Search for Dark Matter at the LHC

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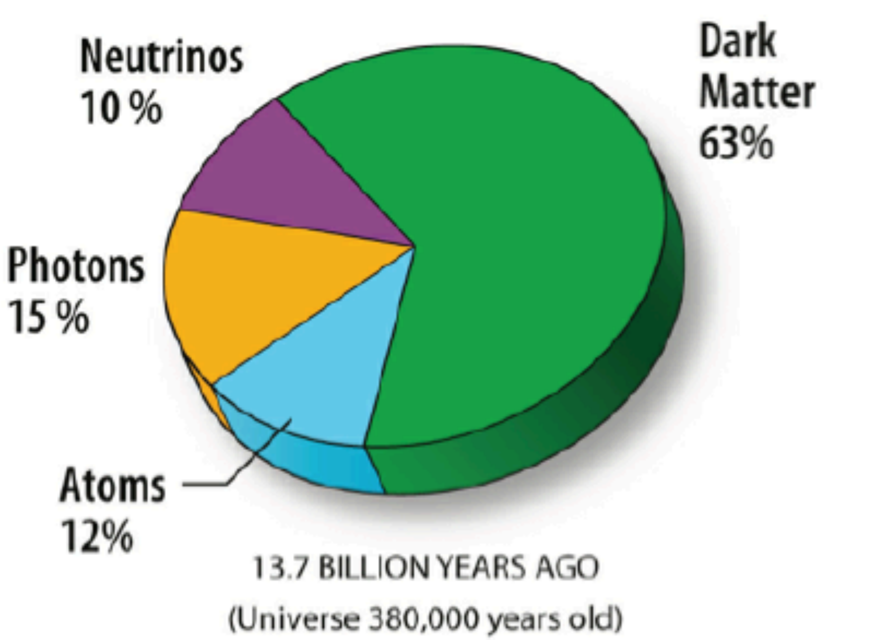
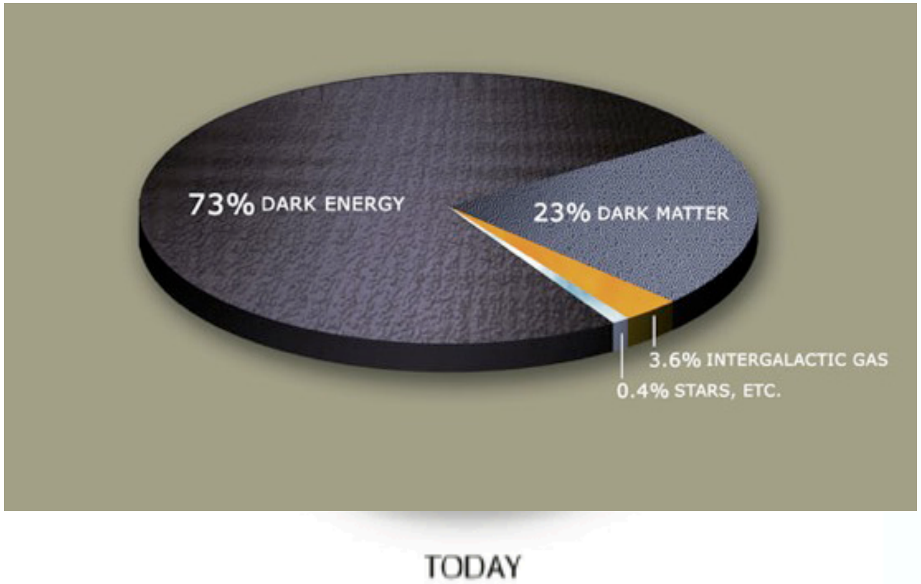
Second International Workshop on recent LHC Physic's results and related topics

Universe composition





- 23% of universe energy/matter is a new type of (non-baryonic) matter
- 73% is a new type of energy (cosmological constant)
- SM is 4%

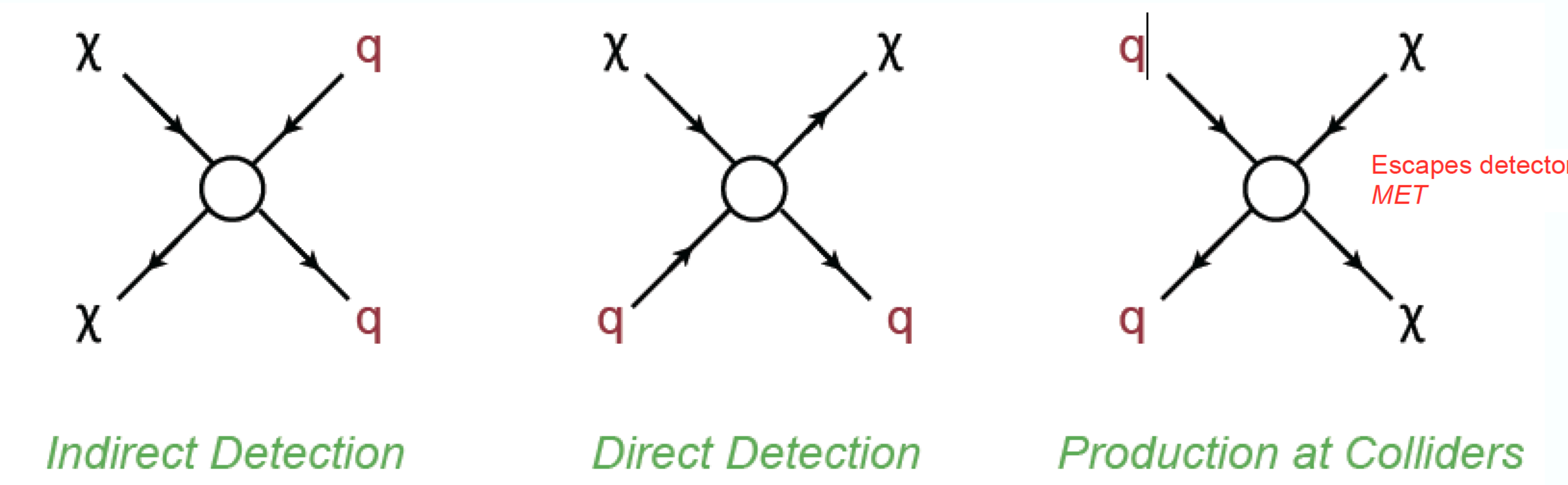
Candidate dark matter particles

- Properties
  - long lived (old)
  - non-relativistic (slow)
  - no electric or color charge
  - very weak interaction with Standard Model particles
  - subject to gravity interaction

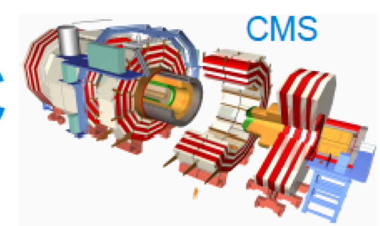
No such particle exists in the SM

- Several potential candidates fulfilling these requirements for dark matter
  - Dark: weakly interacting with electromagnetic radiation
  - Hot & dark: ultra-relativistic velocities
    - neutrinos
  - Warm & dark: very high velocity
    - sterile neutrinos, gravitinos
  - Cold & dark: moving slowly
    - Lightest SUSY particle (neutralino, gravitino as LSP), Lightest Kaluza-Klein particles
  - Nonthermal relics:
    - Bose-Einstein condensate (BEC), axions, axion clusters, solitons, supermassive wimpzillas

Dark Matter interaction → LHC

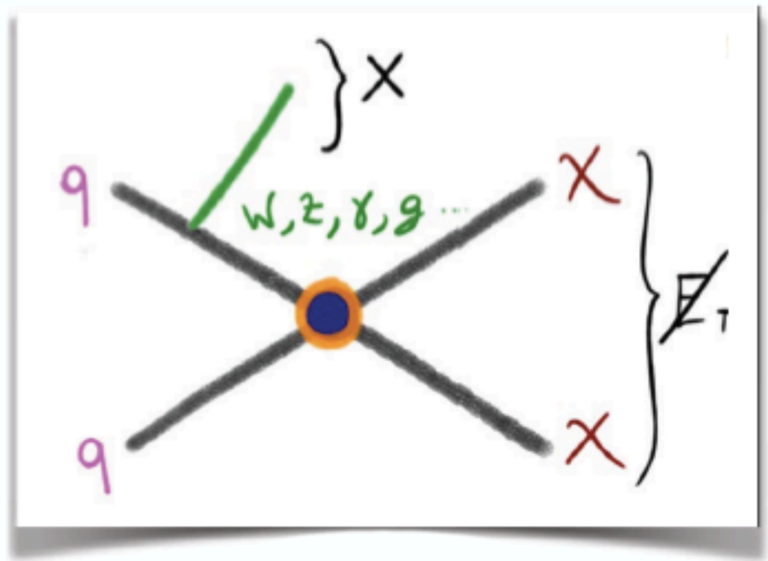


@LHC



Searches for Dark Matter at the LHC

- Typically look for E_T^{miss} + X
  - X= jet (g, q), γ, W, Z, H, tt, bb, t
- Use simplified models to interpret results (arXiv: 1507.00966)
  - DM particle is a Dirac fermion
  - DM particles are pair-produced
  - A new massive particle mediates the DM-SM interaction
  - Minimal flavor violation
  - Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM}, g_{DM}



CMS 13 TeV Searches for Dark Matter

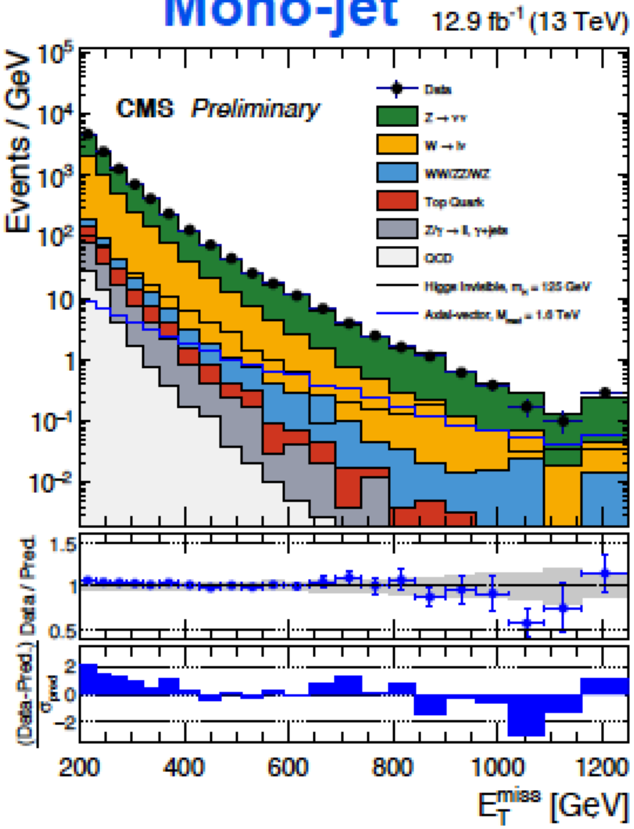
	X	Dataset	CMS Documentation
Focus of this talk	jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
	photon	2016, 12.9 fb	EXO-16-039
	Z (ll)	2015, 2.3 fb	EXO-16-010
	Z (ll)	2016, 12.9 fb	EXO-16-038
	Higgs (bb)	2015, 2.3 fb	EXO-16-012
	Higgs (γγ)	2015, 2.3 fb	EXO-16-011
	tt (semilep+had)	2015, 2.2 fb	EXO-16-005
	t (hadronic)	2016, 12.9 fb	EXO-16-040
Previous Results	jet or V (hadronic)	2015, 2.3 fb	EXO-16-013
	photon	2015, 2.3 fb	EXO-16-014
	bb and tt	2015, 2.2 fb	B2G-15-007
	t (hadronic)	2015, 2.3 fb	EXO-16-017

Mono-Jet/Jets/Hadronic W And Z

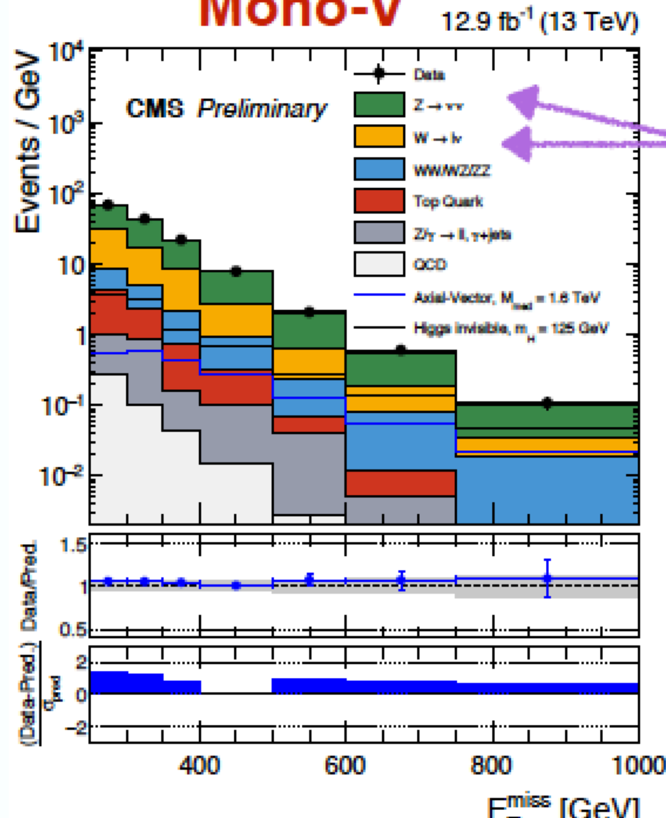
2016 data

- Look for large E_T^{miss} and ≥1 high-p_T jet, veto e, μ, τ, γ, b-jet
  - Mono-V: p_{Tj1}^{AK8}, E_T^{miss} > 250 GeV, mass 65-105 GeV, τ_{21} < 0.6
  - Mono-jet: remaining events p_{Tj1}^{AK4} > 100 GeV, E_T^{miss} > 200 GeV
- Fit background and signal predictions to E_T^{miss} in data

Mono-jet



Mono-V



90% of the total background

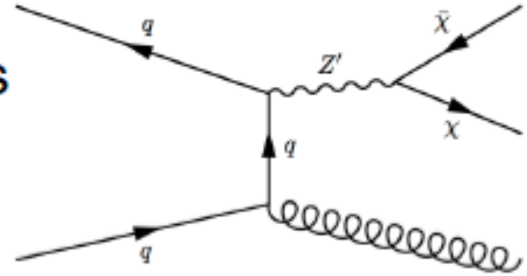
Modeled with 5 control regions ee/μμ/e/μ/γ

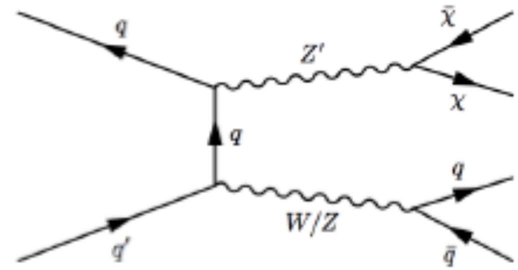
NLO QCD + EWK for the transfer factors

Mono-Jet/Jets/Hadronic W And Z

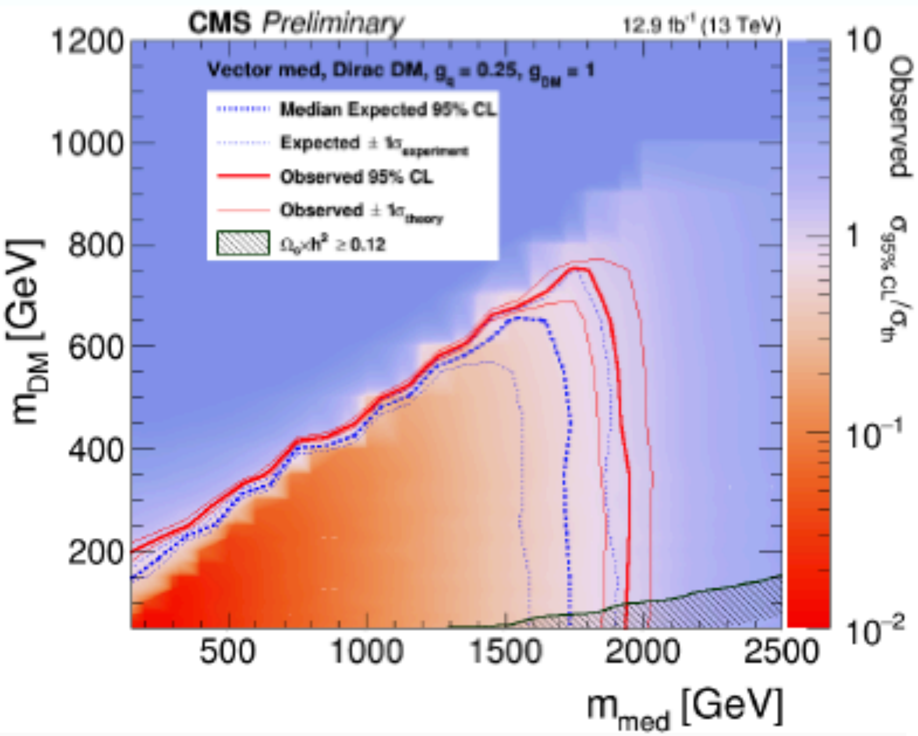
2016 data

- No excess observed
- Vector/Axial mediator mass up to 1.95 TeV excluded
- (Pseudo) scalar mediator mass up to (430) 100 GeV

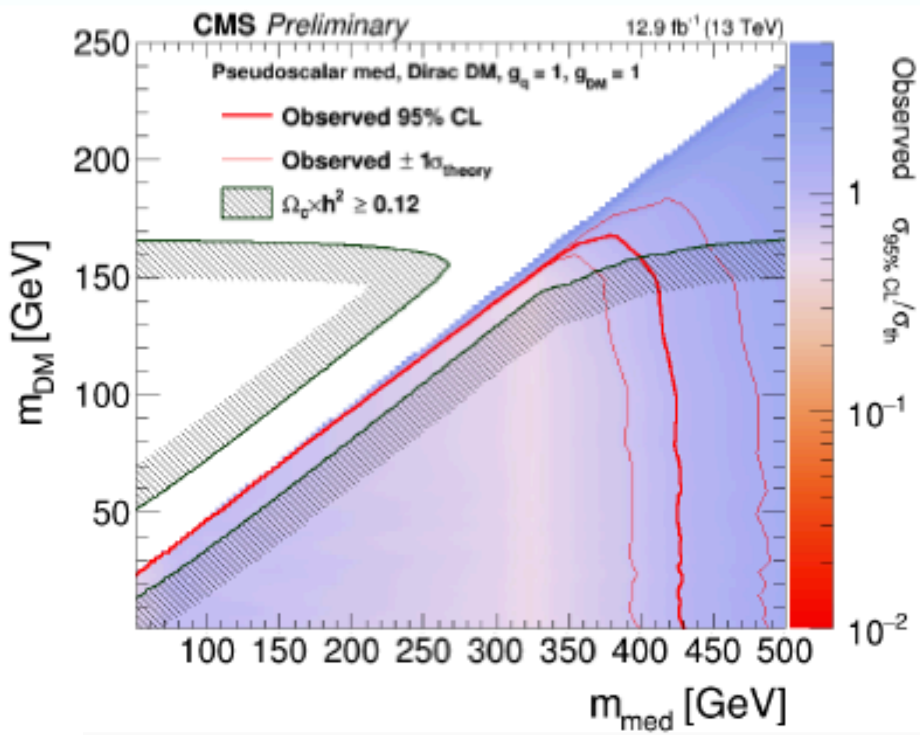




Vector Mediator



Pseudo-scalar Mediator

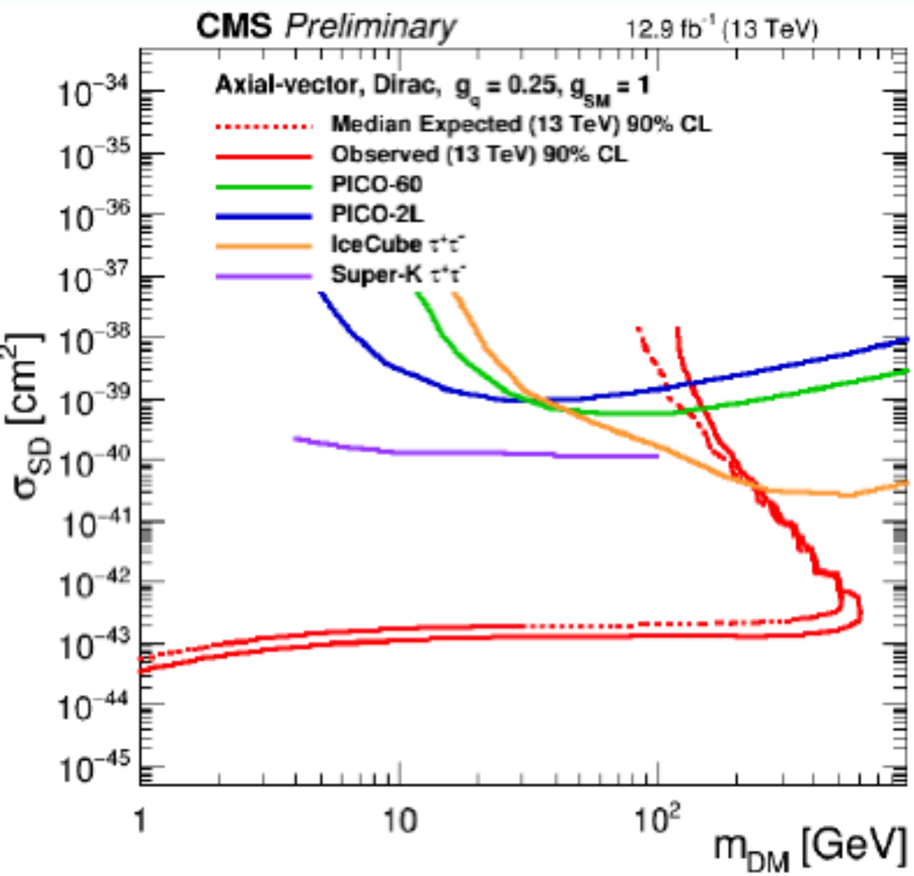


Mono-Jet/Jets/Hadronic W And Z

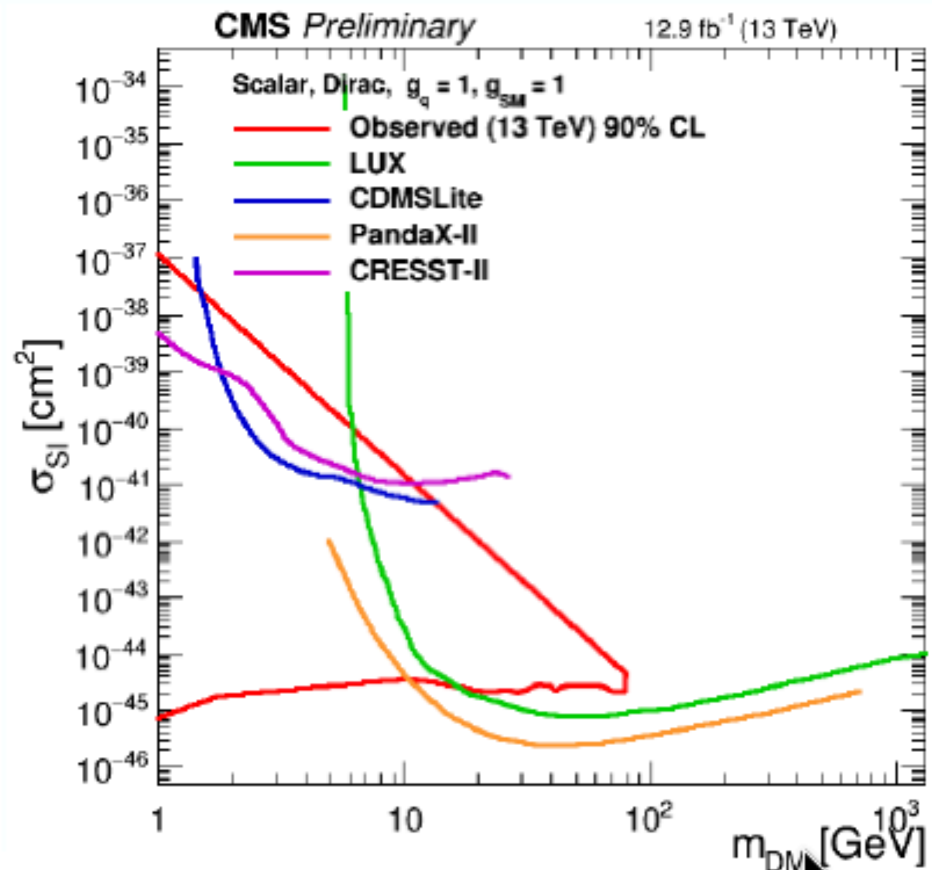
2016 data

- BR(h(125)→ invisible) < 0.44 (0.56 expected)
- Results recast to limits on SI/SD DM-nucleon scattering cross sections

Axial-vector Mediator



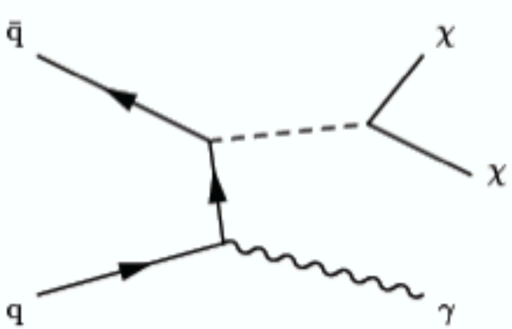
Scalar Mediator

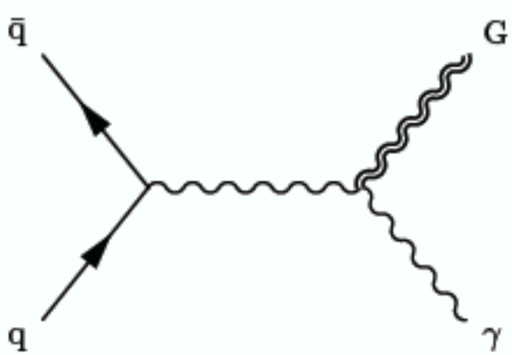


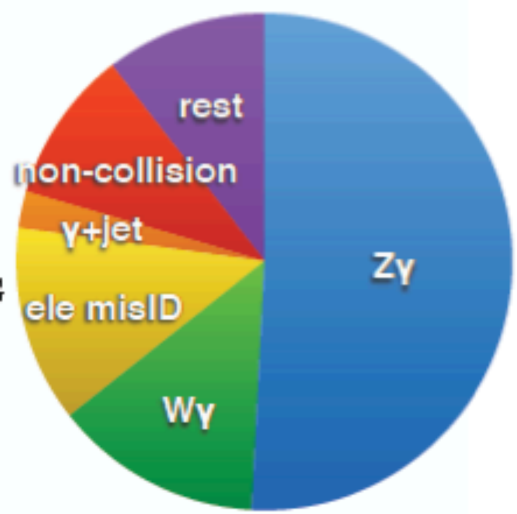
Mono-Photon

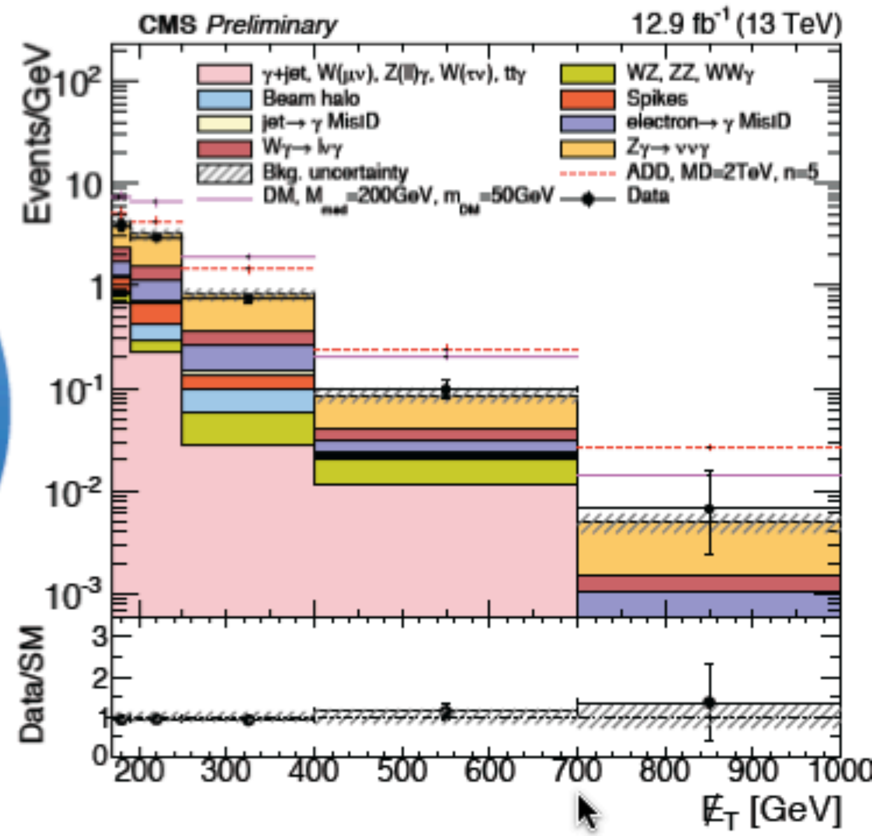
2016 data

- Look for events with E_T^{miss} > 170 GeV and ≥1 central photon with p_T > 175 GeV, veto e, μ
- Z(νν)γ and W(lν)γ estimated using MC with NNLO QCD (DYRES) +NLO EWK corrections, misID and non-collision background estimated from data





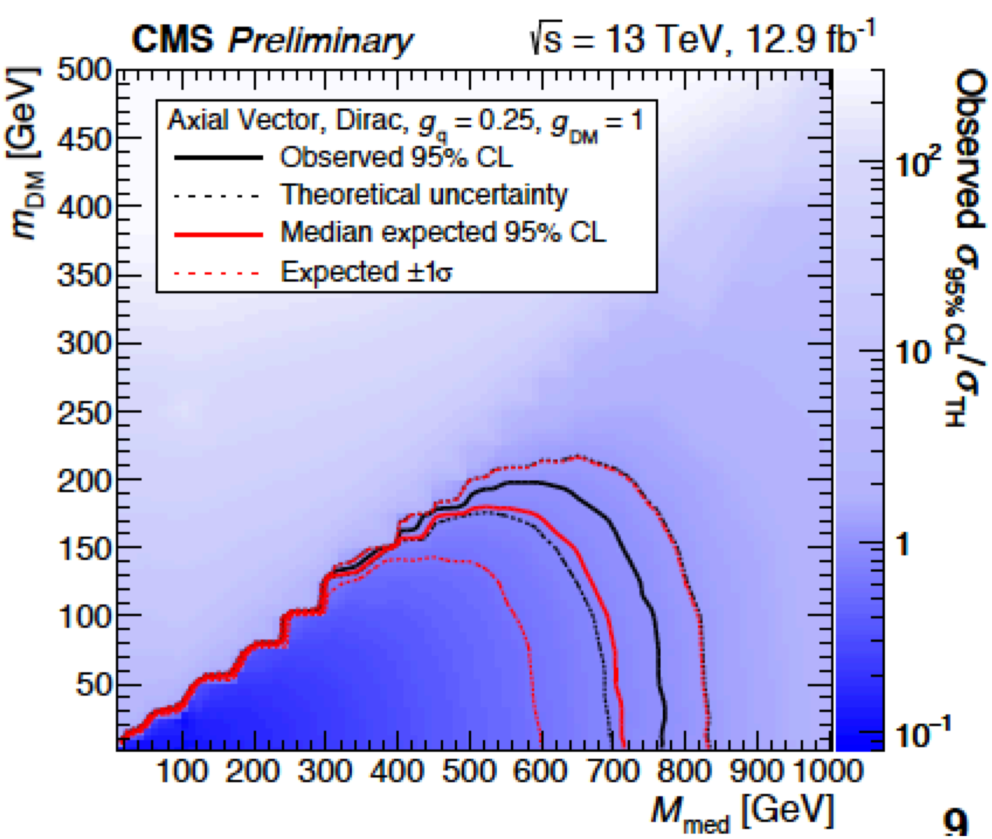


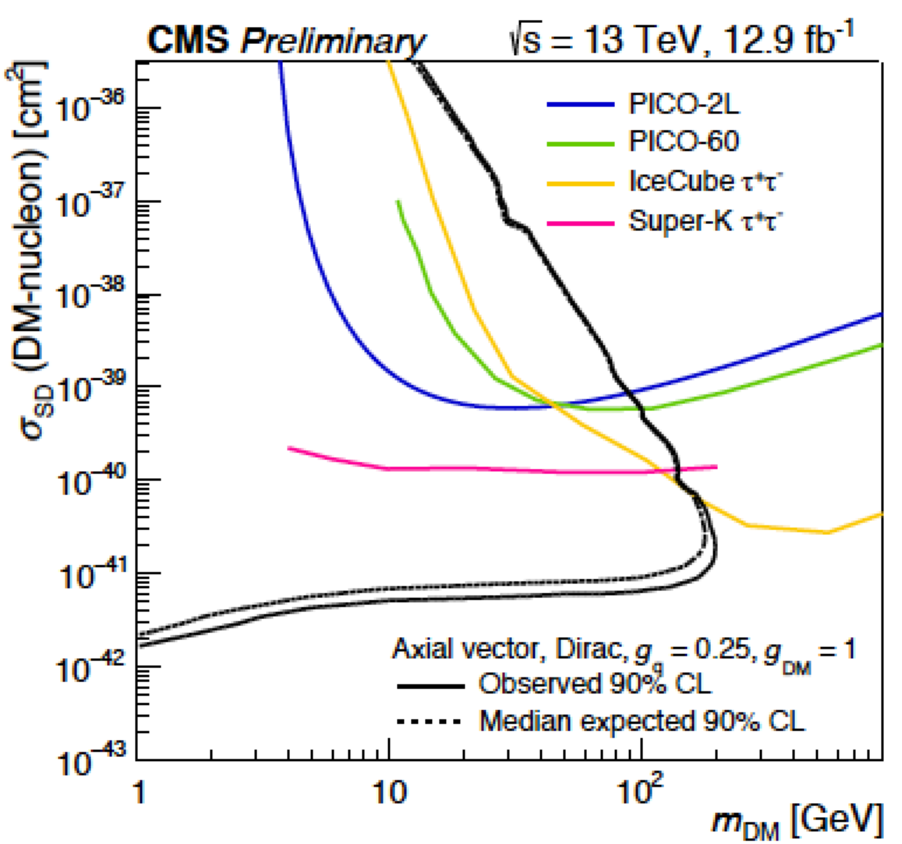


Mono-Photon

2016 data

- No excess observed, set limits on DM and ADD LED graviton
  - Mediator mass up to 760 GeV excluded (vector/axial vector)
  - Dim-7 EFT scale Λ up to 620 GeV excluded
  - ADD LED M_D > 2.44 to 2.60 TeV for n=3 to n=6 extra dimension

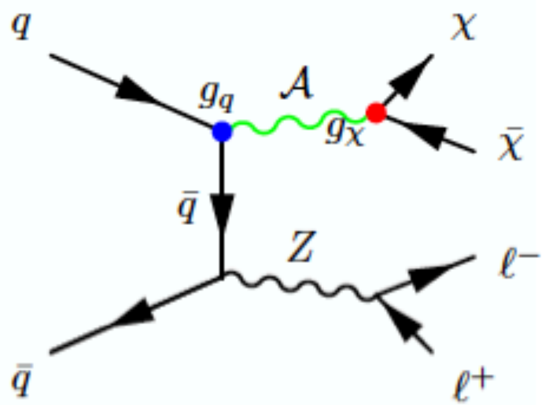


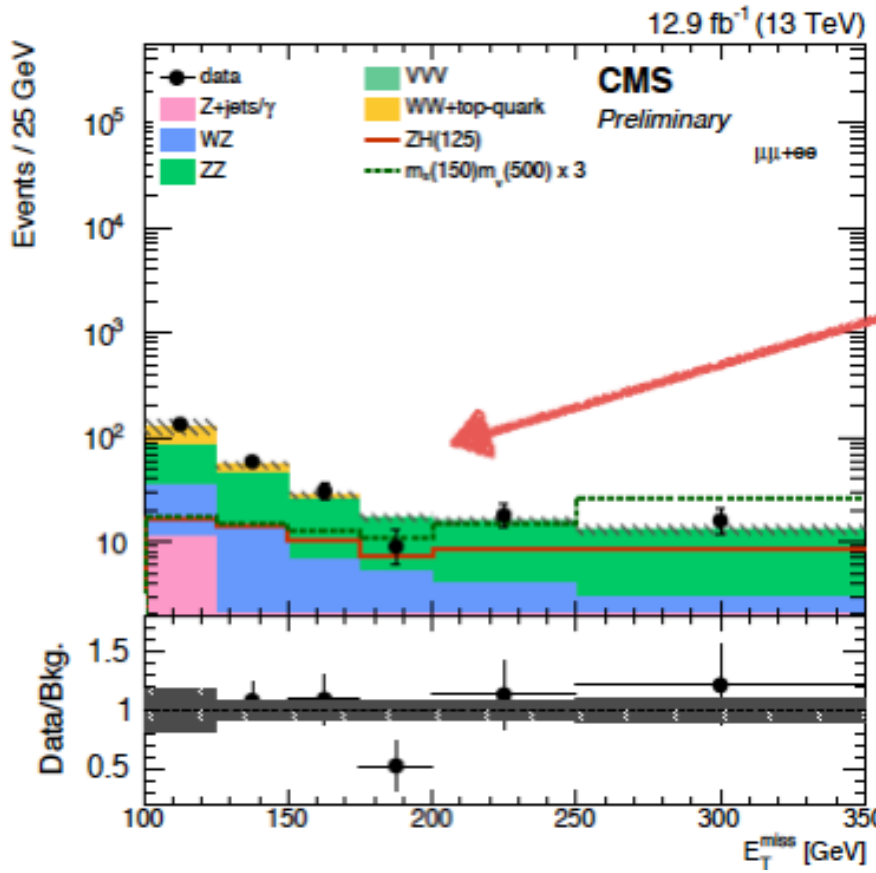


Mono-Z (ll)

2016 data

- Require E_T^{miss} > 100 GeV and ee/μμ with p_T^{ll}>60 GeV, E_T^{miss} and p_T^{ll} balance, veto extra e, μ, τ, b-jet, events with more than 1 jet
- ZZ/WZ background estimated with MC (with NNLO QCD and NLO EWK corrections), tt, W, WW, tW, Z→ τ τ background estimated from the eμ data



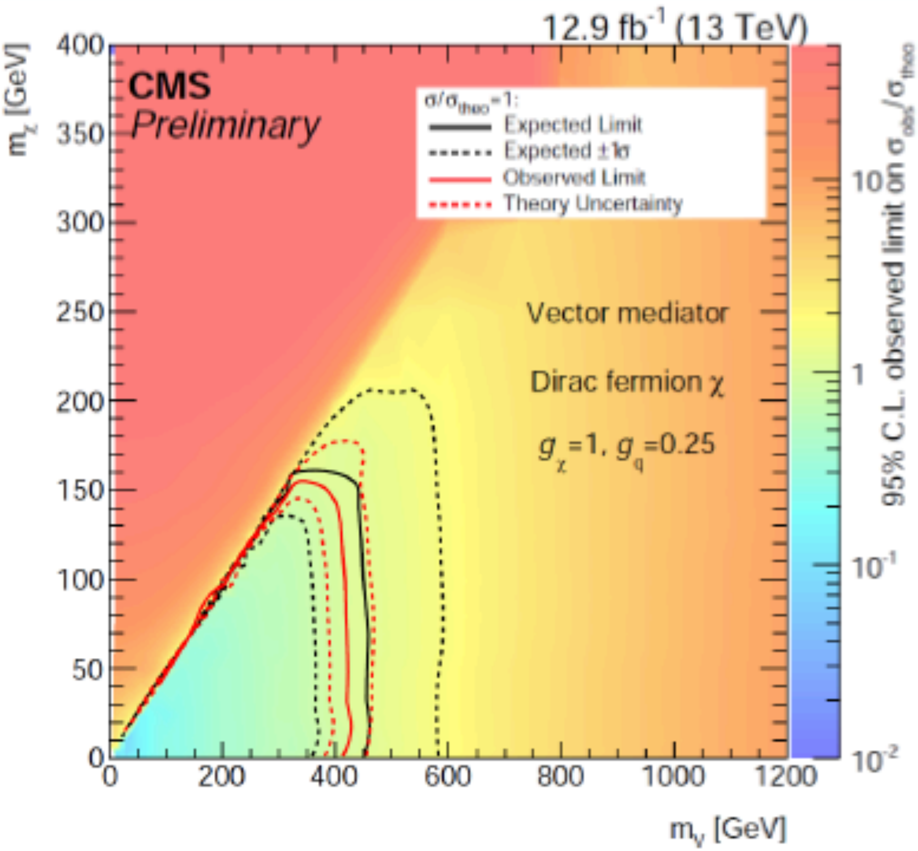


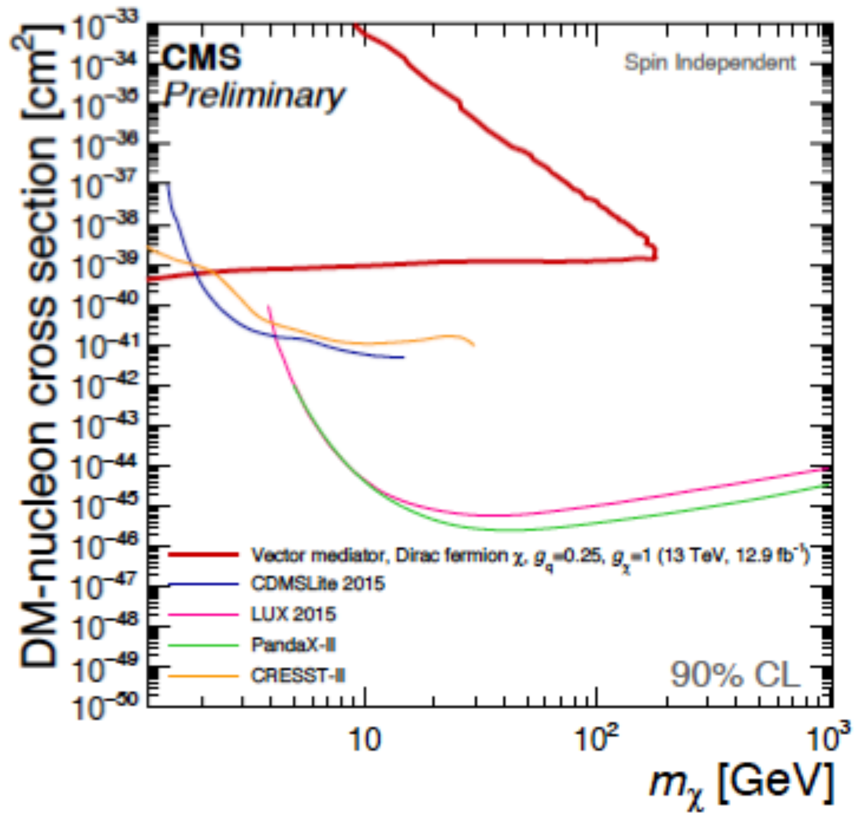
Fit signal and background predictions to the E_T^{miss} distributions in data

Mono-Z (II)

2016 data

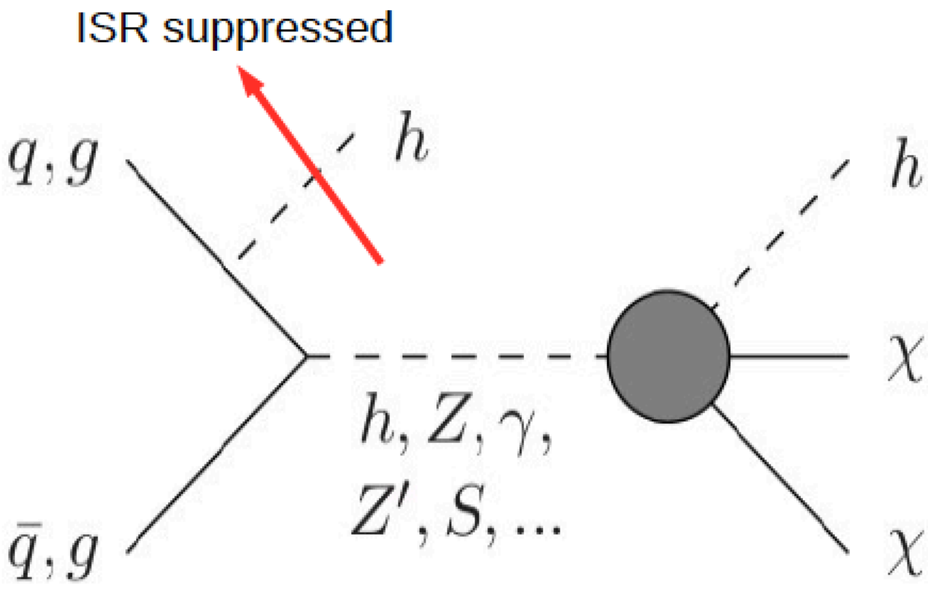
- Limits on cross section with 2D-scan of m_{DM} vs M_{MED} for vector/axial mediators
- BR(h(125)→ invisible) < 0.86 (0.70 expected), included ggZh





Mono-Higgs approach

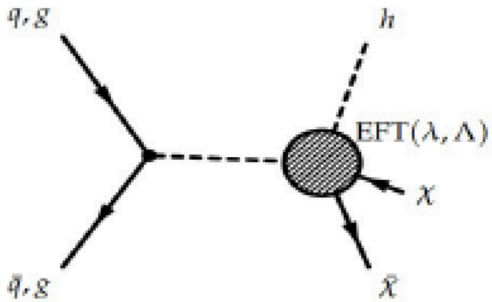
- Higgs discovery provides new portal into DM coupling to SM
- DM searches at the LHC include analyses with mono-X + MET signatures for X=W, Z, jet, and γ
- In general, X can be emitted as ISR or from the new vertex coupling DM to SM
- Higgs ISR is highly suppressed, so mono-H can directly probe the effective DM-SM coupling



Reference papers: *arXiv:1312.2592v2 [hep-ph], arXiv:1404.3716v2* [hep-ph]

Mono-higgs models

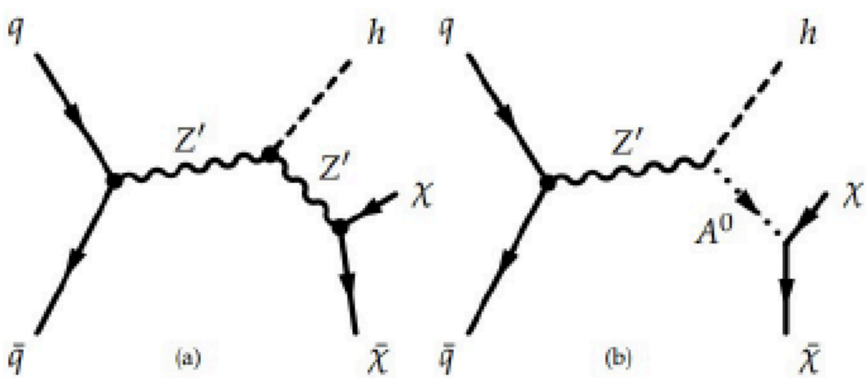
- Models consist of the union of models from Phenom papers arXiv:1312.2592 arXiv:1402.7074 and ATLAS-CMS DM Forum, with phenomenology studies for new models coming.
- Six EFTs: dimension 4 to 8 contact operators valid below cutoff scale Λ

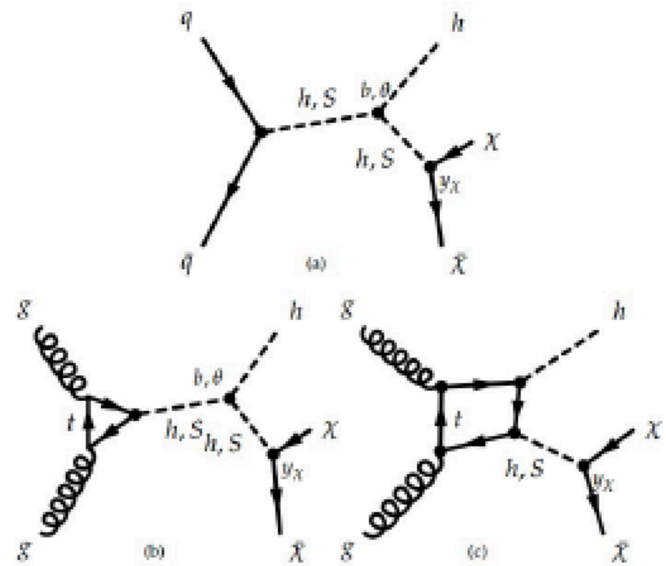


$$\lambda|H|^2\chi^2 \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}\chi \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi \qquad \frac{1}{\Lambda^2}\chi i\partial^\mu\chi H^\dagger iD_\mu H$$

$$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H \qquad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,.$$

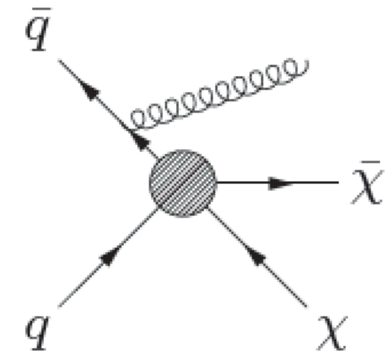
- Four simplified models: new massive mediator – Z', S, A^0 – for Higgs-DM coupling





EFT for mono-Higgs

- Effective Field Theory (EFT)
  - Assume heavy particle mediating interaction: contact interaction (integrate out mediator)
  - For M → ~40 TeV, where $\Lambda \equiv M/\sqrt{g_\chi g_q}$

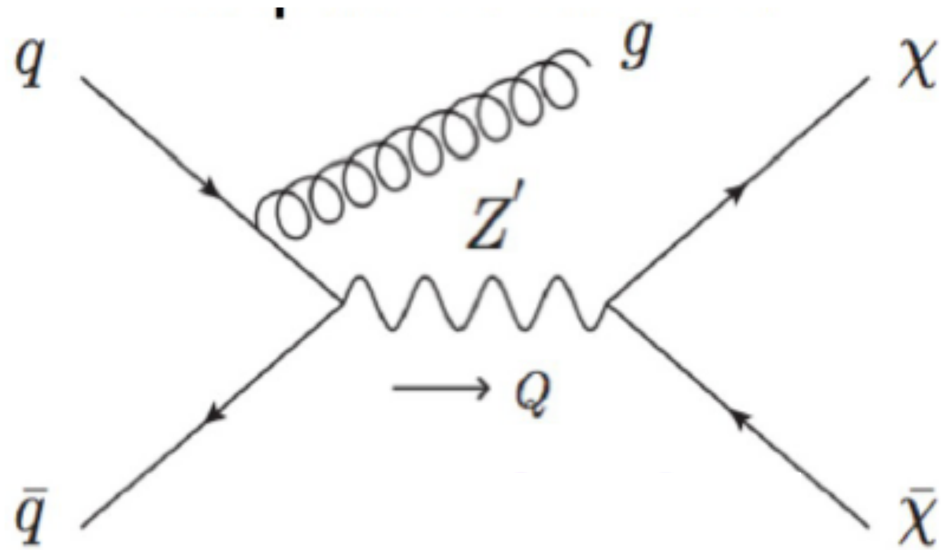


$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2 \approx \Lambda^{-4} E^2$$

- Simple model for comparison
  - ✓ Only a few parameters; dark matter mass m_χ and cut-off scale Λ
  - ✓ Much easier than e.g. a full SUSY model
  - ✓ Easy comparison to direct or indirect DM experiments
  - ✓ DM can be fermion (Dirac or Majorana) or scalar (complex or real)
  - ✗ Limitations on model validity ⇐ EFT lacks validity for high Q^2 since it violates unitarity
  - ✗ Probe only one interaction at a time

Simplified models for mono-Higgs

- Complete enough:
  - explicitly include mediators
- Simple enough:
  - minimal number of renormalizable interactions
- Valid enough:
  - satisfy all non-high pT constraints within parameter space



Dark matter models

- EFT
  - Dim 4: $\lambda|H|^2\chi^2$,
  - Dim 5: $\frac{1}{\Lambda}|H|^2\bar{\chi}\chi$, $\frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi$,

    Constrained by Br(H > invisible)
  - Dim 6:

    $$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H \quad \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi H^\dagger iD_\mu H\,, \quad \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi H^\dagger iD_\mu H\,.$$

    Constrained by Br(Z > invisible)
  - Dim 8:

    $$\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,, \quad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi W^a_{\mu\nu}H^\dagger t^a D^\nu H$$

    $$\frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}H^\dagger H\,, \quad \frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi W^a_{\mu\nu}H^\dagger t^a H$$

    Derivative couplings lead to more MET, better acceptance efficiency
- Simplified
  - Z' from extended gauge group: Gauge Baryon number B. Z' is (leptophobic) gauge boson of corresponding U(1)_B symmetry, spontaneously broken by "Baryonic Higgs" hB, which mixes with SM H.

    $$\mathscr{L}_{\text{eff}} = -\frac{g_q g_\chi}{m_{Z'}^2}\bar{q}\gamma^\mu q\bar{\chi}\gamma_\mu\chi\left(1 + \frac{g_{hZ'Z'}}{m_{Z'}^2}h\right)$$

  - Z' from hidden sector mixing with SM: DM charged under new U(1)', SM states neutral. Mass mixing between Z and Z' induces hZ' coupling.

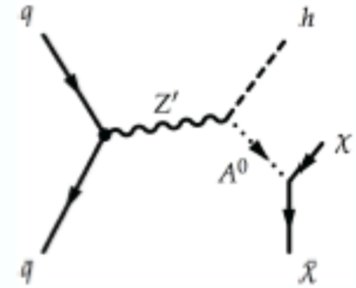
    $$\mathscr{L} \supset \frac{g_2}{2c_W}J^\mu_{\text{NC}}Z_\mu + g_\chi\bar{\chi}\gamma^\mu\chi Z'_\mu\,, \qquad \mathscr{L} \supset \frac{m_Z^2 s_\theta}{v}hZ'_\mu Z^\mu$$

  - Scalar S coupling to H: Real scalar singlet S with Yukawa coupling to DM mixes with SM through H only (renormalizability, gauge invariance). hS coupling from scalar potential:

    $$V_{\text{cubic}} \approx \frac{\sin\theta}{v}(2m_h^2 + m_S^2)h^2 S + bvhS^2 + \ldots$$

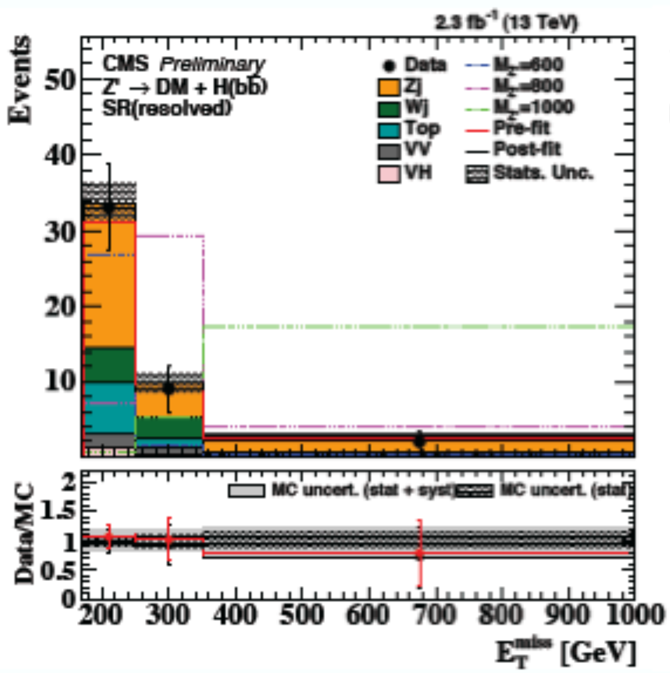
  - Z' coupled to a 2HDM: Type 2 2HDM with Z' gauge boson of U(1)_z'. Z' on shell decays to H and pseudoscalar A0. A0 has large branching fraction to DM

Mono-Higgs (bb,γγ)

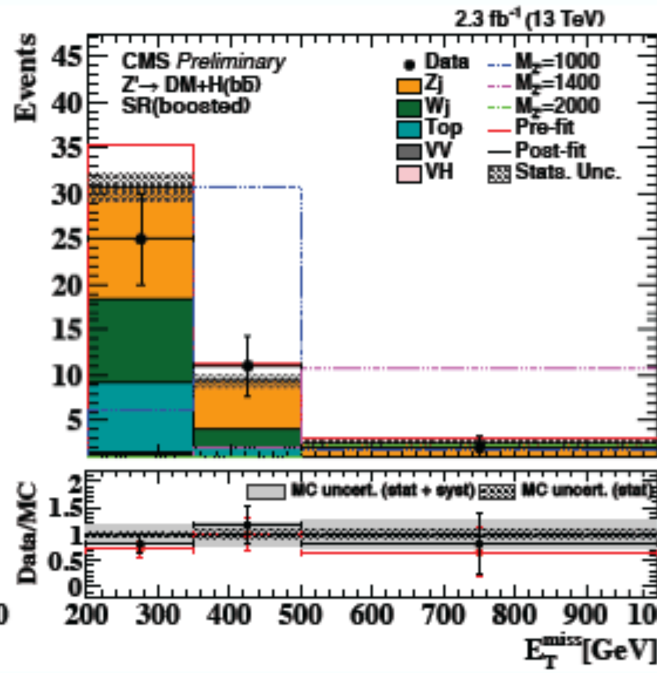


- Higgs→bb
  - Resolved: 2 AK4 b-tagged jets, p_T^{bb} / E_T^{miss} > 150 / 170 GeV
  - Boosted: 1 AK8 jet with subjets b-tagged, p_T^{j} / E_T^{miss} > 200 GeV
- Higgs→γγ: E_T^{miss}>105 GeV, $p_T^{\gamma\gamma}$>90 GeV, $p_T^{\gamma 1}(p_T^{\gamma 2})/m^{\gamma\gamma}$ > 0.5 (0.25)

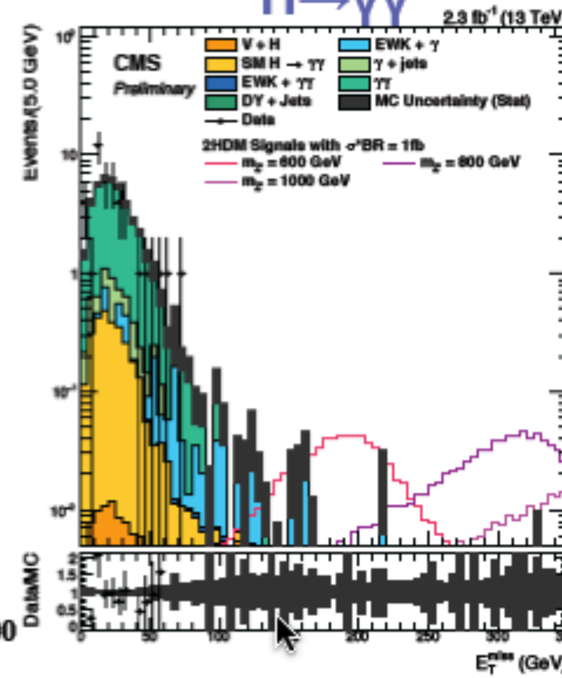
H→bb Resolved



H→bb Boosted

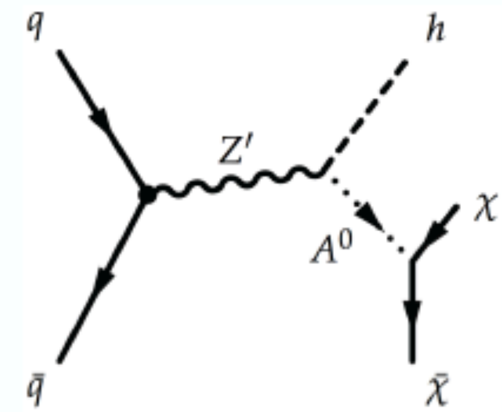


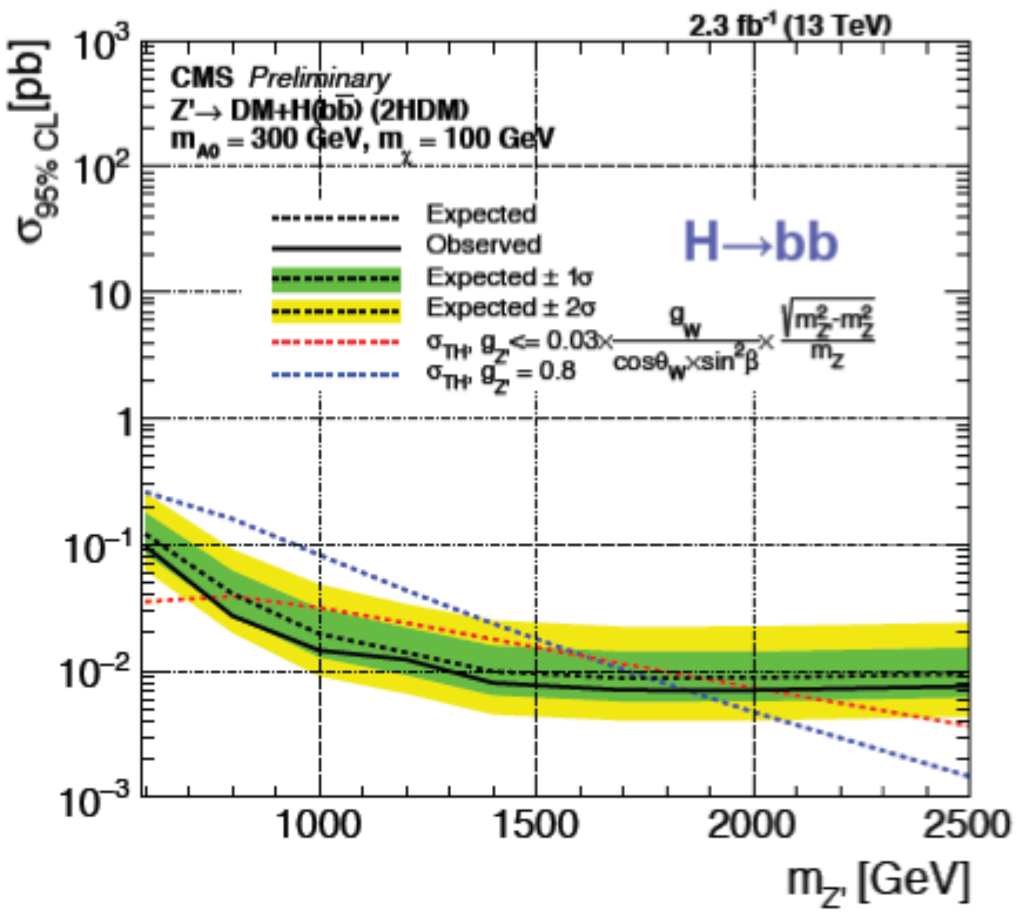
H→γγ

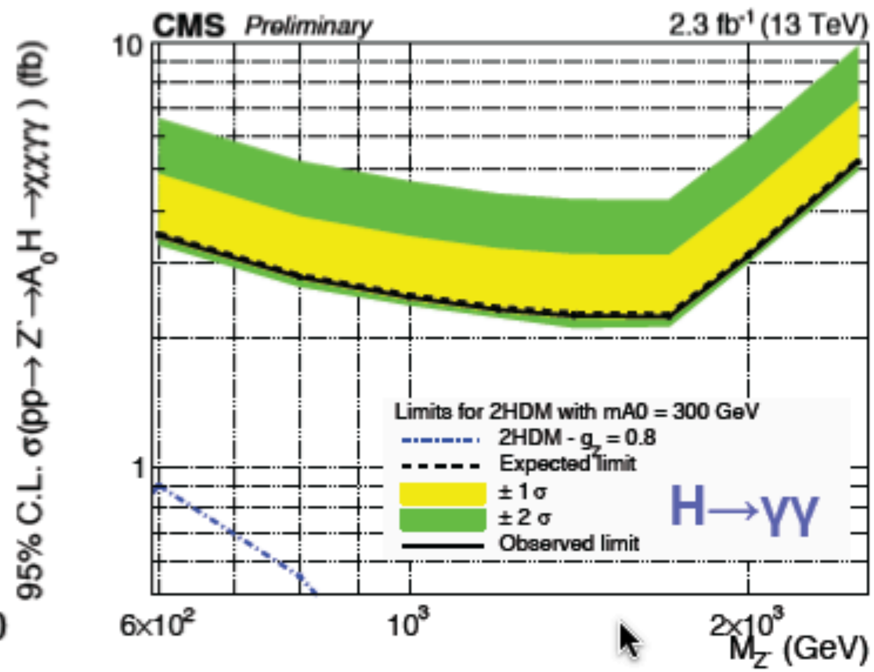


Mono-Higgs (bb,γγ)

- No excess observed, set limits on Type-2 2HDM
  - Excluded Mz'=600 (768) GeV to 1863 (2036) GeV with g_Z=0.8 (formula)

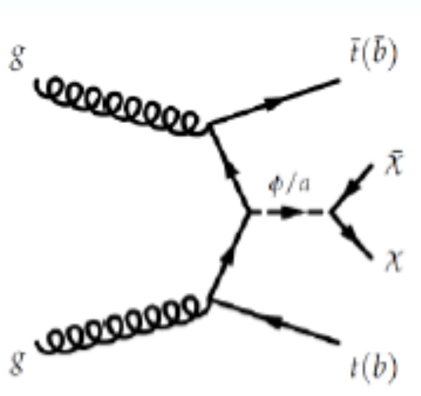


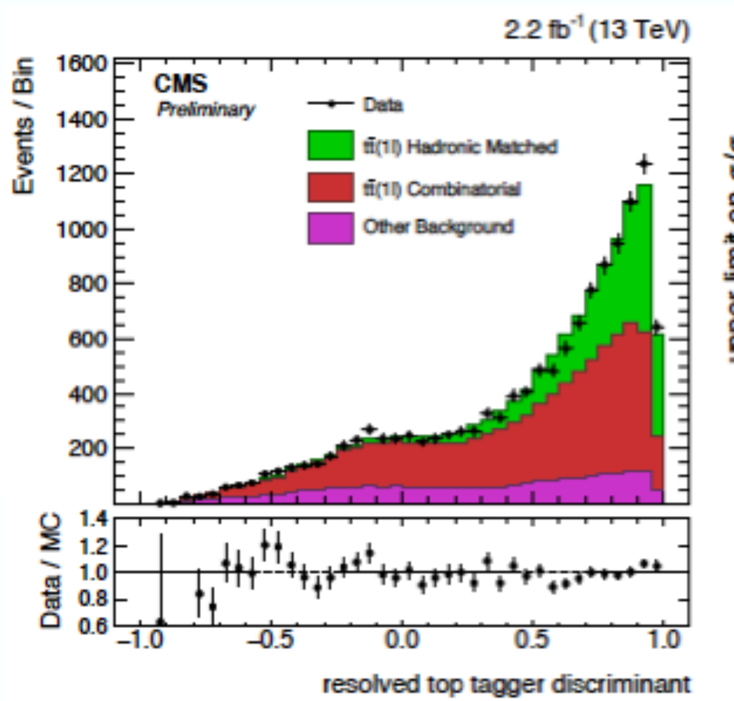


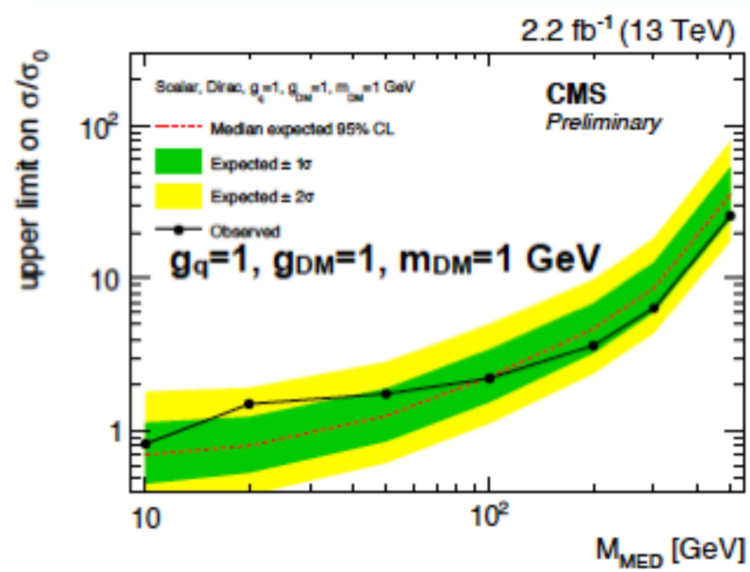


Mono-tt

- Hadronic (semileptonic) channel with E_T^{miss}> 200 (160) GeV
- Major background from ttbar events with one less hadronic top
  - Apply resolved-hadronic-top tagger to the hadronic channel and categorize events based on the number of top tags, b-tagged jets, and $\Delta\Phi(\text{jet}, E_T^{miss})$, up to 30% improvement
- No excess observed, limits on scalar/pseudoscalar mediators





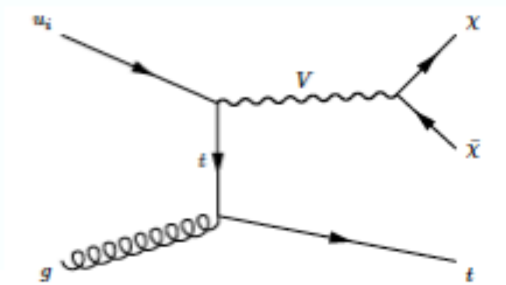


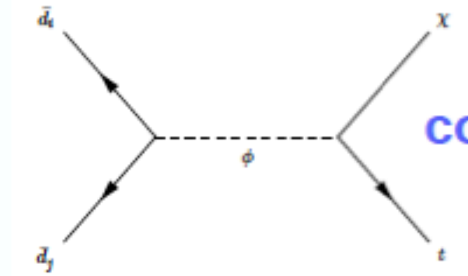
Mono-Top

2016 data

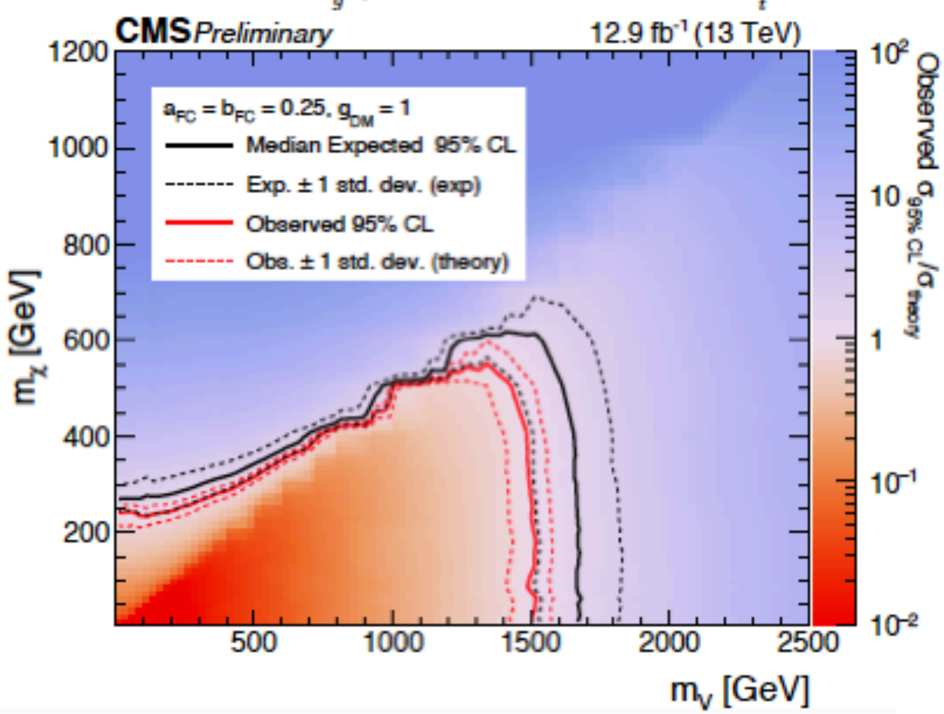
- p_{Tj}^{CA15} and E_T^{miss}> 250 GeV, mass 110-210 GeV, τ_{32}, subjet b-tag
  - Use PUPPI for pileup removal: JHEP10(2014)059
  - FCNC vector up to 1.5 TeV, charged scalar 0.9-2.7 TeV excluded

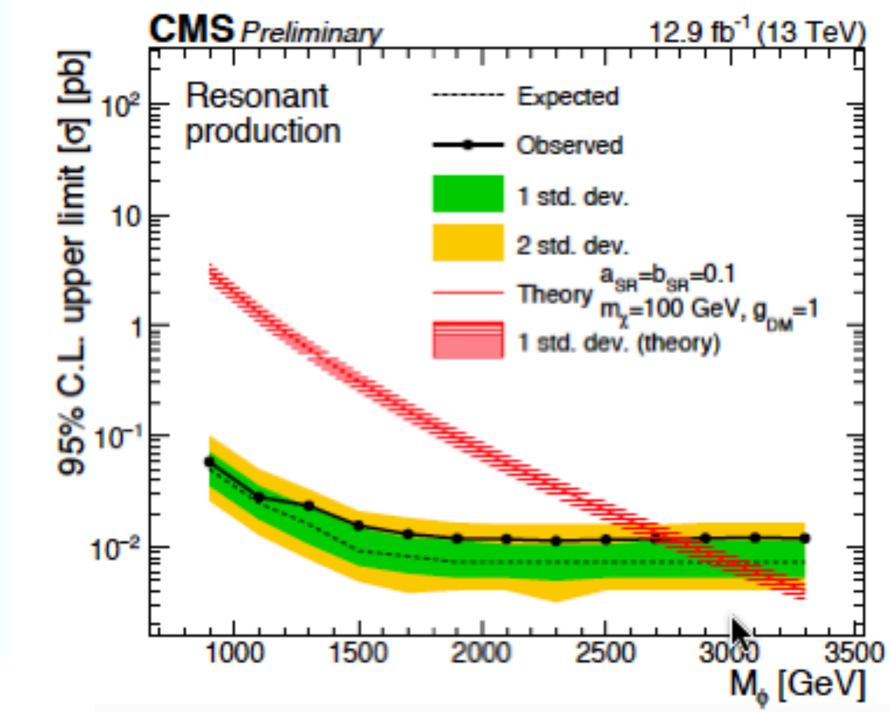
FCNC





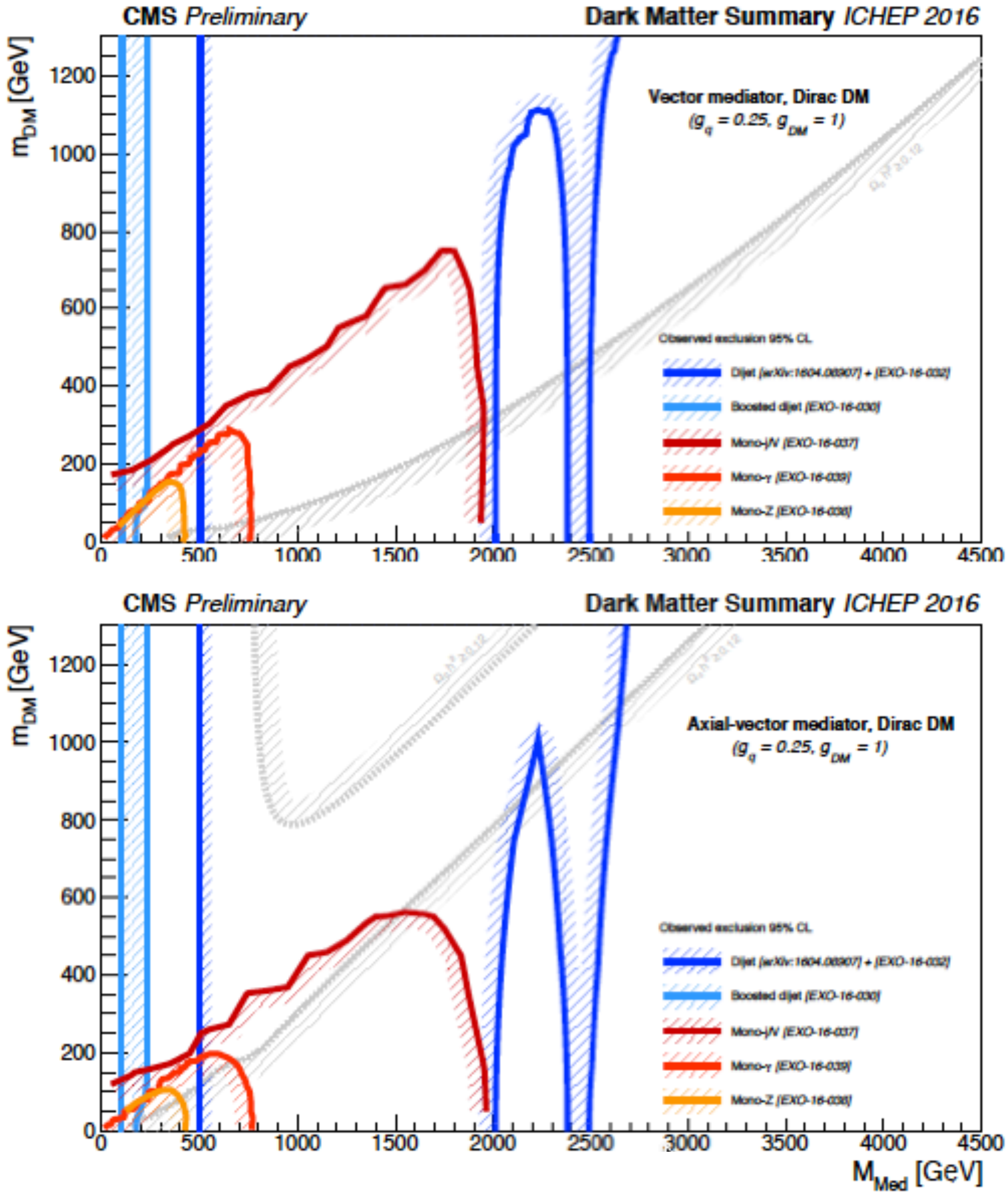
color-charged scalar





Summary Of Mono-X And Dijet Searches

- Fix g_q=0.25 and g_{DM}=1
- Reinterpret dijet searches with resolved and boosted jets
    - Cover the off-shell region
    - With reach of mediator mass 100-230 GeV and 600-2600 GeV



Summary and conclusions

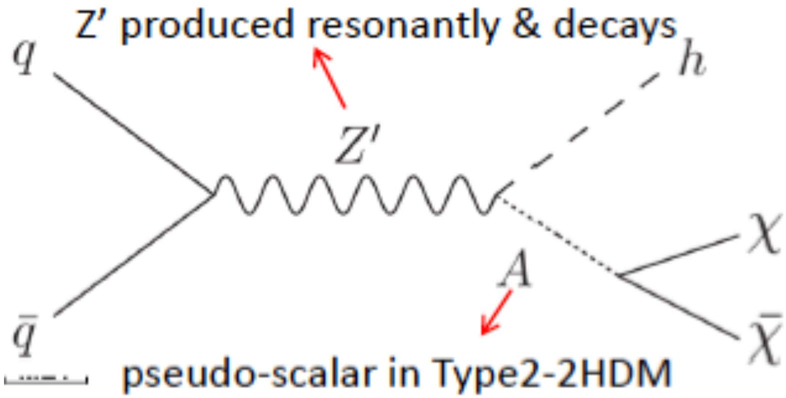
- Collider searches for DM: large **E_T^{miss} + visible object(s)**
  - Complementary to (in)direct detections; sensitive to both EFT and simplified models
  - The Increased LHC energy in 2015 and 2016 critical for searches in Run II → LHC has ability to complement other experiments

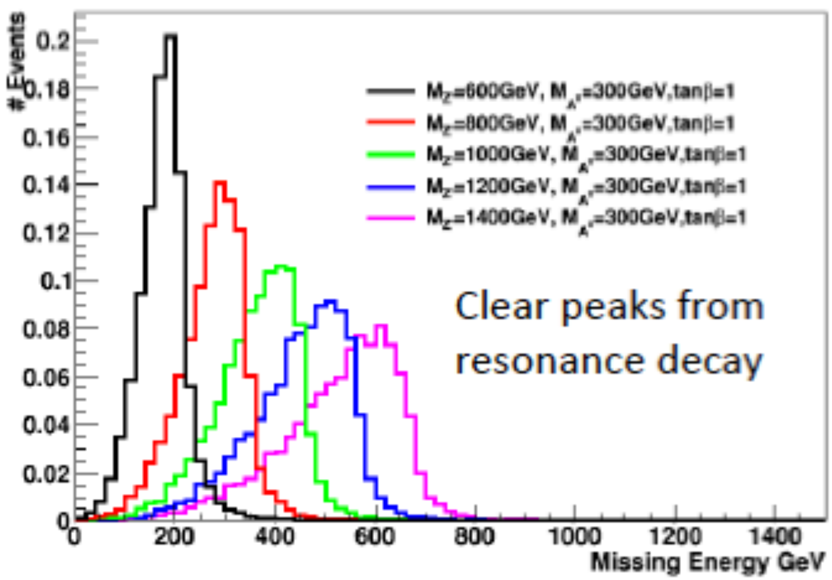
- CMS searches for dark matter have been performed with various mono-X final states
  - Results with 2016 data from mono-jet/photon/Z/top
  - First results from mono-Higgs and mono-tt (hadronic)
- No sign of excess yet
  - Provide limits on simplified models and EFTs
  - Results were recast in terms of nucleon-DM scattering cross section
- Expect updates with the full 2016 data and combinations of different mono-X channels

Backup

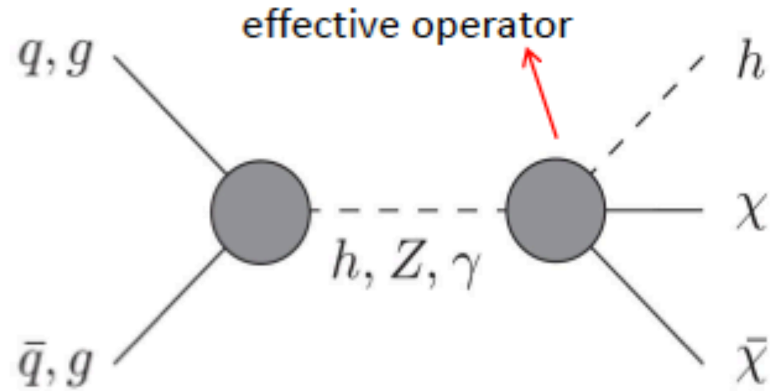
Simplified vs EFT models

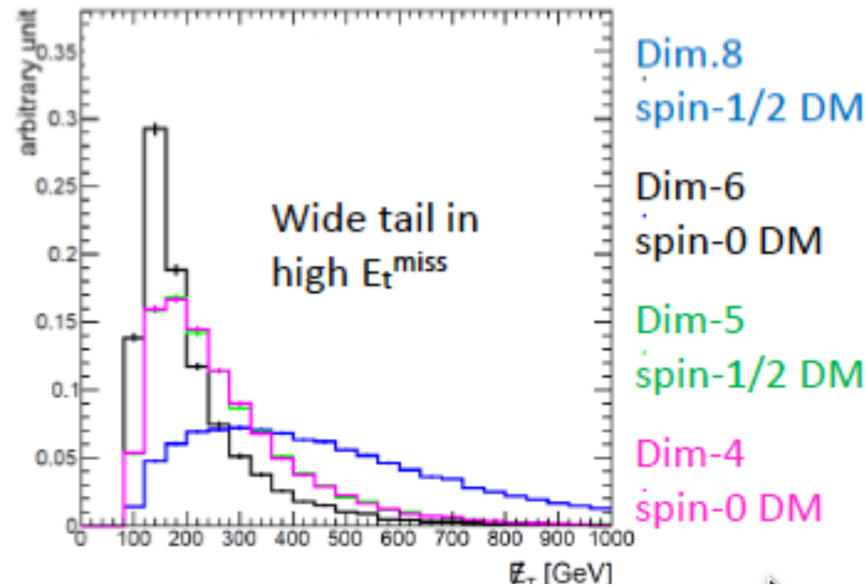
Simplified Model arXiv:1402.7074





EFT Model arXiv:1312.2592





Benchmark models cross sections

- Parameters for models taken from ATLAS-CMS DM Forum summarized in table below

Model:	Dim	SChi	Λ	Mchi [GeV]
hhxx_scalar	4	0	0.1	1,10,50,65,100,200,400,800,1000,1300
hhxx_combined	5	1/2	1000 GeV	""
hhxg5x	5	1/2	100 GeV	""
xdxhDhc	6	0	100,1000 GeV	""
xdxhDhs	6	0	1000 GeV	""
xgxFhDh	8	1/2	200 GeV	""

Model	Fixed parameters	Scan parameters
Z'_B	(gDM, gf, gz) = (1, 1/3, Mzp)	(Mchi, Mzp) = (Table 2.1)
Z'_H	(gDM, sp) = (1, 0.1)	(Mchi, Mzp) = (Table 2.1)
Scalar S	(gDM, sp, b) = (1, 0.3, 3)	(Mchi, Msc) = (Table 2.5)
Z' 2HDM	(Mchi, gz, Tb) = (100 GeV, 0.8, 1)	(Mzp, MA0) = ({0.6,0.8,1,1.2,1.4}TeV, {300,400,500,600,700,800}GeV, with MA0 < Mzp - mh)

(5 channels)*(6*8+36+36+33+30 mass points)*(100k events) = 91.5M events

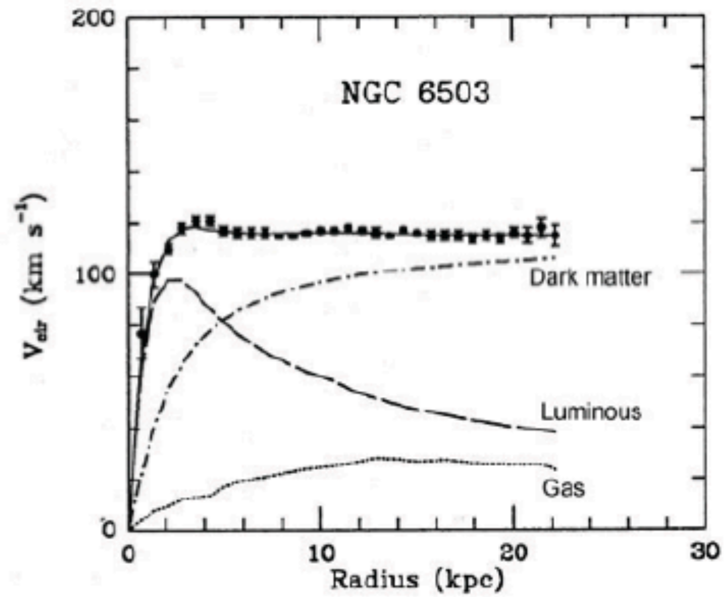
Evidence for Dark Matter: Coma cluster

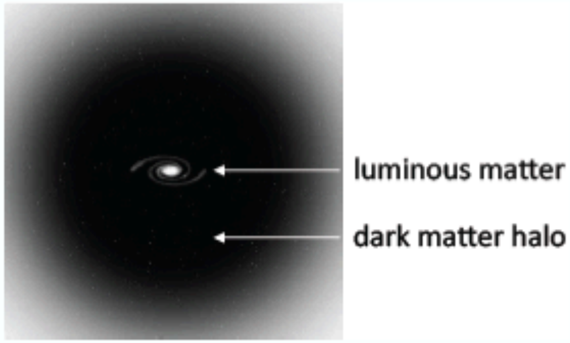
In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times larger than expected.

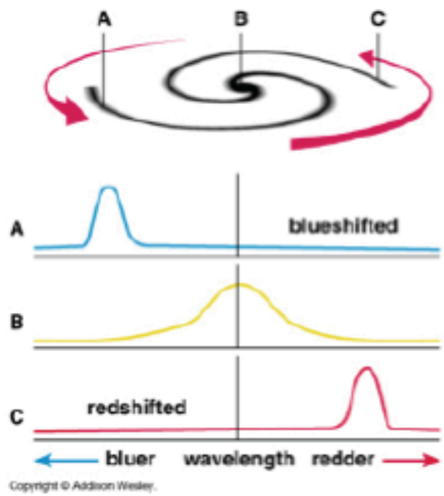
Now we know 90% of its mass due to Dark Matter

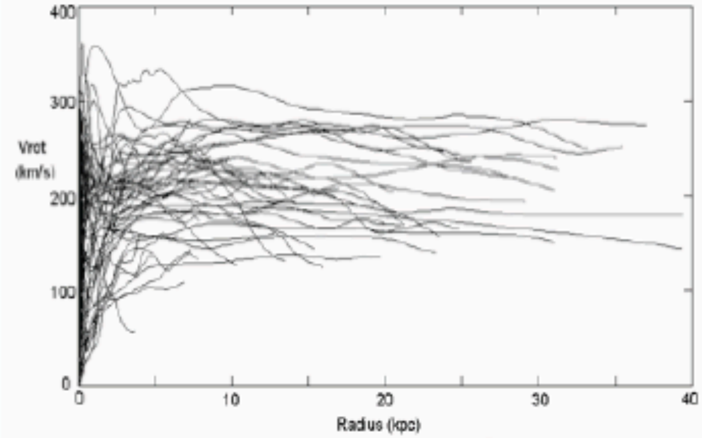
Evidence for Dark Matter: Galactic rotation

- Starting in 1970's, first measurements of the velocity curve of edge-on spiral galaxies
- Velocity found to be flat, consistent with ~10x as much "dark" mass for more than one galaxy









Evidence for Dark Matter: Bullet cluster

- Collision of galaxies in bullet cluster
  - lensing of background objects suggest at least 10x more Dark matter than visible mass

Evidence for Dark Matter: Gravitation lensing

- visible mass not sufficient to explain observed lensing effect