University of Victoria

Accelerator Searches for Dark Matter

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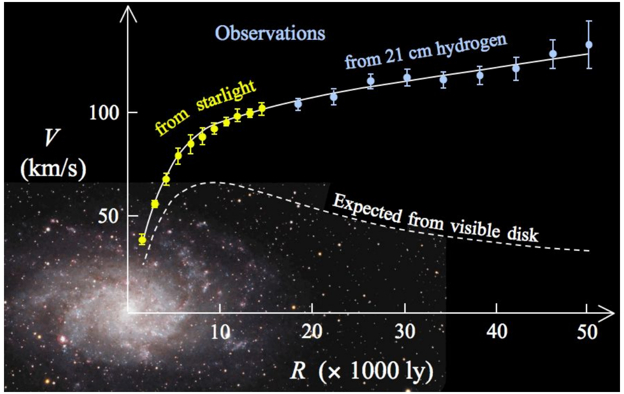
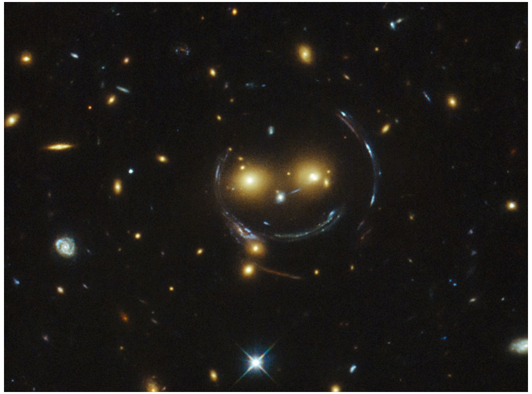
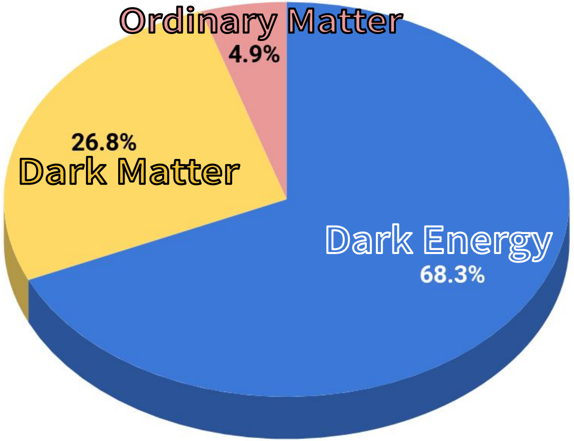
On behalf of ATLAS LHCb CMS

Hints at Dark Matter



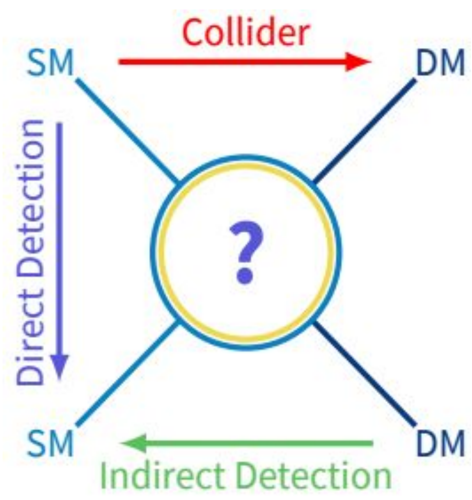


- A range of astrophysical measurements point to the existence of a non-baryonic form of matter (Phys.Rept.405:279-390,2005)
  - Galaxy rotation curves, gravitational lensing, colliding galaxy clusters…
- Weakly Interacting Massive Particles (WIMPs) are an attractive Dark Matter (DM) candidate, especially for the LHC
  - Lead to the correct relic density of non-relativistic matter
  - Non-gravitational interactions with the SM ∴ could be seen at colliders!!



Methods for Detecting Dark Matter

Various methods exist for detecting DM, covering different ranges of DM mass, m_χ



Direct Detection (DD):

➟ Nuclear recoil from elastic scattering

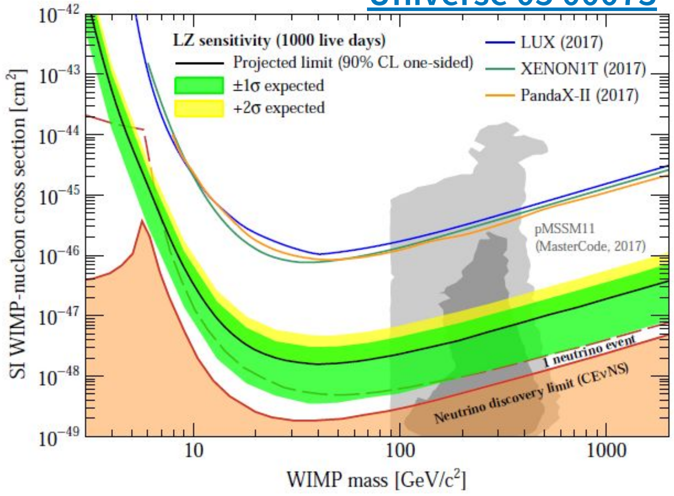
Indirect Detection (ID):

➟ DM annihilation

Collider Searches:

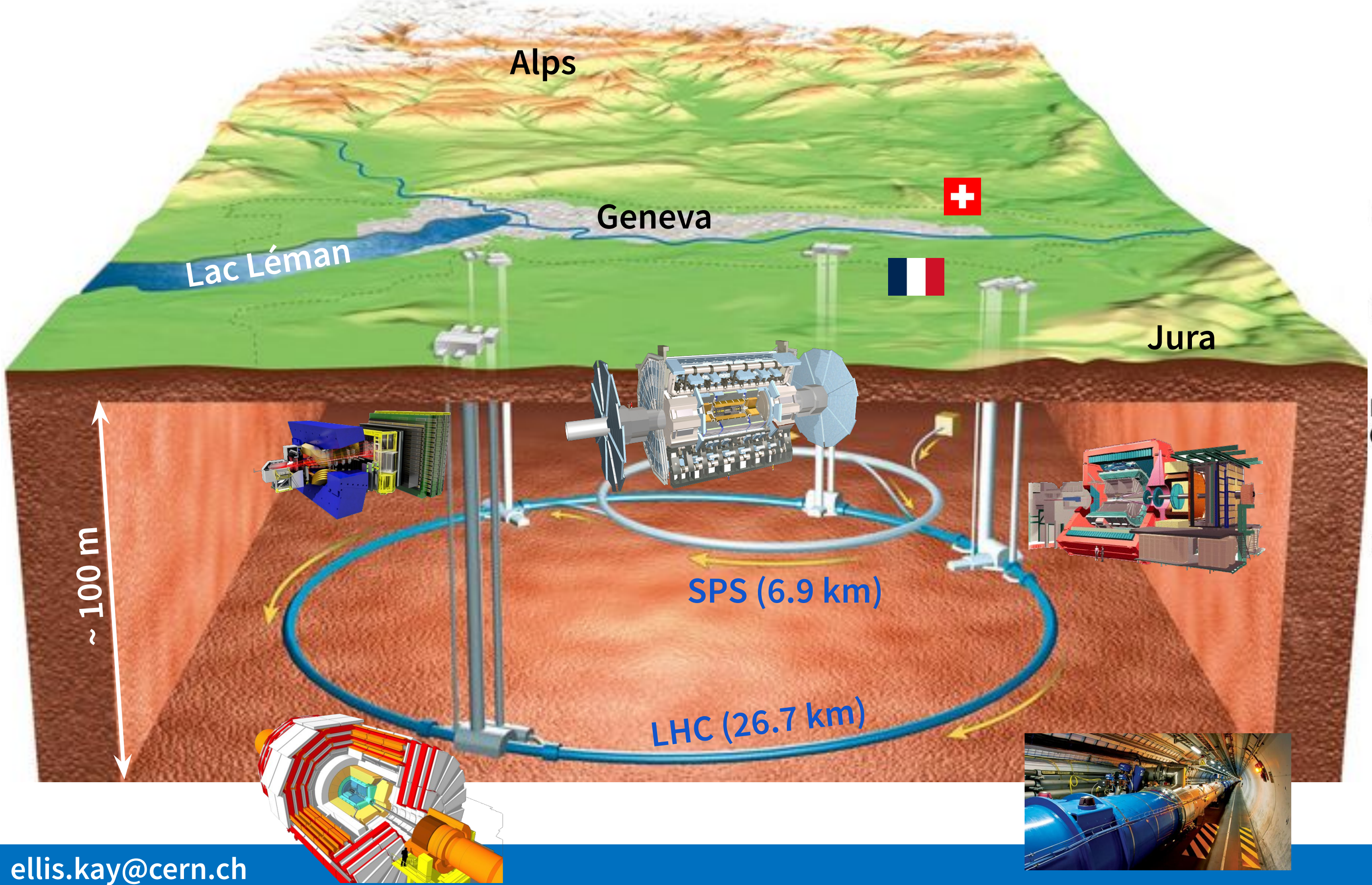
➟ DM production in high energy particle interactions

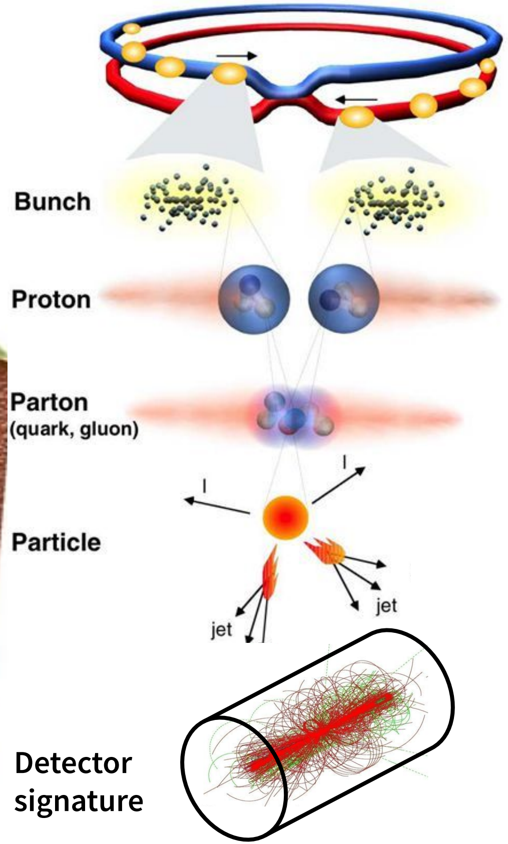
[Universe 05 00073]



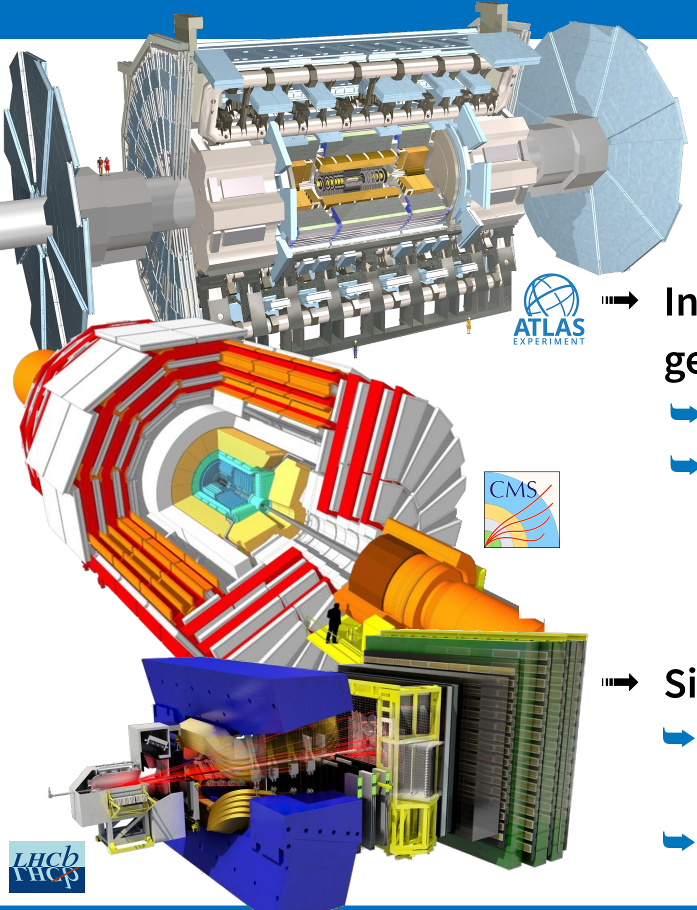
All three complementary methods continue to put mounting pressure on the WIMP hypothesis...

The Large Hadron Collider





Dark Matter Detectors at the LHC



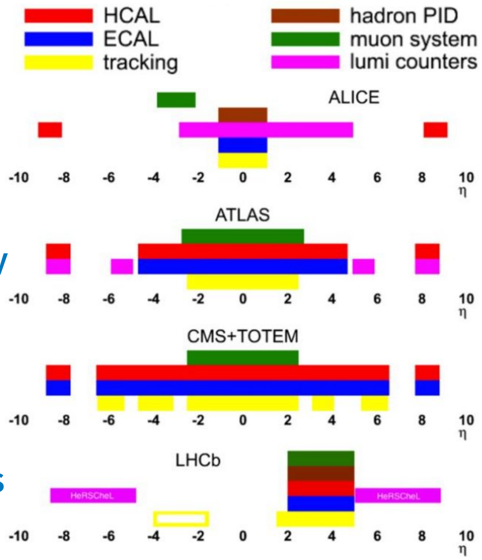
Three of the four main LHC experiments exploit distinct technologies to conduct complementary searches for DM

ATLAS & CMS

- Independently designed hermetic general-purpose detectors
  - Investigate largest range of physics possible
  - Can reconstruct missing transverse momentum (E_T^{miss}) using all measured decay products

LHCb

- Single arm forward spectrometer
  - Probes the forward rapidity region & triggers on particles with low p_T
  - Can explore relatively small boson masses

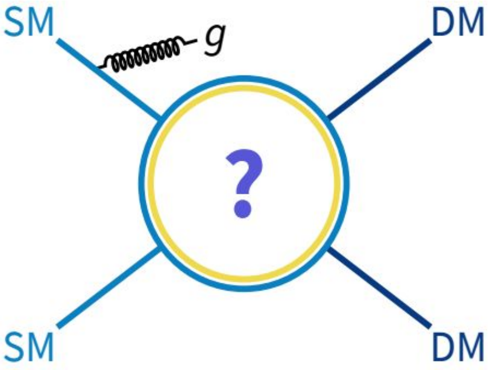


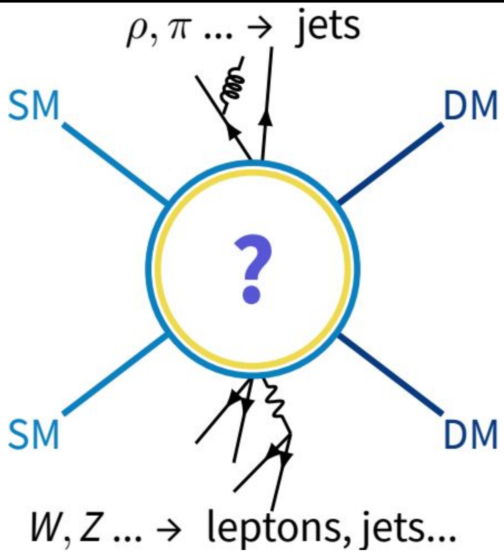
Types of LHC DM Searches

See Phys. Dark Univ. 26 (2019) 100371
& LHC DM Working Group

Dark matter is invisible to our detectors → look for associated production of visible (SM) particles

Generic Searches & Simpler Models ⟷ Specific Searches & More Complete Models



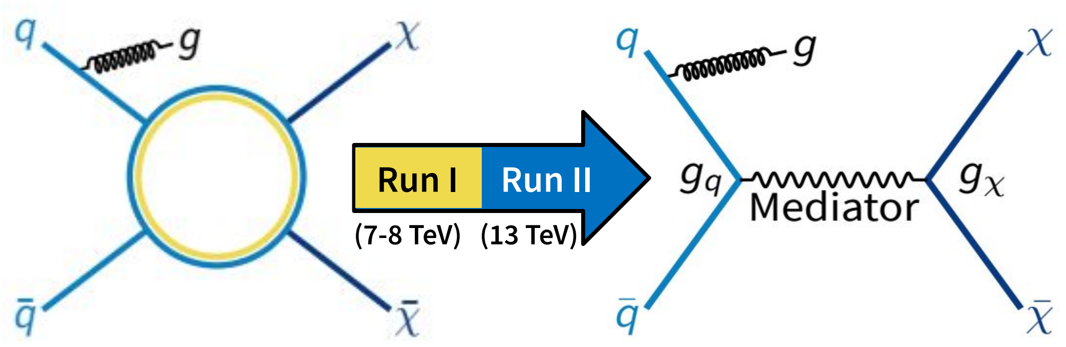


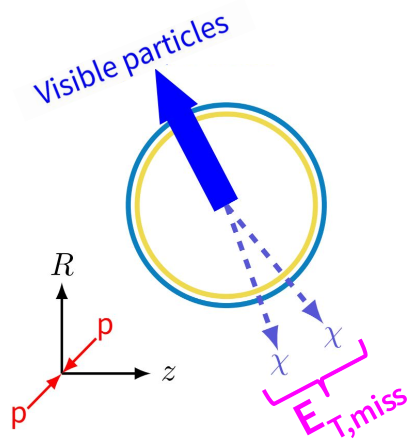
- Simple signals e.g. a single mediator
- Sizeable cross-sections
- Fewer assumptions on specific model parameters

- More reliant on model assumptions
- E.g. supersymmetry, UV complete models

Simplified Models - 'Mono-X'

- The most general models involve contact interaction operators in Effective Field Theories (EFTs)
- These become invalid at large momentum transfer, Q^2, which is problematic for Run-II
  - Favour 'simplified' models with a mediator, introducing m_χ, m_{med}, g_q and g_χ



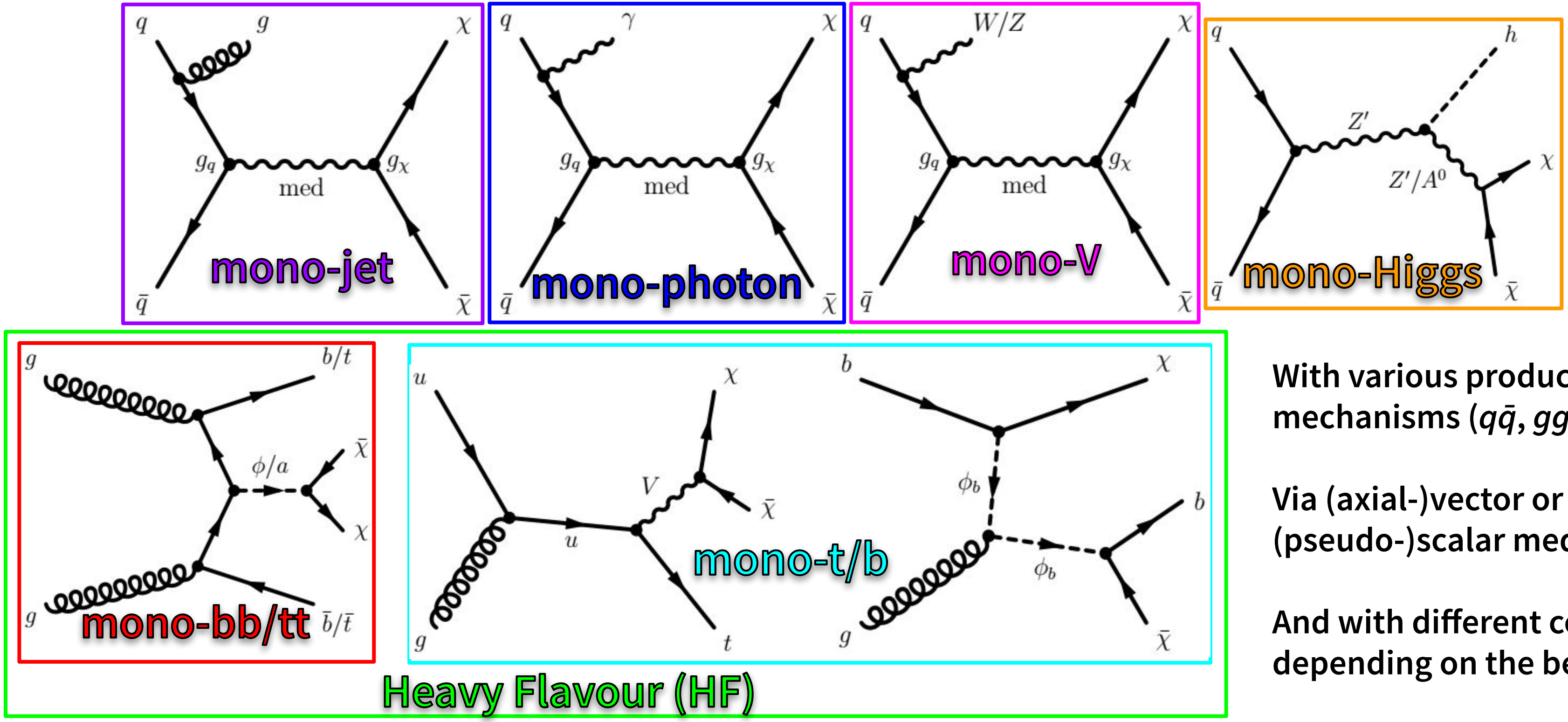


CERN-TH-2017-102

- Look for 'mono-X' signatures
  - Select events with 'X' (jet/γ/W/Z/t/H), veto other objects, precisely model backgrounds, check E_T^{miss}
  - Fix g_q, g_χ and exclude m_χ, m_{med} → CERN-LPCC-2016-001
- Also look for visible decays of the mediator to complement these searches → CERN-LPCC-2017-01
  - Re-interpret other analyses as mediator searches

Mono-X Signatures

There is a wealth of mono-X final states to be investigated at the LHC...

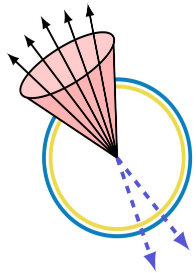


With various production mechanisms ($q\bar{q}$, gg etc.) ...

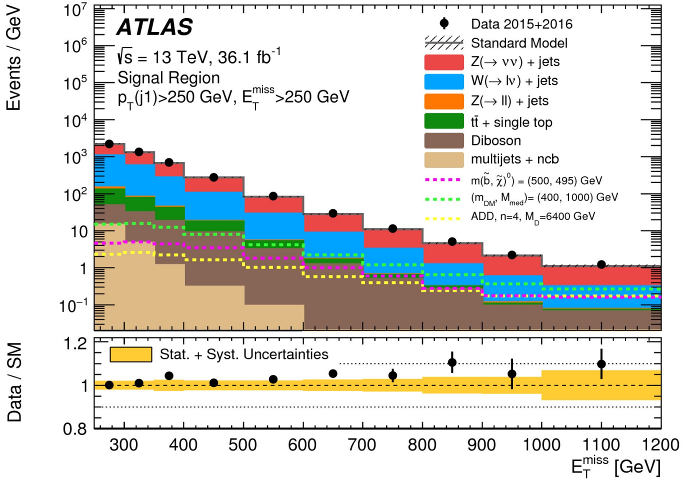
Via (axial-)vector or (pseudo-)scalar mediators...

And with different couplings, depending on the benchmark

Mono-jet



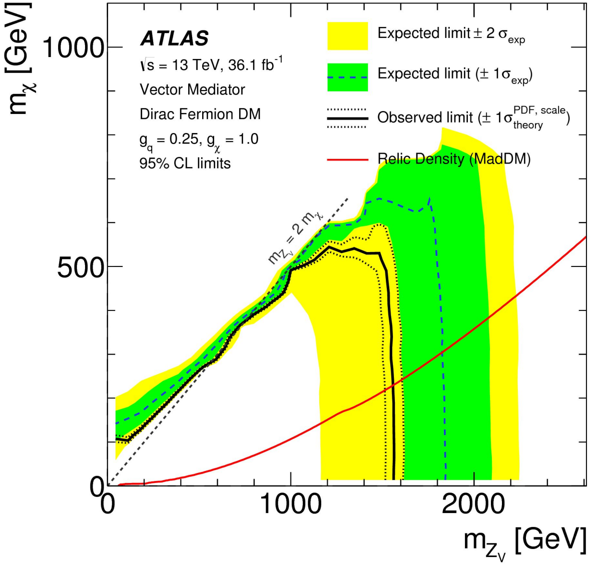
- Gluon ISR is by far the most prevalent at the LHC!
- m_{med} < 1.6 TeV (ATLAS) - 1.8 TeV (CMS) excluded at 95% CL for (axial-)vector mediators
- Pseudoscalar m_{med} < 0.4 TeV excluded for CMS
- Re-interpretations for a series of scenarios
  - CMS: fermion portal, nonthermal, *H→inv*, ADD
  - ATLAS: coloured scalar, squark pair production (compressed-mass), ADD



Dominant backgrounds = *Z/W*+jets

Constrained using enriched *V*+jet CRs

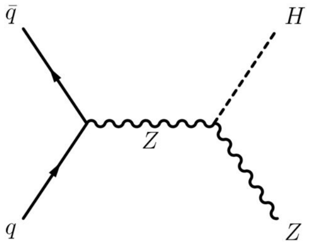
Perform simultaneous bg-only likelihood fit to E_T^{miss} distributions

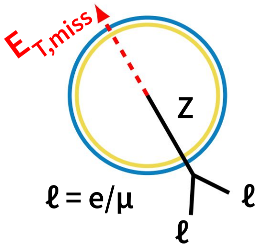


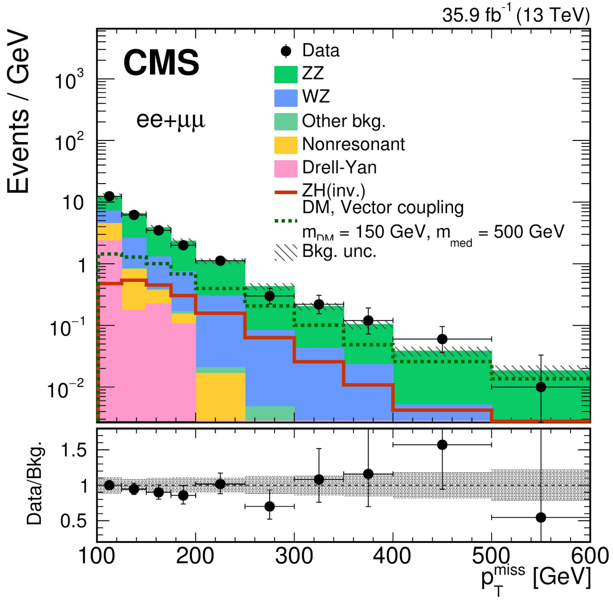
Mono Z(ℓℓ)

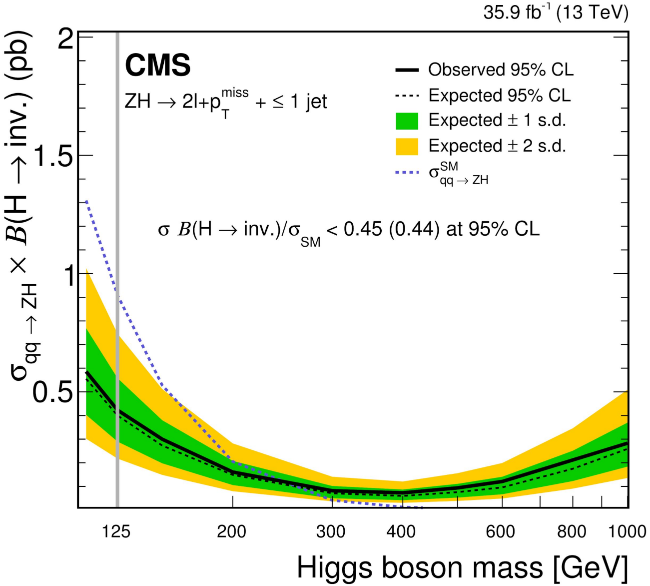
ATLAS: Phys. Lett. B 776 (2017) 318
CMS: Eur. Phys. J. C. 78 (2018) 291

- ➟ Single lepton triggers offer sensitivity to signals with lower E_T^{miss}
- ➟ WIMP production with *Z′* mediator or *H→inv* decays
- ➟ ATLAS: B(*H→inv*) = 0.67 (obs, 95% CL)
- ➟ CMS: B(*H→inv*) = 0.4 (obs, 95% CL, *ZH→ℓℓ+inv*)









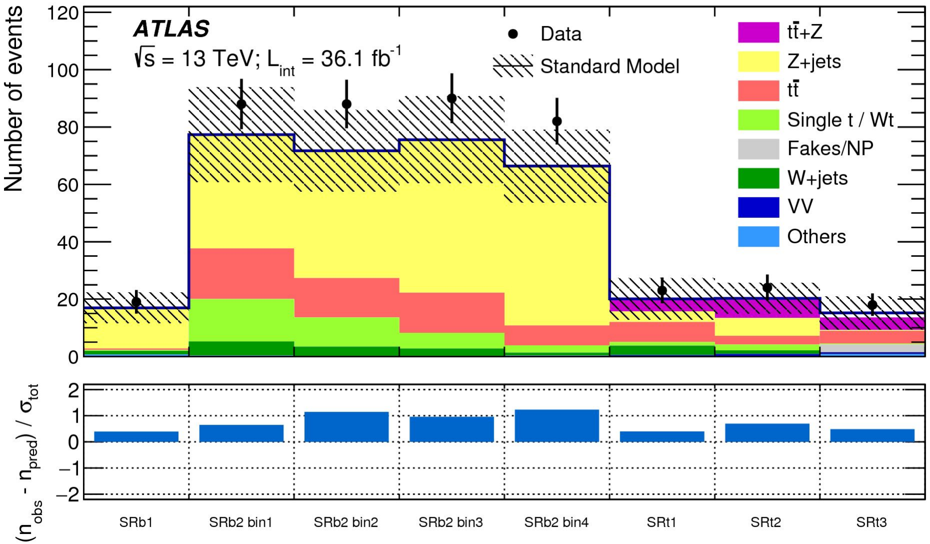
CMS: For *H→inv* interpretation, perform multivariate boosted decision tree (BDT) to increase sensitivity (12 variables)

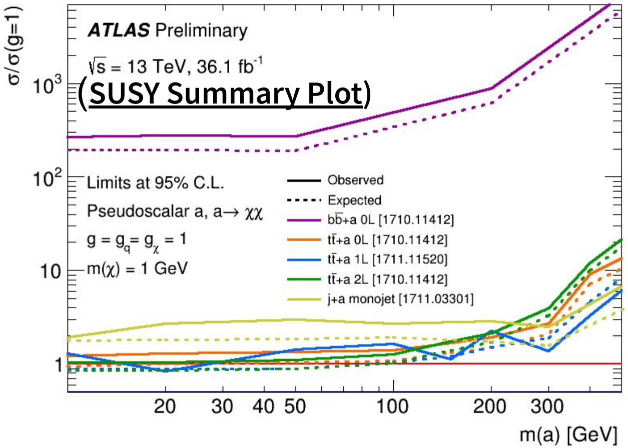
HF + X

ATLAS: JHEP 05 (2019)a 41 (t)
ATLAS: ATLAS-CONF-2018-052 ($b\bar{b}$, boosted)
ATLAS: EUR. PHYS. J. C 78 (2018) 18 ($b\bar{b}/t\bar{t}/b/t$)

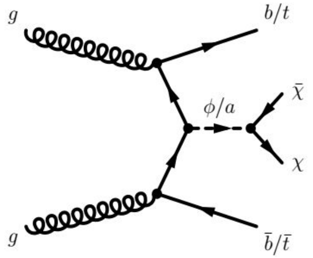
CMS: JHEP 03(2019)141 ($t/t\bar{t}$)
CMS: Phys. Rev. Lett. 122, 011803 (2019) ($t\bar{t}$)

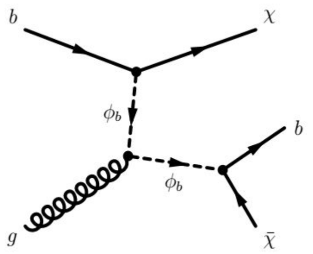
- Assuming minimal flavour violation, interactions between SM matter and any new neutral spin-0 state is proportional to fermion masses via Yukawa-type couplings
  - Colour-neutral mediators sizeably produced in association with Heavy Flavour (HF) quarks
- *Z*+jets & *$t\bar{t}$* dominant backgrounds

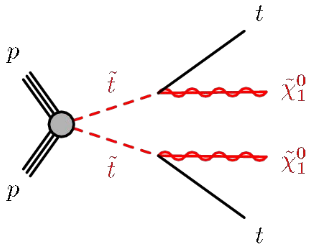




(SUSY Summary Plot)







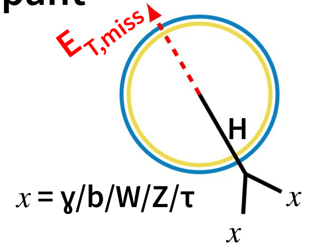
$b\bar{b}/t\bar{t}$ searches have same final state as SUSY searches:
ATLAS: JHEP 06 (2018) 108
CMS: Phys. Rev. D 97, 032009 (2018)

Mono Higgs

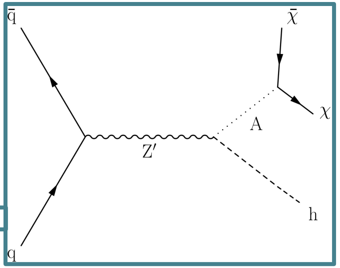
ATLAS: ATLAS-CONF-2018-039 (bb)
ATLAS: Phys. Rev. D 96 (2017) 112004 (γγ)

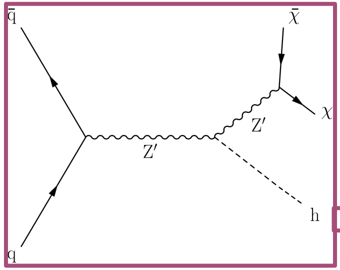
CMS: Eur. Phys. J. C 79 (2019) 280 (bb)
CMS: JHEP 09 (2018) 046 (γγ/ττ)
CMS: CMS-EXO-18-011 (bb+γγ+ττ+WW+ZZ)

➟ Higgs ISR is strongly suppressed ∴ target interactions in which H is a direct participant

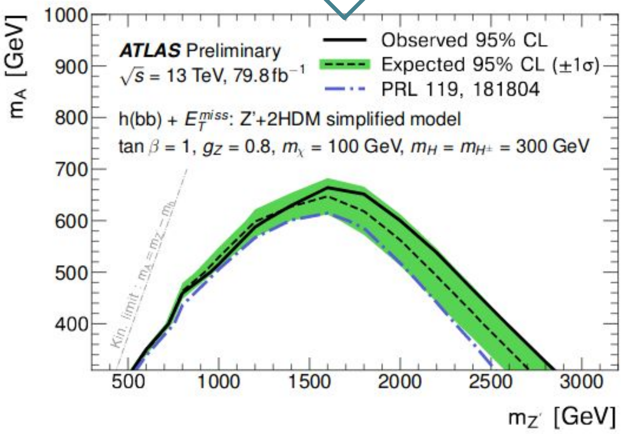


Z′-2HDM
New pseudo-scalar *A*
resonant

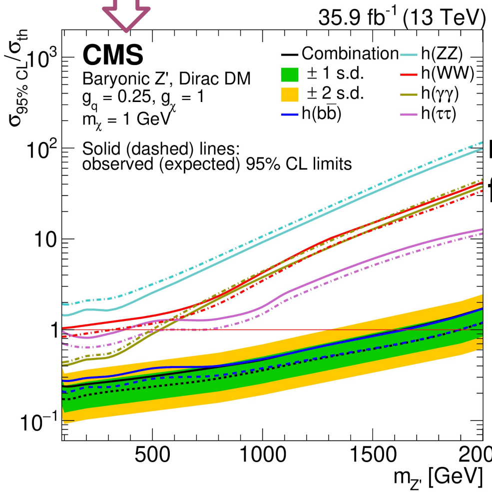




Baryonic *Z′* model
New U(1) with baryon number symmetry
non-resonant



$m_{Z'}$ < 2.8 TeV excluded for m_A = 300 GeV



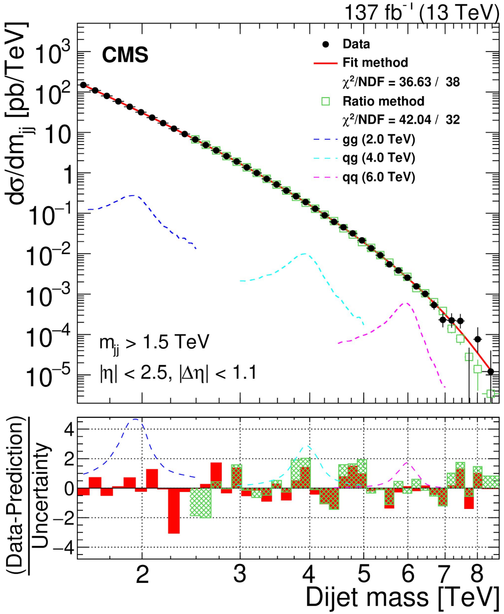
$m_{Z'}$ < 1.6 TeV excluded for m_χ = 1 GeV

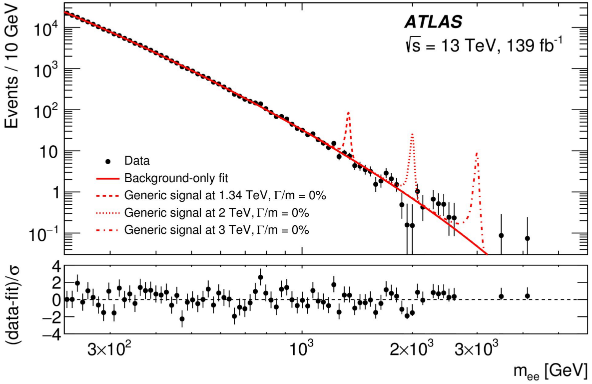
Visibly Decaying Mediator Searches

- DM cannot be produced on-shell if $2m_{DM} > m_{med}$
  - Mediator decays back to SM
  - Need to probe visible signatures to see DM interactions off-shell
- The LHC is a “mediator machine”!
- Probe high masses in search of BSM mediators.
- Look for bumps on the smoothly falling di-object distribution, which is modeled by a parameterized function.
- In absence of bump, set limits for different physics scenarios.

Dijet

- ATLAS: CERN-EP-2019-1
- CMS: CERN-EP-2019-222





Dilepton

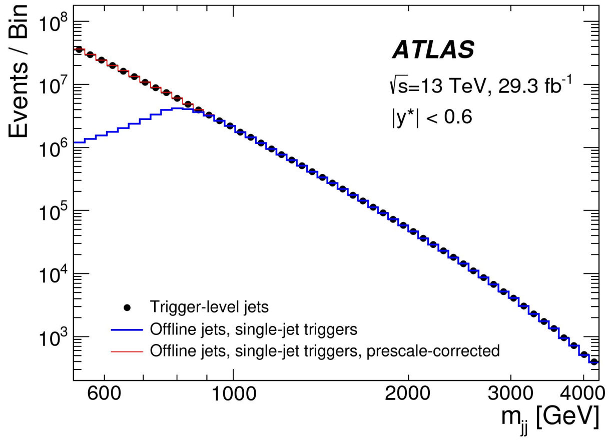
- ATLAS: PHYS. LETT. B 796 (2019) 68
- CMS: JHEP 06 (2018) 120

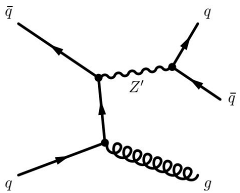
Low Mass Di-jet Searches

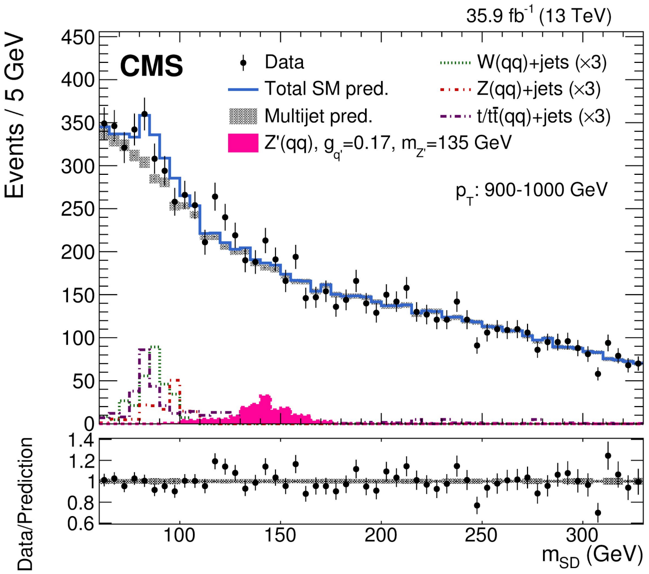
ATLAS: PHYS. LETT. B 795 (2019) 56
CMS: JHEP 01 (2018) 097

- Sensitivity at low (< 1 TeV) m_{jj} is limited by jet triggers
  - Data collection rates for inclusive single-jet triggers << SM multijet production rate
- "Data-scouting" / "Trigger-object Level Analysis" (TLA)
  - Use reduced data format to allow high trigger rate with low bandwidth

PHYS. REV. LETT. 121, 081801 (2018)





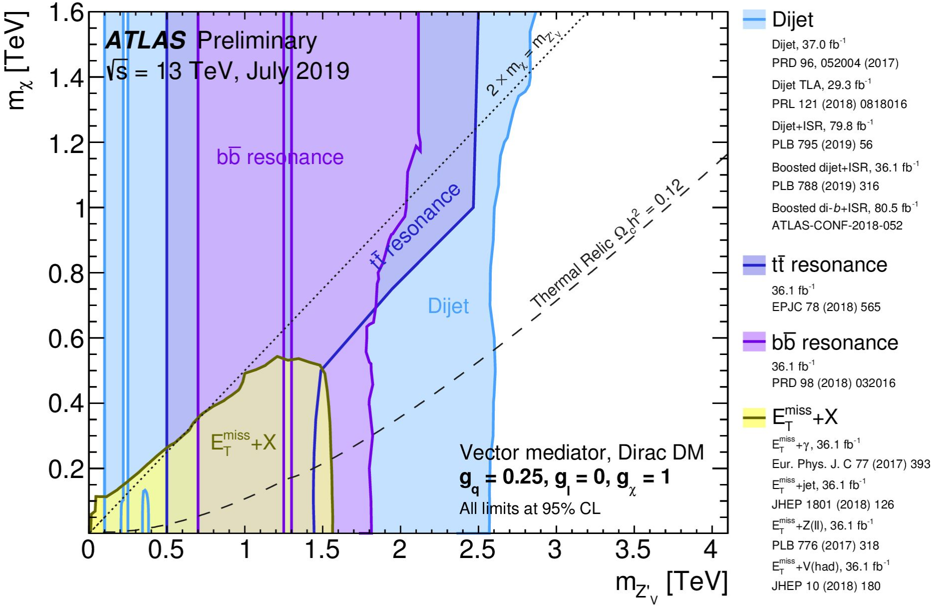


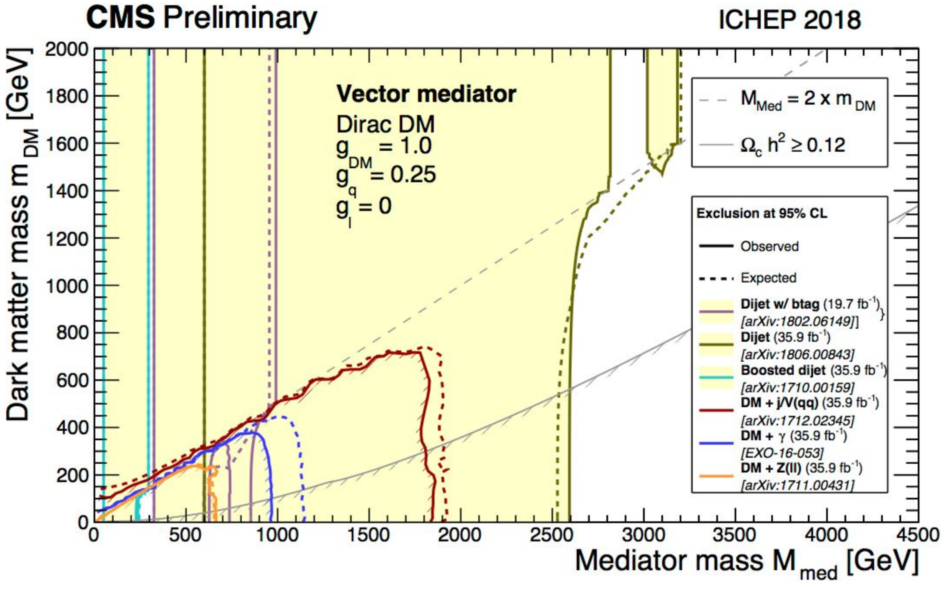
- Introduce hard Initial-State Radiation (ISR) requirement
  - Require ≥ 1 high p_T ISR jet in association with the *qq* resonance
  - Provides enough energy to satisfy trigger
  - Min p_T high enough that hadroisation from *qq* gives a large-R jet
  - Achieve sensitivity to even lower mediator masses
  - ATLAS: 225 - 1100 GeV, CMS: < 100 GeV!

Combined Results

ATLAS: JHEP 05 (2019) 142
CMS: ICHEP 2018

Vector mediator, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$





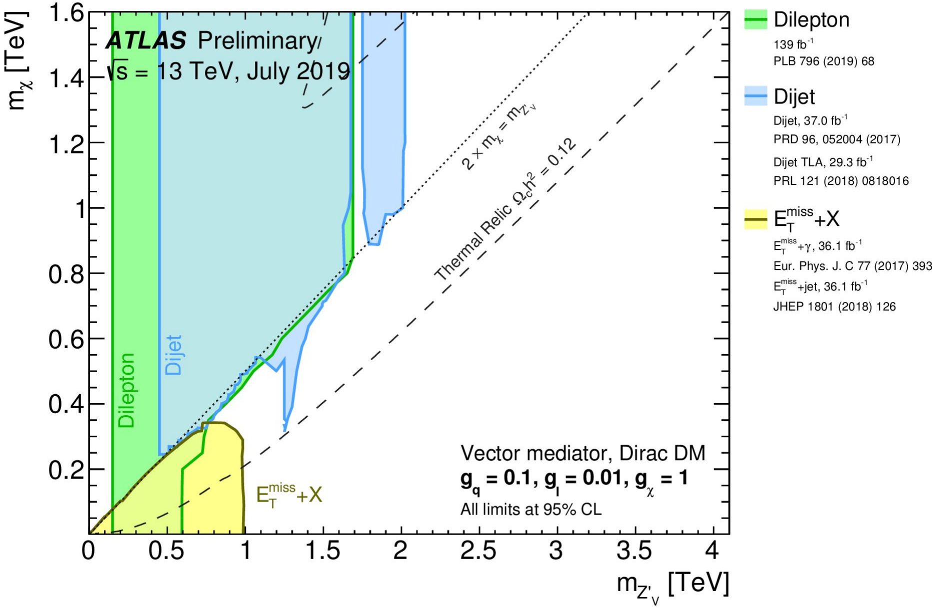
m_{med} ~ 2.5 TeV reach from mediator searches

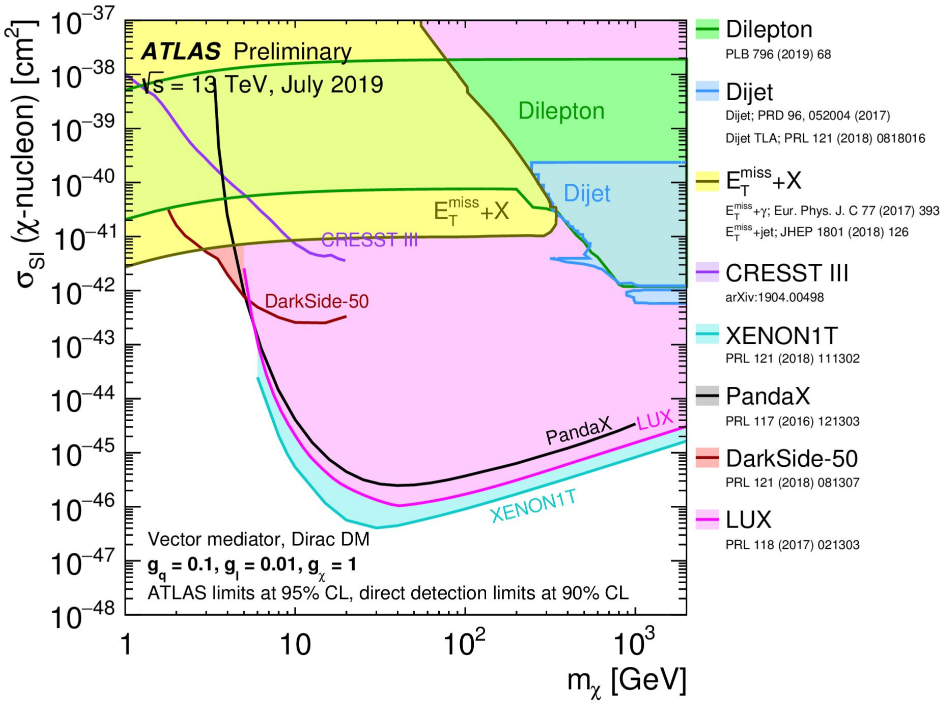
Combined Results

ATLAS: JHEP 05 (2019) 142
CMS: ICHEP 2018

SI WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1, g_q = 0.1, g_l = 0.01$

➟ For <u>these couplings in this model</u>, the mono-jet search has higher sensitivity than DD at low m_χ!

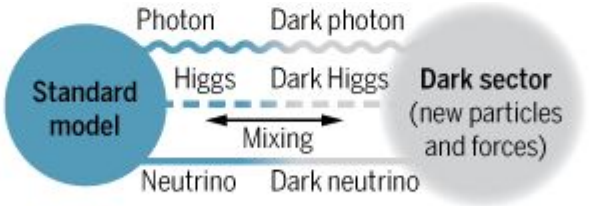




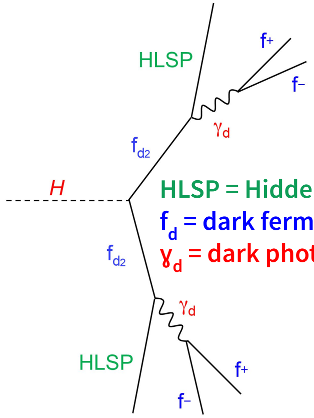
Dark Sector Searches

e.g. ATLAS: CERN-EP-2019-140 (dark ɣ)
& CMS: JHEP 10 (2019) 139 (dark ɣ)

- What if DM exists in a hidden sector, composed of particles which don't undergo SM gauge interactions?
- Dark mediators could couple to SM via portal interactions
  - Coupling to SM encoded in a mixing term in the Lagrangian
  - Look for SM particles from DM decays via these portals
  - Set limits on coupling strength to SM… ε^2 (dark γ), f_a (ALPs)…
  - Small mixing → long lifetime

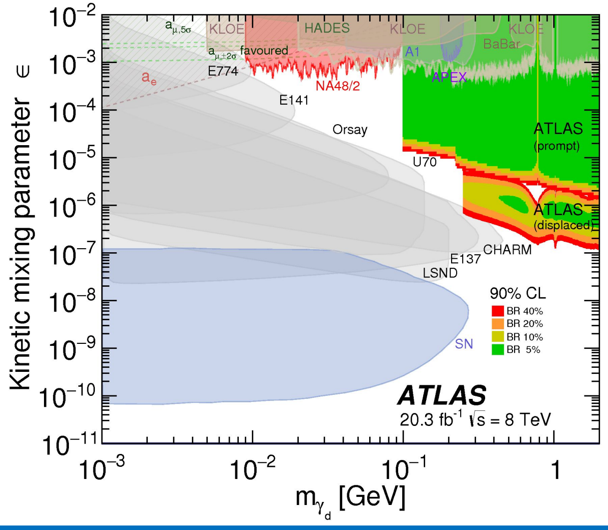


C.BICKEL/SCIENCE



HLSP = Hidden Lightest Stable Particle
f_d = dark fermion
γ_d = dark photon

- LHC detectors can extend to high masses and low couplings
  - Complementary to fixed target/beam-dump experiments (JHEP02(2016)062)



LHCb Dark Photon Search

LHCb-PAPER-2019-031

- Search for dark photons, *A′*
  - In $A' \to \mu^+\mu^-$
  - Prompt-like (PL): $2(m_\mu) < m_{A'} < 70$ GeV
  - Long-lived (LL): $214 < m_{A'} < 350$ MeV
- Coupling arises via kinetic mixing between SM hypercharge & *A′* field strength tensors
- PL: most stringent limit to date for *μμ* production in $214 < m_{A'} < 740$ MeV & $10.6 < m_{A'} < 30$ GeV
  - Comparable to best existing limits for $m_{A'} < 0.5$ GeV
- LL: first to achieve sensitivity using a displaced-vertex signature, world leading constraints for low mass *A′* *with* lifetimes O(1) ps

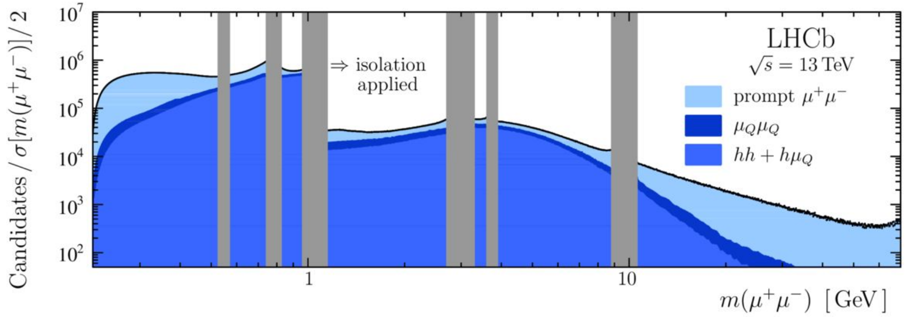
$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

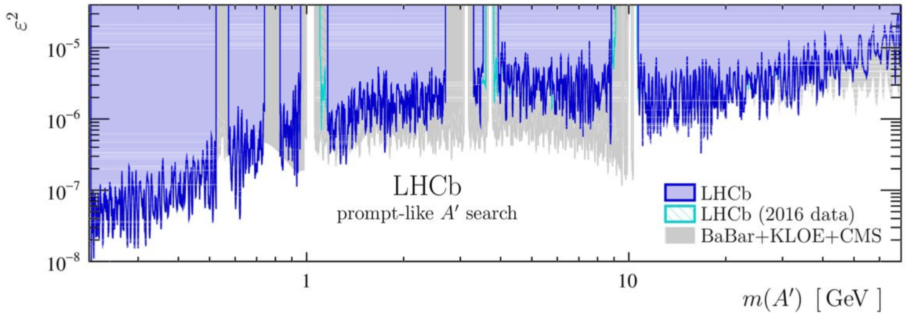
Coupling to EM current suppressed relative to that of SM γ

Off-shell $\gamma^* \to \mu^+\mu^-$ yield

Phase-space

A'/γ^* detection eff. ratio ≈1 for PL

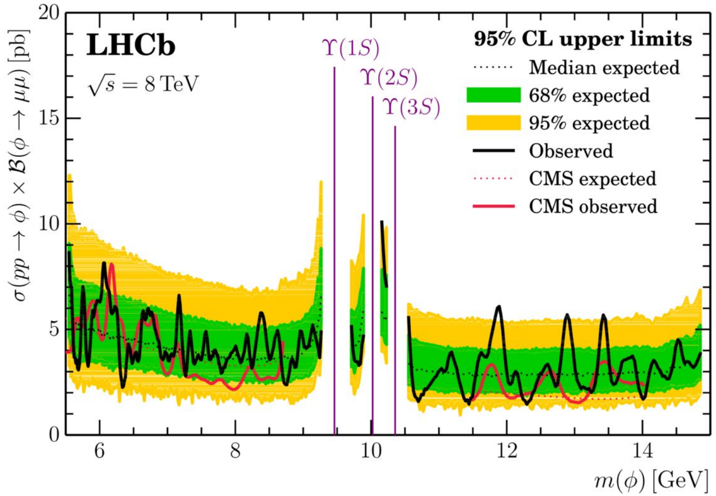




LHCb Dark Boson Searches

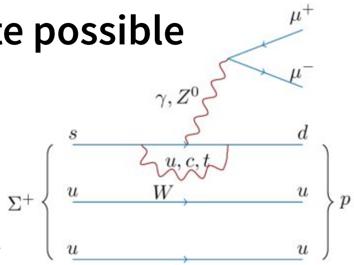
$pp \to \phi \to \mu^+\mu^-$ In *gg* fusion JHEP 09 (2018) 147

- ➡ Narrow resonance search in Υ mass region
- ➡ Analysis designed is model-independent
  - ➥ Independent of production mech, spin
- ➡ First limits set in previously unexplored $8.7 < m(\phi) < 11.5$ GeV

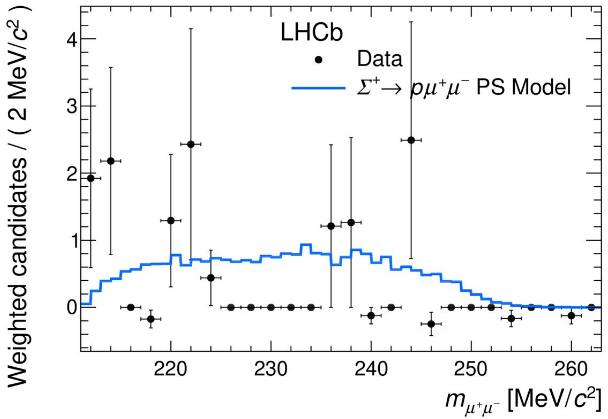


In $\Sigma^+ \to p\mu^+\mu^-$ PRL 120, 221803 (2018)

- ➡ Narrow range of $\mu\mu$ masses from 3 candidates observed at HyperCP indicate possible intermediate particle X^0



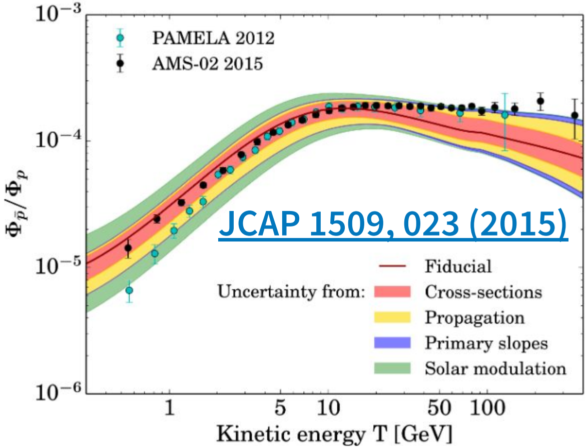
- ➡ LHCb observes the Σ^+ decay
- ➡ BUT no significant $m_{\mu\mu}$ *peak!*

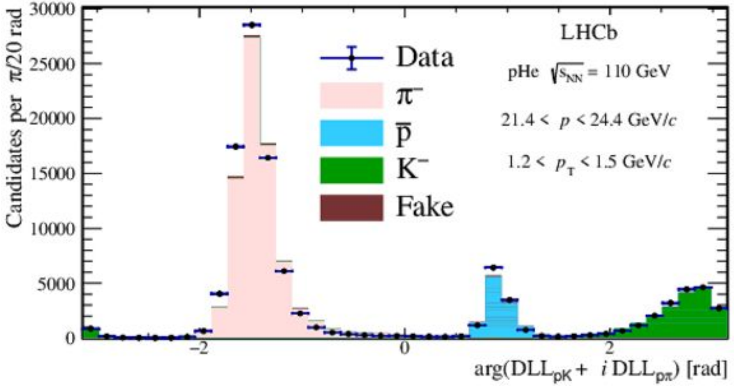


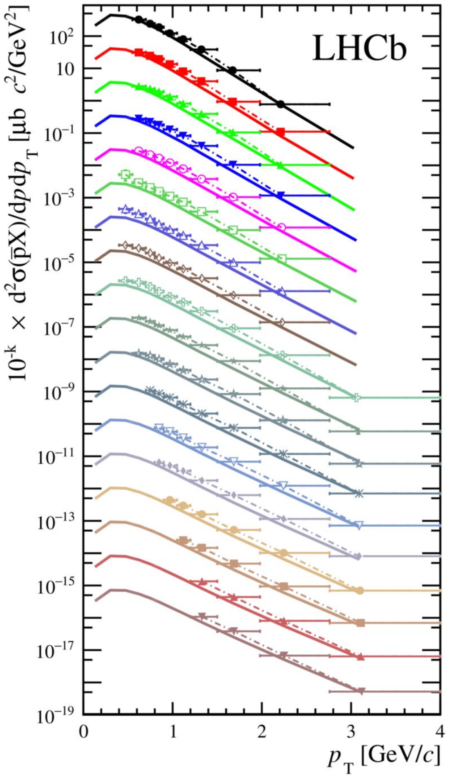
Antiproton Production σ

PRL 121, 222001 (2018)

- ➟ The antiproton fraction in cosmic rays is a sensitive probe of dark matter annihilation
- ➟ Large uncertainties due to limited knowledge of $\bar{p}$ production cross-section in 10-100 GeV $\bar{p}$ range
  cannot cover observed excess of $\bar{p}$ yields over current prediction
- ➟ System for Measuring Overlap with Gas (SMOG) CERN-LHCC-2019-005 allows injection of He in THE LHCb interaction region
  - ➥ 6.5 TeV protons collide with He







Conclusion & Outlook

- The LHC has an extensive DM search program
  - Three different detectors exploit different technologies to conduct complementary searches
- Mono-X searches in many complementary channels covering a broad range of benchmarks
- Mediator searches extending to the TeV scale to hunt of-shell DM interactions
  - Lower masses also probed thanks to TLA and boost from ISR
- Also producing constraints in EW SUSY & $H \rightarrow inv$ interpretations
- These searches complement results from other detection methods
  - Strong limits for SD DM-nucleon cross section and model-dependent limits for $m_\chi < 10$ GeV!
- Now delving into the dark sector
  - With distinct and complementary coverage of mass & lifetimes from hermetic & forward detectors
- Ongoing analysis of full Run 2 dataset!