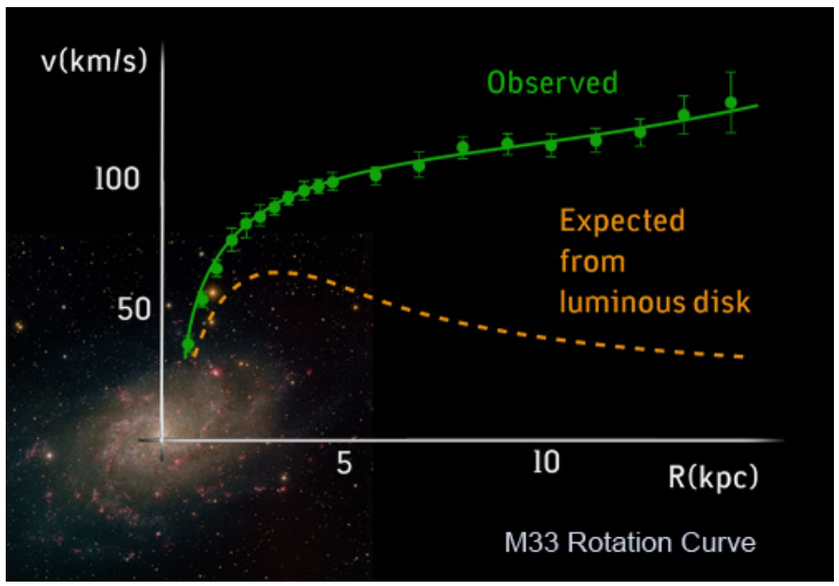
DARK MATTER AT THE LHC

Vasiliki Kouskoura
on behalf of ATLAS, CMS
and LHCb Collaborations

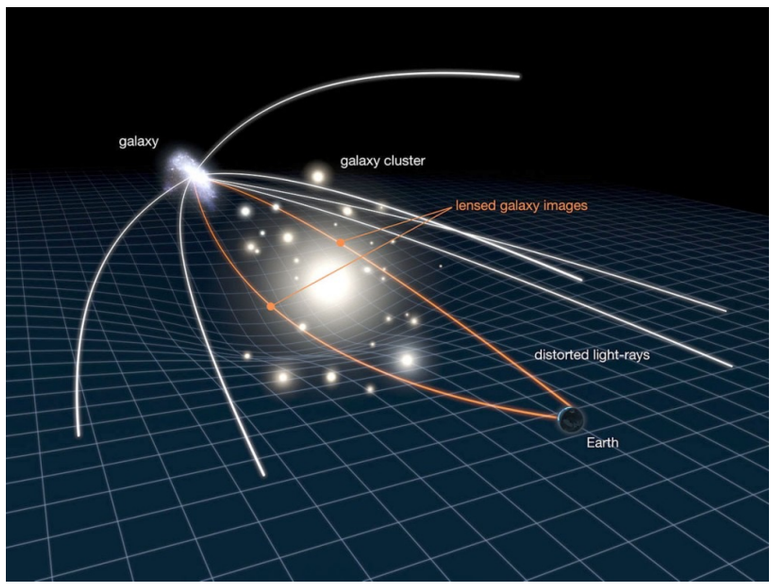
25th Rencontres du Vietnam 2018

Evidence for Dark Matter

Astrophysical observations point to the existence of Dark Matter (DM)



Galaxy rotation curves show something invisible holds the stars in observed orbit

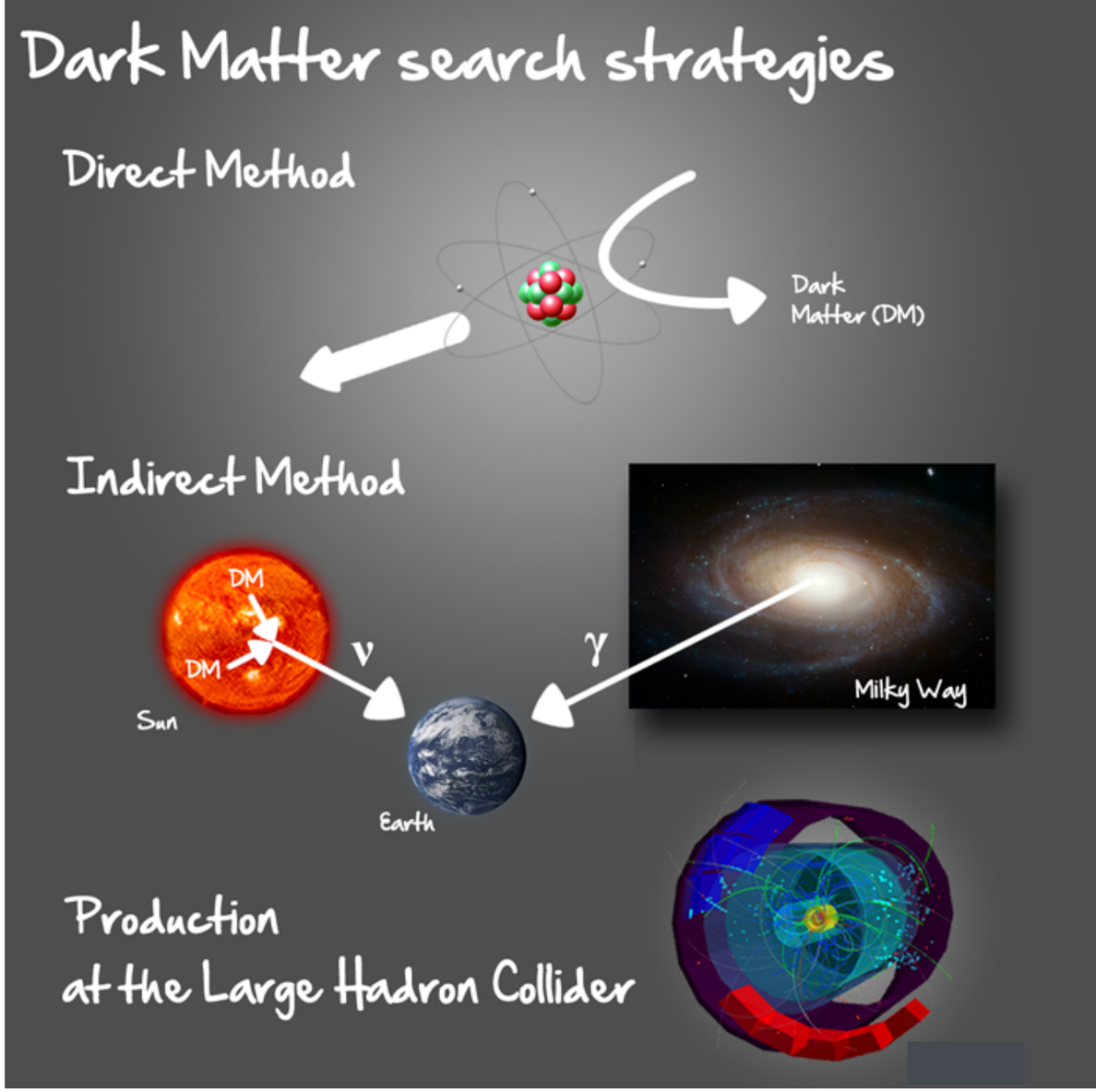


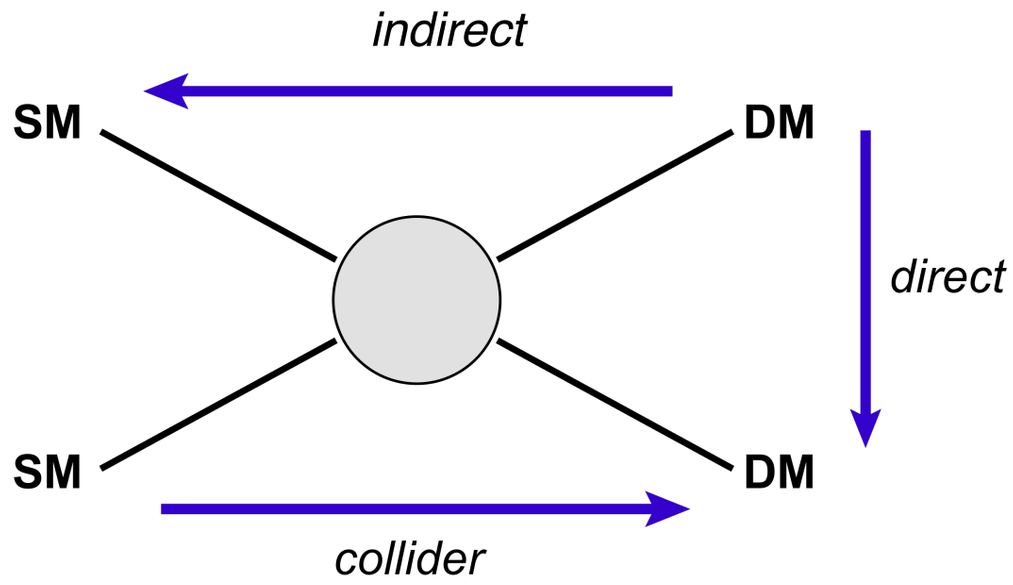
Gravitational lensing: light rays being bent by DM gravitational field

Two galaxies collide, leaving behind the interacting gas, while the DM of both galaxies passed through

Search Strategies

- **Direct**
  - Signals from nuclei kicked on by DM particle
- **Indirect**
  - Signs of annihilation of DM; SM products detected by telescopes
- **Collider**
  - DM produced in high energy particle interactions





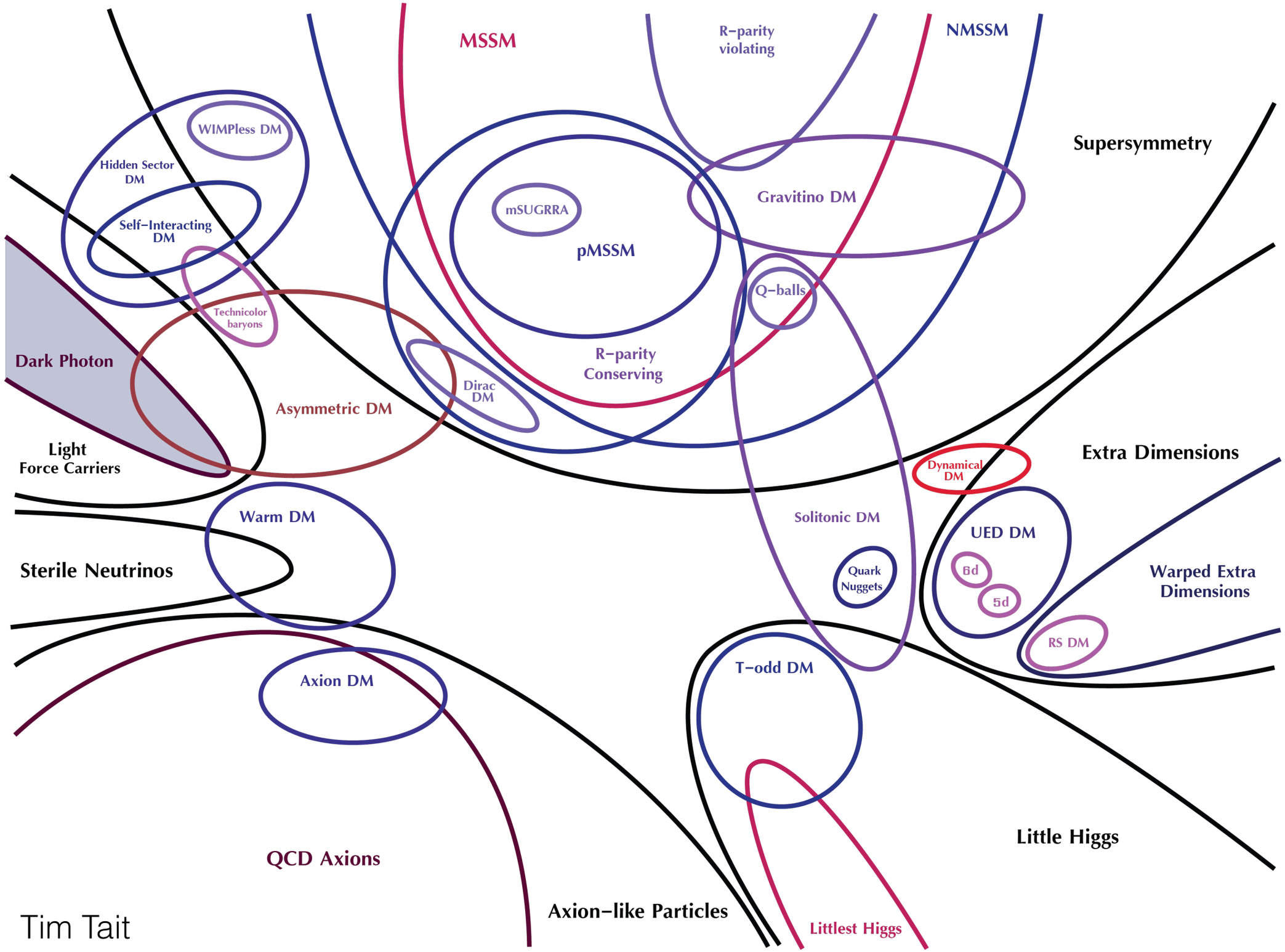
* Underlying assumption: DM has non-gravitational interaction with SM particles

So what is Dark Matter?

- Particle Physicists need to fit Dark Matter into a particle description of Nature
  - Barely interacts with ordinary matter (e.g. WIMPs - weakly interacting massive particles)
  - Massive
  - Stable or with a lifetime of order of the life of the universe

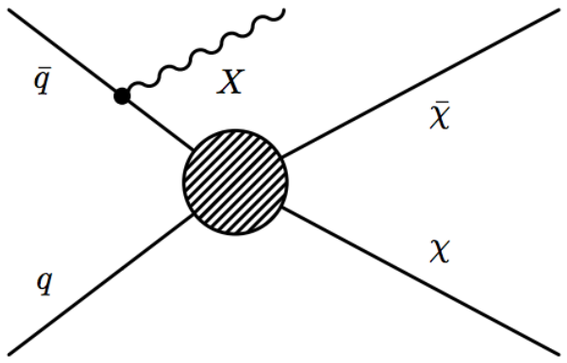
- For the moment no particle was found to be consistent with a DM candidate

Illustration of the sea of various dark matter candidates

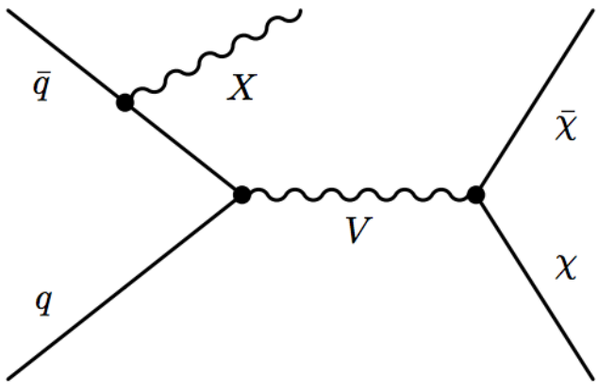


Theoretical Models for Dark Matter

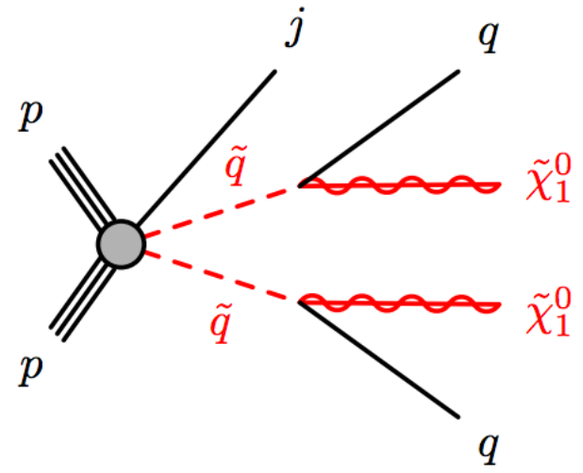
Effective field theories



Simplified Models

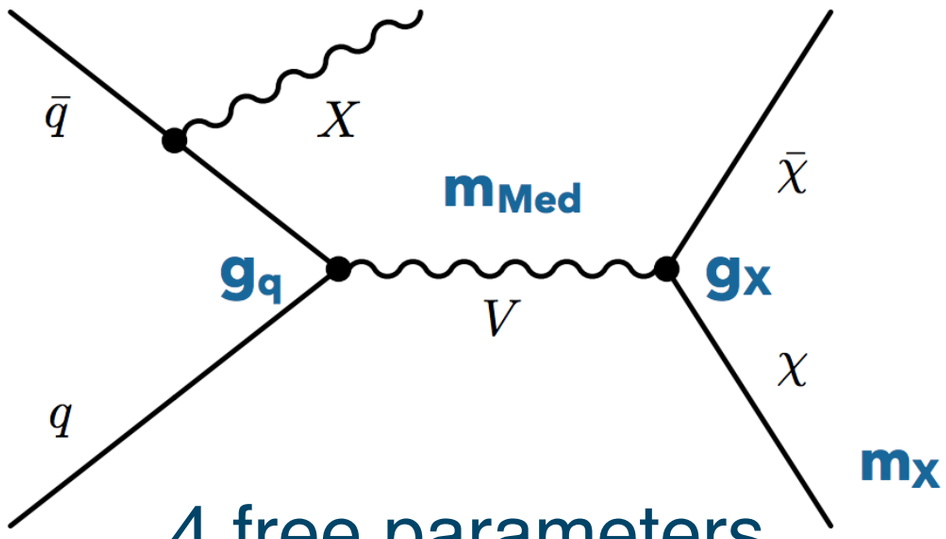


SUSY Models



Less Complete → More Complete

Number of free parameters



4 free parameters

(axial-) vector or (pseudo-) scalar mediator

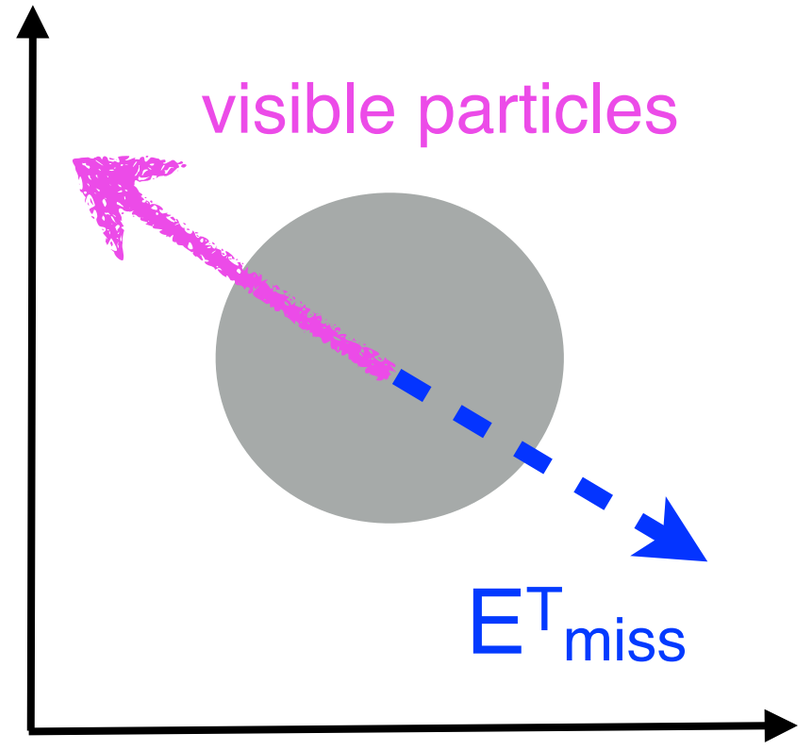
A set of well-defined simplified diagrams with heavy mediators motivated by a number of different considerations

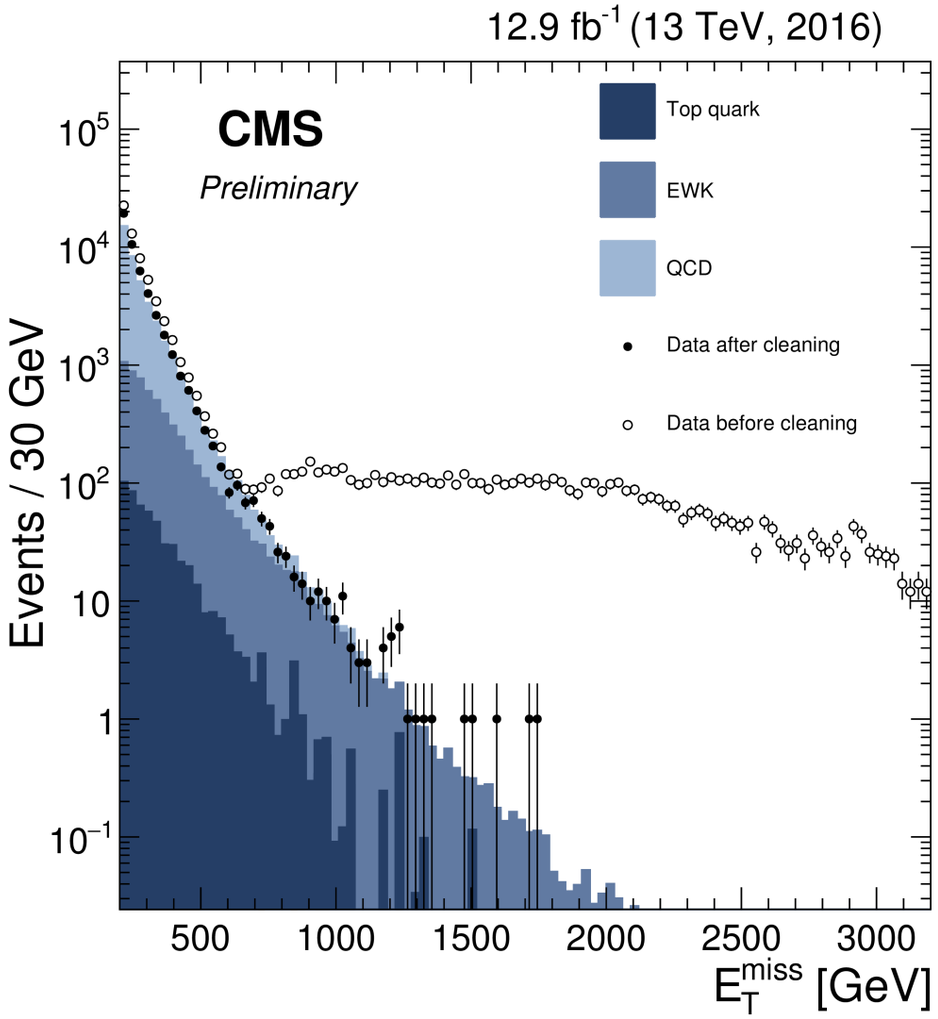
DM benchmark models at the LHC

https://arxiv.org/abs/1507.00966

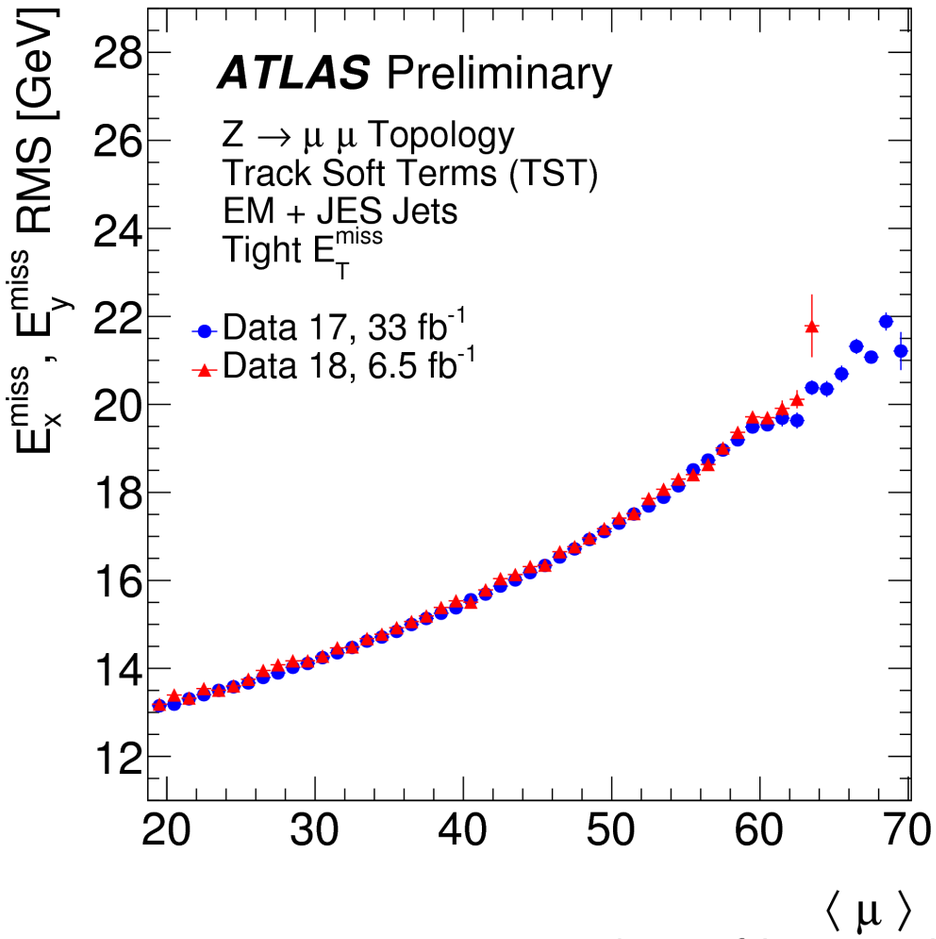
Signatures in the detector

- Missing transverse energy E^{T}_{miss}
  - Number of searches rely on large E^{T}_{miss} balancing against visible objects (jets, boosted jets, b-jets, photons, charged leptons)
- Understanding E^{T}_{miss} is not an easy task





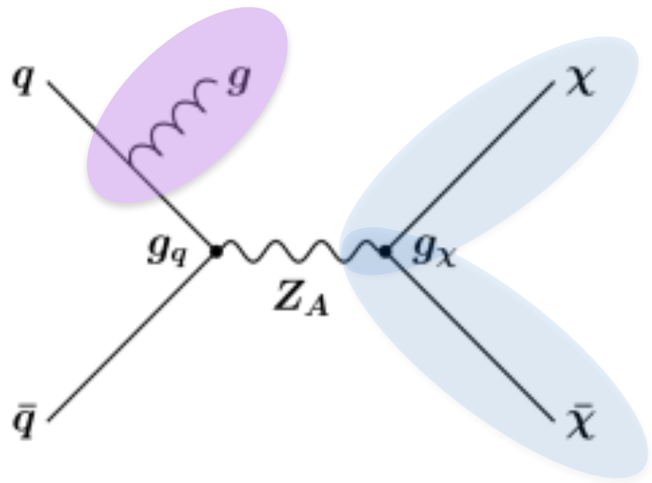
CMS-PAS-JME-16-004



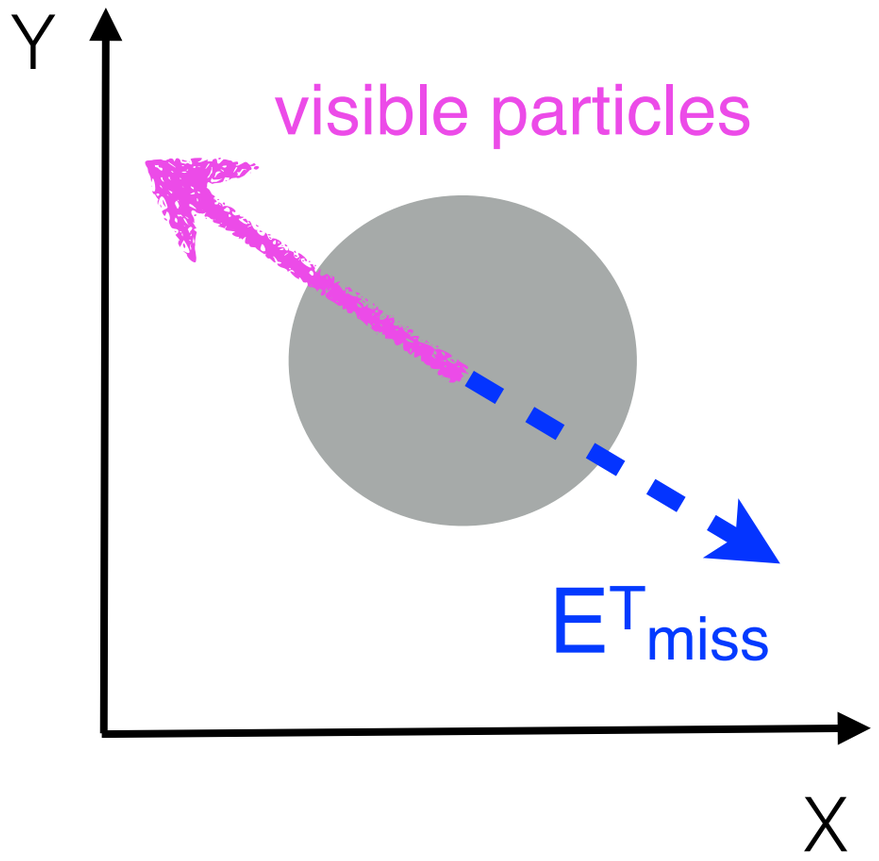
JETM-2018-004/

Mono-X searches: an easy way to search for DM at the LHC

a recoiling jet



Missing energy from DM



Mono-X searches: an easy way to search for DM at the LHC

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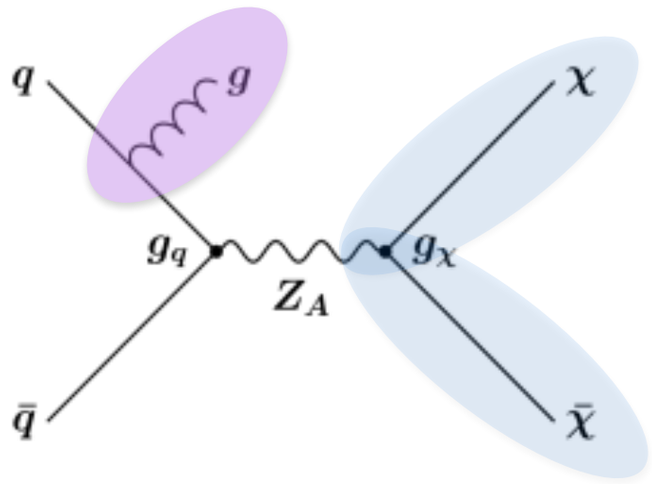
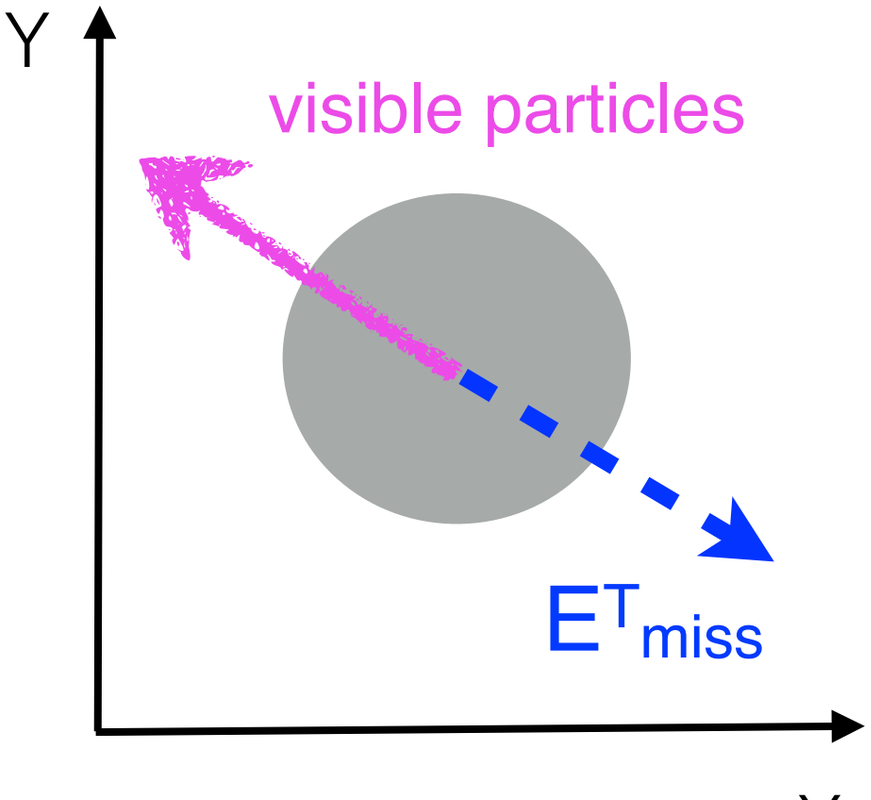
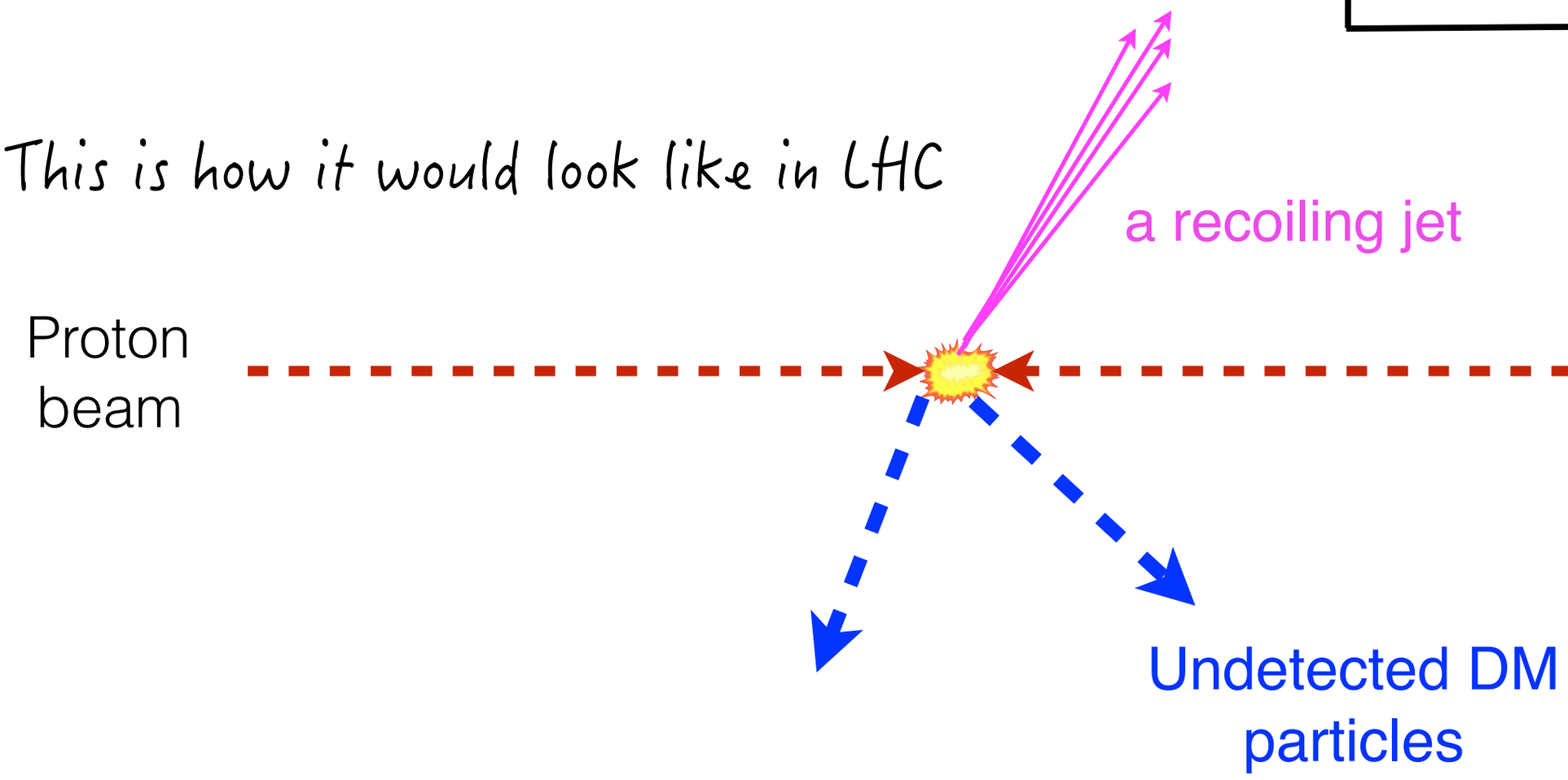


Missing energy from DM

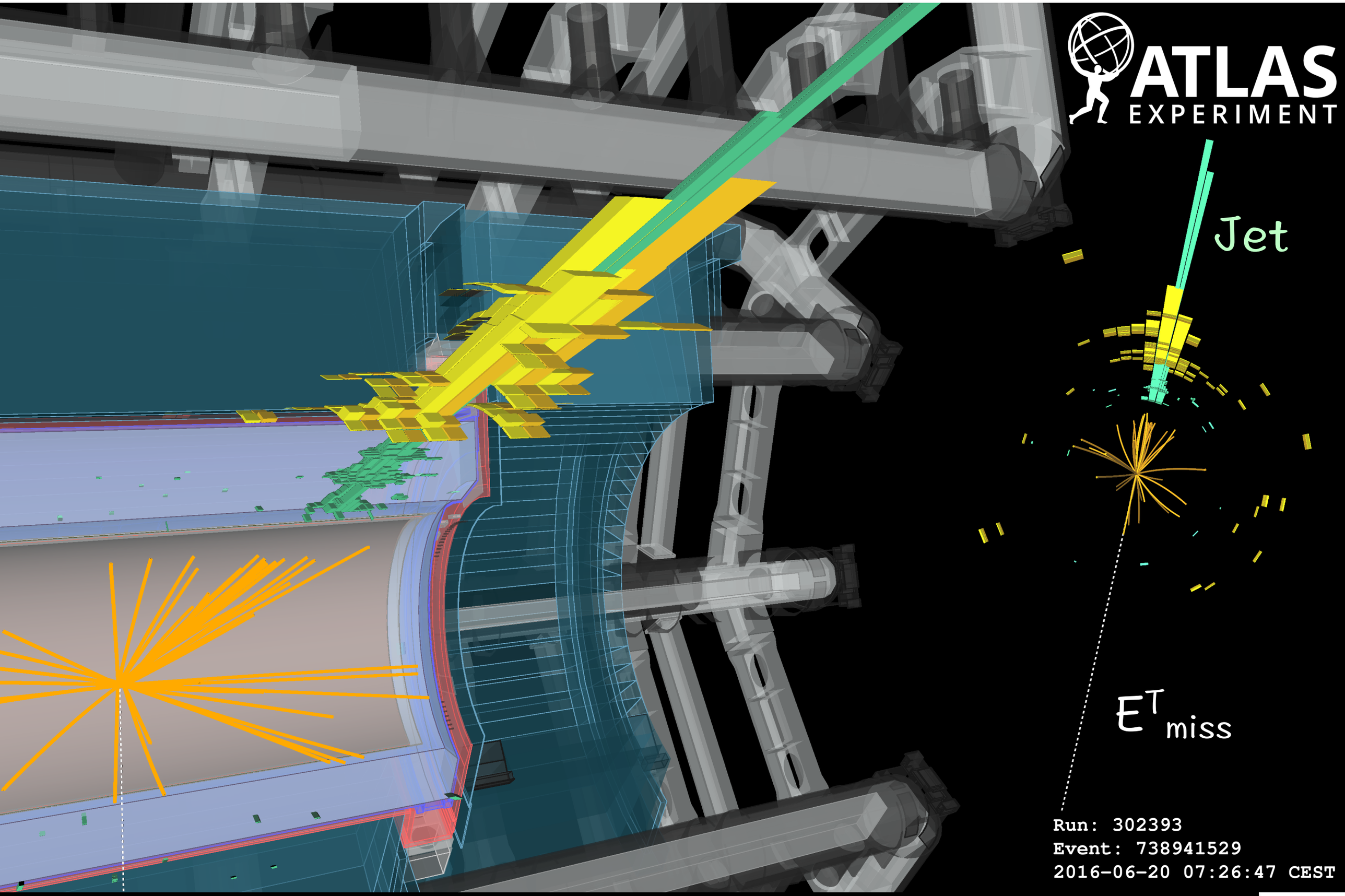


This is how it would look like in LHC



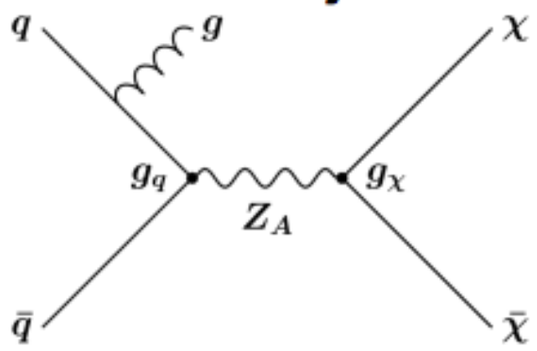
Mono-Jet event

ATLAS-CONF-2017-060

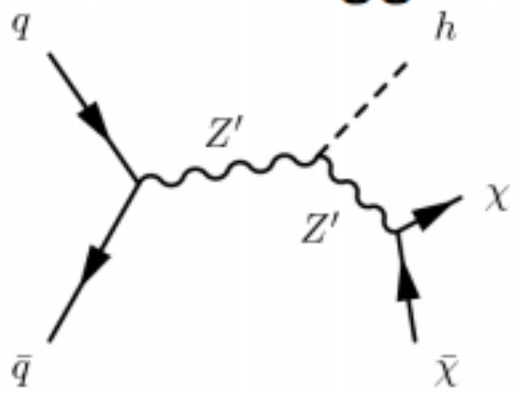


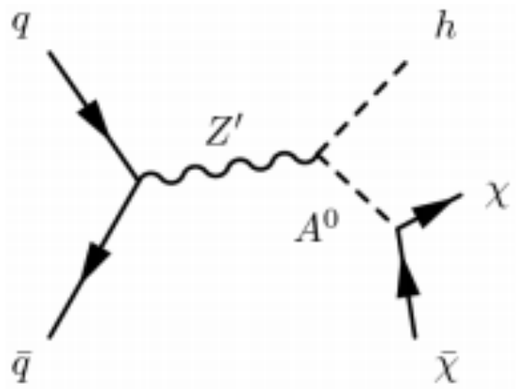
Mono-X searches: an easy way to search for DM at the LHC

Mono-jet



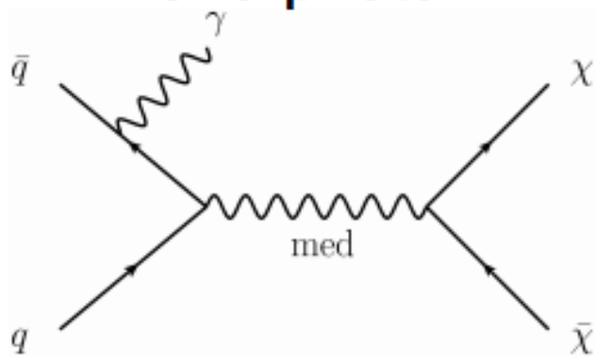
Mono-Higgs



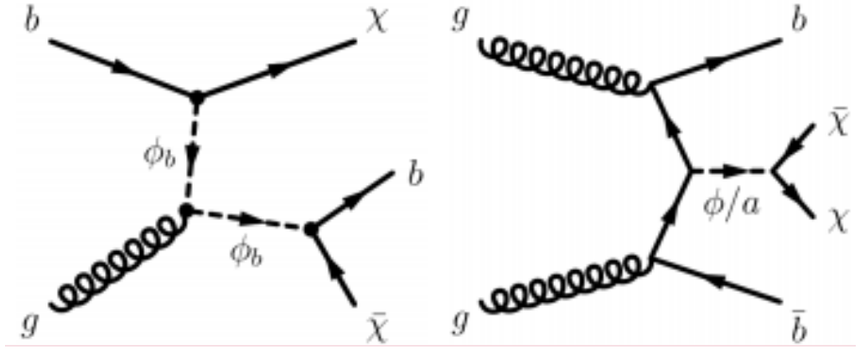


A wide range of final states can be investigated with LHC

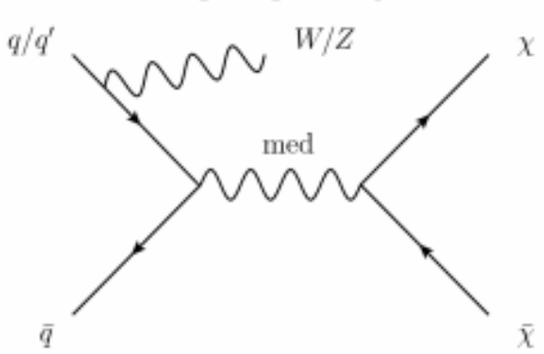
Mono-photon

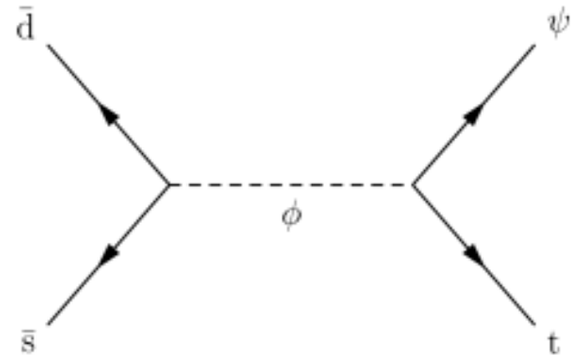


Mono-b/bb

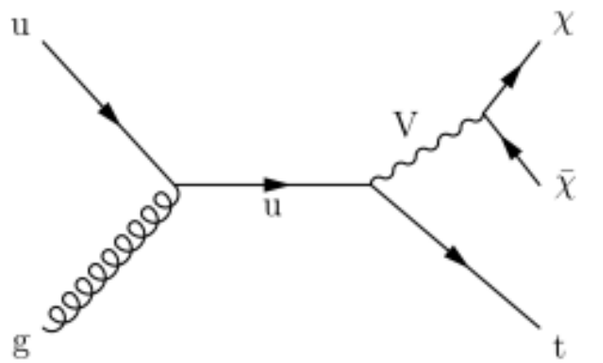


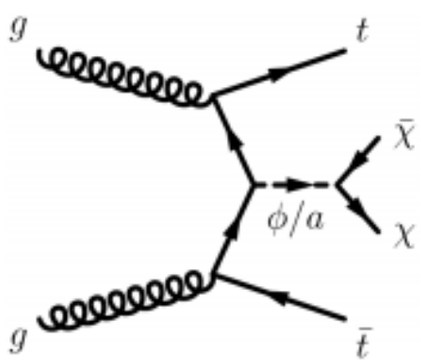
Mono-W/Z





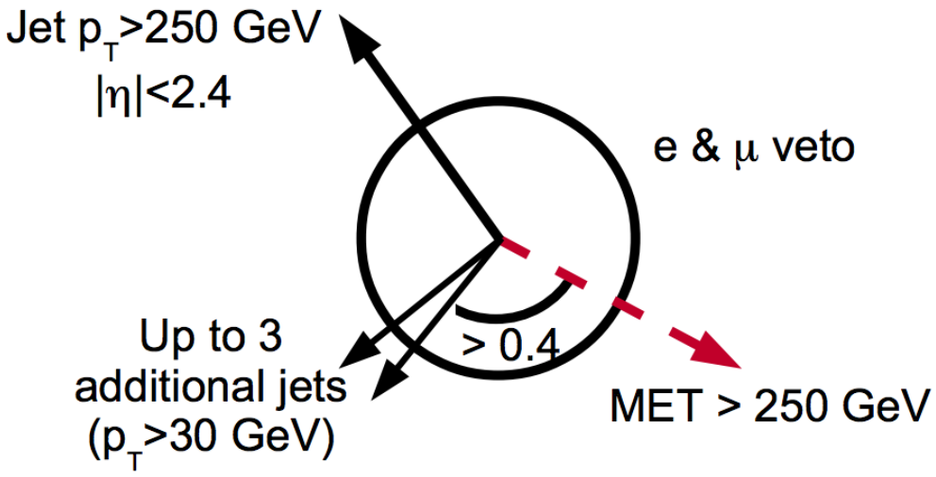
Mono-t/tt





Mono-Jet analysis

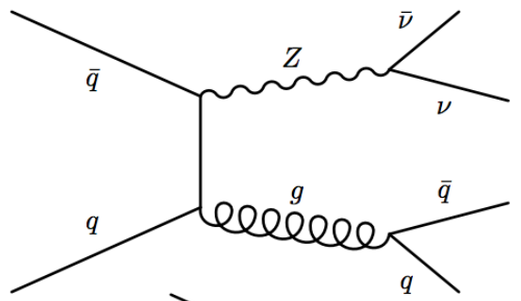
Event Selection



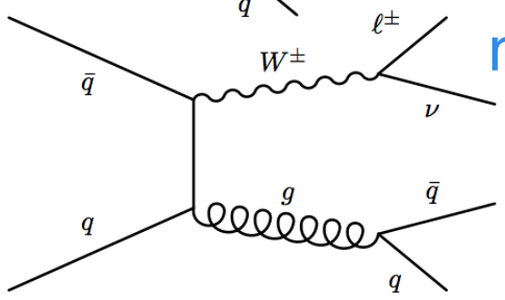
*example from ATLAS analysis

Main Backgrounds

- Z+jets, W+jets
- Estimated from data control regions

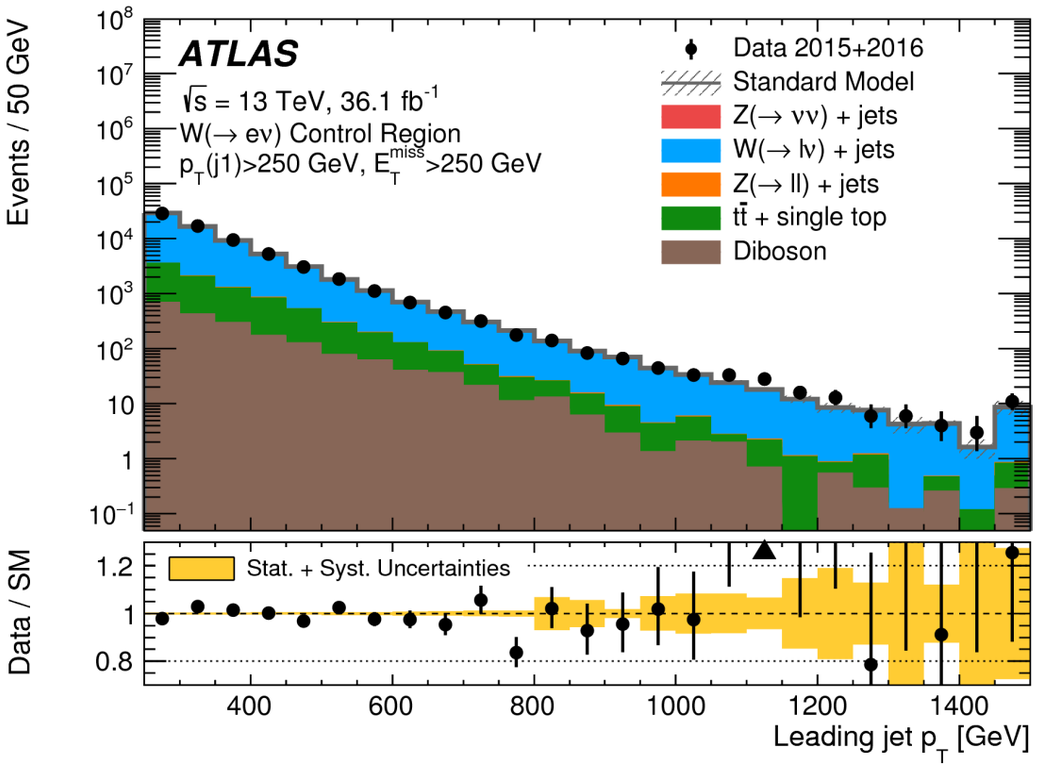


real E^T_{miss}

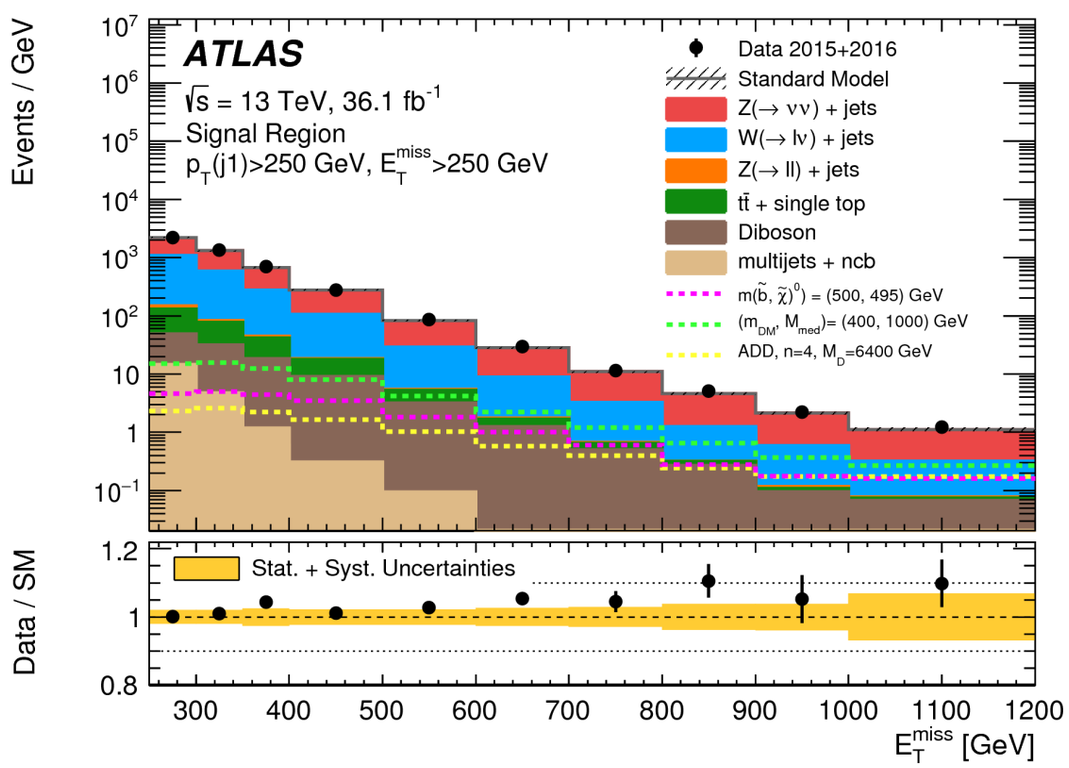


missed lepton

CR after fit to data

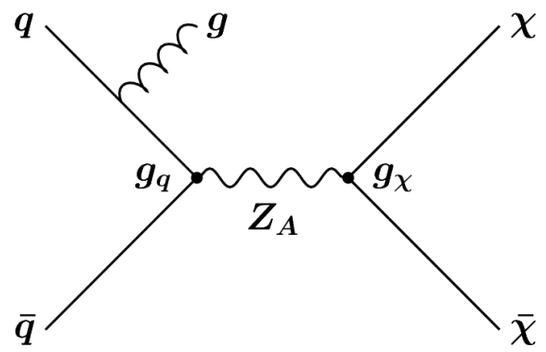


Signal Region



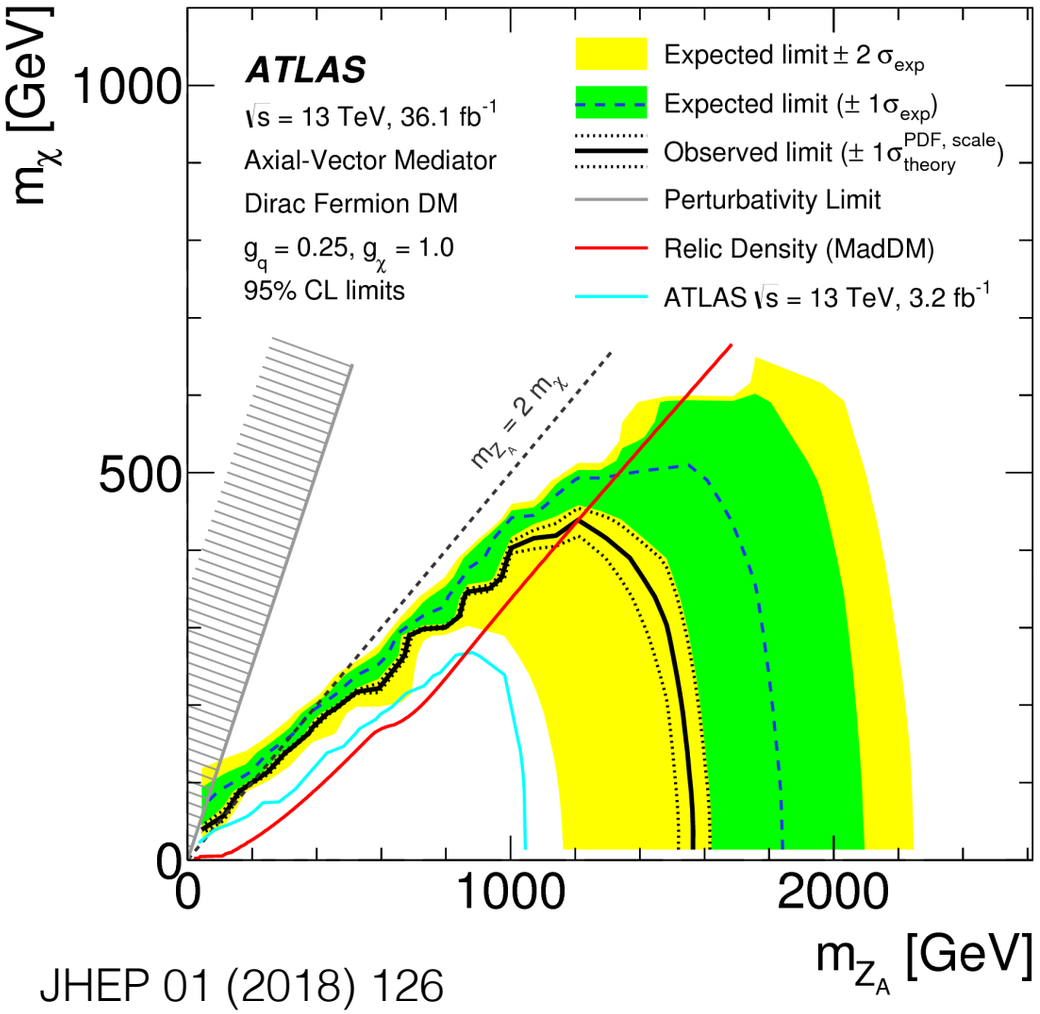
Mono-Jet analysis

- Simultaneous fit to control and signal regions
- No excess in data compared to expectations from predictions
- Exclusion limits



(axial-)vector couplings

Axial-vector and vector models are excluded for mediator masses up to 1.55 TeV to 1.8 TeV for very low DM masses



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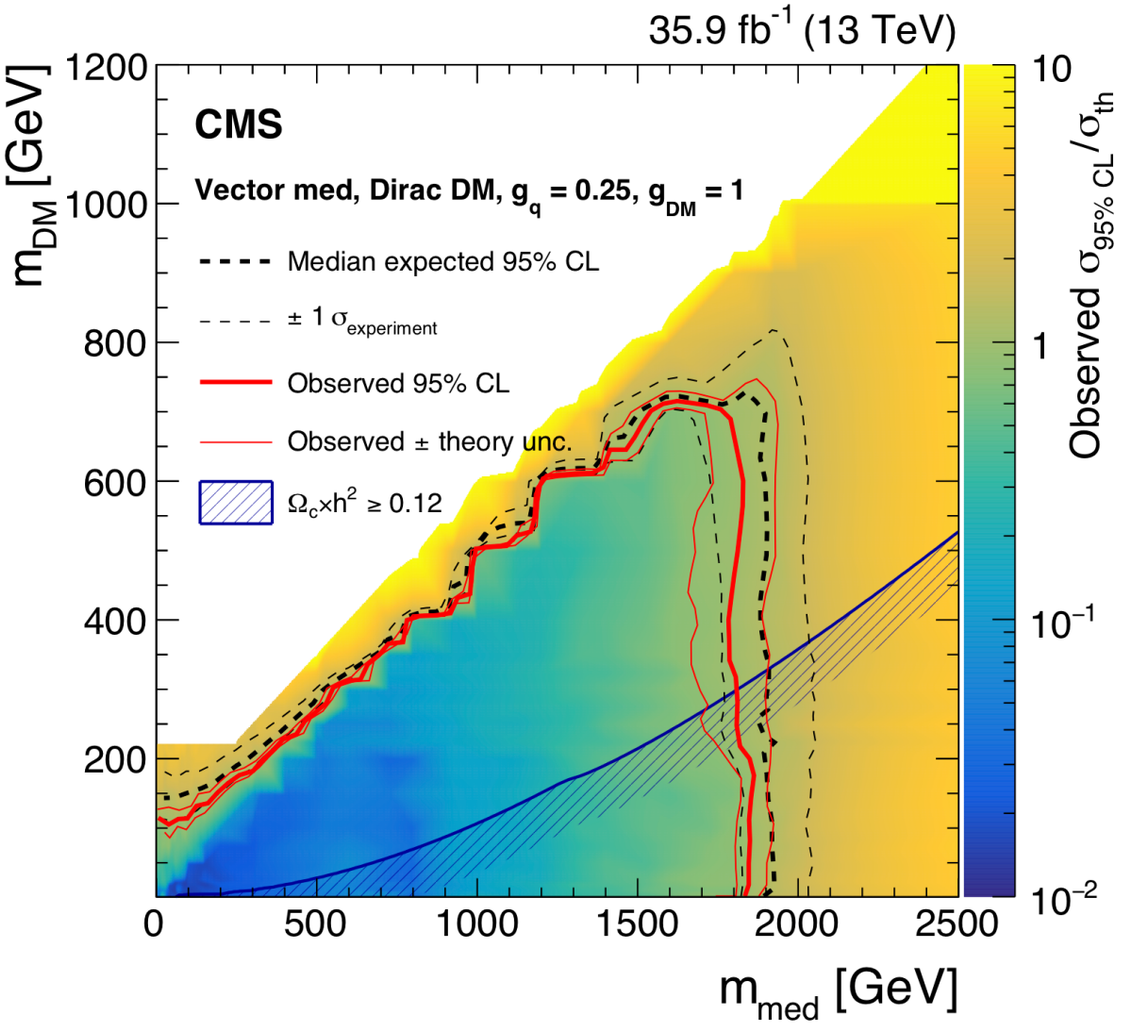
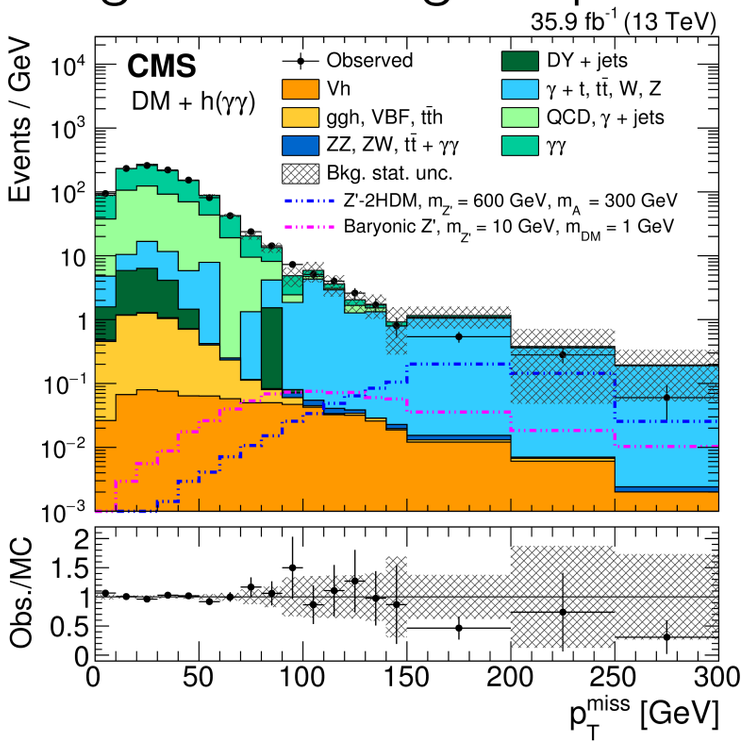
CMS-EXO-16-048

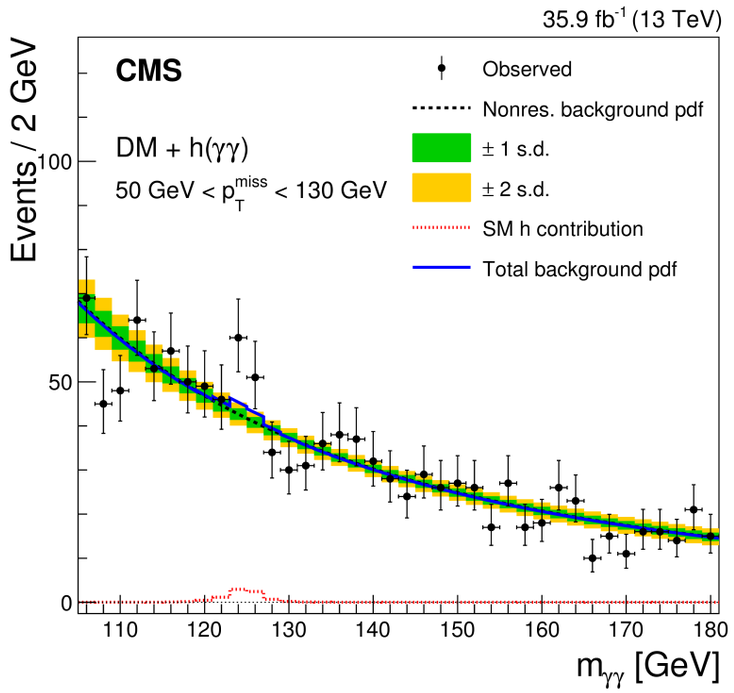


Dark Matter in association with Higgs boson in ATLAS & CMS

Event selection

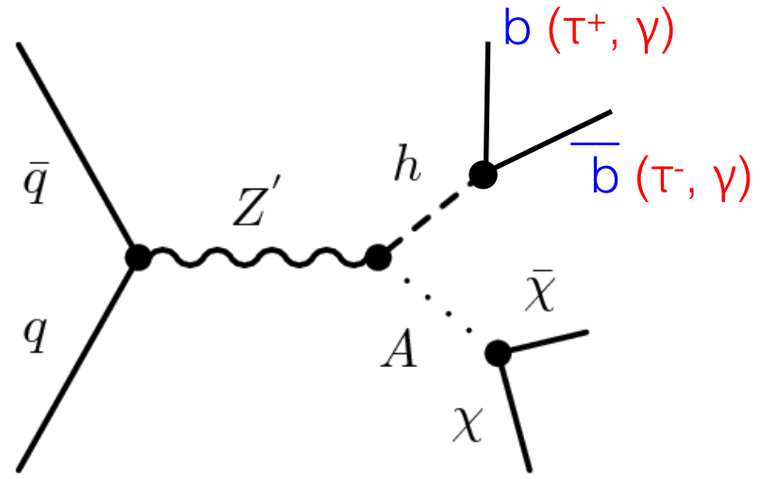
- diphoton trigger
- fit to the diphoton mass spectrum
- signal and bkg shapes





Backgrounds

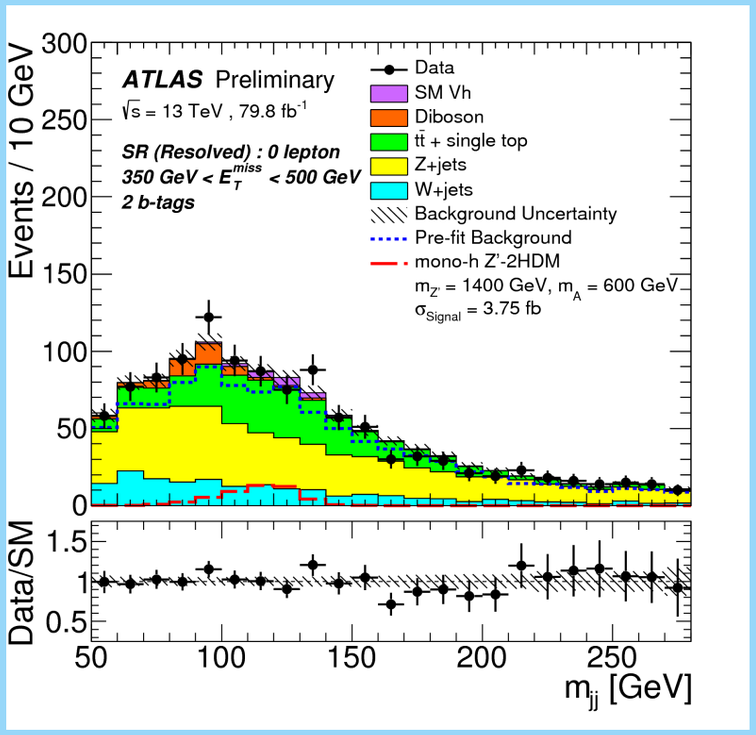
- resonant backgrounds from Higgs boson (MC)
- non resonant background due to γγ and EW processes (data)



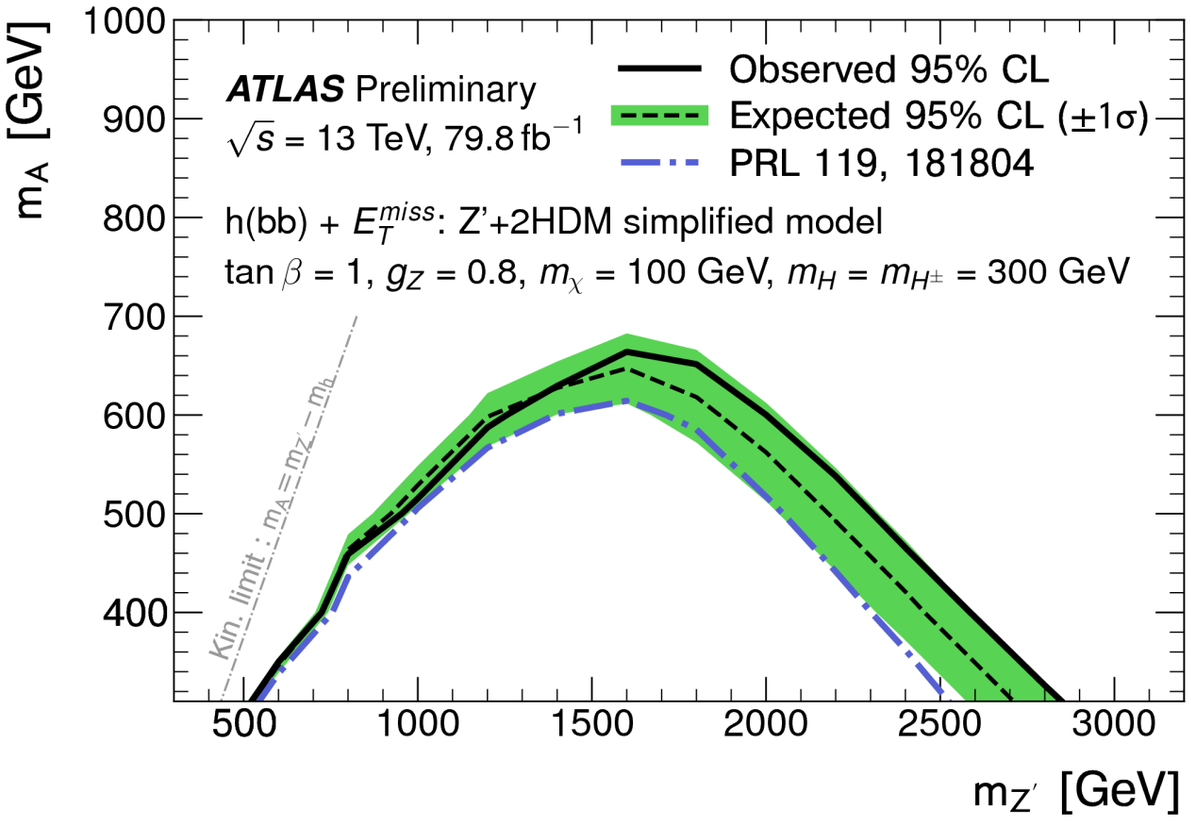
A: pseudoscalar

Event selection and Backgrounds

- E^T_{miss} trigger
- Resolved and merged SR
- Z+jets, W+jets, top from data



Dark Matter in association with Higgs boson in ATLAS & CMS

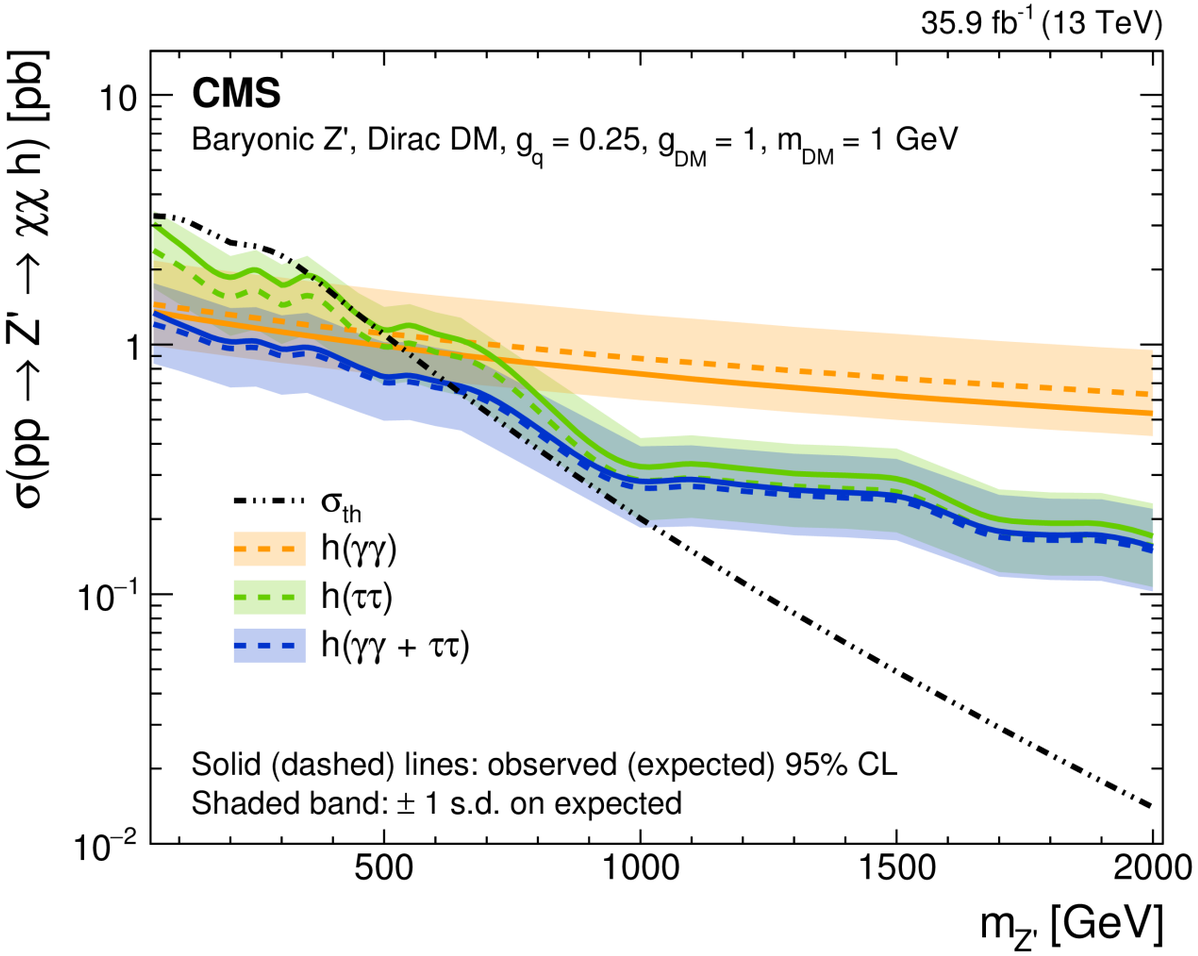


Exclusion contours for the Z'-2HDM scenario in the (mZ'-mA) plane for DM associated production with a Higgs boson

ATLAS-CONF-2018-039

CMS-EXO-16-055

Expected and observed 95% CL upper limits on the Z'-2HDM cross section for DM associated production with a Higgs boson



Dark Matter plus Heavy Flavor

Signal regions and Backgrounds

- various SRs for different models
- Z+jets and ttbar dominant backgrounds estimated from CRs from data and validated in different regions

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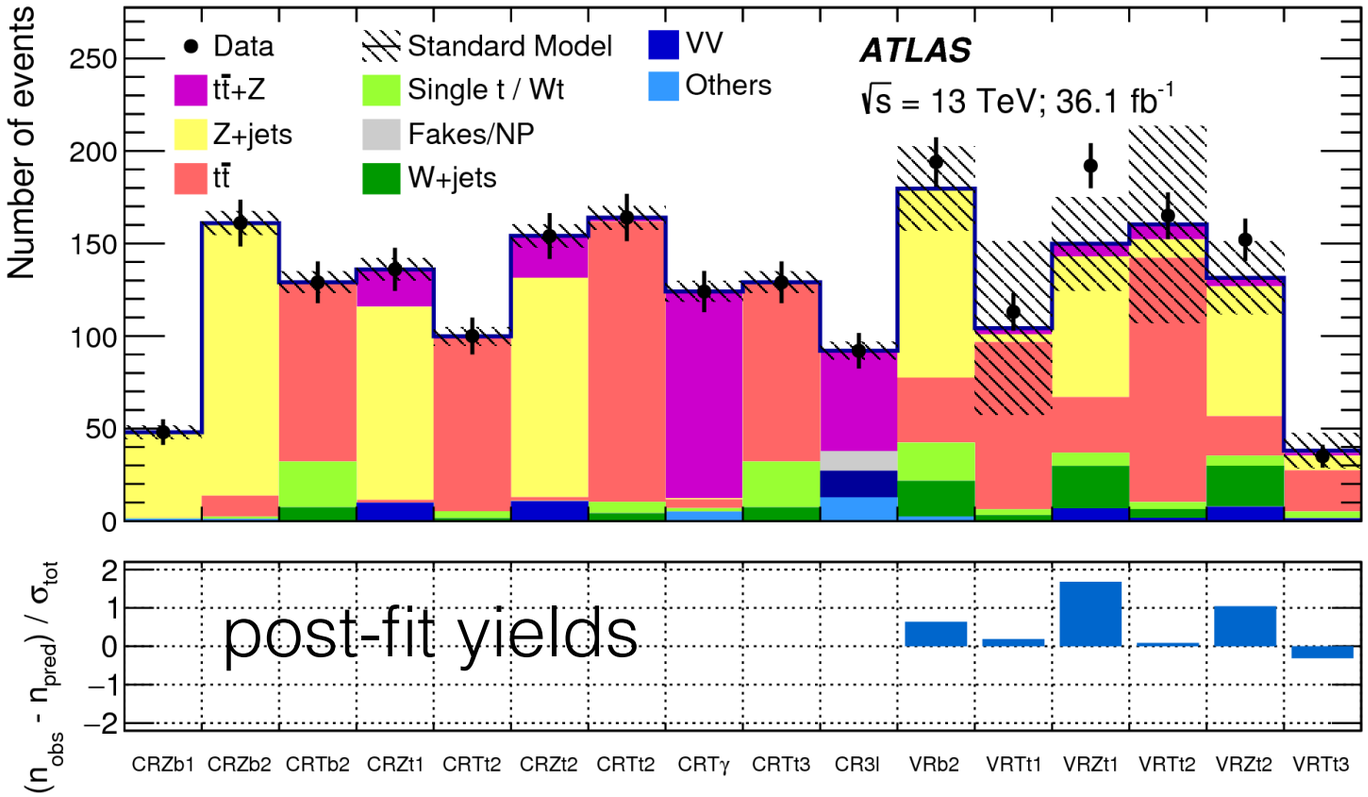
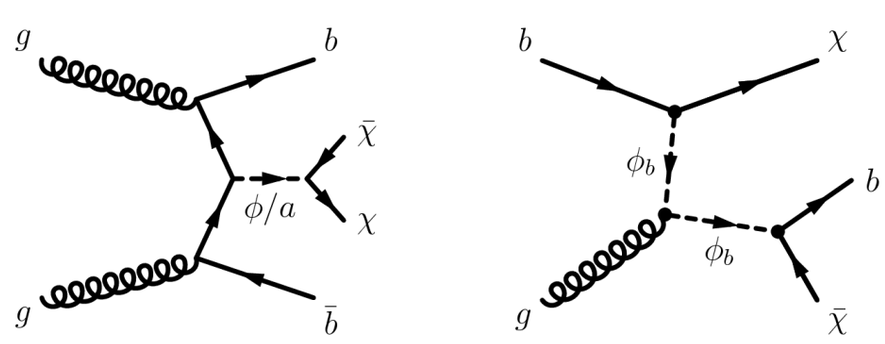
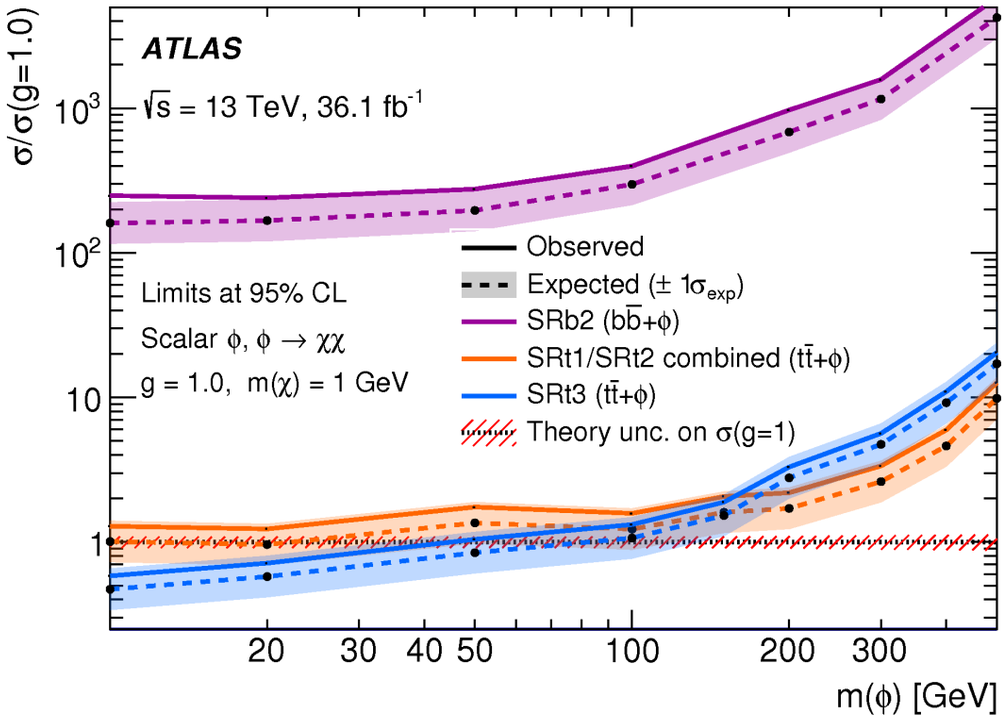
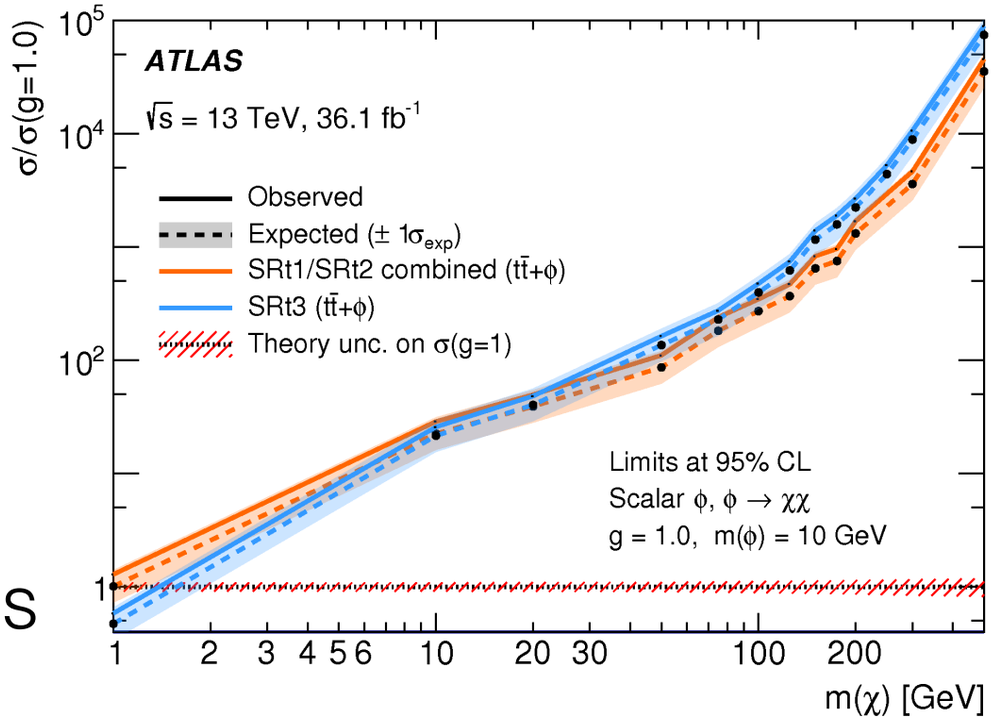


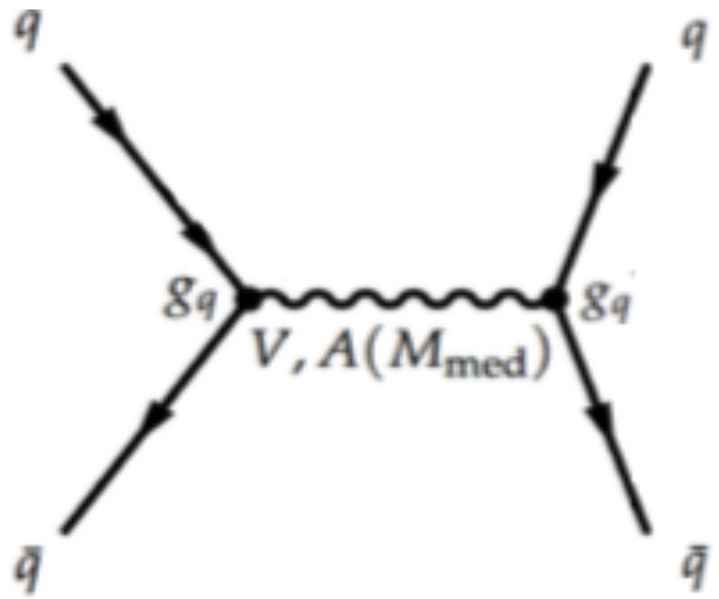


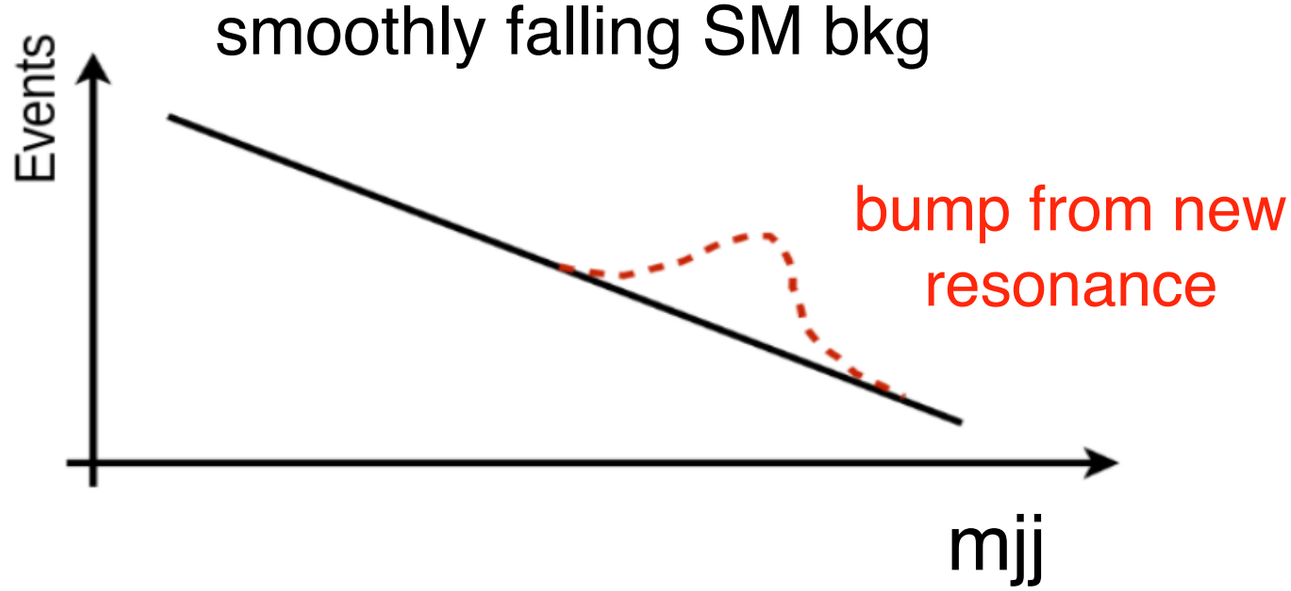




model-independent fit with CRs and SRs

Dijet searches for mediators: bumps on high mass tails



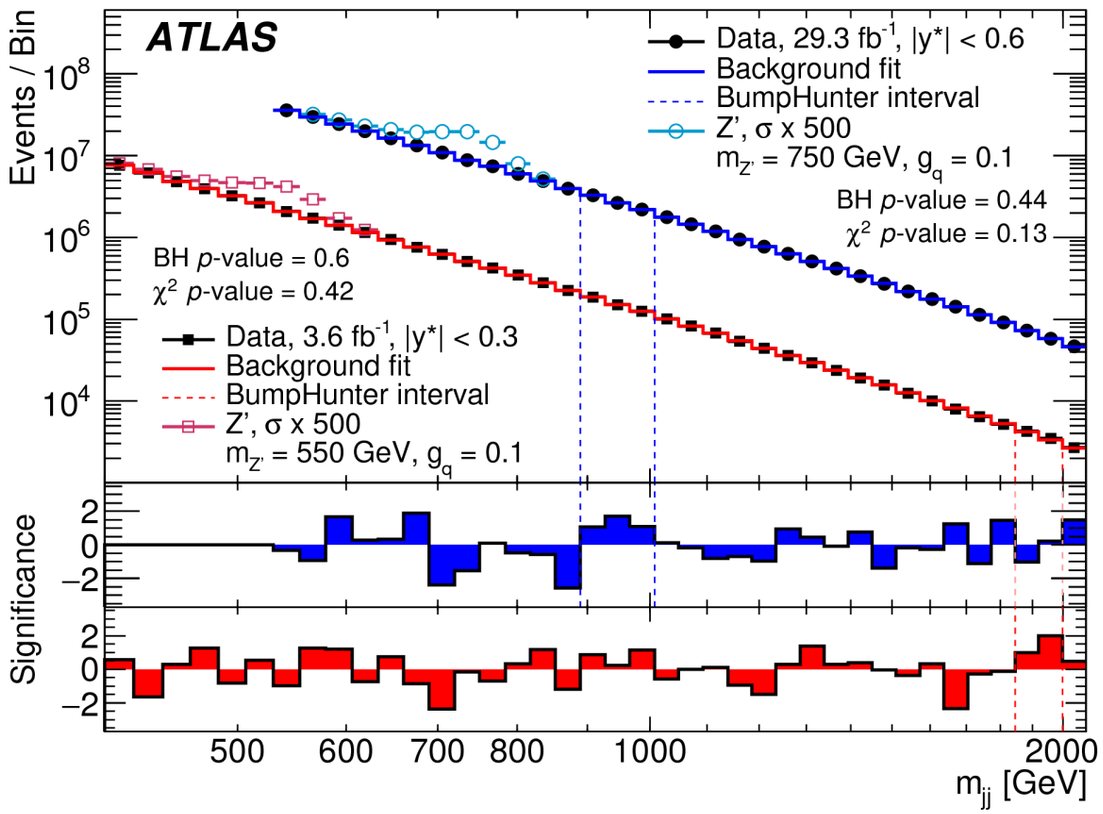


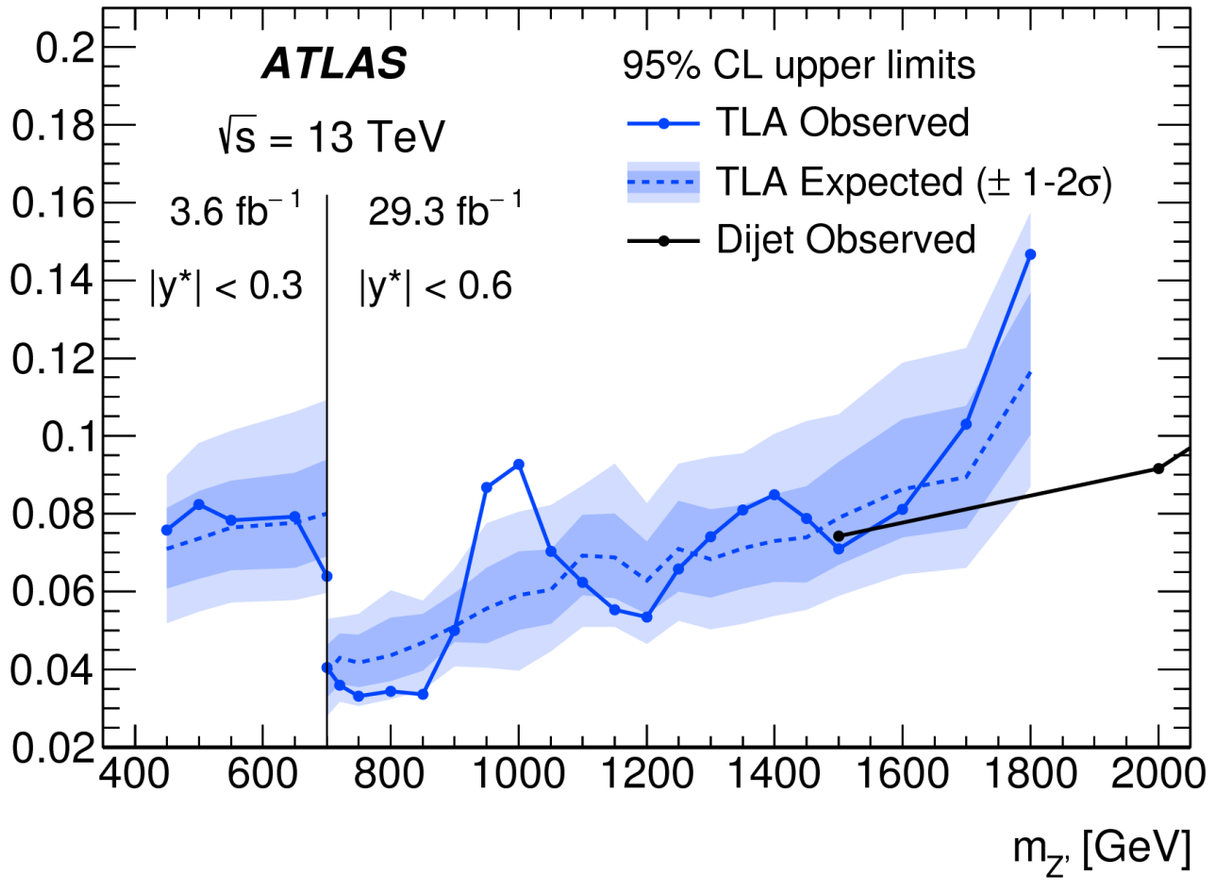
Trigger level analysis in ATLAS

- Innovative data-taking approach developed by the LHCb collaboration, used by CMS and ATLAS
- TLA allows for data taking at a peak rate twice the total rate of events using less than 1% of total trigger bandwidth

Event Selection and Backgrounds

- di-jet events with at least two trigger-level jets (pT>85 GeV)
- searches for resonance 700 < mjj < 1800 GeV with |y*|<0.6 and mjj>450 GeV with |y*|<0.3
- sliding window fit to determine the SM bkg





$y^*=(y_1-y_2)/2$

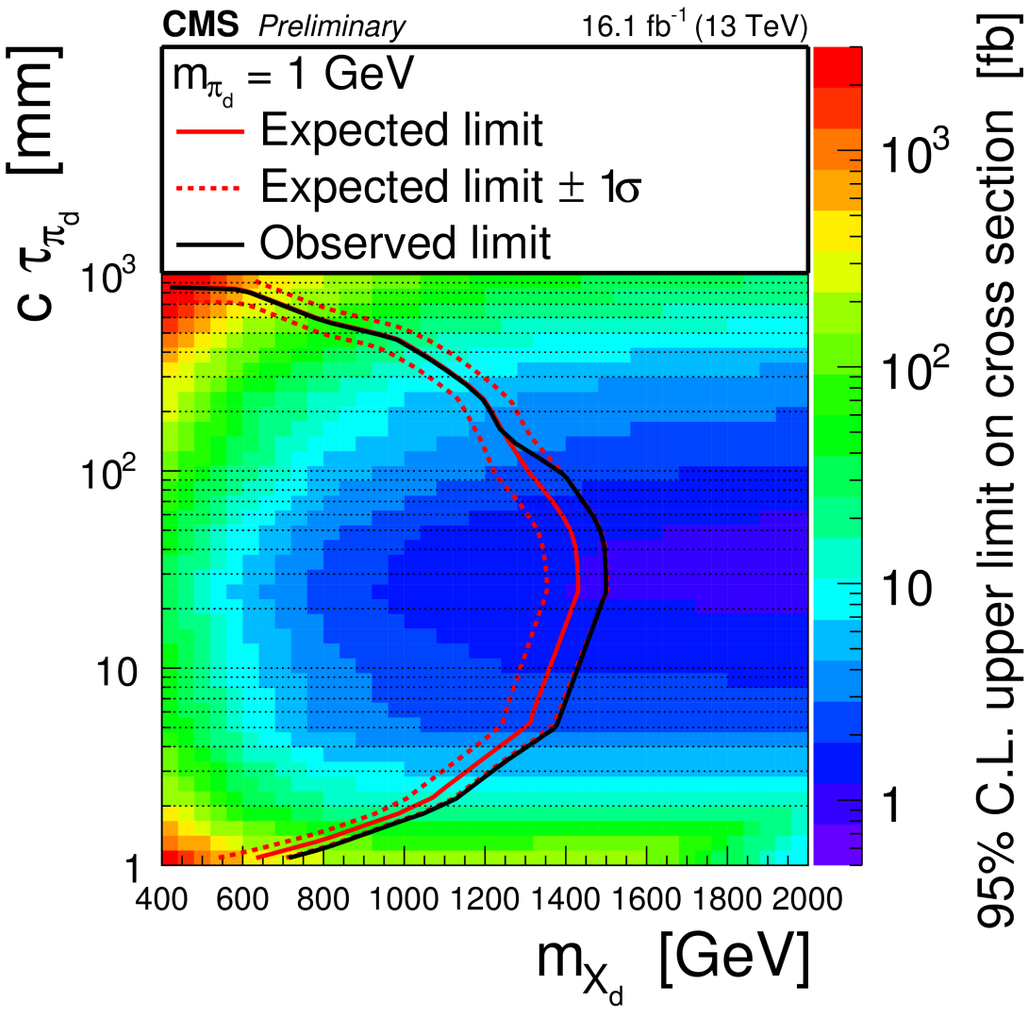
EXOT-2016-20

New particles decaying to a jet and an emerging jet

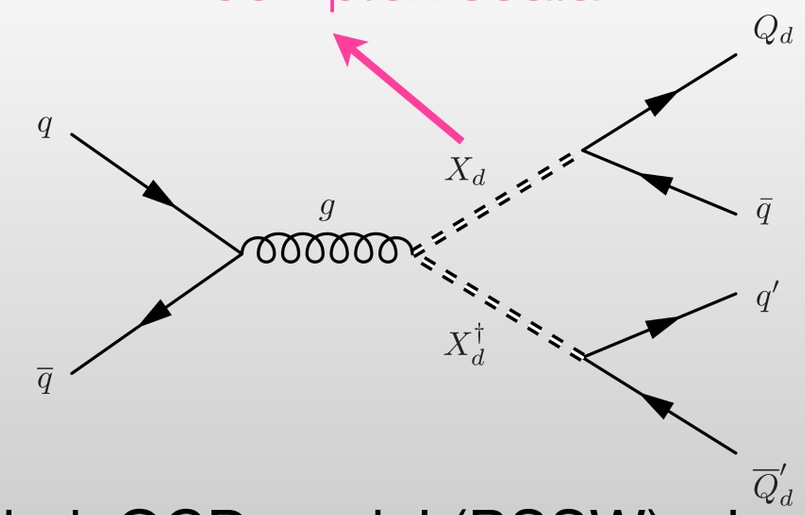
Event Selection and Background

- trigger based on transverse momenta of jets
- emerging jet: multiple displaced vertices (multiple tracks with large impact parameter)
- 4 jets and pass thresholds on scalar sum of jets pT (H_T)

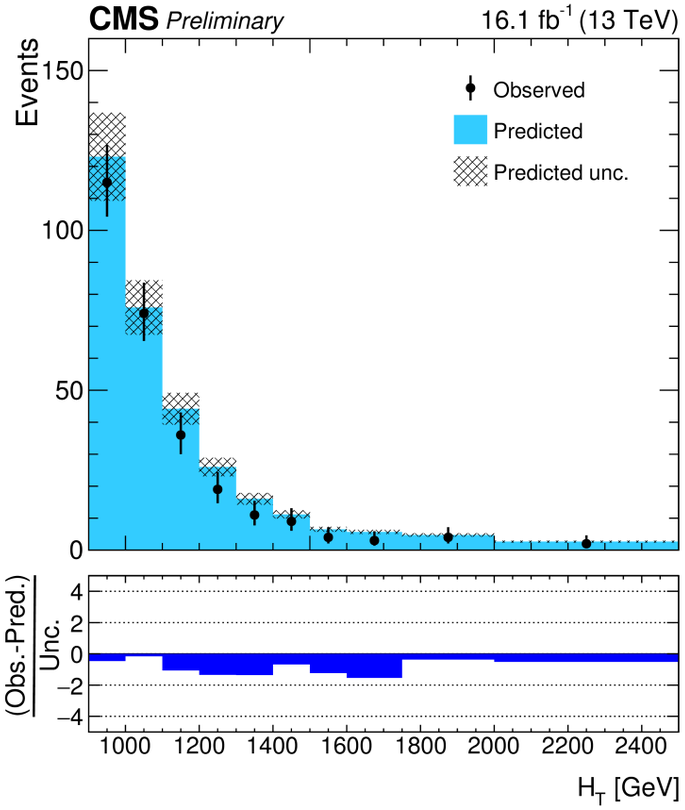
CMS-PAS-EXO-18-001



complex scalar



dark QCD model (BSSW) where new fermions are charged under a new force in the dark sector



Search for prompt-like and long-lived dark photons with LHCb

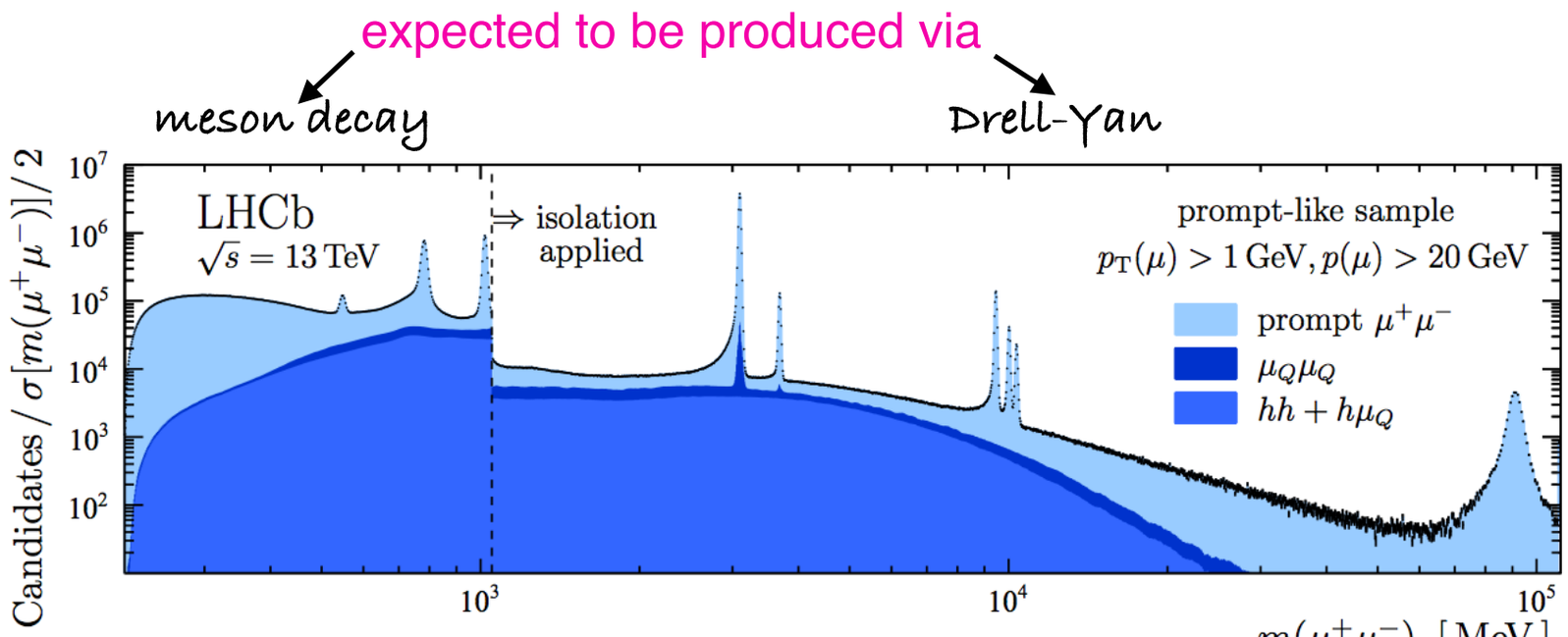
Event Selection and Backgrounds

- high-pT muon triggers
- consistent with originating from PV

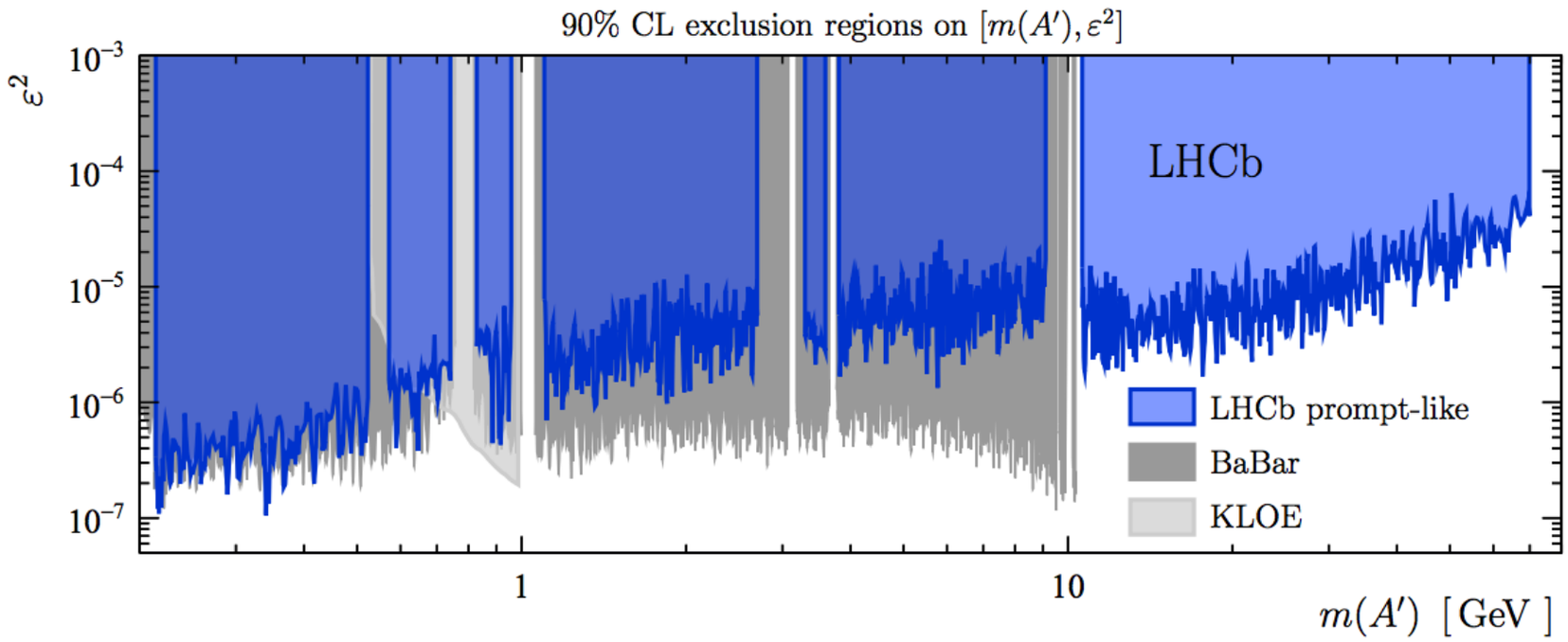
- prompt $\gamma^* \rightarrow \mu^+\mu^-$ (irreducible)
- resonant decays to $\mu^+\mu^-$
- various mis-reconstructed objects

LHCb-PAPER-2017-038

prompt-like mass spectrum used to search for A'



first limits above 10 GeV

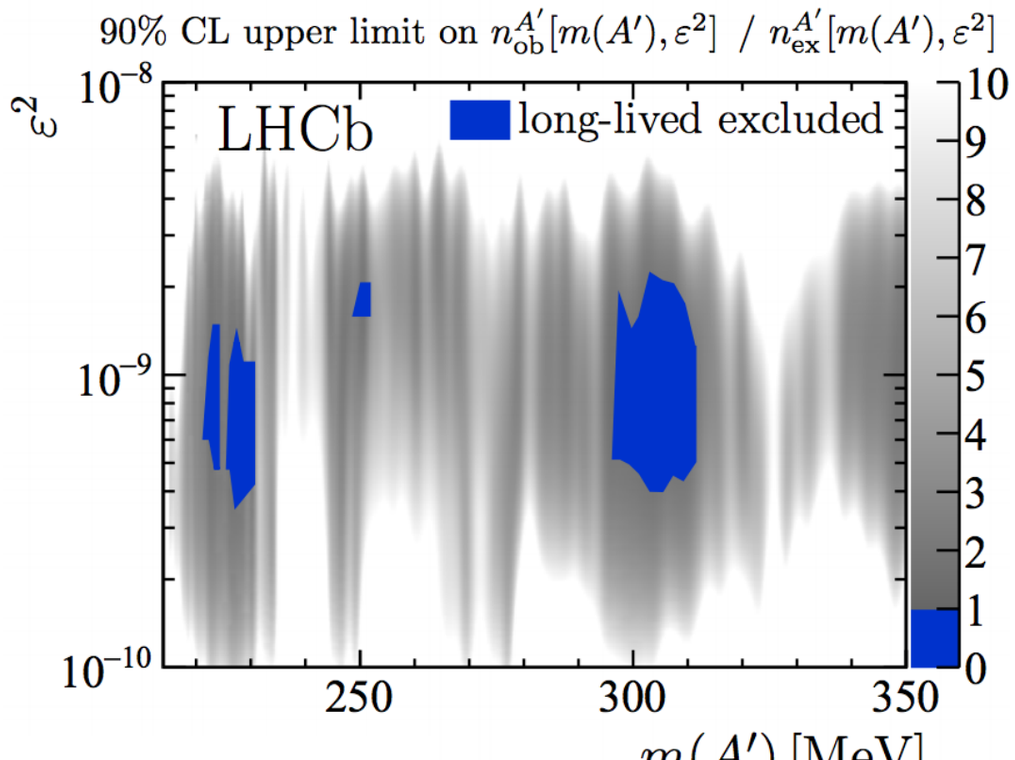


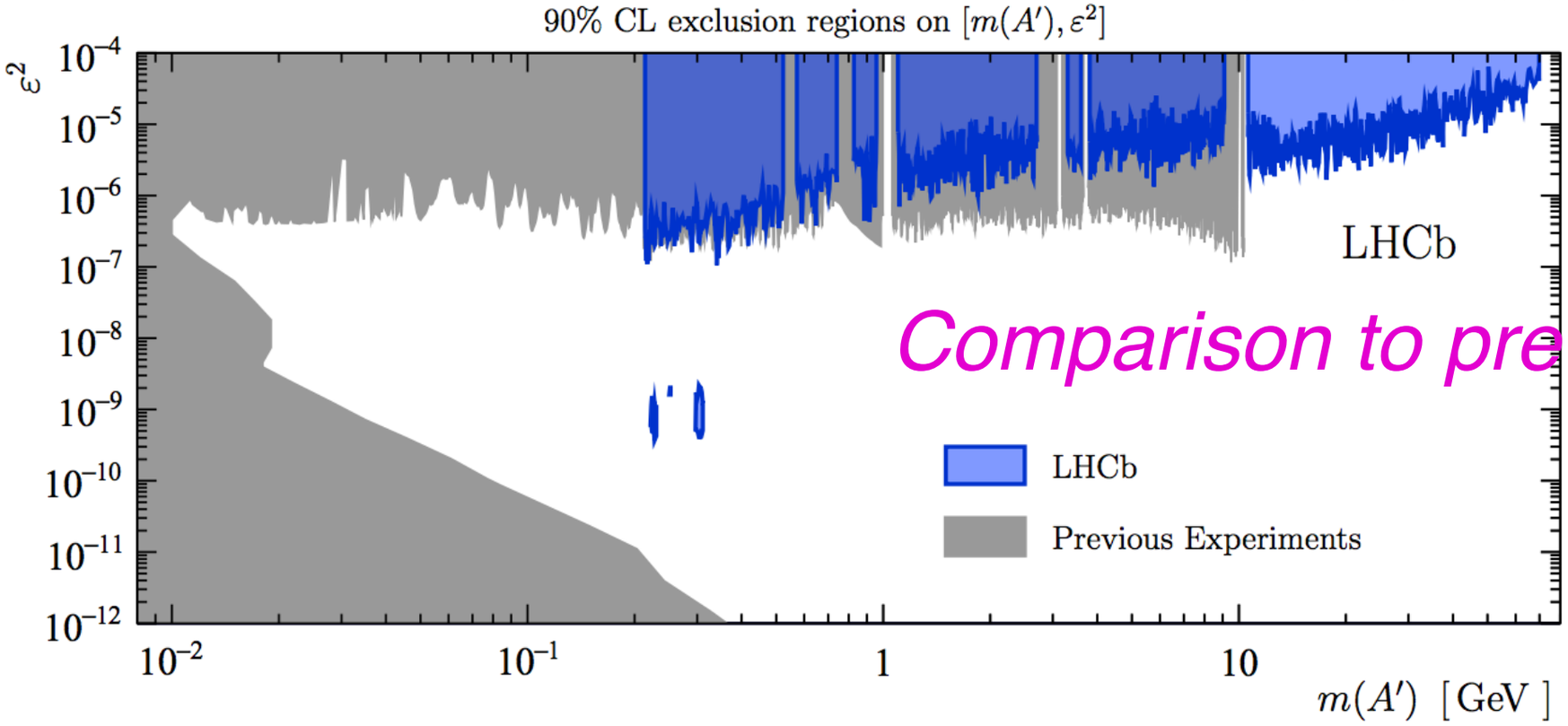
Search for prompt-like and long-lived dark photons with LHCb

Event Selection and Backgrounds

- stringent trigger criteria; no contamination from prompt muons
- photon conversions to $\mu^+\mu^-$
- b-hadron decays with 2 muons
- low mass tail from K0s decays with mis-identified pions

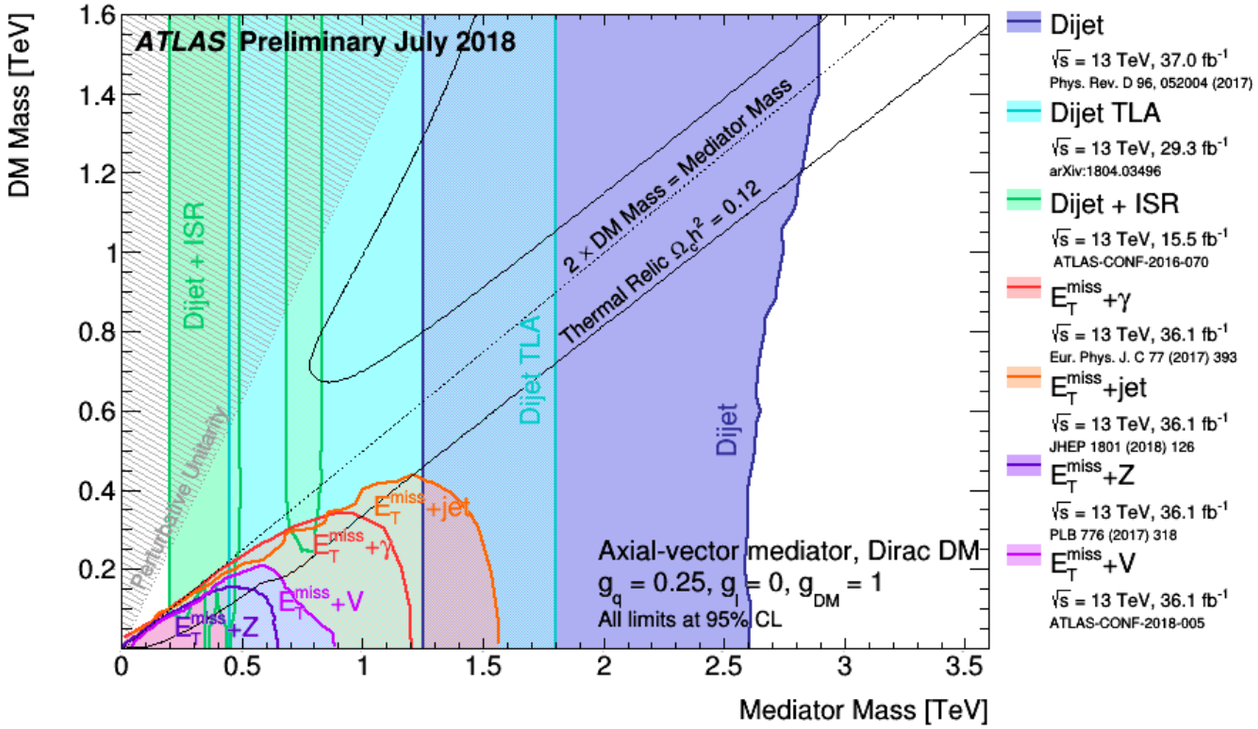
long-lived A' search





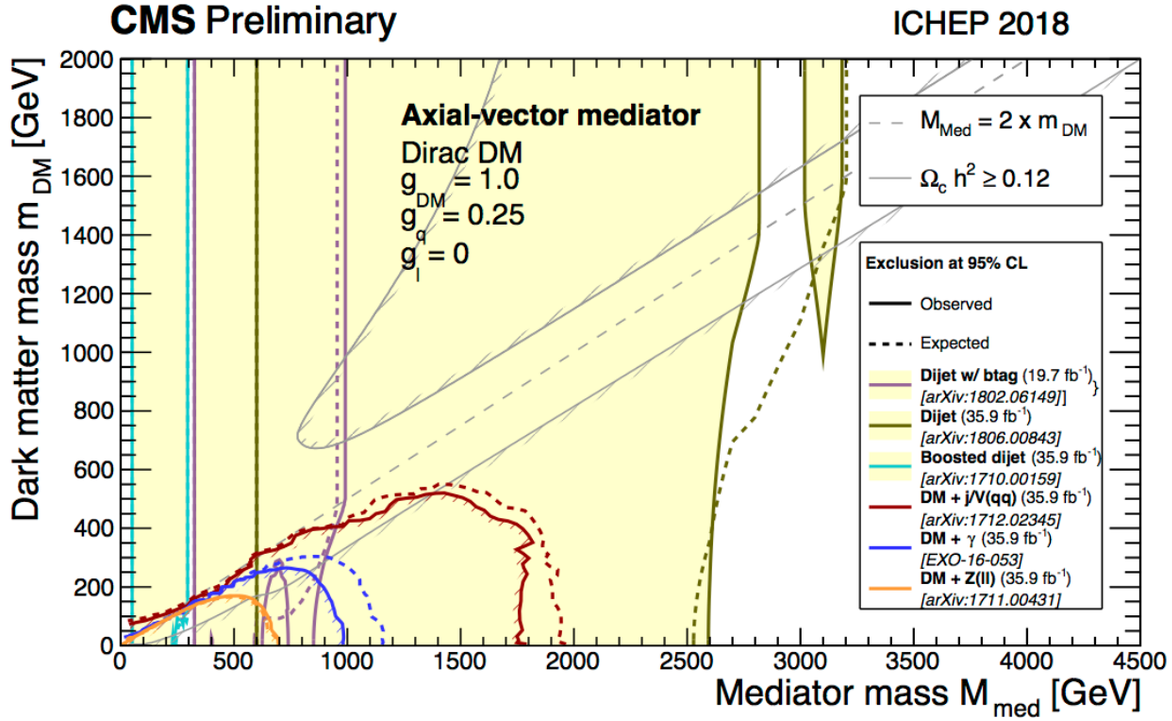
Comparison to previous experiments

Excluded regions in a DM mass-mediator mass plane



Regions in a dark matter mass-mediator mass plane excluded at 95% CL by a selection of ATLAS dark matter searches, for one possible interaction between the Standard Model and dark matter, the leptophobic axial-vector mediator. The exclusions are computed for a dark matter coupling gDM = 1.0, a quark coupling gq = 0.25 universal to all flavors, and lepton coupling gl set to zero

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

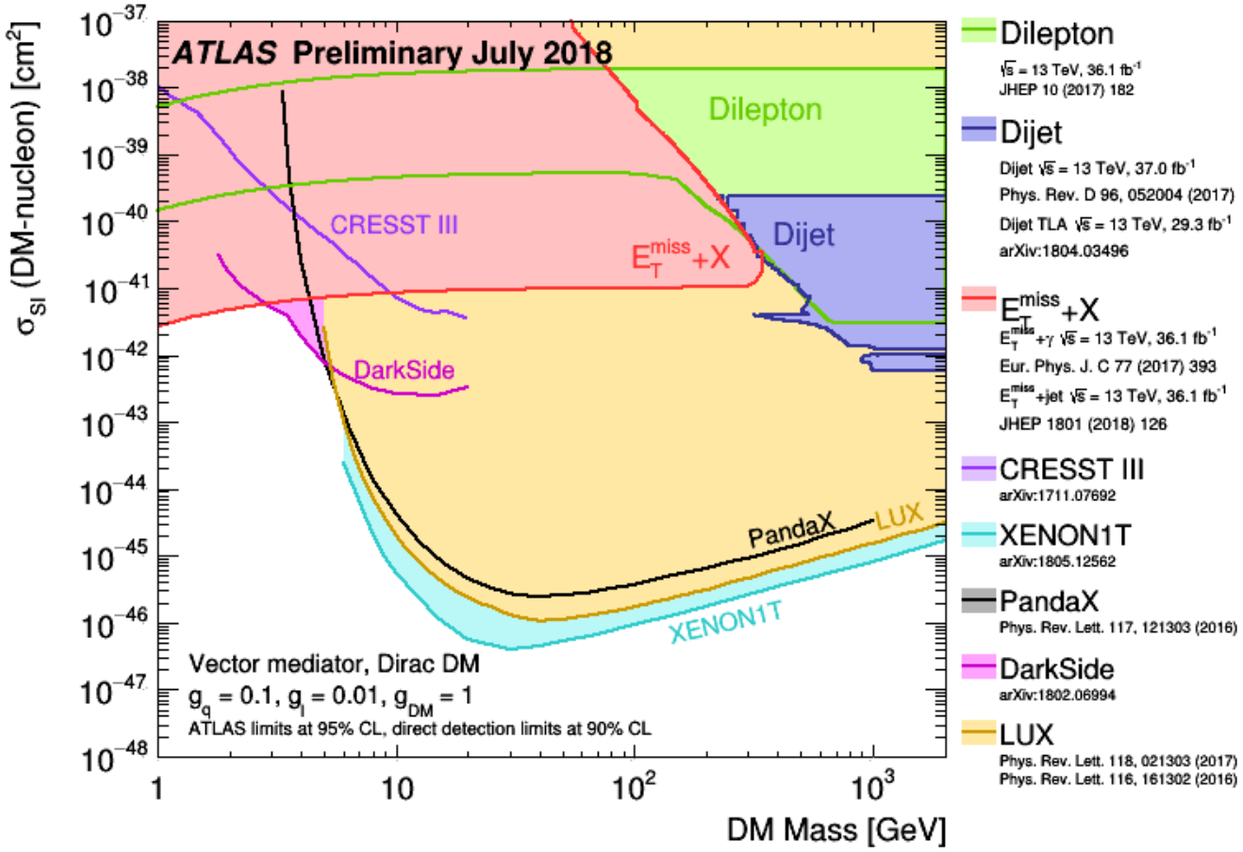


95% CL observed and expected exclusion regions in mMed-mDM plane for di-jet searches and different MET based DM searches from CMS in the lepto-phobic Axial-vector model. The exclusions are computed for a universal quark coupling of g_q = 0.25 and for a DM coupling of gDM = 1.0

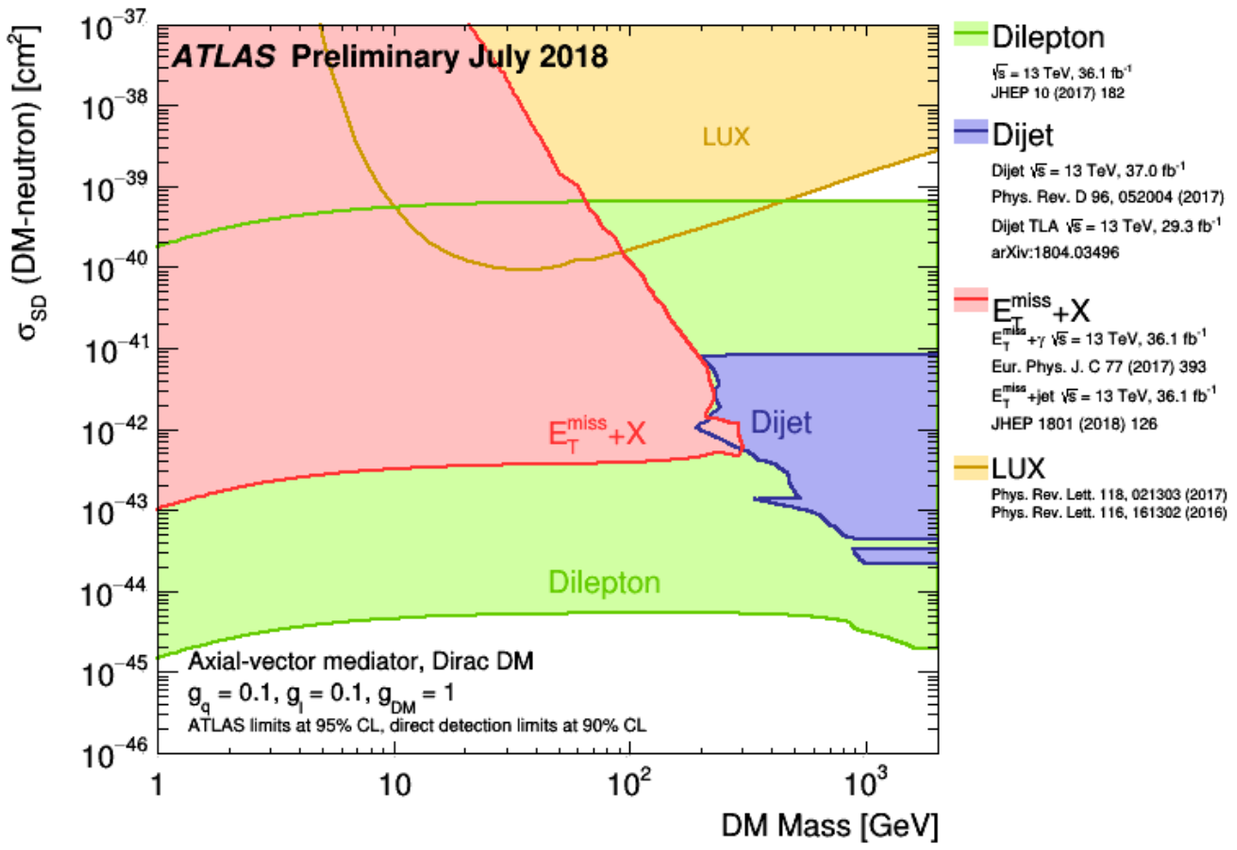
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Comparison to Direct detection experiments

Spin-Independent DM-nucleon cross-section

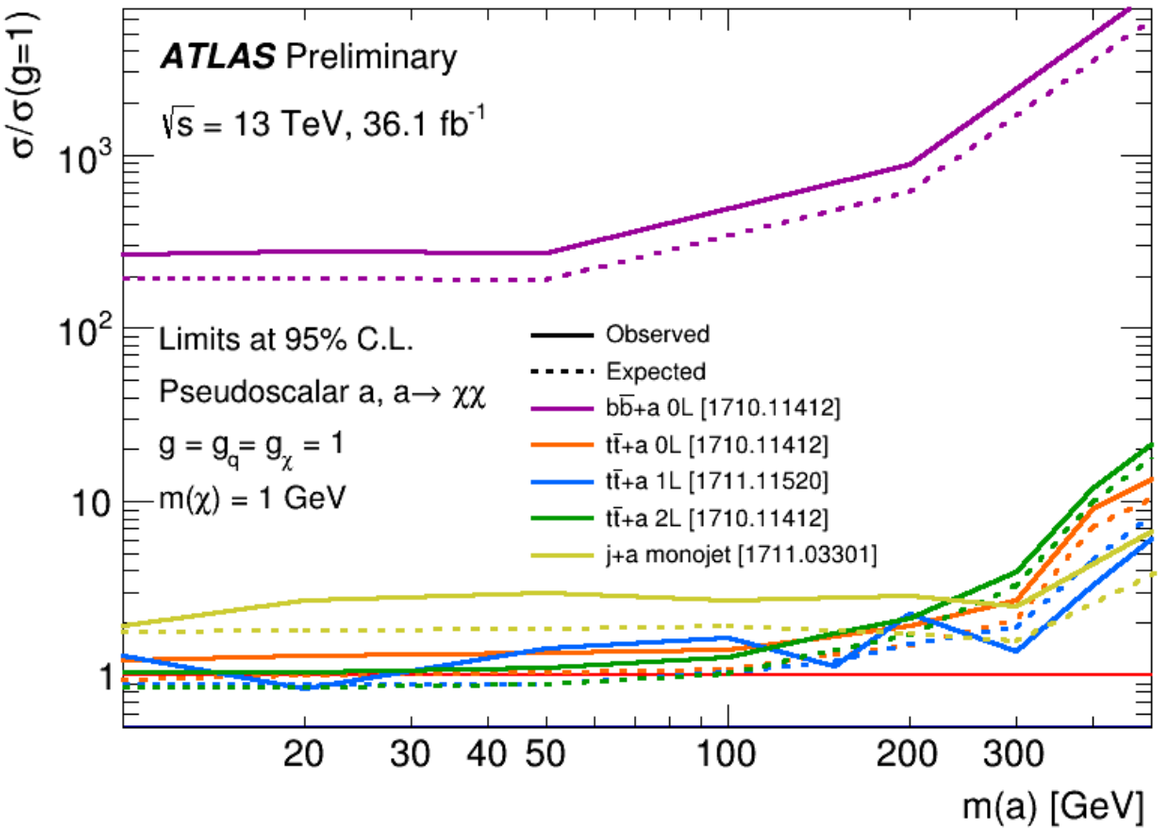


Spin-dependent DM-proton cross-section



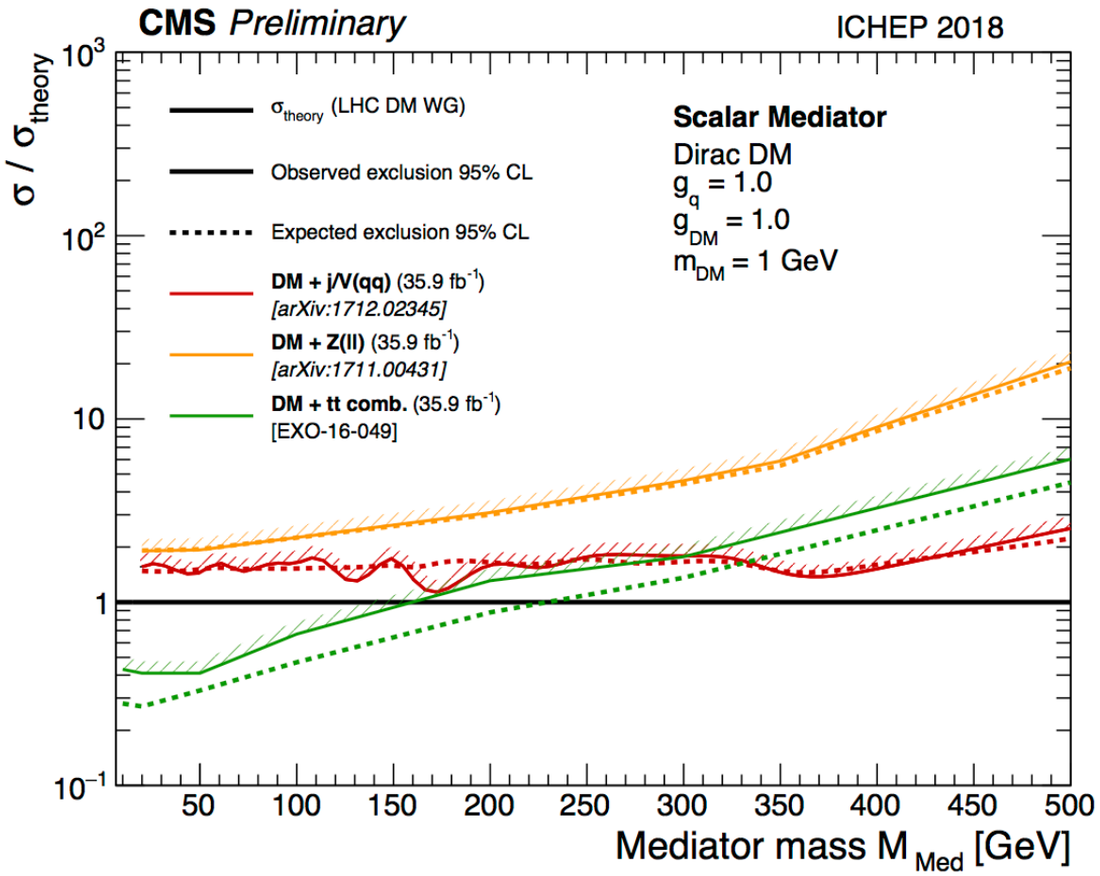
- Collider searches complement DD experiments for DM masses below 5GeV for spin-independent DM-nucleon cross-section
- Strong limits for spin-dependent DM-proton cross-section

Exclusion limits for (pseudo-)scalar mediator mass



Exclusion limits for color-neutral ttbar/bbbar + a pseudo scalar models as a function of the mediator mass for a DM mass of 1 GeV. Limits calculated at 95% CL and expressed in terms of the ratio of the excluded cross-section to the nominal cross-section for a coupling assumption of $g=g_q=g_\chi=1$

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



95% CL observed (full-line) and expected (dashed-line) exclusion limits for the Scalar model as a function of Mmed for different MET based DM searches from CMS. The exclusions are computed for quark coupling of g_q = 1.0 and for a DM coupling of gDM = 1.0

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Conclusions

- Experiments at the LHC have a large program on Dark Matter searches which expand also on Dark Sector searches
- No hint for a DM candidate from these searches
- Extend exclusion limits on the DM candidate and mediator masses
- Looking forward to exploit the rich LHC dataset for more results!

back-up slides