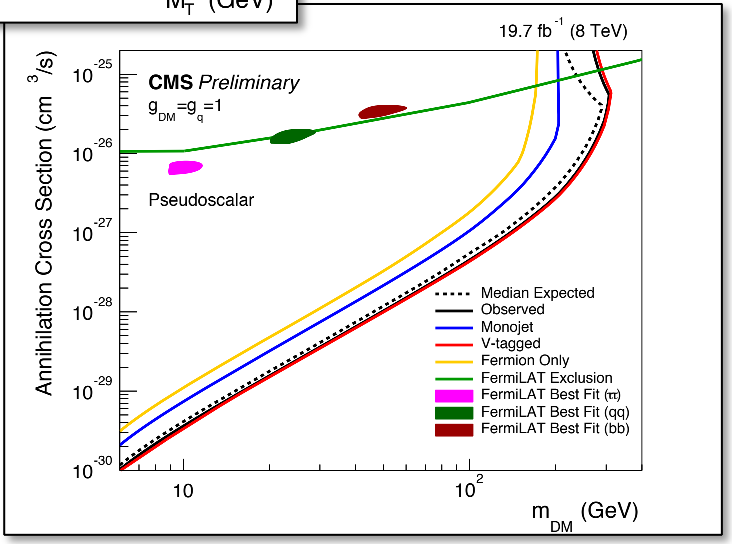
- ✧ Mono-mania (X+E_T^{miss}) searches are simple yet powerful tools to look for DM production

- ✧ Interpretation of the data under EFT models → useful for comparing sensitivities between searches and direct detection

- ✧ First use of simplified models to interpret DM searches in Run-1





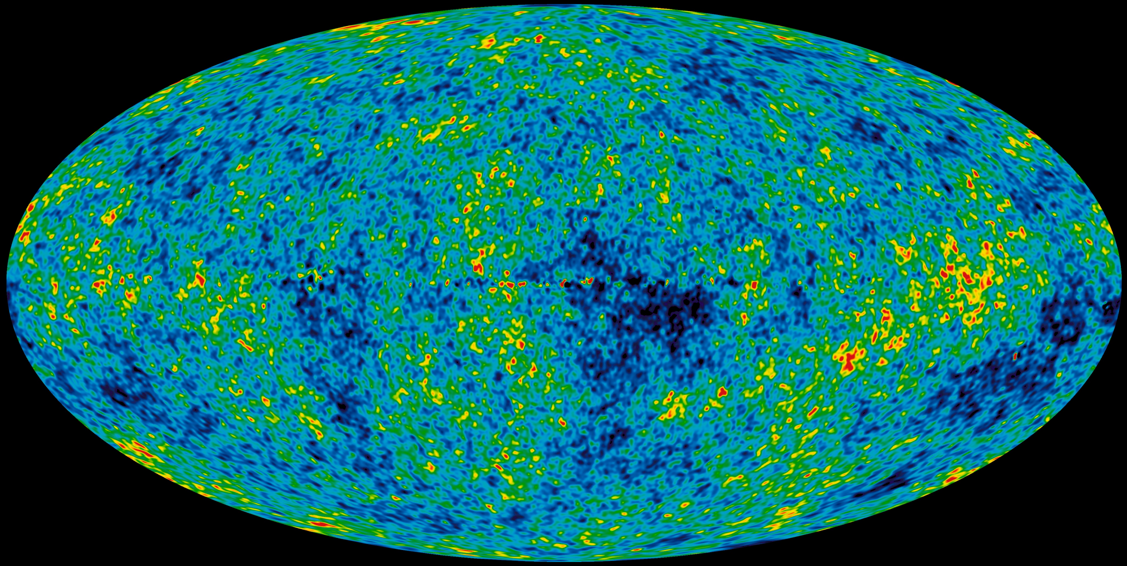


Run-2 is in progress!

- ✧ 2015 pp run complete (Results coming next week!)
- ✧ Benefit from increased cross-sections and harker kinematics at 13TeV
- ✧ 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!

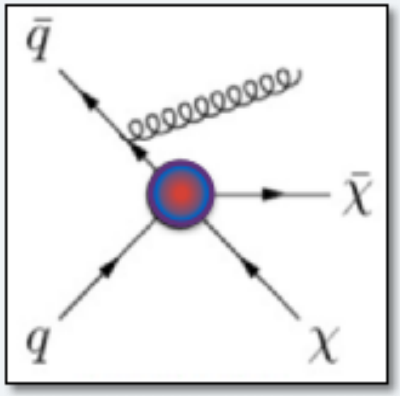
BACKUP SLIDES

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



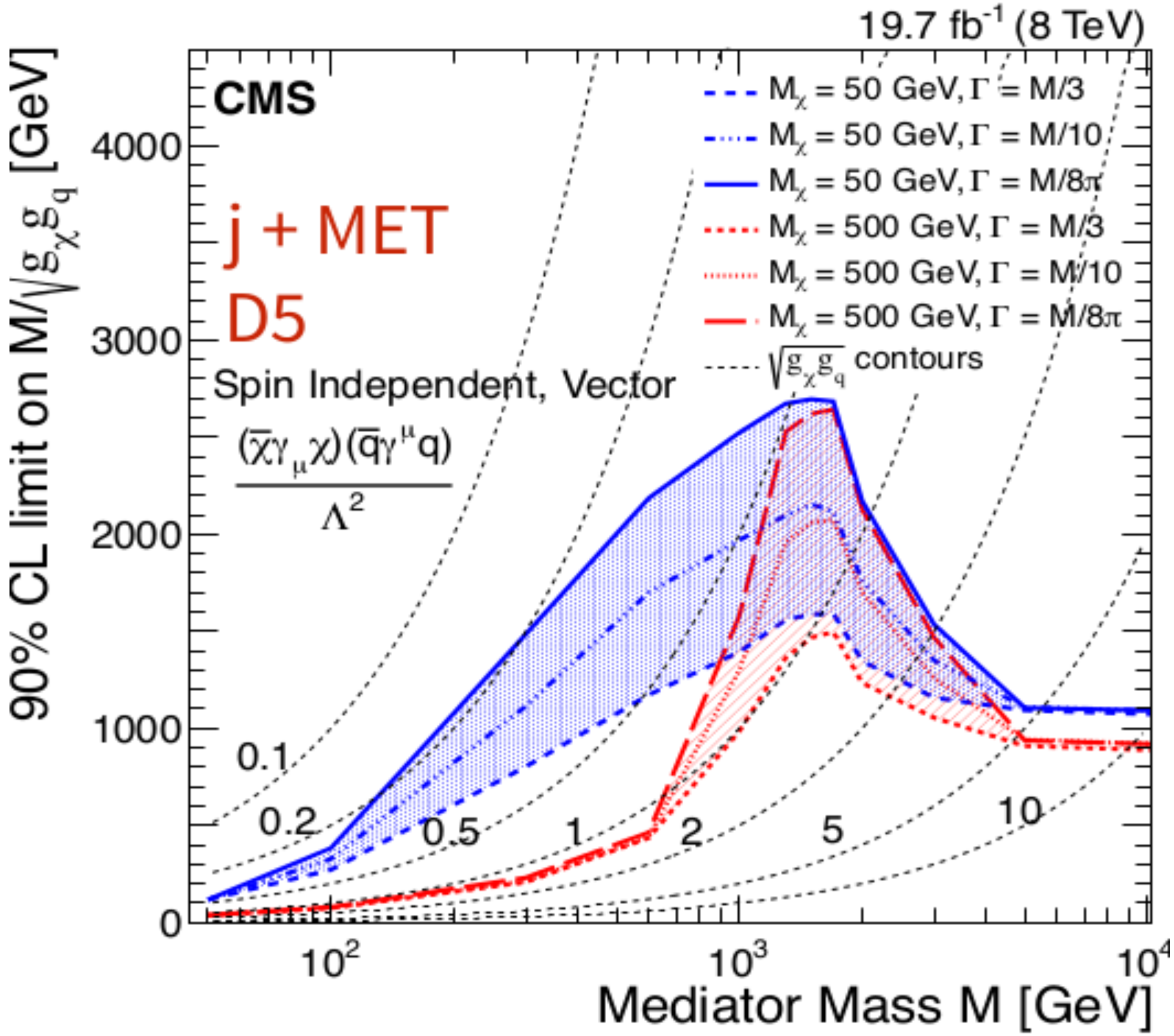
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_*^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_*^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector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

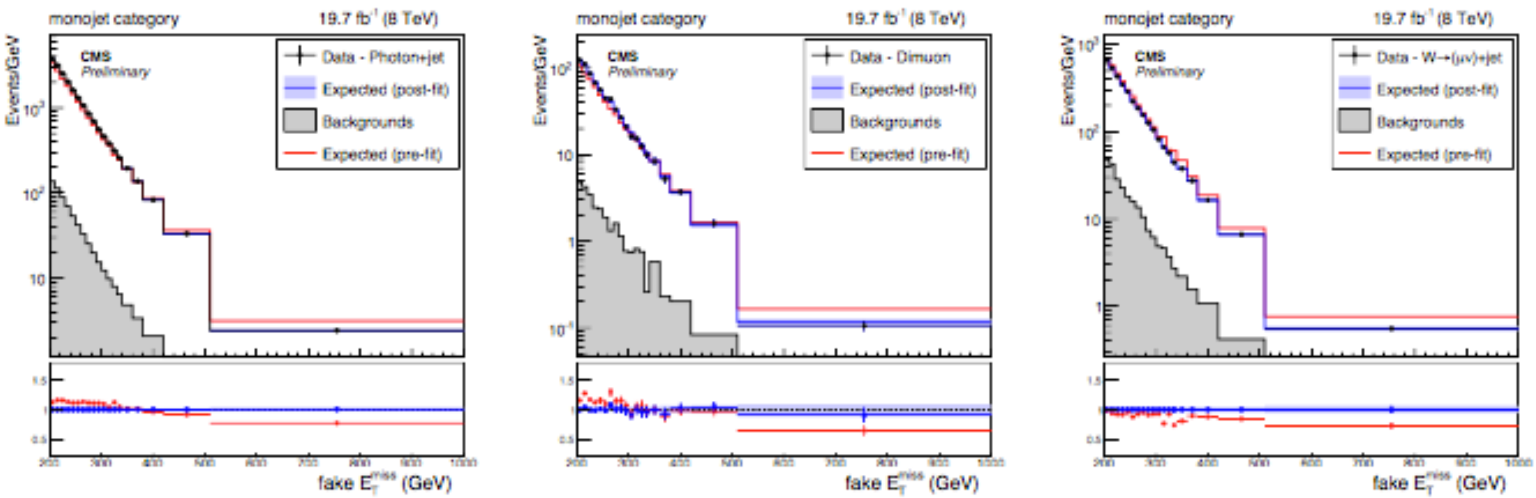
A. de Cosa (LHCP 2015)

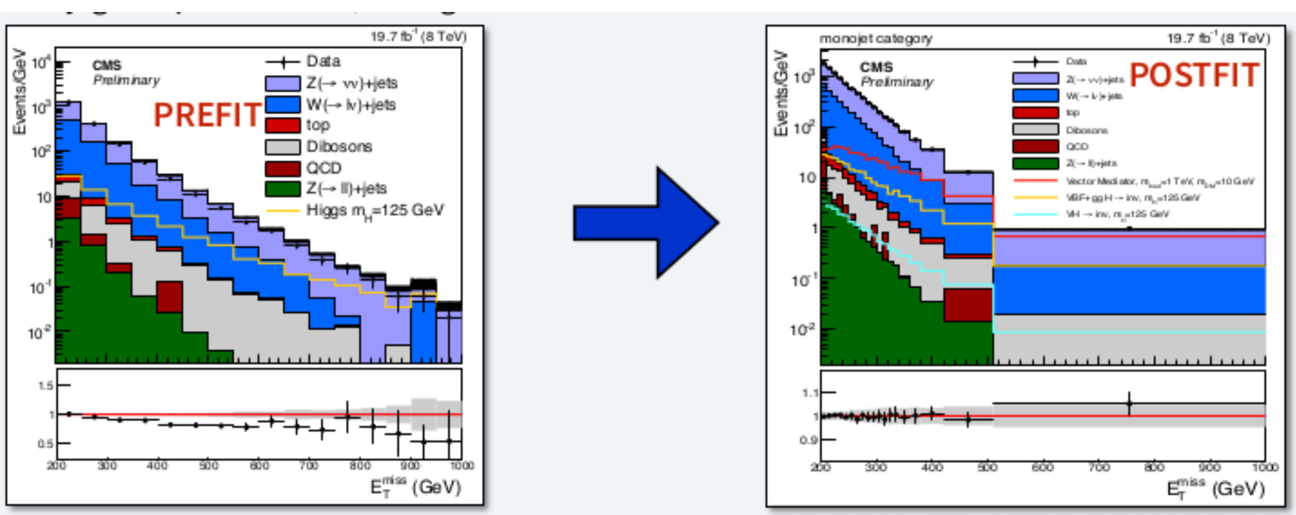
CMS monojet


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)

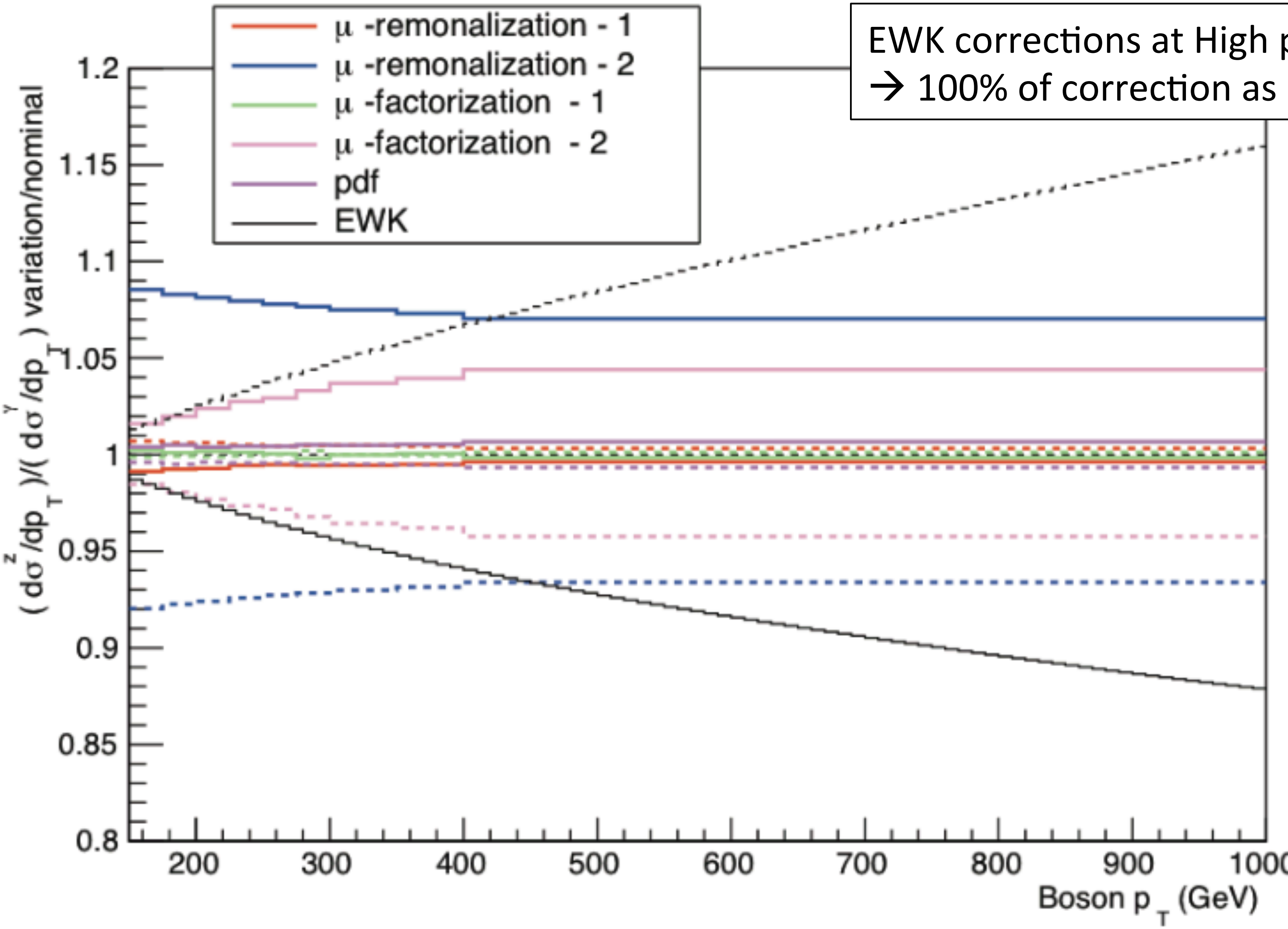
Simultaneous multi binned likelihood fit to 3 Control Regions (photon, muon, dimuon) (example, monojet category)





Corrects both shape and normalisation of V+jets backgrounds

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

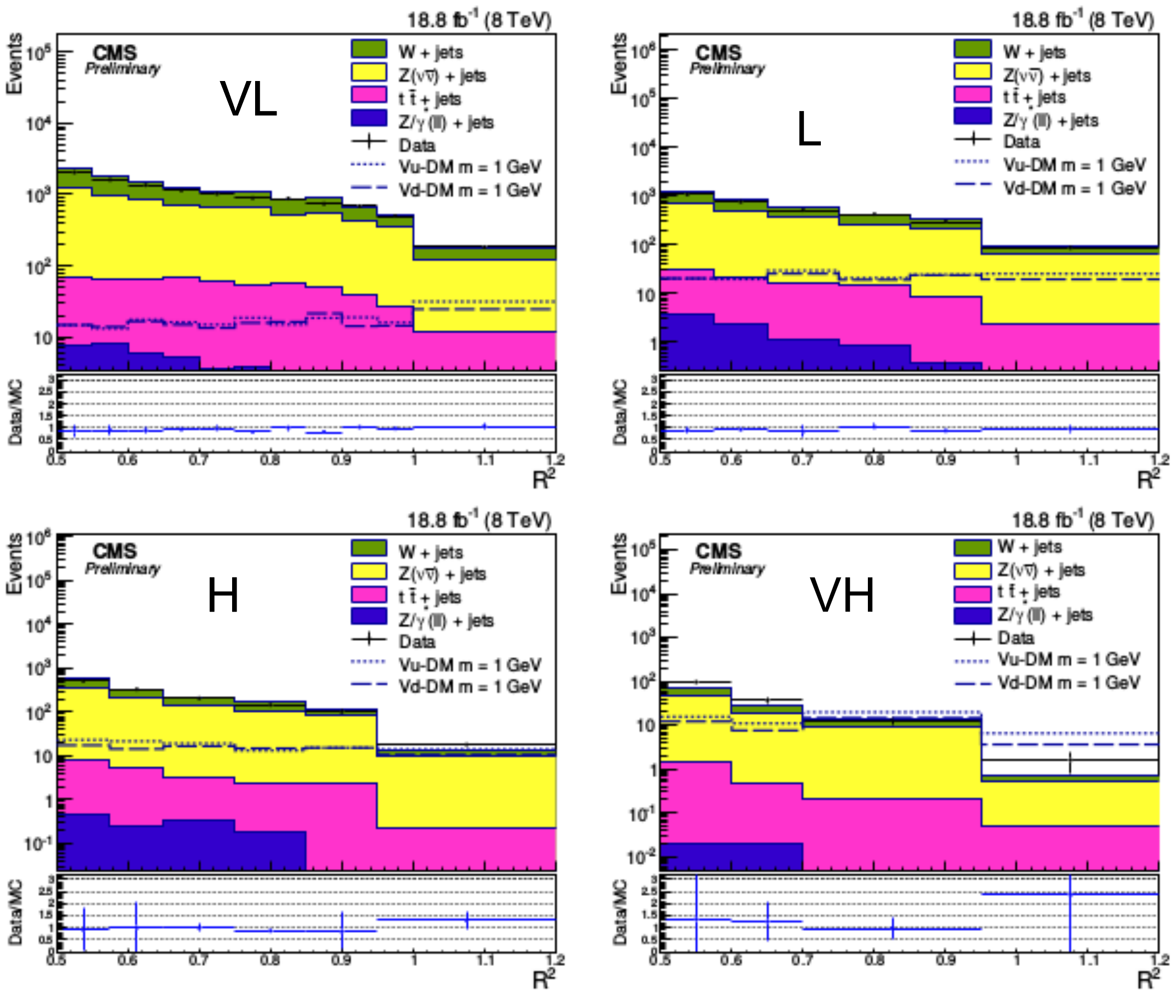


CMS Razor

Categorise events based on MR variable

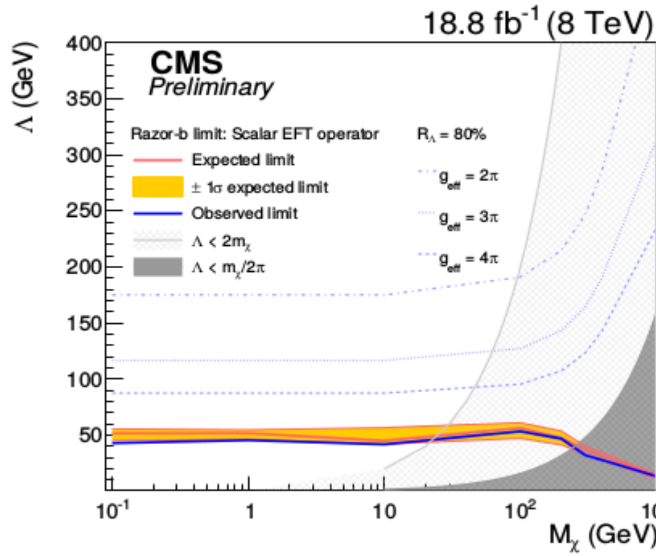
Table 2: Definition of the event categories based on the M_R value, the muon multiplicity, and the output of the CSV b-tagging algorithm. For all the samples, $R^2 > 0.5$ is required.

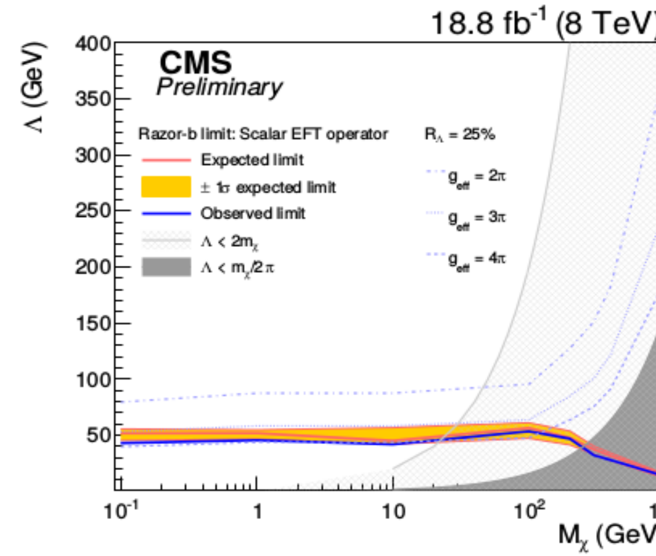
Sample	b-tagging selection	M_R selection
0μ, 1μ, and 2μ	no CSV loose jet	$200 < M_R \leq 300$ GeV (VL) $300 < M_R \leq 400$ GeV (L) $400 < M_R \leq 600$ GeV (H) $M_R > 600$ GeV (VH)
$0\mu bb$	≥ 2 CSV tight jets	$M_R > 200$ GeV
$0\mu b$	=1 CSV tight jets	
$1\mu b$	≥ 1 CSV tight jets	
$2\mu b$		
$Z(\mu\mu)b$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



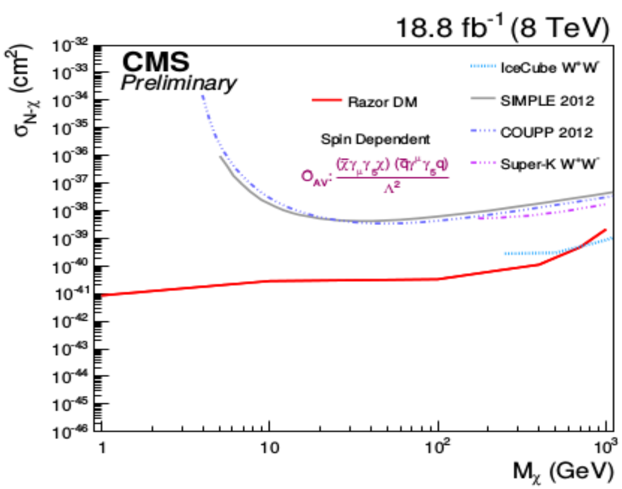
Events with >2 reconstructed jets are included by forming 2 “megajets” (sum jet 4-momenta) to calculate Razor variables

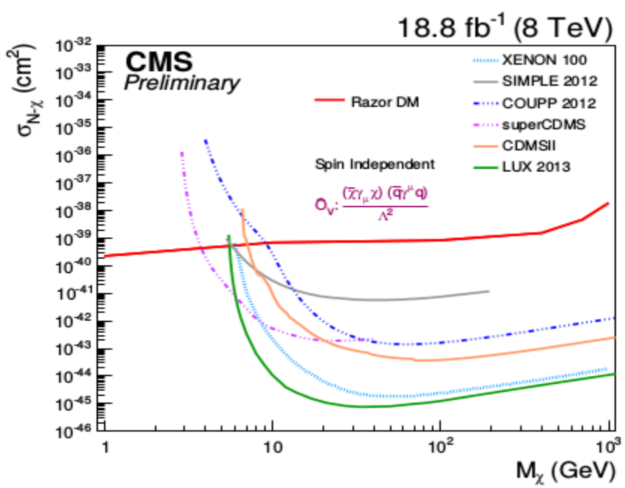
B-tagging brings sensitivity in scalar/pseudo-scalar models





V/A Comparison to Direct Detectors



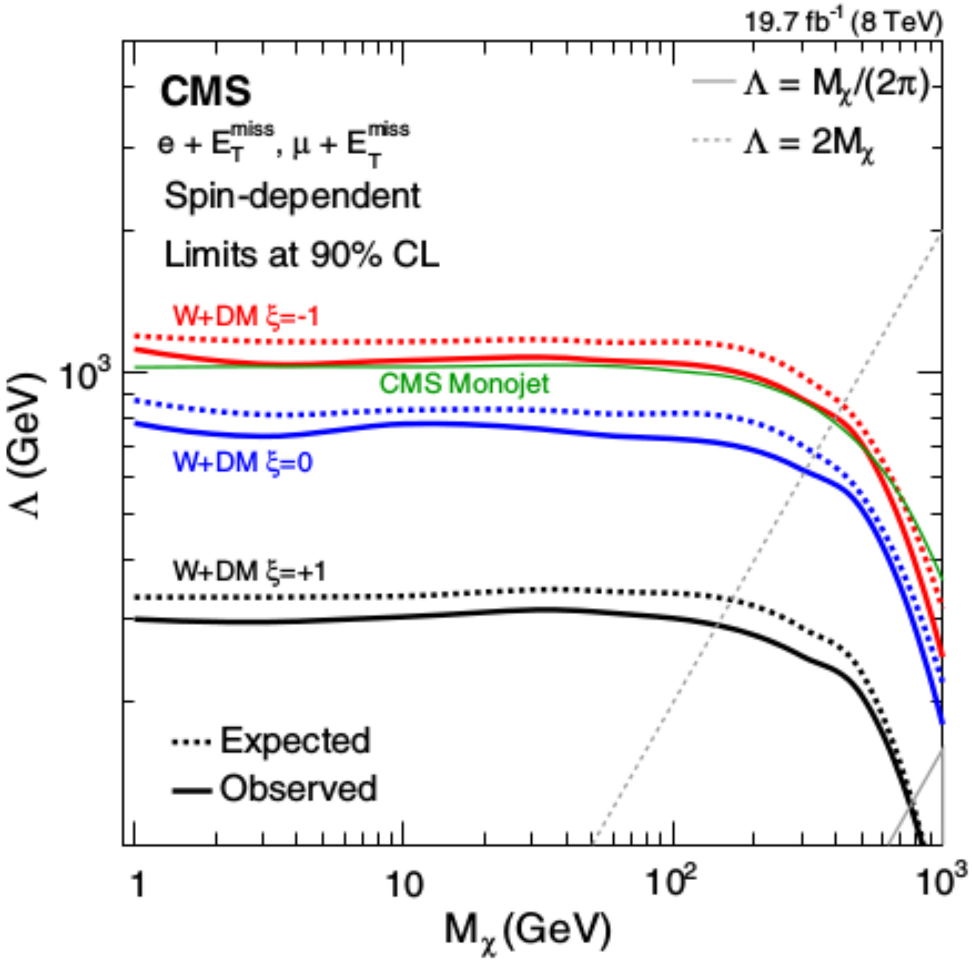


$$\sigma_{N-\chi}^{SD} = 0.33\frac{\mu^2}{\pi\Lambda_{LL}^4},$$

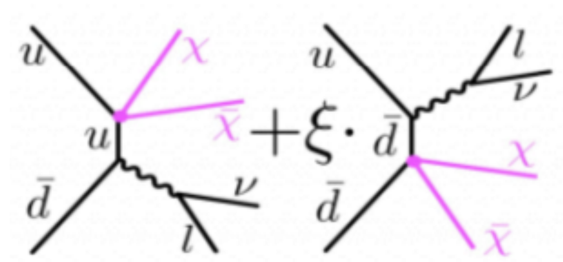
$$\sigma_{N-\chi}^{SI} = 9\frac{\mu^2}{\pi\Lambda^4},$$

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

Comparison of mono-V analyses



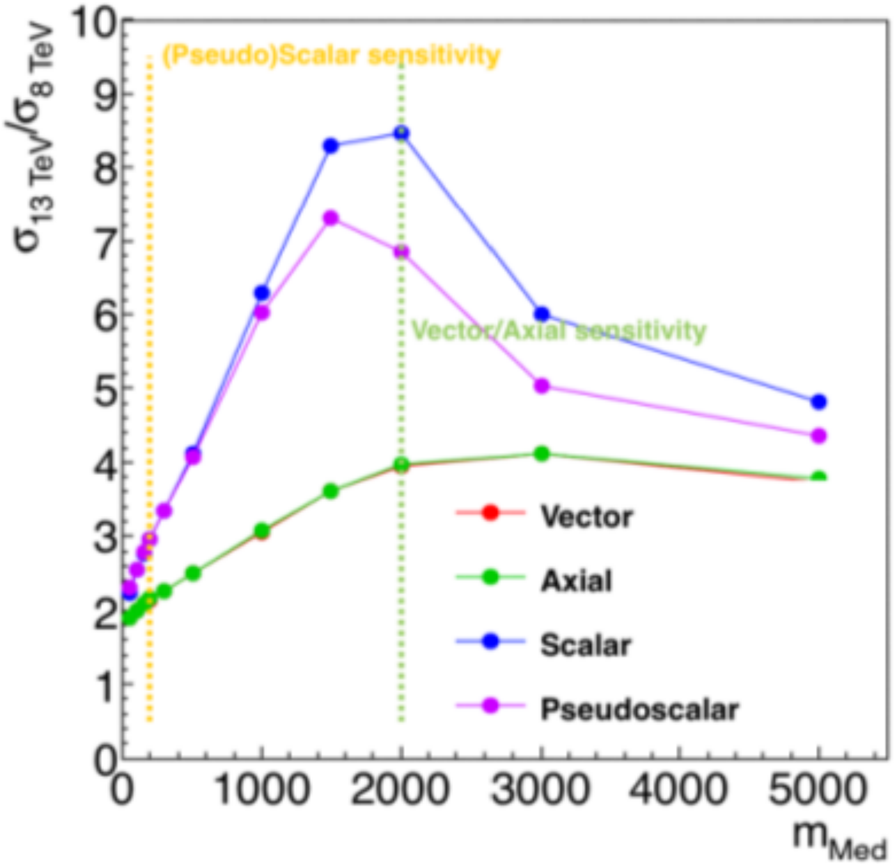
Improved sensitivity in models interference in couplings to up/down quarks



not particularly favoured model since potentially violates gauge invariance*

*arxiv.org/abs/1503.07874

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



Invisible Standard Model

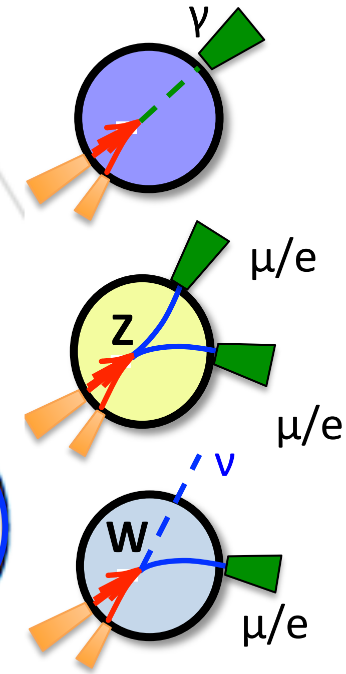
Compare the predictions with the data in the CRs → Maximize likelihood to obtain corrected prediction for backgrounds in signal regions

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

Number of observed events

Expected 'other background' contamination in CR

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



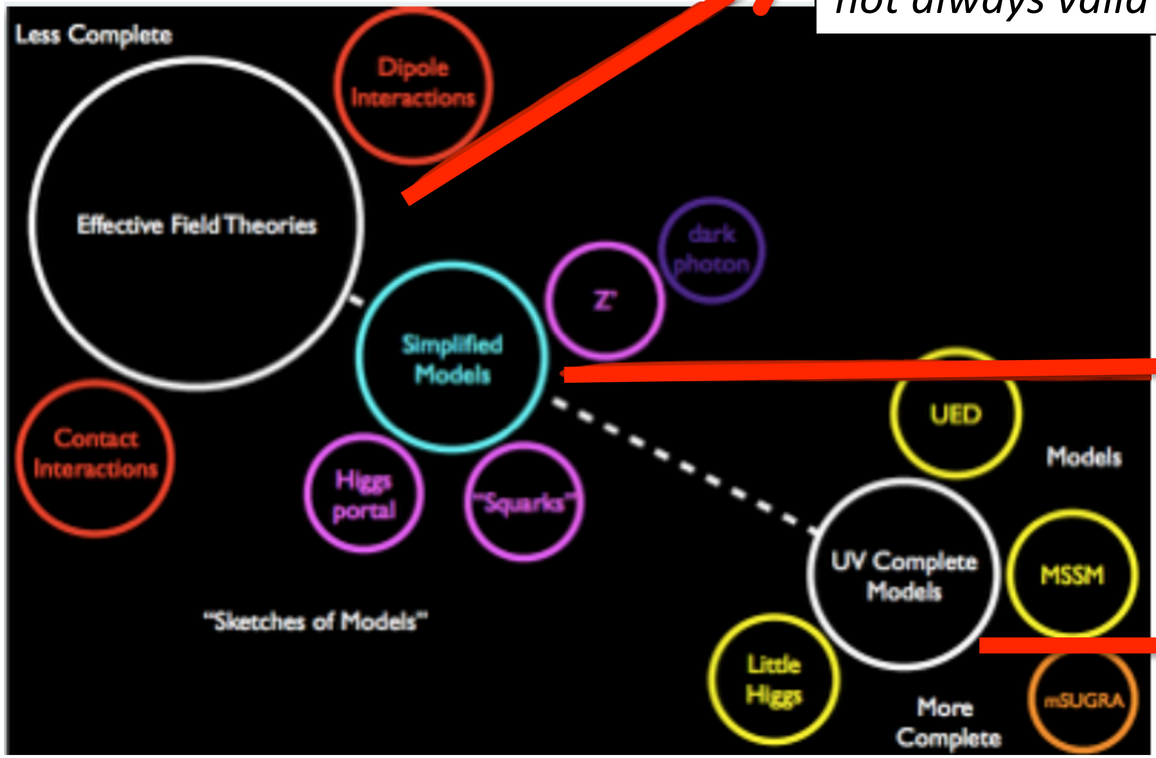
Simultaneous likelihood used in several places instead of simple `count and scale approach'

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

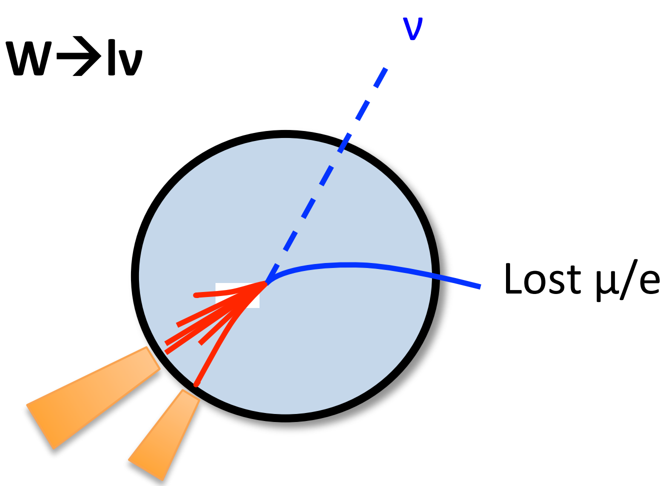
Large parameter space in complete models

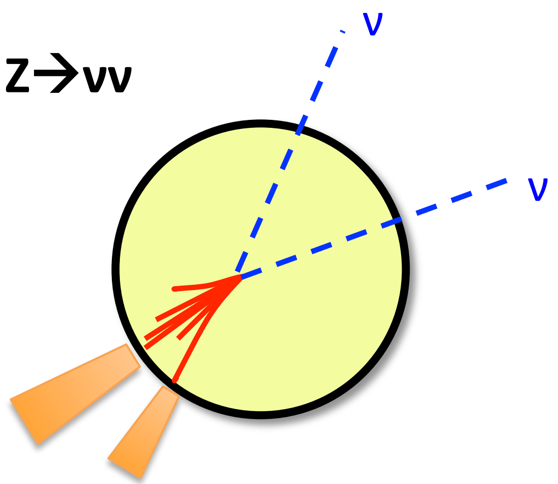
Invisible Standard Model

Common enemies shared by many of the searches for DM

Neutrinos escape detection to mimic a DM signal!

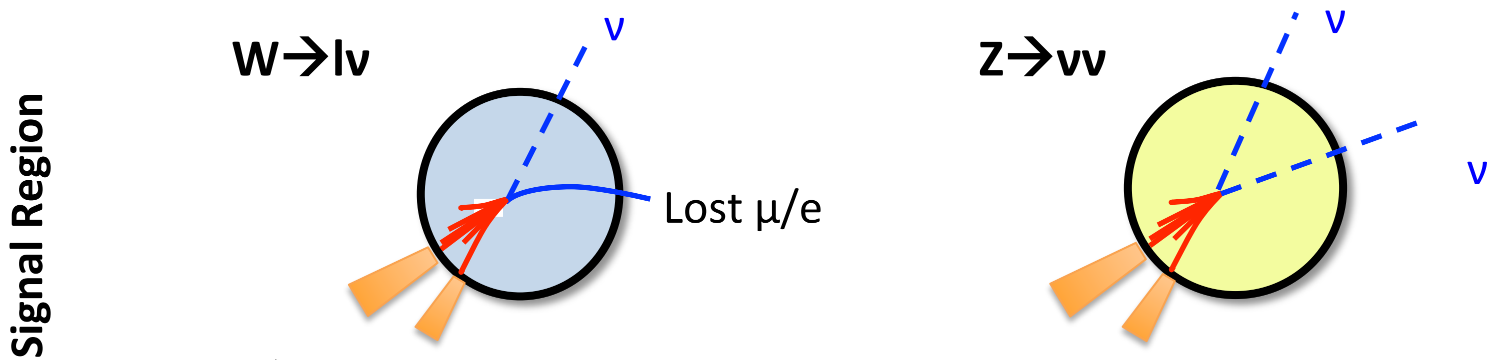
Most common are Z decays to neutrinos and leptonic W decays where the lepton falls outside of the acceptance or isn't reconstructed.

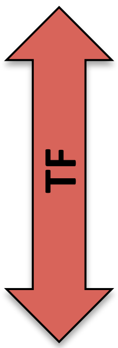




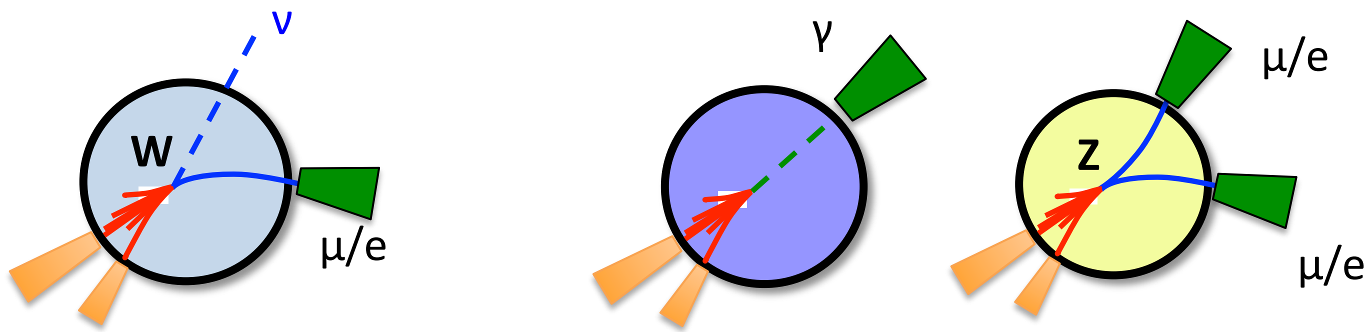
Relatively large cross-sections for these processes mean backgrounds are sizable compared to real signals.

Invisible Standard Model



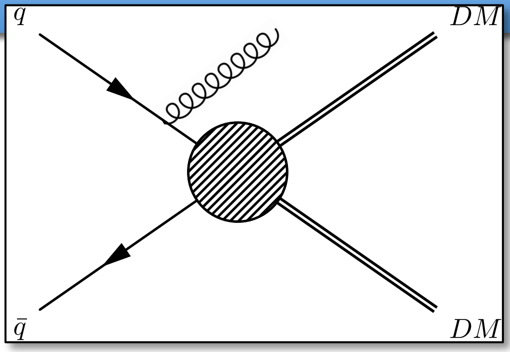


Extrapolate yields/shapes in well understood control regions CR) in data to constrain backgrounds in signal region (SR)
→ Transfer Factors (TF) taken from simulation/theory used for extrapolation: eg BR(Z→νν)/BR(Z→μμ)



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

Monojet



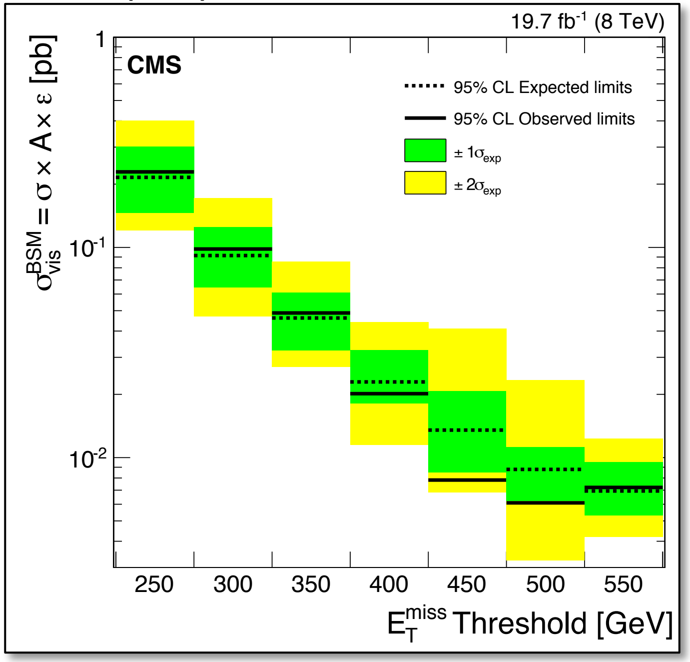
High-momentum jet, from initial state radiation (ISR), recoils against DM

- ✧ 1 central jet with high p_T > 110 GeV
- ✧ 2nd jet allowed provided if $\Delta\phi(j_1,j_2) < 2.5$
- ✧ Veto leptons, photons

Dominant backgrounds from **Z(νν)+jets** and **W(lν)+jets**
→ Estimate the contributions with data using **Z→ll** and **W→lν** events

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

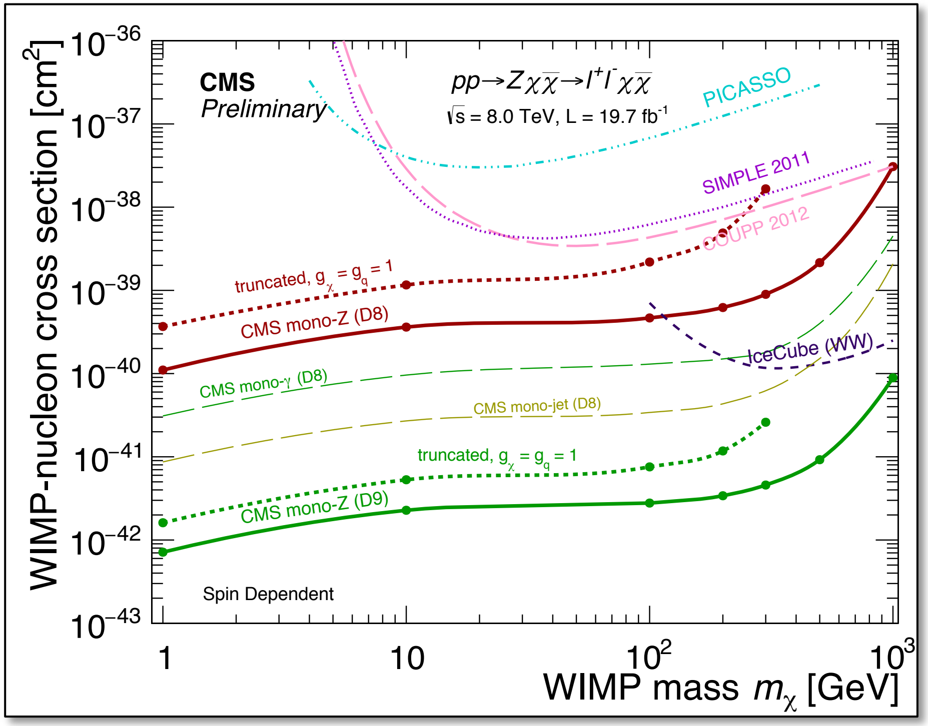
EPJC75 (2015) 235 *Upper limits with CLs*

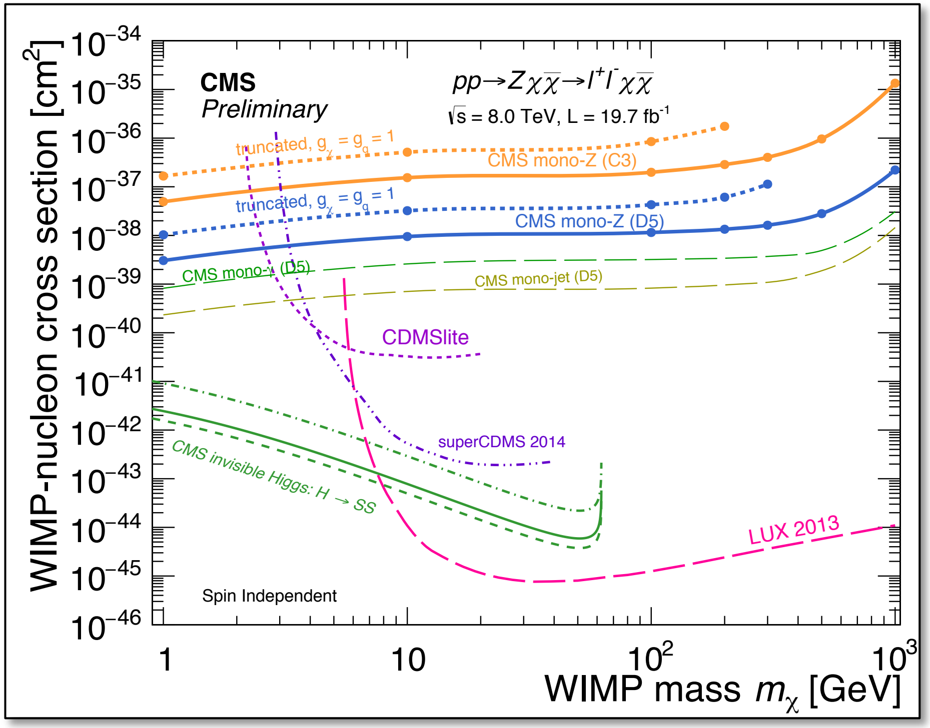


Comparisons to Direct Detectors

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

→ Complementary to DD searches





Simplified Model Lagrangians

$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\,\bar{\chi}\chi - \sum_{q=b,t} g_{\text{SM}}^q S\,\bar{q}q - m_{\text{DM}}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 P^2 - ig_{\text{DM}} P\,\bar{\chi}\gamma^5\chi - \sum_{q=b,t} ig_{\text{SM}}^q P\,\bar{q}\gamma^5 q - m_{\text{DM}}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\text{vector}} \supset \frac{1}{2}m_{\text{MED}}^2 Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{\text{SM}}^q Z'_\mu \bar{q}\gamma^\mu q - m_{\text{DM}}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\text{axial}} \supset \frac{1}{2}m_{\text{MED}}^2 Z''_\mu Z''^\mu - g_{\text{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{\text{SM}}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q - m_{\text{DM}}\bar{\chi}\chi$$