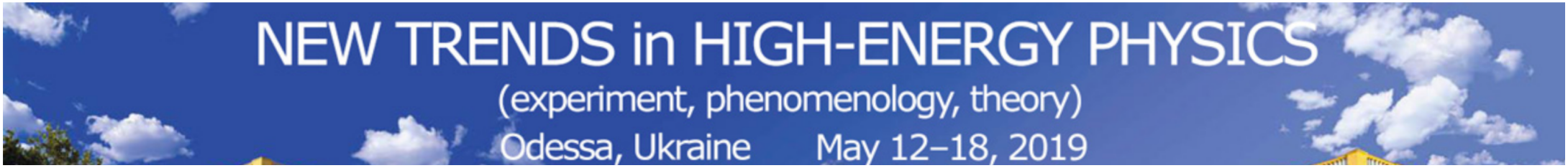


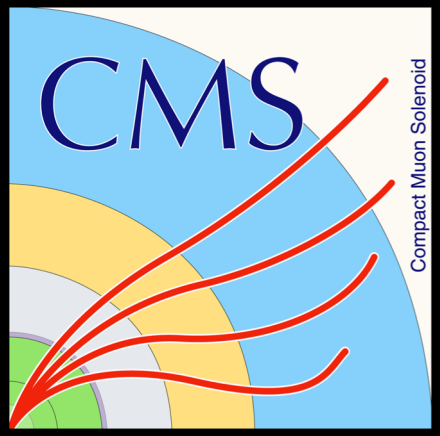
Dark Matter Searches at the LHC

B. Laforge

on behalf of the ATLAS, CMS and LHCb experiments

LPNHE PARIS

SORBONNE UNIVERSITÉ

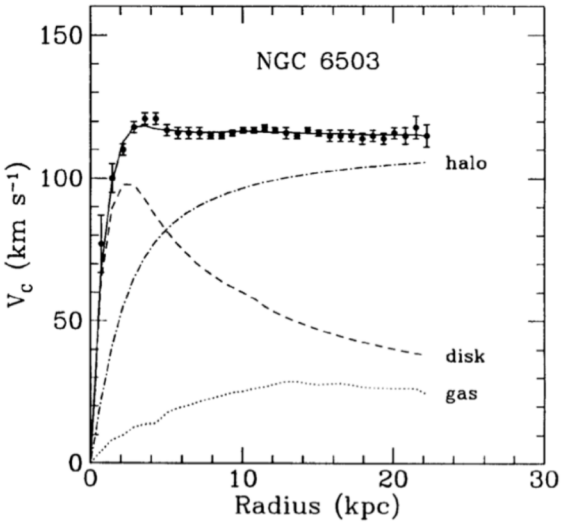


One fundamental question is open:

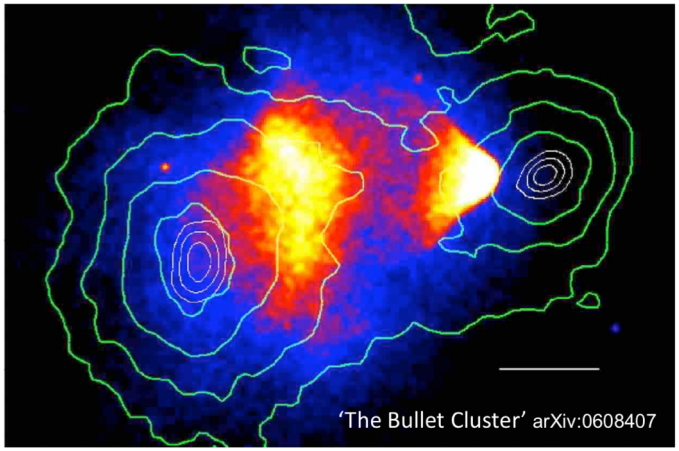
Does DM exist ? (or is GR wrong ?)

Radial speed of stars in galaxies requires DM

Mon. Not. R. astr. Soc. (1991) 249, 523-537

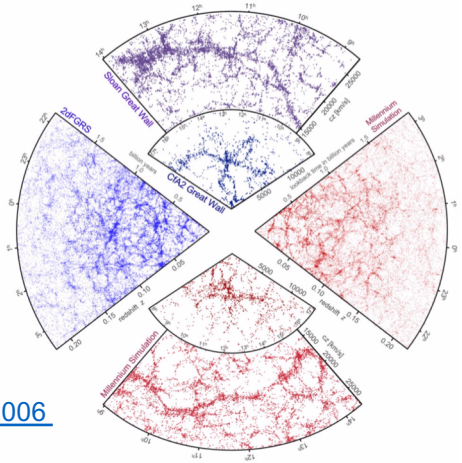


The Astrophysical Journal, 648:L109–L113, 2006

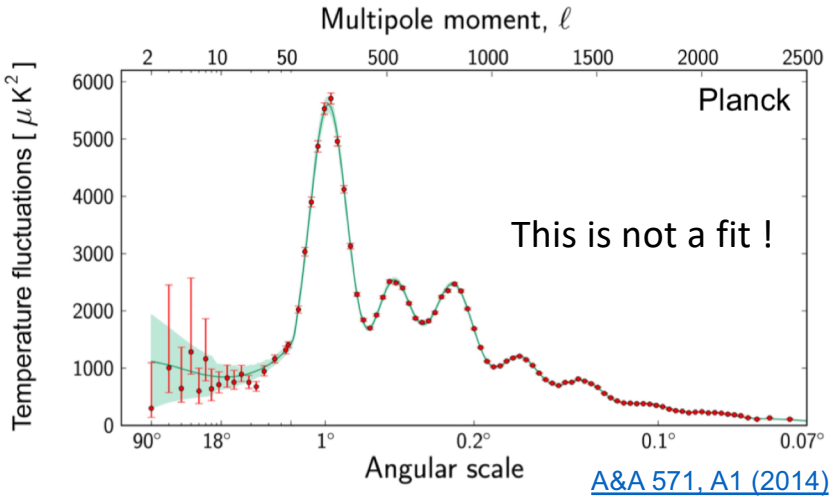


Galaxy clusters collisions fit well with DM expectations

Large Structure Formation requires DM



Nature, Vol. 440, Avril. 2006



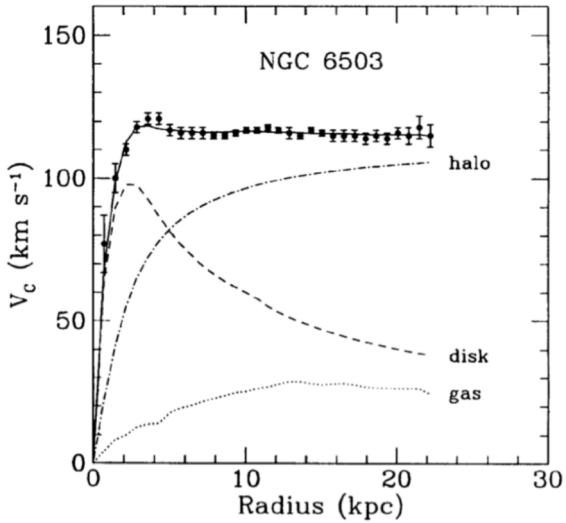
A&A 571, A1 (2014)

CMB fluctuations are well described by the ΛCDM model

One fundamental question is open:

Does DM exist ? (or is GR wrong ?)

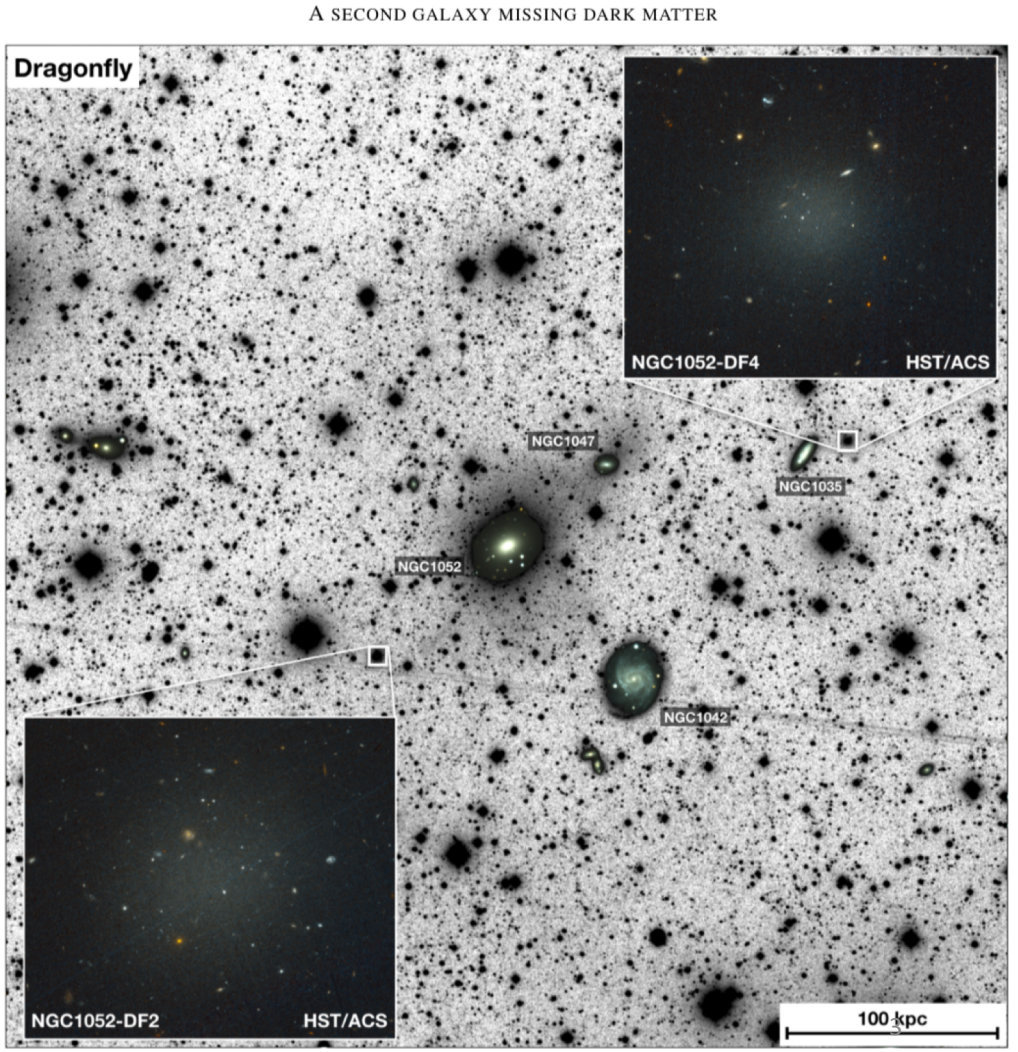
Radial speed of stars in most galaxies requires DM



« A Second Galaxy Missing Dark Matter in the NGC 1052 Group » [Astrophysical Journal Letters, March 2019]

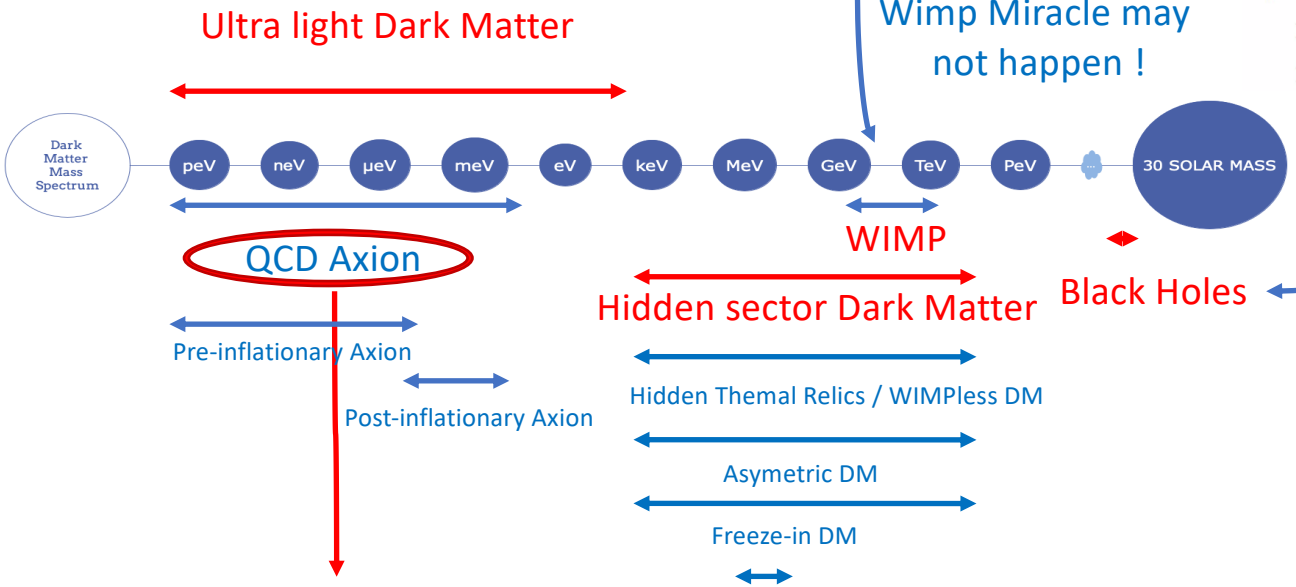
i.e. two galaxies are well described by General Relativity and are a good sign that Modified gravity is a weak solution unless these are specific cases also explainable in MOND

How homogeneous is DM density in the universe ?

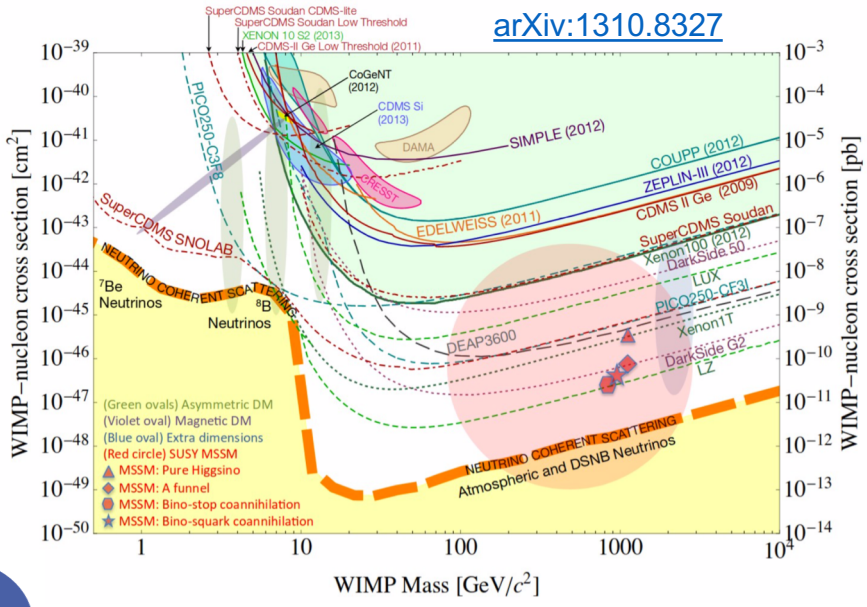


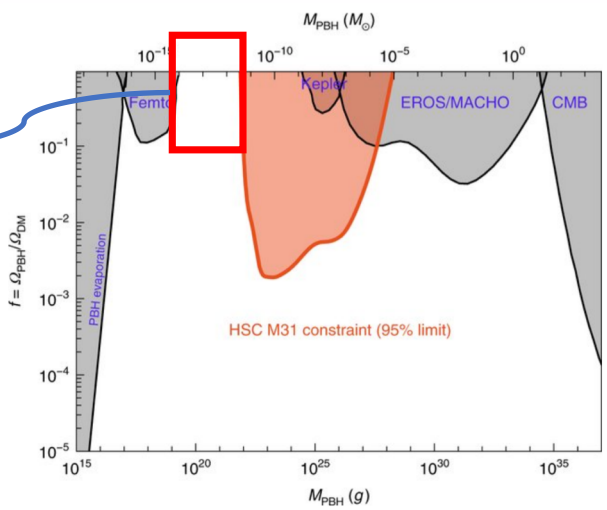
The subsidiary question is :

What is the DM microscopic nature?



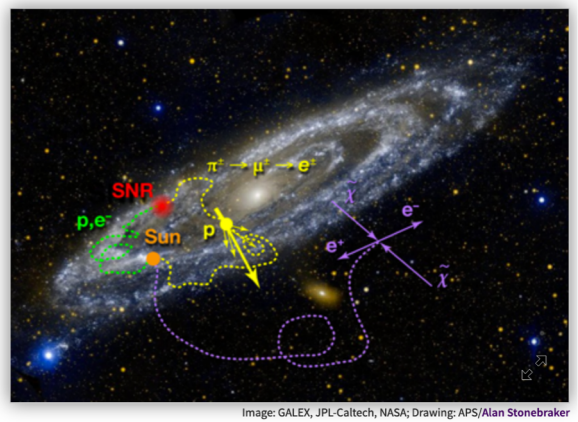
A prediction to protect CP violation in QCD
Axion-like particles predicted
from global symmetries in various models

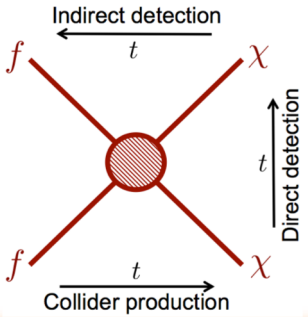


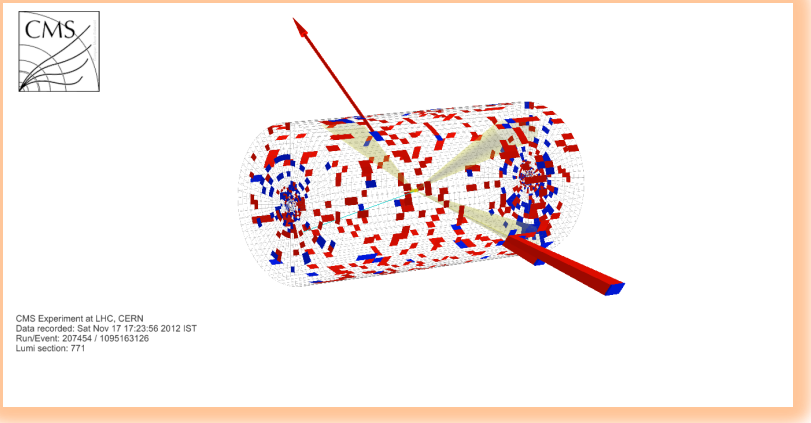


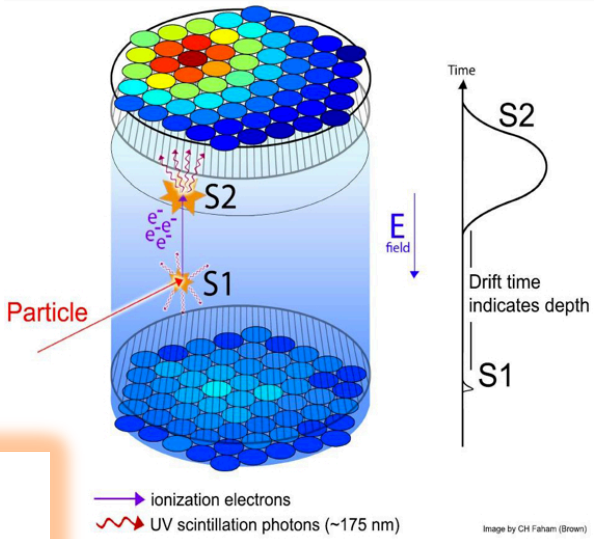
Search for microlensing of M31 stars based on the single-night HSC/Subaru data (1/04/2019, Nature Astronomy)

Complementary approaches of the DM search







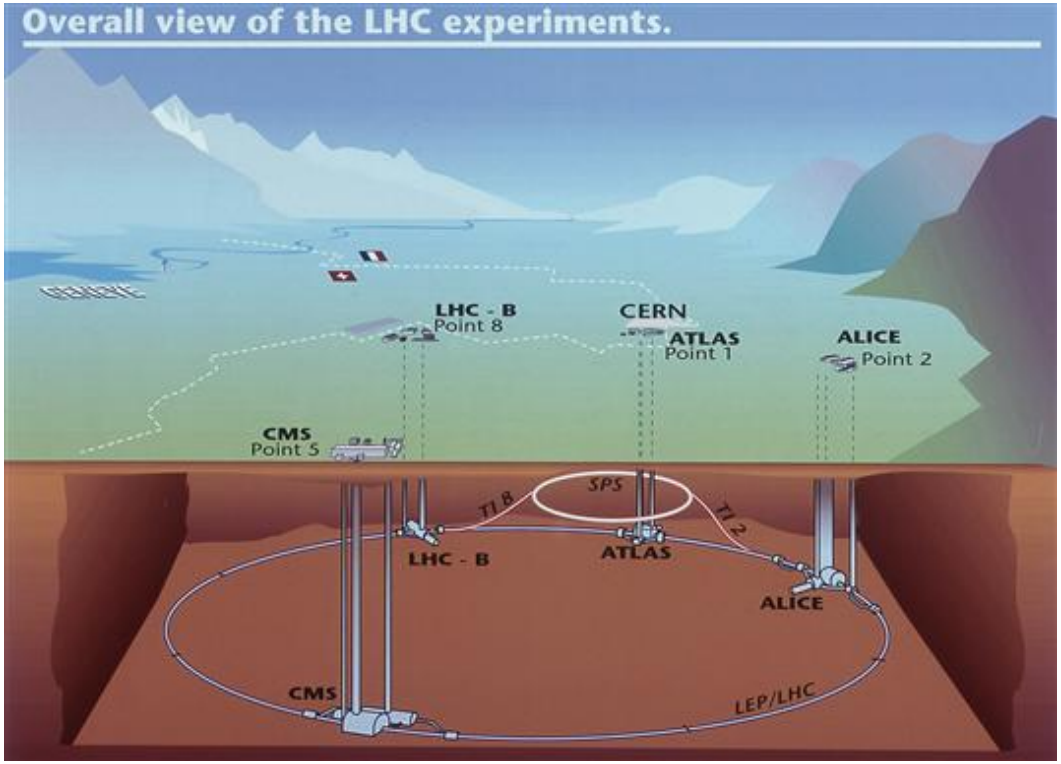


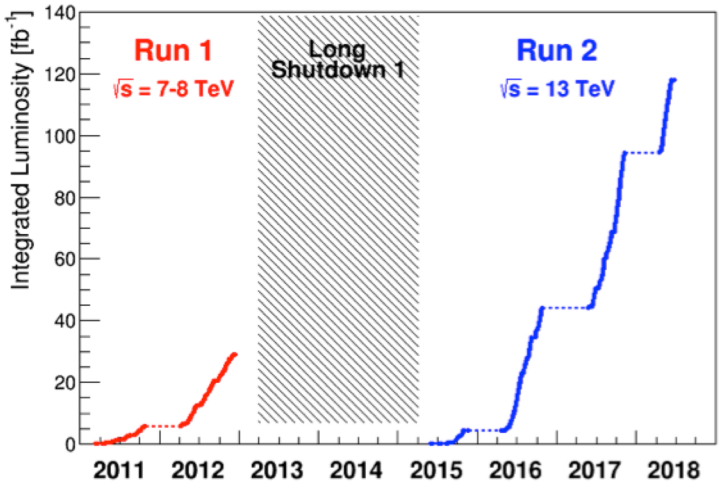
Search for DM @ LHC:

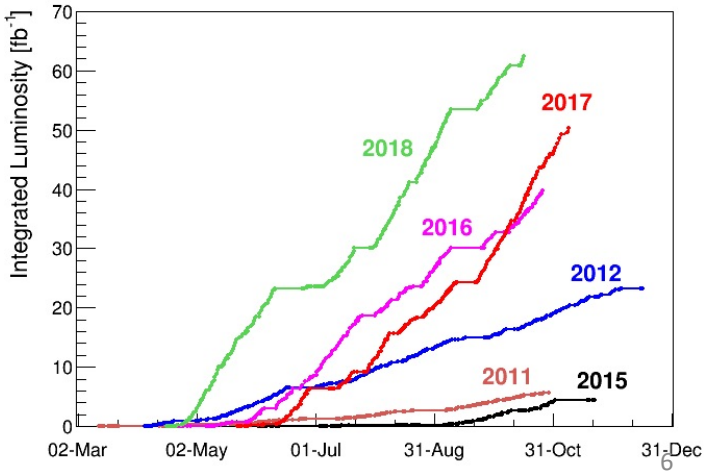
- Mono-X+DM (MET)
- Long Lived Particles
- Higgs boson invisible decay

  (Not covered in this talk, see backup slide)

LHC and its experimental setup to tackle DM







LHC – a high intensity proton-proton collider
2 main general purpose experiments : ATLAS and CMS
2 specialized experiments : LHCb, Alice

{ the energy frontier allow to produce massive DM candidates

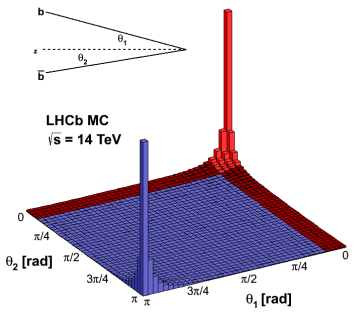
LHCb and the DM

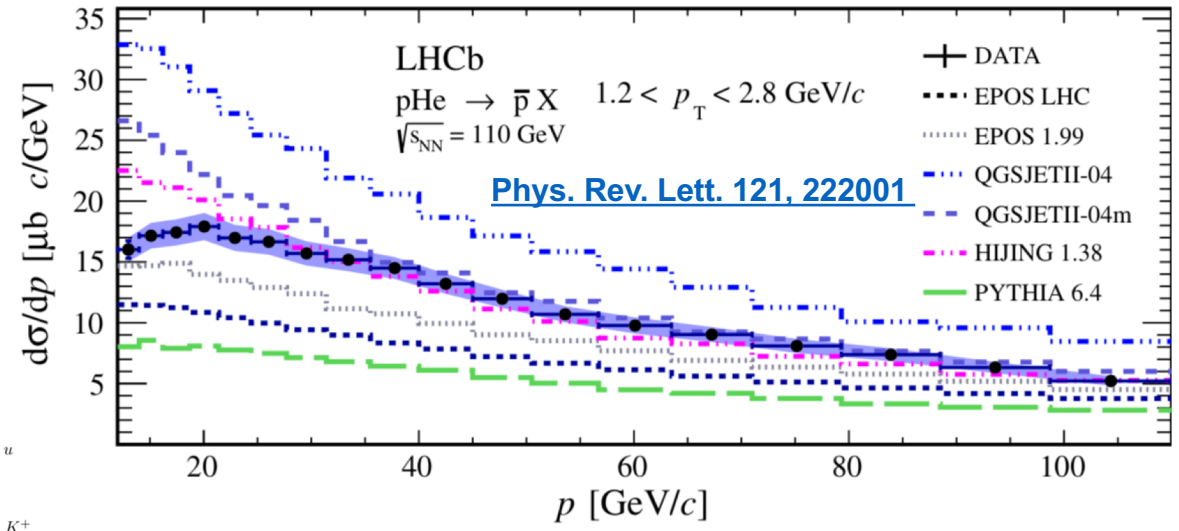
- pp collisions at 7, 8 and 13 TeV
- 3 (2) /fb in Run I (II) of the LHC
- Produce b $\bar{b}$ pairs produced correlated in the forward region

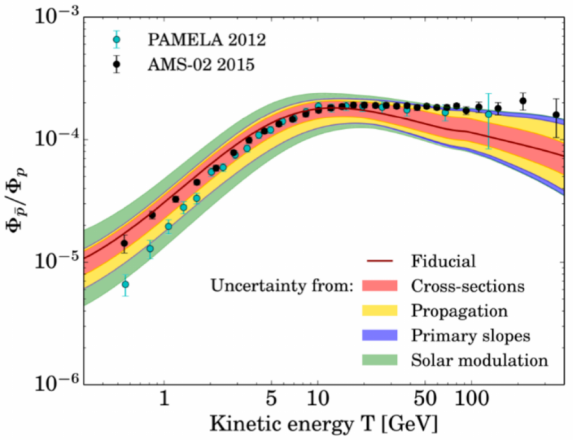
- LHCb is a multi-purpose detector in the forward region
- Allows the measurement of p He ⟶ antiproton to help constraining backgrounds for astroparticle searches :

LHCb can be turned into a fixed-target experiment using the injection of a noble gaz jet colliding with one LHC proton beam.

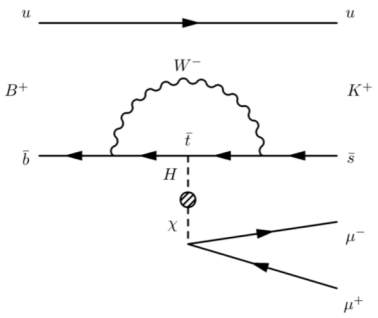
First measurement using 0.5 nb^{-1} dataset of p-He







[PAMELA - Jetp Lett. (2013) 96: 621]

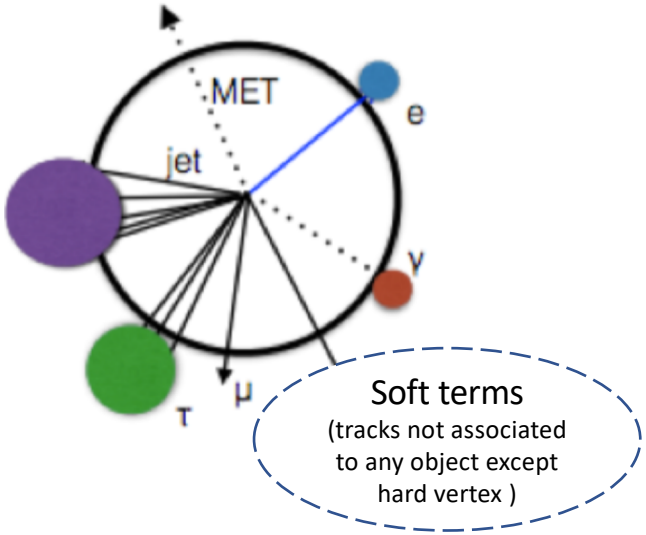


B-Physics is sensitive to loop contributions, including DM contributions

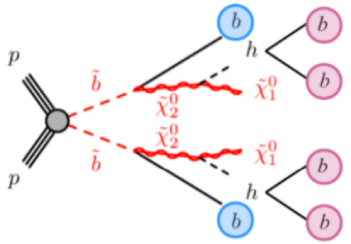
Can also probe direct production mechanisms in forward production complementary to ATLAS/CMS but at lower mass. For instance Long Lived Particles.

Importance of MET as DM signature at the LHC :

Assume that DM is composed of a neutral, weakly interacting particle ⟶ Missing Transverse Energy (MET)



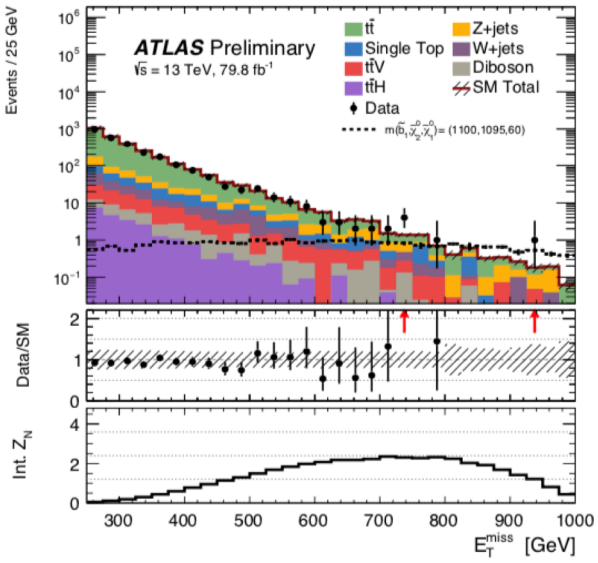
Example:



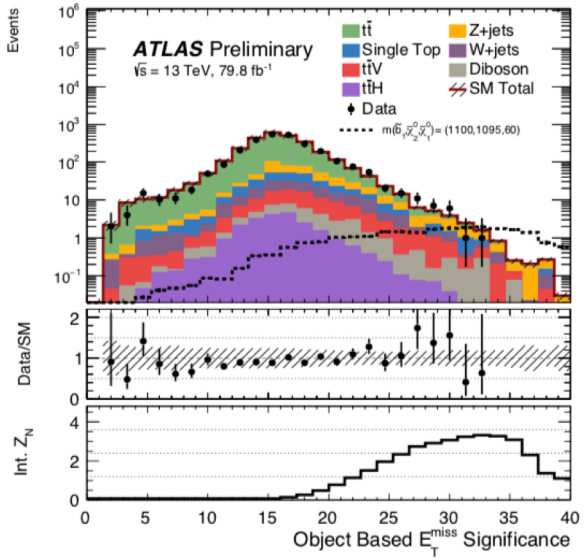
Experimental challenge :

Huge effort to built pile-up resilient MET reconstruction in all LHC experiments
Even better : MET significance (MET/Sigma)

MET



Object-based MET Significance

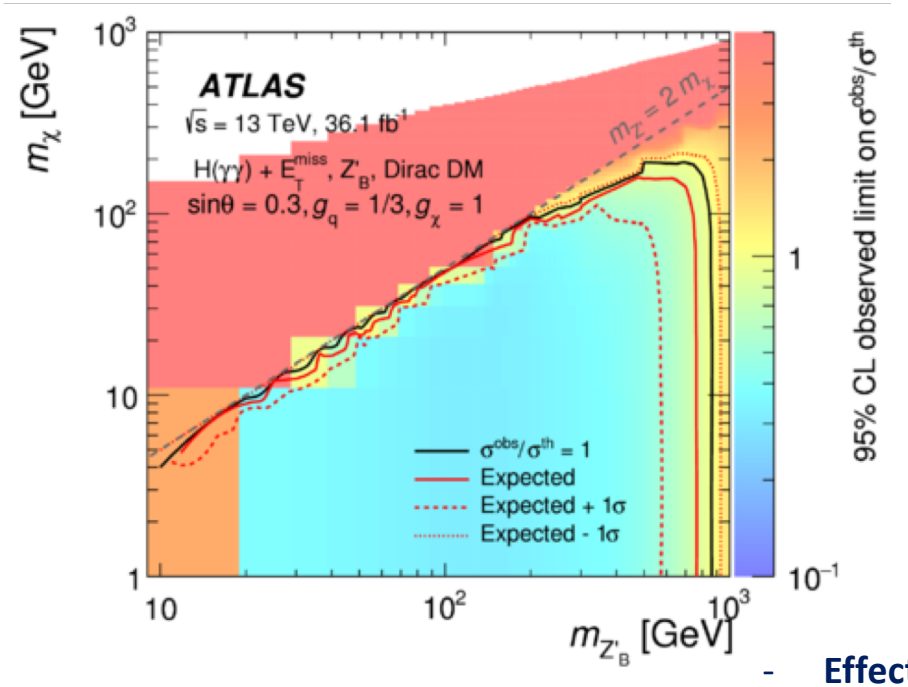


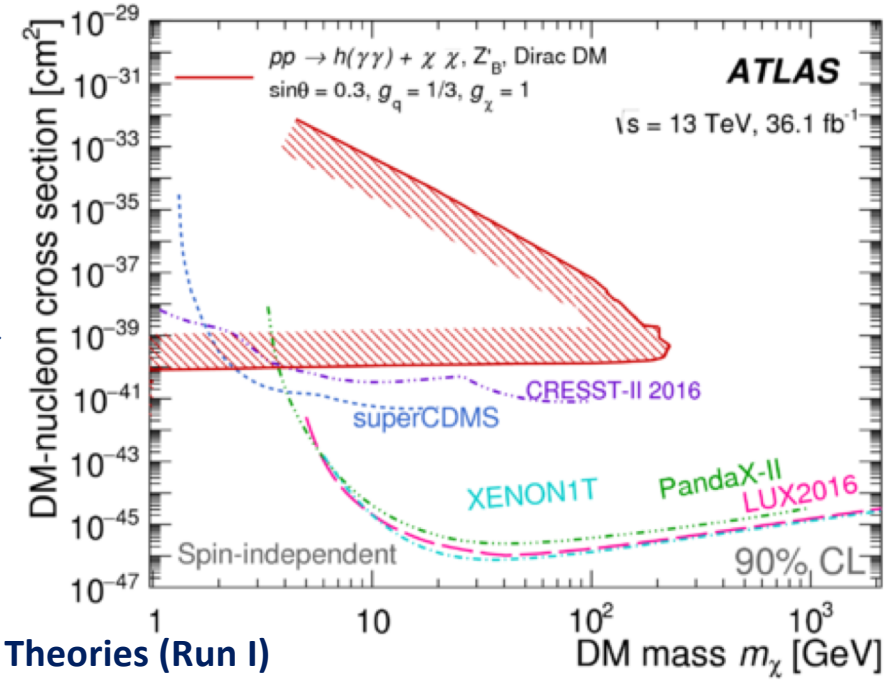
ATLAS-CONF-2018-038

ATLAS-CONF-2018-039

When no DM signal seen, how do we interpret null results ?

- Interpret these null results as limits ⟶ limit plots exploring the space parameters of simplified models or more complex models (Z'_B, 2HDM+a, SUSY).
- Some of these results are recast on **Model dependent** limits on the nucleon-DM cross-section for comparison with direct searches (each plot has the values of the model parameters chosen to cast the results !).

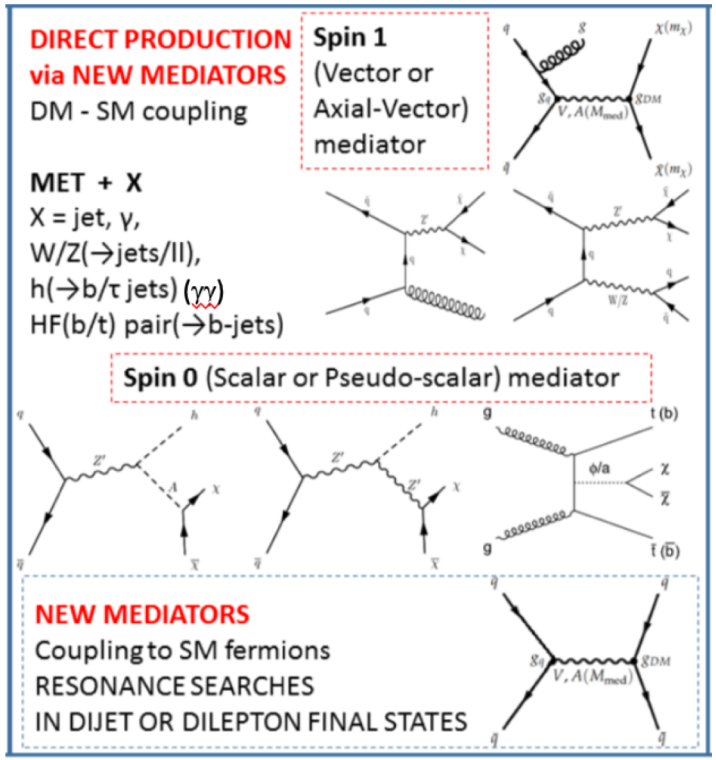




Theoretical frameworks :

- **Effective Field Theories (Run I)**
- **Simplified models**
- **UV complete/consistent simplified models**
- **SUSY as a complete model with a complex dynamics**

Mono X channels



- Mono Jet
- Mono photon

} Use the MET distribution to see any potential excess

- Mono Top
- Mono Z/W
- Mono Higgs

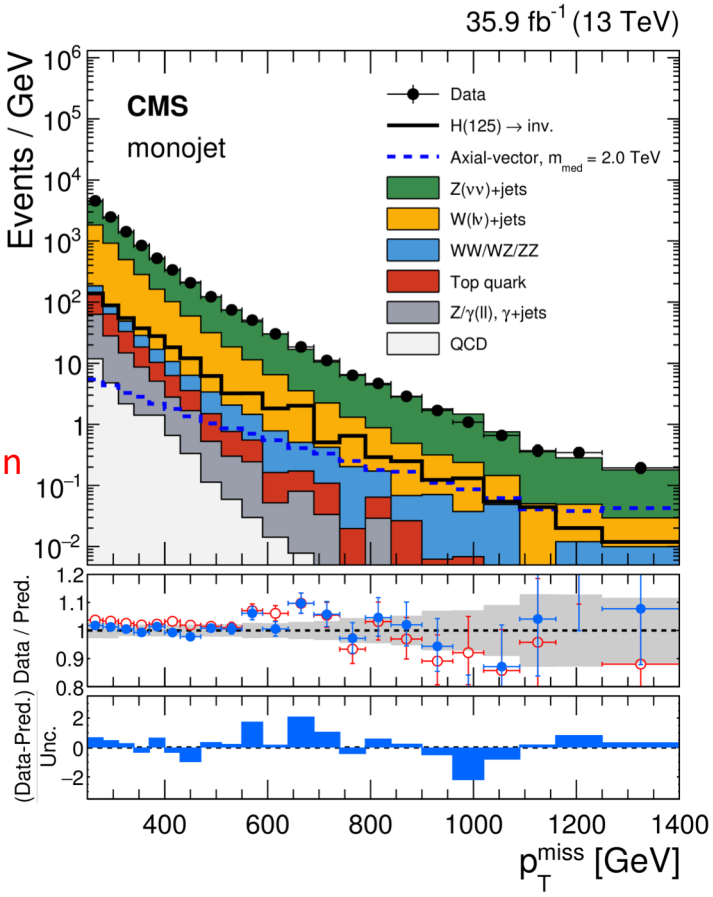
} Use the MET distribution and kinematics of the final state decay products to enhance the observation of a potential excess.

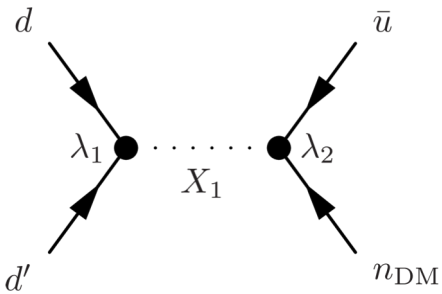
NB : Mono-Higgs is very sensitive to new physics since there is no ISR contributions thanks to very low coupling between H and quarks

(Adapted from M. Felcini)

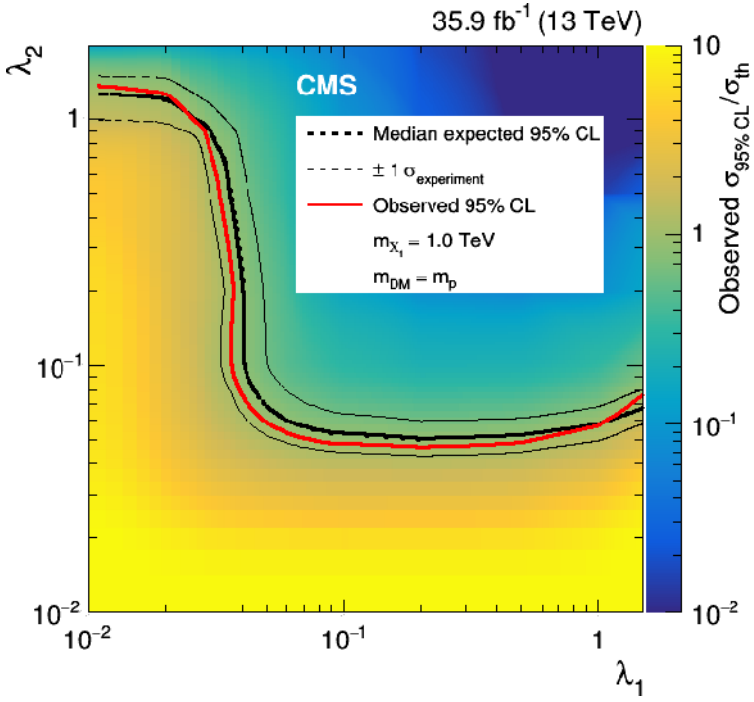
Mono-jet

CMS result: [Phys. Rev. D 97 (2018) 092005]





Interpretation in a non-thermal Dark Matter Model



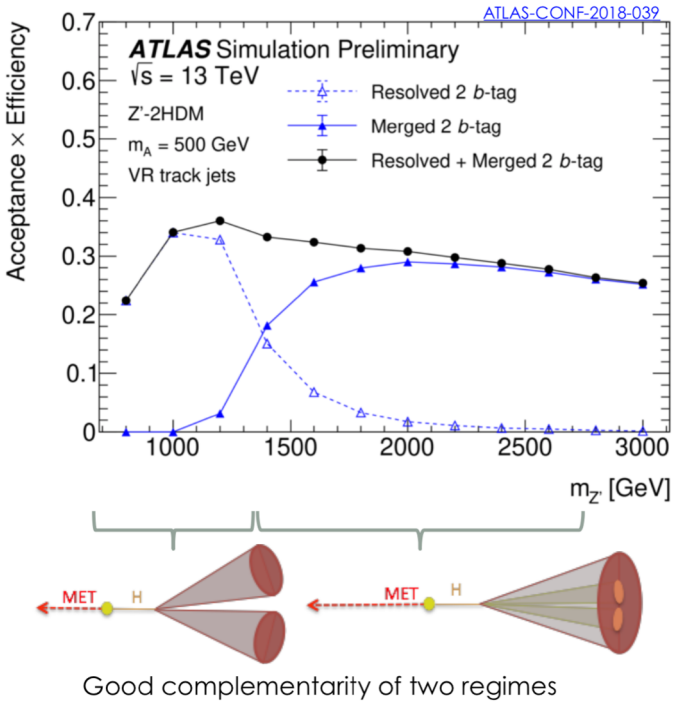
Challenge of the analysis :

- Datadriven measurements of the EW backgrounds from W/Z+jets
- Done using single lepton and dilepton control regions

ATLAS result: [JHEP 01 (2018) 126]

Mono-Higgs

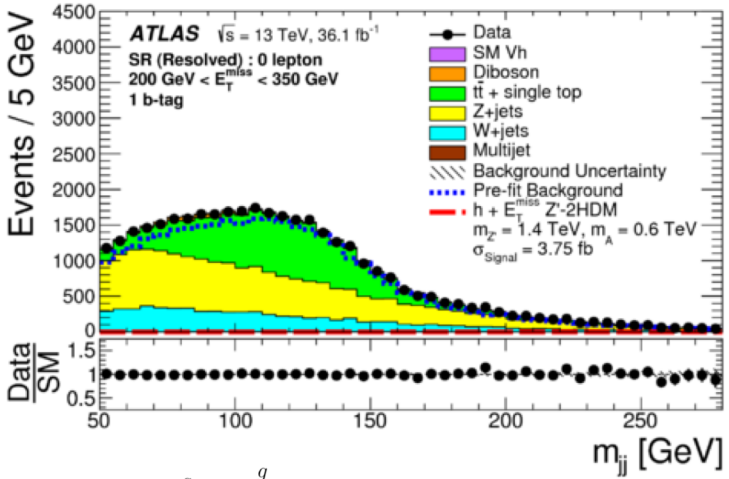
(DM + H⟶γγ/bb)

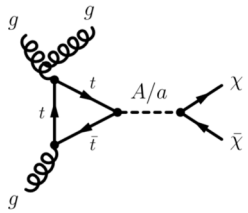


Good complementarity of two regimes

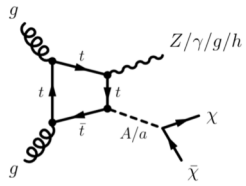
CMS mono-H result: CMS-PAS-EXO-18-011)

PRL 119 (2017) 181804



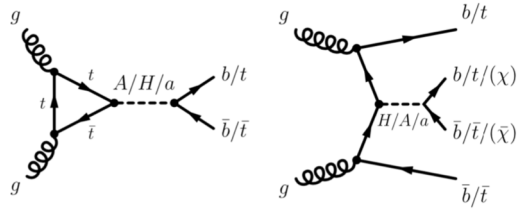


2HDM+a provides a rich phenomenology



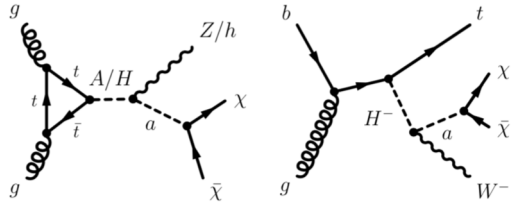
arXiv:1903.01400

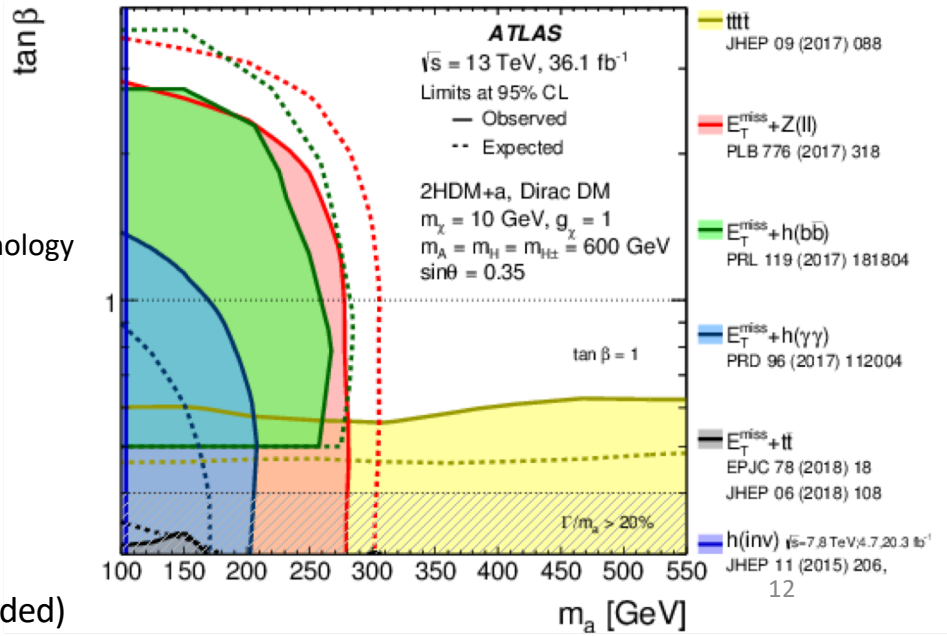
(Constraints on many models included)



2HDM+a

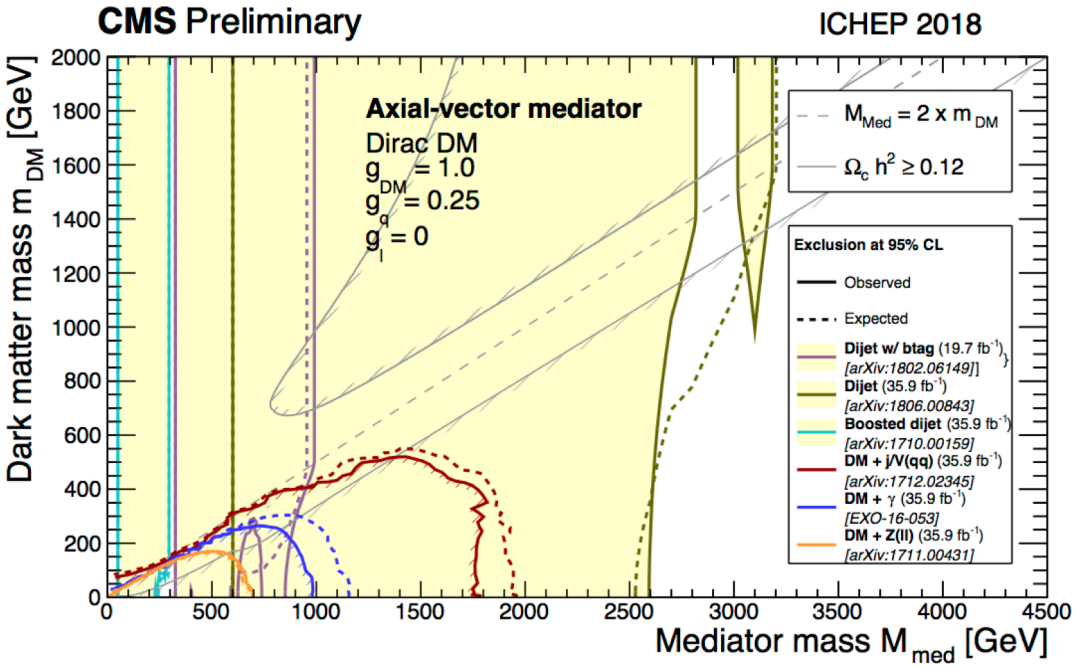
Includes DM as a pseudo-scalar



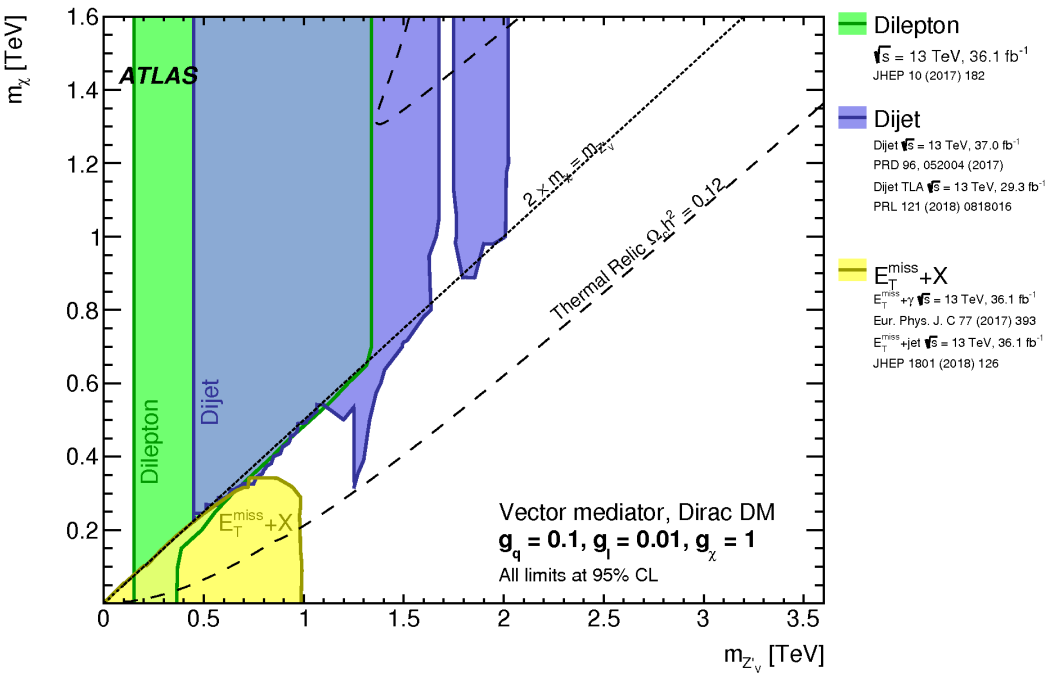


Evolution of exclusion with couplings

Mono-X provides complementary information to dilepton/dijet resonance searches when coupling to fermions is low

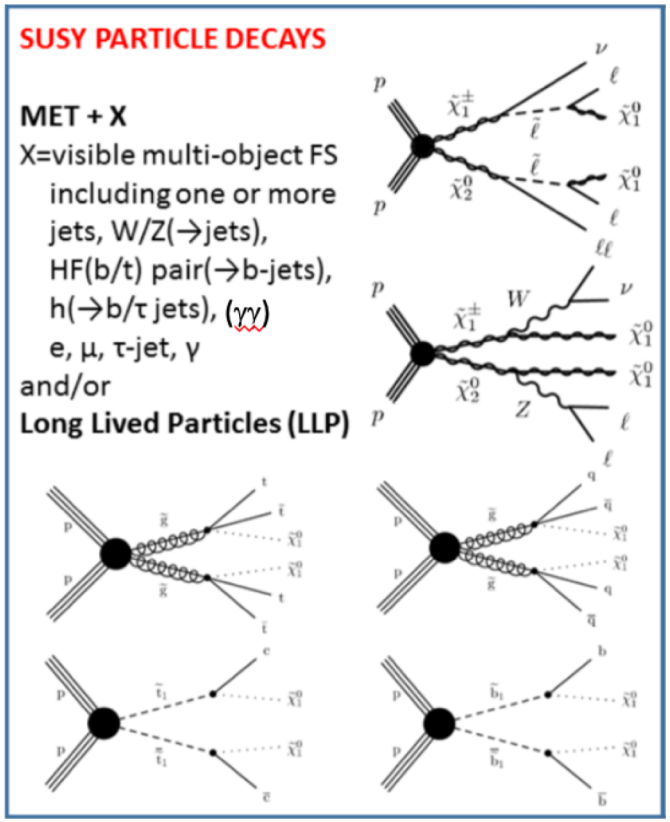


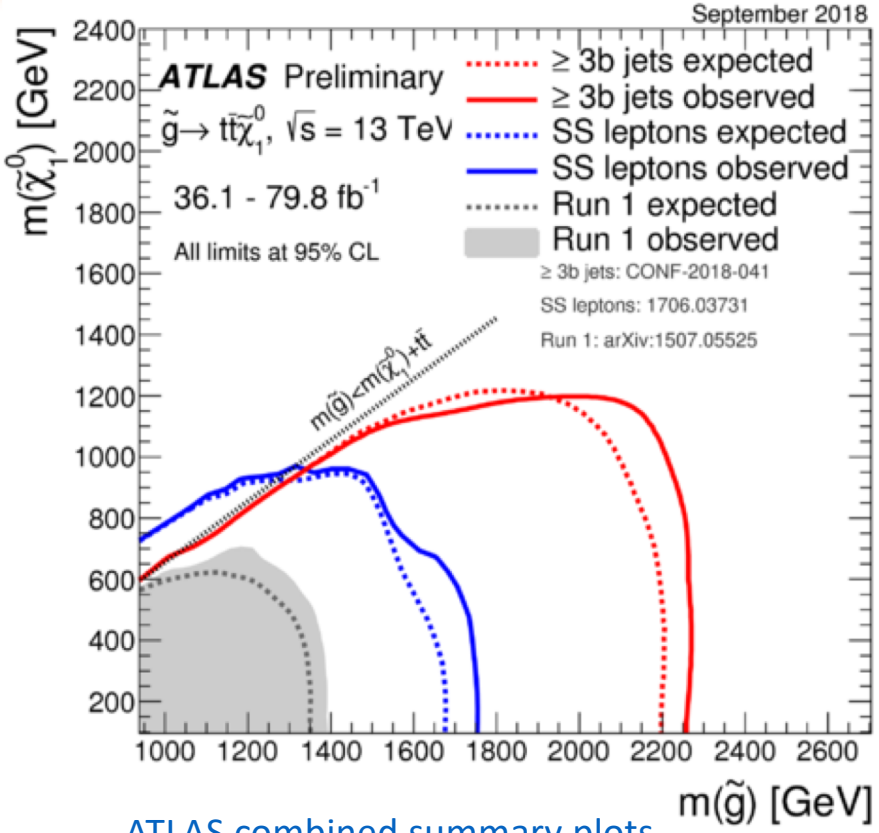
CMS combined summary plots



ATLAS combined summary plots

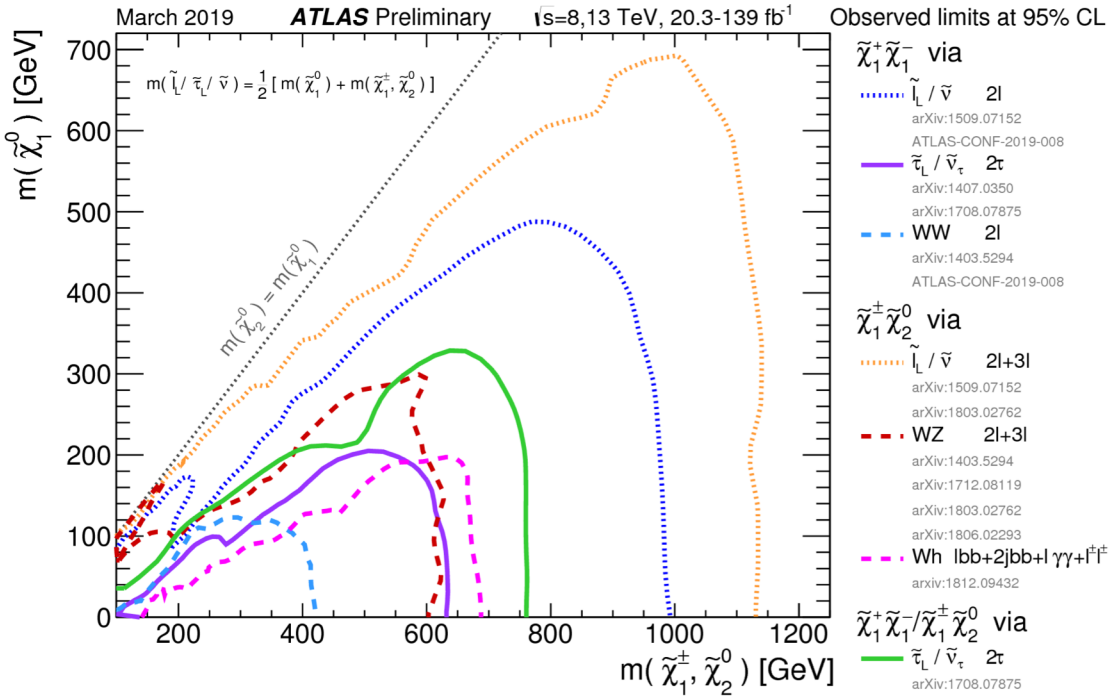
DM as SUSY LSP



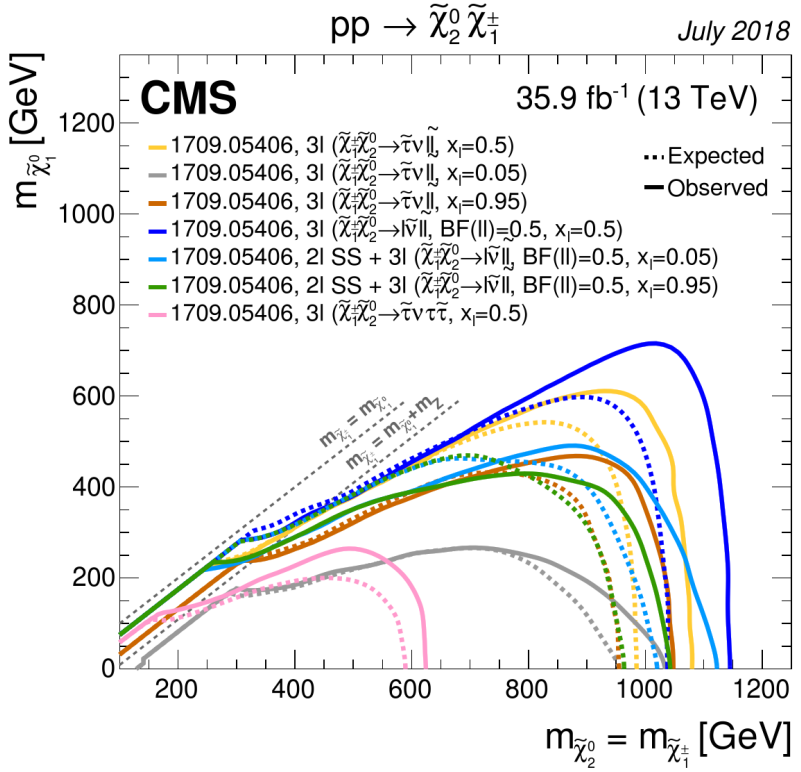


ATLAS combined summary plots

Contraints on the Lightest Supersymmetric Particle mass



[ATLAS combined summary plots](#)
(ATL-PHYS-PUB-2019-012)



[CMS combined summary plots](#)

DM as Long Lived Particles from SUSY and beyond

Sources of Long Lived Neutral particles

Standard Model:

B, D and K mesons
Neutrons
Neutrinos

SUSY:

R-Parity SUSY LSP
R-parity violating SUSY
Gauge Mediated SUSY breaking scenarii
Anomaly mediated SUSY breaking scenarii
Split SUSY
Stealth SUSY
…

Beyond SUSY:

Hidden valley scenarii
Dark QED
Dark QCD
Many DM models
- Left-Right symmetric models (esp. Heavy neutrinos)
- Axion-like particles
- …

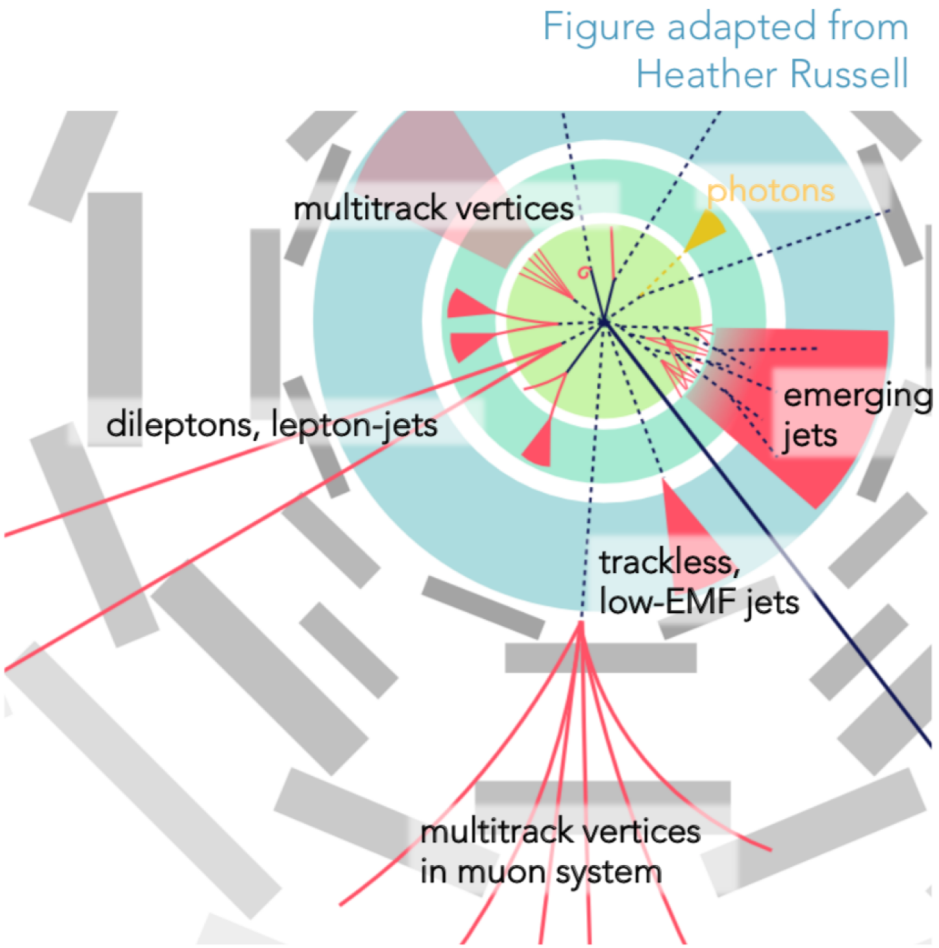
LLP at LHC : rich phenomenology with a lot of experimental challenges (Custom Trigger, Reco, Backgrounds/DQ)

Expect :

- Displaced decays :
  - In trackers
  - In Calos
  - Muon systems

- Delayed decays (late particles) because of the time of flight of a massive particle
  - Interesting application of precise timing detector

- Trapped particles in the detector
  - e.g magnetic monopoles

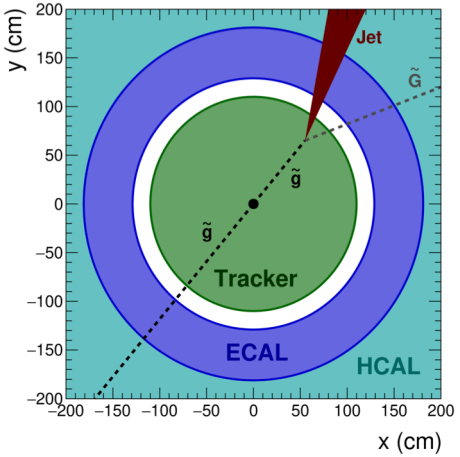


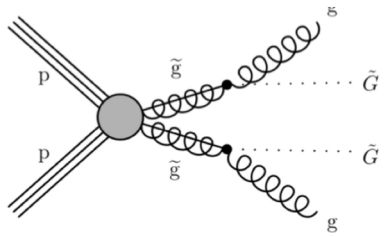
CMS: Delayed jets

Full Run 2 = 137 fb^{-1}

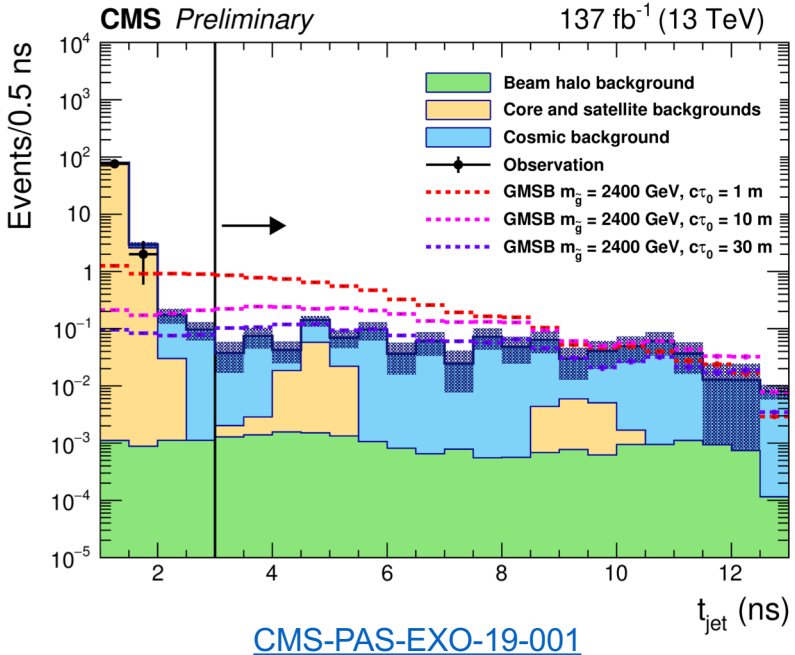
Use ECAL timing (200 ps RMS)

T_{jet} = median time of cells within $\Delta r = 0.4$

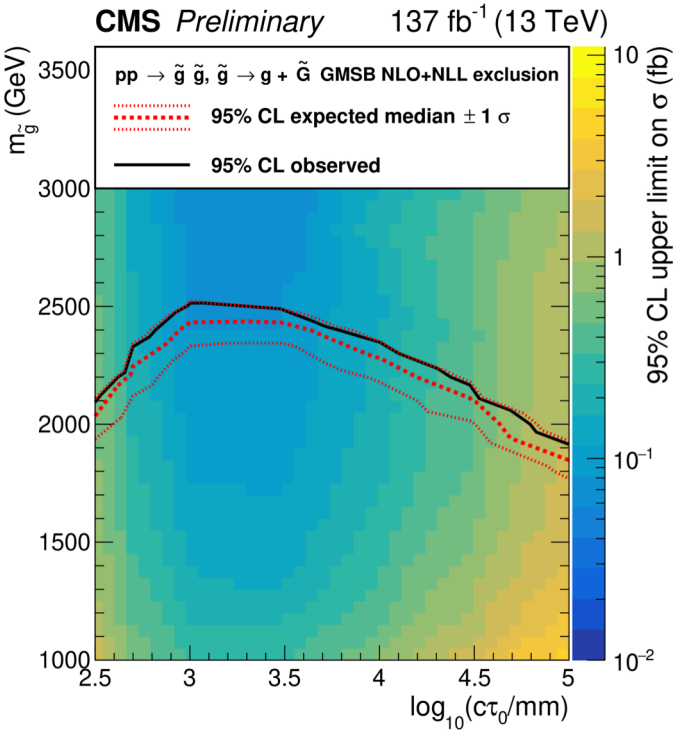




GSMB SUSY : $\tilde{g} \longrightarrow \tilde{G}\, g$

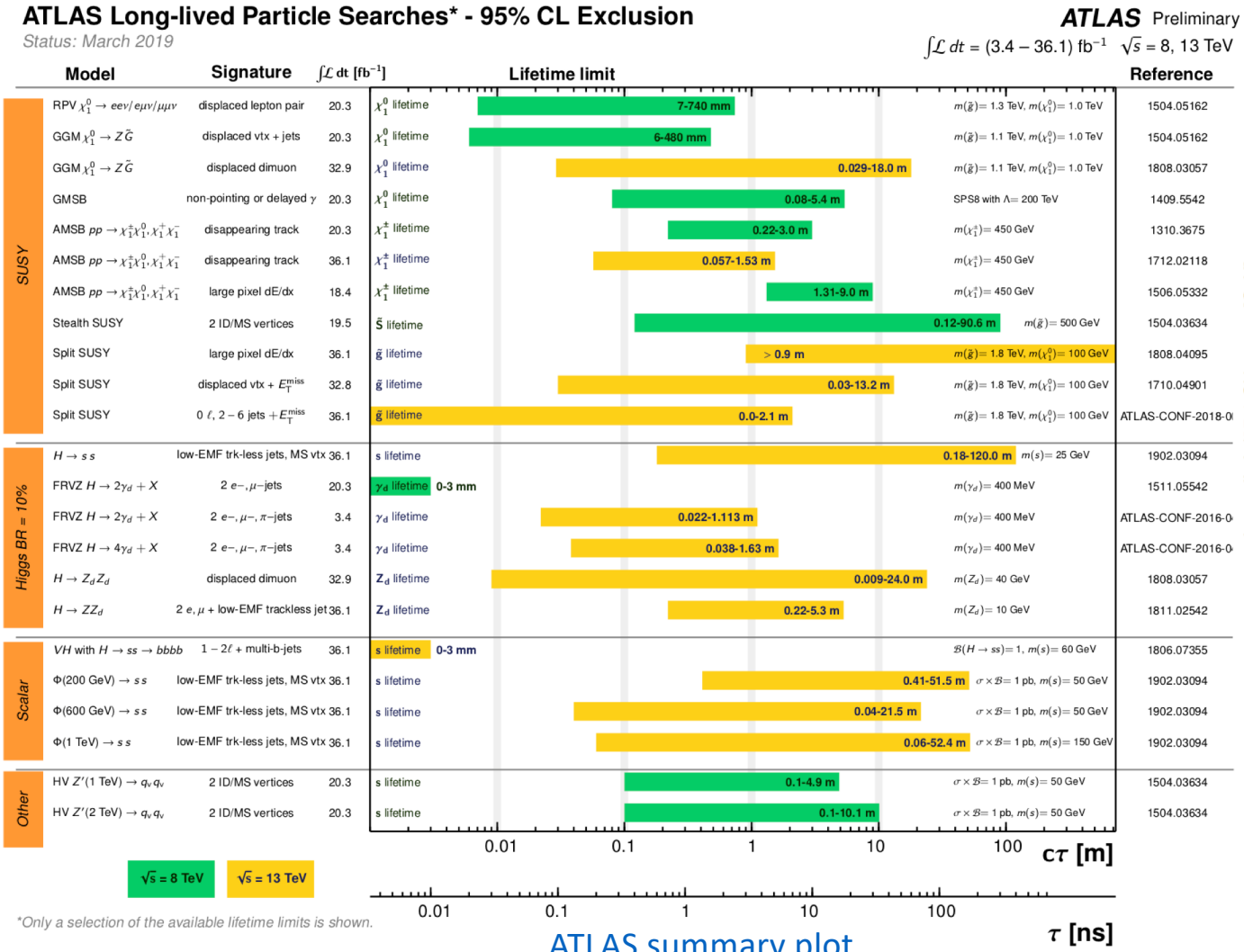


CMS-PAS-EXO-19-001

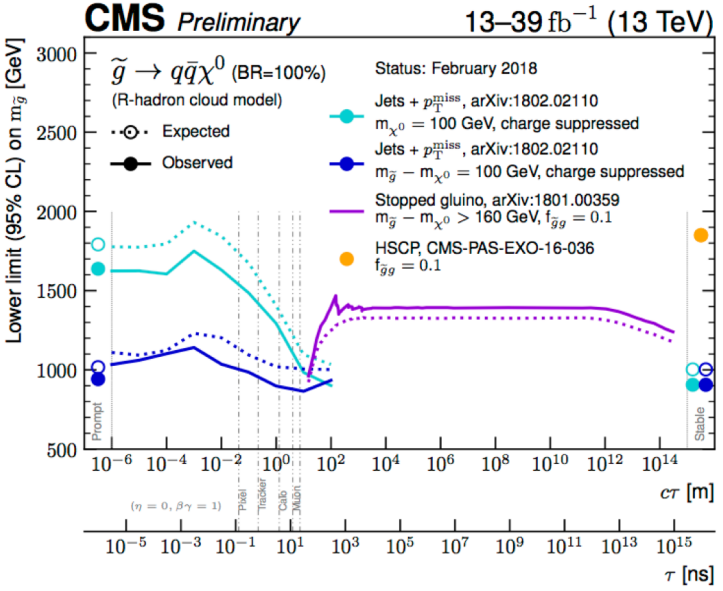


- Selection : MET>120 GeV, 3 ns < t_{jet} < 20 ns
- Reconstruction is using Calo only
- This analysis extends the constraint in cτ beyond track based search
- Gluino masses up to 2.5 TeV/c^2 excluded for cτ = 1 m

Summary of Long Lived Particles



[ATLAS summary plot]

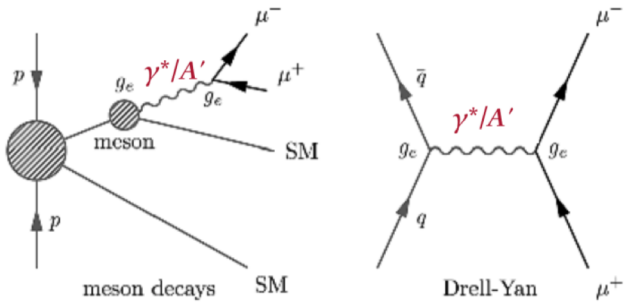


[CMS summary plot]

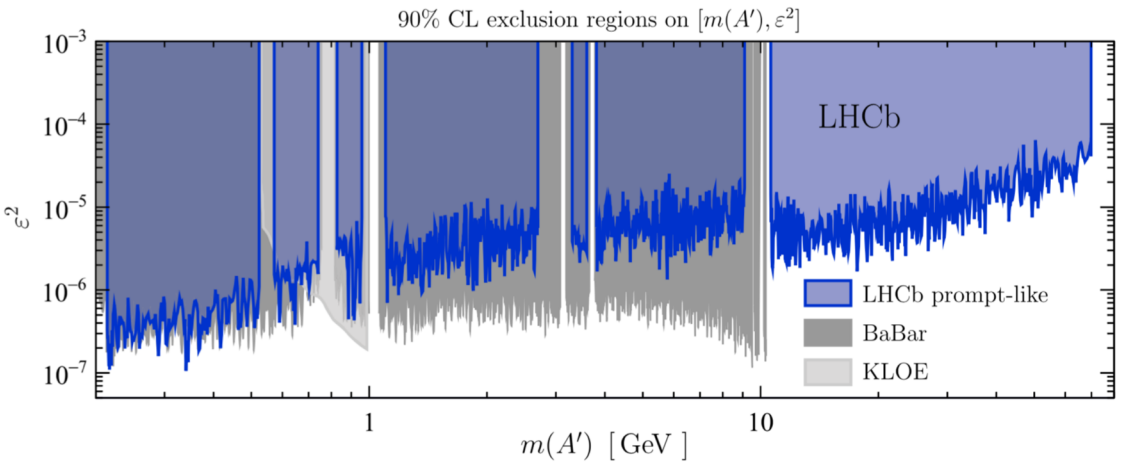
DM from other specific final states

- Angular distribution of dijets (CMS & ATLAS)
- Search for delayed $\mu^-\mu^+$ resonance (LHCb)
- Dark photons (ATLAS, CMS, LHCb)
- …

Dark photons (LHCb)

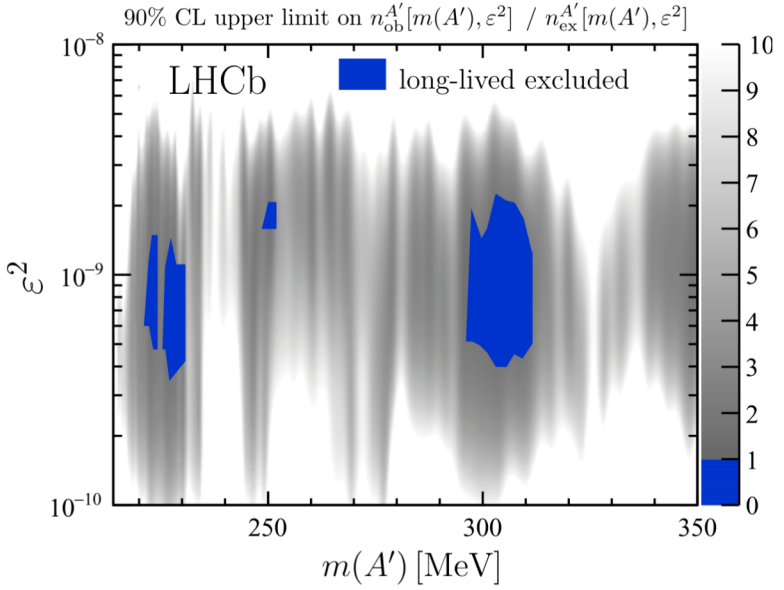


PHYSICAL REVIEW LETTERS **120,** 061801 (2018)

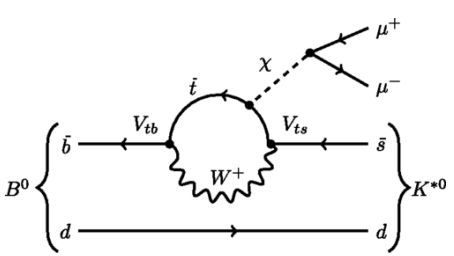


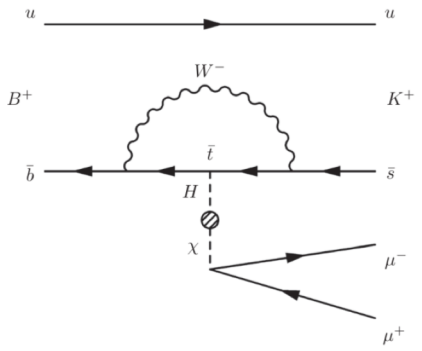
Good vertex reconstruction allows to search for prompt decay or displaced vertex when A' decays.

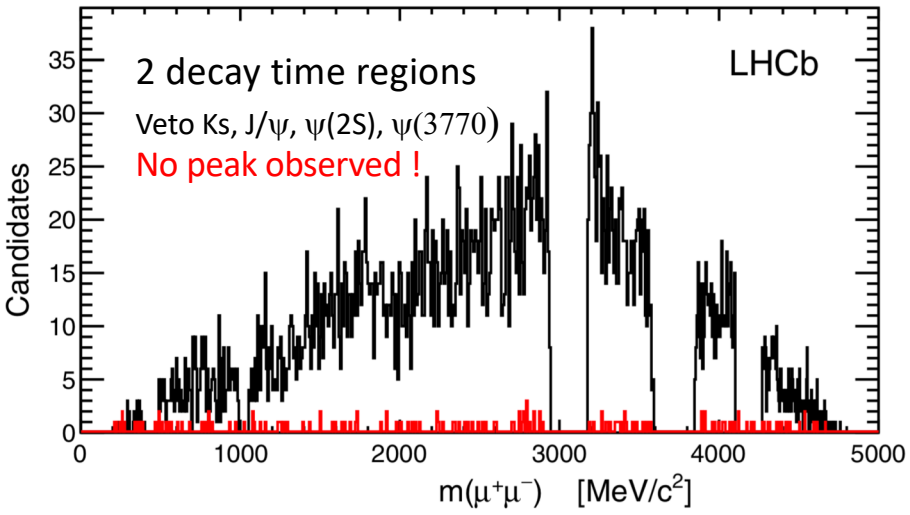
- Can search for Dark Photons (A') in μμ
  - First result with 1.6 fb^{-1} at 13 TeV
  - New μμ trigger with online μ-ID
    - ✓ Only interesting part of the event to disk
    - ✓ No prescale down to threhold 2 m_μ
- Put constraint on the kinetic mixing with off-shell photon (ε^2)



LHCb $B^{(0,+)} \longrightarrow K^{(*0,+)} X(\mu,\mu)$

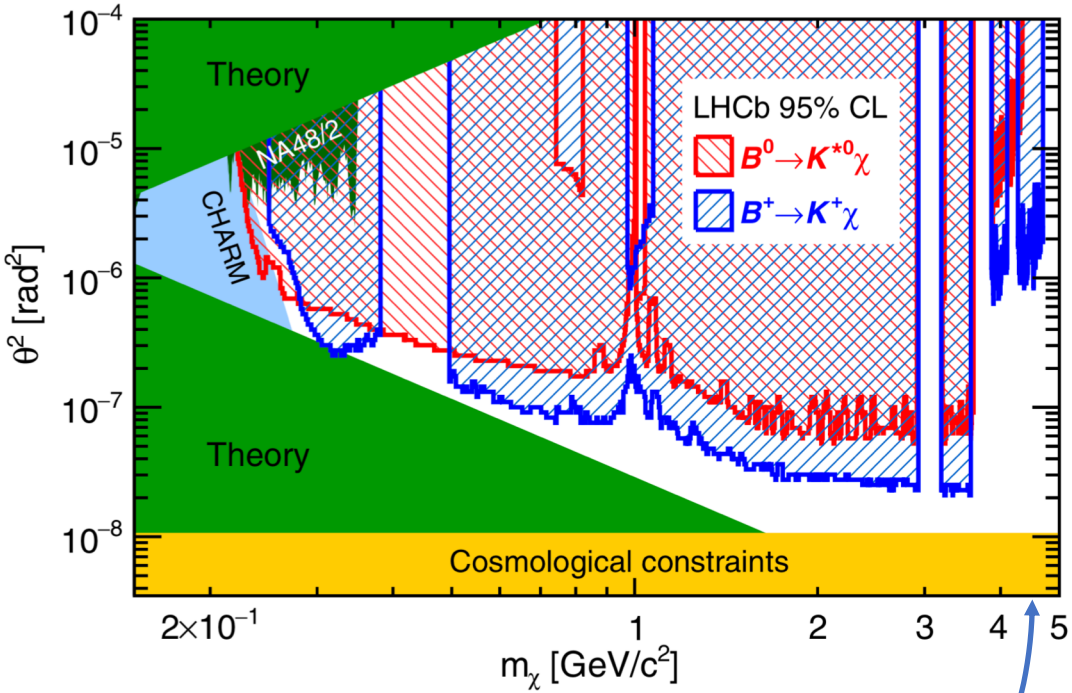






PHYSICAL REVIEW D 95, 071101(R) (2017)

3 fb^{-1} of data at 7 and 8 TeV

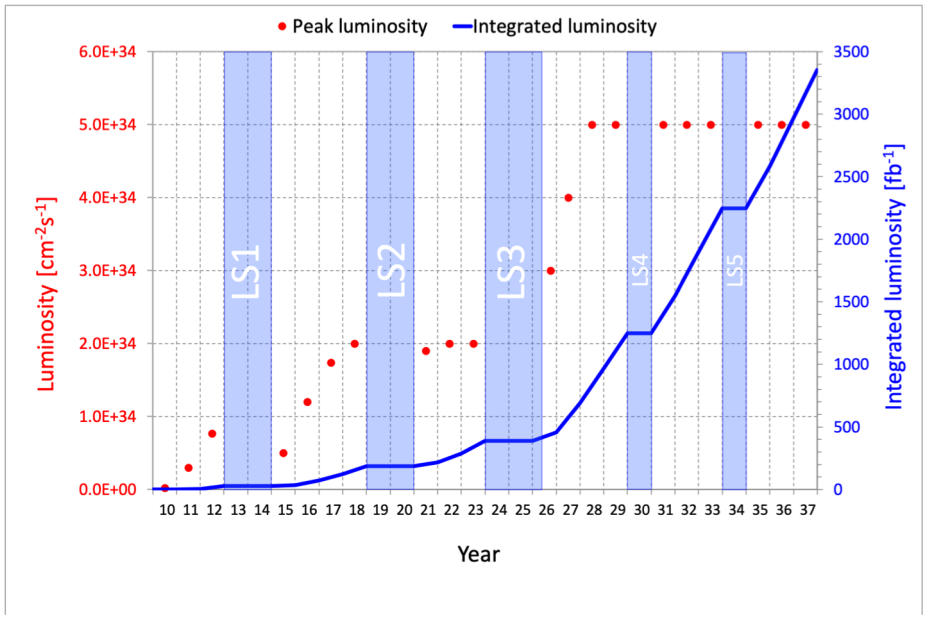


Constrains on different theoretical models:

- Axion model (Phys. Rev D81 034001 2010)
- Inflaton model (Phys. Lett. B736 (2014) 494)
  - Converted in limits on mixing angle with SM Higgs Boson

Conclusion

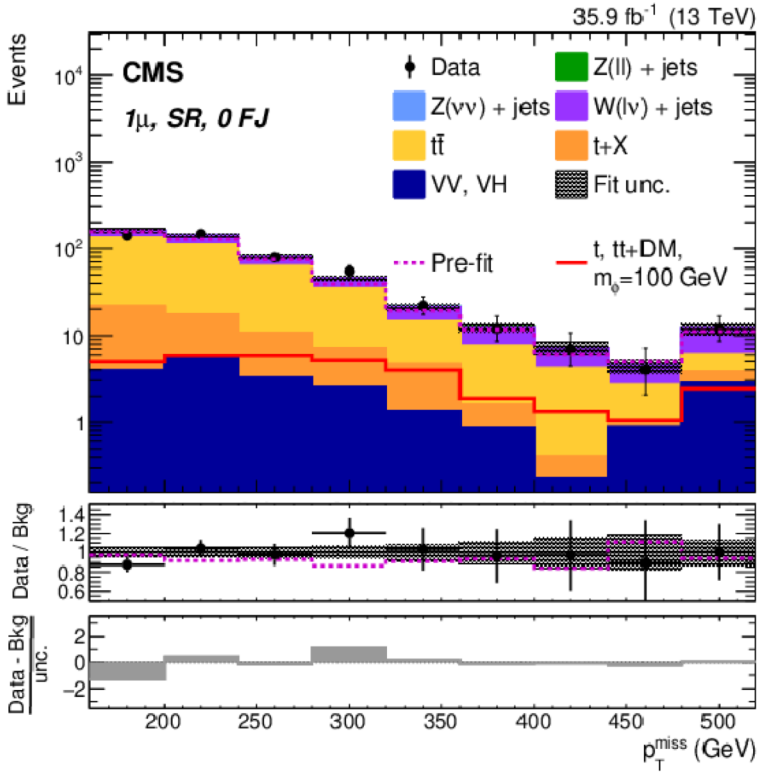
- New experimental arguments strengthen the need for DM
- A huge activity at LHC to search for DM in very different ways beyond the WIMP paradigm, especially LLP
- Up to now, no DM candidate observed
- Extended dataset is coming at the LHC
- Stay tuned !



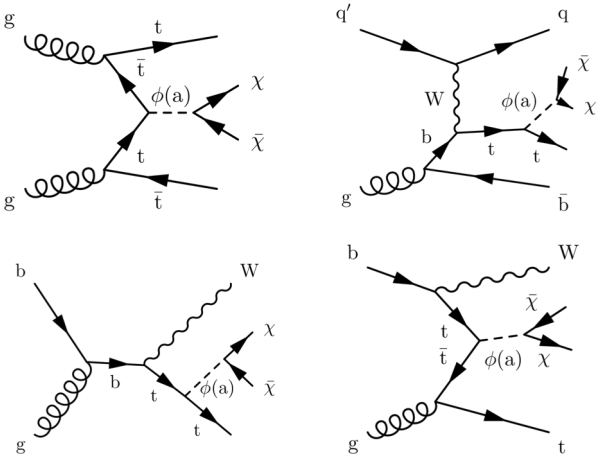
Back-Up Slides

Mono-Top

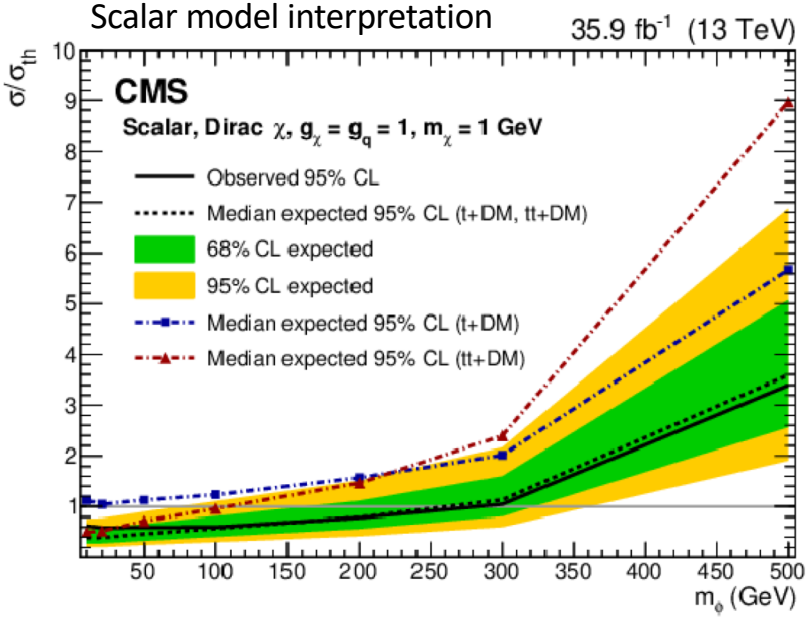
JHEP 03 (2019) 141 (CMS)



No excess observed



Scalar model interpretation



ATLAS result : arXiv:1812.09743

Bibliography

ATLAS

Short Titles	*Journal reference*	*Date*	*√s (TeV)*	L (fb^{-1})
Summary of searches for mediator-based dark matter and scalar dark energy models	Submitted to JHEP	03-mars-19	13	36
Search for MET plus a single top quark	Submitted to JHEP	23-dec-18	13	36
Displaced jets in muon system	Phys. Rev. D 99 (2019) 052005	18-nov-18	13	36
Search for events with MET and VBF signature	DOI: 10.1016/j.physletb.2019.04.024	18-sept-18	13	36
Same-sign dilepton plus b-jet search	JHEP 12 (2018) 039	31-juil-18	13	36.1
Search in the MET plus V hadronic final state	JHEP 10 (2018) 180	30-juil-18	13	36
H to ZdarkZdark or ZZdark search in the llll final state	JHEP 06 (2018) 166	09-feb-18	13	36
Stop pair, WIMP DM pair; 1 lepton	JHEP 06 (2018) 108	30-nov-17	13	36
MET plus jet search	JHEP 01 (2018) 126	09-nov-17	13	36
WIMP DM pair + HF quarks; 0, 2 leptons	Eur. Phys. J. C 78 (2018) 18	31-oct-17	13	36
Search ZH(125), H(125)->invisible and Z+MET	PLB 776 (2017) 318	31-aug-17	13	36
MET + H search with H to bb	Phys. Rev. Lett. 119 (2017) 181804	05-juil-17	13	36.1
Search H(125)->gamgam + Missing-ET	Phys. Rev. D 96 (2017) 112004	13-juin-17	13	36.2
MET plus photon search	Eur. Phys. J. C 77 (2017) 393	12-apr-17	13	36.3
MET + H search with H to bb	ATLAS-CONF-2018-039	25-juil-18	13	80

LHCb

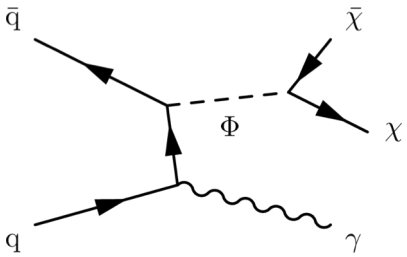
Titles	*Journal reference*	*Date*	*√s (TeV)*	L (fb^{-1})
Search for dark photons produced in 13 TeV pp collisions	10.1103/PhysRevLett.120.061801	08-Oct-17	13	1.6
Updated search for long-lived particles decaying to jet pairs	Eur. Phys. J. C77 (2017) 812	20-May-17	13	2
Search for massive long-lived particles decaying semileptonically in the LHCb detector	Eur. Phys. J. C77 (2017) 224	3-Dec-16	7-8	1-2
Search for Higgs-like bosons decaying into long-lived exotic particles	Eur. Phys. J. C76 (2016) 664	11-Sep-16	7	0.62
Search for long-lived scalar particles in $B^+ \to K^+ \chi(\mu^+\mu^-)$ decays	Phys. Rev. D 95, 071101(R)	14-Apr-17	7-8	3

Bibliography

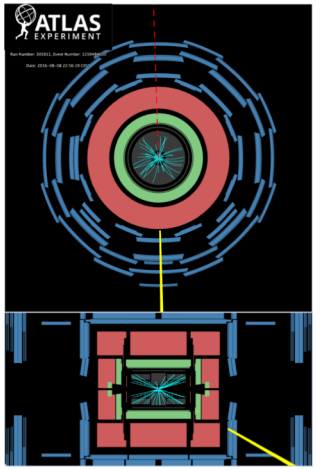
CMS

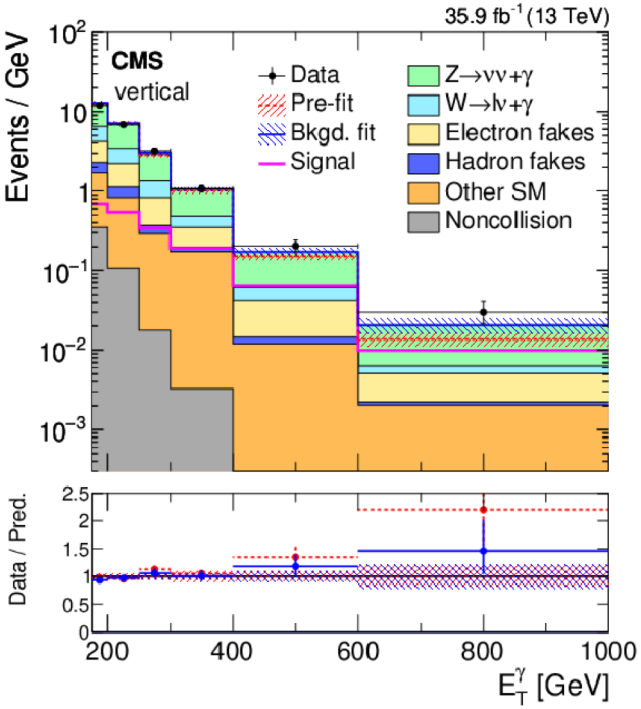
Titles	*Journal reference*	*Date*	*√s (TeV)*	L (fb^{-1})
Search for long-lived particles using delayed jets and missing transverse momentum with proton-proton collisions at √s = 13 TeV	CMS-PAS-EXO-19-001	31-Mar-19	13	137
Search for dark matter particles produced in association with the Higgs boson in proton-proton collisions at s√= 13 TeV	CMS-PAS-EXO-18-011	31-Mar-19	13	35.9
Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at √s= 13 TeV	JHEP 03 (2019) 141	6-Jan-19	13	35.9
Search for dark matter in events with a leptoquark and missing transverse momentum in proton-proton collisions at 13 TeV	EXO-17-015	26-Nov-18	13	77.4
Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton-proton collisions at √s = 13 TeV	Eur. Phys. J. C 79 (2019) 280	16-Nov-18	13	35.9
Search for new particles decaying to a jet and an emerging jet	JHEP 02 (2019) 179	23-Oct-18	13	16.1
Search for dark matter particles produced in association with a top quark pair at √s = 13 TeV	Phys. Rev. Lett. 122 (2019) 011803	18-Jul-18	13	35.9
Search for dark matter produced in association with a Higgs boson decaying to γγ or τ+τ− at √s = 13 TeV	JHEP 09 (2018) 046	13-Jun-18	13	35.9
Search for new physics in dijet angular distributions using proton-proton collisions at s√= 13 TeV and constraints on dark matter and other models	Eur. Phys. J. C 78 (2018) 789	21-Mar-18	13	35.9
Search for dark matter in events with energetic, hadronically decaying top quarks and missing transverse momentum at √s= 13 TeV	JHEP 06 (2018) 027	25-Jan-18	13	36
Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at √s = 13 TeV	Phys. Rev. D 97 (2018) 092005	6-Dec-17	13	35.9
Search for new physics in events with a leptonically decaying Z boson and a large transverse momentum imbalance in proton-proton collisions at s√ = 13 TeV	Eur. Phys. J. C 78 (2018) 291	31-Oct-17	13	35.9
Search for new physics in the monophoton final state in proton-proton collisions at √s= 13 TeV	J. High Energy Phys. 10 (2017) 073	12-Jun-17	13	12.9

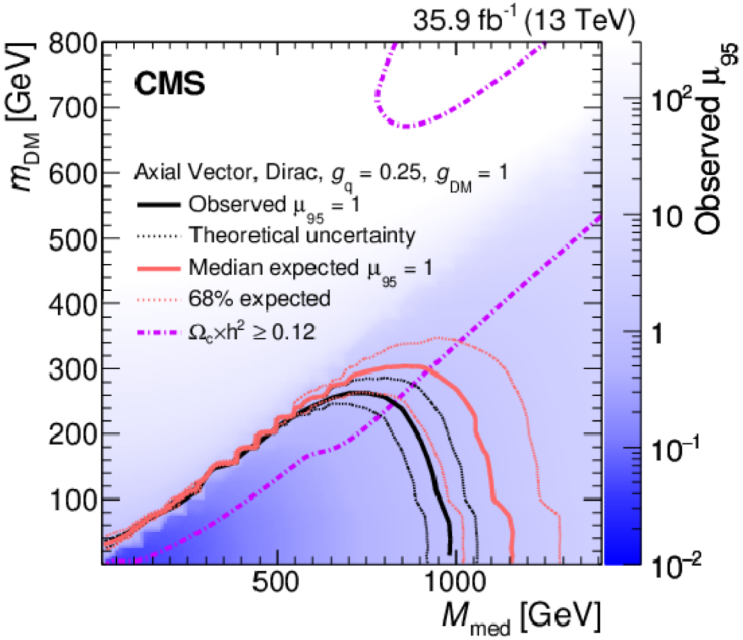
Mono-photon

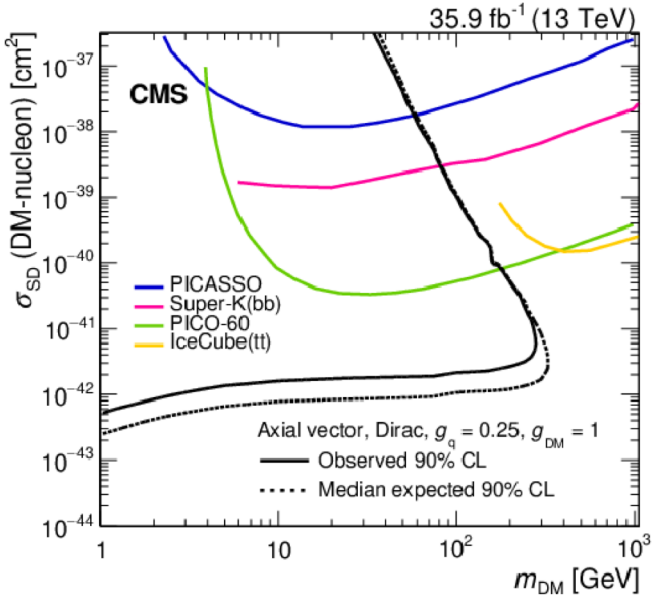


ATLAS mono-photon
Eur. Phys. J. C 77 (2017) 393



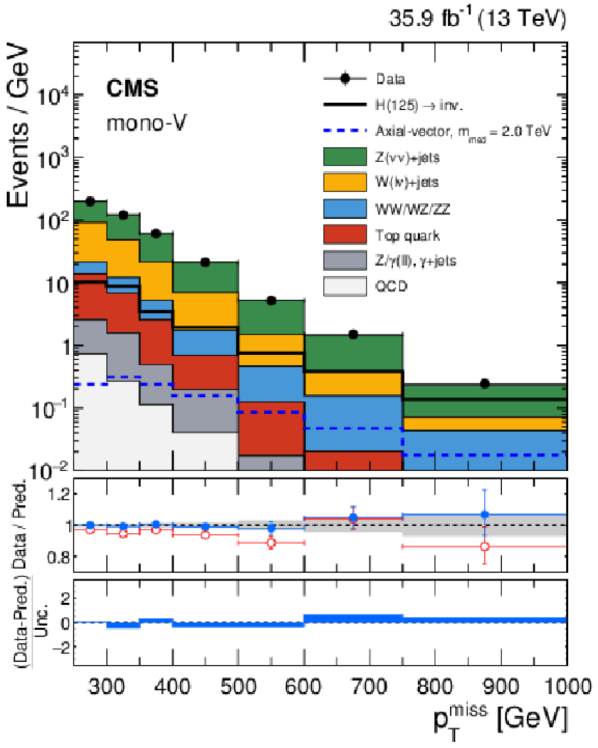


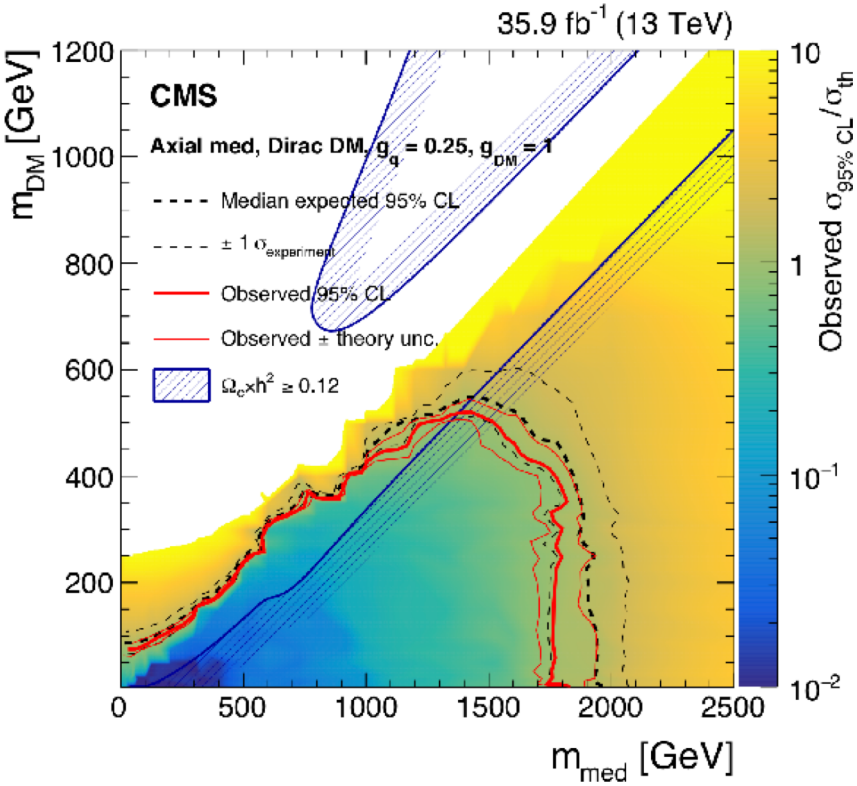




JHEP 02 (2019) 074

Mono-V (Z or W)

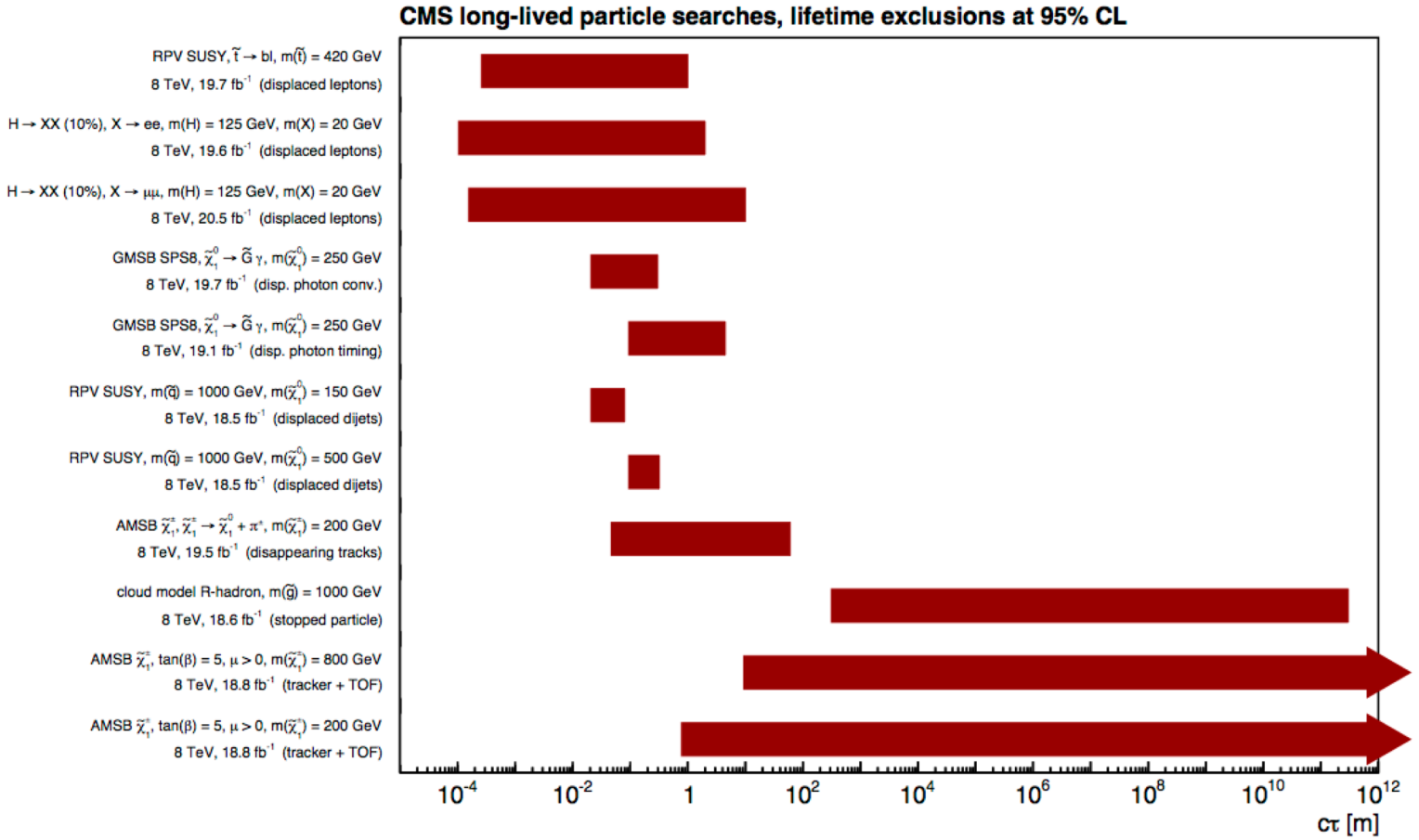




Phys. Rev. D 97 (2018) 092005

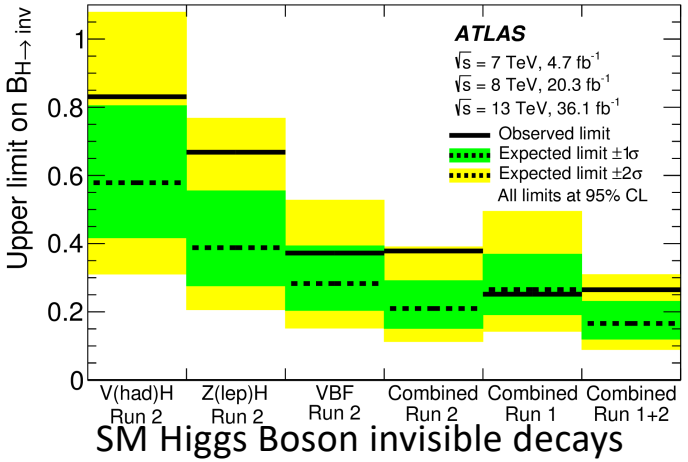
(includes also monojet)

Summary LLP@ CMS

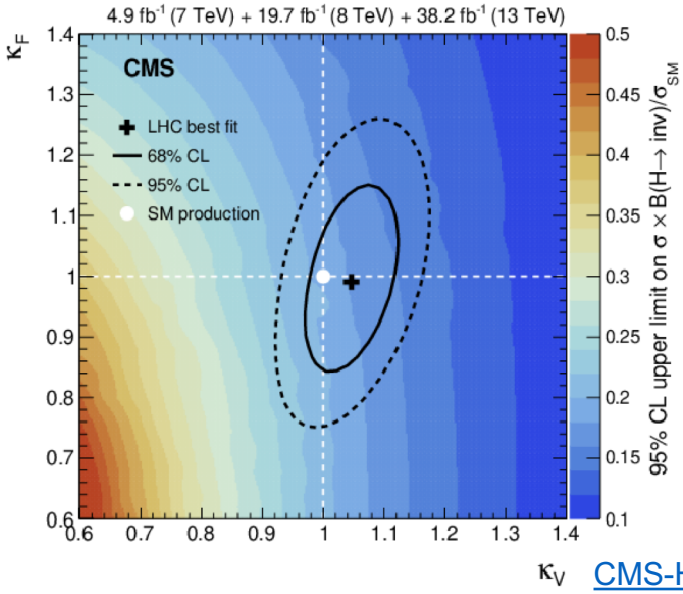


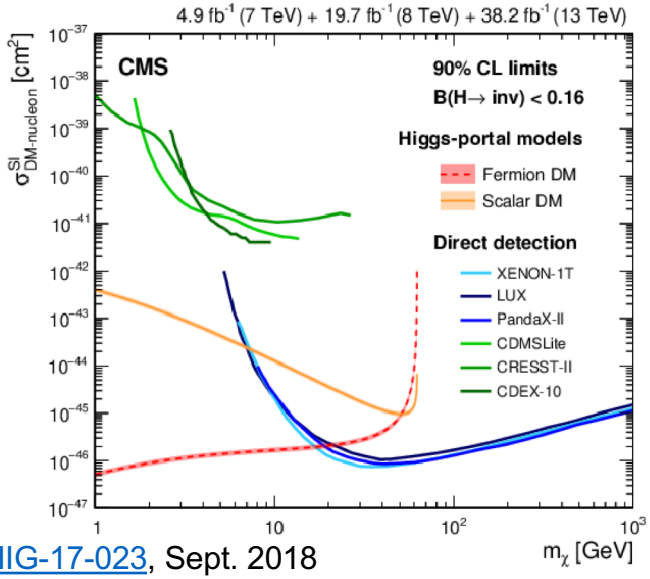
DM from invisible Higgs decay

(ATLAS arXiv:1904.05105)

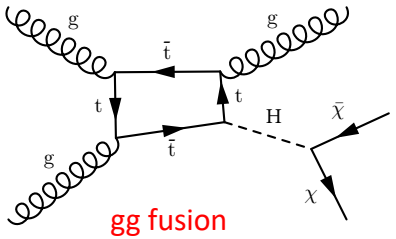


SM Higgs Boson invisible decays

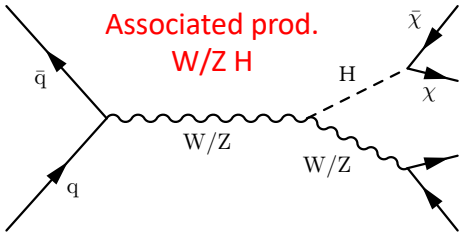


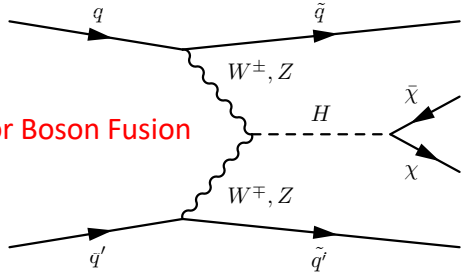


CMS-HIG-17-023, Sept. 2018



gg fusion





The Higgs portal to Dark sector

LHC can explore the idea that connection between SM and a dark sector arises through Higgs sector.

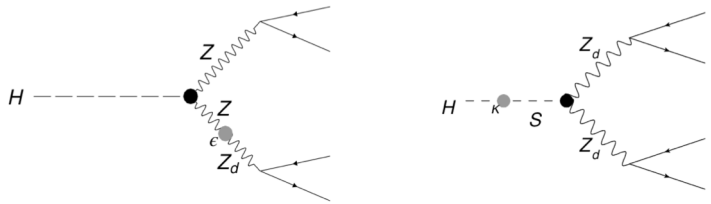
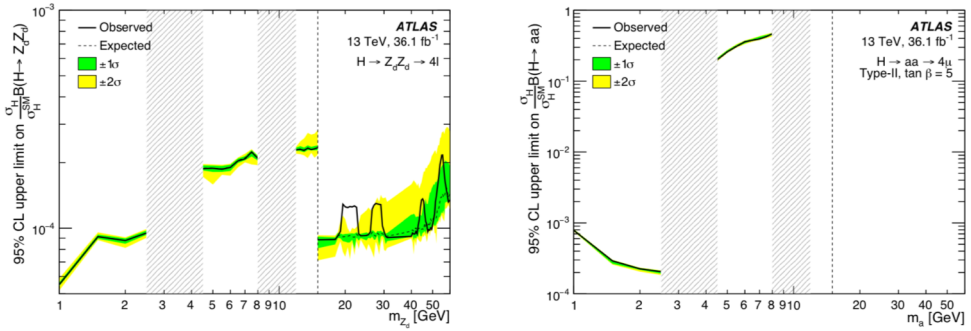


Figure 1: Exotic Higgs boson decays to four leptons induced by intermediate dark vector bosons via (left) the hypercharge portal and (right) the Higgs portal, where S is a dark Higgs boson [14]. The Z_d gauge boson decays to SM particles through kinetic mixing with the hypercharge field or through mass mixing with the Z boson. The HZZ_d vertex factor is proportional to ϵ whereas the HZ_dZ_d vertex factor is proportional to κ.



(a) $H \to Z_dZ_d$ (b) $H \to aa$

Figure 10: Upper limit at 95% CL on the branching ratios for processes (a) $H \to Z_dZ_d$ and (b) $H \to aa$, for the two benchmark models studied in this paper. The limit on $H \to aa$ is greater than 1 for $m_a > 15$ GeV. The step change in (a) at the $m_X = 15$ GeV boundary is due to the addition of sensitivity to 4e and $2e2\mu$ final states (lowering the limit). The shaded areas are the quarkonia veto regions.

ATLAS *JHEP 06 (2018) 166*

(see also CMS Eur. Phys. J. C (2018) 78: 29)