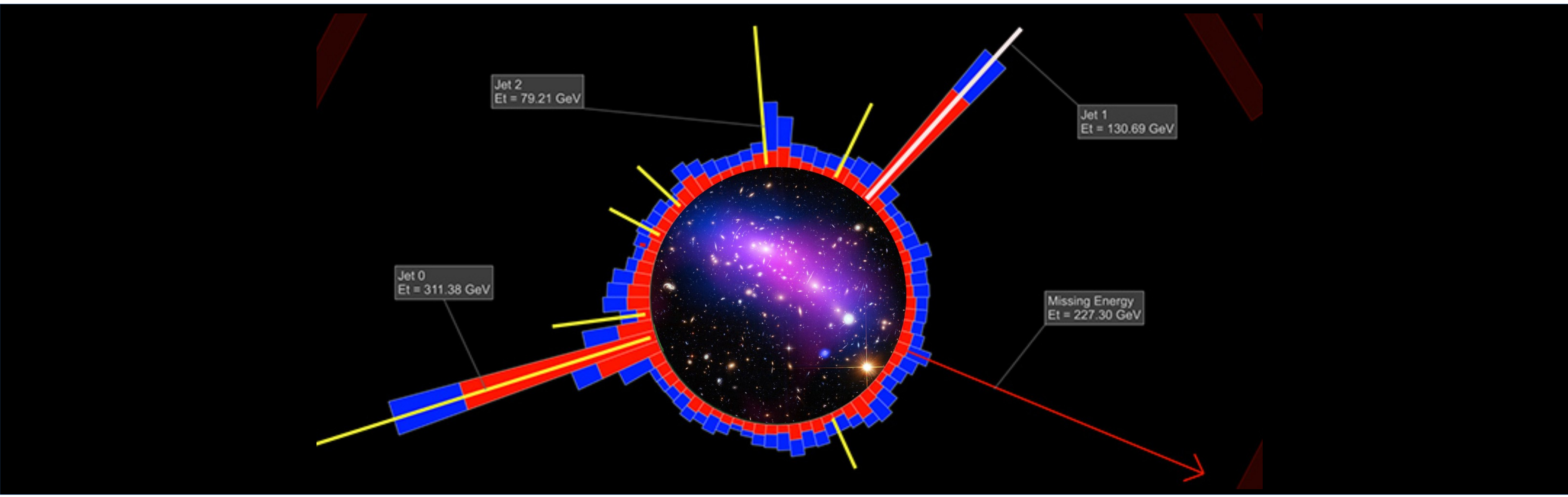
Dark Matter Searches at the LHC



Kristian Hahn
Northwestern University
on behalf of the ATLAS & CMS Collaborations

Topics in Astroparticle and Underground Physics
TAUP 2017, Sudbury ON, Canada
July 25, 2017

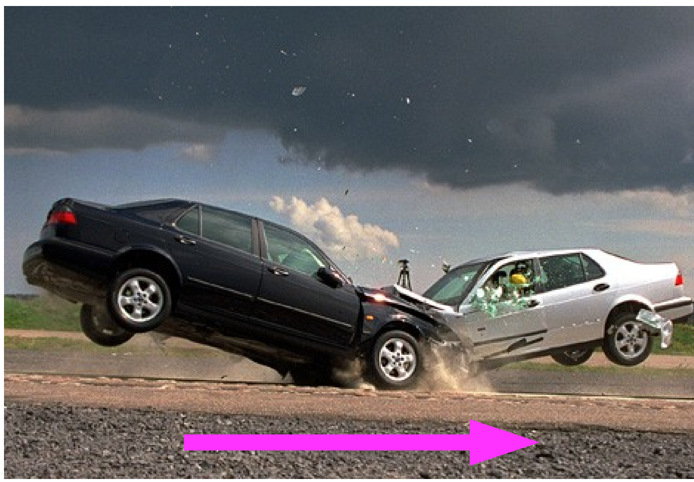
Dark Matter Detection

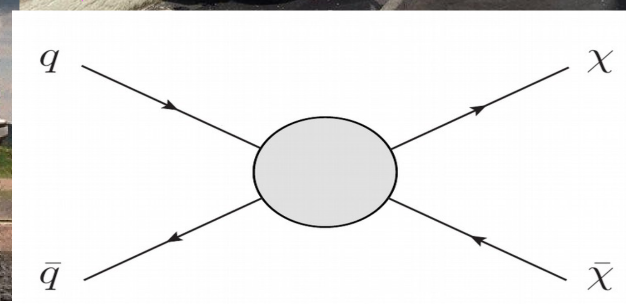
Complementary capabilities for observing DM interactions

Collider Production

Direct Detection (DD)
DM-Nucleon Scattering

Indirect Detection (ID)
DM annihilation





WIMP DM falls under the LHC "lamppost" ...

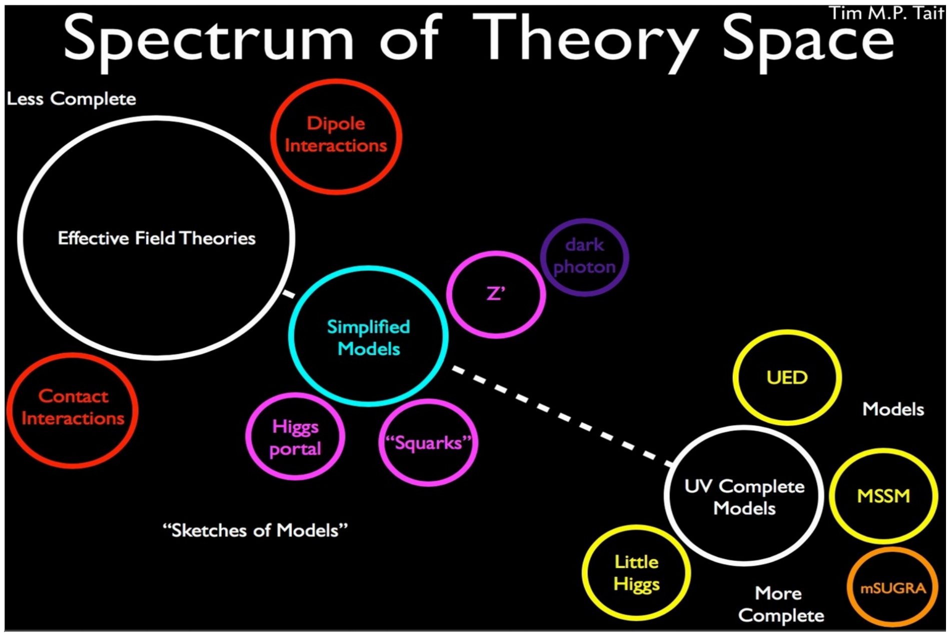
- DM as a thermal relic implies weak-ish mass/interaction scales

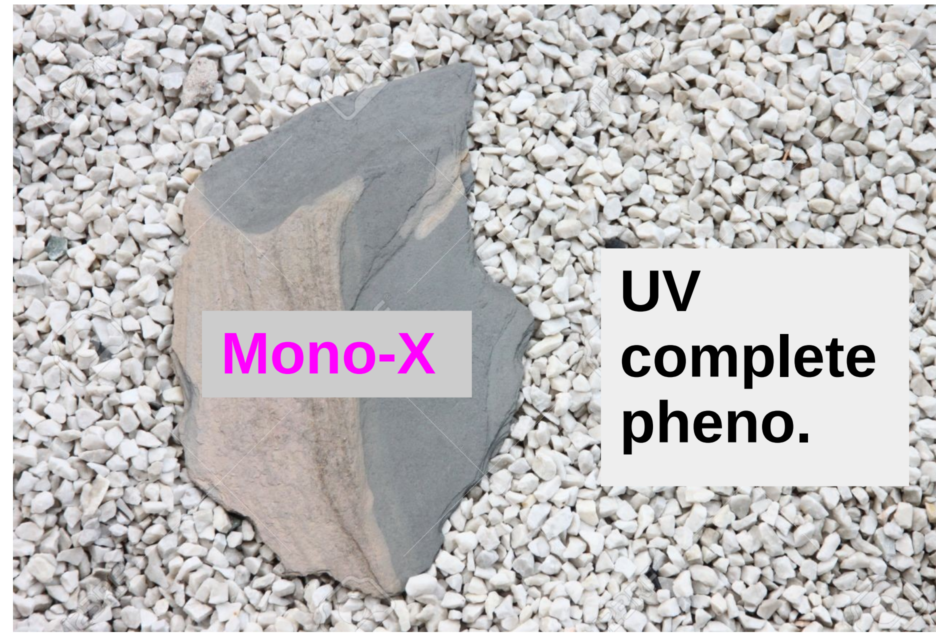
Some of the benefits of collider searches:

- Excellent control of systematic uncertainties
- No velocity / p-wave suppression
- Possible resonant enhancement
- Possibility to characterize DM particle properties

Many BSM models provide DM candidates

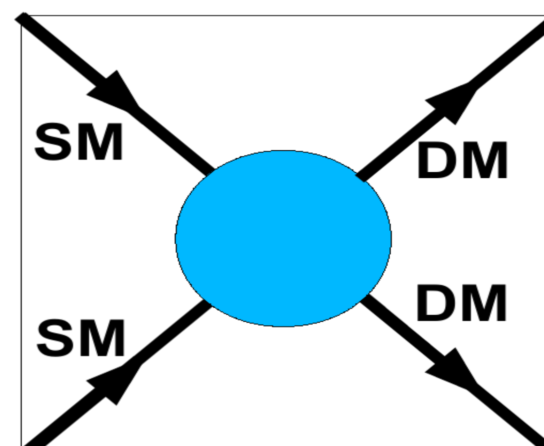
- Eg: SUSY (nMSSM, cMSSM, …), UED/ADD, Little Higgs …
- Large numbers of parameters, wide range of phenomenology



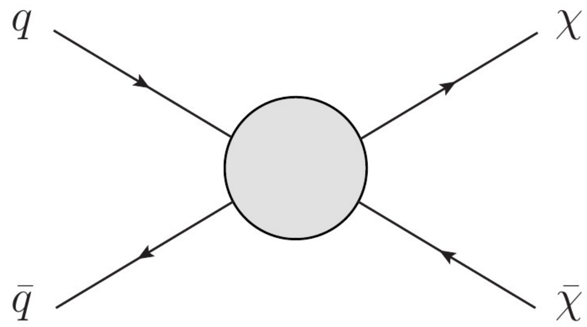


Can we take a more general approach?

- Perform broad searches based on general DM phenomenology
- Use "models" that are simple as possible, even if they are incomplete (eg: EFT →)
- Turn as large a stone as possible … mono-X!



Simplest mode of DM production *unobservable* @ LHC



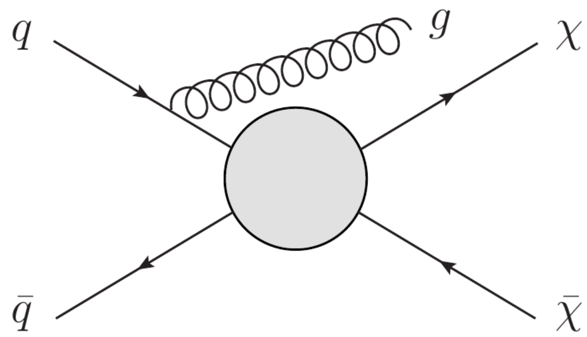
Dark Matter is **DARK**

- Leaves no activity in the detector
- Nothing to trigger on / reconstruct above

DM must instead recoil against *something* to become "visible"

"Mono-X" (or "MET+X") includes "X" for viable detection

- X: quarks/gluons, photons, W/Z …

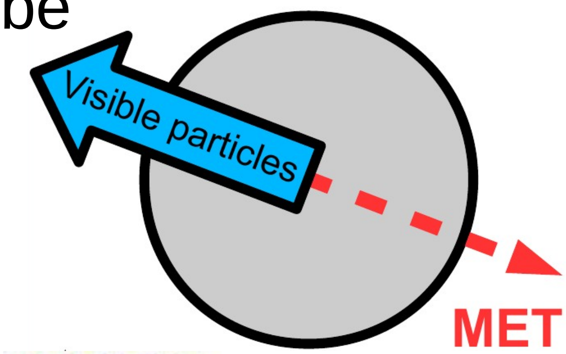


Non-interacting particles escape the detector

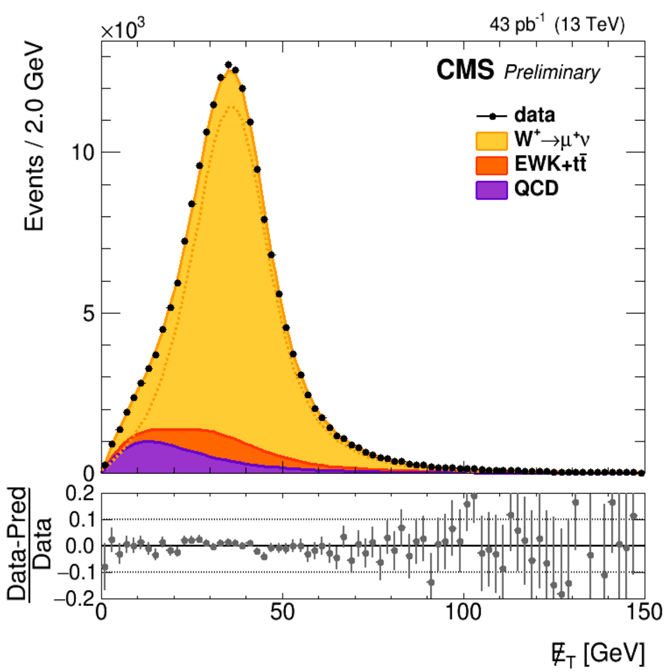
- Their presence inferred from energy/momentum imbalance

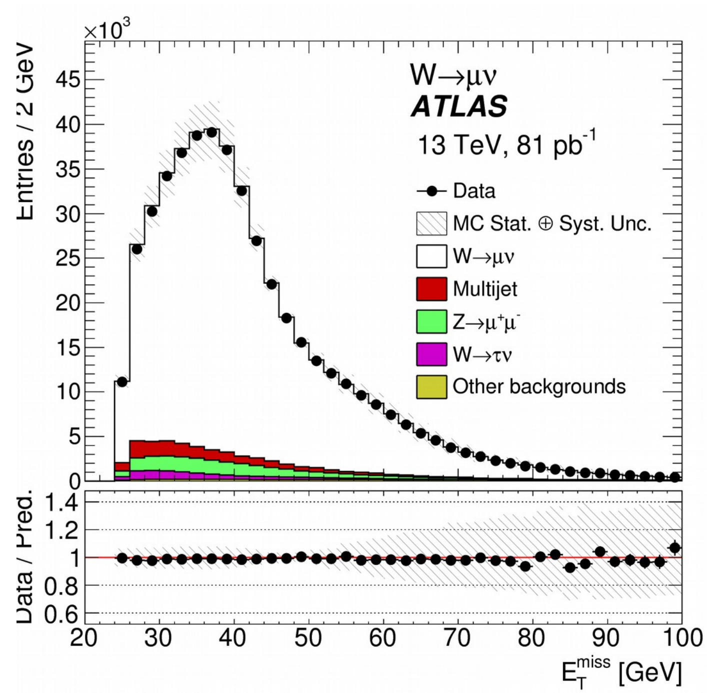
(Transverse) analog of nuclear recoil in DD …

- Transverse → because final state particles can be lost in the beampipe
- E_T^{miss} = Negative vector sum of all visible pT



$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{\text{all visible}} \vec{E}_T$$



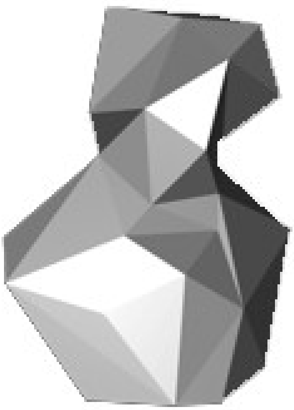


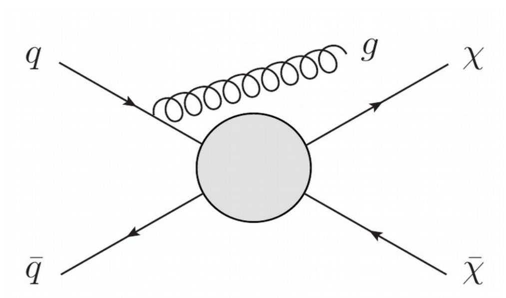
A well understood collider observable

- Wide use in SM measurements

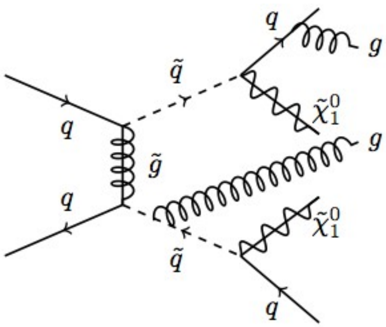
Modeling DM Collider Production

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





EFTs



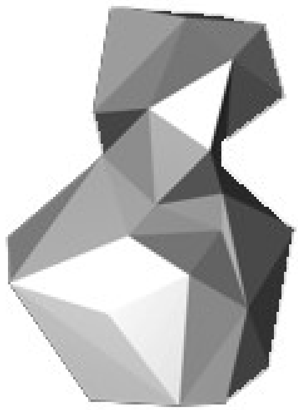
UV-complete Models

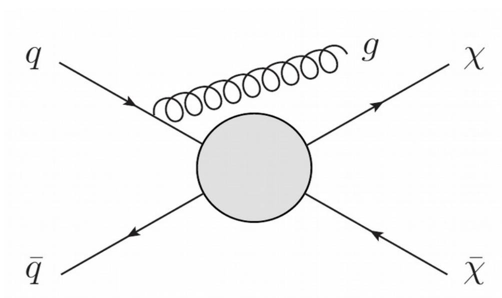
Validity issues @ LHC ..
cf: 1307.2253, 1308.6799

Too specific?
Theory baggage?

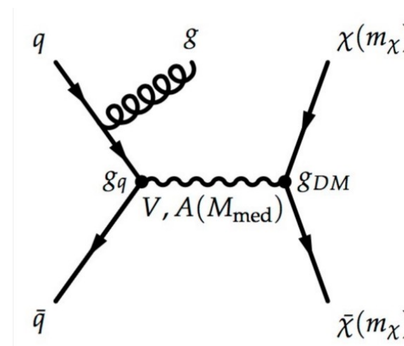
Modeling DM Collider Production

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

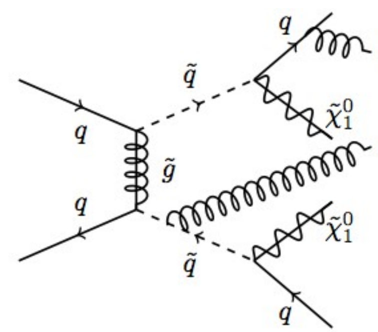




EFTs



Simplified Models



UV-complete Models

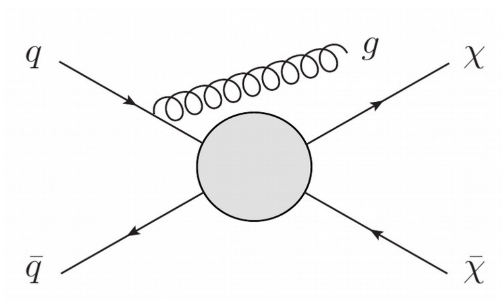
Validity issues @ LHC ..
cf: 1307.2253, 1308.6799

Just right?

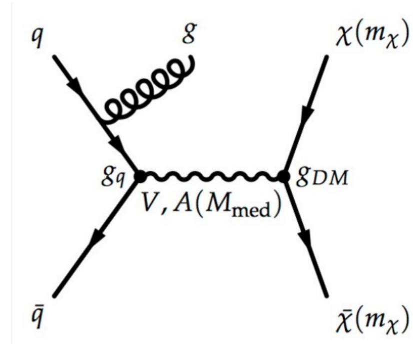
Too specific?
Theory baggage?

Modeling DM Collider Production

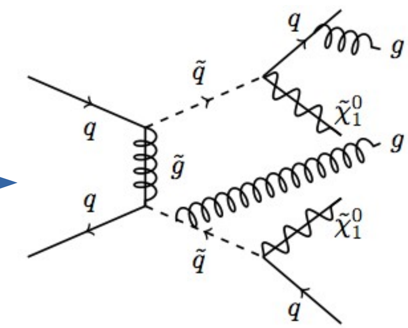
- Models used in the design and interpretation of DM searches
- Need to balance model complexity with predictive accuracy ...



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}

LHC DM searches using simplified models/benchmarks from the LHC Dark Matter Forum: 1507.00966

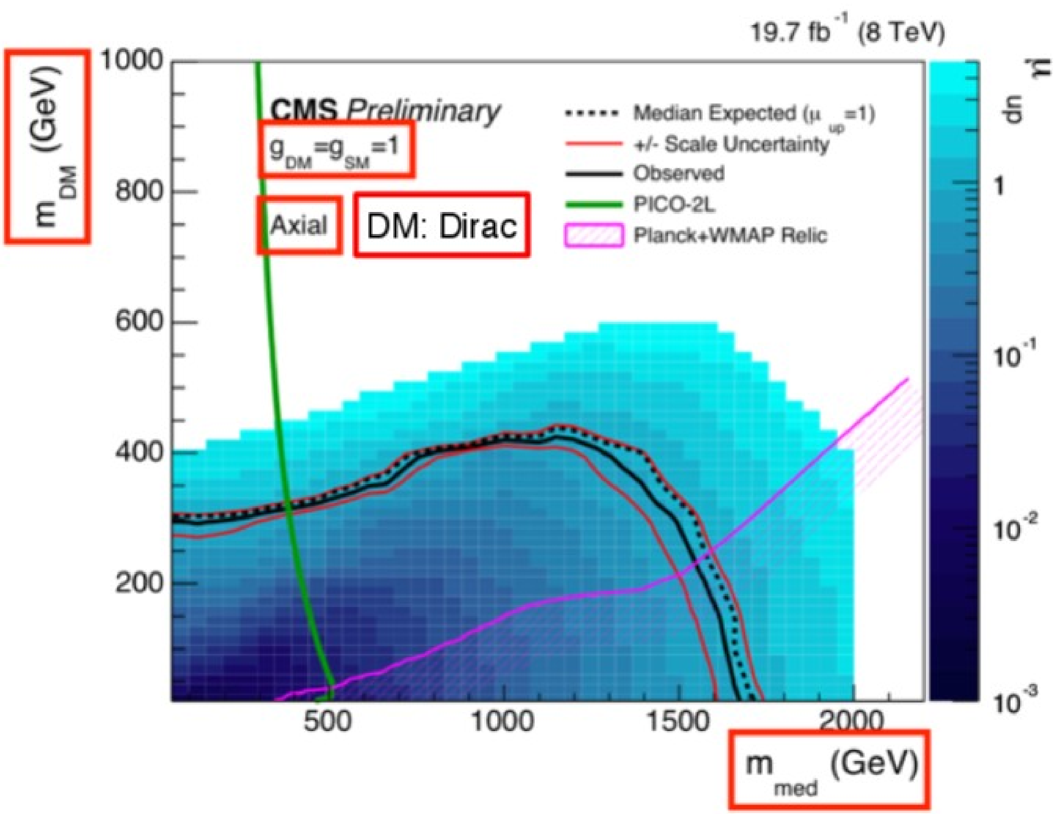
Extraction of potential DM signals …

In absence of excess: limit setting, model constraints

- NB: 95% CLs limits are standard in collider world

m(Med)-m(DM) plane: provides natural representation of collider results

- Results shown as limit on signal cross section or on signal strength ($\mu = \sigma_{obs}/\sigma_{th}$)
- Fixed gDM & gSM
- All model assumptions (eg: mediator & DM type) specified



Comparison of collider results with (in)direct detection

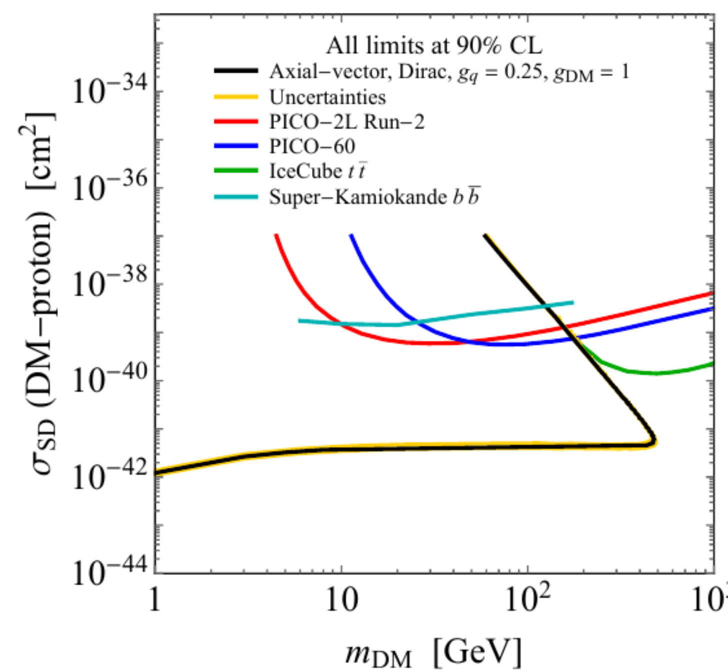
- Recent focus of LHC Dark Matter Working Group (DMWG)
- Developed recommendations for collider/non-collider comparison

Translate collider limits to $\sigma_{DM\text{-}N}$ & σv_{rel} , rather than reverse

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

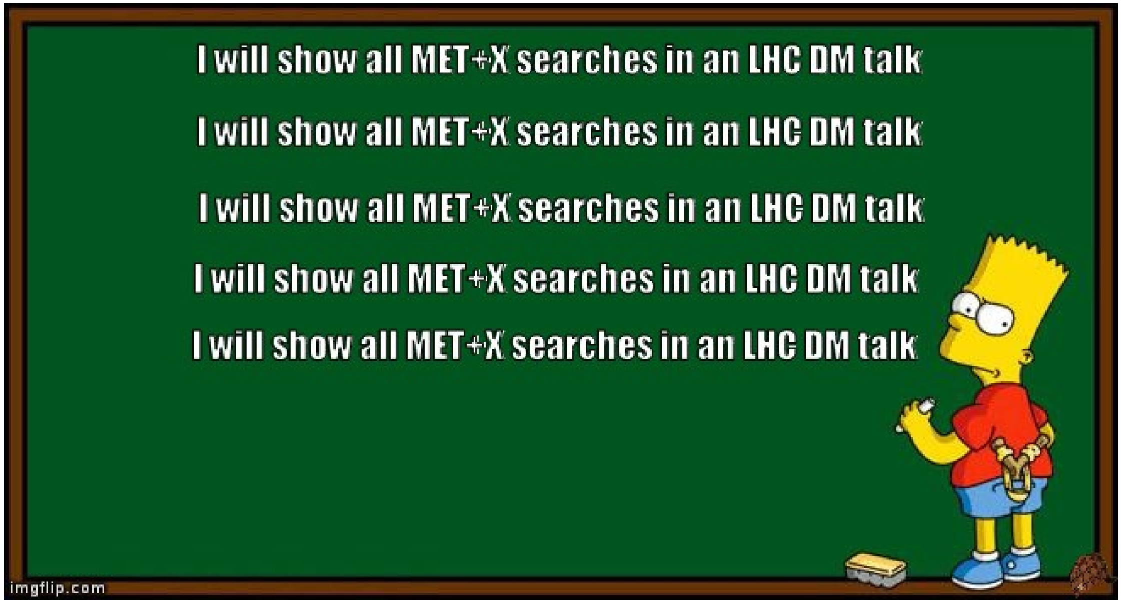
Recommendations on presenting LHC searches for missing transverse energy signals using simplified *s*-channel models of dark matter

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

Recent ATLAS & CMS DM Results



Focusing on the hadronic search channels

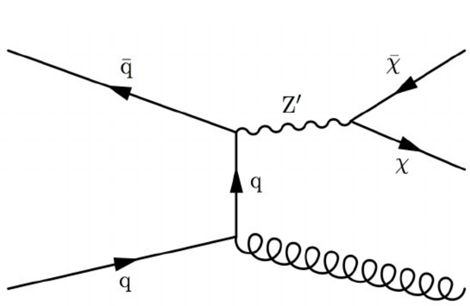
- Monojet, tt/bb + DM, dijet
- In the simplified model framework, these provide most of the DM reach at the LHC

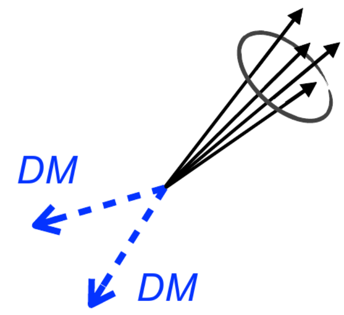
Complete list of recent results in the backups

Monojet

A generic & powerful DM search strategy at the LHC

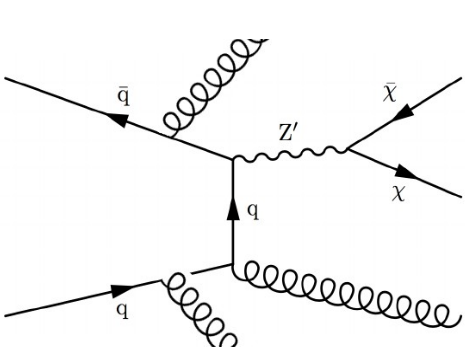
- Assumes only that DM couples in someway to incoming quarks
- Require energetic recoiling jet to trigger detector

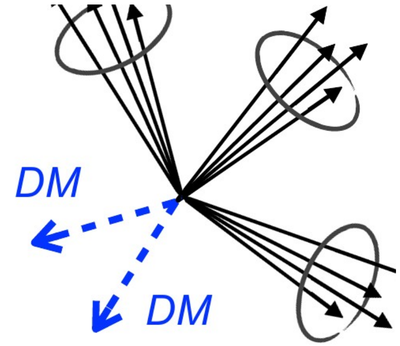




But no need to limit to a single recoiling jet ...

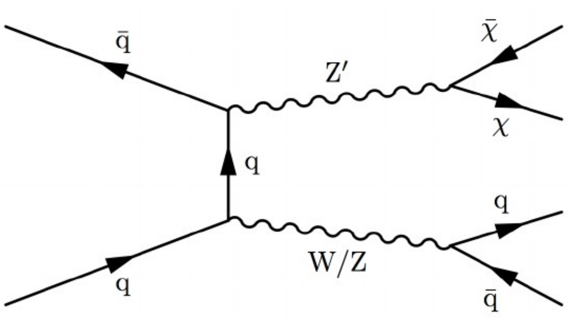
- The “monojet” search actually targets multijet + E_T^{miss} !

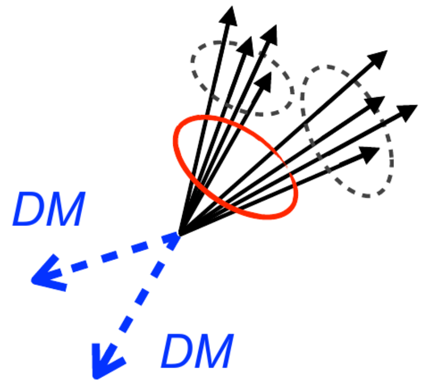


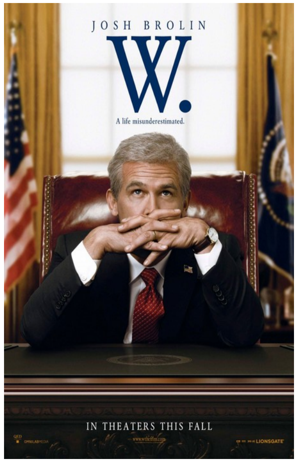


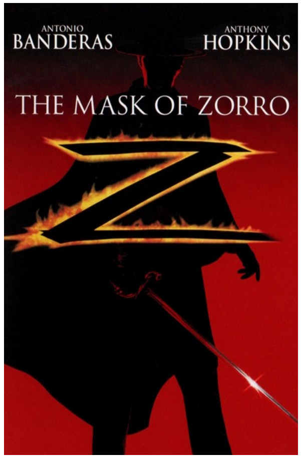
Monojet / Mono-V

DM + hadronic decays of EWK bosons can also produce a multijet + E_T^{miss} signature … mono-V

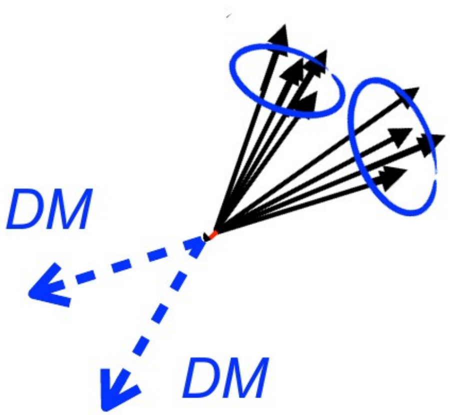








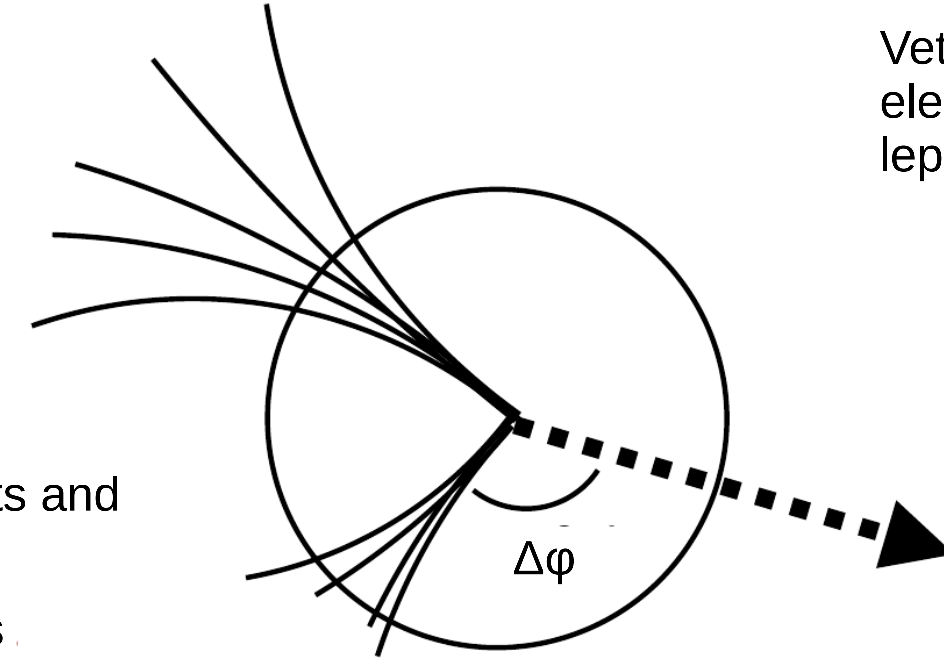
- W/Z decay products will be **boosted** when DM recoil is significant
- Reconstruction algorithms can merge these into a ~small radius jet
- But can use jet grooming / substructure techniques to identify the underlying 2-prong nature



Monojet : general strategy

At least one central ($|\eta| < 2.4$), good-quality, high-pT (eg >250 GeV) jet

Veto additional objects: electrons, muons, tau leptons, photons, bjets ...

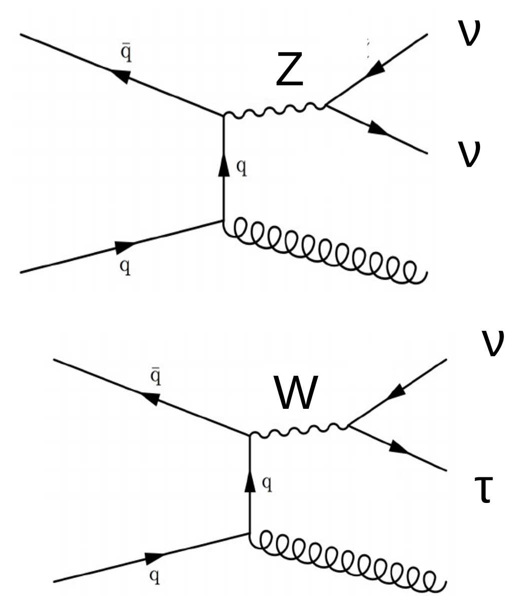


Require minimum Δφ separation between jets and E_T^{miss} to suppress misreconstruction BGs

Significant E_T^{miss} (eg >200 GeV)

Dominant backgrounds from SM processes with real E_T^{miss} and/or leptons out of detector acceptance

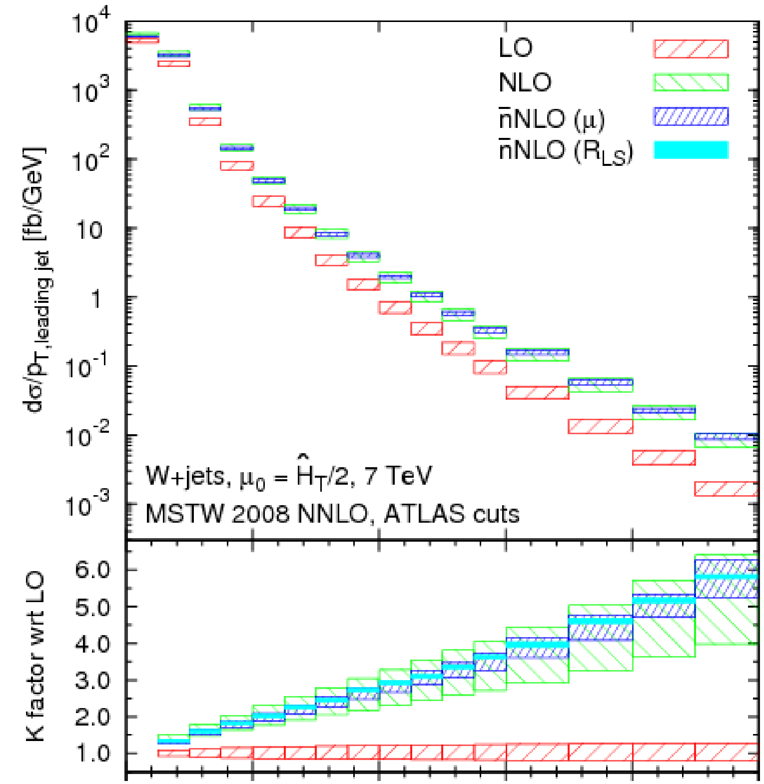
- $Z(\nu\nu)$ + jets, $W(\tau[qq']\,\nu)$ + jets, $W(l\nu)$ + jets
- Bread & butter EWK processes @ the LHC
- Wealth of precise calculations & simulation tools available

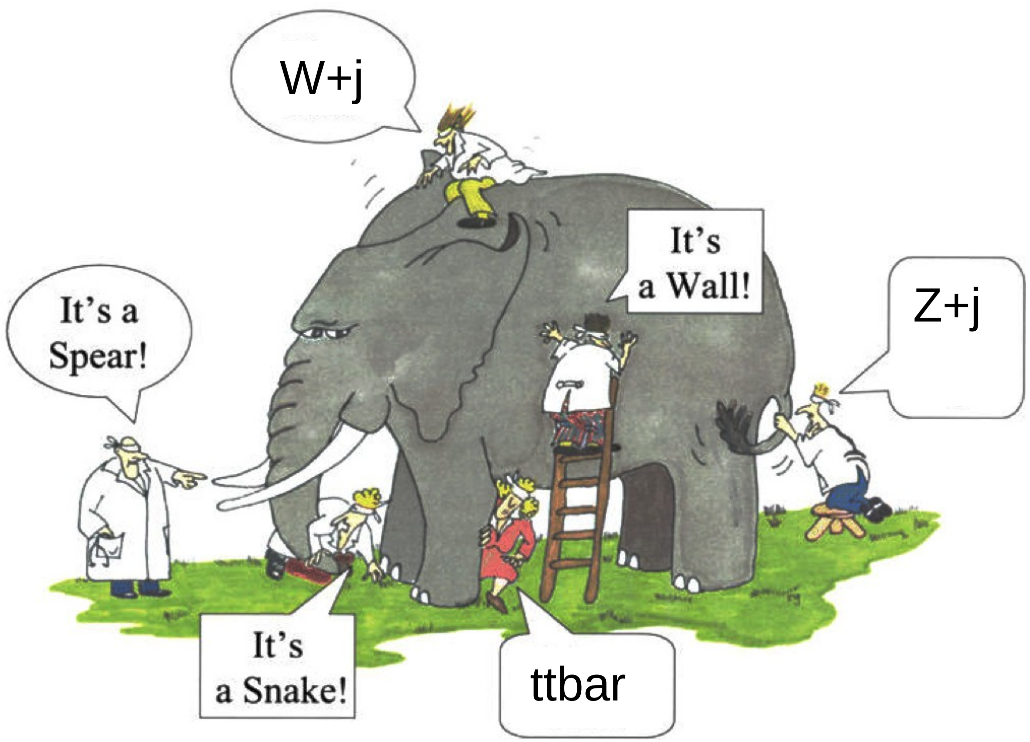


Monojet : general strategy

Selections define signal enriched regions (SR) in data

- Residual backgrounds in these regions from events in tails of E_T^{miss} kinematic distributions
- Associated SM theory uncertainties are typically large here ...





BG dominated control regions (CR) help constrain SM rates & kinematics in the SRs

- *Augment* precise calculations of EW processes with measurements!

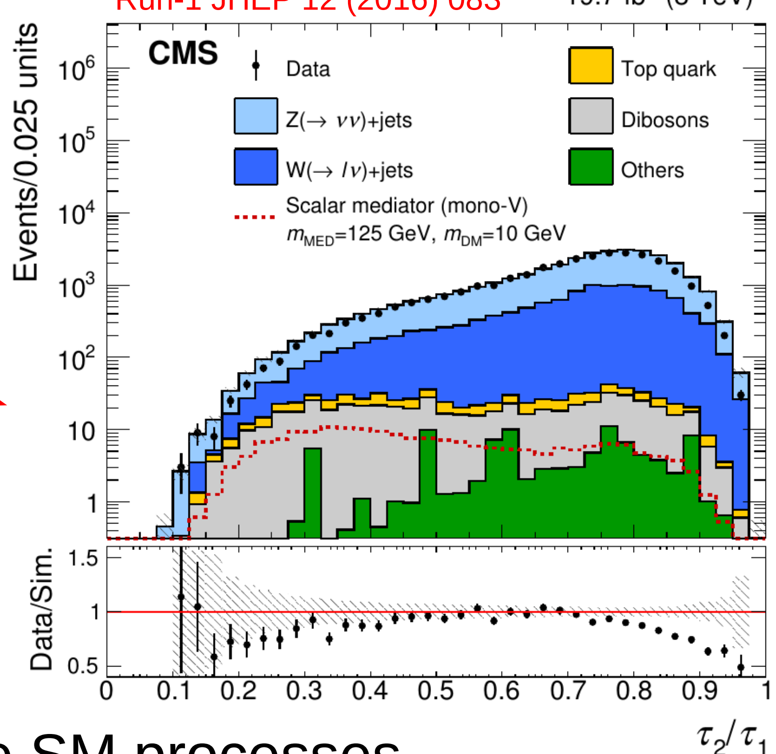
CMS Monojet / Mono-V

35.9 fb-1 : CMS-PAS-EXO-16-048,   12.9 fb-1: JHEP 07 (2017) 014, 1703.01651

SR selection : large E_T^{miss}, ≥ 1 high-p_T jet, Δφ > 0.5 radian

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

Run-1 JHEP 12 (2016) 083



5 (categorized) SM control regions to constrain high-E_T^{miss} BGs

- Use observable analogues of the invisible SM processes
  - Z(μμ), Z(ee), W(μν), W(eν) + jets, high-stat γ+jet
- Subtract visible signatures → hadronic recoil, a proxy for E_T^{miss}
- Use NLO QCD + NLO EWK calculations to translate rates + distributions in CRs into SR predictions!

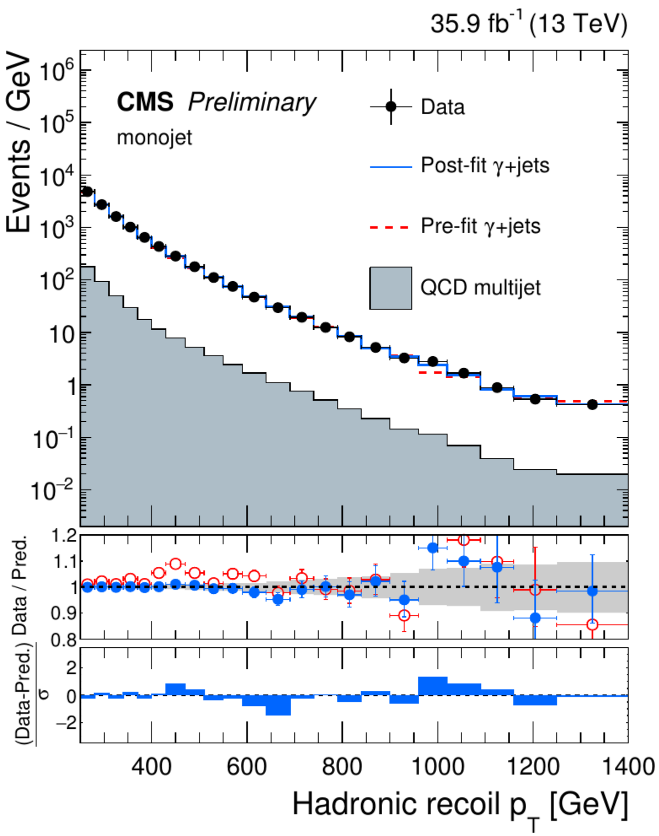
Extract signal from combined likelihood fit to E_T^{miss} distributions

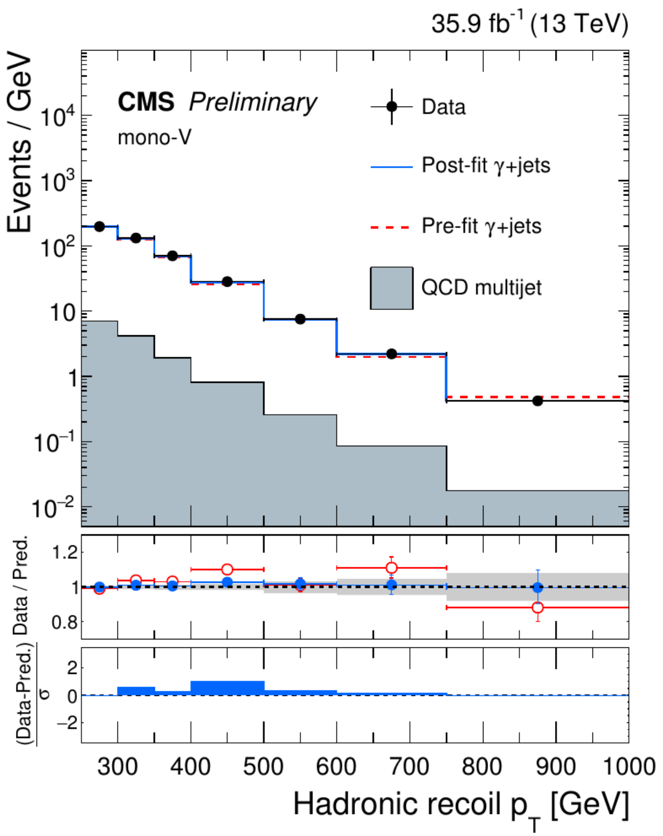
Uncertainties & correlations on transfer factors (see 1705.04664)

- Incorporated as nuisance parameters in the fit
- Pure QCD effects: scale/normalization, recoil shape pT dependence, cross section ratios
- Pure EWK effects: missing NNLO, unknown Sudakov logs, NLL Sudakov approximation
- Combined multiplicatively, nuisance added for possible non-factorization

Control regions fit simultaneously with the signal regions

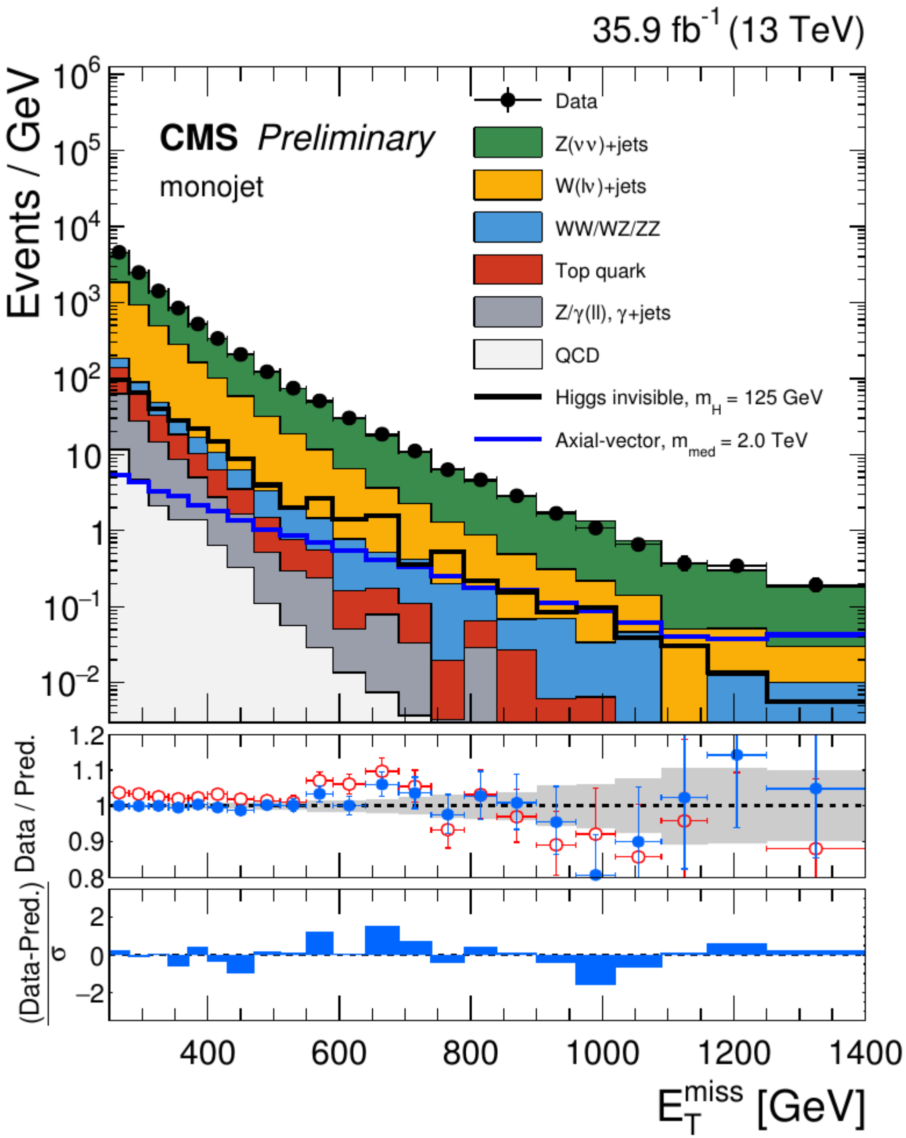
- Excellent post-fit agreement in CRs

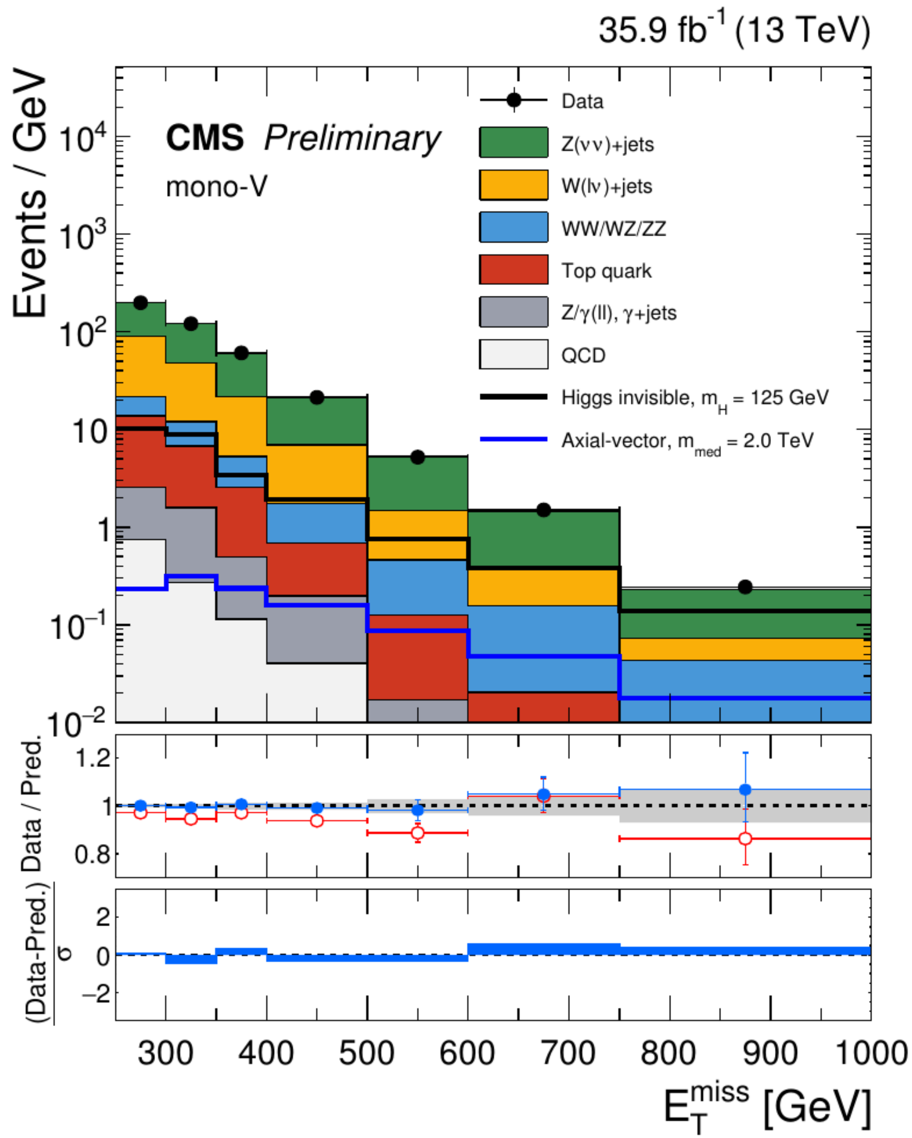




CMS Monojet / Mono-V

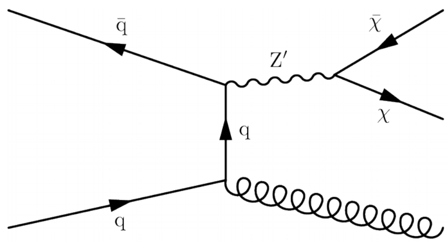
Data in signal region consistent w/ post-fit SM expectations …

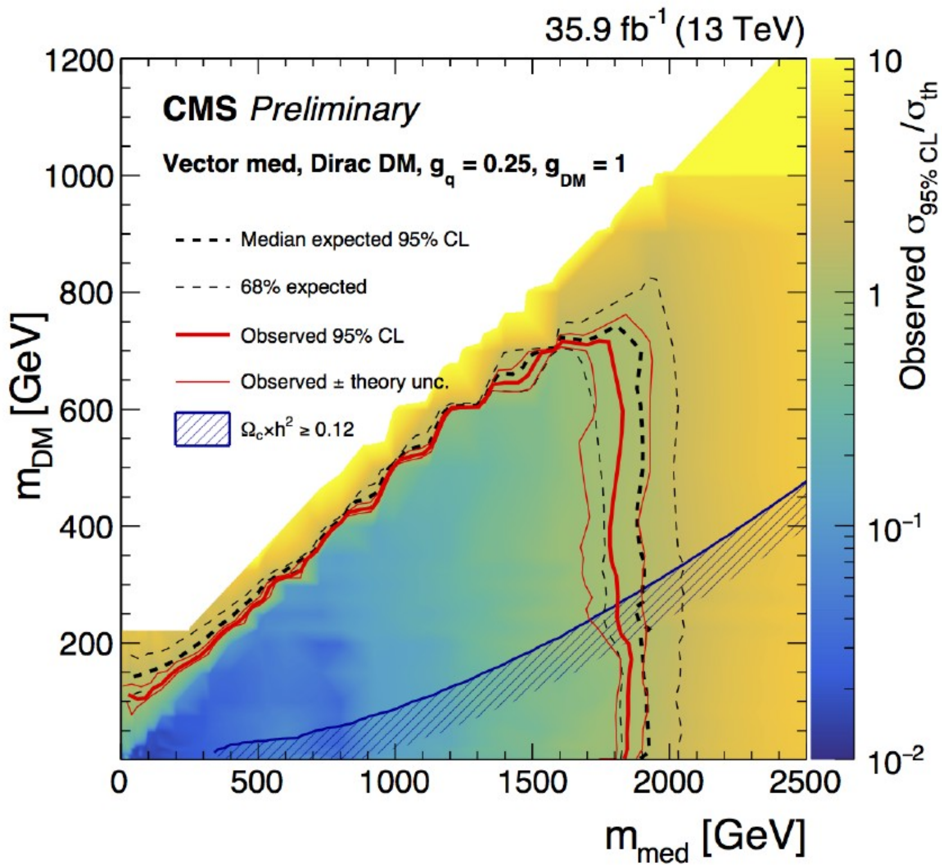


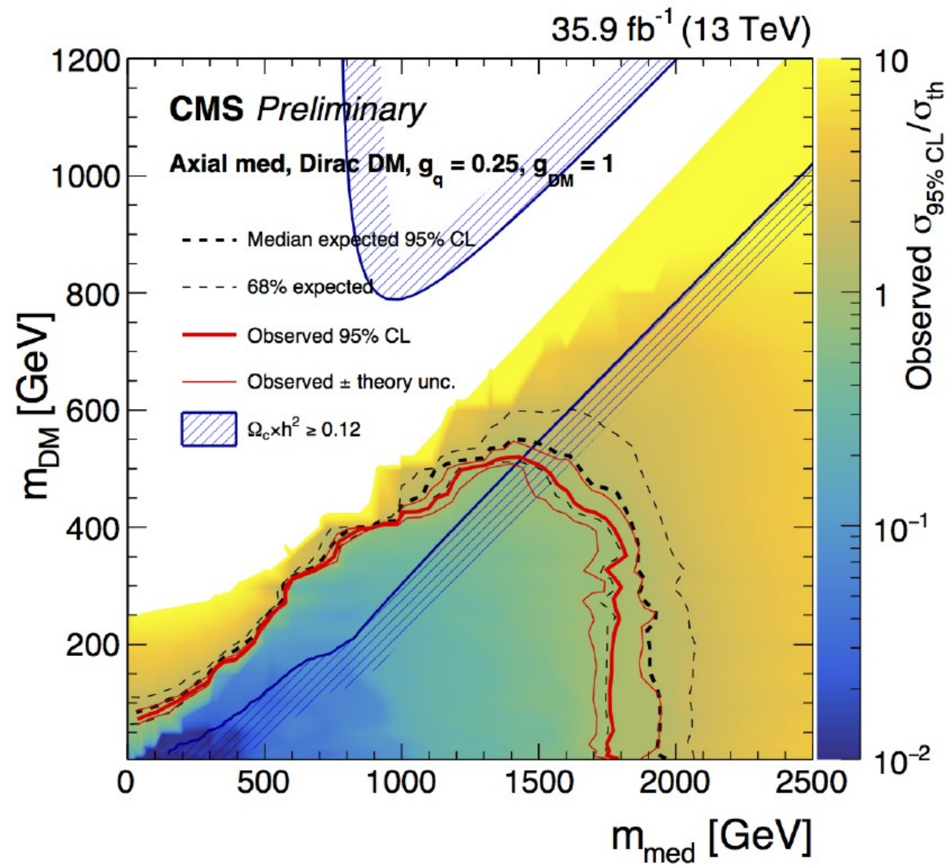


Limits on both spin-1 and spin-0 mediators

- Vector/Axial exclusion (this slide) up to 1.8 TeV
- Pseudoscalar (backup) up to 400 GeV

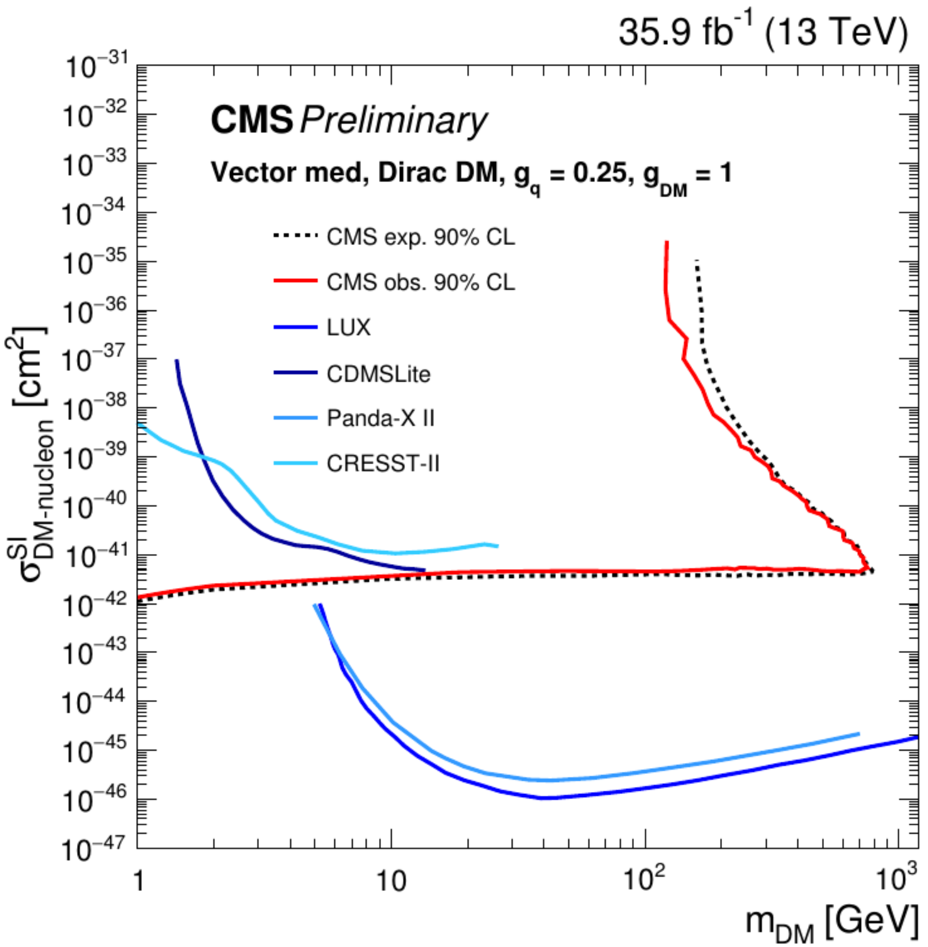


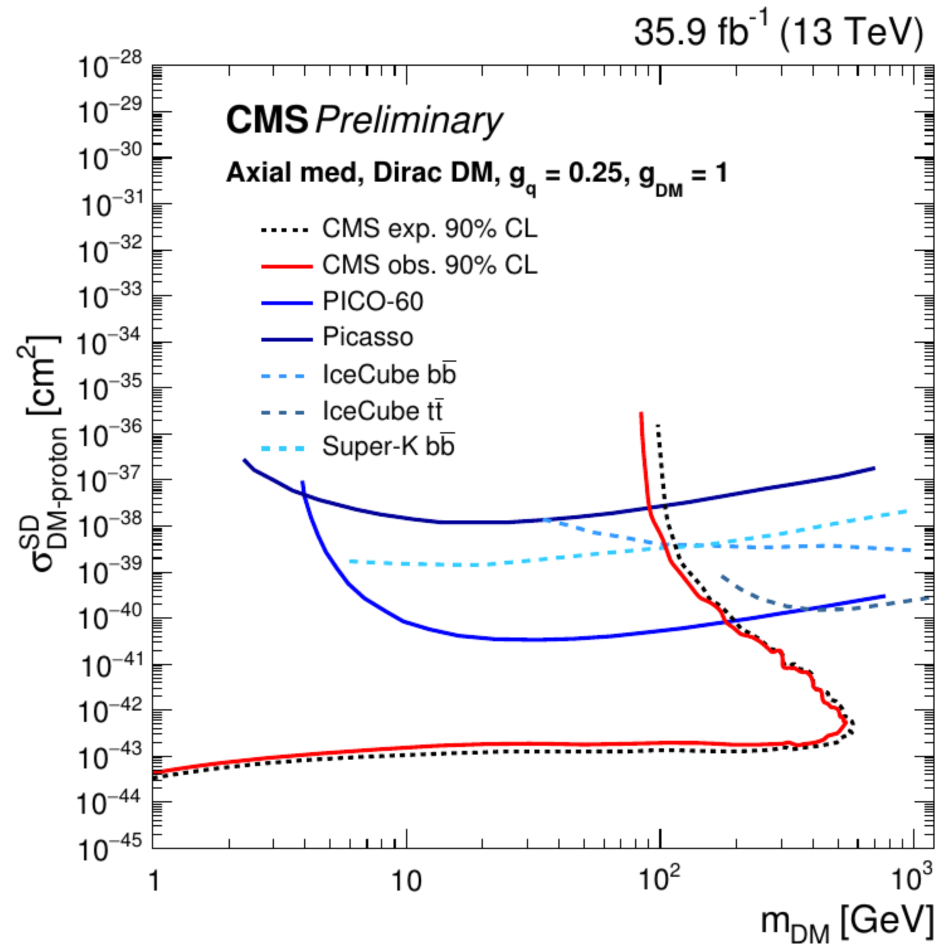




Reinterpret as invisible Higgs : BR(h→inv.) < 0.53 (0.4 exp.)

And recast as limits on SI/SD DM-nucleon cross section (1603.04156)





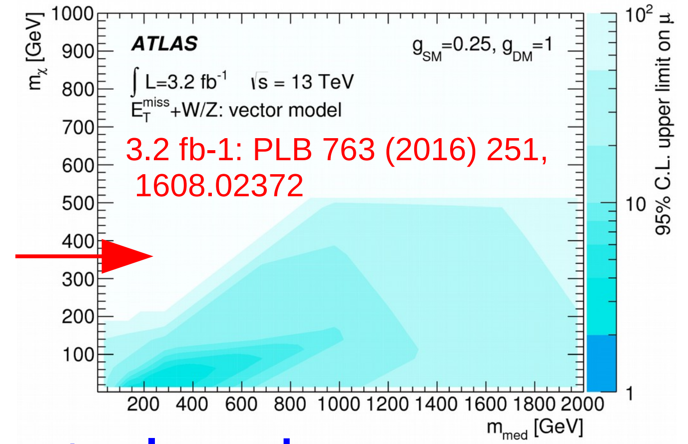
Low-mDM reach complementary to direct detection!

ATLAS Monojet

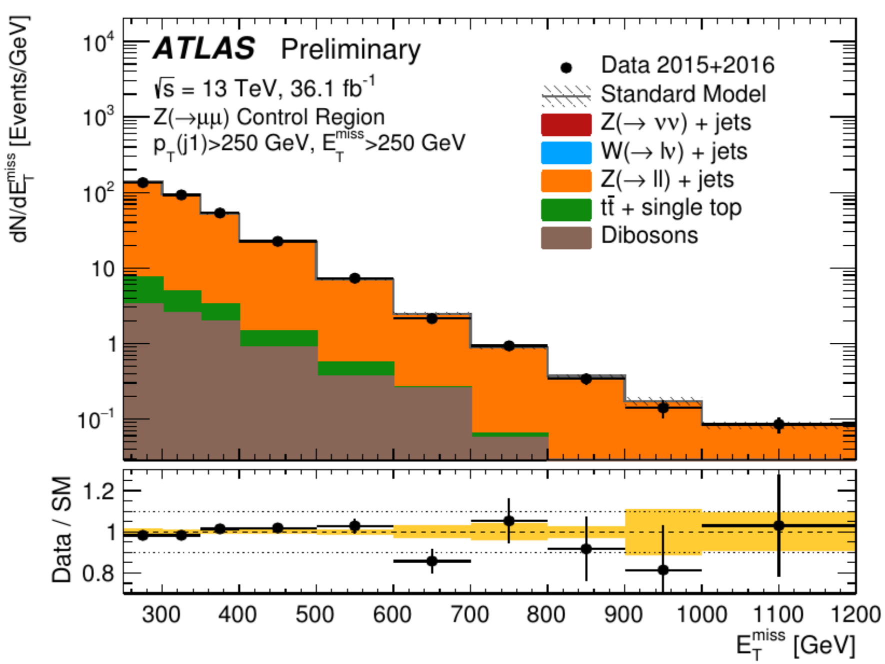
36.1 fb-1 : ATLAS-CONF-2017-060, 3.2 fb-1: PRD 94 (2016) 032005, 1604.07773

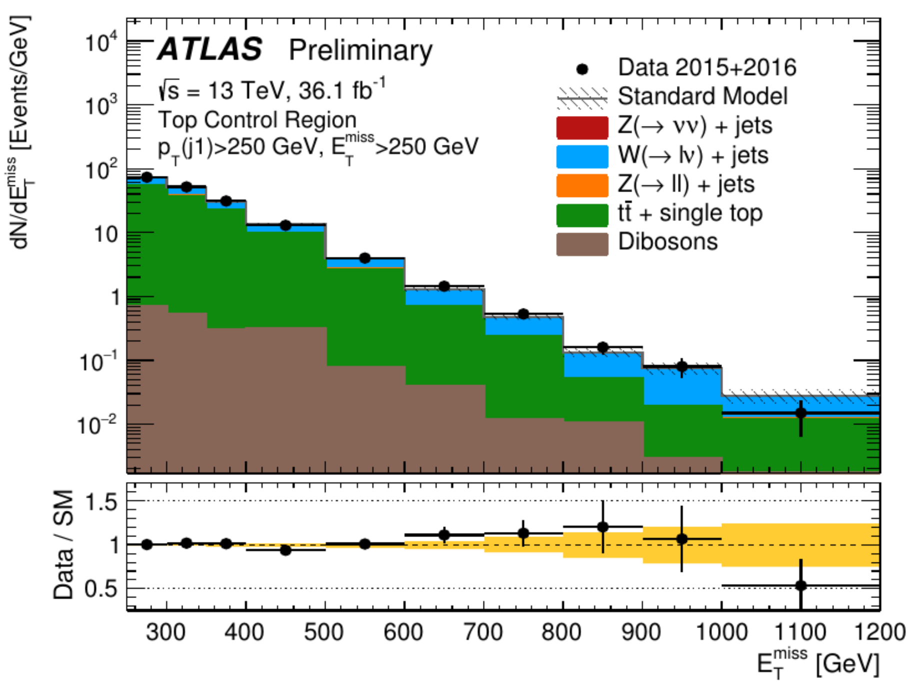
Similar monojet search strategy pursued in ATLAS:

- p_T^{AK4} , E_T^{miss} > 250 GeV, Δφ > 0.4 radian, vetos
- Simultaneous binned likelihood fit to E_T^{miss}
- No mono-V category, dedicated mono-W search
- No Z(ee) + jets, γ+jets CRs, adds ttbar CR

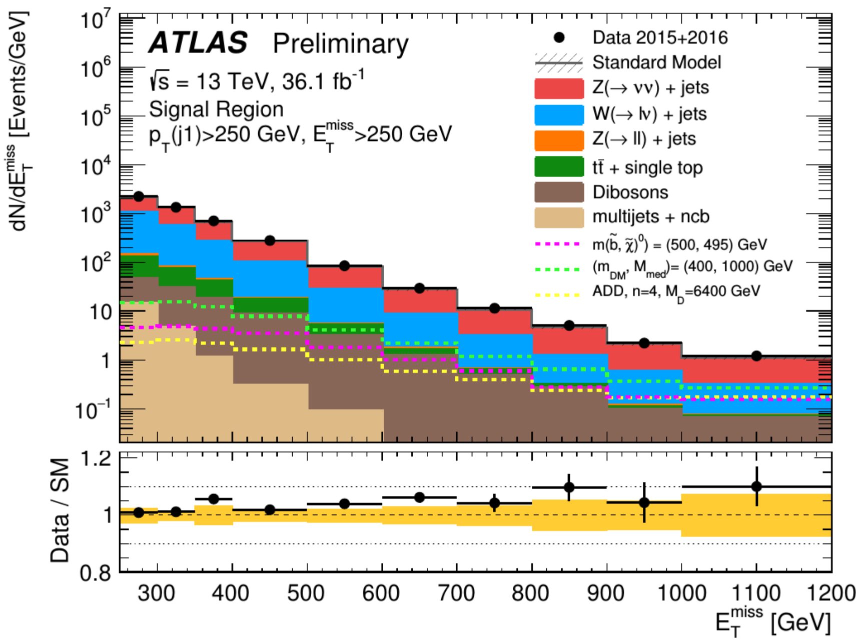


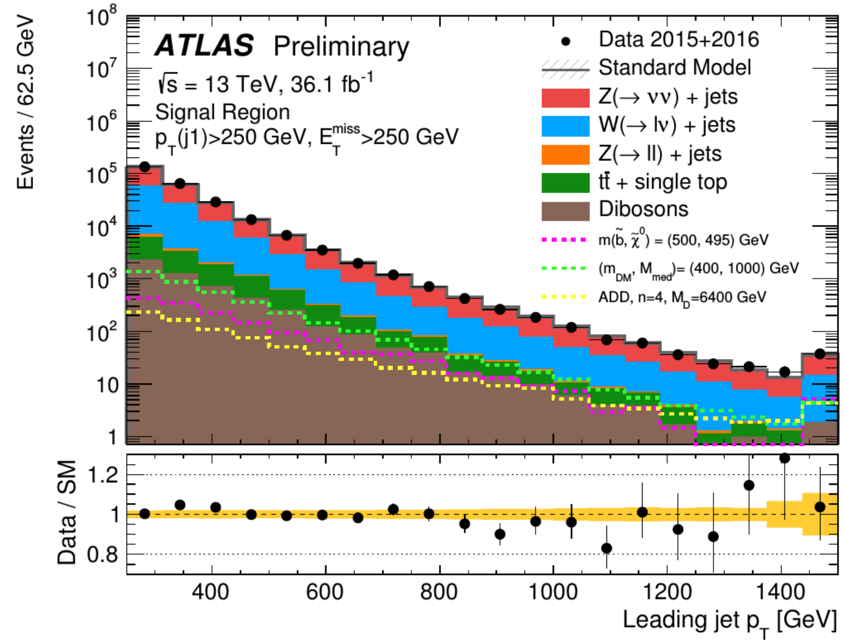
Good agreement in Z(ll)+jets & W(lν)+jets control regions

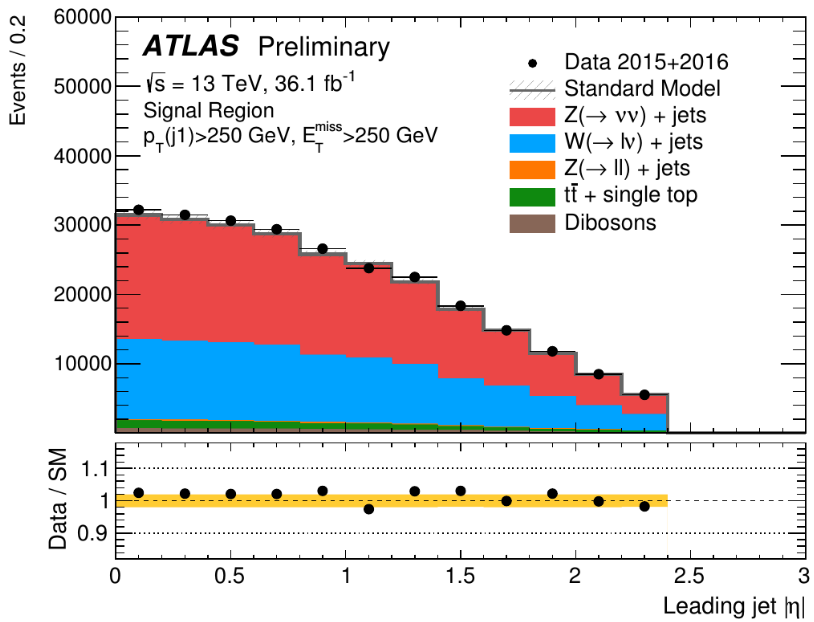


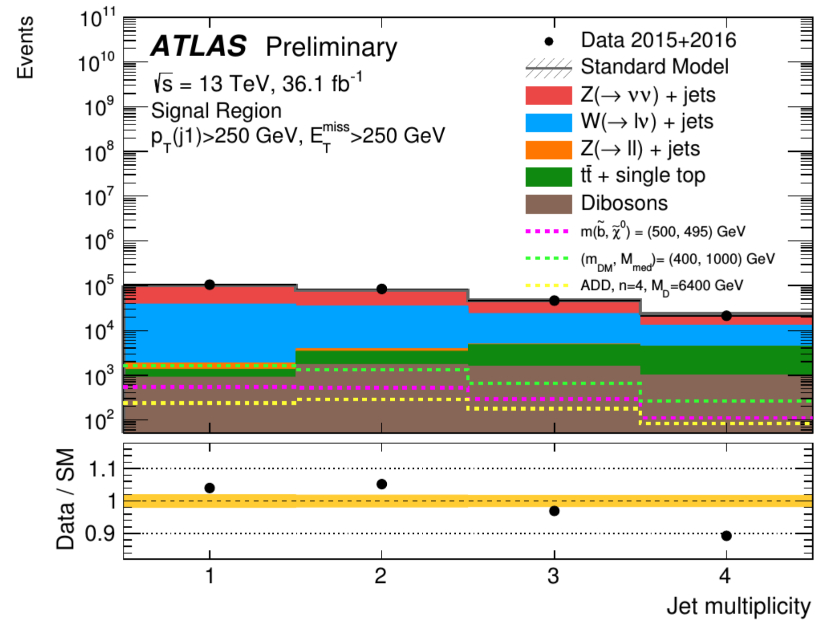


And good agreement in the signal region ...





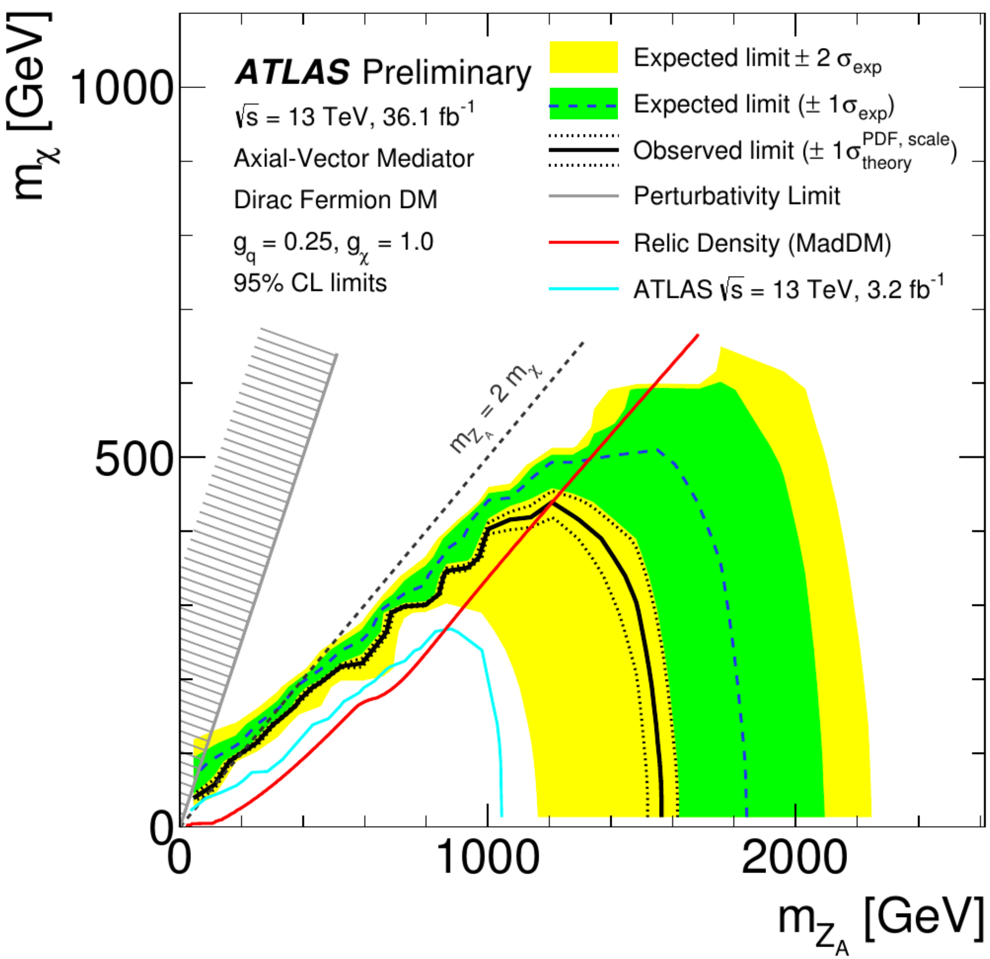


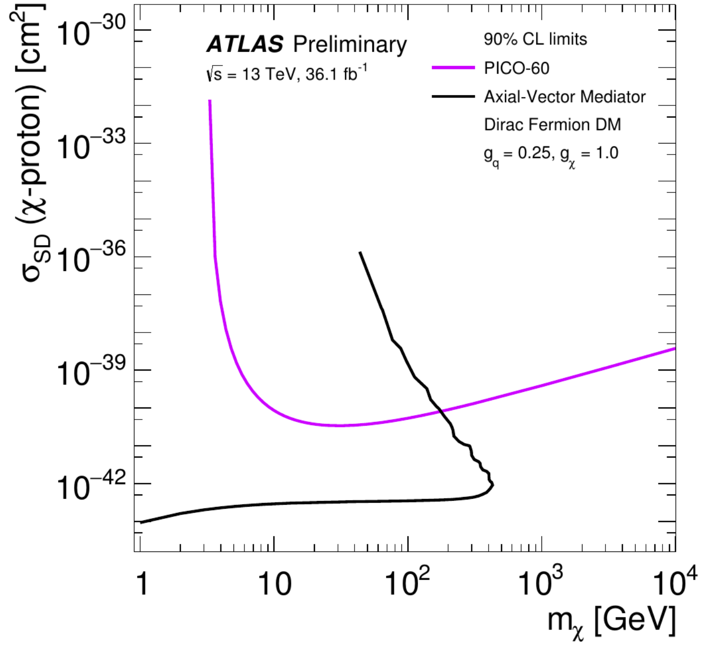


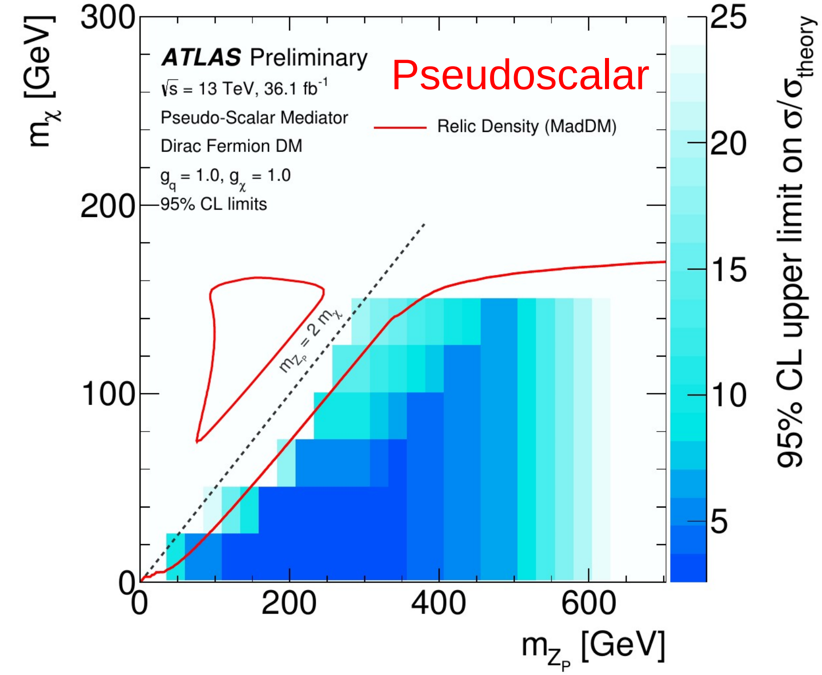
ATLAS Monojet

Limits on both spin-1 and spin-0 mediators

- Axial-vector exclusion up to 1.55 TeV
- Not yet sensitive to pseudoscalars



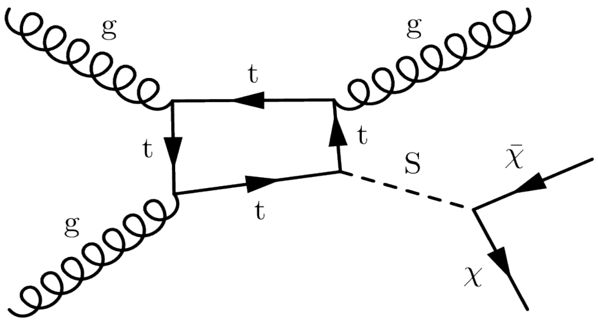


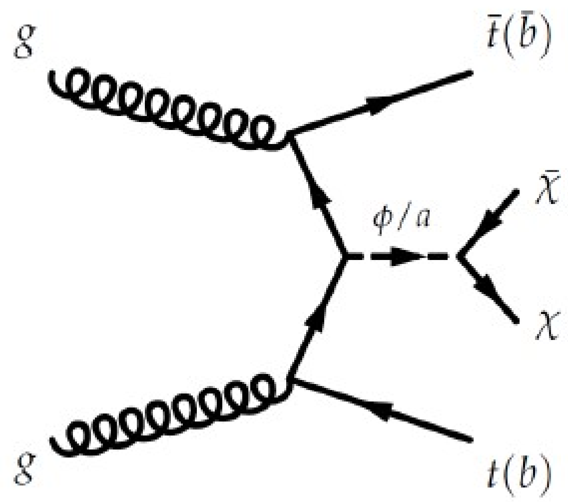


ttbar + DM

Monojet drives sensitivity to spin-1 mediator scenarios

- Picture more nuanced for spin-0 models ...
  - MFV → mediator has Yukawa coupling
  - Monojet through heavy quark loops
- Implies tree-level couplings to top and bottom
  - Same mediator as in monojet
  - Yukawa enhancement → tt+DM competitive with monojet at low mMed!
- Can also anticipate a "monotop" signature …
  - Assumes specialized signal model (see backup)





DM+ heavy quarks = rich signatures!

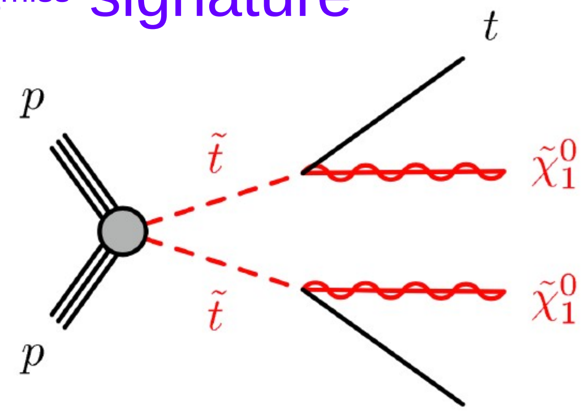
- tt final states: all-hadronic, semileptonic, dileptonic
  - Produces leptons, high-pT jets, b jets, E_T^{miss}
- Many experimental handles → many viable DM search strategies

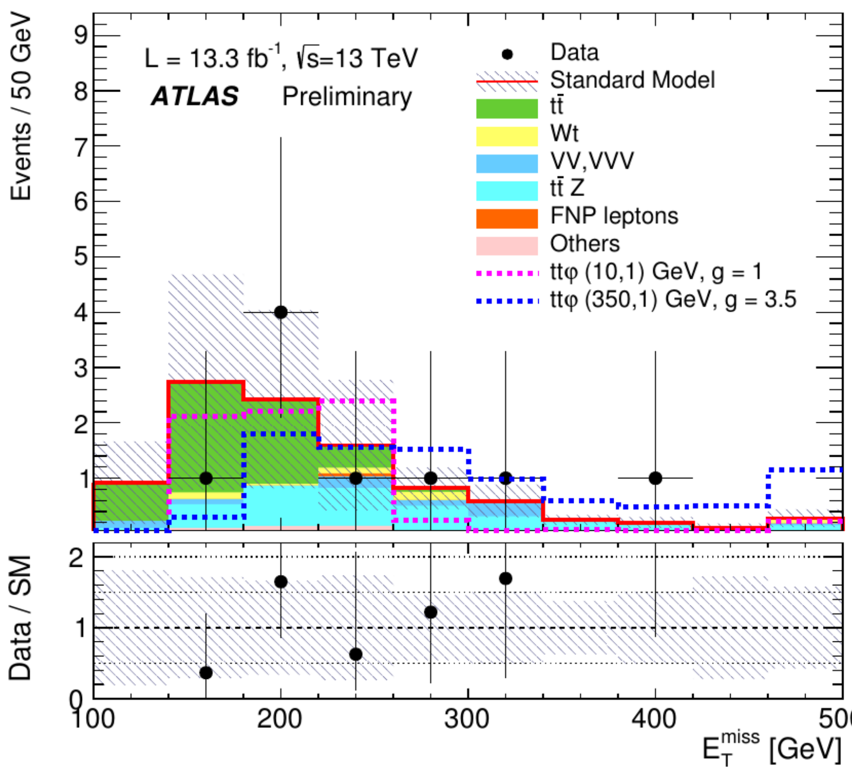
Backgrounds : mostly SM ttbar (with a lost lepton), single top, ttV

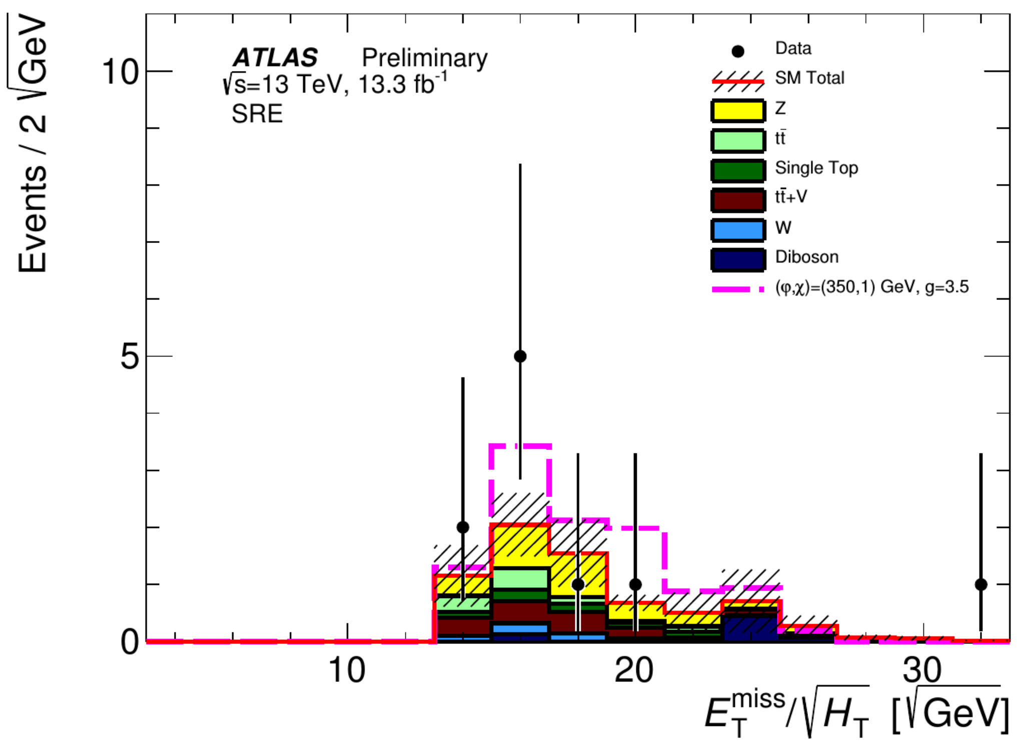
ATLAS tt/bb + DM

SUSY stop searches also looking for the tt+E_T^{miss} signature

- These generally involve many SRs & CRs to explore wide range of SUSY scenarios
- Leverage SUSY observables (eg: mT2) optimized for selecting E_T^{miss} from decays of heavy particles
- Extend SUSY search with regions that target DM production, add DM interpretation







ATLAS-CONF-2016-076 (13.3 fb-1)

ttbar (dilepton) + E_T^{miss}

ATLAS-CONF-2016-076 (13.3 fb-1)

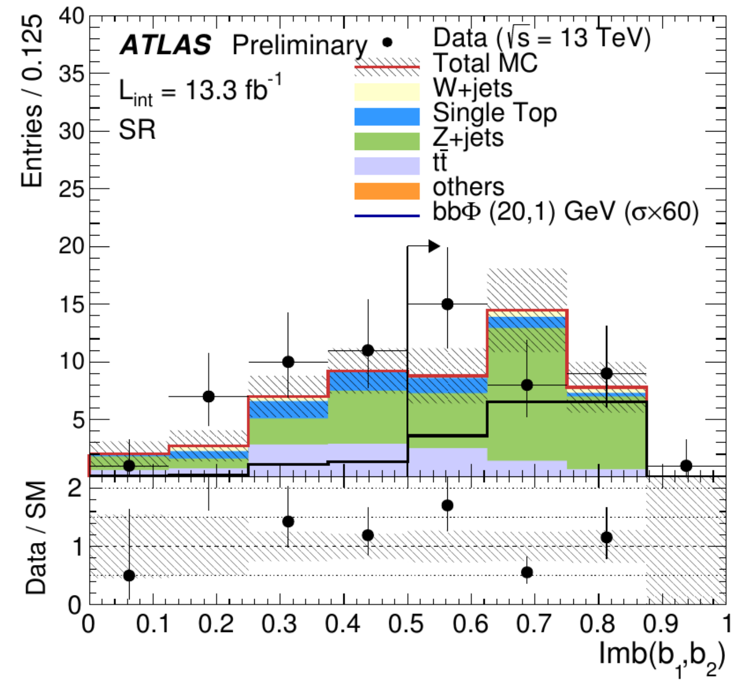
ttbar (dilepton) + E_T^{miss}

ATLAS tt/bb + DM

ATLAS-CONF-2016-086 (13.3 fb-1)

Dedicated bb+E_T^{miss} search

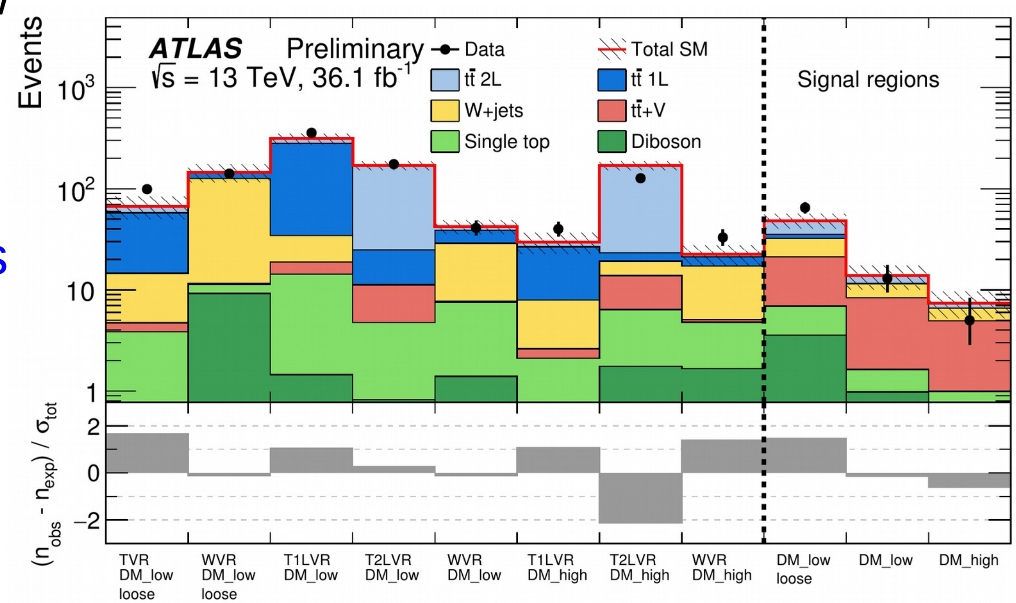
- Sensitive to models (eg: 2HDM w/ large tanβ) in which coupling to down-type quarks enhanced
- Select events with large pT imbalance between 2 high-pT b-tagged jets
- 3 CRs to control Z+jets, W+jets and ttbar



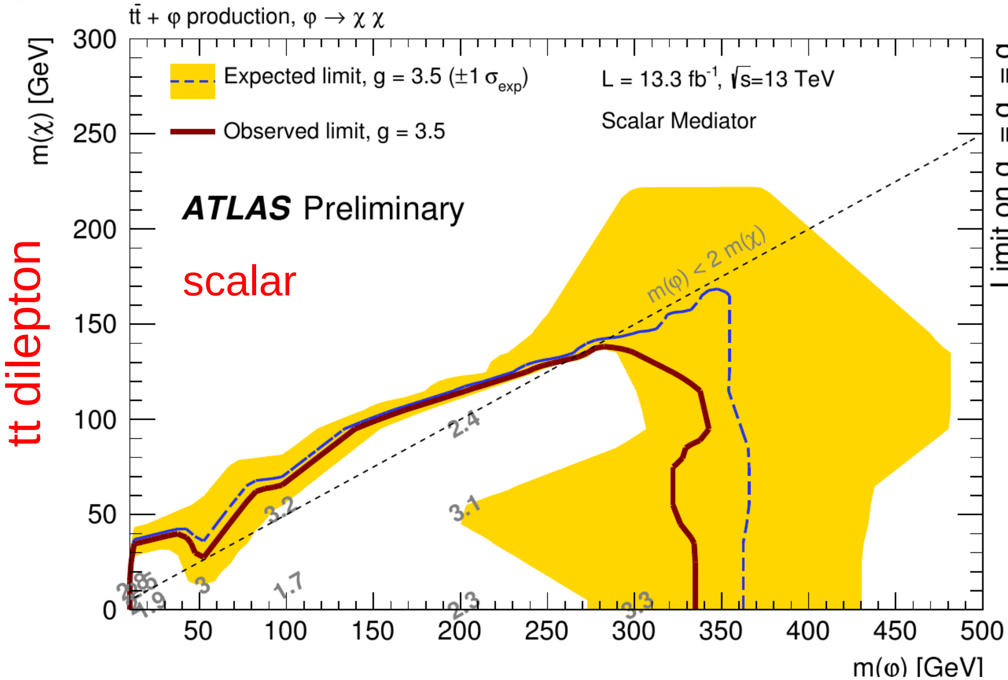
ATLAS-CONF-2017-037 (36.1 fb-1)

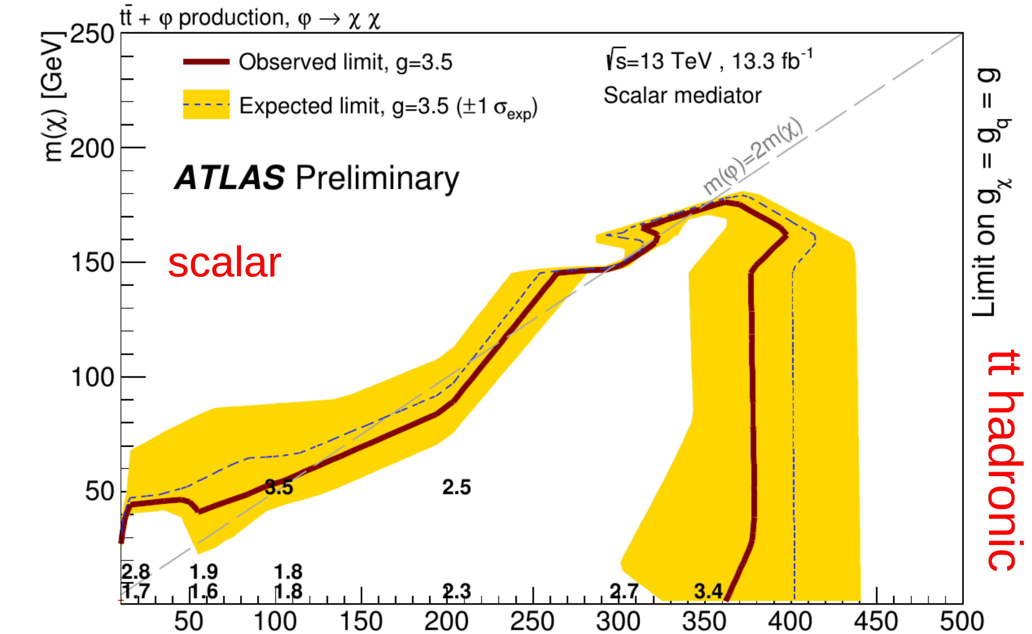
Update: tt(semileptonic)+E_T^{miss} search

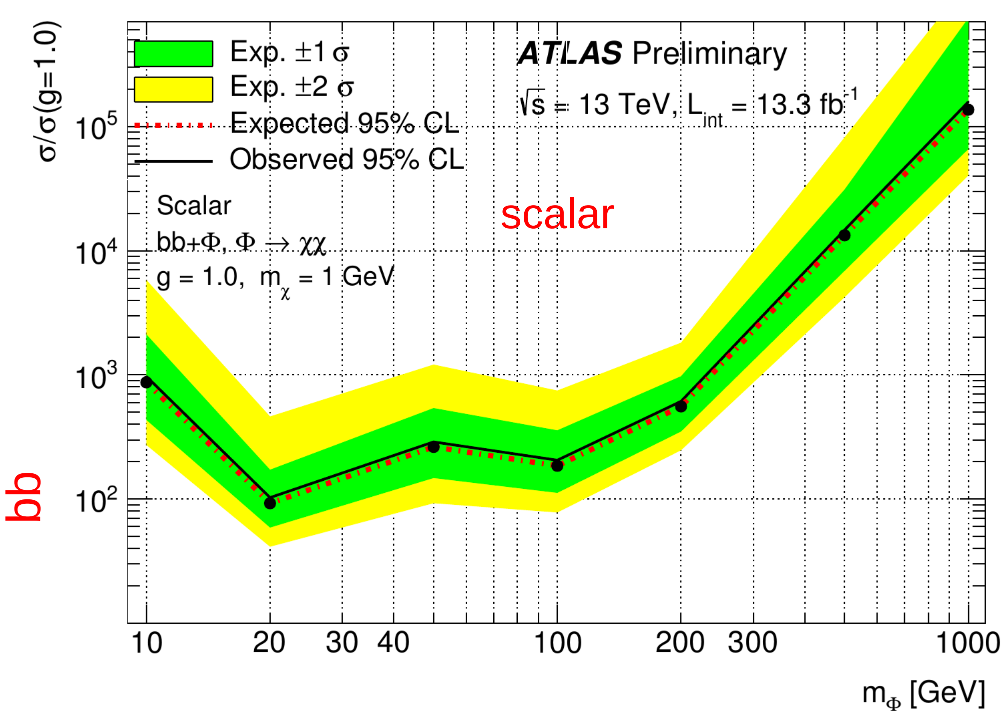
- DM categories provide sensitivity to low (~20 GeV) and high (~300 GeV) mass DM mediators
- New SRs use boosted top-tagging discriminant to identify hadronic decays of high-pT top quarks
- ttbar normalized via CR fit, signal extraction from 3 bin cut & count analysis

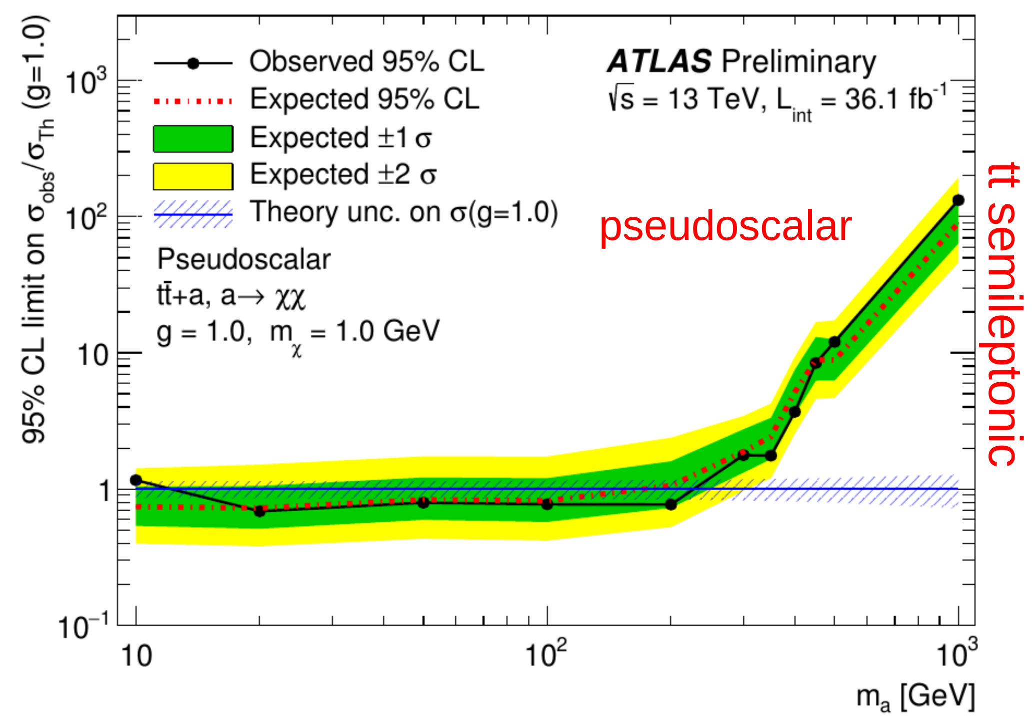


ATLAS tt/bb + DM Limits

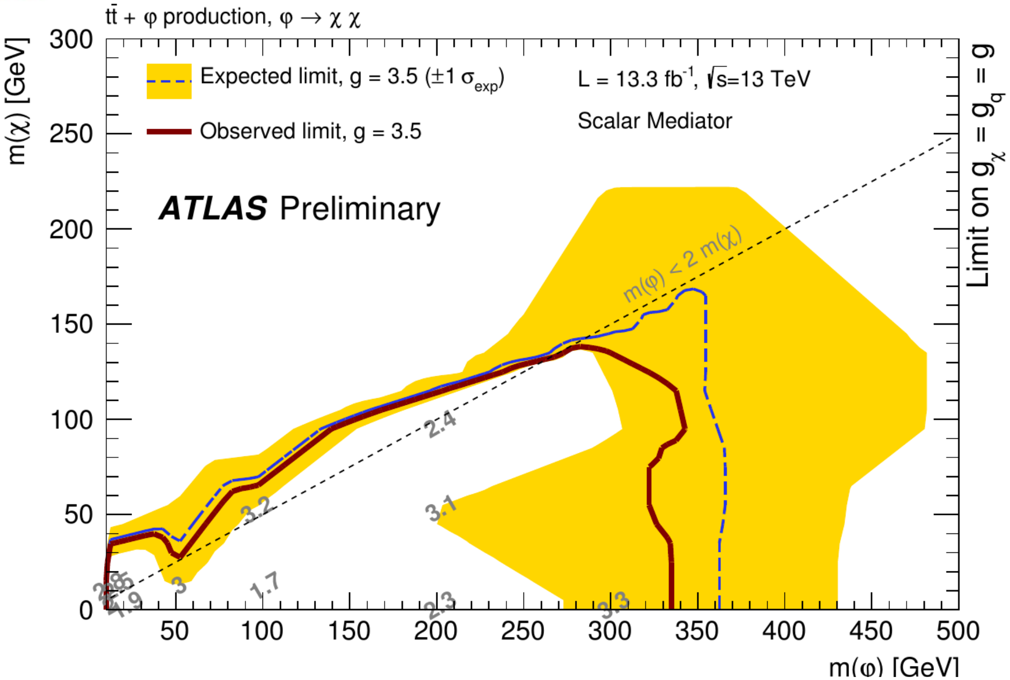


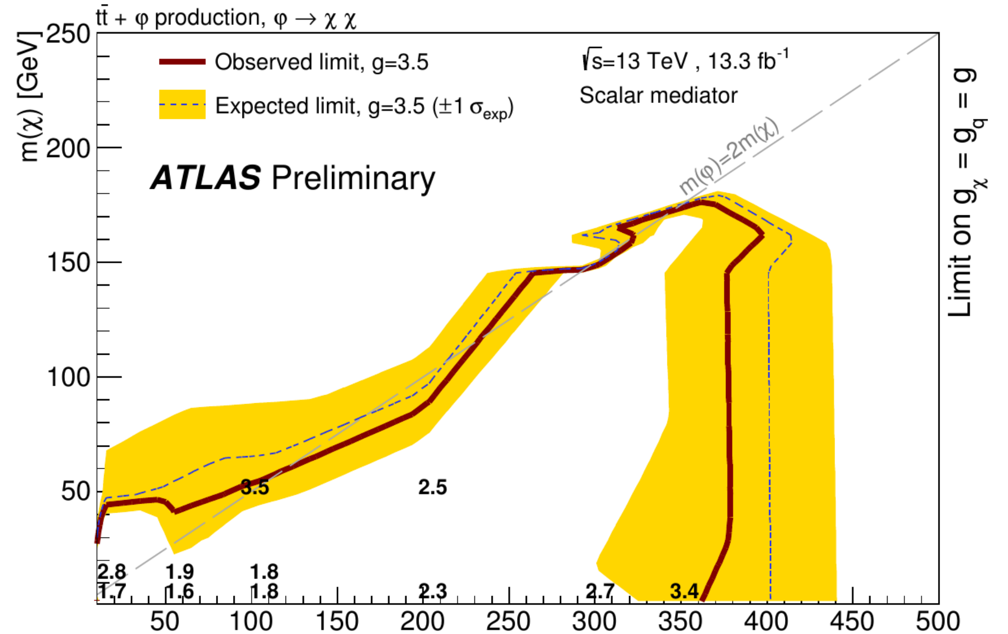


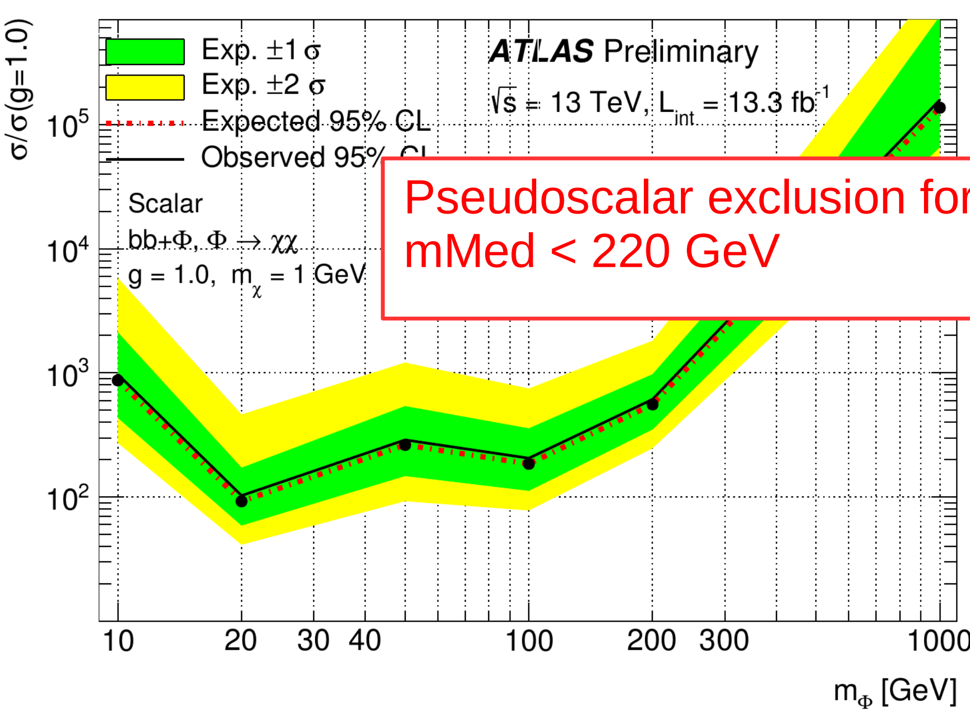


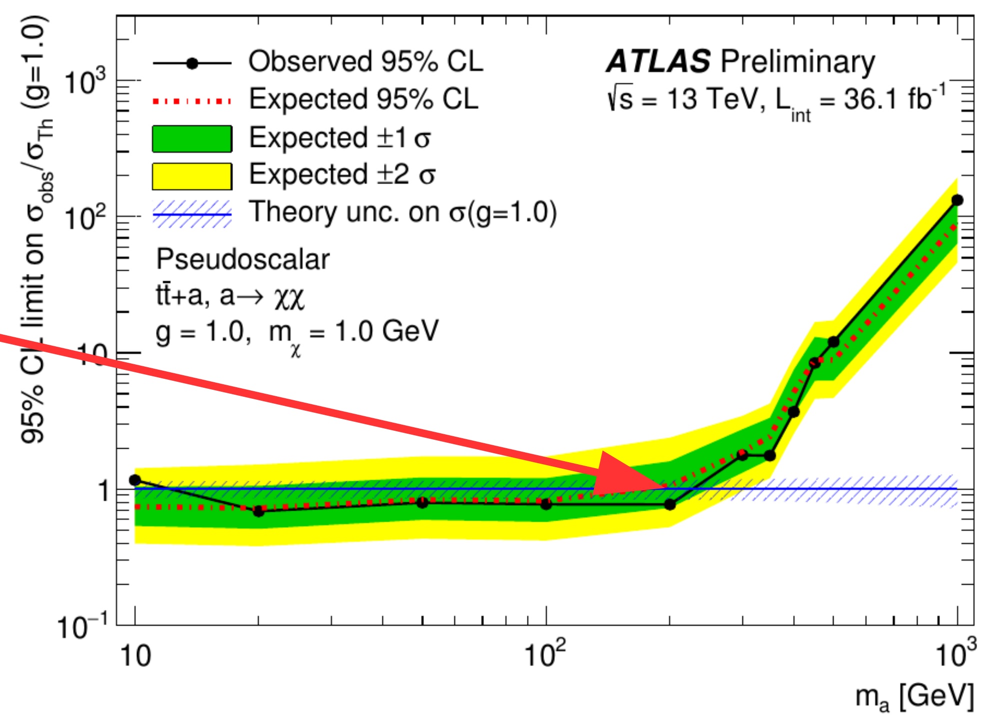


ATLAS tt/bb + DM Limits









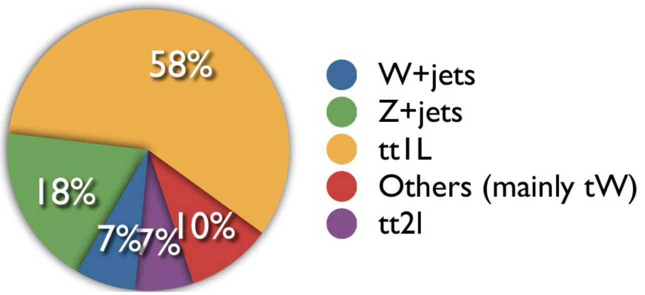
Pseudoscalar exclusion for mMed < 220 GeV

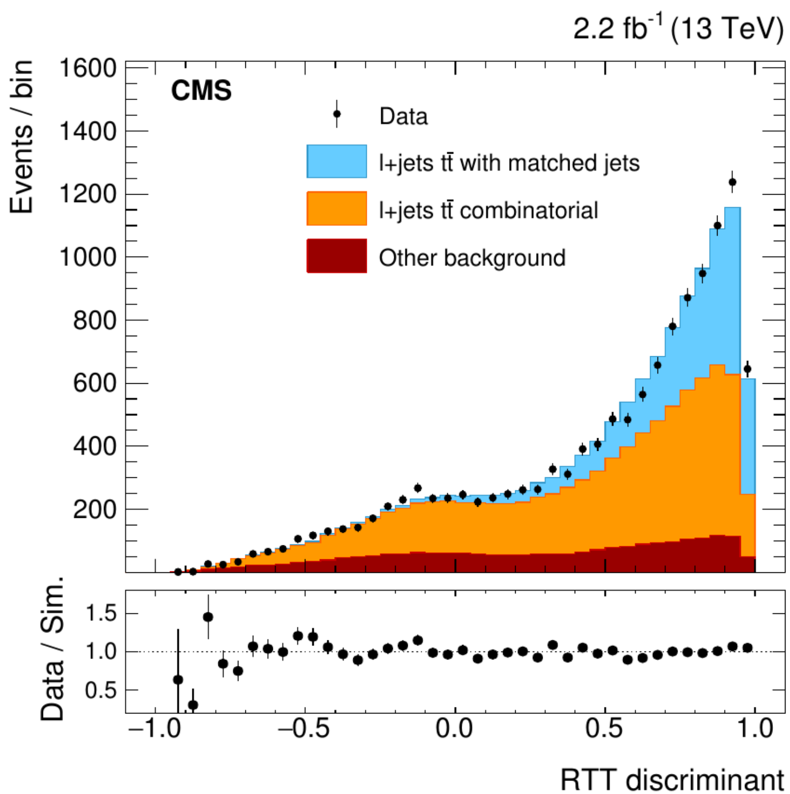
2.2 fb-1 : 1706.02581, CMS-PAS-EXO-16-005, CMS-PAS-EXO-16-028

Combined search using all tt+E_T^{miss} and bb+E_T^{miss} channels

- E_T^{miss} > 200 for bb & all-hadronic tt, E_T^{miss} > 160 GeV for semileptonic tt, E_T^{miss} > 50 GeV for dileptonic tt
- Employs novel *resolved* top quark tagger to reconstruct low/moderate pT hadronic decays
  - Top pT is soft in for mediator masses for which there is LHC sensitivity
  - BG from SM tt with missing lepton
  - Categorize signal and bkg according to number of top tags
- Simultaneous E_T^{miss} fit using 8 SRs + 19 CRs

BG yields in all-hadronic tt+DM



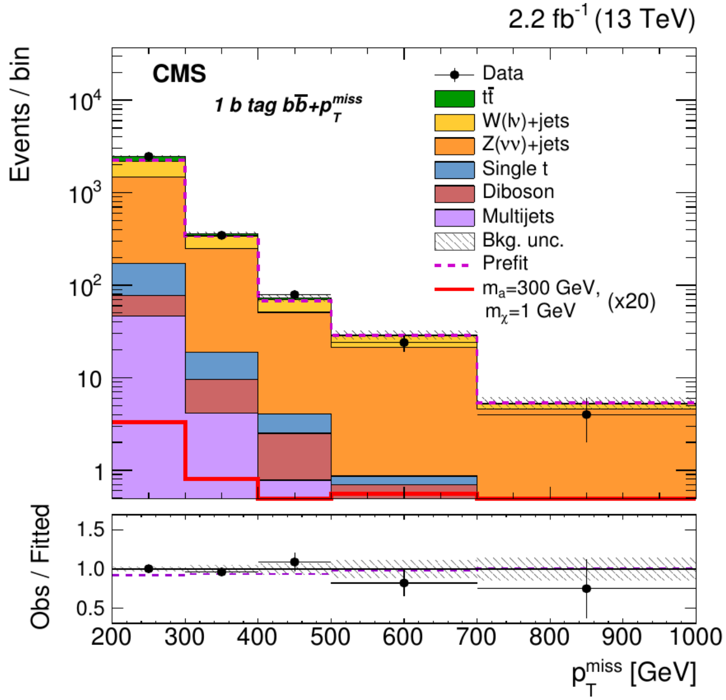


Search uses just 2.2 fb-1 from Run2

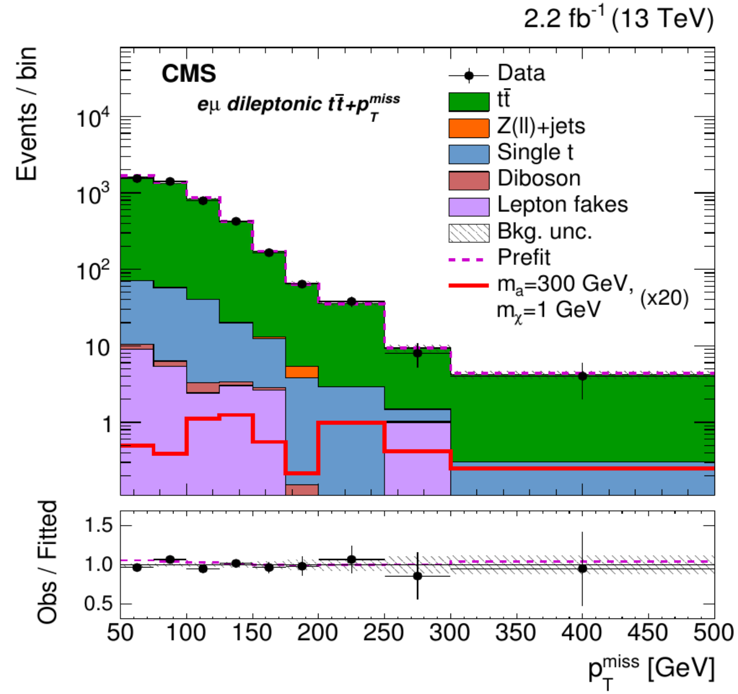
- Analysis of full 35.9 fb-1 in progress

CMS tt/bb + DM

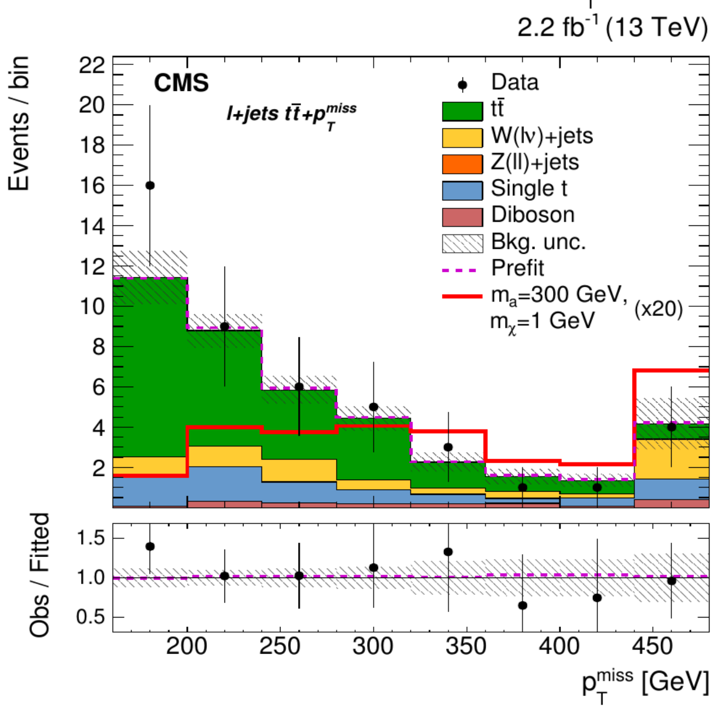
bb signal region



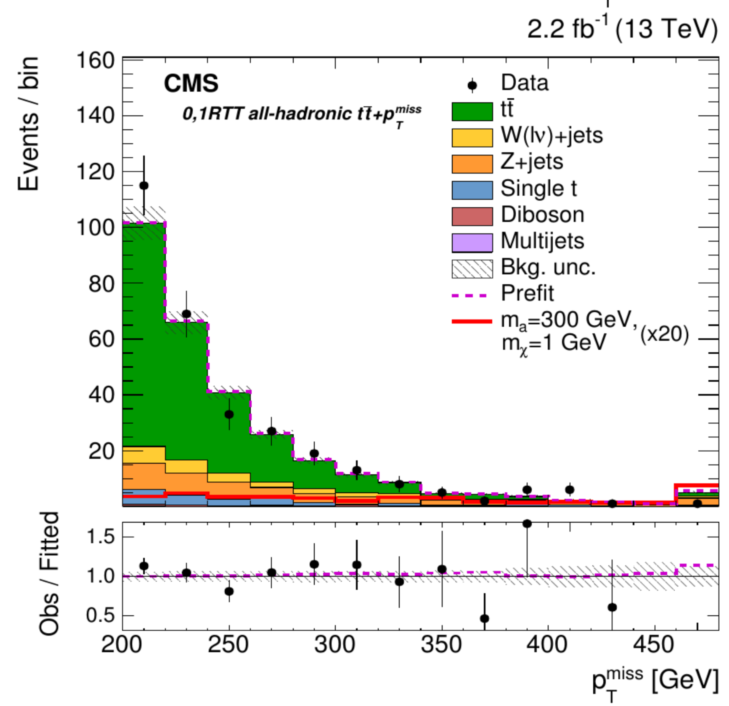
dileptonic eμ signal region



semileptonic signal region

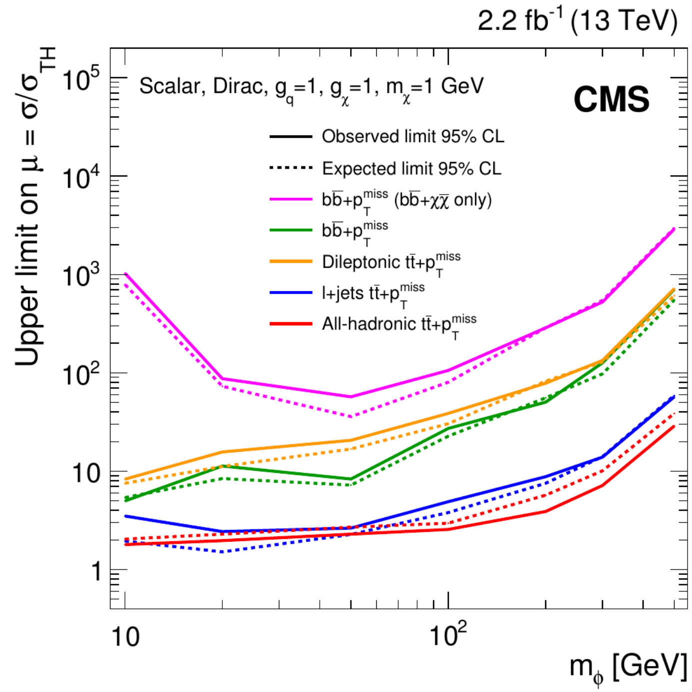


all-hadronic 01RTT signal region

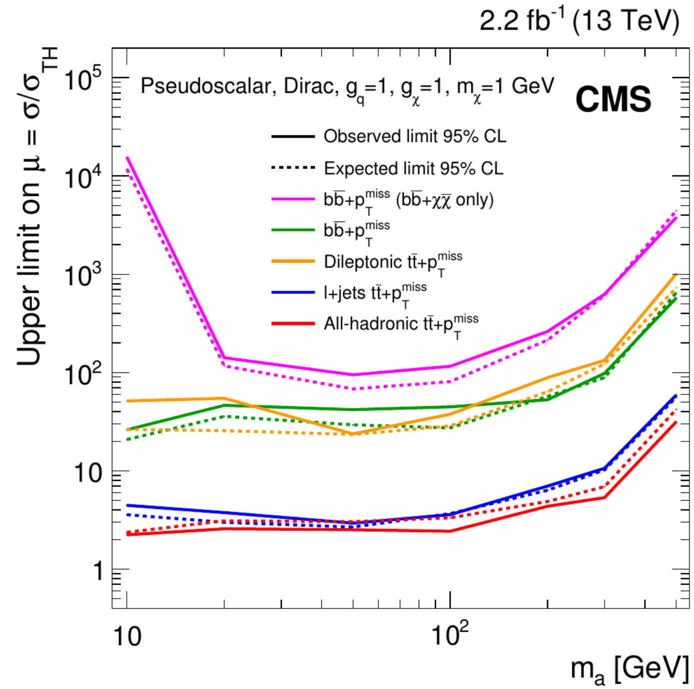


CMS tt/bb + DM Limits

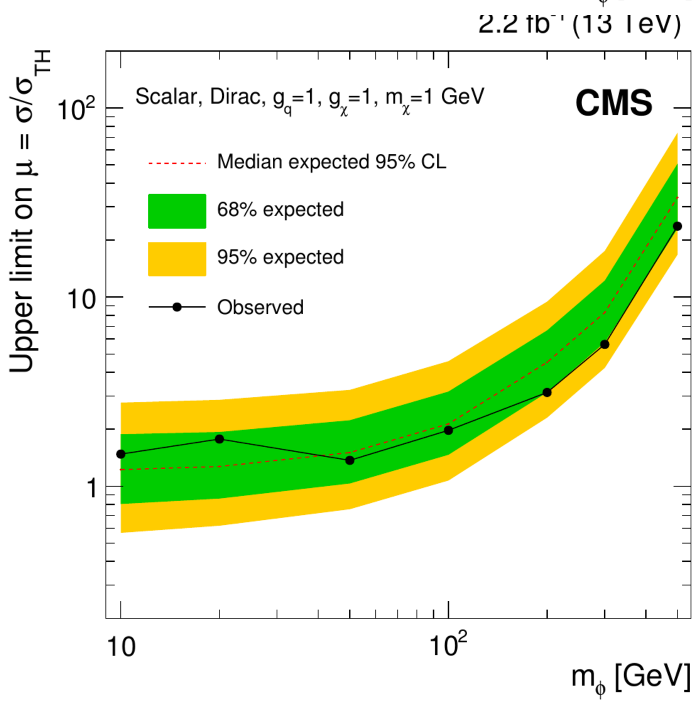
Per-channel, scalar



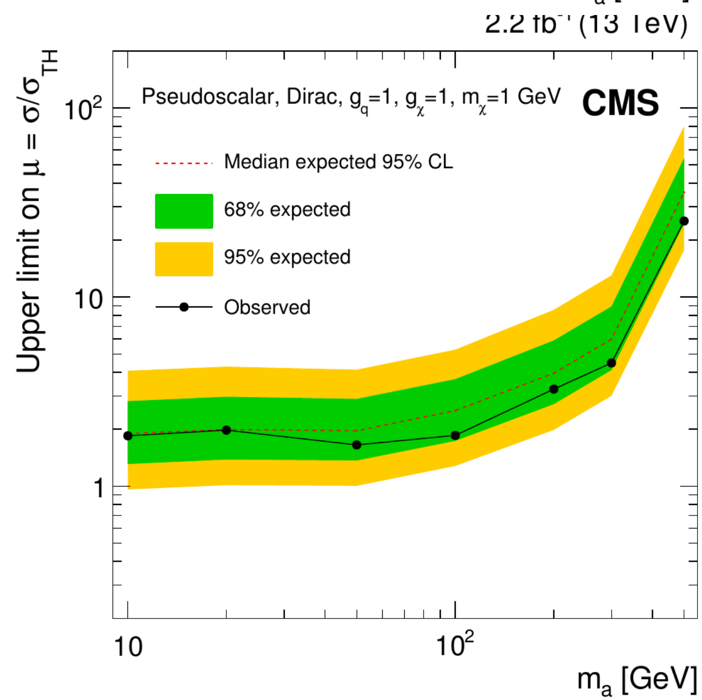
Per-channel pseudoscalar



Full combination, scalar



Full combination, pseudoscalar

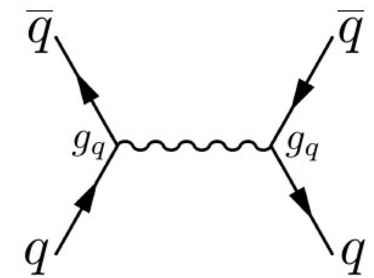


Direct Mediator Searches

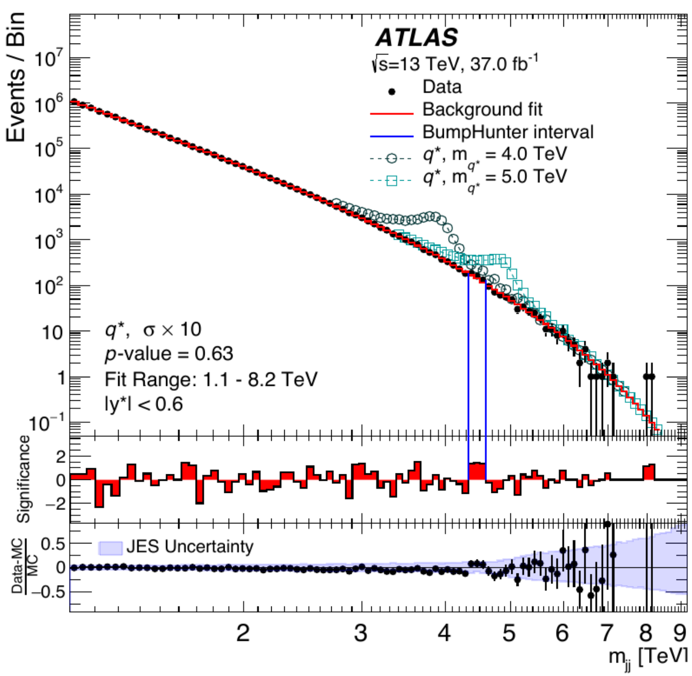
If mediator couples to quarks, then also decay to SM particles

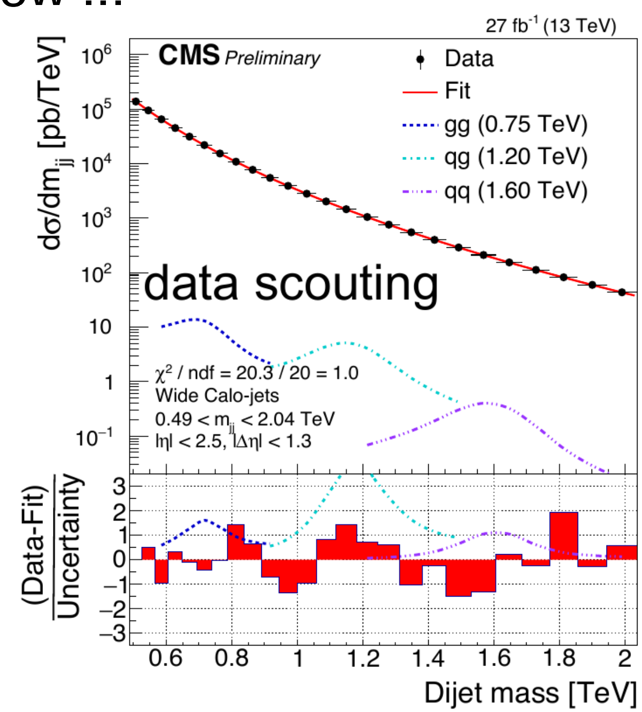
- Search for the DM mediators directly via traditional LHC “bump hunts”
  - Dijet (+ISR), dilepton, di-bjet, etc … eg:

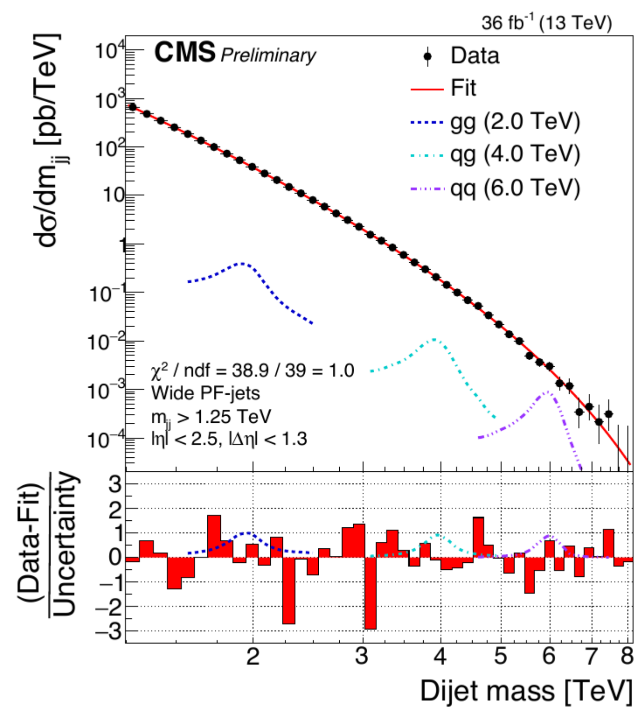
Dijet : 15.7 fb -1 ATLAS-CONF-2016-069, 27 & 36 fb-1 CMS-PAS-EXO-16-056
Dijet angular, 3.6 fb -1 (ATLAS) PLB 754 (2016) 302-322, 36 fb-1 CMS-PAS-EXO-16-046
Boosted dijet : 3.2 fb-1 (bjets) ATLAS-CONF-2016-031, 36 fb-1 CMS-PAS-EXO-17-001
Dilepton :: 36 fb-1 (ATLAS) 1707.02424, 2.9+19.7 fb-1 (CMS) PLB 768 (2017) 57



- New techniques (data scouting [CMS], Trigger Level Analysis [ATLAS]) allows searches to now push to lower mediator masses
- Dijet search results below ...



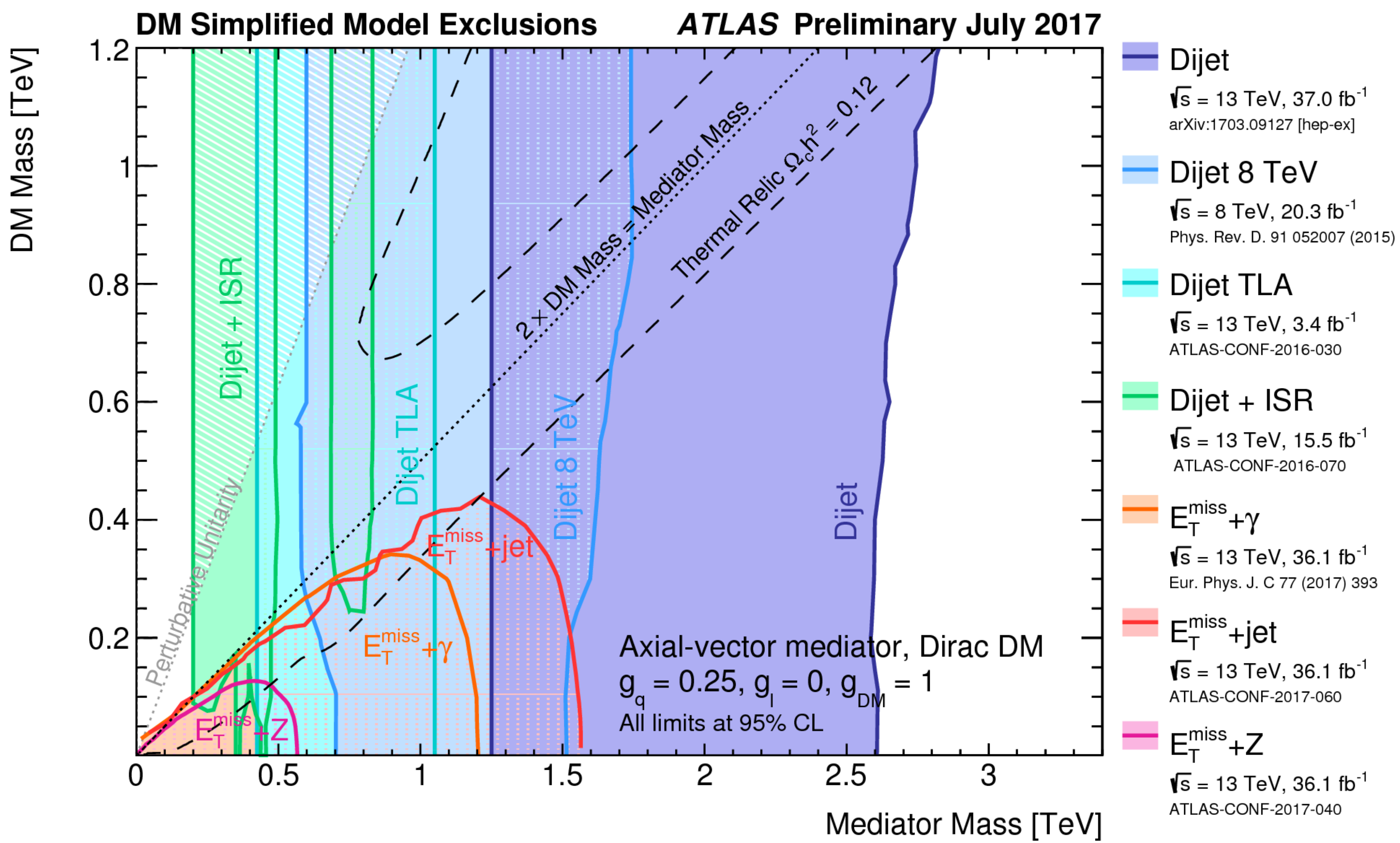




Collider DM Summaries

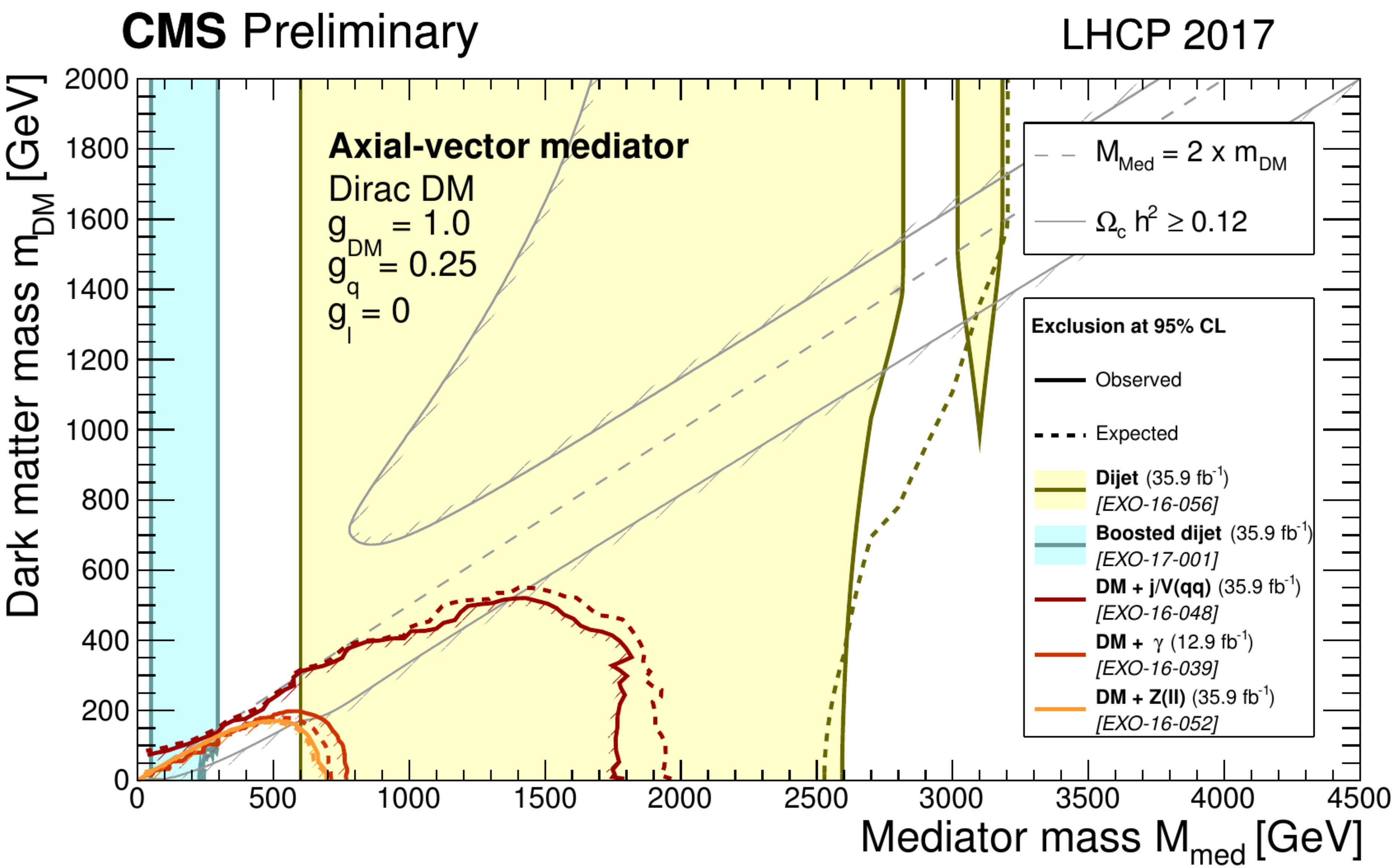
Comprehensive picture of LHC sensitivity to DM simplified models

- Axial-vector mediator shown here (see ATLAS Exotica Summaries)



Comprehensive picture of LHC sensitivity to DM simplified models

- Axial-vector mediator shown here (see CMS DM Summaries)

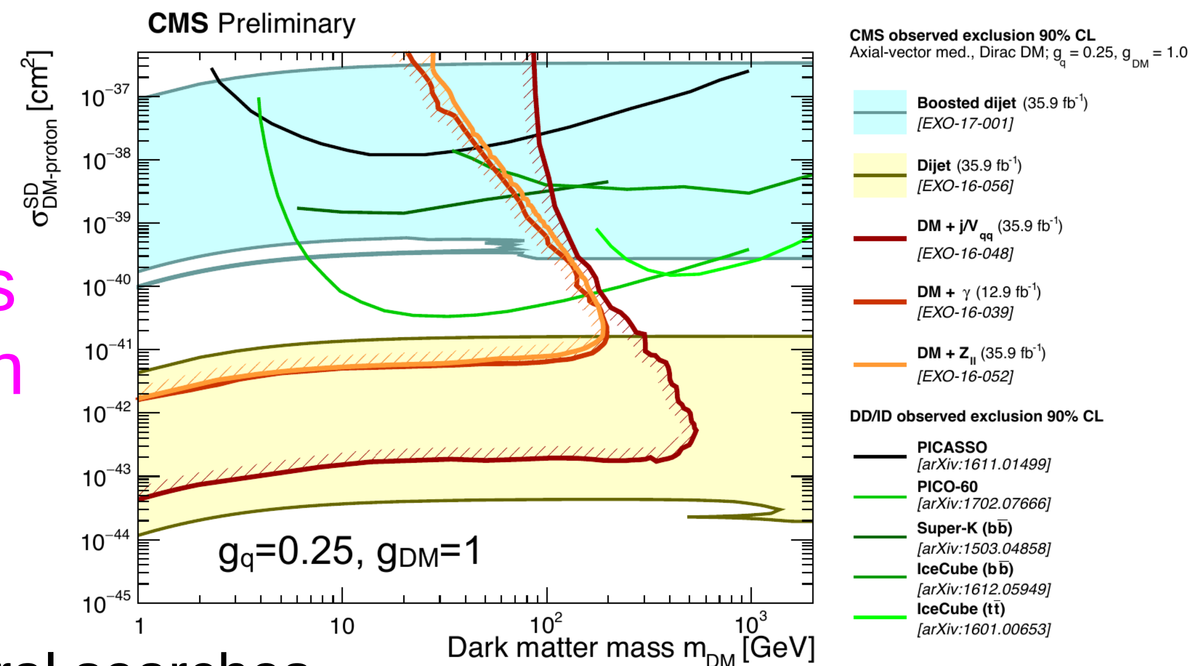


Robust program of E_T^{miss} +X DM searches at the LHC

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
- New methods for treating SM systematics (eg: arxiv: 1705.04664)
- Interpretations with somewhat-less-simplified models (eg: 1701.07427)

“SOMEBODY CALL FOR BACKUP!”

CMS mono-X Searches

X	Dataset	Documentation
jet + hadronic V	36.1 fb-1	EXO-16-048
photon	12.9 fb-1	1706.03794
Z(ll)	35.9 fb-1	CMS-EXO-16-052
Higgs (γγ)	36.1 fb-1	CMS-EXO-16-054
Higgs (bb), with γγ	2.3 fb-1	1703.05236
tt (hadronic + semileptonic + dileptonic) & bb	2.2 fb-1	1706.02581
t hadronic	36.1 fb-1	EXO-16-051

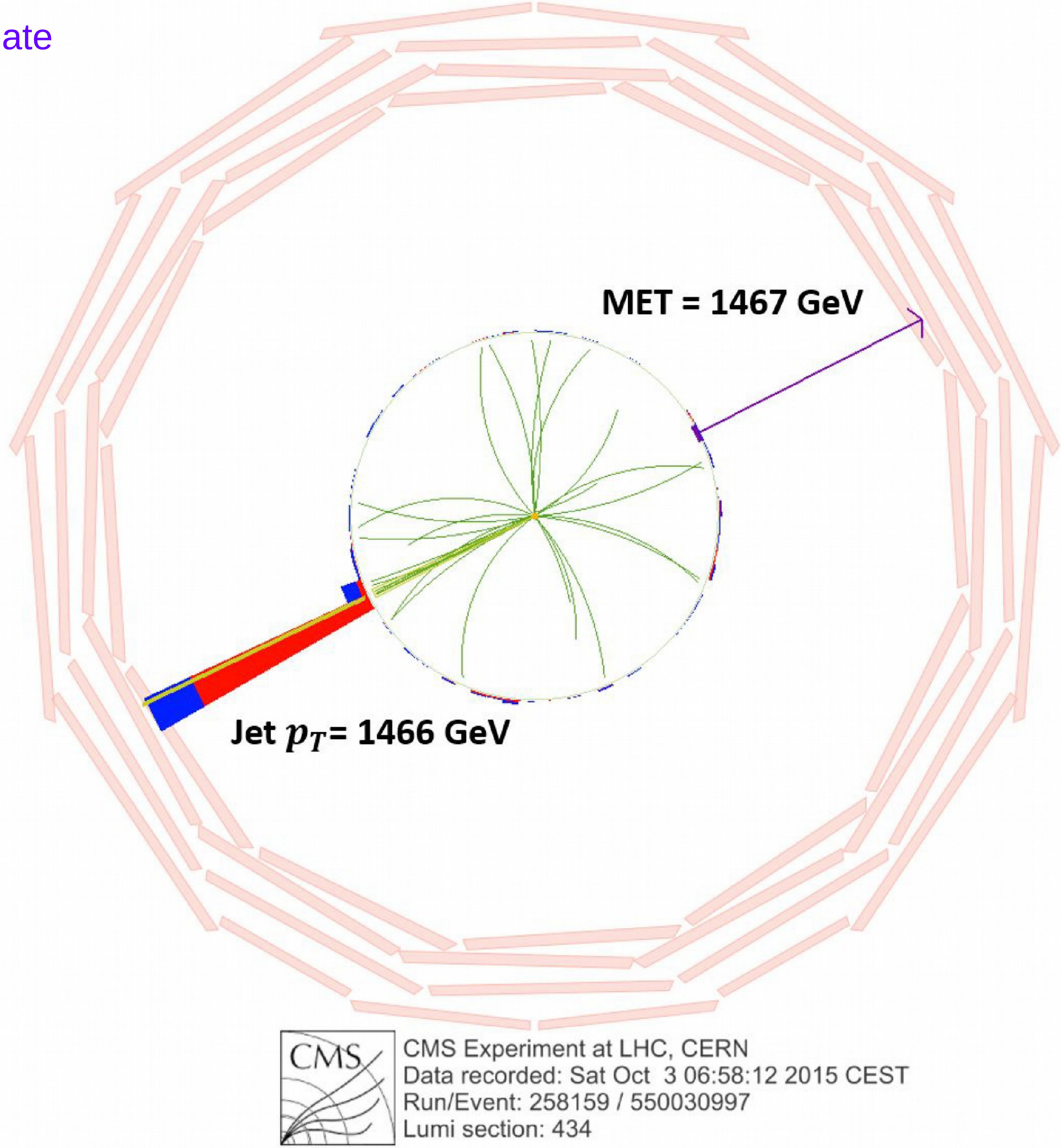
Direct Mediator Production	Dataset	Documentation
dijets	36.1 fb-1	CMS-EXO-16-056
dijets (angular)	36.1 fb-1	CMS-EXO-16-046
boosted dijets	36.1 fb-1	CMS-EXO-17-001
dilepton	13.1 fb-1	CMS-EXO-16-031

ATLAS Mono-X Searches

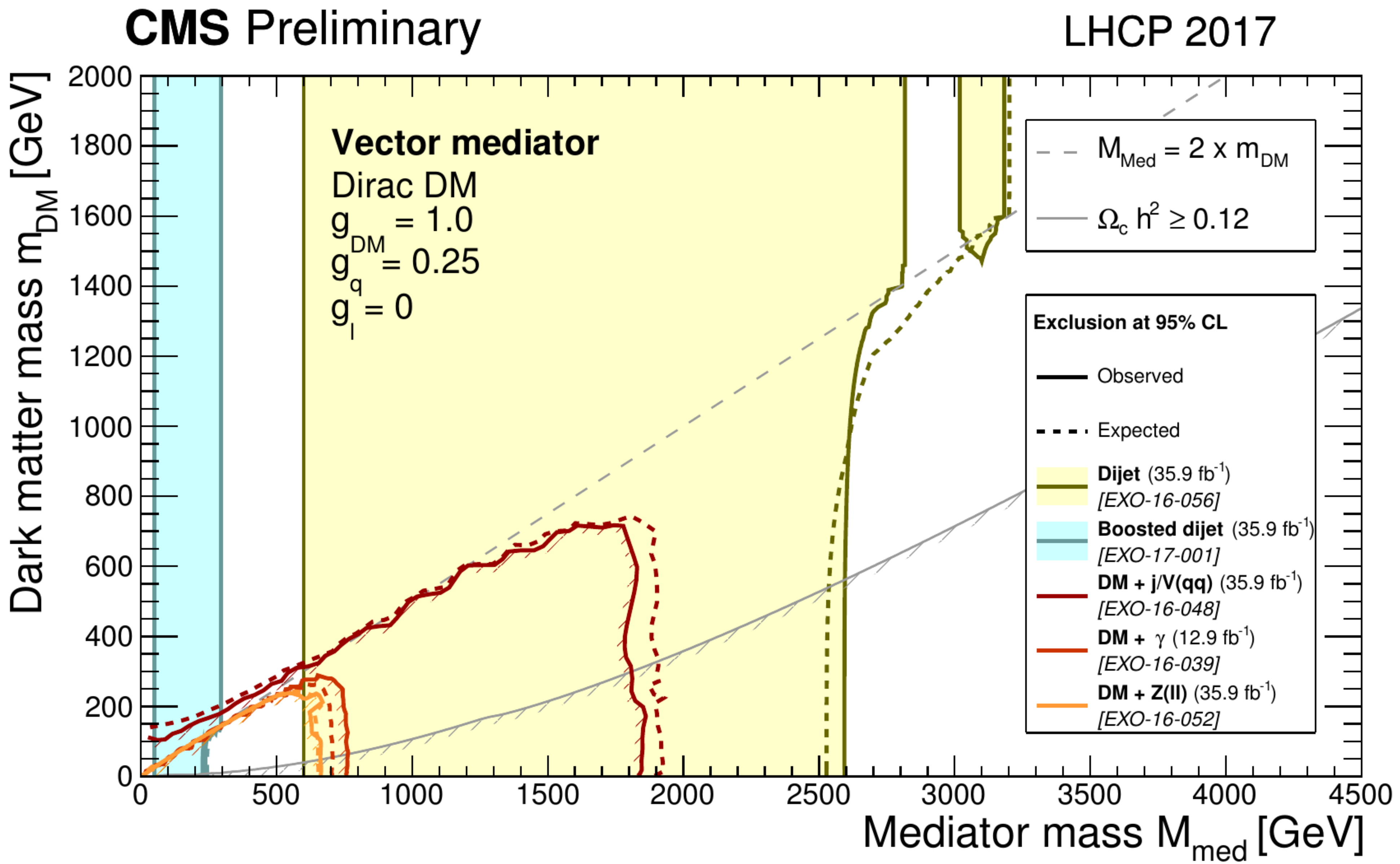
X	Dataset	Documentation
jet	36.1 fb-1	ATLAS-CONF-2017-060
photon	36.1 fb-1	EPJC 77 (2017) 393 1704.03848
W & Z (hadronic)	3.2 fb-1	PLB 763 (2016) 251
Z (leptonic)	36.1 fb-1	ATLAS-CONF-2017-040
Higgs (γγ)	36.1 fb-1	1706.03948
Higgs (bb)	36.1 fb-1	1707.01302
tt (hadronic)	36.1 fb-1	ATLAS-CONF-2016-077
tt (semileptonic)	36.1 fb-1	ATLAS-CONF-2017-037
tt (dilepton)	13.3 fb-1	ATLAS-CONF-2016-076
bb	13.1 fb-1	ATLAS-CONF-2016-086

Direct Mediator Production	Dataset	Documentation
dijets	3.5+33.5 fb-1	1703.09127
dijet ISR	15.5 fb-1	ATLAS-CONF-2016-070
dijet TLA	3.4 fb-1	ATLAS-CONF-2016-030
dilepton	36.1 fb-1	ATLAS-CONF-2017-027

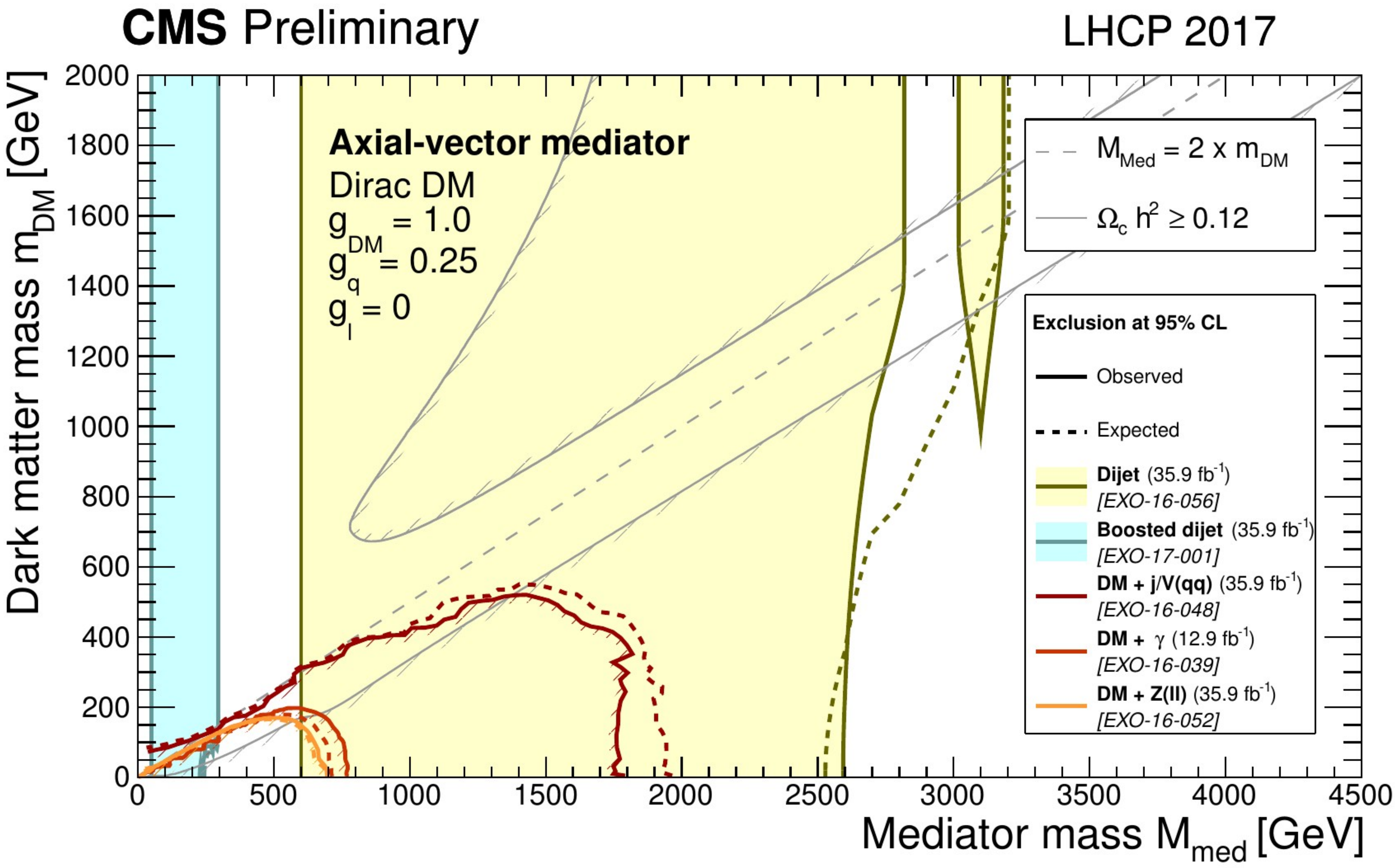
Monojet candidate
at √s = 13 TeV

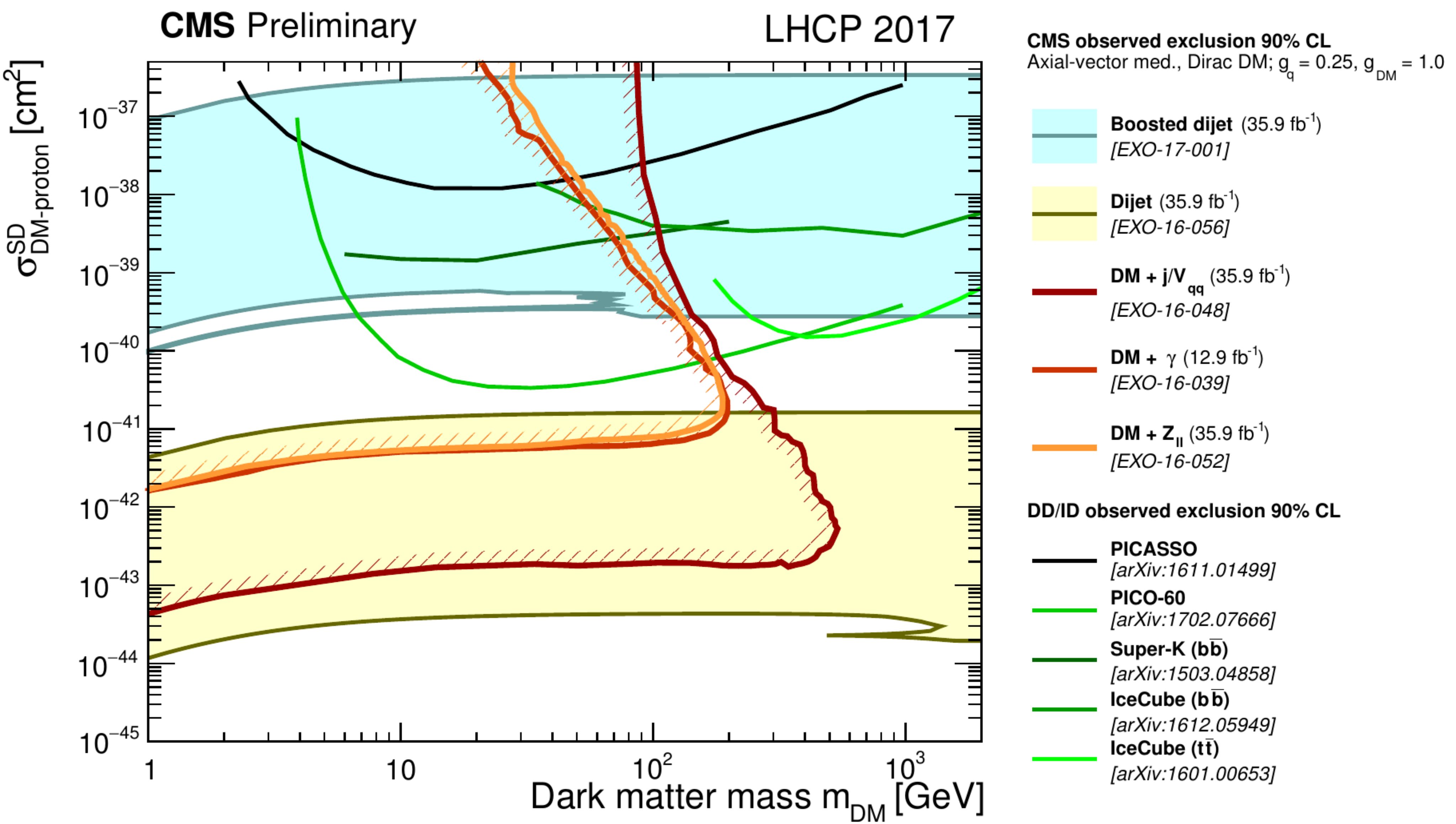


More CMS summary plots

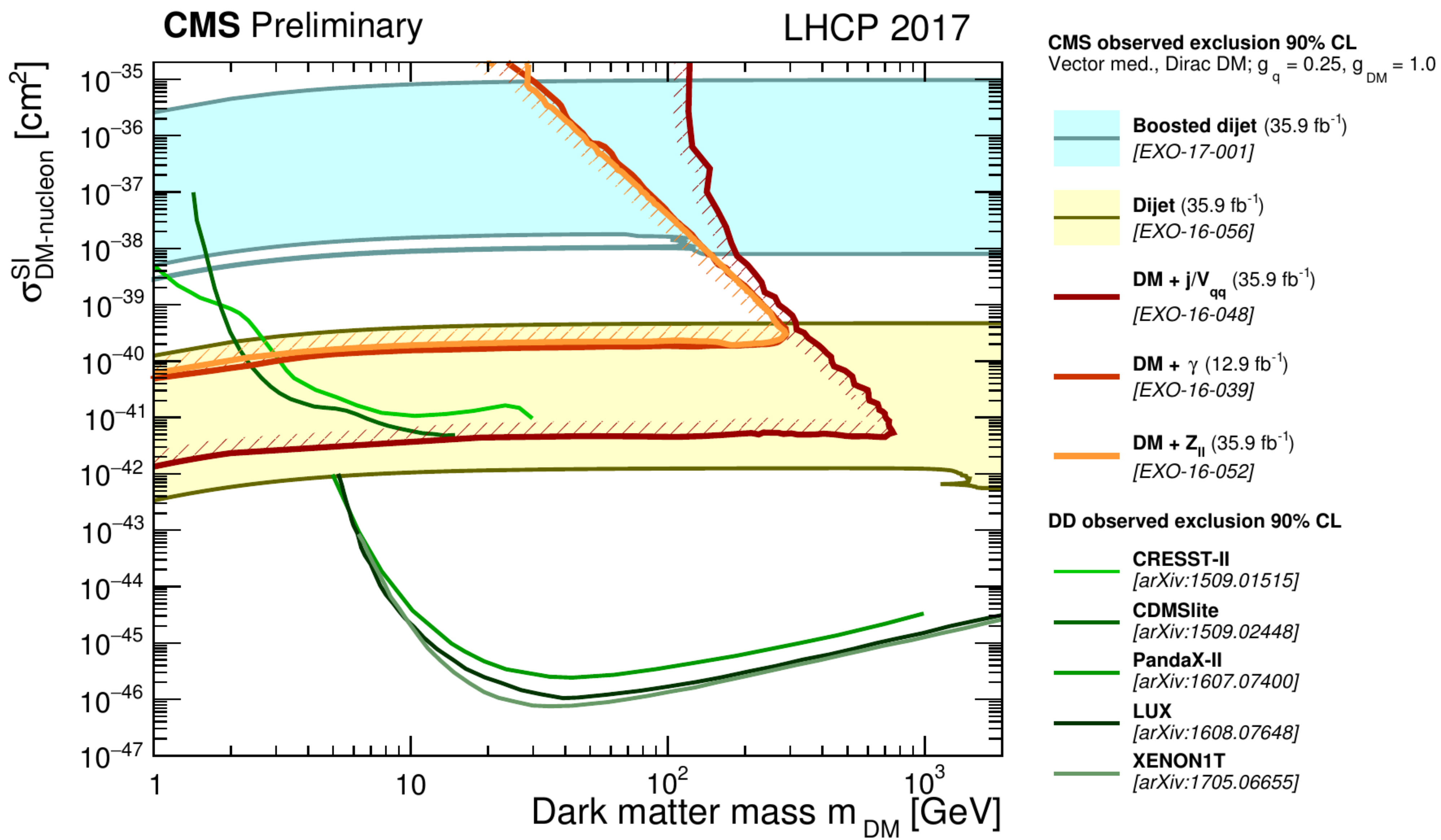


CMS Preliminary
LHCP 2017
Vector mediator
Dirac DM
$g_{DM} = 1.0$
$g_q = 0.25$
$g_l = 0$
$M_{Med} = 2 \times m_{DM}$
$\Omega_c h^2 \geq 0.12$
Exclusion at 95% CL
Observed
Expected
Dijet (35.9 fb^{-1})
[EXO-16-056]
Boosted dijet (35.9 fb^{-1})
[EXO-17-001]
DM + j/V(qq) (35.9 fb^{-1})
[EXO-16-048]
DM + γ (12.9 fb^{-1})
[EXO-16-039]
DM + Z(ll) (35.9 fb^{-1})
[EXO-16-052]
Dark matter mass m_{DM} [GeV]
Mediator mass M_{med} [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500


CMS Preliminary
LHCP 2017
Axial-vector mediator
Dirac DM
g_{DM} = 1.0
g_q = 0.25
g_l = 0
$M_{Med} = 2 \times m_{DM}$
$\Omega_c h^2 \geq 0.12$
Exclusion at 95% CL
Observed
Expected
Dijet (35.9 fb^{-1}) [EXO-16-056]
Boosted dijet (35.9 fb^{-1}) [EXO-17-001]
DM + j/V(qq) (35.9 fb^{-1}) [EXO-16-048]
DM + γ (12.9 fb^{-1}) [EXO-16-039]
DM + Z(ll) (35.9 fb^{-1}) [EXO-16-052]
Dark matter mass m_{DM} [GeV]
Mediator mass M_{med} [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500

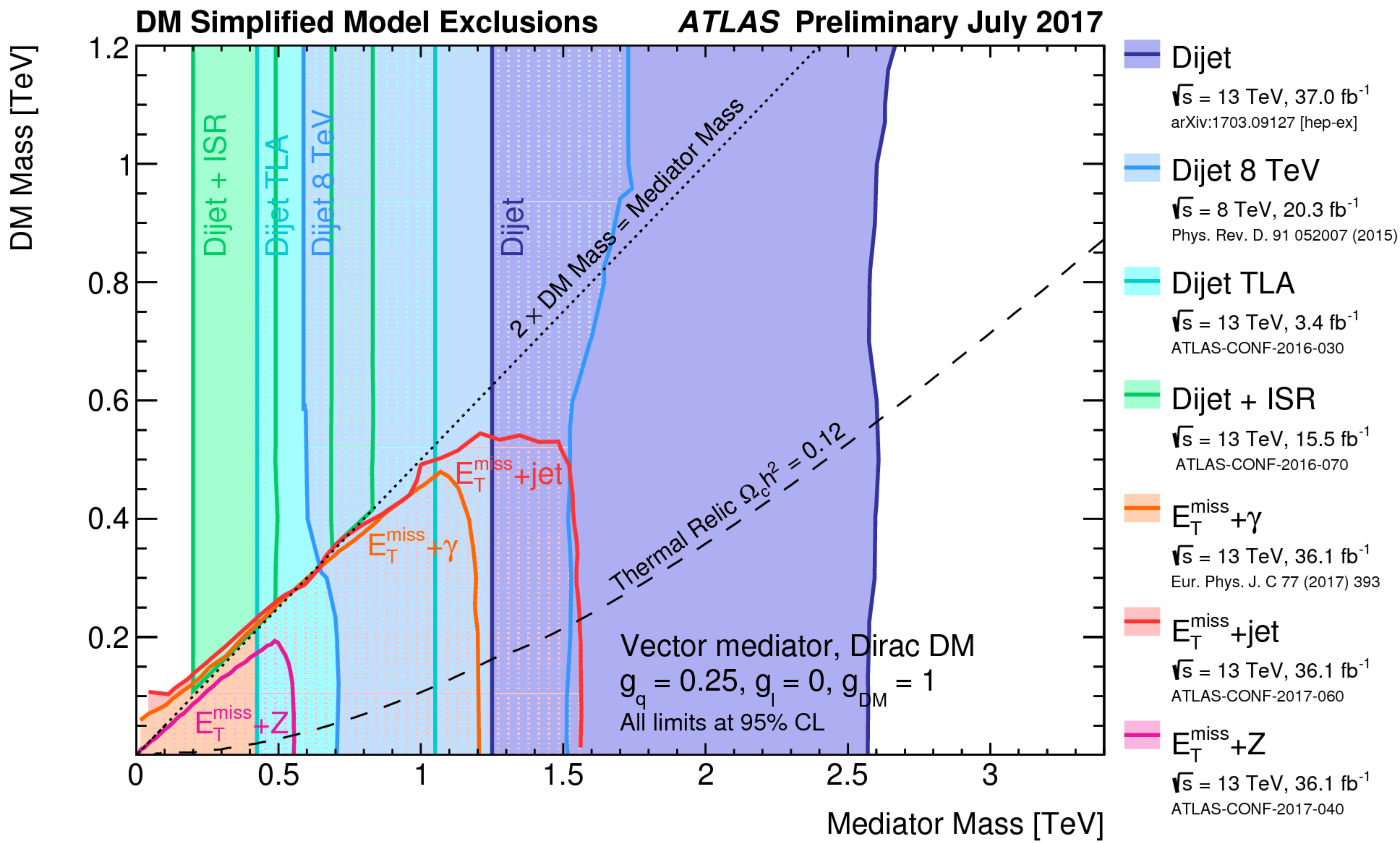


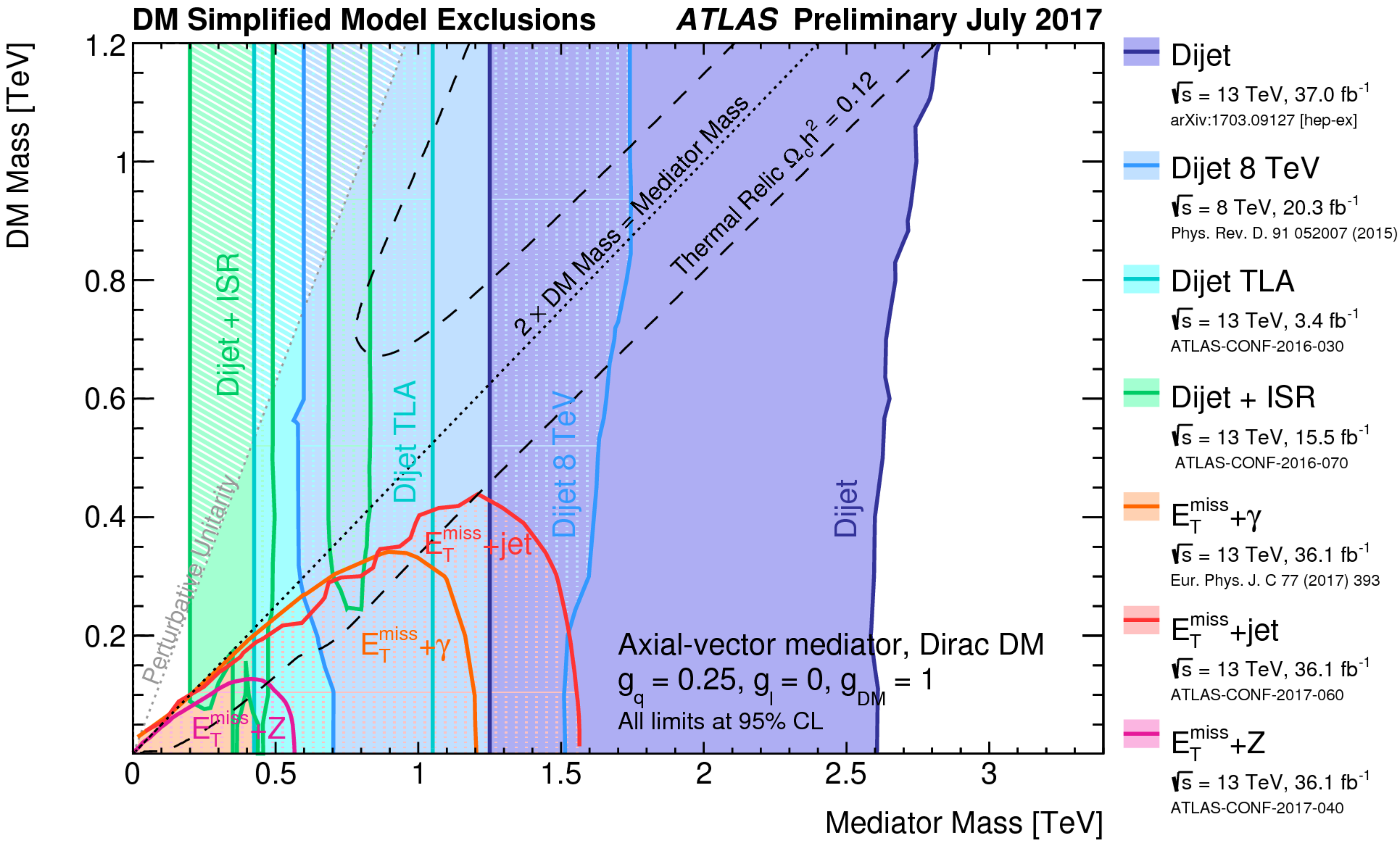
CMS Preliminary
LHCP 2017
$\sigma^{SD}_{DM-proton}$ [cm^2]
Dark matter mass m_{DM} [GeV]
CMS observed exclusion 90% CL
Axial-vector med., Dirac DM; g_q = 0.25, g_{DM} = 1.0
Boosted dijet (35.9 fb^{-1})
[EXO-17-001]
Dijet (35.9 fb^{-1})
[EXO-16-056]
DM + j/V$_{qq}$ (35.9 fb^{-1})
[EXO-16-048]
DM + γ (12.9 fb^{-1})
[EXO-16-039]
DM + Z$_{ll}$ (35.9 fb^{-1})
[EXO-16-052]
DD/ID observed exclusion 90% CL
PICASSO
[arXiv:1611.01499]
PICO-60
[arXiv:1702.07666]
Super-K (b$\bar{b}$)
[arXiv:1503.04858]
IceCube (b$\bar{b}$)
[arXiv:1612.05949]
IceCube (t$\bar{t}$)
[arXiv:1601.00653]



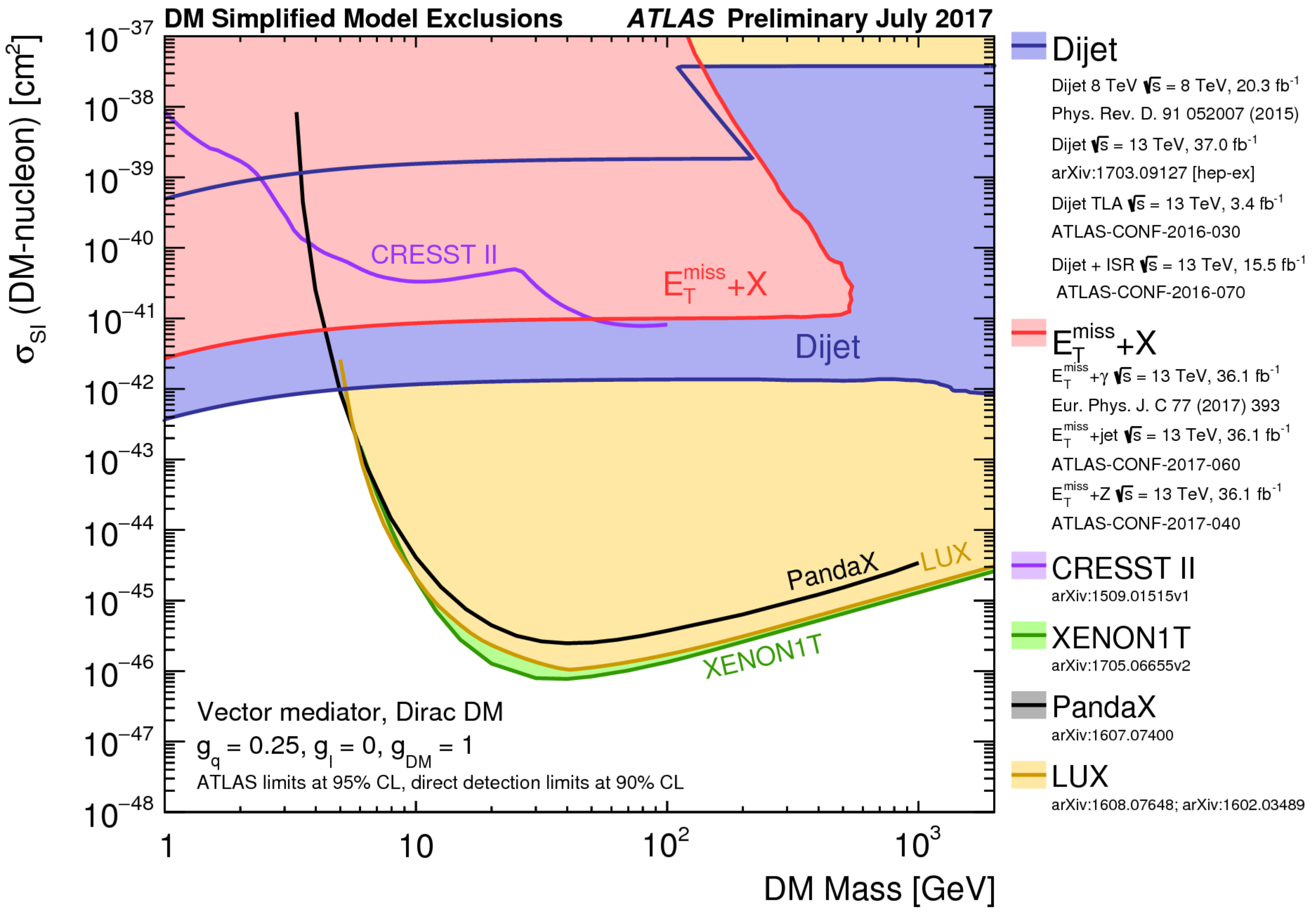
CMS Preliminary
LHCP 2017
$\sigma^{SI}_{DM\text{-nucleon}}$ [cm^2]
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
1
10
10^2
10^3
Dark matter mass m_{DM} [GeV]
CMS observed exclusion 90% CL
Vector med., Dirac DM; g_q = 0.25, g_{DM} = 1.0
Boosted dijet (35.9 fb^{-1})
[EXO-17-001]
Dijet (35.9 fb^{-1})
[EXO-16-056]
DM + j/V$_{qq}$ (35.9 fb^{-1})
[EXO-16-048]
DM + γ (12.9 fb^{-1})
[EXO-16-039]
DM + Z$_{ll}$ (35.9 fb^{-1})
[EXO-16-052]
DD observed exclusion 90% CL
CRESST-II
[arXiv:1509.01515]
CDMSlite
[arXiv:1509.02448]
PandaX-II
[arXiv:1607.07400]
LUX
[arXiv:1608.07648]
XENON1T
[arXiv:1705.06655]

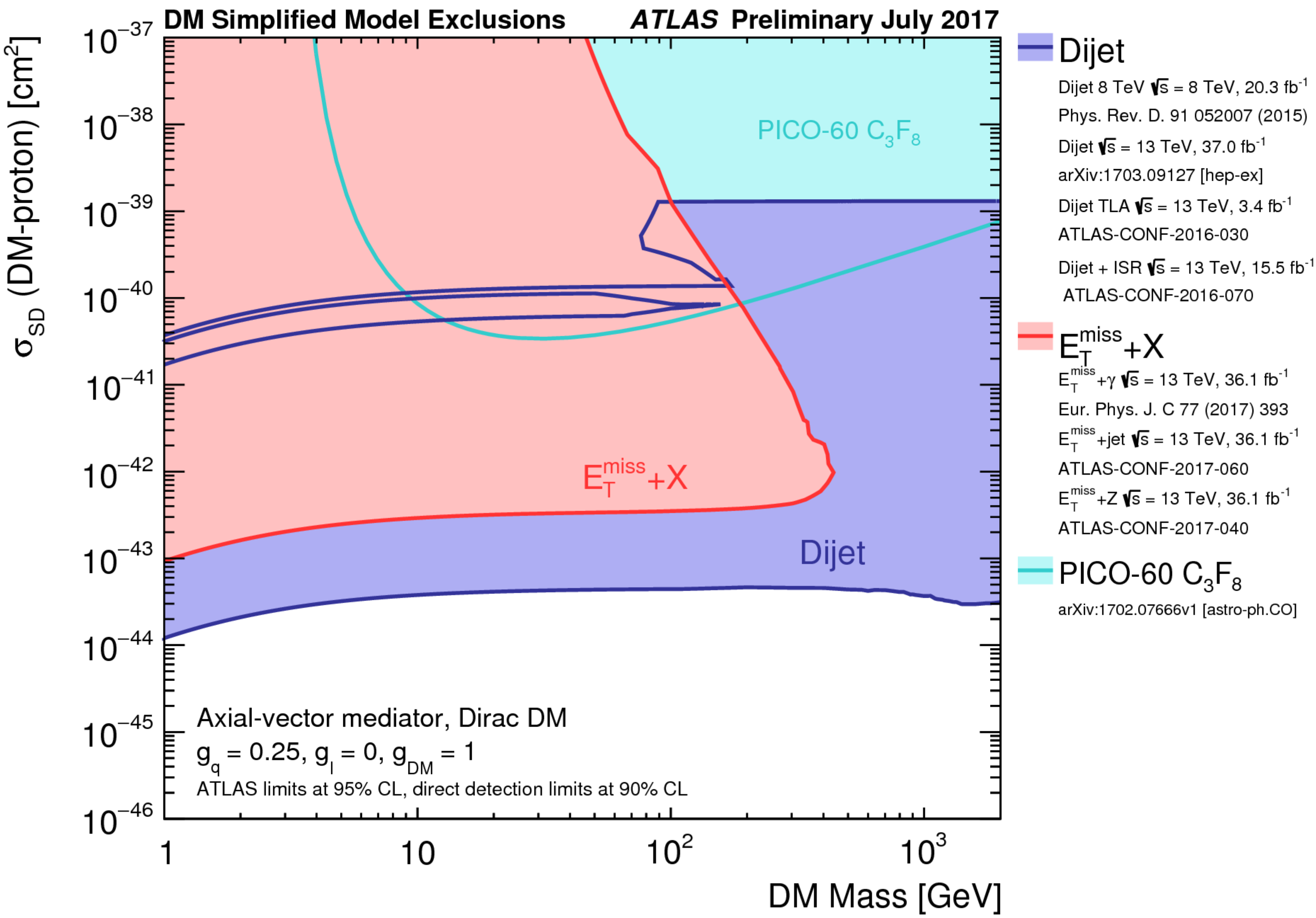
More ATLAS summary plots


DM Simplified Model Exclusions
ATLAS Preliminary July 2017
DM Mass [TeV]
Mediator Mass [TeV]
Dijet + ISR
Dijet TLA
Dijet 8 TeV
Dijet
2 × DM Mass = Mediator Mass
Thermal Relic $\Omega_c h^2 = 0.12$
E_T^{miss}+jet
E_T^{miss}+γ
E_T^{miss}+Z
Vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
All limits at 95% CL
Dijet
$\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet 8 TeV
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet TLA
$\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR
$\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+γ
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060
E_T^{miss}+Z
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-040



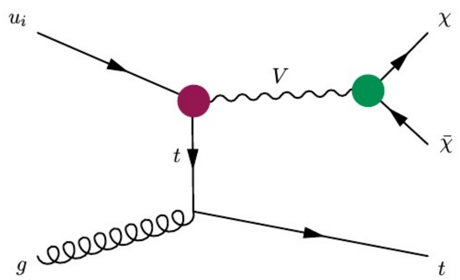
DM Simplified Model Exclusions
ATLAS Preliminary July 2017
DM Mass [TeV]
Mediator Mass [TeV]
Dijet + ISR
Dijet TLA
Dijet 8 TeV
Dijet
Perturbative Unitarity
2 × DM Mass = Mediator Mass
Thermal Relic $\Omega_c h^2 = 0.12$
E_T^{miss}+jet
E_T^{miss}+γ
E_T^{miss}+Z
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
All limits at 95% CL
Dijet
$\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet 8 TeV
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet TLA
$\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR
$\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+γ
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060
E_T^{miss}+Z
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-040

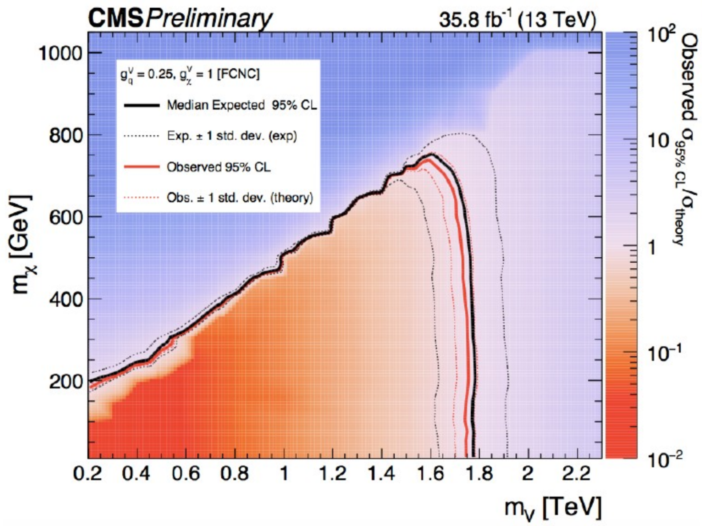

DM Simplified Model Exclusions
ATLAS Preliminary July 2017
σ_{SI} (DM-nucleon) [cm^2]
DM Mass [GeV]
CRESST II
E_T^{miss}+X
Dijet
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet 8 TeV √s = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet √s = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet TLA √s = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR √s = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+X
E_T^{miss}+γ √s = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet √s = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060
E_T^{miss}+Z √s = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-040
CRESST II
arXiv:1509.01515v1
XENON1T
arXiv:1705.06655v2
PandaX
arXiv:1607.07400
LUX
arXiv:1608.07648; arXiv:1602.03489

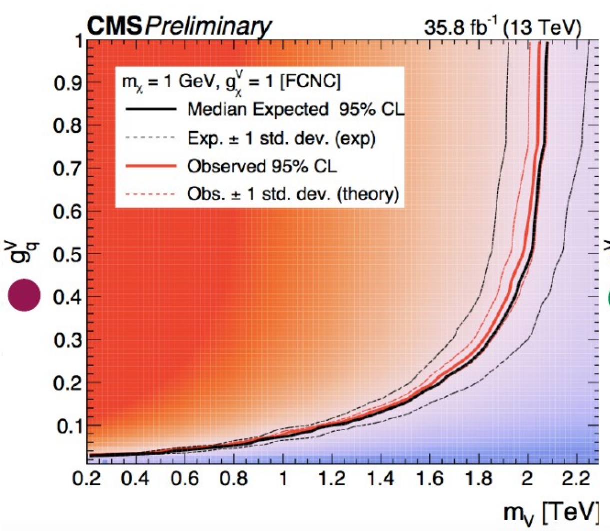

DM Simplified Model Exclusions
ATLAS Preliminary July 2017
σ_SD (DM-proton) [cm²]
DM Mass [GeV]
PICO-60 C3F8
E_T^miss+X
Dijet
Axial-vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_DM = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet 8 TeV √s = 8 TeV, 20.3 fb-1
Phys. Rev. D. 91 052007 (2015)
Dijet √s = 13 TeV, 37.0 fb-1
arXiv:1703.09127 [hep-ex]
Dijet TLA √s = 13 TeV, 3.4 fb-1
ATLAS-CONF-2016-030
Dijet + ISR √s = 13 TeV, 15.5 fb-1
ATLAS-CONF-2016-070
E_T^miss+X
E_T^miss+γ √s = 13 TeV, 36.1 fb-1
Eur. Phys. J. C 77 (2017) 393
E_T^miss+jet √s = 13 TeV, 36.1 fb-1
ATLAS-CONF-2017-060
E_T^miss+Z √s = 13 TeV, 36.1 fb-1
ATLAS-CONF-2017-040
PICO-60 C3F8
arXiv:1702.07666v1 [astro-ph.CO]

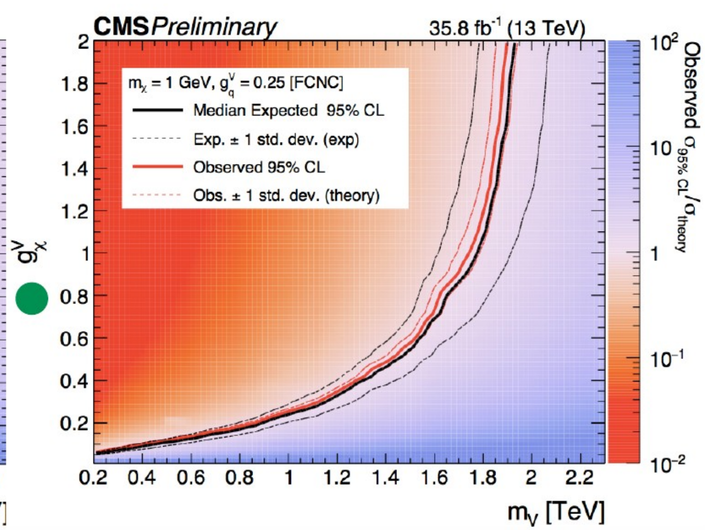
non-resonant model

g_V=0.25 g_χ=1



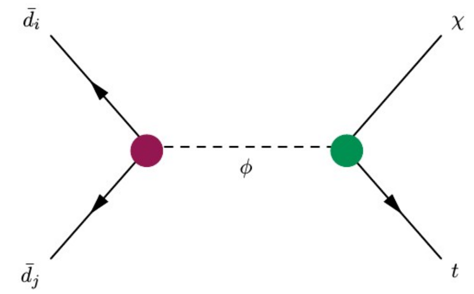


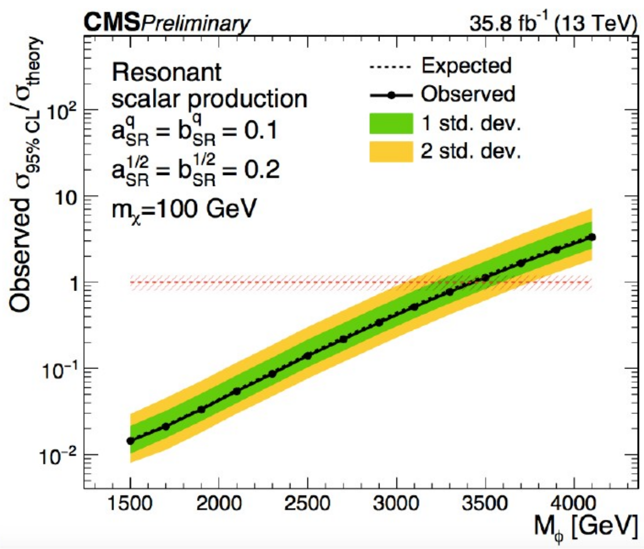




resonant model

a_q=b_q=0.1 $a_{1/2}$=$b_{1/2}$=0.2

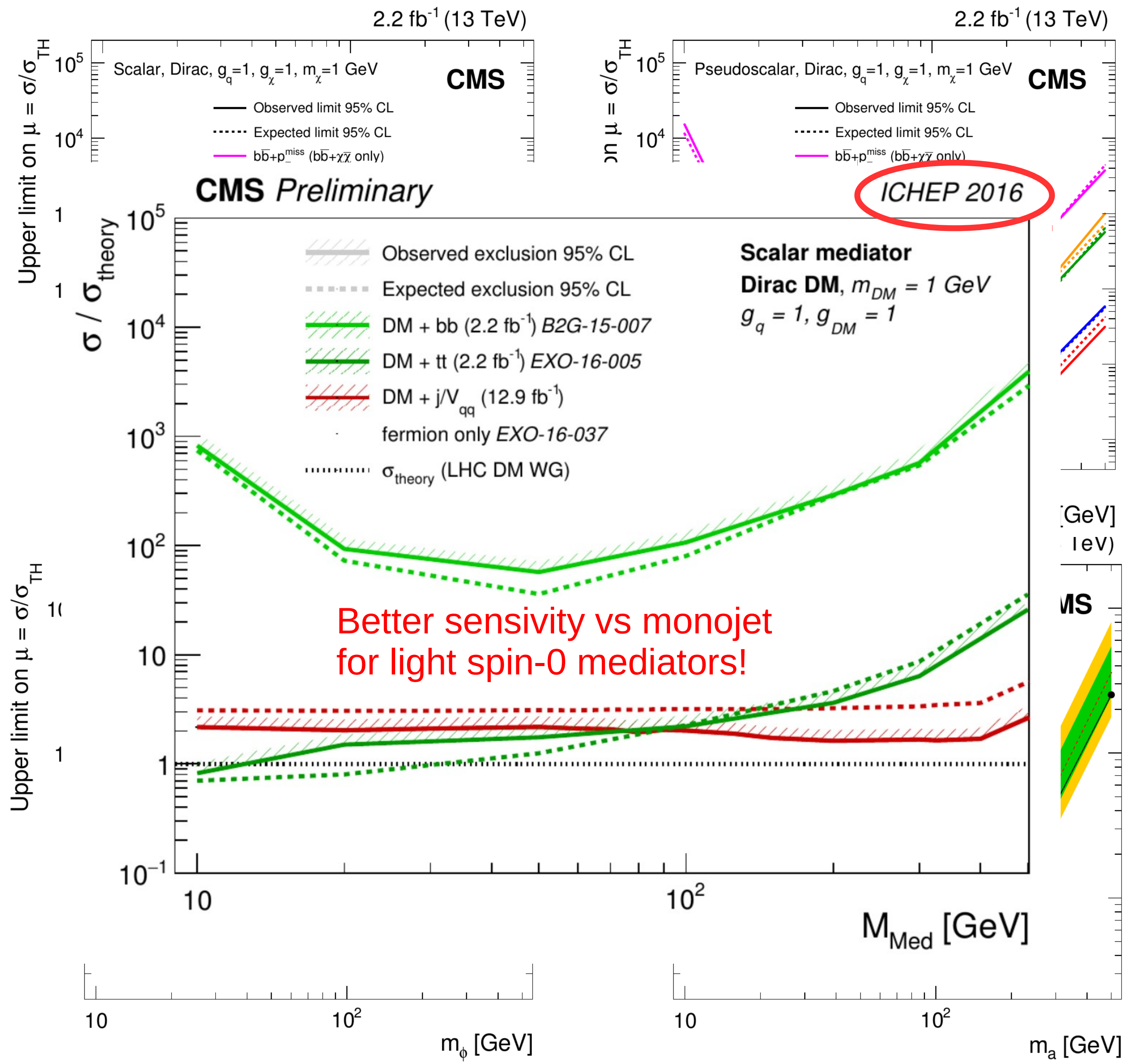




CMS tt/bb + DM Limits

Per-channel, scalar

Full combination, scalar



Per-channel, pseudoscalar

Full combination, pseudoscalar

SI/SD Translation

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

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

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

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

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

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

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

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