Corfu Summer Institute 2018: Workshop on the Standard Model and Beyond (Sep 2018, Greece)

Dark Matter Searches in ATLAS and CMS

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On behalf of ATLAS and CMS collaborations

Dark Matter Searches in ATLAS and CMS

- Dark Matter (DM) has been thoroughly probed in both ATLAS and CMS collaborations
  - Covering a large amount of models, final states and parameter space….

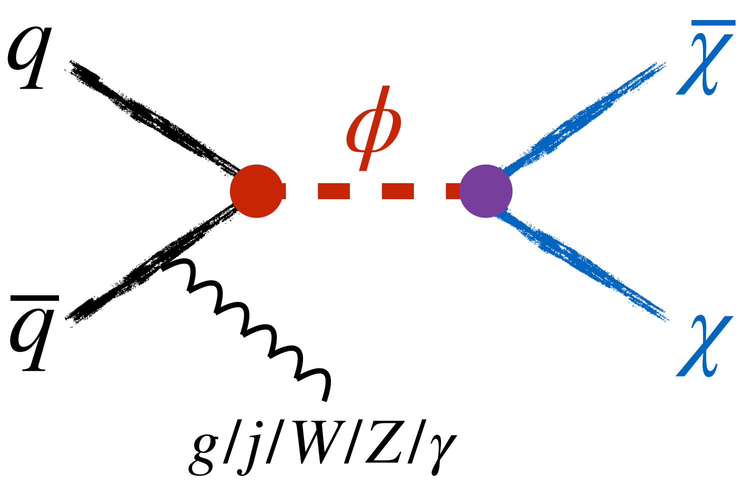
TLA & Data Scouting
Leptonic
Mono-Z/W
Resonance
Di-Boson
Mono Jet
Di-Jet
Higgs Portal
Boosted
Di-Jet+ISR
VH
Di-Jet+ISR
Resolved
RPC SUSY
DM with Bottom Pair
Mono-Photon
Met + H
Met + H to bb
DM with Top Pair
Di-Lepton
Di-b-Jet
DM with Top

- This offers critical complementarities to direct and indirect DM detection as DM is generated in a controlled experiment

Categorize the Searches

- If DM particles or mediators are produced at the LHC, ATLAS and CMS have many approaches to detect them. We will discuss the following three in this talk:

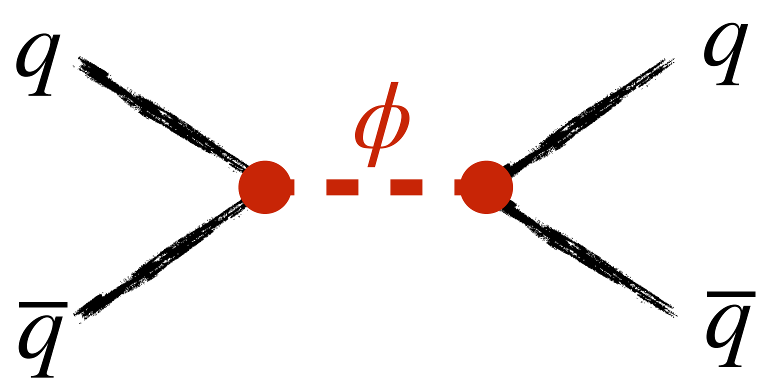
Initial State Radiation



DM particles are recoiled against initial state radiations

Mono+X Signatures

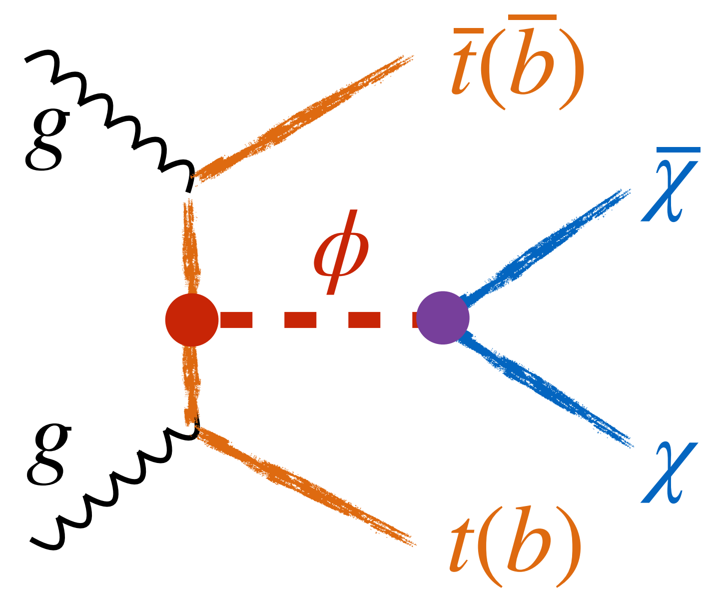
Visible Mediator Decays



Mediator decays to visible SM particles

Resonance Signatures

Associated Production



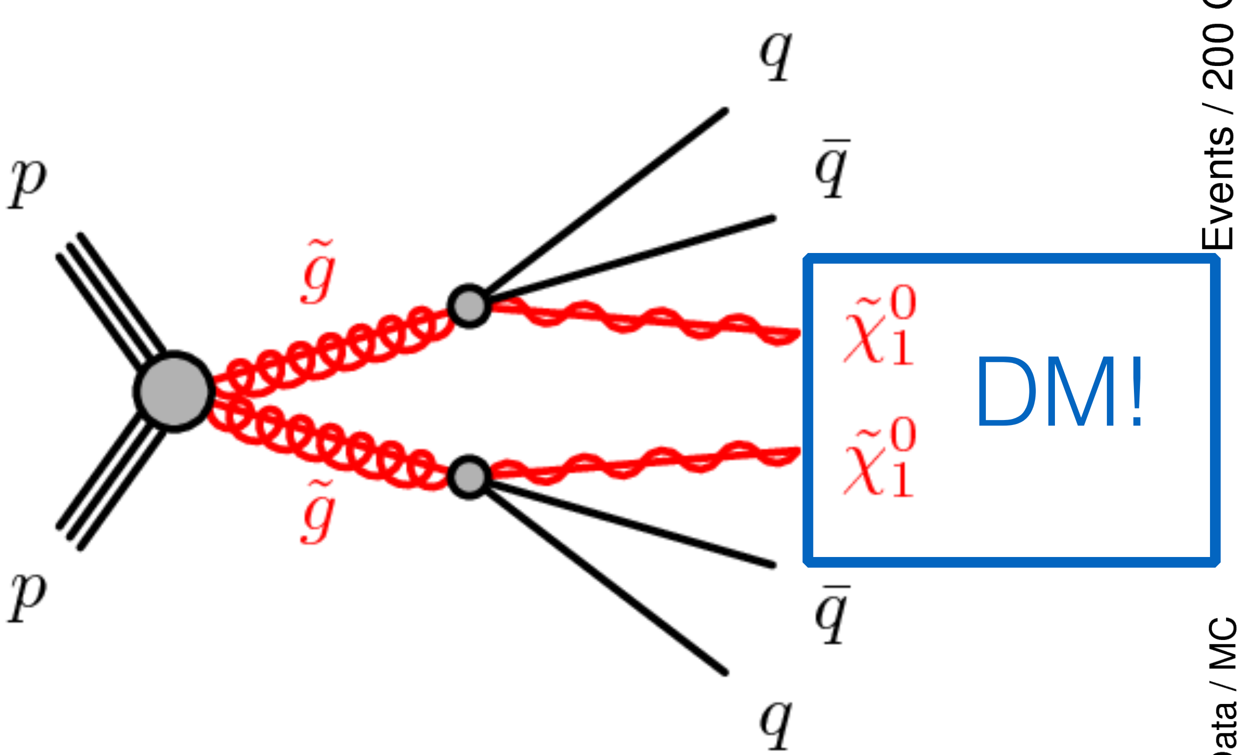
DM particles are produced associated with other spectators (t, b, higgs)

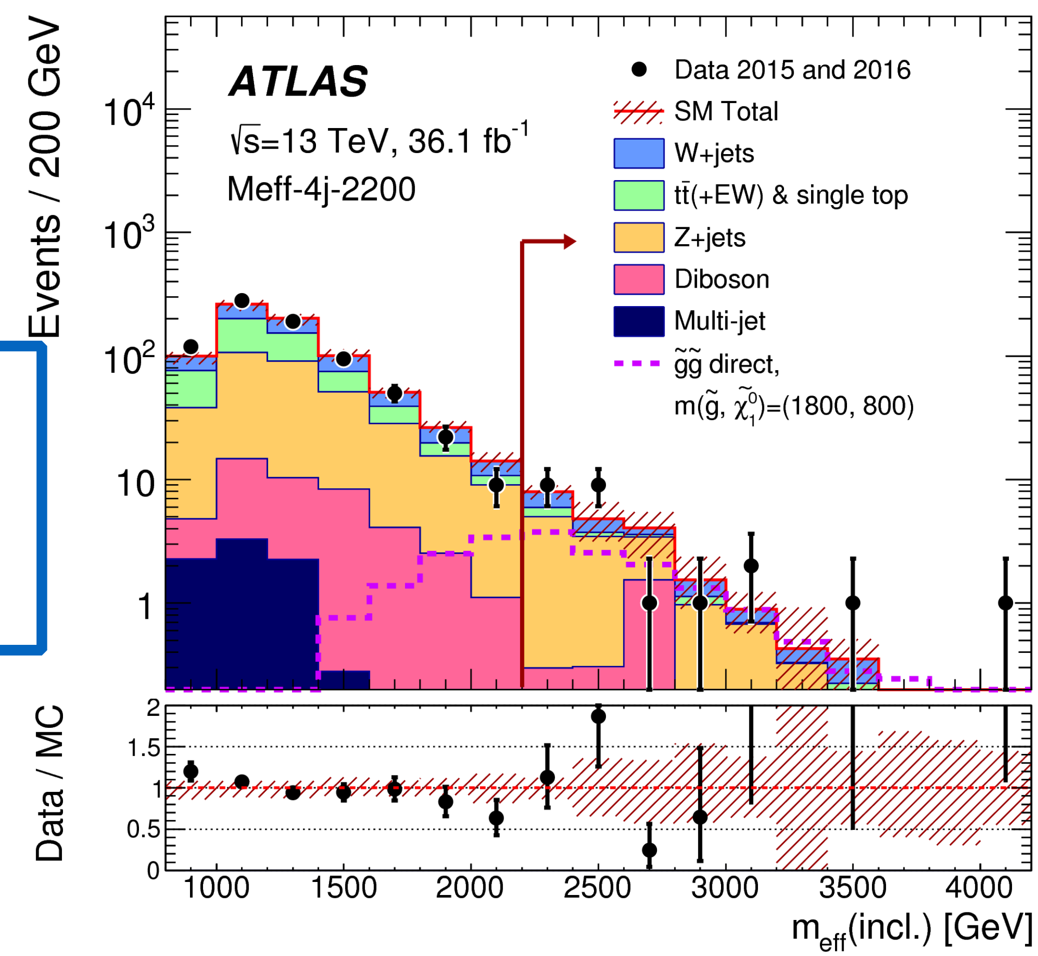
Spectators + MET

Important But not Covered Here: SUSY Searches

- R-parity Conserving (RPC) SUSY provides a natural DM candidate
  - Lightest Supersymmetric Particle (LSP) can not decay to SM particles and has to be a weakly interacting massive particle (WIMP)

For instance: PhysRevD.97.112001

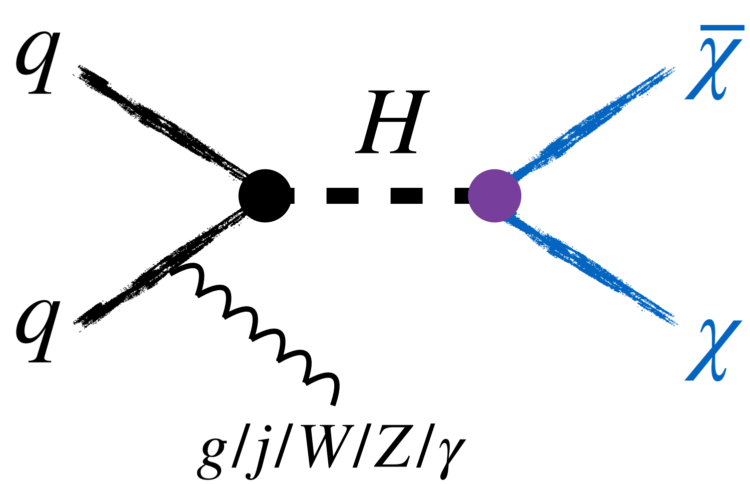


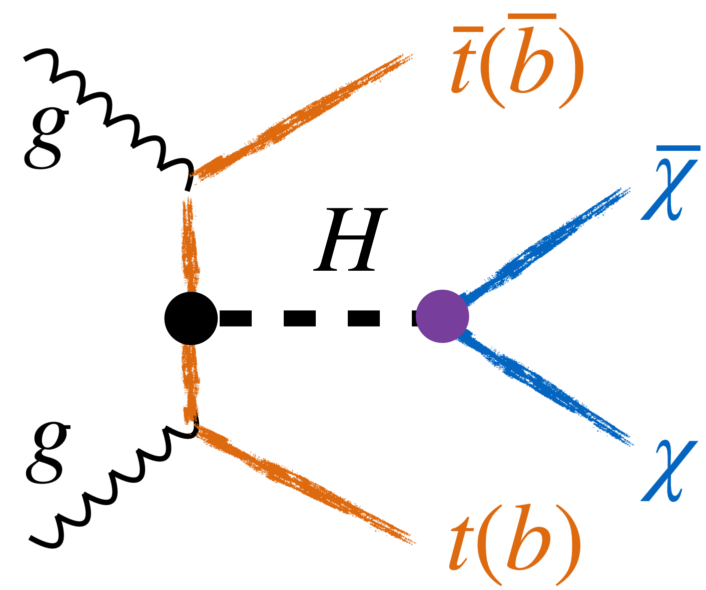


More in Arka's Talk!

Important But not Covered Here: The SM Higgs Portal

- The SM Higgs Boson is the biggest discovery at the LHC so far
  - Higgs ($\rightarrow$ inv) branching ratio is well constrained in SM
  - A powerful tool to perform DM searches if $m_\chi <= \frac{m_H}{2}$
- Very similar signatures as many searches to discuss today
  - But with a known mass of 125 GeV

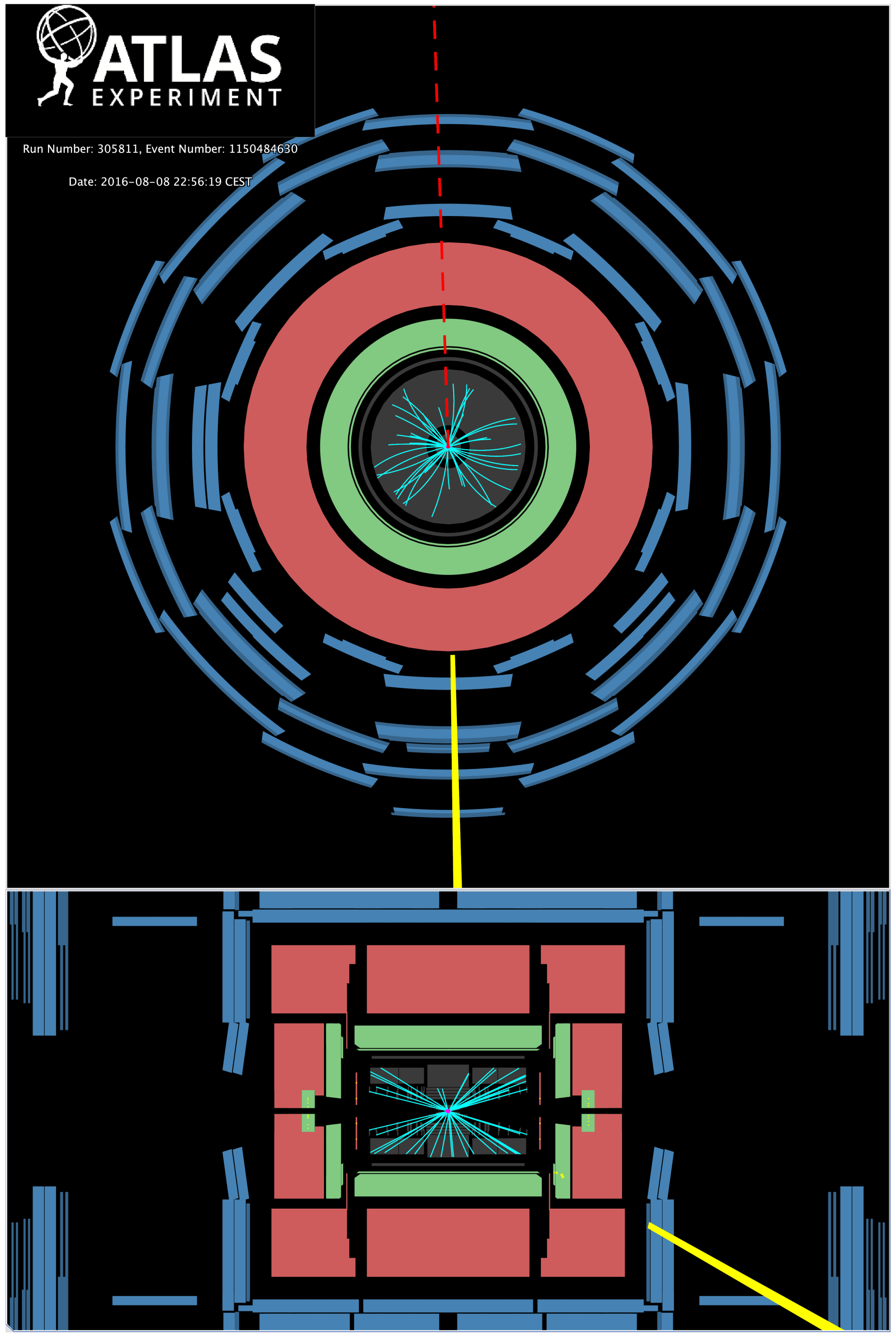




- CMS Higgs to Invisible public results
- ATLAS Higgs to Invisible public results

See Albert's Talk

DM with Initial State Radiation: Mono-X Searches



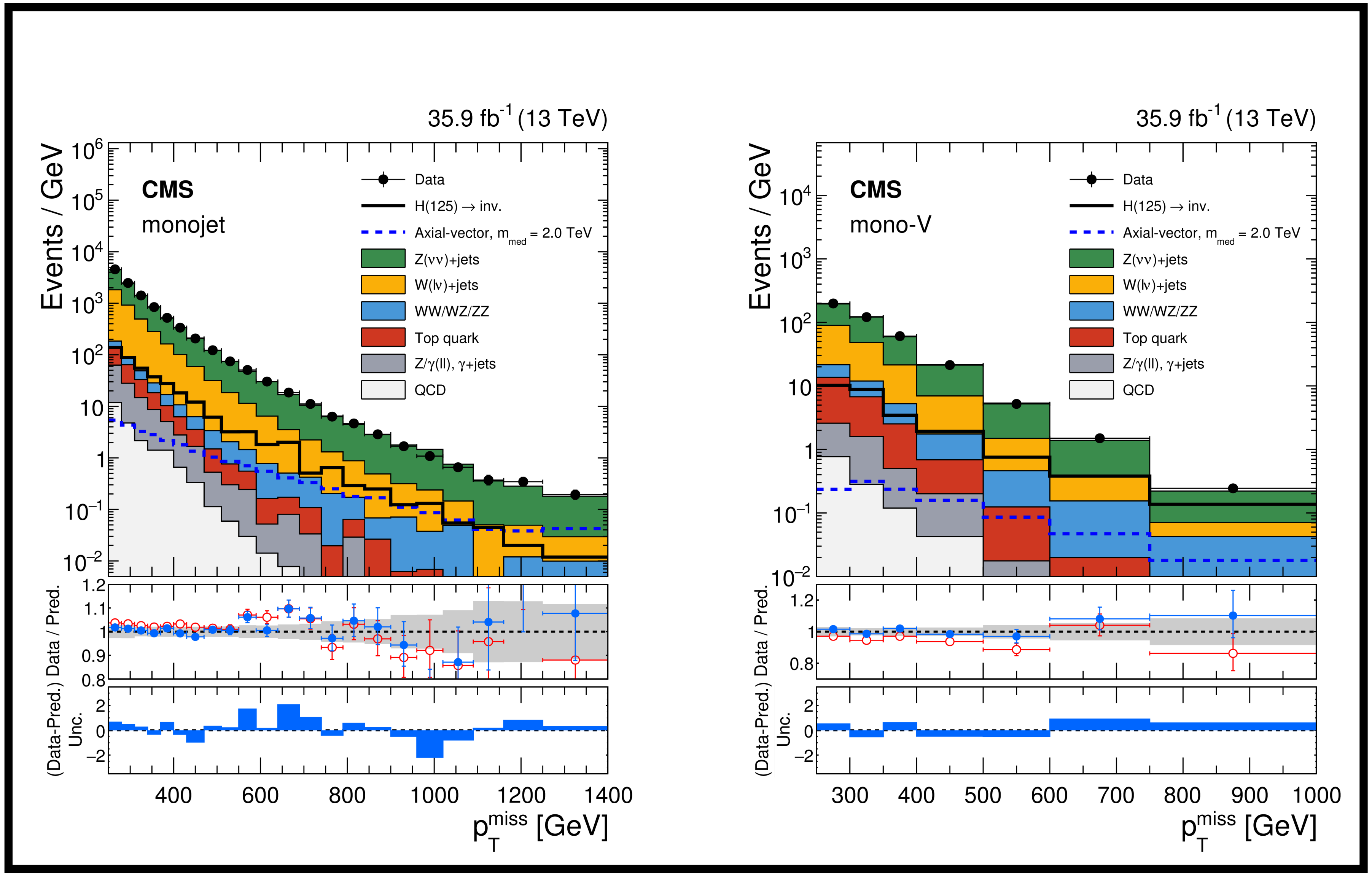
Eur. Phys. J. C 77 (2017) 393

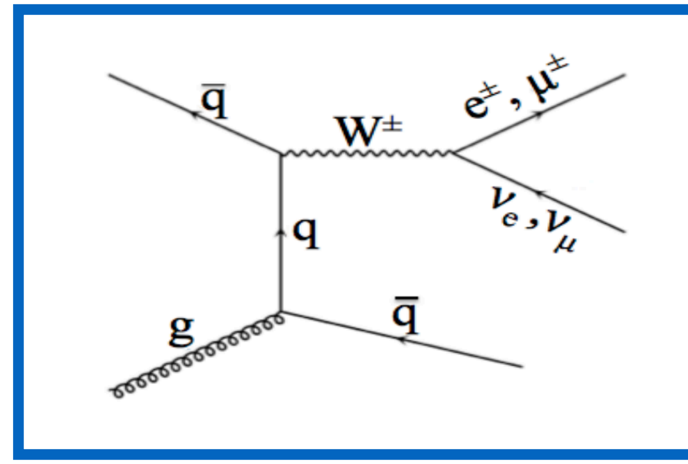
- Mono-X Signature:
  - DM particles do not leave traces in the detector
  - ATLAS and CMS can still trigger on them if they are produced with energetic initial state radiation
    - Jet, Photon, Vector Bosons
  - Momenta have to be balanced in the transverse plane
  - There is an imbalance in the measured transverse momenta
    - E_T^{miss} ($\vec{p}_T^{miss}$)

    Observables!

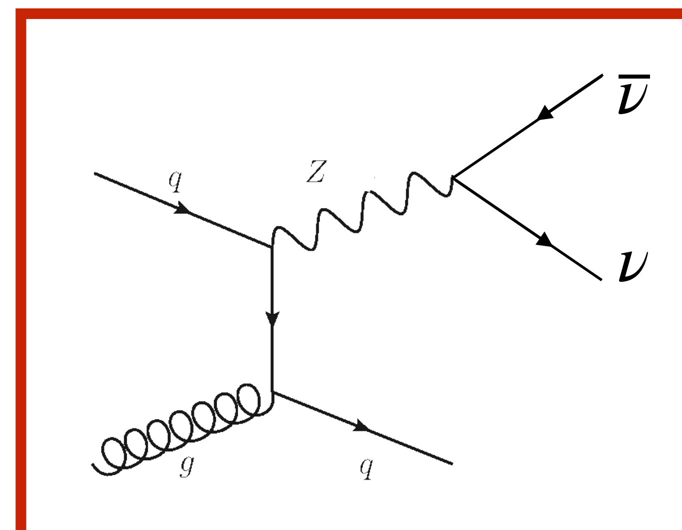
Mono Jet/Hadronically Decaying W/Z

- DM is recoiled against transverse momentum from an ISR jet or W/Z boson



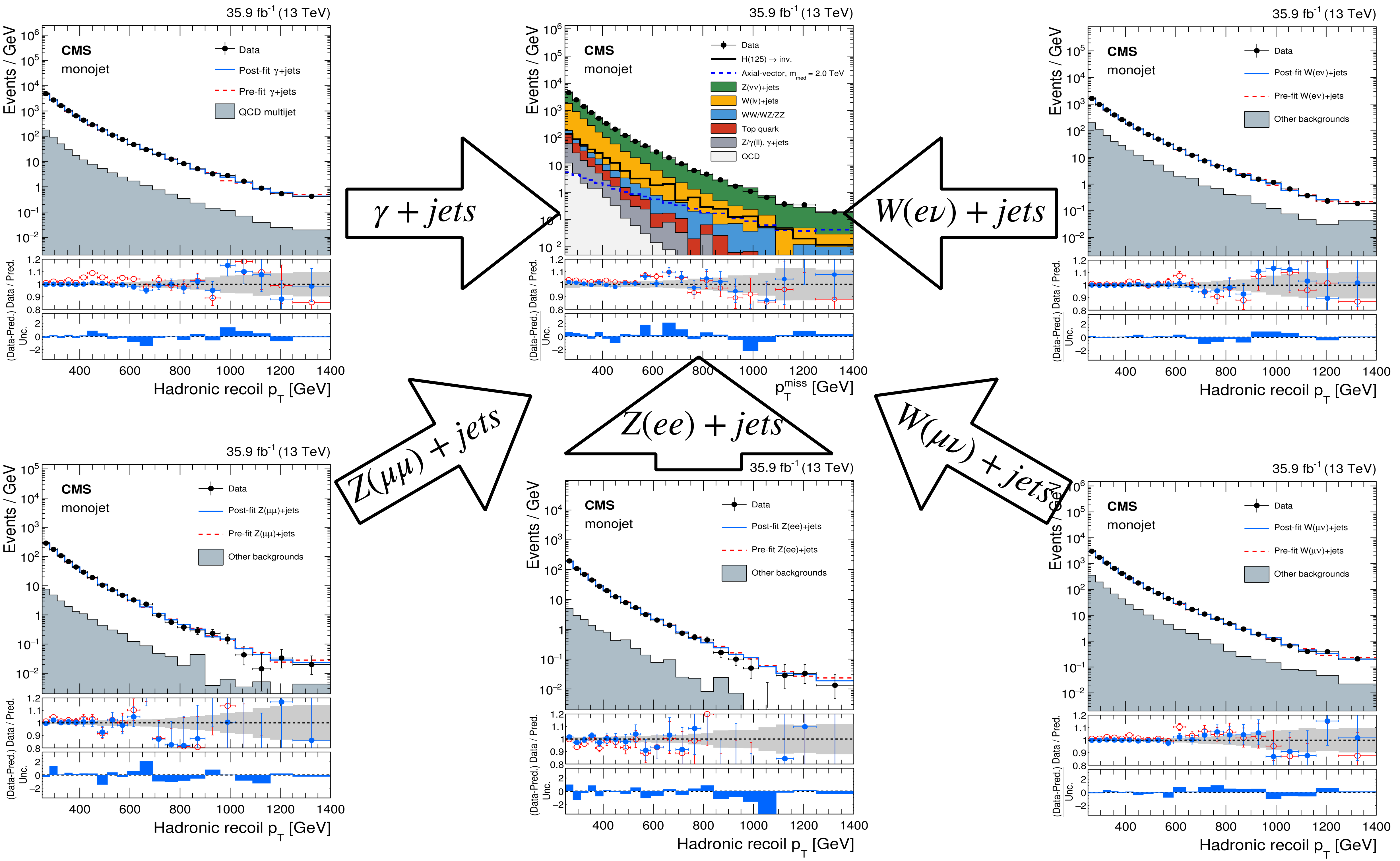


Phys. Rev. D 97 (2018) 092005



- Major Irreducible background: Jet + Z (W) $\longrightarrow$ Inv (nv + l)

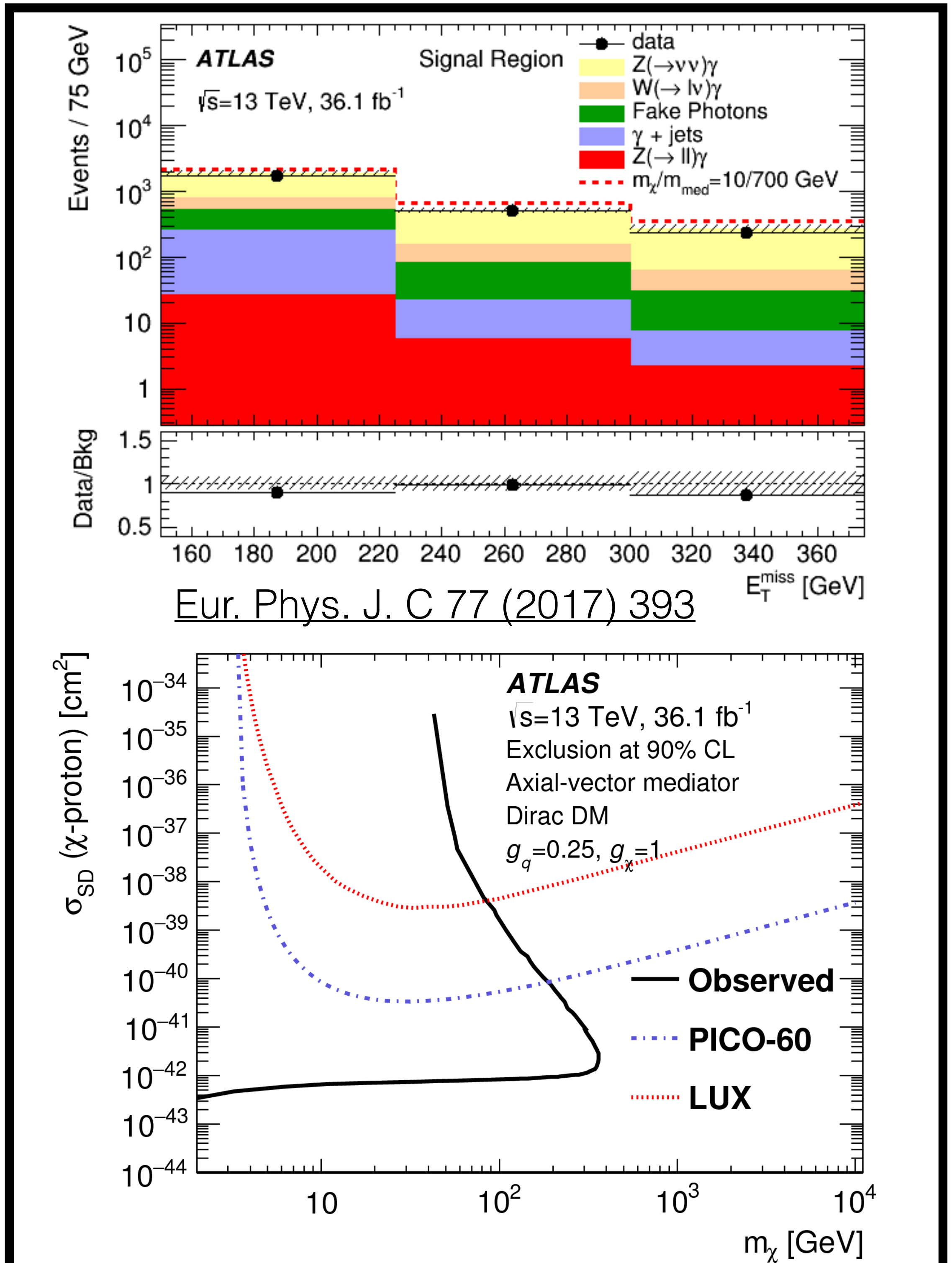
Simultaneous Fit in Control Regions

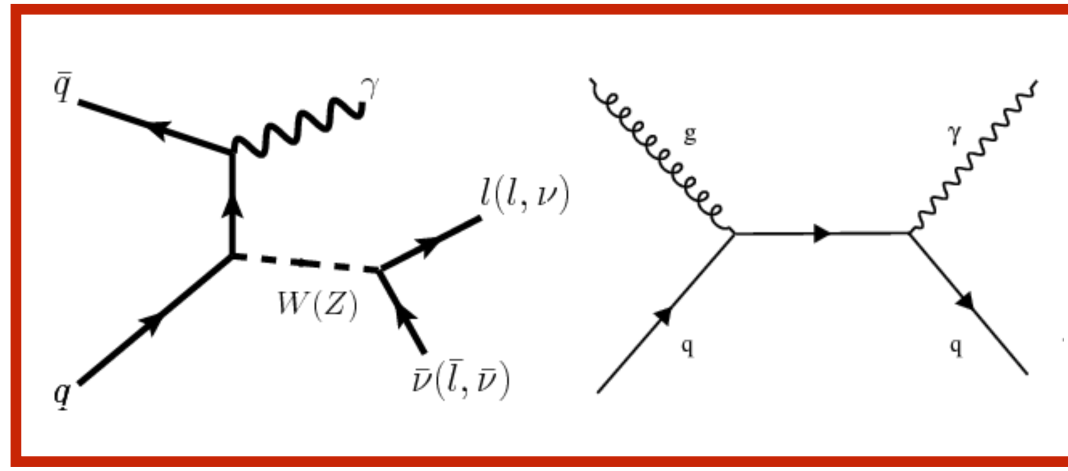


Note: DM + Leptonically Decaying W/Z is also done in both *CMS* (Eur. Phys. J. C 78 (2018) 291) and ATLAS (PLB 776 (2017) 318)

Mono Photon

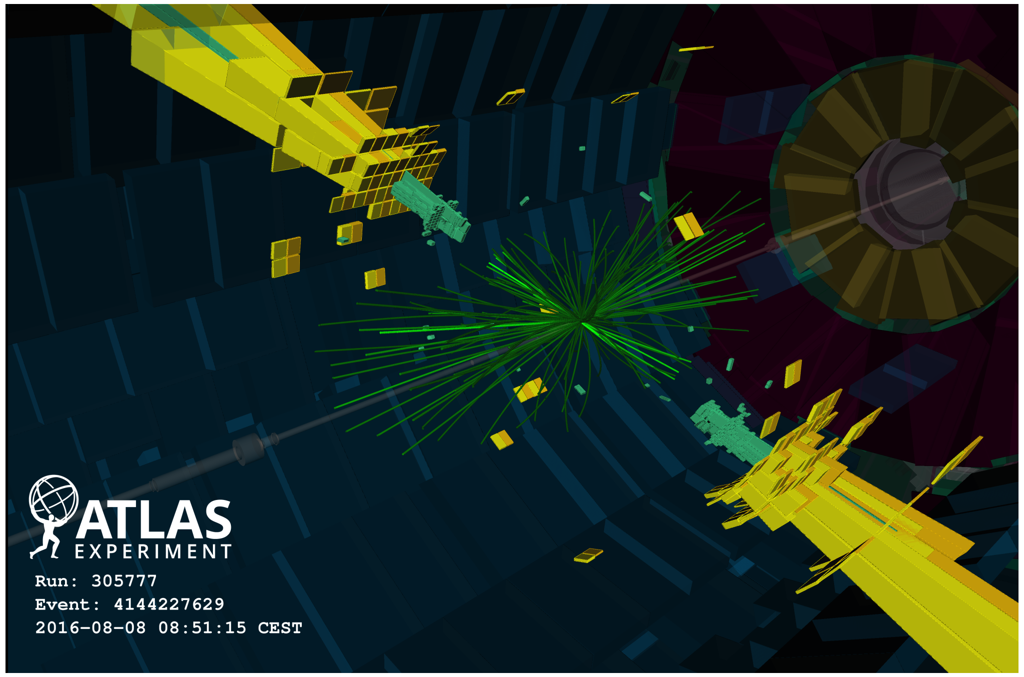
- DM is recoiled against an energetic ISR photon



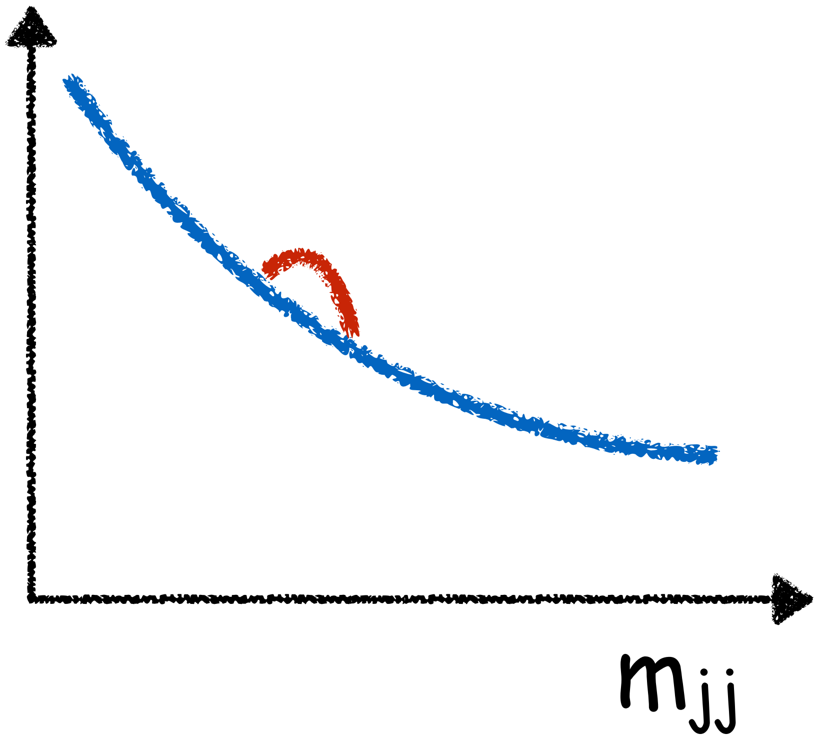


- Main backgrounds from $W/Z+\gamma$ and $\gamma+jet$ are estimated by a simultaneous fit in control regions
- Fake photons from electrons and jets are estimated separately using control region mis-identification scaling and sidebands counting methods

Visible Mediator Decays: Resonance Searches



Phys. Rev. D 96 (2017) 052004

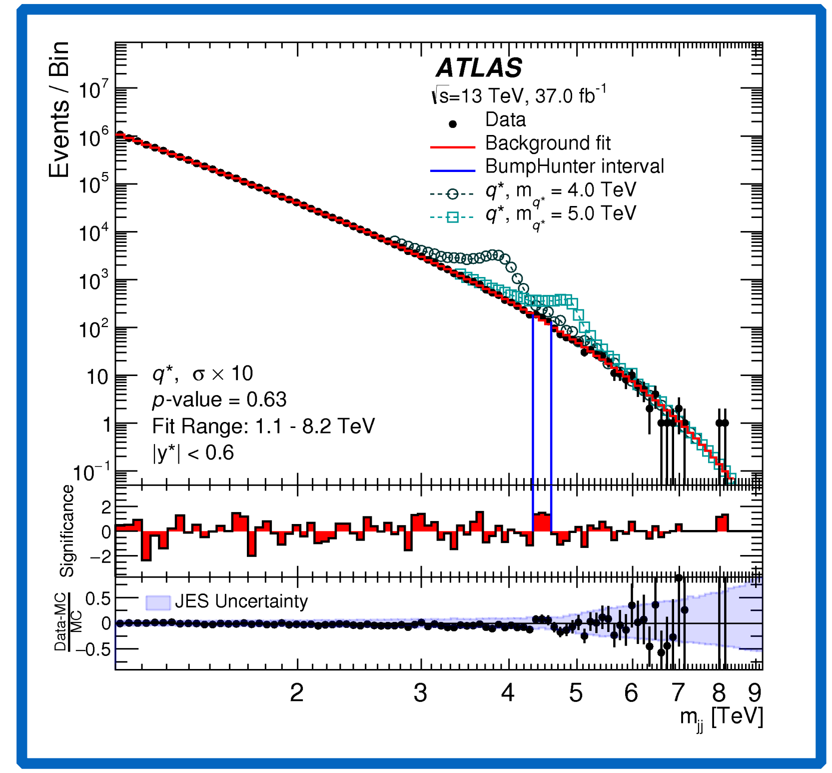


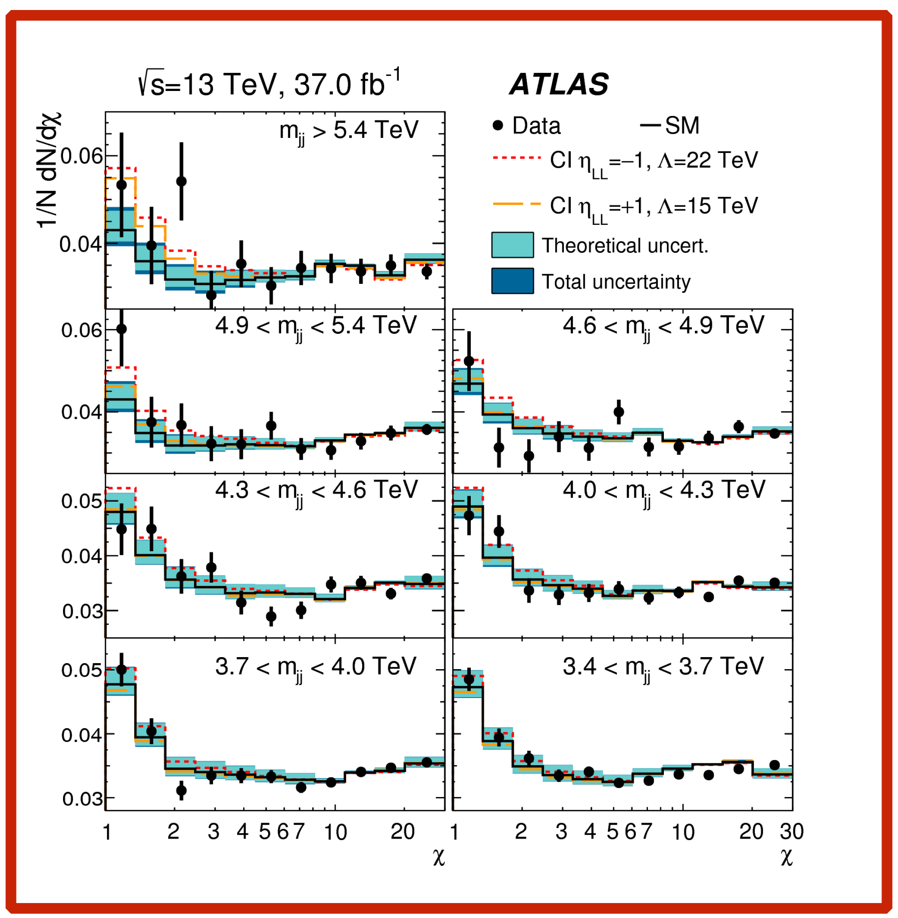
- Resonance Signature:
  - Heavy mediator decays to visible energetic objects
    - Jets, Photons, Leptons
  - The decay products form a peak in the invariant mass spectra
  - The SM processes yield smoothly falling invariant mass spectrum
  - If the resonance is narrow, there will be a bump!
    - m_{jj} or similar variables

    Observables!

Di-jet Searches I: Inclusive Search

- Di-jet resonance search is very inclusive and powerful!
  - Collect events with energetic hadronic activities (Jet or H_T)
  - Fit the m_{jj} spectrum in data (narrow)
  - See if there are significant deviations





- For contact interaction that yields broad resonances, an angular variable χ is used

$$\chi = e^{2|y^*|}$$ ($|y^*|$ is the rapidity difference)

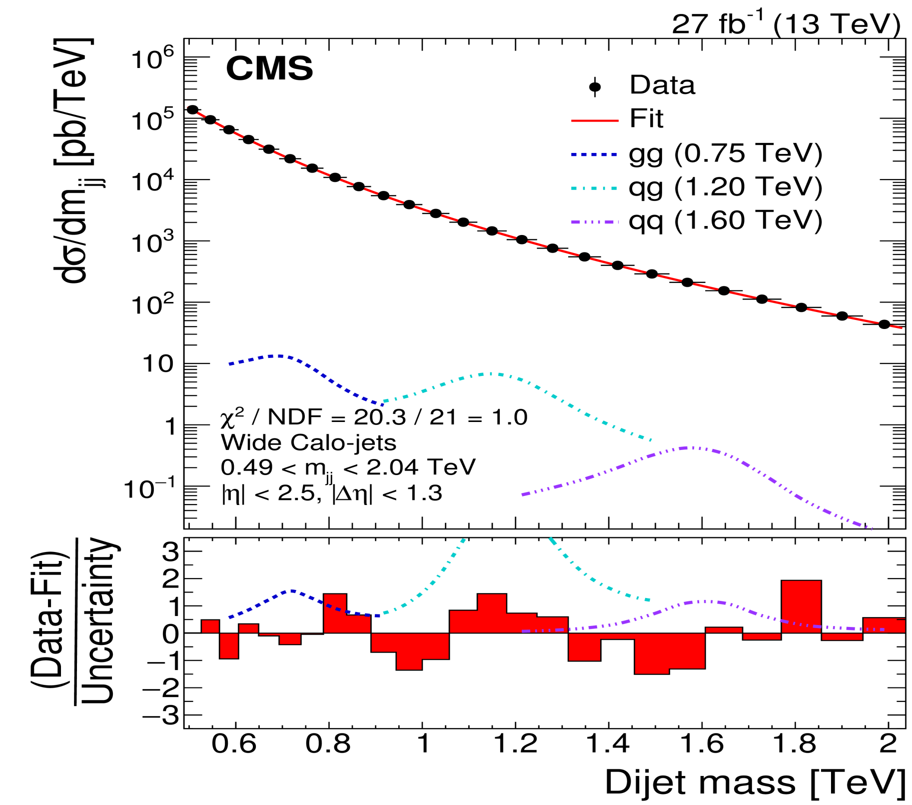
- New physics populates at small χ

Phys. Rev. D 96 (2017) 052004

Di-jet Searches II: Trigger Farm Analysis

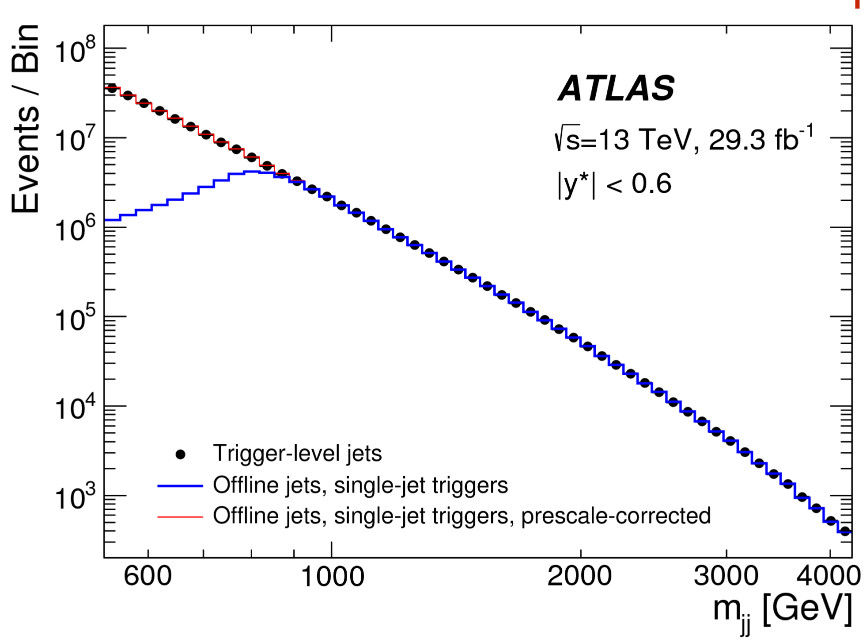
- Saving only the information at trigger level (a significantly reduced subset of higher level objects) allows ATLAS and CMS to record events at much higher rates

arxiv:1806.00843



- Lower the thresholds

arxiv:1804.03496

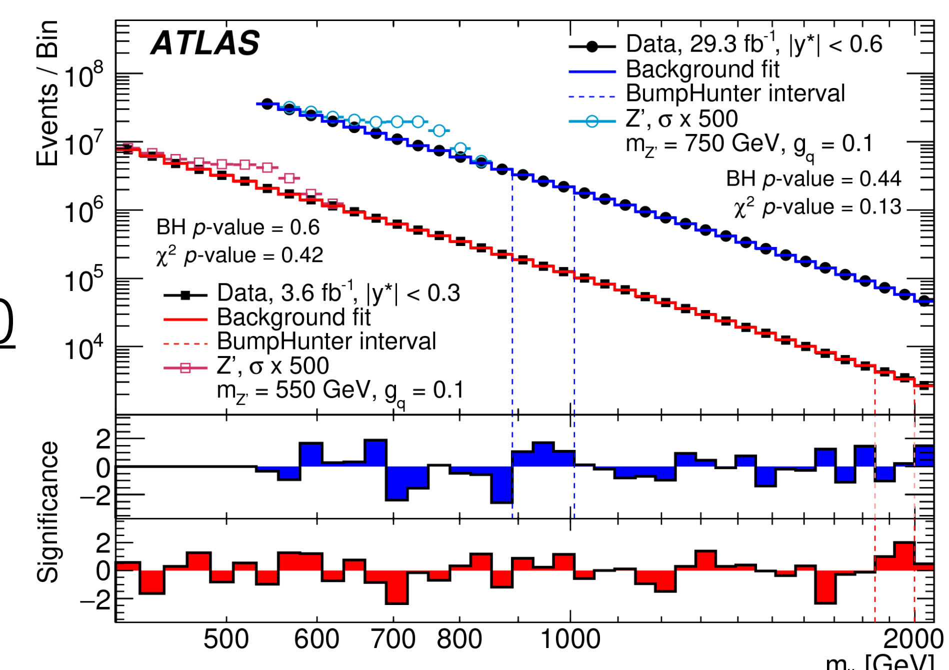


Trigger Level

vs

Offline

arxiv: 1804.03496



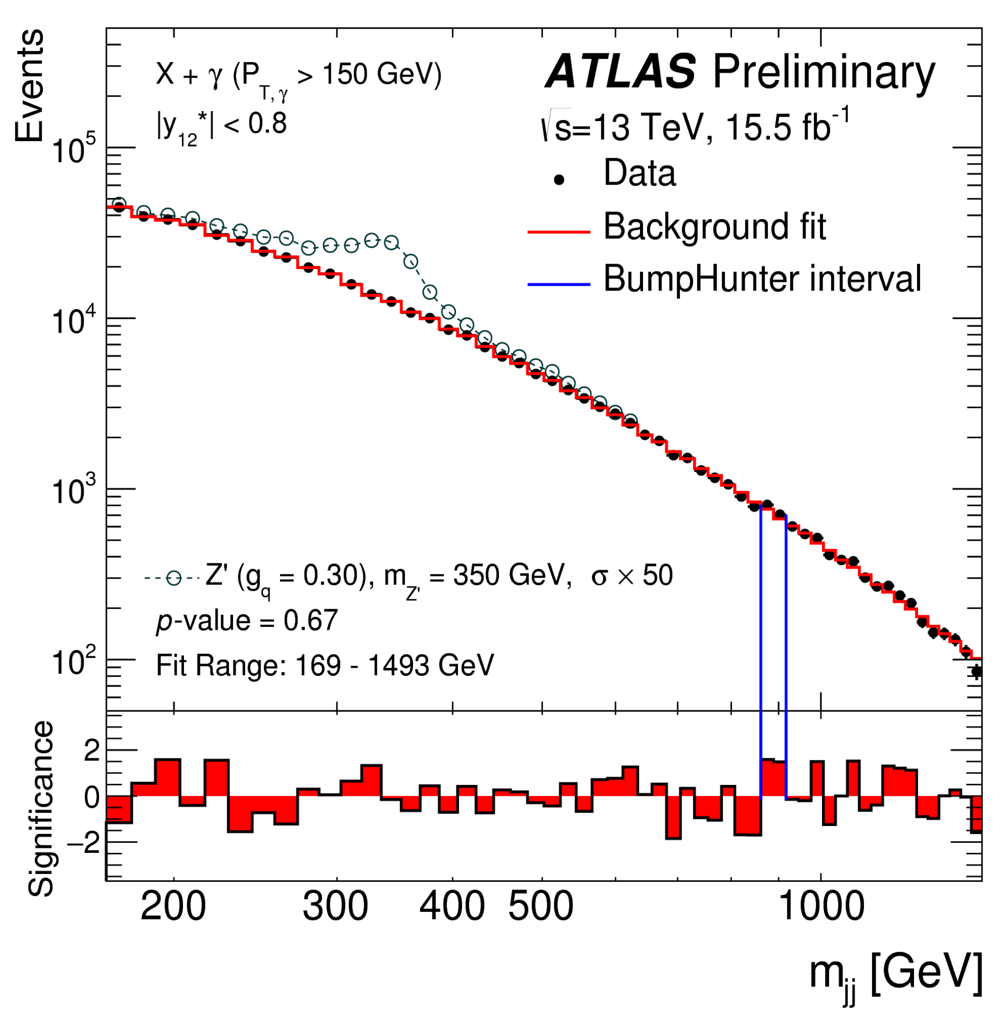
Terminology:

CMS: Data-Scouting

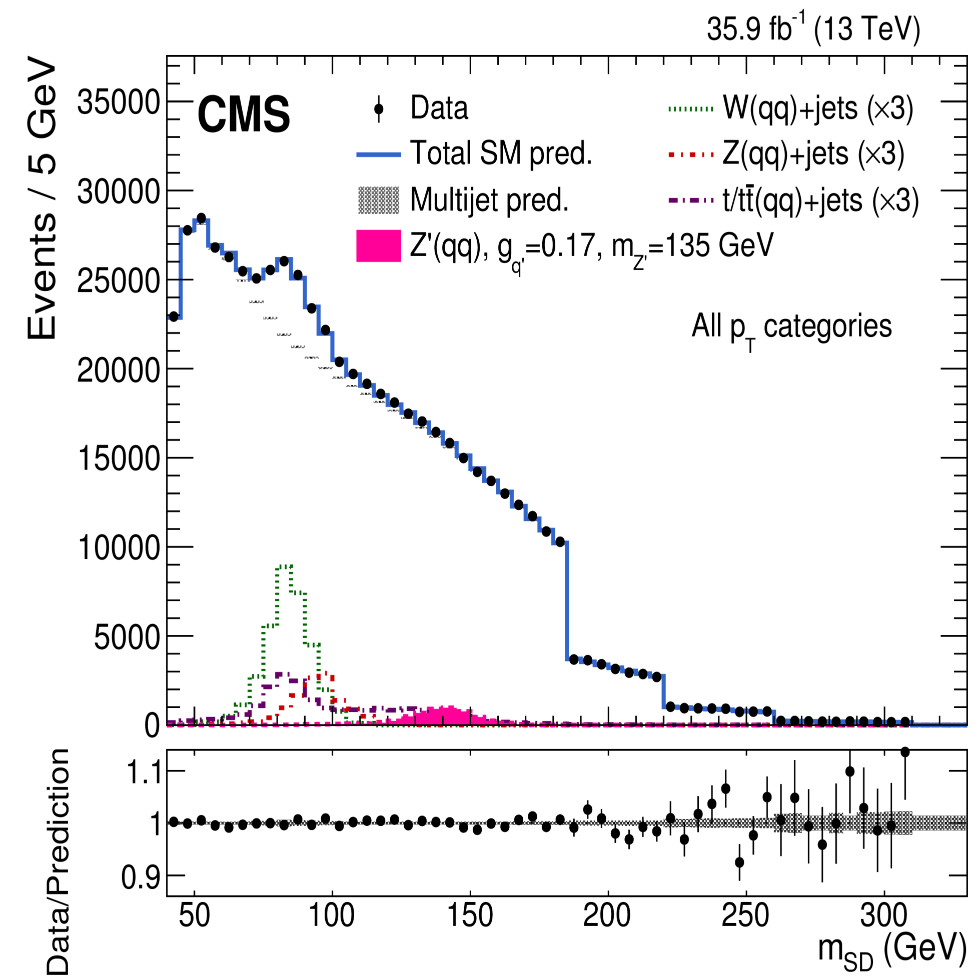
ATLAS: Trigger Level Analysis

Di-jet Searches III: Resonance with ISR

- Another way to reach lower mass region is to target the resonance produced with initial state radiation
  - Trigger on the ISR objects
- The two jets can be resolved or merged



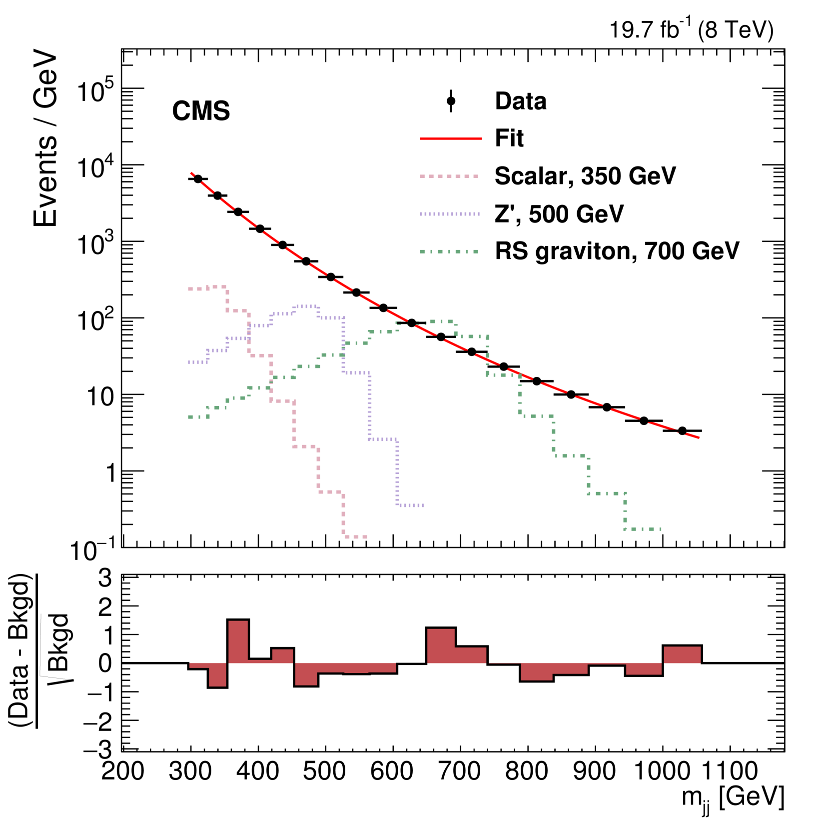
ATLAS-CONF-2016-070

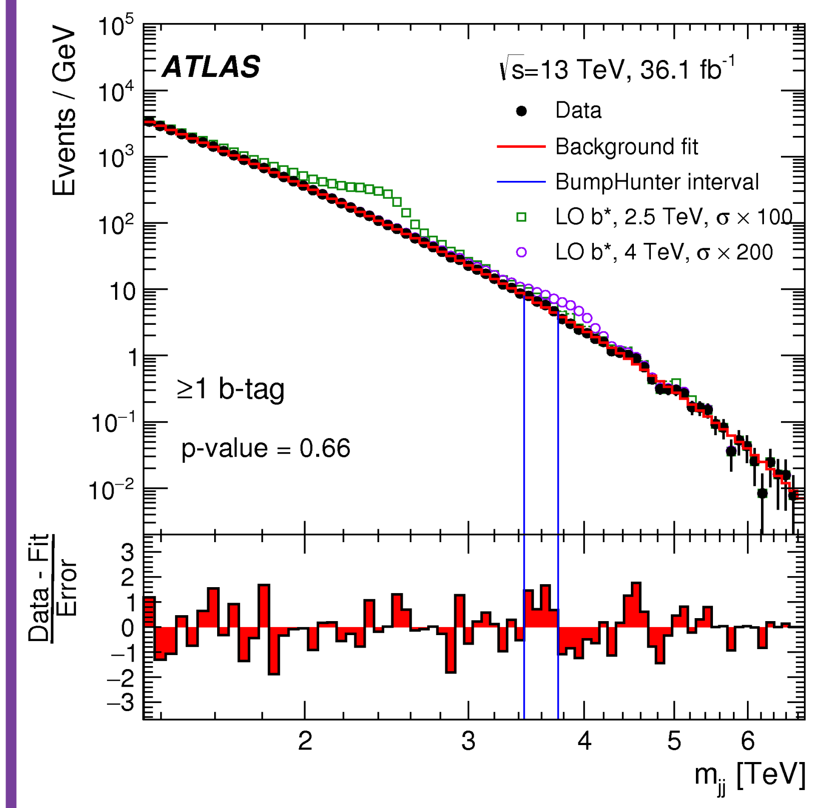


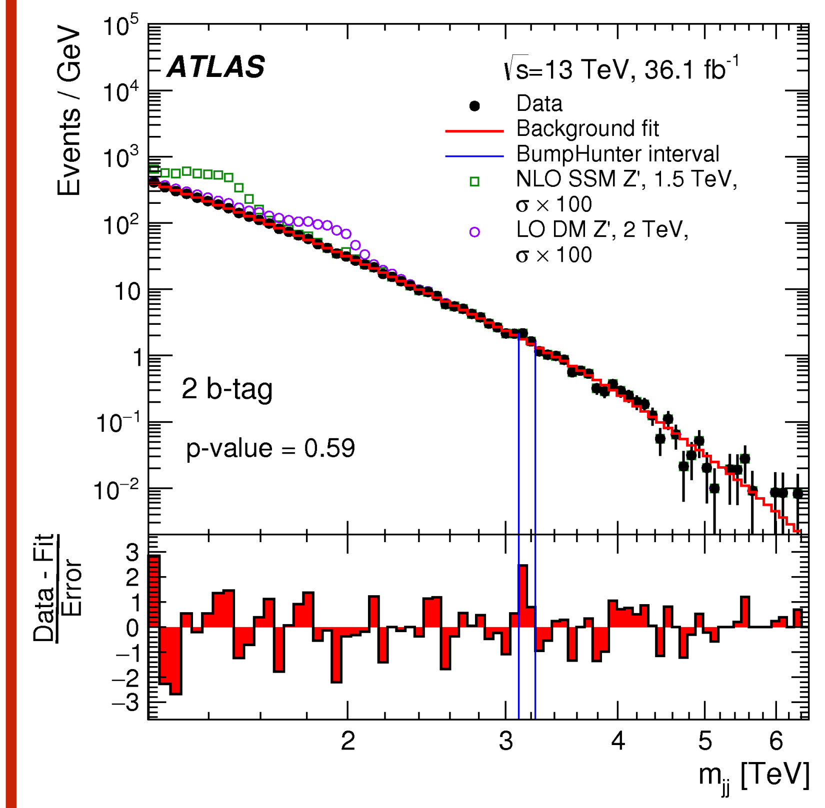
JHEP 01 (2018) 097

Di-jet Searches IV: B-tagged Di-jet

- The new mediator may have larger couplings to bottom quarks
  - Apply b-tagging increases the sensitivity and lowers the trigger thresholds
  - CMS 8 TeV Result
    - Low mass via tight b-jet trigger; High mass via loose b-jet trigger
  - ATLAS 13 TeV Result
    - High mass via jet trigger, >=1 b-jet or 2 b jets; Low mass via b-jet trigger, 2 b jets



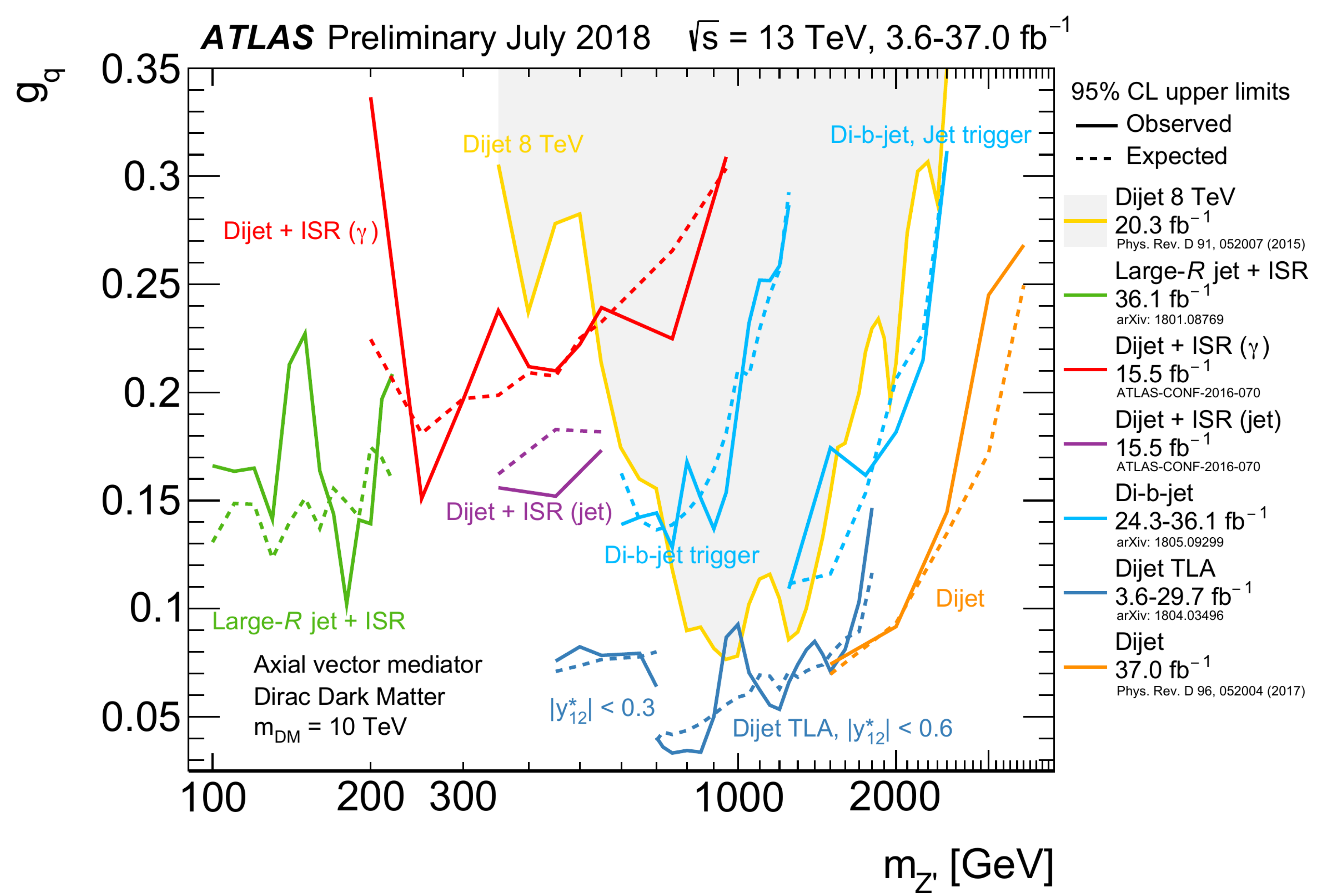




CMS: Phys. Rev. Lett. 120 (2018) 201801

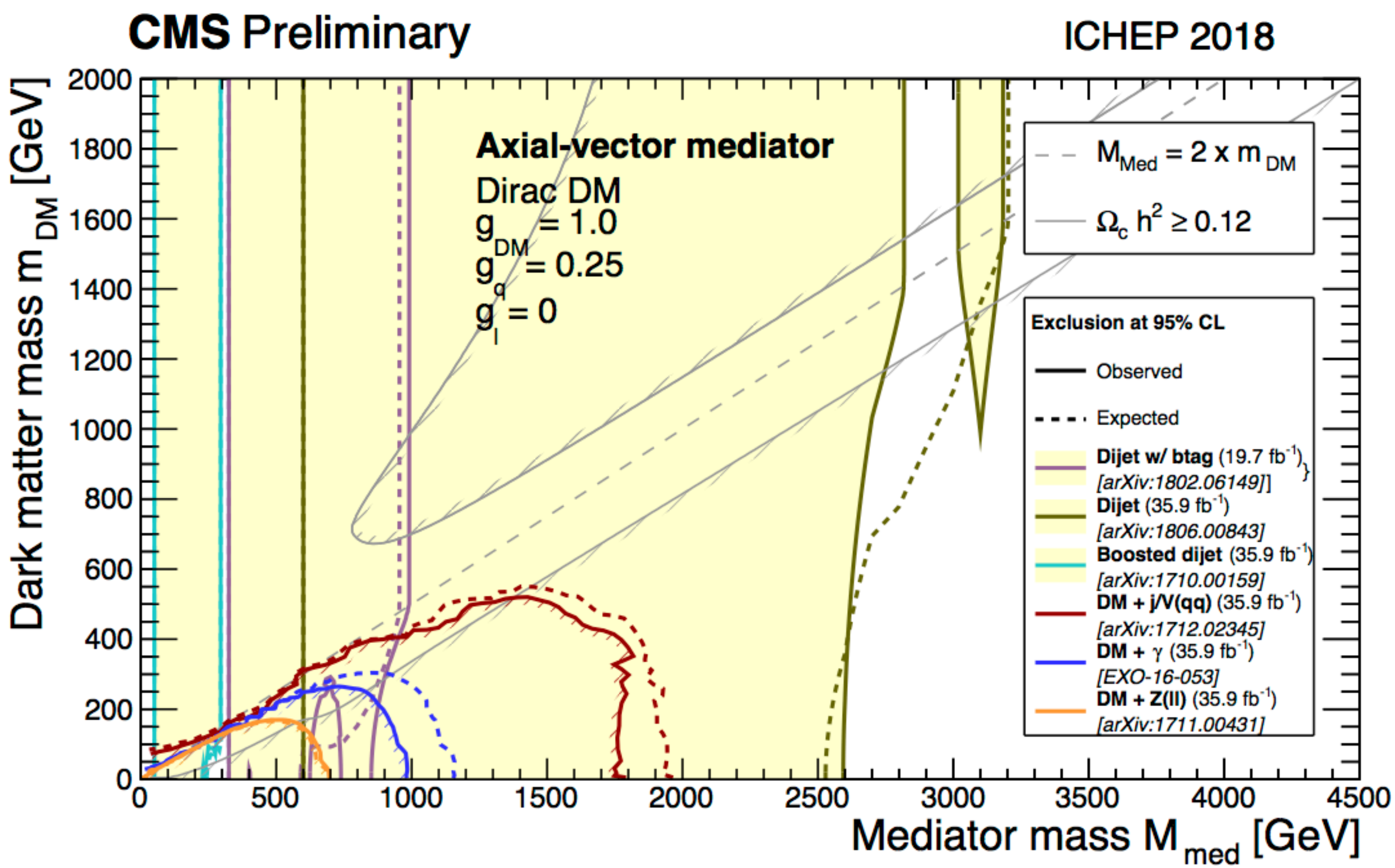
ATLAS: arxiv:1805.0929

Resonance Summary



- Di-jet resonance searches via various techniques cover a wide mediator mass range

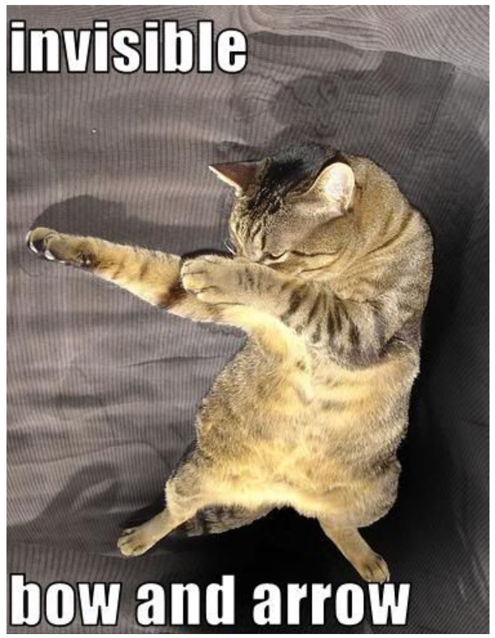
Resonance vs Mono-X



- Resonance and Mono-X searches complements each other

Associated Production: DM with Heavy Flavor Quarks/Higgs

Internet Preliminary



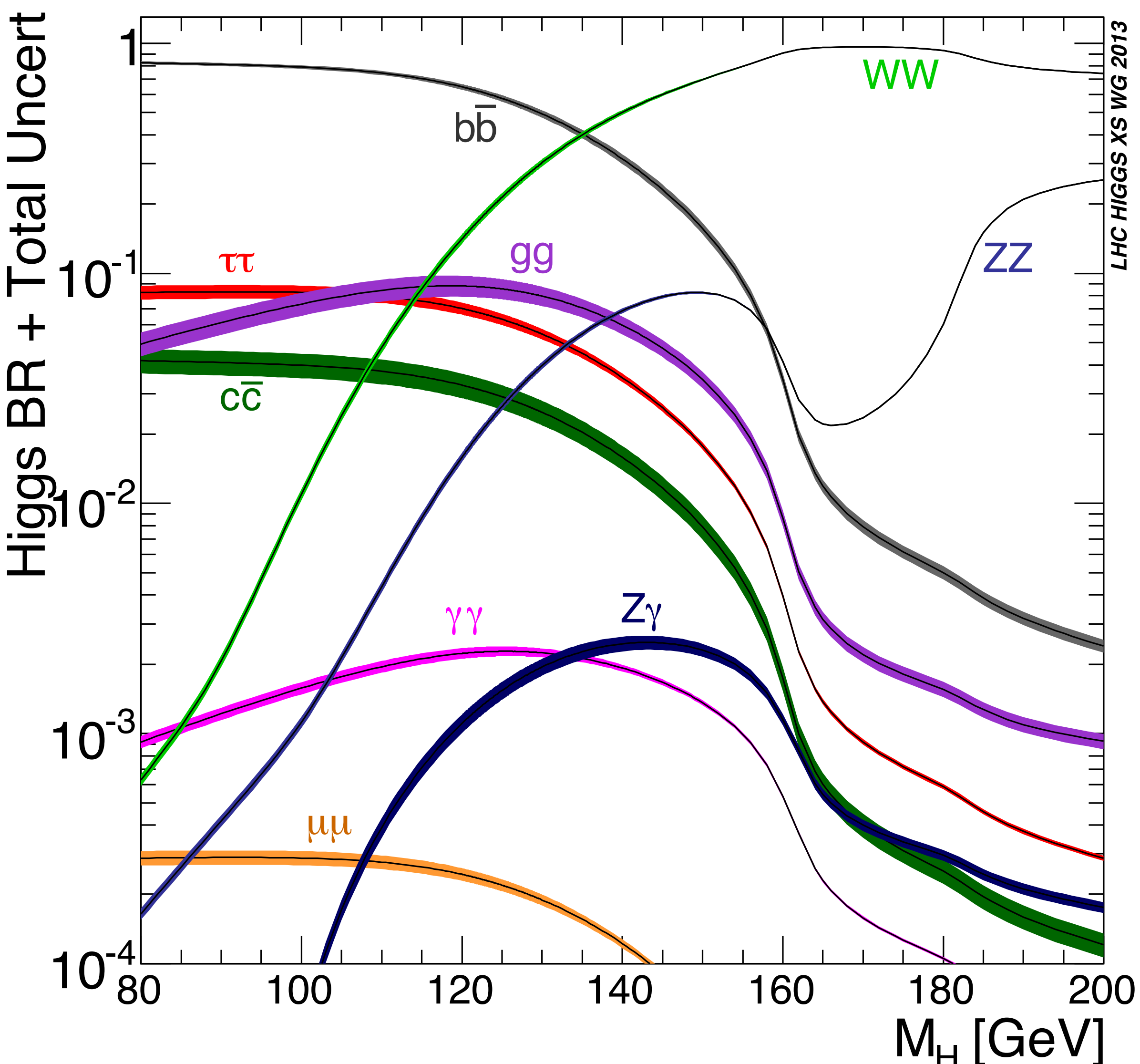
so we know what is missing exactly

- Signatures:
  - DM produced associated with objects with unique signatures
    - Top, Bottom, Higgs,
  - Lower production rates but much higher background rejection
    - E_T^{miss} ($\vec{p}_T^{\,miss}$)
    - Other variables specific for the spectators

Observables!

DM Produced with SM Higgs

- SM Higgs has unique signatures that provide us a good opportunity to probe DM
- Many channels are available:



Arxiv:1201.3084

- Several of the channels have been searched
  - $b\bar{b}$, $\gamma\gamma$, $\tau\bar{\tau}$

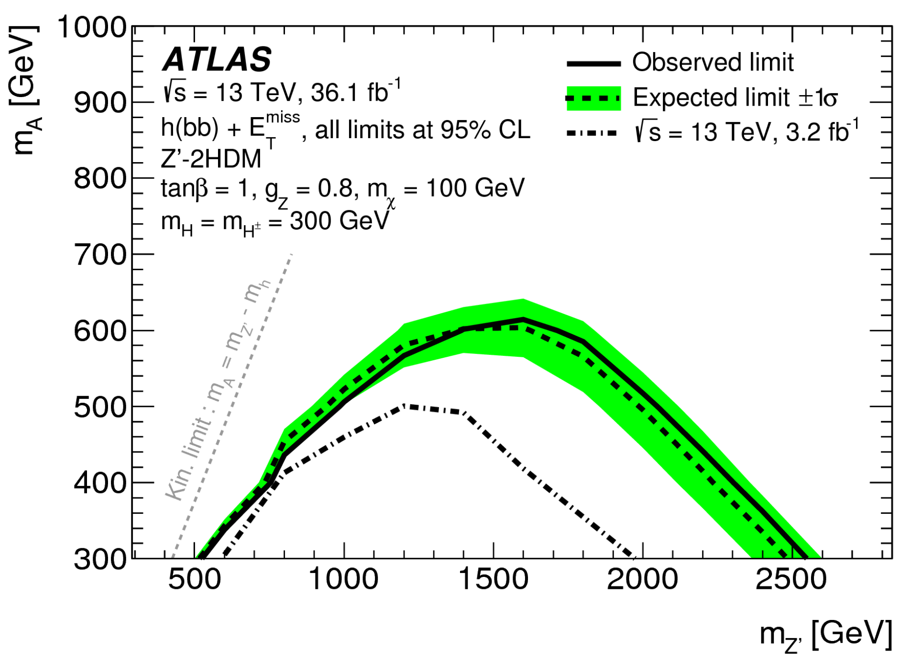
E_T^{miss} + H	ATLAS	CMS
$H(b\bar{b})$	ATLAS-CONF-2018-039	
$H(b\bar{b}$ or $\gamma\bar{\gamma})$		JHEP 10 (2017) 180
$H(\gamma\bar{\gamma})$	PhysRevD.96.112004	PAS-EXO-16-054
$H(\gamma\bar{\gamma}$ or $\tau\bar{\tau})$		PAS-EXO-16-055

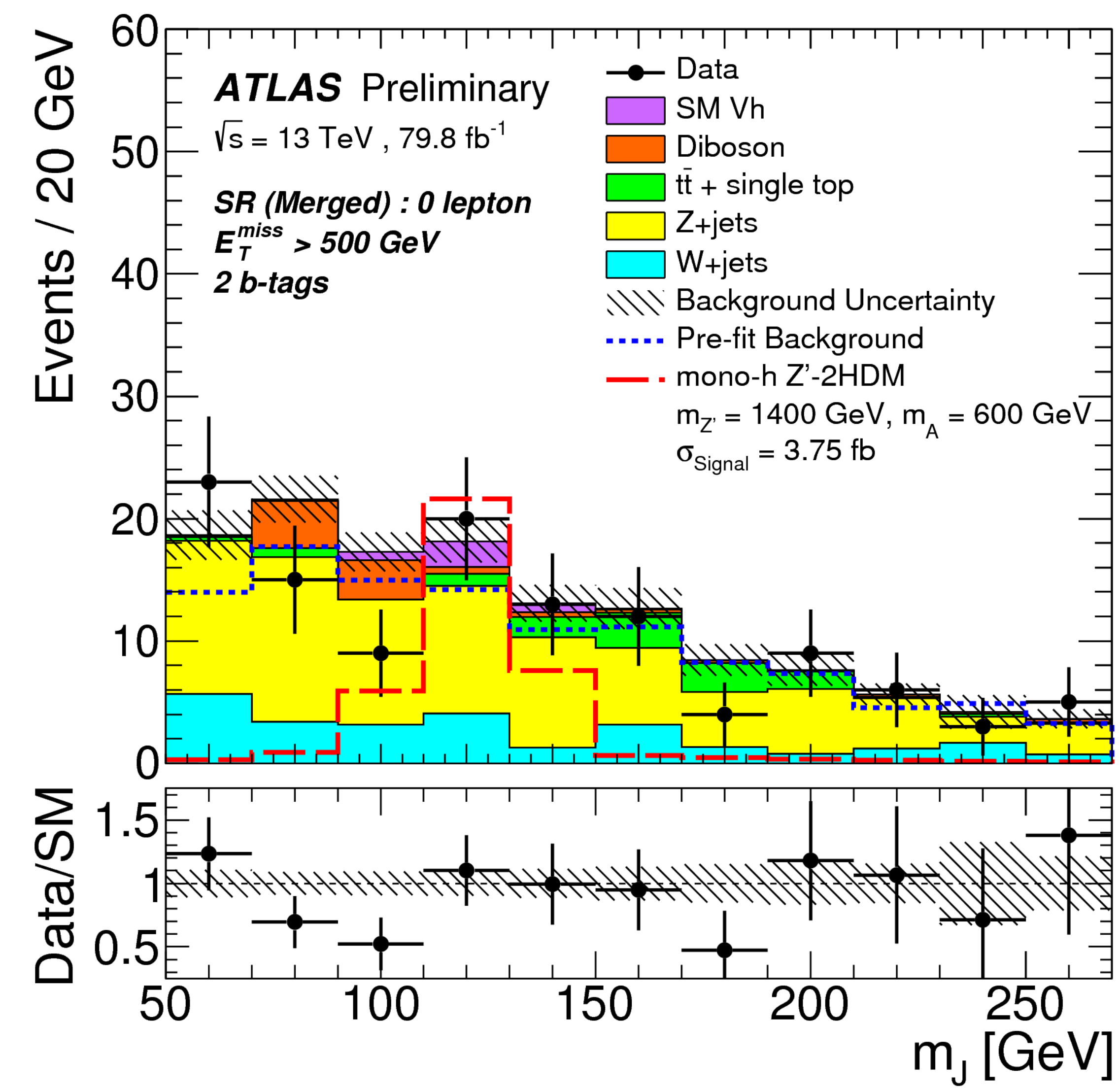
MET + Higgs ($\rightarrow b\bar{b}$)

- Higgs Boson produced with DM is highly boosted when the DM particle is massive
  - Two bottom jets can be merged
  - Benefit from a dedicated boosted Higgs ($\rightarrow b\bar{b}$) Boson tagger (ATLAS-CONF-2016-039)

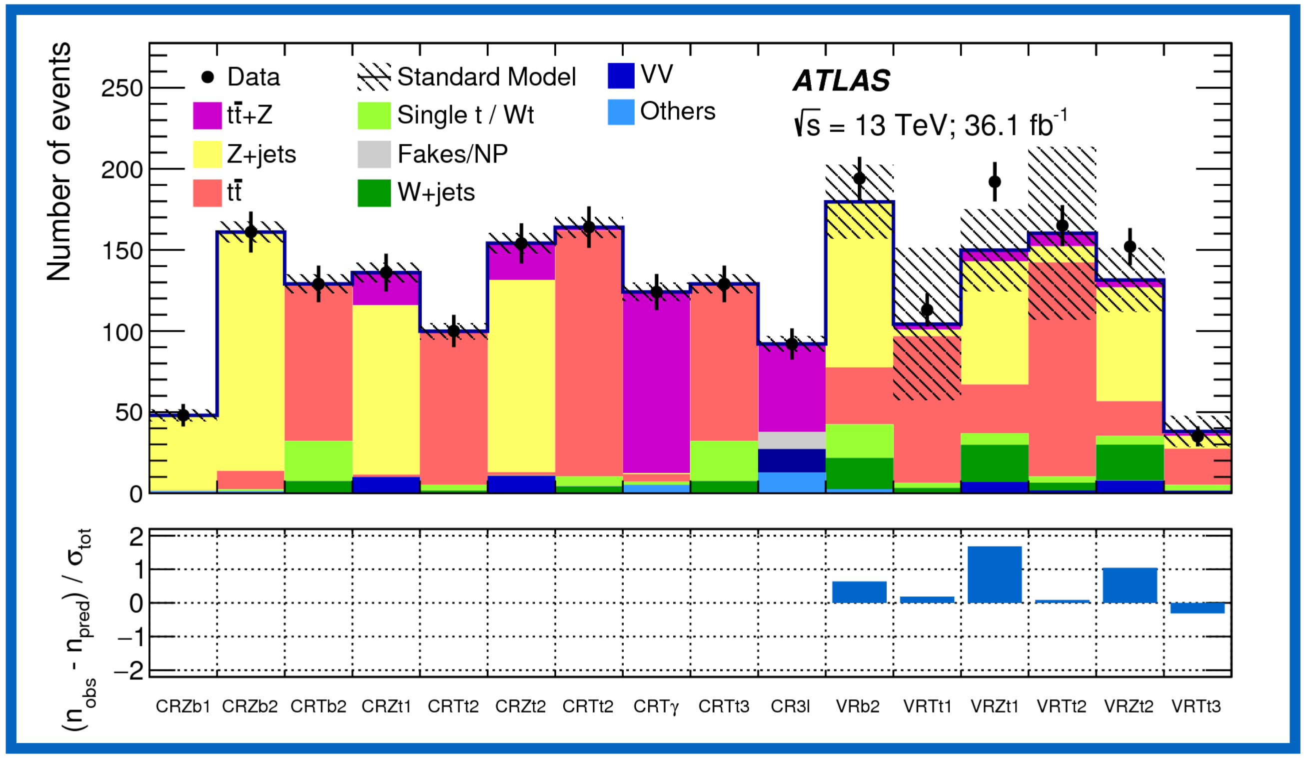
ATLAS-CONF-2018-039

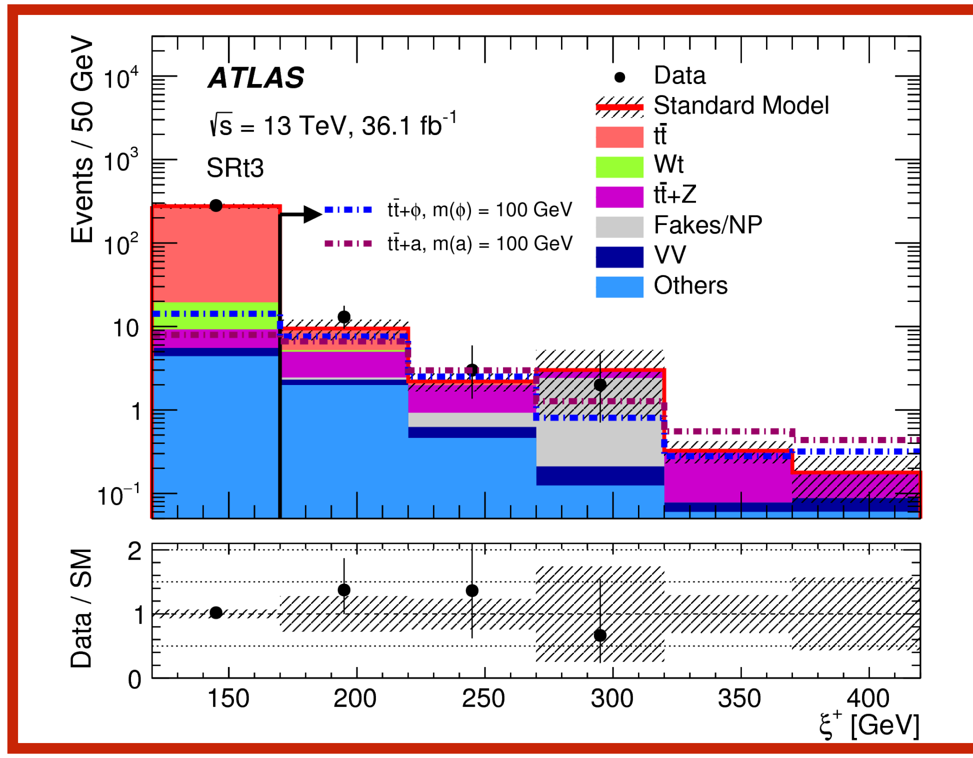
- Four signal regions to cover a large E_T^{miss} range
- A binned likelihood fit to the m_H observable

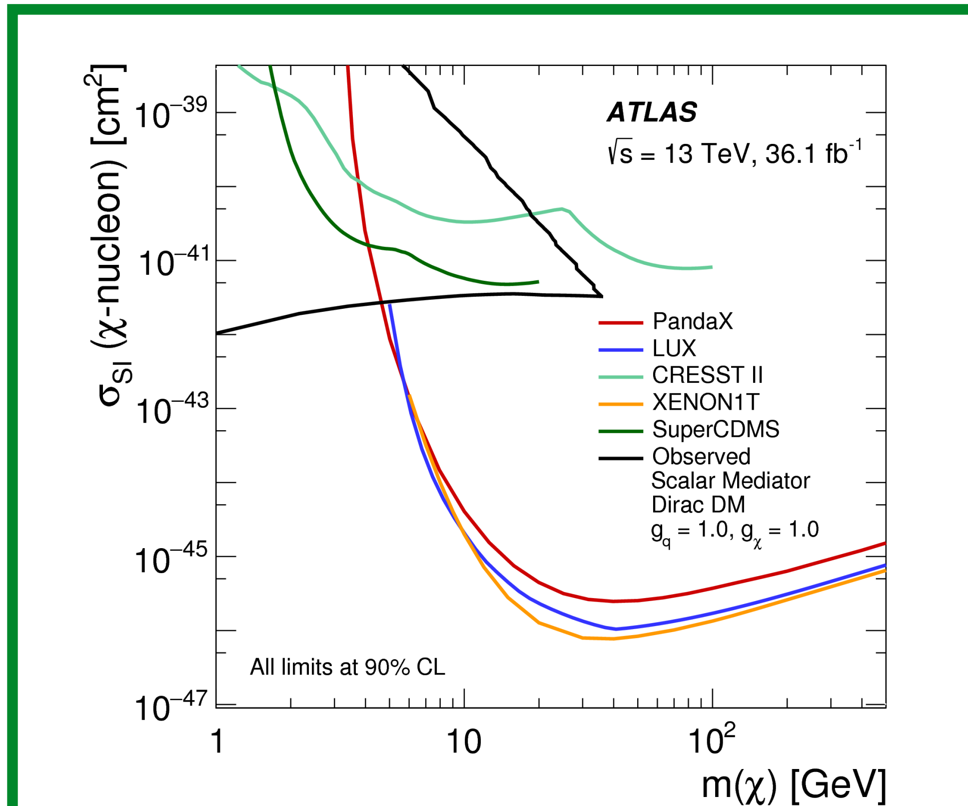




DM Produced with A Top Quark Pair







- Simultaneous fit in control regions and checked in validation regions
- Three signal regions optimized for top associated production (SRt3 is shown)
- Limits on spin-independent DM-nucleon are compared with direct detection experiments

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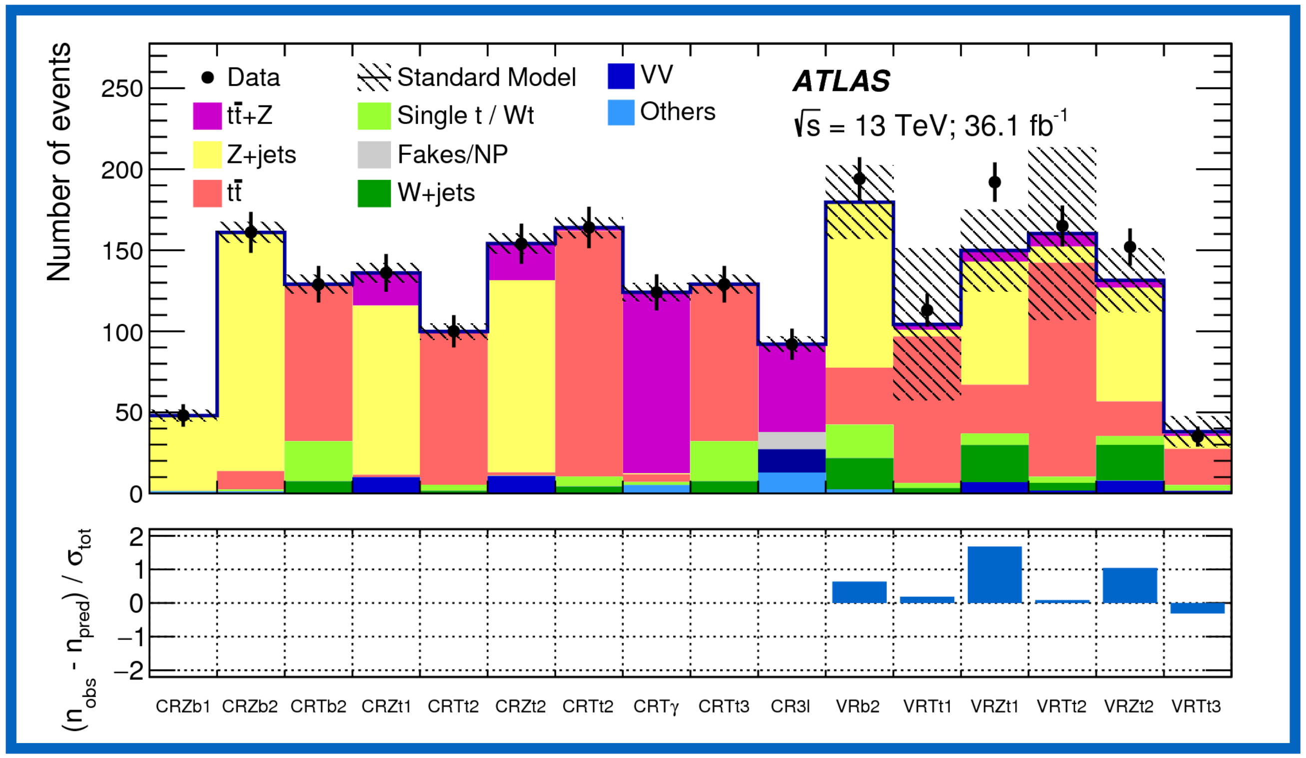
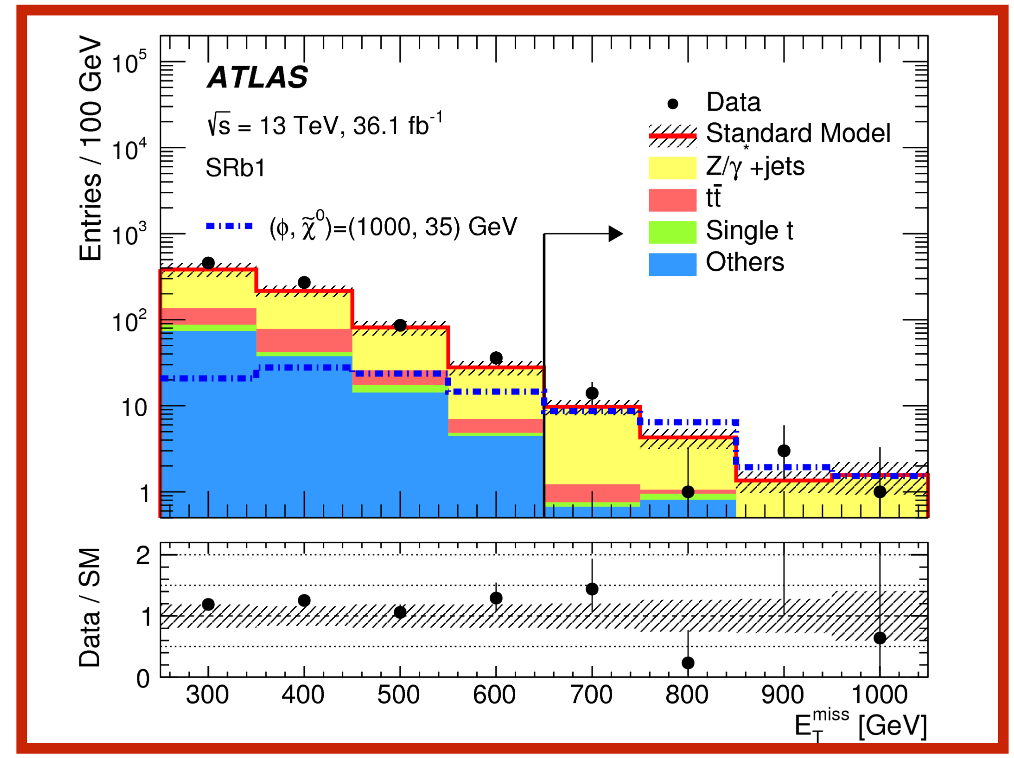
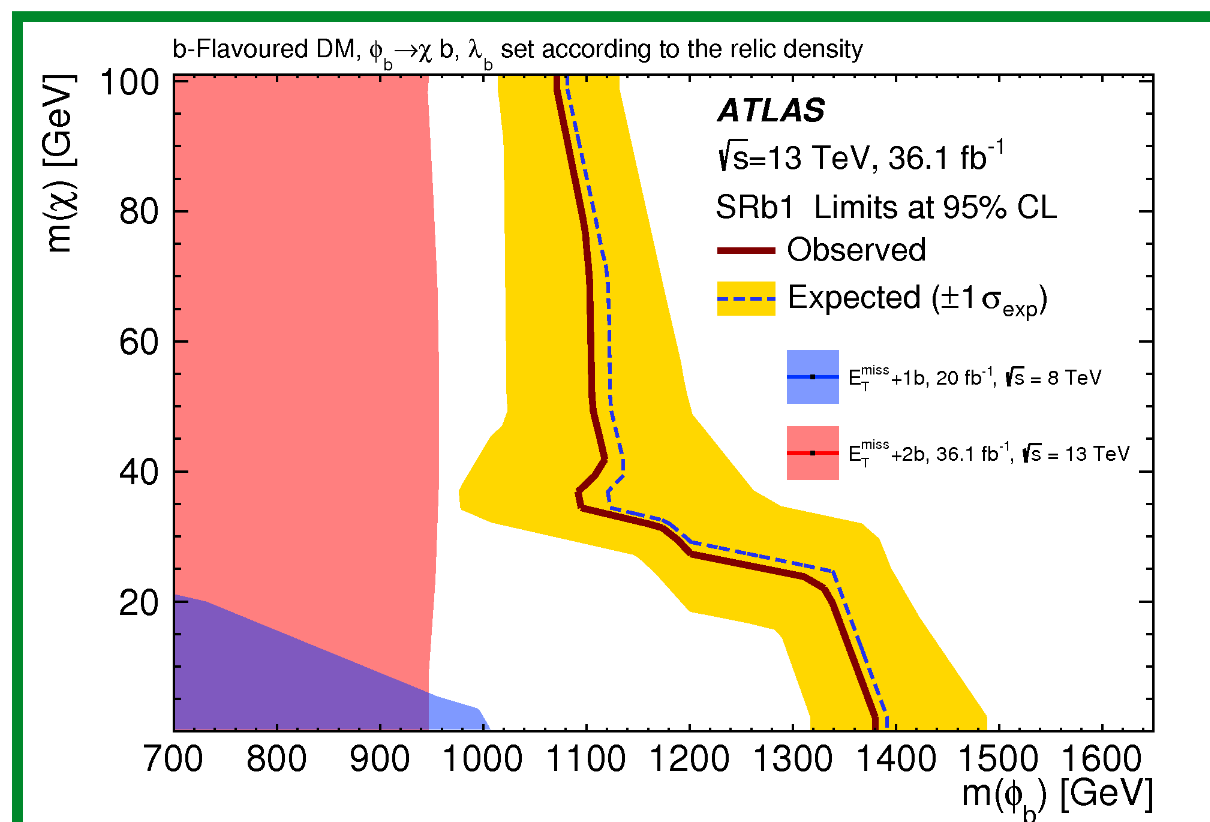
DM Produced with A Bottom Quark Pair





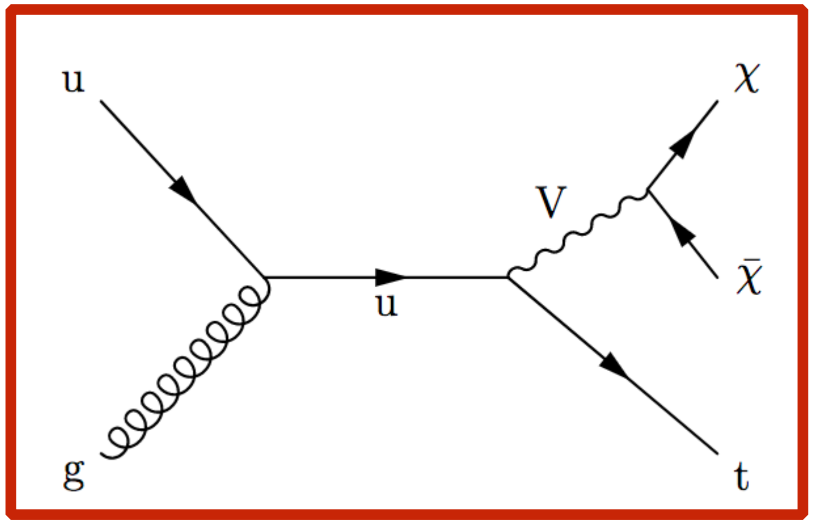


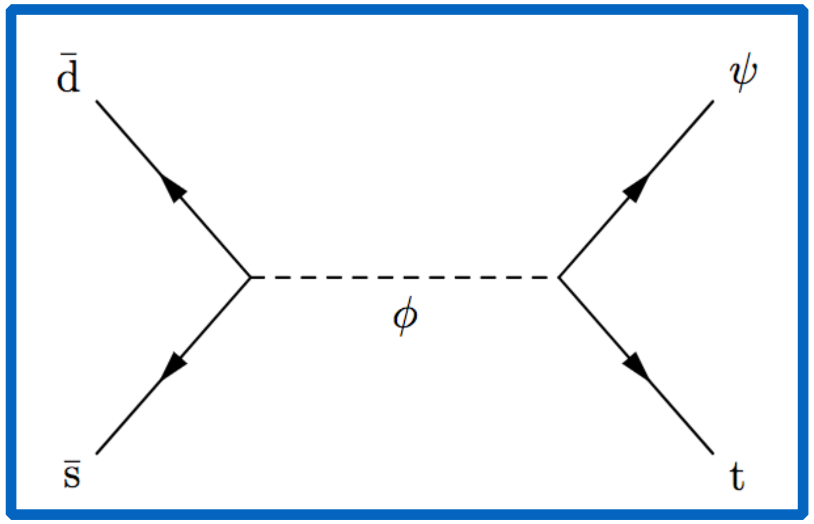
- Simultaneous fit in control regions and checked in validation regions
- Two signal regions optimized for bottom associated production (SRb1 is shown)
- Limits are compared with the bottom squark pair search and b-FDM search

Eur. Phys. J. C 78 (2018) 18

DM Produced with A Top Quark

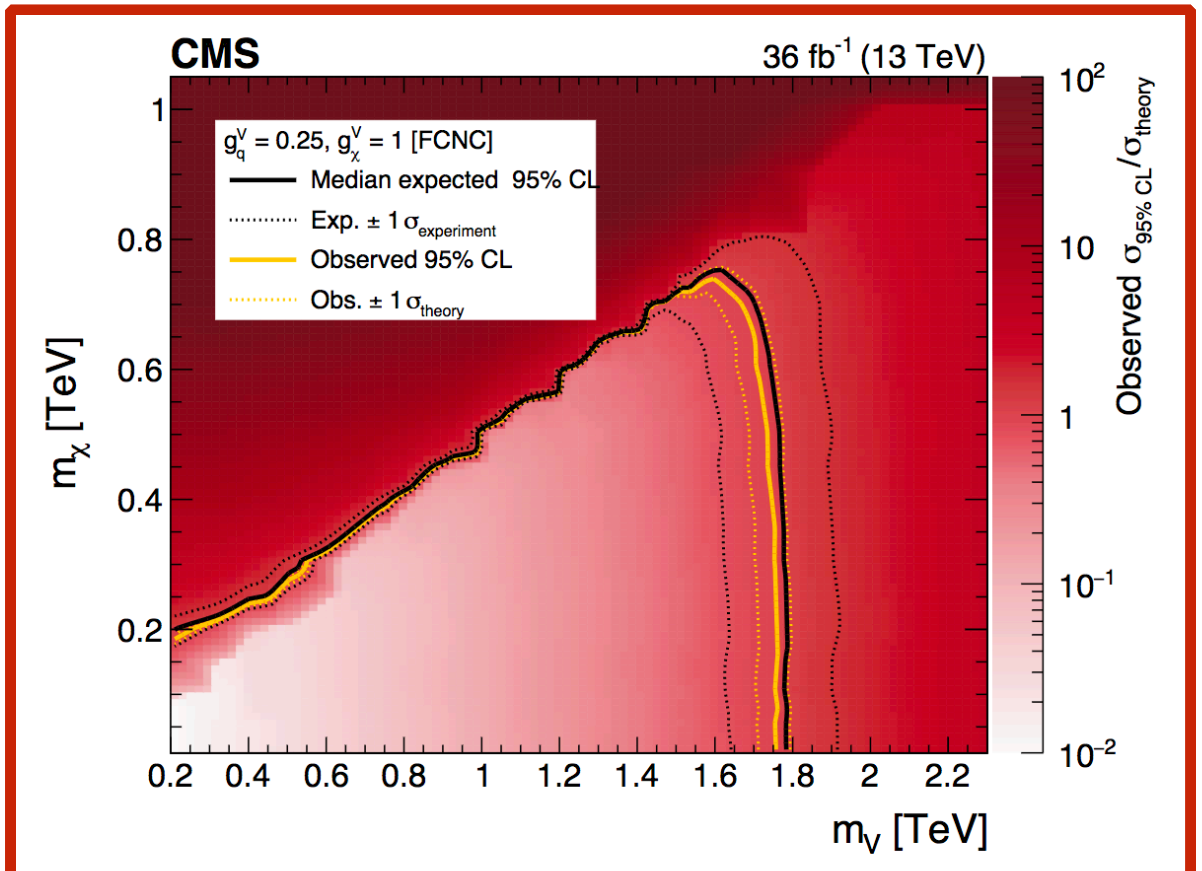
Arxiv: 1801.08427

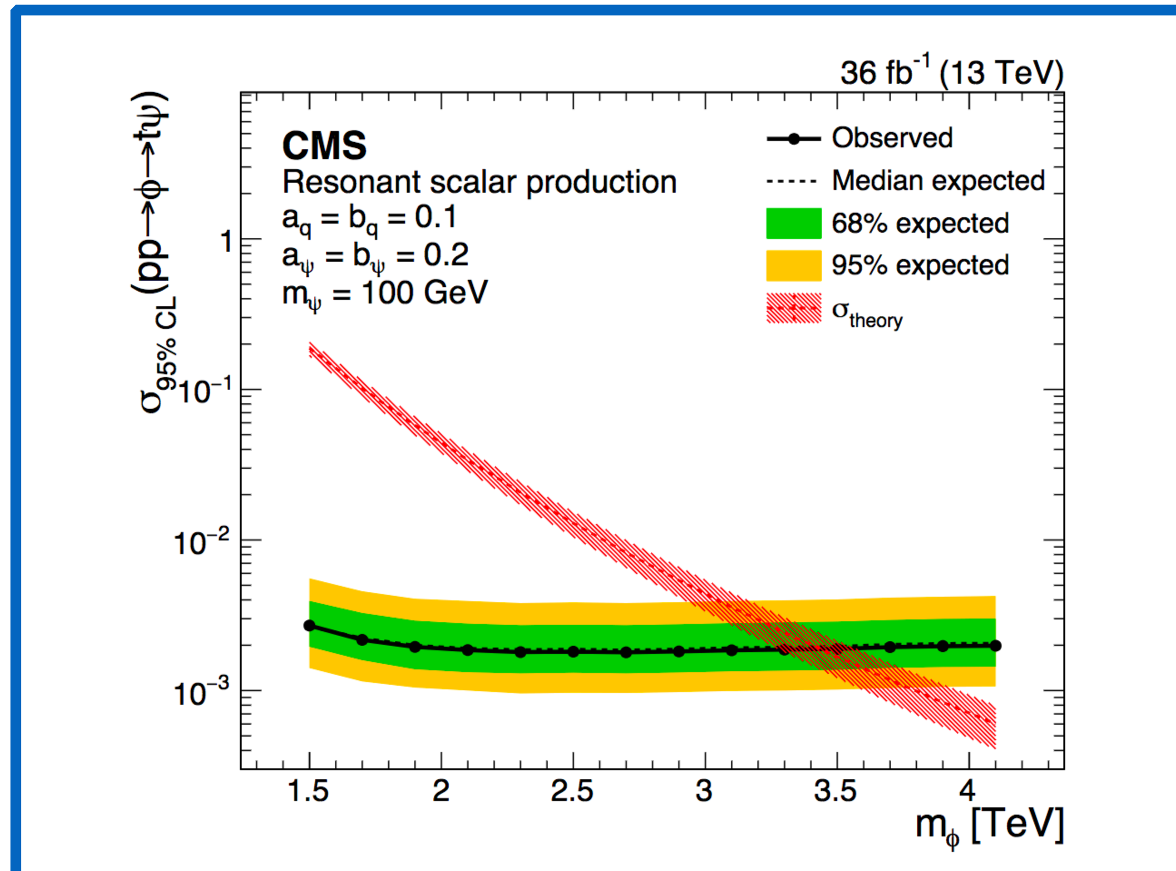




Non-resonant Mode (FCNC)

Resonant Mode





Other CMS top + DM Results: Arxiv:1807.06522 and CMS-PAS-EXO-18-010

Conclusion and Outlook

- The Run 2 programs at both ATLAS and CMS have searched for a large variety of DM models in a rich set of final states
  - No significant deviations from SM are found so far :(
- The LHC has a lot more data to deliver :)
  - Rare channels will be probed
- We have learned great lessons from the past
  - New directions in both theory and experiment sides to overcome the bottlenecks encountered
    - Theory uncertainties on Mono+X searches
    - Data-driven background modeling in Resonance searches
    - Innovative bottom/top/Higgs tagging techniques
  - Talk with each other more often — Dark Matter Forum
- Stay tuned!


Thank you!!