Mono-X, dijet, and long-lived particle searches at the LHC

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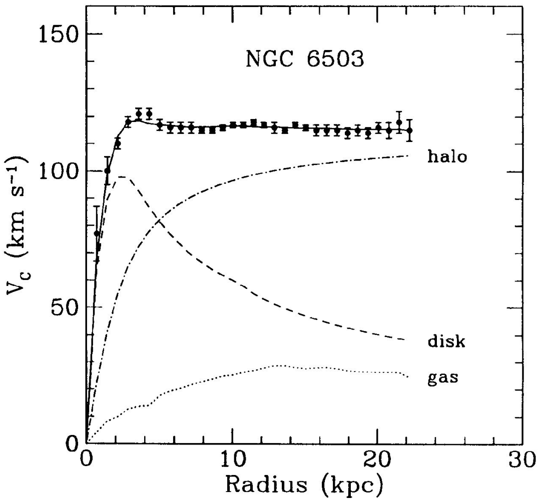
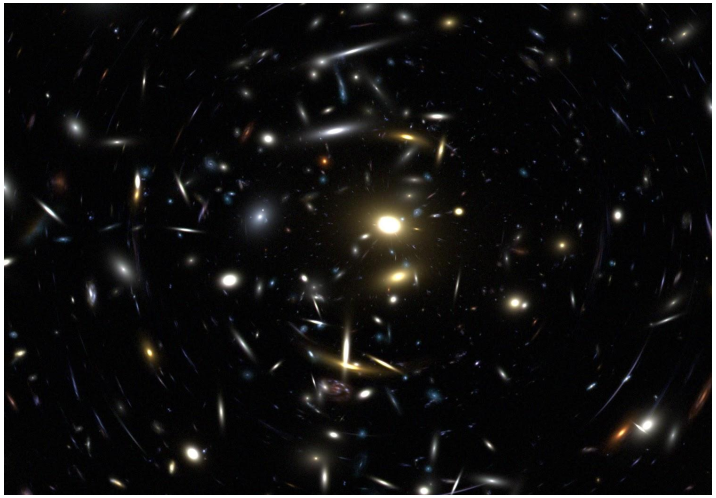
On behalf of the ATLAS and CMS Collaborations

13th International Symposium on Cosmology and Particle Astrophysics
Sydney, Australia
Nov. 28 - Dec. 2 2016

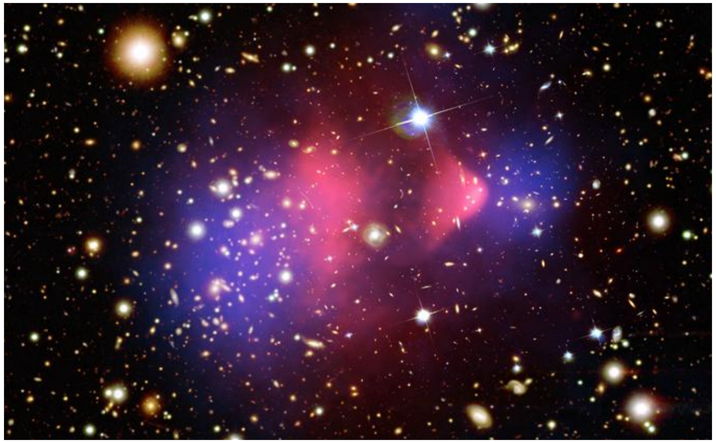
Observational Evidence of Dark Matter



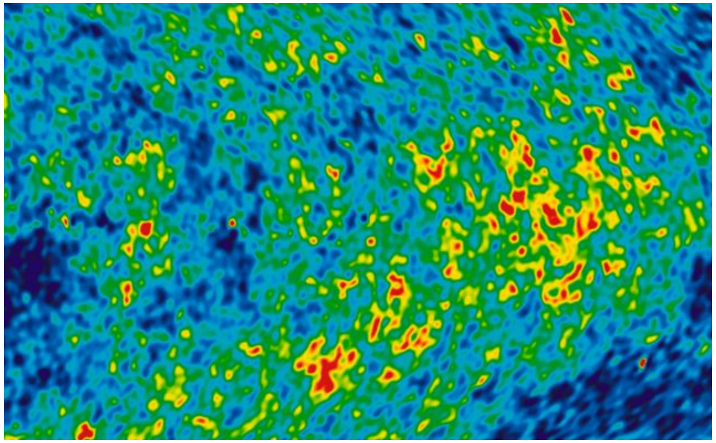
Galaxy rotation curves



Gravitational lensing



Cluster mergers



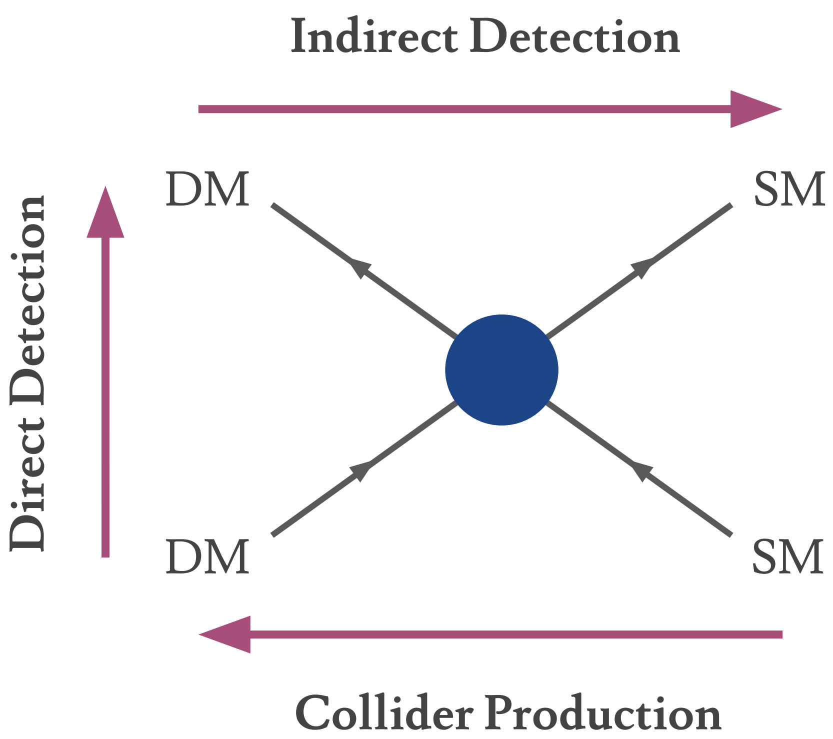
CMB

And much more!

Dark Matter Detection

Experimental evidence motivates a DM sector composed dominantly of Weakly Interacting Massive Particles (WIMPs)

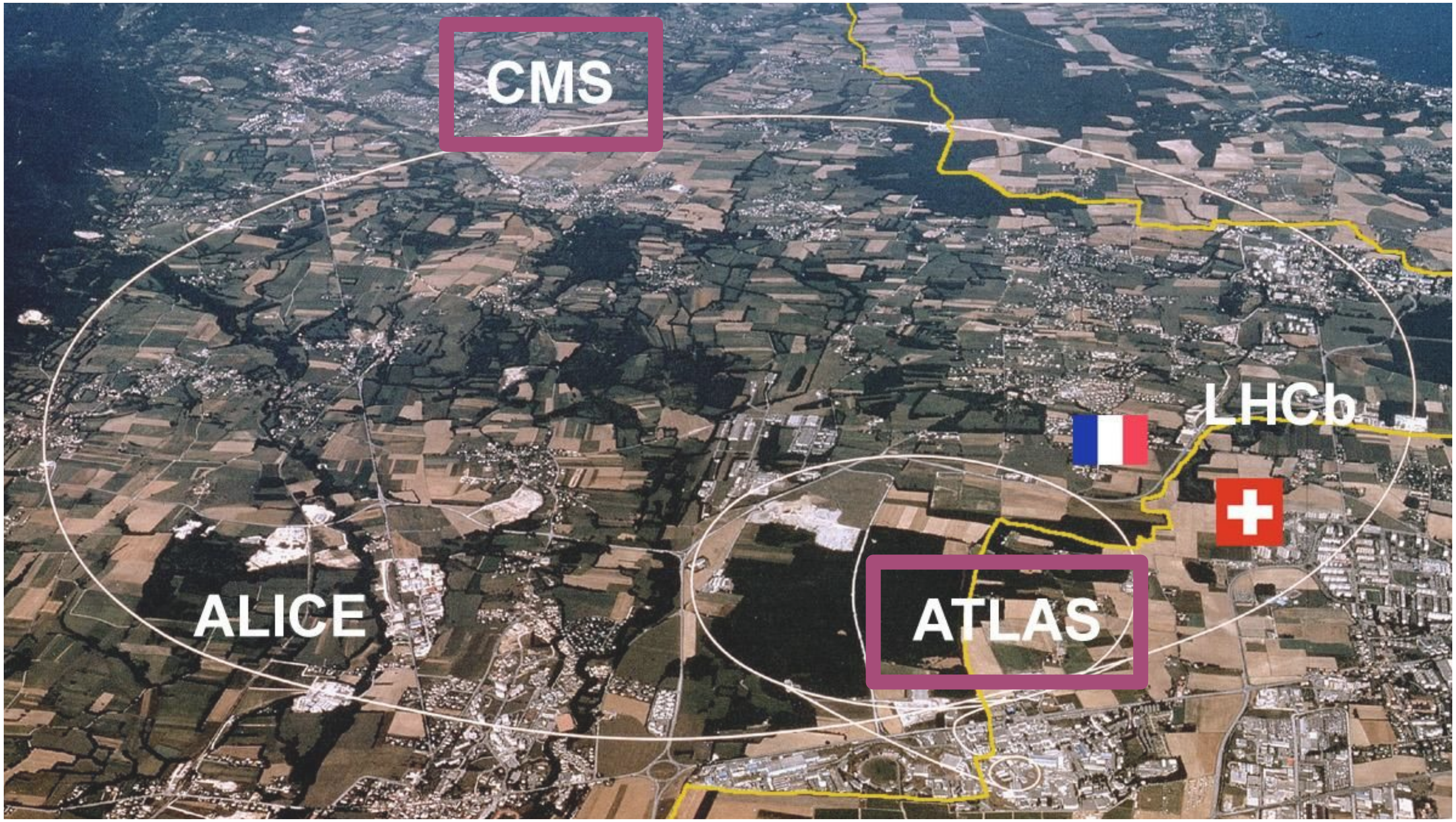
➔ Facilitate comparison of results in the three main DM detection avenues



The Large Hadron Collider (LHC)

A proton-proton and heavy ion collider in Geneva, Switzerland

➔ Four collision points, two of which are housed within general-purpose detectors; **ATLAS** (A Toroidal LHC ApparatuS) and **CMS** (Compact Muon Solenoid)

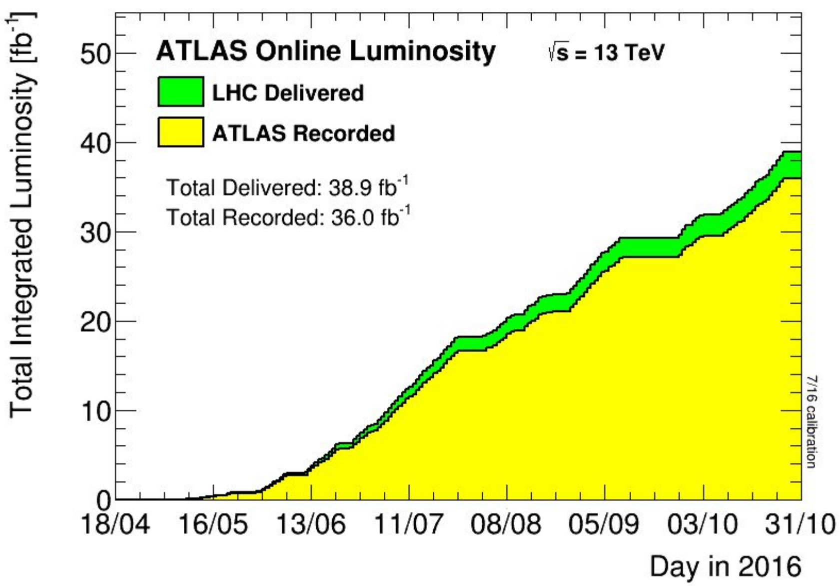


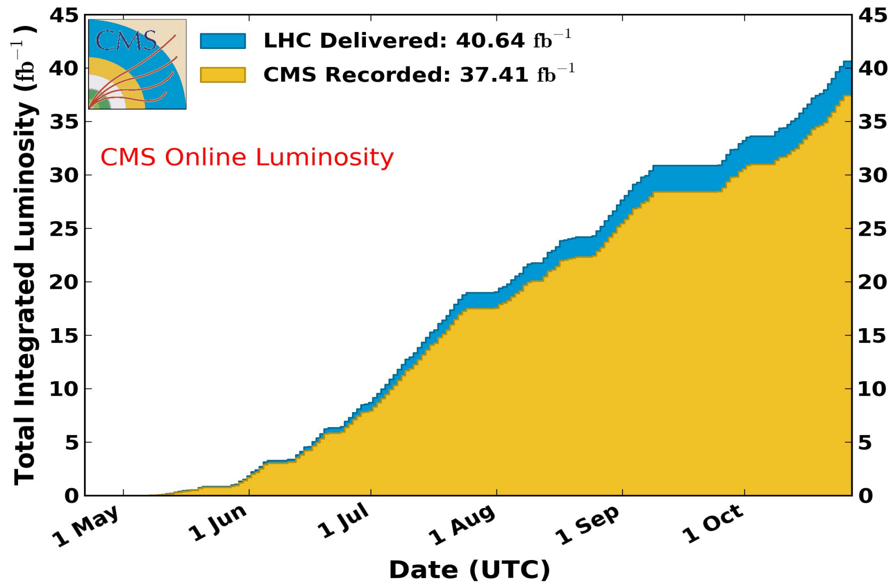
The Large Hadron Collider (LHC)

Dedicated proton-proton collision schedule

➔ From 2010 to 2012 (Run-I), collected ~25 fb^{-1} of data at a centre-of-mass energy ($\sqrt{s}$) of 7 and 8 TeV

➔ In 2015 and 2016, moved to $\sqrt{s}$ = 13 TeV (Run-II) → ~36 fb^{-1} (ATLAS) and ~37 fb^{-1} (CMS) of recorded data

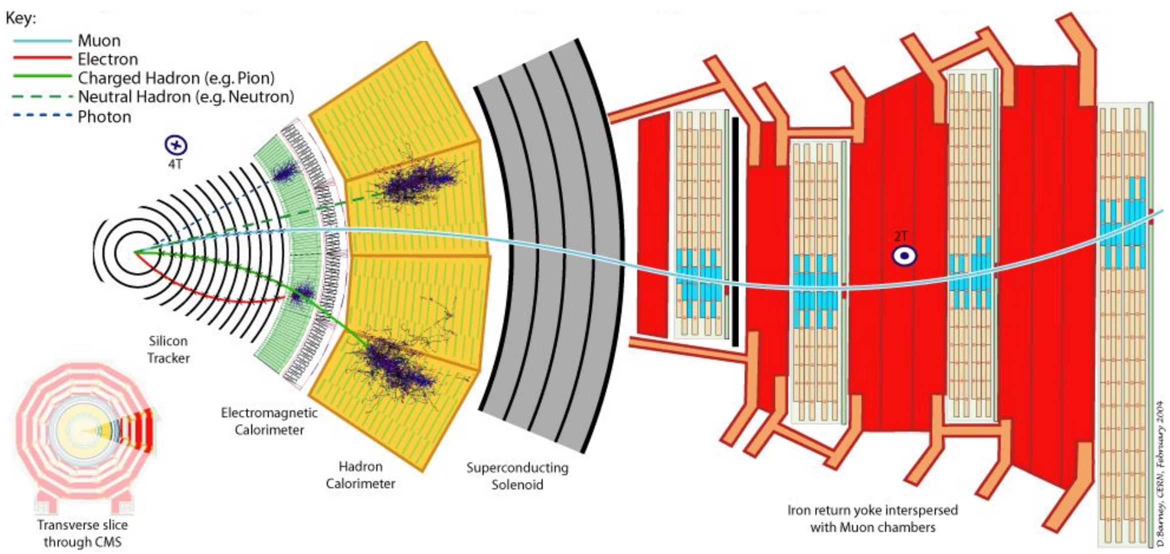




The ATLAS and CMS Experiments

ATLAS and CMS aim to detect a wide range of possible New Physics signals

- ➔ Particles reconstructed with information from detector sub-components
- ➔ Efficient identification of particle type, energy, and momentum



- ➔ Invisible particles escape detection but present as a momentum imbalance in the transverse plane; Missing Transverse Energy, $E_{\mathrm{T}}^{\mathrm{miss}}$

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

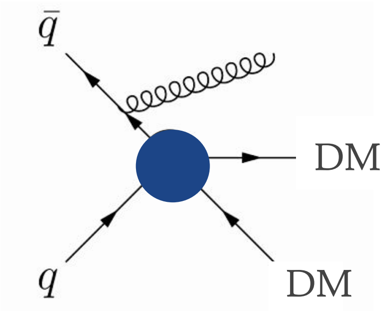
$$\phi^{\mathrm{miss}} = \arctan(E_x^{\mathrm{miss}}, E_y^{\mathrm{miss}})$$

Dark Matter Collider Detection Channels

Mono-X Signal

WIMP DM doesn't interact with detector
➔ Require a SM particle, X, in the FS

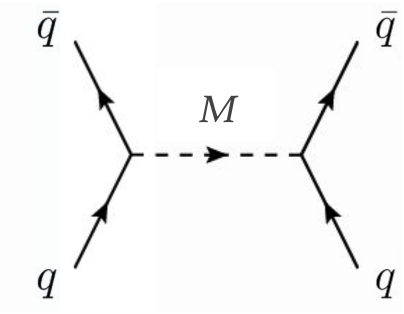
Search strategy: look for jet(s), W/Z/Higgs, or γ plus large E_T^{miss}



Di-jet Signal

DM produced via decay of a new heavy resonance
➔ SM coupling permits decay to light qq pair
➔ Decays to tt, WW, ZZ also permitted (di-X signal)

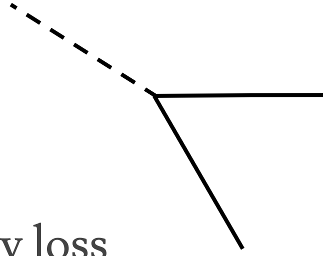
Search strategy: look for bumps in m_{jj} distribution



Long-lived Particle Signal

Heavy mediator with small couplings to SM/DM particles
➔ Mediator lifetime O(ns) → displaced decay

Search strategy: look for displaced jets/vertices, large ionisation energy loss



Theoretical interpretation of results

Run-I searches interpreted with **Effective Field Theories (EFTs)**

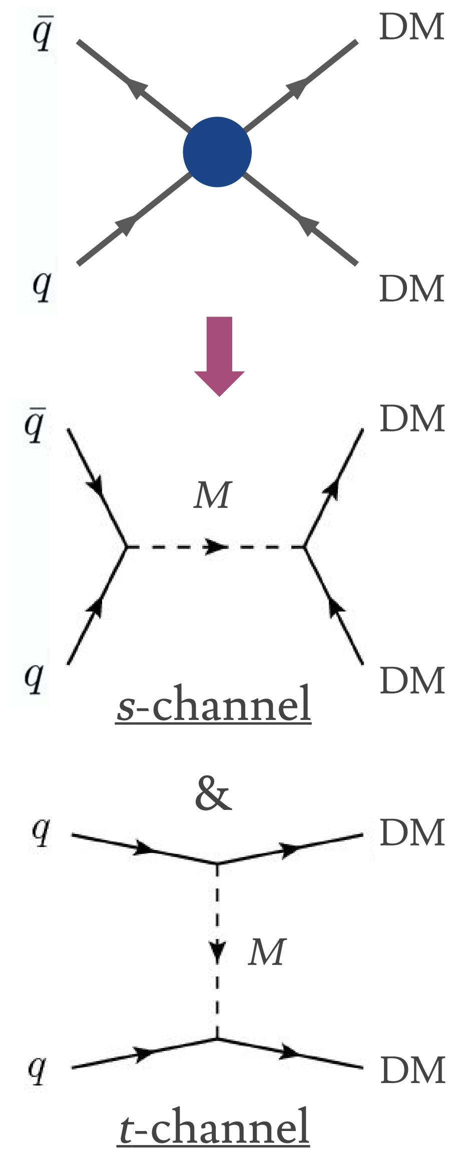
- ➔ Free parameters: m_{DM}, and $M_* = M/\sqrt{(g_q q_\chi)}$
- ➔ Valid when M >> Q
- ➔ Heavily restricted range of validity at the LHC

Run-II searches focus on **Simplified Models of DM (SiMs)**

- ➔ Five parameters: M, Γ, m_{DM}, g_q and q_χ
- ➔ Benchmark set of SiMs/parameters agreed upon at joint theory-experimental **LHC DM Forum**
- ➔ Results presented in a universal manner
- ➔ arXiv: 1507.00966, arXiv:1603.04156

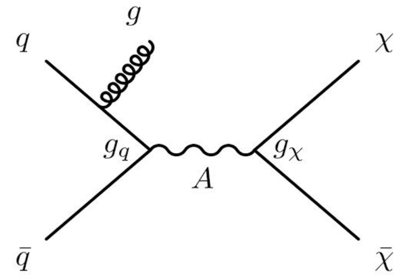
This talk will focus on SiM and EFT interpretations of the most recent Run II DM searches

- ➔ SUSY and BSM/Invisible Higgs searches covered in next talk



Mono-X Searches

Mono-jet channel most sensitive to DM production at the LHC



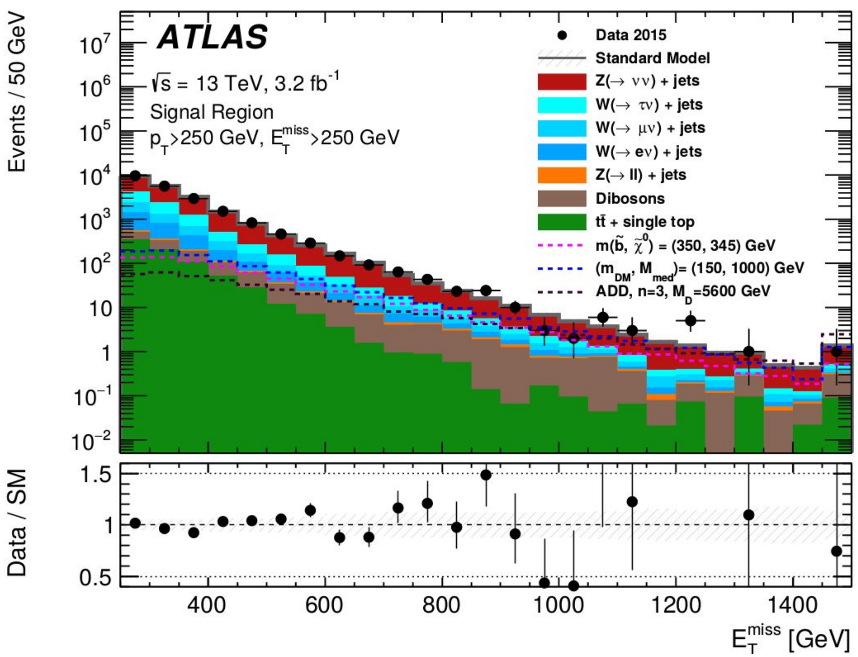
Selection: At least one high-p_T jet and large E_T^{miss}

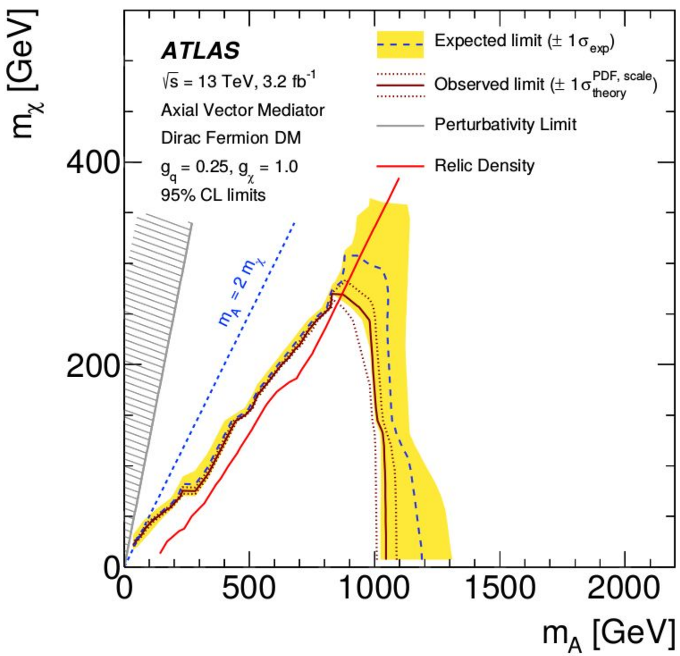
➔ Jet clustered with anti-k_T algorithm with R = 0.4

Dominant Background: $Z(\rightarrow \nu\nu)$ + jets

➔ contribution normalised in control regions for several E_T^{miss} bins, using a global fit

Model(s): Leptophobic Z' mediator with axial-vector couplings





Phys. Rev. D 94, 032005 (2016)

ATLAS Mono-W/Z (hadronic) Analysis

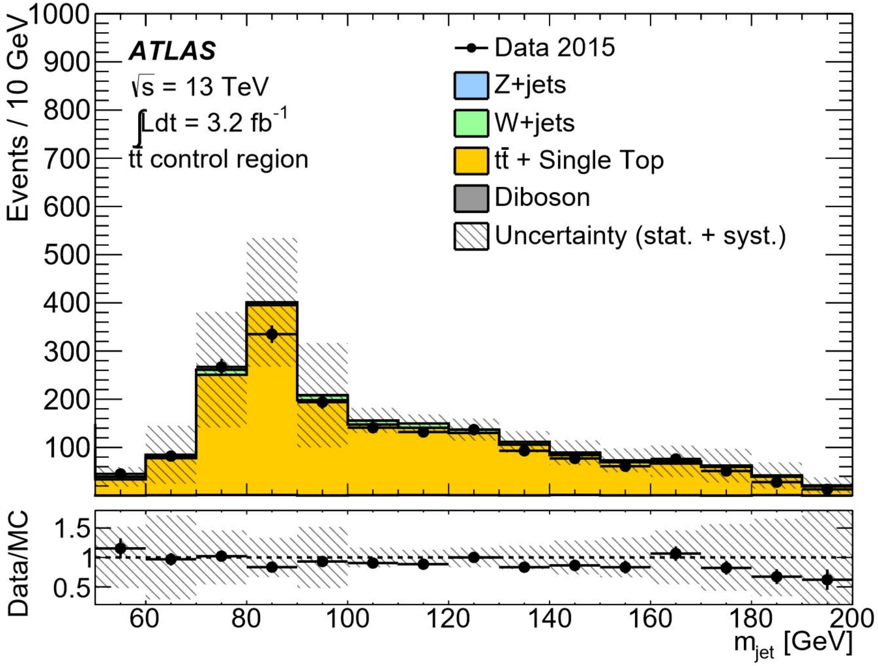
Selection: At least one large-radius jet plus large E_T^{miss}

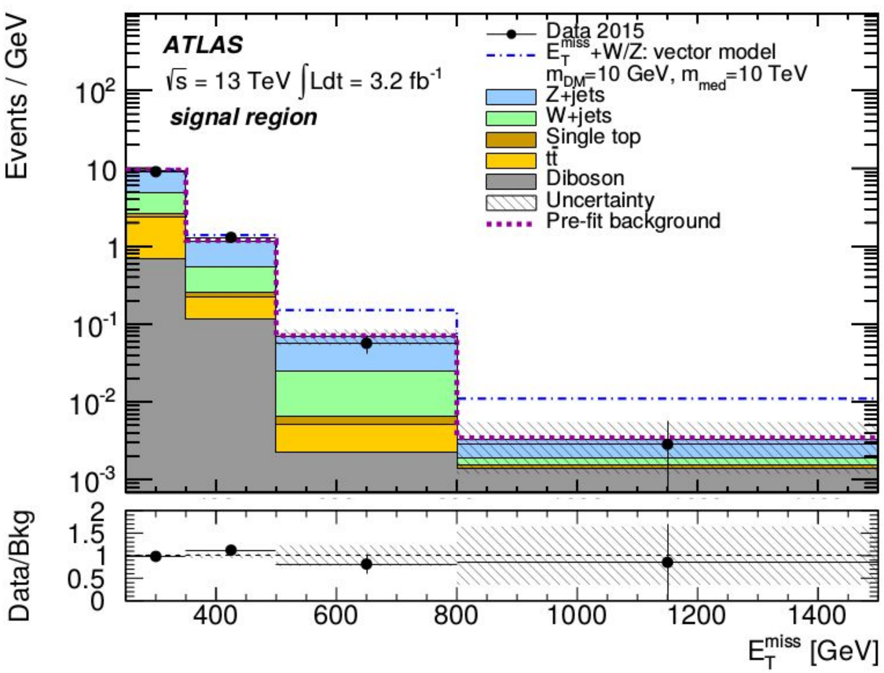
➔ Hadronic decay of Lorentz-boosted W/Z boson yields merged 'wide radius' jet

➔ Jet reconstructed with anti-k_T algorithm with R = 0.8

➔ Distinguish W/Z jets by exploiting jet mass and substructure variables

Dominant Background: W/Z + jets





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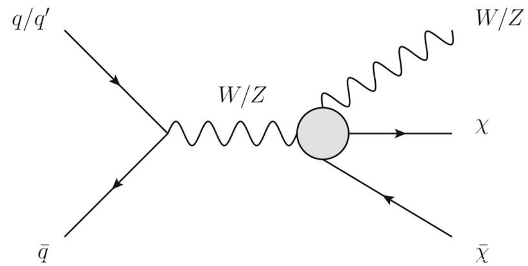
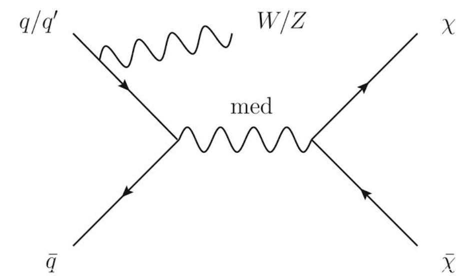
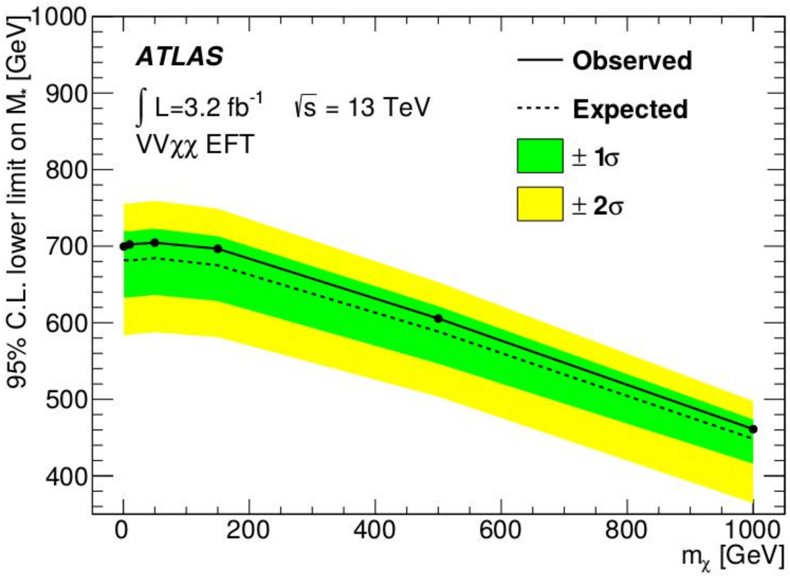
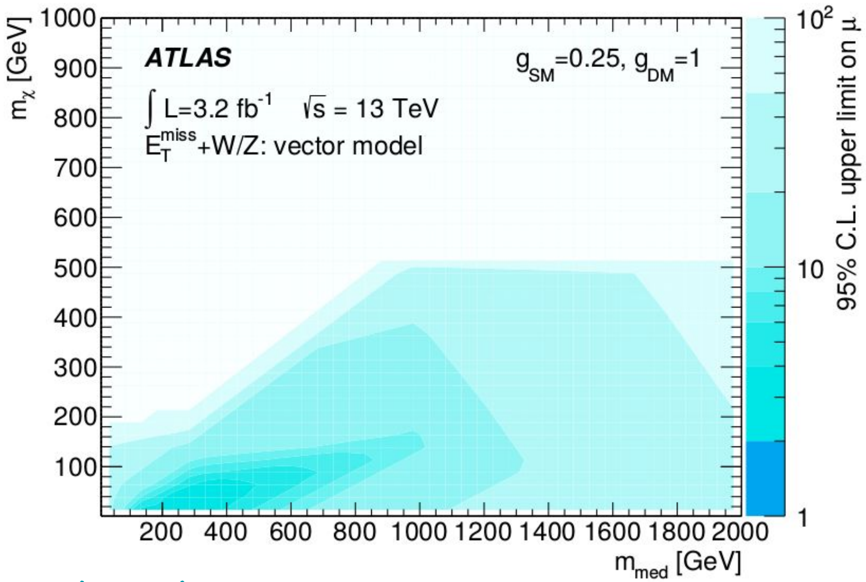
Model(s)

1. EFT ZZχχ model: limit on suppression scale, M_*, with respect to m_{DM}
2. Vector-mediator simplified model: limit on signal strength, μ, in m_{DM}-M plane







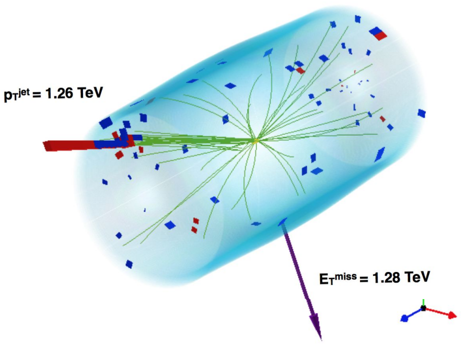


[Phys. Lett. B 763 (2016) 251]

CMS Mono-Jet and Mono-W/Z (hadronic) Analysis

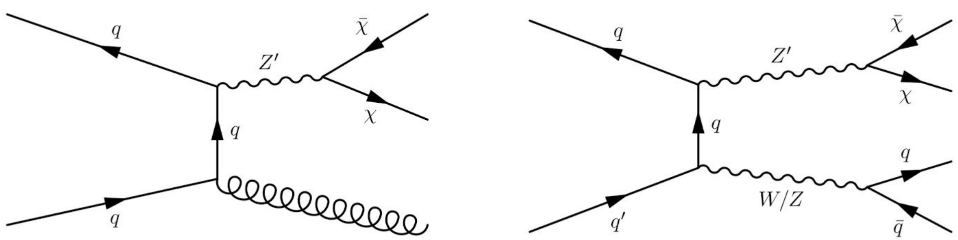
Selection: At least one high p_T R=0.4 jet or one R=0.8 jet from boosted W/Z boson decay plus large E_T^{miss}

➔ Again identify W/Z jets using jet mass and substructure

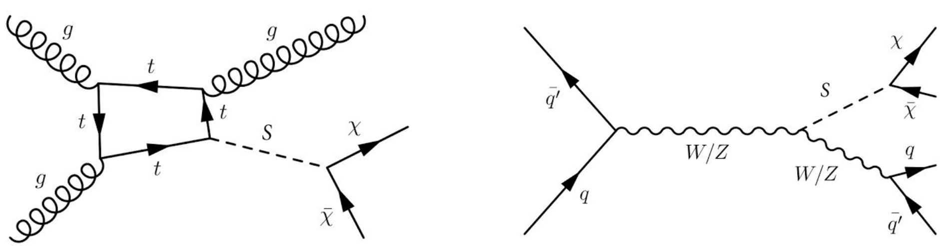


Dominant backgrounds: Z(→νν) + jets, W(→lν) + jets

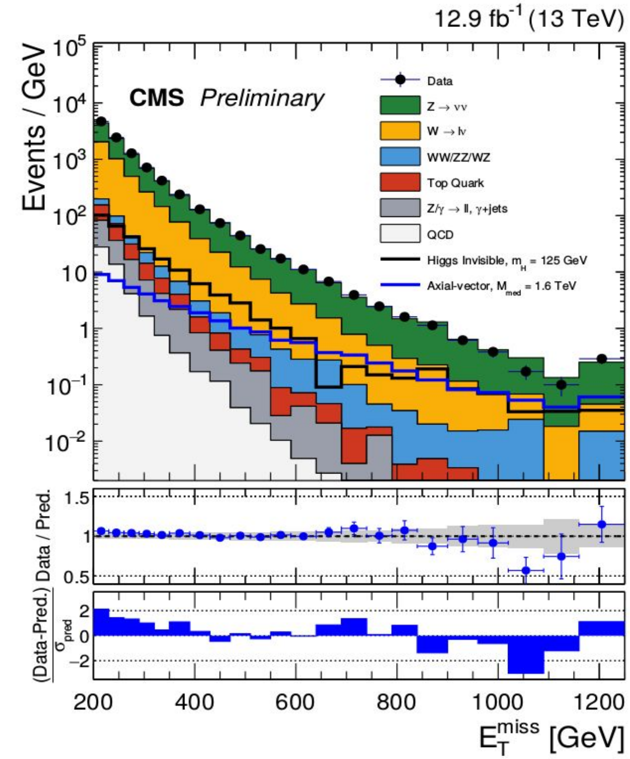
Model(s): Heavy spin-0 and spin-1 mediators coupling to quarks and Dirac fermion DM



Spin-1 mediator

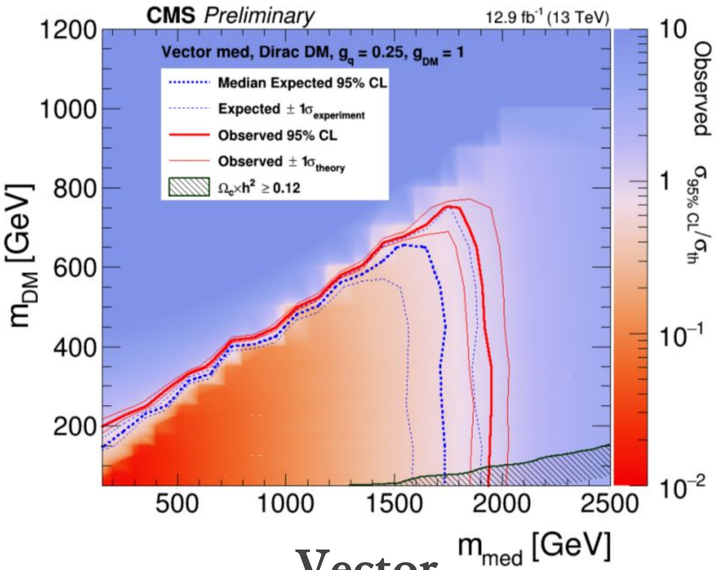


Spin-0 mediator

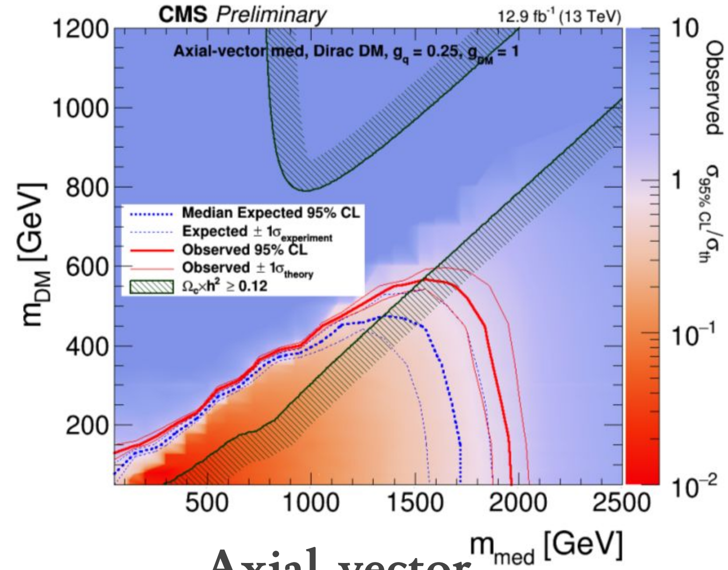


CMS PAS EXO-16-037

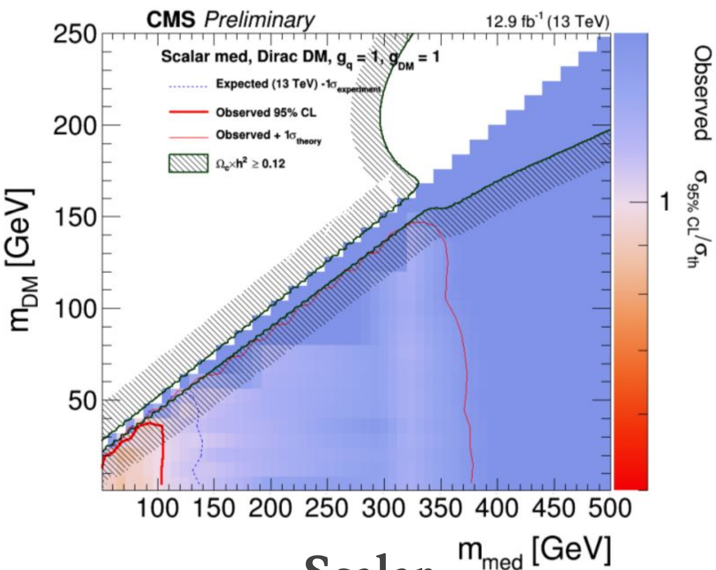
CMS Mono-Jet and Mono-W/Z (hadronic) Analysis



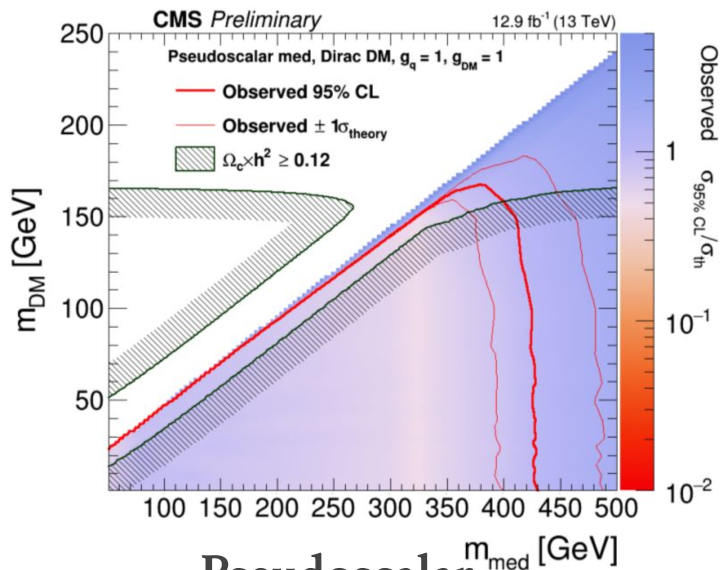
Vector



Axial-vector



Scalar

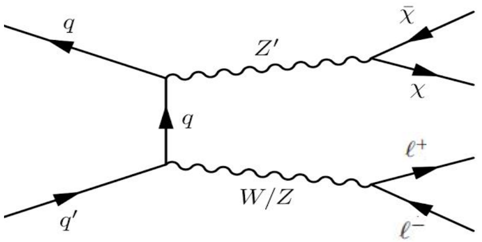


Pseudoscalar

CMS PAS EXO-16-037

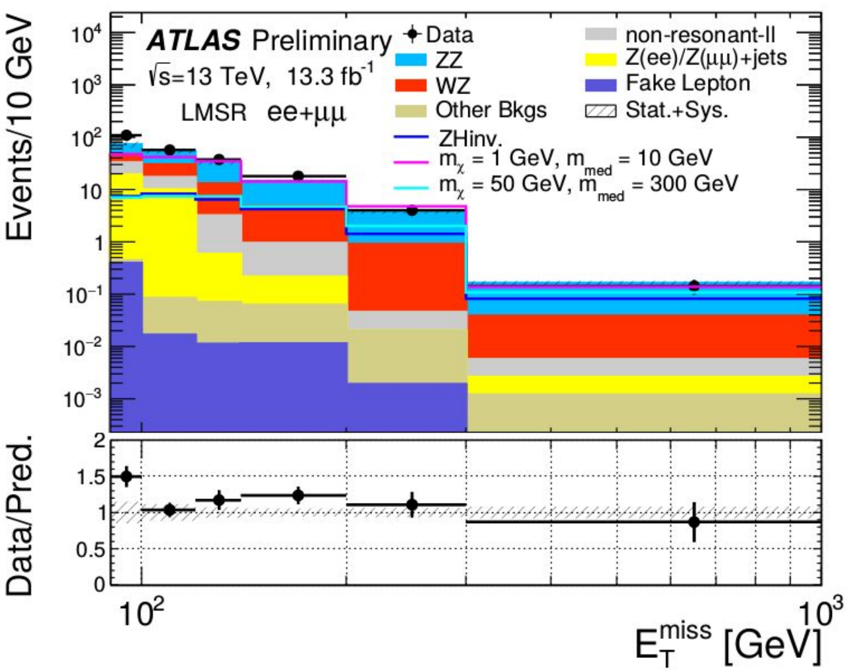
ATLAS & CMS Mono-Z (leptonic) Analyses

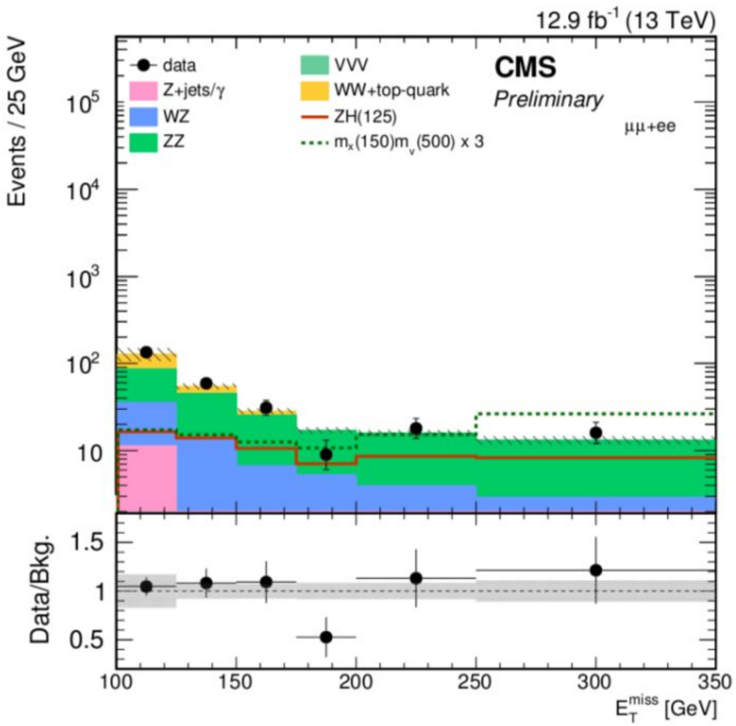
Selection: Two opposite-charge same-flavor leptons (e or μ) with m_T close to the Z mass, plus large E_T^{miss}



Dominant backgrounds: Z(→νν)Z(→ll) and WZ

Model(s): Heavy mediator with vector couplings. CMS also includes a SiM with axial-vector couplings

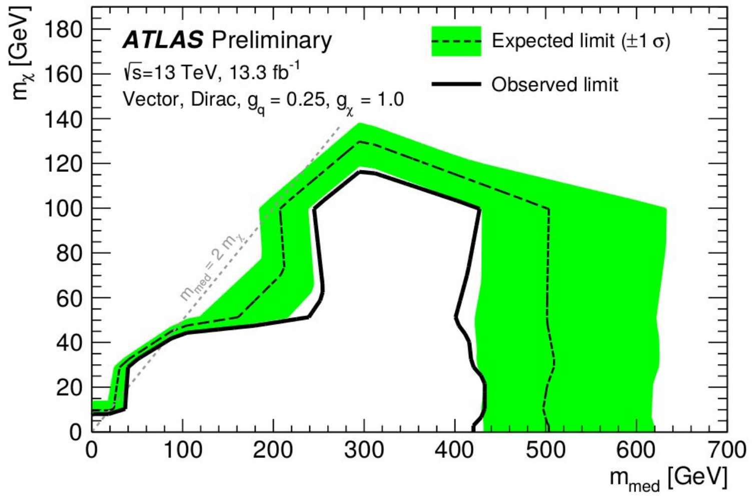




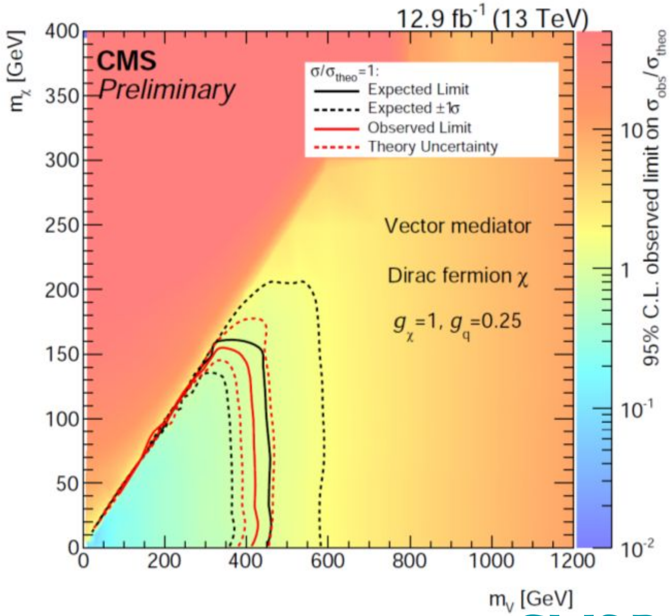
ATLAS-CONF-2016-056

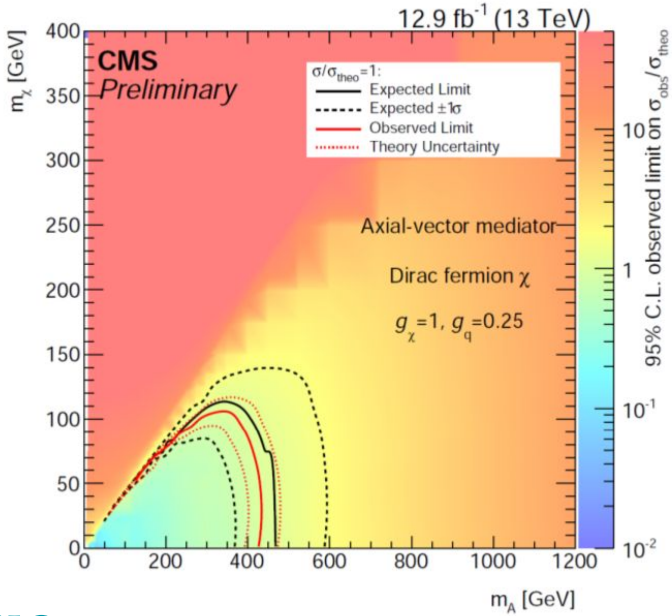
CMS PAS EXO-16-038

ATLAS & CMS Mono-Z (leptonic) Analyses



ATLAS-CONF-2016-056





CMS PAS EXO-16-038

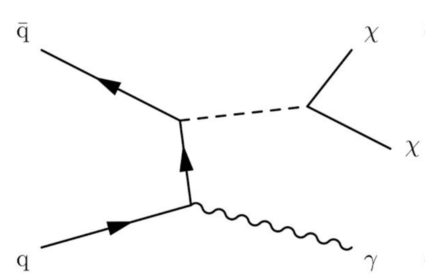
ATLAS & CMS Mono-γ Analyses

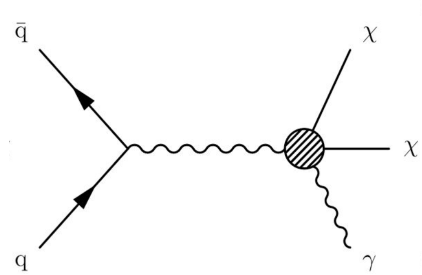
Selection: At least one high p_T isolated γ plus large E_T^{miss}

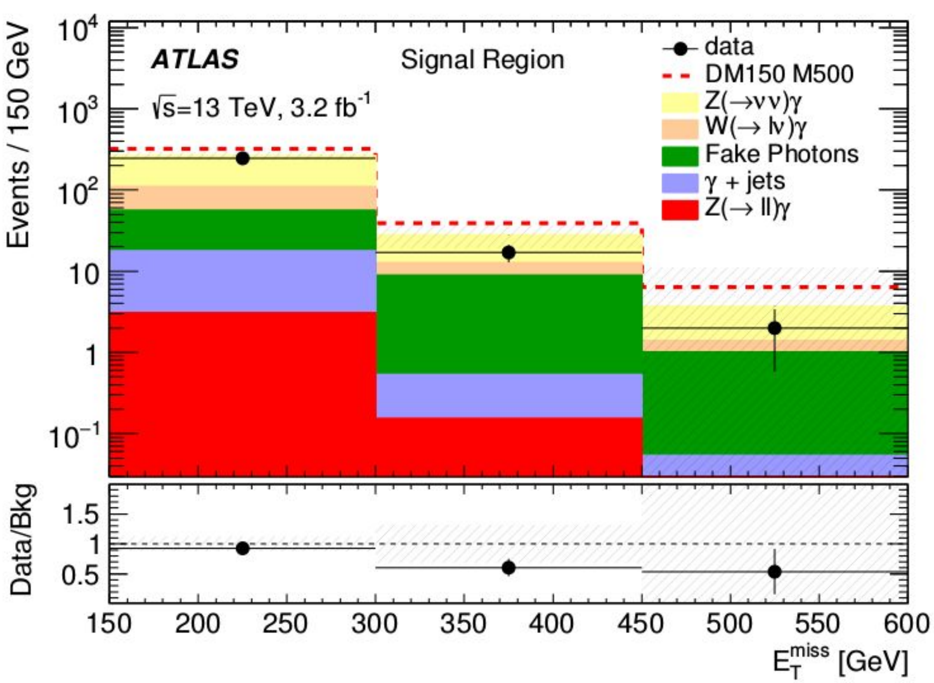
➔ Low cross-section but clean signal

Dominant background: $Z(\rightarrow \nu\nu) + \gamma$

Model(s): SiMs and an EFT γγχχ model







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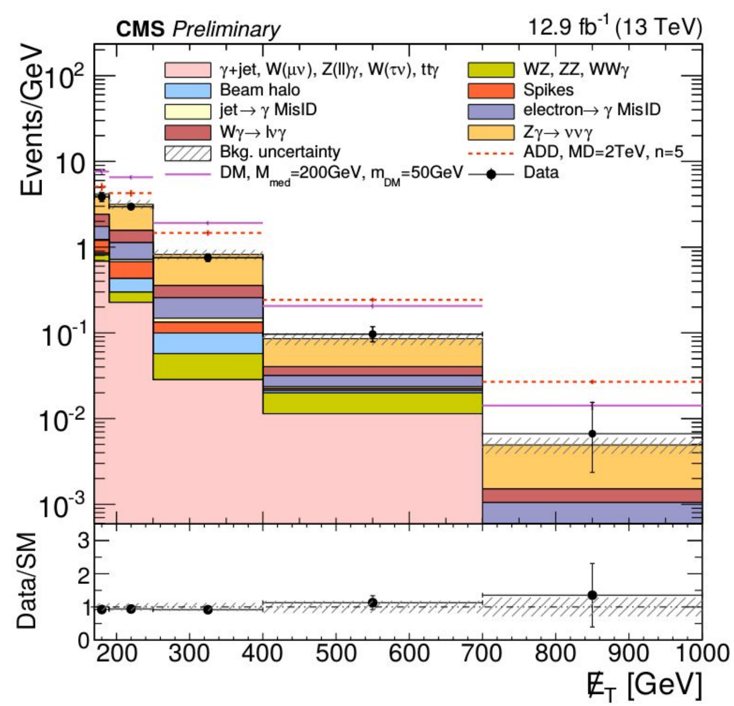
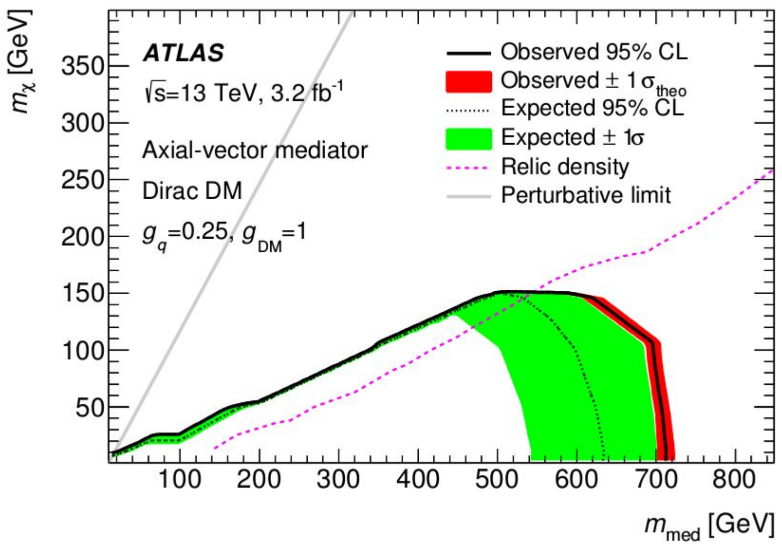
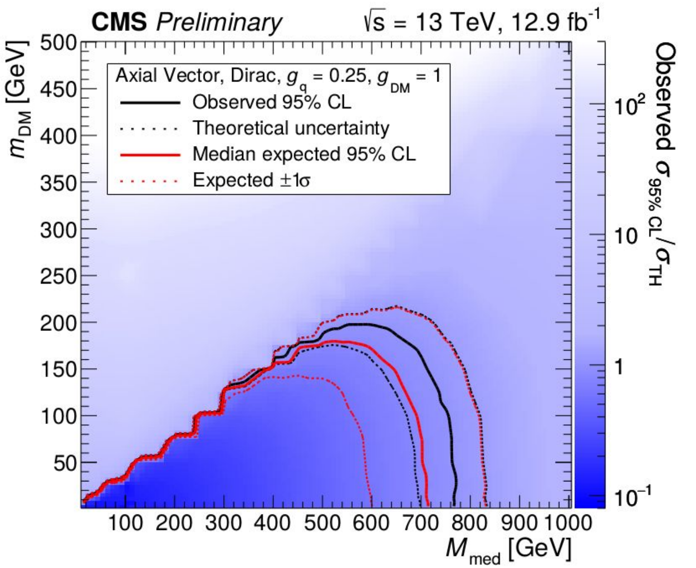
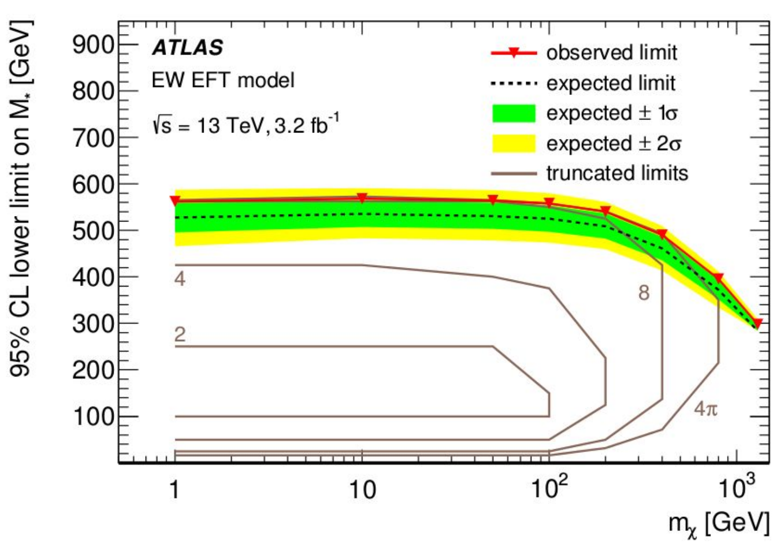


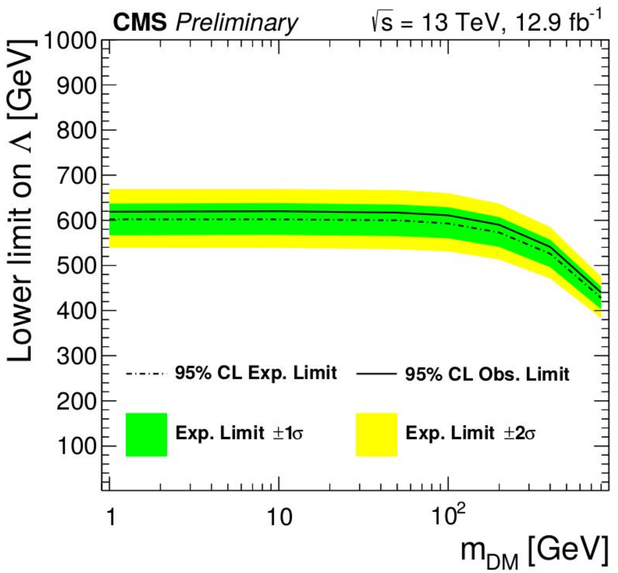
CMS PAS EXO-16-039

ATLAS & CMS Mono-γ Analyses









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CMS PAS EXO-16-039

ATLAS & CMS Mono-Higgs(→bb) Analyses

Higgs boson ISR highly suppressed → mono-Higgs signal provides direct probe of DM-SM coupling

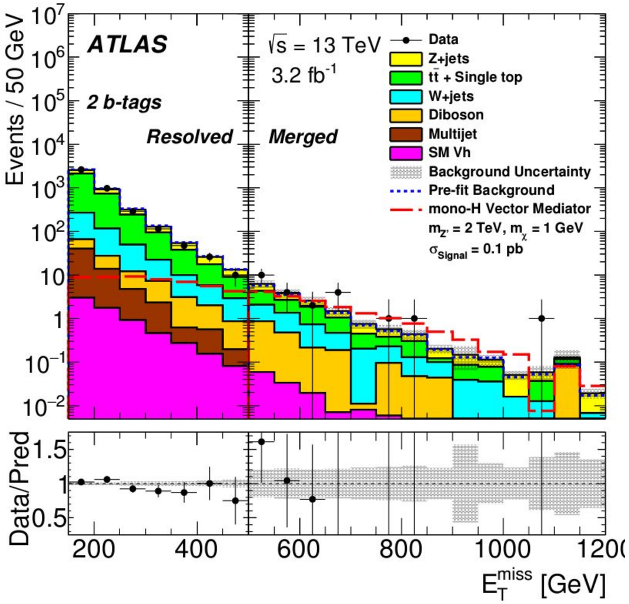
➔ h → bb dominant decay mode

Selection: resolved/merged b-jets plus large $E_{\mathrm{T}}^{\mathrm{miss}}$

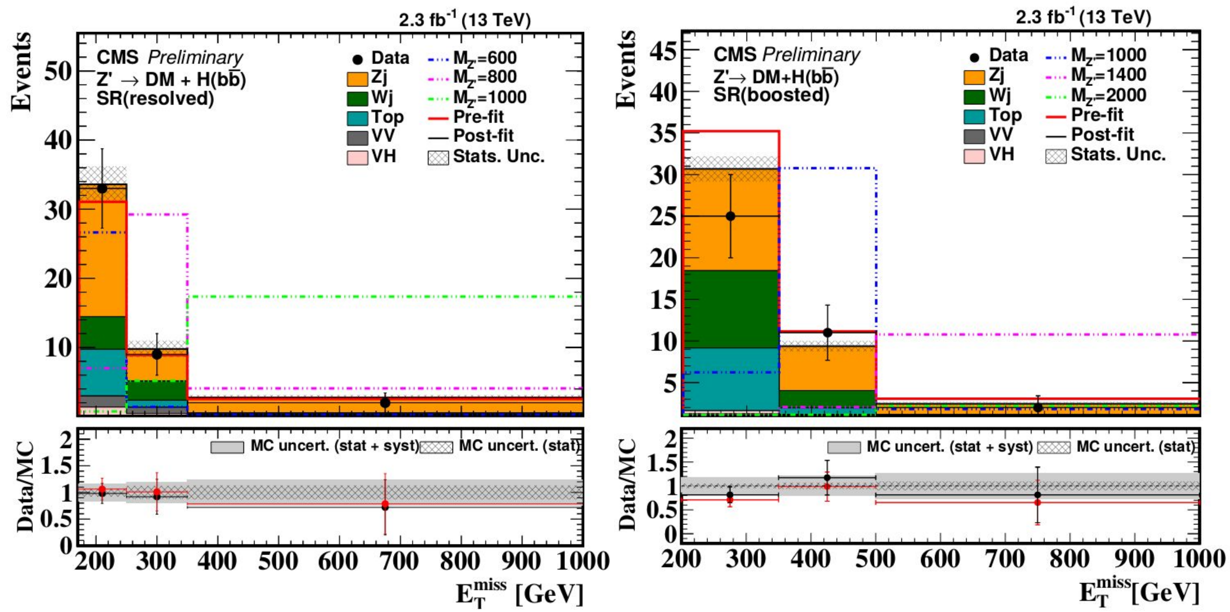
➔ Jet selection dependent on $E_{\mathrm{T}}^{\mathrm{miss}}$

Dominant background: W/Z + jets

> Search for mono-Higgs(→γγ) in ATLAS-CONF-2016-087 and CMS PAS EXO-16-011, and mono-Higgs(→4l) in ATLAS-CONF-2015-059

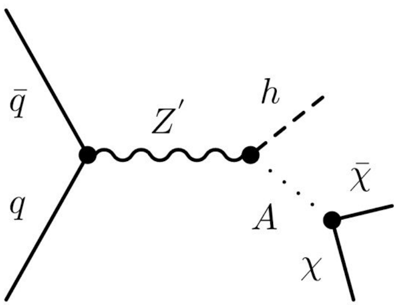


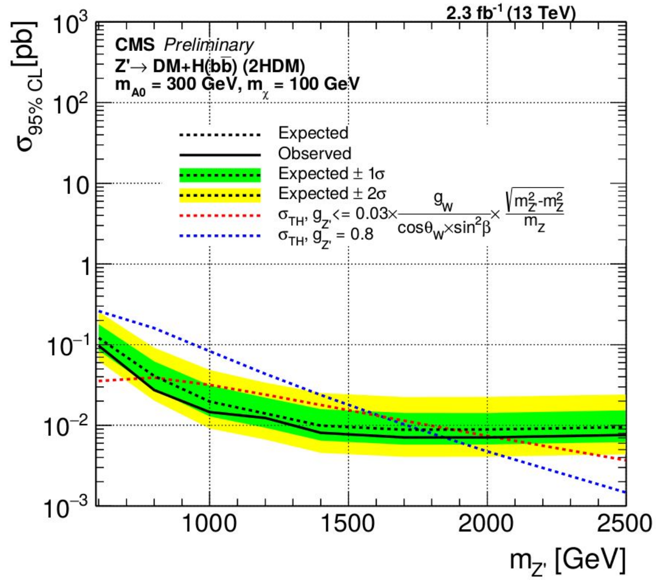
arXiv:1609.04572

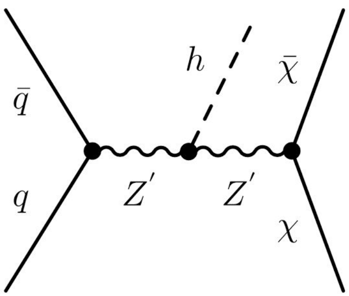


CMS PAS EXO-16-012

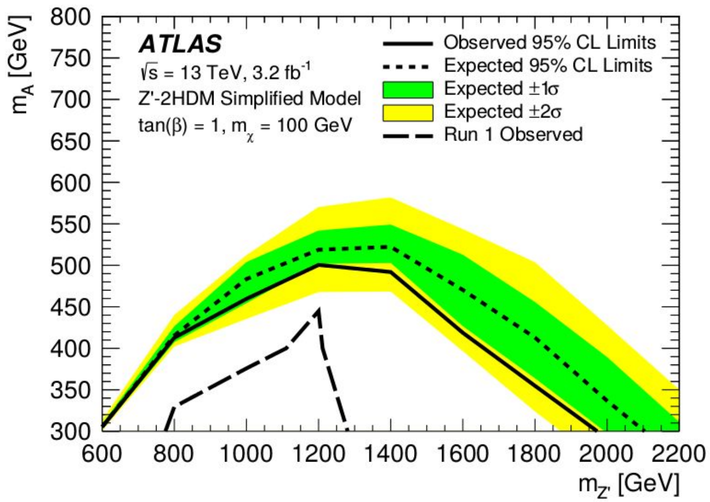
Model(s)
Z' leptophobic models

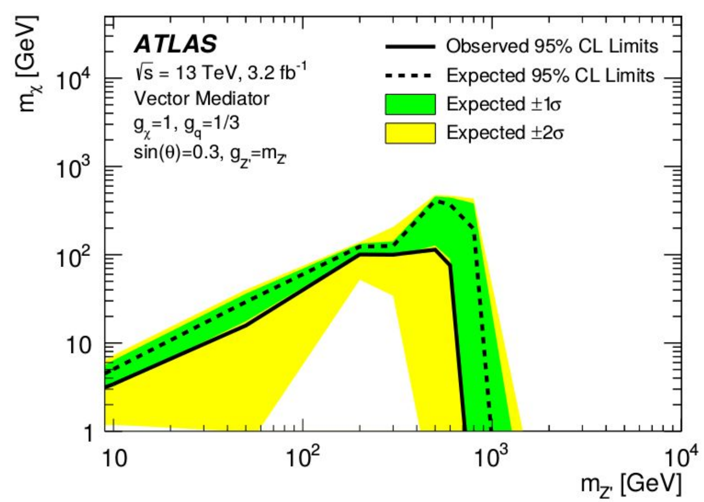






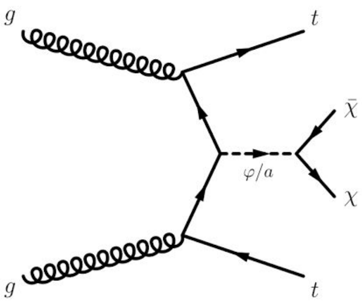
[CMS PAS EXO-16-012]





[arXiv:1609.04572]

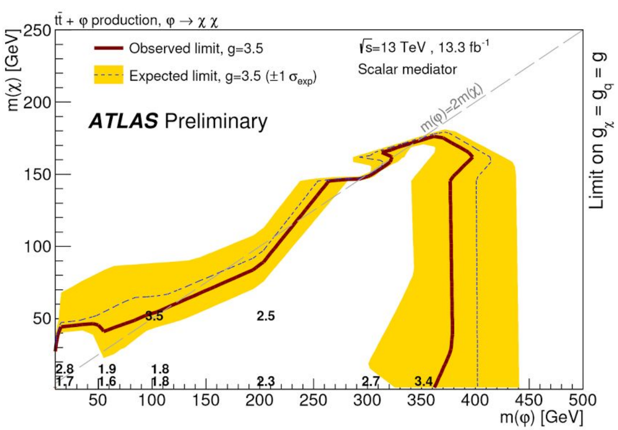
Search for DM produced in association with top quarks
- ➔ Complement to mono-X analyses
- ➔ Most sensitive channel for spin-0 mediators



Selection: Large $E_{\mathrm{T}}^{\mathrm{miss}}$, cuts optimised for separate top quark decay modes

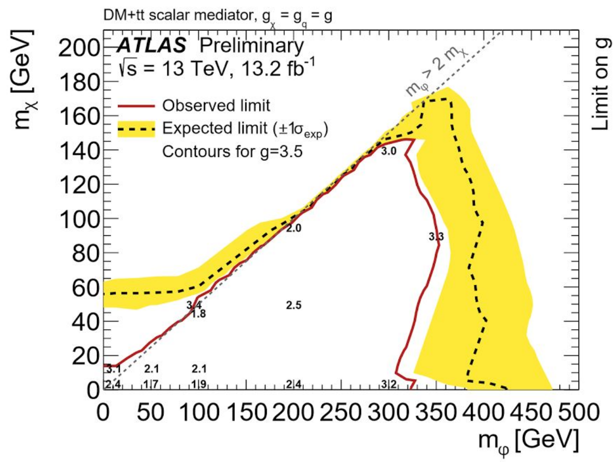
Model(s): SiMs with scalar and pseudoscalar mediators

Fully hadronic (0 leptons)



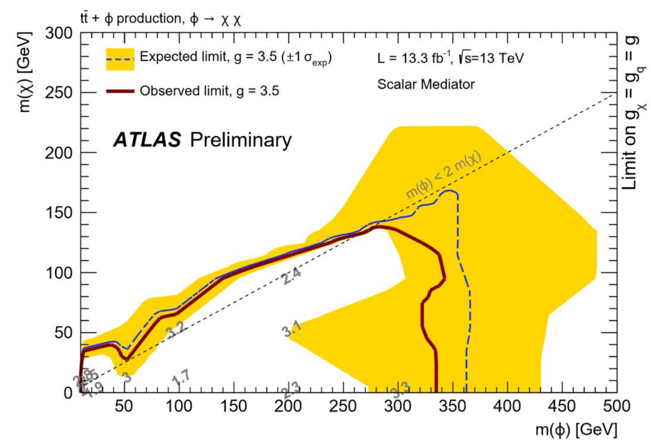
ATLAS-CONF-2016-077

Semi-leptonic (1 lepton + jets)



ATLAS-CONF-2016-050

Fully leptonic (2 leptons + jets)



ATLAS-CONF-2016-076

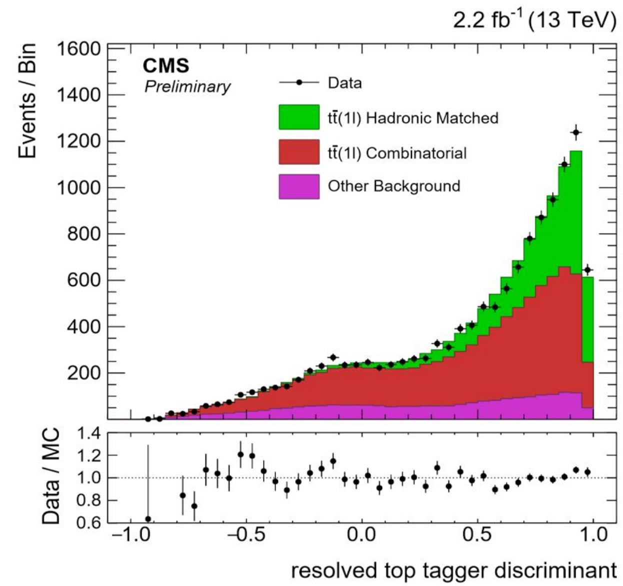
Associate production of bottom quarks also studied in ATLAS-CONF-2016-086

CMS DM Plus Top Quarks Analyses

Selection: Optimised for top decay mode

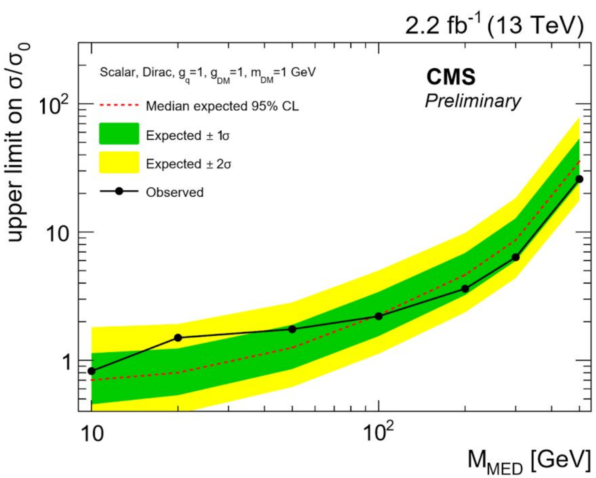
➔ Fully hadronic decays categorised by number of top-tags

Dominant Backgrounds: SM top pairs

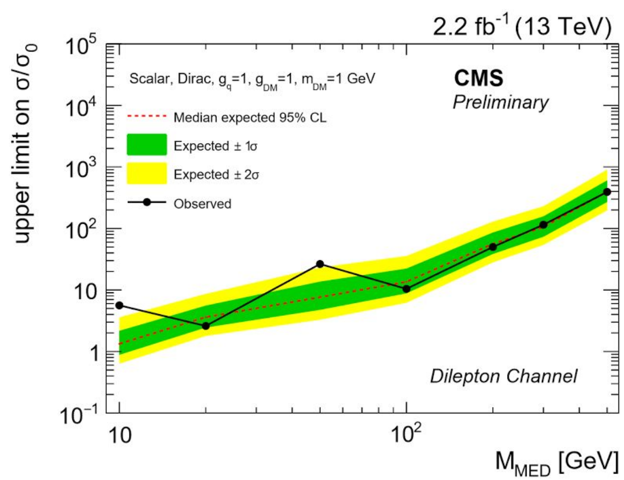


> Associate production with bottom quarks studied in CMS-PAS-B2G-15-007. Mono-top production studied in CMS PAS EXO-16-040

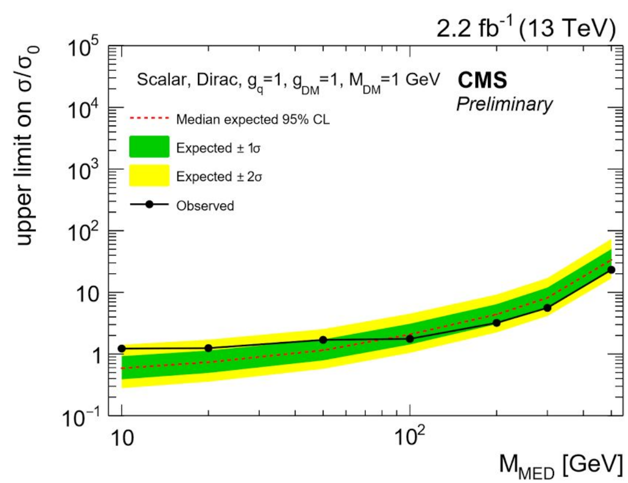
Semi-leptonic + hadronic



Fully leptonic



Combined



CMS-PAS-EXO-16-005

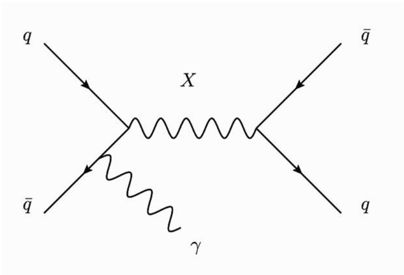
CMS-PAS-EXO-16-028

Dijet Searches

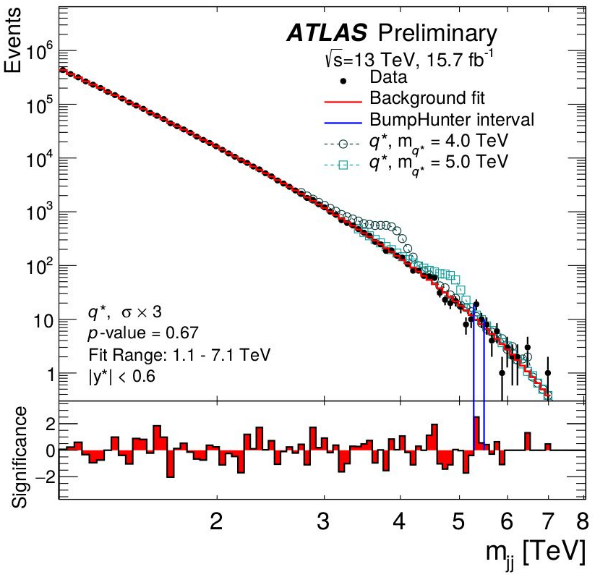
Model(s): Z' leptophobic Z' models assuming negligible branching to DM

Selection: Two jets with |y*| < 0.3, |y*| < 0.6 or |y*| < 0.8

Jet p_T determines m_{jj} which can be probed
➔ different searches covering different mass ranges

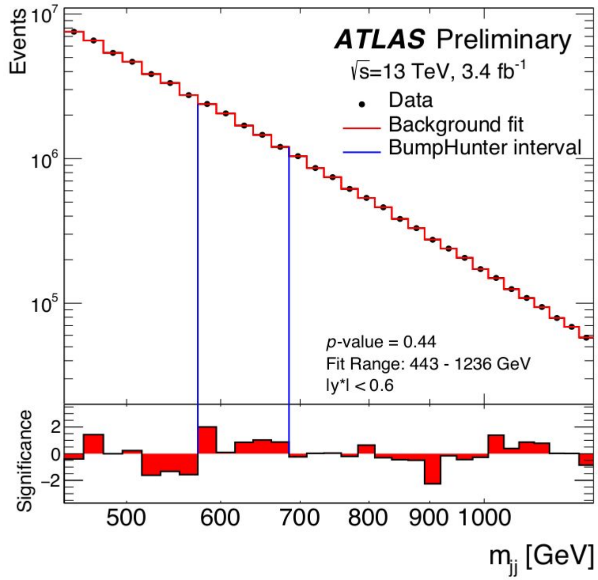


Range: m_{jj} > 1.5 TeV



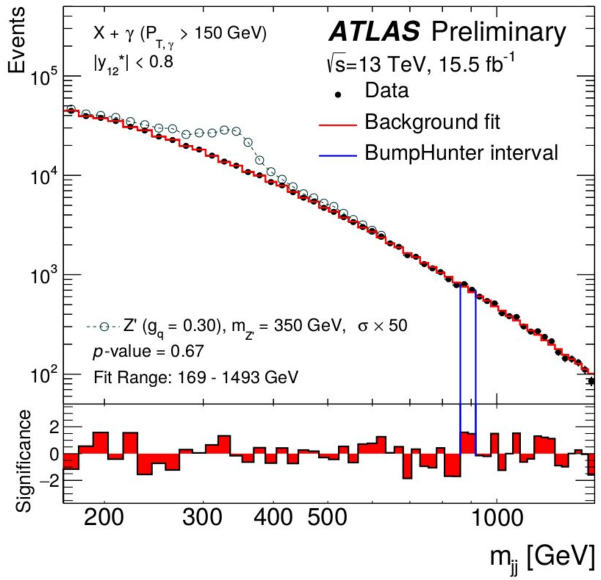
ATLAS-CONF-2016-069

Trigger-Level Analysis for sub-TeV masses



ATLAS-CONF-2016-030

Retain events with ISR γ or jet for sub-TeV masses



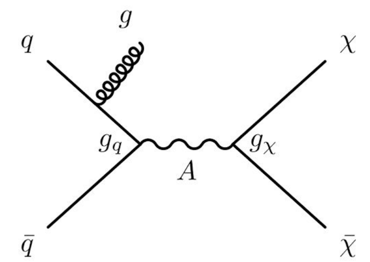
ATLAS-CONF-2016-070

Resonance searches also conducted in di-b-jet channel in ATLAS-CONF-2016-031

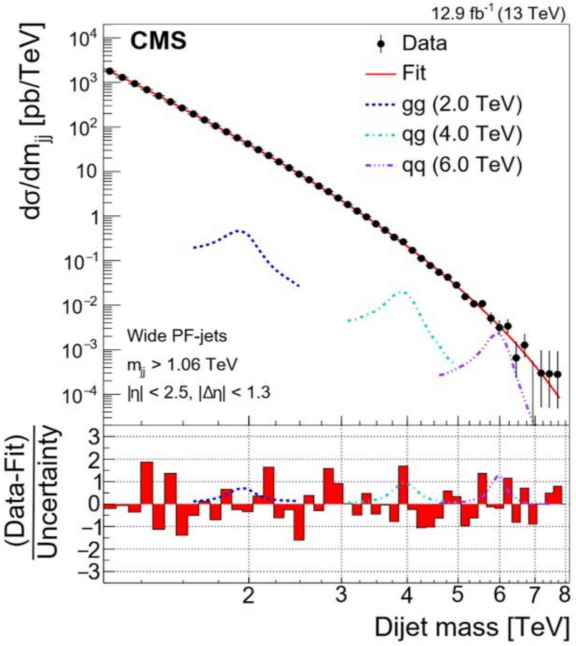
CMS Dijet Analyses

Model(s): Z' leptophobic vector and axial-vector models

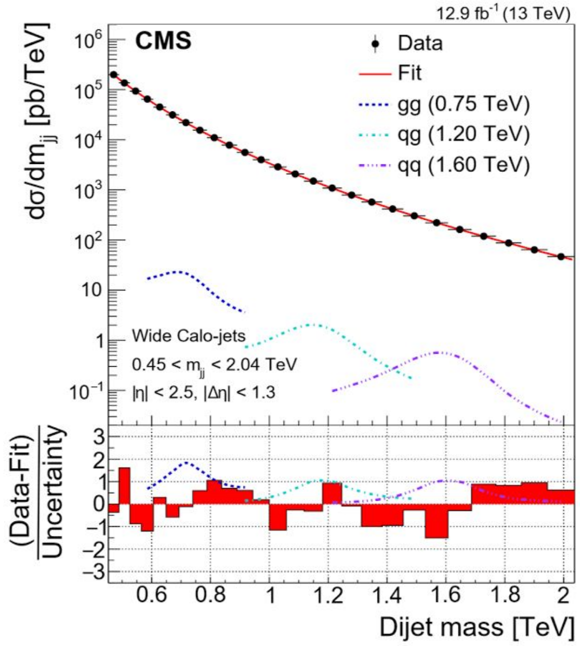
Selection: Two jets with $|\Delta\eta_{jj}| < 1.3$



> TeV masses using PF-jets

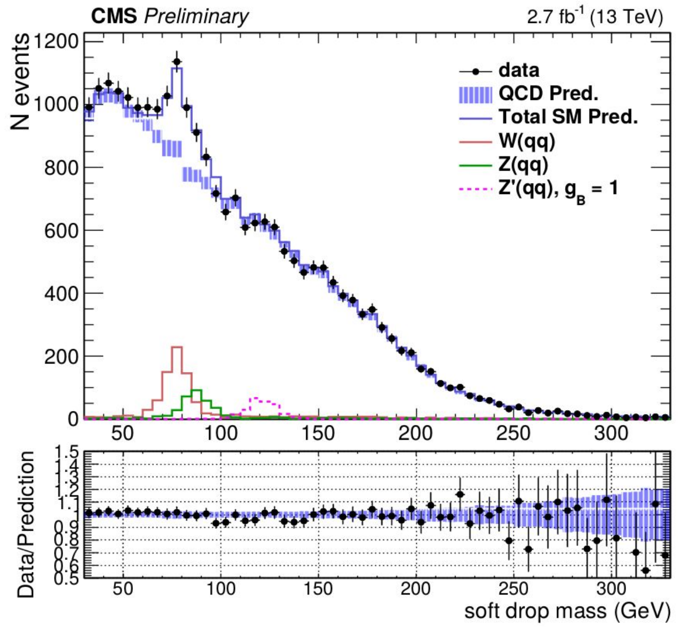


< 2 TeV masses using trigger-level objects



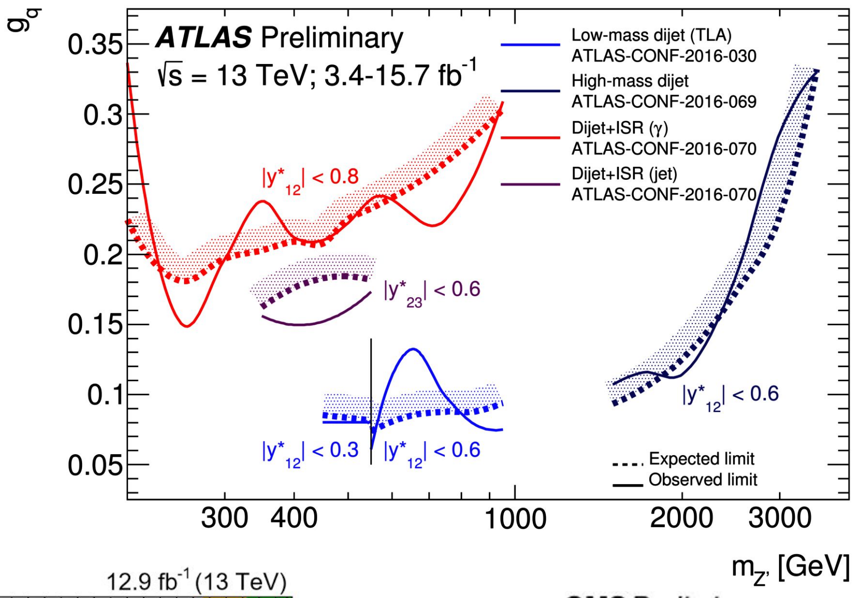
arXiv:1611.03568

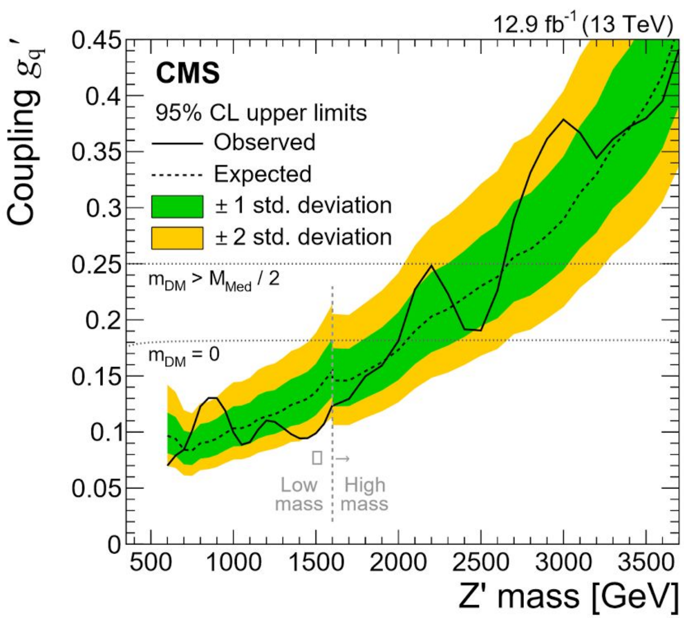
sub-TeV masses using events with ISR jet



[CMS PAS EXO-16-030](CMS PAS EXO-16-030)

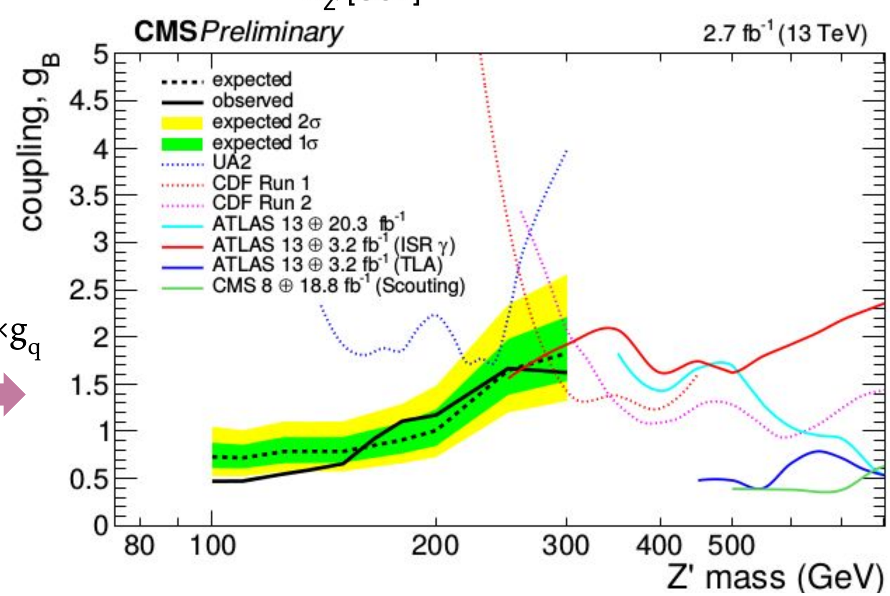
ATLAS & CMS Dijet Analyses





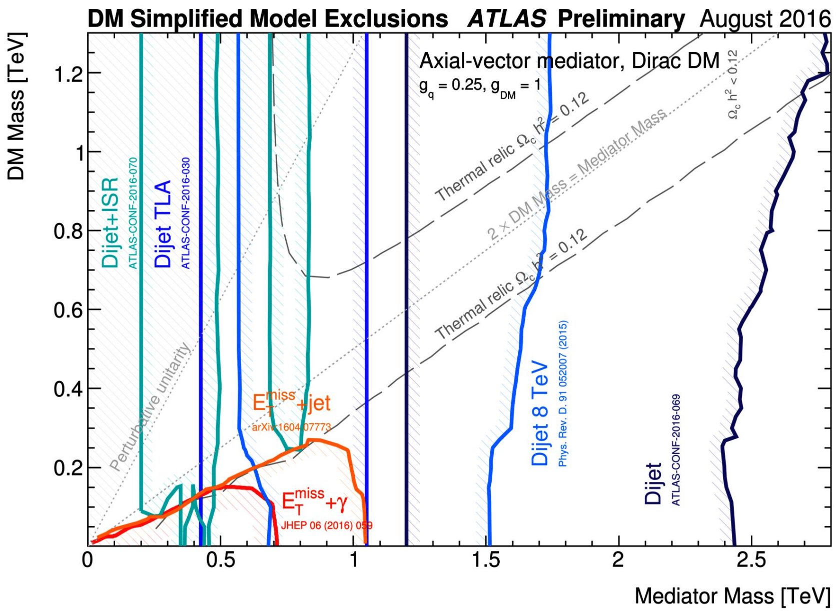
arXiv:1611.03568

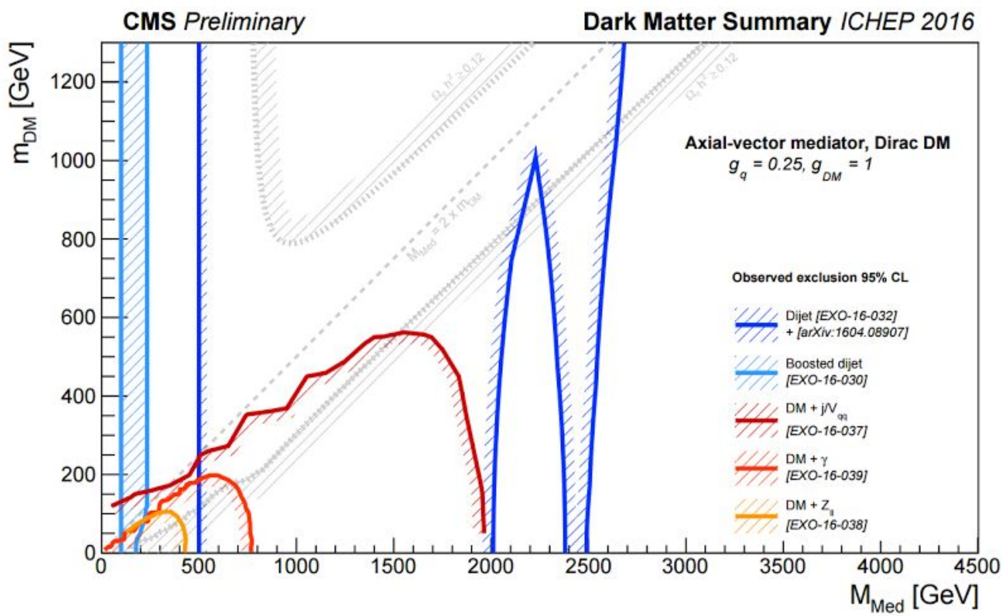
$g_B = 6 \times g_q$



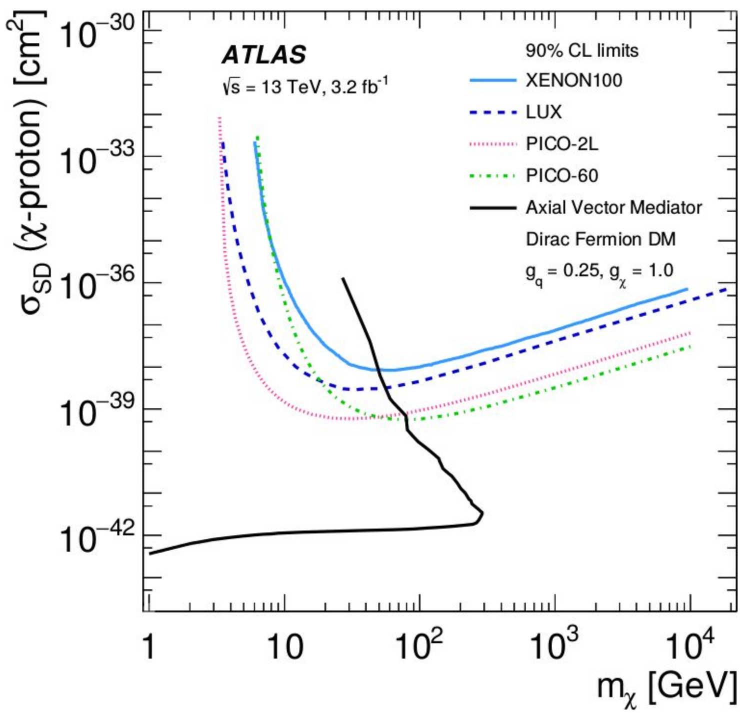
[CMS PAS EXO-16-030](CMS PAS EXO-16-030)

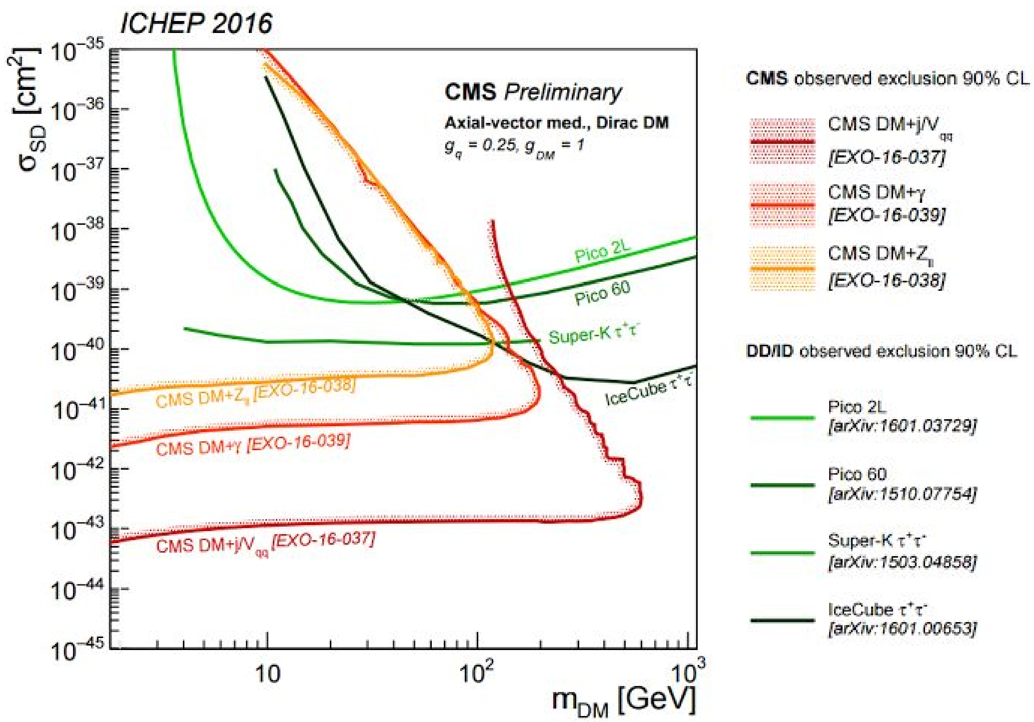
Summary of Mono-X and Dijet Search Results





Comparison with Direct & Indirect Detection Constraints





Phys. Rev. D 94, 032005 (2016)

Long-Lived Particle Searches

ATLAS & CMS Long-lived Charged Particle Analyses

Slow-moving heavy charged LLPs exhibit a higher rate of energy loss via ionisation

- ➔ Large *dE/dx* in ID measurements
- ➔ β from time-of-flight (TOF) measurements

Phys.Rev. D93 (2016) 112015

Particle mass extracted with parametric Bethe-Bloch function:

$$\frac{dE}{dx} = \frac{p_1}{\beta^{p_3}} ln\left[1 + (p_2\beta\gamma)^{p_5}\right] - p_4$$

Selection

'Metastable' signal region ($\tau_{LLP} < 50$ ns)

➔ Tracks reconstructed in ID only

'Stable' signal region ($\tau_{LLP} \geq 50$ ns)

➔ Tracks reconstructed in ID and muon system

See also Phys.Lett.B (2016) 647-665

CMS PAS EXO-16-036

Particle mass extracted via *dE/dx* discriminator:

$$I_{\mathrm{h}} = K\frac{m^2}{p^2} + C$$

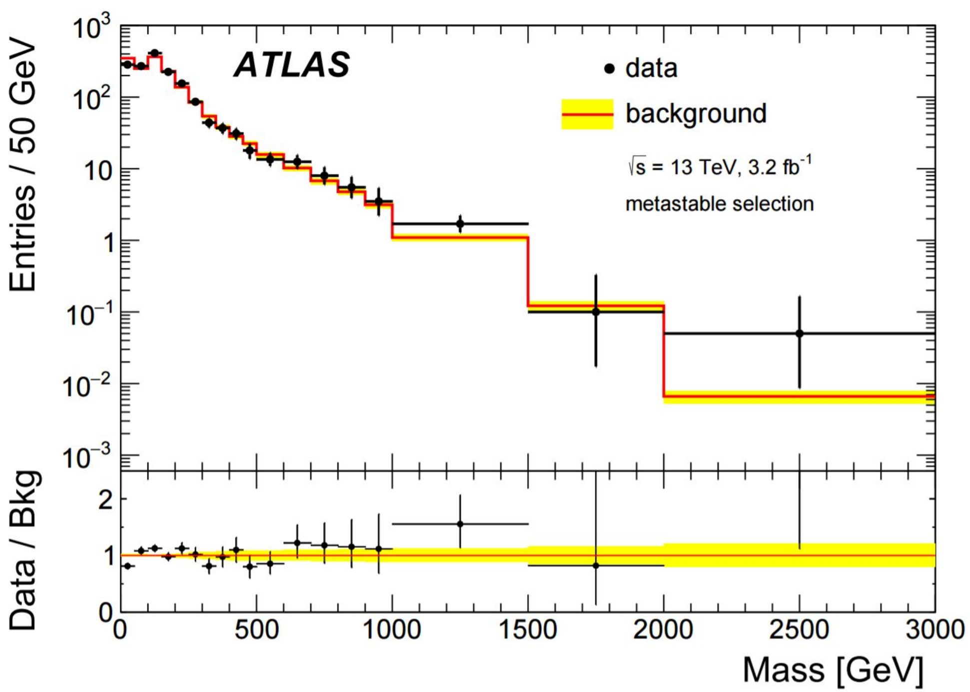
Selection

'Tracker-only' signal region (for Q-suppressed LLPs)

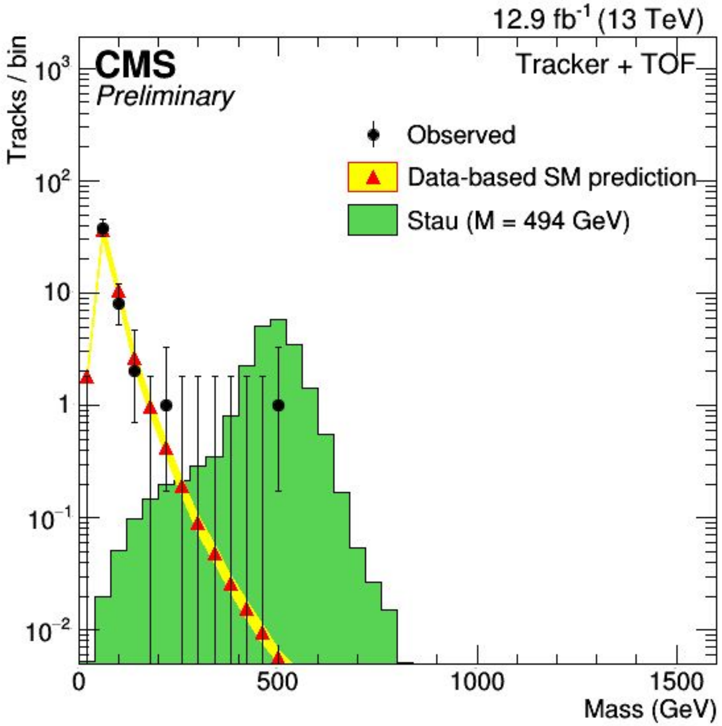
➔ Tracks reconstructed in the silicon detectors

'Tracker+TOF' signal region

➔ Tracks reconstructed in the silicon and muon detectors



Phys.Rev. D93 (2016) 112015



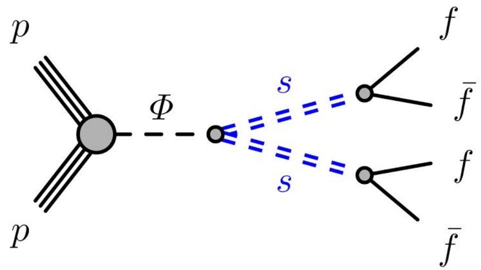
CMS PAS EXO-16-036

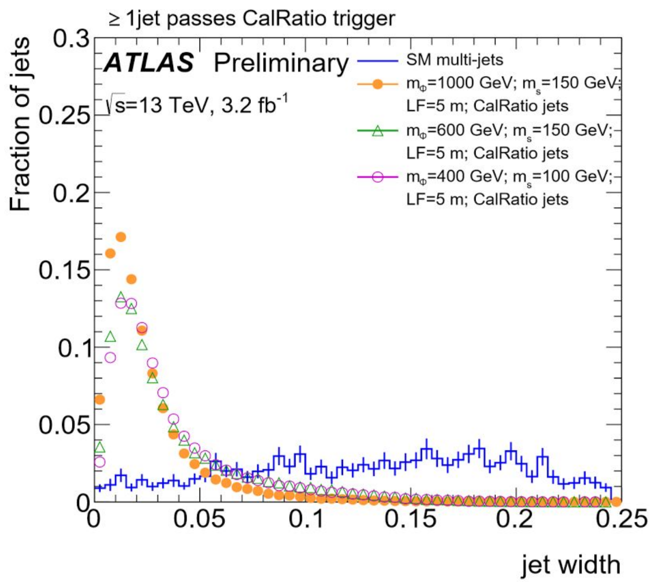
Selection: Two displaced hadronic-jets

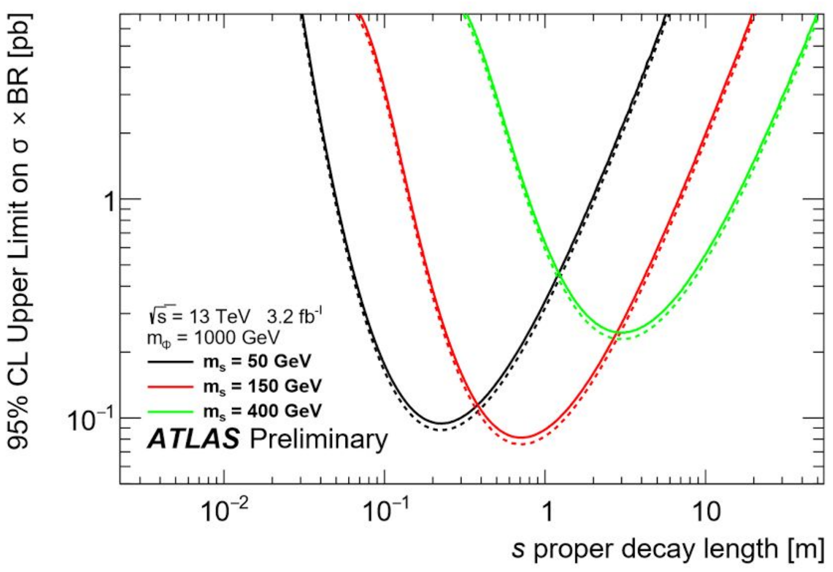
➔ No tracks in the ID, minimal energy in the EM calorimeter

Dominant Backgrounds: Multi-jet processes, cosmic-ray μs, and BIBs

Model(s): Simplified hidden sector toy model, with τ_{LLP} as a free parameter







ATLAS-CONF-2016-103

Search for displaced 'lepton-jets' in ATLAS-CONF-2016-042

Conclusions

Extensive search program for dark matter within the ATLAS and CMS experiments

➔ Complement to direct and indirect detection searches

Dark matter detection in mono-X (X = jets, W/Z/Higgs bosons, γ) plus missing transverse energy channels

Mediator detection in dijet resonance searches

Hidden sector interrogation via long-lived particle searches

No excess over SM predictions

➔ Exclusion limits interpreted within the context of a benchmark set of Simplified Dark Matter Models and Effective Field Theories

Doubling of 2016 dataset since publication of most analyses

➔ New results soon to follow!

Backup

ATLAS Mono-Jet Analysis: Background Estimation Technique

The W/Z + jets , and Z/γ*(→ll) + jets (l = μ, τ) backgrounds are constrained using MC samples normalized with data in dedicated control regions (CRs)

➔ Significantly reduces MC-based theoretical/experimental systematic uncertainties

Example: Z(→νν) + jets

1. Define a SR-orthogonal CR by reversing veto on muon
2. MC-based scale factors to extrapolate background contribution to SR:

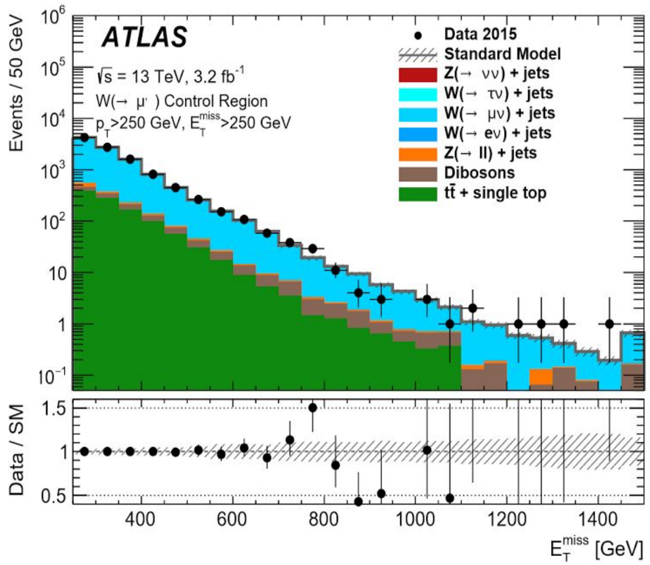
$$N_{\text{signal}}^{Z(\to\nu\bar{\nu})} = \left(N_{W(\to\mu\nu),\text{control}}^{\text{data}} - N_{W(\to\mu\nu),\text{control}}^{\text{non-W}}\right) \times \frac{N_{\text{signal}}^{\text{MC},Z(\to\nu\bar{\nu})}}{N_{\text{control}}^{\text{MC},W(\to\mu\nu)}}$$

where $N_{\text{signal}}^{\text{MC},Z(\to\nu\bar{\nu})}$ = background from MC in the SR

$N_{W(\to\mu\nu),\text{control}}^{\text{data}}$ = number of data events in the CR

$N_{\text{control}}^{\text{MC},W(\to\mu\nu)}$ = number of W(→ μν) + jets in MC

$N_{W(\to\mu\nu),\text{control}}^{\text{non-W}}$ = non-W(→ μν) contribution (mainly due to top-quark and diboson processes)



3. Normalization factors extracted simultaneously with a global fit to all CRs which includes systematic uncertainties (and correlations)

Remaining SM backgrounds (tt, single top, and dibosons) determined using MC, non-collision/ multijet contributions extracted from data

ATLAS Mono-Jet Analysis Systematic Uncertainties

Source of Uncertainty	Total Background Uncertainty
Absolute jet and MET energy scales and resolutions	±0.5% for IM1 and ±1.6% for IM7
Jet quality requirements, pileup description and corrections to the jet pT and MET	±0.2% to ±0.9%
Lepton identification and reconstruction efficiencies, energy/momentum scale and resolution	±0.1% - ±1.4% for IM1 and ±0.1% - ±2.6% for IM7
W/Z + jets renormalization/factorization, and parton-shower matching scales and PDFs	±1.1% to ±1.3%
Model uncertainties and NLO electroweak corrections for W/Z + jets	±2.0% and ±3.0% for IM1 and IM5, ±3.9% for IM7
MC-based estimate of tt and single-top cross-sections	±2.7% and ±3.3% for IM1 and IM7
MC-based estimate of diboson contribution	±0.05% and ±0.4%
±100% uncertainty on multijet and NC backgrounds	±0.2% for IM1
Statistical limitations (CRs and MC samples)	±2.5% for IM1 and ±10% for IM7

- All systematic uncertainties treated as nuisance parameters with Gaussian shapes in fit to MET bins

CMS Mono-Z (leptonic) Analysis Systematic Uncertainties

Source of uncertainty	Bkg. unc. (%)	Simplified Model unc. Exp. (%)	Simplified Model unc. Theory (%)	Impact
Integrated luminosity	6.2	6.2	—	9.5
Lepton trigger & identification efficiency	4	4	—	7.7
Lepton momentum scale and resolution	2	2	—	
Jet energy scale, resolution	0.5	0.4	—	
b tagging efficiency	2	2	—	
Pileup	0.6	0.6	—	
Efficiency for missed lepton (WZ)	2.2	—	—	
PDFs, α_S	1.4	—	1.0	0.9
Renorm./fact. scales (signal)	—	—	5.0	5.4
Renorm./fact. scales (VV)	2.5	—	—	
Renorm./fact. scales (VVV)	5.5	—	—	
Renorm./fact. scales ($gg \to ZZ$)	1.0	—	—	
Electroweak corrections on $q\bar{q} \to VV$	7.6	—	—	5.5
Underlying event	—	—	3	2.9
DY normalization	100	—	—	1.4
$t\bar{t}$, tW, W^+W^-, W+ jets normalization	14.0	—	—	1.2
MC statistics (signal)	—	1.1	—	2.4
MC statistics (ZZ, WZ, VVV)	1.4	—	—	
MC statistics (DY)	41	—	—	
MC statistics ($t\bar{t}$, tW, W^+W^-)	10.5	—	—	

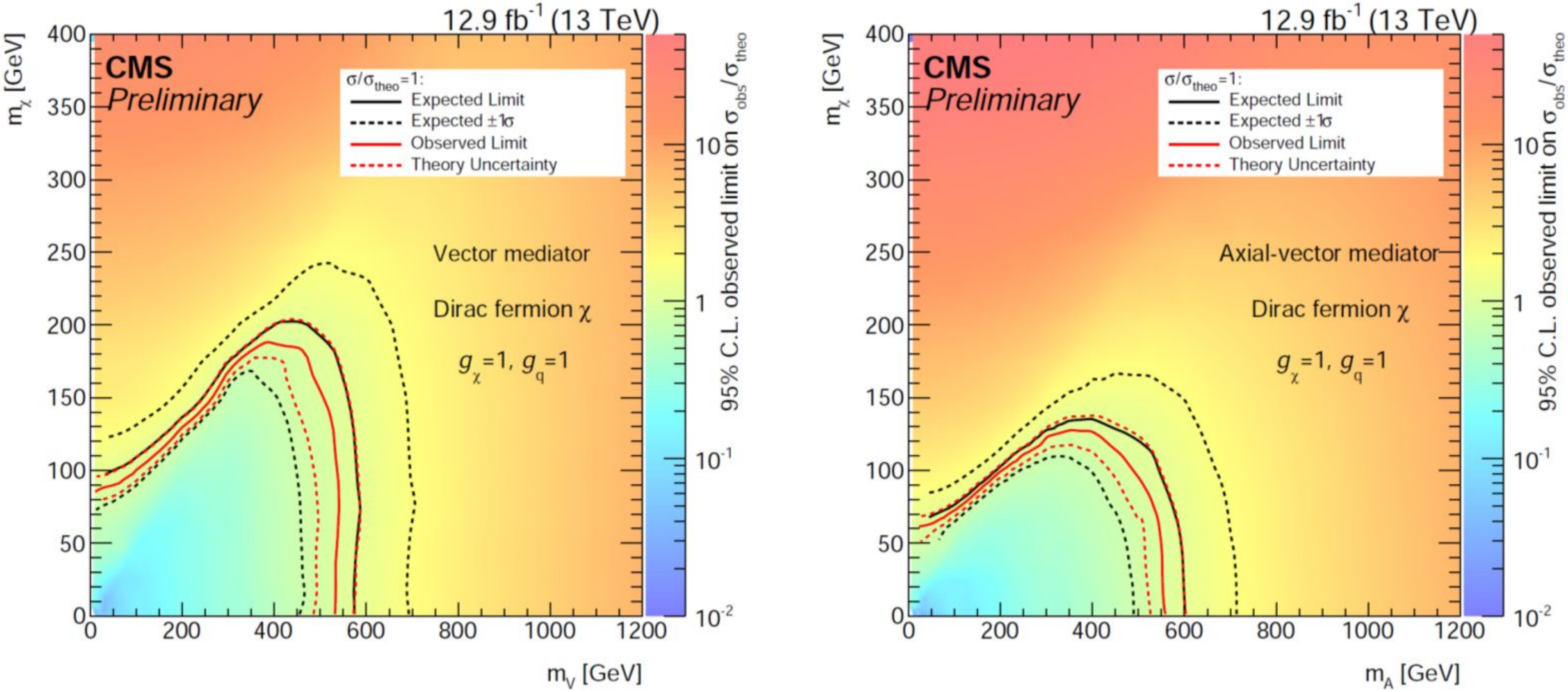
Impact: relative change of the expected best fit signal strength that is introduced by the variation for a simplified model signal scenario with a vector mediator of mass 200 GeV and m_{DM} = 50 GeV

CMS Search for Long-Lived Charged Particles

Source of Systematic Uncertainties	Relative Uncertainty (%)		Gluino M=1800 GeV	Stau M=651 GeV
Signal acceptance	Trk-only	Trk+TOF	Trk-only	Trk+TOF
- Trigger efficiency	13	13	13	13
- Track momentum scale	0 – 5	0 – 14	0.8	0.7
- Track reconstruction	0 – 2	0 – 2	0.5	0.7
- Ionization energy loss	0 – 13	0 – 7	3	3
- HIP background effect	0 – 10	0 – 10	7	10
- Time-of-flight	-	0 – 6	–	2
- Muon reconstruction	-	2	–	2
- Pileup	0 – 2	0 – 2	0.4	0.2
Total uncertainty on signal acceptance	0 – 20	0 – 20	15	17
Collision background uncertainty	20	20	20	20
Luminosity uncertainty	6.2		6.2	

Systematic uncertainties for the various HSCP searches. All values are relative uncertainties. The middle columns show the range of values while the last two columns show two example cases: gluino (f=0.1, M=1800 GeV) and GMSB stau (M=651 GeV).

CMS Mono-Z (leptonic) Analysis



CMS PAS EXO-16-038

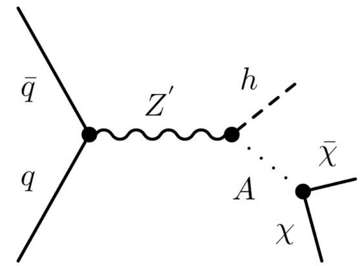
ATLAS & CMS Mono-Higgs(→γγ) Analyses

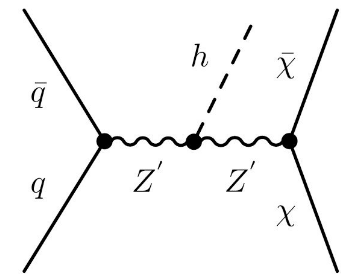
$h \to \gamma\gamma$ has low BR but clean signal
➔ look for **excess in** the $m_{\gamma\gamma}$ spectrum

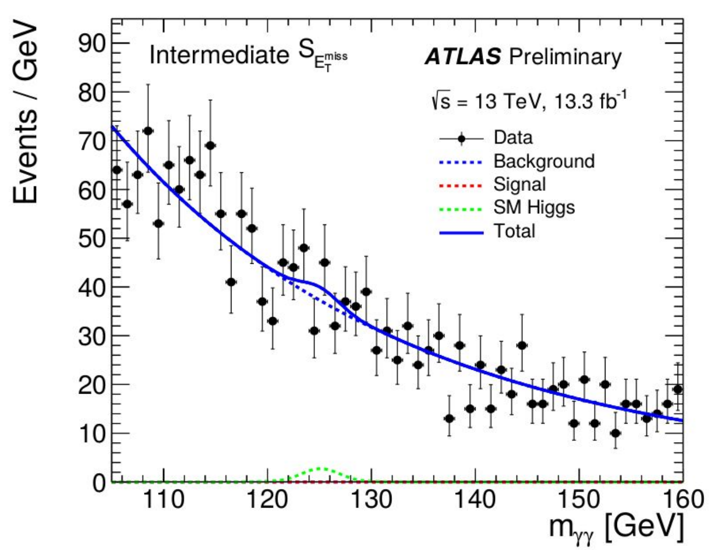
Selection: Two high p_T isolated photons plus large E_T^{miss}

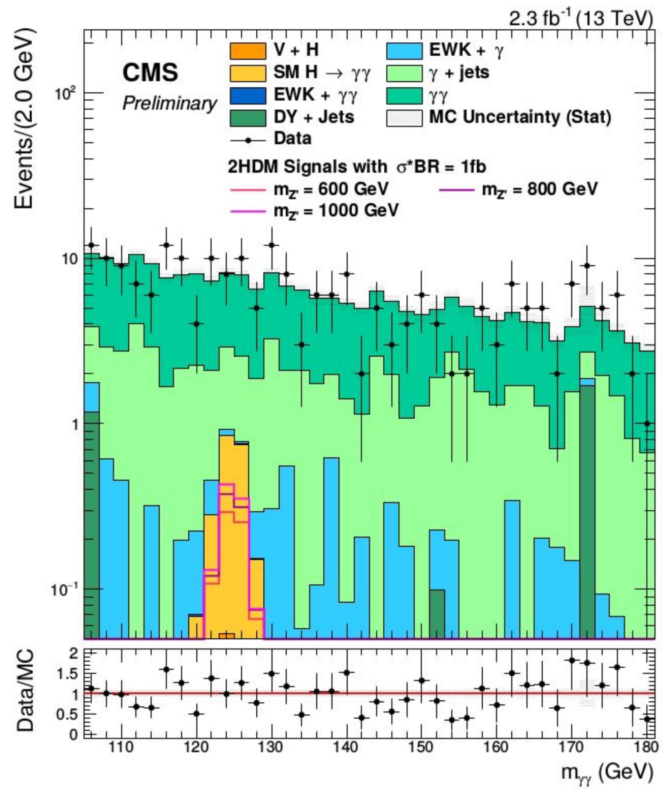
Dominant backgrounds: Resonant and non-resonant contributions

Model(s): Z' leptophobic models





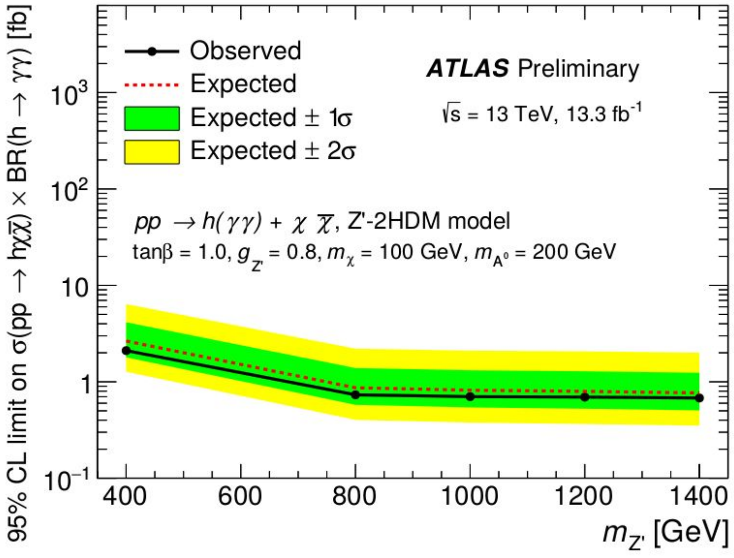


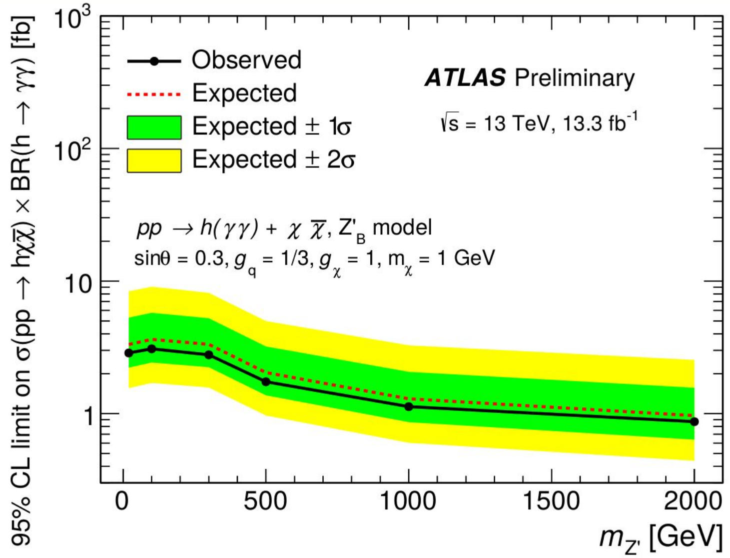


ATLAS-CONF-2016-087

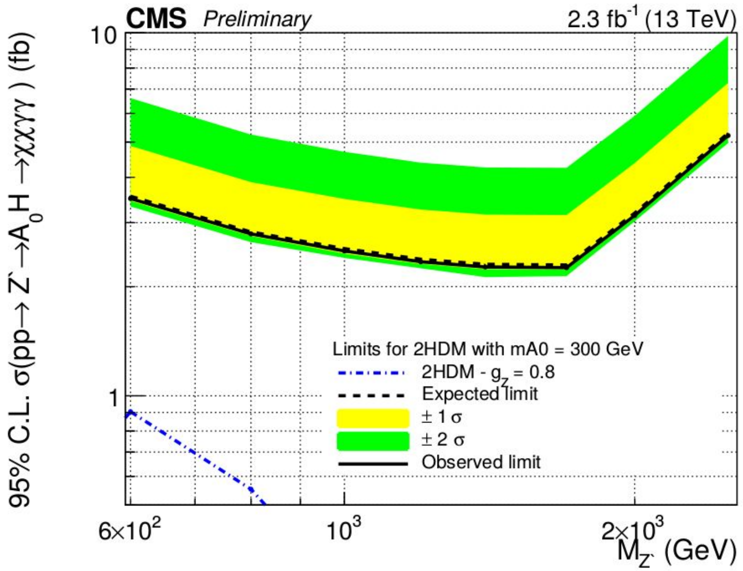
CMS PAS EXO-16-011

ATLAS & CMS Mono-Higgs(→γγ) Analyses





ATLAS-CONF-2016-087



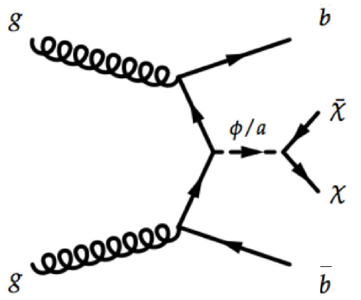
CMS PAS EXO-16-011

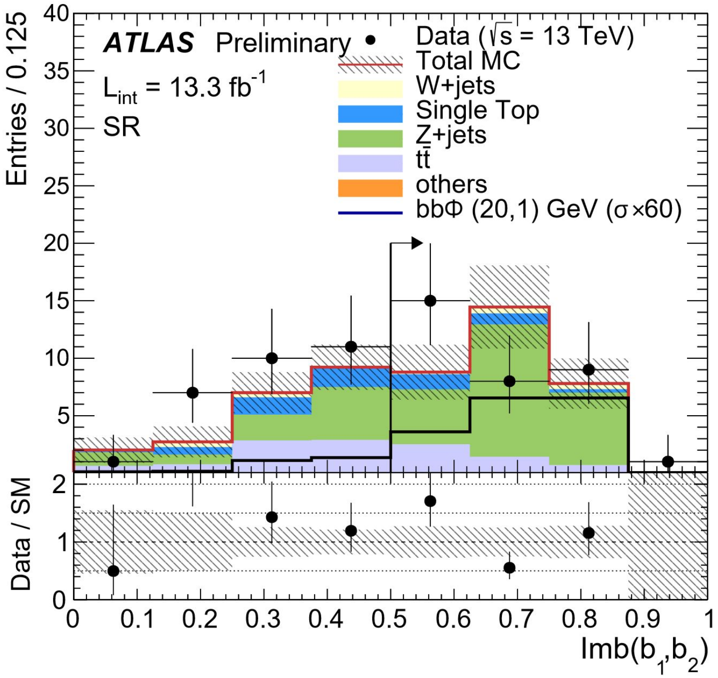
ATLAS DM Plus Bottom Quarks Analysis

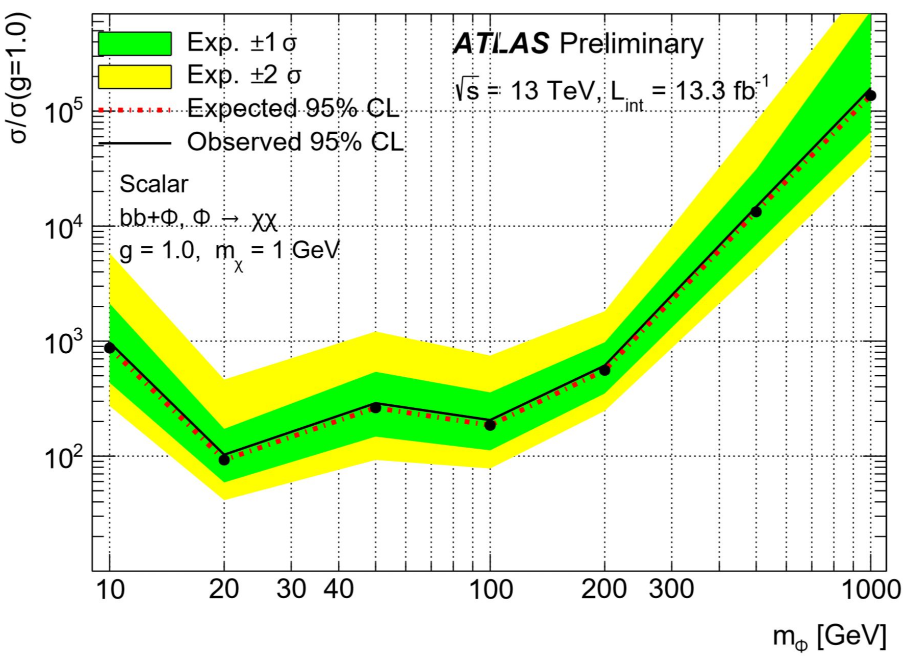
Search for DM produced in association with bottom quarks

Selection: Two b-tagged jets plus large $E_{\mathrm{T}}^{\mathrm{miss}}$

Model(s): Scalar and pseudoscalar mediators with Dirac fermion DM







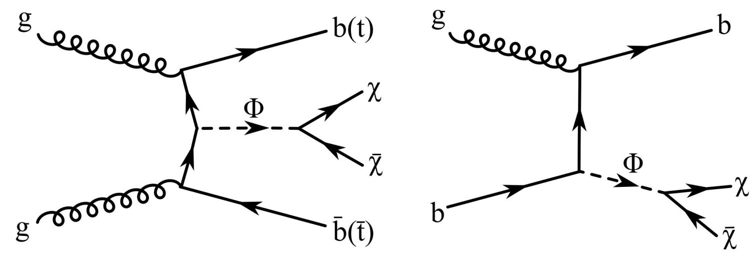
ATLAS-CONF-2016-086

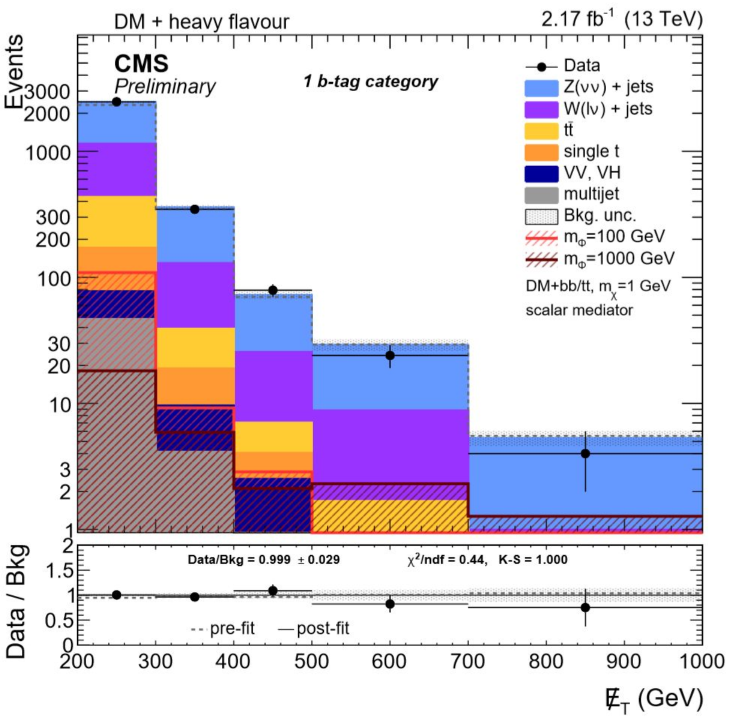
CMS DM Plus Bottom Quarks Analysis

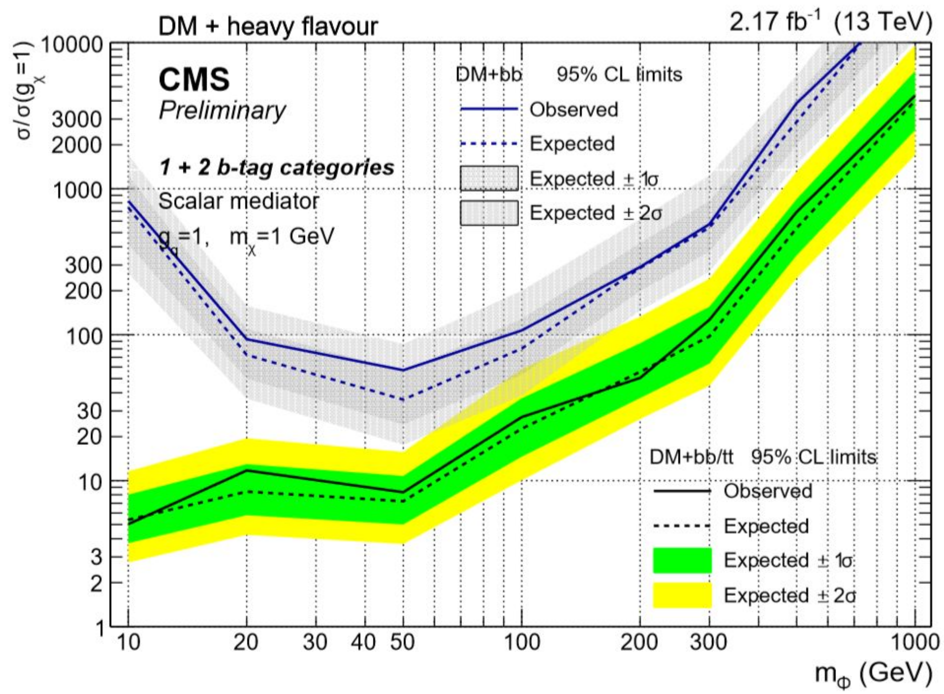
E_T^{miss}+ bb searches also sensitive to E_T^{miss} + tt production

➔ b quarks produced in top quark decays

Selection: Two signal regions categorised by either one or two b-tagged jets plus large E_T^{miss}







[CMS PAS B2G-15-007](#)

Trigger-Object Level Analysis

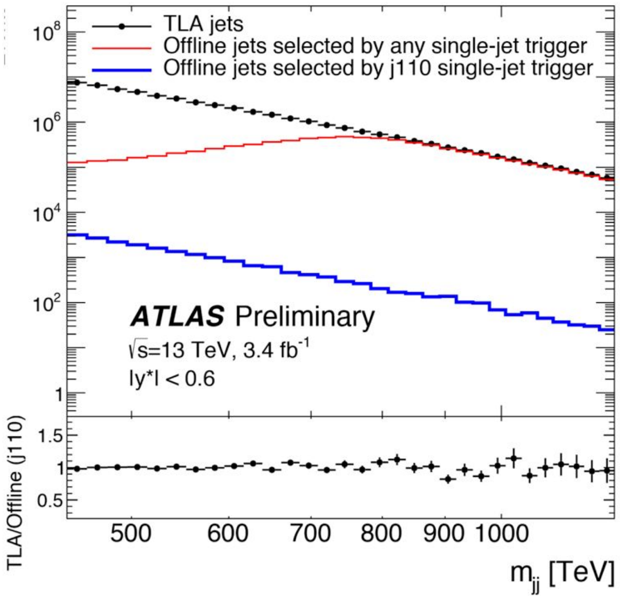
Bandwidth allocation for single-jet triggers limits statistics for particles lighter than 1 TeV
➔ Full event information requires trigger prescale (1/prescale factor events recorded)

To avoid prescaling, threshold p_T of the jet must be large → restricts minimum m_{jj}

For lighter masses, instead record partially-built event information
1. L1 identifies ROI in 0.2 x 0.2 calorimeter segments
2. HLT reconstructs and calibrates 'trigger' jet
3. ROI with E_T > 75 GeV at EM scale → record summary of trigger jet to **Trigger-Object Level Analysis (TLA)** stream, including 4-momentum and jet ID variables, excluding readout from tracking and muon detectors

Partially-built events are <5% of full event size, allowing for higher rates to be recorded (2 kHz)

Offline trigger jets calibration akin to fully-reconstructed jets
➔ μ correction
➔ Trigger jet specific MC-based JES calibration
➔ No GSC correction (missing ID and muon spectrometer information)
➔ Dedicated correction for trigger jets

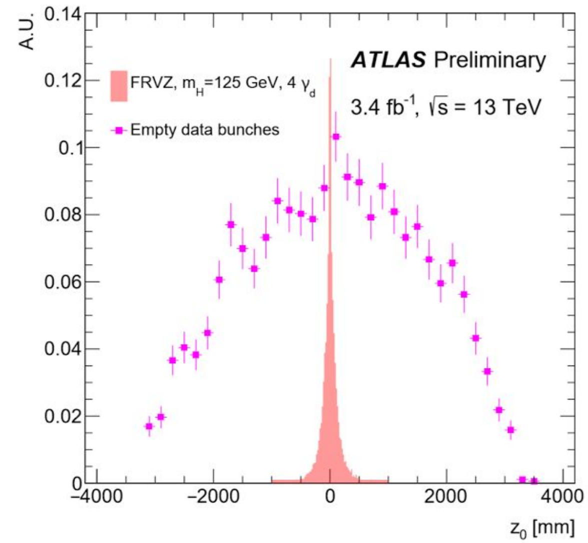


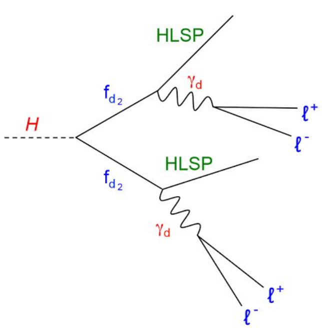
ATLAS Long-lived Neutral Particle Analysis

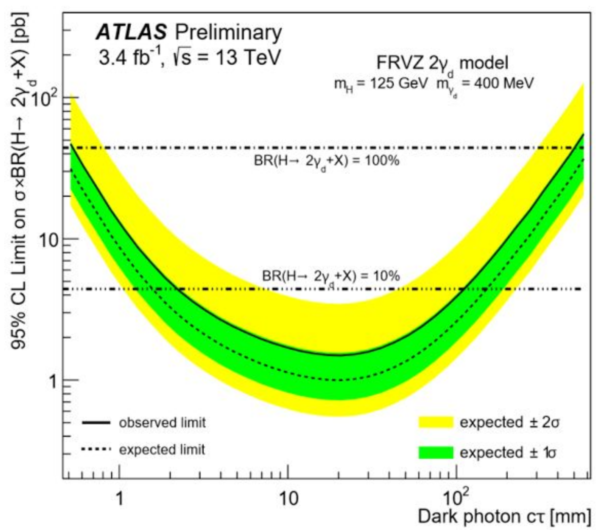
Selection: At least two ‘lepton-jets’, categorised by species of the constituent particles:

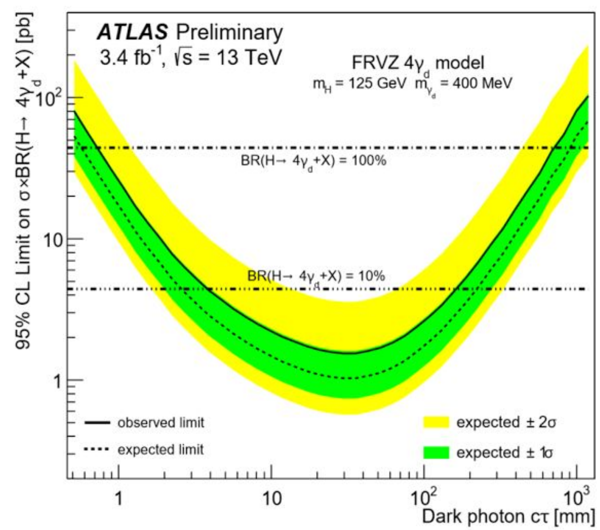
➔ Two non-combined μ, one non-combined μ and one CalRatio jet, two CalRatio jets

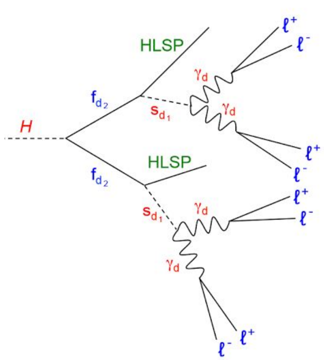
Model(s): Two Falkowsky-Ruderman-Volansky-Zupan models where the Higgs decays to either 2 or 4 dark γ











ATLAS-CONF-2016-042