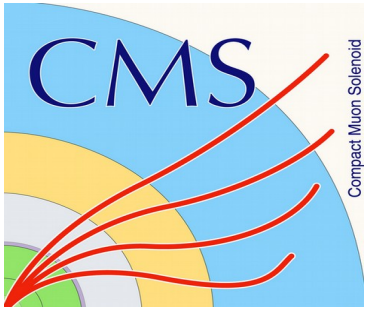


Searches for Dark Matter with mono-X at ATLAS and CMS in Run2

S.Chekanov (ANL)

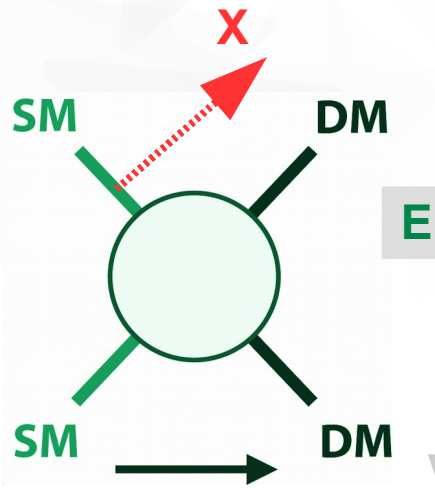
on behalf of the ATLAS and CMS collaborations

MoriondEW2019, March 16-26 2019

Searches for Dark Matter (DM) at the LHC

- Overwhelming evidence for DM
- If new particle → DM & SM particles in thermal equilibrium in the past
  - DM abundance determines annihilation cross section at freeze-out
  - DM is at electroweak scale? → within LHC energy reach

- LHC collides pp under well-controlled conditions
  - SM particles can radiate other SM particles "**X" (via ISR)**
  - Undetected DM → imbalance in transverse momentum



EFT

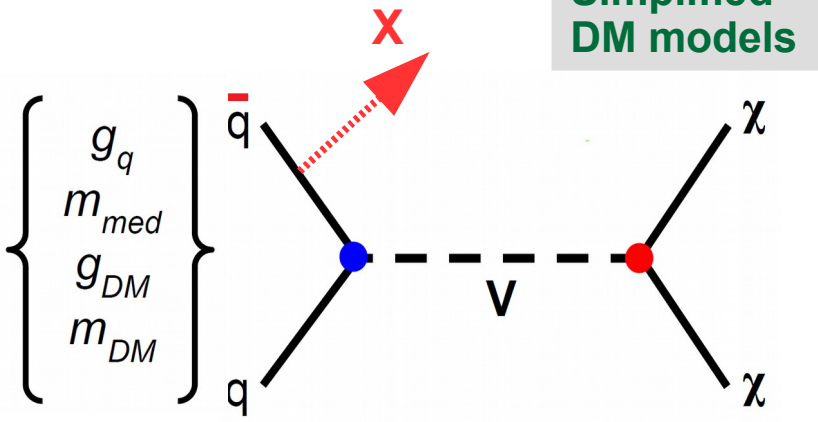
Simplified DM models

Adopt simplified DM model with a "mediator" **V**

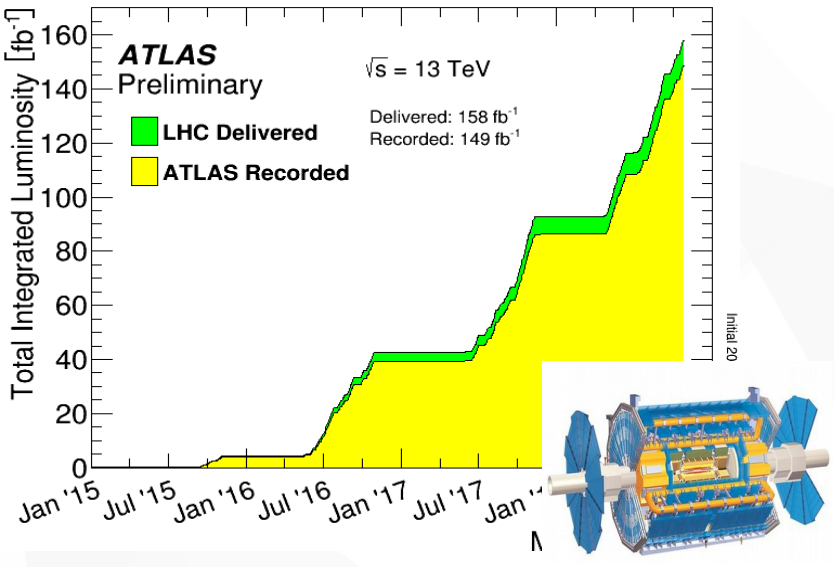
- g_q (g_{DM}) – mediator coupling to quarks (DM)
- m_{med} (m_{DM}) – mass of mediator (DM)

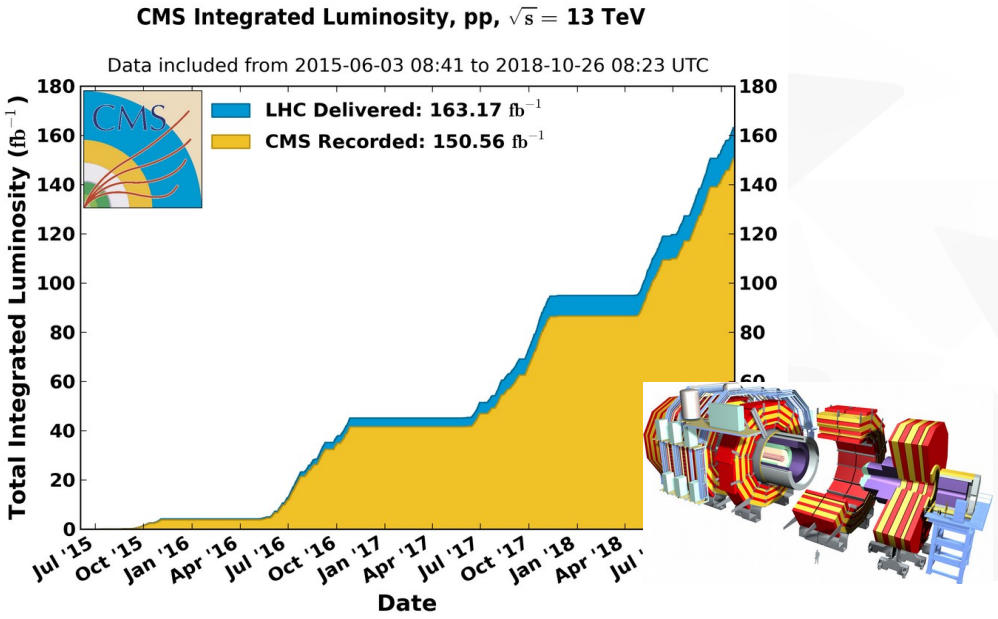
ATLAS & CMS: **g_q=0.25 (S=1), g_q=1 (S=0), g_{DM}=1**

Γ=minimum width formula

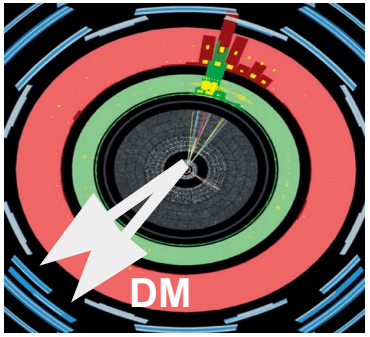


LHC operation in run II. Search strategy



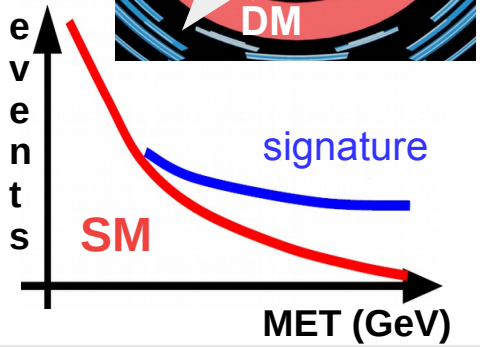


- Both experiments collected ~150 fb^{-1} . Most covered results published in 2018 (~20 papers!) use fraction of Run II
- SUSY provides natural DM candidates *(talks on March 18)*



Search strategy:

- Select events with "X" (= jet, γ, Higgs, top, Z, W)
  - Veto other activity (μ,e,..)
  - Measure missing transverse momentum (MET) → deviations?
  - Fix $\{g_q, g_{DM}\}$ → exclude $\{m_{MED}, m_{DM}\}$

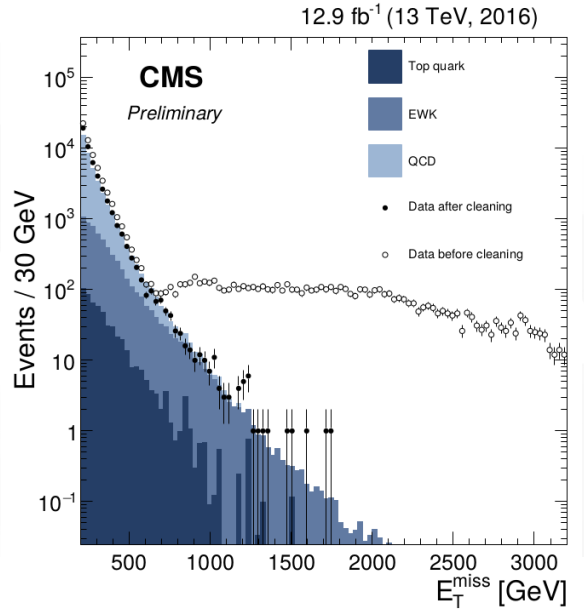


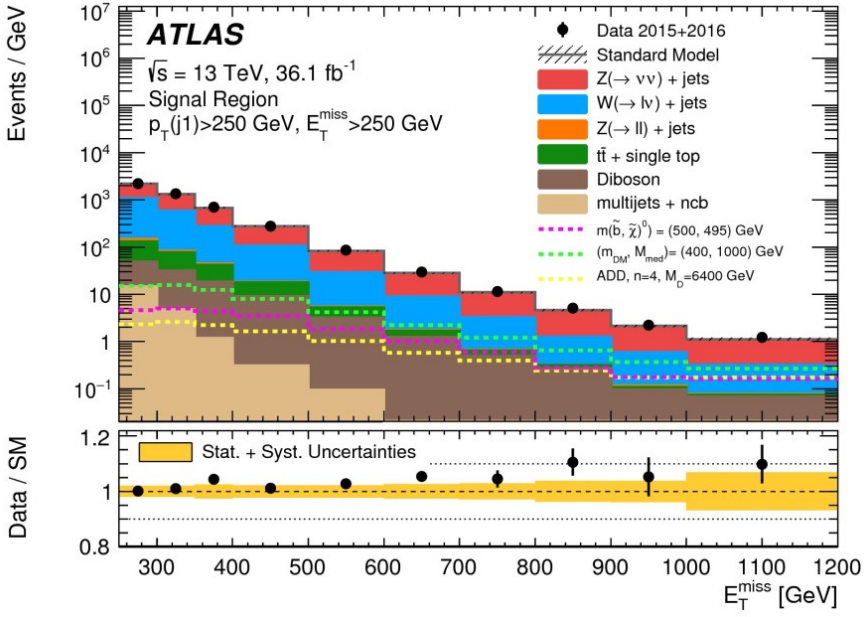
Jet and MET measurements

CMS: CMS (CMS-PAS-JME-16-004)
ATLAS: Eur. Phys. J. C 78 (2018) 903

- Mono+X searches rely on MET $\vec{\not{E}}_T = -\sum_{i \in all} \vec{p}_{Ti}$
- MET > 150 GeV for typical searches
- Challenging pileup and non-collision background
- SM background:
  - **Z(νν)+j – irreducible (real MET)** → MC with data on Z→ ll
  - **W(lν)+j, $t\bar{t}$ – reducible (loss of leptons from W)** → MC
  - **QCD multi-jet, non-collision BG** → data driven
- Required high-precision SM measurements
  - Examples:
    - **jet+γ –** missing NNLO effects for Z(νν) (CMS)
    - **W+jet** control region also for Z(νν) (ATLAS)

Typical precision for SM description

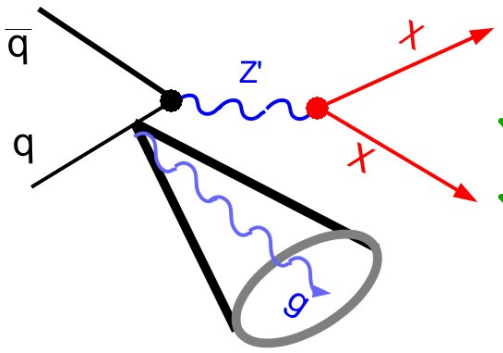




See Dilia Maria Portillo Quintero's talk on MET

Mono-jet searches

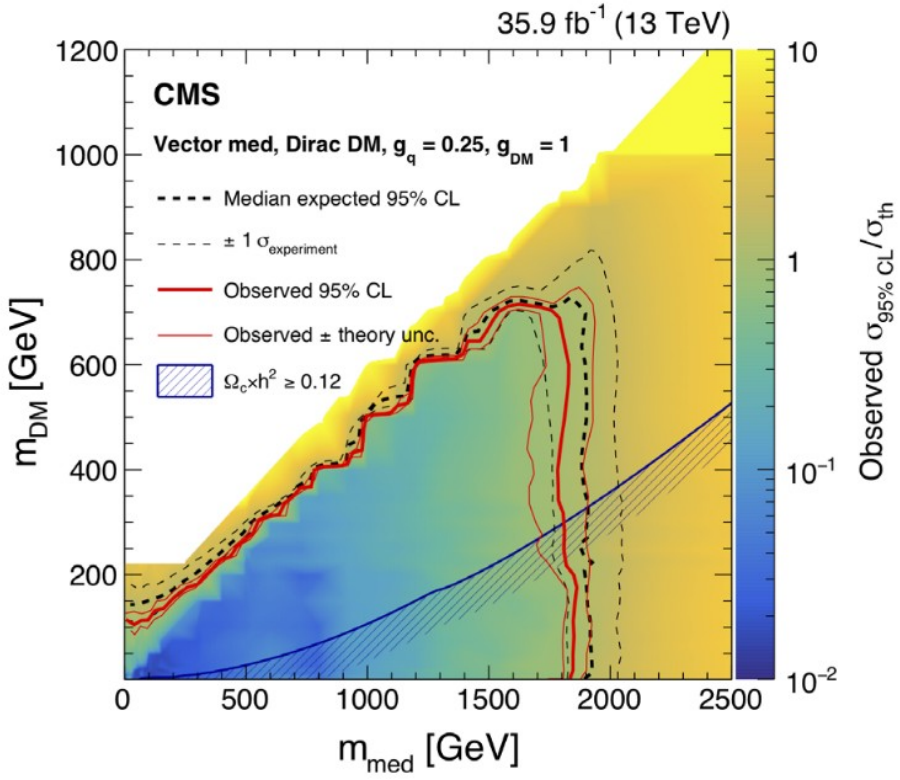
ATLAS: JHEP 01 (2018) 126
CMS: Phys. Rev. D97 (2018) 09200

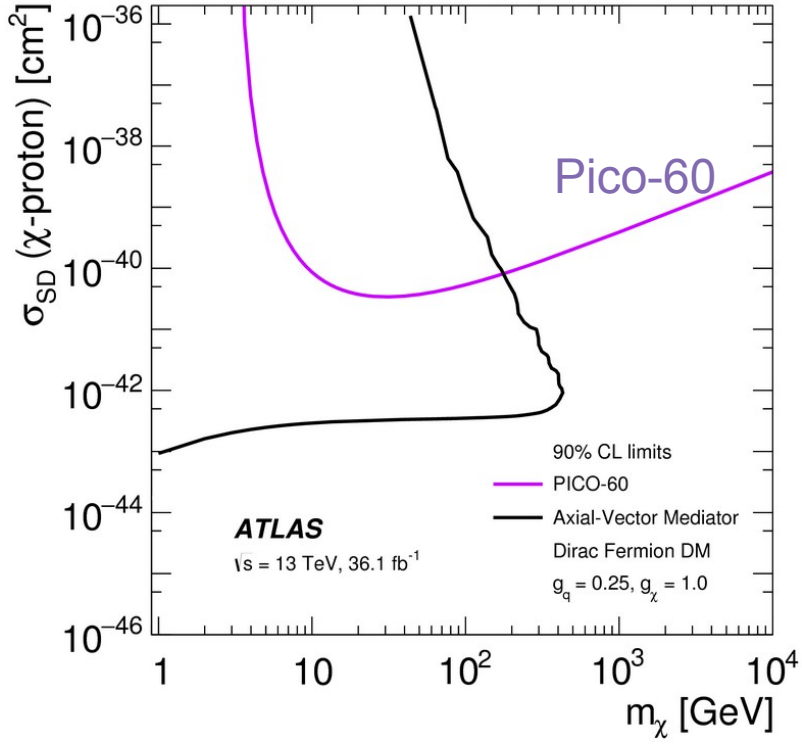


ISR g: high production rate

- m_{MED} below 1.6 TeV (ATLAS) -1.8 TeV (CMS) excluded at 95% for axial-vector or vector mediators
- Sensitivity to exclude pseudoscalar scenario at <0.4 TeV at CMS
- Some difference between experiments for exclusion limits (CMS includes MET ~1.2-1.4 TeV)

$$\sigma^{\mathrm{sd}}_{\mathrm{DM}\text{-}p} \sim \left(g_q \cdot g_{\mathrm{DM}} \cdot \frac{m_{\mathrm{DM}\text{-}p}}{(m_{\mathrm{med}})^2} \right)^2$$



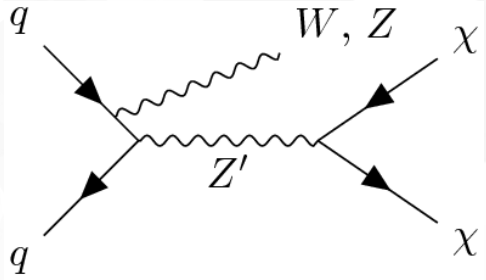


Comparison with direct detection experiments (model dependent)

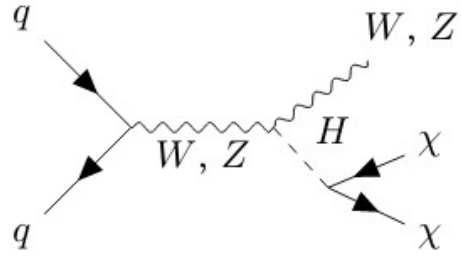
Strong limits for small m_χ compared to direct detection experiments

Mono-V searches

ATLAS: JHEP 10 (2018) 180
CMS: Phys. Rev. D97 (2018) 09200



Scalar mediator ("Higgs strahlung")?

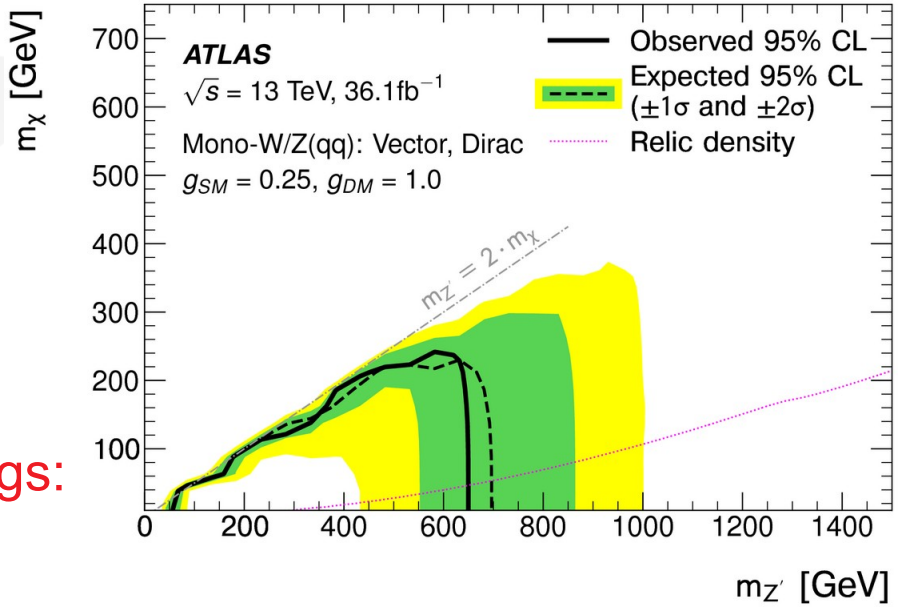


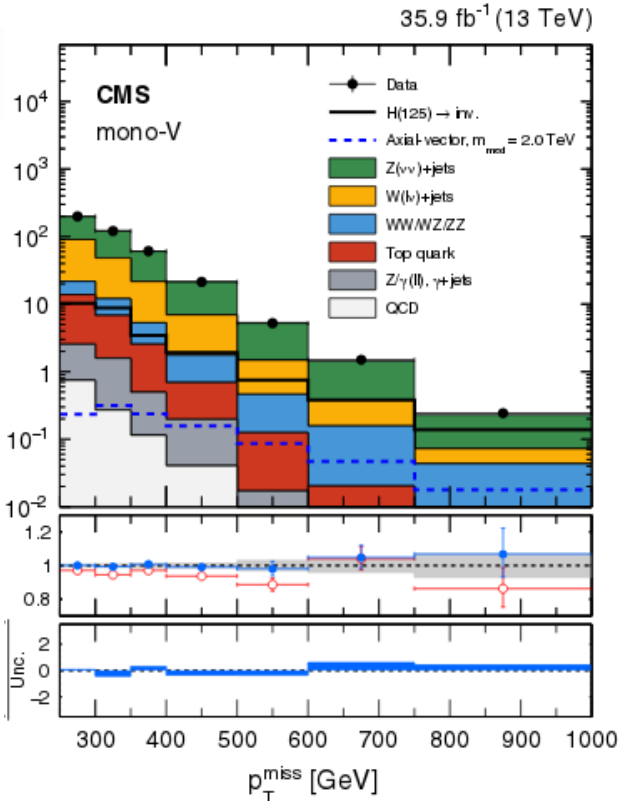
- *See* Mono+Z(ll): Eur. Phys. J. C 78 (2018) 291, PLB 776 (2017) 318
- *Present:* Explore hadronic decays of W or Z bosons
  - Large-R jets: 0.8 (CMS) or 1.0 (ATLAS)
- ATLAS used "resolved" topology with small R jets (low pT)
- Large R-jets required: Mass & substructure cuts
  - ~70% efficiency, ~ 5% misidentification

H(125)→ Inv

Excluded:
Vector & axial-vector with m_{MED}=0.65 TeV
→ similar to Z(ll)

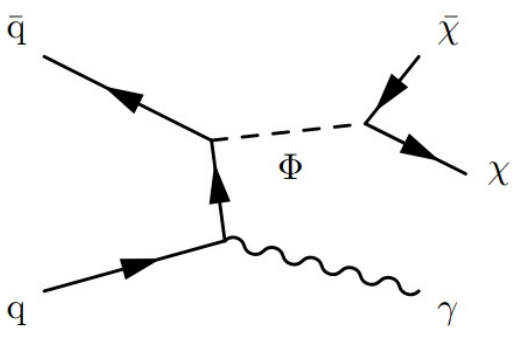
Limit on invisible Higgs:
B(H→ inv) = 0.83



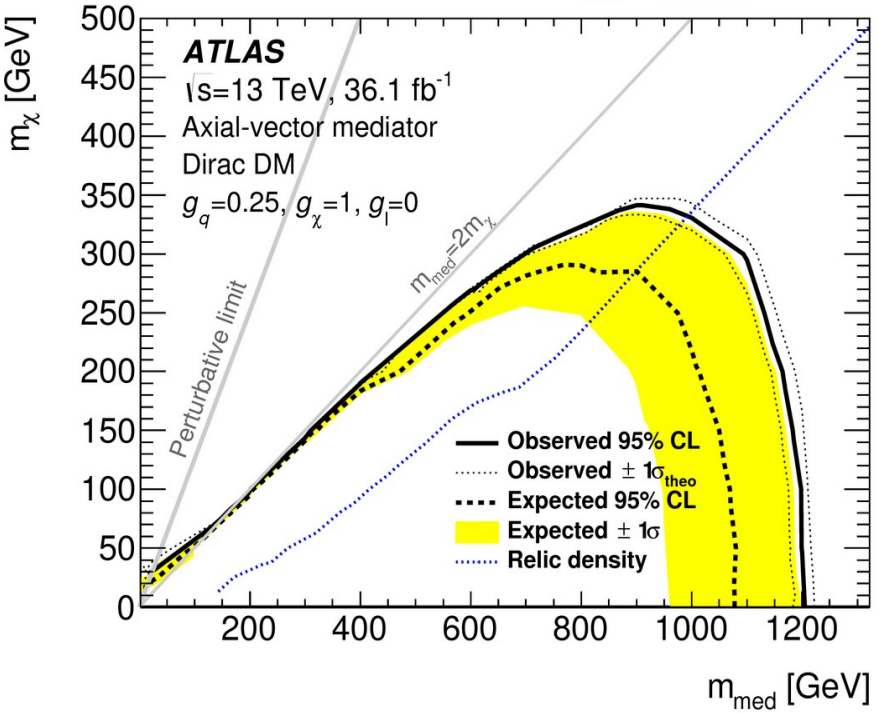


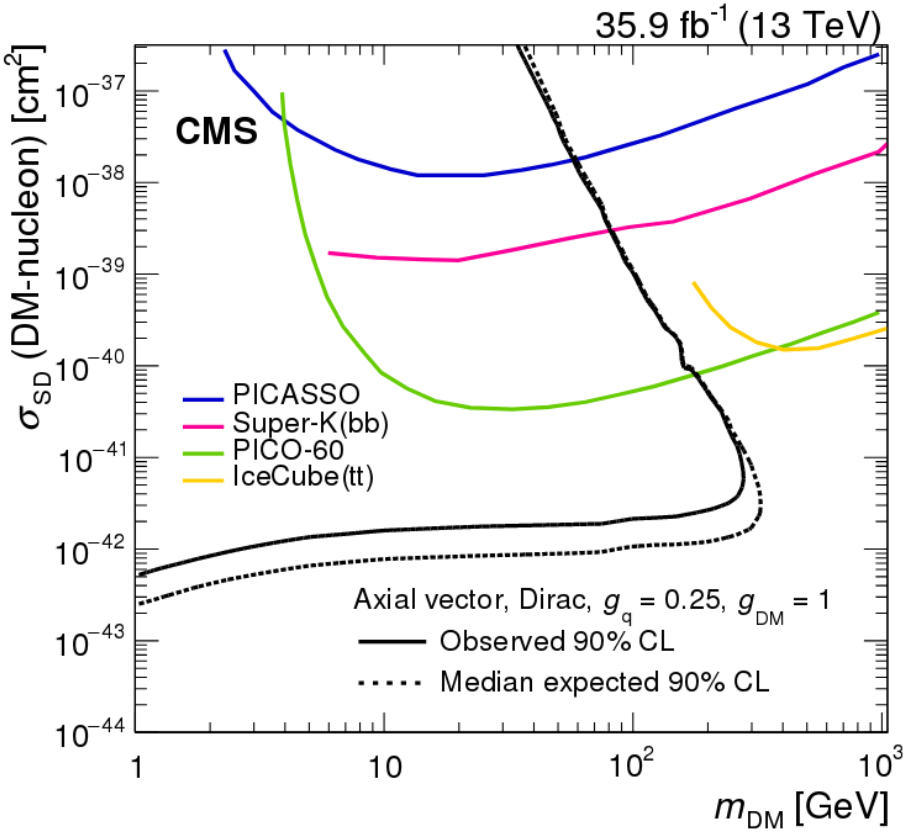
Mono photon searches

CMS: JHEP 02 (2019) 074
ATLAS: Eur. Phys. J. C 77 (2017) 393



γ+MET → clean signature and complementary to other channels



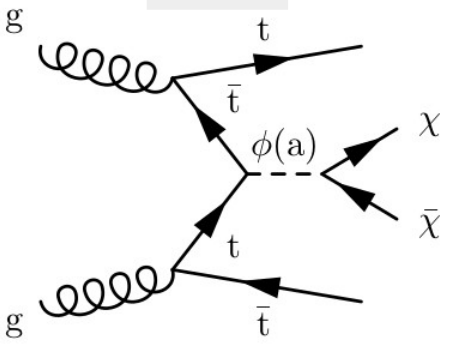


- Limits on m_{MED} are 950 (1150) GeV for m_χ = 1 GeV
- **Compared to the direct detection experiments:** stronger constraints for DM masses:
  - <2 GeV (spin independent)
  - <200 GeV (spin dependent)

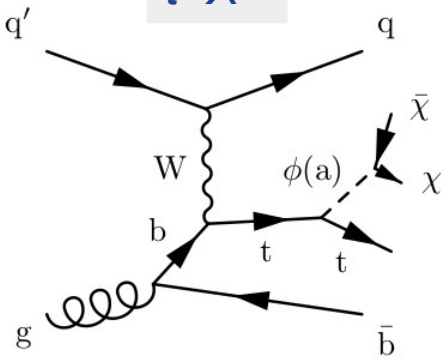
t($t\bar{t}$)+X from CMS

CMS:CMS-EXO-18-010
CMS:Phys. Rev. Lett. 122, 011803 (2019)

$t\bar{t}$+X



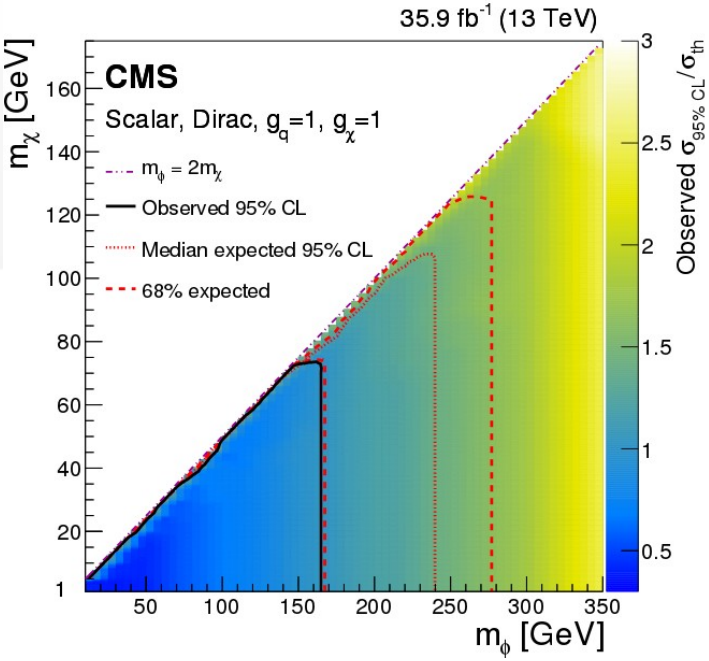
t+X

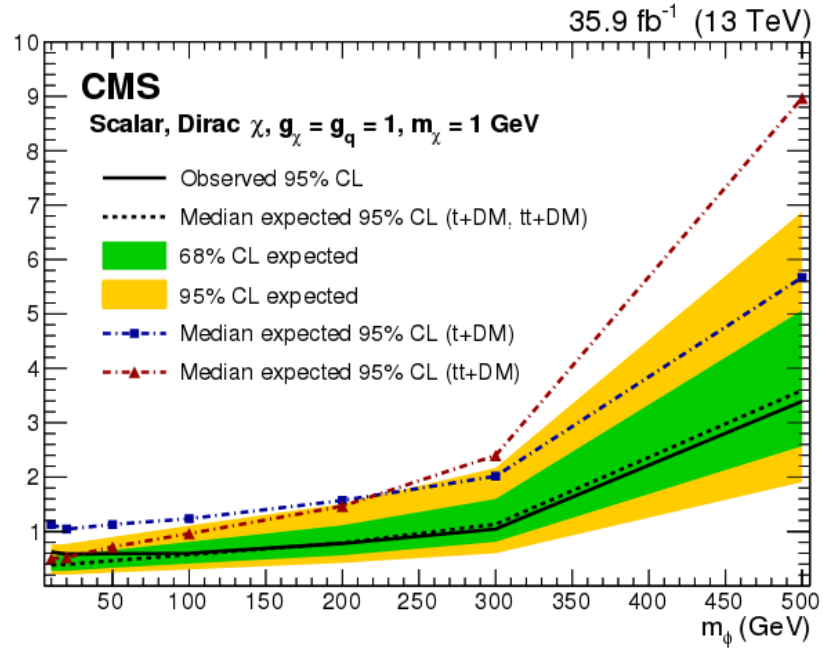


- If DM respects minimal flavor violation, spin-0 mediator would couple preferentially to heavy 3rd-generation quarks
- Single and all-hadron decays of t ($t\bar{t}$)
- For M(χ)=1 GeV, m_{MED}<300 GeV for scalar and pseudoscalar excluded

+ diagrams with associated W

Includes $t\bar{t}$ and single-top





New method called "resolved top tagger" to identify hadronic decays of top quarks for $t\bar{t}$+MET

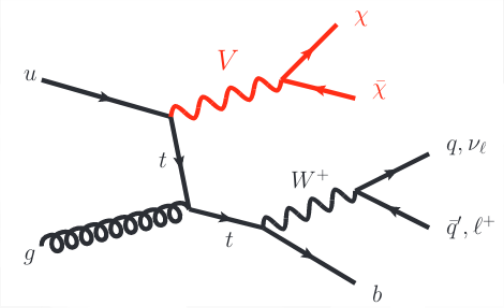
Observed upper limits on μ exclude scalar and pseudoscalar masses of 160 and 220 GeV, respectively

See CMS publications for pseudoscalar case

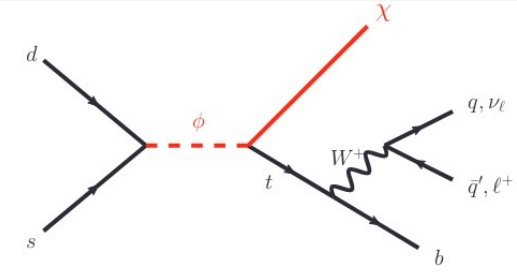
t($\bar{t}$)+X from ATLAS

ATLAS: CERN-EP-2018-301
ATLAS: JHEP 06 (2018) 108

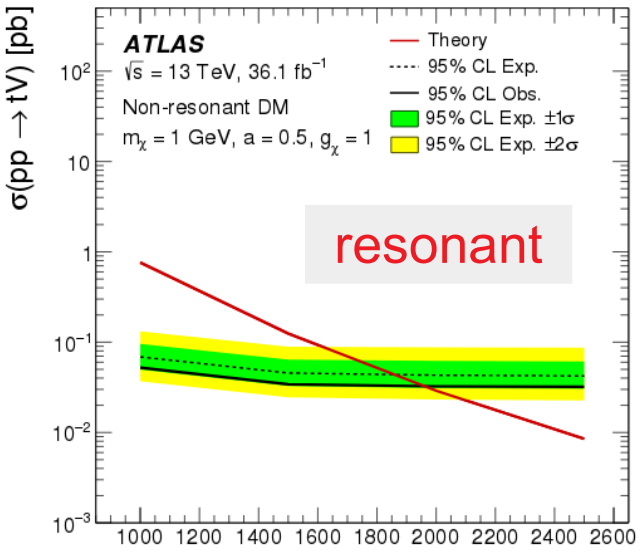
non-resonant top production

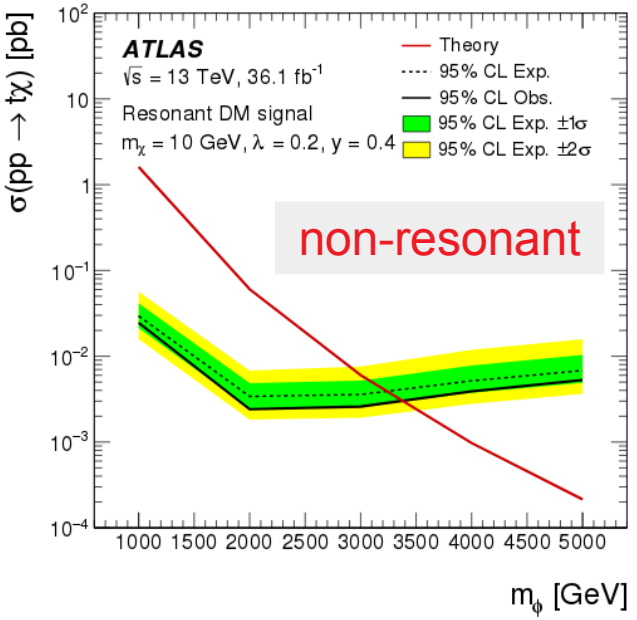


resonant top production

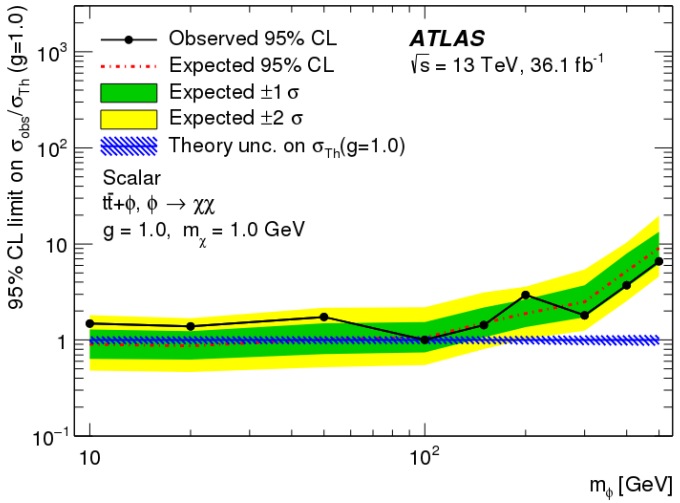


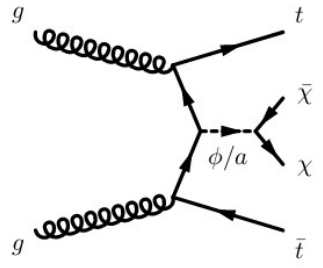
- Resonant and non-resonant production
- Lepton and hadron decays are explored





- t+X: Non-resonant case excluded:
  - < 2 TeV (m_χ = 1 GeV, g_χ =1)
- t+X: Resonance case excluded:
  - < 3 TeV for different values of couplings of charged scalar to d-quarks
- t$\bar{t}$+X: A scalar (pseudoscalar) m_{MED} ~100 GeV (20 GeV) excluded assuming m_{DM} = 1 GeV



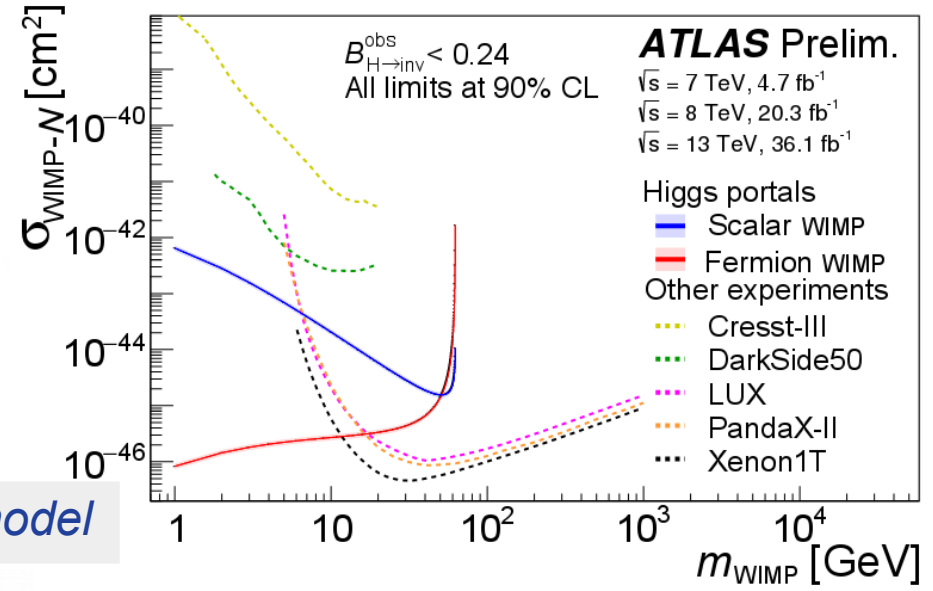


Mono Higgs (I)

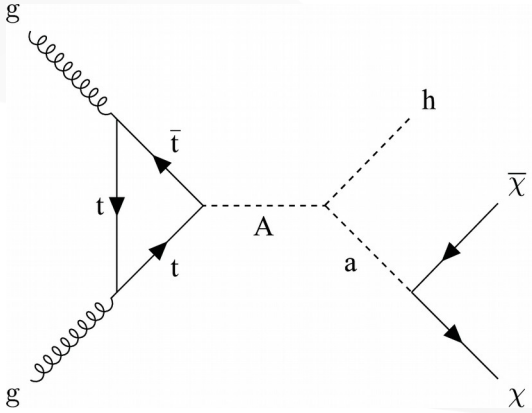
ATLAS: ATLAS-CONF-2018-054
ATLAS: ATLAS-CONF-2018-039
CMS: CERN-EP-2018-139
CMS: CERN-EP-2018-287

- Higgs boson decay to DM particles? H → invisible
- X+MET signatures + SM Higgs rates assumption
- Run I-II combinations:
  - CMS: ***B* (H→ inv) < 0.19 (expect: 0.15)**
  - ATLAS: ***B* (H→ inv) < 0.26 (expect: 0.17)**

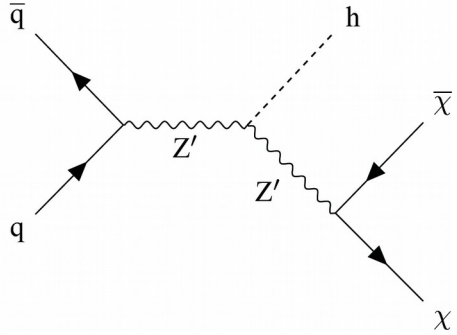
Based on EFT



2HDM+a



Baryonic Z' simplified model



- ISR Higgs is Yukawa suppressed (small coupling to u/d quarks),
- Mono-Higgs signal requires BSM effective vertex

- 2HDM+a model is tested experimentally for the first time:
  - h(125) SM scalar
  - a- pseudoscalar

- "Baryonic Higgs" mixes with SM Higgs boson
  - a vector mediator Z′ is exchanged in the s-channel

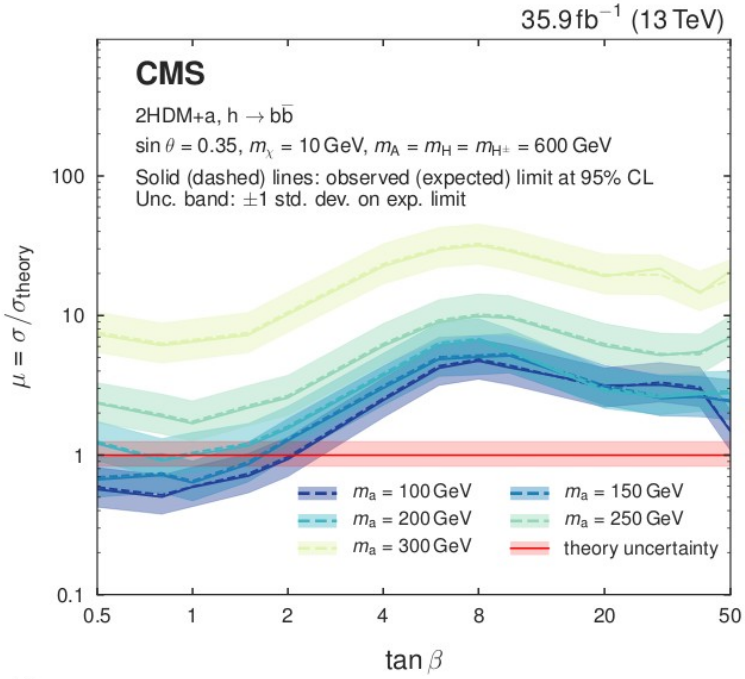
L. Carpenter et al., "Mono-H-boson: A new collider probe of dark matter", Phys.Rev. D89(2014) 075017

Mono Higgs (II)

ATLAS:ATLAS-CONF-2018-039
CMS: CERN-EP-2018-28

2HDM+a:

- First experimental limits on 2HDM+a
- Limits using several scans in parameters
- Example for tan(β) exclusions

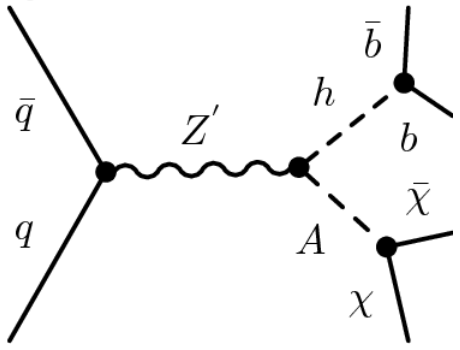


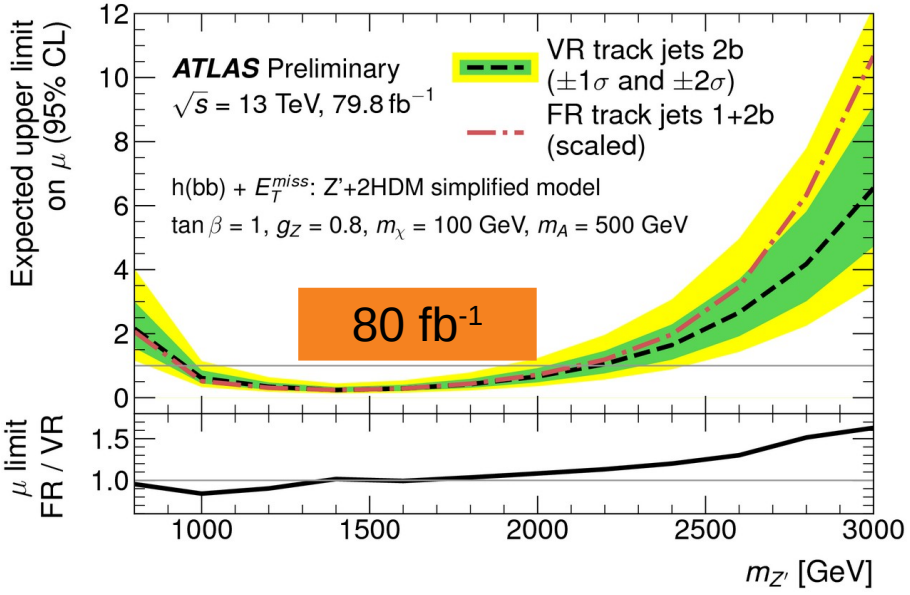
Baryonic Z´ boson:

- Exclusion up to M=1.6 TeV for a m_χ =1 GeV
- 2HDM-Z' excluded up to 2.3 TeV in $m_{Z'}$ for m_A=0.5 TeV

2HDM-Z' model

A *- new pseudoscalar Higgs boson*



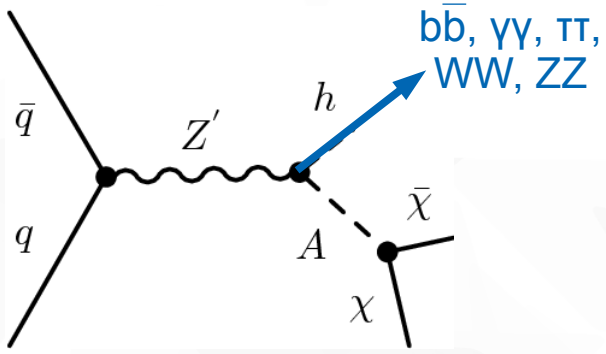


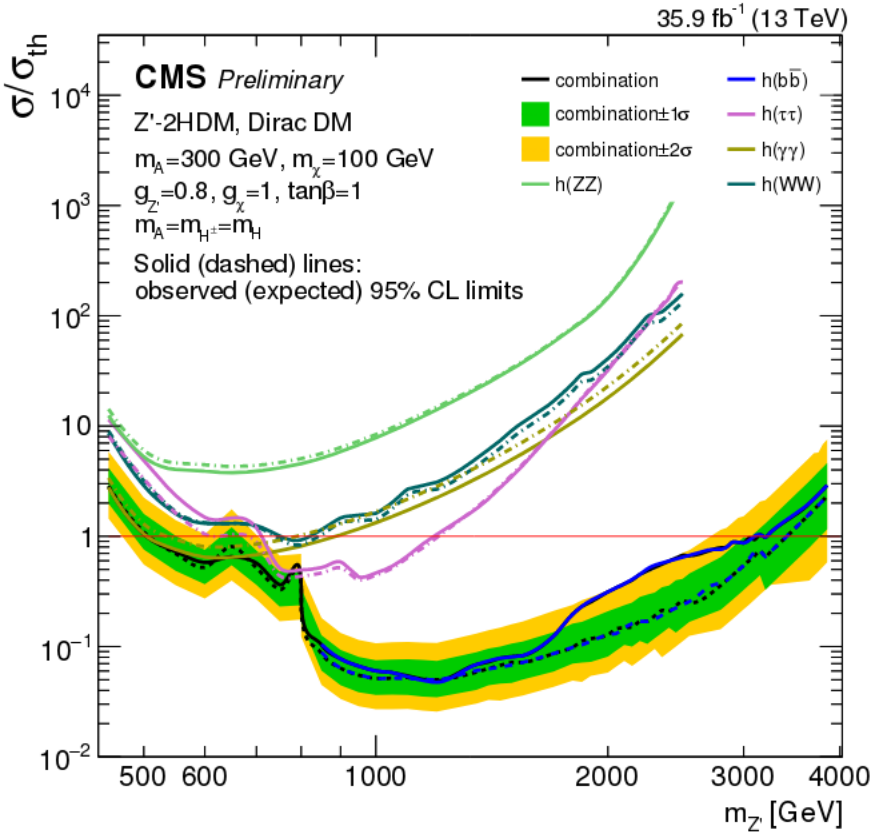
Mono Higgs (III). Combinations

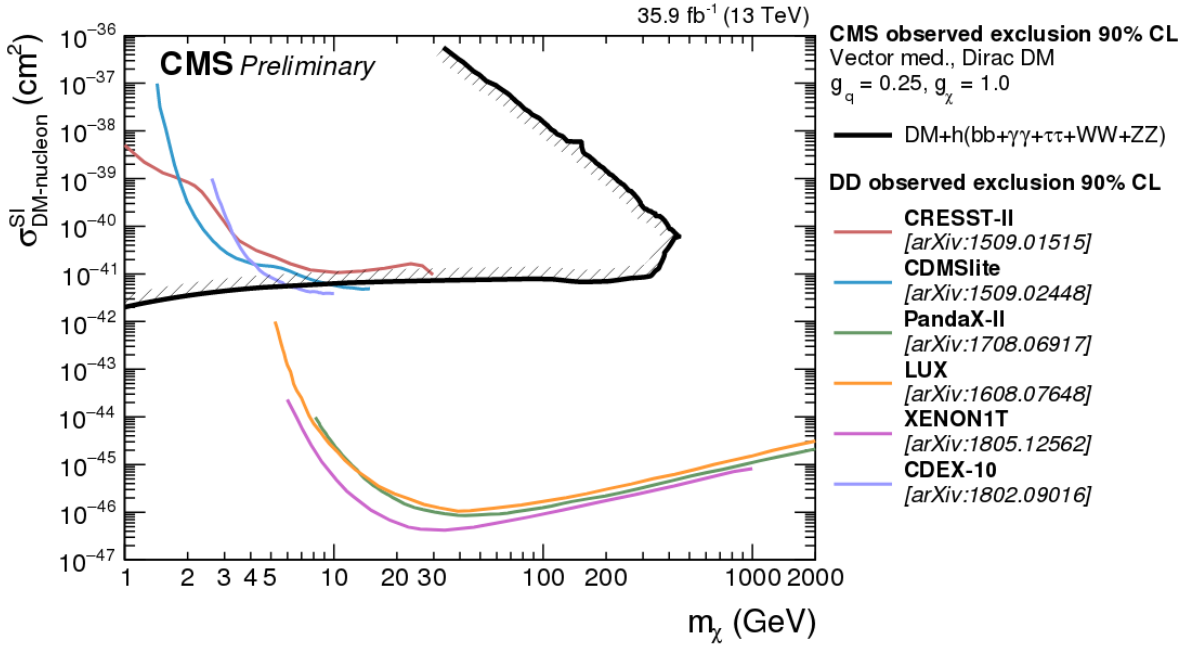
CMS: EXO-18-011

2HDM+Z':

- Combination of H+X using $b\bar{b}$, γγ, ττ, WW, ZZ decays
- Limits using several scans in parameters
- tan(β) exclusions (see backup)





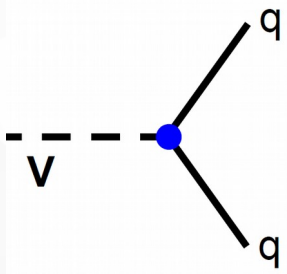


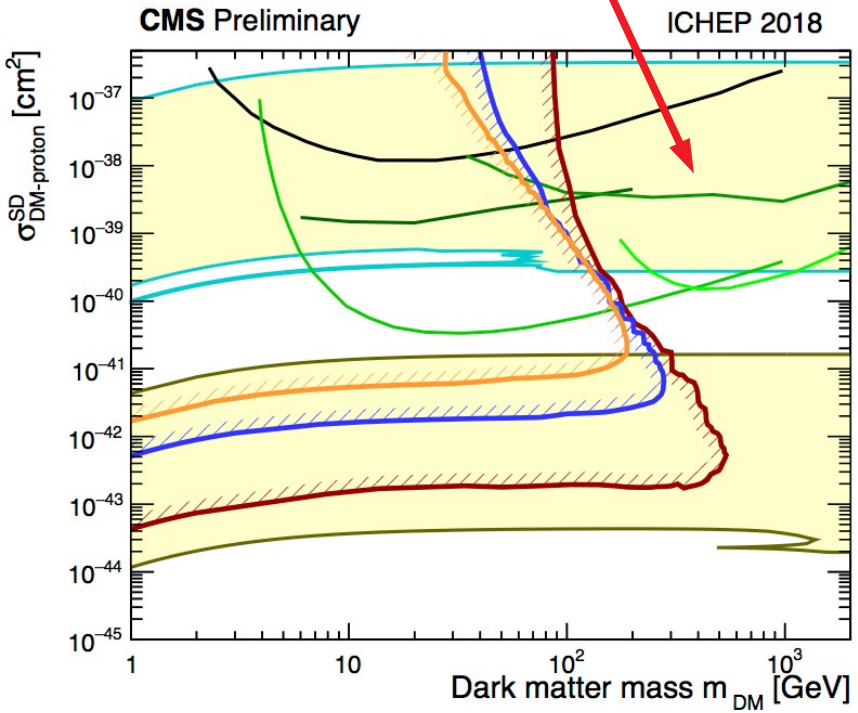
Higher sensitivity than for direct-detection experiments for m(χ)<5 GeV for the chosen benchmark model parameters

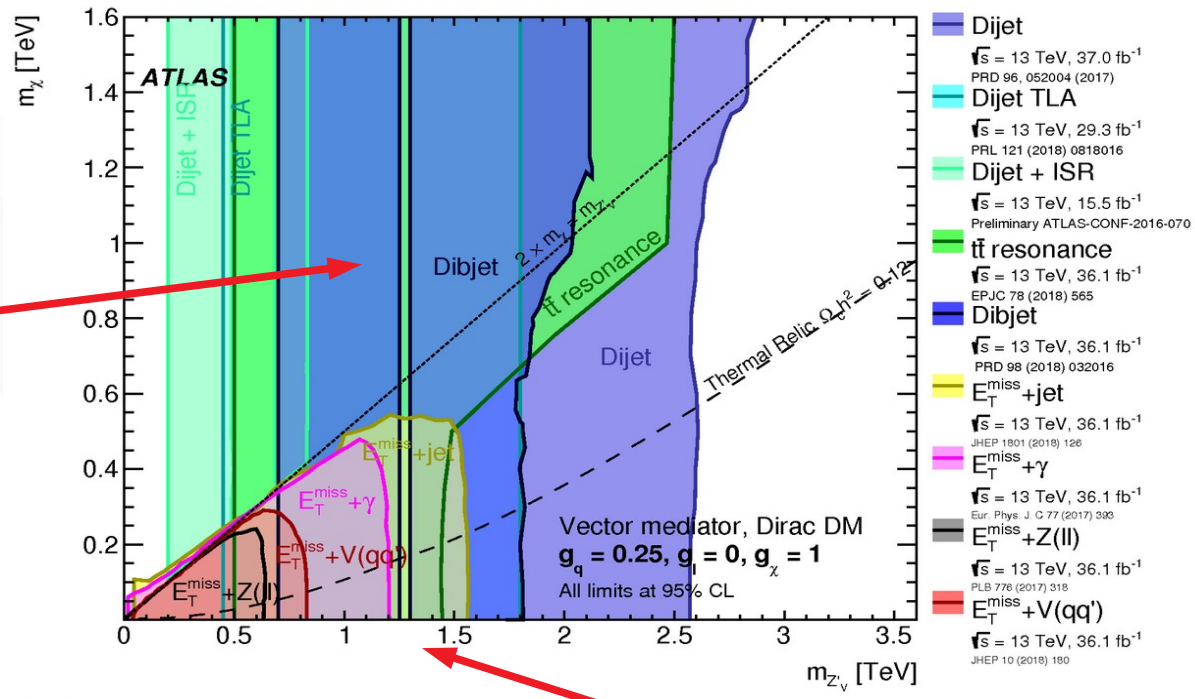
Summary plots

CERN-EP-2018-334
CMS: summary plots

m_{MED} ~ 2.5 TeV exclusion reach for direct mediator searches







Mono-X searches

Mono-X searches are complementary to direct (indirect) detection experiments

Note: model dependent comparisons

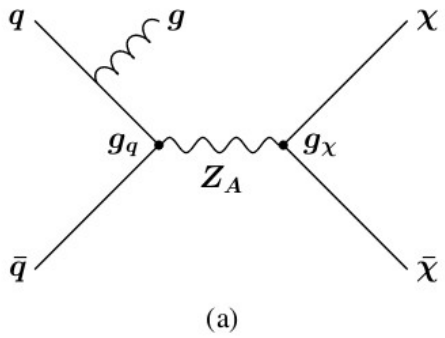
Conclusions

- **Extensive DM search program in MET+X channels at the LHC**
  - Refined studies with complex final state (jet, top, γ, $t\bar{t}$, W, Higgs, etc,)
- **Constraints on simplified DM models:**
  - Mono-jet, γ, Z, H, t exclude m_{MED} / m_{χ} masses in TeV / hundreds of GeV range
- **LHC searches complement direct detection experiments:**
  - Strong (model-dependent) limits for low mass m_{DM} (<10 GeV)
  - Strong limits for spin-dependent DM-nucleon cross section
  - Comprehensive searches for DM-SM mediators

- **Stay tuned: Ongoing analysis using full Run 2 data (x 4 statistics)**

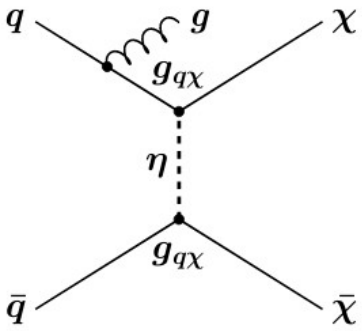
Backup

Mono-jet models

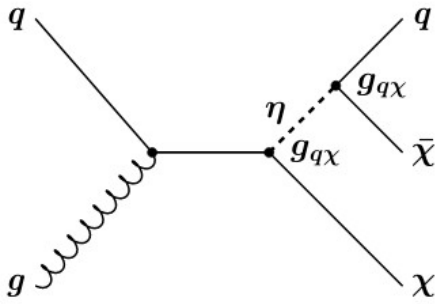


(a)

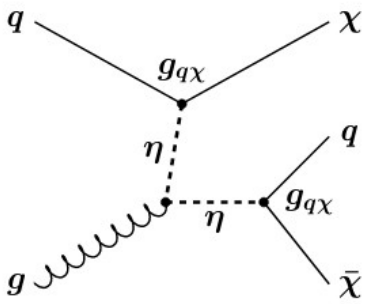
axial-vector couplings exchanged in the s-channel



(b)



(c)



(d)

pair-production of weakly interacting massive particles χ via a colored scalar mediator η

Assumes first two generations of quarks

Theoretical uncertainty for jet+X

TABLE III. Theoretical uncertainties considered in the V-jets and γ + jets processes, and their ratios. The correlation between each process and between the p_T bins are described.

Uncertainty source	Process (magnitude)	Correlation
Factorization and renormalization scales (QCD)	$Z \to \nu\nu/W \to \ell\nu$ (0.1–0.5%) $Z \to \nu\nu/\gamma$ + jets (0.2–0.5%)	Correlated between processes; and in p_T
p_T-shape dependence (QCD)	$Z \to \nu\nu/W \to \ell\nu$ (0.4–0.1%) $Z \to \nu\nu/\gamma$ + jets (0.1–0.2%)	Correlated between processes; and in p_T
Process dependence (QCD)	$Z \to \nu\nu/W \to \ell\nu$ (0.4–1.5%) $Z \to \nu\nu/\gamma$ + jets (1.5–3.0%)	Correlated between processes; and in p_T
Effects of unknown Sudakov logs (EW)	$Z \to \nu\nu/W \to \ell\nu$ (0–0.5%) $Z \to \nu\nu/\gamma$ + jets (0.1–1.5%)	Correlated between processes; and in p_T
Missing NNLO effects (EW)	$Z \to \nu\nu$ (0.2–3.0%) γ + jets (0.1–1.0%) $W \to \ell\nu$ (0.4–4.5%)	Uncorrelated between processes; correlated in p_T
Effects of NLL Sudakov approx. (EW)	$Z \to \nu\nu$ (0.2–4.0%) $W \to \ell\nu$ (0–1.0%) γ + jets (0.1–3.0%)	Uncorrelated between processes; correlated in p_T
Unfactorized mixed QCD-EW corrections	$Z \to \nu\nu/W \to \ell\nu$ (0.15–0.3%) $Z \to \nu\nu/\gamma$ + jets (<0.1%)	Correlated between processes; and in p_T
PDF	$Z \to \nu\nu/W \to \ell\nu$ (0–0.3%) $Z \to \nu\nu/\gamma$ + jets (0–0.6%)	Correlated between processes; and in p_T

Mono photons (I)

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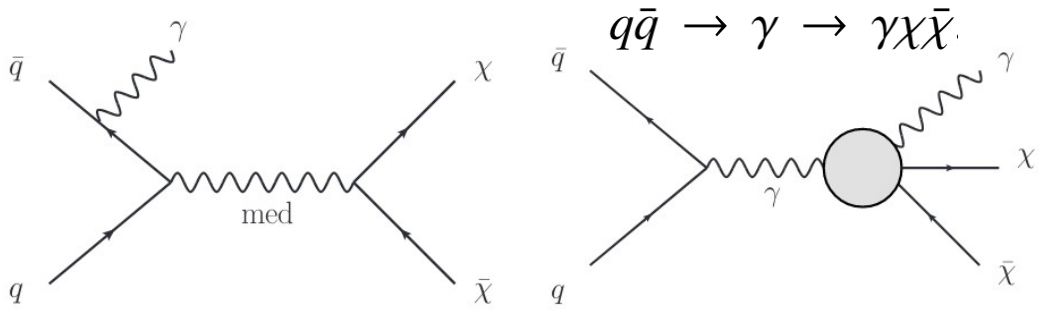
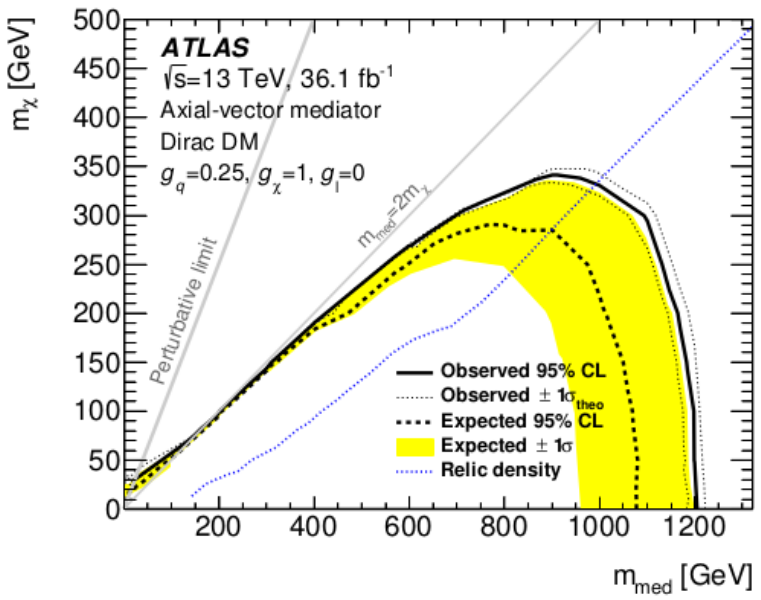


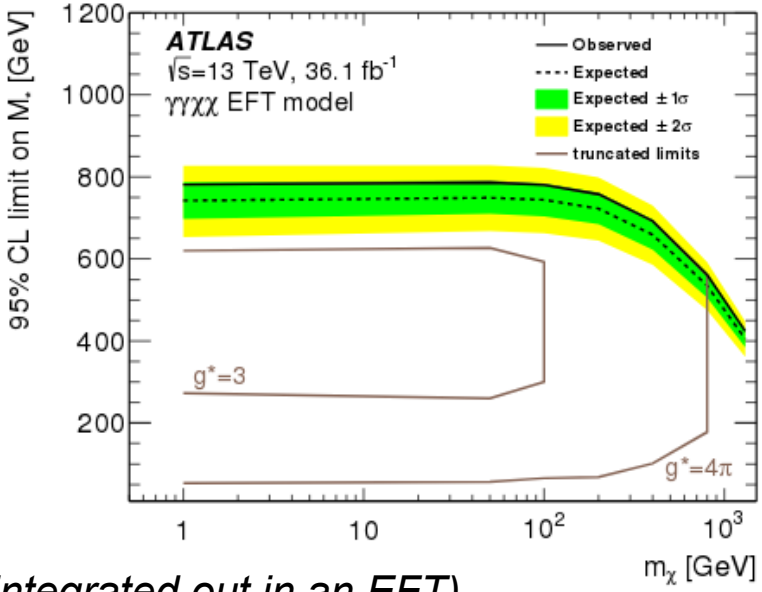
Similar signature: ADD model with G

- γ+MET has the advantage of a clean signature providing good complementary with respect to the other channels
- Unique possibility to probe DM models in which γ does not come from initial-state radiation (dimension-7 EFT operator with direct couplings)

ATLAS Results:

- Axial-vector and vector mediators with masses below 750–1200 GeV for χ masses below 230–480 GeV are excluded at 95% CL
- For EFT γγχ model of dark-matter production, M* up to 0.8 TeV are excluded at 95% CL





(M suppression scale is effective mass scale of particles that are integrated out in an EFT)*

Limits on g_q from jets+X

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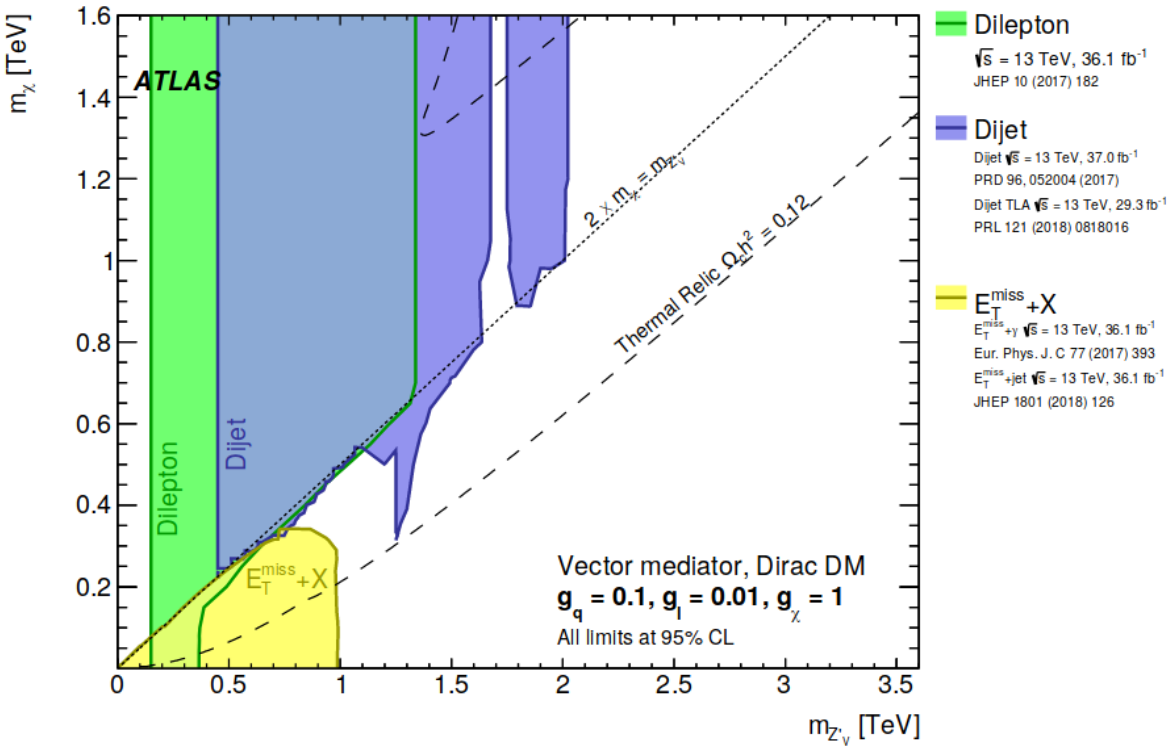
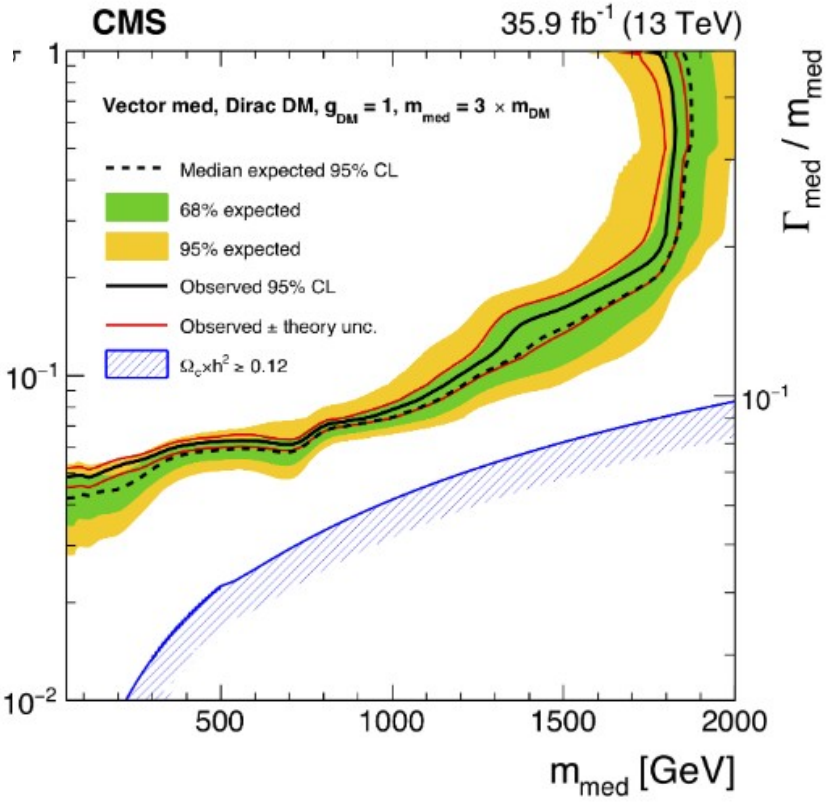
CMS: summary plots





Higgs+X: Combination of 2HDM models

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