



Dark Matter Searches at the LHC

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CLHCP2019

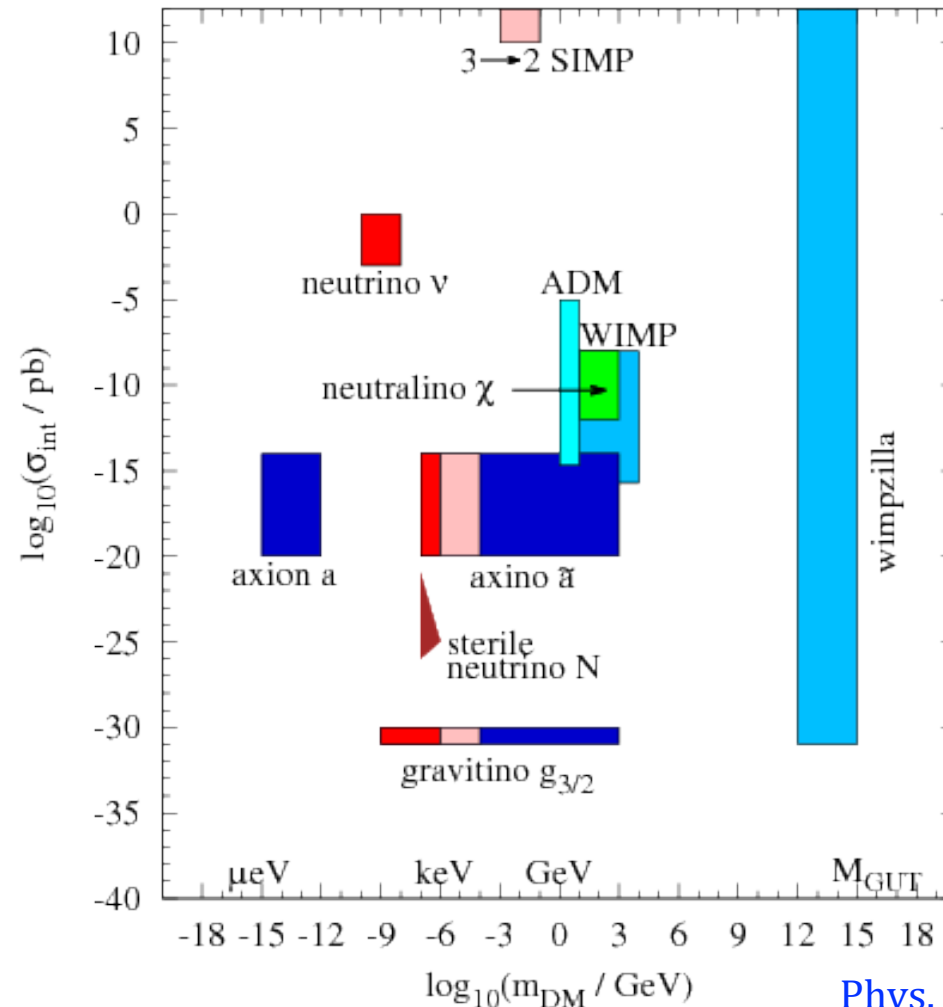
Dalian, 2019-10-27

Outline

- Introduction of dark matter at colliders
- Dark matter benchmark models
- WIMP searches
- Non-WIMP searches
- Summary

Dark Matter Candidates

- Unknown feature of DM beyond Gravity
- Large range of candidates



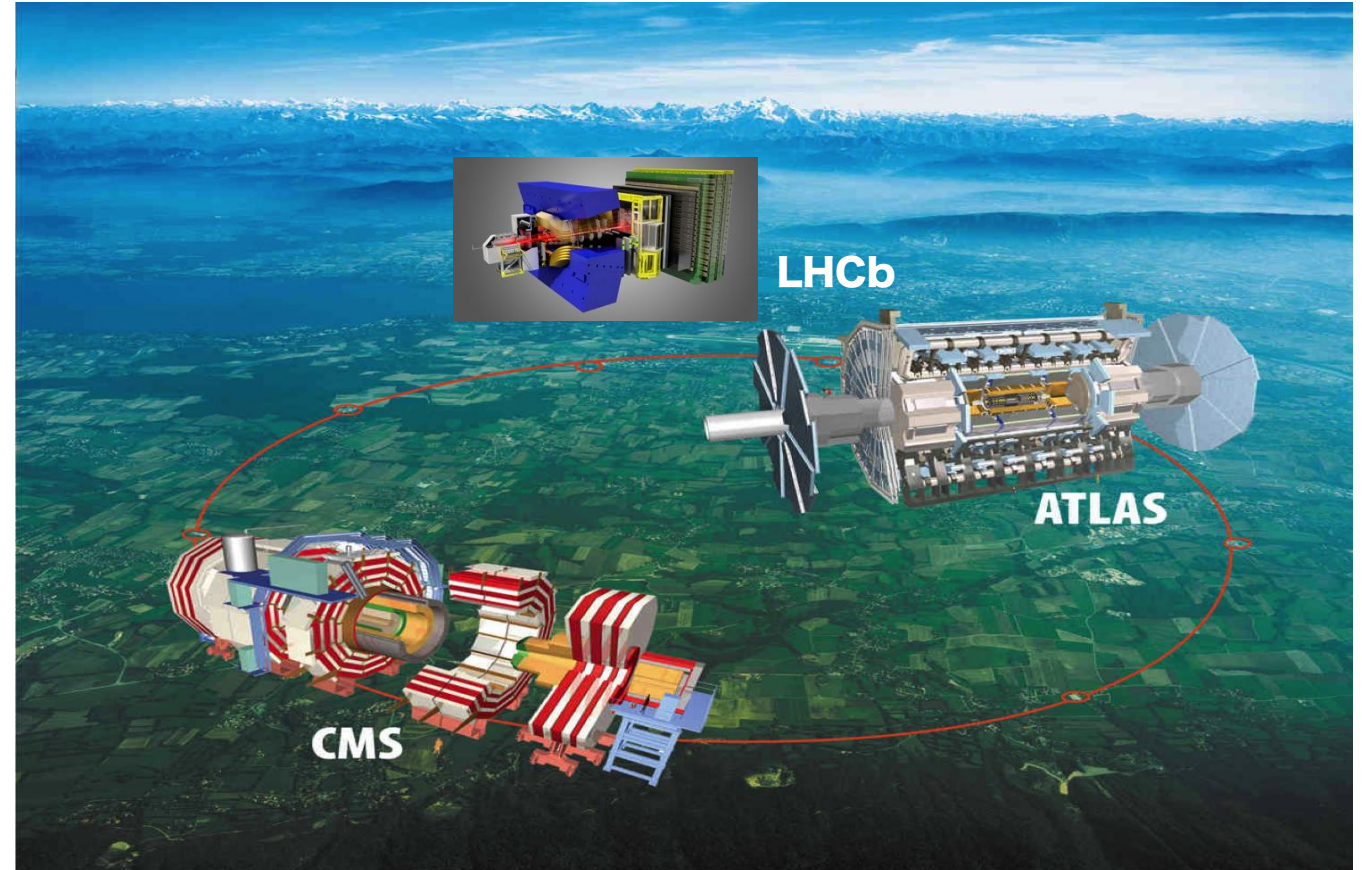
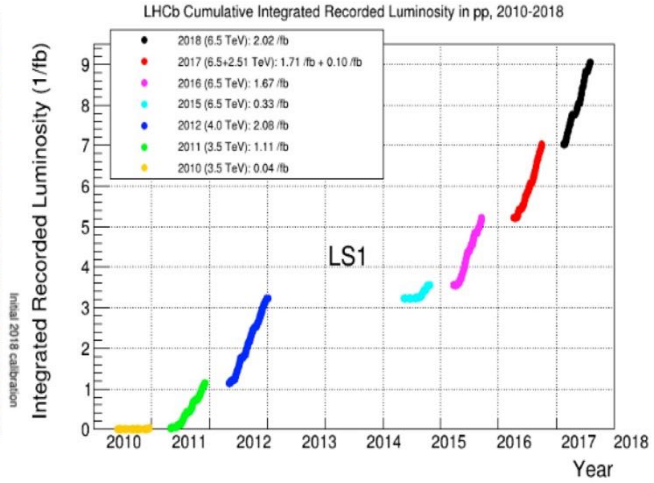
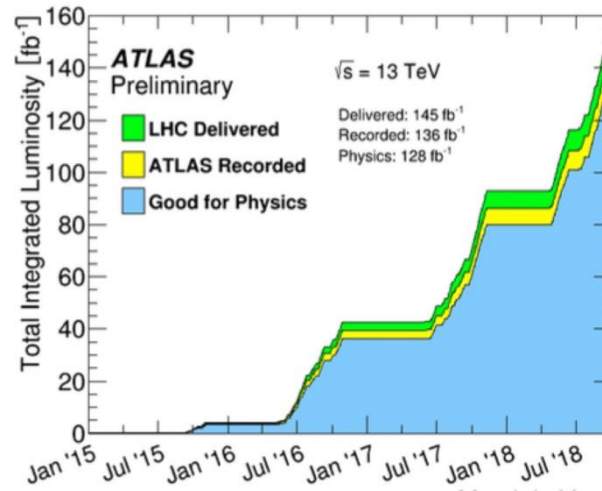
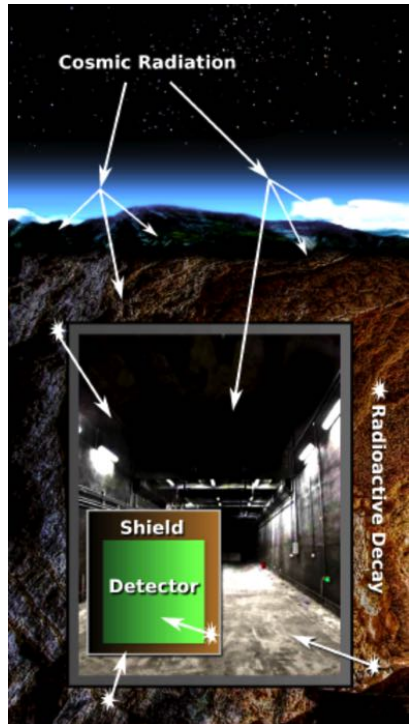
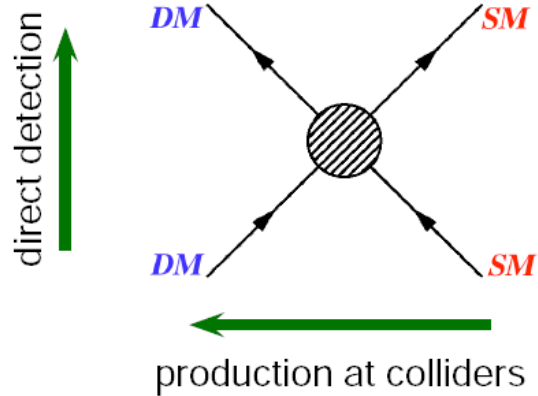
Phys. Rept. 555 (2015) 1-60 arXiv:1407.0017

Dark Matter Searches

- Collider search: dark matter production
- Indirect and direct searches



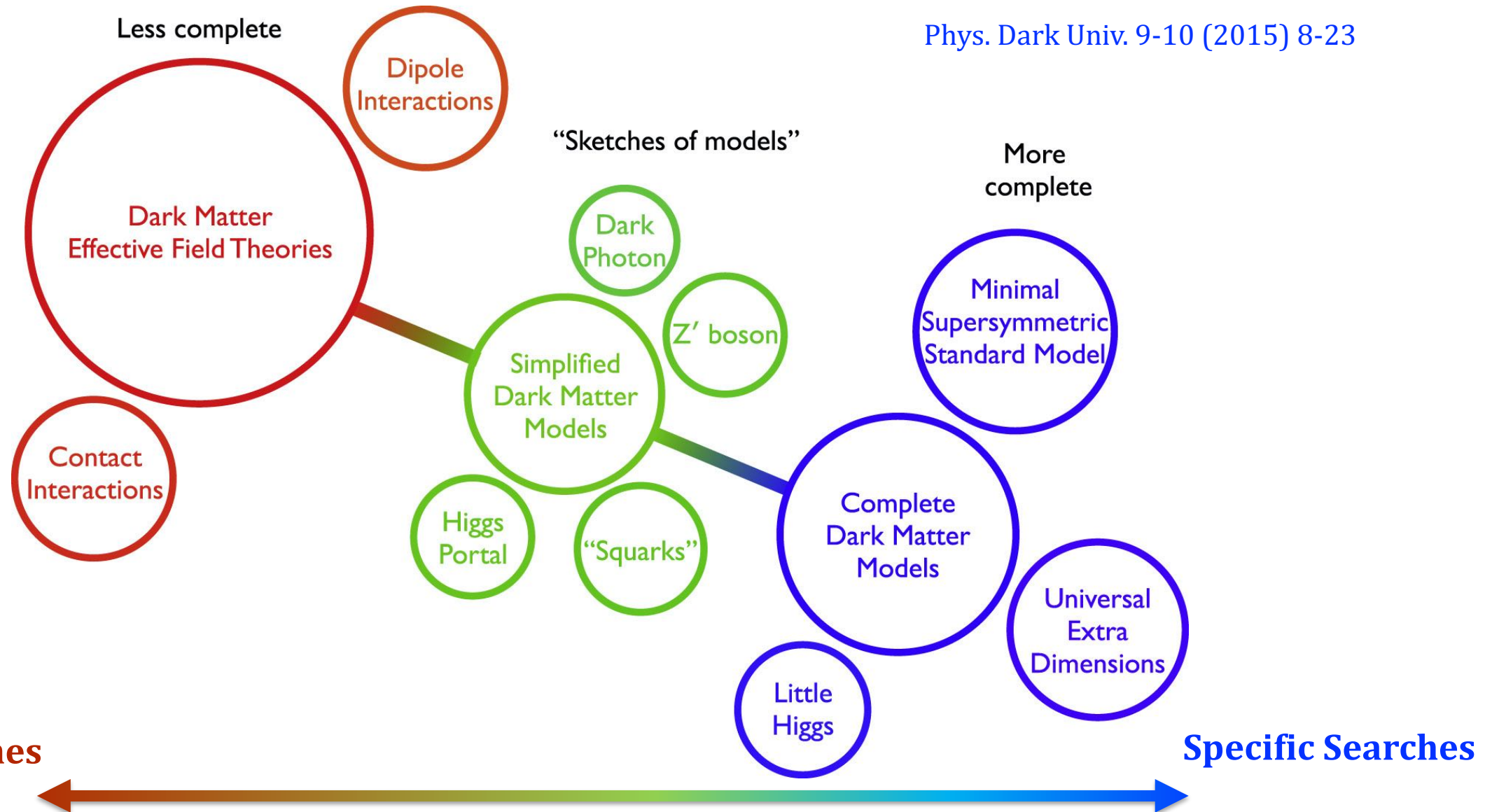
thermal freeze-out (early Univ.)
indirect detection (now)



Dark Matter Production at LHC

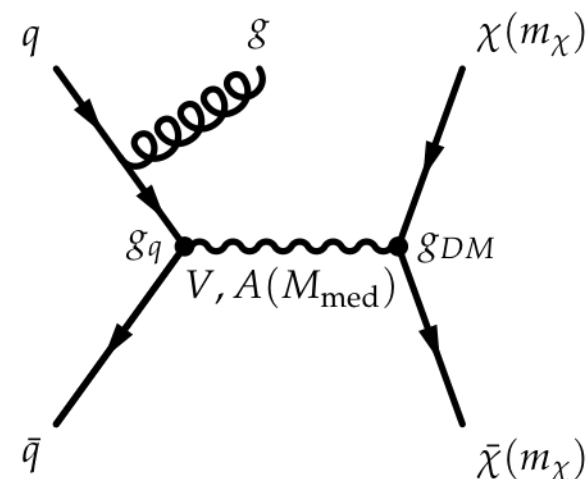
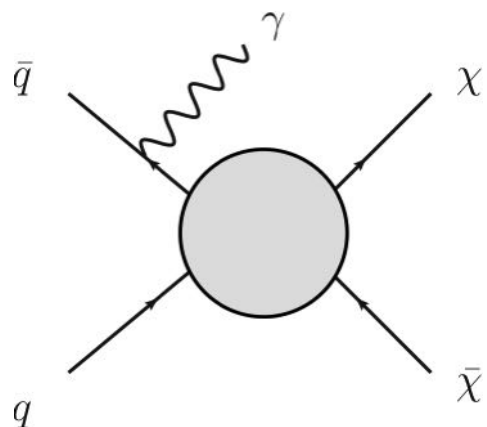
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Phys. Dark Univ. 9-10 (2015) 8-23



From EFT to Simplified Model

- Keep the mediator information
 - Mass, spin, coupling, width, etc



LHC DM forum
arXiv:1507.00966

- Simplified model:
 - Starting point to build complete theories
 - Colliders can search for the mediator directly
 - Benchmark model @ Run II

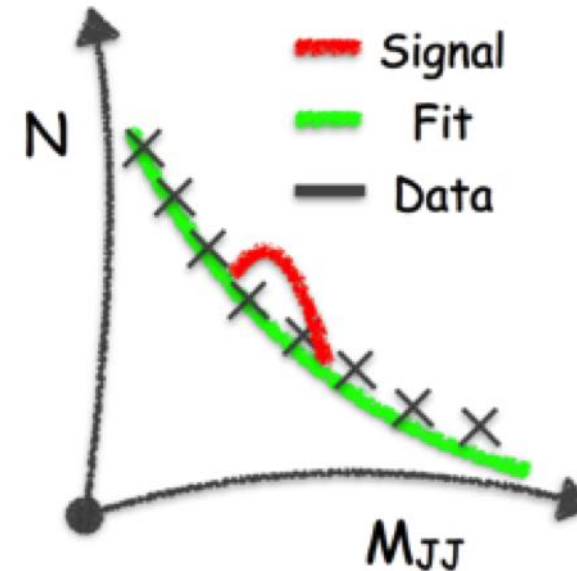
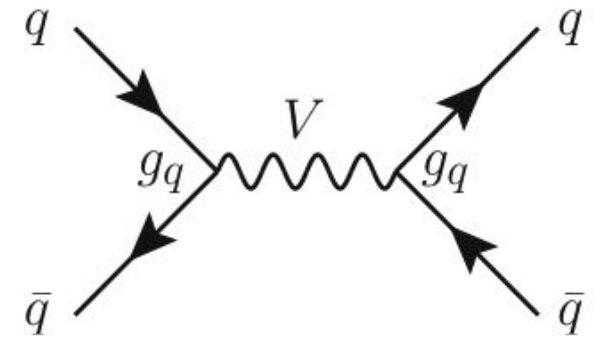
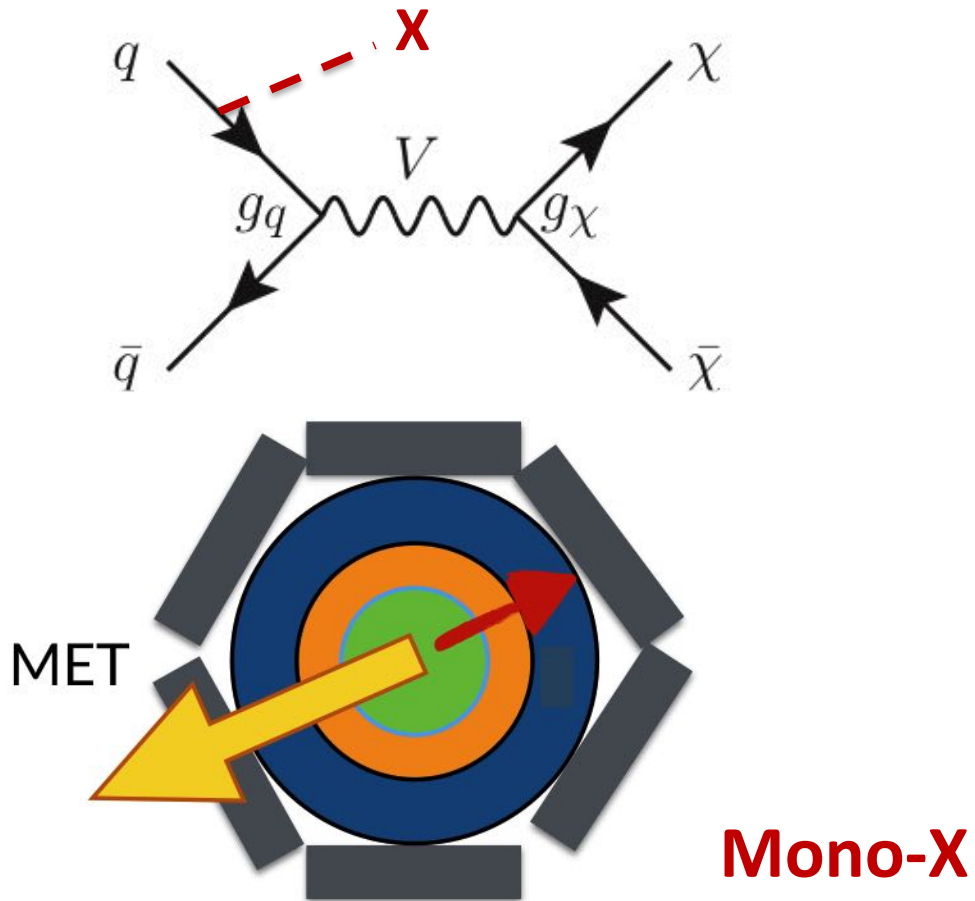
$$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

Simplified Model

- Dark matter production in association with visible particles

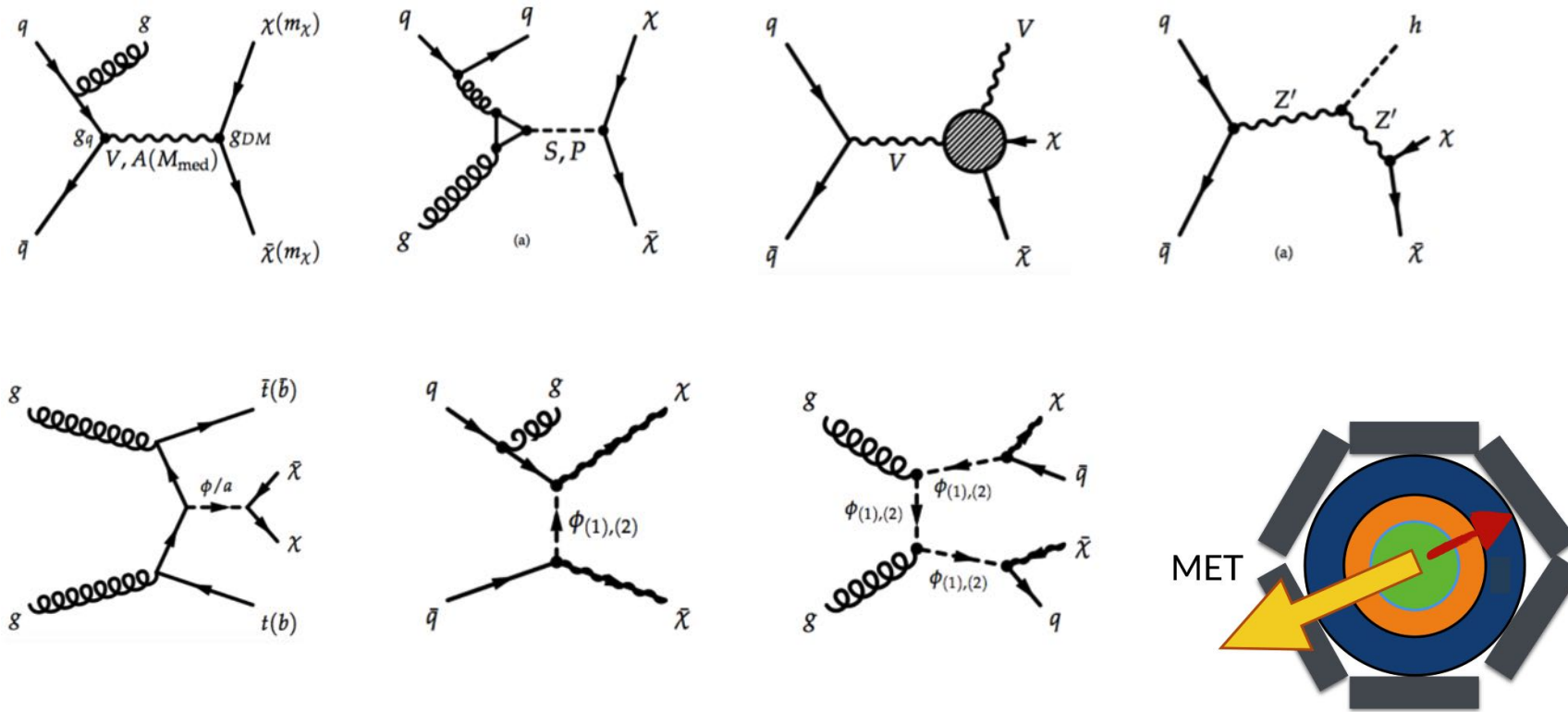
- WIMP-SM Mediator searches



Dijet

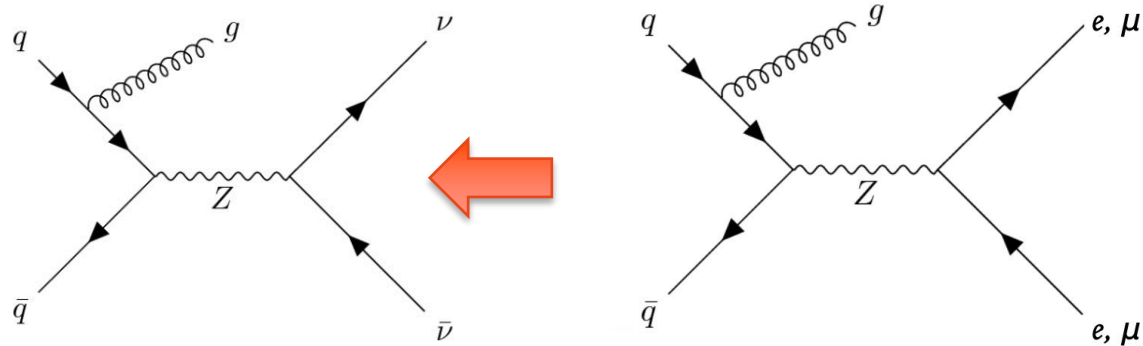
Mono-X

- Pair-produced DM via massive mediator (vector, axial-vector, scalar, pseudoscalar, etc)
- X: visible particles as DM tagger
 - Jets, b/bbbar, t/ttbar, photon, W/Z (hadronic or leptonic decay), Higgs (bb, $\gamma\gamma$), etc



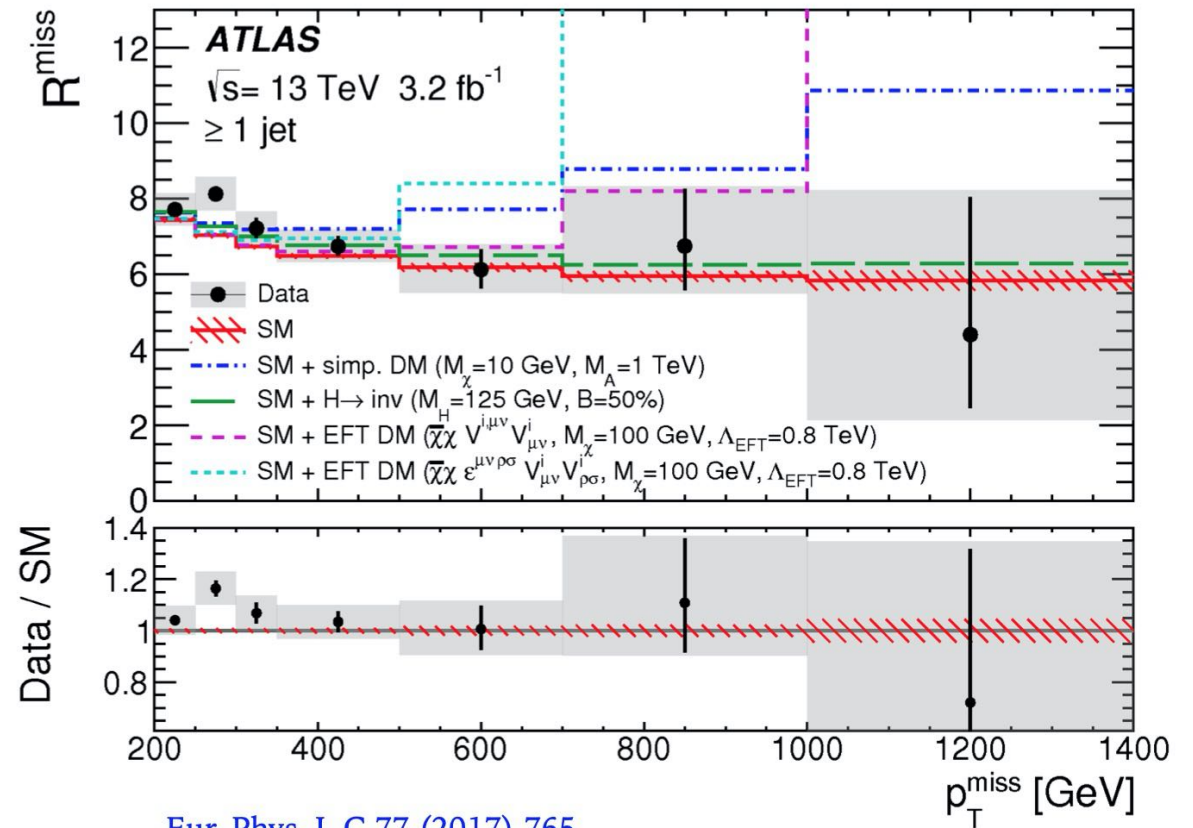
Mono-X Search: General Strategy

- Dominant background: $Z(\nu\nu) + \text{ISR } X$
 - Data-driven estimation from $Z(\ell\ell) + \text{ISR } X$



$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}(p_{\text{T}}^{\text{miss}} + \text{jets})}{\sigma_{\text{fid}}(\ell^+\ell^- + \text{jets})}$$

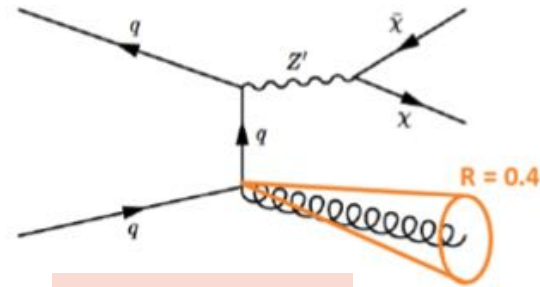
- Searching for non-resonance excess in the Missing E_{T} tail region



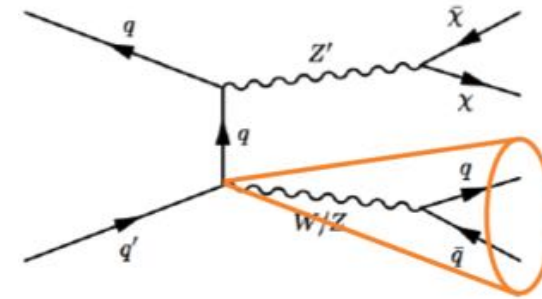
[Eur. Phys. J. C 77 \(2017\) 765](#)

Mono-jet

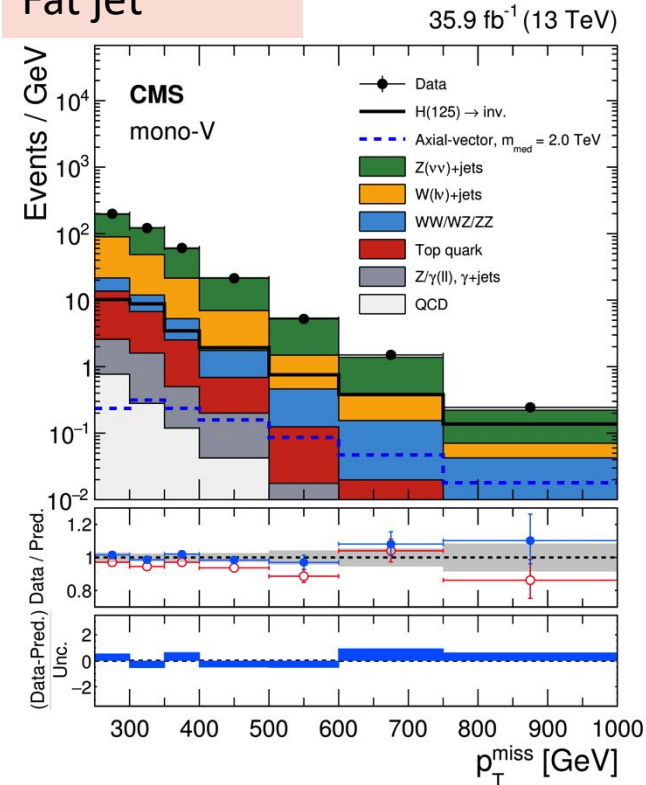
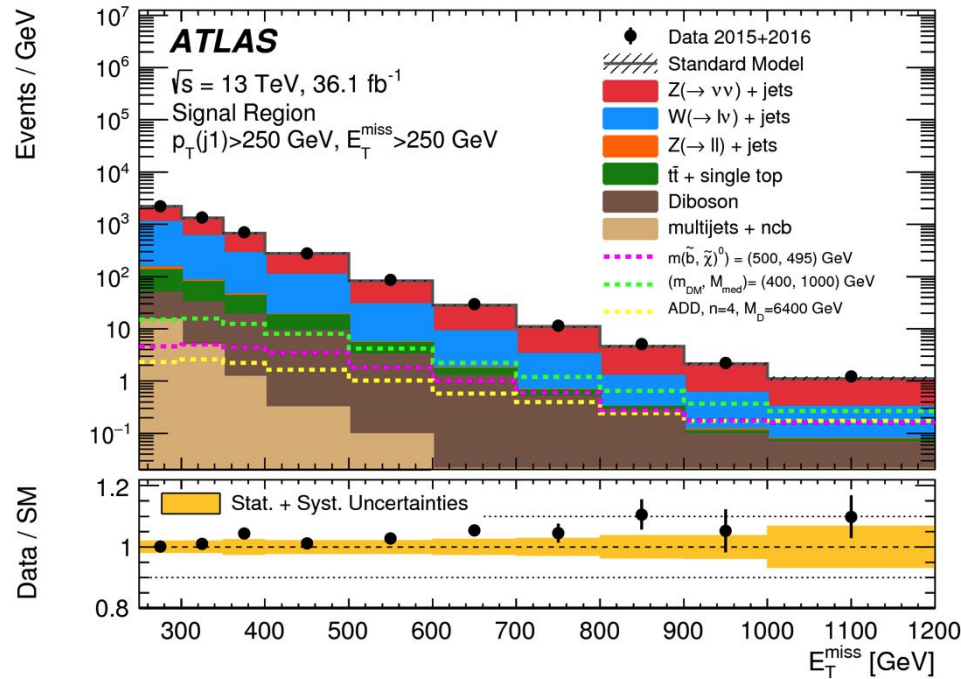
- Look for events with large MET, at least one energetic jet (narrow or fat), vetoing other objects



Narrow jet



Fat jet

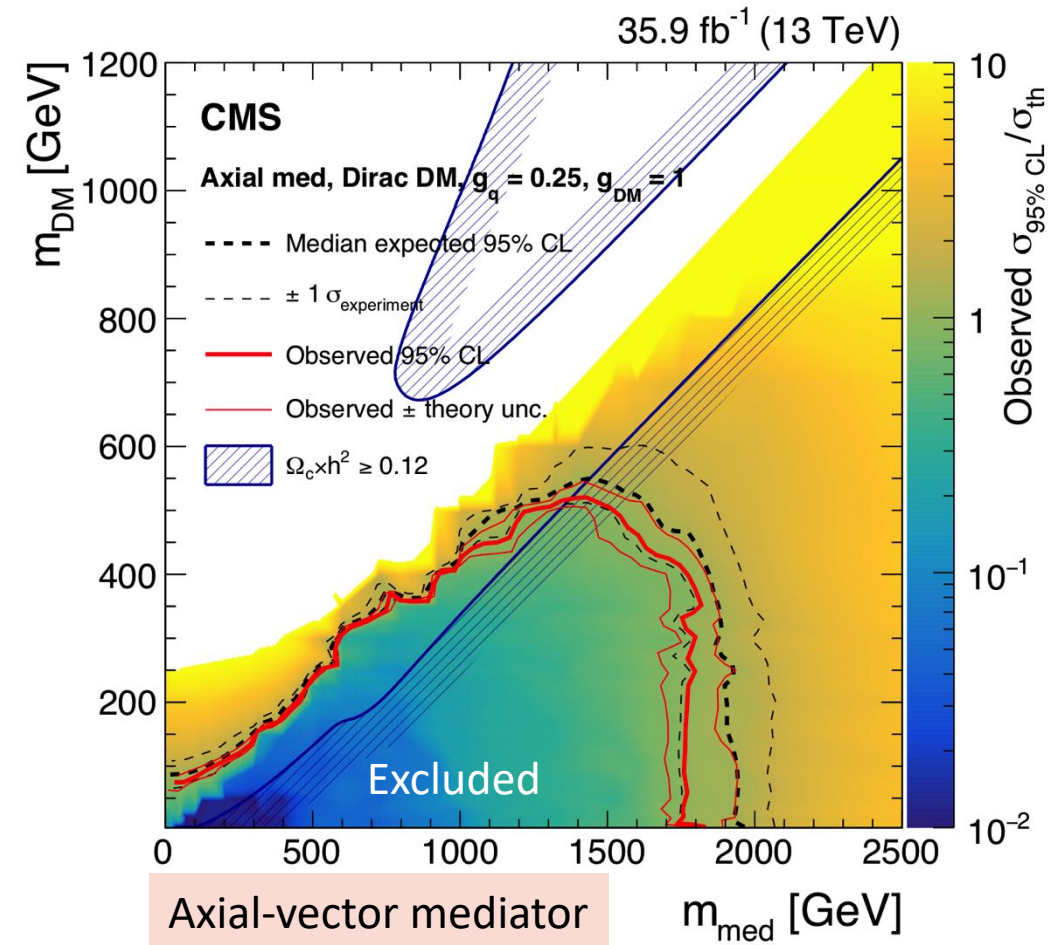
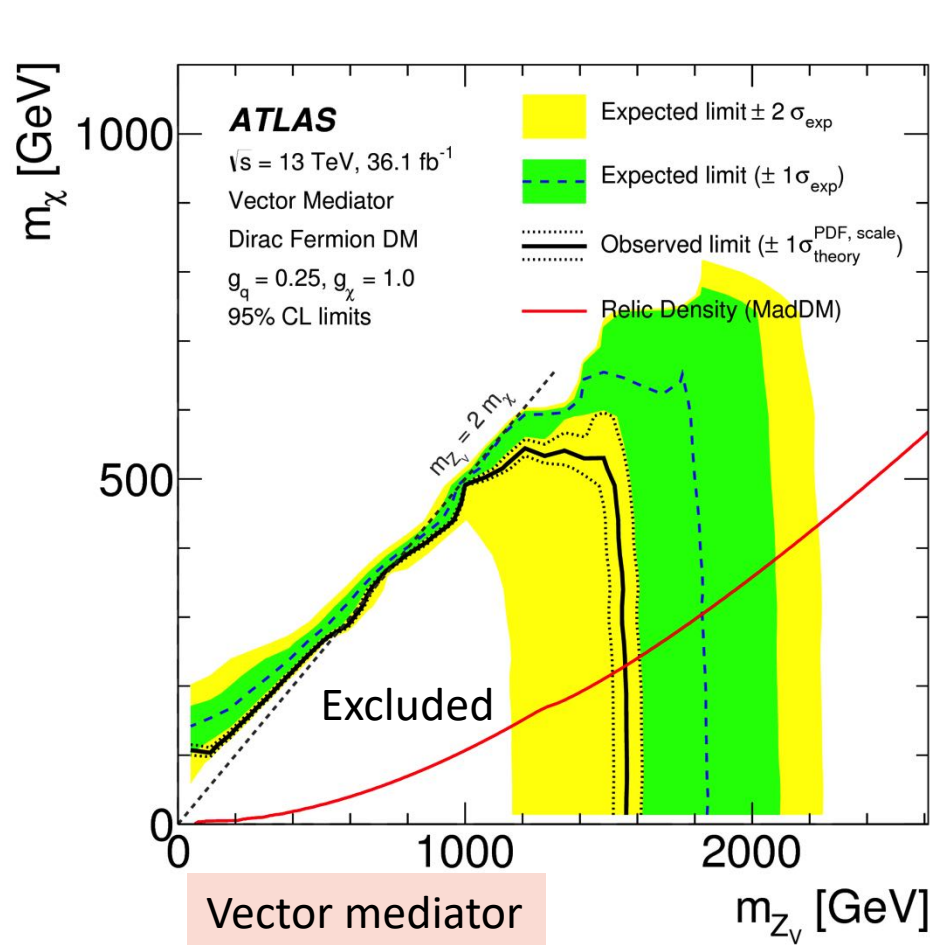


JHEP 01 (2018) 126
 PRD 97 (2018) 092005

DM Constraints from Mono-jet

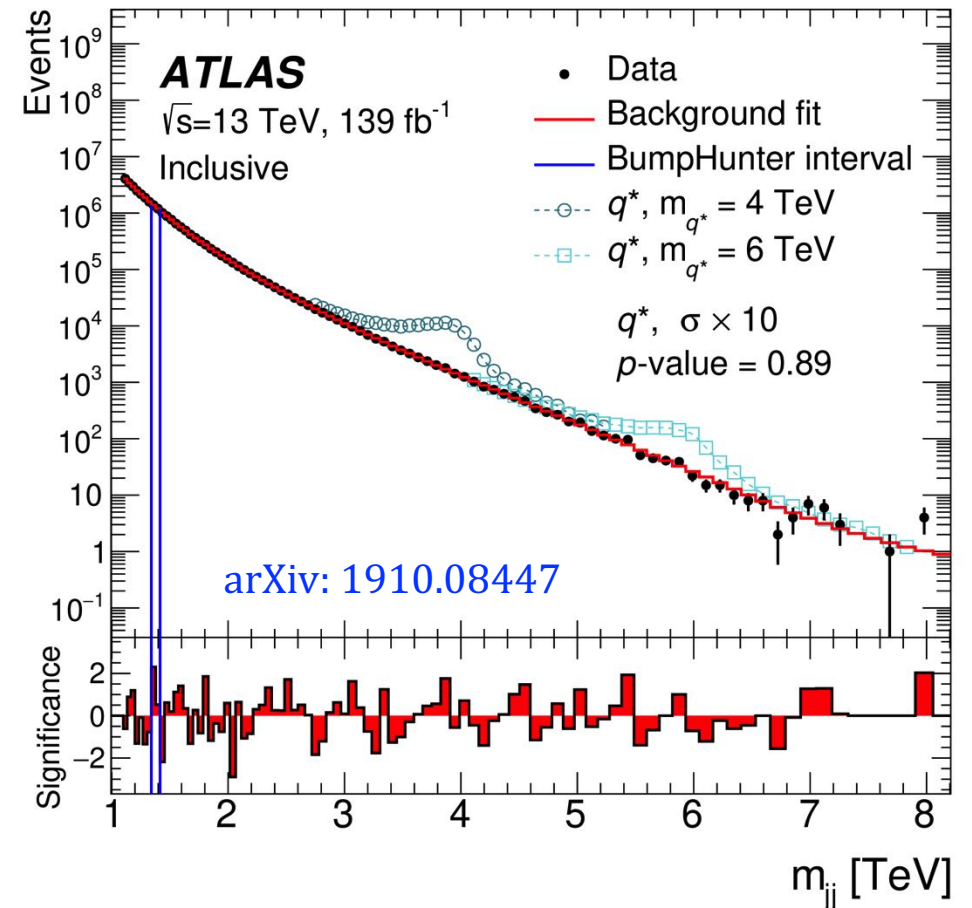
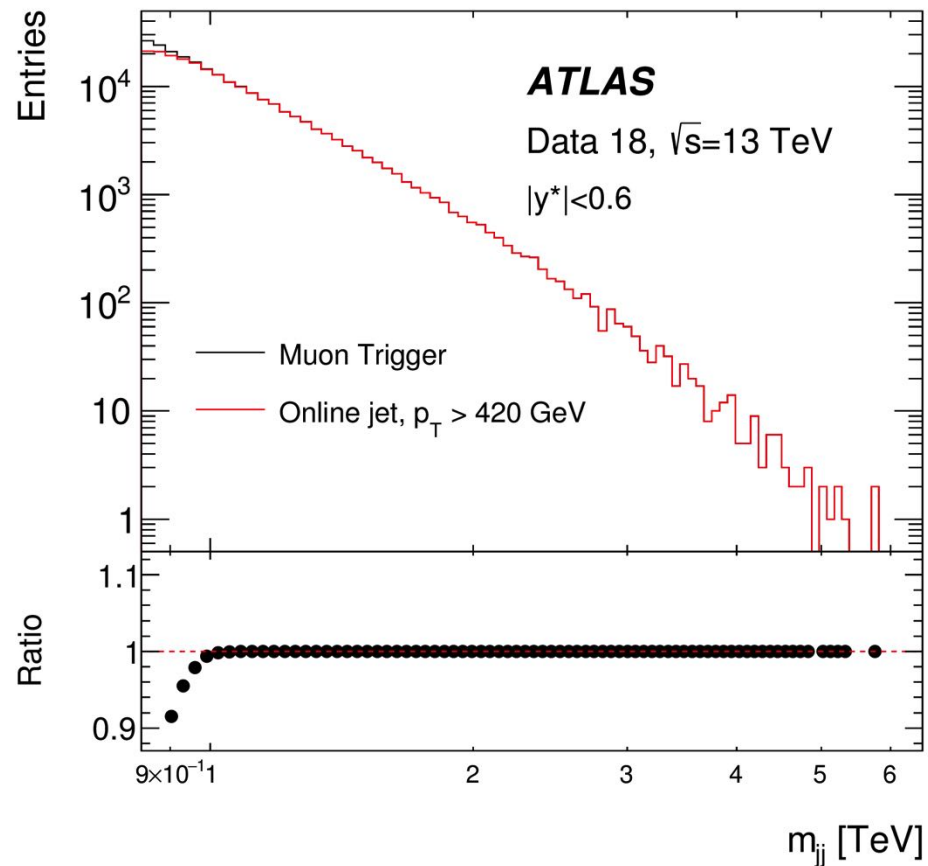
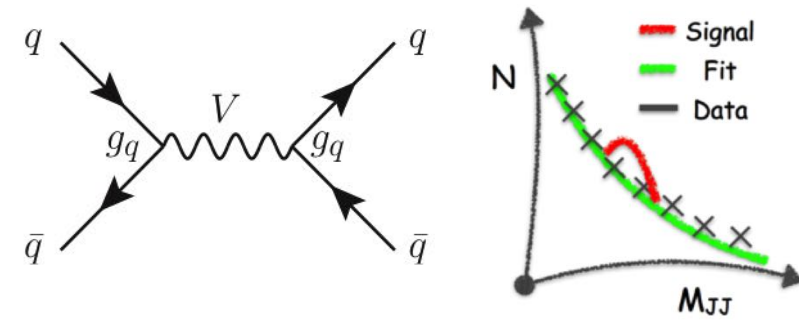
JHEP 01 (2018) 126
PRD 97 (2018) 092005

- With $g_q=0.25$, $g_{DM}=1.0$, current constraints
 - On DM mass ~ 700 GeV for vector mediator and ~ 500 GeV for axial-vector
 - On mediator mass ~ 1.8 TeV



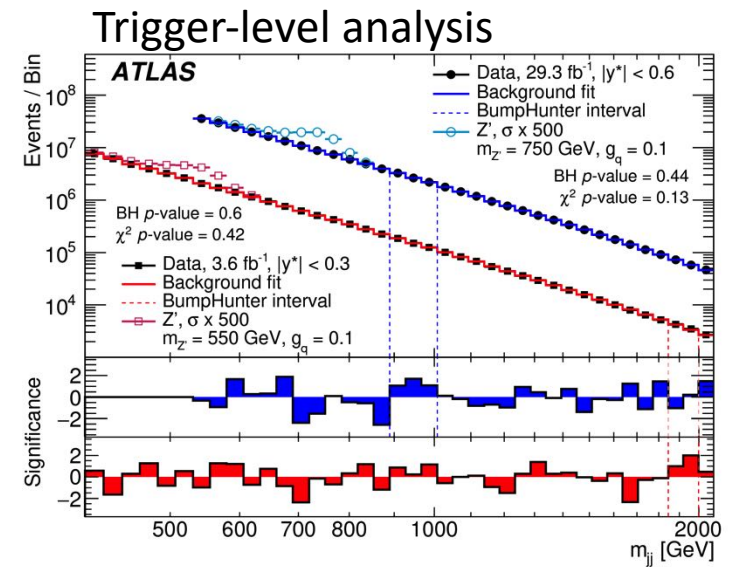
Mediator Search: High Mass

- Mediator of simplified model searched in dijet final state
- Full Run2 dijet search
 - Single jet trigger ($p_T > 420$ GeV threshold)

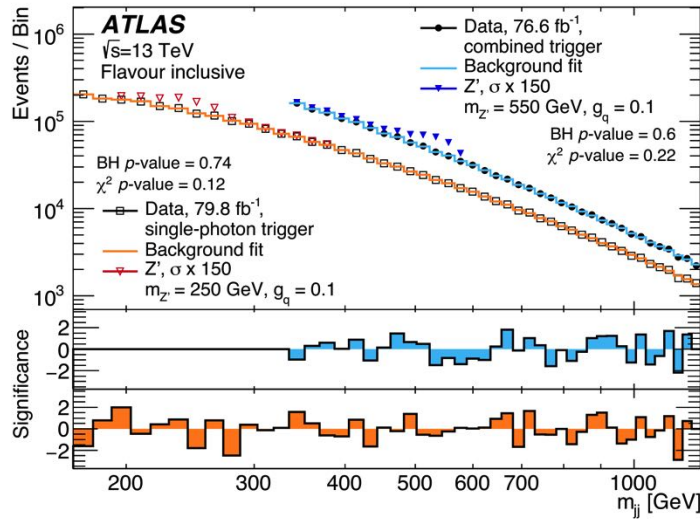


Mediator Search: Low Mass

- Trigger-level Analysis: lower the jet trigger p_T threshold
- Dijet + ISR: triggered on the ISR object
 - Resolved dijet + photon
 - Boosted dijet + photon/jet

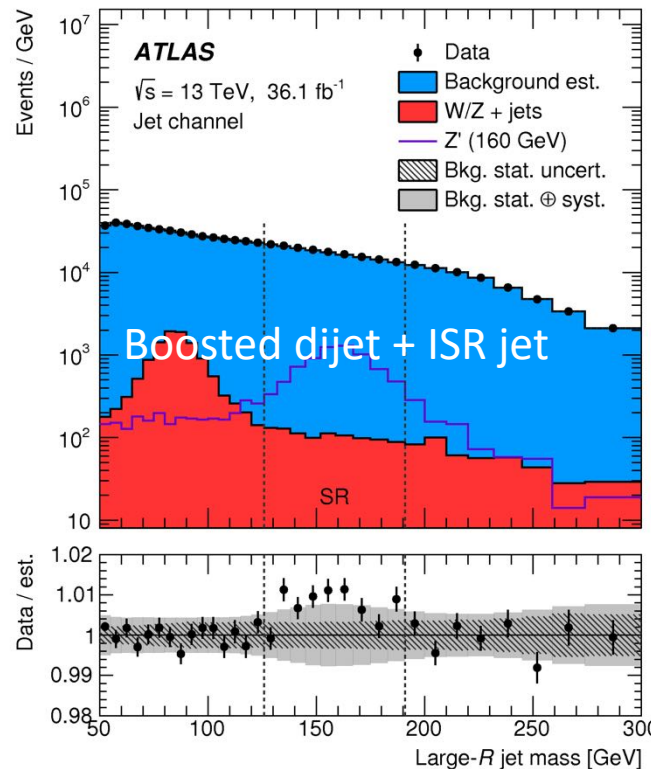


PLB 788 (2019) 316

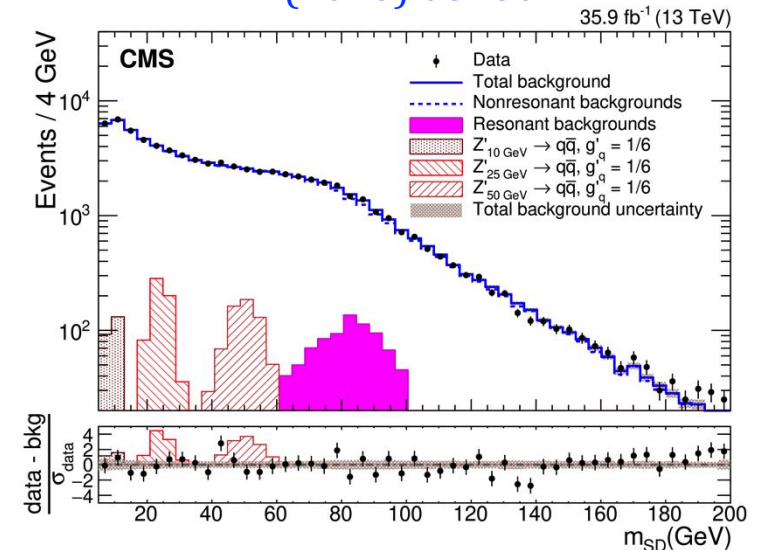


PLB 795 (2019) 56

Resolved dijet + ISR photon



PRL 121 (2018) 081801

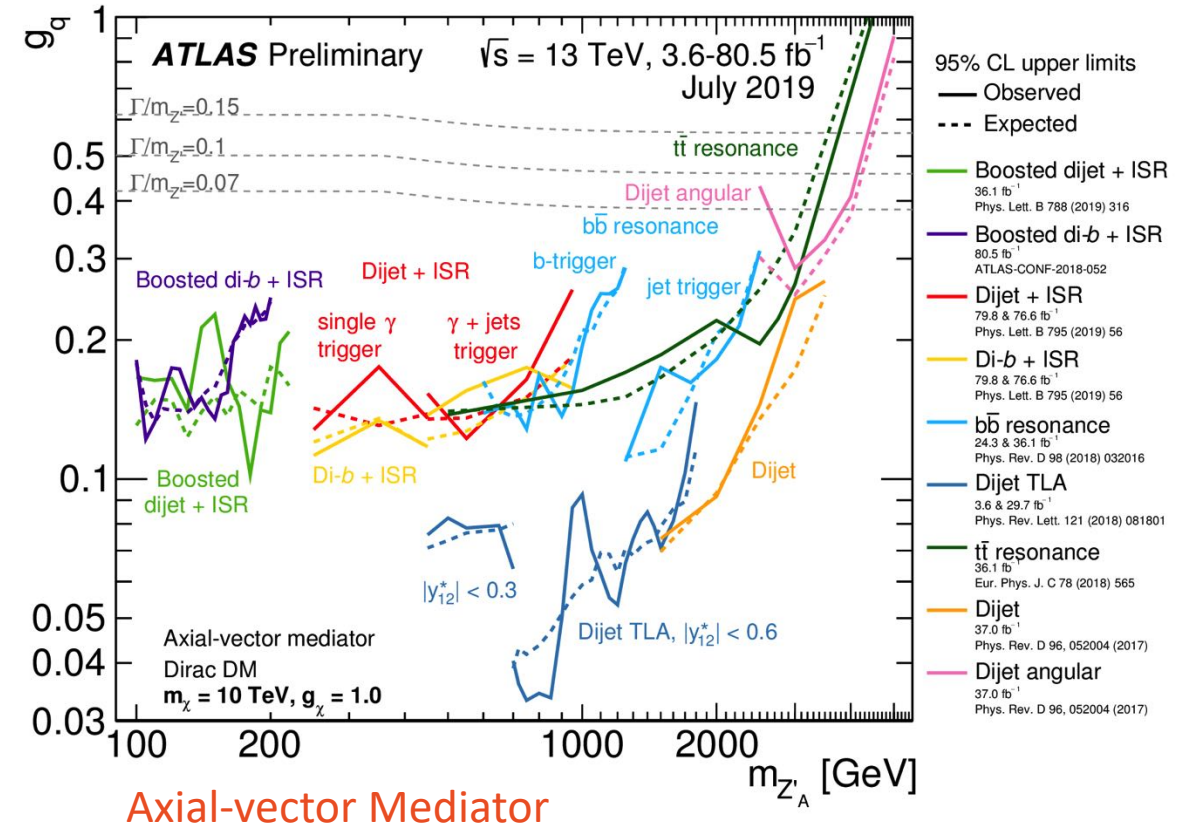
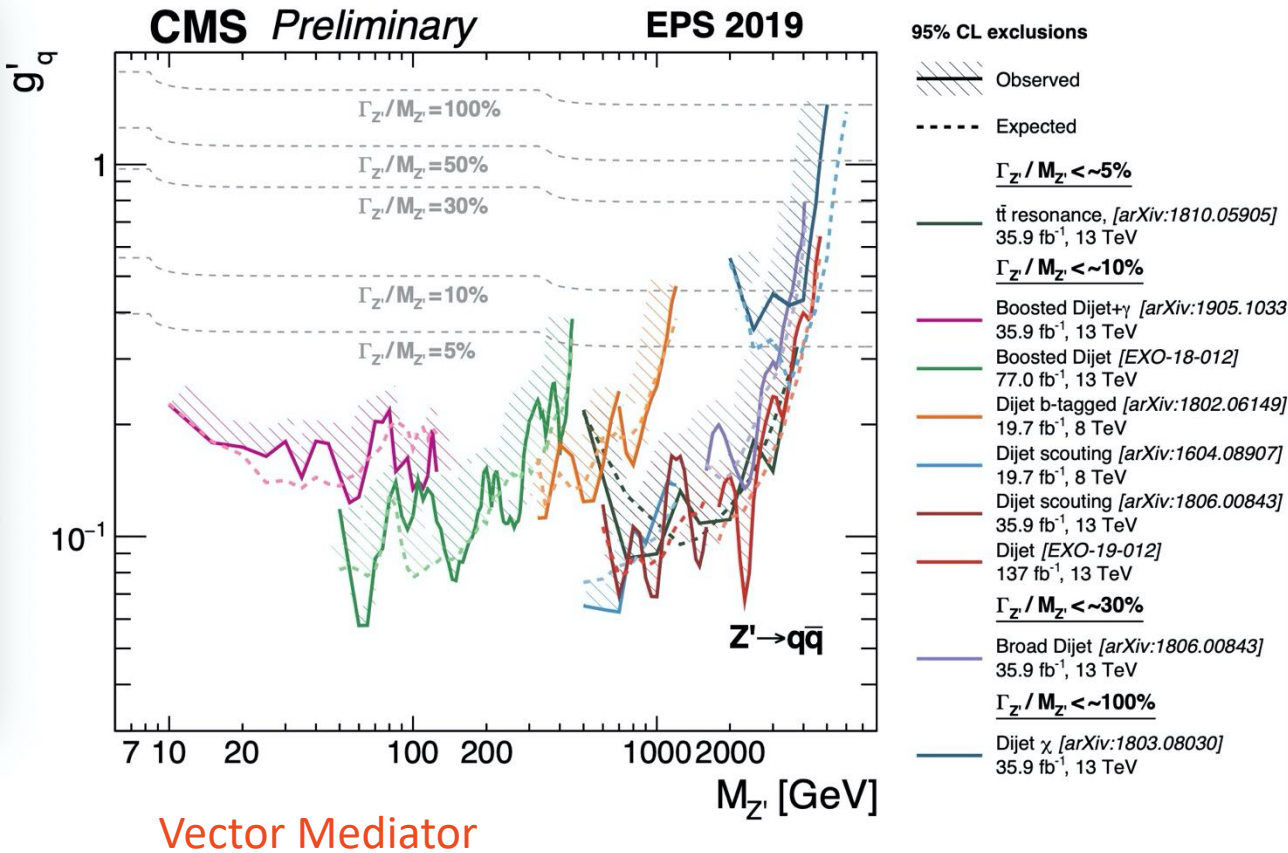


arXiv:1905.10331

Boosted dijet + ISR photon

Mediator Search: dijet

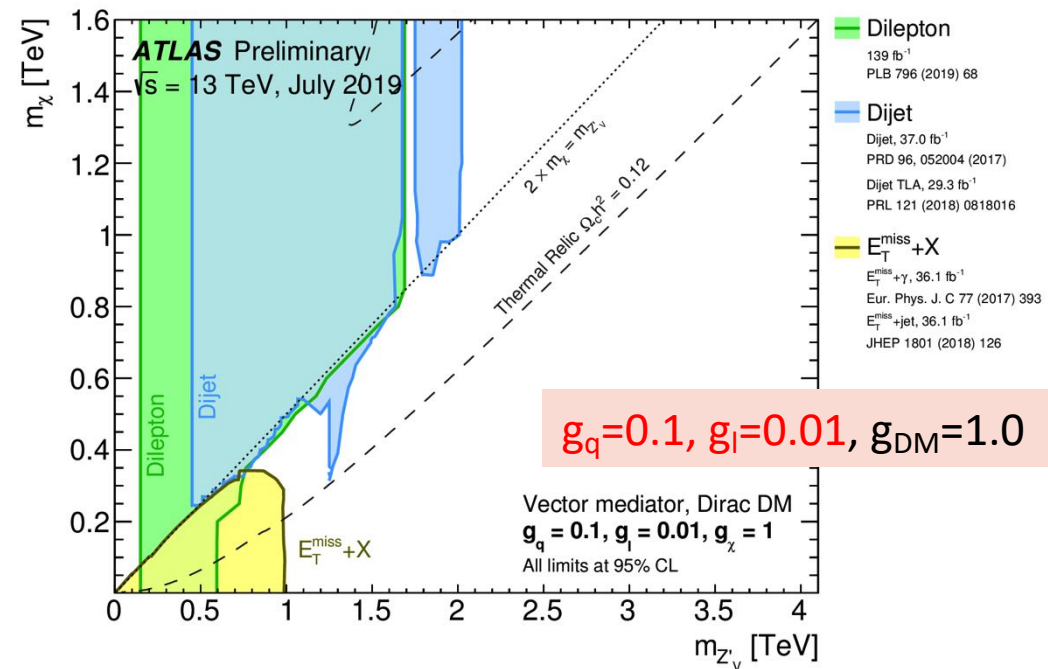
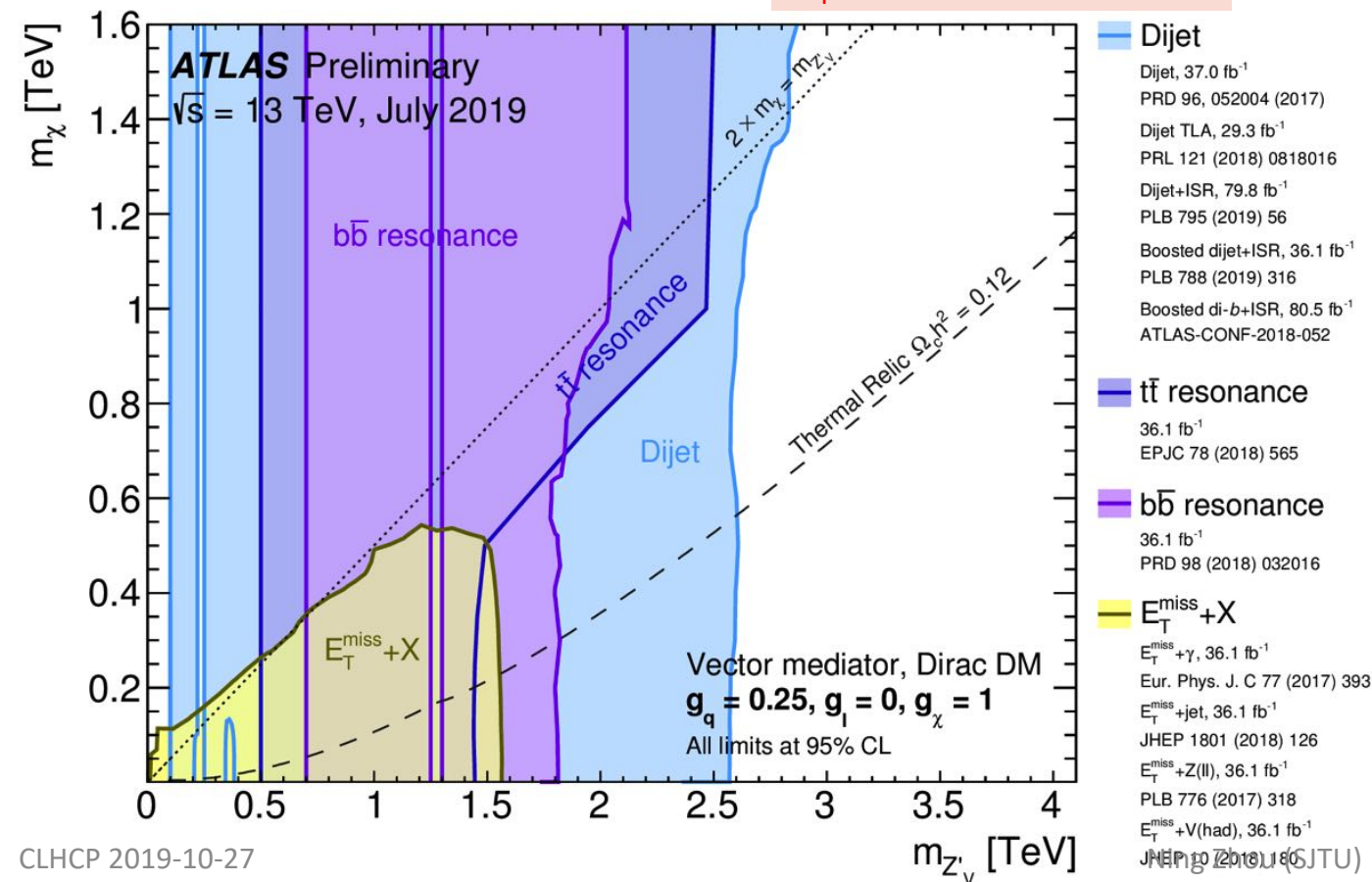
- Leptophobic mediator



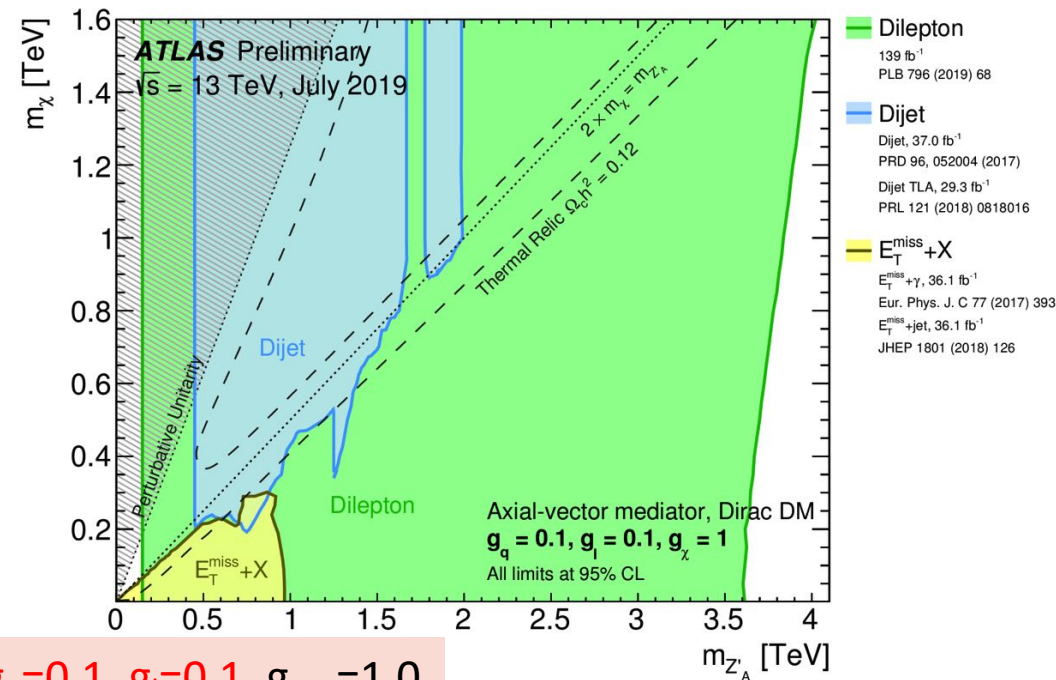
Constraints on DM/Mediator

- DM mass – mediator mass plane excluded at 95% CL
- LHC constraints largely depend on the couplings choice

$g_q=0.25, g_l=0, g_{DM}=1.0$



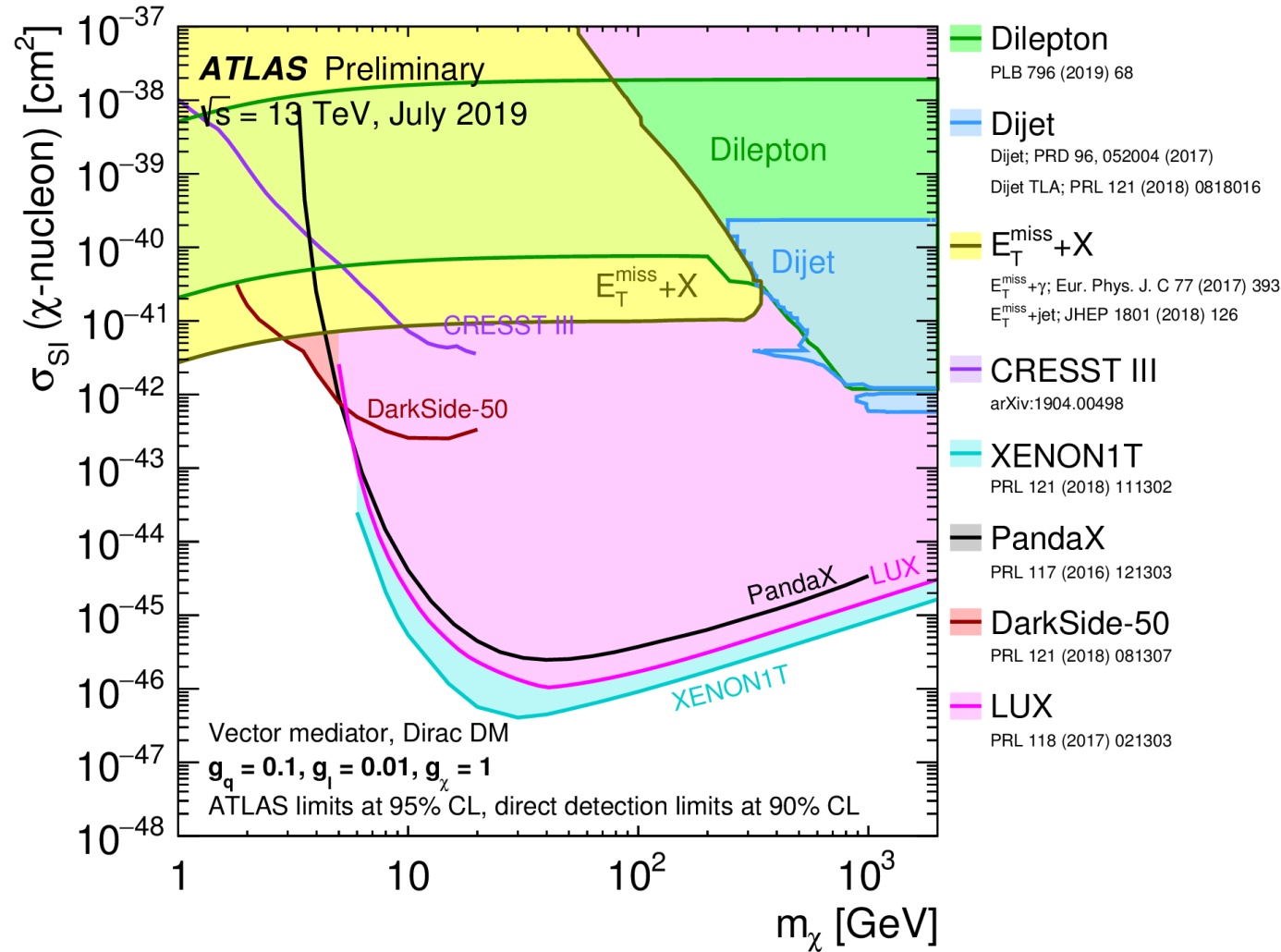
$g_q=0.1, g_l=0.01, g_{DM}=1.0$



$g_q=0.1, g_l=0.1, g_{DM}=1.0$

Constraints on Spin-Independent DM

- Vector mediator : spin-independent scattering
- Mono-X and dijet mediator searches: **low mass region**



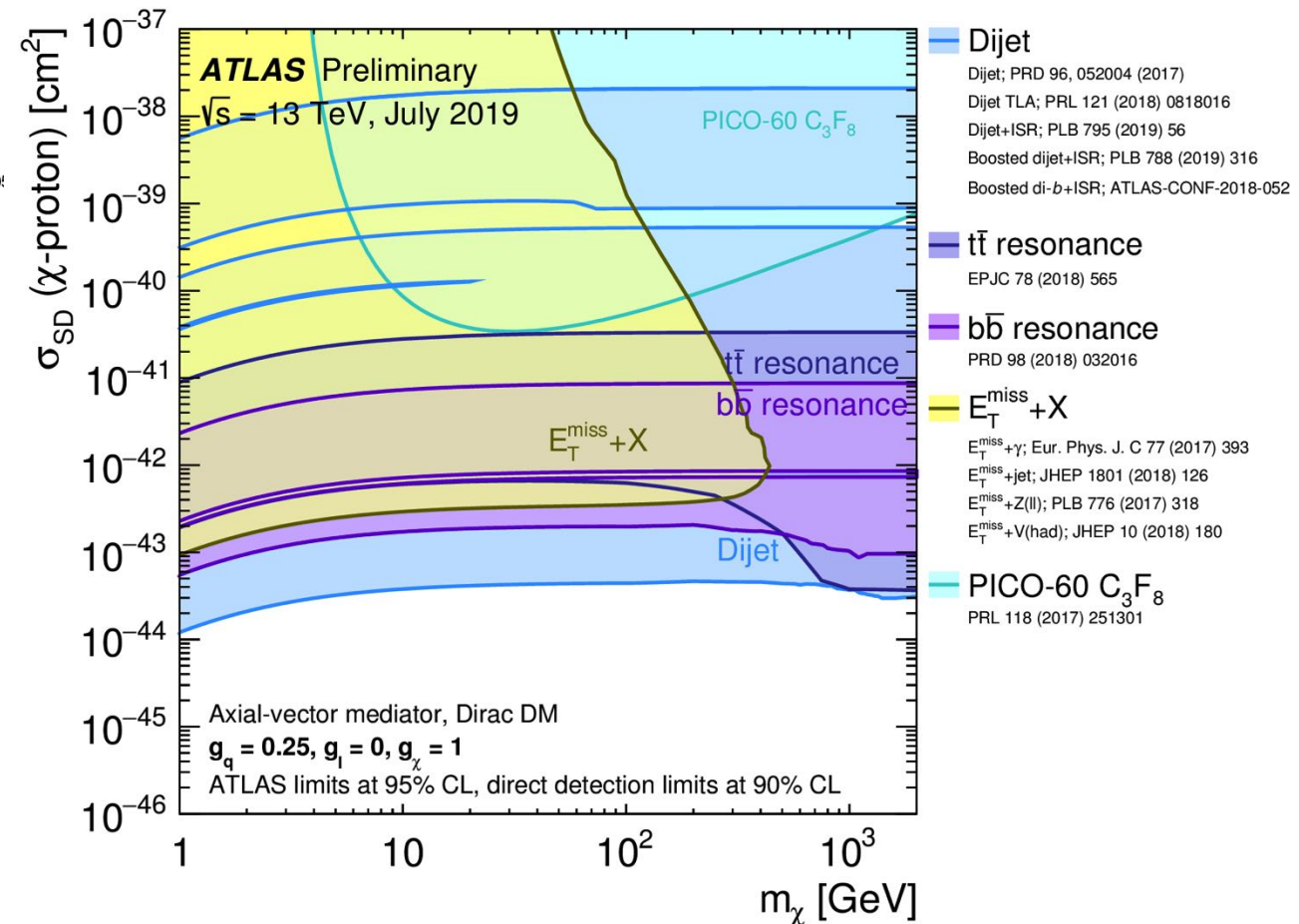
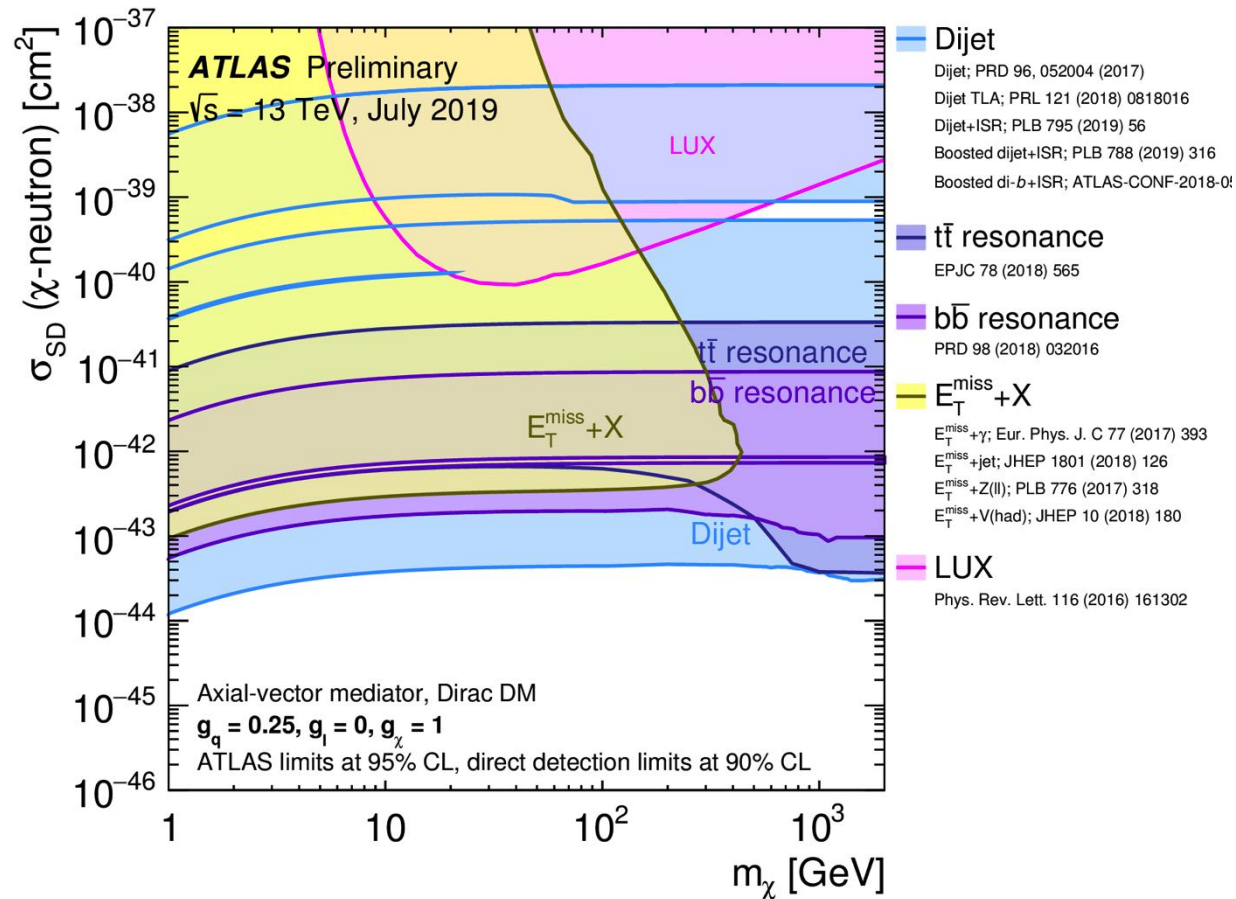
Complementary to Direct Detection

LHC coverage sensitive to the couplings

$g_q=0.1, g_l=0.01, g_{DM}=1.0$

Constraints on Spin-Dependent DM

- Axial-vector: Spin-dependent scattering
- Mono-X and dijet mediator searches cover a large area of parameter space

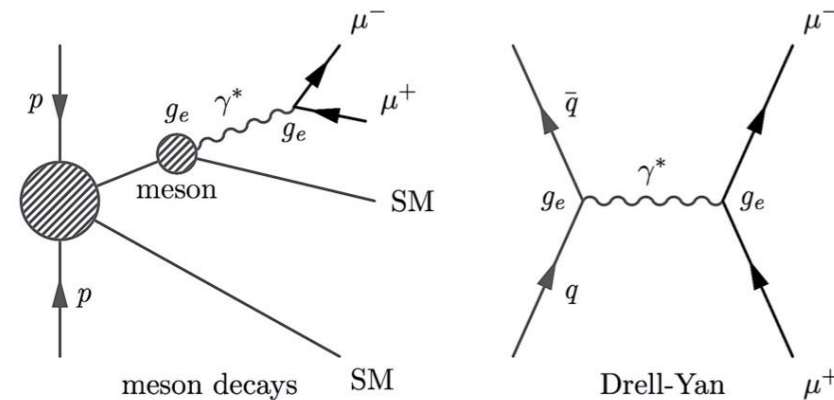
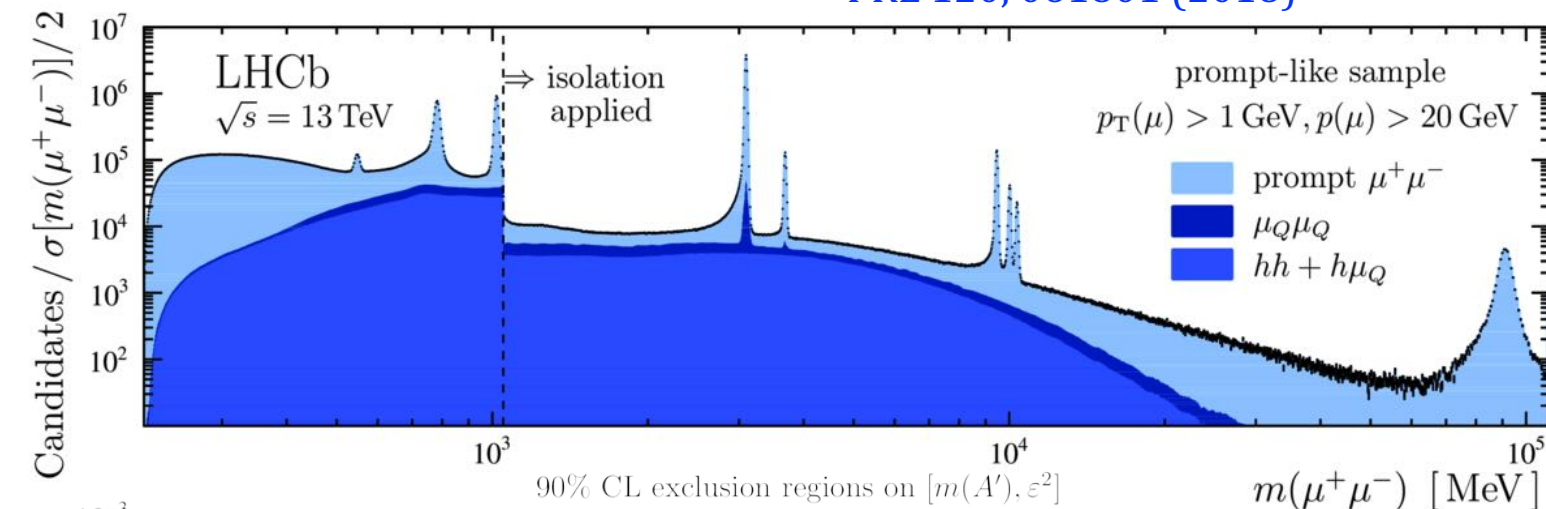


Light Mediator Search: dark photon

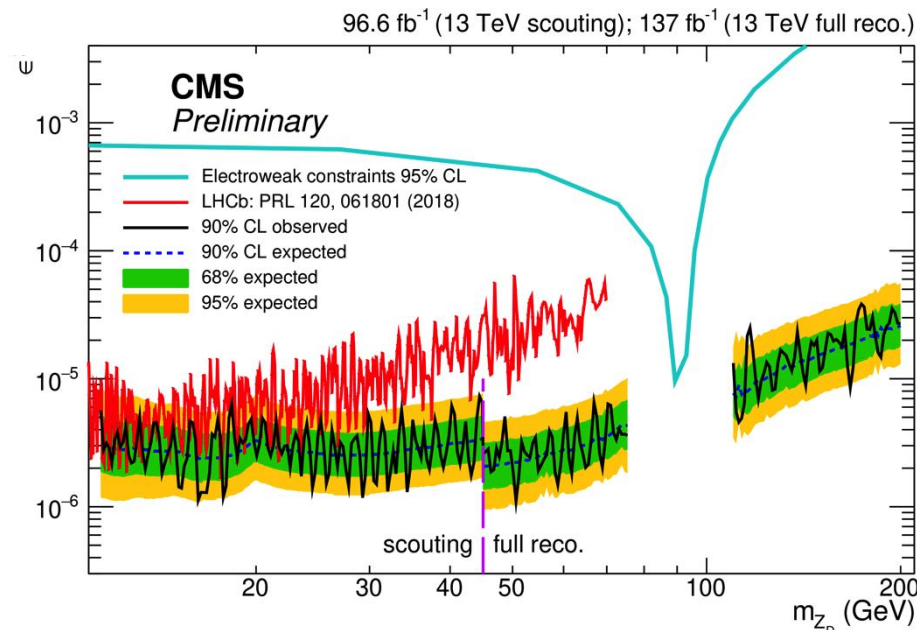
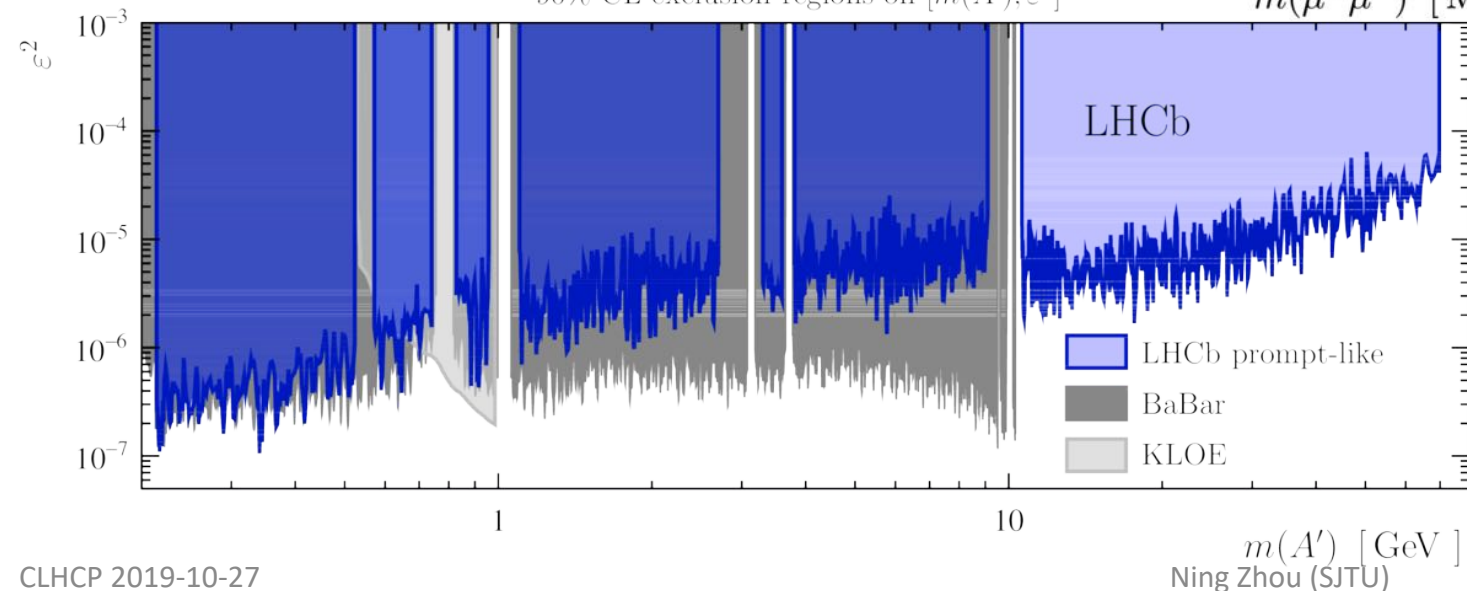
- Dark photon: kinetic mixing with SM $U(1)_Y$

– Mixing coefficient ϵ

PRL 120, 061801 (2018)

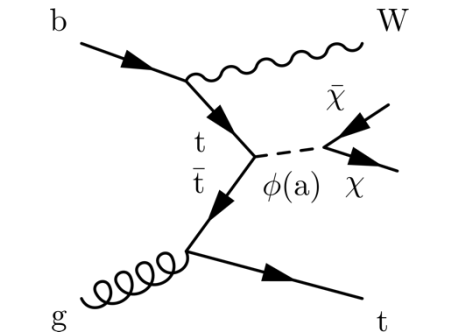
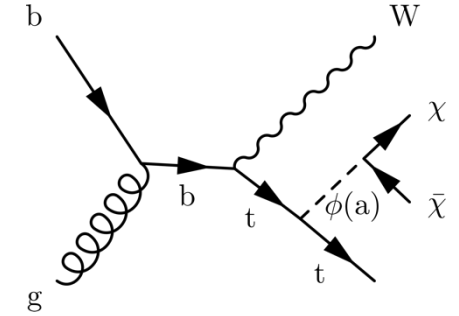
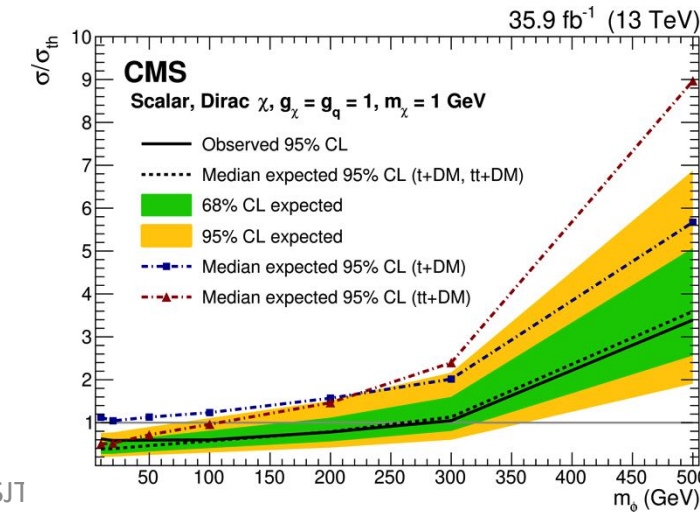
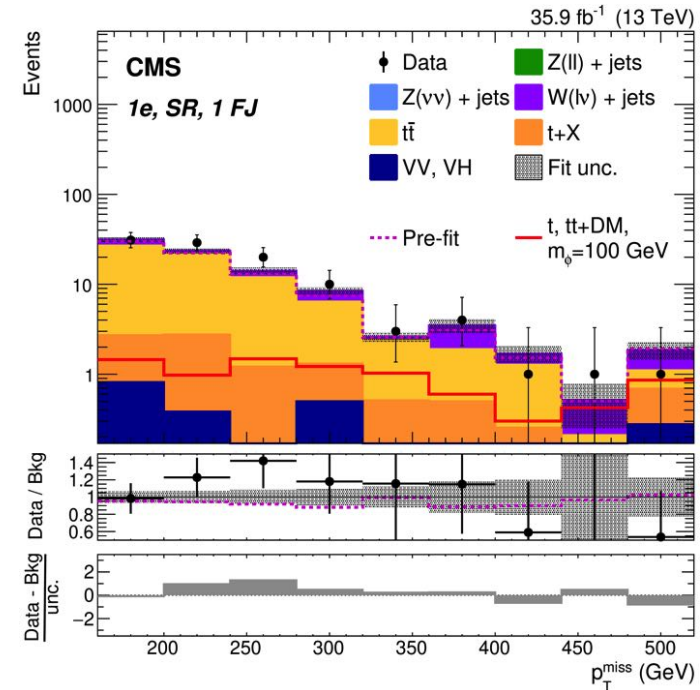
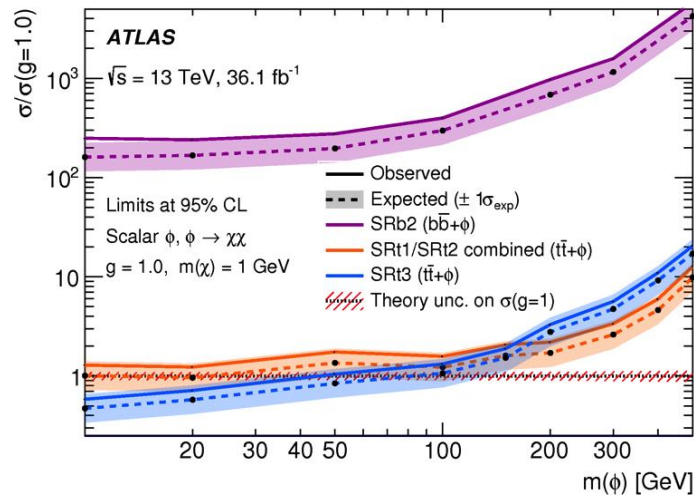
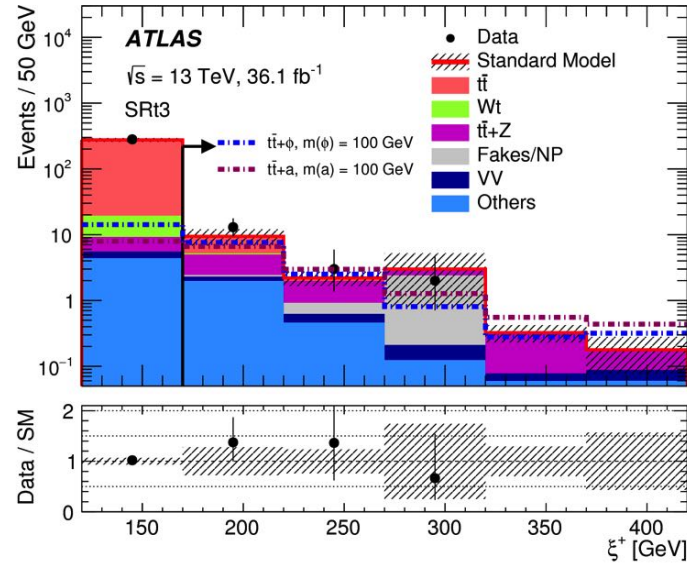


CMS-PAS-EXO-19-018



Scalar/Pseudoscalar Mediator

- Higgs-like Yukawa coupling to quarks
- DM + $t\bar{t}$ ($b\bar{b}$), single top(bottom)

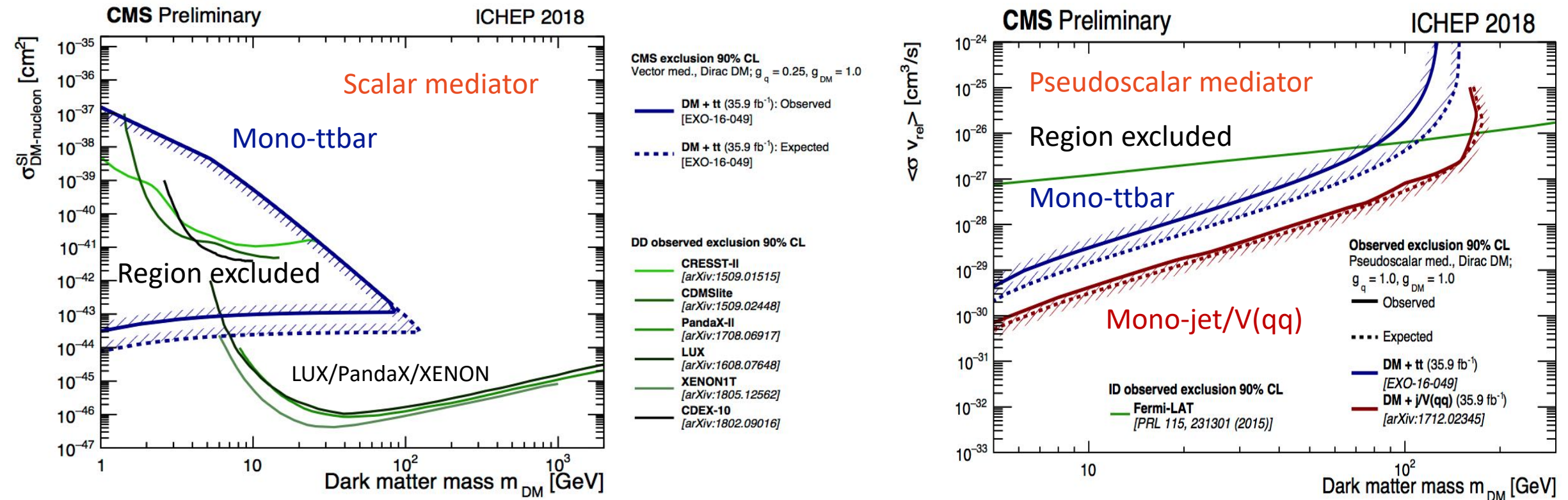


EPJC 78 (2018) 18

JHEP 03 (2019) 141

Constraints on Scalar/Pseudoscalar Mediator

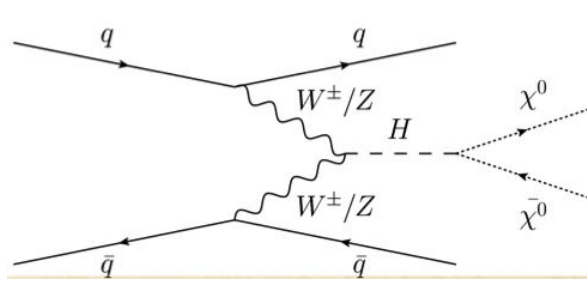
- Scalar mediator: DM-nucleon Spin-independent Interaction
- Pseudoscalar mediator: velocity averaged DM annihilation cross-section



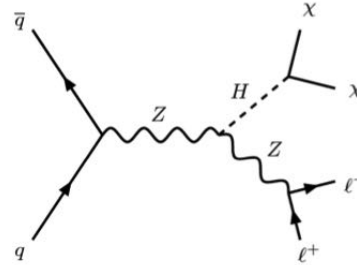
Higgs-portal DM Model Search

VBF production
PLB 793 (2019) 499

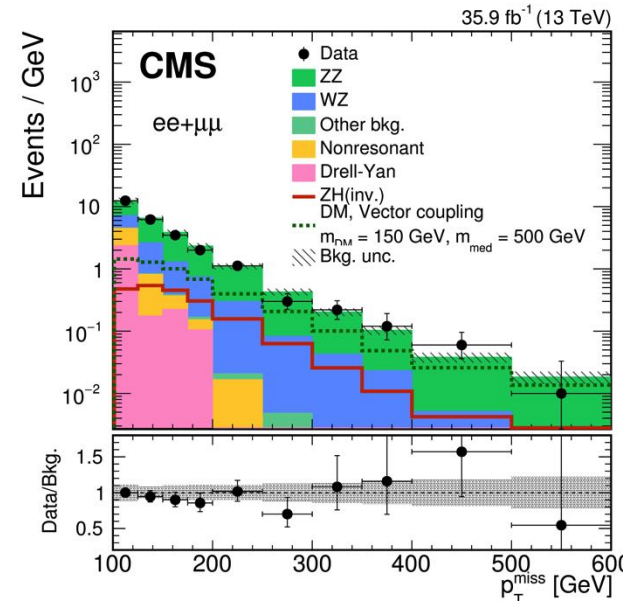
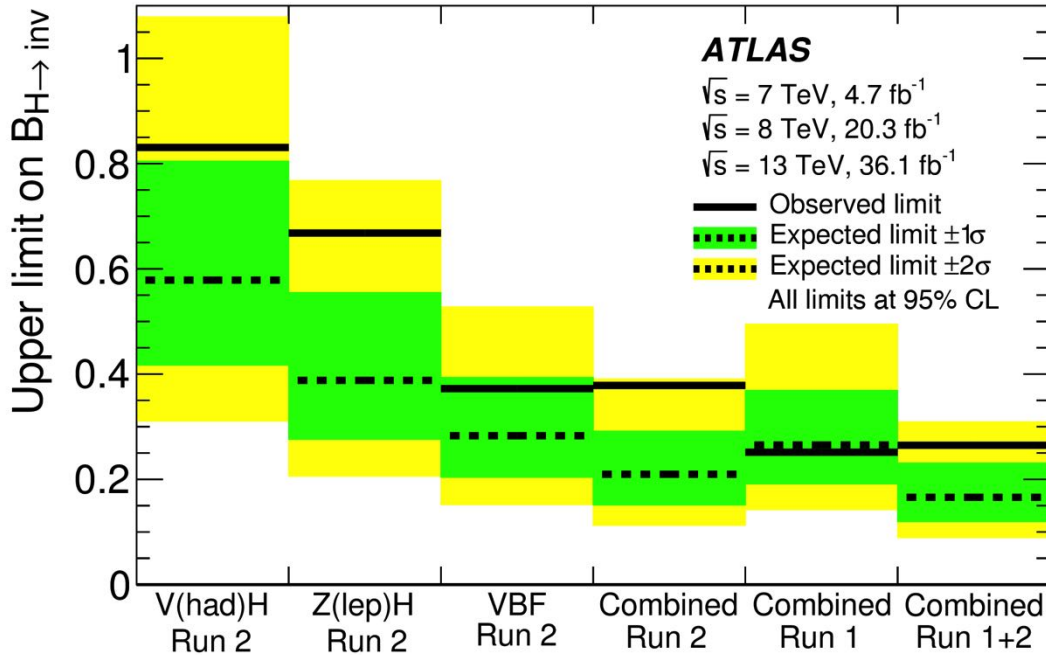
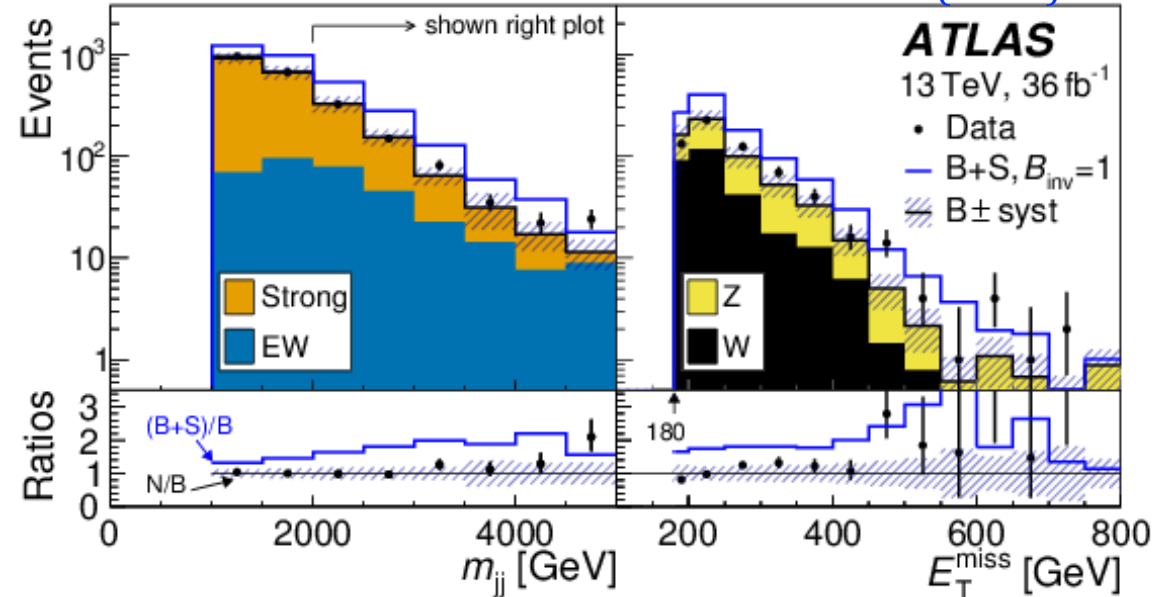
- Higgs invisible decay



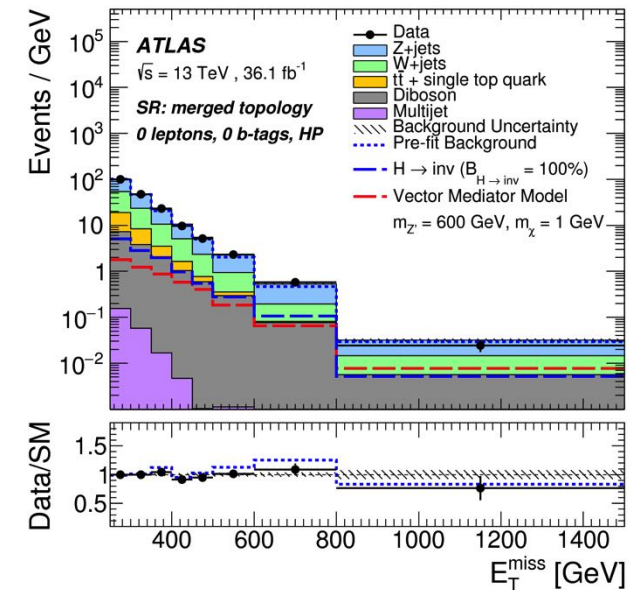
VBF process



VH process



Z(l)H production
EPJC 78 (2018) 291

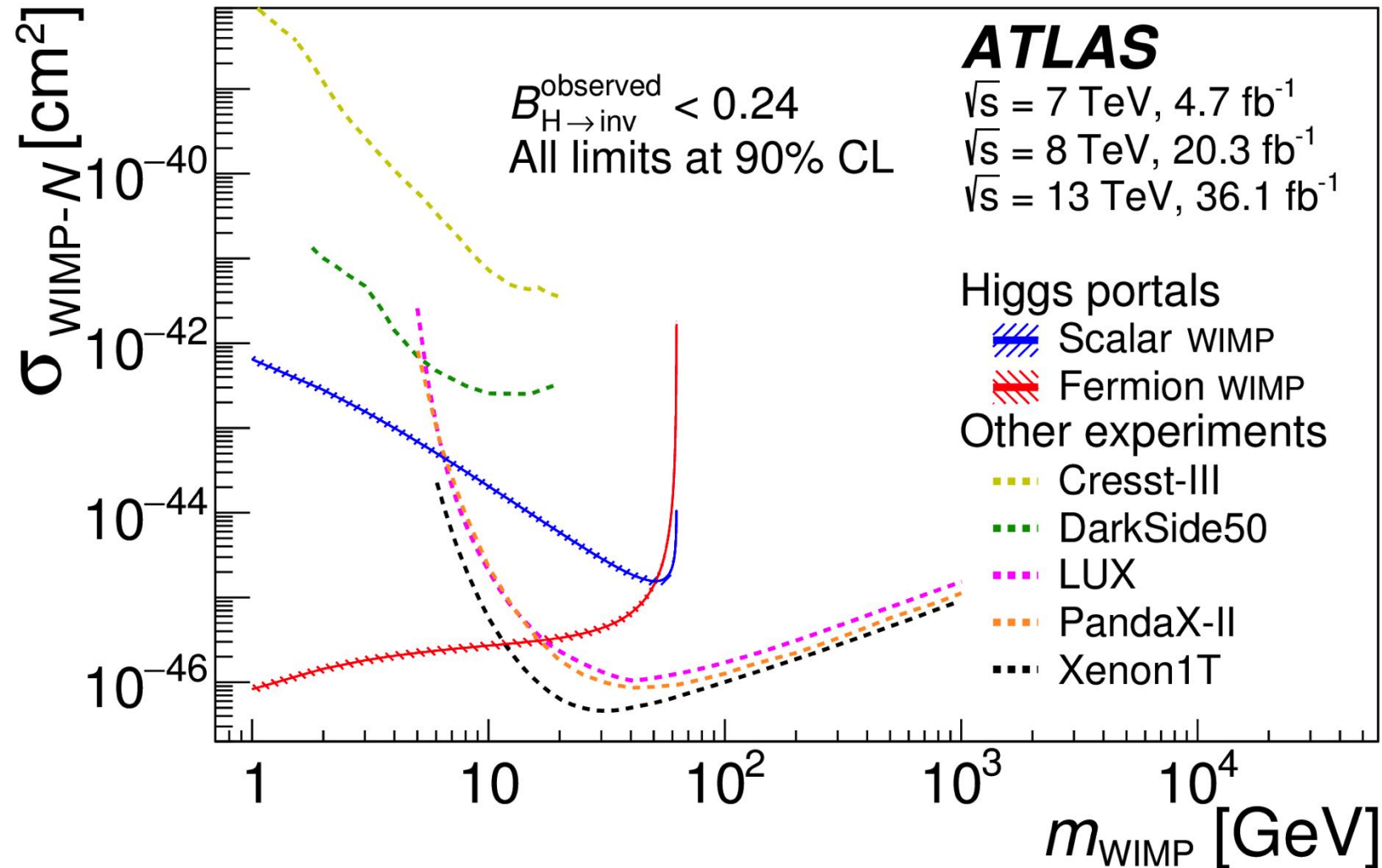


W/Z(jj)H production
JHEP 10 (2018) 180

Higgs-portal DM

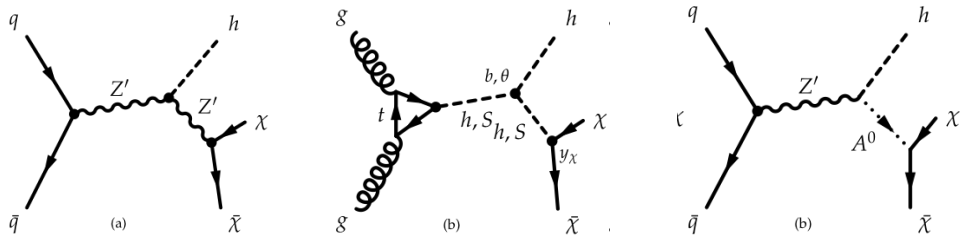
- Very sensitive to DM with mass below $m_H/2$

Combined H invisible
PRL 122 (2019) 231801

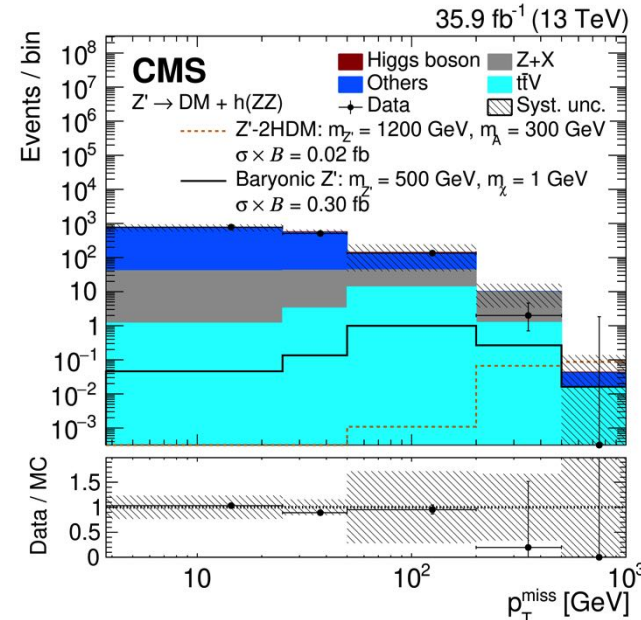
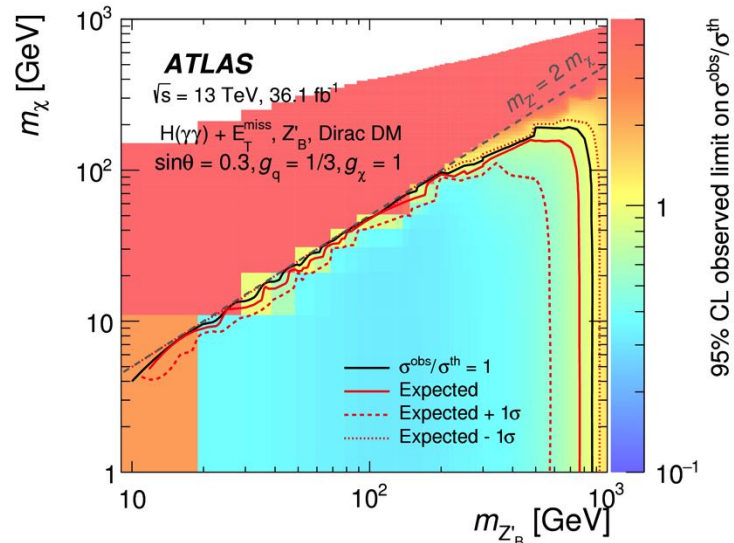


Mono-Higgs

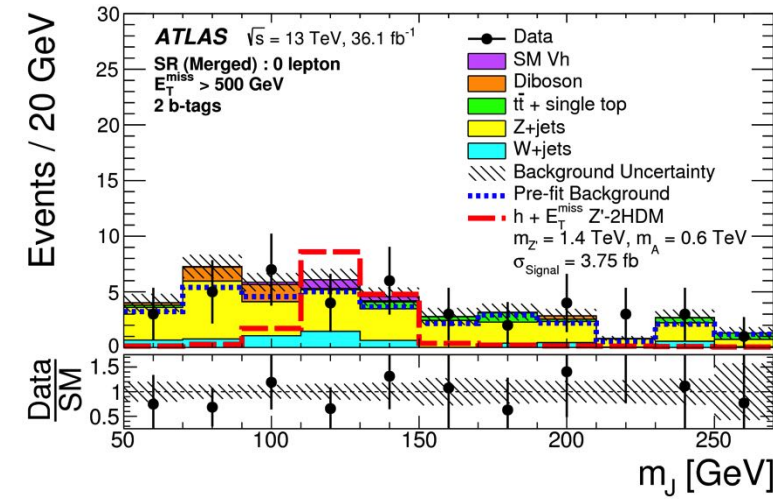
- Higgs as a new tagger
 - Vector, scalar, pseudoscalar
- $bb, \gamma\gamma, \tau\tau, WW, ZZ$ final states



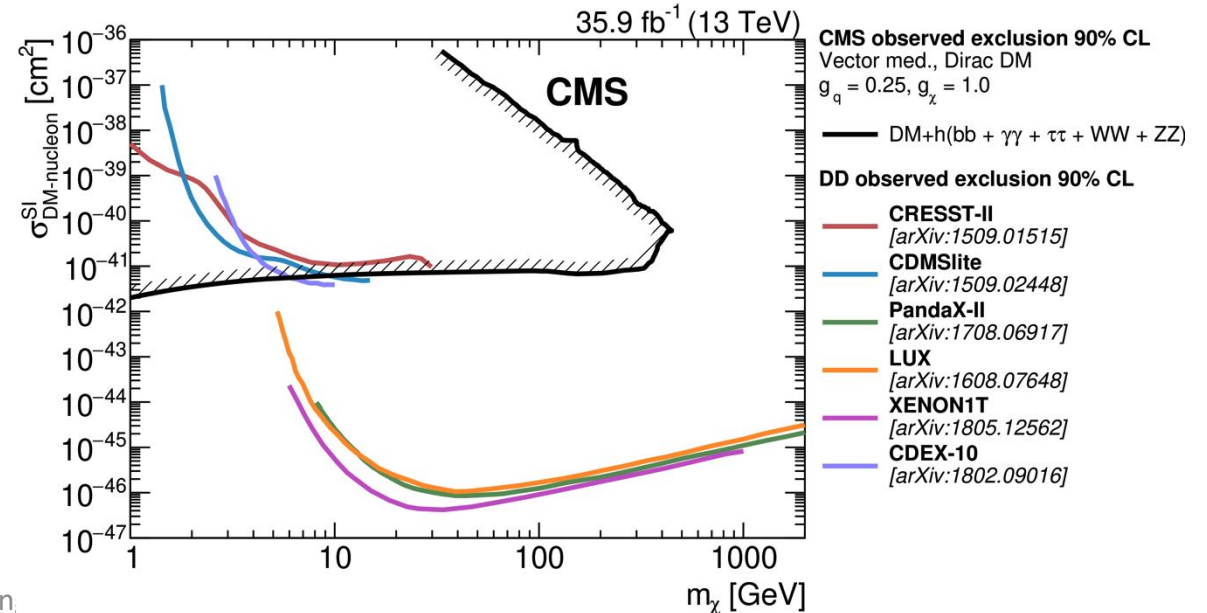
- Constraints on DM, Z'_B model



arXiv:1908.01713



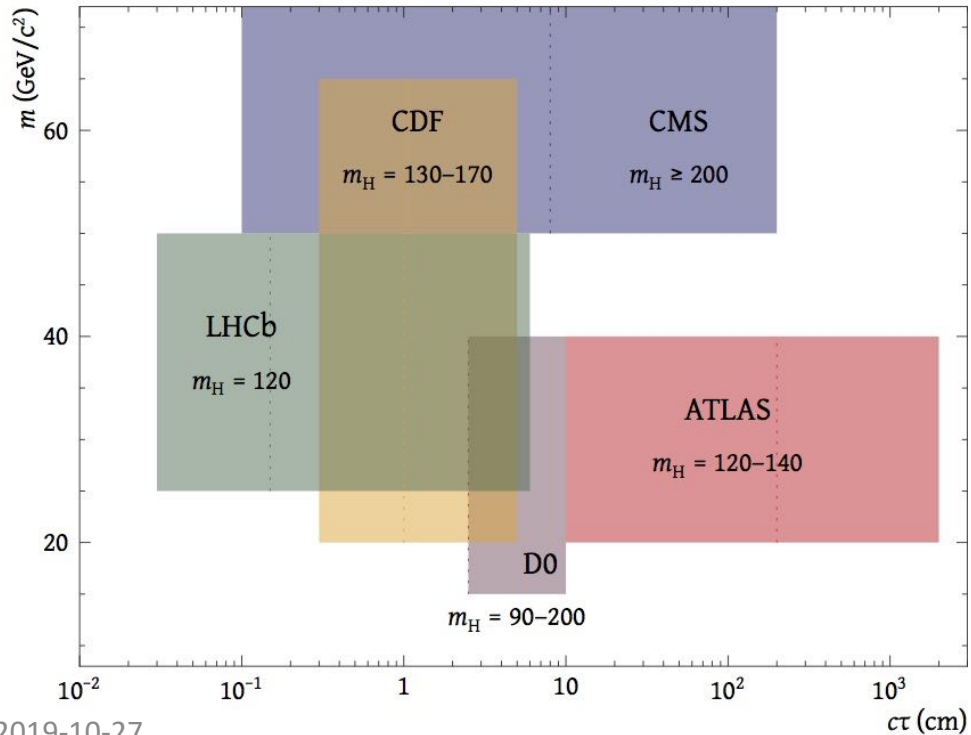
PRL 119 (2017) 181804



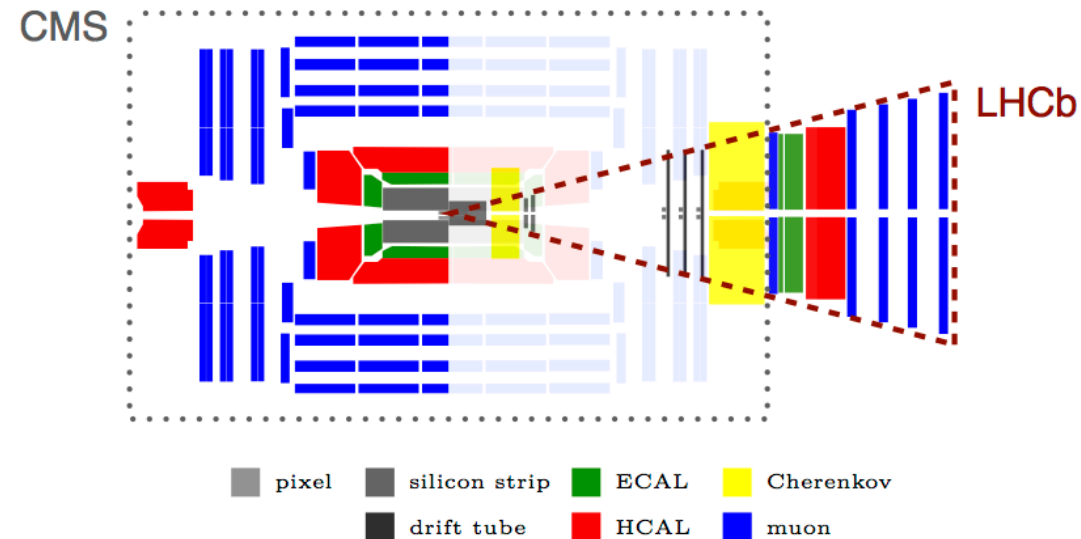
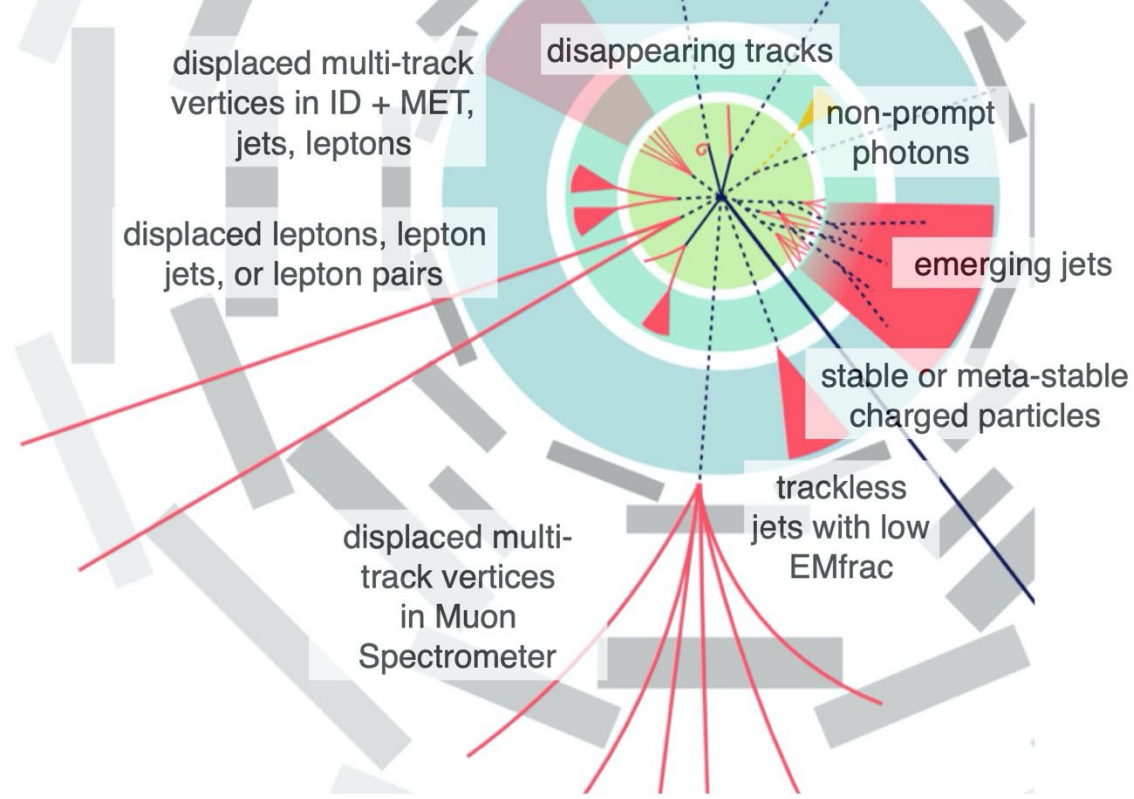
Nin,

Dark Matter Searches at LHCb

- Long-lived particles ($\sim 1\text{ps}$)
 - displaced objects (vertices, leptons ...)
- LHCb:
 - Excellent vertex and mass resolution: lower lifetime
 - very soft triggers: lower mass
 - Unique coverage



Pieter David PhD thesis

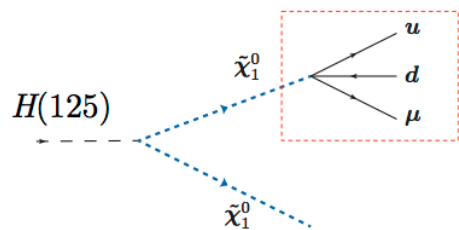


Ning Zhou (SJTU)

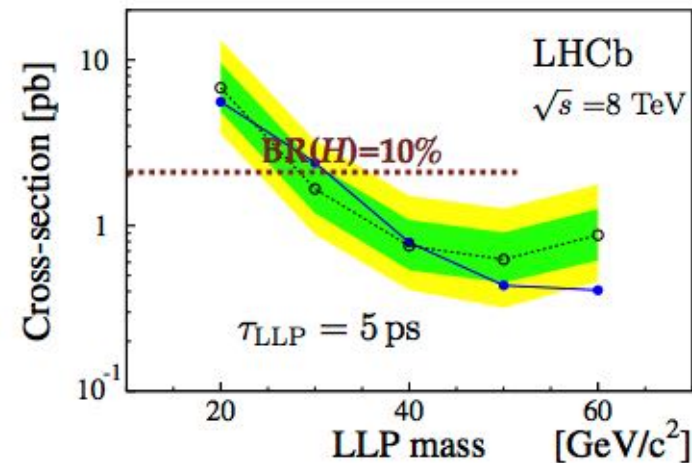
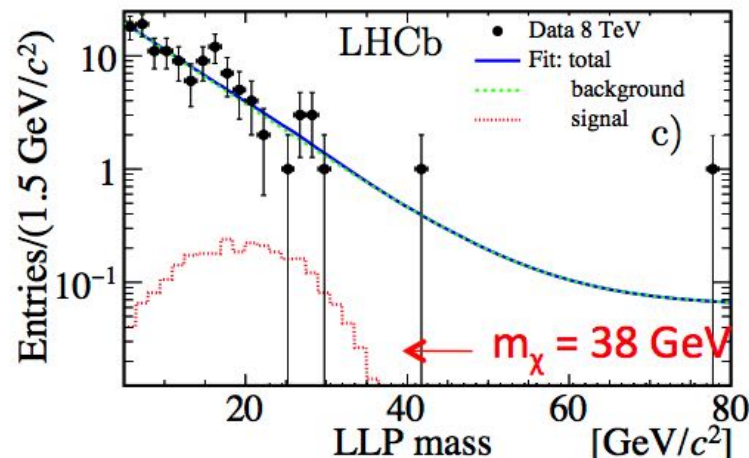
Long-lived Particle Search at LHCb

EPJC (2017) 77:224

- LLP decays to muon + jets

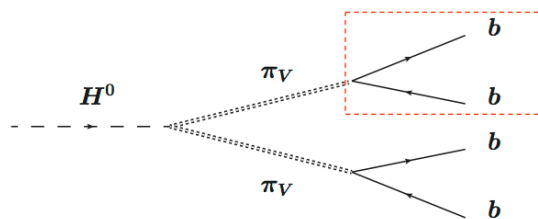


Exclude BR>10% down to $m_\chi=30\text{GeV}$, $\tau_\chi=5\text{ps}$

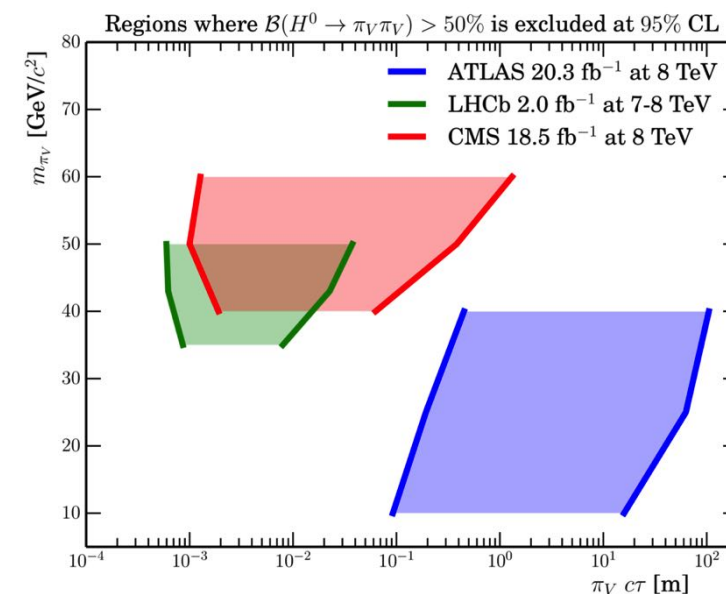
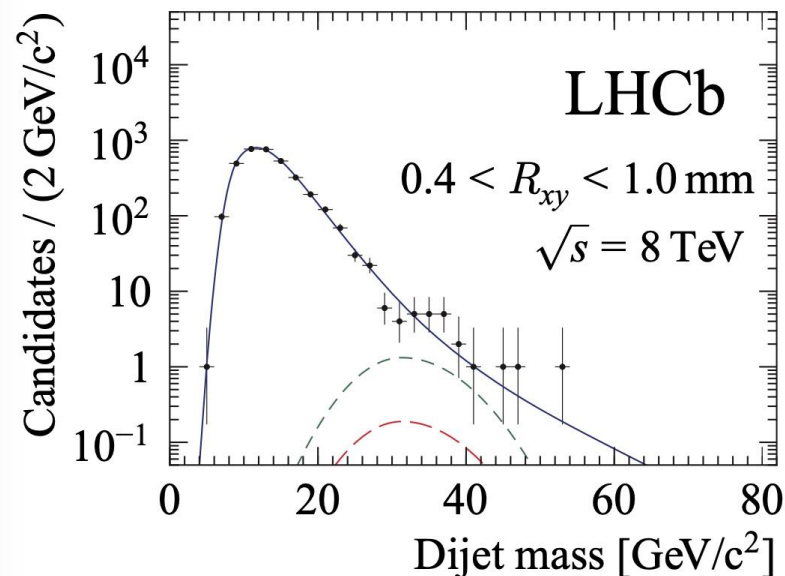


- LLP decays to dijet

EPJC (2017) 77: 812

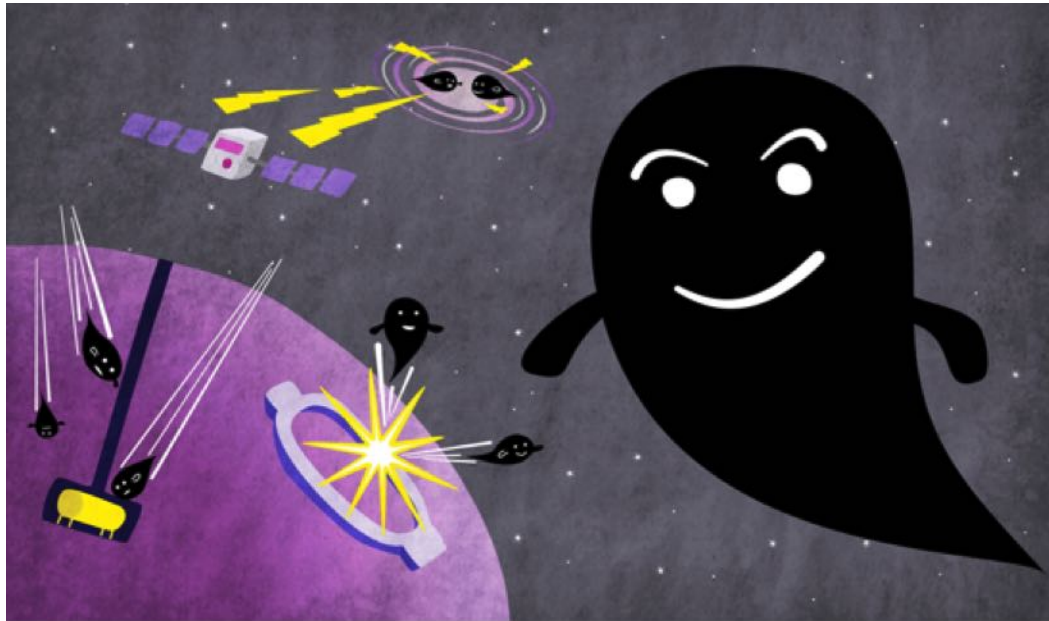


For $m_\pi=50\text{ GeV}$, exclude BR>30% for $\tau=[5-50]\text{ ps}$ ($c\tau=[1.5,15]\text{mm}$)



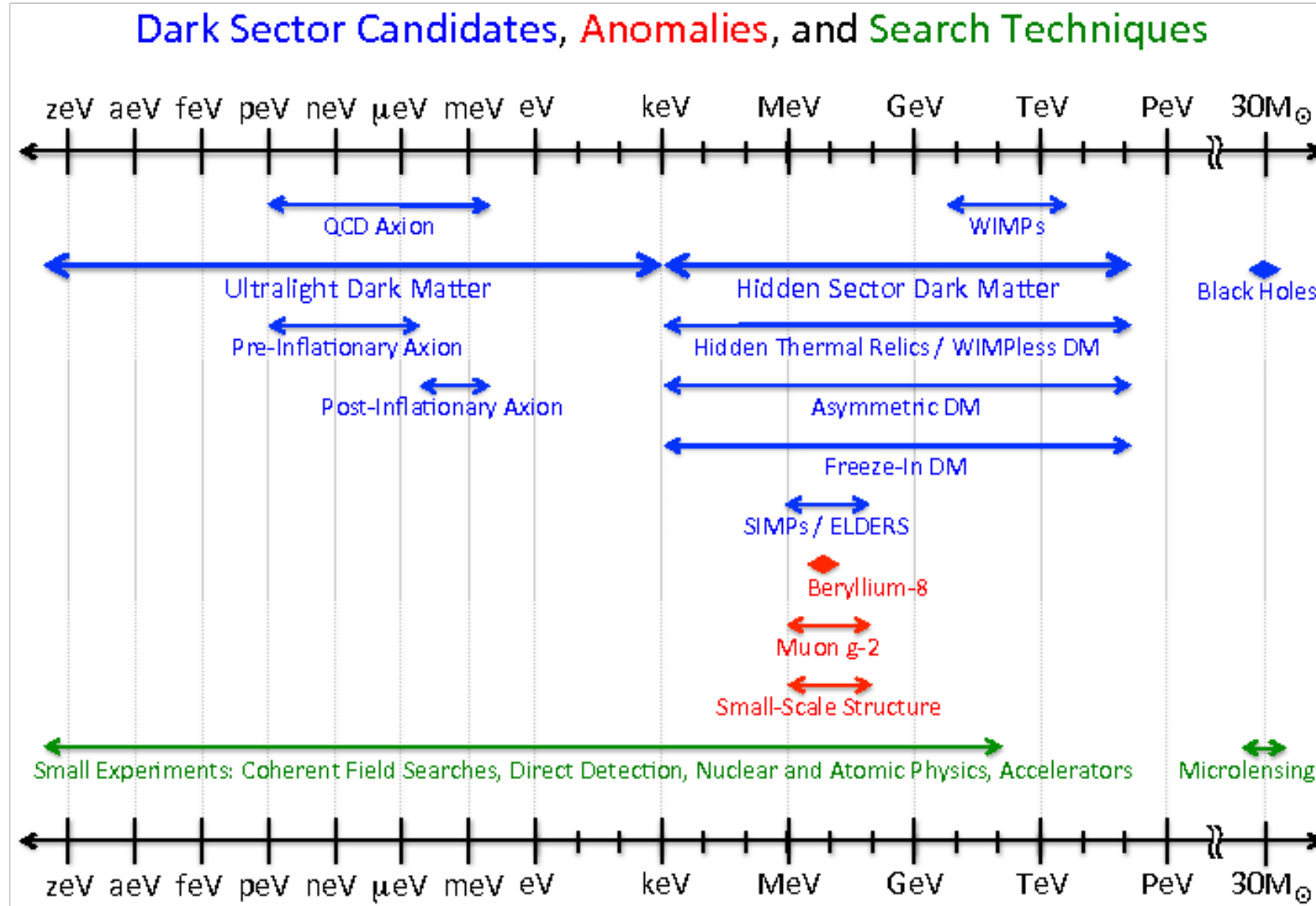
Summary

- Search for dark matter have been performed intensively at LHC
 - Invisible DM production, DM-SM mediator searches, long-lived particle, dark photon
- LHC's sensitivity is more on the low mass dark matter
 - Excludes SI $\times \text{sec } 10^{-42}\text{-}10^{-43}\text{cm}^2$ and SD $\times \text{sec } 10^{-43}\text{-}10^{-44}\text{cm}^2$ with couplings $g_q=0.25, g_l=0, g_{DM}=1.0$
- Stay tuned!



Thank You!

Dark Matter Candidates



arXiv:1707.04591

Constraints on DM and Mediator

- DM mass – mediator mass plane excluded at 95% CL.
- For Axial-vector mediator, $g_q=0.25, g_l=0, g_{DM}=1.0$

