Associated production of Dark Matter and Heavy Quarks at LHC

COSMOLOGY2018
DUBROVNIK

Alberto Zucchetta

on behalf of the **ATLAS** and **CMS** collaborations

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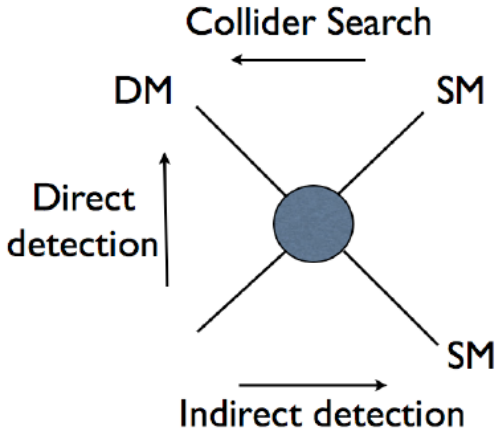
Interpreting Dark Matter signals at the LHC

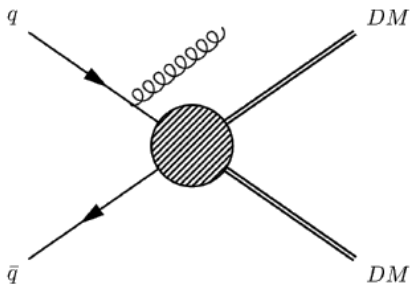
More general

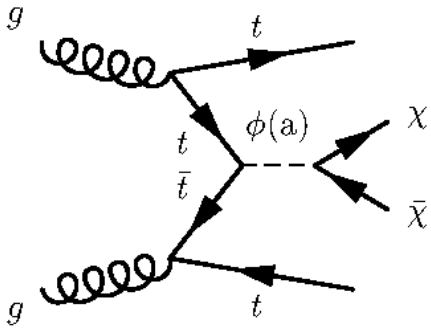
More complete

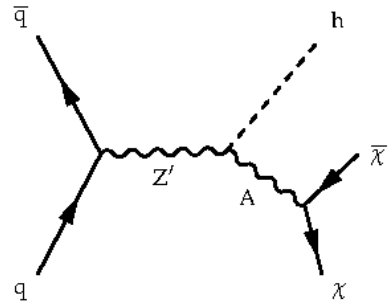
- **Effective Field Theories**:
  - simpler description of the phenomenology, valid only when momentum transfers $\ll$ mediator mass (problematic at the LHC)
- **Simplified models**:
  - limited number of parameters (g_q, g_χ, $M_{\phi,a}$, m_χ)
  - remain valid when mediator is produced on shell

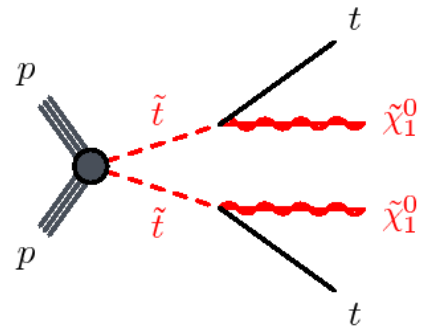


- **Dedicated models**:
  - peculiar phenomenology, often considered in single searches (mono-Higgs, mono-top, and more other exotic models)
- **Complete models**:
  - complete predictions but less general approach, large number of free parameters (e.g. SUSY)







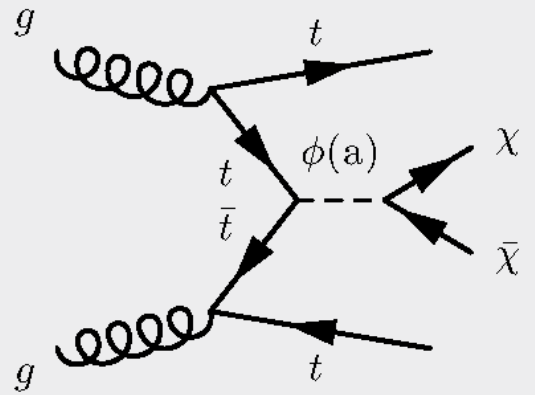


- Guidelines for searches: LHC Dark Matter Working Group, a collaboration between ATLAS, CMS, and theorists for harmonization of interpretations (arxiv:1507.00966).

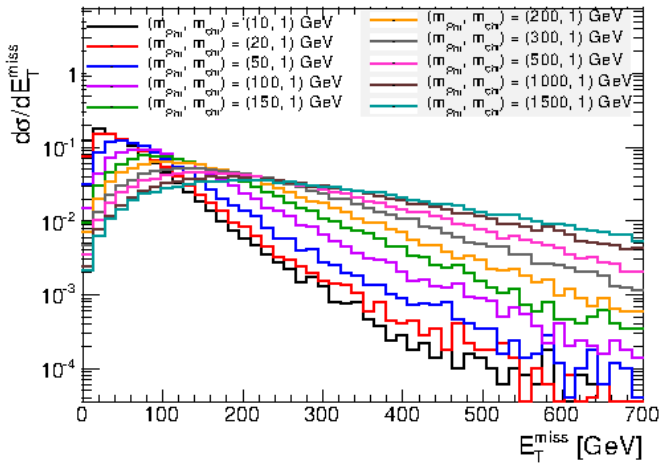
Simplified models and heavy flavors

- different assumptions can be made on the mediator particle and on the kind of interaction (spin, parity, . . .)

	scalar	pseudo-scalar
spin-0	$g_q \frac{\phi}{2} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{2} \sum_f y_f \bar{f} \gamma^5 f$
spin-1	$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$ vector	$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$ axial-vector

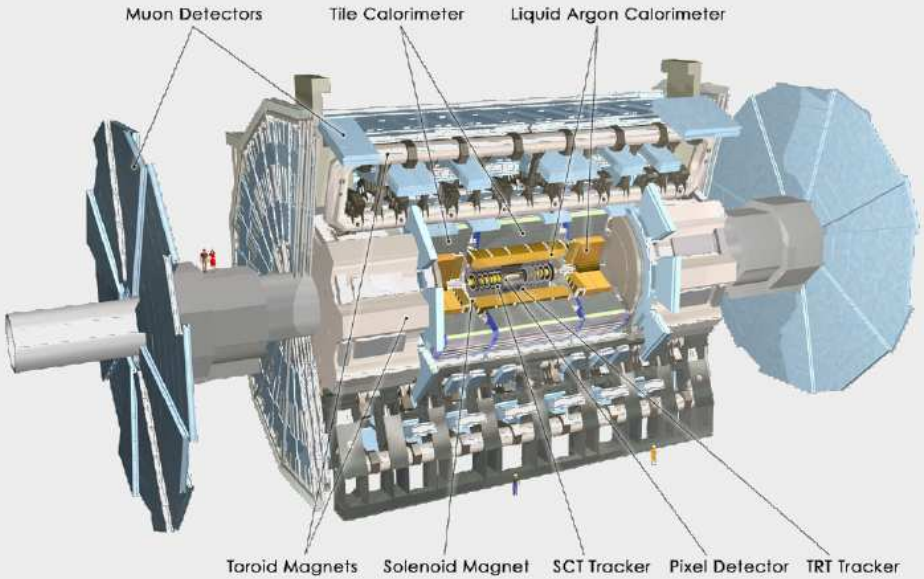


- Spin-0 simplified model: Phys. Rev. D91 015017, arXiv:1507.00966
- Reduced number of parameters:
  - $y_f = \sqrt{2} m_f / v$
  - $g_q = g_\chi = 1$
  - m_χ, m_ϕ free parameters
  - minimal flavor violation
- See also Alison's talk for spin-1 results



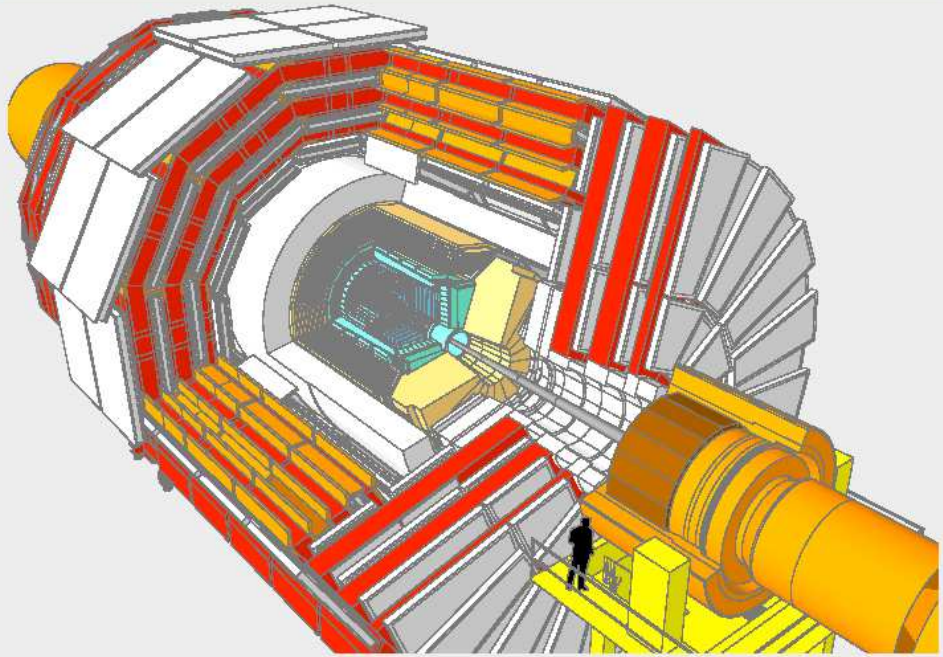
ATLAS and CMS

ATLAS



- 2 Tesla solenoid + barred and endcap toroid
- Silicon detector (new pixel IBL) and Transition Radiation Tracker (TRT)
- Em. calorimeter (PB+Lar, $\sigma(E)/E \sim 10\%/\sqrt{E} + 0.007$)
- Had. calorimeter (Iron Tile+scint., Cu+Lar HEC, $\sigma(E)/E \sim 50\%/\sqrt{E} + 0.03$)
- Muon Chambers (Drift Tubes)

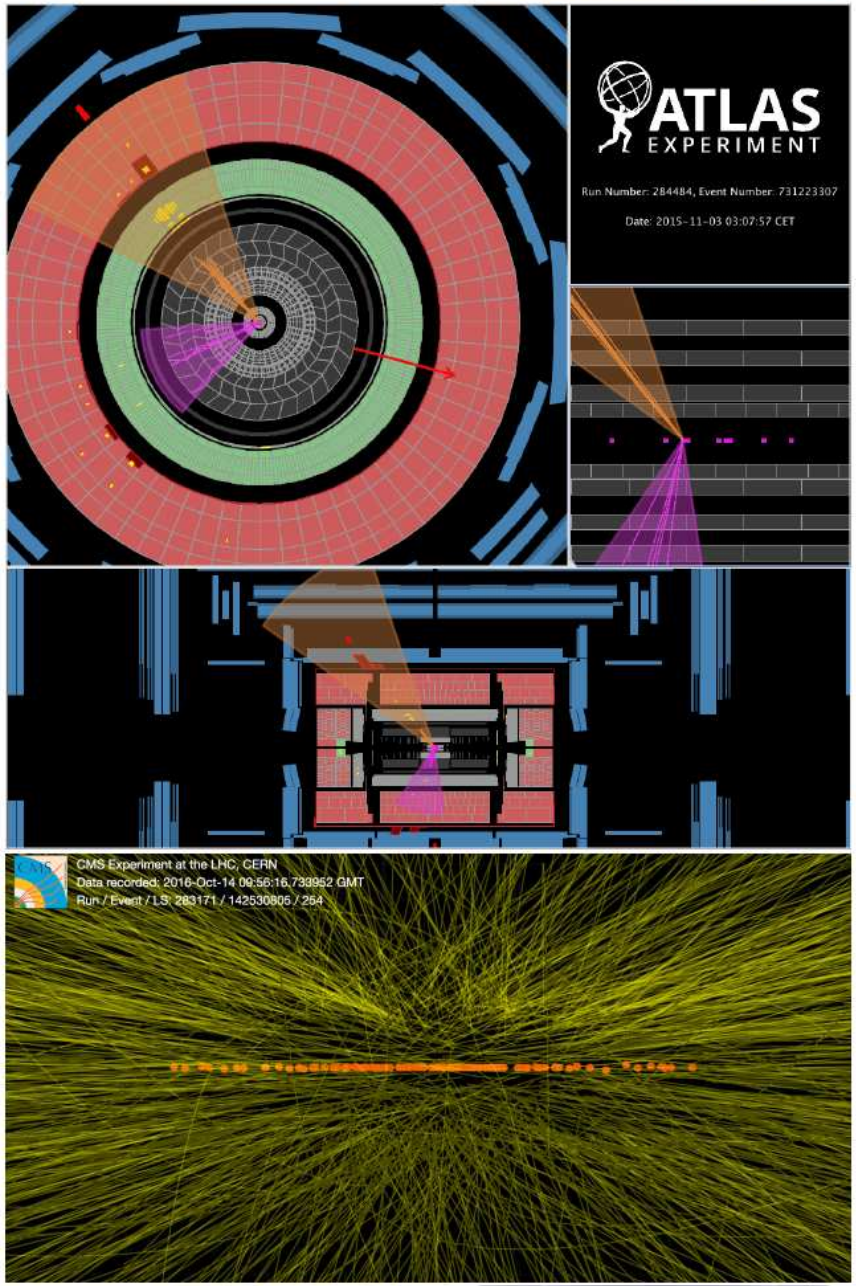
CMS



- 4 Tesla solenoid + return yoke
- Huge silicon detector (pixel and strips)
- Em. calorimeter (PbWO4 crystals, $\sigma(E)/E \sim 3\%/\sqrt{E} + 0.003$)
- Had. calorimeter (Brass+scint., $\sigma(E)/E \sim 100\%/\sqrt{E} + 0.05$)
- Muon Chambers (DT, RPC, CSC, $\sigma(p_T)/p_T \sim 1\%@50GeV$, $10\%@100GeV$)

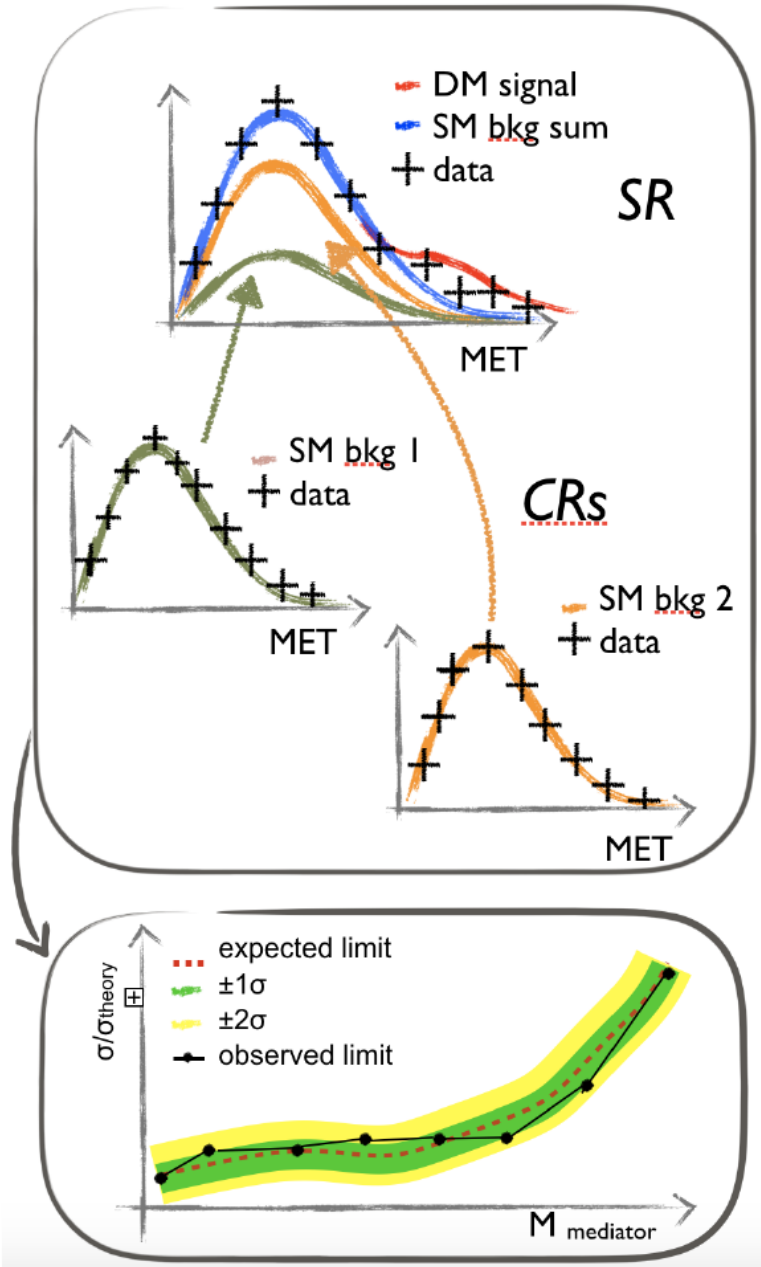
Experimental challenges at the LHC

- Dark Matter (DM) does not interact with the detector
  - presence inferred from imbalance in visible transverse momentum $\vec{p}_T^{miss} = -\sum \vec{p}_T^{vis}$
- Optimal calibration of visible objects (e.g. jets) crucial for an accurate p_T^{miss} estimate
  - detector **noise** and QCD multijet rejection
  - reconstruction and identification of other objects to identify accompanying particles (b and top quarks, W, Z, H)
- Very high rate in the collisions, especially in 2016/2017/2018:
  - need to filter out and save ("trigger") interesting events $\rightarrow$ p_T^{miss} threshold not always optimal
  - large number of additional collisions (pileup) spoils the p_T^{miss} computation $\rightarrow$ dedicated algorithms to mitigate the effect



Analysis strategy: how we look for DM at LHC

1. Select a **final state** (number and type of particles produced from the hard process), and try to **identify** the particles in the detector
2. Reject most of the SM backgrounds with kinematic selections
3. Search for excess in the tail of the p_T^{miss} distribution in **signal enriched region (SR)**
   - other SM **background** processes mimick the signal characteristics
4. A proper modeling and estimation of the main bkg processes in the SR is crucial
   - verify/improve predictions using simulation or data using dedicated **control regions (CR)**
     - kinematically similar but orthogonal to SR
   - other minor bkg estimated from simulation
5. Look at data in the SR:
   - significant excess: evidence of DM?
   - no excess: perform a statistical analysis to interpret result in terms of theory model parameters



DM and heavy flavor searches at ATLAS and CMS

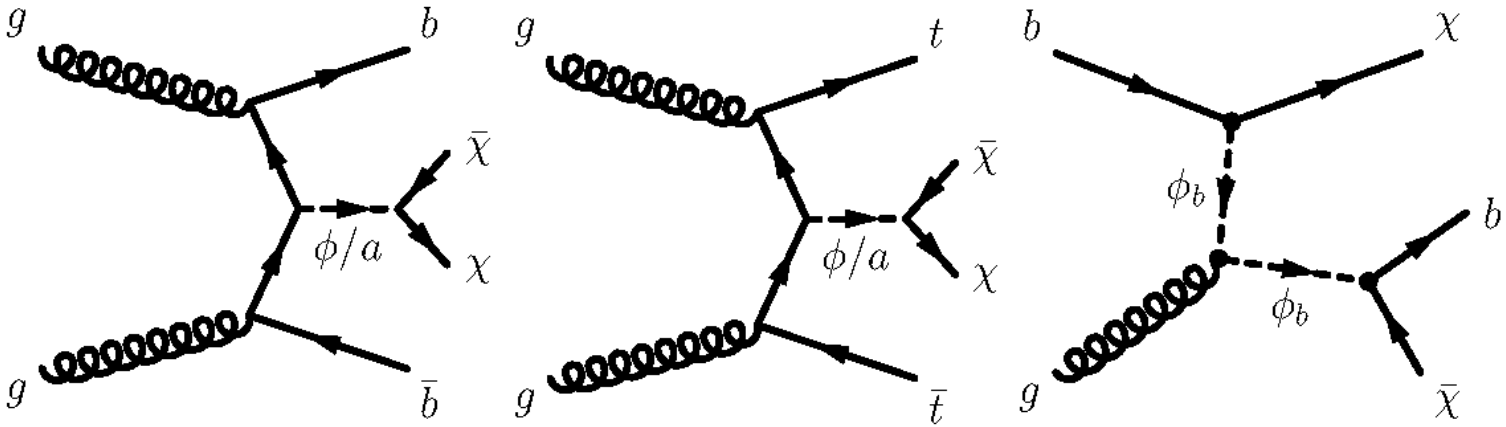
model	ATLAS EXPERIMENT	CMS
b(b)+DM	EPJC 78 (2018) 18	EPJC 77 (2017) 845 *
tt+DM	EPJC 78 (2018) 18 JHEP 06 (2018) 108	EXO-16-049
t+DM	-	EXO-18-010
b-FDM	EPJC 78 (2018) 18	-
mono-top	-	EXO-16-051
mono-H (Z'-2HDM)	ATLAS-CONF-2018-039 †	B2G-17-004
mono-H (Z' baryonic)	Phys. Lett. B 765 (2016) 11 *	EXO-16-050
mono-H (2HDM-a)	-	EXO-16-050

- All results from 2016 data set (36 fb^{-1}), except:
  - $*$ which is based on 2015 data (2.3 - 3.2 fb^{-1})
  - † which is based on 2016+2017 data (80 fb^{-1})
- See also Alison's talk for other ATLAS and CMS DM searches!

ATLAS DM+heavy flavor

Eur. Phys. J. C 78 (2018) 18

- Analysis that targets both bb+DM and tt+DM signatures:

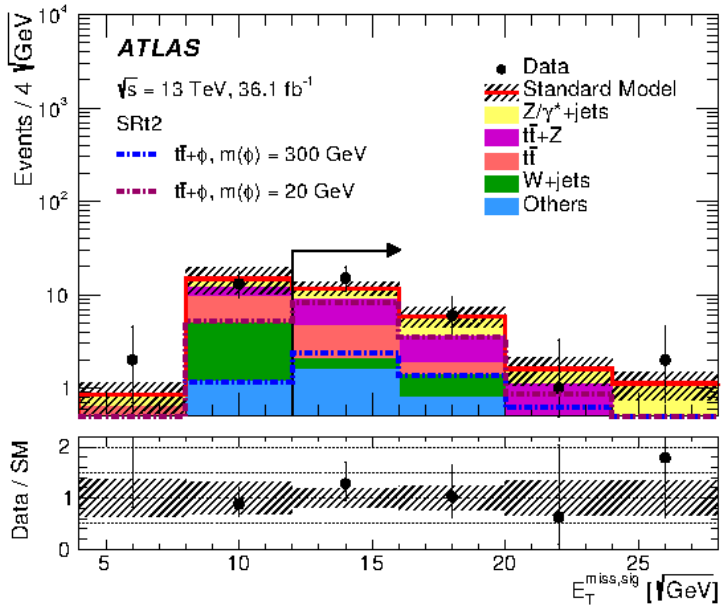


- Experimental signature: large p_T^{miss}, large N jet and b-jet, isolated leptons (from top)
- 3 signal regions for tt+DM:

SRt1: $p_T^{miss} > 300$ GeV, ≥ 4 jets, ≥ 2 b-jets, AK8 boosted $W \to qq$ (tt with moderate boost)

SRt2: same as SRt1, but with boosted top AK12 (boosted top)

SRt3: 2 OS SF leptons, ≥ 1 b-jet, $m_T^{\ell\ell} > 100$ GeV (tt dileptonic)



ATLAS bb+DM, tt+DM

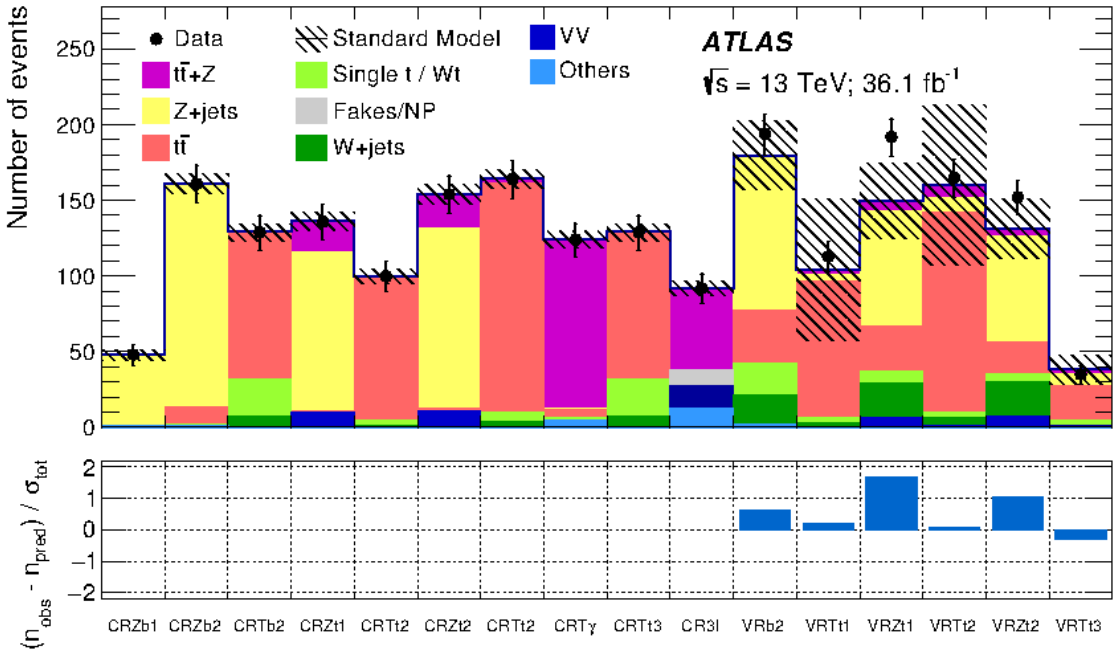
Eur. Phys. J. C 78 (2018) 18

- 2 more SRs for b+DM and bb+DM:

SRb1: $p_T^{miss} > 650$ GeV, ≥ 2 jets, ≥ 1 b-jet (mono-b)

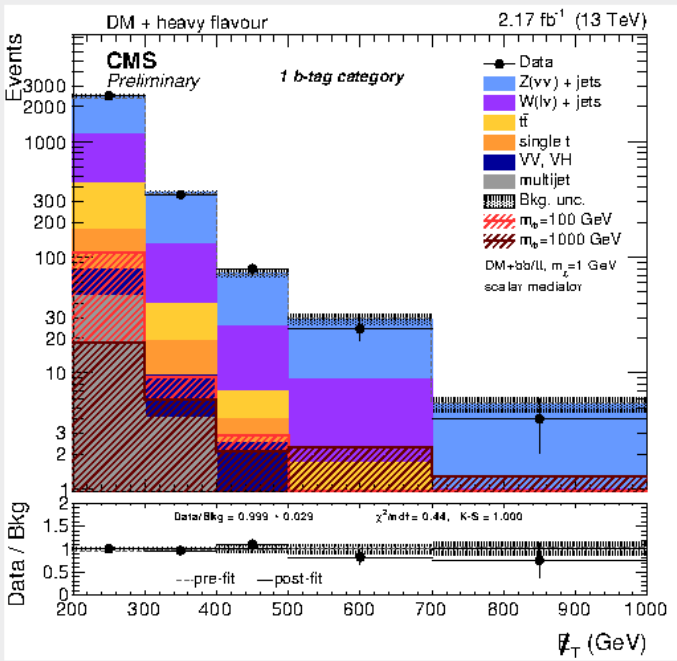
SRb2: $p_T^{miss} > 180$ GeV, 2 or 3 jets, ≥ 2 b-jet (bb)

- CR derived by inverting selections, enriched in one background
- Simultaneous fit to SR and CR:



CMS search (EPJC 77 (2017) 845)

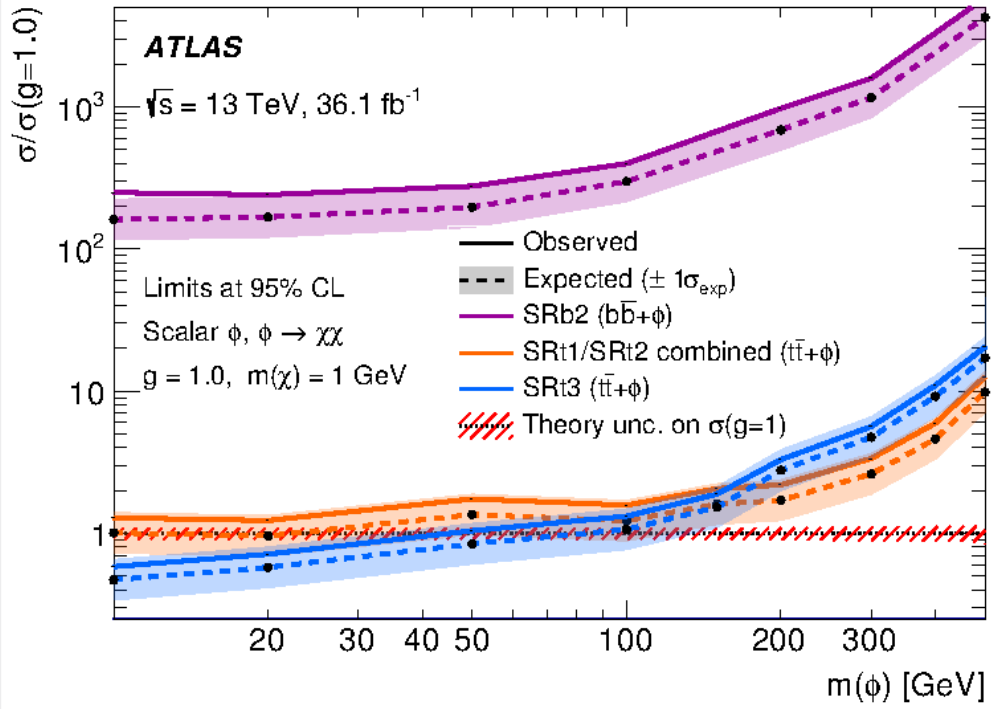
- Same topology and similar selection: 1 and 2 b SR
- Based on 2.3 fb^{-1} (2015)



ATLAS bb+DM, tt+DM

Eur. Phys. J. C 78 (2018) 18

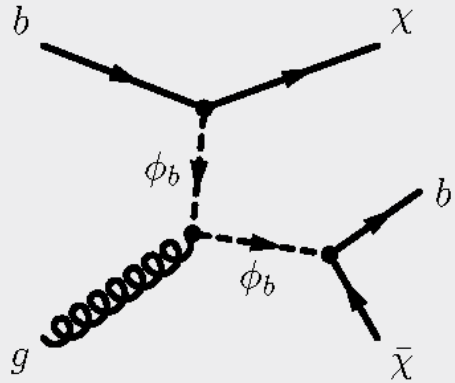
Scalar mediator

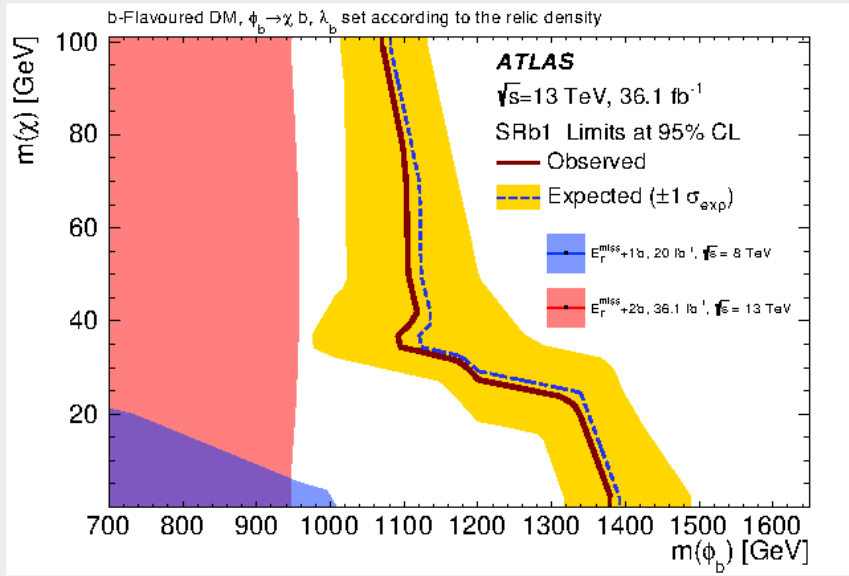


- Exclusion up to $m_\phi = 40$ GeV for $g_q = 1$ and $m_\chi = 1$ GeV
- Exclusion for b-only much less stringent

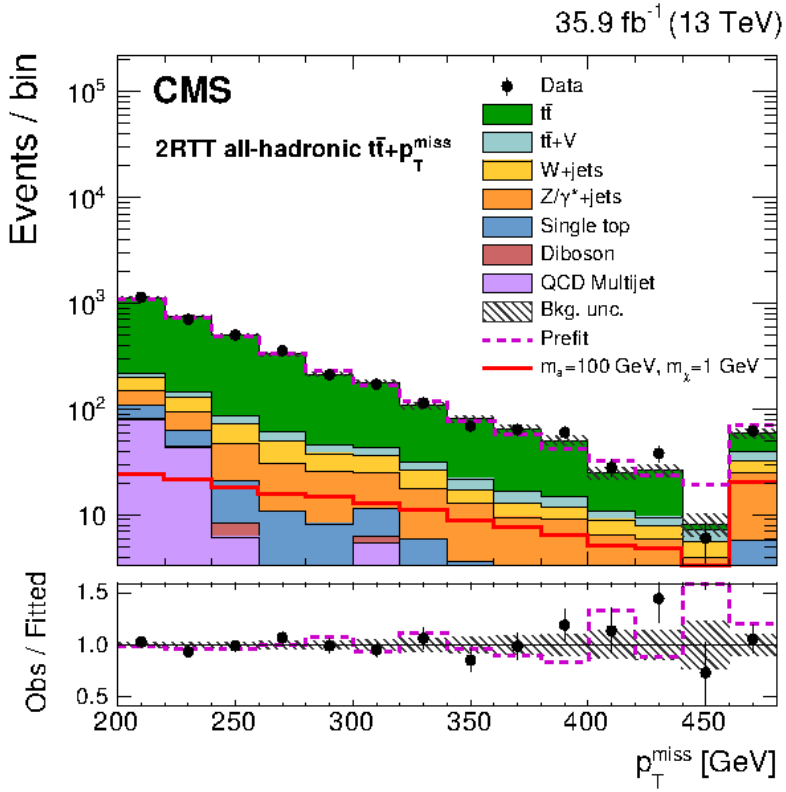
b-flavored DM (b-FDM)

- Model developed to explain the Fermi-LAT excess gamma rays [1]





- CMS search on 36 fb^{-1} for tt+DM, resolved topology
- Introduces the Resolved Top Tagger (RTT): multivariate discriminator to identify $t \to qqb$ from event kinematics
- Combination of 3 categories:
  - 0ℓ (all-hadronic): $p_T^{miss} > 200$ GeV, ≥ 4 jets, 1 or 2 b-jets, 0, 1, 2 RTT
  - 1ℓ (semileptonic): $p_T^{miss} > 160$ GeV, $m_T < 160$ GeV, ≥ 3 jets, 1 b-jet, $m_{T2}^W > 200$ GeV
  - 2ℓ (dileptonic): 2 jets, 1 b-jet, $m_T^{\ell\ell} > 110$ GeV



Analysis strategy

- Select CR inverting SR selections to enrich in one background

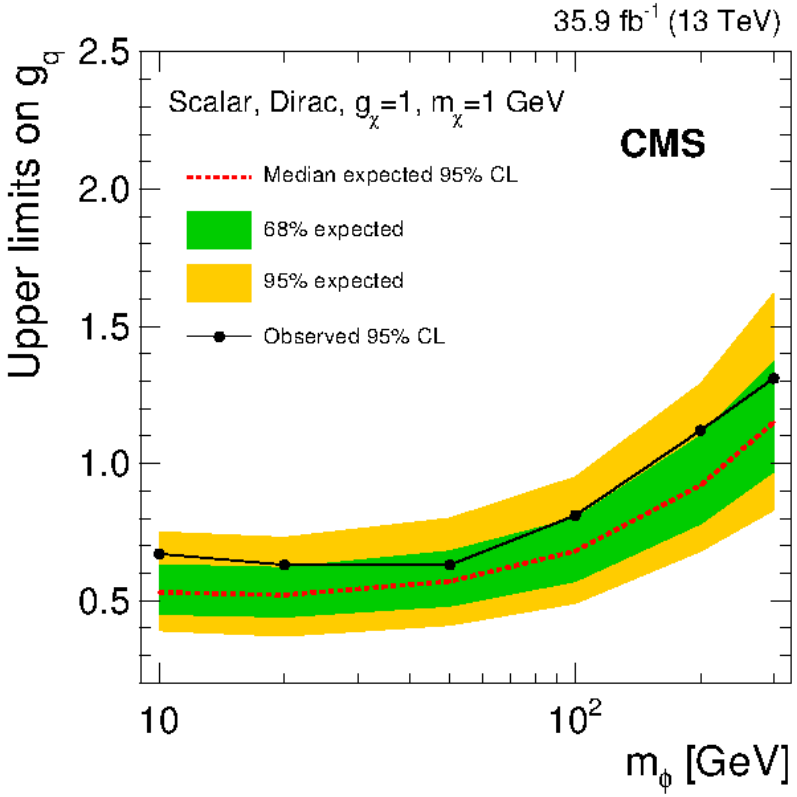
top: 1ℓ, invert m_T^W
W+jets: 1ℓ, invert b-jet identification
Z+jets: 2ℓ compatible with m_Z, invert N jets

- Fit "á la mono-jet":
  - simultaneous fit in all regions and bins (uncorrelated)
  - bin-by-bin uncorrelated SF from CR $\to$ SR for each background
  - normalization and shape taken from data

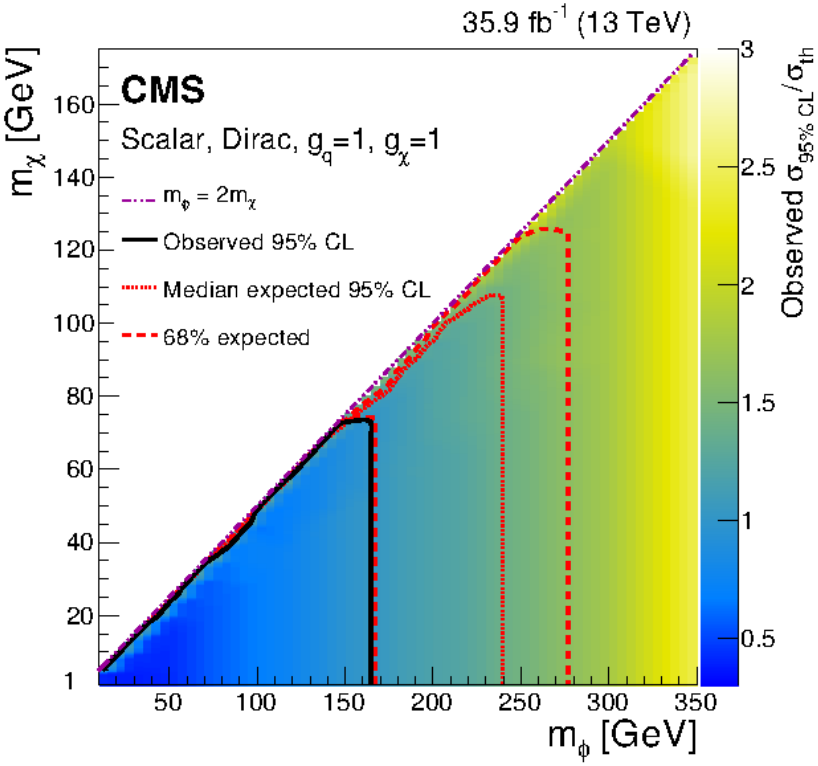
CMS tt+DM

CMS-EXO-16-049

Scalar



Scalar 2D

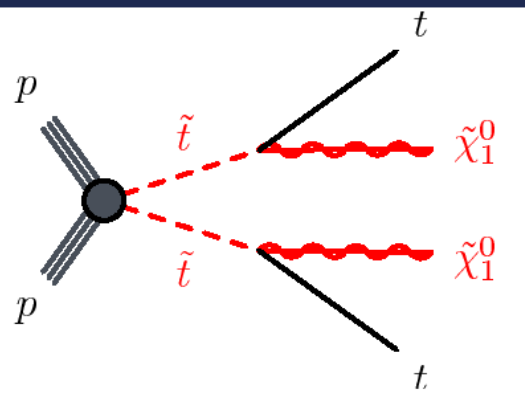


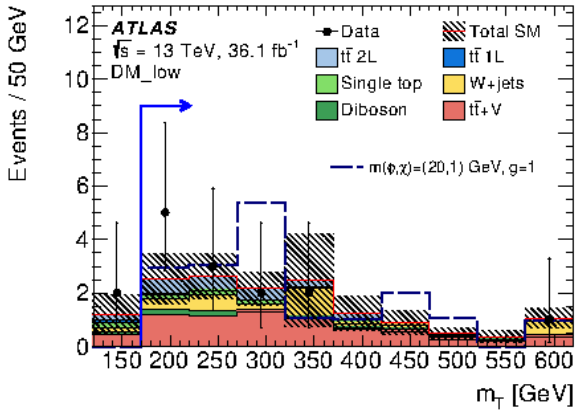
- Simultaneous fit in SR and CR to the p_T^{miss} distribution
- Scalar (pseudoscalar) mediator excluded up to 220 (320) GeV for the benchmark scenario $g_q = g_\chi = 1$
- Exclusion provided also in the the 2D m_ϕ vs m_χ
- Results available also for **pseudoscalar** mediator

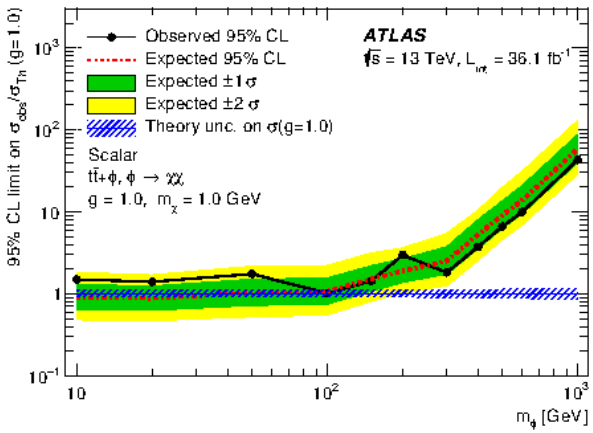
Constraints from ATLAS SUSY search

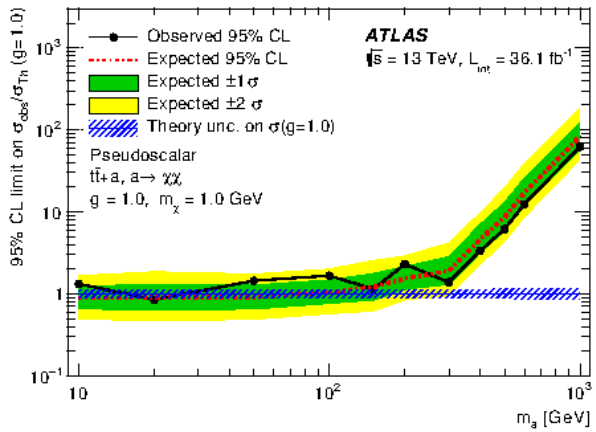
JHEP 06 (2018) 108

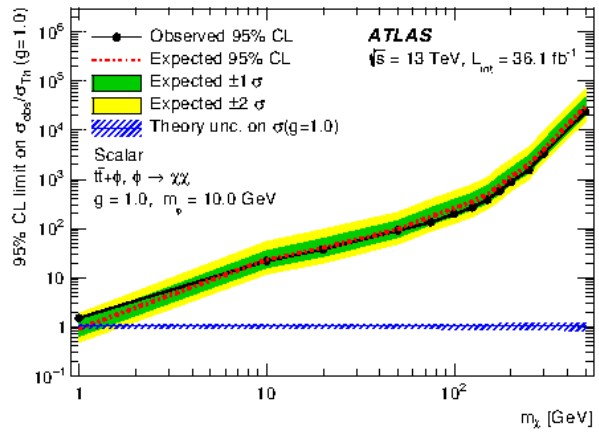
- Search on SUSY stop pair production in 2016 data
- Also used to place constraints on tt+DM production
- Same final state: 2 top quarks + p_T^{miss}, 1ℓ final state, but dedicated SR for tt+DM
- Complete event variables to reject events with no genuine p_T^{miss}
- Kinematic reconstruction of the top decays
- Simultaneous fit to SR and CR (cut & count)
- Limited sensitivity in the $g_q = g_\chi = 1$





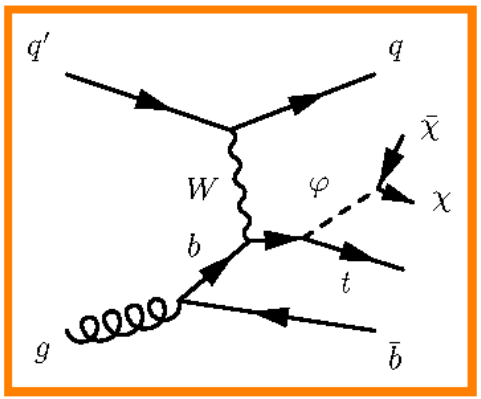


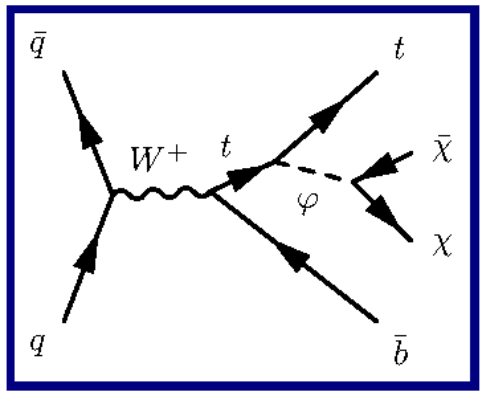


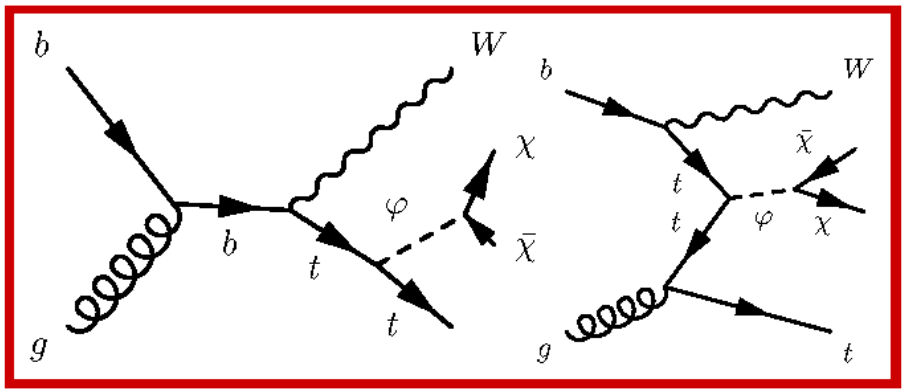


Dark matter and single top

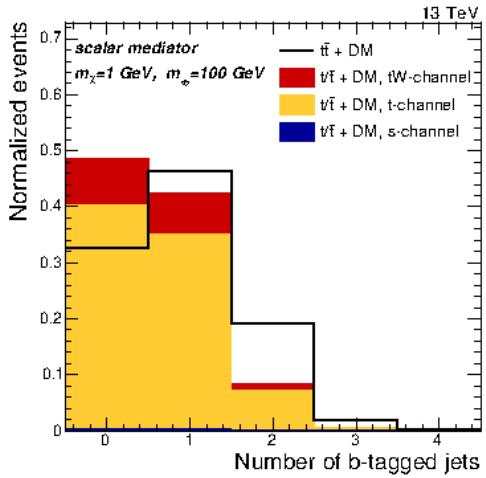
- If the mediator couples to top quarks, single top + DM (t+DM) is also possible [arXiv:1701.05195]
- The total t+DM cross section can be similar or larger than tt+DM
  - difference in kinematics, initial state, PDF
- As in SM, 3 separate production processes:

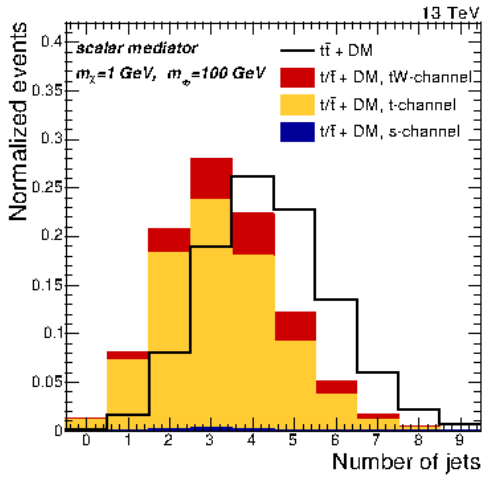






- Large cross-contamination between t+DM and tt+DM
- Different final state and particle multiplicity: less jets and b-jets (1 vs 2), less leptons
- Single top in s-channel is negligible

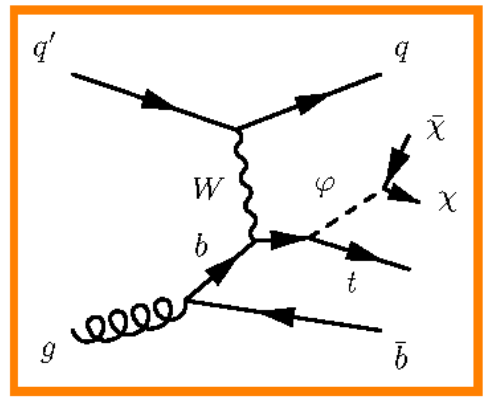




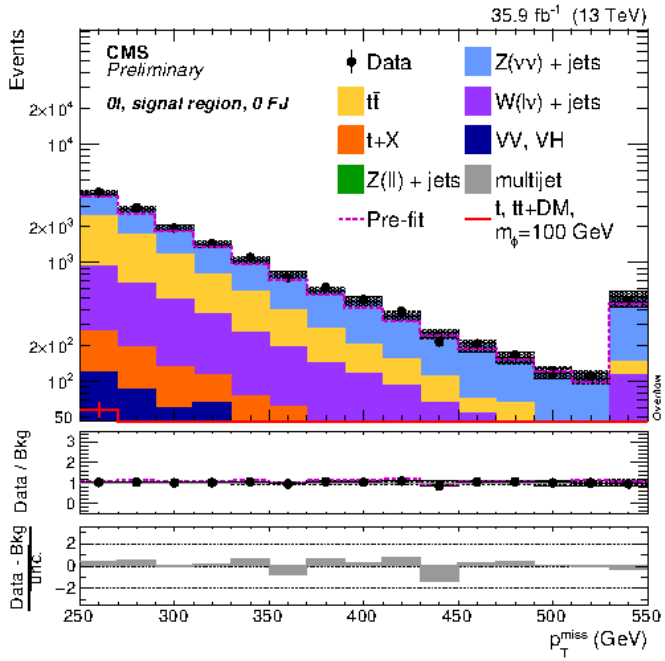
- Search based on 36 fb^{-1} of data by CMS
- Two categories: All-hadronic and single-leptonic

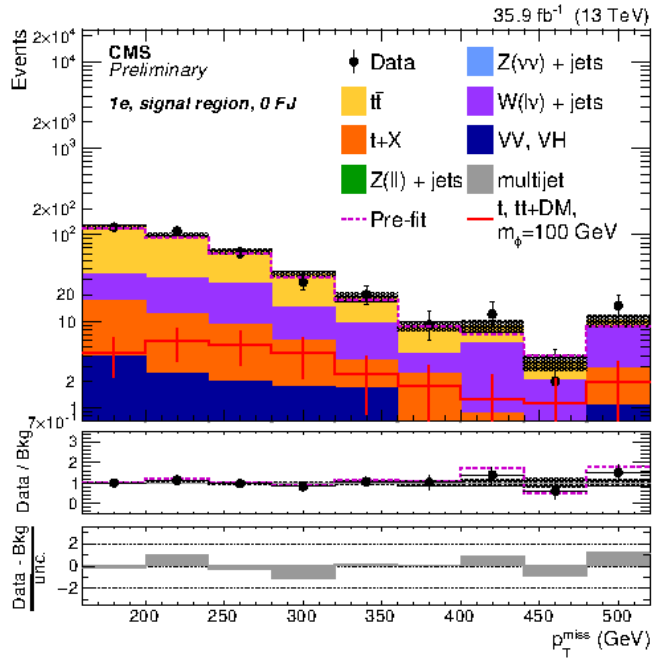
  AH: $p_T^{miss} > 250$ GeV, lepton veto, ≥ 3 jets, 1 b-jet

  SL: $p_T^{miss} > 160$ GeV, 1 isolated lepton, ≥ 2 jets, 1 b-jet
- Categorize in number (0 or $\geq$1) of forward jets ($2.4 < |\eta_j| < 4.0$)
  - exploit forward quark from t-channel production



- Similar strategy to tt+DM: simultaneous bin-by-bin fit to SR and CR
- p_T^{miss} shape of main backgrounds (Z+jets, W+jets, $t\bar{t}$) taken from data

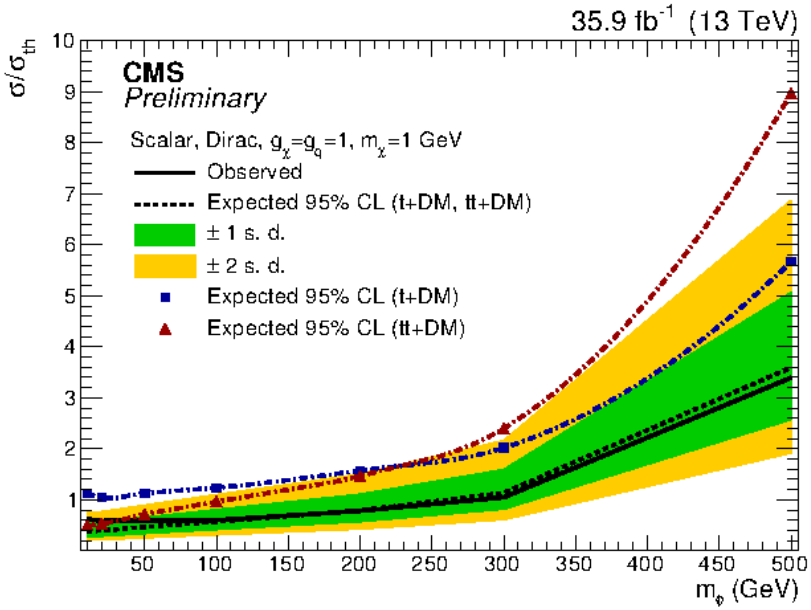


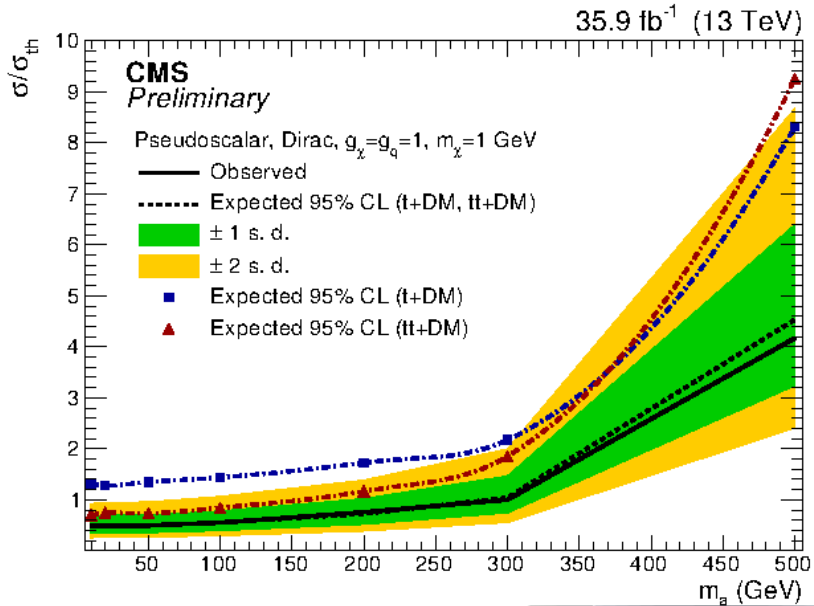


CMS t+DM

EXO-18-010

- Add also 2 b-jet categories and tt+DM signal for a realistic estimation of the sensitivity
  - very similar selections to the tt+DM analysis, but no RTT
- Fit simultaneously for t+DM and tt+DM with a single signal strength modifier parameter
  - both cross sections are determined from the same set of parameters
- Single top + DM kinematically favored at large m_ϕ (harder p_T^{miss} spectrum)
- Best results from the combination t+DM and tt+DM
- Most stringent limits to date on the scalar (pseudoscalar) mediators: excluded mass $<$ 290 (300) GeV

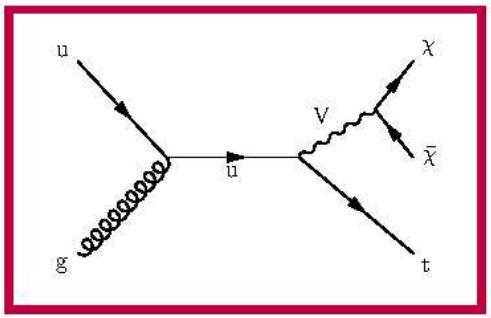


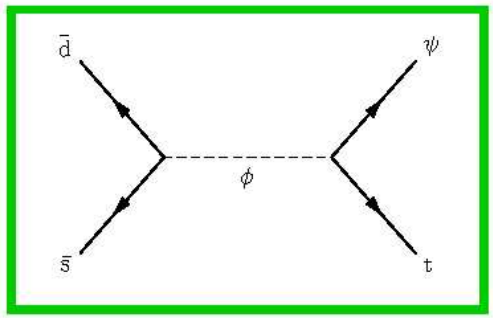


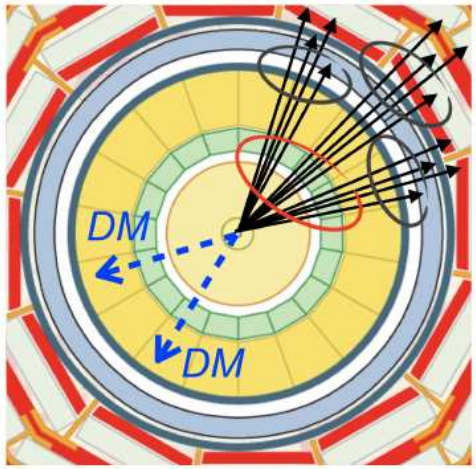
CMS mono-top

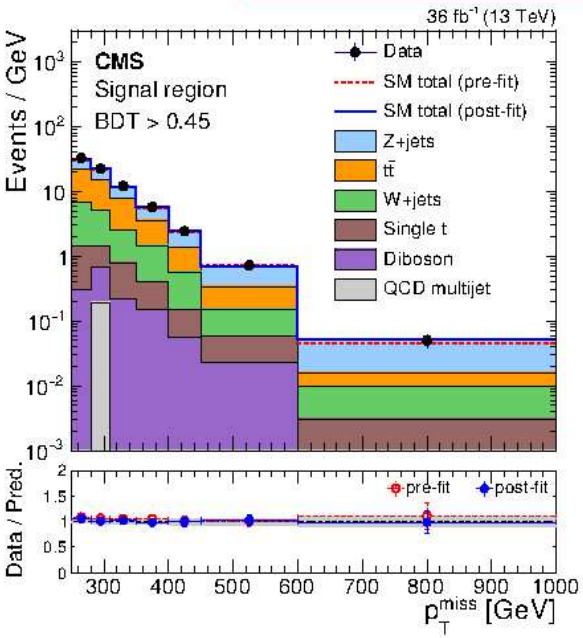
EXO-16-051

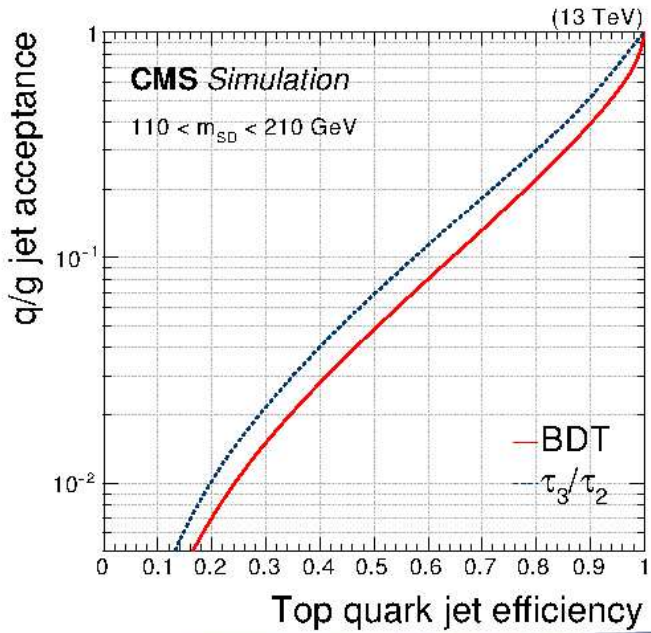
- Final state with single top and large p_T^{miss} (mono-top)
- Two main BSM production modes:
  - FCNC interaction with an invisible Vector/Scalar DM particle
  - Resonant production through colored mediator to invisible exotic state











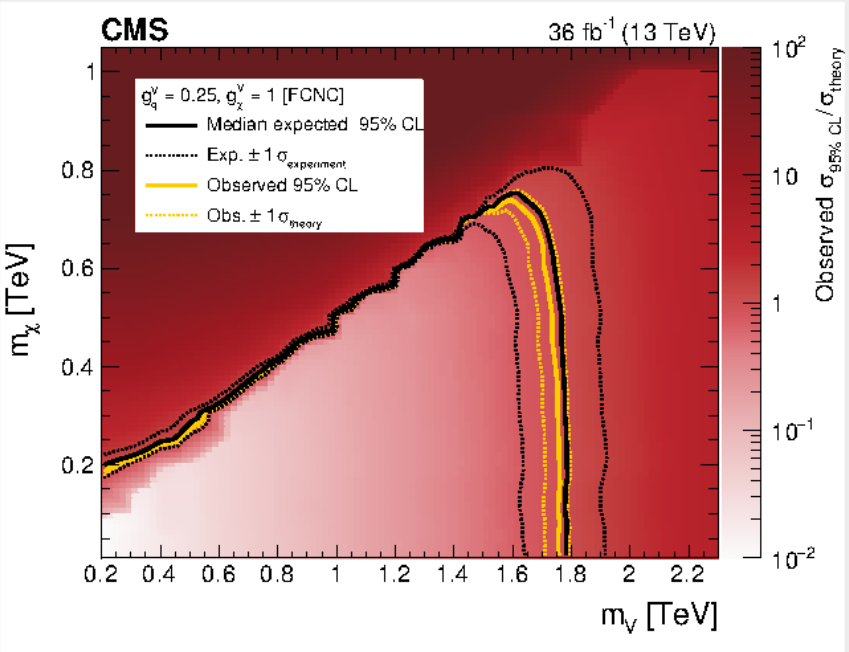
Boosted top reconstruction

- Contained in CA R=1.5 large cone jet
- BDT for identification on 13 substructure variables (τ_3/τ_2, ECF, mass)
- Better performance than simple cut

- Introduced γ+jets CR to correct $Z(\nu\nu)$+jets background
- Multi-region (combined CR and SR) fit "á la mono-jet"

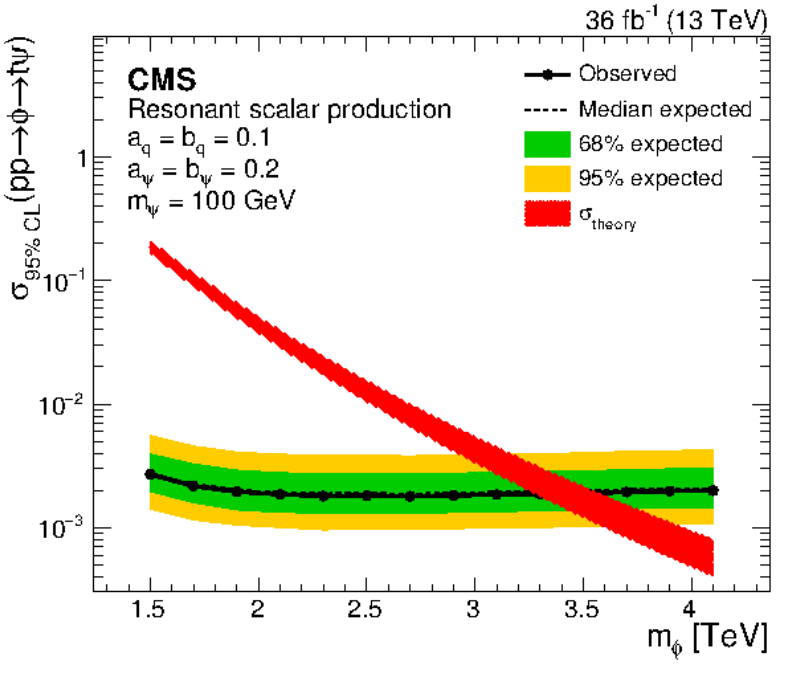
FCNC model

- Limits expressed on the 2D plane of mediator mass vs. DM mass



Resonant model

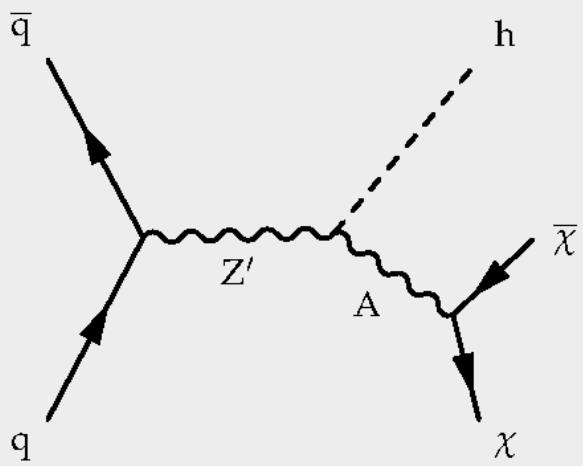
- m_ϕ is the fundamental parameter



Mono-Higgs

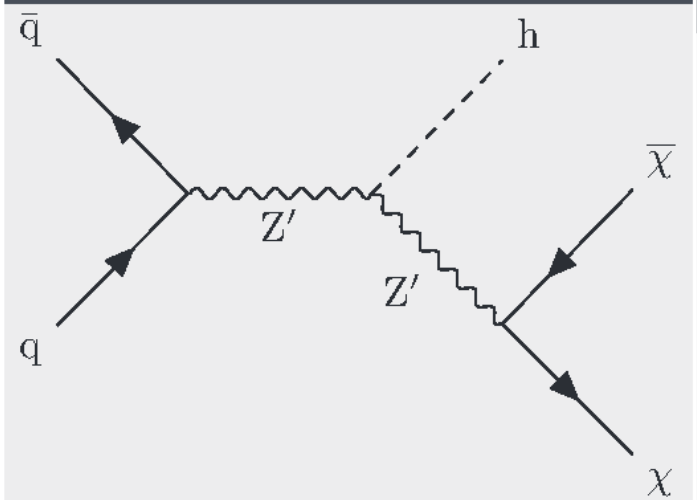
- The discovery of the Higgs boson opens a new opportunity through the H+MET signature (mono-Higgs)
  - $H \to b\bar{b}$ being the most probable decay channel
- 3 main models, each one with its own peculiarities
- Different kinematics and reconstruction techniques

Z'-2HDM [**ATLAS, CMS**]



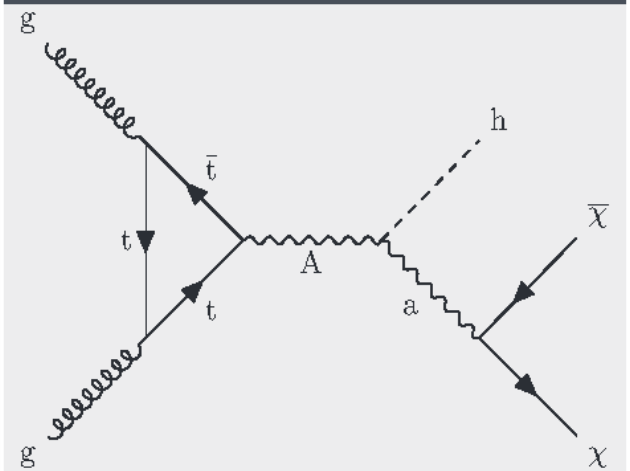
- one heavy vector Z' + 2HDM phenomenology
- A boson mediator for DM
- "resonant" to the Z' mass

Z' baryonic [**ATLAS, CMS**]



- Higgs boson radiated from Z'
- Non-resonant
- soft p_T^{miss} spectrum

2HDM + a [**CMS**]

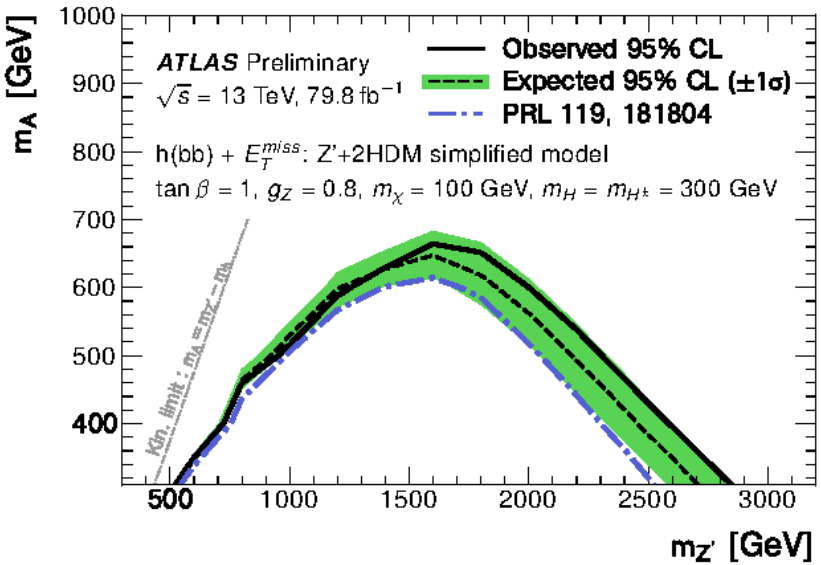


- 2HDM + one light pseudoscalar (a)
- a mixes with h, A, and DM; $a \to \chi\chi$

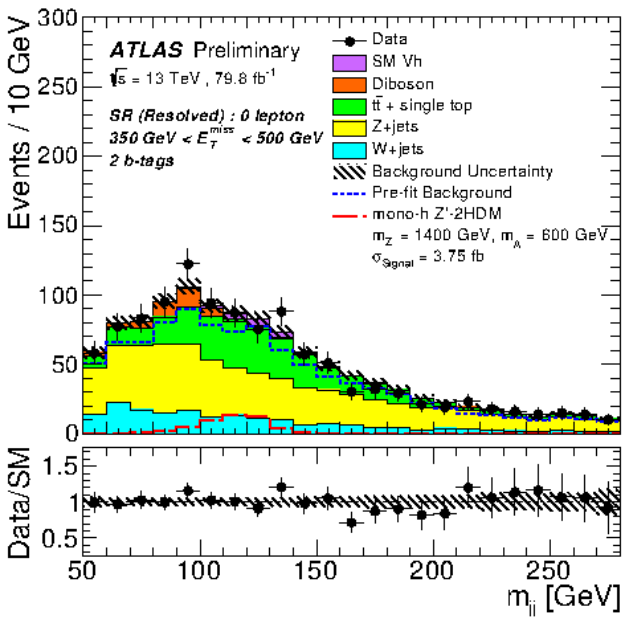
ATLAS mono-Higgs

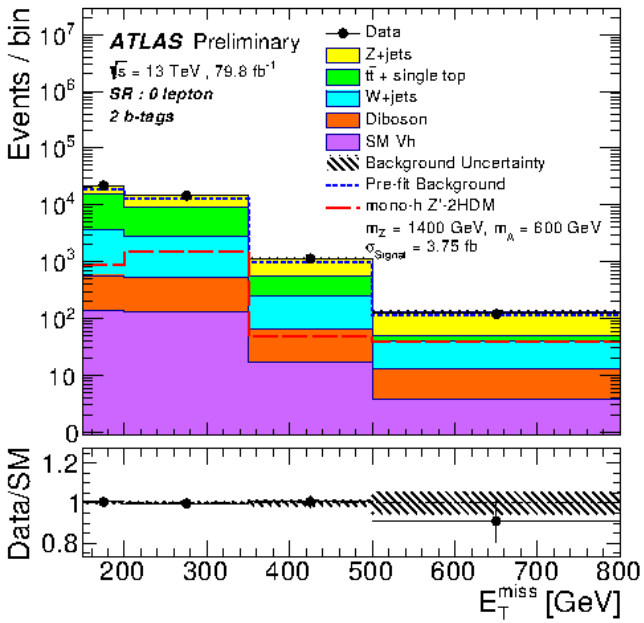
ATLAS-CONF-2018-039

- First analysis based on **2016 + 2017** data
- Two ways to reconstruct the Higgs (4 p_T^{miss} bins):
  - 3× $p_T^{miss} < 500$ GeV: two resolved b-jets,
  - 1× $p_T^{miss} > 500$ GeV: one large-cone with double subjet tagging
- Control regions: 1ℓ for W+jets, 2ℓ for Z+jets
- Exclusions on Z'-2HDM the 2D plane $m_{Z'}$ vs m_A
- Excluded $m_{Z'} < 2900$ GeV, $m_A < 660$ GeV



- Results on Z' baryonic on **PLB 765 (2016) 11** (2015 dataset)

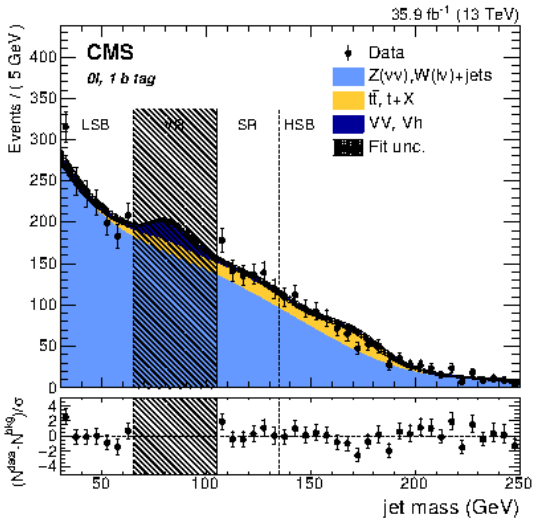


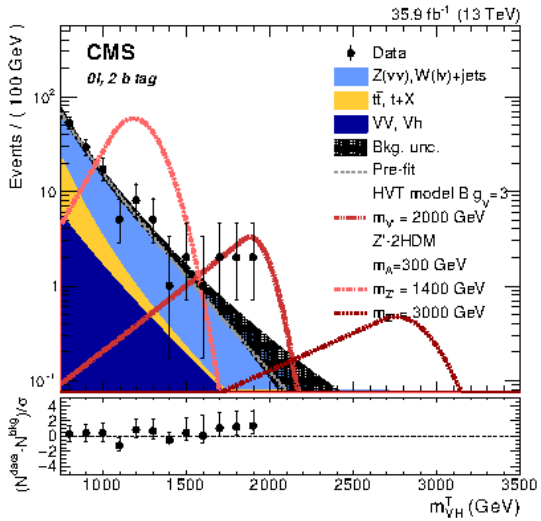


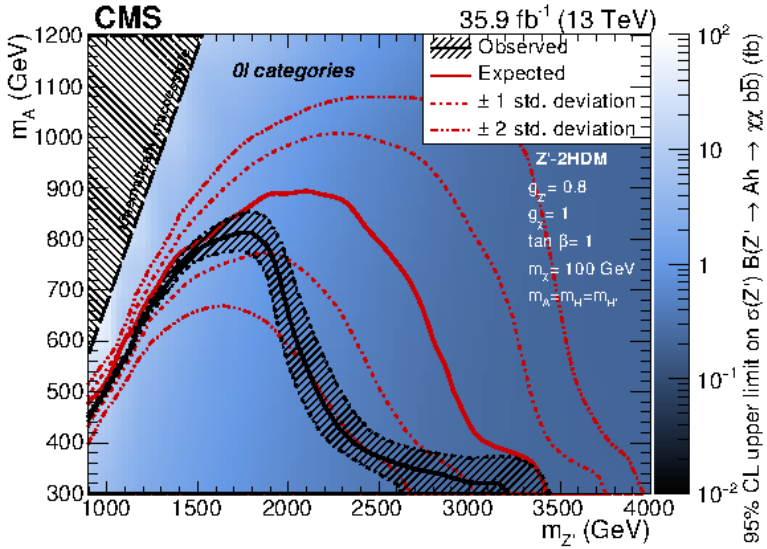
CMS mono-Higgs

CMS-B2G-17-004

- Resonant diboson searches interpreted in Z'-2HDM model
  - identical signal topology of $Z' \to ZH \to \nu\nu qq$ ($A \to \chi\chi$ instead of $Z \to \nu\nu$)
  - fully optimized for high mass searches
- Large Z' mass, large H boost: merged AK8 jets tagged with mass and 1 or 2 b-subjets
- Reconstruct $m_{Z'}$ on the transverse plane: $m_T = \sqrt{p_T^{miss} p_T^H (1 - \cos\Delta\phi)}$
- Adopt a data-driven/MC hybrid method (α-method)
- Take main background normalization (V+jets) fitting the jet mass
- Extrapolate m_T shape from m_j sidebands to SR with function from MC
- Exclude Z'-2HDM $m_{Z'} < 3200$ GeV vs $m_A < 800$ GeV



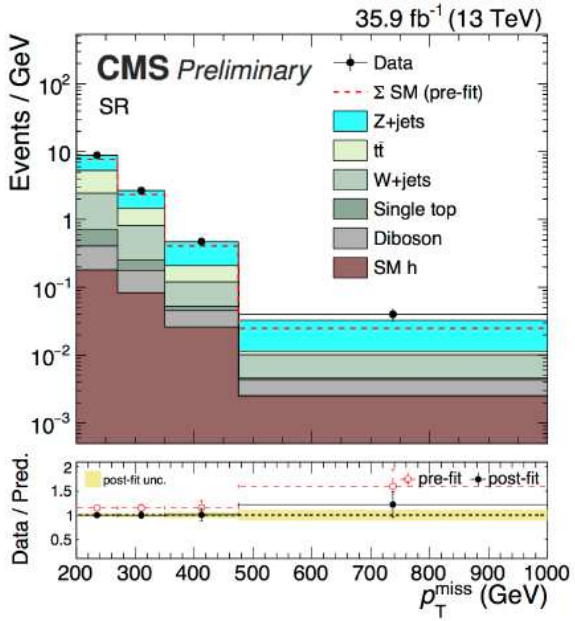


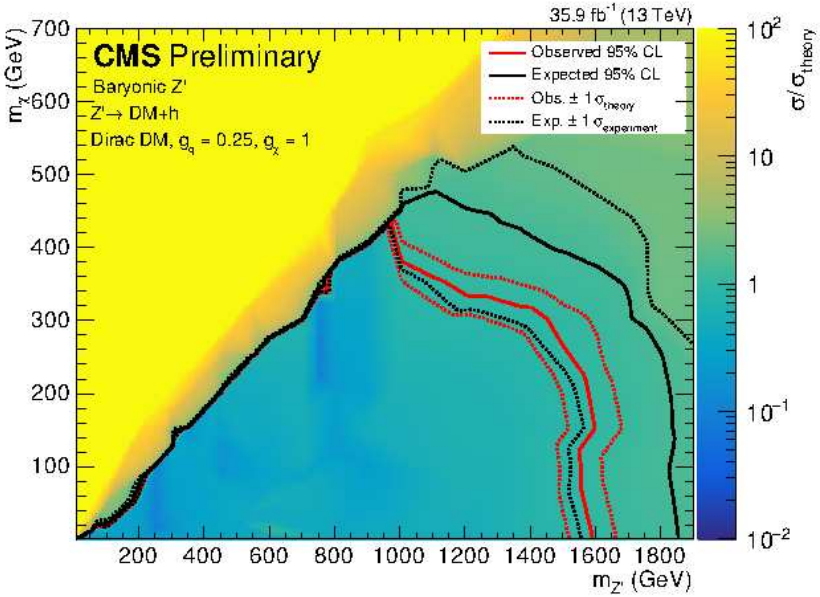


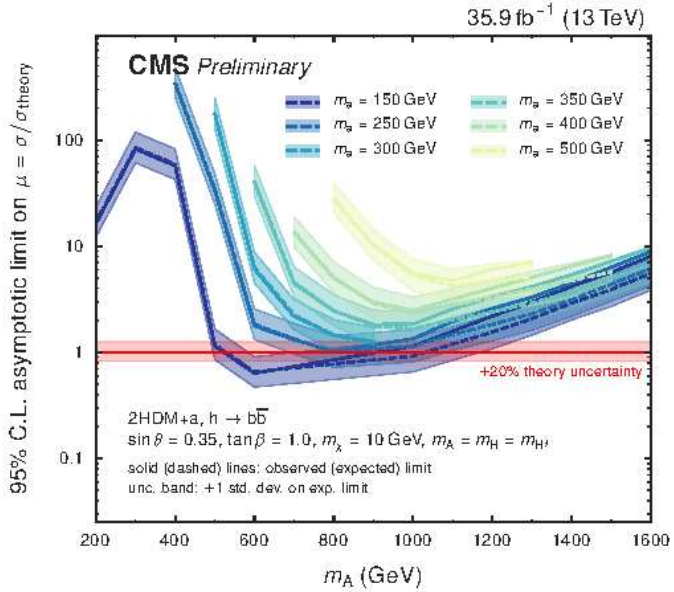
CMS mono-Higgs

EXO-16-050

- Targets Z' baryonic and 2HDM-a models
- Final state with moderate boost: Higgs contained in $R = 1.5$ CA jets
  - identification through jet mass and "double-b" tagger, energy correlation functions
- Besides 1ℓ and 2ℓ CR, also 0ℓ CR with "anti-tagged" jet
- Simultaneous bin-by-bin fit to the p_T^{miss} shape
- First results on the 2HDM-a model



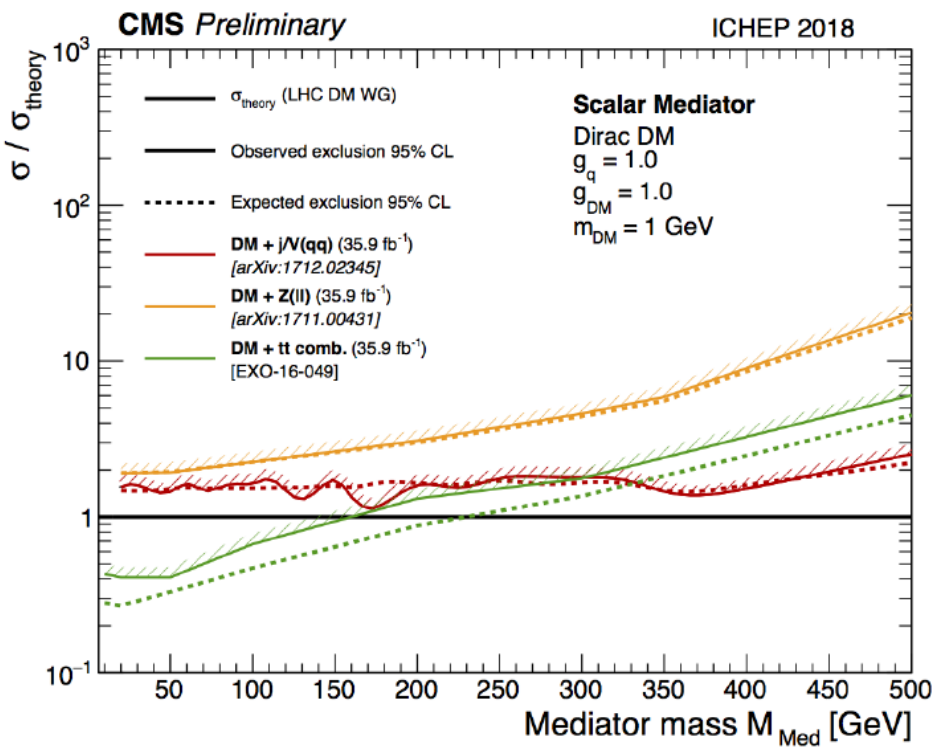




DM and heavy flavor summary

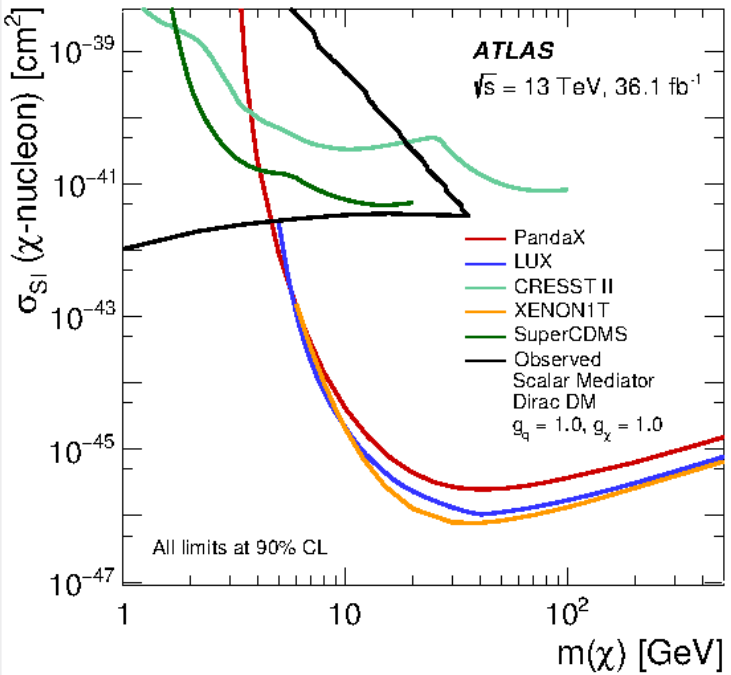
Simplified models

- tt+DM still one of the best way to discover scalar/pseudoscalar mediators
  - especially at low mass
- Exclusion now at ≈ 300 GeV with 2016 data with t+DM



Comparison with DD

- tt+DM limits as $\sigma_{\chi-nucleon}$ and comparison with direct-detection experiments (after **some** assumptions)



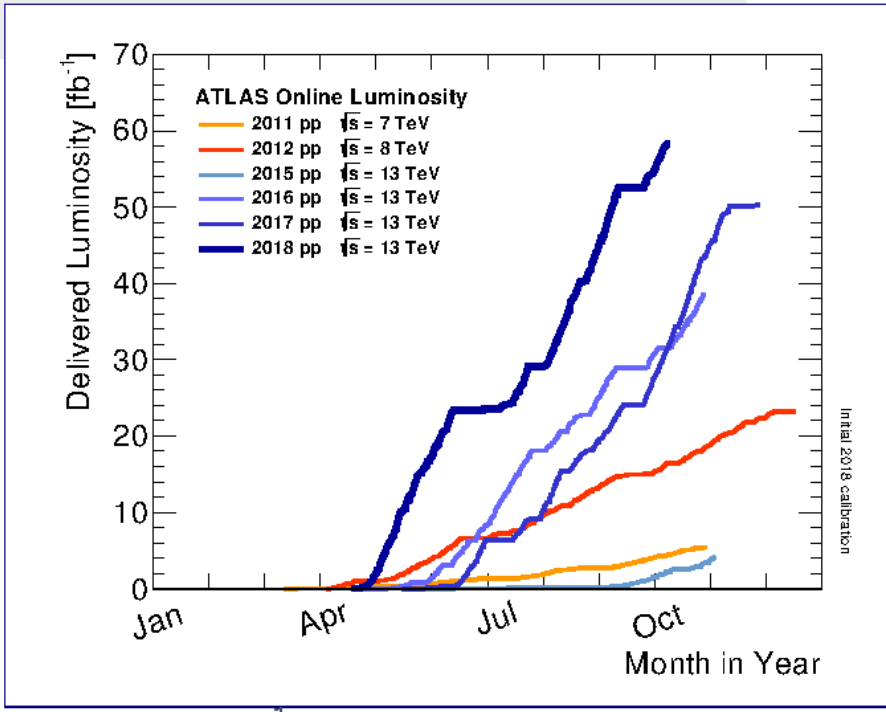
Summary

Concluding remarks

- A lot of possible interactions between DM and heavy flavor quarks
- Wide and varied phenomenology
  - simplified models with bb+DM, tt+DM, **t+DM**
  - flavor violating b-FDM, mono-top
  - several mono-Higgs declinations

Future outlook

- Analyses are progressing well
- In Run-I, we had mostly cut & count analyses with standard objects
- In Run-II we saw **a lot** of developments on the experimental side:
  - shape and complex multi-regions fits
  - bin-by-bin fits to estimate the shape from data
  - Boosted techniques
  - Multivariate discriminators
- What next? Full Run-II and Run-III?
- For now, we are still taking data...



- 150 fb^{-1} collected!
- Expect significant improvements in the next 1-2 years!

Backup slides

SI and SD intepretations

https://arxiv.org/pdf/1603.04156.pdf

- Spin-independent (SI) interaction for vector and scalar mediator
- Spin-dependent (SD) interaction for axial-vector and pseudo-scalar mediator
- The pseudo-scalar interaction has additional velocity-suppression in the non-relativistic limit
- The mediator-nucleon coupling is $f(g_q)$
- For the vector mediator, $f^p(g_q) = f^n(g_q) = 3g_q$
- For the scalar mediator, $f^{n,p}(g_q) = 1.16 \cdot 10^{-3} g_q$
- Under the assumption that the coupling g_q is equal for all quarks, $f(g_q) = 0.32 g_q$ in the SD case (equal coupling to all quarks)
- SI case:

$$\sigma_{SI} \approx 6.9 \cdot 10^{-43} cm^2 \cdot \left(\frac{g_q g_\chi}{1}\right)^2 \left(\frac{125\,GeV}{m_\phi}\right)^4 \left(\frac{\mu_{n\chi}}{1\,GeV}\right)^2$$

where $\mu_{n\chi} = \frac{m_n m_\chi}{m_n + m_\chi}$ is the DM-nucleon reduced mass

- SD case:

$$\sigma_{SD} \approx 2.4 \cdot 10^{-42} cm^2 \cdot \left(\frac{g_q g_\chi}{0.25}\right)^2 \left(\frac{1\,TeV}{m_\phi}\right)^4 \left(\frac{\mu_{n\chi}}{1\,GeV}\right)^2$$