

# Search for dark matter production at ATLAS and CMS

**Alexander Grohsjean**

on behalf of the ATLAS and  
CMS Collaborations



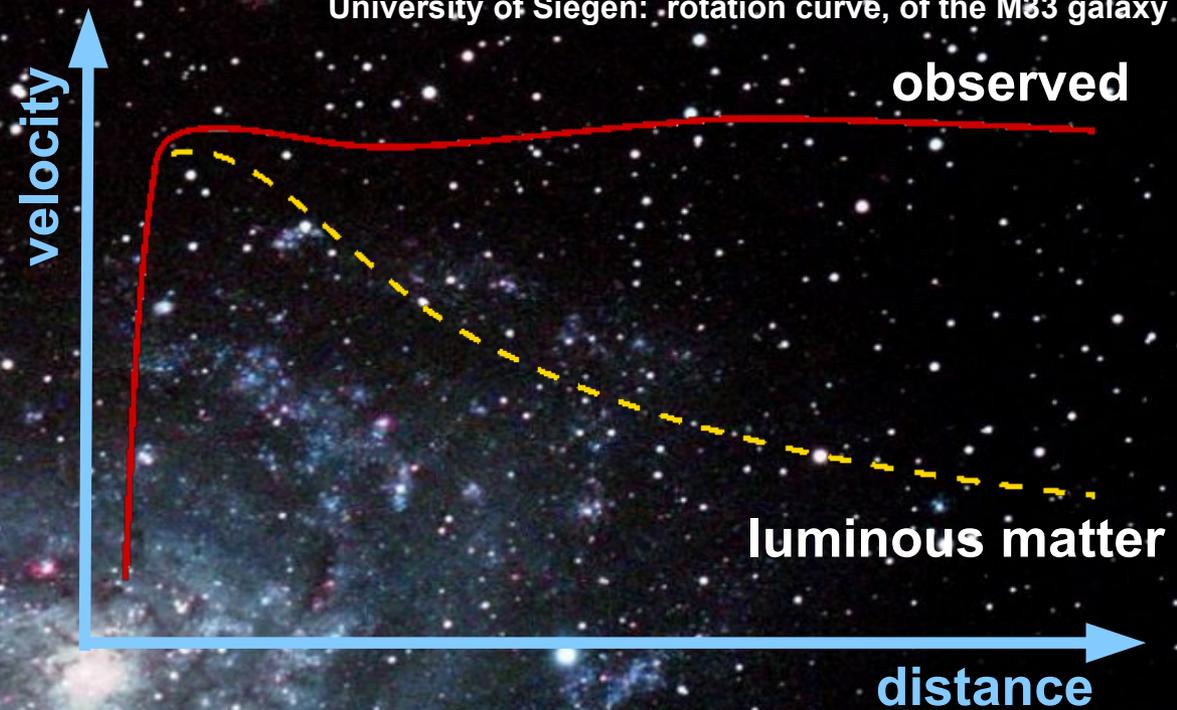
**HELMHOLTZ**  
RESEARCH FOR GRAND CHALLENGES

La Thuile 2018  
XXXII Les Rencontres de Physique de la Vallée d'Aoste

# The Dark Matter puzzle



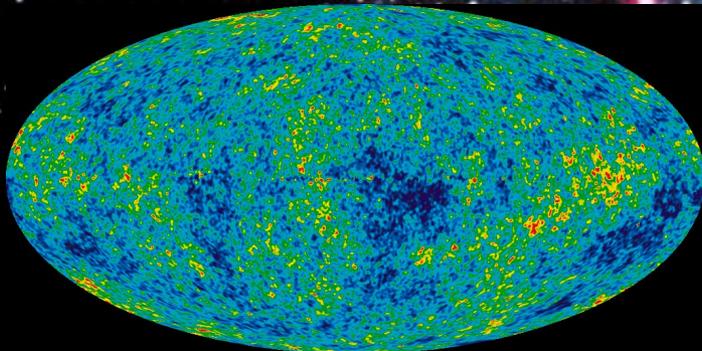
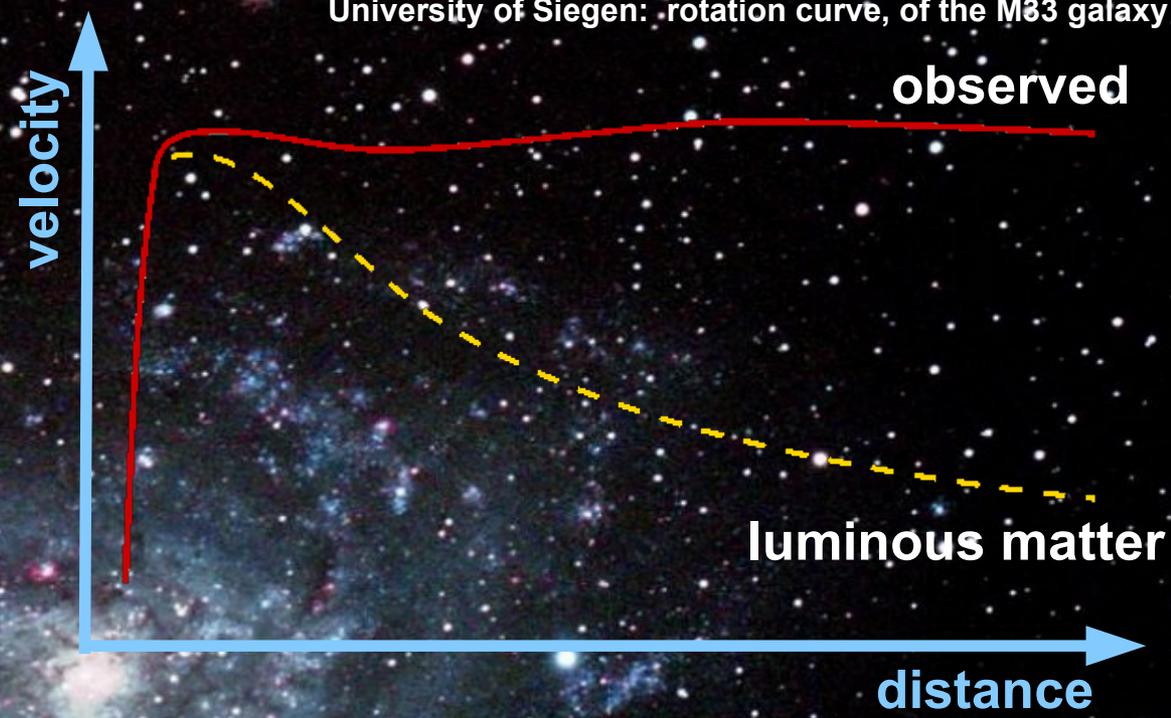
University of Siegen: rotation curve, of the M33 galaxy



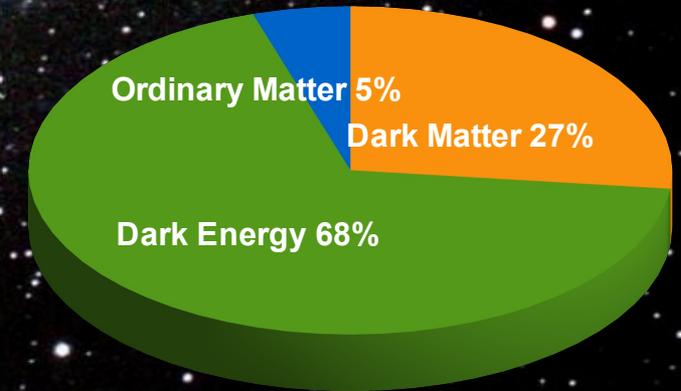
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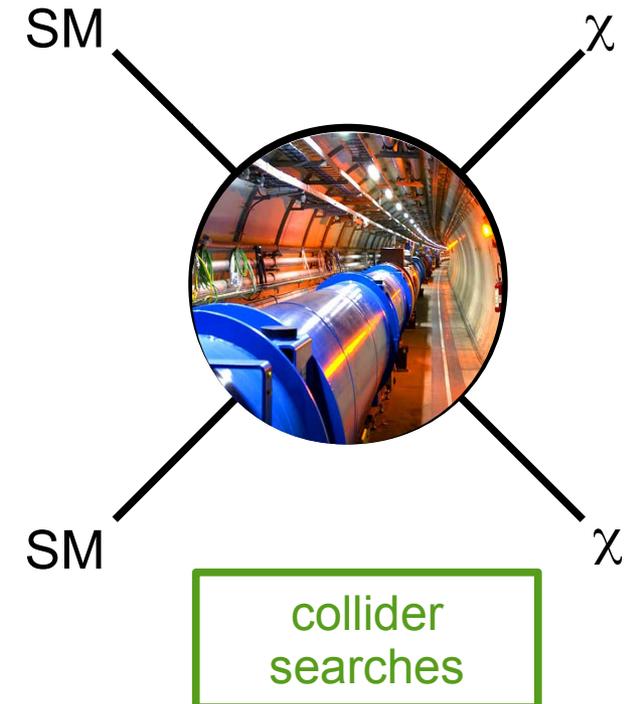
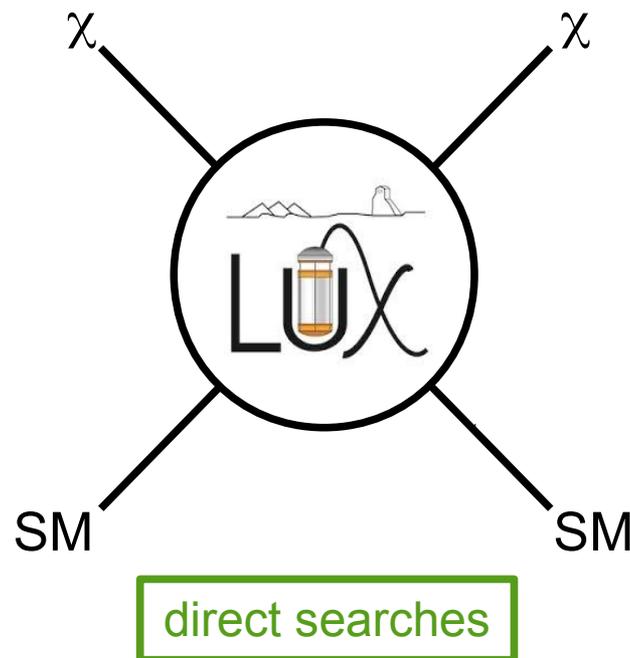
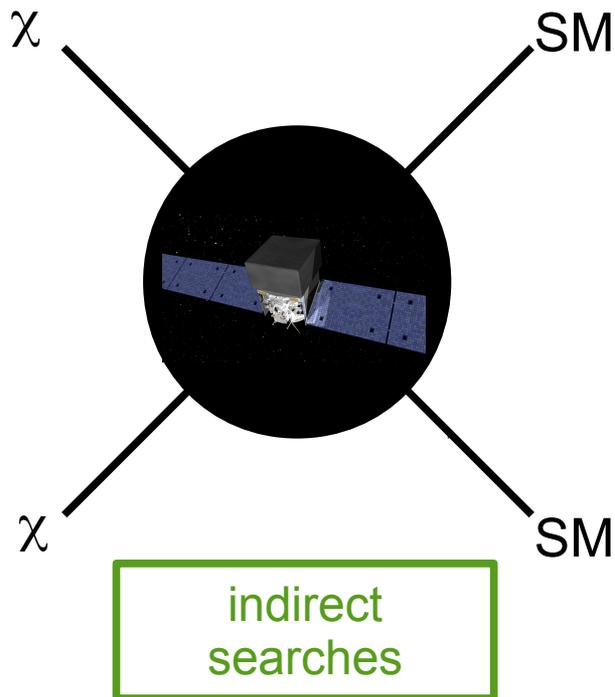
NASA: Nine year microwave sky from Planck



Composition of the Universe from Planck (2015)

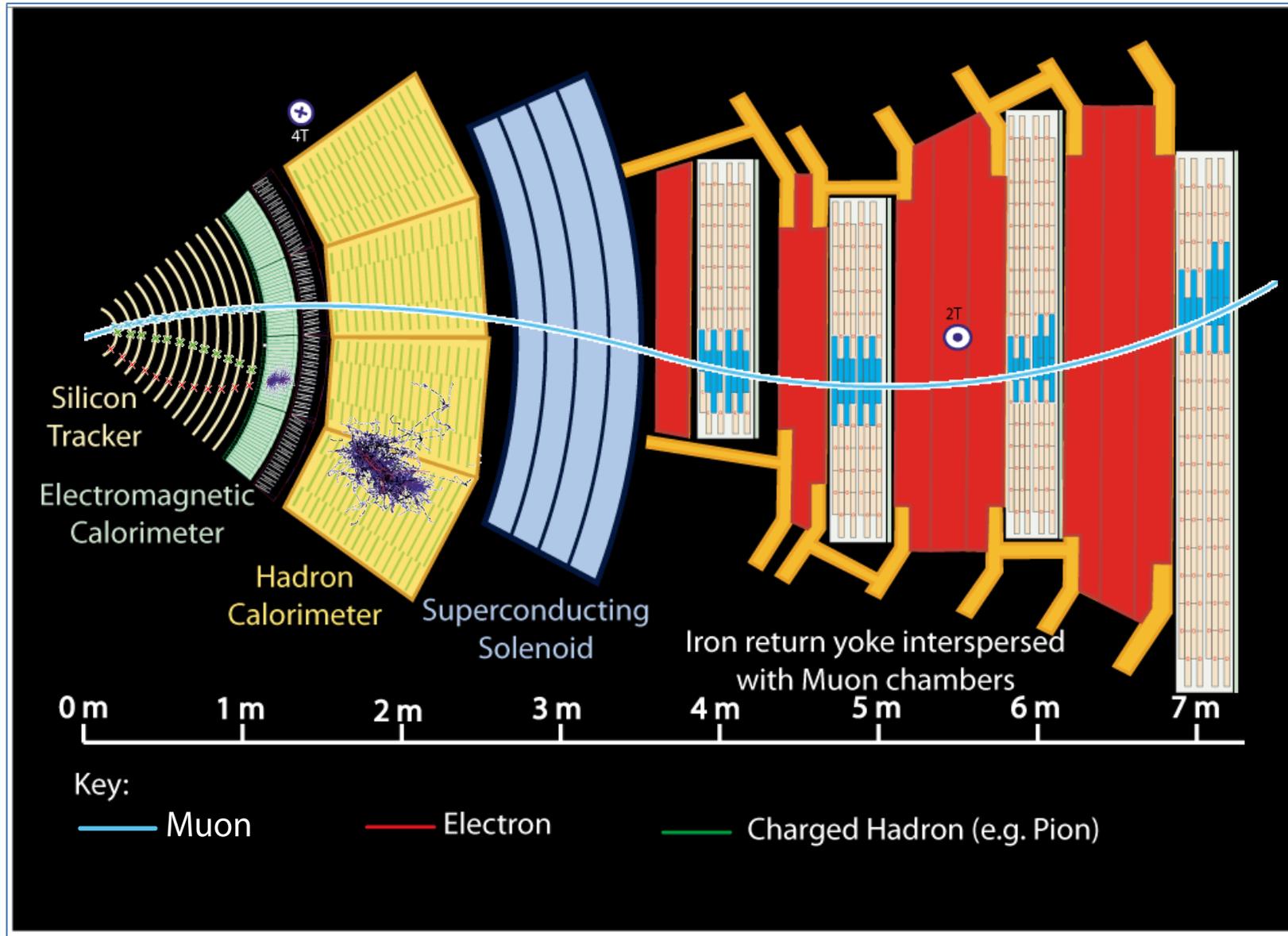


Heinrich Füger, Prometheus brings fire to mankind



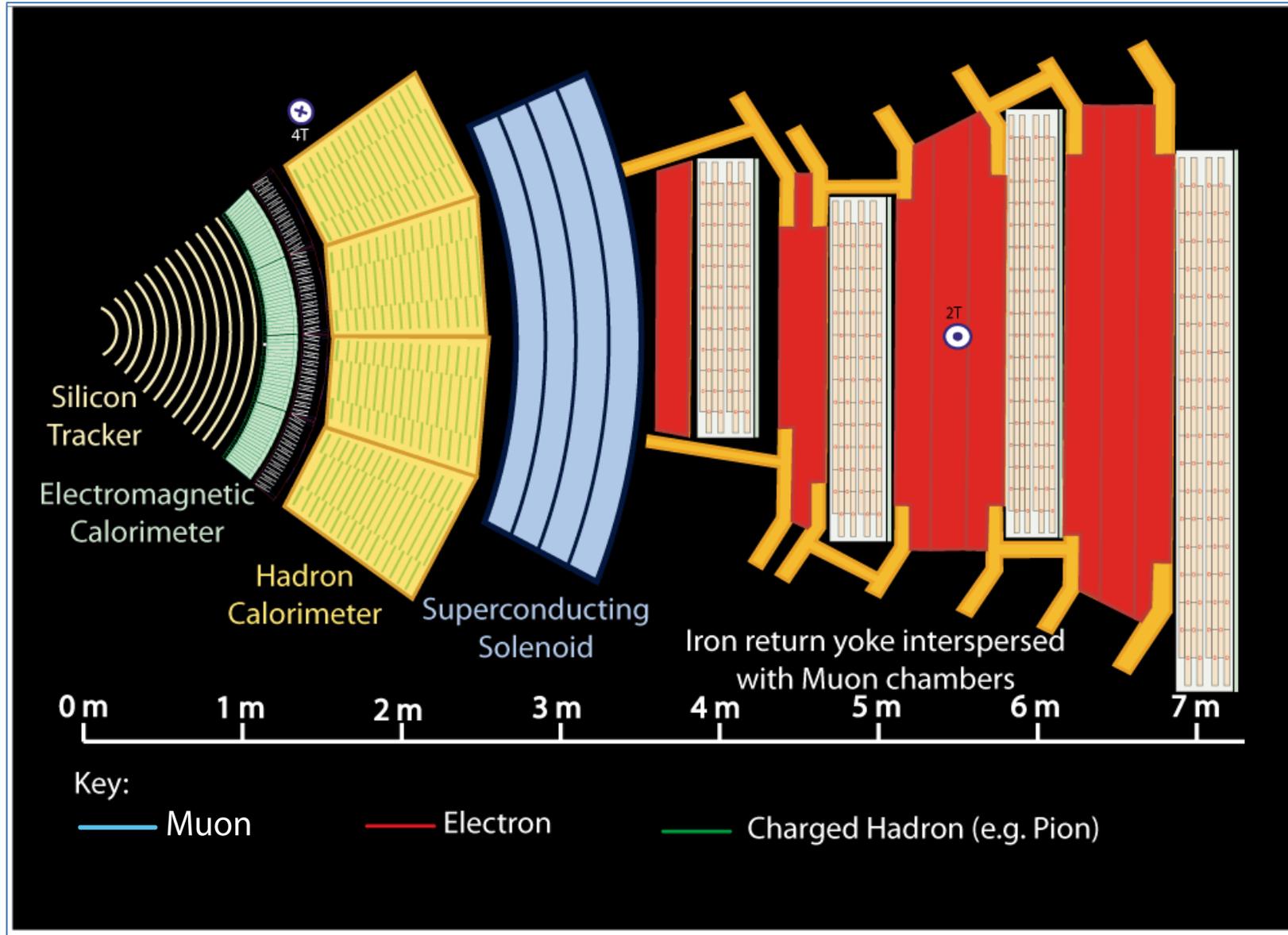
comprehensive DM research program at LHC

# SM particles in CMS



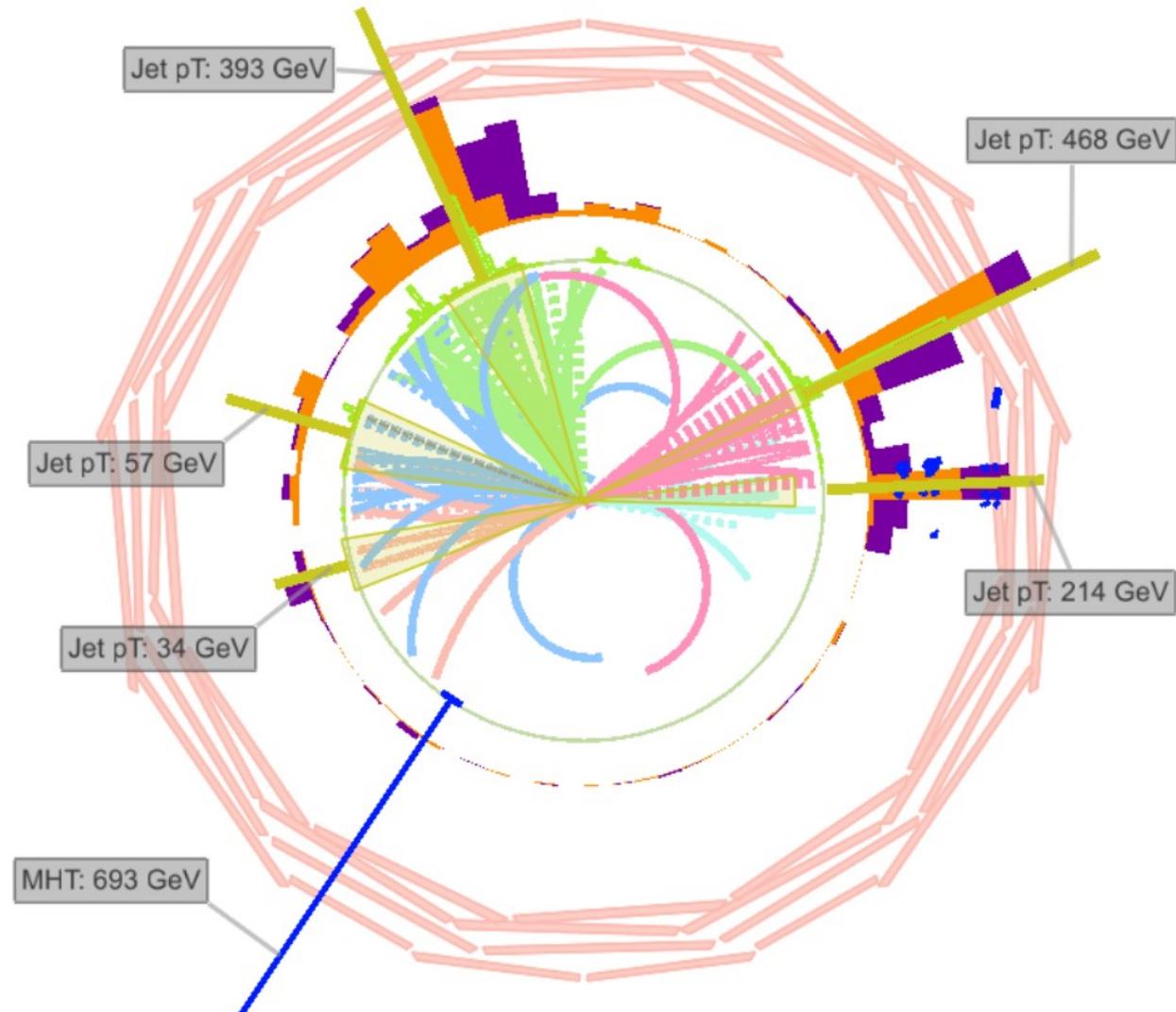
geometry allows distinguishing various particles

# DM particles in CMS



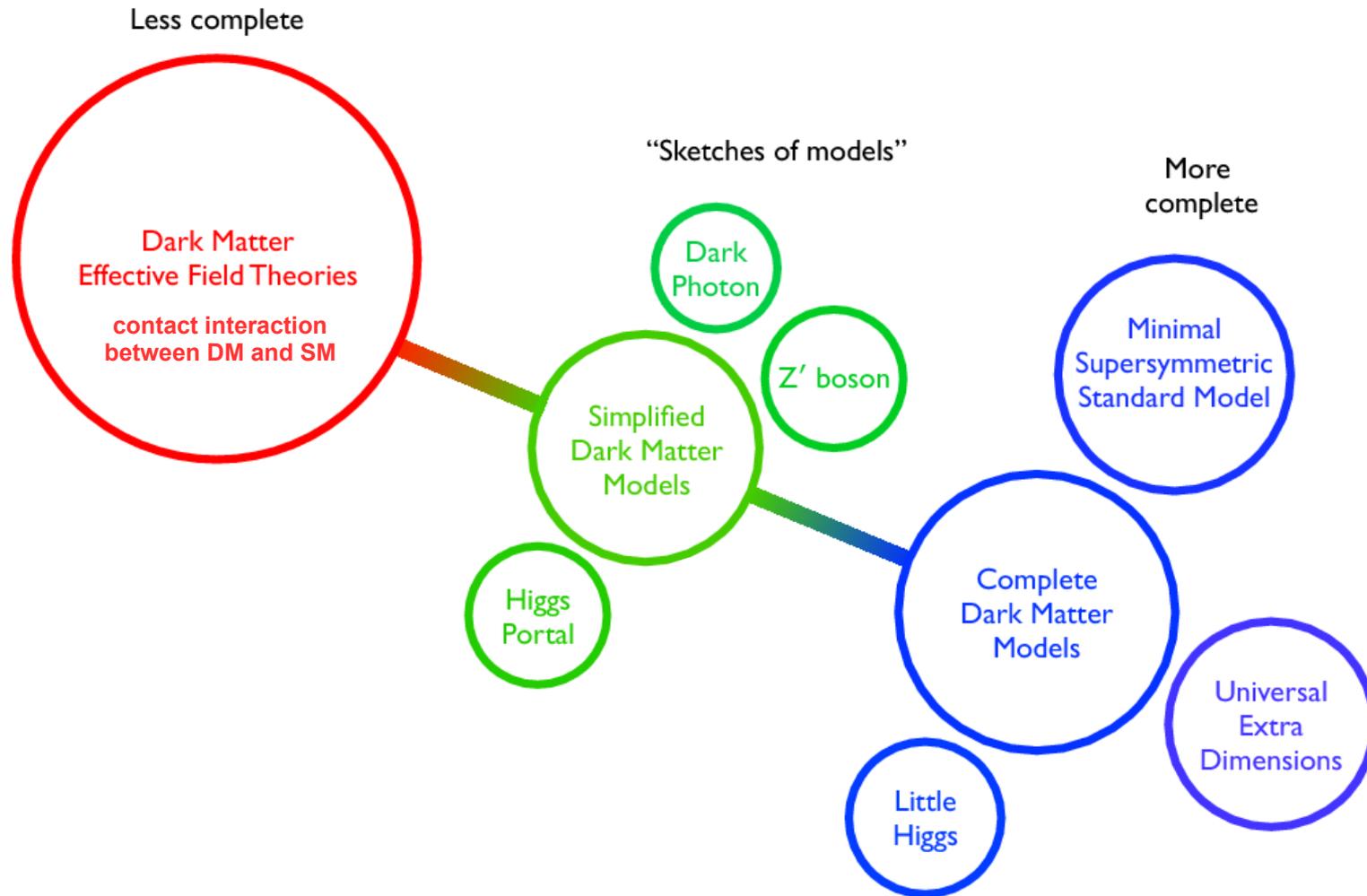
... but not DM

# DM fingerprint



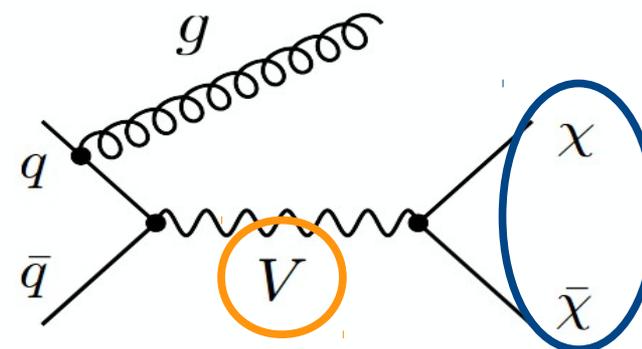
transverse momentum imbalance

by Tim Tait (simplified)



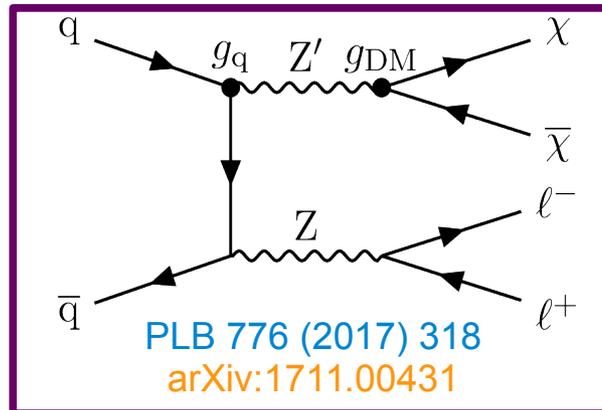
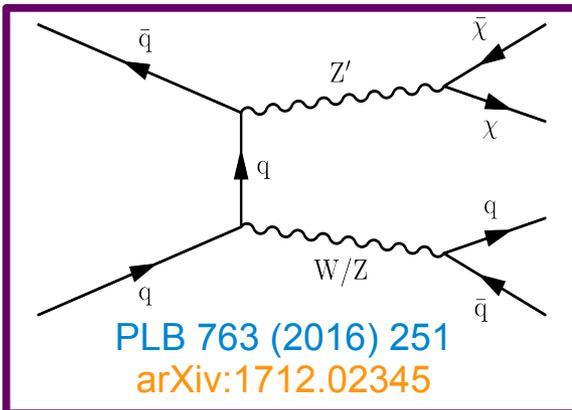
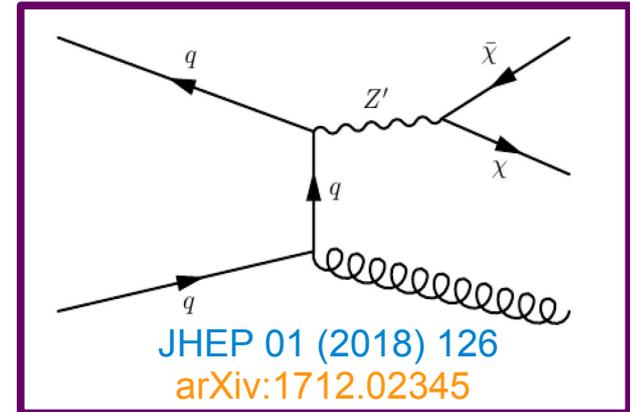
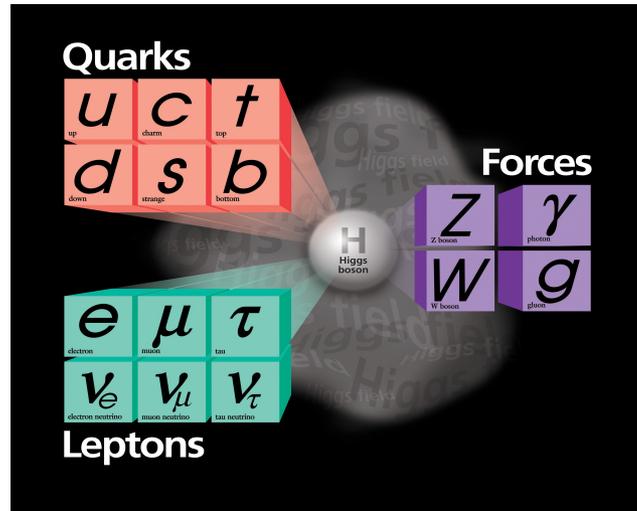
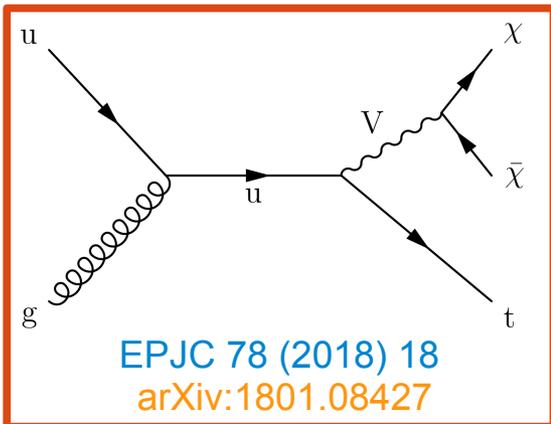
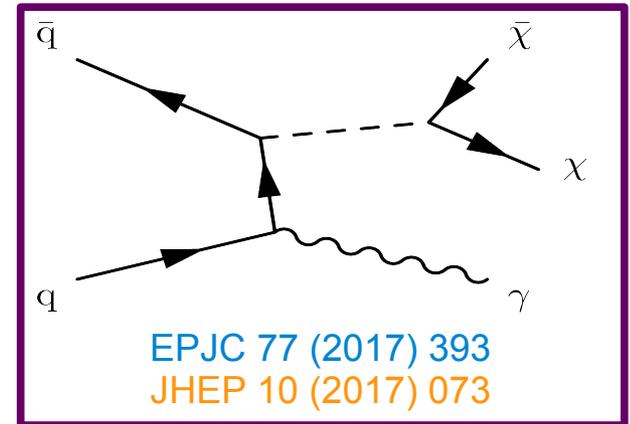
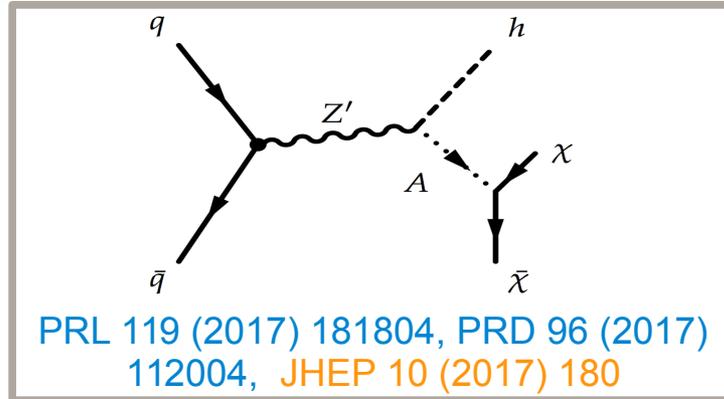
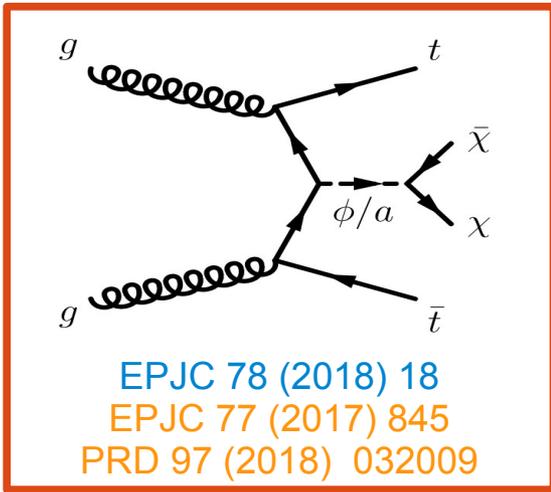
simplified models to guide analysis strategy

- ◆ idea:
  - restrict to relevant aspects aiming at maximal experimental coverage
- ◆ ingredients beyond SM:
  - mediator
  - DM particle
- ◆ free parameters:
  - masses, spins, coupling structure and strength
- ◆ recasting results in full models:
  - caveats may apply
  - parameter scans manageable



well established since 2015 for LHC searches

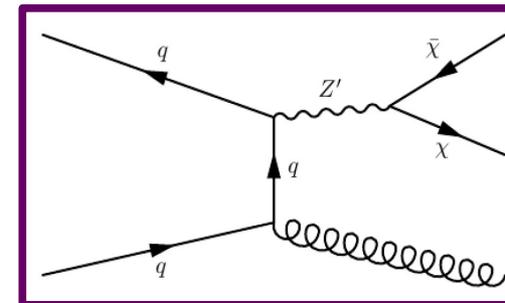
# Overview of LHC DM searches



wide spectrum of topologies

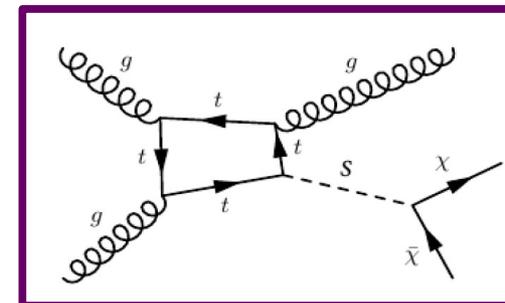
- ◆ hard QCD ISR jet recoils against DM  $\rightarrow$  large cross section

- ◆ explore missing transverse momentum as sensitive observable:  
reaching down to 250 GeV (trigger thresholds)

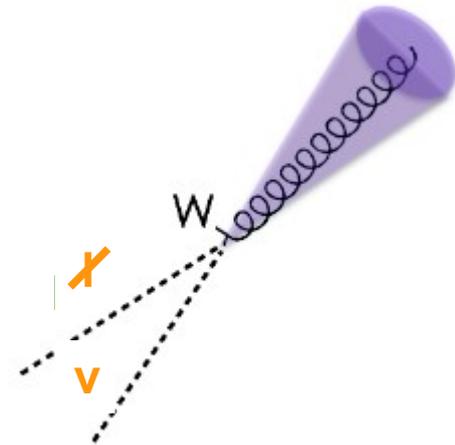
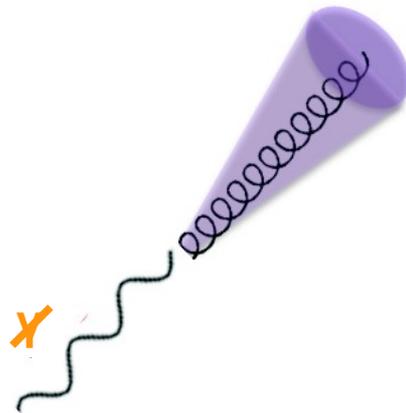
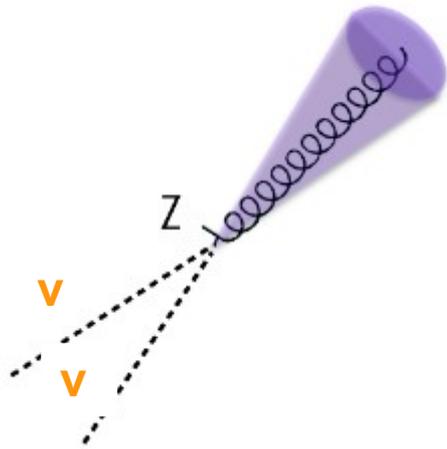


- ◆ key requirements

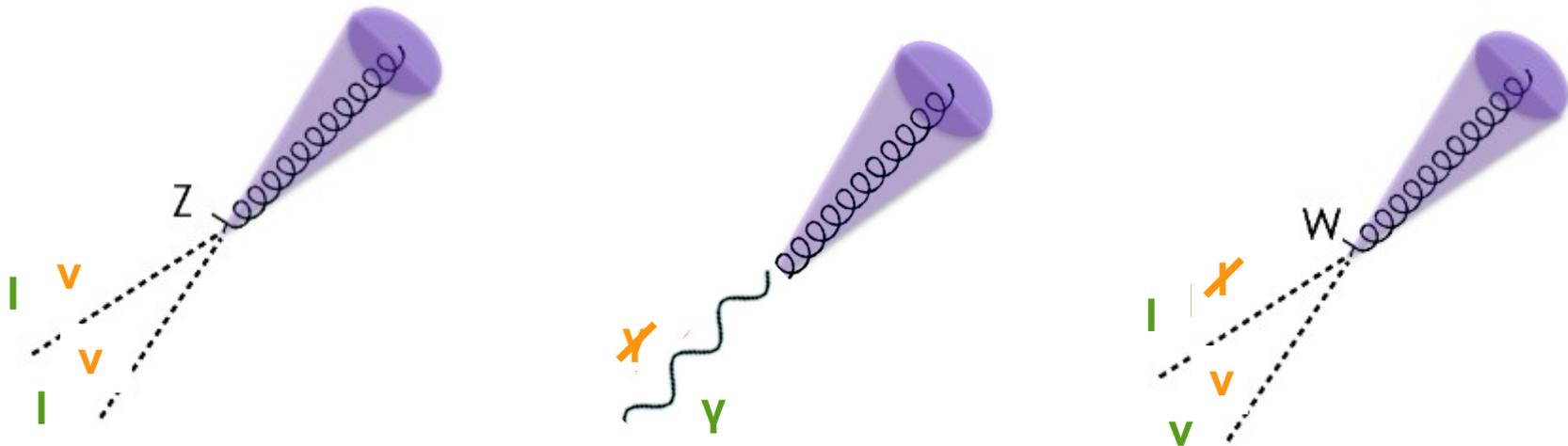
- central jet with high momentum above 100 GeV
- lepton, photon and b jet veto in signal region
- suppression of large jet mis-measurements:  
 $\Delta\phi(\text{jet}_{i=1..4}, \text{MET}) > 0.5$



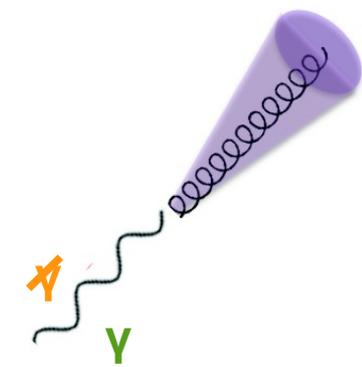
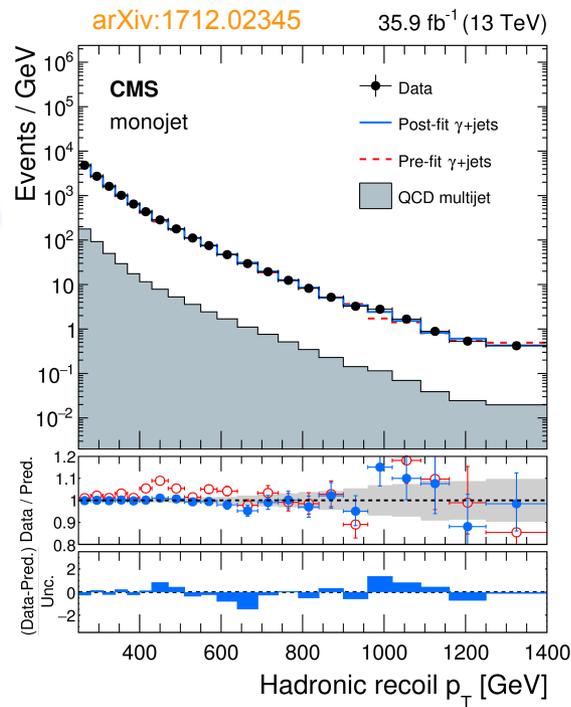
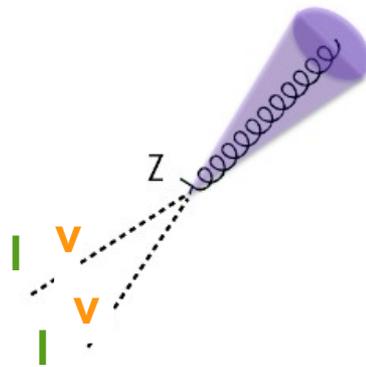
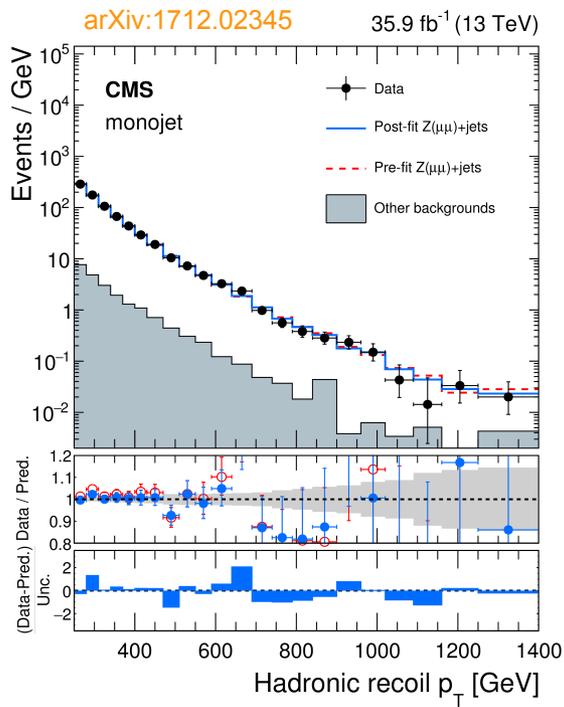
- ◆ major backgrounds from  $Z \rightarrow \nu\nu$  (60%) and  $W \rightarrow l\nu$  (30%)  
constrained from global fit to  $p_T^{\text{miss}}$  in signal (SR) and control regions (CR)



- ◆ major backgrounds from  $Z \rightarrow \nu\nu$  (60%) and  $W \rightarrow l\nu$  (30%)  
constrained from global fit to  $p_{\text{T}}^{\text{miss}}$  in signal (SR) and control regions (CR)
  - take **hadronic recoil as proxy** for  $p_{\text{T}}^{\text{miss}}$  in CR
  - bin-by-bin transfer factors linking yields in SR and CR
  - 20%-40% reduced systematics
    - ◆  $p_{\text{T}}$  - dependent NLO QCD K-factors from MG5\_aMC@NLO
    - ◆ electroweak corrections from theory calculation (arXiv:1705.04664)

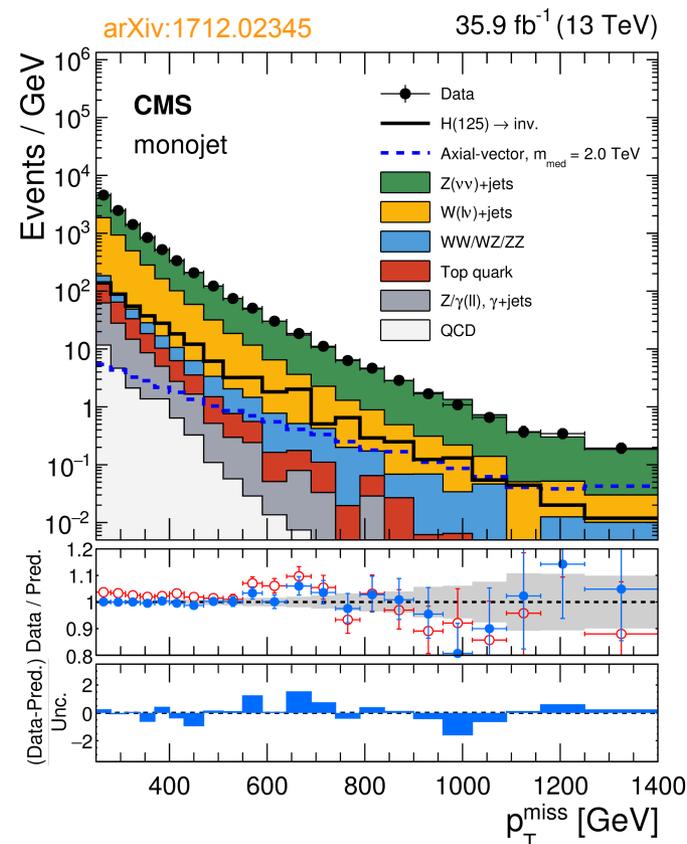
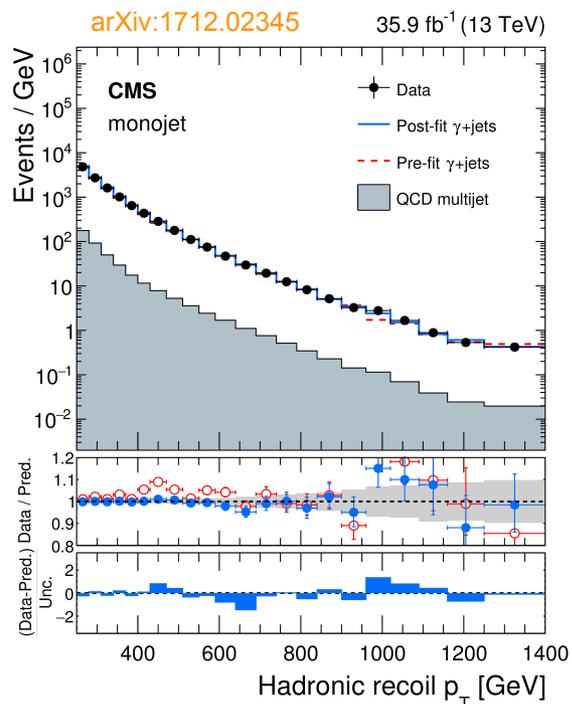
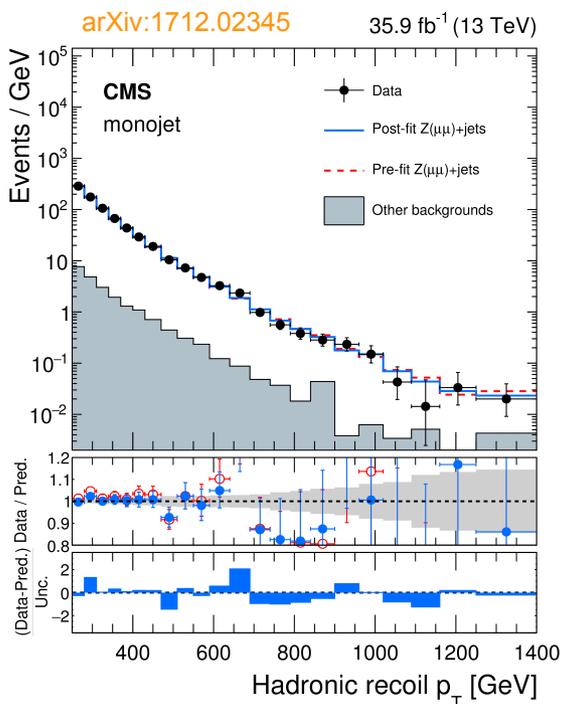


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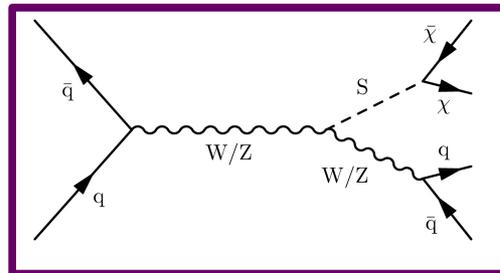
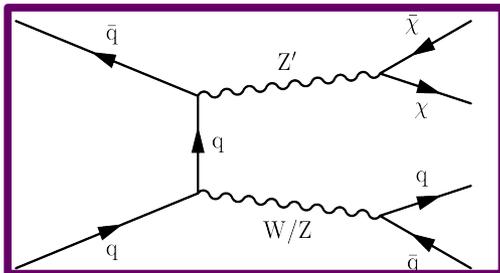
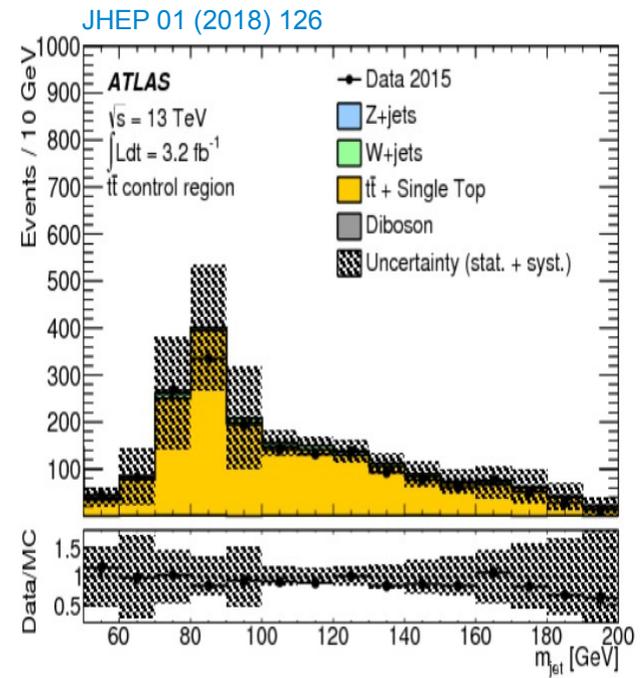
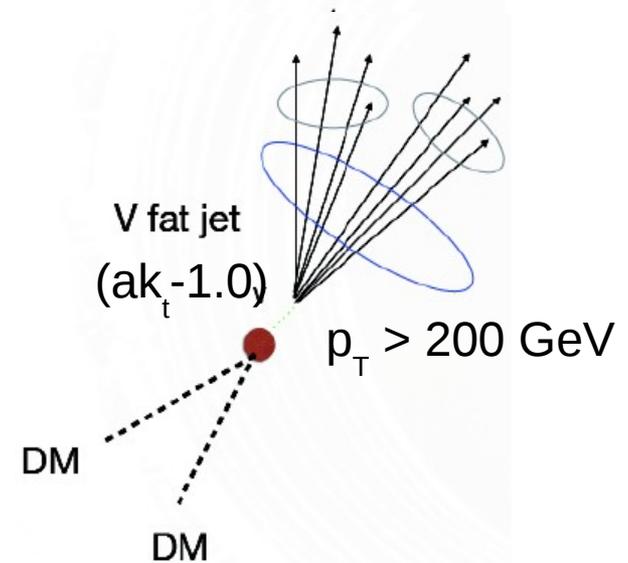
excellent background modeling

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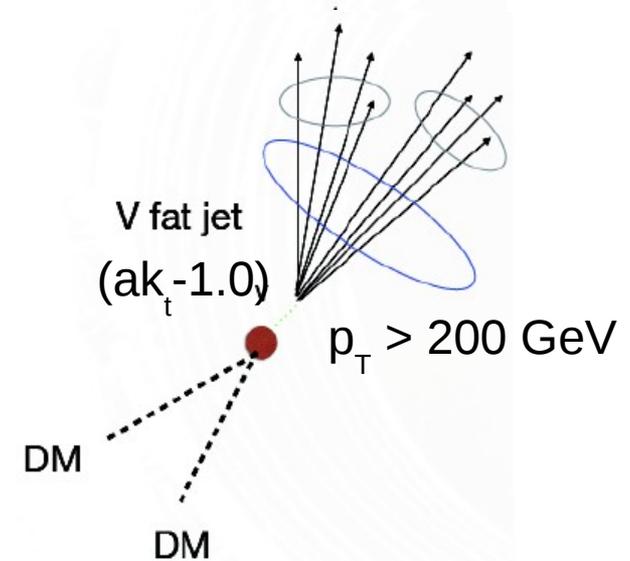


no significant deviation from SM background

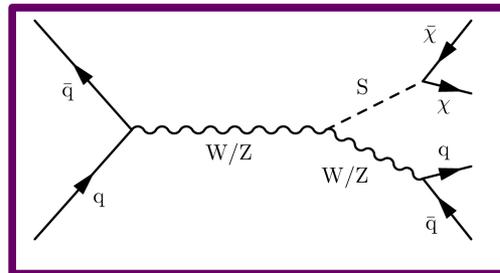
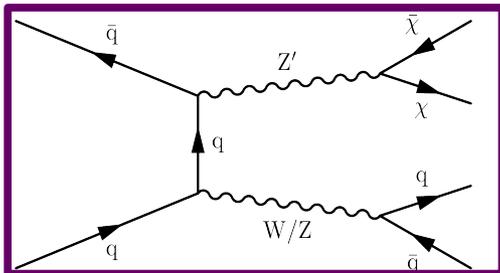
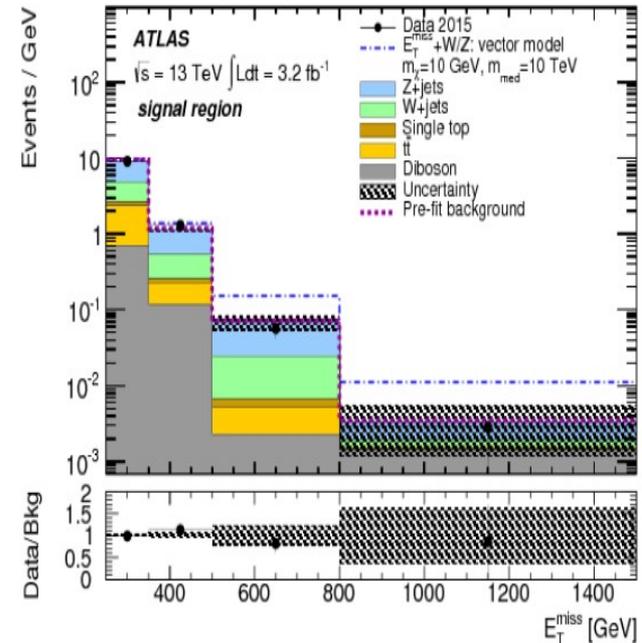
- ◆ DM recoils against **hadronically decaying Z or W**
  - large Lorentz-boost:  
decay products merge in single fat jet
- ◆ particularly interesting: **Higgs-strahlung** with scalar mediator
  - ISR Z/W production always smaller than mono-jet
- ◆ **Z/W/t $\bar{t}$  background** scale estimated from CR
- ◆ main uncertainty from **modeling fat jet**



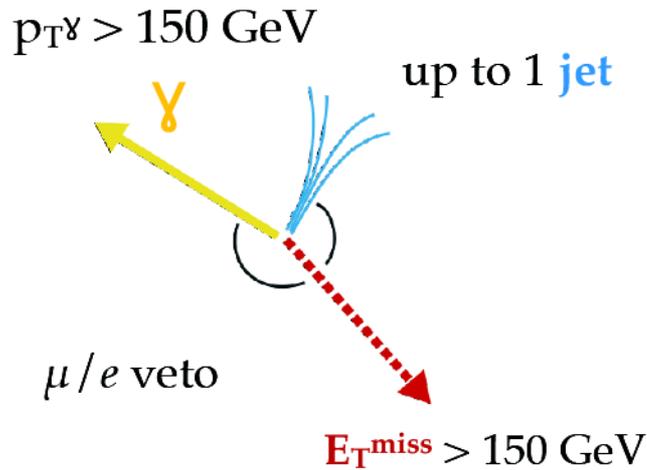
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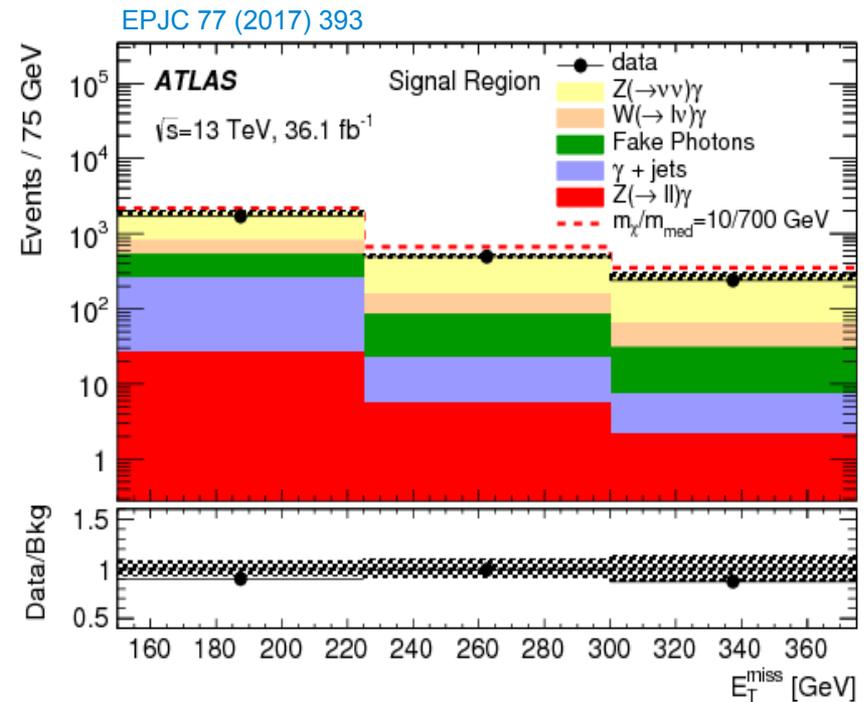


no excess over SM background



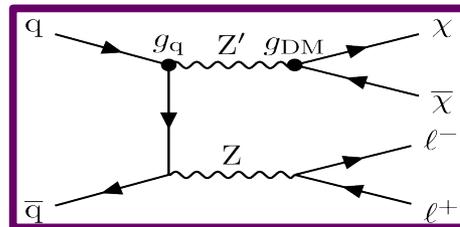
- ◆ DM recoils against a **photon from QED ISR**
  - clean signal, but  $\alpha_{\text{QED}} < \alpha_{\text{QCD}}$

- ◆ major backgrounds  $(Z \rightarrow \nu\nu) + \gamma$  (55%) and  $(W \rightarrow l\nu) + \gamma$  (15%) from  $(Z \rightarrow ll) + \gamma$  and  $(W \rightarrow \mu\nu) + \gamma$  CR where  $E_T^{\text{miss}}$  includes corresponding charged lepton
- ◆ difficult (but subdominant) instrumental backgrounds
  - jets/electrons faking photons estimated from data

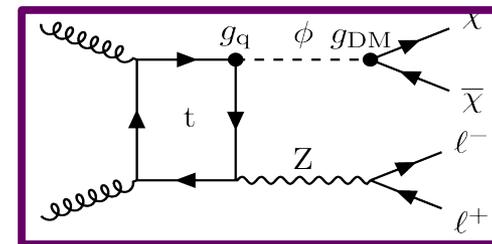
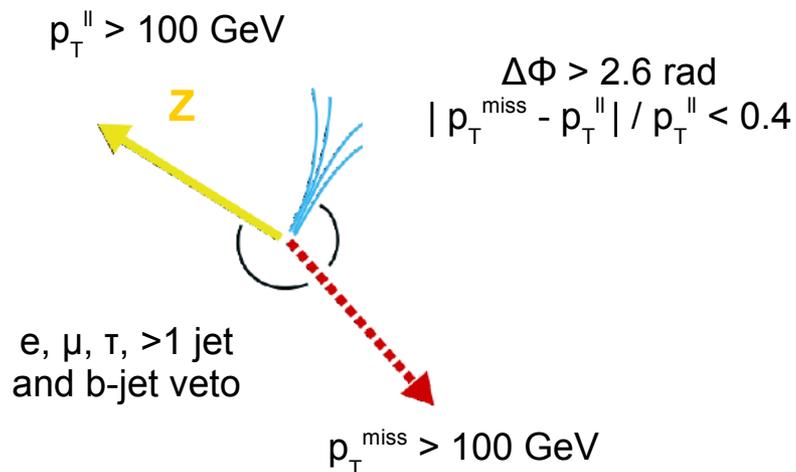


good match of data to background-only prediction

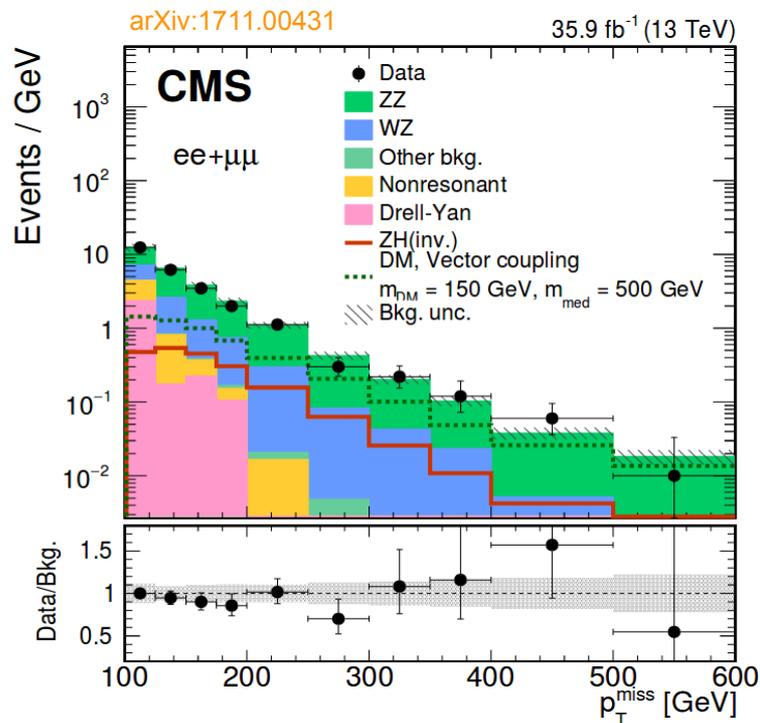
- DM recoils against a Z boson from electroweak ISR



- dilepton trigger give access to low missing momentum

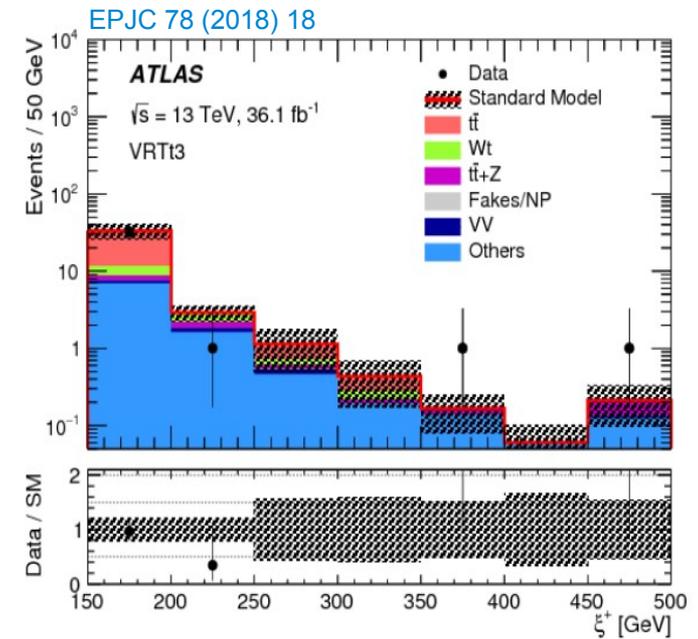
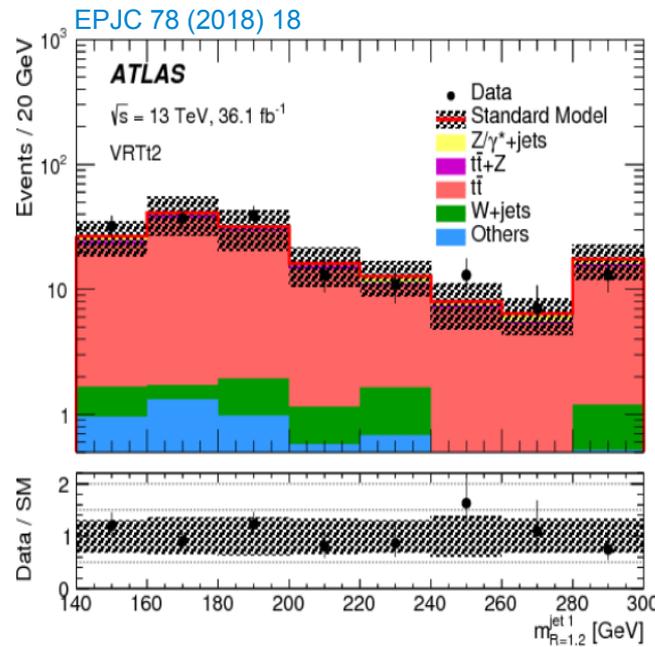
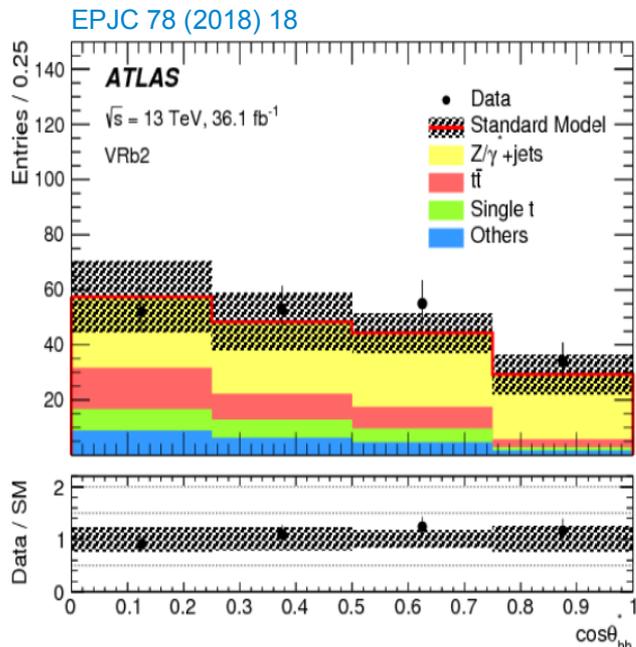
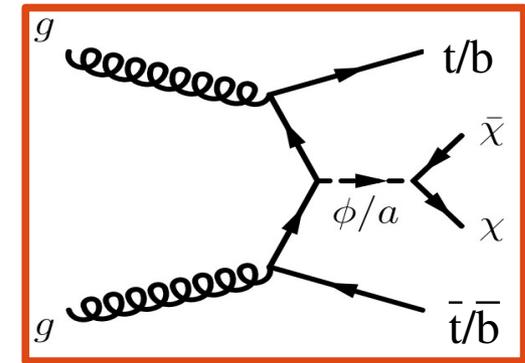


- very clean backgrounds of mainly ZZ (60%) and WZ (25%) from 4 resp. 3 lepton CR
- non-resonant background (e.g. tt, tW, WW) from electron-muon enriched data sample



no excess over SM background

- ◆ favored if couplings Yukawa-like
  - high sensitivity to (pseudo)scalar mediators
- ◆ optimize selection according to different experimental signatures
- ◆ dominant backgrounds of  $t\bar{t}$ ,  $t\bar{t}+Z$  and  $Z$ +jets constrained from several CR



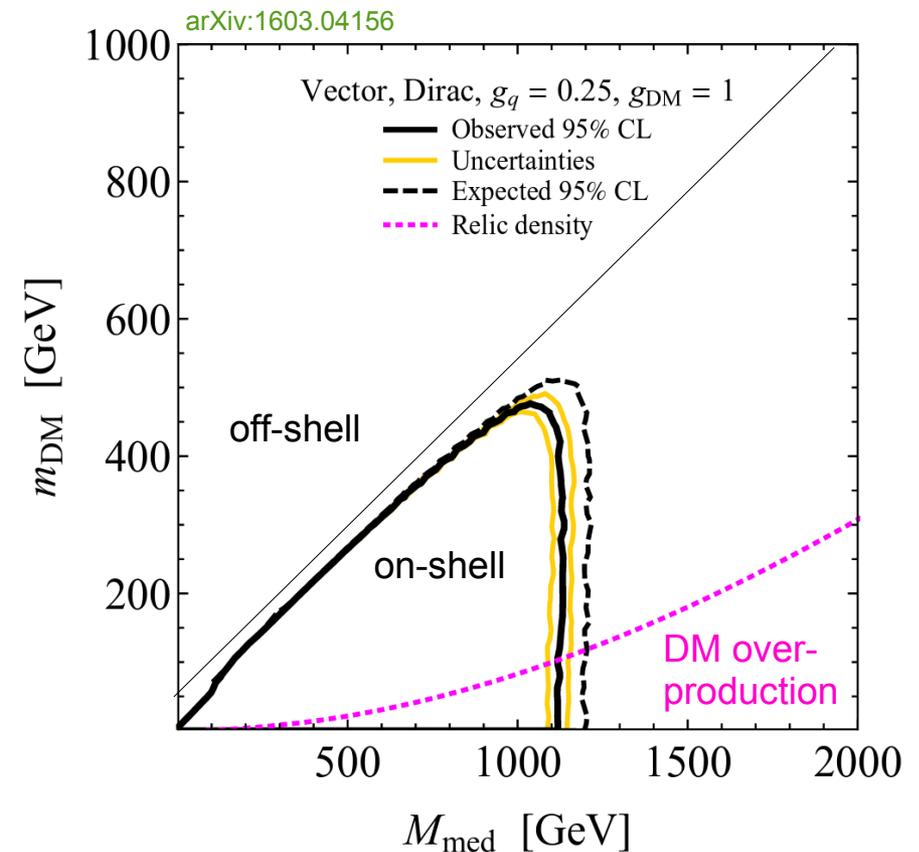
$$b\bar{b} : \cos \theta_{b\bar{b}}^* = \tanh (\Delta \eta_{b\bar{b}} / 2)$$

$$t\bar{t} \text{ (all-had)} : m_J$$

$$t\bar{t} \text{ (dilepton)} : \xi^+ = m_{T2}^{\text{ll}} + 0.2 E_T^{\text{miss}}$$

no significant deviation from SM background

- ◆ presented analysis found data compatible with background-only expectation
- ◆ use results to set **limits on simplified models**
  - resonant enhancement when mediator produced on-shell (s-channel)
  - limits suppressed when going off-shell
  - cross section (sensitivity) drops at high mediator mass
- ◆ limits **depend on assumptions**
  - mediator type
  - coupling strength
  - ...



use simplified models to interpret DM searches

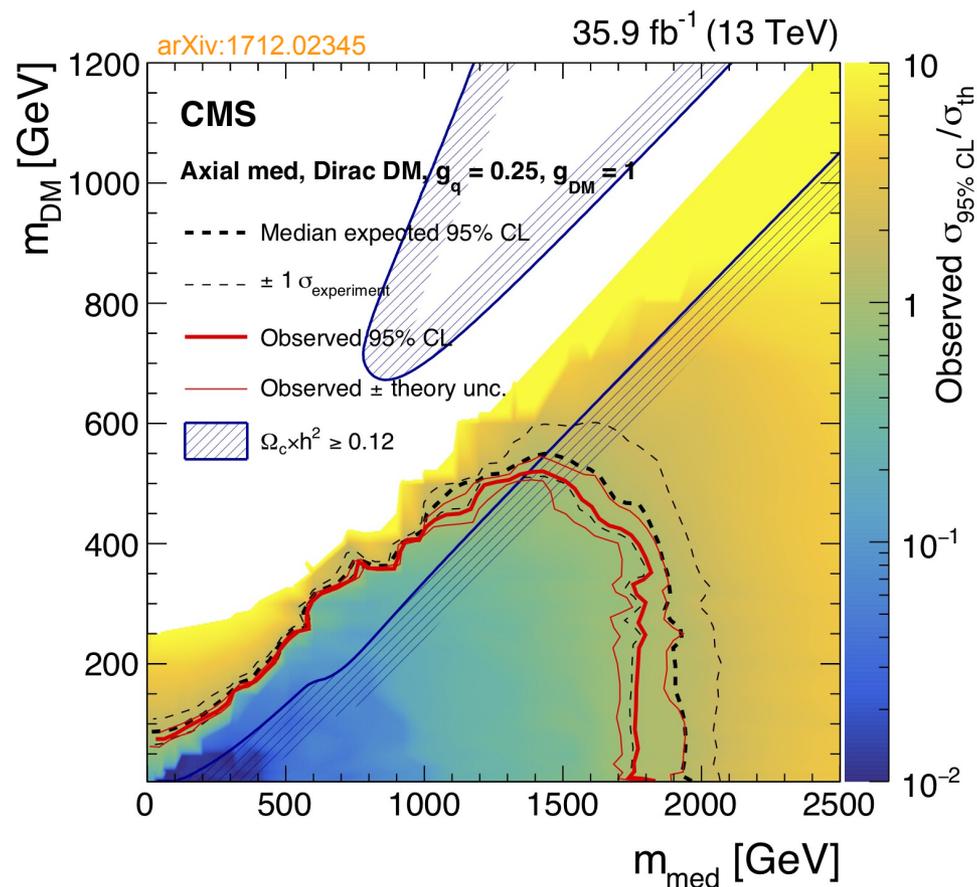
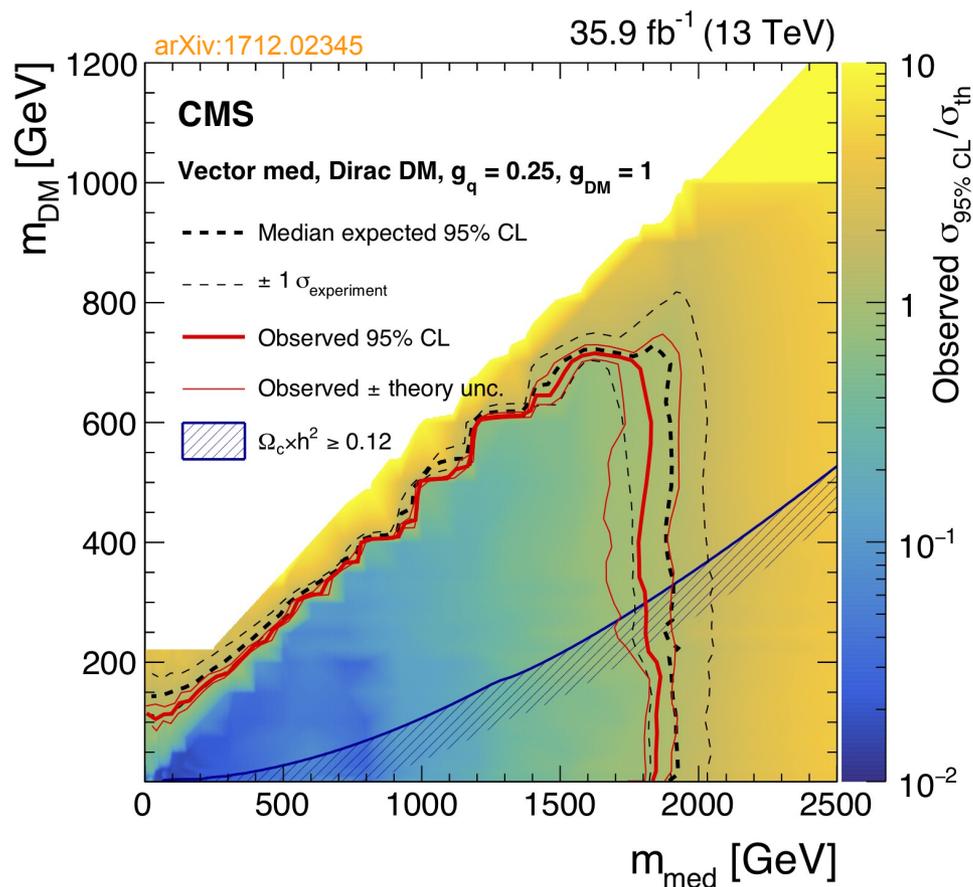
# Strongest limits on (axial)vector mediators



◆ **mono-jet channel** most sensitive

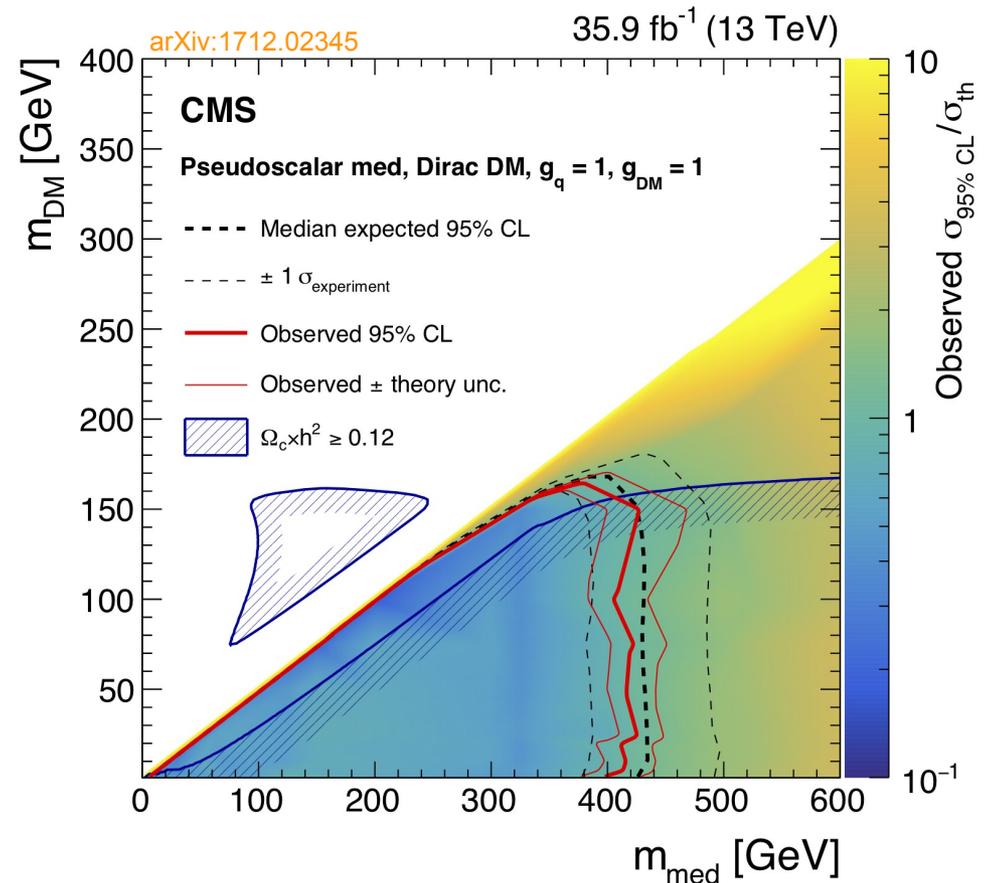
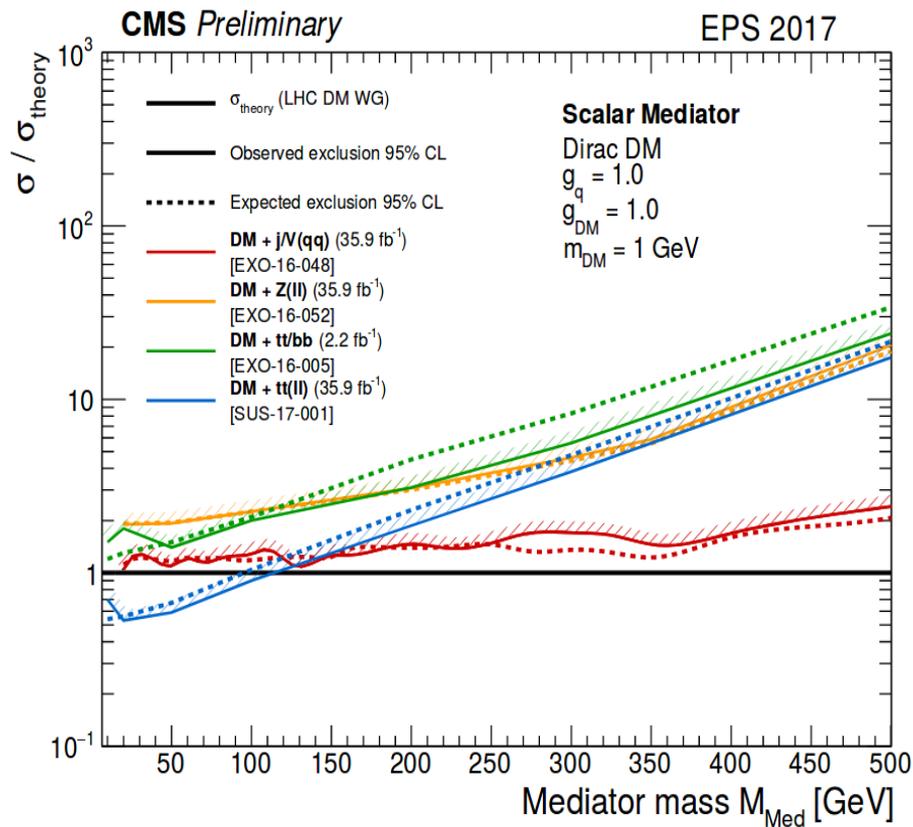
- exclude **mediator** masses up to  $\sim 1.8$  TeV and **DM** masses up to  $\sim 700/500$  GeV
- similar sensitivity for ATLAS and CMS

◆ need much more luminosity to improve results



# Strongest limits on (pseudo)scalar mediators

- ◆ heavy flavor searches allow excluding **scalar** mediator masses up to **~120 GeV**
  - can reach increased sensitivity by combining all  $t\bar{t}$  final states
- ◆ mono-jet searches most sensitive to **pseudoscalar** mediators
  - exclude masses up to **~400 GeV**

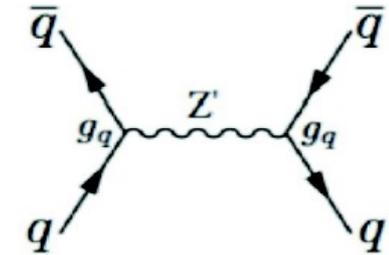


# Visible mediator searches



- ◆ dark matter searches can be constrained by **visible mediator decays**

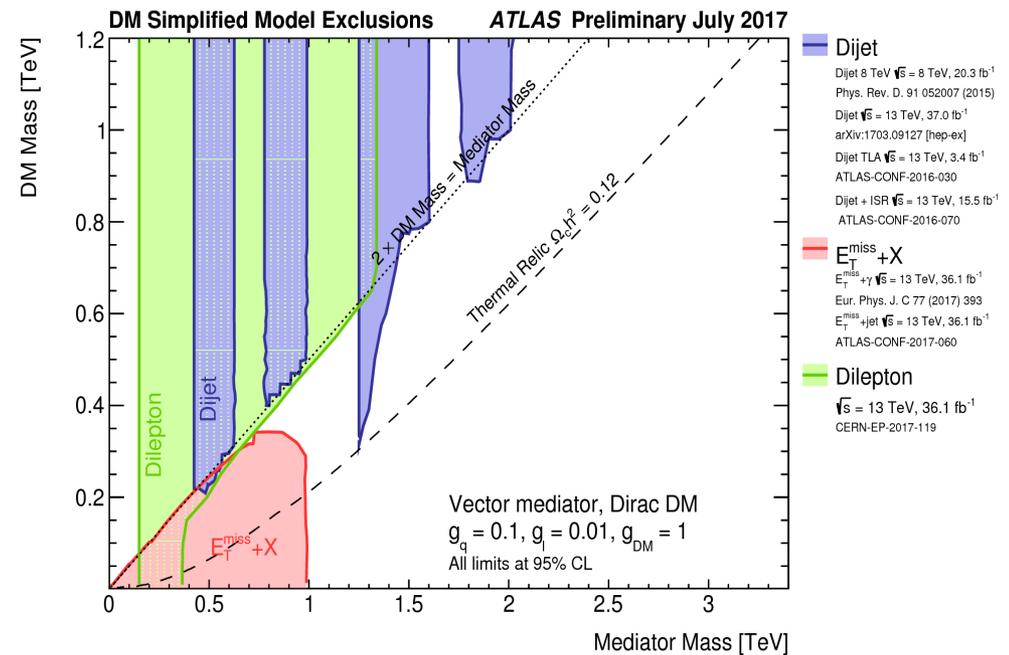
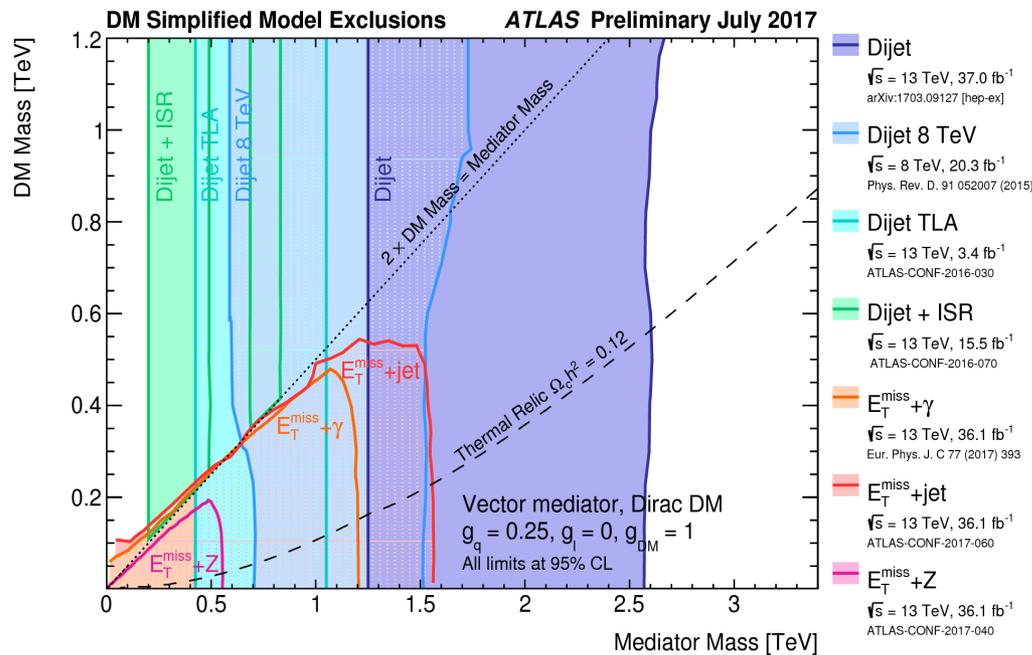
- probe region where mediator cannot decay to DM



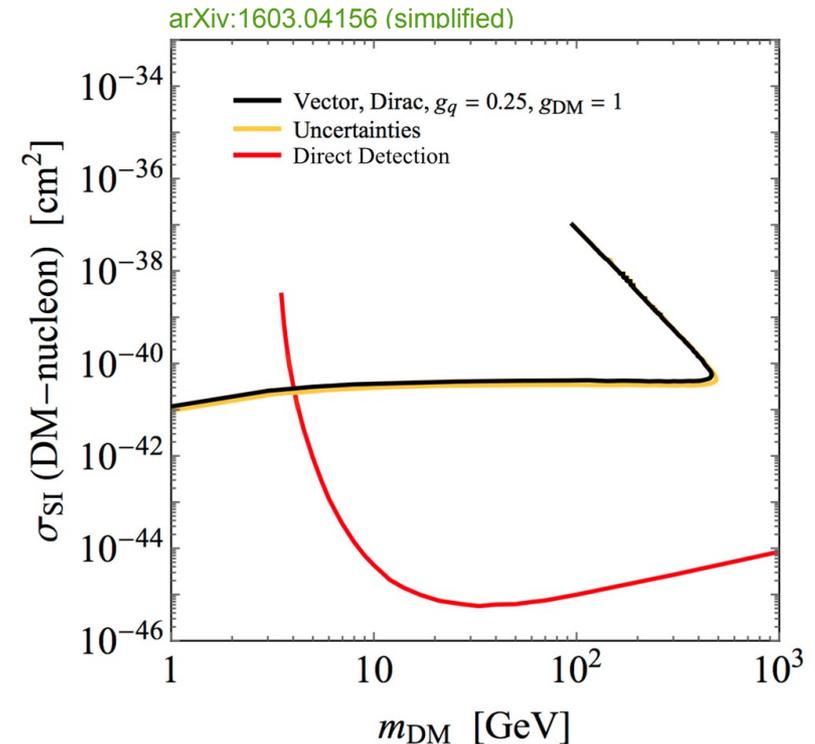
- ◆ search for a **bump** in dijet or dilepton invariant **mass spectrum**

- coupling choices determine interplay between DM and resonance searches
- for e.g.  $g_q=0.25$  and  $g_l=0$  mediator masses down to  $\sim 50$  GeV

(CMS, JHEP 01 (2018) 097) and up to 2.5 TeV can be excluded

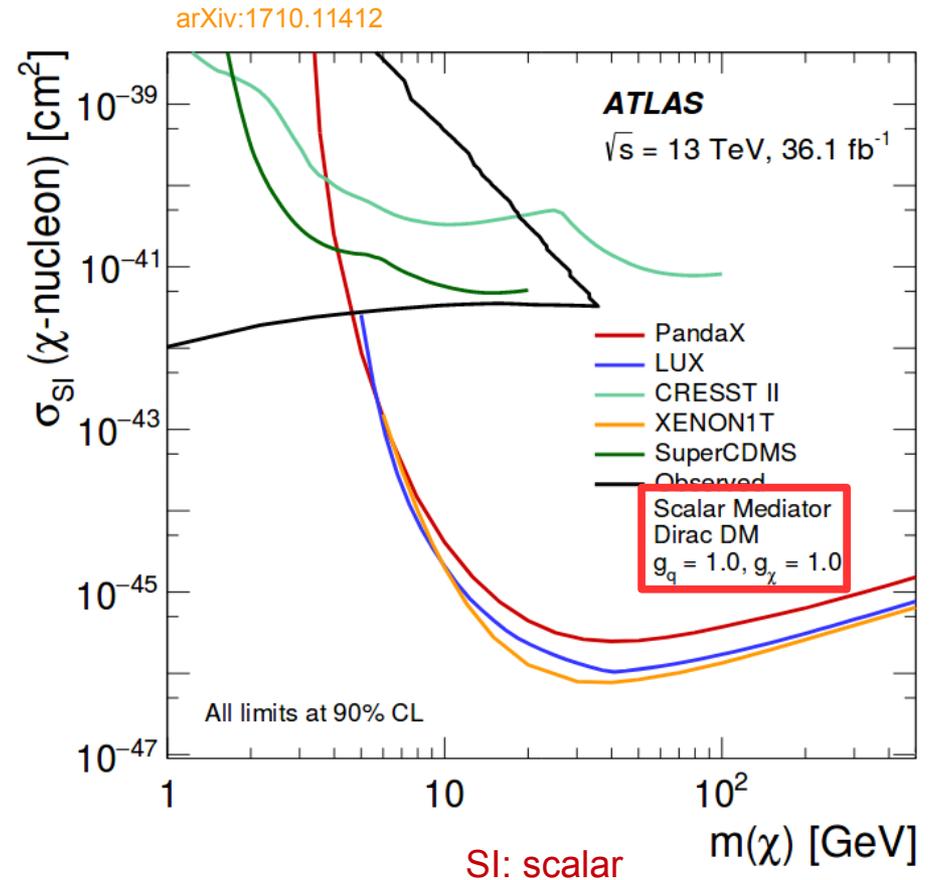
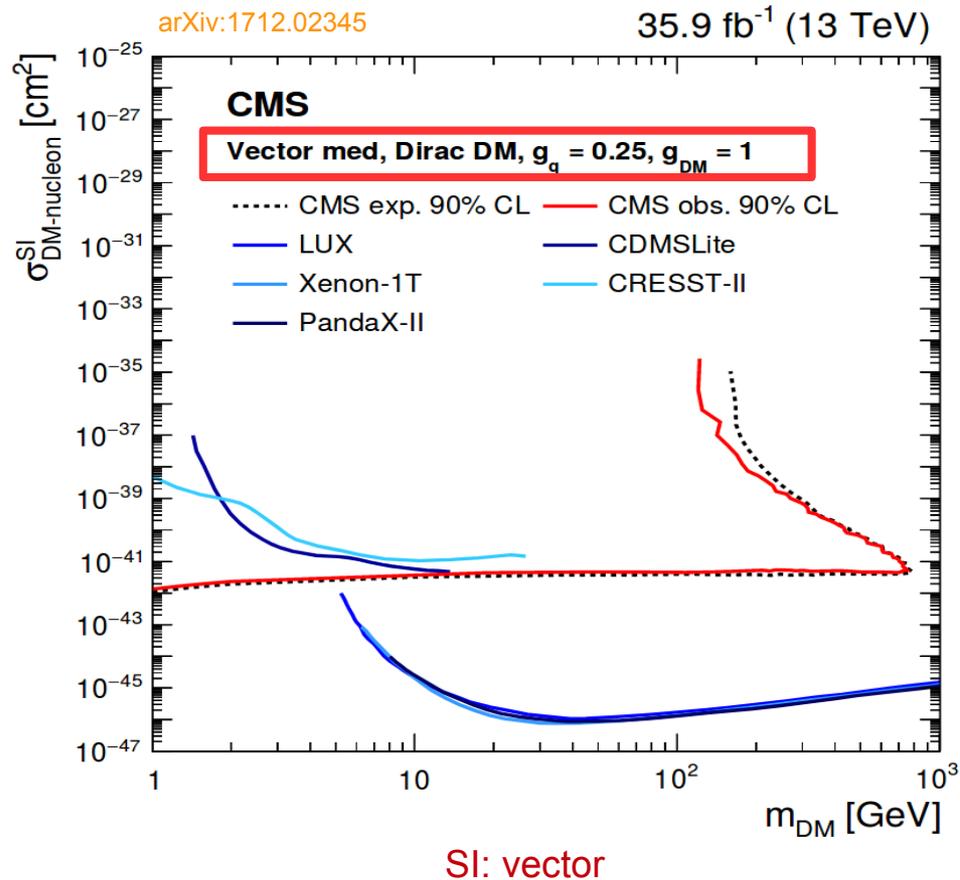


- ◆ simplified models allow unambiguous comparison in the **WIMP-DM cross section versus DM mass plane**
- ◆ advantage:
  - visualizes the **complementarity** of collider and other DM searches
- ◆ disadvantage:
  - comparison **model-dependent**
  - oversimplification can lead to misinterpretation

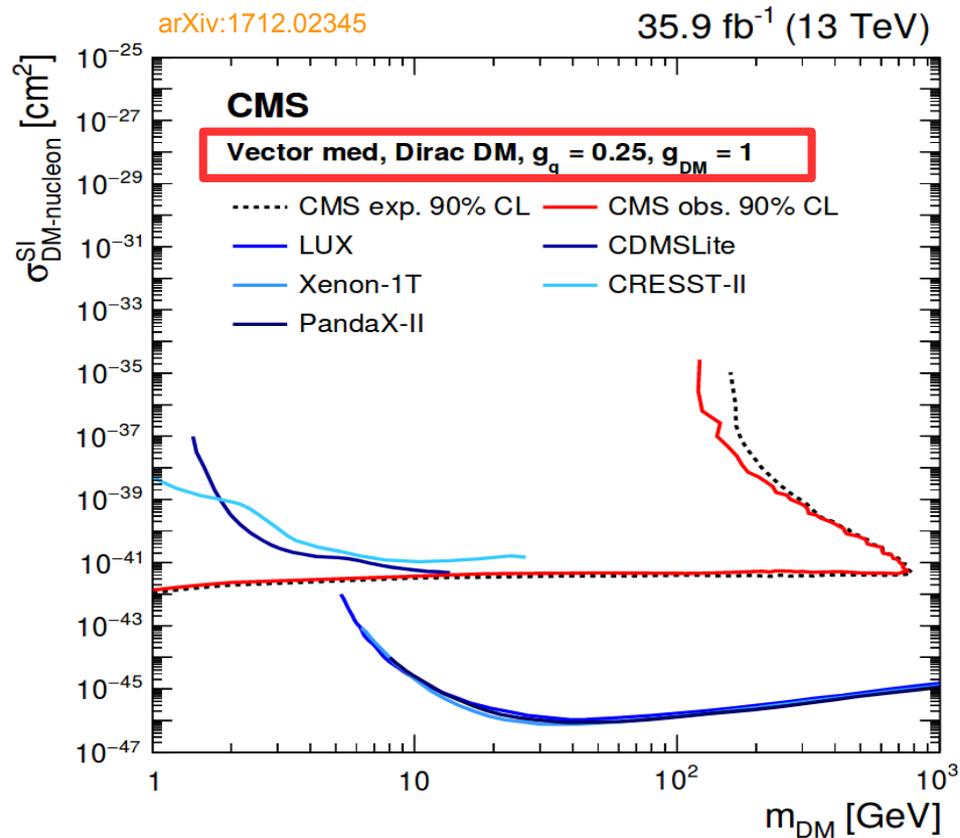


use simplified models to compare different results

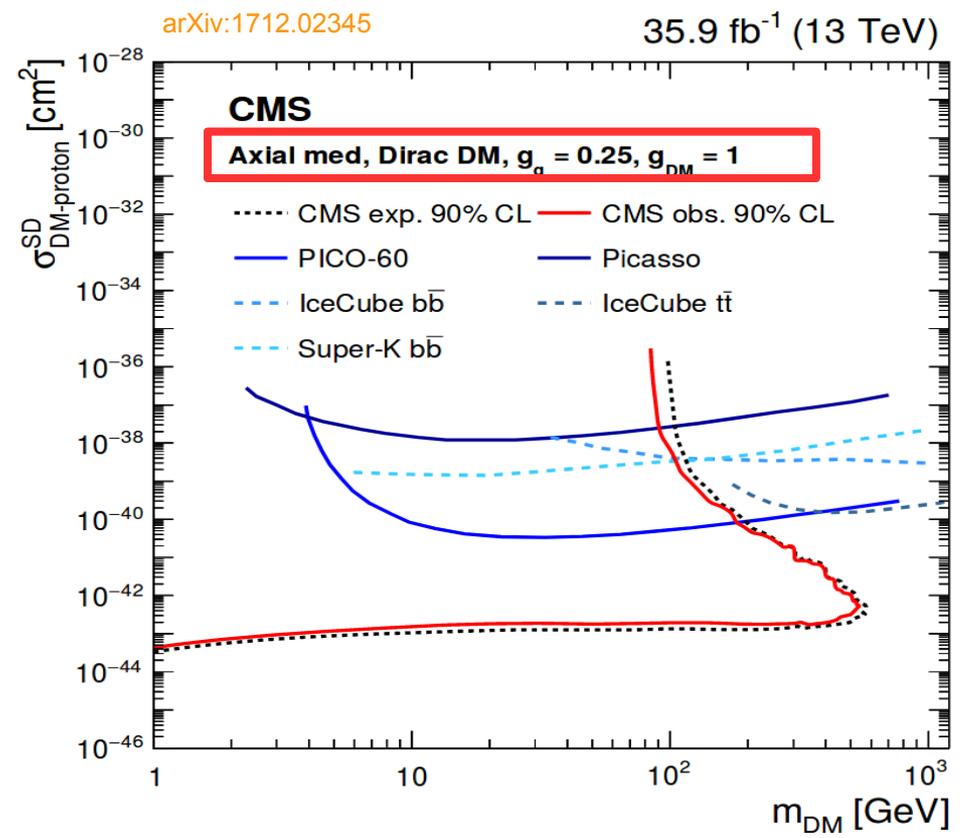
- ◆ nice complementarity between LHC and direct detection experiments
  - LHC searches more sensitive to low DM masses



- ◆ nice complementarity between LHC and direct detection experiments
  - LHC searches more sensitive to low DM masses
  - axialvector couplings

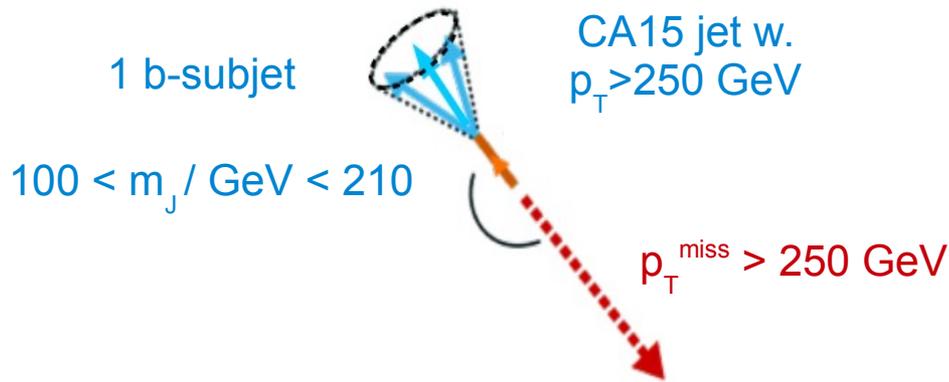


SI: vector

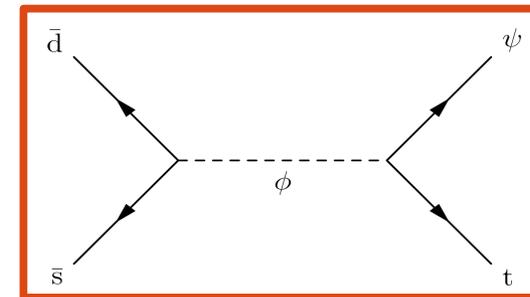
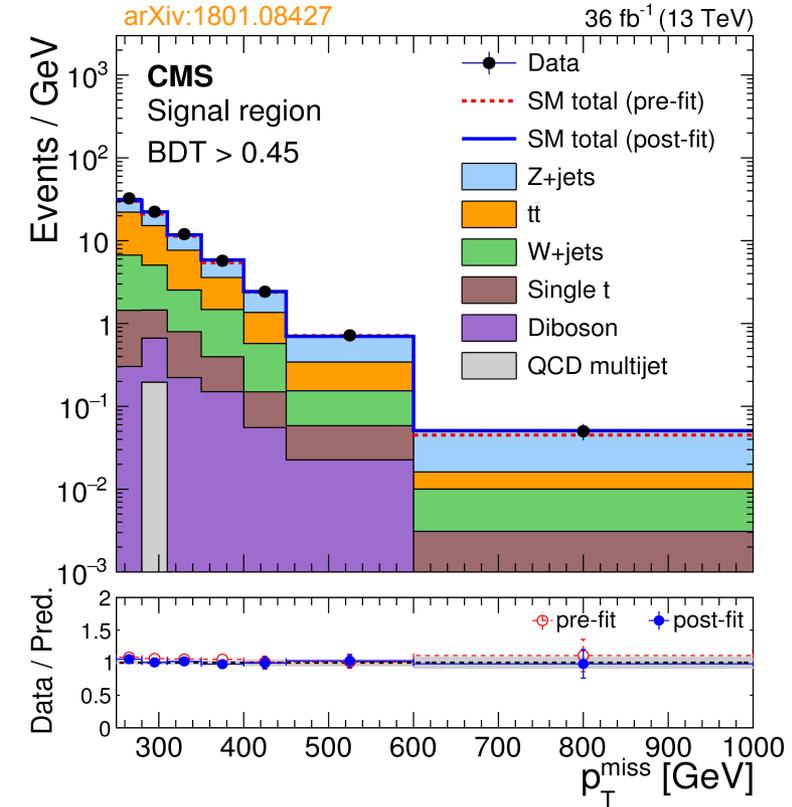
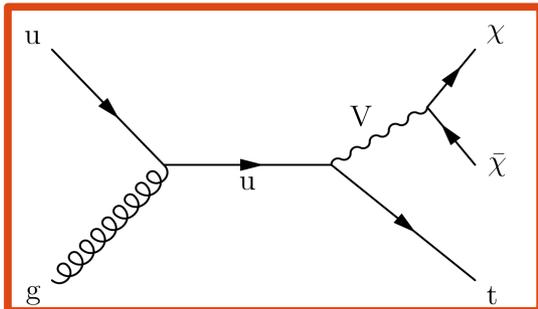


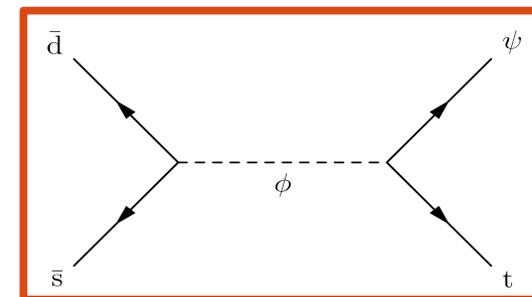
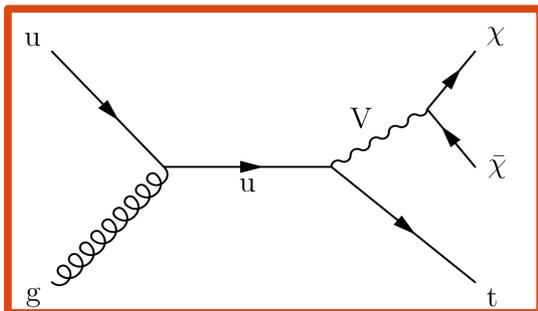
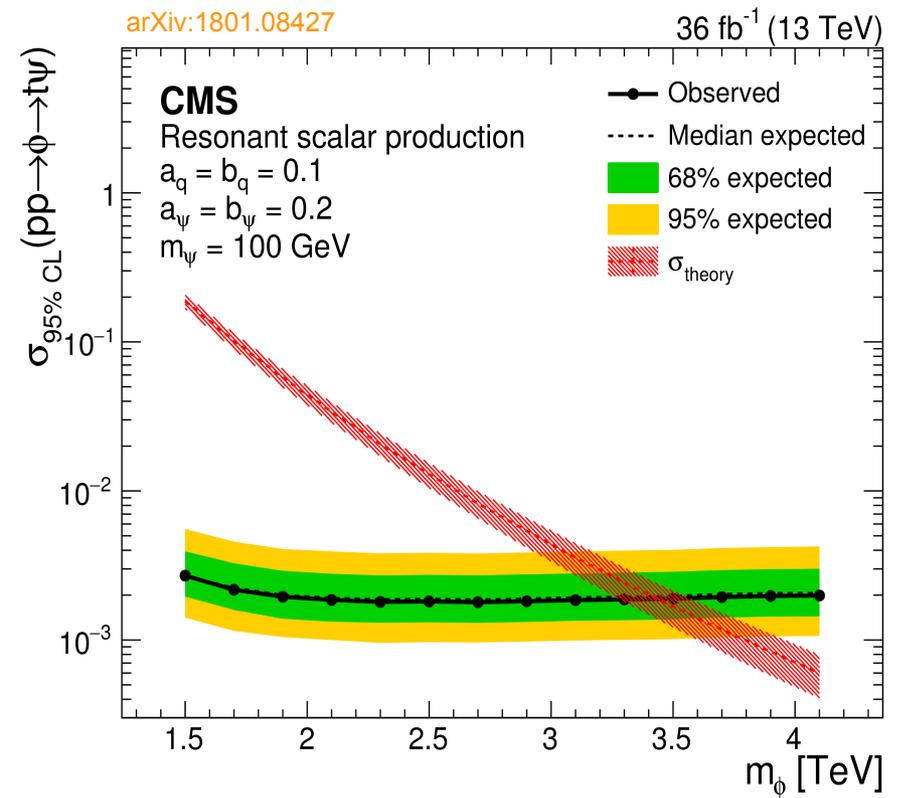
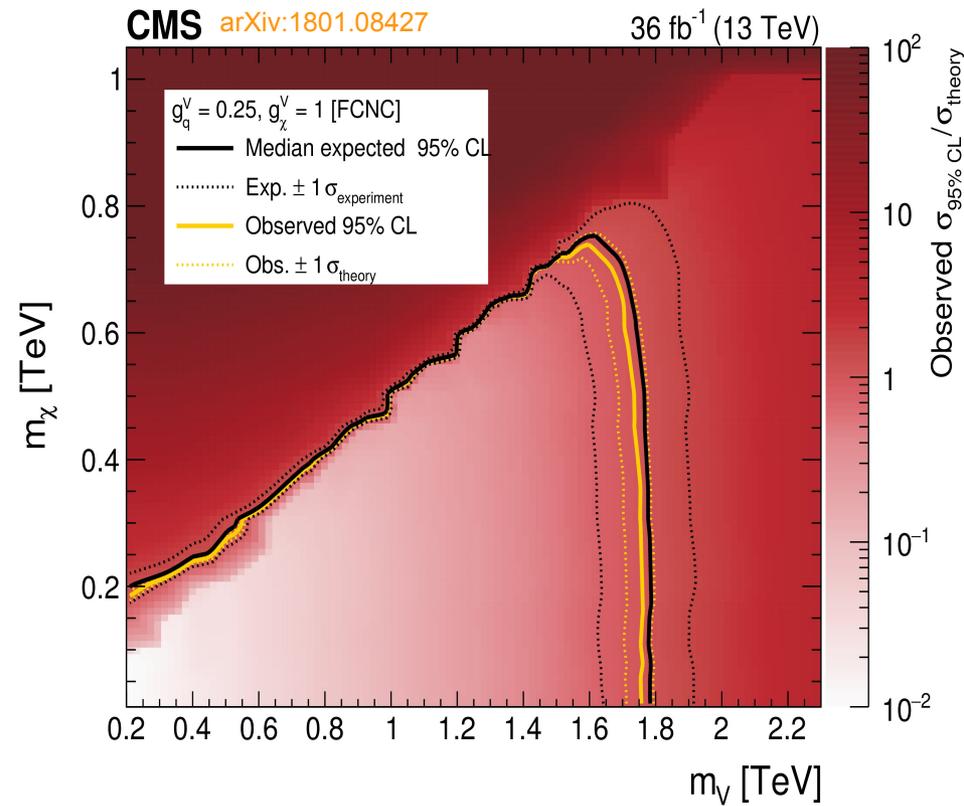
SD: axialvector

- ◆ DM recoils against a **single top quark**
  - **flavor-changing** simplified model or
  - **colored, charged scalar**
- ◆ explore **hadronically decaying boosted top quarks**



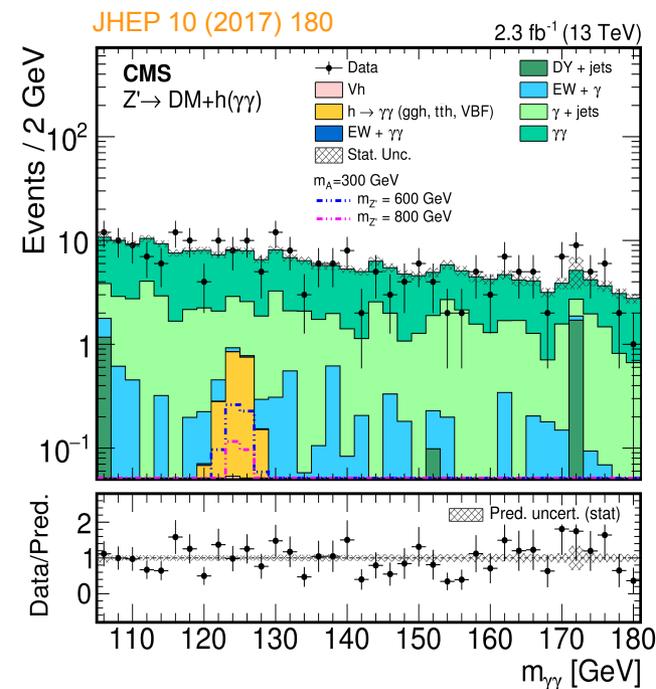
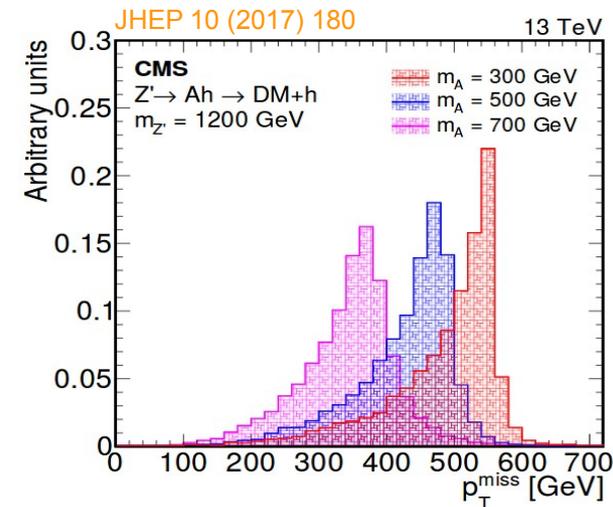
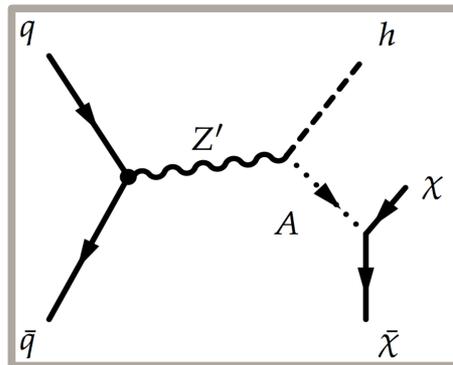
- ◆ BDT discriminating fat jets from top vs quark/gluon initiated
- ◆ extract signal strength from fit to  $p_T^{\text{miss}}$  in 2 BDT bins



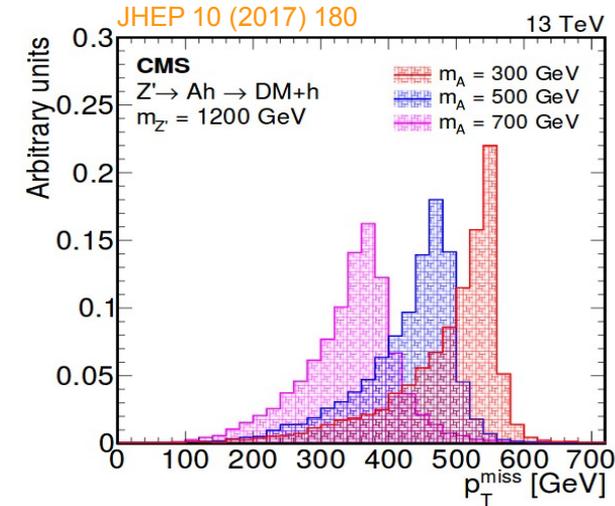
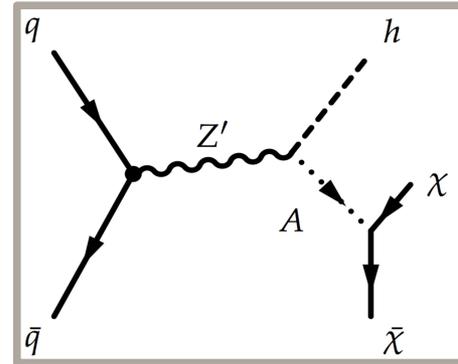


no excess over SM expectation observed

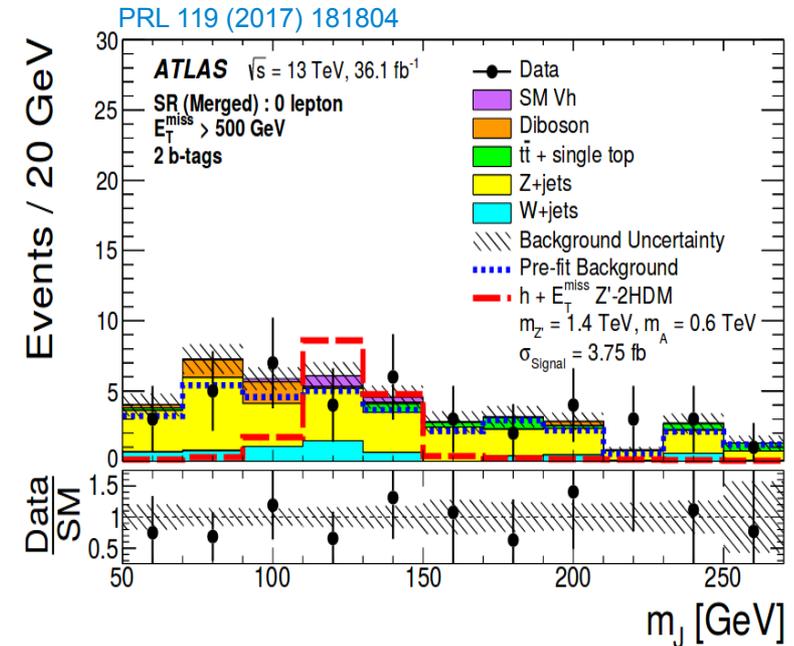
- ◆ DM recoils against a **Higgs boson**
- ◆ need to boost production cross section with dedicated models (eg. **Z'-2HDM**)
  - Higgs initial state radiation tiny
- ◆  $H(\rightarrow\gamma\gamma)$ :
  - excellent mass resolution (<2%)
  - use  $p_{\text{T}}^{\text{miss}}$  inside Higgs mass window



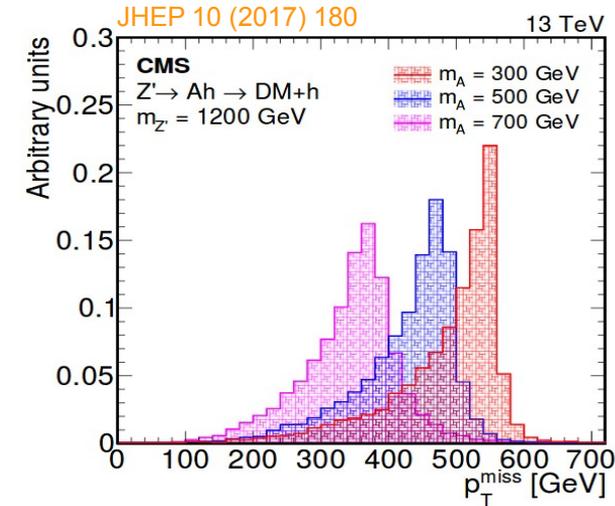
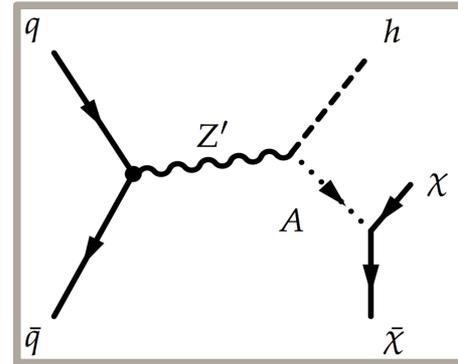
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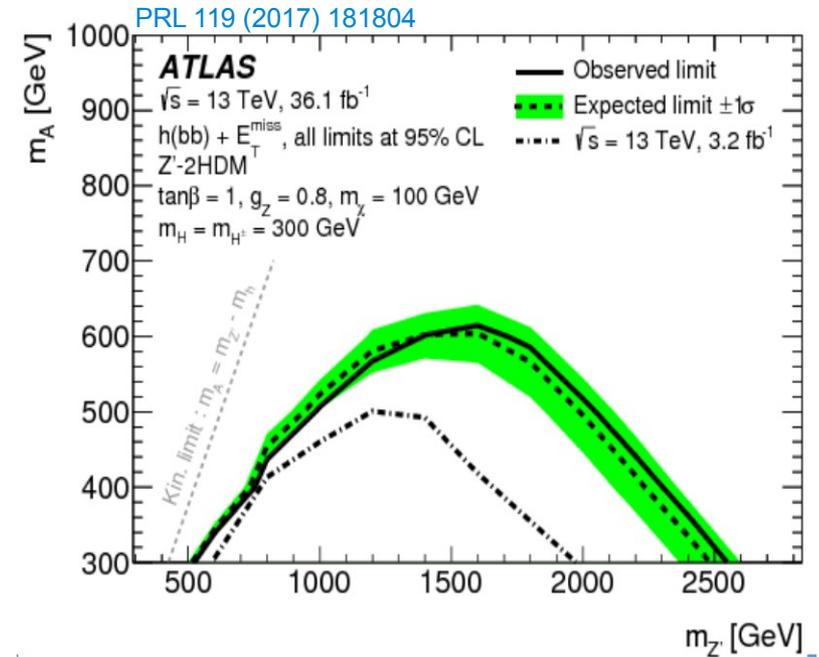
- ◆  $H(\rightarrow\gamma\gamma)$ :
  - excellent mass resolution (<2%)
  - use  $p_{\text{T}}^{\text{miss}}$  inside Higgs mass window
- ◆  $H(\rightarrow b\bar{b})$ :
  - largest branching fraction (~60%) but poor mass resolution (~10%)
  - explore resolved  $m_{b\bar{b}}/\text{merged } m_J$  in 4 different  $p_{\text{T}}^{\text{miss}}$  bins



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exclude  $Z'$  up to  $\sim 2.5$  TeV for pseudoscalar of 300 GeV

- ◆ manifold DM program at ATLAS and CMS
  - missing transverse momentum signatures and visible mediator searches
  - completed by rich SUSY research program providing natural DM candidate in a UV complete theory
  - complementarity to direct and indirect searches
  
- ◆ LHC Run-II going full speed
  - factor 3 more collisions to analyze during LHC Run-II
  
- ◆ many developments, e.g.
  - more realism/**complexity** in scalar sector (extra scalar with H mixing)
  - include scenarios with **longlived** particles



Heinrich Füger, Prometheus brings fire to mankind

not yet ...