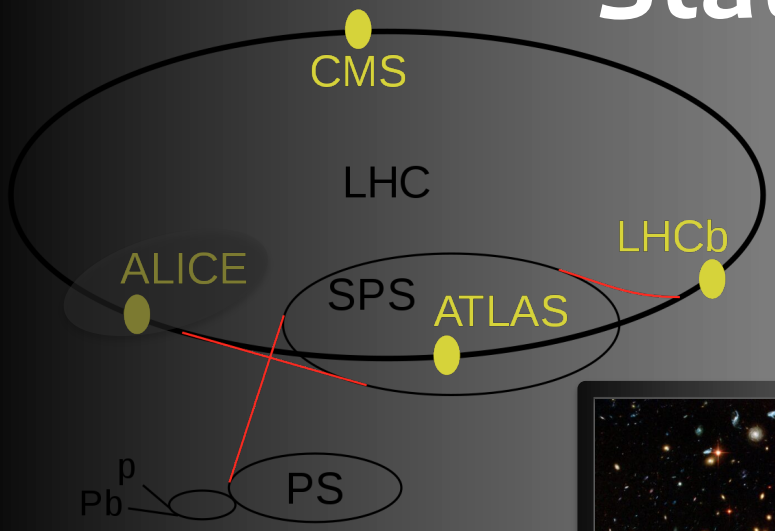
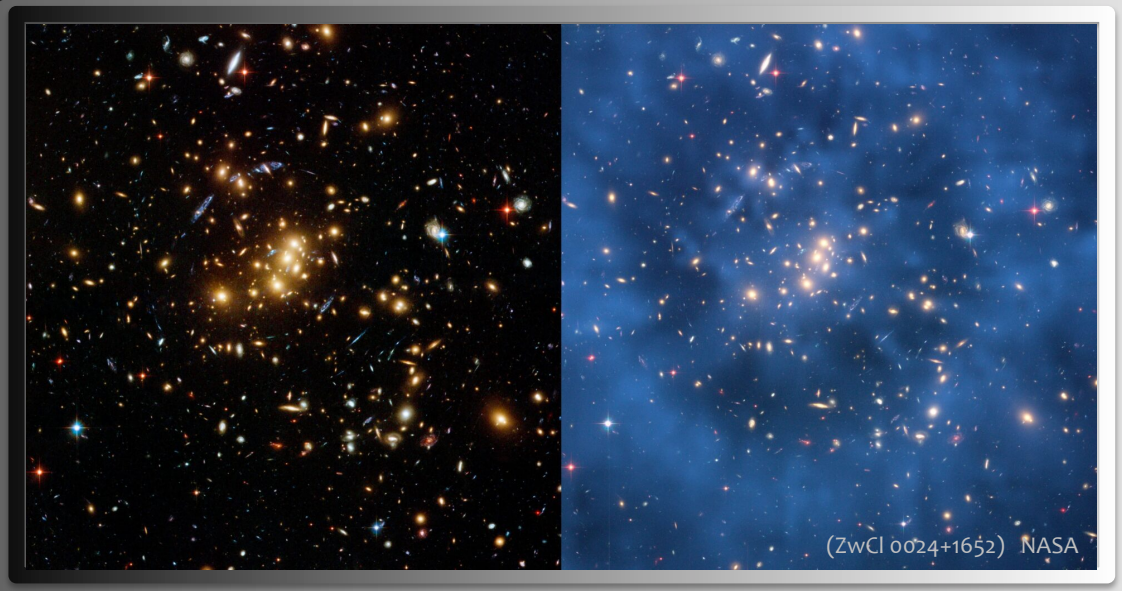
Status of Dark Matter searches at LHC (ATLAS+CMS+LHCb)





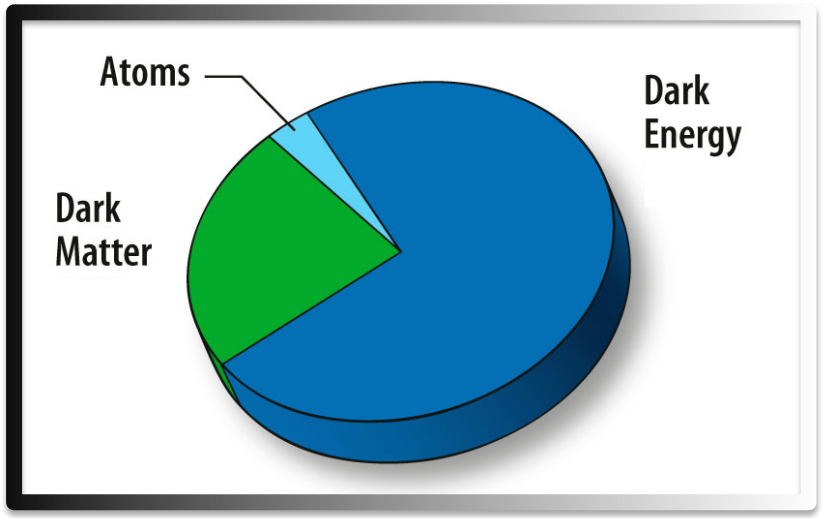
Małgorzata Kazana
CMS Collaboration

NCBJ National Centre for Nuclear Research **Poland**

IPA 2022: Interplay between Particle and Astroparticle Physics
5 - 10 Sep 2022
Vienna, Austria

Mystery of Dark Matter

- Astrophysical observations **strongly suggest** a presence of **Dark Matter** in the Universe



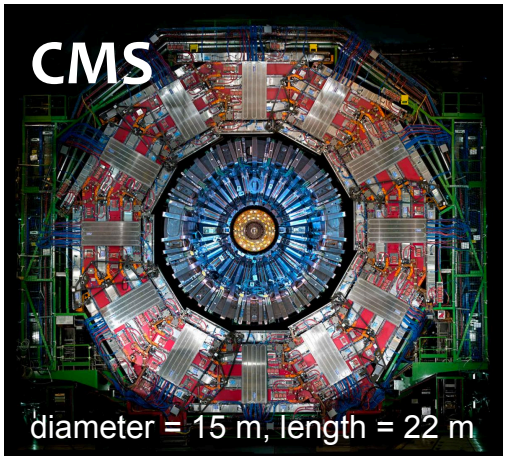
- *Unknown nature* of DM particles but:
  - **Dark** because does not interact with electromagnetic filed
  - Interacts **gravitationally**
  - **Non-baryonic** matter
  - No Standard Model candidate
    - Neutrinos are too *hot* since they have high speed close to speed-of-light

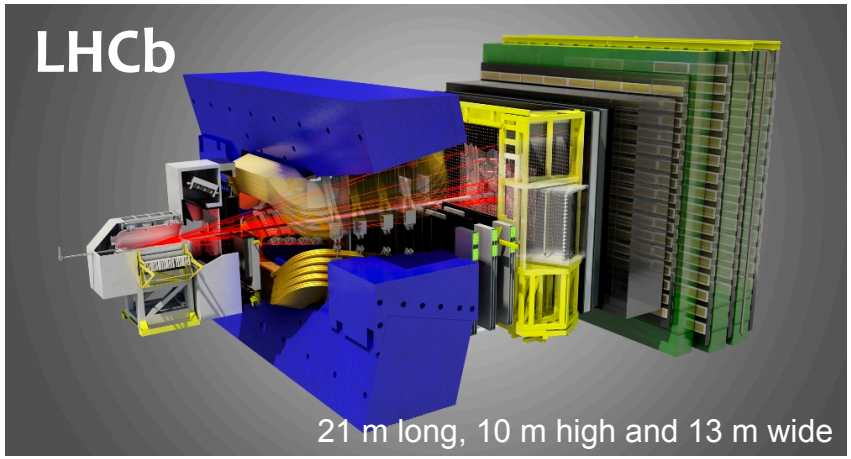
- Plenty of DM particle candidates: (new kind of unknown particles BSM)
  - **WIMPS,** weakly (only gravitionally) interacting massive particles
  - Weak scale particles: from SUSY, Extra Dimensions, No-SM Higgs boson models and more
  - **Axions,** light bosons which can resolve a CP problem in QCD
  - **Dark Sector** particles: Dark Higgs, Dark photons
  - **SIMPs,** Strongly interacting massive particles
  - and many others

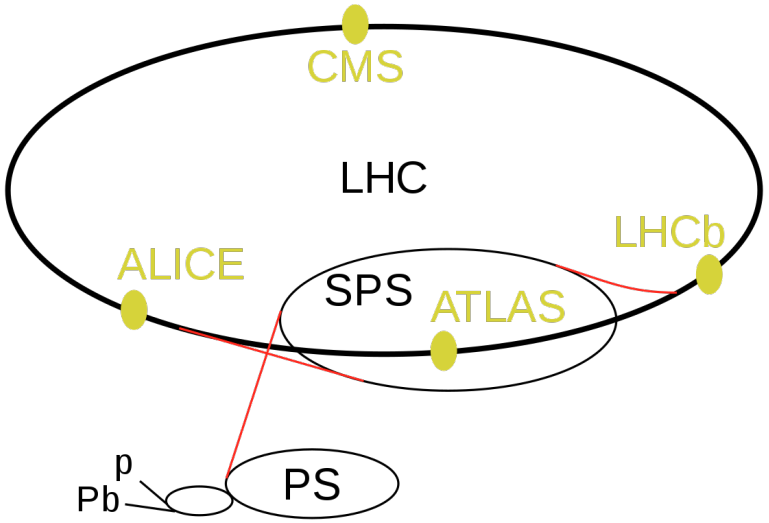
Exotic

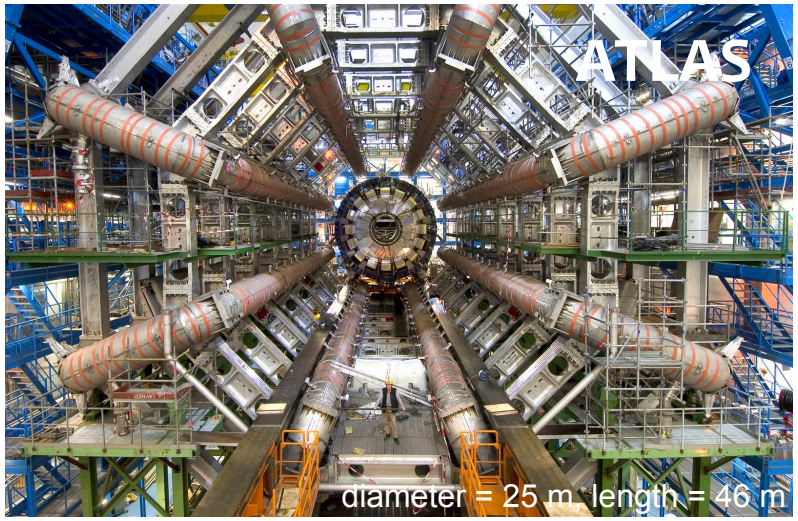
Dark Matter at colliders (LHC)

- DM particles (if exist) **may be produced at colliders** in a controlled experimental conditions
- **LHC Run 2** proton-proton collision at **13 TeV** provided **~ 140/fb** of data



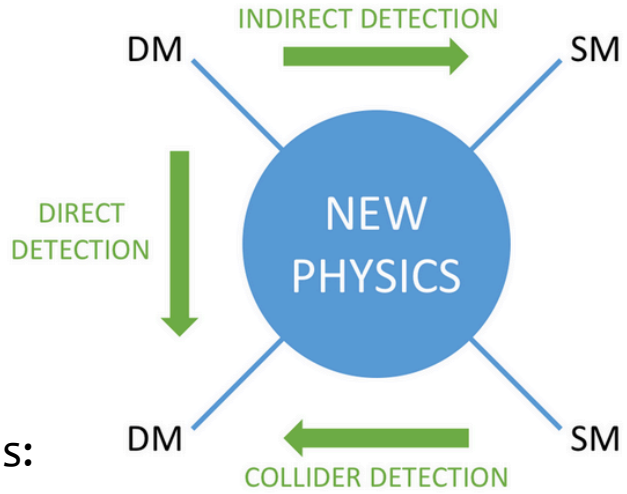






Dark Matter at colliders (LHC)

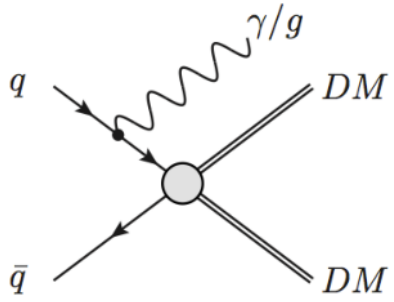
- DM particles (if exist) **may be produced at colliders** in a controlled experimental conditions



- We do **not** look for **direct detection** at colliders:
  - We can **not** have appropriate **triggers** anyways
  - We are sensitive to **DM production associated with creation of anything** one could trigger on
  - In such case **undetected DM particles** give rise to **transverse momentum imbalance**
- **DM production** can be described by different approaches:
  - To balance **signatures** vs **model-dependent searches**

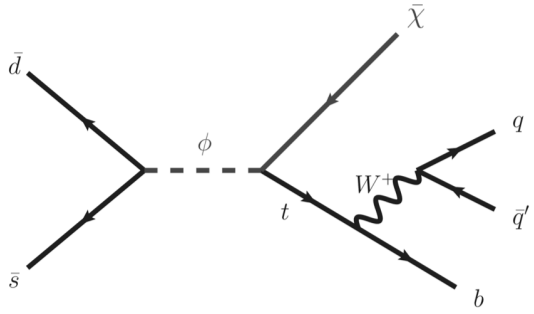
Effective Field Theories (EFT)

- DM production mechanism undefined
- Explored in Run-1



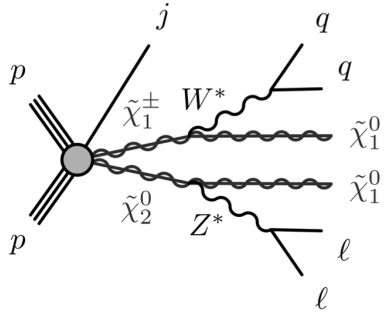
Simplified models

- DM production by mediator
- Signature-driven



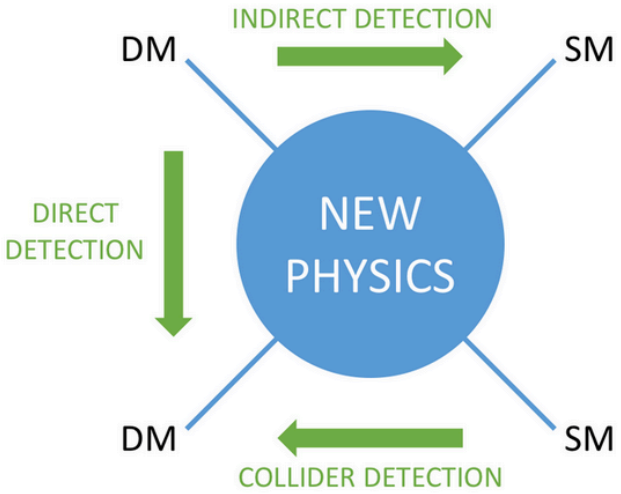
Complete models

- DM production emerges from theory
- Model-dependent



Dark Matter at colliders (LHC)

- DM particles (if exist) **may be produced at colliders** in a controlled experimental conditions

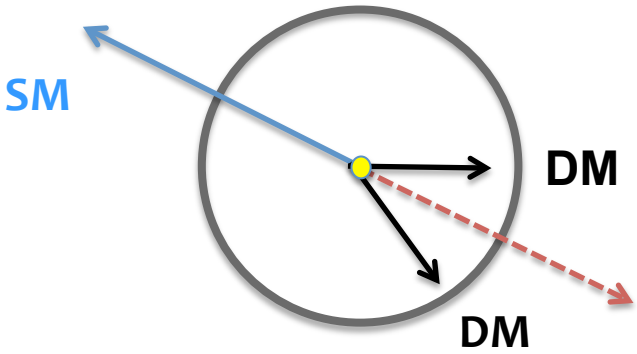


- We do **not** look for **direct detection** at colliders:
  - We can **not** have appropriate **triggers** anyways
  - We are sensitive to **DM production associated with creation of anything** one could trigger on
  - In such case **undetected DM particles** give rise to **transverse momentum imbalance**

➢ **Generic signature of WIMPs**

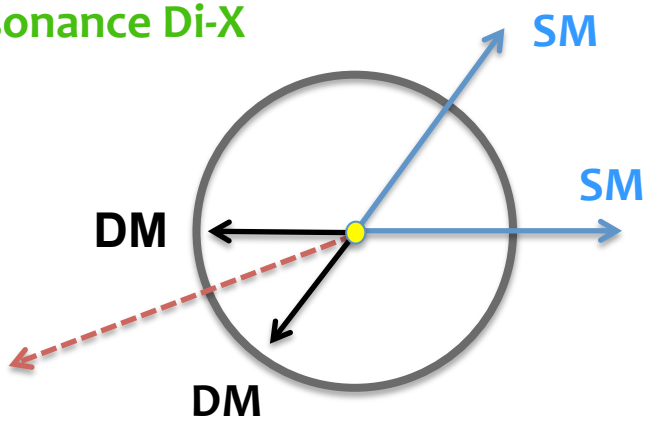
missing (transverse) momentum (MET)
and back-to-back **SM** or **pair of SM objects**

Signature: Mono-X



MET
from invisible **DMs**

Signature: Resonance Di-X



DM searches at LHC– outline

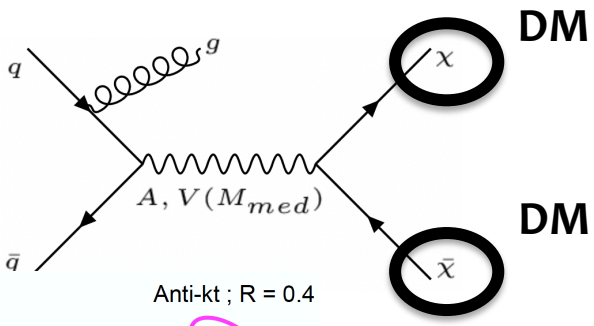
- Experiments at LHC analyze various **signatures** and different **DM models**
- **ATLAS** and **CMS** compete each other
- **LHCb** has sensitivity in low mass DM particles searches
- In this talk, the focus is on lately published **results** for DM with the **full LHC Run 2** data to present a **rich and evolving programme** of DM searches at LHC

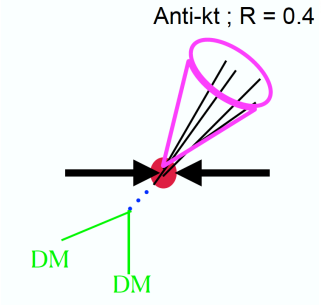
Credits: D. Pérez Adán

Mono-J/V with jets

- **Signature mono-X: SM particle** (jet, Z, γ, h, …) **recoils** against **MET**
  - Tagging from initial state radiation (ISR) or associated production
  - Expect signal in **the tail of MET distribution** over the SM background
- **Analysis strategy:**
  - Discriminating variables: **Jet (high p_T dominant jet)** and **back-to-back MET**
  - Events with leptons or photons are vetoed
  - Analysis is performed in three exclusive categories [CMS]:

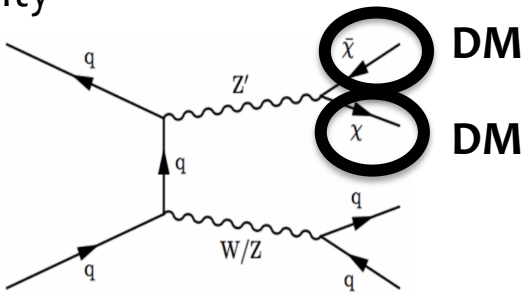
- **Mono-J category:**

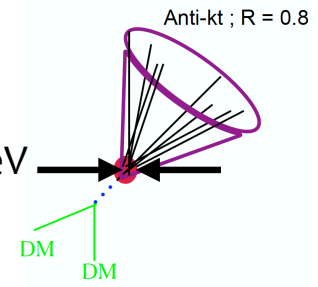




narrow jet
pT > 100 GeV
|η| < 2.4

- **Mono-V sub-categories w/:**
  - high purity (based on jet structure from NN)
  - low purity





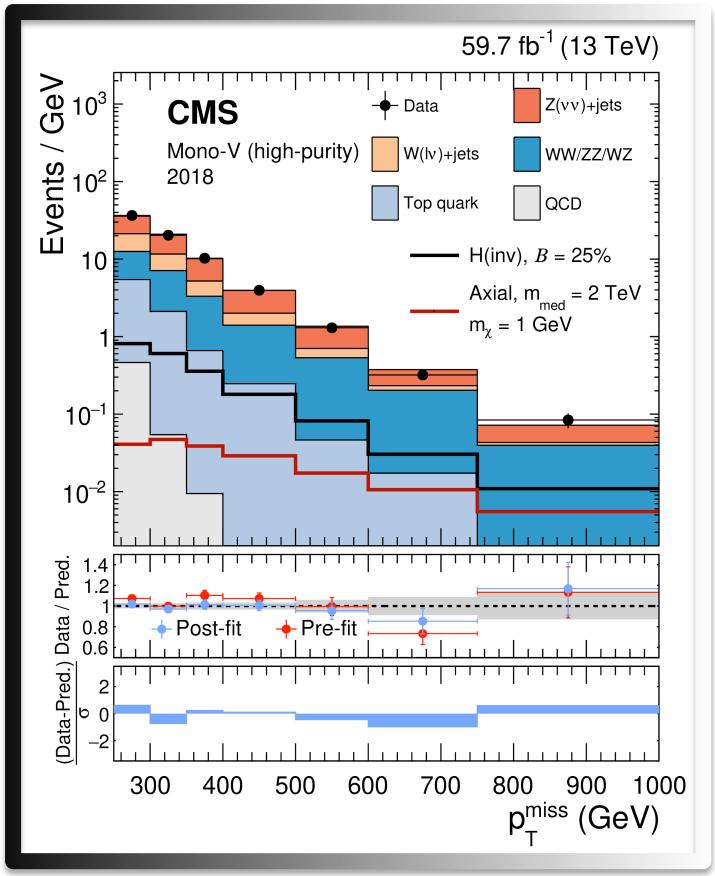
fat jet
pT > 250 GeV
|η| < 2.4

CMS [JHEP 11 (2021) 153]

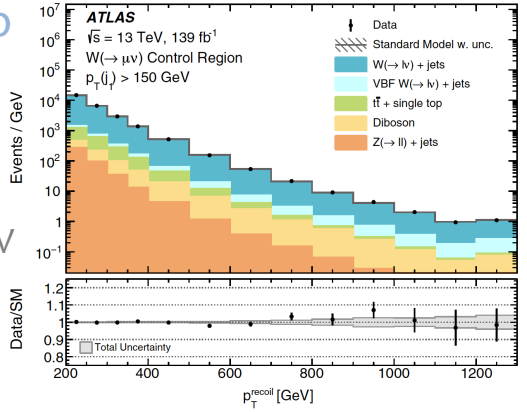
ATLAS [Phys. Rev. D 103, 112006]

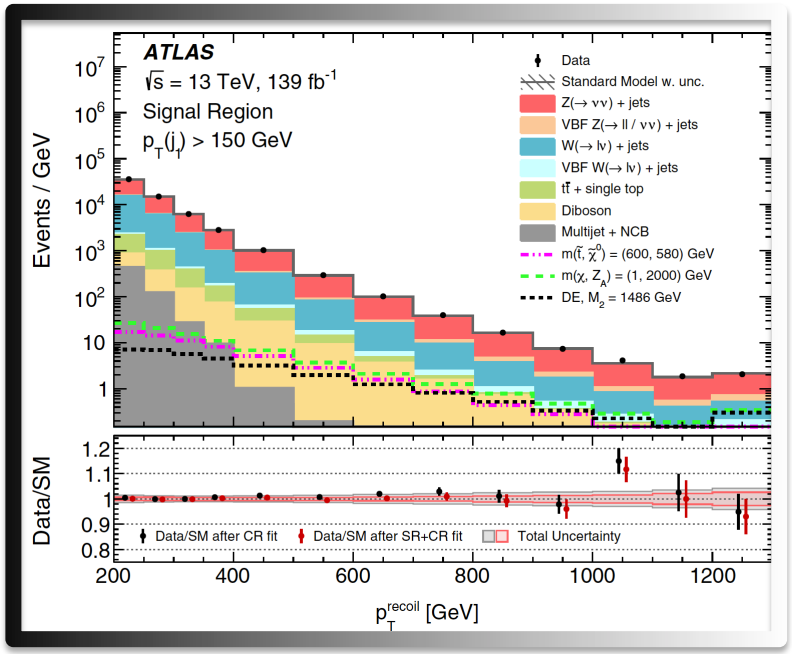
Mono-J/V with jets

- **Background predictions:**
  - High MET threshold (CMS: trigger & offline > 250 GeV) removes dominant QCD bkg
  - Main backgrounds: Z(νν)+jet, W(lν)+jet, WW/ZZ/WZ, top
    - Extensive use of control data samples for precise prediction of background contributions



ATLAS: MET> 200 GeV

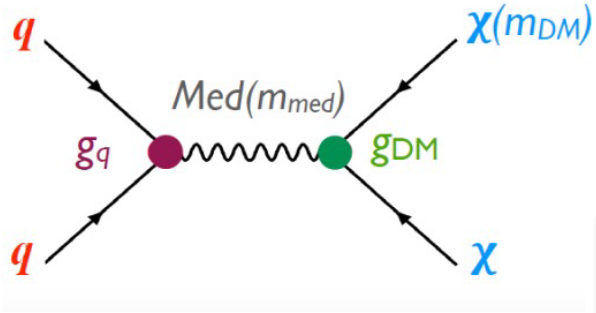




Mono-J/V result interpretation

- All observation consistent with bkg-only hypothesis
- Limits are set on DM particle production in the context of **Simplified Models** with **Mediator**

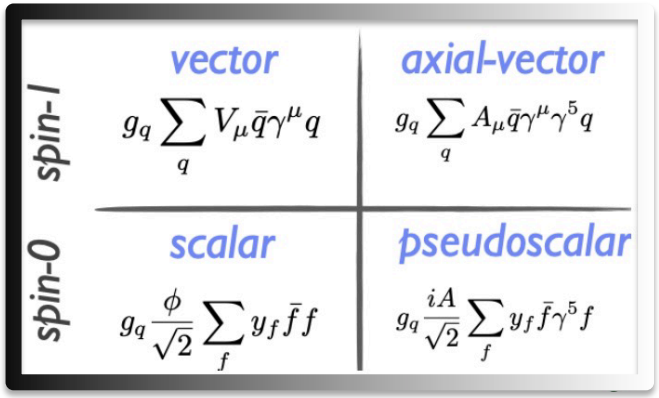
- Set of **benchmark models** identified by ATLAS/CMS DM forum [arXiv:1507.00966]



- **Simplified Models**

  with minimal set of parameters:
  - Mediator mass (M_{med})
  - DM Mass (M_{DM})
  - Mediator coupling to DM (g_{DM})
  - Mediator coupling to quarks (g_q)

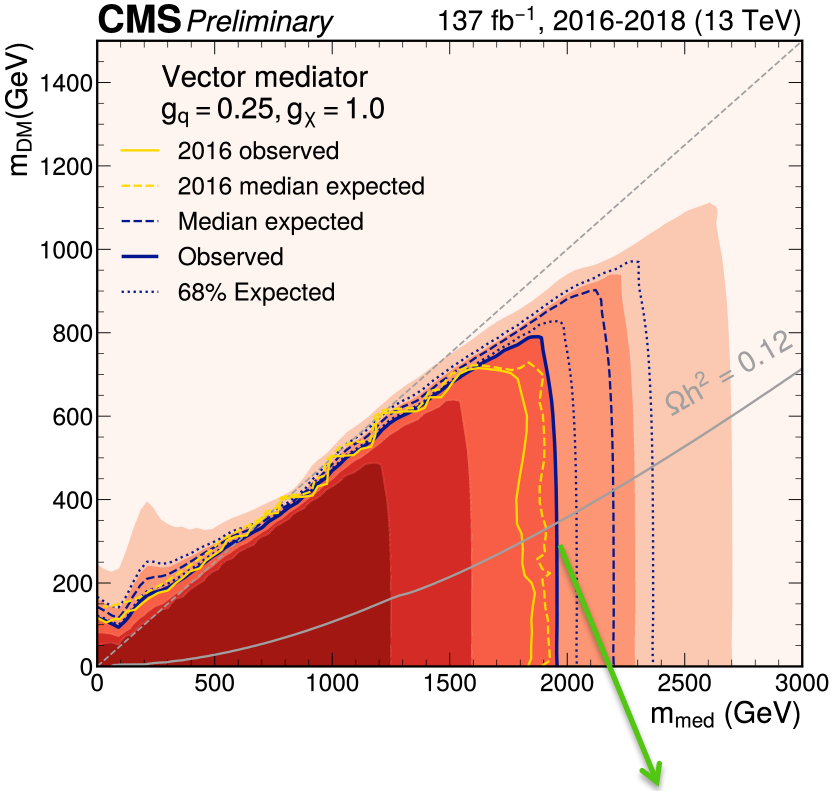
Multiple type of mediators

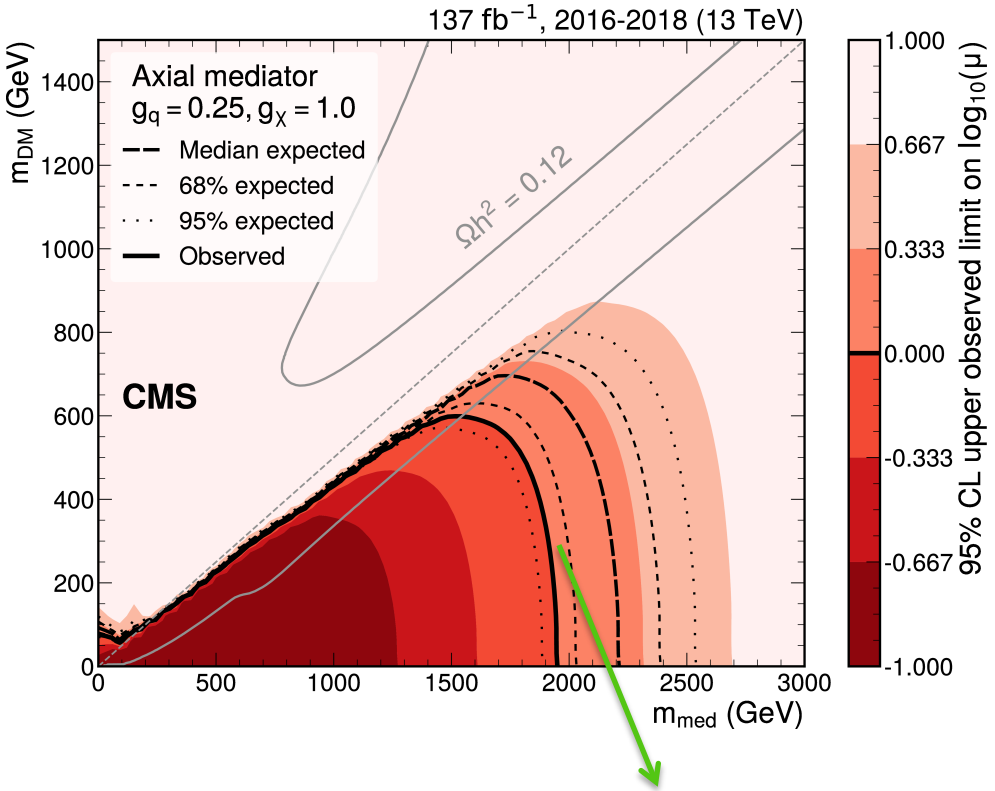


- Extended to models with **t-channel mediator** and **dark sectors**

Mono-J/V result interpretation

- All observation consistent with bkg-only hypothesis
- Limits are set on DM particle production in the context of **Simplified Models** for spin-1 **Vector (Axial) Mediator**



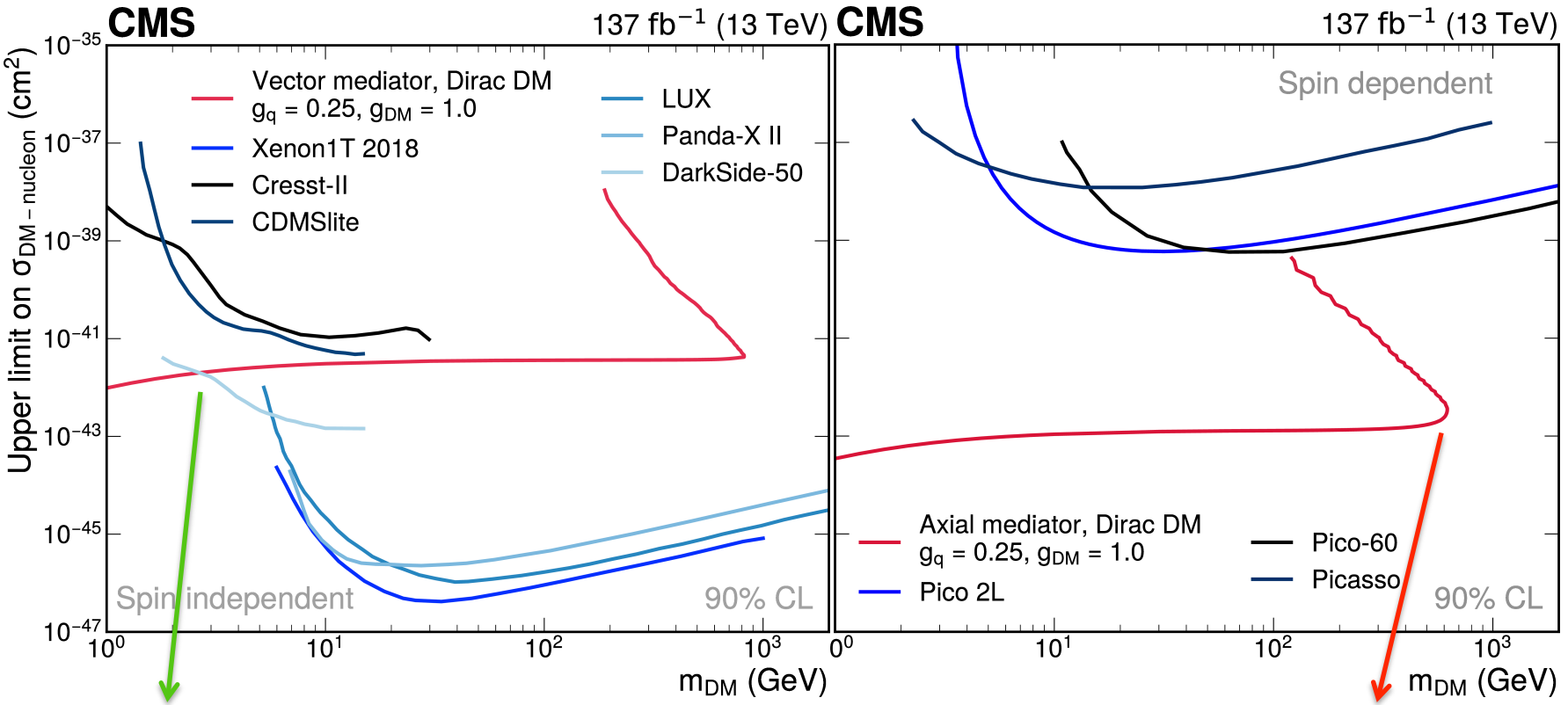


Observed values of the mediator mass are excluded up to 1.95 TeV

Mono-J/V result interpretation

- Limits are set on DM particle production in the context of **Simplified Models** for spin-1 **Vector (Axial) Mediator**

- Comparison to **direct detection (DD) experiments**



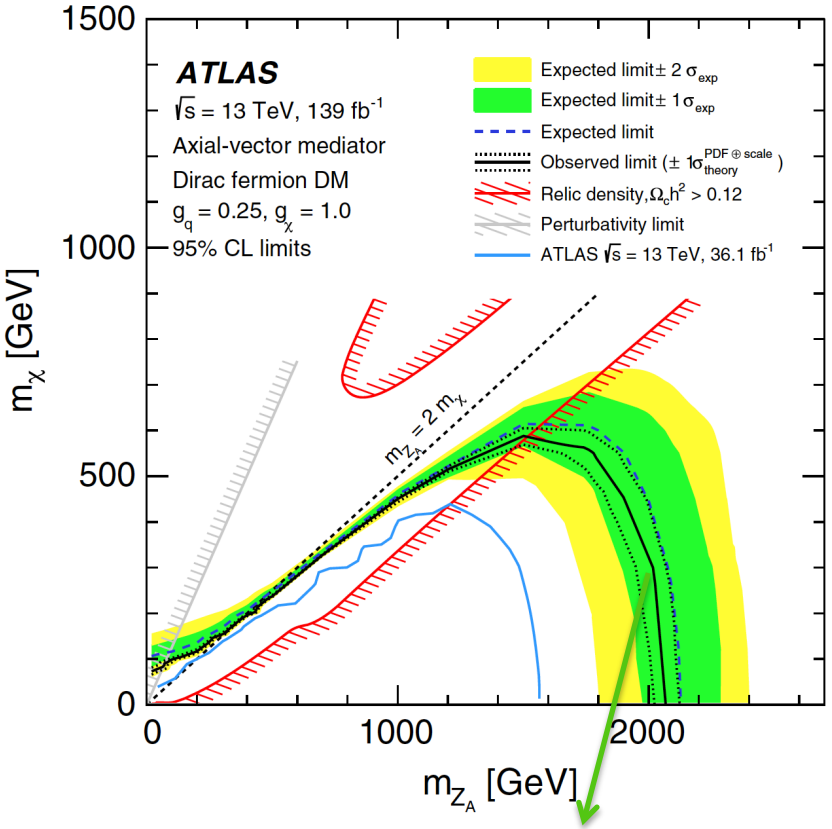
CMS compatible with DD at low mass

CMS competitive with DD up to 600 GeV

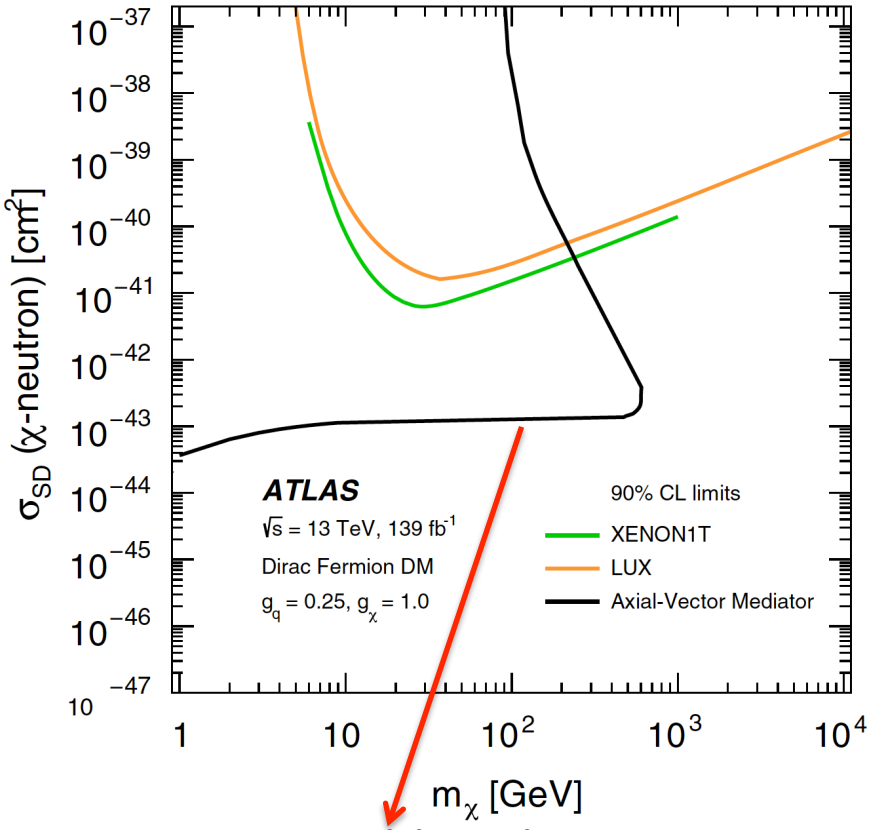
Mono-J/V result interpretation

- Limits are set on DM particle production in the context of **Simplified Models** for spin-1 **Axial Mediator**

- ATLAS and CMS limits at the same level of precision/exclusion



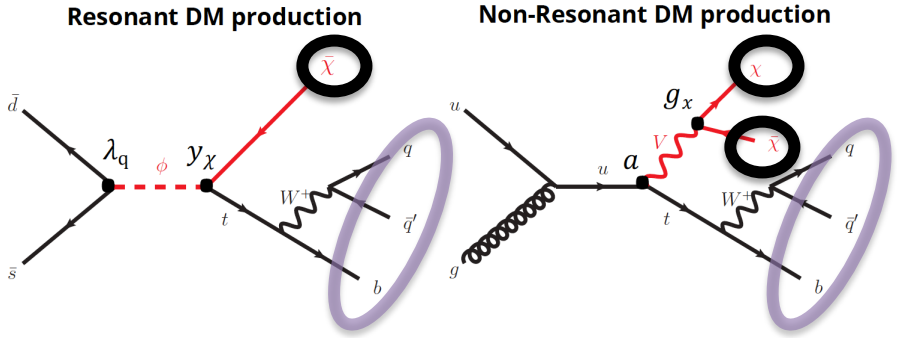
Observed values of the mediator mass are excluded up to 2.1 TeV



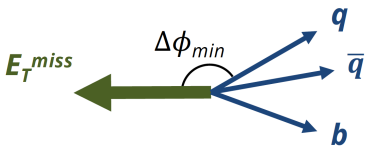
ATLAS competitive with DD up to 600 GeV

Mono-top with boosted jets

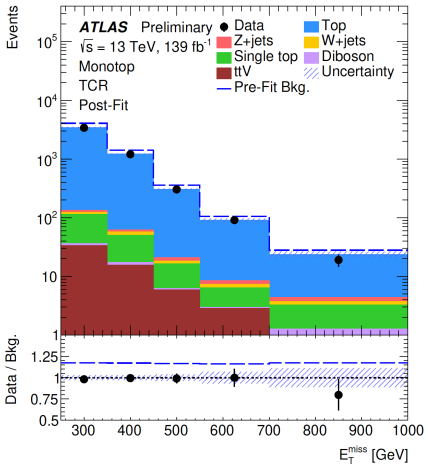
- Many BSM theories predict production of DM associated with top quarks:
  - Exotics particles (DM mediators) could decay preferentially to **top quarks**

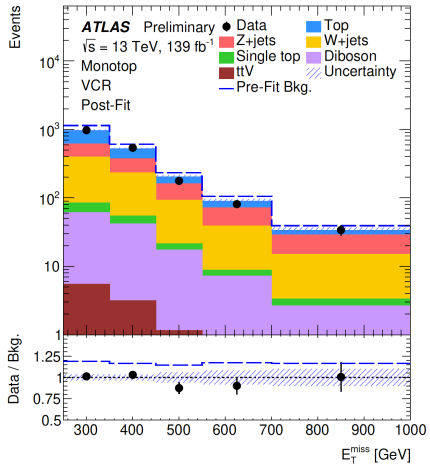


- **Signature:** **MET** (≥ 250 GeV) and **Large-R jet** (pT > 250 GeV &|η| < 2.4)
  - Exactly zero leptons (hadronic channel)
  - At least one boosted large-R jet associated to the top quark
    - use top-tagging for S/B separation



- **Analysis strategy:**
  - **Main backgrounds:** tt and Z/W+jets constrained in the control regions
  - **Multivariate Analysis** (MVA) approach to discriminate signal (XGBoost):
    - MET-based variables and ΔR_{max} among the most important features in the training
    - Further reduce backgrounds by selection requirement on the number of b-jets and $\Delta\varphi_{min}$



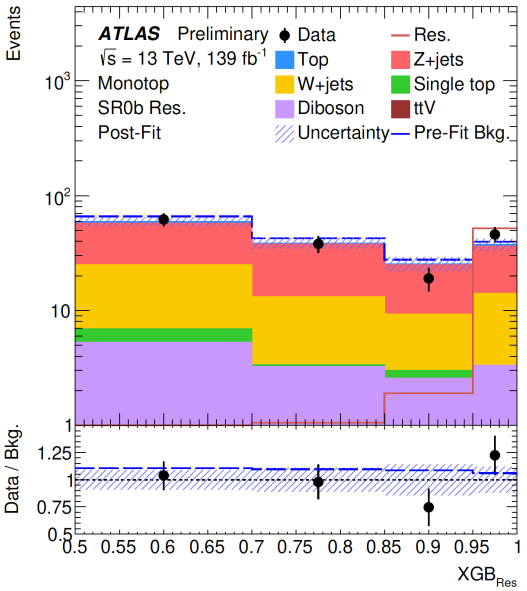


- Good description of data in the control and validation regions of the post-fit background model

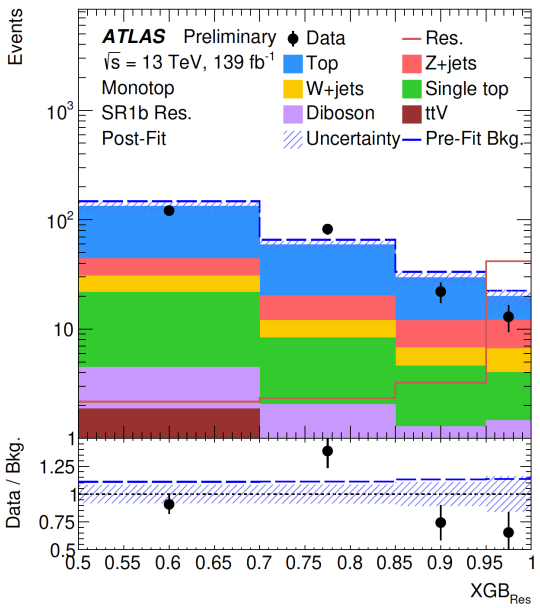
Mono-top – results and limits

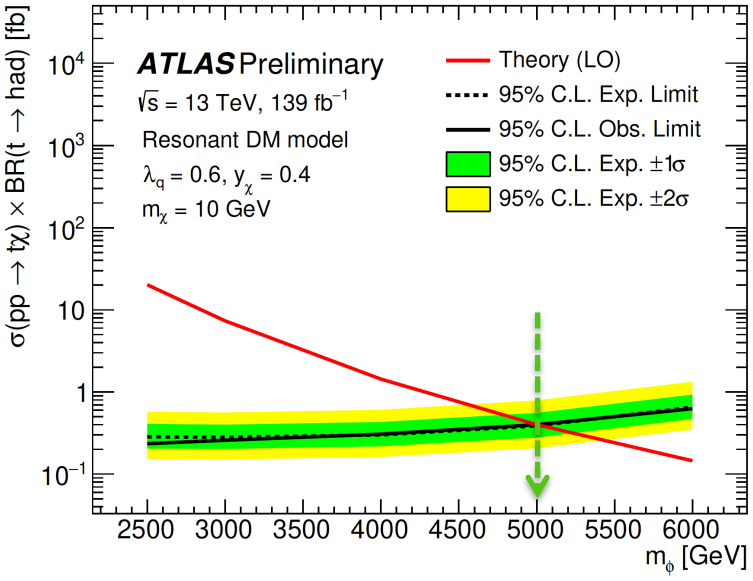
- No significant excess above the SM expectation is found in any of the **Resonant top DM model** signal regions
- Results interpreted in terms of expected and observed upper limit on the signal cross

No b-jet category



1 b-jet category





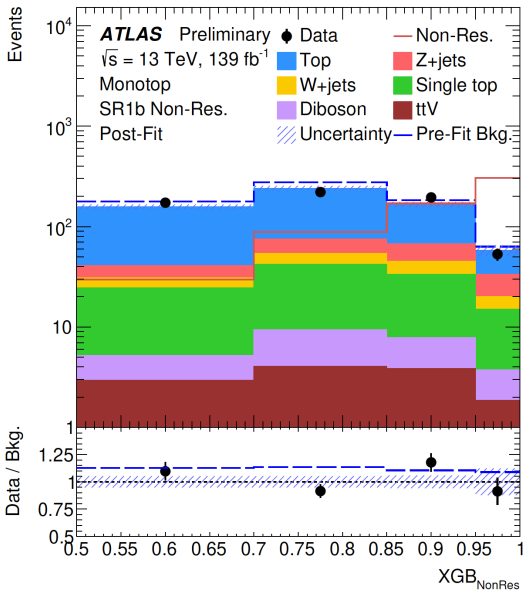
Resonant DM model is excluded for $m_{\Phi} < 5.0$ TeV considering given parameters with $m_{dark} = 10$ GeV

extending the previous mediator mass limits by 1.5 TeV

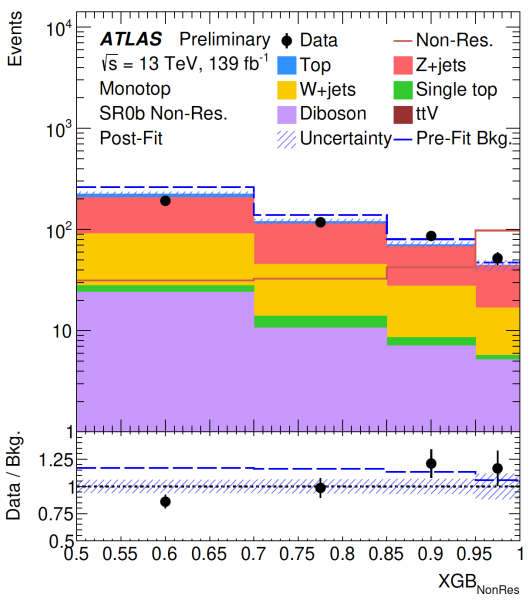
Mono-top – results and limits

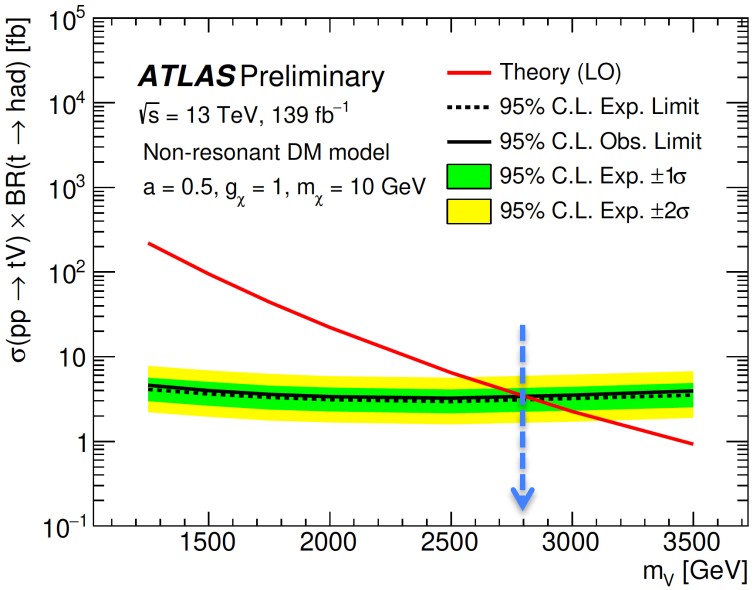
- No significant excess above the SM expectation is found in any of the **Non-resonant top DM model** signal regions
- Results interpreted in terms of expected and observed upper limit on the signal cross

No b-jet category



1 b-jet category



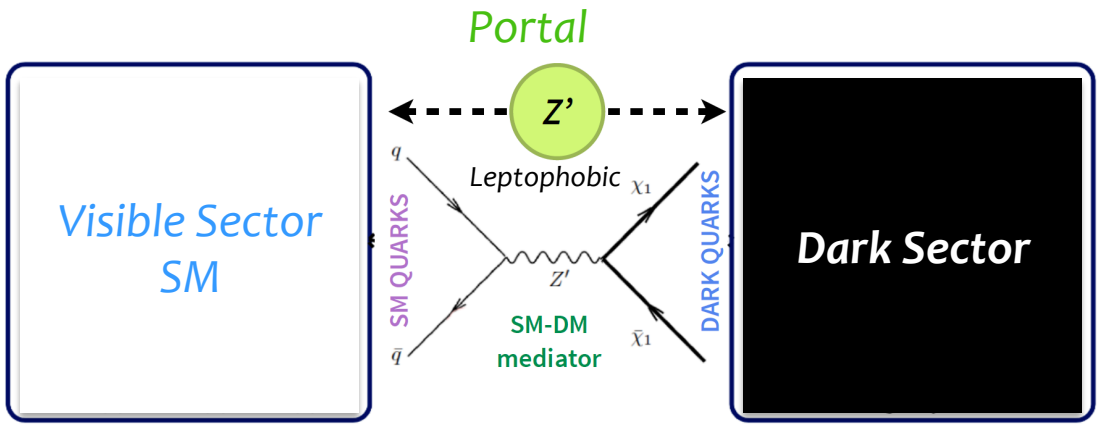


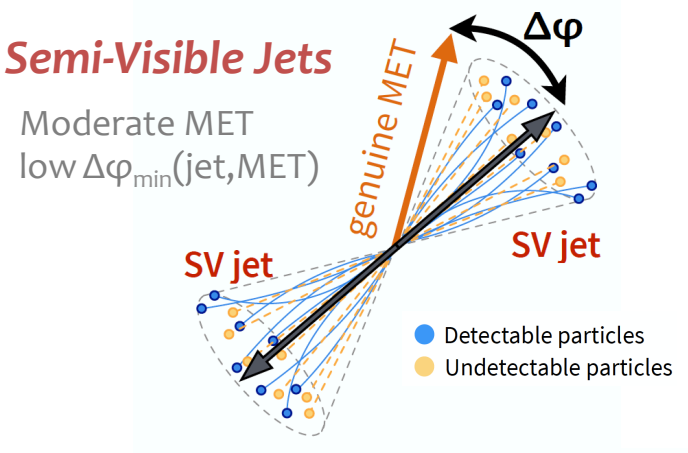
Non-resonant DM model is excluded for $m_V < 2.8$ TeV considering given parameters with $\mathbf{m_{dark} = 10}$ **GeV**

extending the previous mediator mass limits by 0.9 TeV

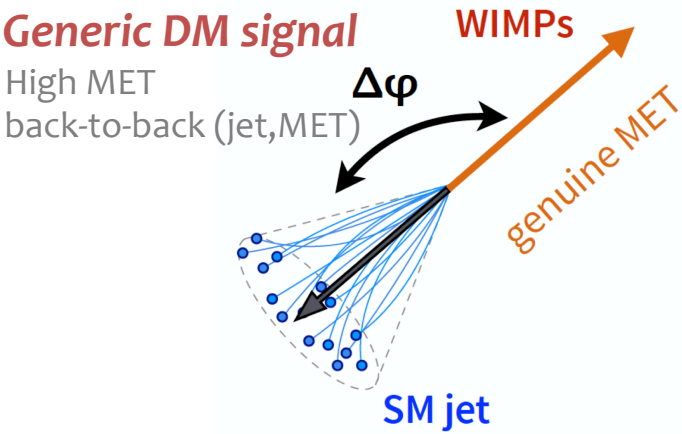
Dark QCD – semivisible jets

- Search for resonant production of strongly coupled dark matter





- New $SU_{dark}(N)$ force: Dark QCD & associated particles
  - Hadronization in the dark sector
- Connected to SM by weakly-coupled mediators: S, V, etc.
  - Prompt decay of unstable dark hadrons to visible SM hadrons
  - Stable **dark hadrons** remain **invisible**
    - Can be considered as **DM candidates**

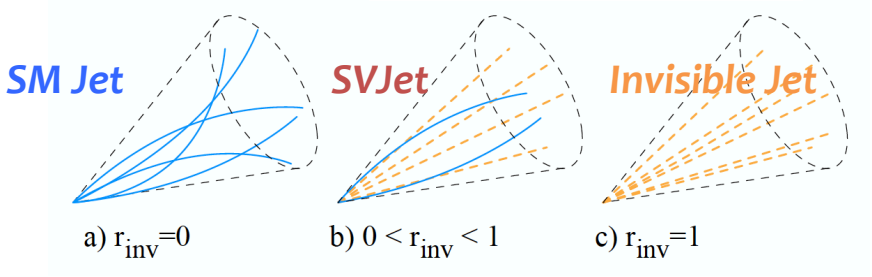


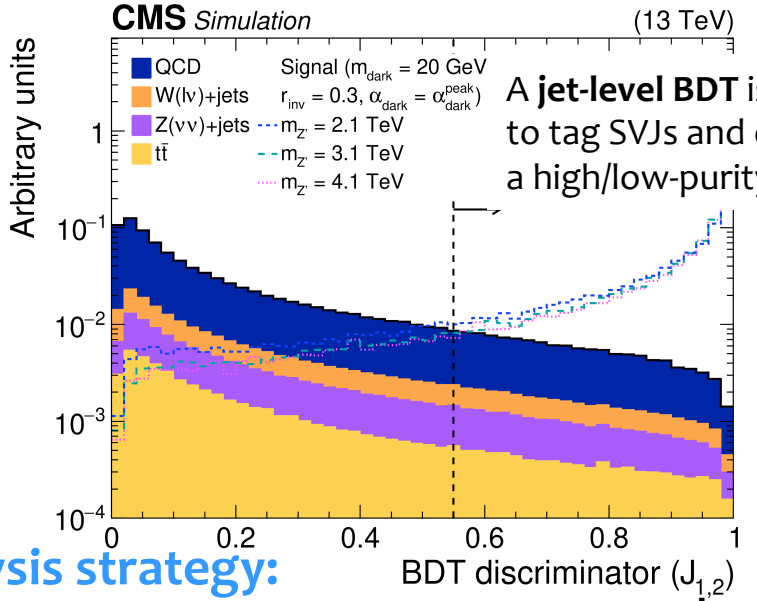
- **Unstable dark hadrons** decays resulting in a **visible fraction** of the dark jet energy
  - Unexplored signatures with non-SM behaviour
  - **Semivisible jets** not covered by existing DM searches

Dark QCD – semivisible jets

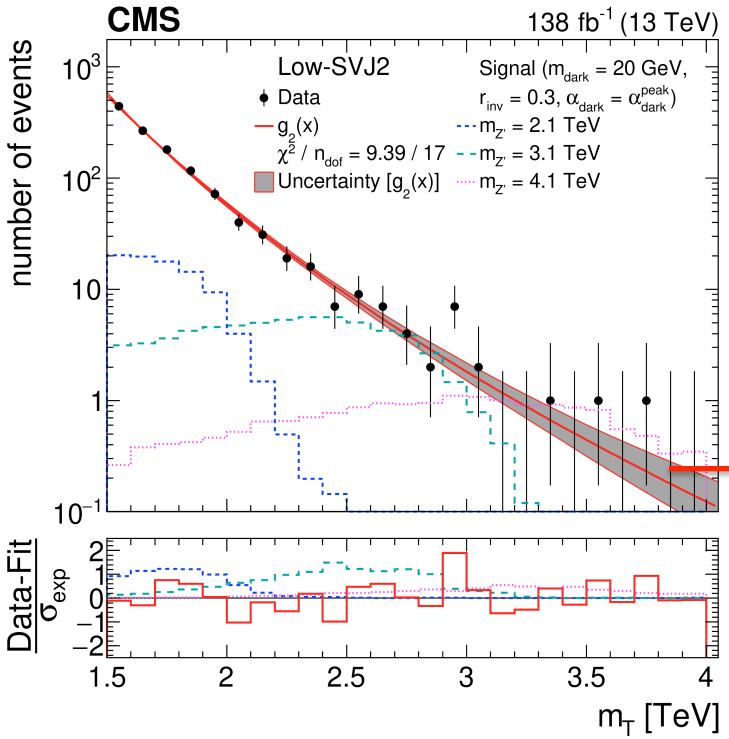
- **Signature:** SVJ are defined by $\mathbf{r_{inv}}$ – fraction of visible and invisible particles in the jet

Signal parameter: $r_{inv} = \left\langle \frac{\text{N stable dark hadrons}}{\text{N dark hadrons}} \right\rangle$





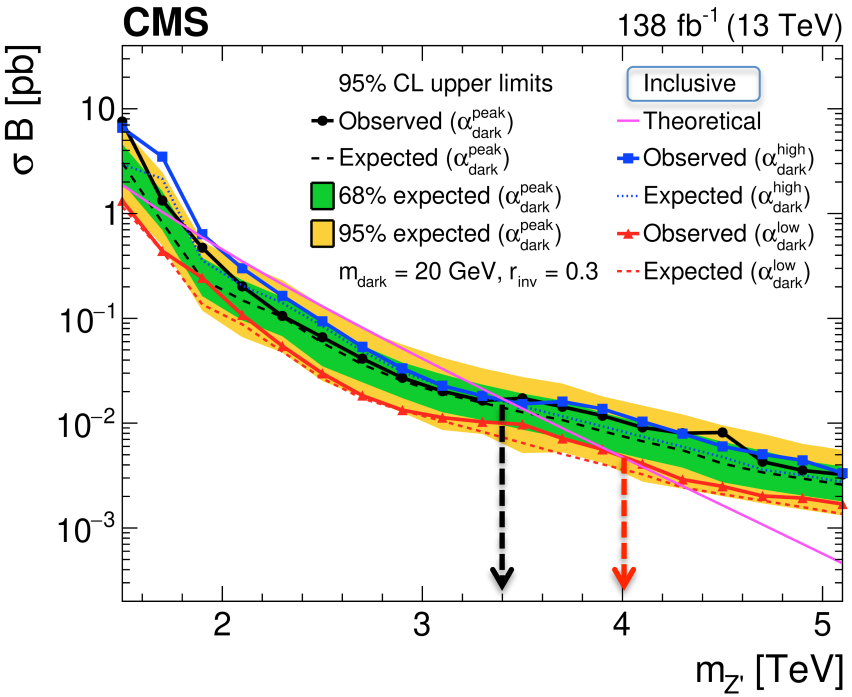
A **jet-level BDT** is used to tag SVJs and define a high/low-purity category

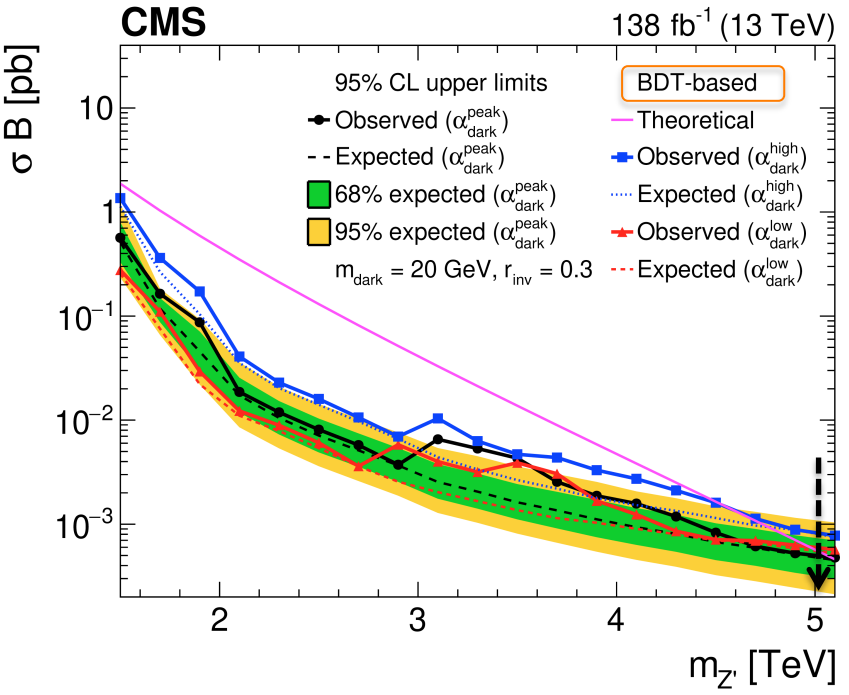


- **Analysis strategy:**
  - Resonance dijet search:
    2 jets with pT > 200 GeV and $|\eta| < 2.4$
  - Discrimination variable:
    transverse mass $\mathbf{m_T}$ of dijet system and MET
  - QCD background rejected with cut on
    $R_T = MET/m_T > 0.15$
    - Bkg normalization extracted in fit
    - Dedicated SVJ tagger reduces bkg by ~O(100)

Dark QCD – results and limits

- No structure (~ resonance peak) in the SVJ dijet transverse mass spectra compatible with the signal is observed
- Present results for two conditions:
  - Inclusive, signal-independent cut-based approach (*most conservative*), $R_T = MET/m_T > 0.15$
  - BDT-based, improved by almost a factor 10 (*most aggressive*), $R_T > 0.15$ + BDT



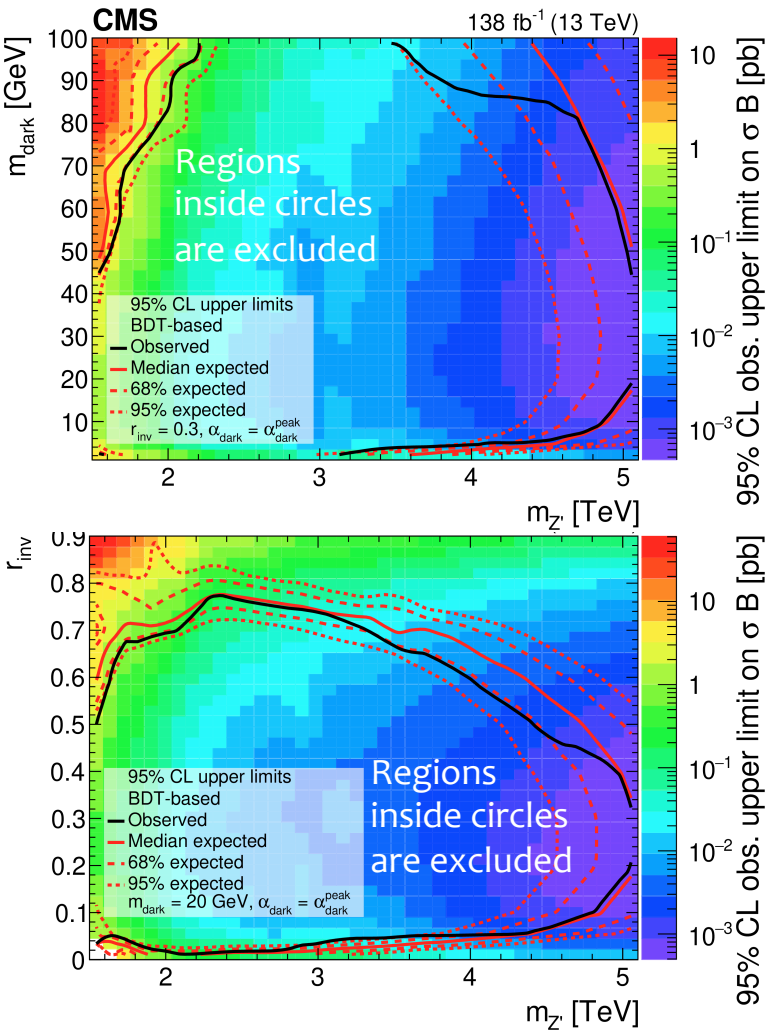


Inclusive analysis excludes the mediator masses in range **$1.5 < m_{Z'} < 4.0$ TeV**

When the BDT is employed to identify each jet in the dijet system as semivisible, the mediator mass exclusion increases to **5.1 TeV**

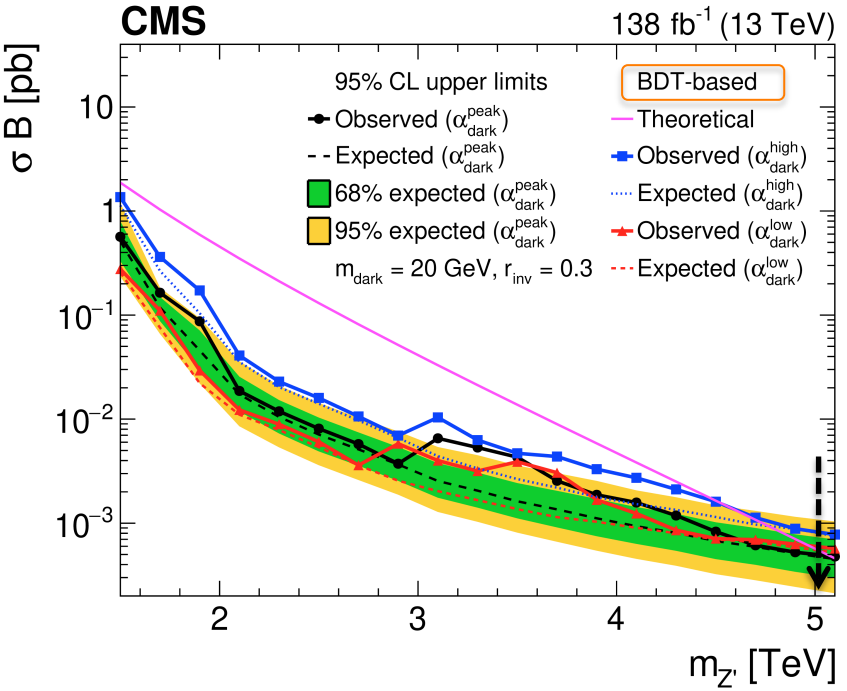
Dark QCD – BTD limits

- BDT-based, improved by almost a factor 10 (*most aggressive*), $R_T > 0.15$ + BDT



Assuming the Z' boson has a universal coupling of 0.25 to the SM quarks:

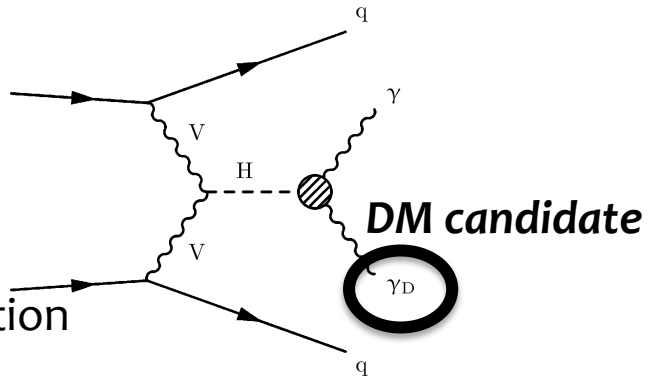
- $1.5 < m_Z < 5$ TeV excluded for $r_{Inv} = 0.3$
- $0.02 < r_{Inv} < 0.77$ excluded for $m_{dark} = 20$ GeV



- Small excess around $m_{Z'} \sim 3.5$ TeV w/ small ~2σ local significance weakened exclusion limit

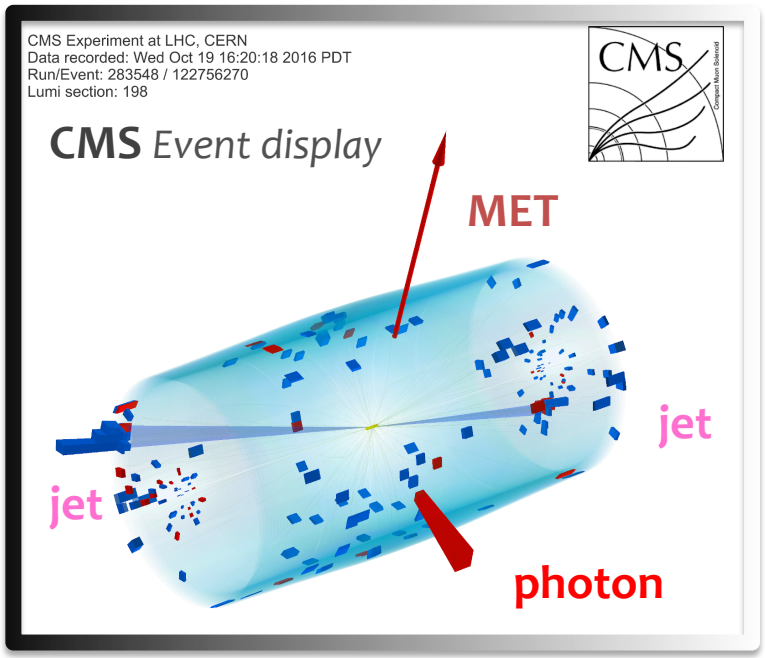
These limits exclude a wide range of strongly coupled hidden sector models for the first time

Dark photons from VBF Higgs



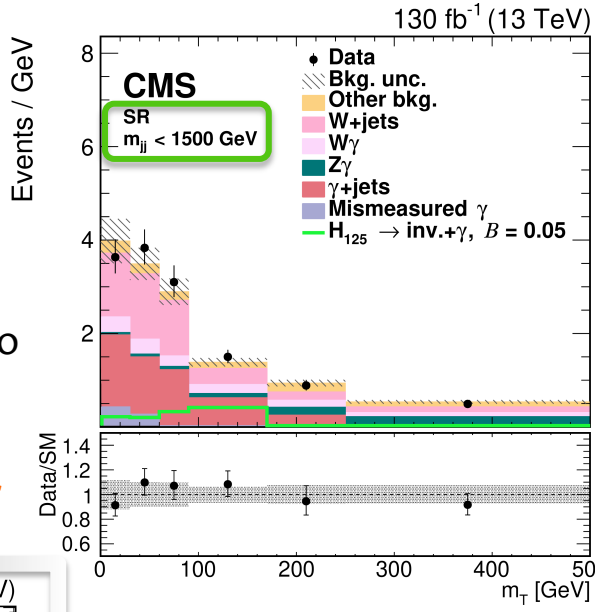
- **Signature γ_{Dark}:**
  - **MET** and **≥2 jets** with relatively high separation in η and at ≥ **1 photon**
  - Triggering with MET or single-γ or VBF online selection

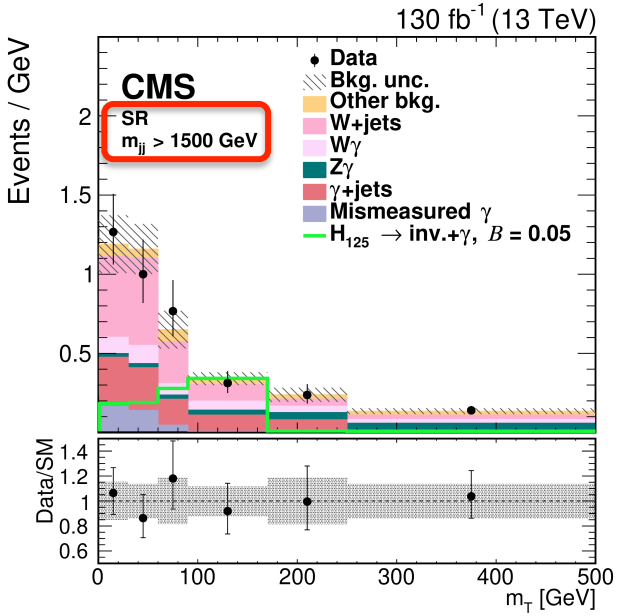
- **Analysis strategy:**
  - Discriminating variables: **transverse mass of photon p_T^{γ} and MET, m_T=** $\sqrt{2 \cdot p_T^{\gamma} \not{E}_T \cdot (1 - \cos \Delta\phi(\gamma, \not{E}_T))}$
  - Events with leptons are vetoed
  - **≥ 1 photon** wit p_T >230 GeV $|\eta| < 1.47$
  - ≥2 jets with p_T >50 GeV with mass m_{jj} >500 GeV
    - in opposite detector hemispheres $\eta_{j1}\eta_{j2} < 0$
    - large separation between the jets and MET
  - Moderate MET threshold (offline > 140 GeV)
  - Extensive use of control data samples for precise prediction of background contributions: W+jets, W+γ, Z+γ, γ+jets

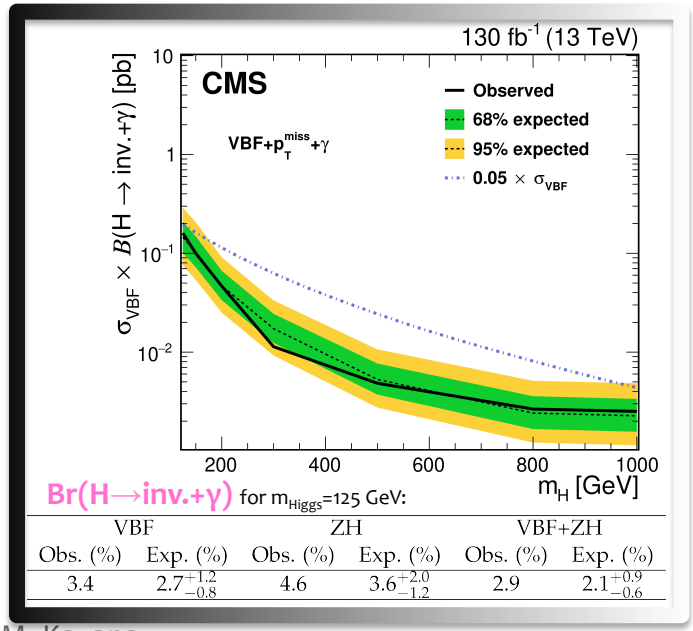


Invisible VBF Higgs constrains

- CMS final search performed in 6 signal m_T regions for m_{jj} <1500 GeV and m_{jj} >1500 GeV
  - Small statistics
- **First results** for Higgs decays to undetected particle and a photon in the VBF channel
  - **ALTAS estimate stronger**

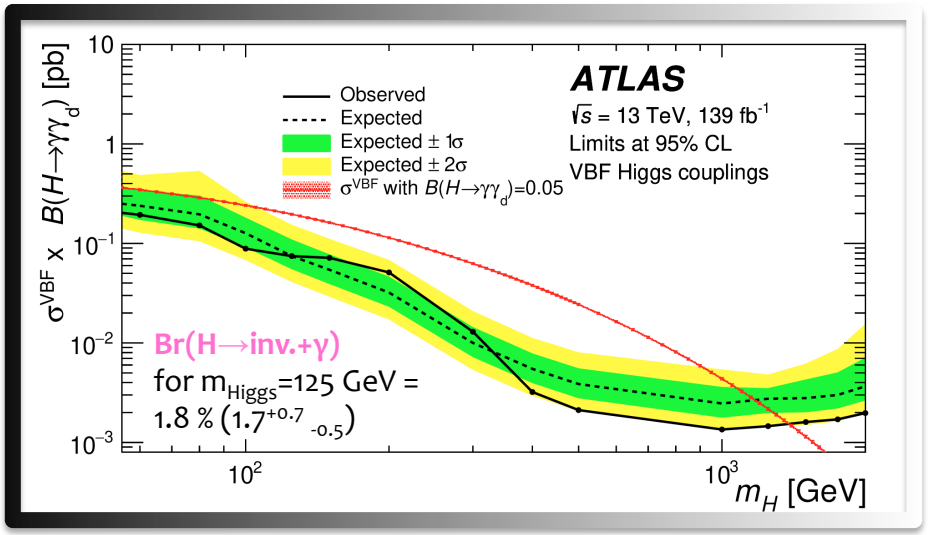






Br(H→inv.+γ) for m_{Higgs}=125 GeV:

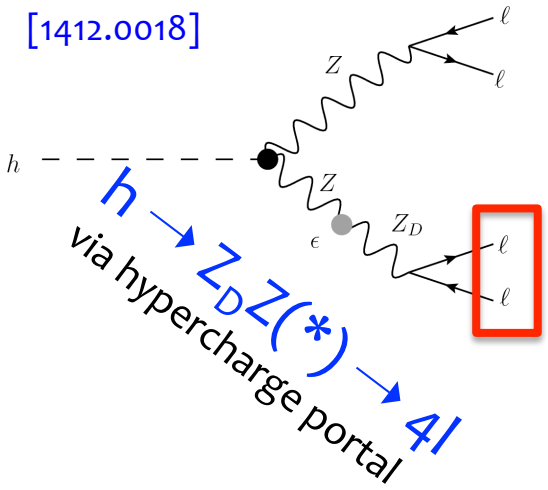
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$



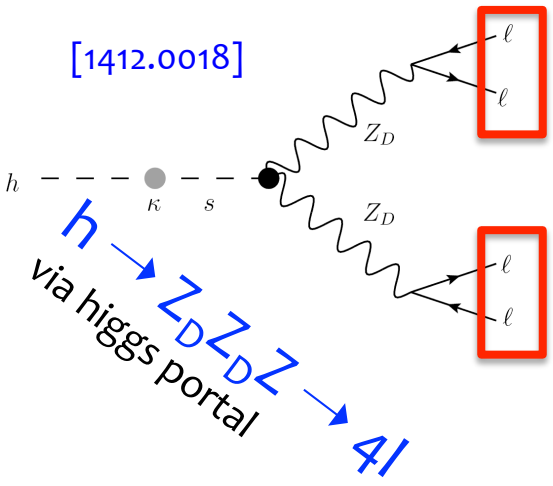
Dark photon decay– low mass di-muons

Higgs boson decays to a pair of **long-lived dark photons**

[1412.0018]



[1412.0018]



Triggering: CMS newly use of high rate triggers (***scouting***):

- Bypass the high-level trigger (HLT) thresholds by directly sending HLT objects to disk instead of saving raw data
- Reduced event info compared to offline reconstructed objects
- **DoubleMu trigger path** allow sensitivities to **otherwise inaccessible low-mass** events

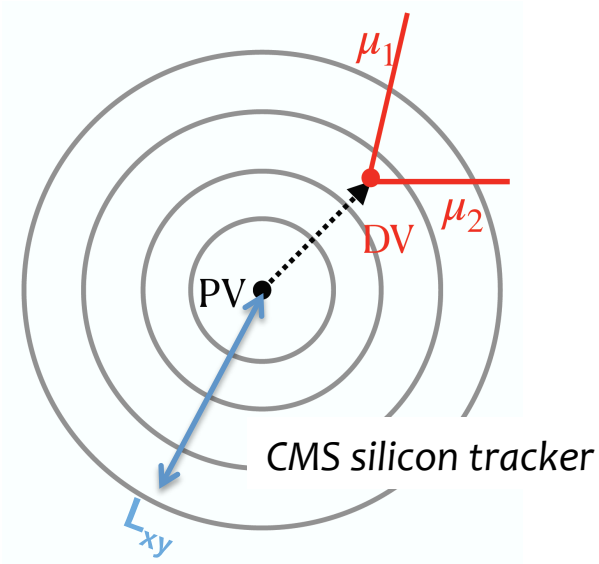
Benchmark models: Z_D **:** 0.5 GeV ≤ $m(Z_D)$ ≤ **50 GeV** 0.1 mm ≤ $c\tau_0(Z_D)$ ≤ 1 m

Very low mass search for long-lived dimuons

for a muon pair with **displaces vertex** (DV)

- masses **down to ~2m_μ** and **displacements L_{xy} up to 11 cm**

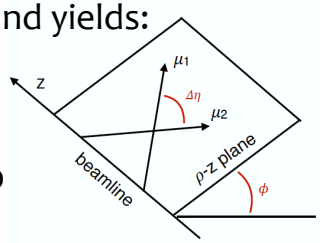
- **Signature :** At least 2 opposite sign muons (p_T > 3 GeV, $|\eta|$ < 2.4) and **1 displaced vertex**

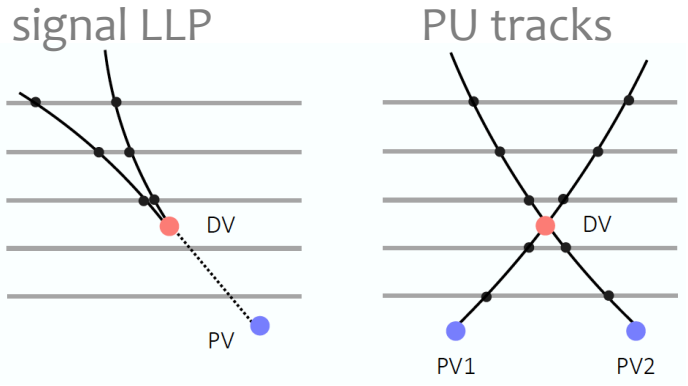


Dark photon decay– results

Backgrounds:

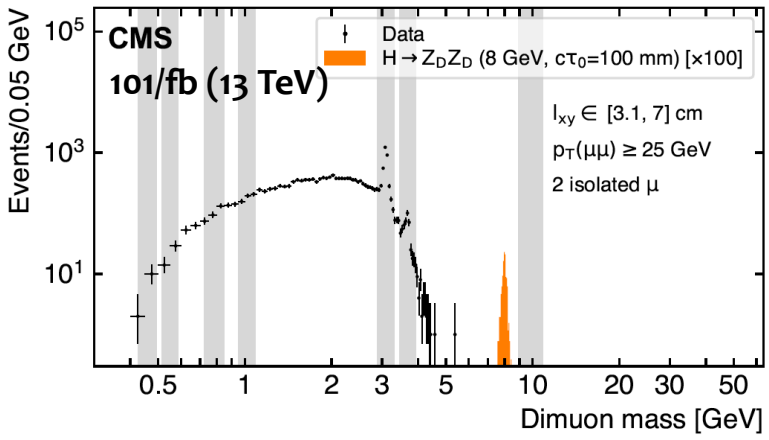
- Controlled with a set of kinematical cuts
- DV/dimuon kinematics & displacement requirements, material veto to reduce background yields:
  - Sophisticated cuts:
    - $\log_{10}(\Delta\eta/\Delta\phi) < 1.25$
    - # excess pixel hits ≤ 0



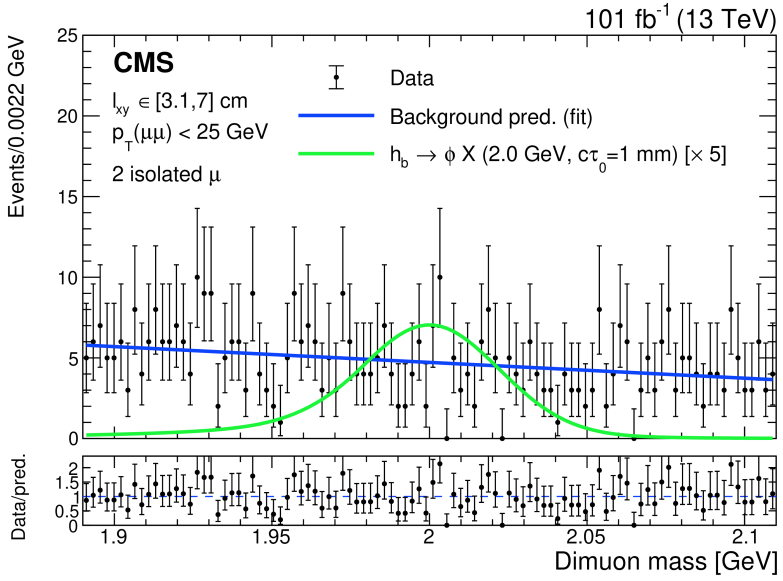


Strategy:

- Search for a **narrow peak** in dimuon invariant mass spectrum
- SM bkg estimated directly from data can be parameterized by analytical functions
  - SM resonances are masked ($\pm 5\sigma_{res.}$ window) for the result
- Events are **categorized in bins** of muon isolation (2,1,0 iso-mu), di-mu momentum $p_T(\mu\mu)$

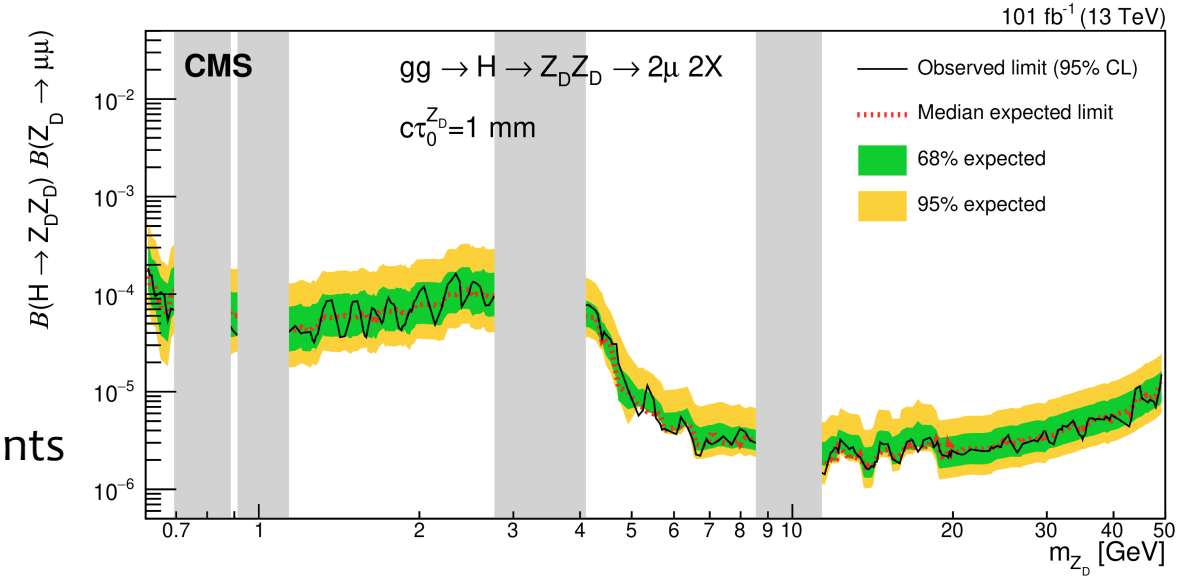


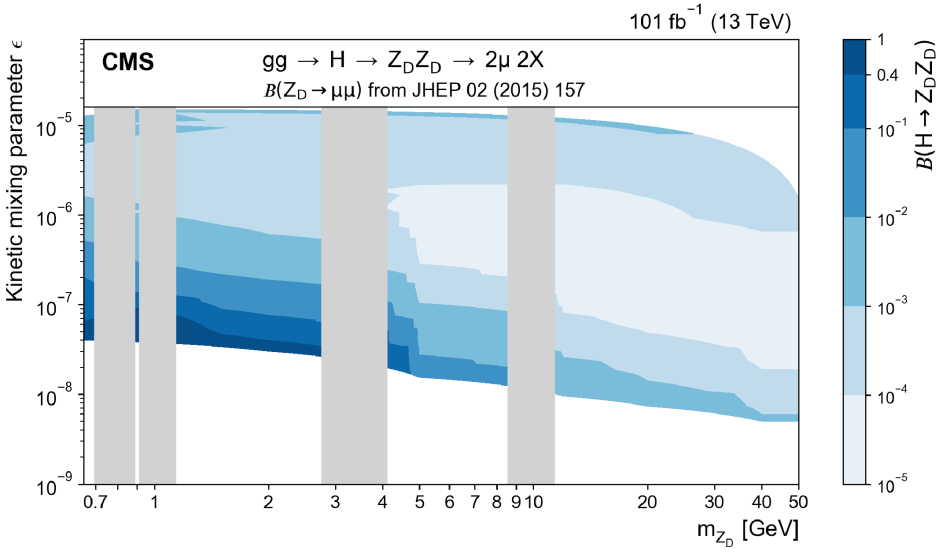
- **Simultaneous fit** in all search bins either bkg-only or bkg+ signal hypotheses

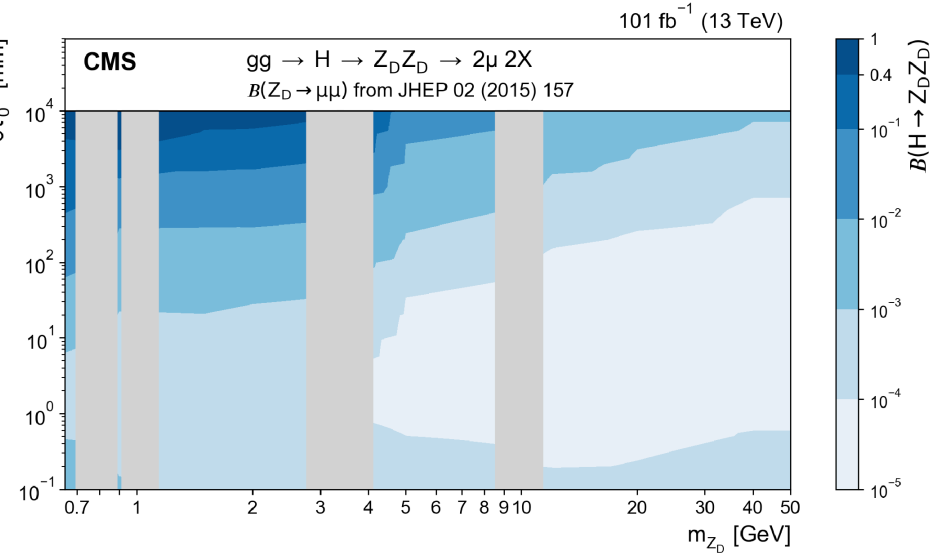


Dark photon decay– limits

- No significant excess is observed
- Bkg+signal fits are used to set limits signal models
- The CMS most stringent constraints to date in a wide range of signal mass and lifetime hypotheses

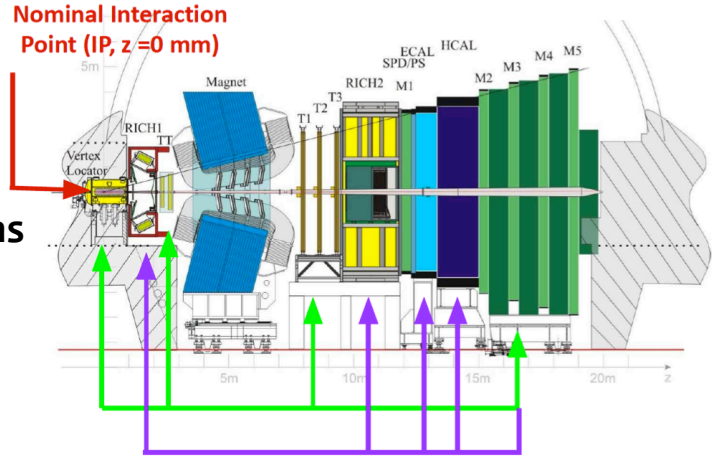






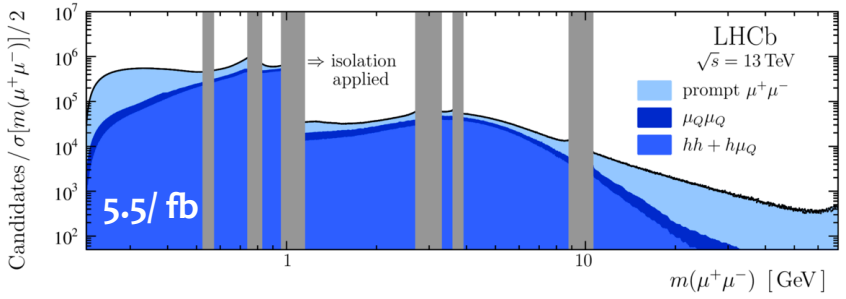
Dark Matter at LHCb

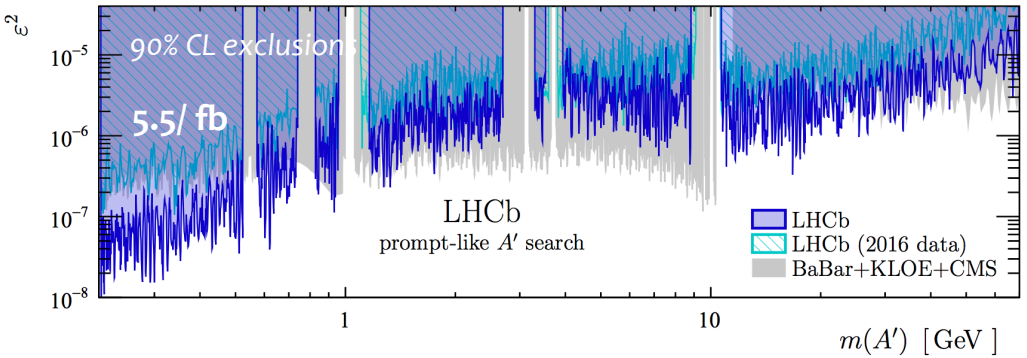
- **Single-arm spectrometer** originally devoted to **heavy flavour physics,** but can serve as a general purpose experiment covering (QCD, SM, heavy ion and fixed-target)
  - Complementary in pseudorapidity: $2 < \eta < 5$
  - Excellent momentum resolution (tracking detectors), IP determination and particle identification



- Search for **dark photons A'** decaying into a **pair of muons**
  - **Low mass sensitivity: (very low-pT trigger)** prompt-like A′ search covers the mass range from near the dimuon threshold up to 70 GeV
  - Fully data-driven analysis
  - Event categorization as prompt $\mu^+\mu^-$, $\mu_Q\mu_Q$, and $hh+h\mu_Q$ determined using the $\min[\chi^2\,\mathrm{IP}(\mu^\pm)]$ fits

➢ Most stringent to date for the mass range: **$214 < m_{A'} \lesssim 740$ MeV (long-lived selection)** and **$10.6 < m_{A'} < 70$ GeV**





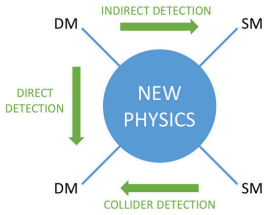
LHCb detached anti-proton in pHe collisions at 110 GeV

LHCb linked to indirect detection of DM

- A first measurement of prompt anti-p production in pHe collisions at 110 GeV using **LHCb fixed-target program SMOG** (System for Measuring Overlap with Gas)
  - A noble gas (He, Ne, Ar) at ~ 2×10^{-7} mbar pressure injected into the LHC vacuum around the LHCb interaction region
  - Originally used to determine luminosity, since 2015 started to collect fixed-target collision data

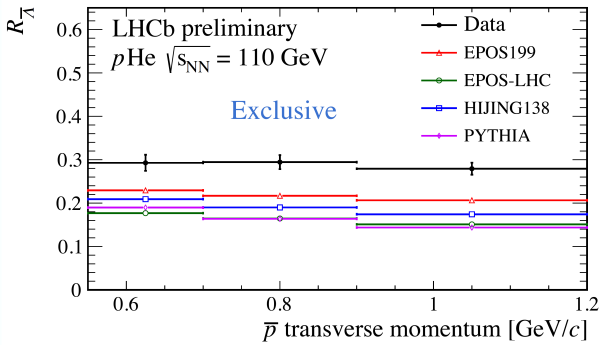
$\sqrt{s_{NN}} = 110$ GeV

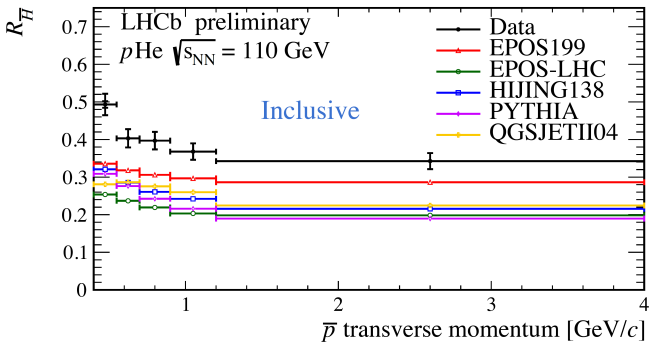
p → Gas (He,Ne, Ar…)

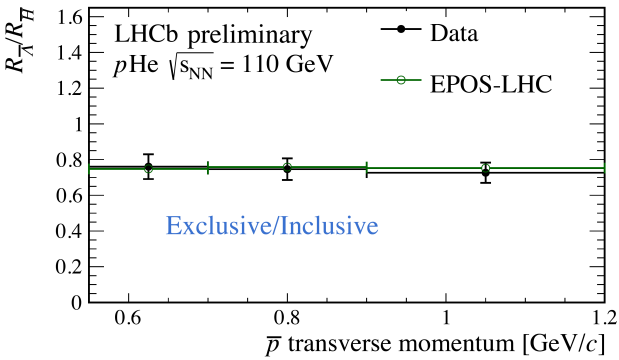


- It may help determine whether or not any antimatter seen by (indirect detection) experiments in space (Pamela, AMS-02) originates from dark matter
- Detached anti-p (from displaced decay of anti-hyperon) can be distinguished from prompt p by the separation of their original vertex and the primary pHe collision vertex

$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda}X \to \bar{p}\pi^+X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)} \qquad R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$







- All considered **generators** significantly (exclusive, inclusive searches) **underestimate** the anti-Λ contribution to the production of anti-p:
  - Indicate a **sizable underestimation** of detached anti-p contribution in most hadronic production models used cosmic ray physics

DM in CMS summary

- LHC experiment builds up a rich program of **Dark Matter** searches:
  - Large variety of **signatures:**
    - Generic analyses with **mono-X and resonances**
    - Signals with **heavy flavours**
    - Higgs giving light to a **dark sector** which may hide a dark matter
    - Distinctive signatures of **long-lived particles** open window to DM

  optimized for a wide range of model types

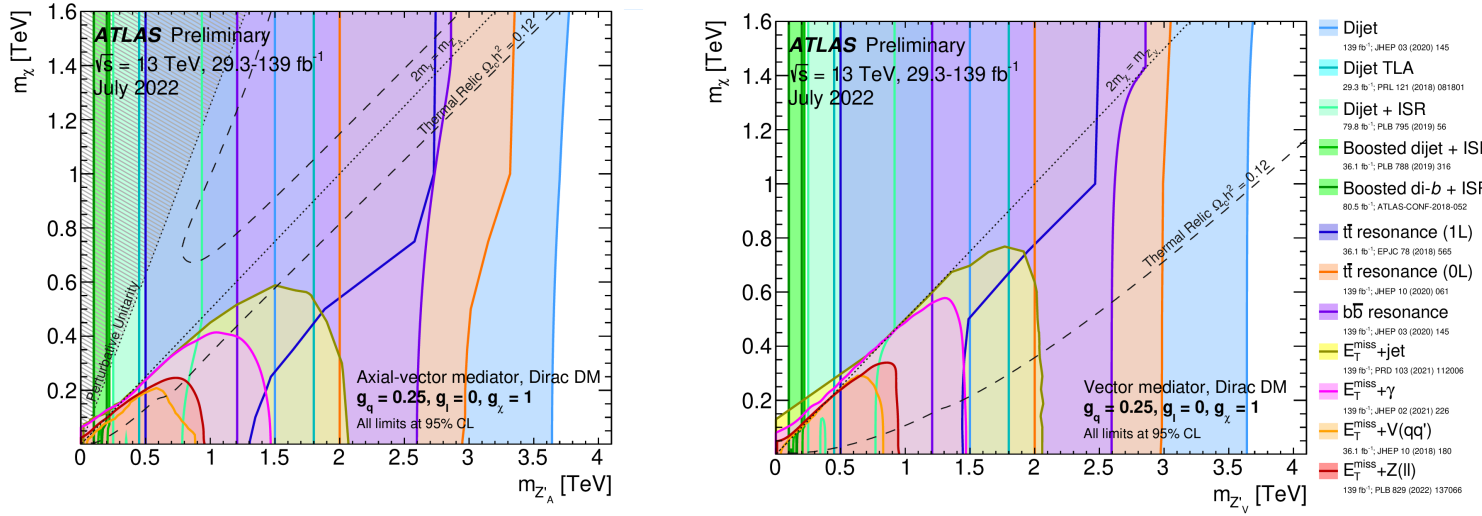
- Precise predictions of the Standard Model background underlines the searches
- Experimental techniques evolves to more **sophisticated approaches**
- Use of **machine learning** brings substantial improvements
  - Important to **control of systematic uncertainties**
- More improvements and analyses with *full Run 2* data expected while *new Run 3 data* will be available soon

- http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/DM.html
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-036/

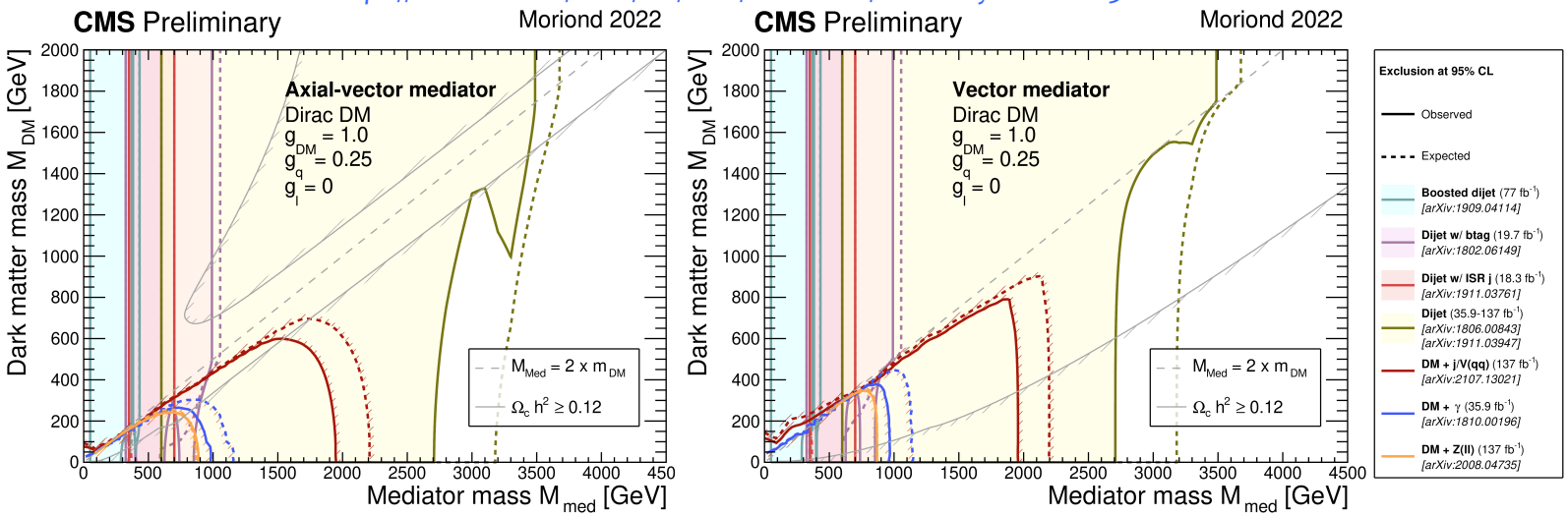
Thank you!

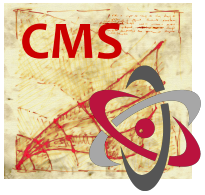
Selection of limits for DM searches at ATLAS and CMS

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-036/



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV





Backup slides

Dark Matter at LHCb

- Search for **dark photons A'** decaying (promptly or long-lived) into a **pair of muons**