



WIMP Dark Matter interpretation of SUSY and Exotics results

Collider Physics and the Cosmos

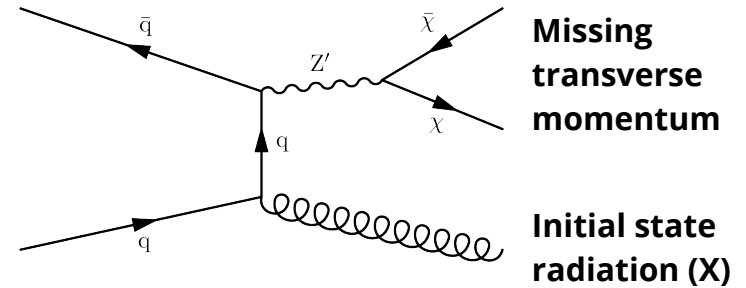
Galileo Galilei Institute
October 2017

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IMAPP Radboud University Nijmegen / Nikhef
On behalf of the ATLAS and CMS collaboration

WIMP searches at the LHC

Direct pair production -- mono-X

- Back-to-back pair production invisible in detector
- Visible particles needed to 'tag' event (from e.g. initial state radiation)
- Recoil of DM particles visible as momentum imbalance



Mediator searches -- resonant searches

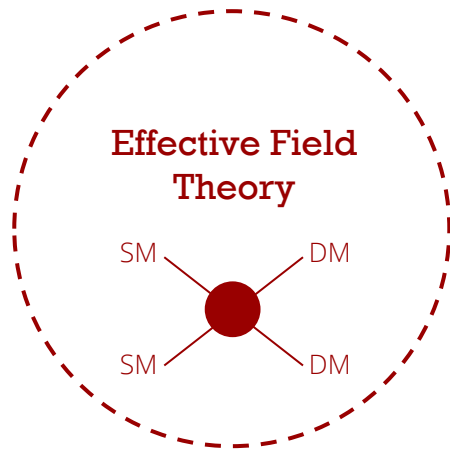
- Search for mediator decaying into SM particles
- Visible as resonant peak in mass spectrum

Cascade decays

- Heavier particles are produced
- Decay into pairs of WIMPs and SM particles

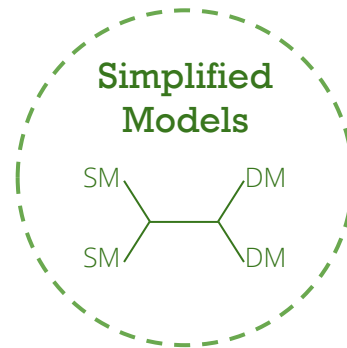


Simplified Models

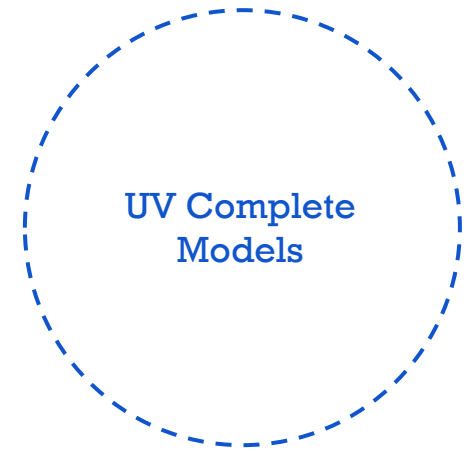


- Oftentimes used in Run 1
- Contact interactions, small number of degrees of freedom
- Model independent direct detection comparisons
- Valid if mediator is very heavy, invalid at large momentum transfer (Run 2)

less complete ← → more complete



- Includes mediator
- Relevant parameters only (masses/couplings)
- More signatures, mediator can decay back into SM particles
- Comparison direct detection model-dependent
- Used in Run 2
- Caveat: perturbative unitary ([arXiv:1510.02110](https://arxiv.org/abs/1510.02110))



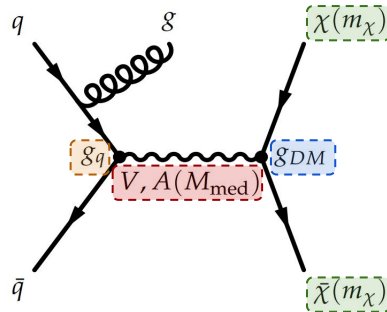
- More complete models
- E.g.: MSSM, UED, Little Higgs

Examples Simplified Models

s-channel mediator \rightarrow mono-X & resonances

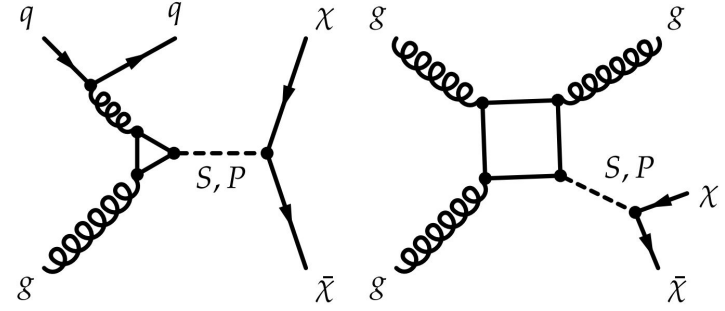
- Spin 1 (axial-)vector mediators
- Decay to SM pair or DM pair (+ISR)
- ISR = QCD parton, γ , W, Z, h
- Dirac fermion DM
- Minimal decay width
- Parameters (values used in results):

- M_{med} mediator mass
- m_χ DM mass
- g_χ (1.0) mediator-DM coupling
- g_q (0.25 / 0.1) mediator-quark coupling
- g_l (0 / 0.01 / 0.10) mediator-lepton coupling



s-channel (pseudo-)scalar mediator

- Example of LO mono-jet production mode
- Other final states: $E_T^{\text{miss}} + Z / h$



Scalar (S, ϕ) / pseudoscalar (P, a) mediator

Theorists

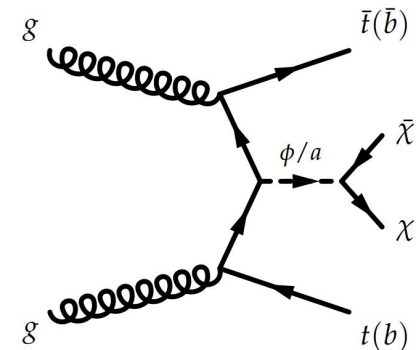
LHC DM
working group

LHC / DD / ID
experiments

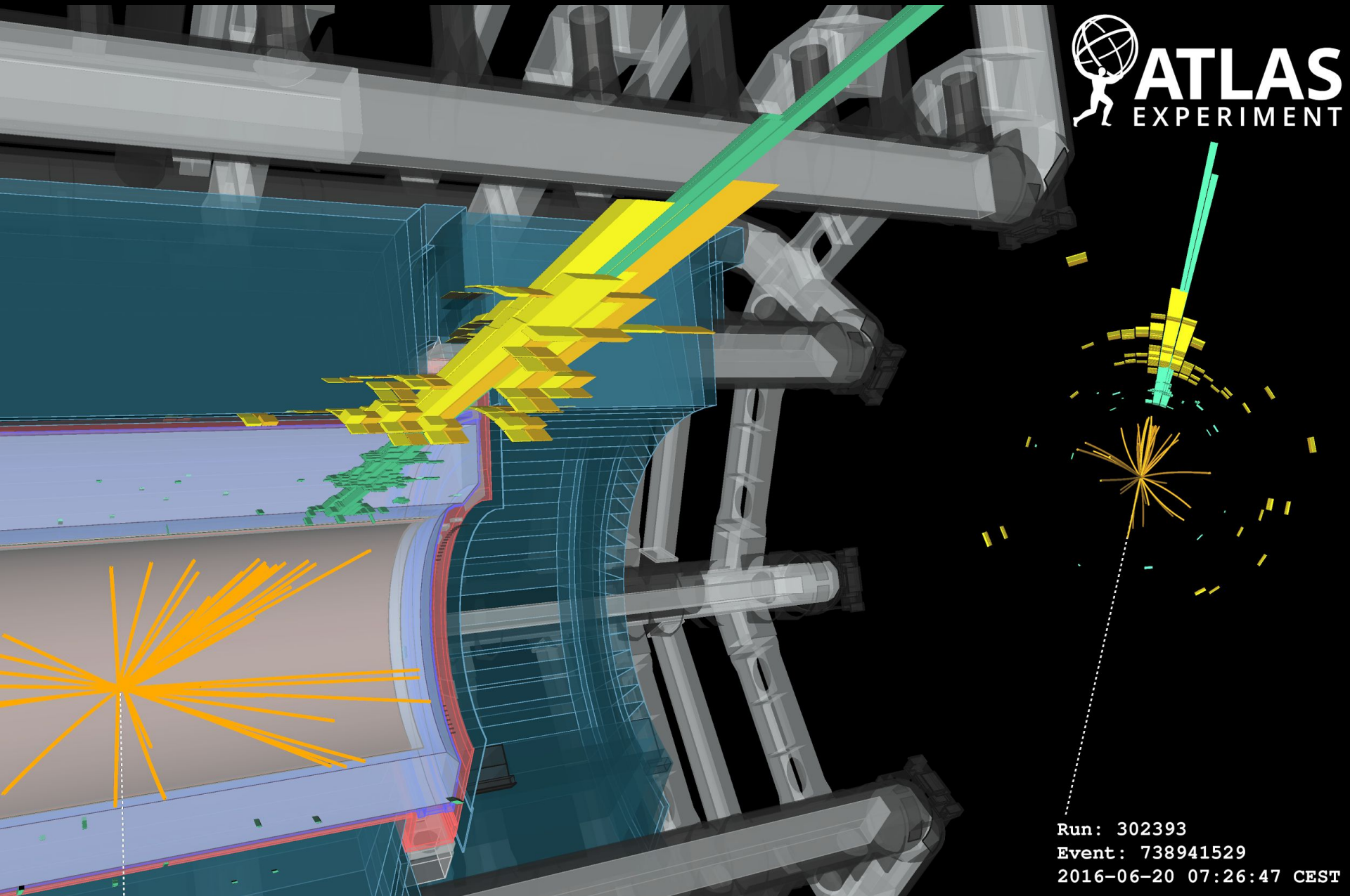
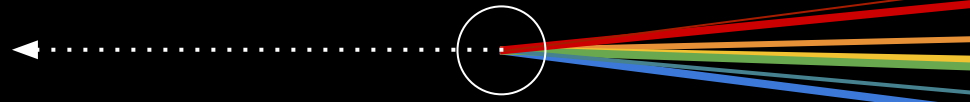
- Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum ([arXiv:1507.00966](https://arxiv.org/abs/1507.00966))
- Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter ([arXiv:1603.04156](https://arxiv.org/abs/1603.04156))
- Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels ([arXiv:1703.05703](https://arxiv.org/abs/1703.05703))

(pseudo-)scalar mediator with heavy flavour pair

- Coupling to bottom favoured in high $\tan\beta$ models



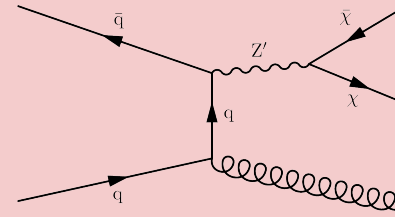
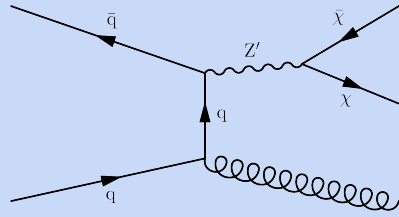
Mono+X searches



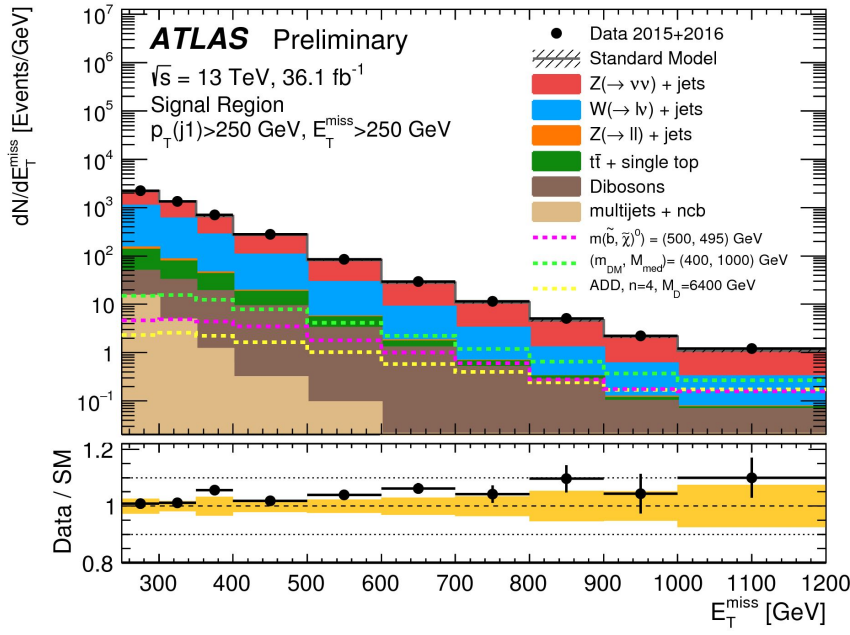
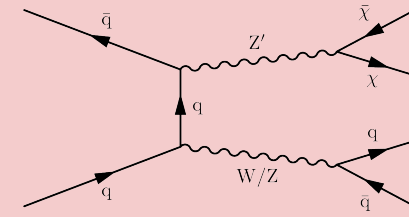
 **ATLAS**
EXPERIMENT

Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Mono+X searches: mono-jet

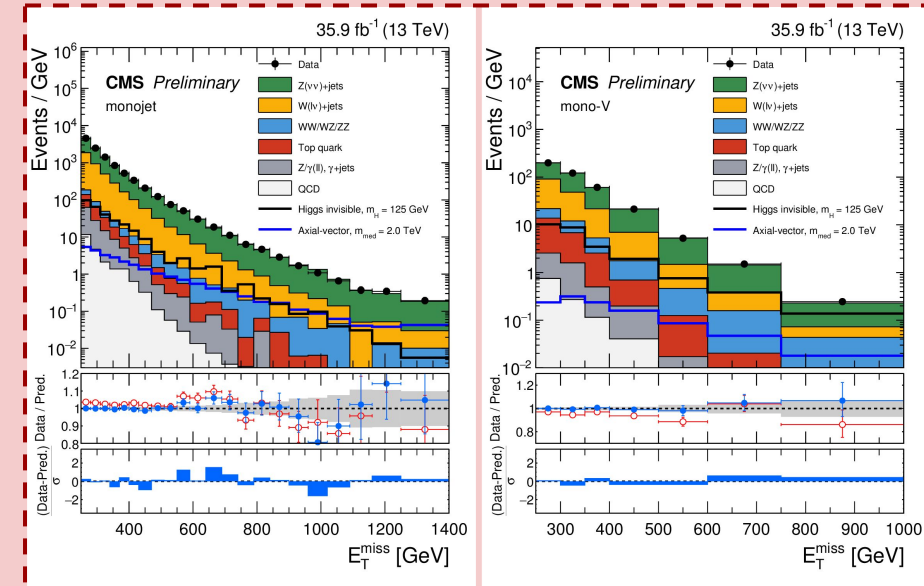


&



- $E_T^{\text{miss}} > 250 \text{ GeV}$
- At least 1 jet ($|\eta| < 2.4$) with $p_T > 250 \text{ GeV}$
- No leptons (e/μ)
- No more than 4 jets ($|\eta| < 2.8$) with $p_T > 30 \text{ GeV}$
- $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.4$

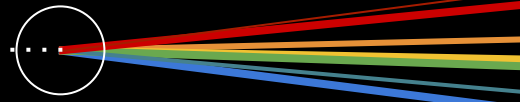
ATLAS-CONF-2017-060



- $E_T^{\text{miss}} > 250 \text{ GeV}$
- Mono-jet: at least 1 $R=0.4$ jet ($|\eta| < 2.5$) with $p_T > 100 \text{ GeV}$
- Mono-V: at least 1 V-tagged $R=0.8$ jet ($|\eta| < 2.4$) with $p_T > 250 \text{ GeV}$
- No leptons ($e/\mu/\gamma$)
- $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.5$

CMS-PAS-EXO-16-048

Mono+X searches: mono-jet



Estimation of dominant SM backgrounds

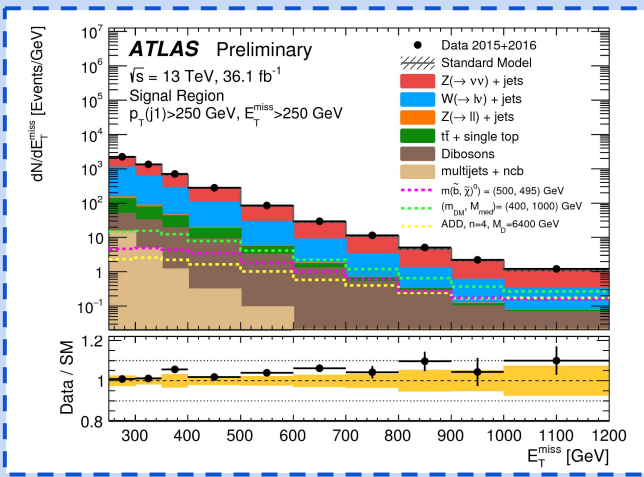
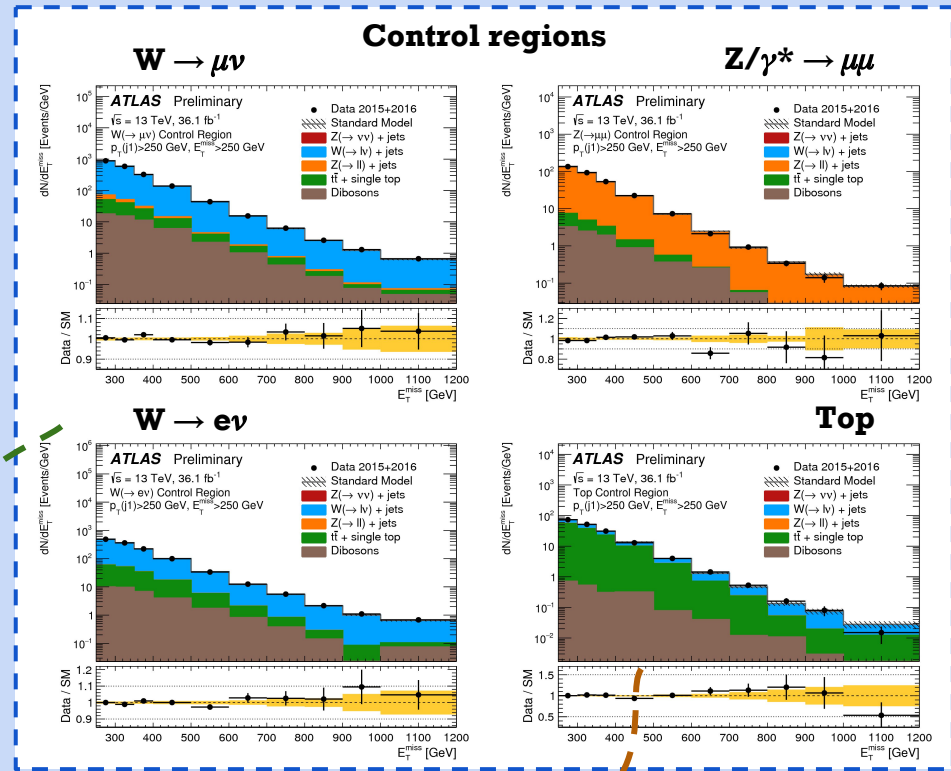
1. $Z (\rightarrow \nu\nu) + \text{jets}$ (56-72%)
2. $W (\rightarrow l\nu) + \text{jets}$ (38-23%)
3. Top pair / single top (3-0.6%)
4. Diboson (2-5%)

State-of-the-art W/Z+jets estimation ([arXiv:1705.04664](https://arxiv.org/abs/1705.04664))

- Carefully developed scheme to estimate uncertainties
- pQCD @ NNLO
- EW corrections @ NLO
- 2-loop EW Sudakov logarithms

Simultaneous global fit to E_T^{miss} distributions in all control regions:

- Systematic correlations / shape taken into account
- Single **k-factor** for all W/Z+jets backgrounds
- Single **k-factor** for single top and top pair



k_{WZ}

k_{top}

Dominant $Z(\rightarrow \nu\nu) + \text{jets}$ & $W(\rightarrow \tau\nu) + \text{jets}$ backgrounds constraint using $Z/\gamma^*(\rightarrow \mu\mu) + \text{jets}$ & $W(\rightarrow l\nu) + \text{jets}$ CRs

$1/\nu$

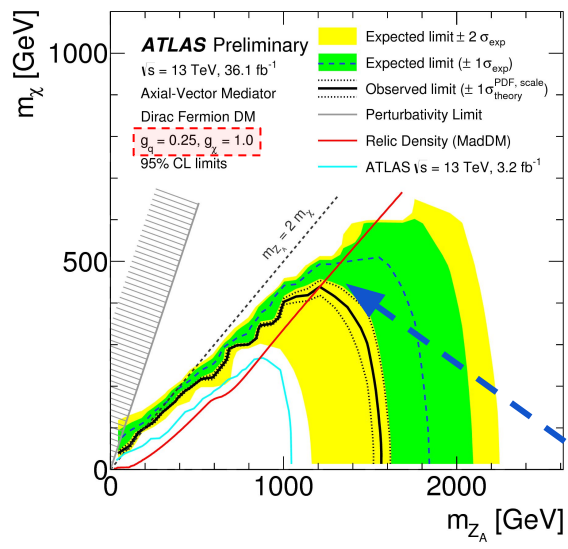
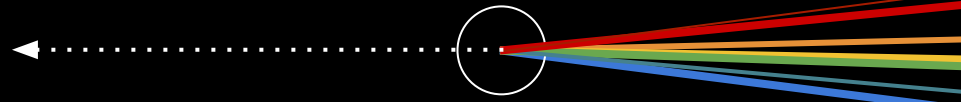
W/Z

$1/\nu$

ATLAS-CONF-2017-060

CMS: additional $\gamma + \text{jets}$ control region (CMS-PAS-EXO-16-048)

Mono+X searches: mono-jet



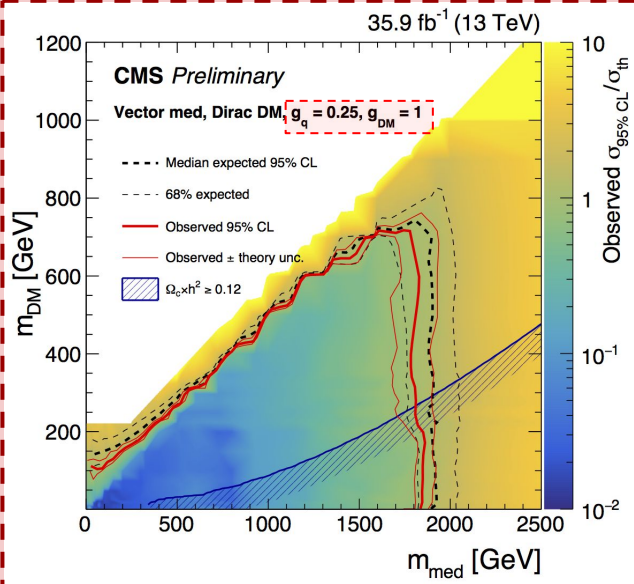
ATLAS-CONF-2017-060

Axial-vector med.
 Excl. med. masses
 (for given couplings)
 up to 1.6 TeV and
 DM masses up to
 400 GeV

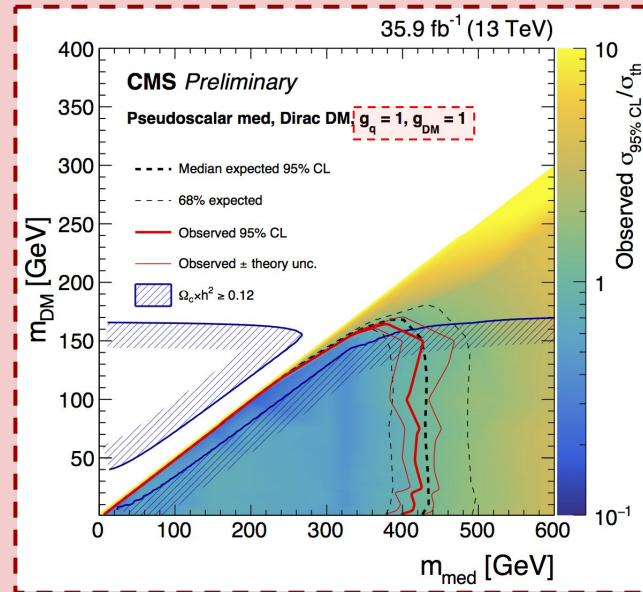
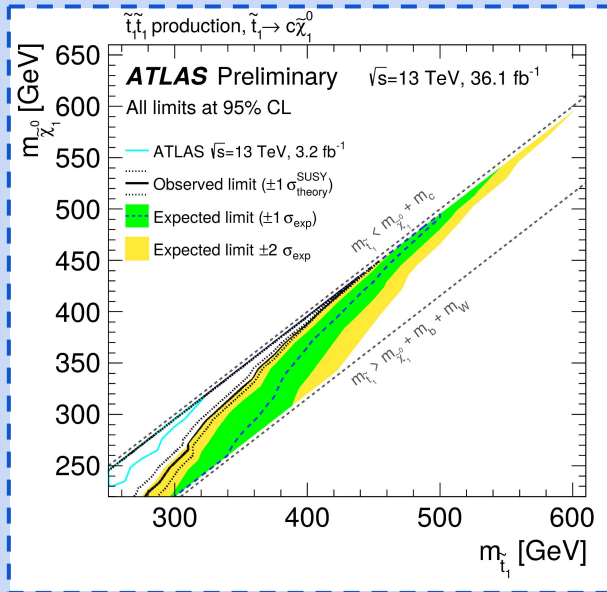
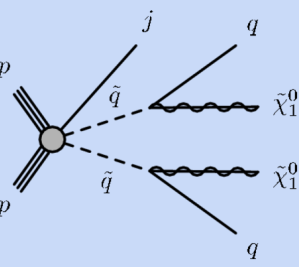
DM over-density

CMS-PAS-EXO-16-048

Vector med.
 Excl. med. masses
 (for given couplings)
 up to 1.8 TeV and
 DM masses up to
 700 GeV

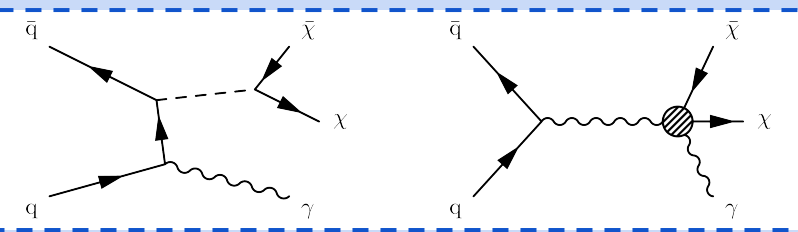


Squark production
 Compressed
 stop-neutralino
 mass region.
 $M(\text{stop}) - M(\chi) > 5$
 GeV



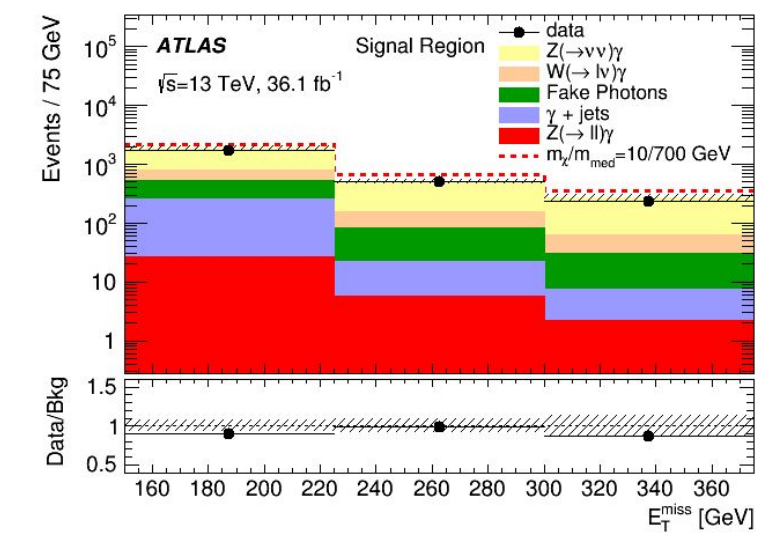
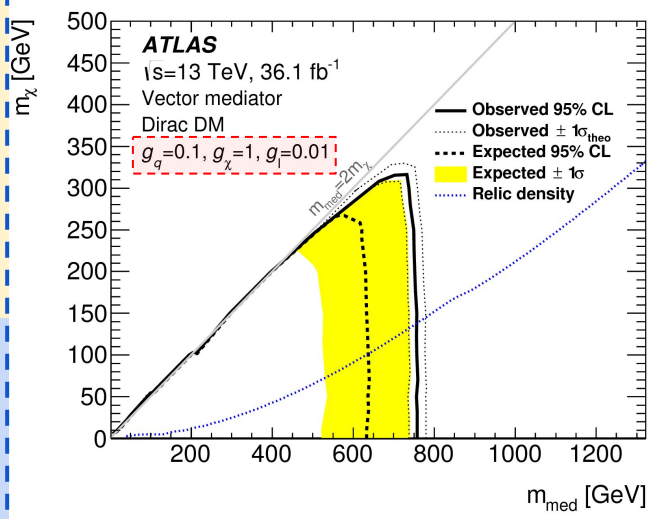
Pseudoscalar med.
 Excl. med. masses
 up to 400 GeV and
 DM masses 150
 GeV

Mono+X searches: mono-photon



- (Axial-)vector med. simplified models
- Dim-7 EFT with $\gamma\gamma X X$ contact interaction

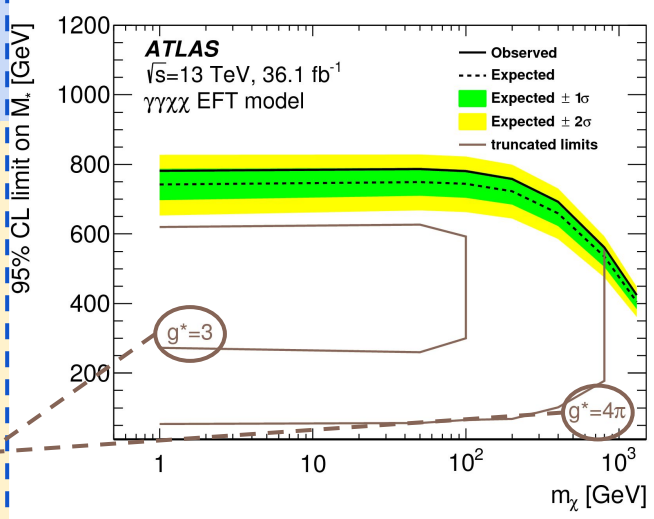
Vector med. with reduced g_q and non-zero g_1
 Excl. med. masses up to 750 GeV and DM masses up to 320 GeV



- CRs: $1\mu, 2\mu, 2e, 1\gamma$
- Simultaneous fit in CRs $\rightarrow k$ -factors for $W\gamma, Z\gamma, \gamma$ +jets
- Fake γ : data driven estimation (misid. factor & ABCD)

- At least 1 photon ($|n| < 2.37$) with $E_T > 150$ GeV
- $|z'| < 0.25$ m
- No leptons (e/μ)
- $E_T^{\text{miss}} > 150$ GeV
- No more than 1 jet ($|n| < 4.5$) with $p_T > 30$ GeV
- $\Delta\phi(\text{jets}/\gamma, E_T^{\text{miss}}) > 0.4$
- $E_T^{\text{miss}} / (\sum E_T)^{1/2} > 8.5 \text{ GeV}^{1/2}$ [Eur. Phys. J. C 77 \(2017\) 393](#)

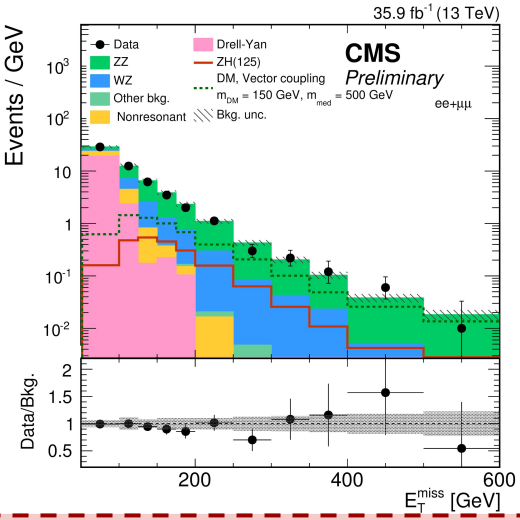
Dim-7 EFT with $\gamma\gamma X X$ contact interaction
 Excl. M_* up to 790 GeV
 Truncated exclusion region, assuming EFT validity up to $g^* M_*$



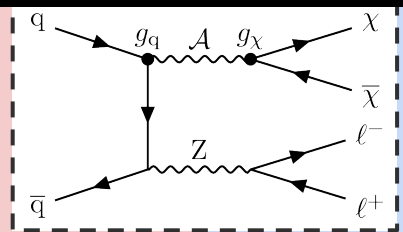
CMS 12.9 fb⁻¹: [arXiv:1706.03794](#)

Mono+X searches: mono-Z($\rightarrow\ell\ell$)

CMS-PAS-EXO-16-052

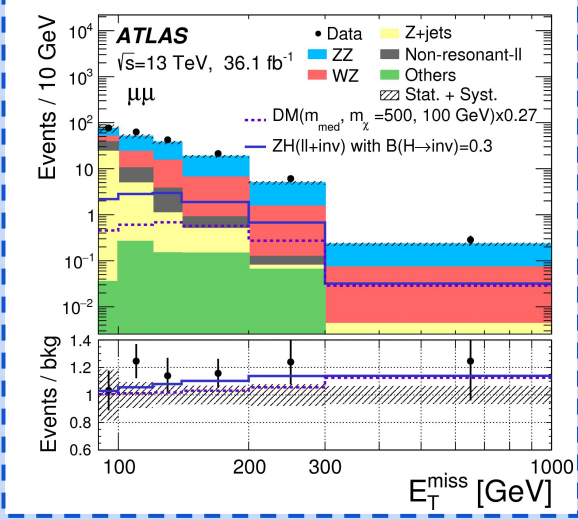


- $m^{1+1-} \sim m^Z$ ($l=e/\mu$)
- $E_T^{\text{miss}} > 100$ GeV
- $N^{\text{b-jet}} = 0$
- $\Delta\phi(\mathbf{p}_T^{\ell\ell}, E_T^{\text{miss}}) > 2.6$
- $|\mathbf{p}_T^{\ell\ell} - E_T^{\text{miss}}|/p_T^{\ell\ell} < 0.4$
- $\Delta R_{\ell\ell} < 1.8$
- $p_T^{\ell\ell} > 60$ GeV
- $N^{\text{jet}}(p_T > 30 \text{ GeV}) < 1$



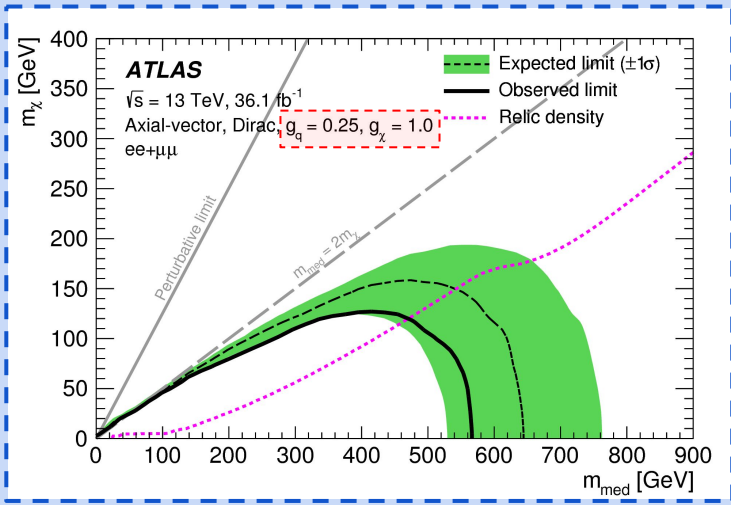
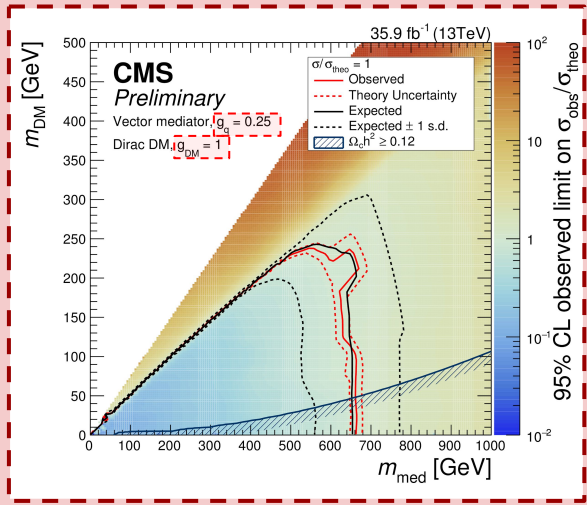
- $m^{1+1-} \sim m^Z$ ($l=e/\mu$)
- $E_T^{\text{miss}} > 90$ GeV
- $N^{\text{b-jet}} = 0$
- $\Delta\phi(\mathbf{p}_T^{\ell\ell}, E_T^{\text{miss}}) > 2.7$
- $|\mathbf{p}_T^{\ell\ell} - E_T^{\text{miss}}|/p_T^{\ell\ell} < 0.2$
- $\Delta R_{\ell\ell} < 1.8$
- $E_T^{\text{miss}} / H_T > 0.6$

arXiv:1708.09624



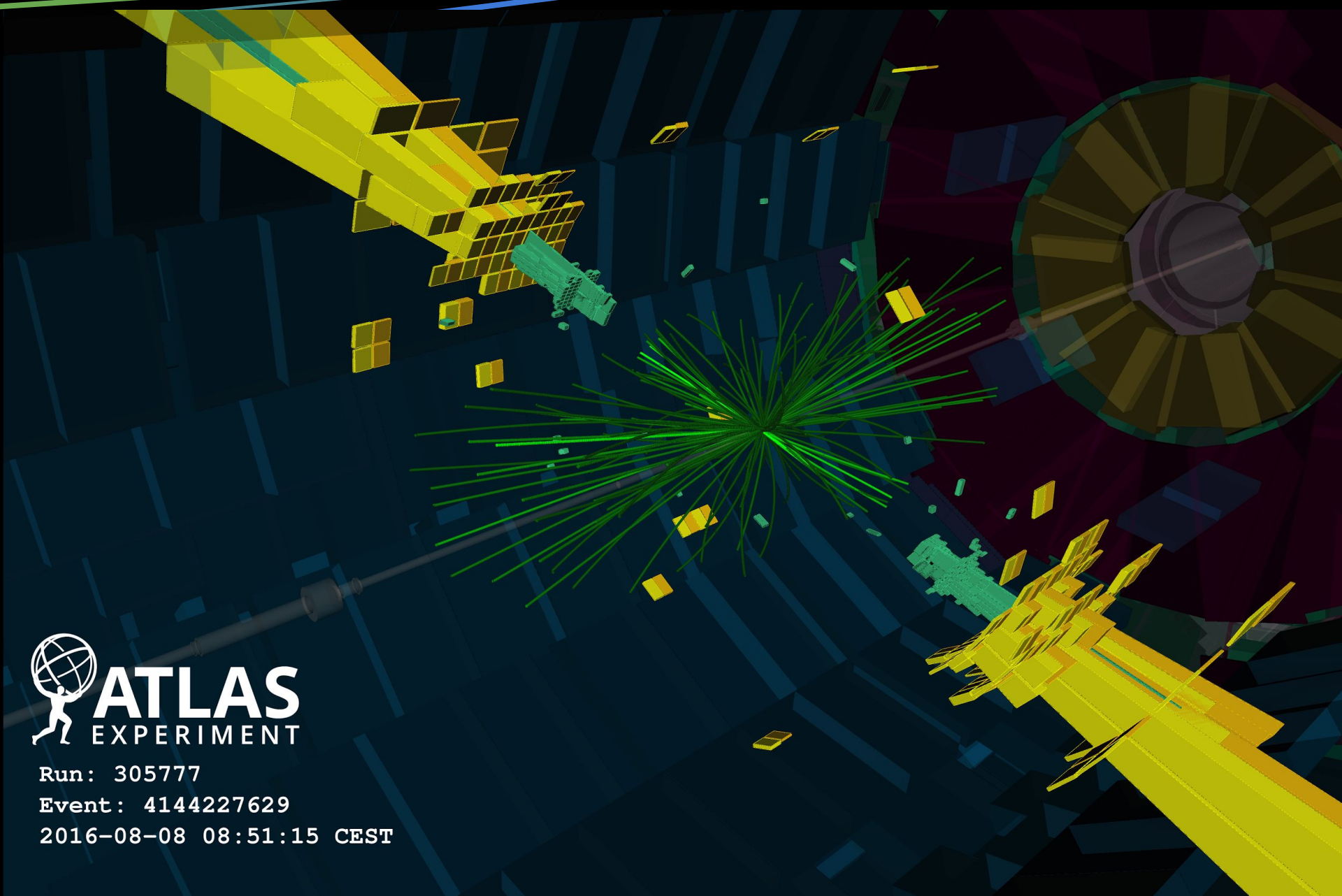
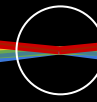
- CRs: WZ / ZZ ratio with NNLO QCD & NLO EW corrections
- Nonresonant / DY background from $e\mu$ CR / sideband
- Dominant uncertainties from VV missing EW corrections

Vector med.
Excl. mediator masses up to 650 GeV
Excl. DM masses up to 240 GeV



Axial-vector med.
Excl. mediator masses up to 560 GeV
Excl. DM masses up to 130 GeV

Resonant searches



Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

Resonant / angular searches: di-jet

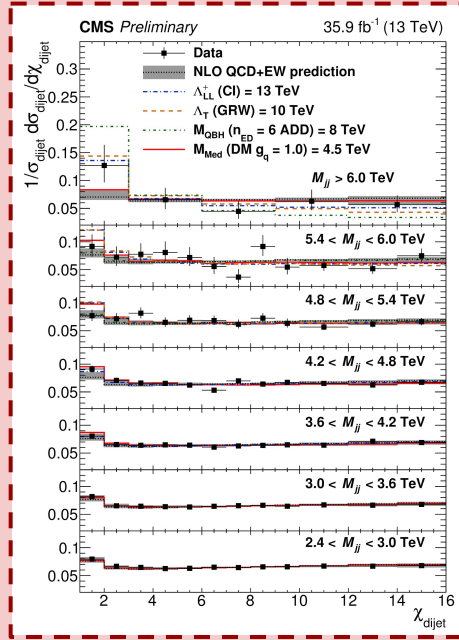
Angular distribution di-jet

- Non/wide-resonant signatures
- $\chi_{\text{dijet}} = \exp |y_1 - y_2|$
- $p_{T,\text{jet}} > 450 \text{ GeV}$ or $H_T > 900 \text{ GeV}$
- Search in bins of m_{jj}

[CMS-PAS-EXO-16-046](#)

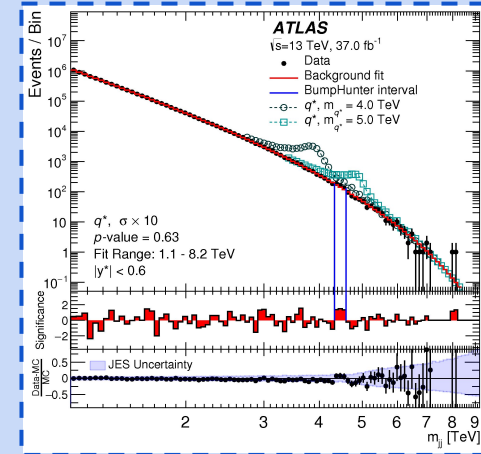
(Axial-)vector mediator

- $g_{\text{DM}} = 1$
- $m_{\text{DM}} = 1 \text{ GeV}$
- Excl. $g_q > 1$ (2.5 - 5.0 TeV)



High mass di-jet

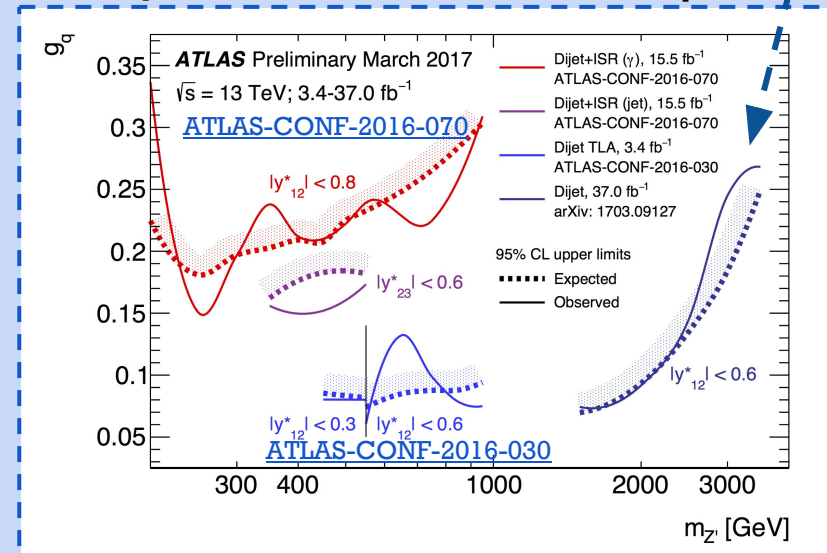
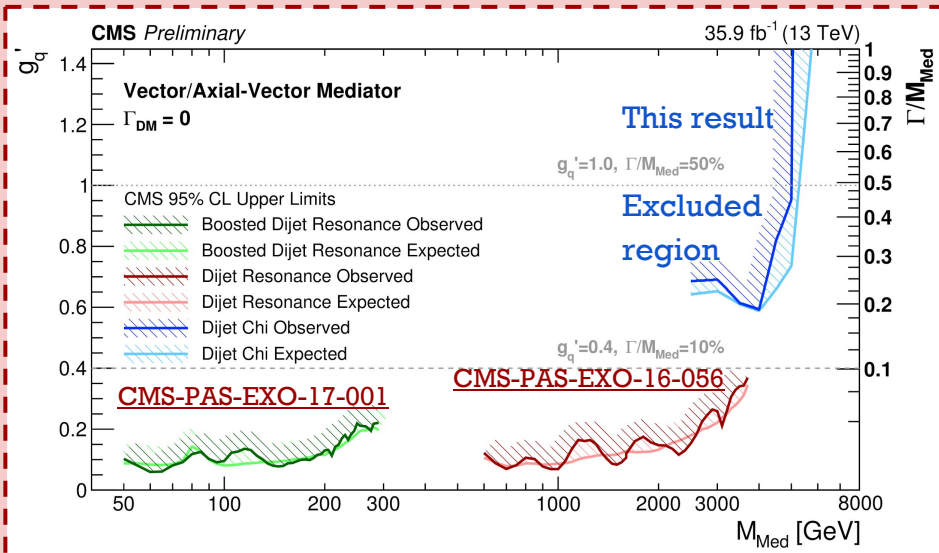
- Resonance search in:
 - $|y^*| < 0.6$ ($m_{jj} > 1.1 \text{ TeV}$)
 - $|y^*| < 1.2$ ($m_{jj} > 1.7 \text{ TeV}$)
- Bkg: sliding-window
- 3-parameter fit
- BumpHunter search in m_{jj}
- (+ angular search in bins of m_{jj})



Axial-vector

- $\Gamma(Z' \rightarrow \text{DM}) \rightarrow 0$
- Parameters: $m_{Z'}$, g_q
- Valid for $g_q < 0.5$ (resonance width)

Excl. Z' masses up to 2.1 TeV ($g_q = 0.1$) or 2.9 TeV ($g_q = 0.2$)



[doi:10.1103/PhysRevD.96.052004](https://doi.org/10.1103/PhysRevD.96.052004)

Resonant searches: di-lepton



Search for non-leptophobic mediators

- Search in di-lepton ($ee/\mu\mu$) mass
- $p_{T,e,\mu} > 30$ GeV
- More than 2 muons: use OS pair

Z' models

Lower limits ranging from 3.8 to 4.5 TeV

Generic limits

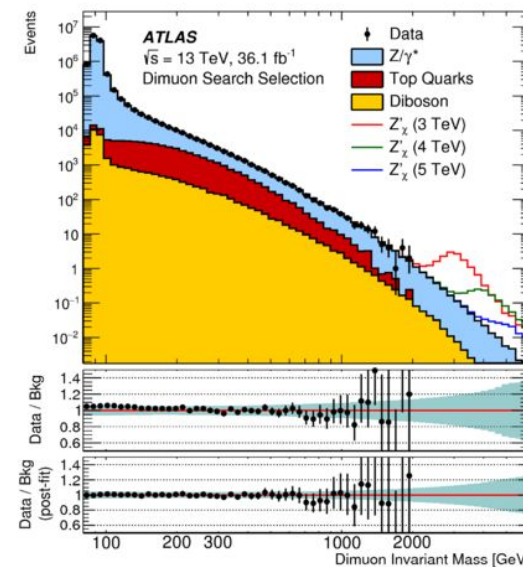
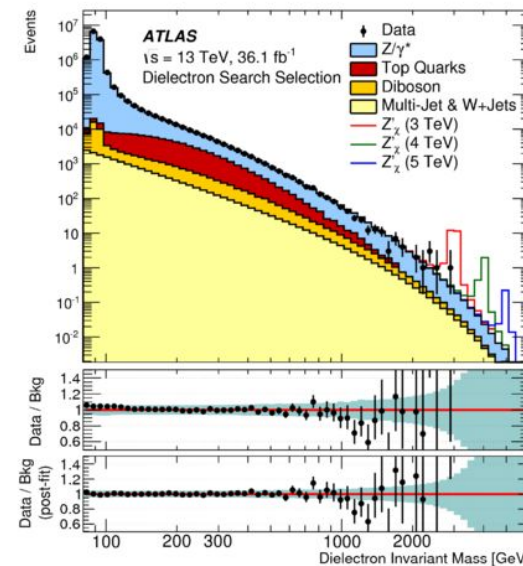
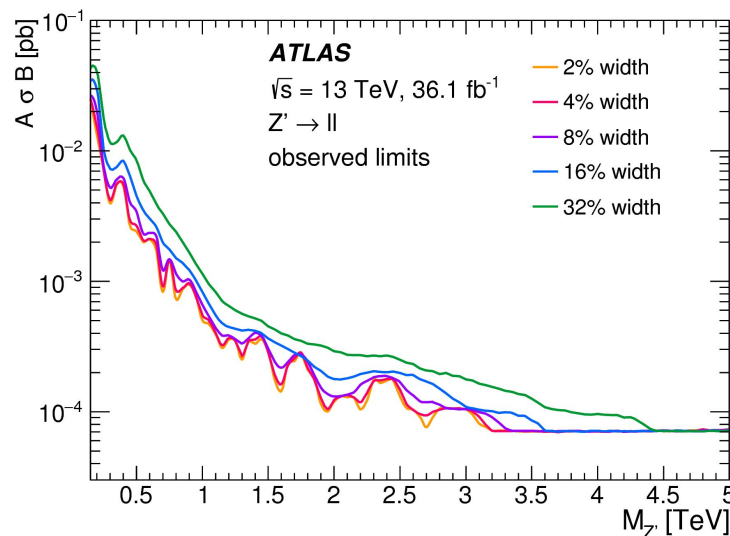
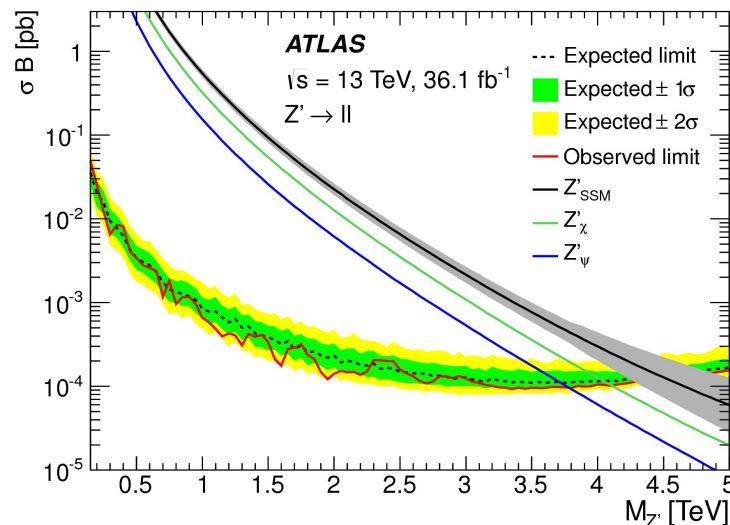
Fiducial region:

$p_{T,e,\mu} > 30$ GeV & $|\eta_{e,\mu}| < 2.5$
 Mass window = 2 · signal width

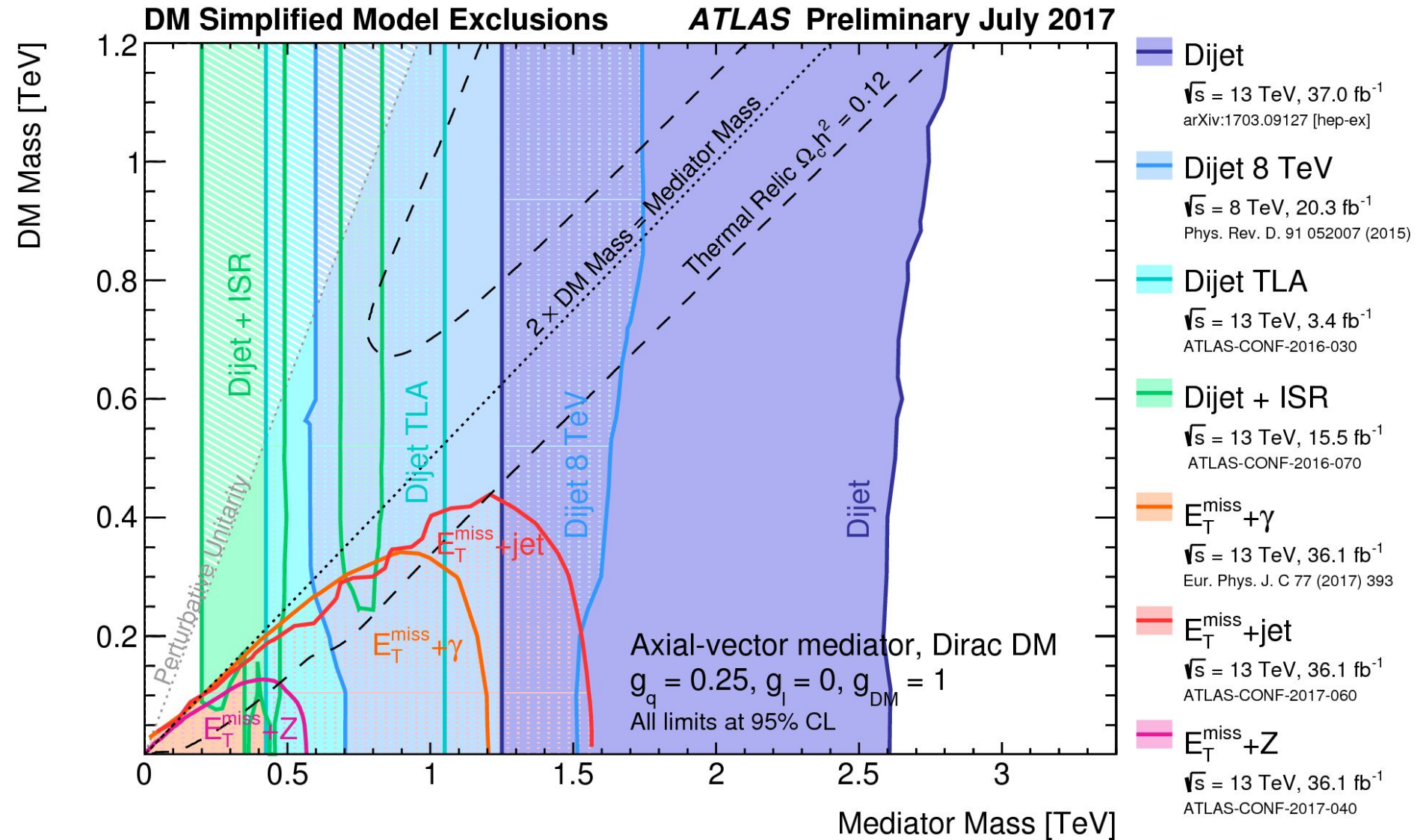
Limits on acceptance · σ · BR

Reinterpreted in simplified models

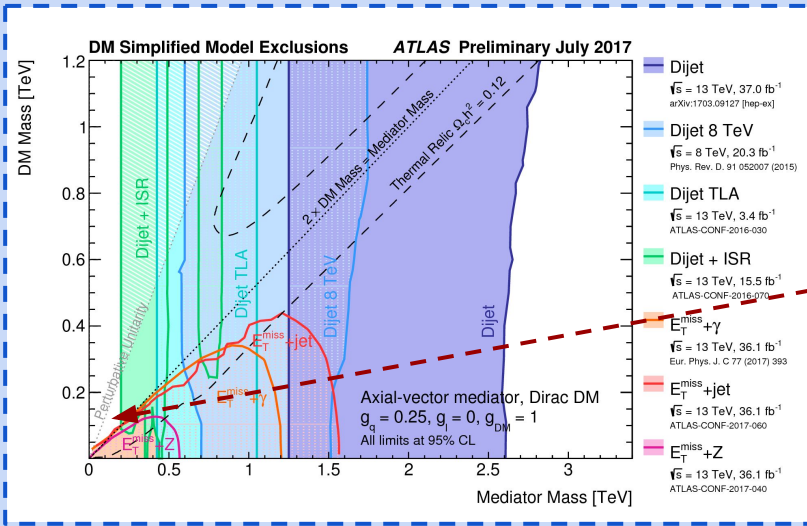
[arXiv:1707.02424](https://arxiv.org/abs/1707.02424)



Constraints (axial-)vector simplified models



Constraints (axial-)vector simplified models

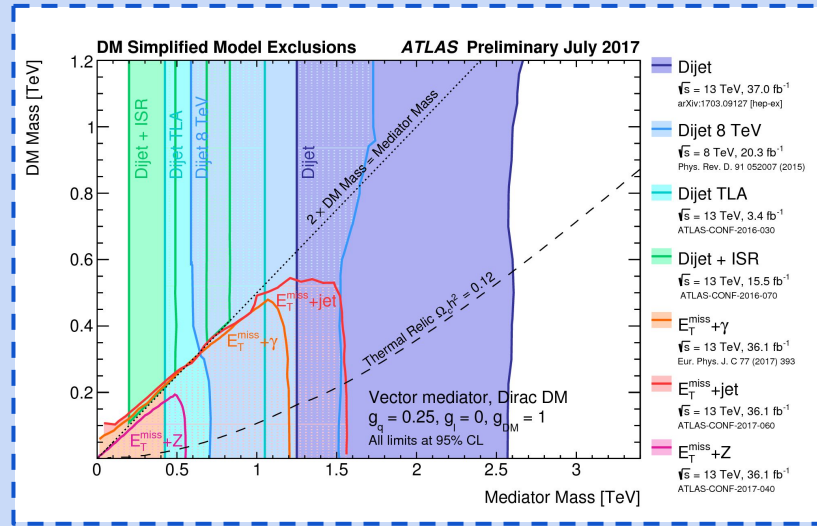


- Excl. (95% CL) m_{DM} v.s. **axial-vector med.** mass
- Illustrates complementarity of searches

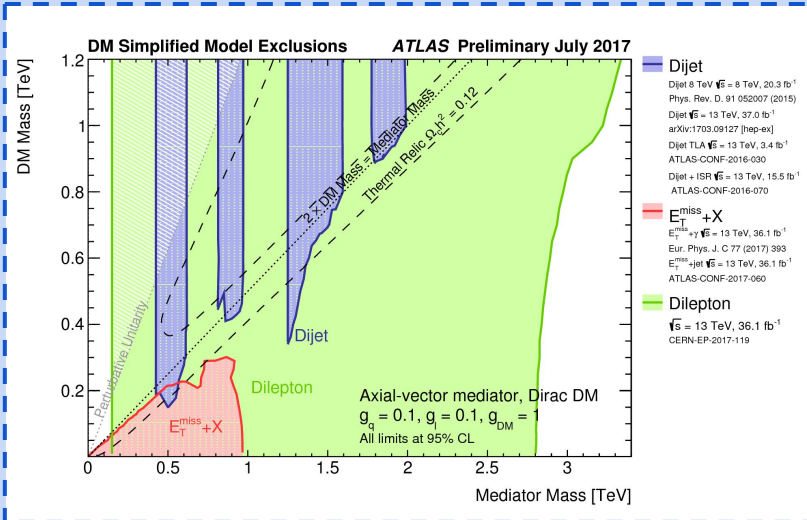
$g_{DM} = 1$
 $g_q = 0.25$
 $g_l = 0$
 (leptophobic)

Excl. by CMS
 boosted-dijet
[arXiv:1710.00159](https://arxiv.org/abs/1710.00159)

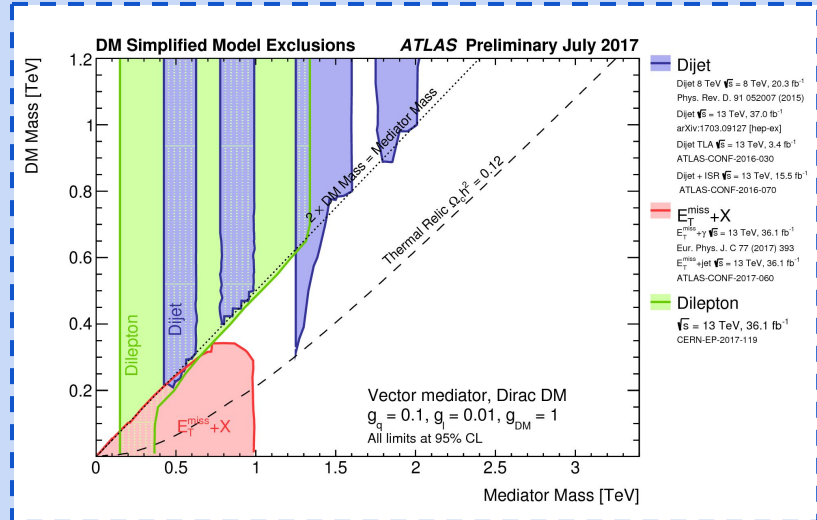
CMS DM summary plots
 ATLAS DM summary plots



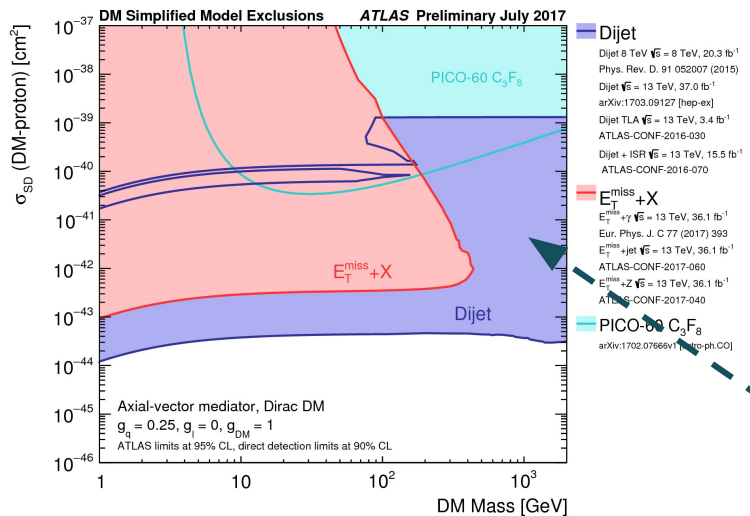
- Excl. (95% CL) m_{DM} v.s. **vector med.** mass
- Excl. regions, Ωh^2 -contours and perturbative unitary border are model-dependent



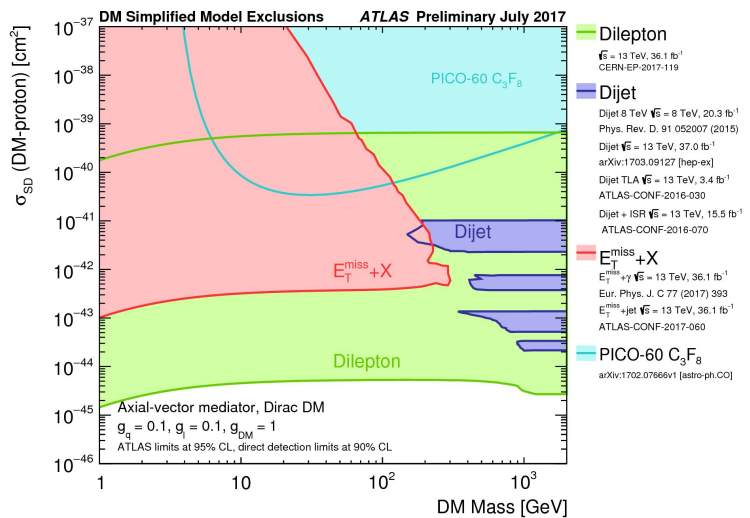
$g_{DM} = 1$
 $g_q = 0.10$
 $g_l = 0.10$
 $g_1 = 0.01 \rightarrow$



Mono-X & resonant searches v.s. direct detection constraints



axial-vector mediator → spin dependent $\sigma(\chi, p)$



Collider Physics and the Cosmos

$$g_{DM} = 1$$

$$g_q = 0.25$$

$$g_l = 0$$

(leptophobic)

Note:
 Excluded region only valid for given model

Resonant searches exclude region of cross sections, not an upper limit

Complementarity from collider searches at low DM masses / low recoil energies

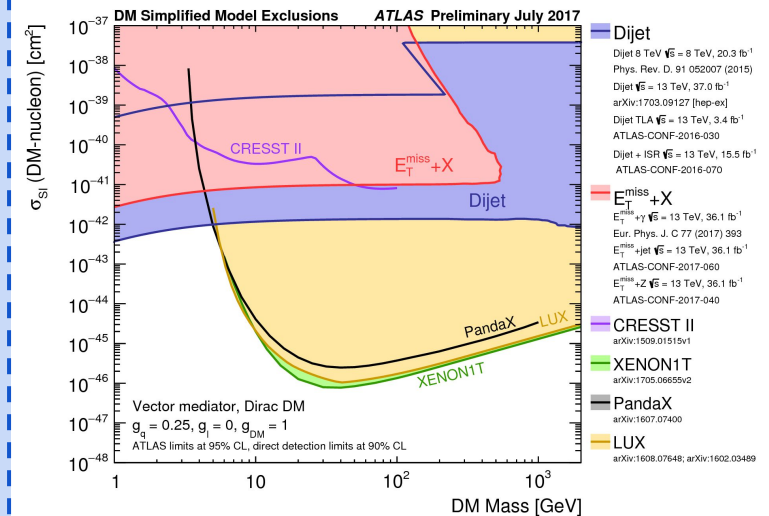
$$g_{DM} = 1$$

$$g_q = 0.10$$

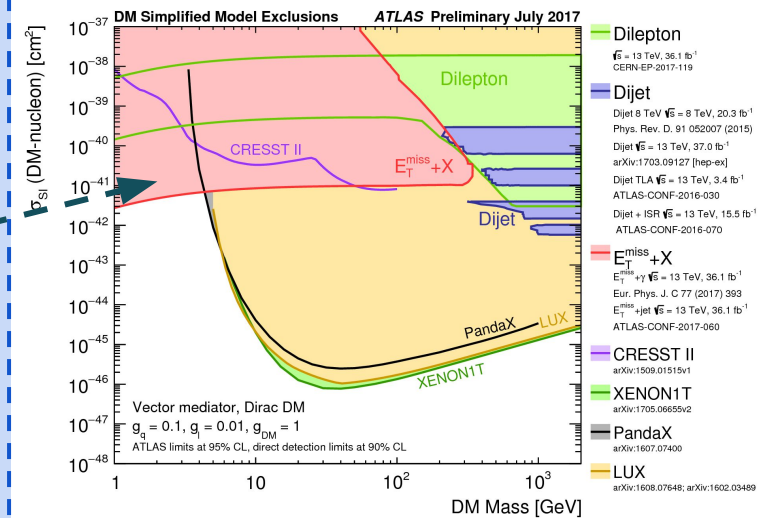
$$g_l = 0.10$$

$$g_l = 0.01 \rightarrow$$

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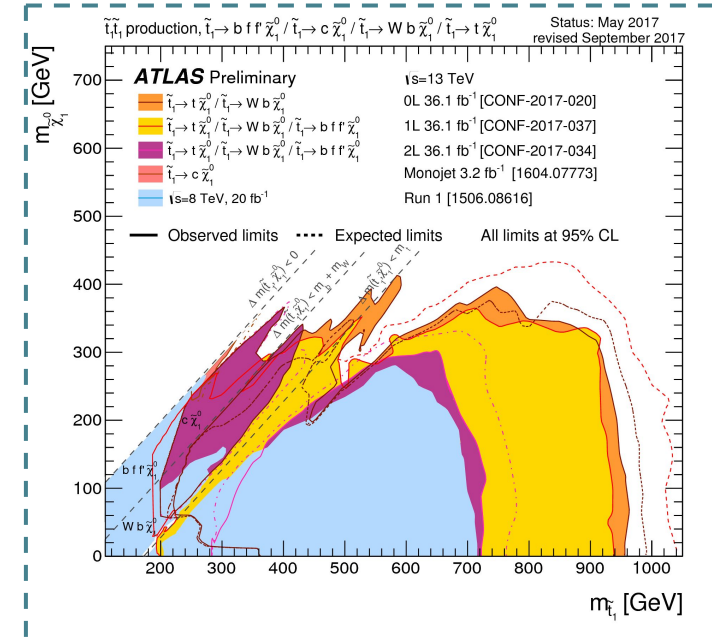
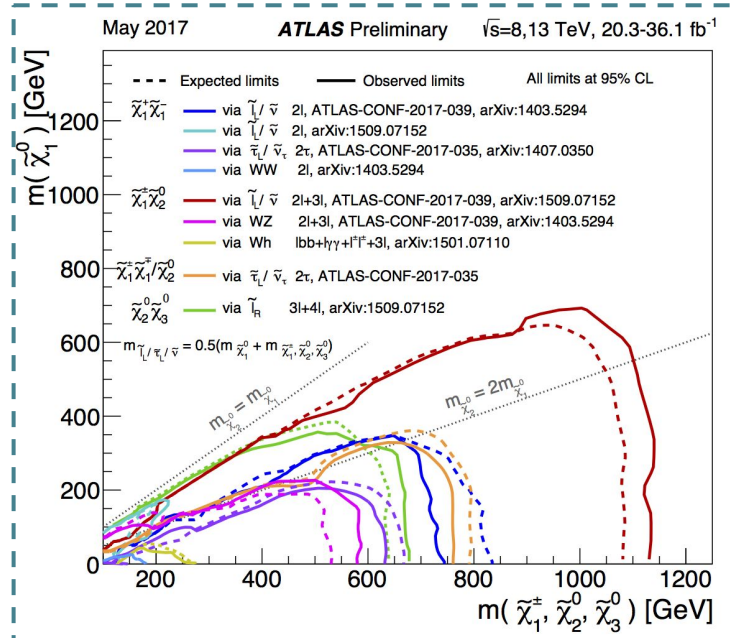
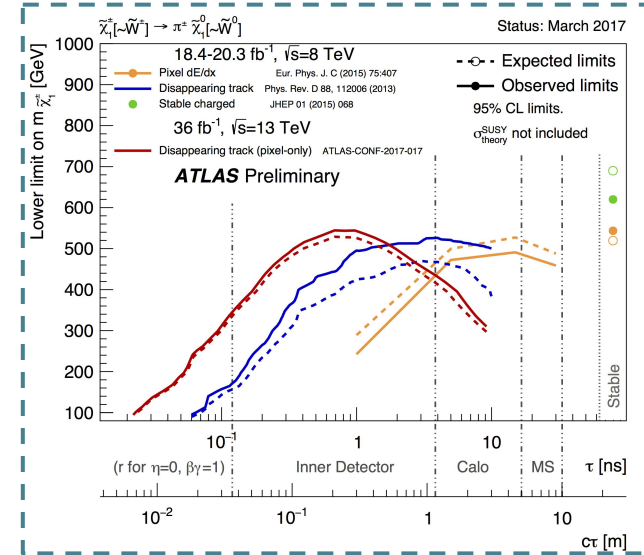
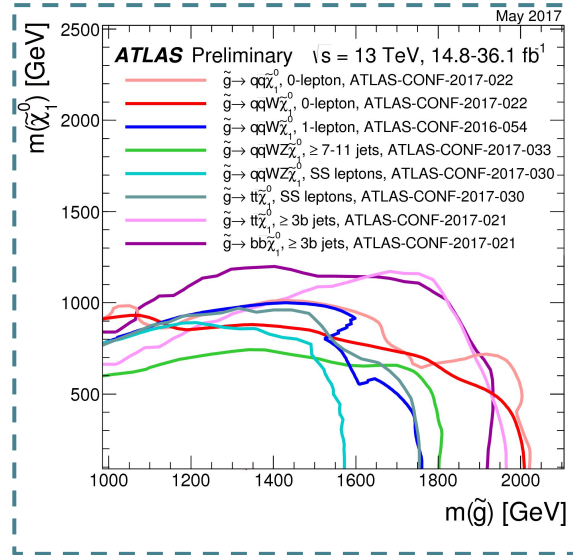
vector mediator → spin independent $\sigma(\chi, p)$



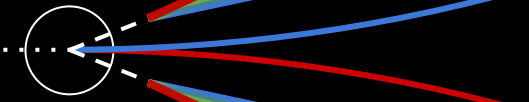
16

Dark Matter & SUSY

- Less simplified models
- Lightest neutralino can be a WIMP-like DM candidate (in R-parity conserving models)
- Extensive search programs at ATLAS and CMS for SUSY:
- EWK produced SUSY searches
- Searches for strongly produced stops and gluinos
- Searches for long-lived particles

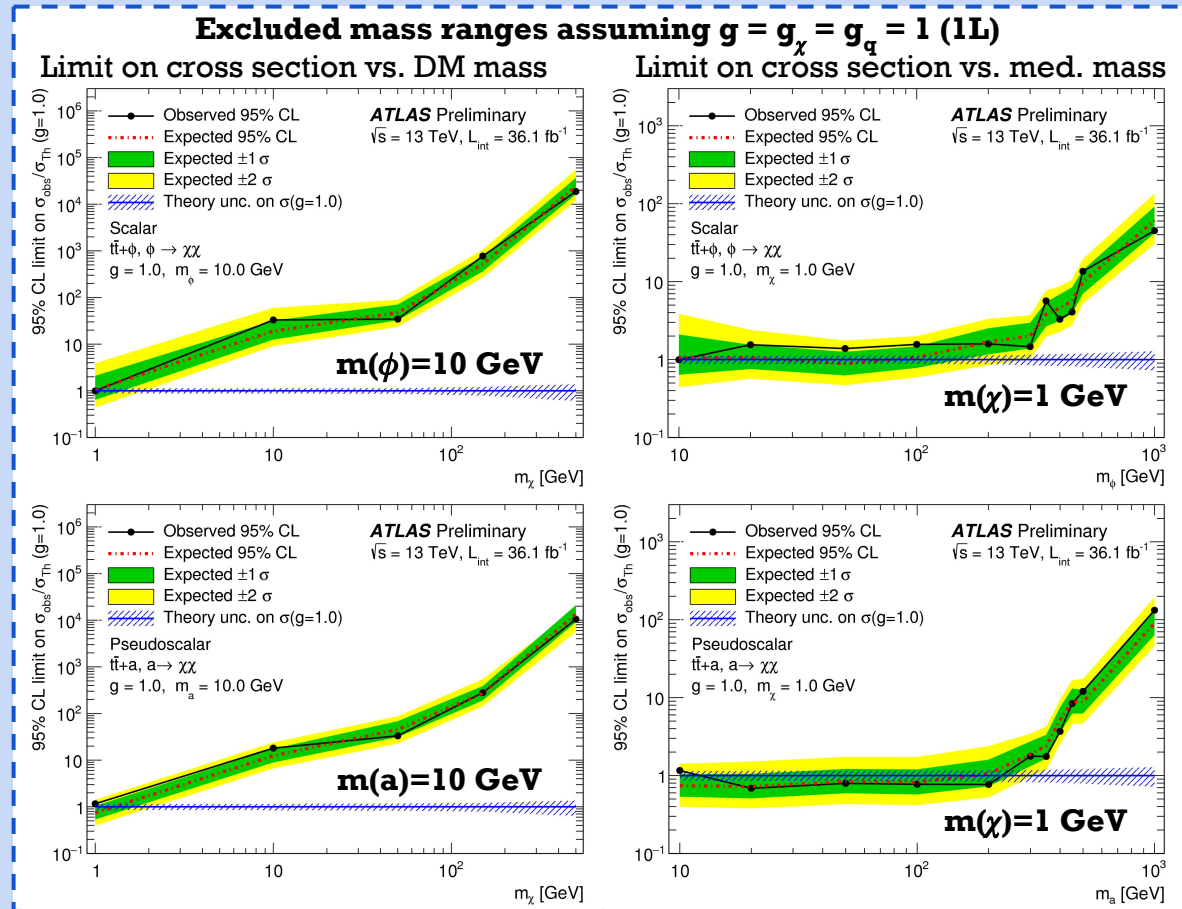
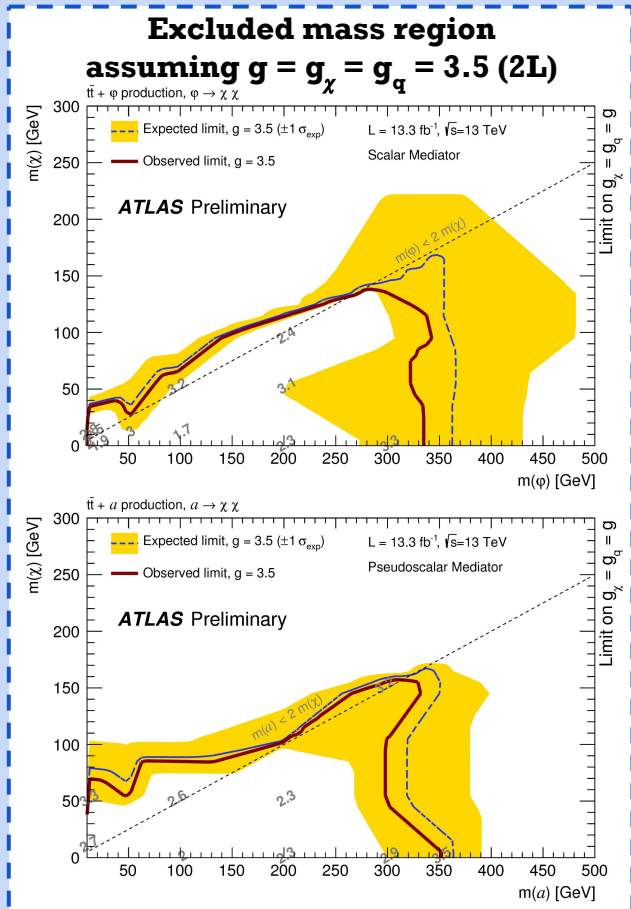
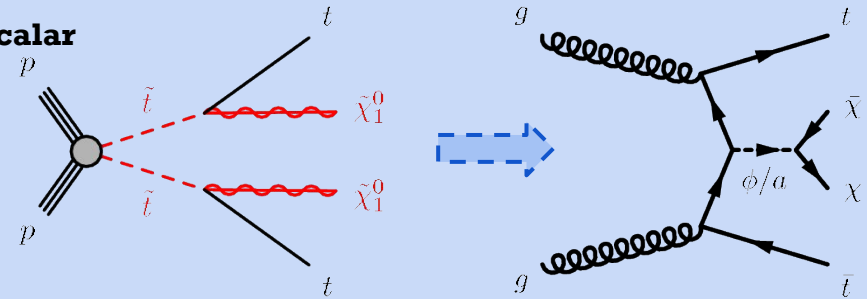


Dark Matter + Heavy Flavour



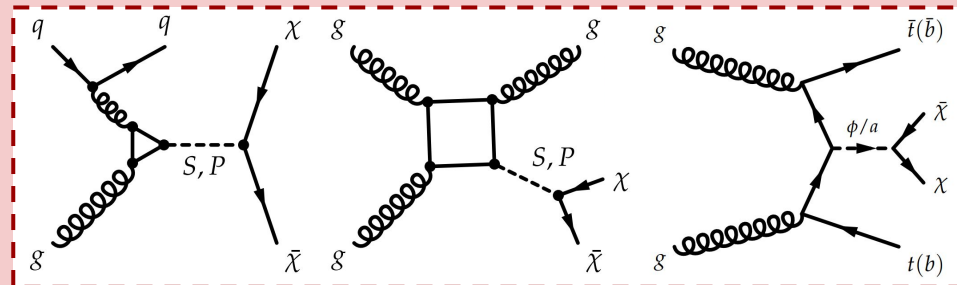
Constraints from stop pair searches on color-neutral (pseudo-)scalar

- 1 lepton [ATLAS-CONF-2017-037](#) (36.1 fb^{-1})
- 0 lepton [ATLAS-CONF-2016-077](#) (13.3 fb^{-1})
- 2 lepton [ATLAS-CONF-2016-076](#) (13.3 fb^{-1})
- Parameters: $m(\phi)$, $m(a)$, m_χ , $g = g_\chi = g_q$



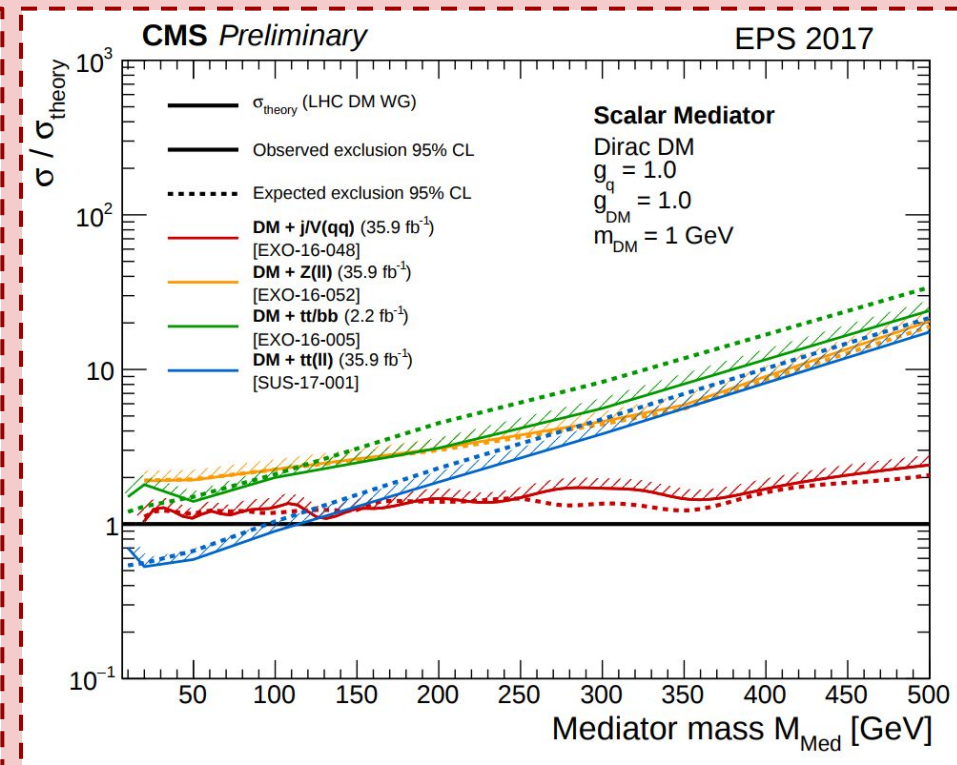
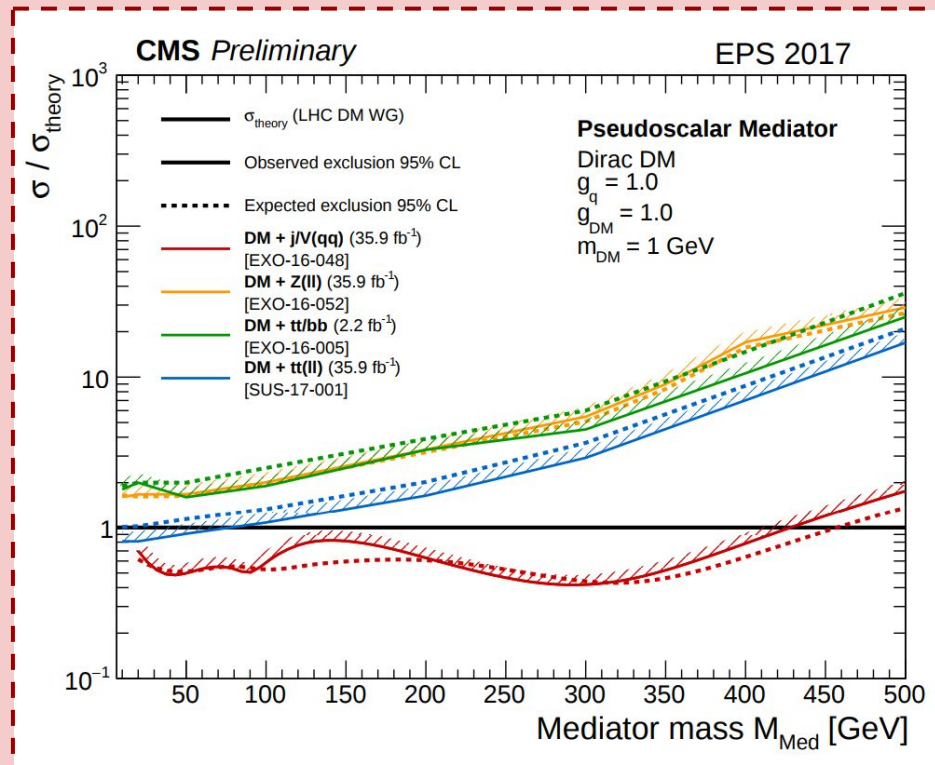
Constraints on (pseudo-) scalar simplified models

- Excl. (95% CL) cross sections for (pseudo-)scalar models as a function of the mediator mass
- Comparison of different E_T^{miss} based analysis
- Excluding $g = 1$ for $m(a) < 420$ GeV and $m(\phi) < 110$ GeV



$$g_{\text{DM}} = g_q = g = 1 \quad m_{\text{DM}} = 1 \text{ GeV}$$

[CMS DM summary plots](#) [ATLAS DM summary plots](#)

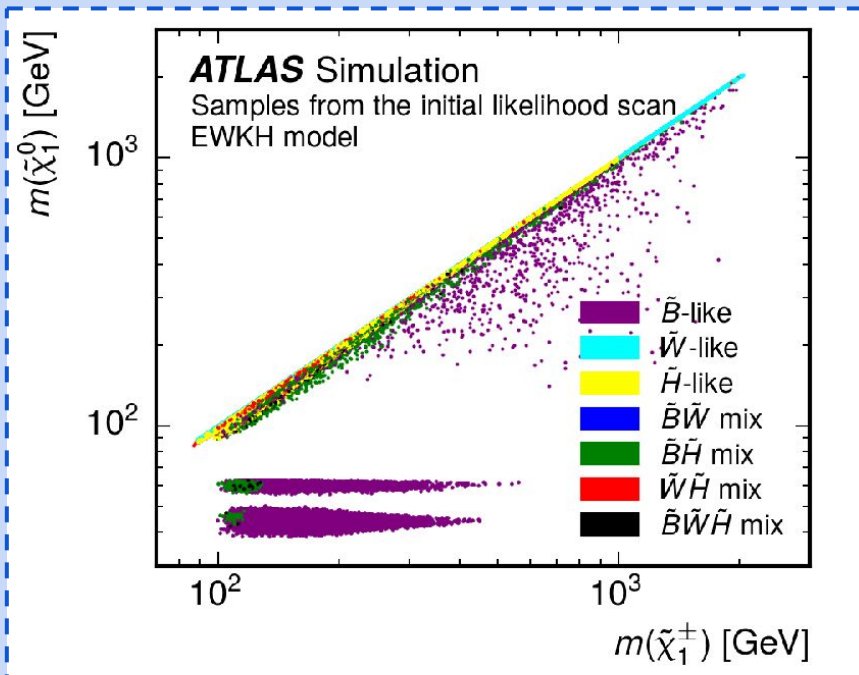


EWK SUSY searches v.s. direct detection constraints

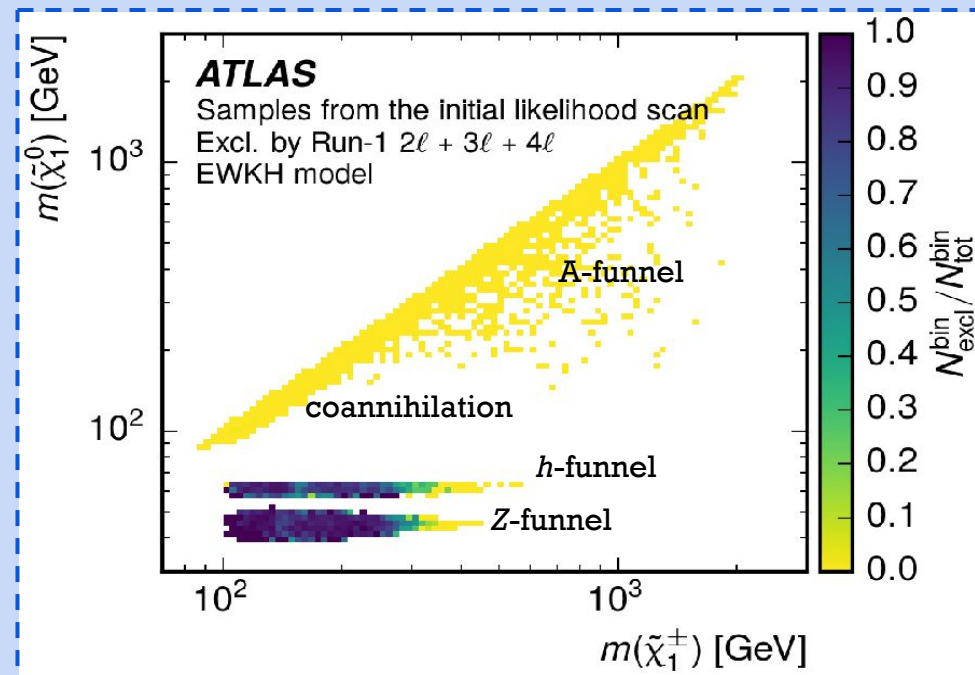
- WIMP interpretations of **Run 1** EWK SUSY searches (2l, 2 τ , 3l, 4l)
- 5 dimensional scan of pMSSM (EWKH): $M_1, M_2, \mu, \tan \beta, m_A$
- Constraints from direct detection, relic DM density, precision flavour physics, Higgs mass, LEP searches
- High excl. sensitivity for LSP masses < 65 GeV
- Four (co-)annihilation enhanced regions
- Low sensitivity for heavy LSPs and compressed mass spectra (Wino/Higgsino-like neutralinos)
- Possible constraints from long-lived particles not included

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Neutralino composition of model points



Neutralino composition of model points

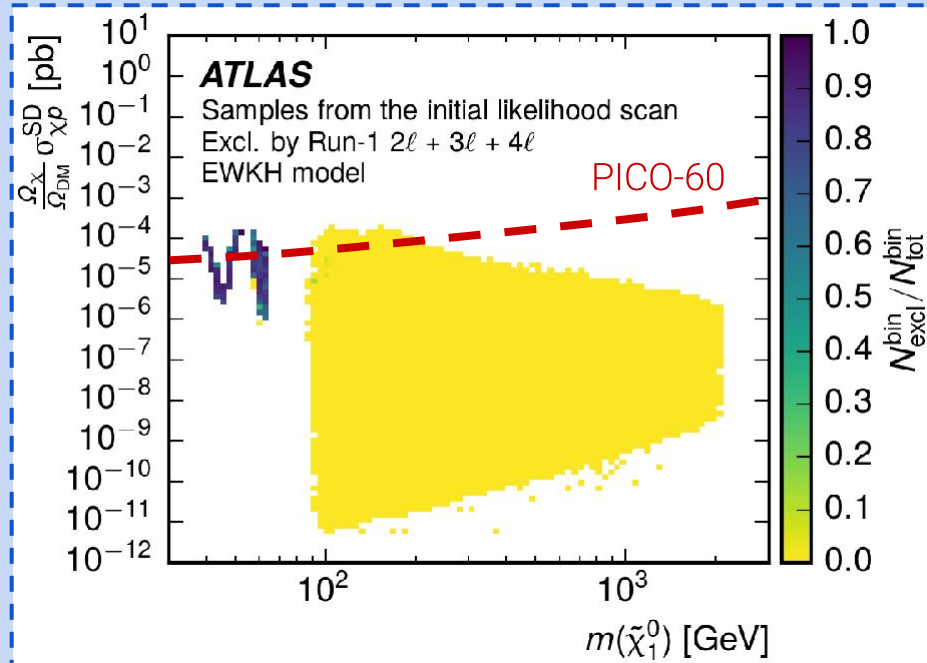
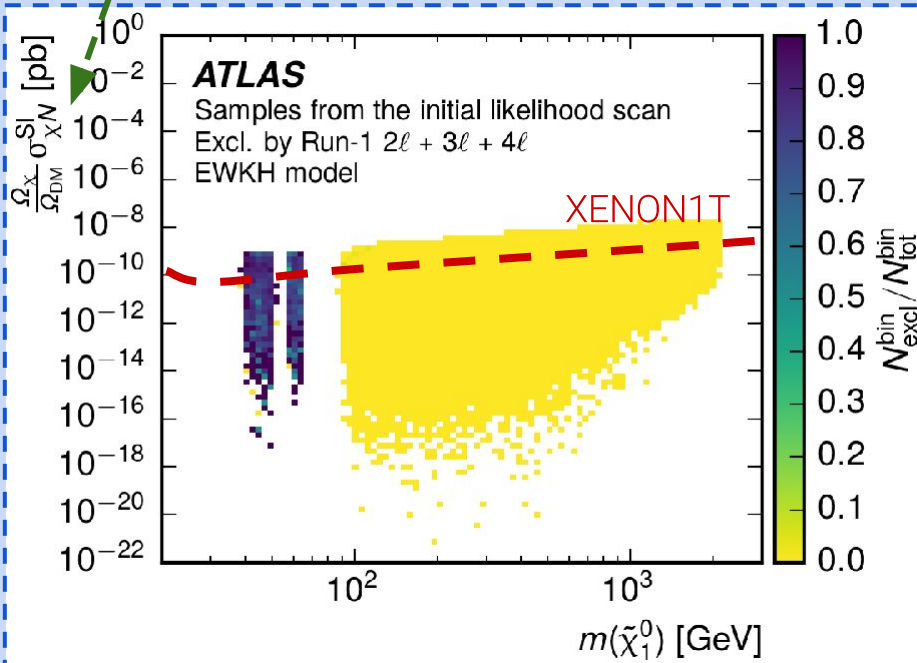
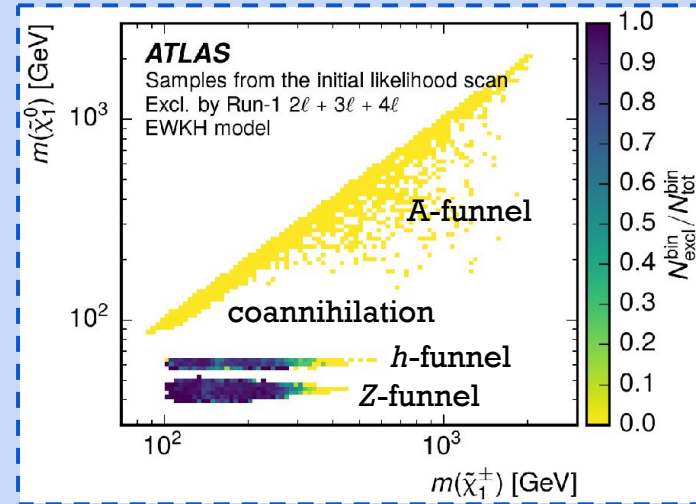


EWK SUSY searches v.s. direct detection constraints

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Cross section times fraction of DM cosmic abundance

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Summary and outlook

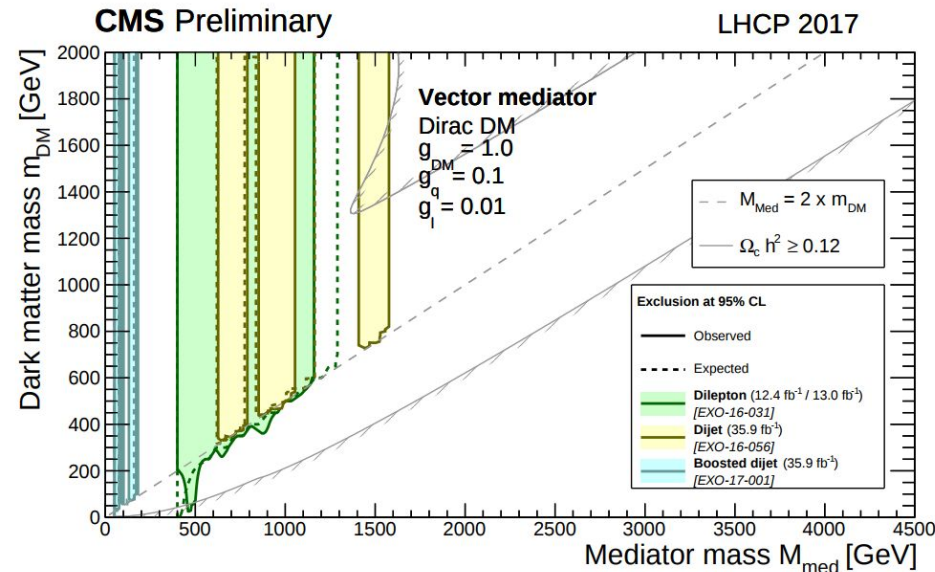
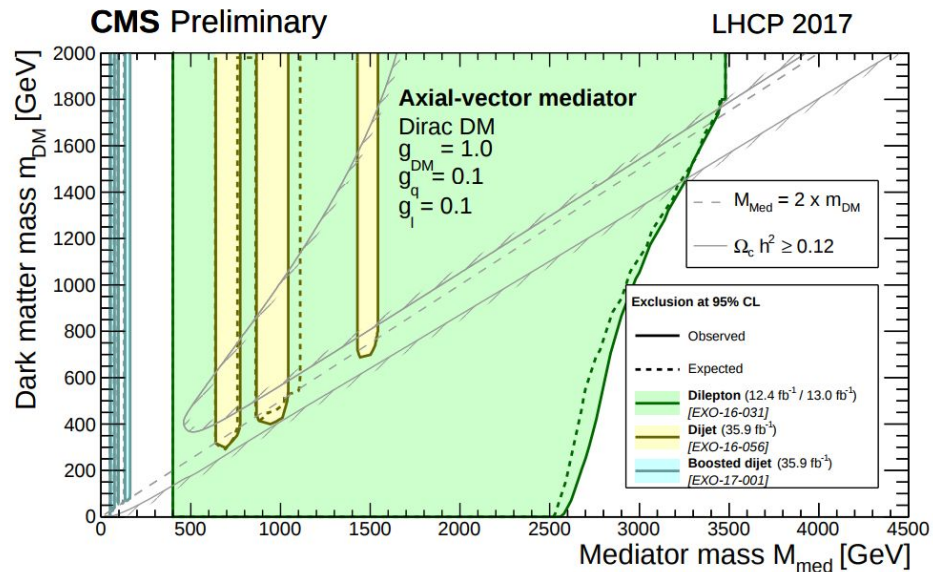
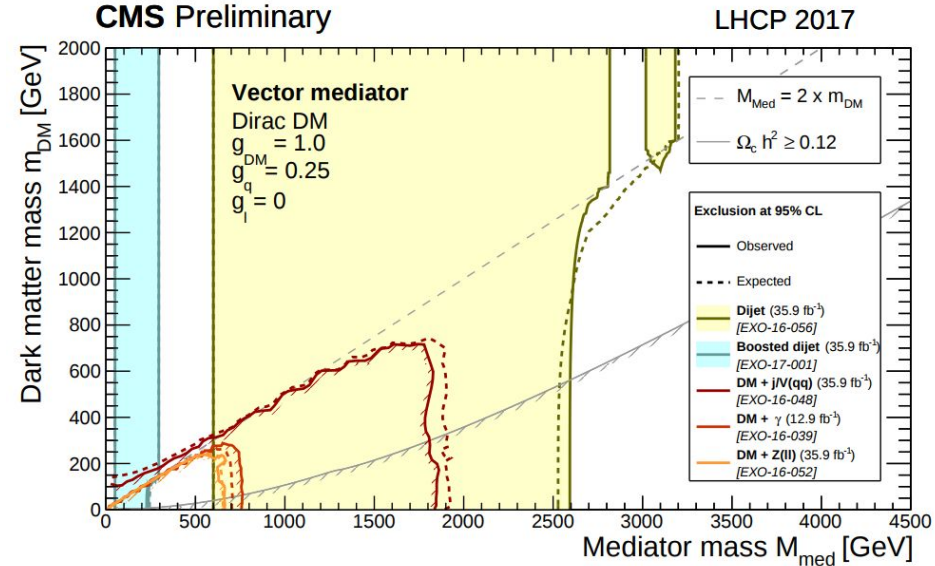
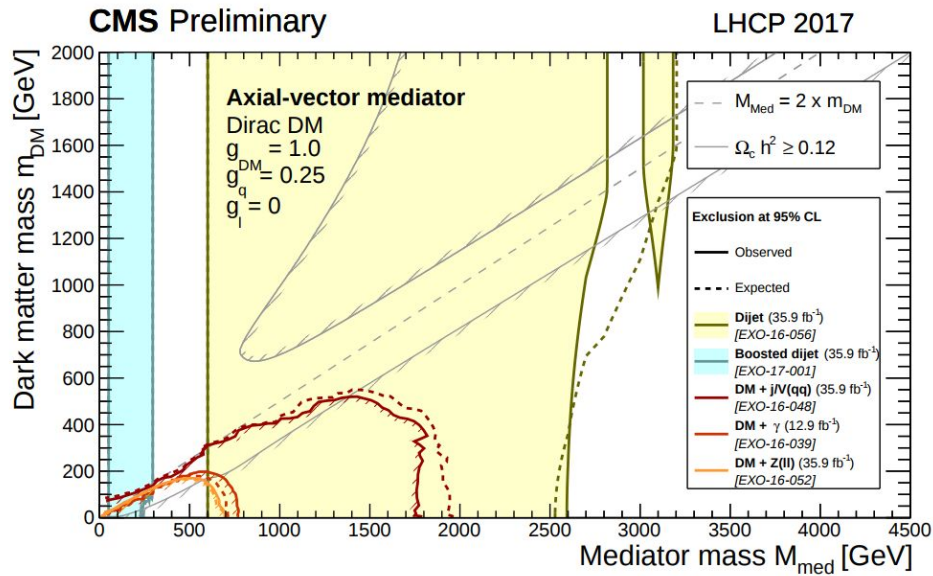
- **Run 2** results constraining WIMP interpretation in terms of LHC DM WG's **simplified models**
 - **Mono-X searches** excluding up to 1.8 TeV mediator masses and 0.7 TeV DM masses in (axial-)vector mediator models
 - Excluding a coupling of $g = 1$ for pseudo scalar masses up to 420 GeV and scalar mediators up to 110 GeV
 - Additional constraints from **resonant/angular searches** on mediator masses

- Impact of Run 1 **EWK SUSY searches** on WIMP DM evaluated
 - Limited sensitivity in compressed mass / coannihilation region → Run 2 analysis
 - Plans for WIMP interpretation of Run 2 SUSY searches

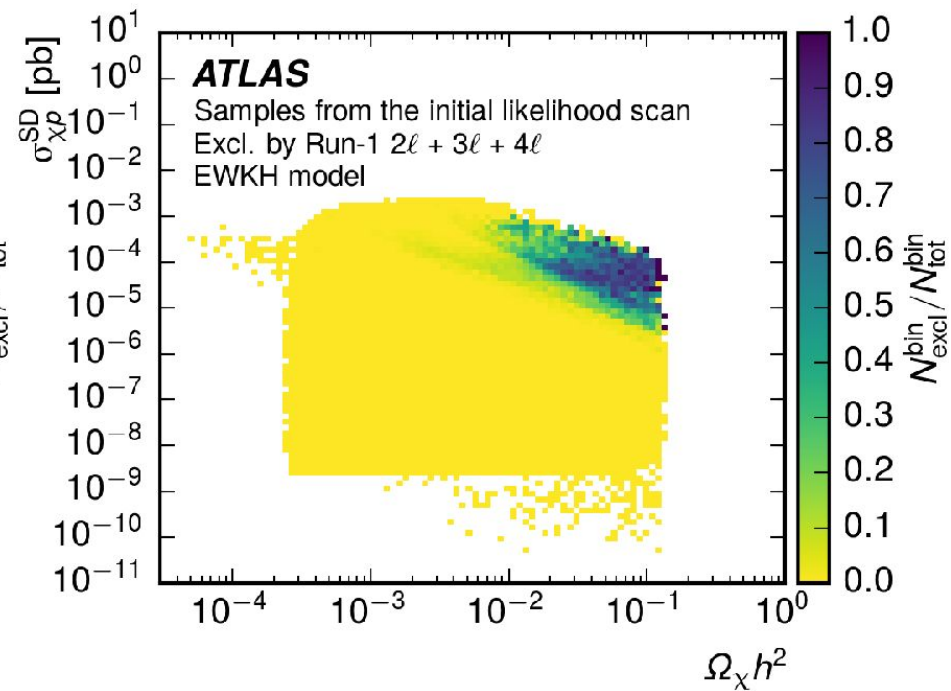
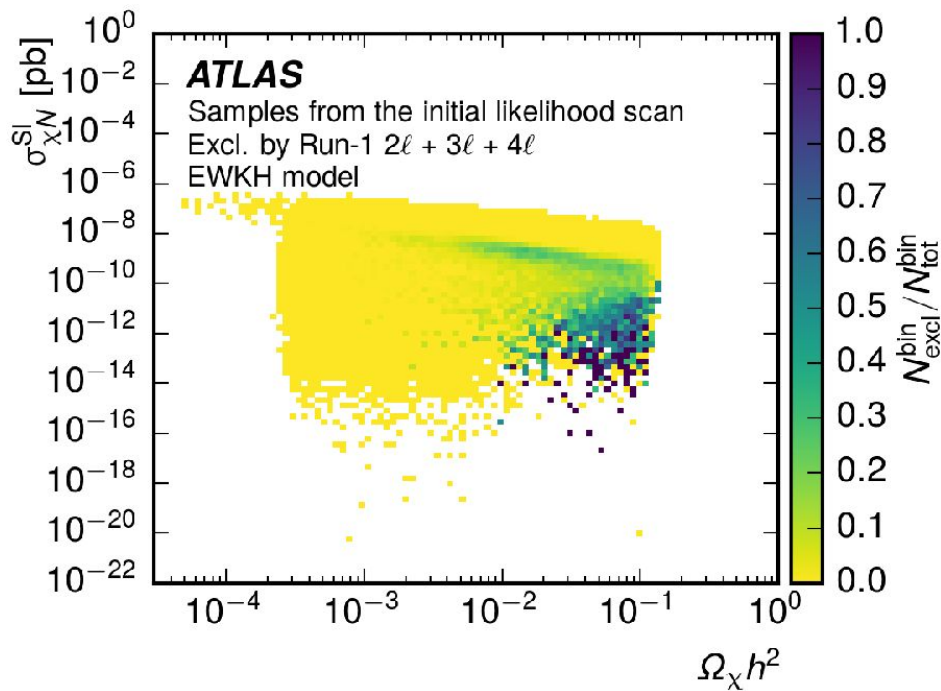
- Other models considered by LHC DM WG, not discussed in this overview
 - Flavour-Changing Neutral Current (FCNC) → $E_T^{\text{miss}} + \text{top}$ / same sign top
 - 2HDM Z' & baryonic Z' & 2HDM+pseudo scalar interpretation (Renjie Wang's talk)

Backup slides

Constraints (axial-)vector simplified models (CMS)



EWK SUSY searches v.s. direct detection constraints



Dark Matter



- **Velocity dispersions, rotation curves**
- **Gravitational lensing**
- **Cosmic microwave background**
- **Structure formation**
- **Colliding clusters**
- **Dwarf galaxies**
- **Redshift-space distortions, supernova**
- ...



Illustration: Sandbox Studio, Chicago

WIMPs -- weakly interacting massive particles

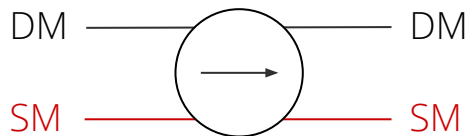
Dark matter appears to be

- Non-luminous / neutral (M/L, rotational velocity, gravitational lensing)
- Non-baryonic (no MACHOs, BBN, CMB)
- Non-relativistic / cold (structure formation)
- Stable

WIMPs

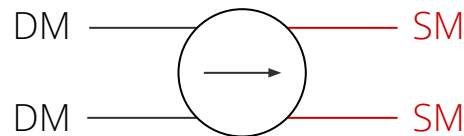
- Particle produced in thermal equilibrium in early universe until “freeze-out”
- Self-annihilation cross section determines freeze-out point and relic density
- Should be compatible with observed DM abundance
- Electroweak particles of 0.1~1 TeV (e.g. neutralinos) fit this description -- “WIMP miracle”

Searching for WIMPs



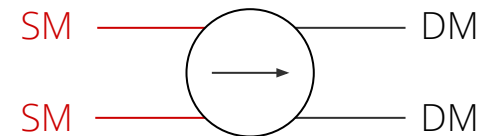
Direct detection (DD)

- Nuclear recoil from scattering
- Upper limits on cross section against DM mass



Indirect detection (ID)

- Self-annihilation of DM
- Gamma-rays, antiprotons, positrons, neutrinos



Production

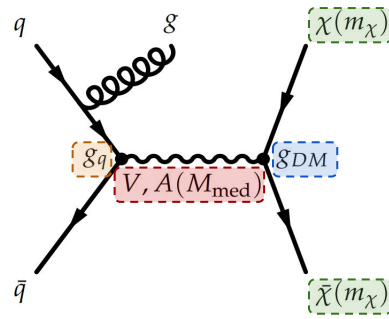
- Search for DM visible as missing momentum
- Also: mediator searches decaying to SM particles

Examples Simplified Models

s-channel mediator \rightarrow mono-X & resonances

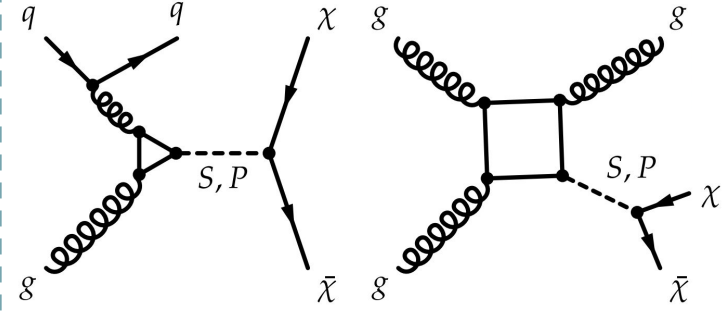
- Spin 1 (axial-)vector mediators
- Decay to SM pair or DM pair (+ISR)
- ISR = QCD parton, γ , W, Z, h
- Dirac fermion DM
- Minimal decay width
- Parameters (values used in results):

- M_{med} mediator mass
- m_χ DM mass
- g_χ (1.0) mediator-DM coupling
- g_q (0.25 / 0.1) mediator-quark coupling
- g_l (0 / 0.01 / 0.10) mediator-lepton coupling



s-channel (pseudo-)scalar mediator

- Example of LO mono-jet production mode
- Other final states: $E_T^{\text{miss}} + Z / h$

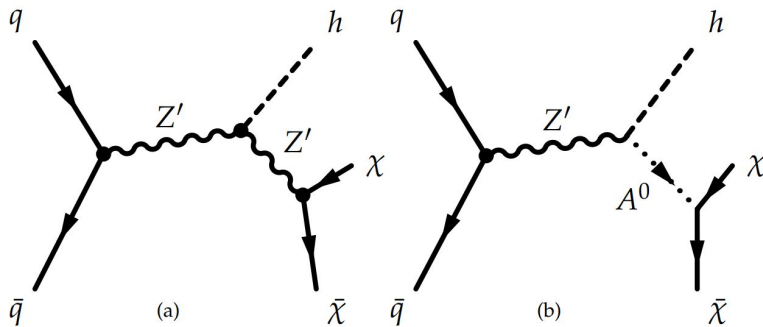


Scalar (S, ϕ) / pseudoscalar (P, a) mediator

Baryonic (a) / 2HDM (b) Z' model \rightarrow mono-Higgs

- Baryonic model parameters
- Two-Higgs-doublet model parameter

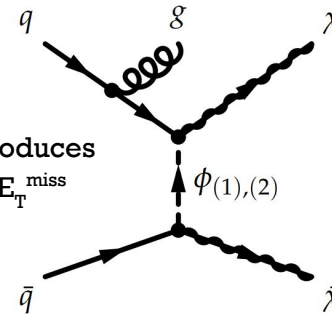
See Renjie Wang's talk:
WIMP interpretation of Higgs searches



t-channel coloured scalar mediator

- 5 more diagrams for LO mono-jet t-channel

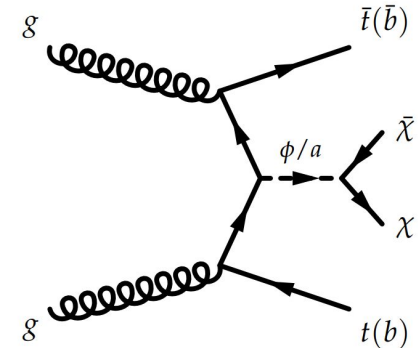
- Also produces dijet + E_T^{miss}



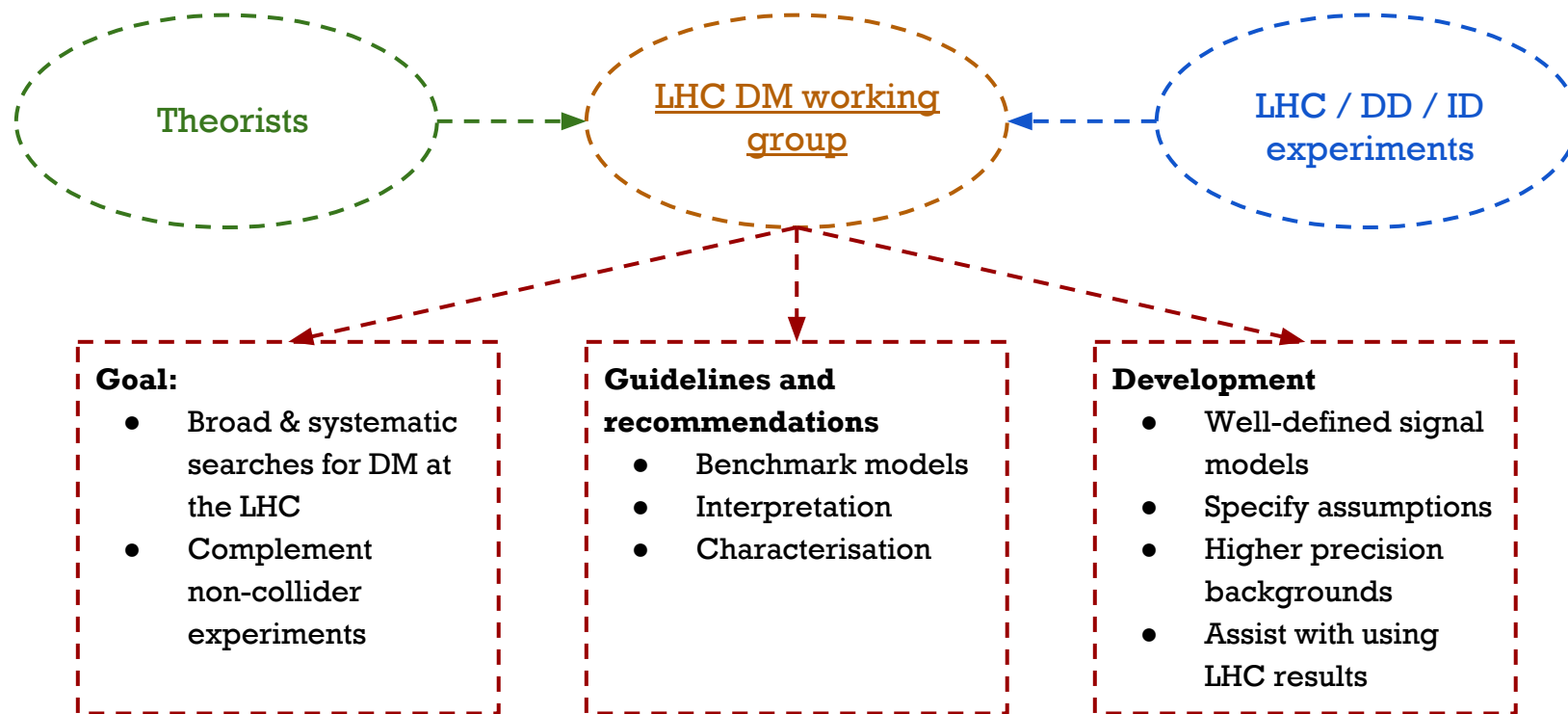
More simplified models: [arXiv:1507.00966](https://arxiv.org/abs/1507.00966)

(pseudo-)scalar mediator with heavy flavour pair

- Coupling to bottom favoured in high $\tan\beta$ models



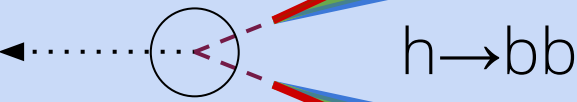
LHC Dark Matter Working Group



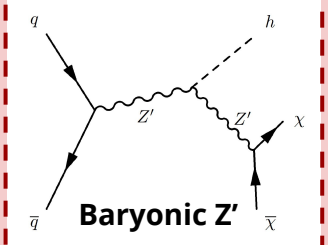
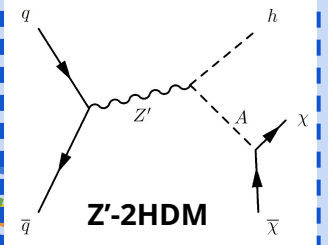
- Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum ([arXiv:1507.00966](https://arxiv.org/abs/1507.00966))
- Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter ([arXiv:1603.04156](https://arxiv.org/abs/1603.04156))
- Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels ([arXiv:1703.05703](https://arxiv.org/abs/1703.05703))

Mono+X searches: mono-Higgs

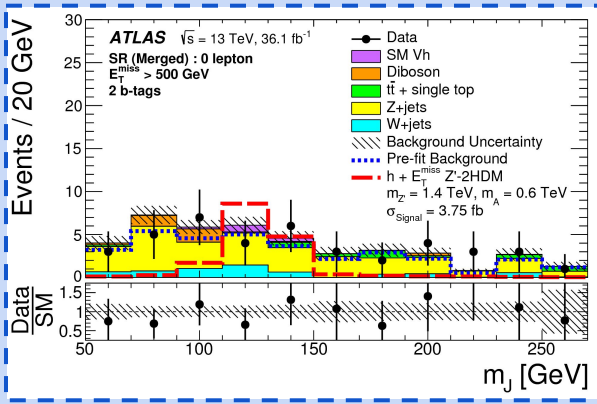
See Renjie Wang's talk:
WIMP interpretation of Higgs searches



arXiv:1707.01302
($H \rightarrow \gamma\gamma$: arXiv:1706.03948)

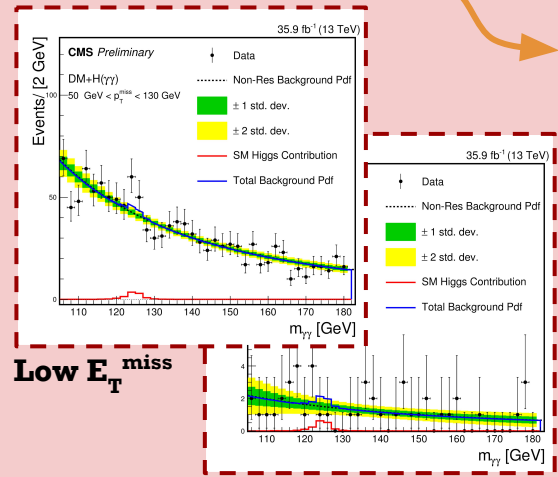


CMS-PAS-EXO-16-052

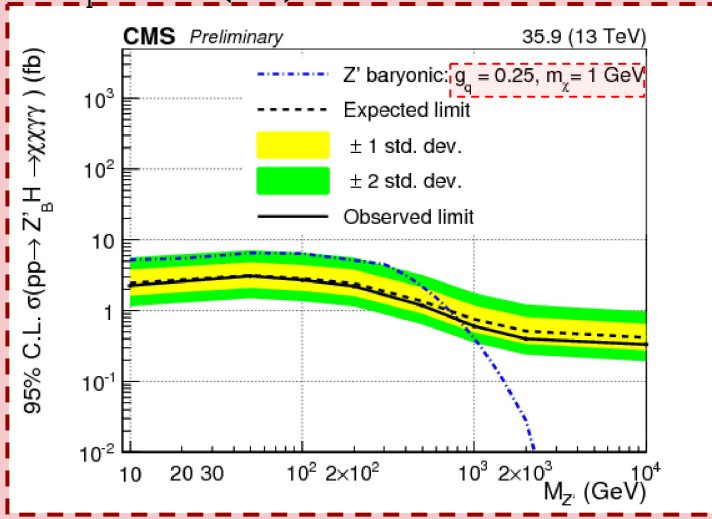
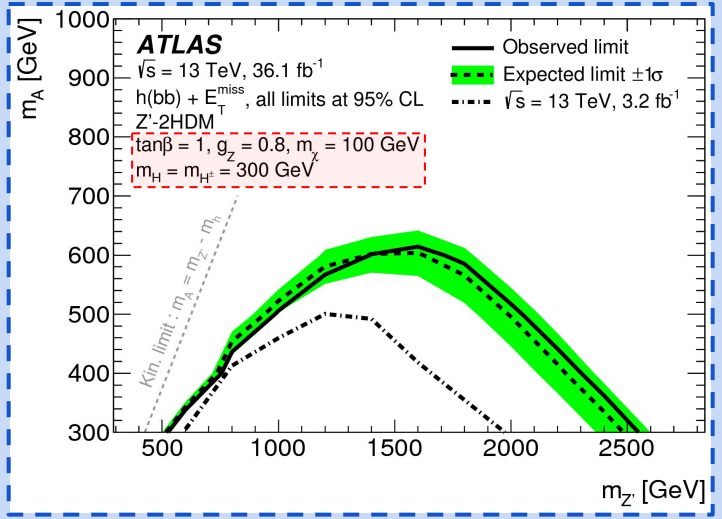


- $E_T^{\text{miss}} > 150$ GeV
- No leptons
- bb fat jet ($E_T^{\text{miss}} > 500$ GeV) or bb jet pair (resolved)
- compatible with Higgs boson
- $\Delta\phi(h, E_T^{\text{miss}}) > 2\pi/3$

- $p_{T,1\gamma(2\gamma)} > 30$ (20) GeV
- $m_{\gamma\gamma} > 95$ GeV
- $\Delta\phi(\gamma\gamma, E_T^{\text{miss}}) > 2.1$
- $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.5$
- Low (high) E_T^{miss} region:
- $p_{T,1\gamma}/m_{\gamma\gamma} > 0.45$ (0.5)
- $p_{T,2\gamma}/m_{\gamma\gamma} > 0.25$ (0.25)
- $p_{T,\gamma\gamma} > 75$ (90) GeV
- $E_T^{\text{miss}} > 50$ (130)

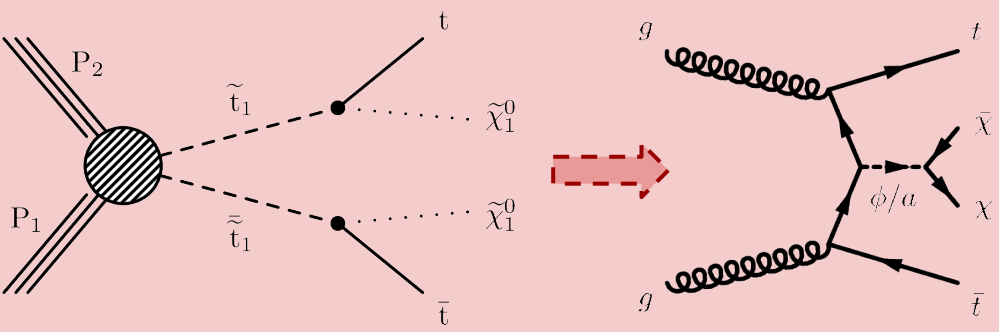
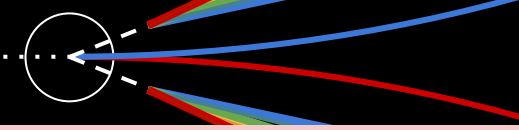


Excl. Z' masses up to 2.6 TeV and pseudoscalar masses up to 600 GeV



Excl. baryonic Z' masses up to 800 GeV for 1 GeV DM mass

Dark Matter + Heavy Flavour



CMS-PAS-SUS-17-001
(Reinterpretation of direct stop pair search)

Color-neutral (pseudo-) scalar

- Parameters: $m_\phi, m_a, m_\chi = 1$ GeV, $g = g_\chi = g_q = 1$
- Excl. $g = 1$ for $m_\phi < 100$ GeV and
- $m_a < 70$ GeV

