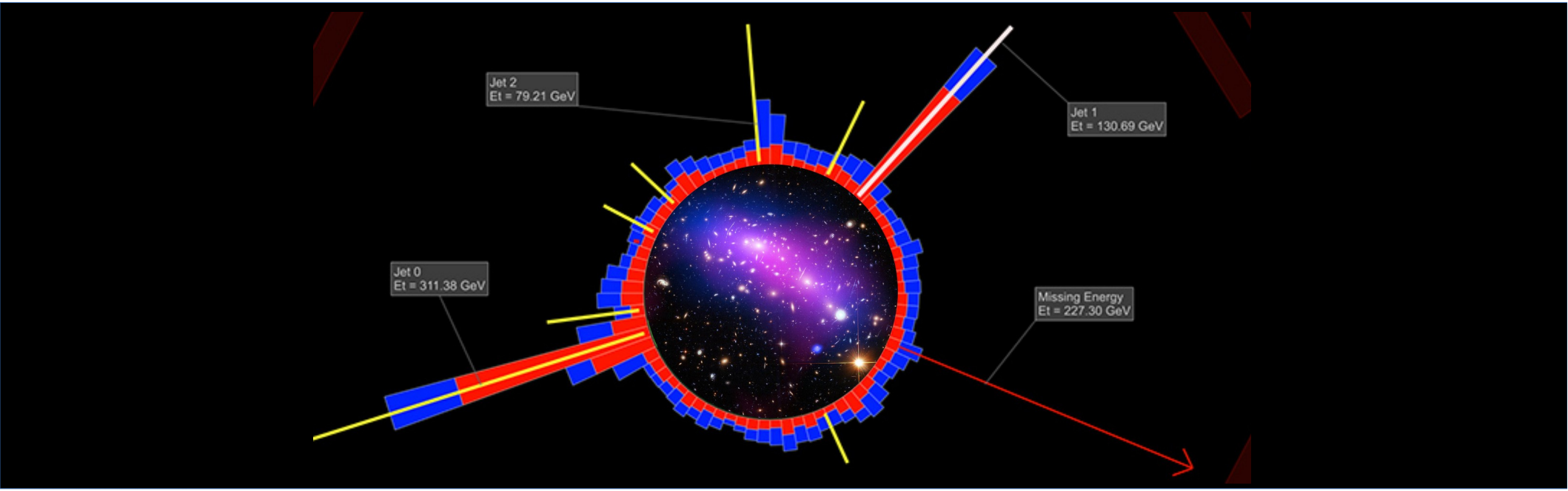
Dark Matter Searches at CMS



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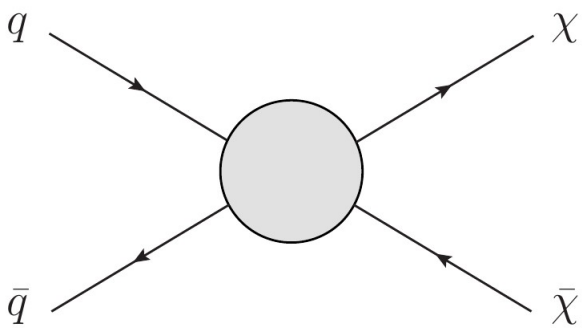
Northwestern University

"From the LHC to Dark Matter and Beyond"
Aspen 2017 Winter Conference
March 21, 2017

Searches for Dark Matter in CMS

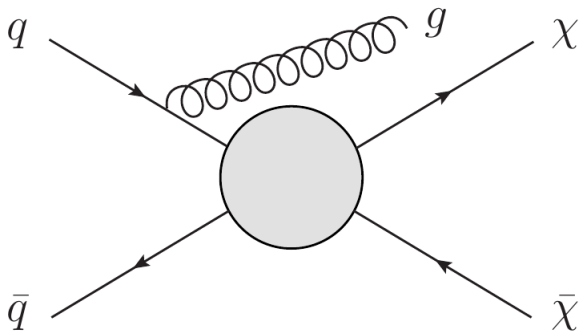
Look for generic DM signature of noninteracting particles



- Leaves no activity in the detector, nothing to reconstruct
- DM must instead recoil against *something* to become "visible"

"Mono-X" (or "E_T^{miss}+X") includes "X" for viable detection

- X: jets, photons, W/Z , Higgs, heavy-flavor ...



Modeling DM collider production

- Models used in the design and interpretation of DM searches
- Need to balance model complexity with predictive accuracy ...

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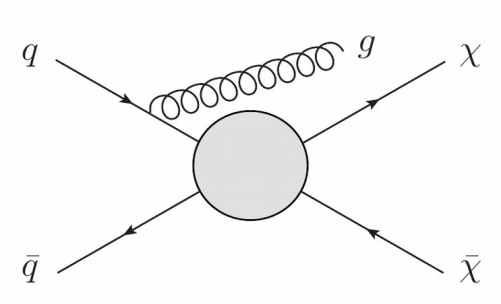
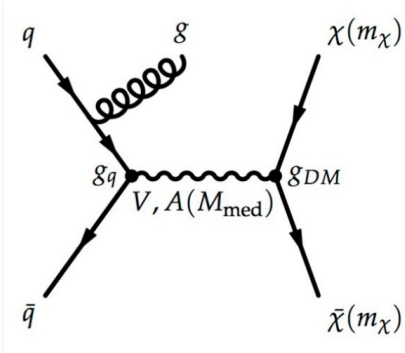
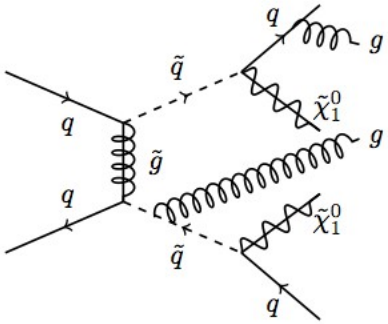


EFTs



Simplified Models



UV-complete Models

Simplified models: capture kinematics, lack completion

- Pair-produced DM Dirac fermions, χ
- Massive DM ↔ SM mediator, on/off-shell production
- Couplings: vector/axial/scalar/pseudo
- Minimal flavor violation
- Minimal mediator width: couples only to SM and χ

Only four parameters:
g_q, g_{DM}, m_χ, M_{med}

Simplified models/benchmarks from the LHC Dark Matter Forum: 1507.00966

The mono-X Searches

X	Dataset	Documentation
jet or hadronic V	2016, 12.9 fb-1	EXO-16-037, 1703.01651
photon	2016, 12.9 fb-1	EXO-16-039
Z(ll)	2016, 12.9 fb-1	EXO-16-038
Higgs (γγ)	2015, 2.3 fb-1	EXO-16-011
Higgs (bb), with γγ combo	2015, 2.3 fb-1	EXO-16-012
tt (hadronic, semileptonic)	2015, 2.2 fb-1	EXO-16-005
tt (dileptonic + tt combination)	2016, 2.2 fb-1	EXO-16-028
t hadronic	2016, 12.9 fb-1	EXO-16-040
bb	2015, 2.2 fb-1	B2G-15-007

Direct Mediator Production	Dataset	Documentation
dijets	2016, 12.9 fb-1	EXO-16-032, 1611.03568
boosted dijets	2016, 2.7 fb-1	EXO-16-030
dijets	2016, 27+36 fb-1	EXO-16-056

monojet / mono-V

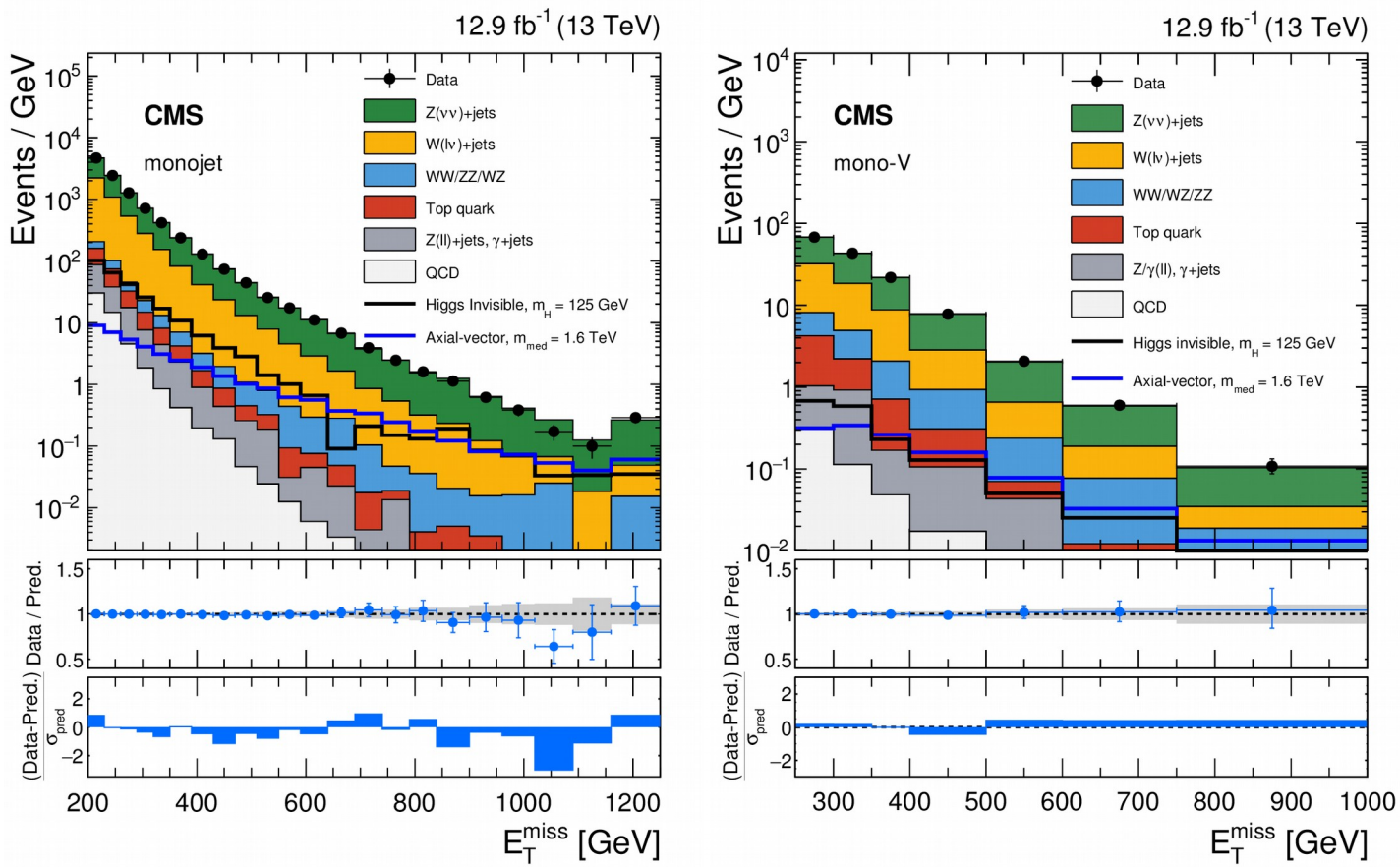
Selection : large E_T^{miss}, ≥ 1 high-p_T jet

- Mono-V : p_T^{AK8}, E_T^{miss} > 250 GeV, m_{jj} 65-105 GeV, τ_{12} < 0.6
- Mono-jet : remaining events, p_T^{AK4} > 100 GeV, E_T^{miss} > 200 GeV

Signal from E_T^{miss} fit, dominant bkgs : Z(νν)+jets, W(l_{lost}ν)+jets

Control regions constrain bkgs. @ high-E_T^{miss}

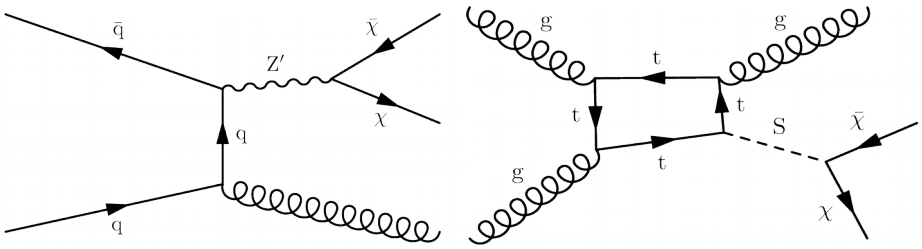
- Z(μμ), W(l_{obs}ν), high-stat γ+jet
- NLO+EWK γ/Z and W/Z transfer factors extrapolate from CR→SR

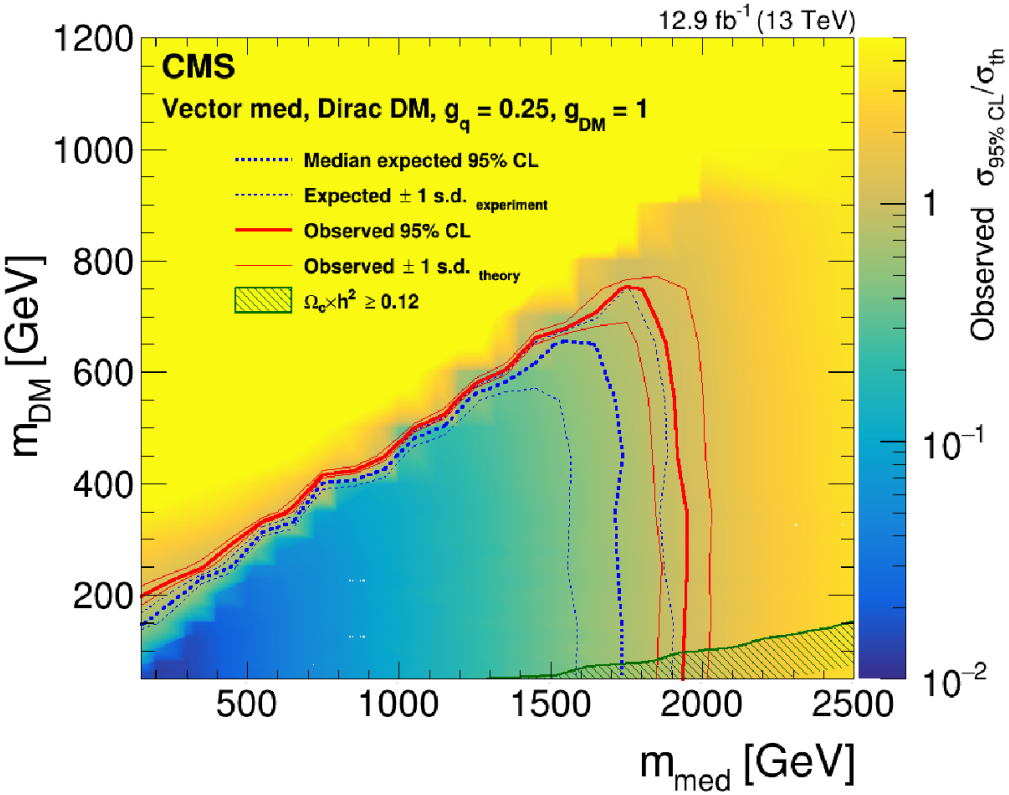


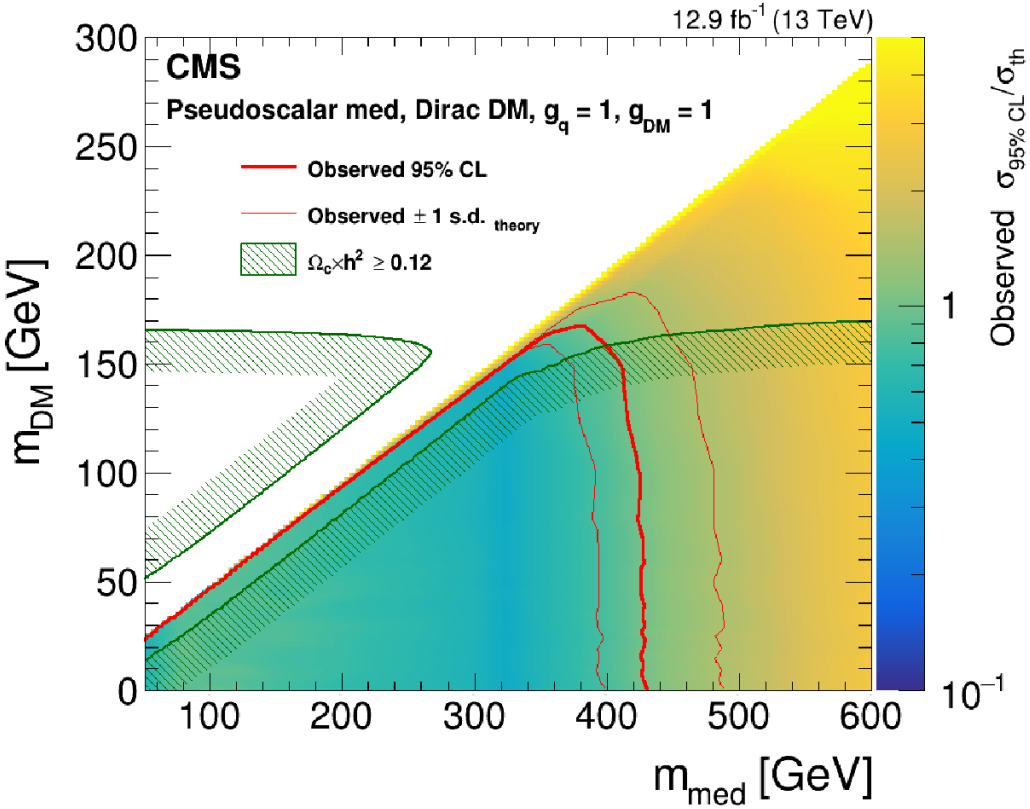
monojet / mono-V

Both spin-1 and spin-0 mediators

- Vector/Axial exclusion up to 1.95 TeV
- Scalar(*)/Pseudo up to 100/400 GeV





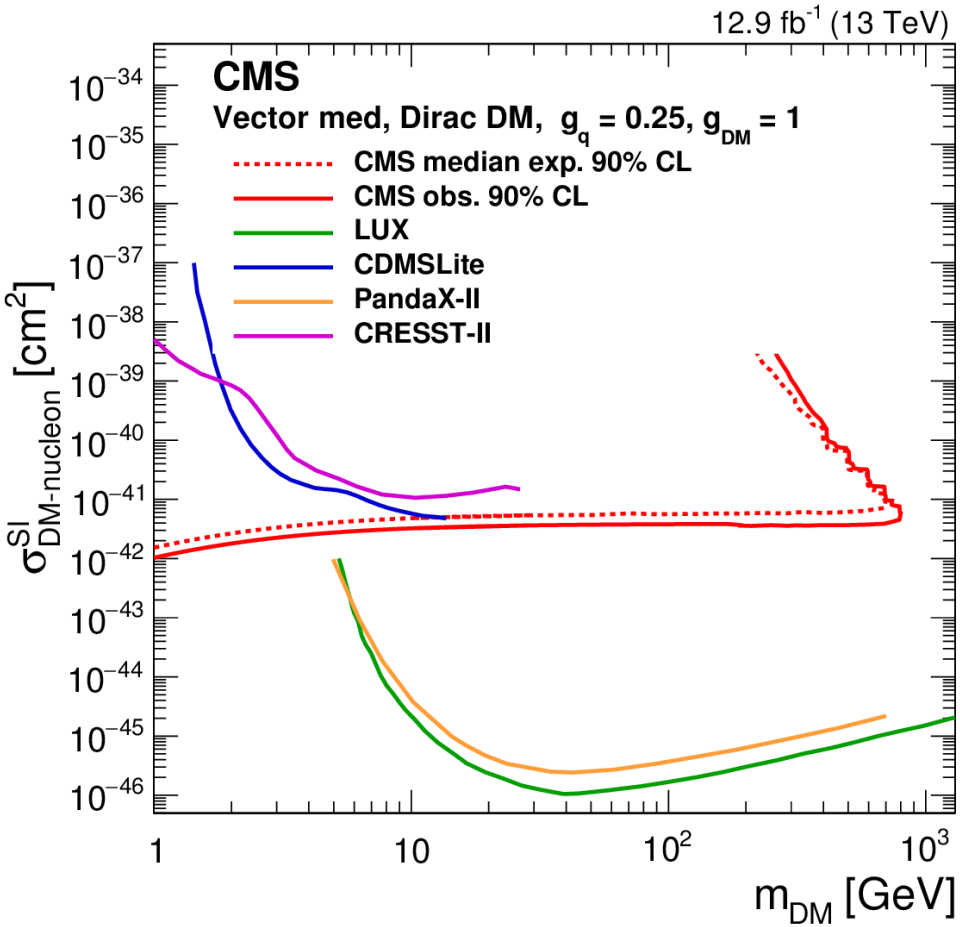


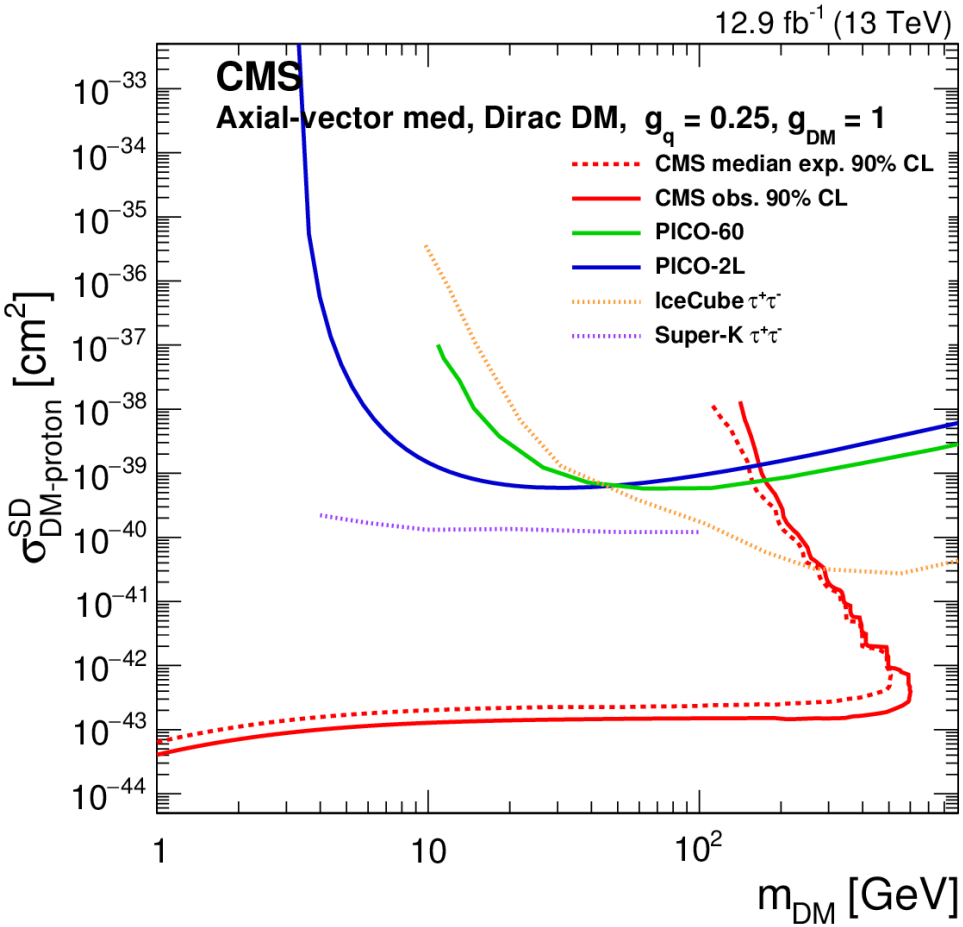
(*) Scalar exclusion assuming mediator coupling to bosons, no exclusion otherwise

monojet / mono-V

Reinterpret as invisible Higgs : BR(h→inv.) < 0.44 (0.56 exp.)

Recast as limits on SI/SD DM-nucleon cross section





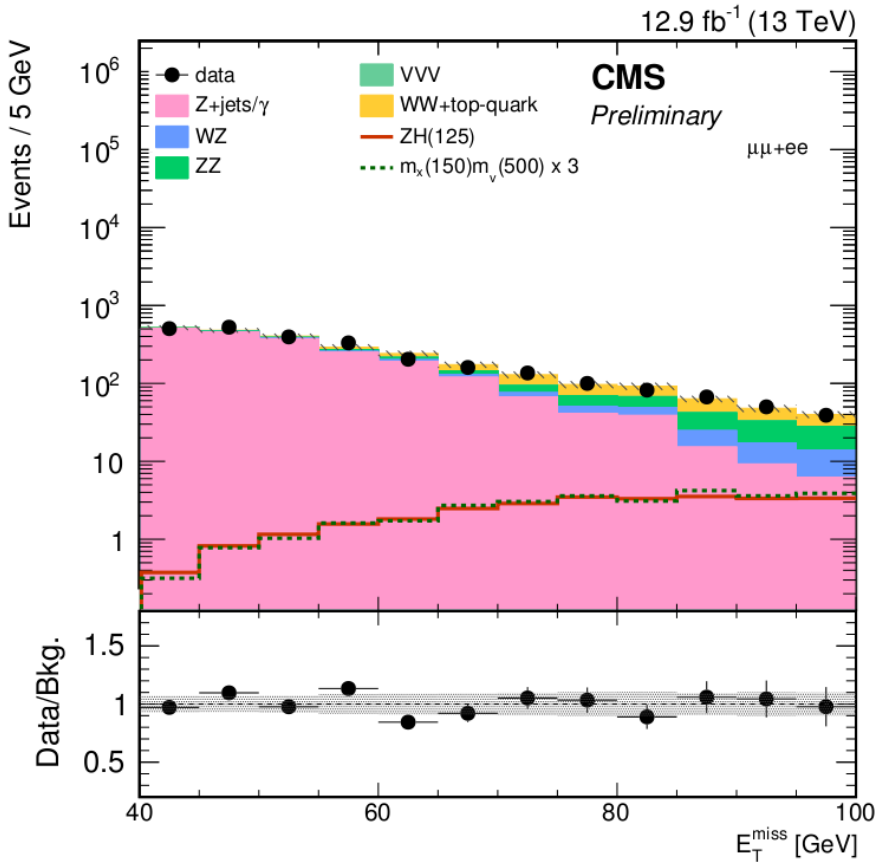
Low-mDM reach complimentary to direct detection!

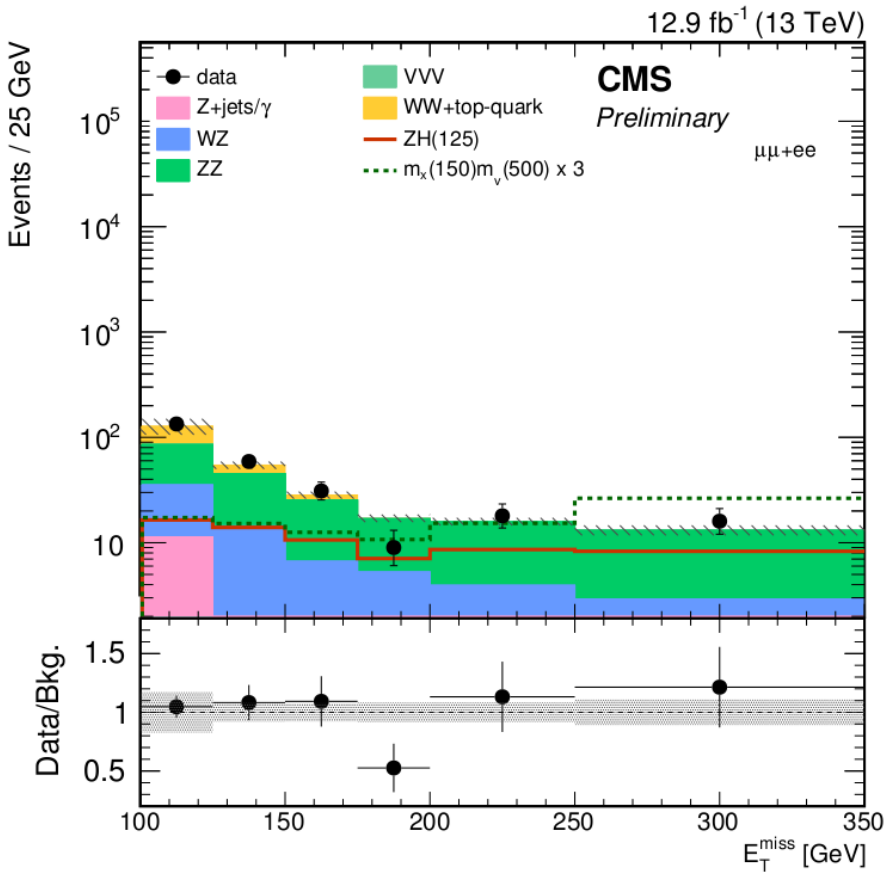
mono-Z(ll)

Selections: E_T^{miss} > 100 GeV, ee/μμ with p_T^{ll} > 60 GeV , E_T^{miss} / p_T^{ll} balance, vetoes on extra e, μ, τ, b-jet, jets

Dominant Bkg: ZZ/WZ, estimated w/ MC @ NNLO-QCD, NLO-EWK

Non-resonant bkgs. (eg: tt, WW, tW) estimated from eμ data

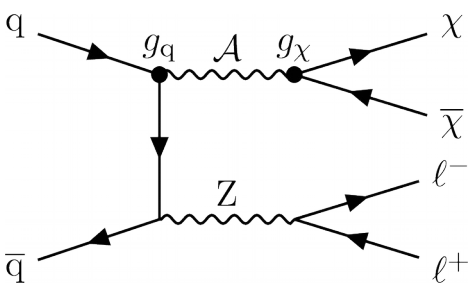


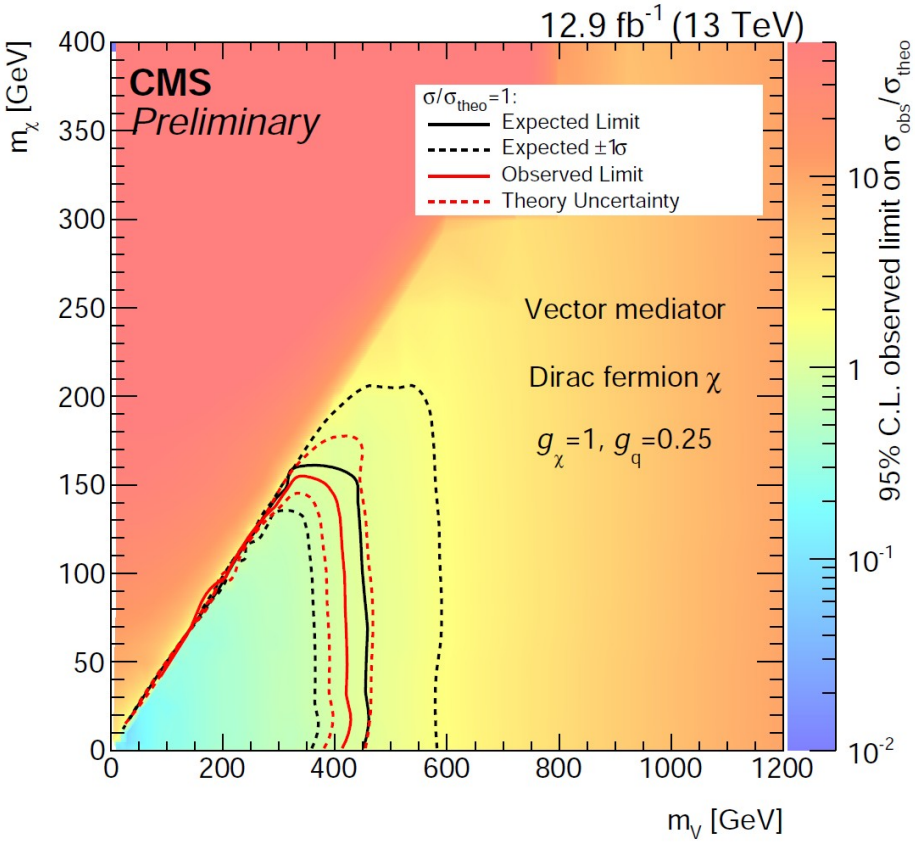


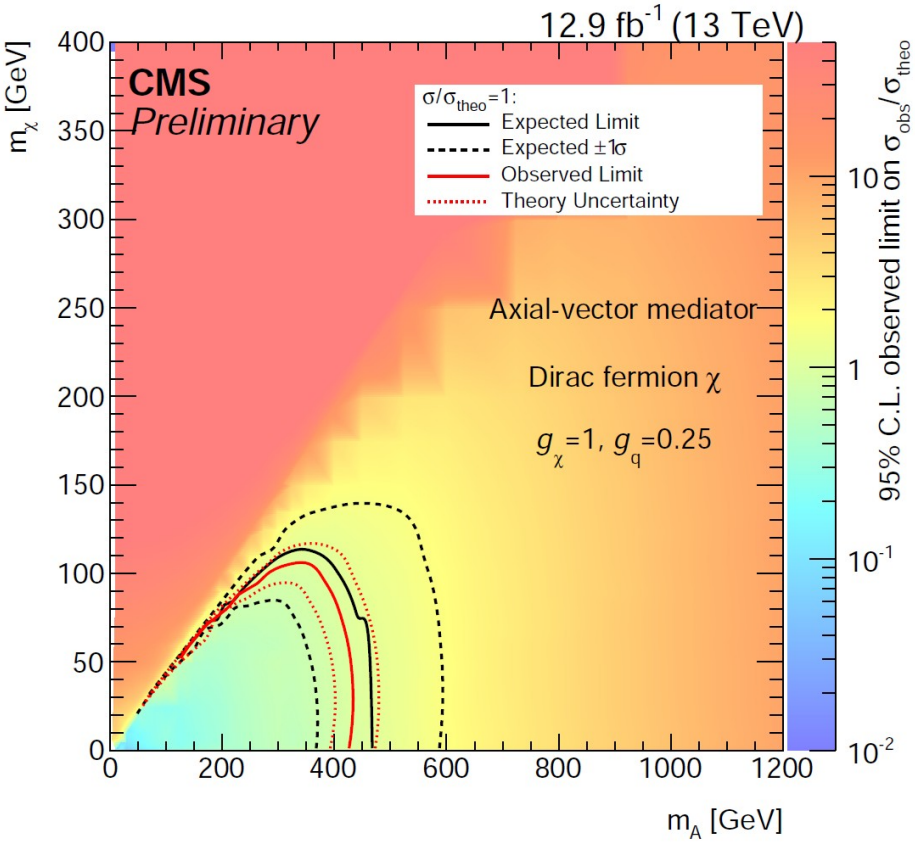
mono-Z(ll)

Limits for vector/axial mediator of 450/470 GeV

BR(h → invisible) < 0.86 (0.70 exp.)





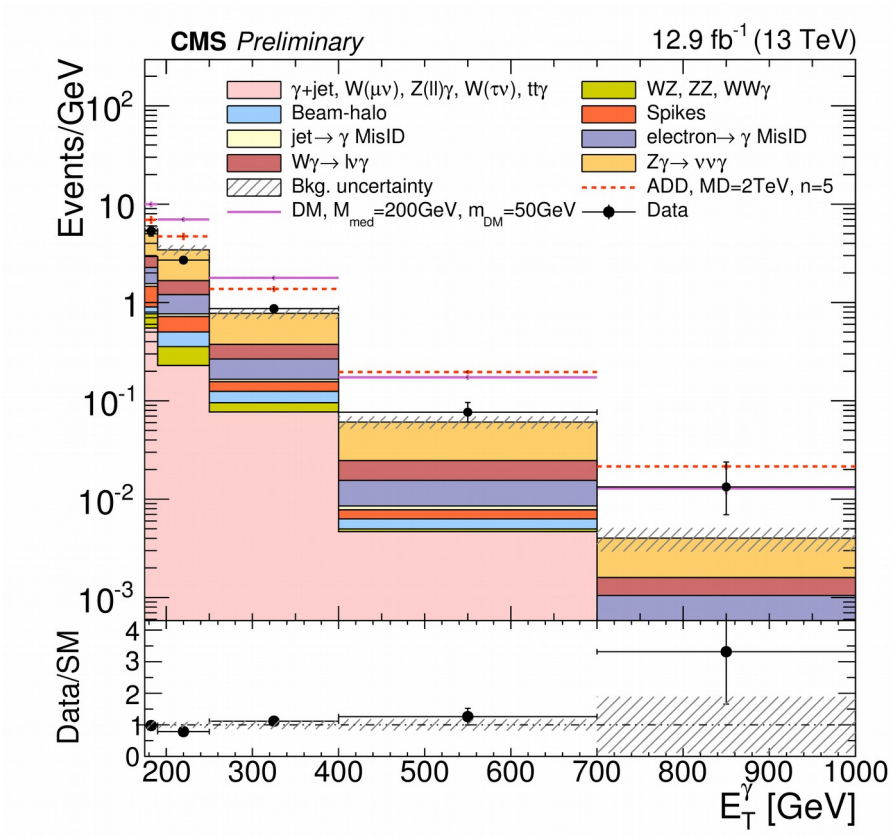


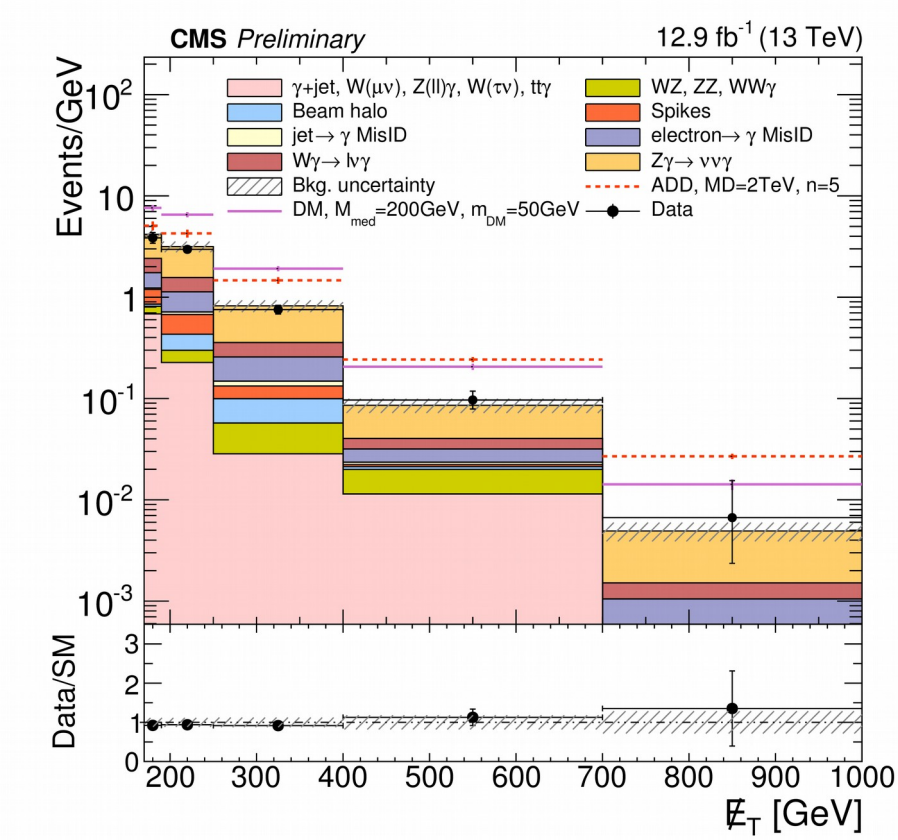
mono-photon

Selections: E_T^{miss} > 170 GeV, p_T^{γ} > 175 GeV , vetoes on extra e, μ

Dominant Bkg: Z(νν)γ, W(lν)γ, estimated with MC @ NNLO-QCD (DYRES), NLO-EWK corrections

MisIDed lepton, noncollision background estimated from data



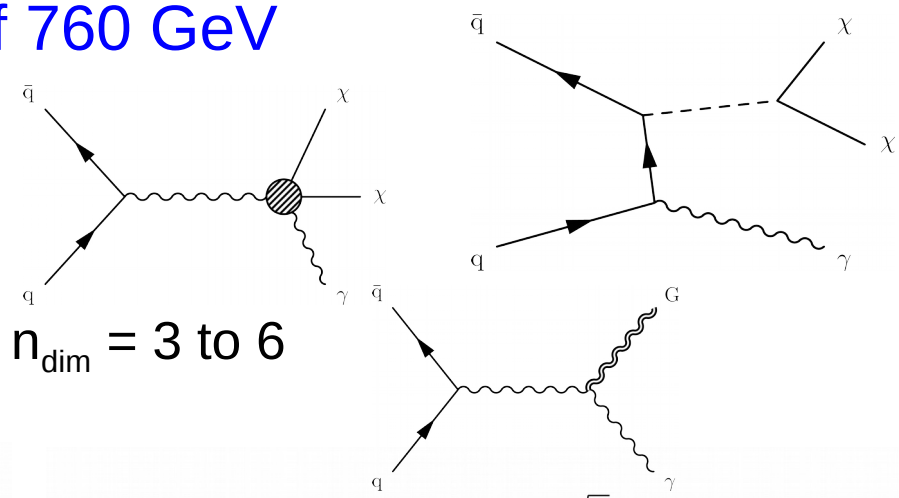


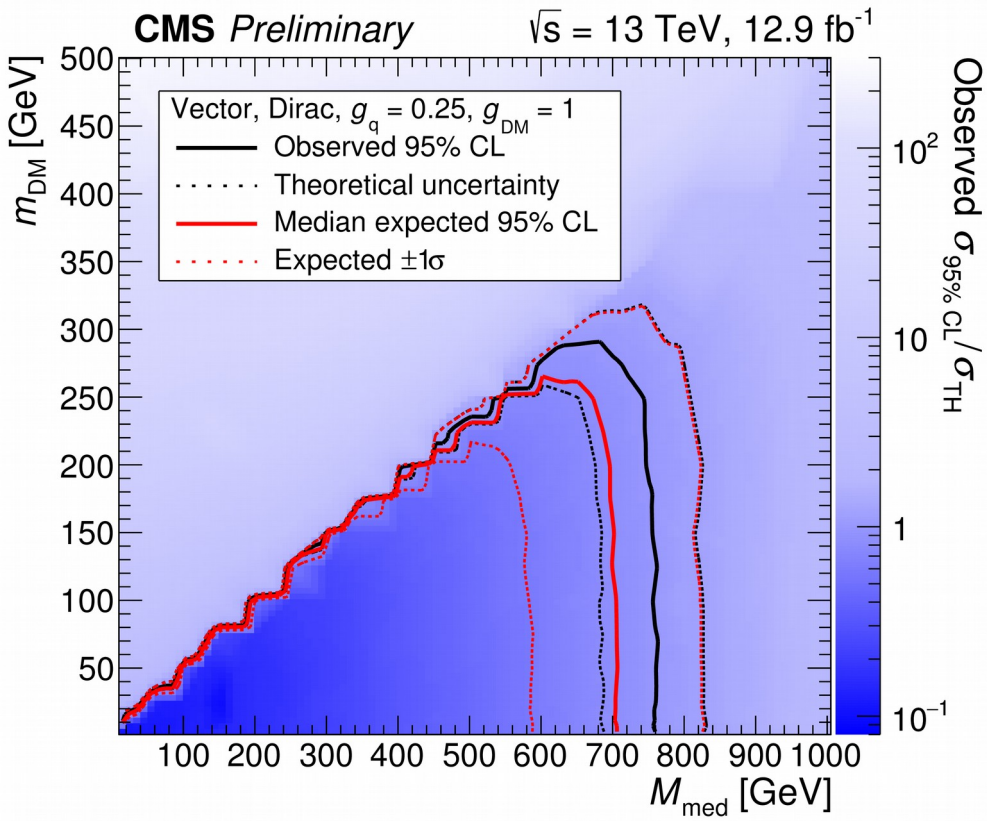
mono-photon

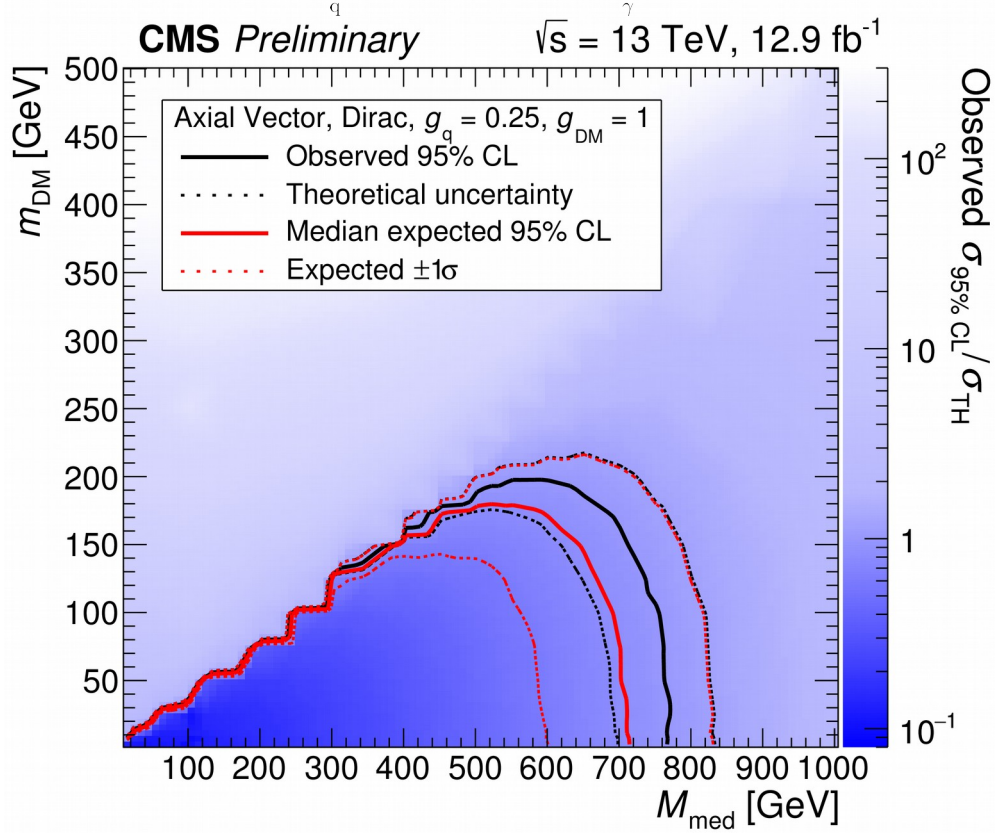
Limits for vector/axial mediator of 760 GeV

Also:

- Dim-7 EFT scale up to 620 GeV
- ADD LED M_D > 2.44 to 2.60 TeV for n_{dim} = 3 to 6





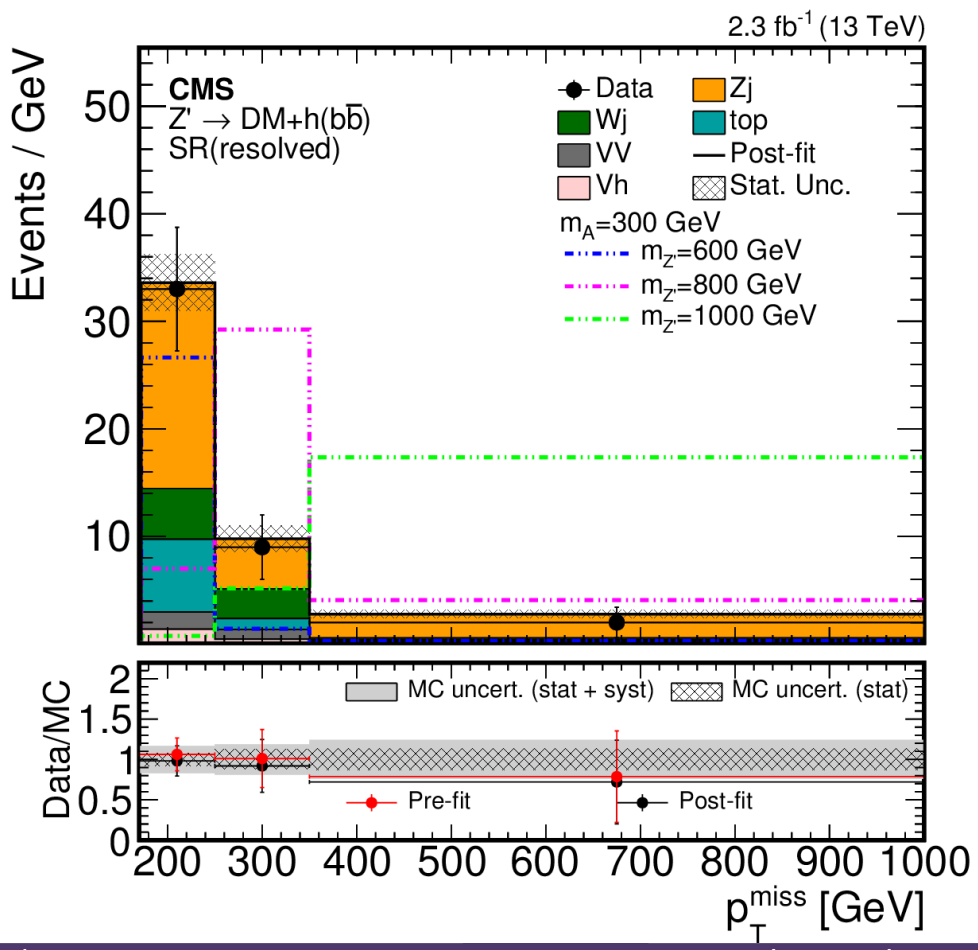


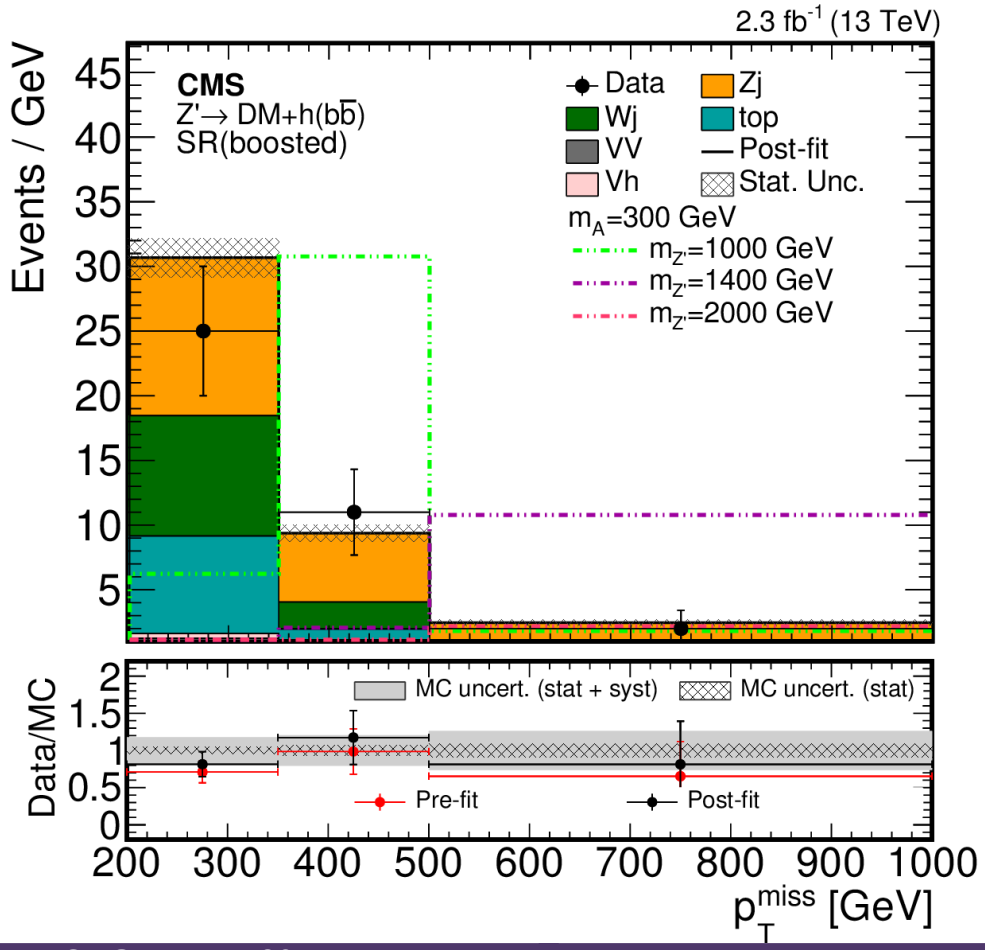
mono-Higgs

Higgs → bb, categorized according to Higgs p_T

- Resolved: 2 AK4 jets, b-tagged, p_T^{bb} > 150 GeV, E_T^{miss} > 170 GeV
- Boosted: 1 AK8 jet, subjet b-tagged, p_T^{j} & E_T^{miss} > 170 GeV

Higgs→γγ: $p_T^{\gamma\gamma}$ > 90 GeV, E_T^{miss} > 105 GeV, $p_T^{\gamma 1}$ ($p_T^{\gamma 2}$) / $m^{\gamma\gamma}$ > 0.5 (0.25)

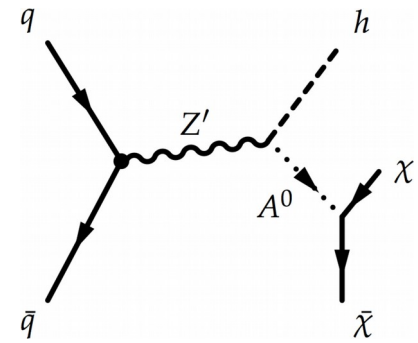


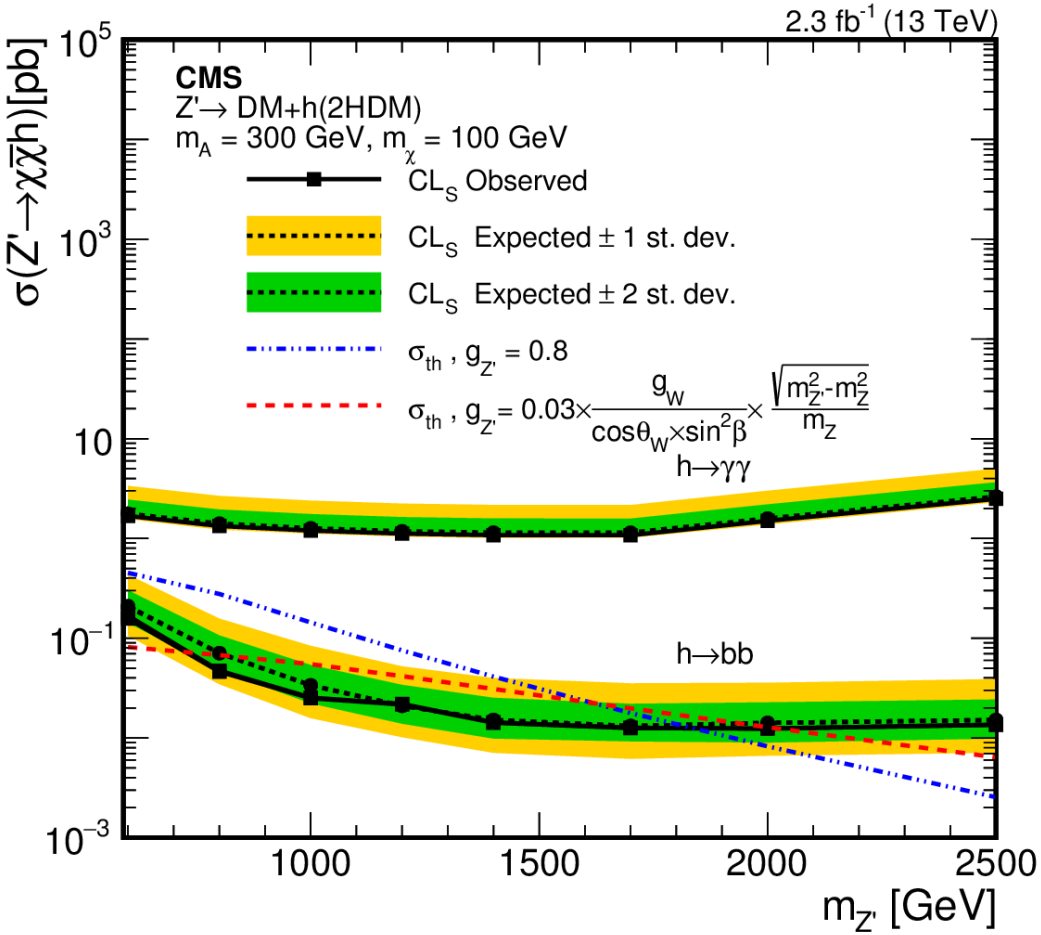


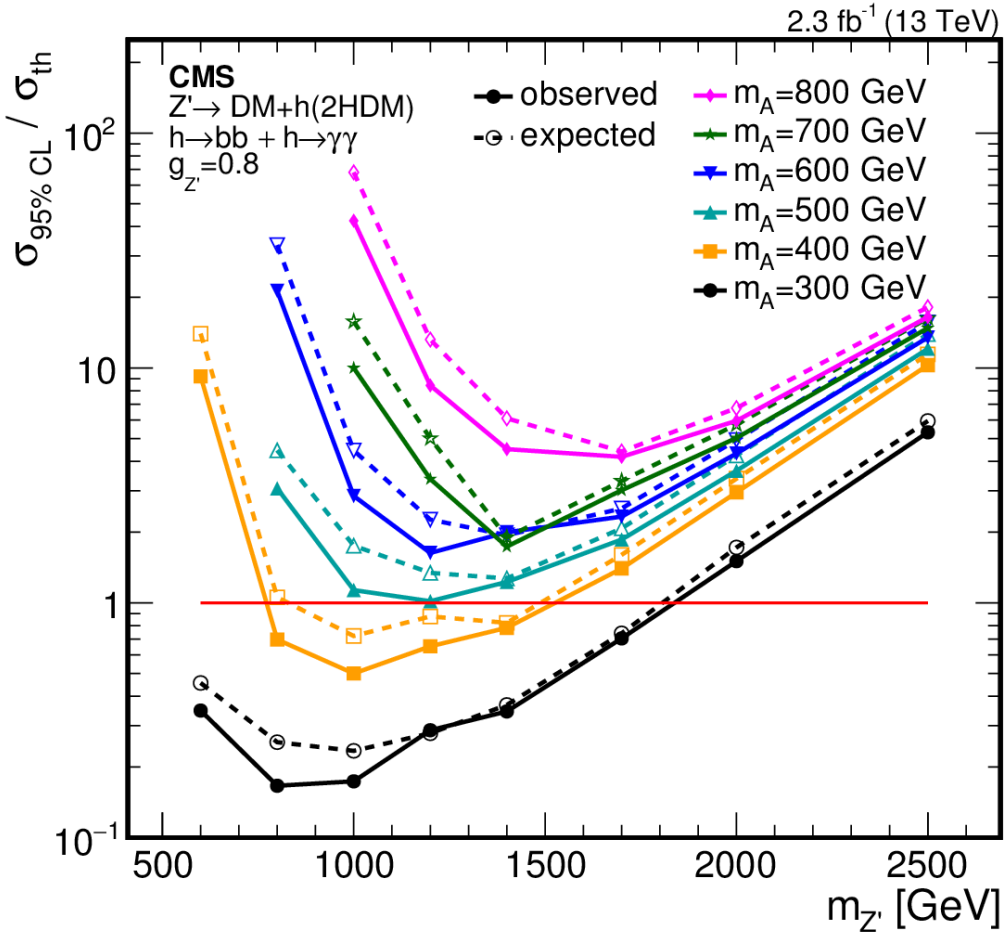
mono-Higgs

Limits on Type-II 2HDM + DM model

- Exclude mZ' between 600-1863 GeV for gZ' = 0.8
- Between 768-2086 GeV for EWK-constrained gZ' (formula)



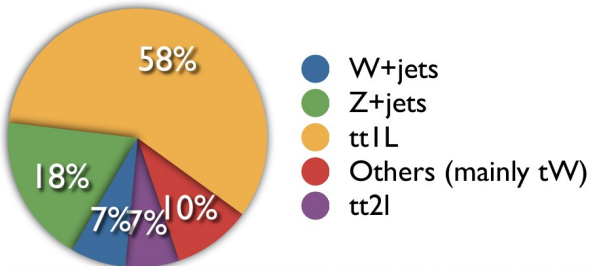


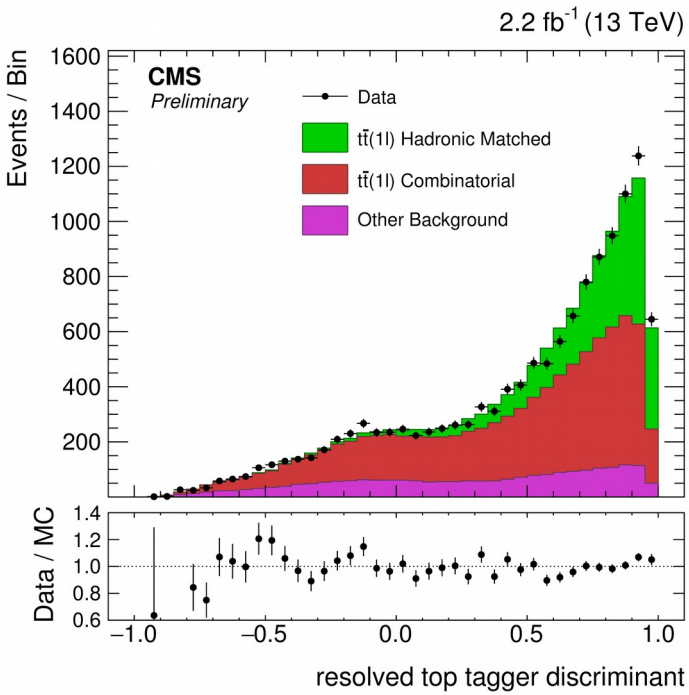


ttbar + DM

CMS-PAS-EXO-16-005: semileptonic + all-hadronic

- E_T^{miss} > 200 for all-hadronic, E_T^{miss} > 160 GeV, p_T^{l} > 30 GeV for semileptonic, both use b tag and min$\Delta\varphi$(jet, E_T^{miss}) requirements
- Dominant background from SM ttbar with one less hadronic top. Not the case for signal
- Employ *resolved* top quark tagger to categorize signal and bkg according to signal purity
- Simultaneous E_T^{miss} fit using 3 signal + 9 control regions



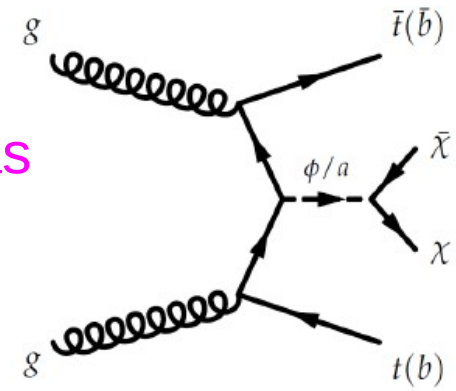


CMS-PAS-EXO-16-029 : dileptonic & combination w/ semileptonic + hadronic

- Dileptonic: E_T^{miss} > 50, 2 leptons p_T^{l} > 30 GeV, ≥ 1 b tag, min$\Delta\varphi$(jet, E_T^{miss})
- Irreducible dileptonic SM ttbar background

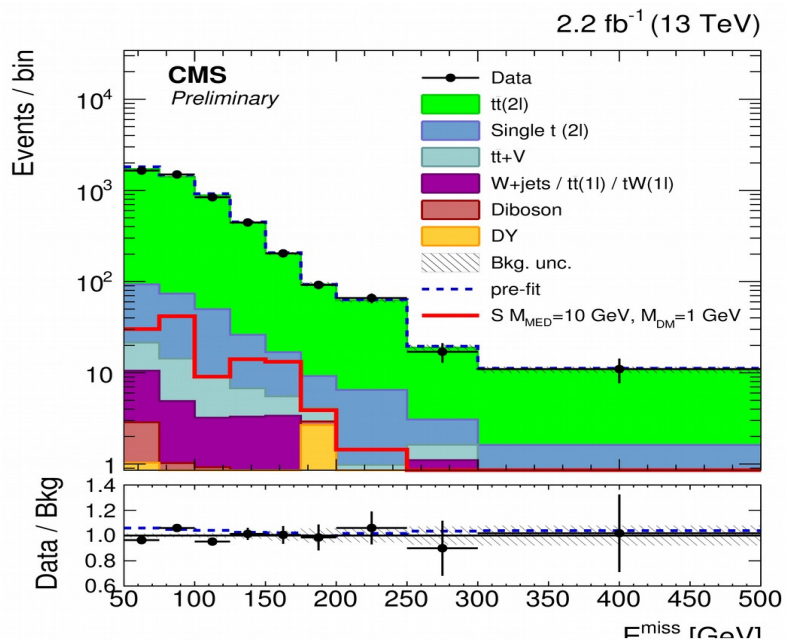
ttbar + DM

Direct probe of Yukawa coupling of spin-0 mediators

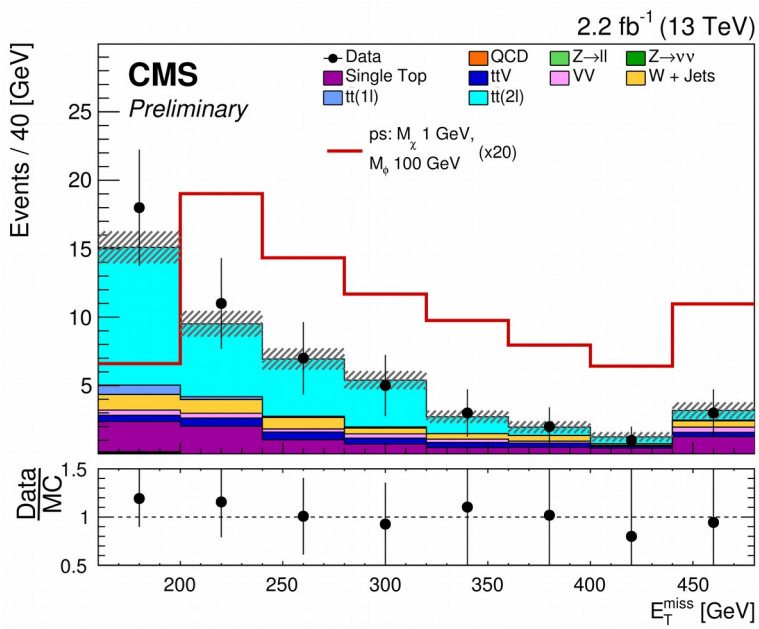


Same DM model as that probed with monojet

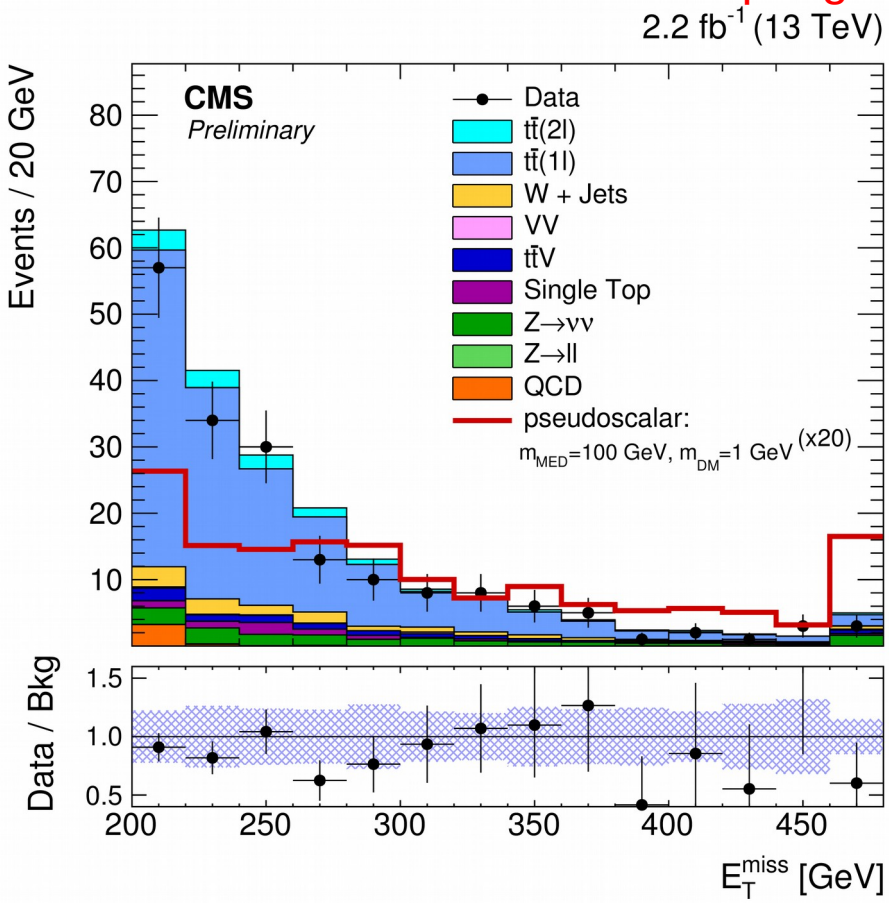
dileptonic eμ signal region



semileptonic signal region



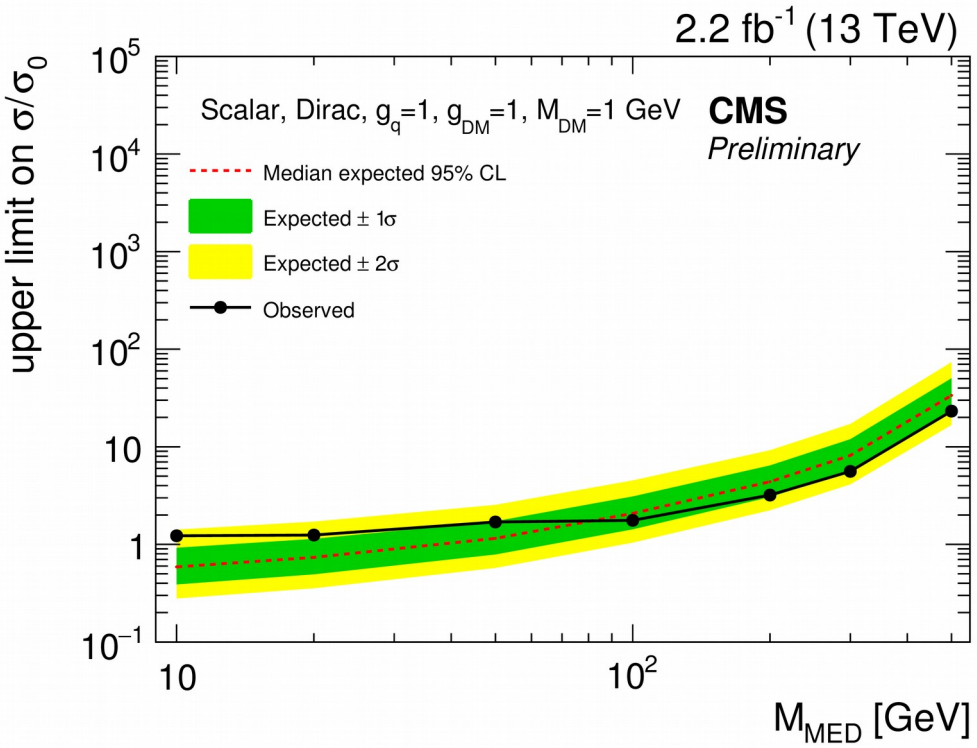
all-hadronic with ≥ 2 resolved top tags



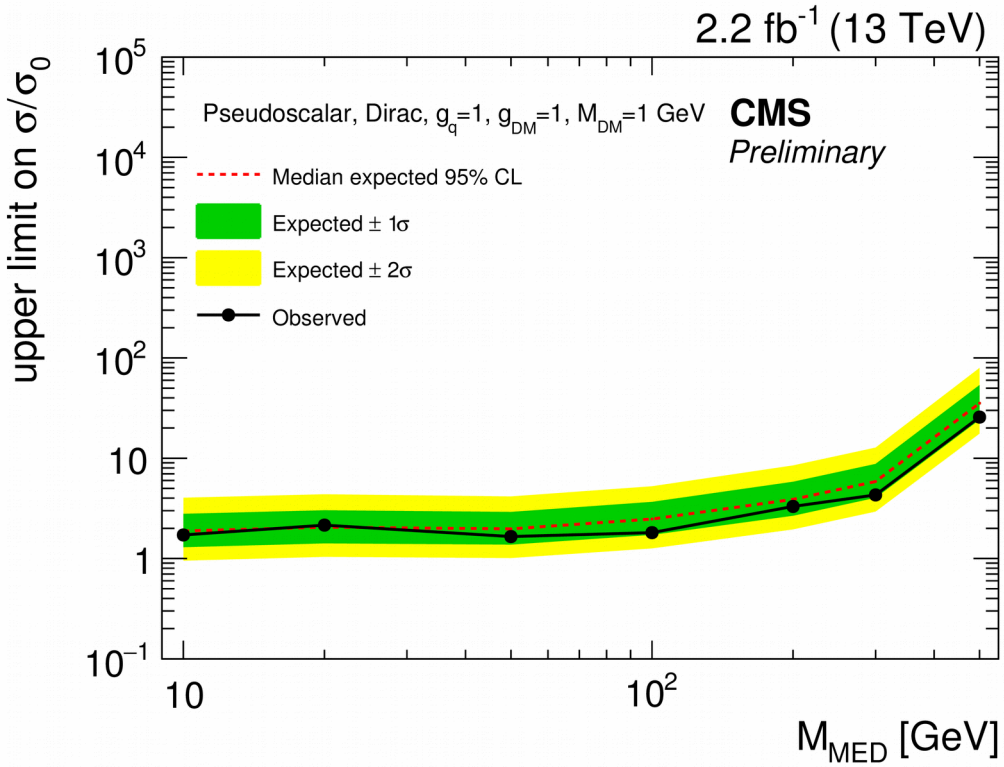
ttbar + DM

First expected exclusion of low-mass scalar mediators

- Observed exclusion of mMed = 10 GeV, mDM = 1 GeV with gSM = gDM = 1 for semileptonic + hadronic combination
- Addition of dileptonic improves expected exclusion, weakens observed ...



Full ttbar combination, scalar

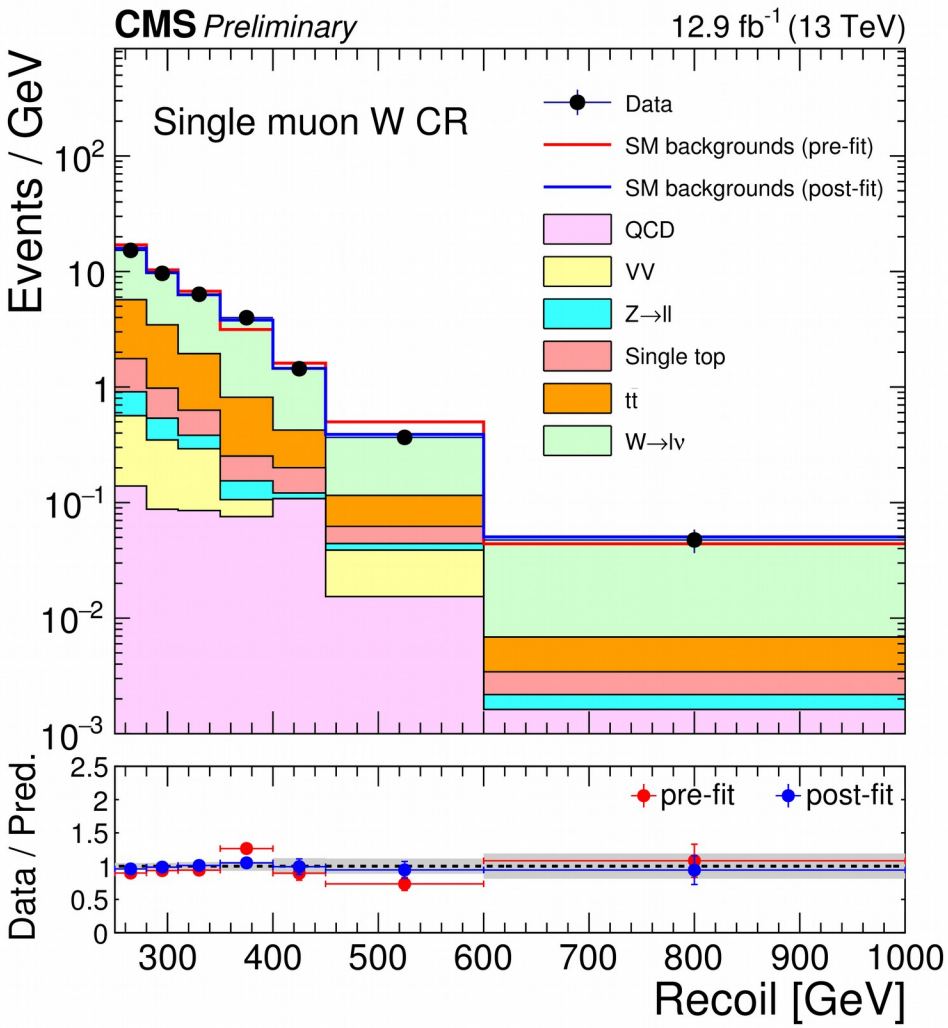


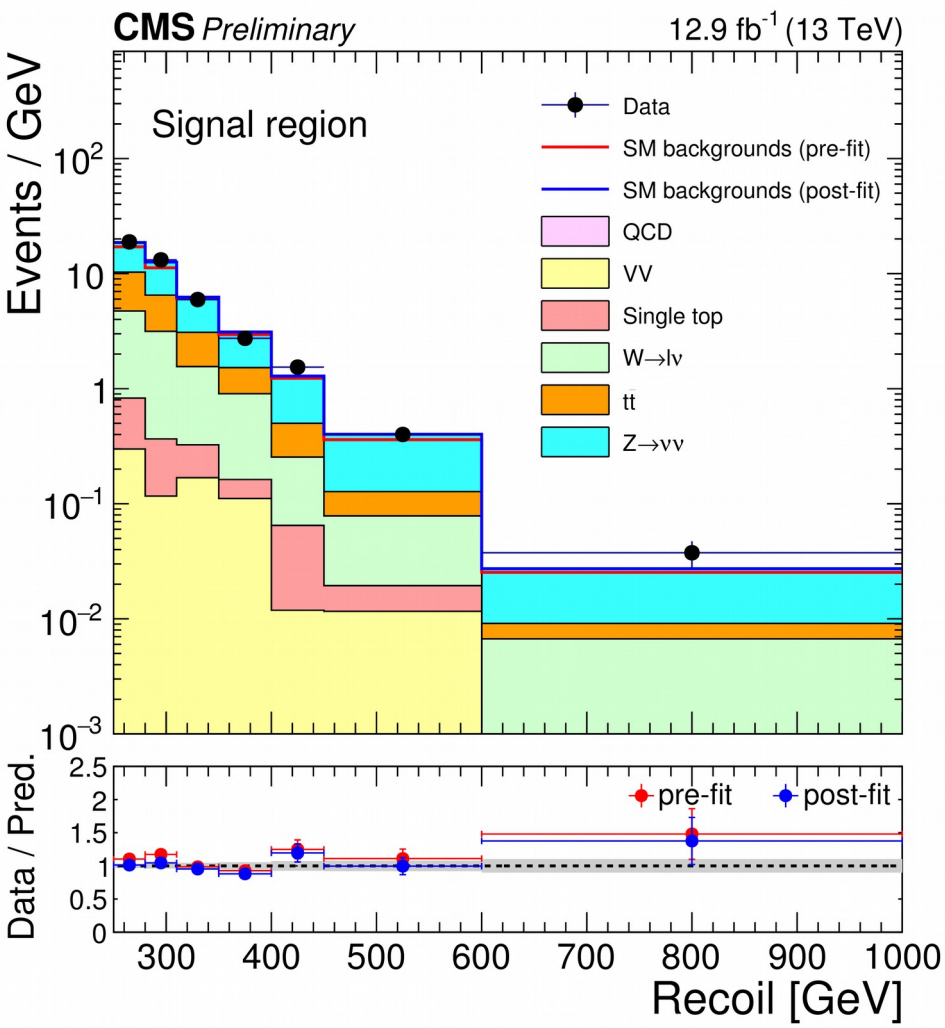
Full ttbar combination, pseudoscalar

mono-top

CA1.5, p_T^j & E_T^{miss} > 250 GeV, m_j 110-210 GeV, τ_{23}, subjet b tag

- Backgrounds from SM ttbar, Z(νν)+jets, W(lν) + jets
- Constrained via simultaneous of signal region with 7 control regions





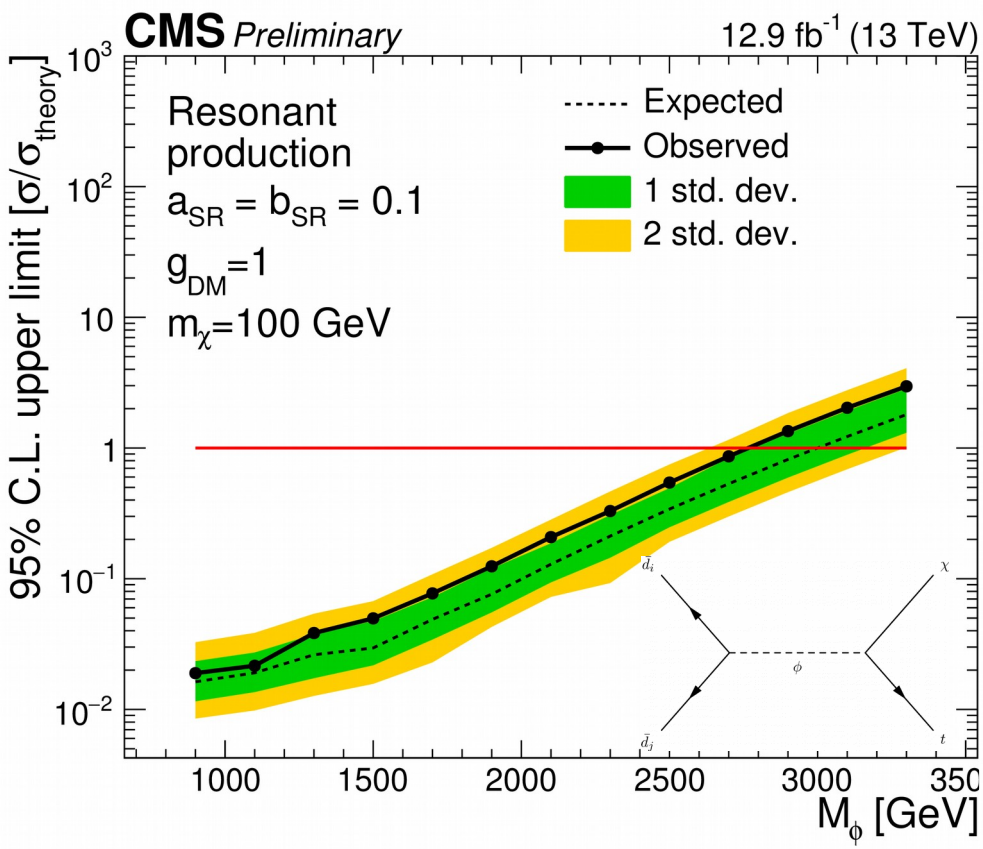
mono-top

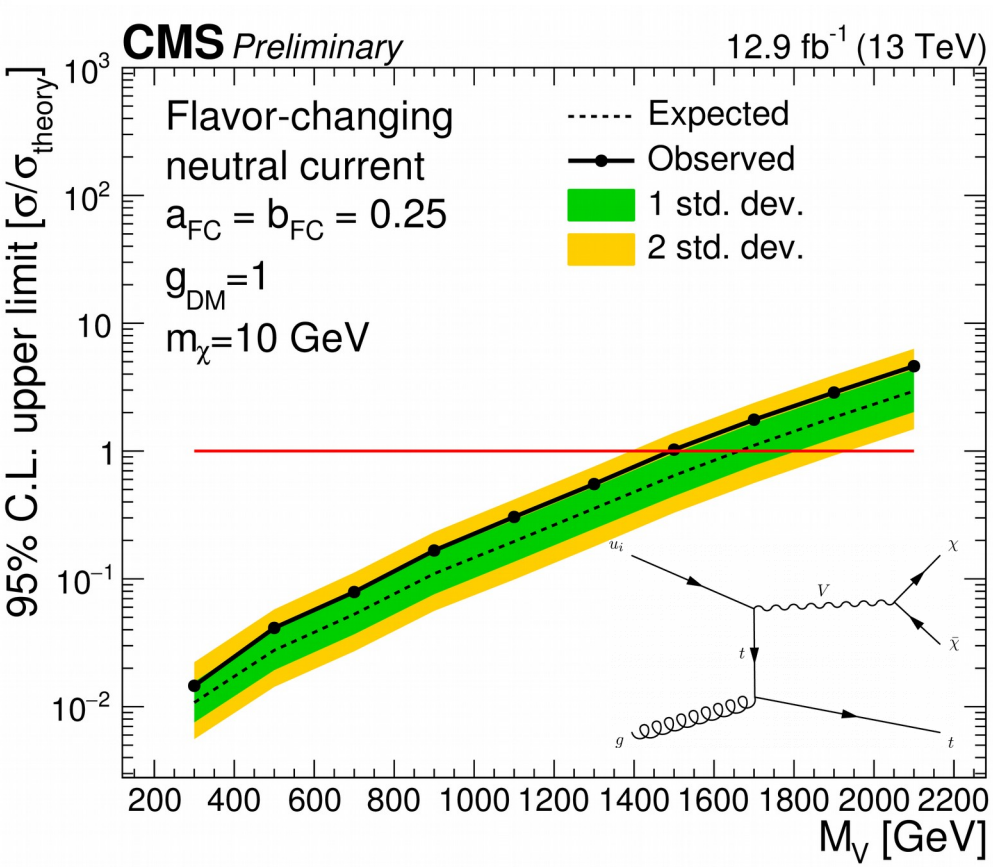
Interpretation with resonant BNV and FCNC signal models

- Distinct model from that used commonly in mono-X searches

Charged scalar excluded up to 2.7 TeV (3.0 TeV expected)

FCNC mediator excluded up to 1.5 TeV (1.7 TeV expected)



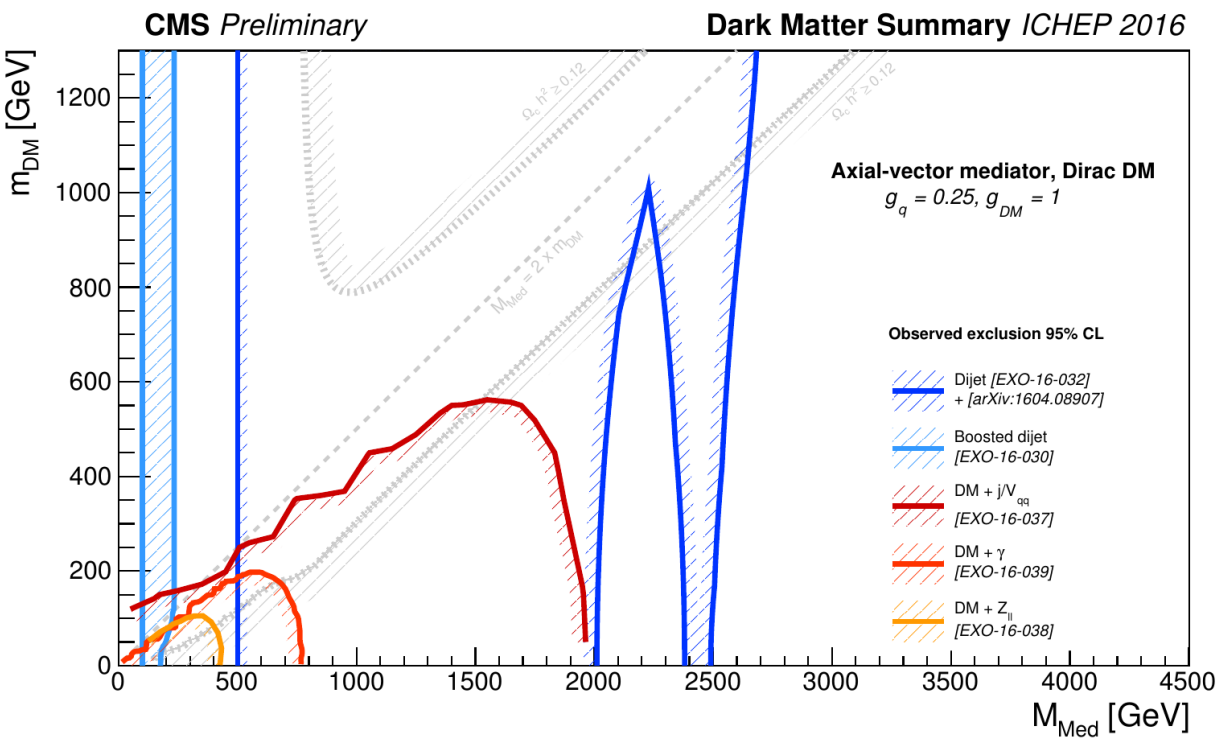


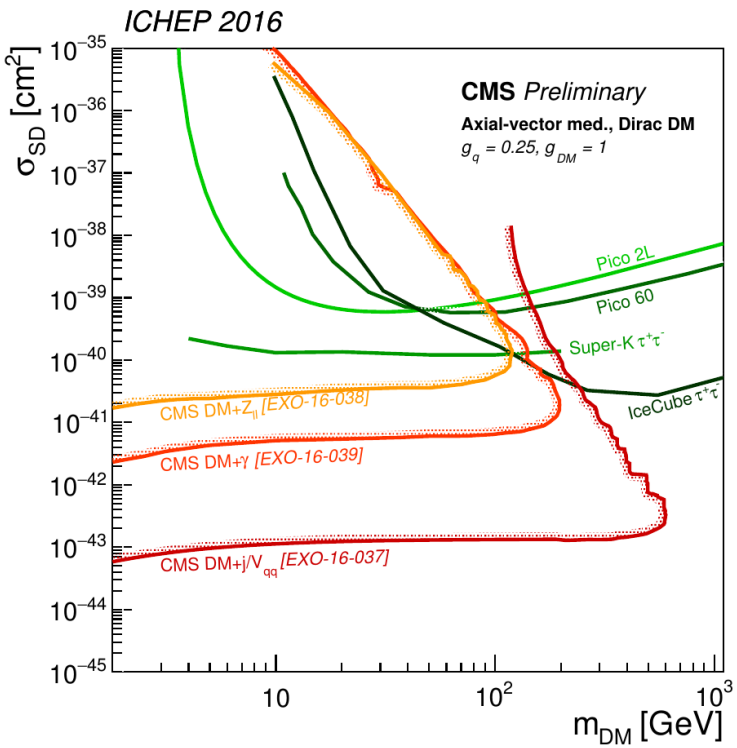
CMS Dark Matter Summary

Comparison of various MET+X channels: CMS-DP-2016/057

Axial vector mediator: monojet/mono-V, mono-Z(ll), mono-photon

- Including search for direct mediator production w/ dijets
- Translation to SD DM-nucleon cross section





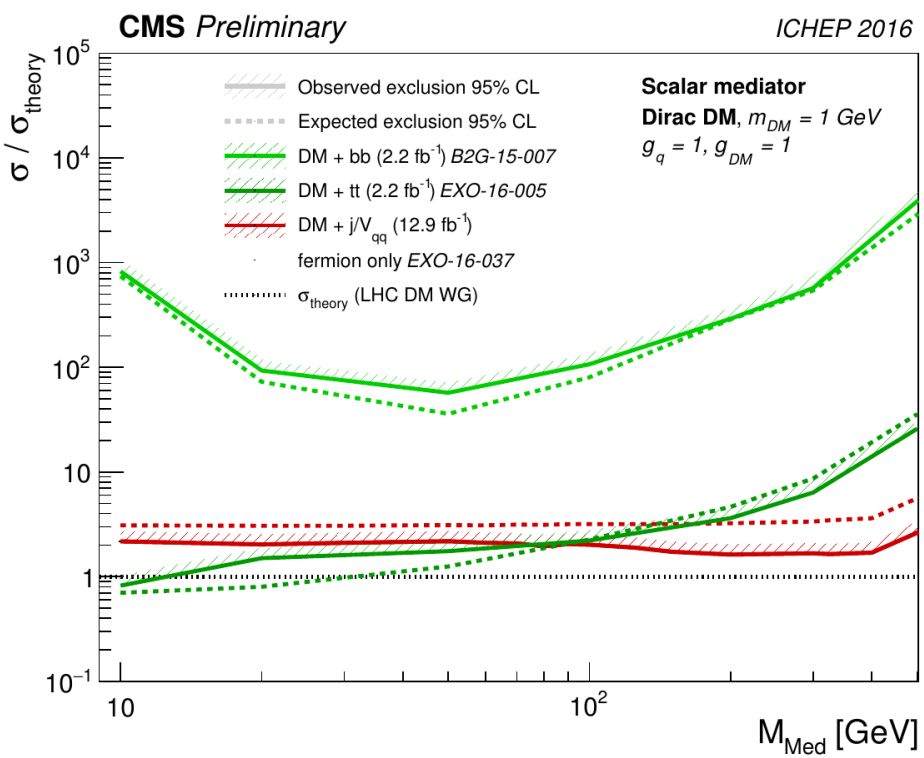
Robust coverage through multiple search channels, sensitivity complementary to direct detection

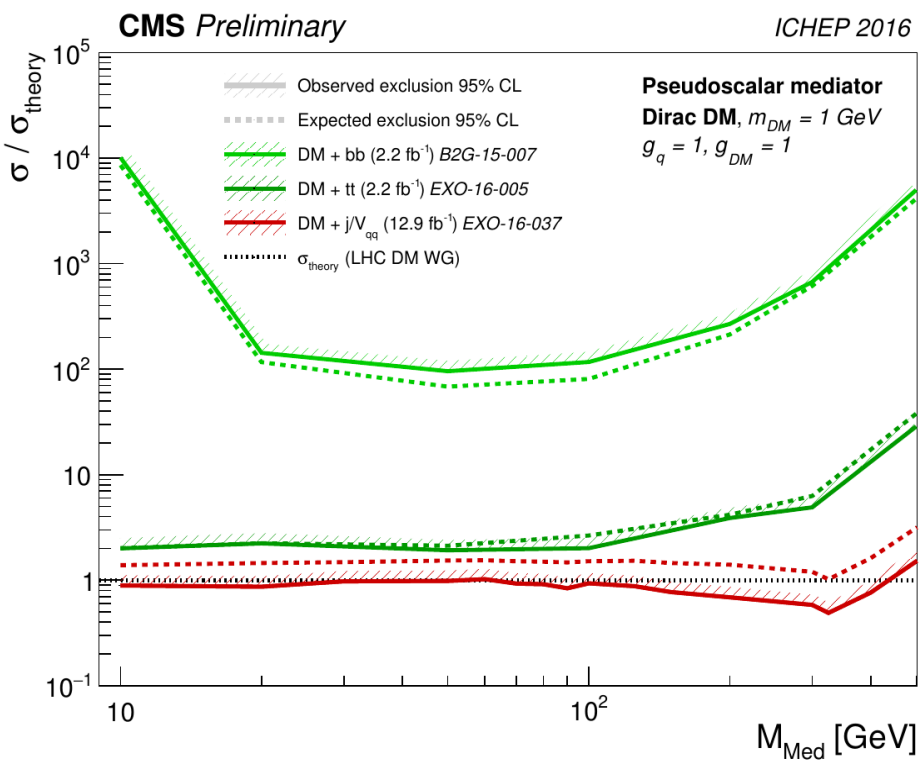
CMS Dark Matter Summary

Comparison of various MET+X channels: CMS-DP-2016/057

Scalar & pseudoscalar: monojet & tt+DM (semileptonic+hadronic)

- Extending reach to low scalar mediator mass
- Both searches contribute for low-mass pseudoscalars





NB: monojet/mono-V uses fermion-only couplings here, consistent with tt+DM

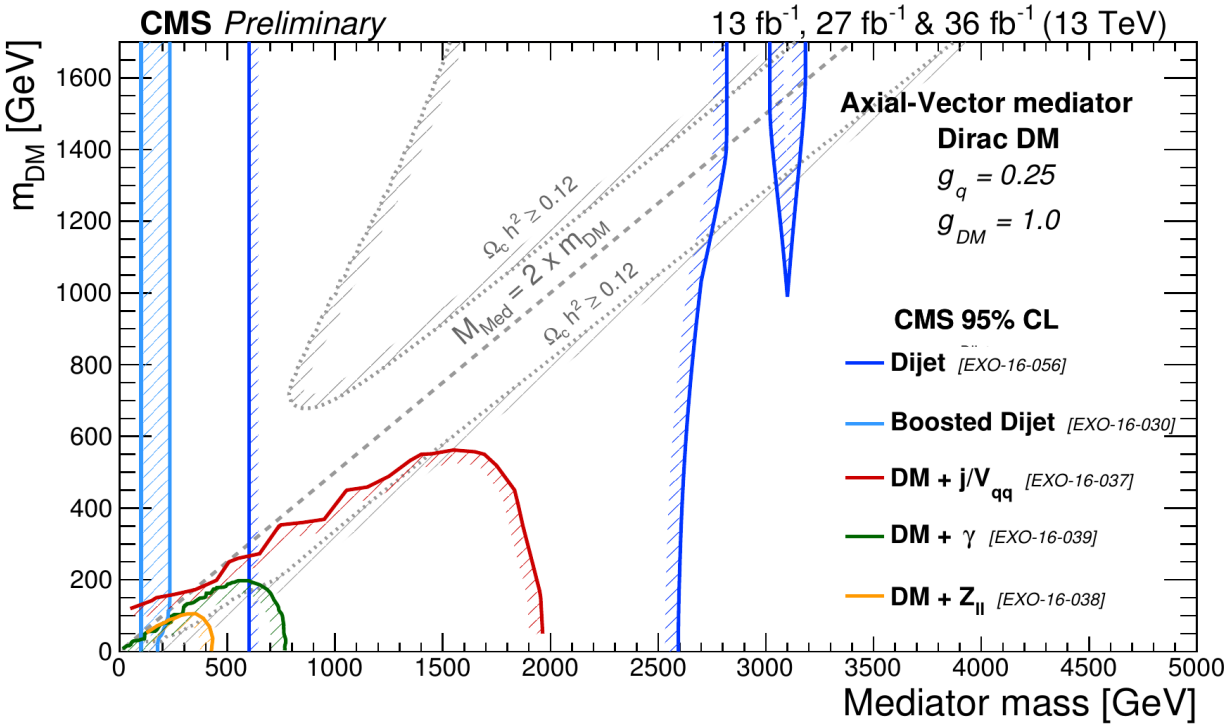
Update: DM Mediator Search w/ Dijets

A combination of :

- Boosted (100-300 GeV) using 13 fb-1
- Low-mass (0.6-1.6 TeV) search with 26 fb-1 using data scouting
- High-mass (> 1.6 TeV) search with 36 fb-1

Model-independent search for excess in dijet mass spectrum

- Sensitive to wide range of BSM, including DM
- AV mediators excluded between 0.6 – 2.6 TeV



Summary

Robust program of E_T^{miss} +X DM searches in CMS

Run 2 results pushing into new territory, limits on

- Multi-Tev spin-1 mediators
- Low-mass spin-0 mediators

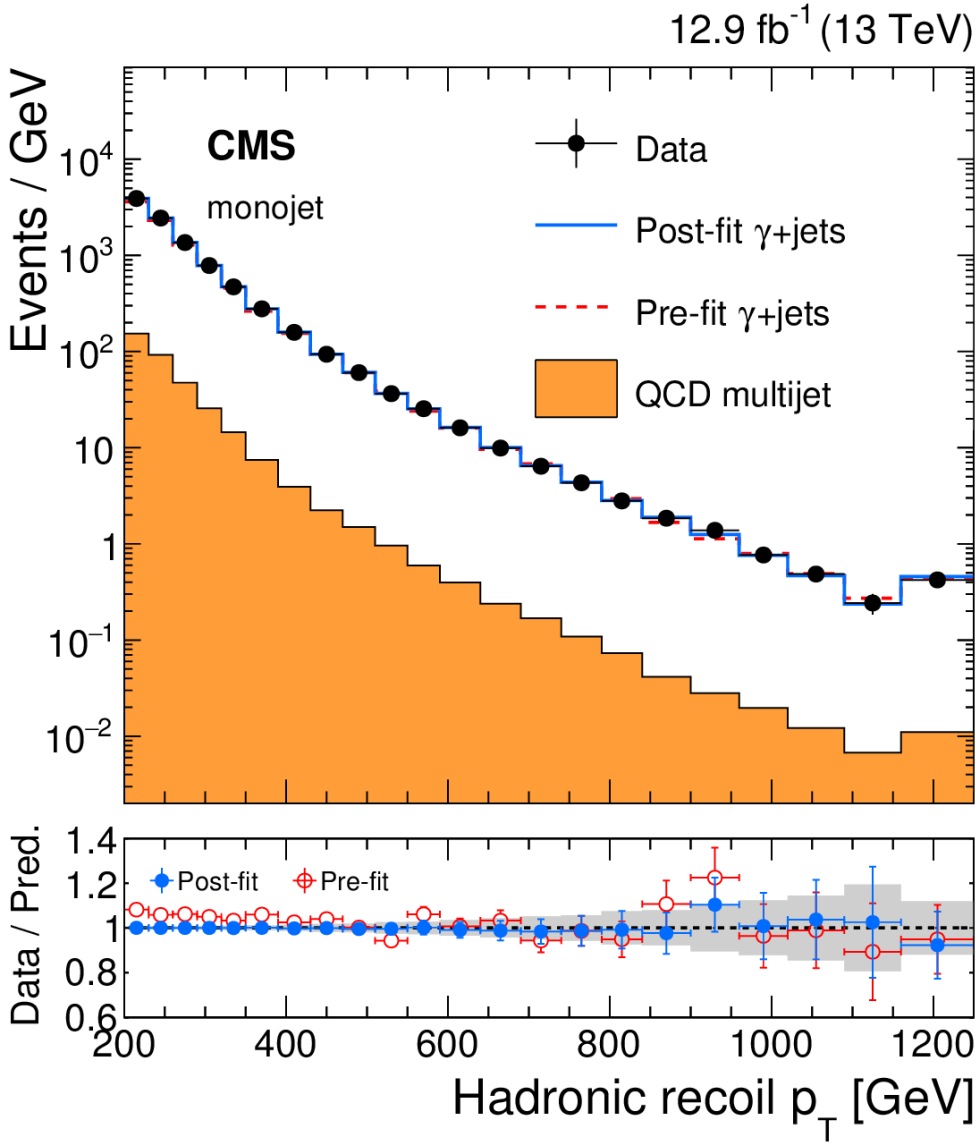
Complementary strengths vs direct/indirect detection

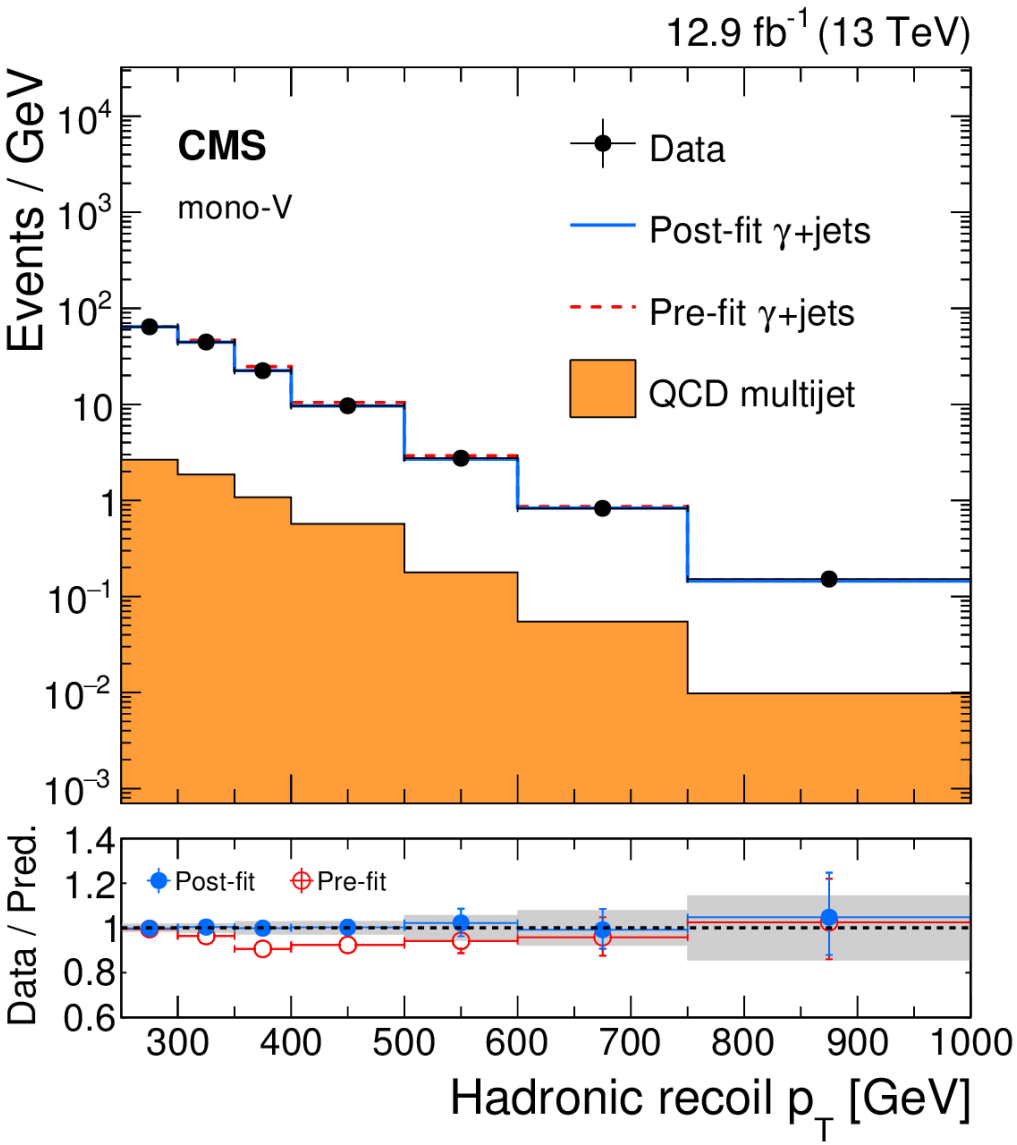
On the horizon:

- Large bump in stats for several searches
- Stronger interplay between DM channels
- Interpretations with somewhat-less-simplified models

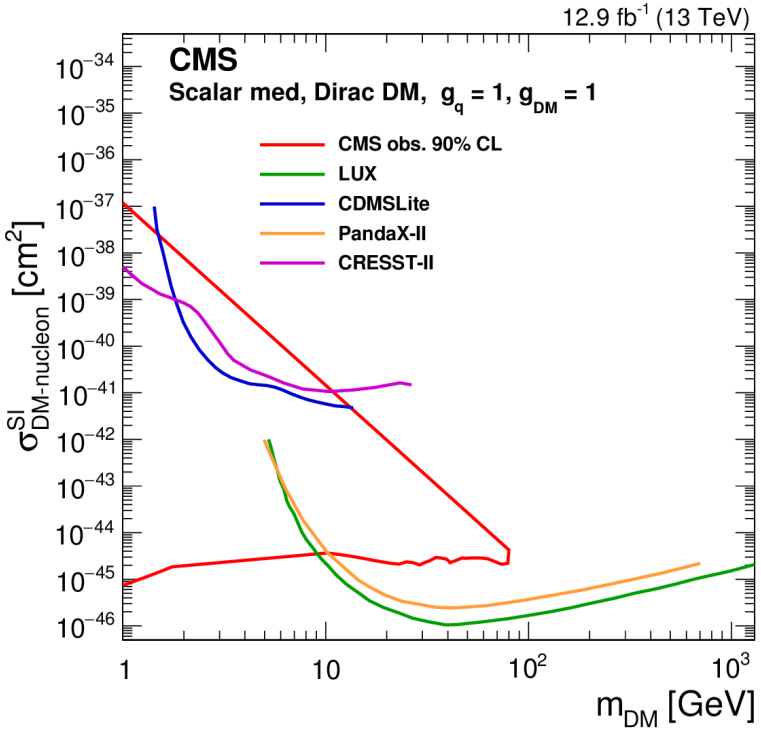
“SOMEBODY CALL FOR BACKUP!”

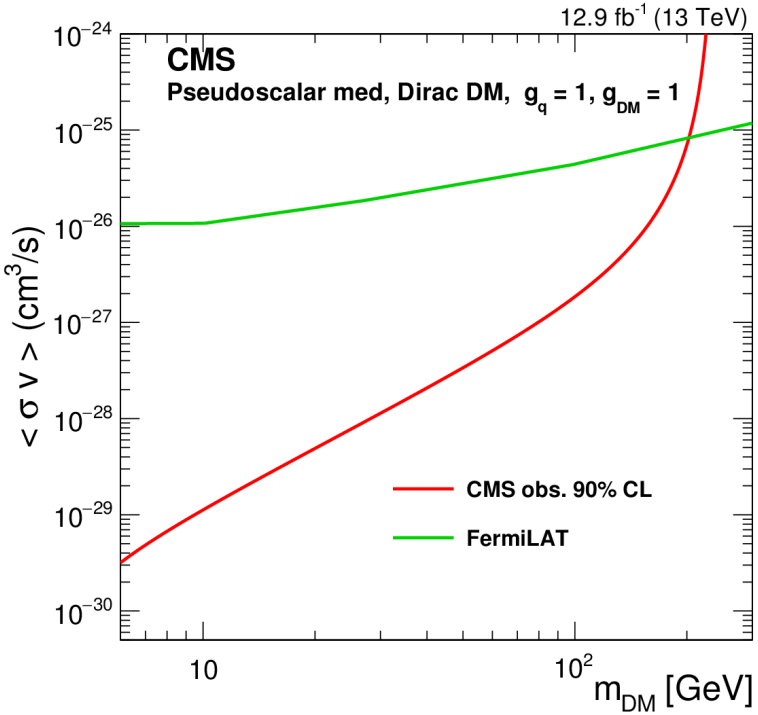
More monojet

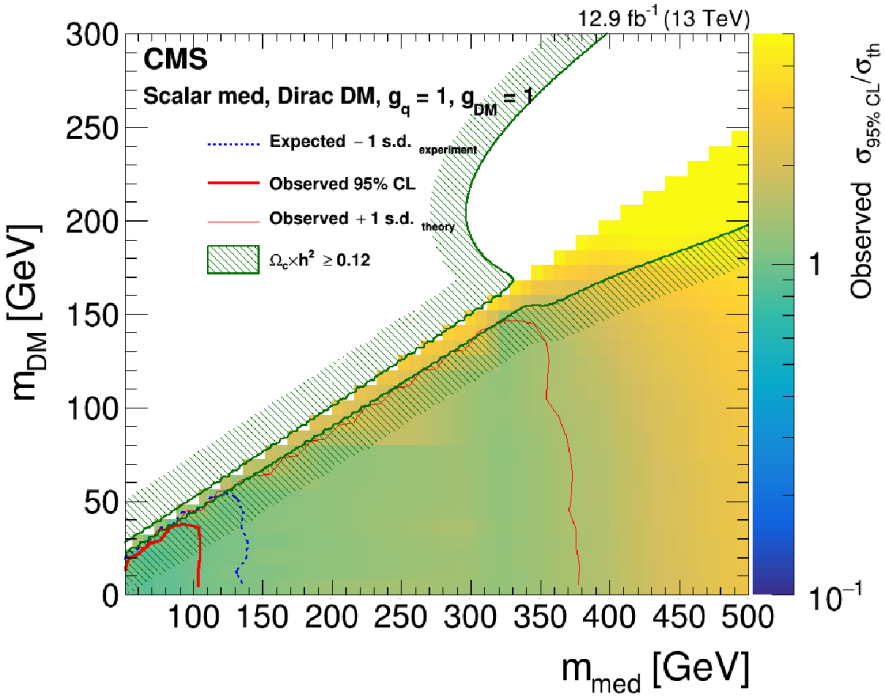


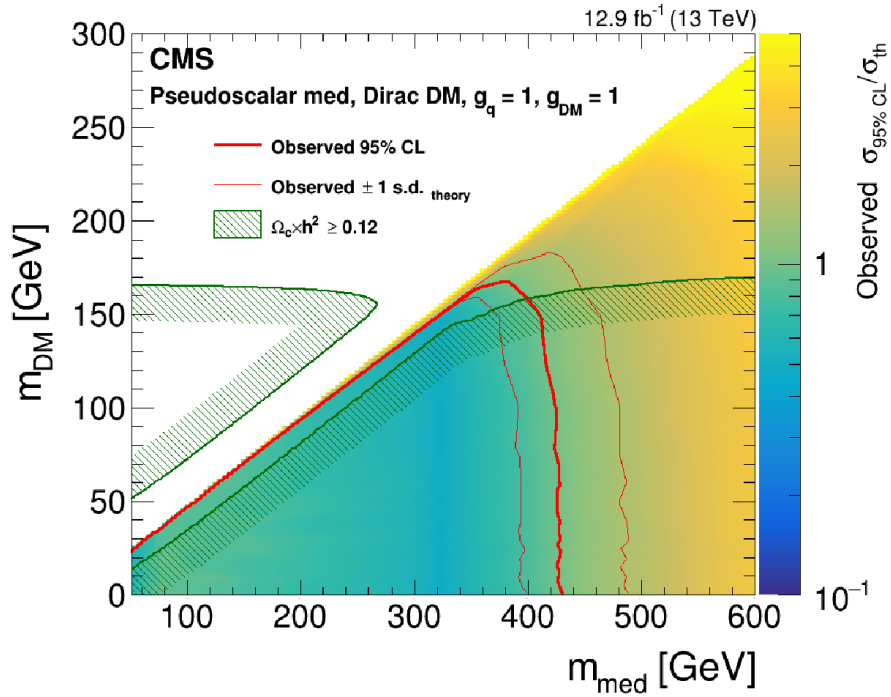


More monojet

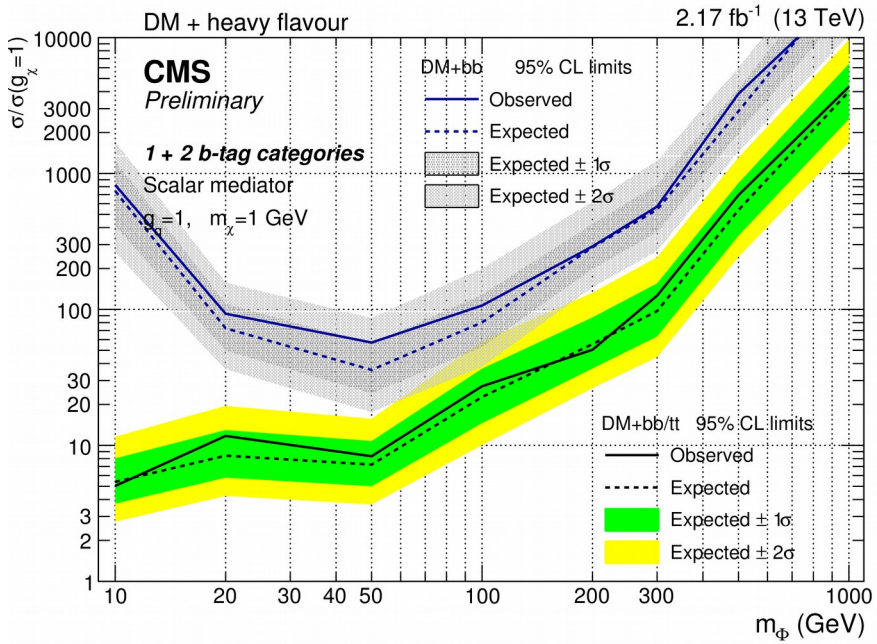


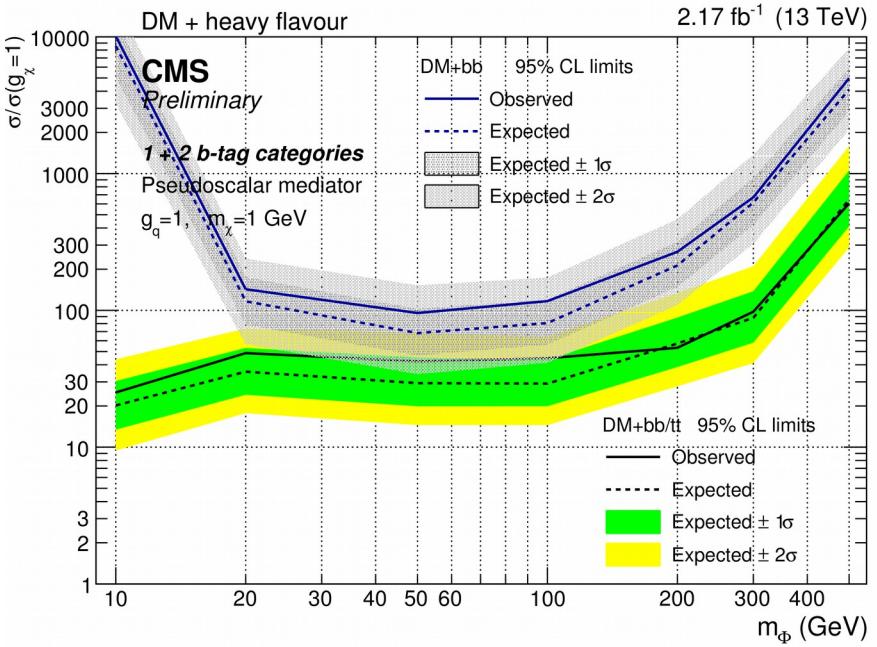






dd+DM


DM + heavy flavour
2.17 fb^{-1} (13 TeV)
CMS
Preliminary
1 + 2 b-tag categories
Scalar mediator
g_q=1, m_χ=1 GeV
DM+bb 95% CL limits
Observed
Expected
Expected ± 1σ
Expected ± 2σ
DM+bb/tt 95% CL limits
Observed
Expected
Expected ± 1σ
Expected ± 2σ
$\sigma/\sigma(g_\chi=1)$
m_Φ (GeV)


DM + heavy flavour
2.17 fb^{-1} (13 TeV)
CMS
Preliminary
1 + 2 b-tag categories
Pseudoscalar mediator
g_q=1, m_χ=1 GeV
DM+bb 95% CL limits
Observed
Expected
Expected ± 1σ
Expected ± 2σ
DM+bb/tt 95% CL limits
Observed
Expected
Expected ± 1σ
Expected ± 2σ
$\sigma/\sigma(g_\chi=1)$
m_Φ (GeV)

More Summary

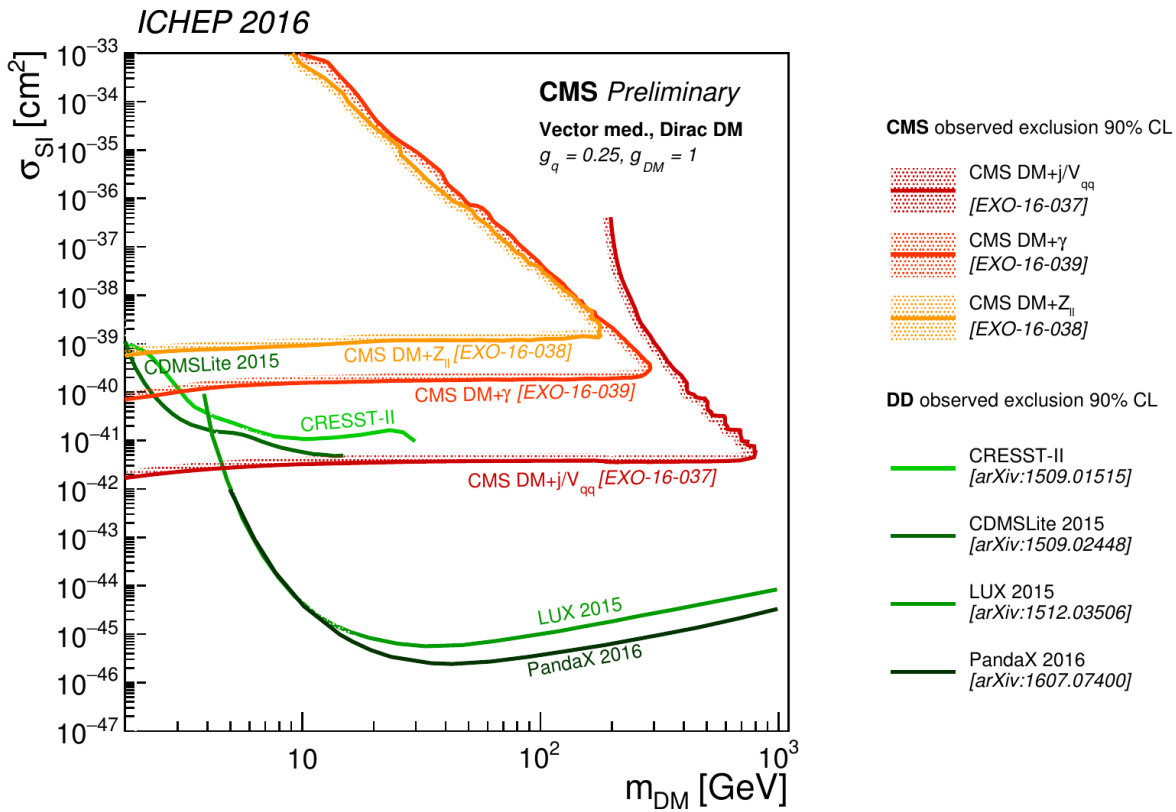


Figure 4. *A comparison of CMS results to the m_{DM}–σ_{SI} plane . Unlike in the mass-mass plane, the limits are shown at 90% CL. The CMS contour in the SI plane is for a Vector mediator, Dirac DM and couplings $g_q = 0.25$ and $g_{\mathrm{DM}} = 1$. The CMS SI exclusion contour is compared with the LUX 2015, PandaX-II 2016, CDMSLite 2015 and CRESST-II 2015 limits, which constitutes the strongest documented constraints in the shown mass range. It should be noted that the CMS limits do not include a constraint on the relic density and also the absolute exclusion of the different CMS searches as well as their relative importance will strongly depend on the chosen coupling and model scenario. Therefore, the shown CMS exclusion regions in this plot are not applicable to other choices of coupling values or models.*

More Summary

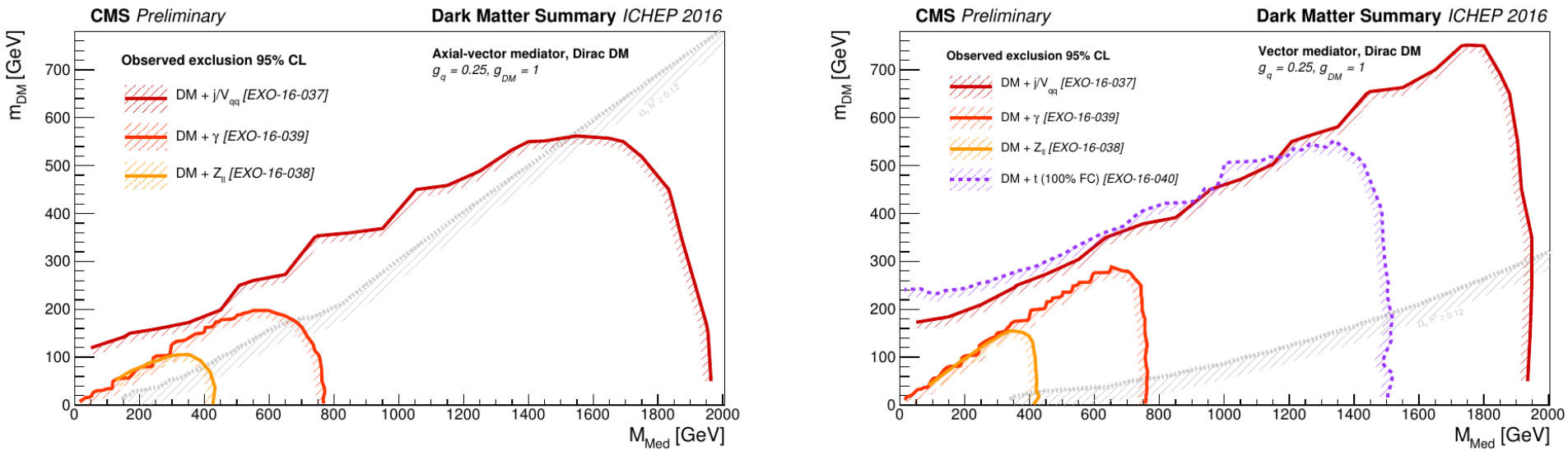
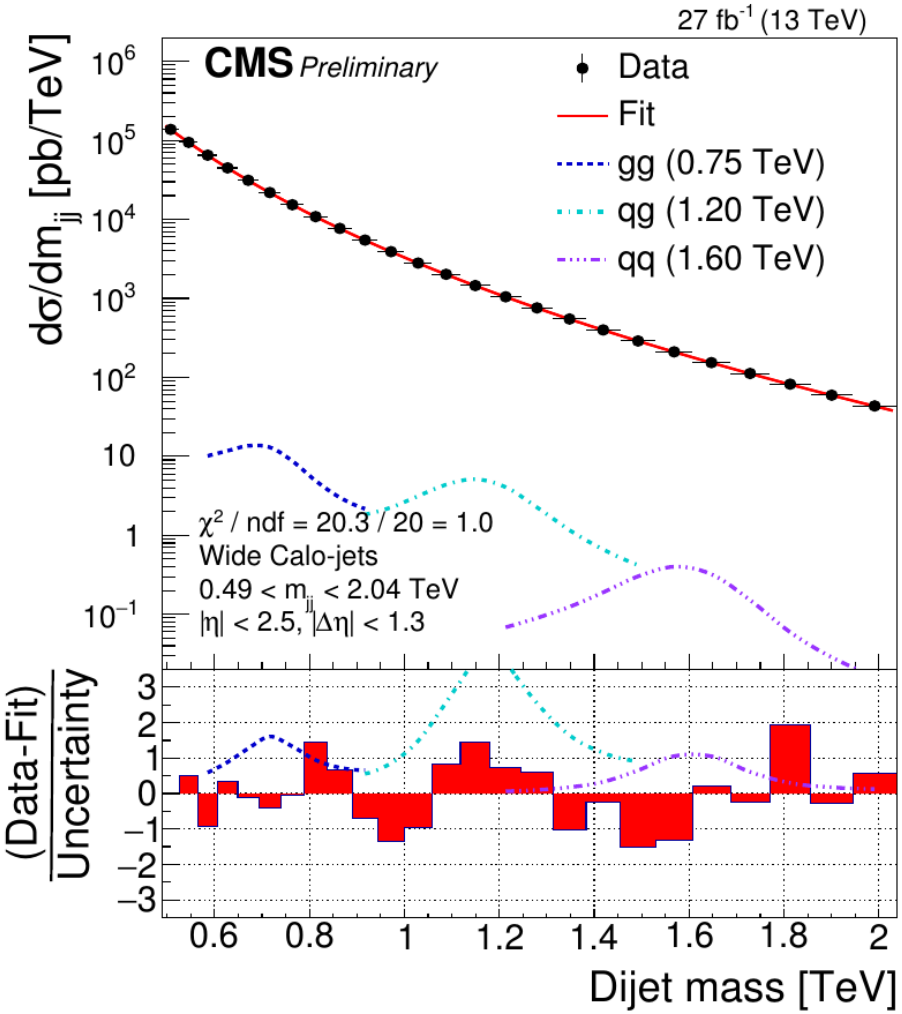


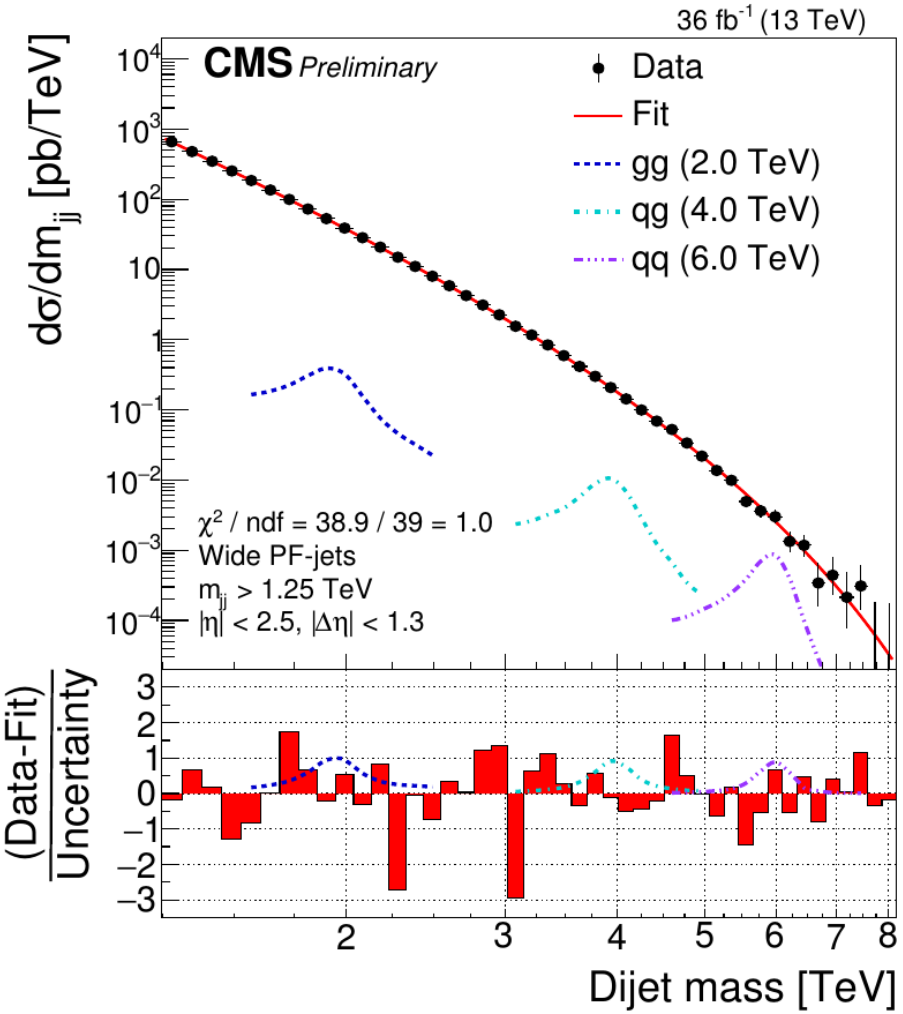
Figure 2. *95% CL exclusion regions in $M_{\mathrm{med}} - m_{\mathrm{DM}}$ plane for different $\not{E}_T$ based DM searches from CMS in the lepto-phobic AV and V models. It should be noted that the exclusion regions and relic density contours in this plot are not applicable to other choices of coupling values or models.*

Dijet

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)+P_4\ln(x)^2}}$$

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$





SI/SD Translation

$$\sigma^0_{\rm SI} = \frac{9\, g^2_{\rm DM}\, g^2_q\, \mu^2_{n\chi}}{\pi M^4_{\rm med}}$$

$$\approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2 .$$

$$\sigma^0_{\rm SD} = \frac{3\, g^2_{\rm DM}\, g^2_q (\Delta_u + \Delta_d + \Delta_s)^2\, \mu^2_{n\chi}}{\pi M^4_{\rm med}}$$

$$\approx 4.6 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

Interpretation

Comparison of collider results with (in)direct detection

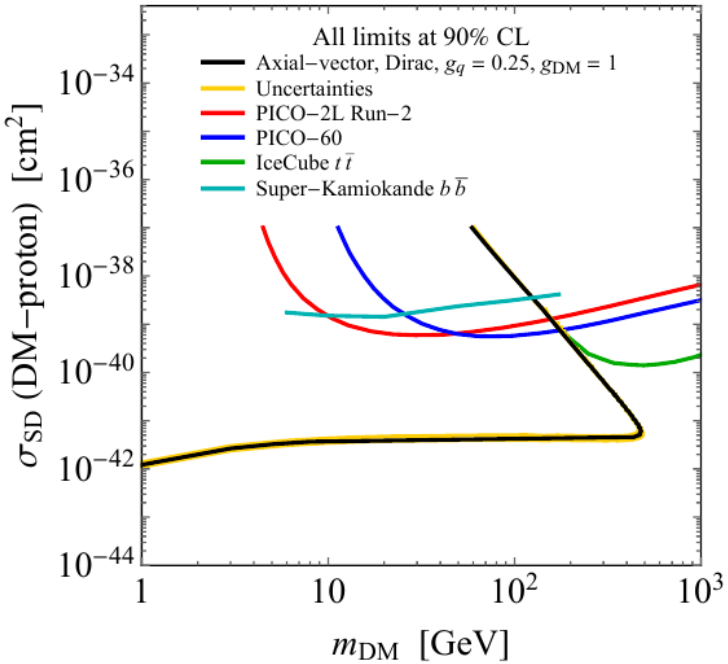
- Recent focus of LHC Dark Matter Working Group (DMWG)
- Developed recommendations for collider/non-collider comparison

Translate collider limits to σ_{DM-N} & σv_{rel} , rather than reverse

- Avoid subtleties and assumptions involved in mapping DD/ID to collider
- DD: vector/scalar (SI) axial (SD) mediators
- ID: pseusdoscalar mediators

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]



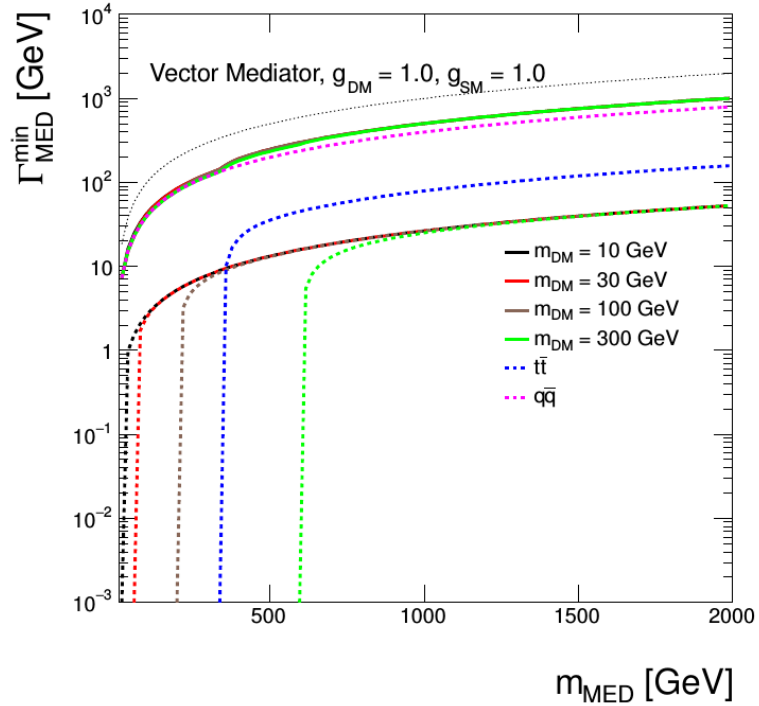
arxiv://1603.04156, CERN-LPCC-2016-001

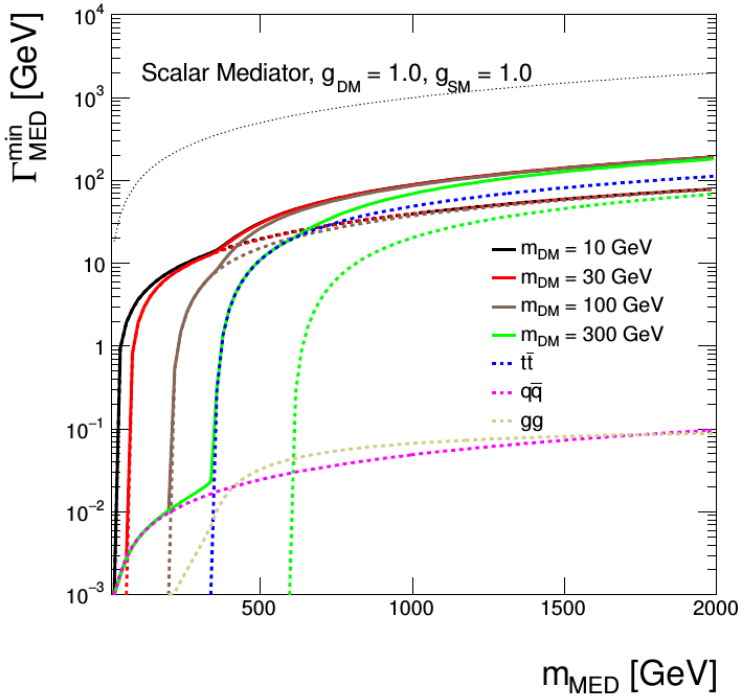
$$\Gamma^{\mathrm{V}}_{\mathrm{min}} = \frac{g_\chi^2 M_{\mathrm{med}}}{12\pi}\left(1+\frac{2m_\chi^2}{M_{\mathrm{med}}^2}\right)\beta_{DM}\theta(M_{\mathrm{med}}-2m_\chi)$$
$$+\sum_q \frac{3g_{\mathrm{q}}^2 M_{\mathrm{med}}}{12\pi}\left(1+\frac{2m_q^2}{M_{\mathrm{med}}^2}\right)\beta_q\theta(M_{\mathrm{med}}-2m_q),$$

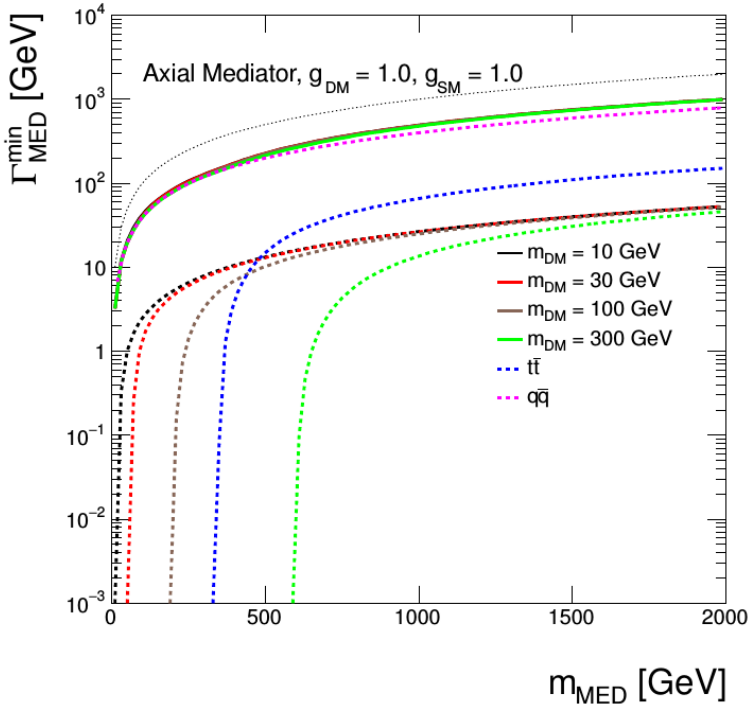
$$\Gamma^{\mathrm{A}}_{\mathrm{min}} = \frac{g_\chi^2 M_{\mathrm{med}}}{12\pi}\beta_{DM}^3\theta(M_{\mathrm{med}}-2m_\chi)$$
$$+\sum_q \frac{3g_{\mathrm{q}}^2 M_{\mathrm{med}}}{12\pi}\beta_q^3\theta(M_{\mathrm{med}}-2m_q)\ .$$

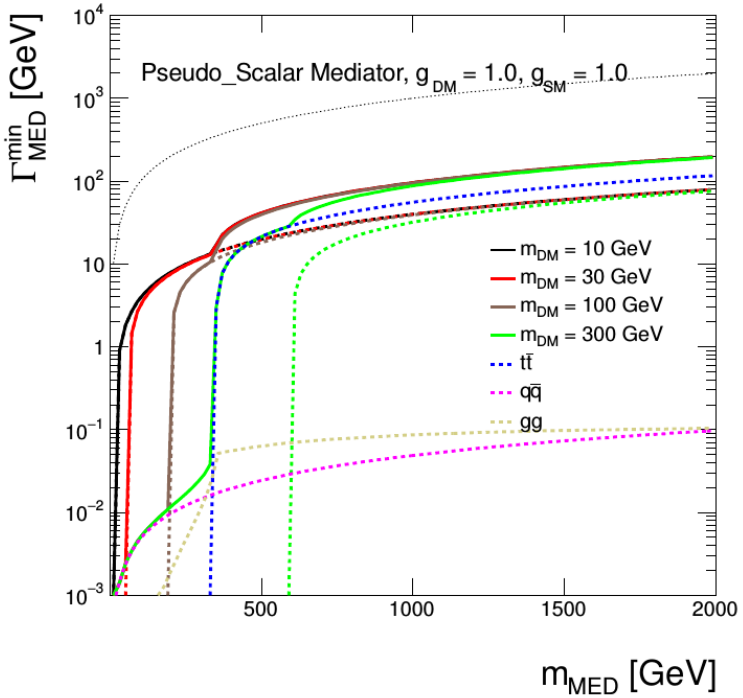
$$\Gamma_{\phi,a} = \sum_f N_c \frac{y_f^2 g_{\mathrm{q}}^2 m_{\phi,a}}{16\pi}\left(1-\frac{4m_f^2}{m_{\phi,a}^2}\right)^{x/2} + \frac{g_\chi^2 m_{\phi,a}}{8\pi}\left(1-\frac{4m_\chi^2}{m_{\phi,a}^2}\right)^{x/2}$$
$$+\frac{\alpha_s^2 y_t^2 g_{\mathrm{q}}^2 m_{\phi,a}^3}{32\pi^3 v^2}\left|f_{\phi,a}\left(\frac{4m_t^2}{m_{\phi,a}^2}\right)\right|^2$$

$$f_\phi(\tau) = \tau\left[1+(1-\tau)\arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right)\right],$$
$$f_a(\tau) = \tau\arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right)$$


Vector Mediator, g_{DM} = 1.0, g_{SM} = 1.0
m_{DM} = 10 GeV
m_{DM} = 30 GeV
m_{DM} = 100 GeV
m_{DM} = 300 GeV
$t\bar{t}$
$q\bar{q}$
Γ^{min}_{MED} [GeV]
m_{MED} [GeV]


Scalar Mediator, g_{DM} = 1.0, g_{SM} = 1.0
m_{DM} = 10 GeV
m_{DM} = 30 GeV
m_{DM} = 100 GeV
m_{DM} = 300 GeV
$t\bar{t}$
$q\bar{q}$
gg
Γ^{min}_{MED} [GeV]
m_{MED} [GeV]


Axial Mediator, g_{DM} = 1.0, g_{SM} = 1.0
m_{DM} = 10 GeV
m_{DM} = 30 GeV
m_{DM} = 100 GeV
m_{DM} = 300 GeV
$t\bar{t}$
$q\bar{q}$
Γ^{min}_{MED} [GeV]
m_{MED} [GeV]


Pseudo_Scalar Mediator, g_{DM} = 1.0, g_{SM} = 1.0
m_{DM} = 10 GeV
m_{DM} = 30 GeV
m_{DM} = 100 GeV
m_{DM} = 300 GeV
$t\bar{t}$
$q\bar{q}$
gg
Γ^{min}_{MED} [GeV]
m_{MED} [GeV]

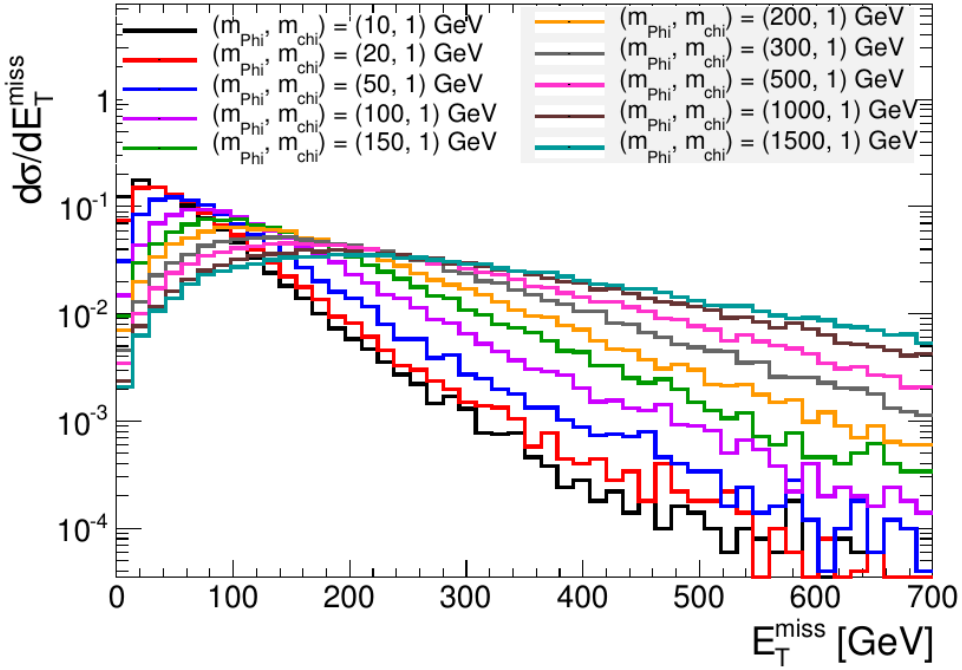


Figure 2.23: Example of the dependence of the kinematics on the scalar mediator mass in the $t\bar{t}$+$\not{E}_T$ signature. The Dark Matter mass is fixed to be m_χ =1GeV.

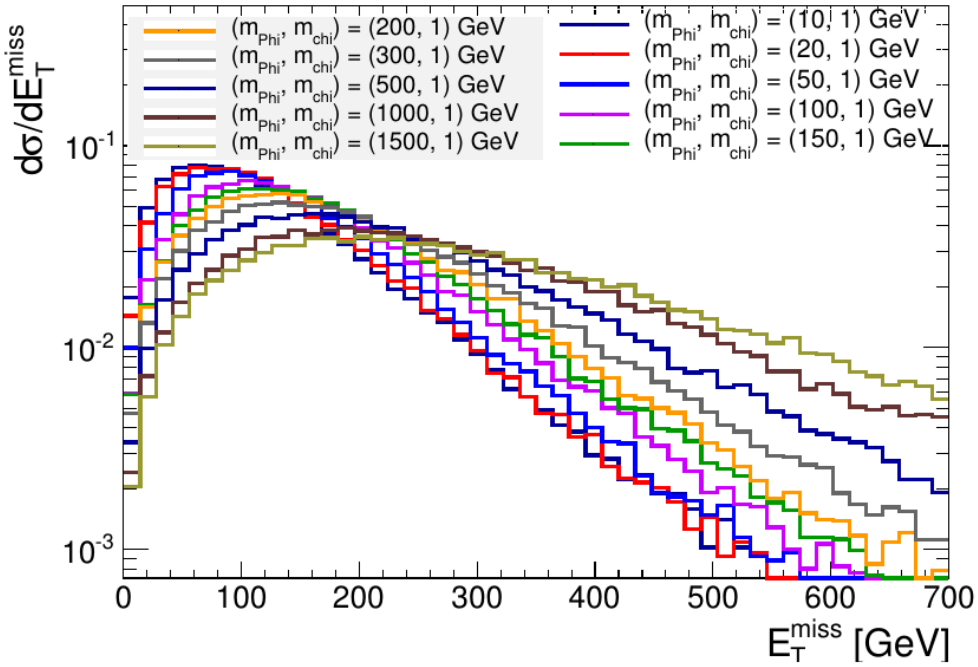
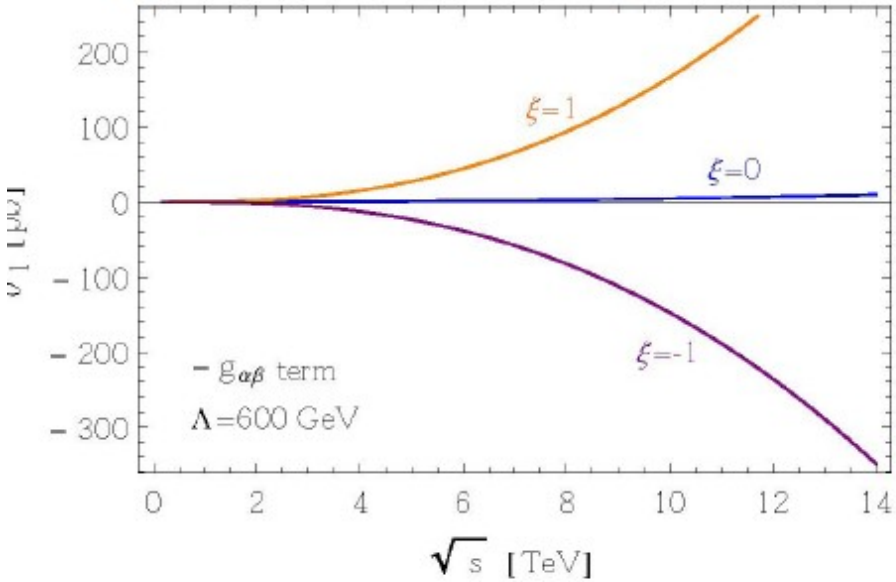
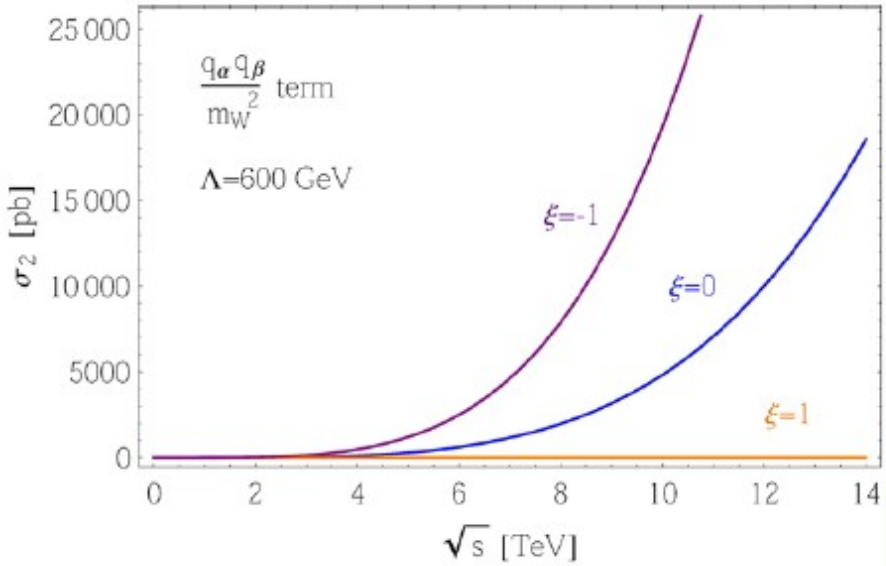


Figure 2.24: Example of the dependence of the kinematics on the pseudoscalar mediator mass in the $t\bar{t}$+$\not{E}_T$. The Dark Matter mass is fixed to be m_χ =1GeV. All figures concerning the $t\bar{t}$+$\not{E}_T$ signature have been produced using a leading order model within MadGraph5_aMC@NLO 2.2.2, using pythia 8 for the parton shower.

Total parton-level cross sections versus energy, for Λ= 600 GeV.
(Notice the differing vertical scales between the two panels.)



Contribution from the $-g_{\alpha\beta}$ term in the W polarization sum ($\approx W_T$ contribution).



Contribution from the $\frac{q_\alpha q_\beta}{m_W^2}$ term ($\approx W_L$ contribution).

This term dominates at LHC energies (unless $\xi \simeq 1$).

Bell, Cai, Dent, Leane & Weiler, arXiv:1503.07874

Goldstone boson equivalence theorem & Ward identity

At high energy, Goldstone boson equivalence theorem says:

- We can replace W_L with the corresponding Goldstone boson.
  - Since the Goldstone boson couples to quarks with strength proportional to their mass, these terms are close to zero.
    - We should not get W_L production.

For $\xi \neq 1$, the relevant Ward identity is broken.
→ Missing diagrams?
→Diagrams where W radiated from the mediator!

CERN-LPCC-2017-01

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

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