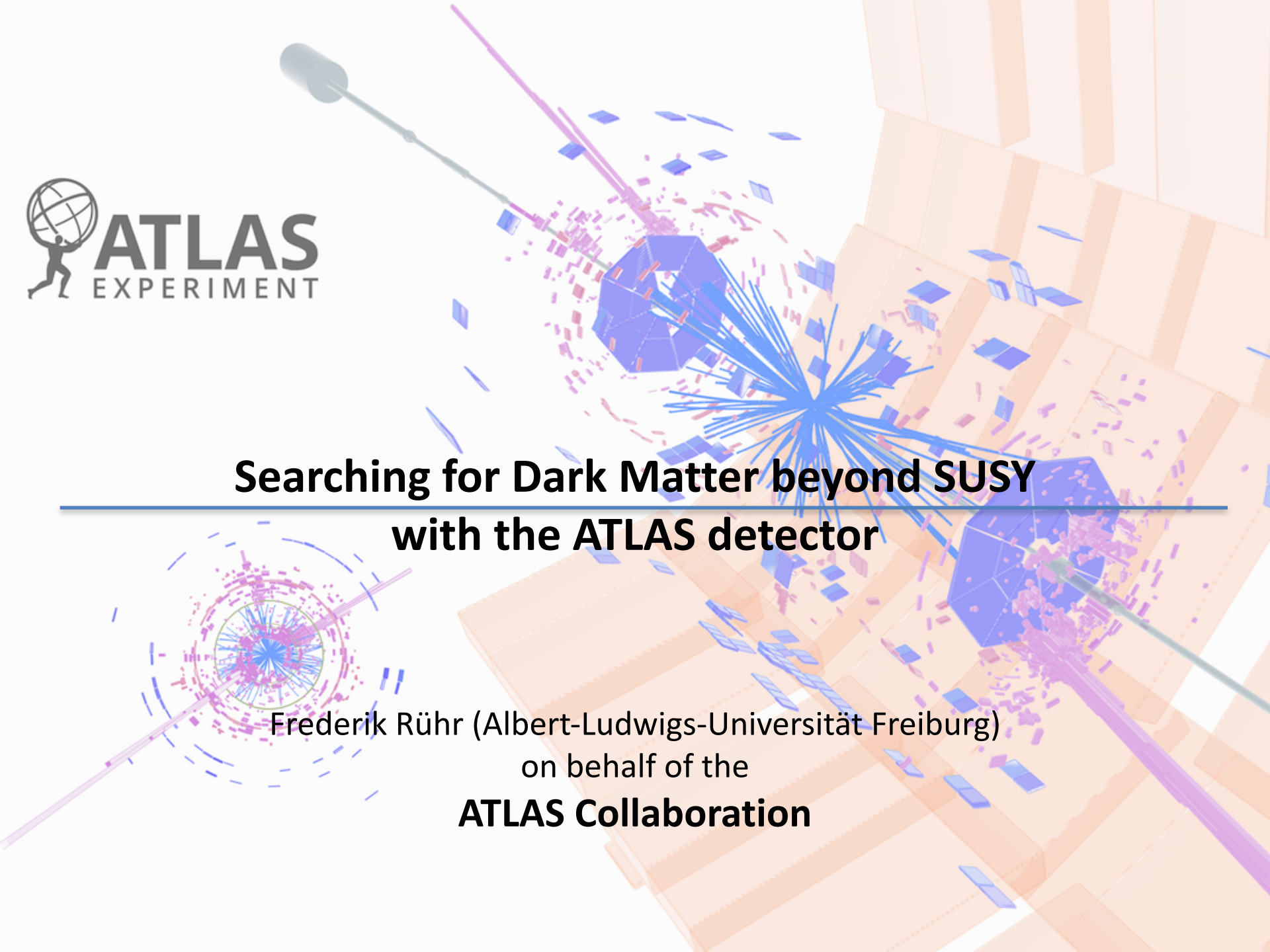
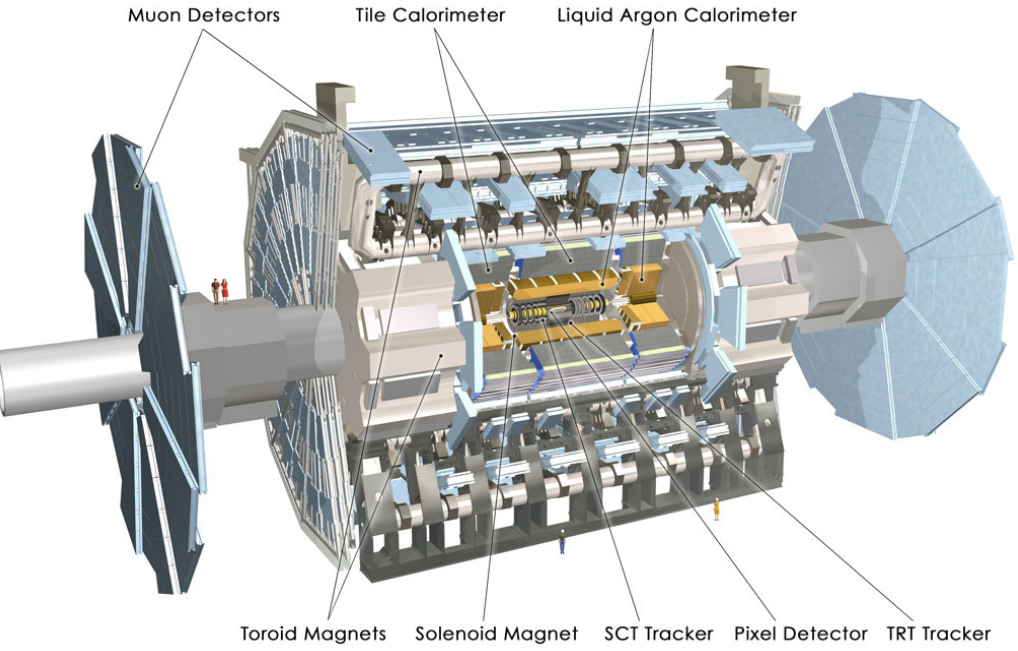


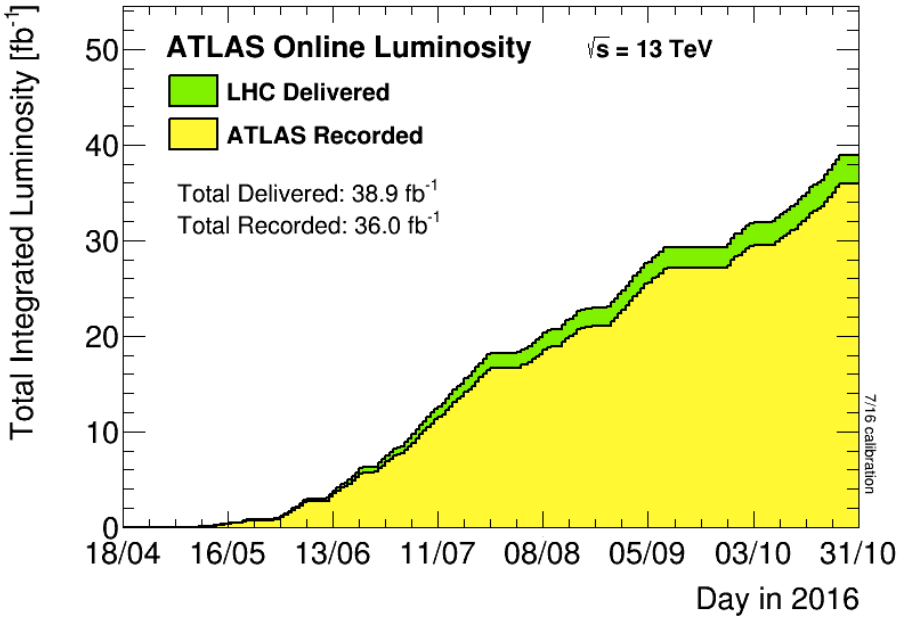
Searching for Dark Matter beyond SUSY with the ATLAS detector

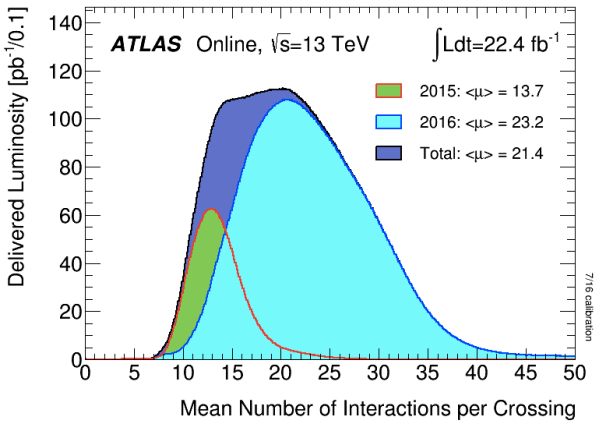
Frederik Rühr (Albert-Ludwigs-Universität Freiburg)
on behalf of the
ATLAS Collaboration

2015+2016 LHC and ATLAS performance

- 2016 was a great year for the LHC
- Between 3 and 16 fb^{-1} selected by presented ATLAS analyses
  - Depending on analysis and final state
- ATLAS had high performance, with data taking efficiencies well above 90%

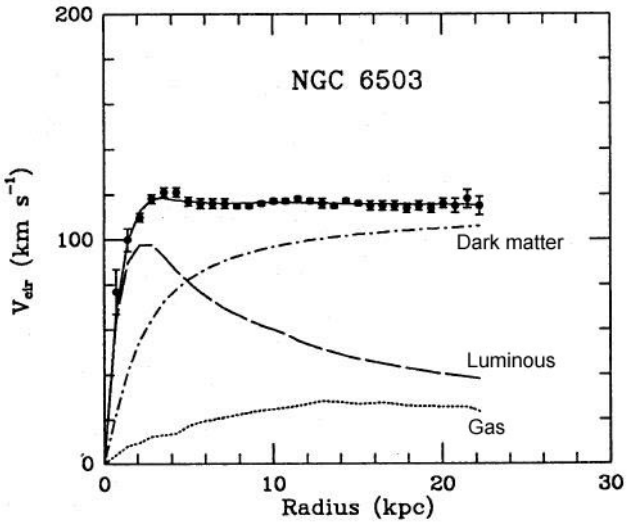


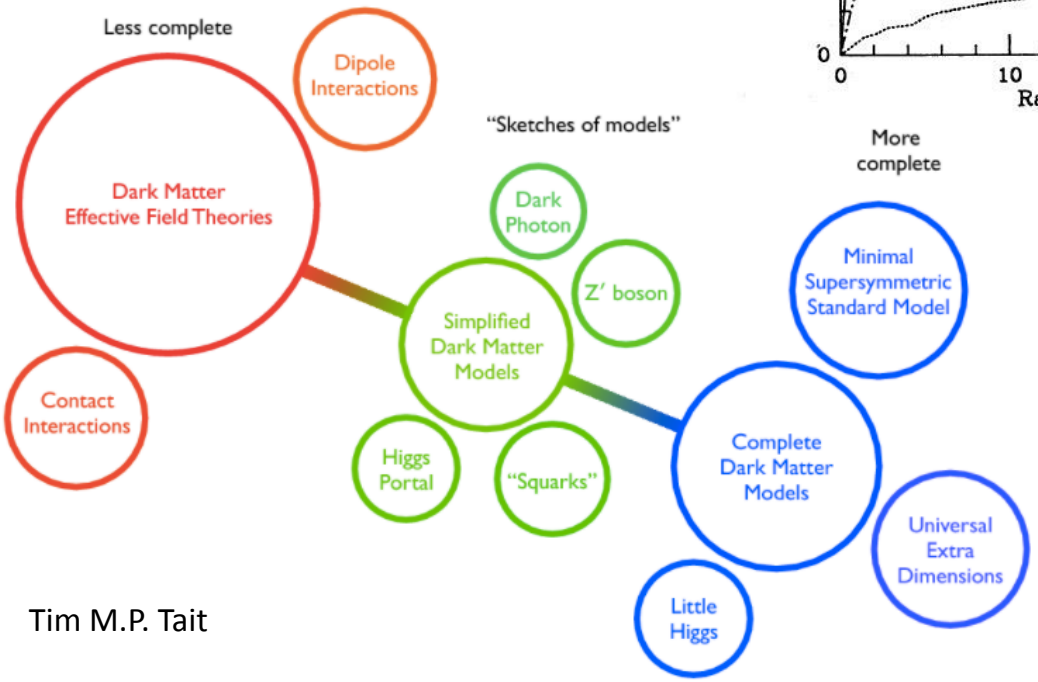




Dark Matter Evidence and Searches

- Evidence for Dark Matter (DM) first found in galactic rotation curves in 1970s
  - By now only one of many pointers
- We do NOT know what a Dark Matter signal would look like @LHC and would like to cast a wide net
  - But we need to make some assumptions

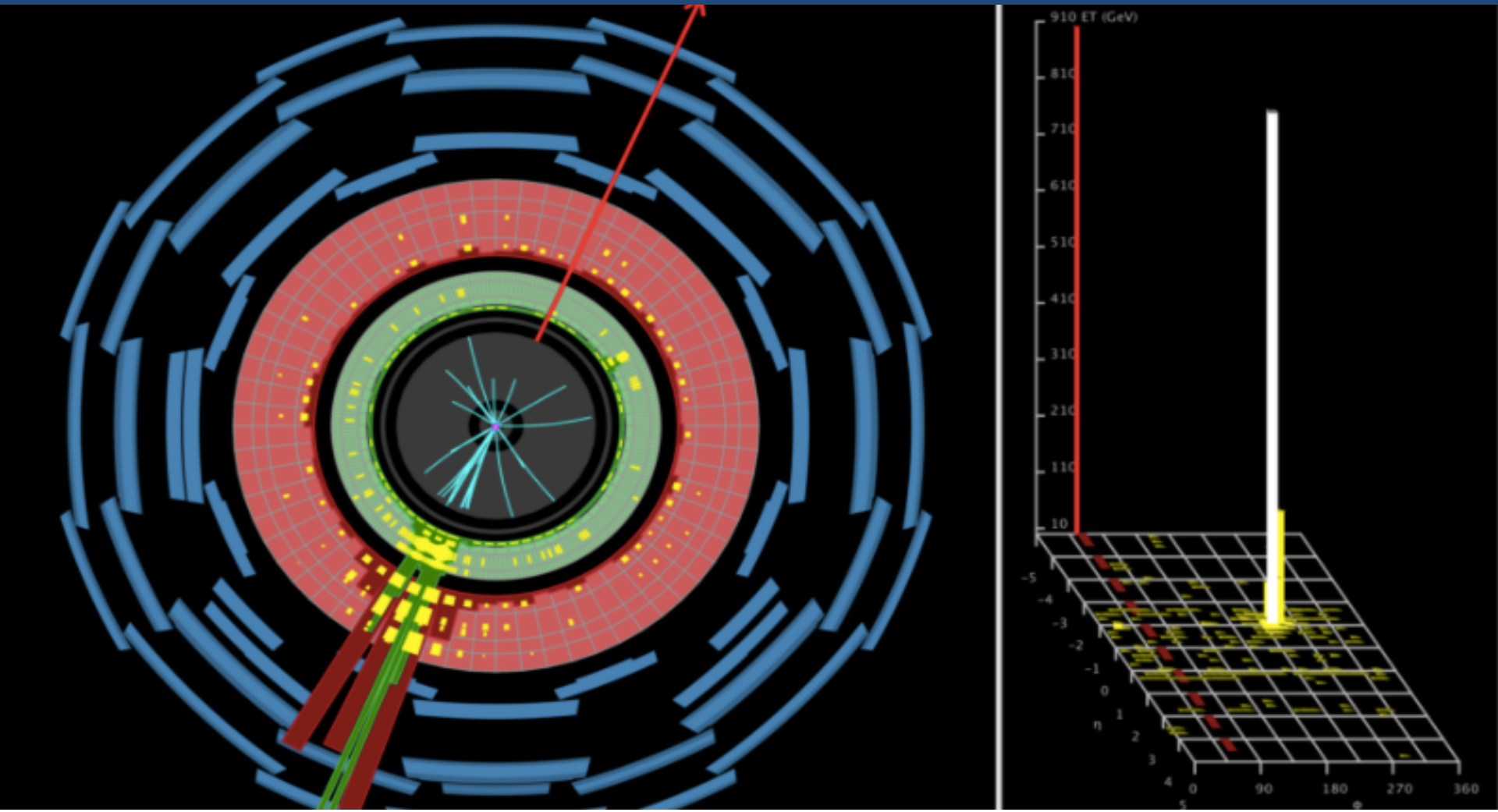




Tim M.P. Tait

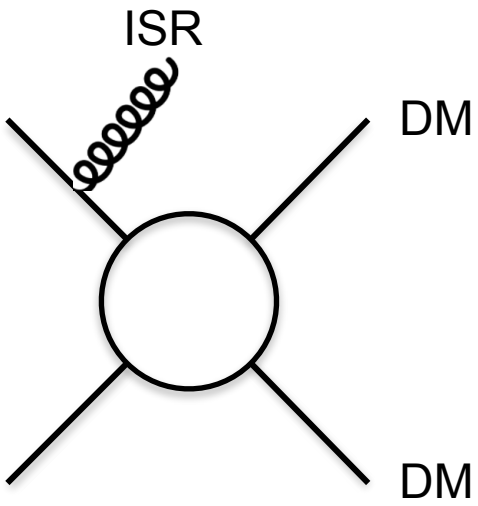
DM forum provides guidelines/benchmarks to navigate this space @LHC (arXiv:1507.00966)

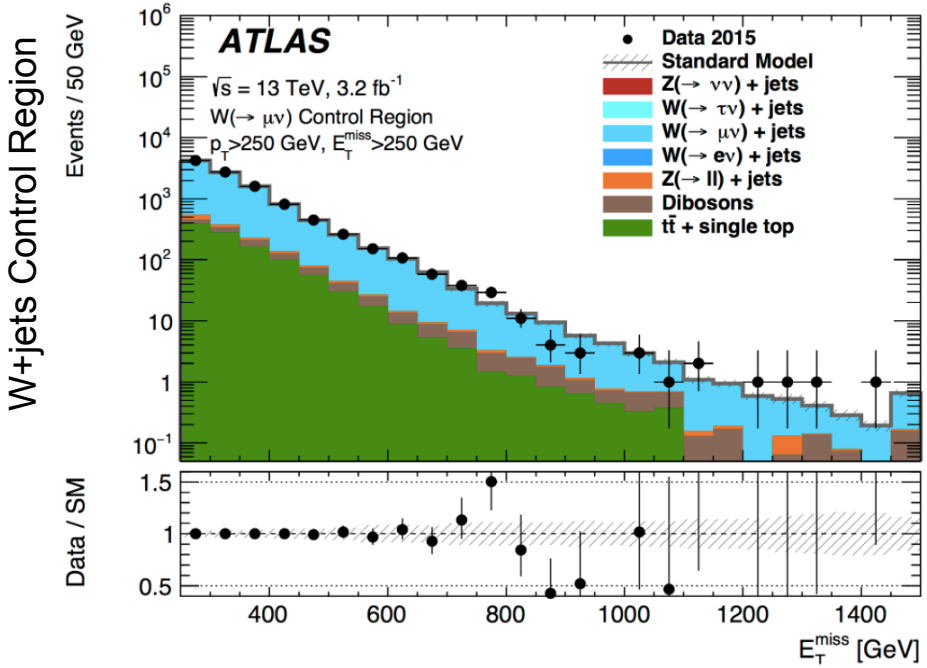
Monojet Search



Event with single high pT jet and 954 GeV of missing transverse momentum

Monojets - Background



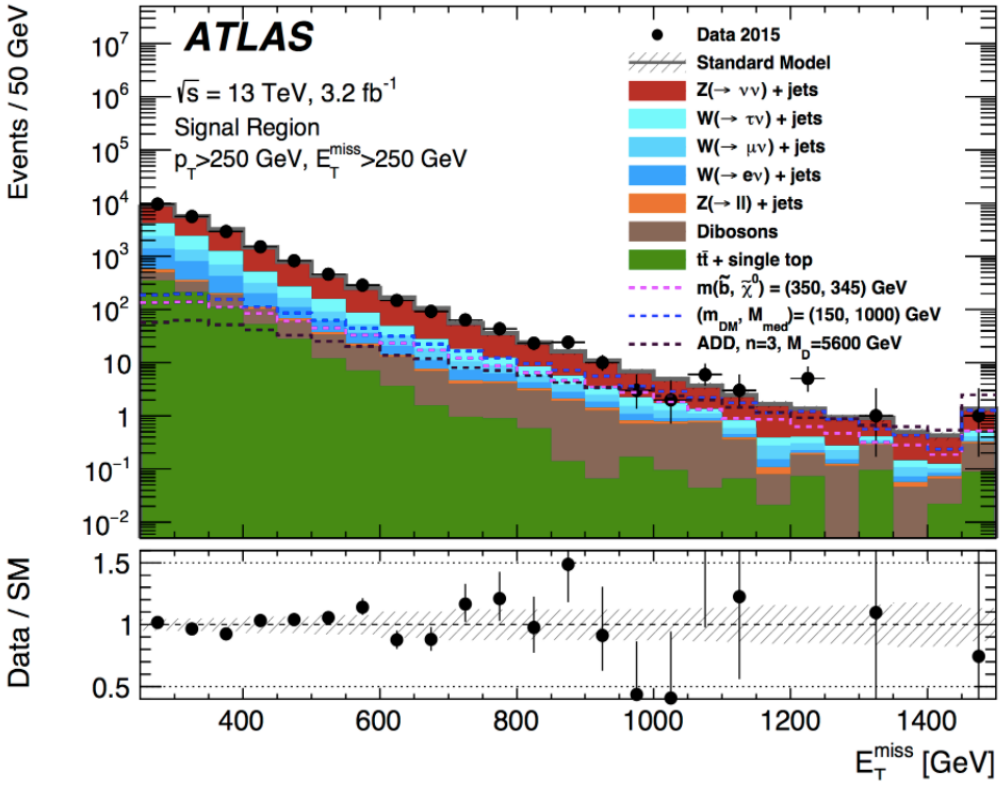


- "Classic" dark matter search, looking for invisible final state recoiling against initial state radiation (ISR)
- Main SM backgrounds:
  - Z (->νν) + jets and W (->τν) + jets
- Constrained by two control regions (CRs) - W (->μν) + jets (treating μ as invisible) and W (->eν) + jets,
  e.g. using

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

arXiv:1604.07773

Monojets - Signal selection



Leading jet with $p_T > 250$ GeV and $|\eta| < 2.4$
At most four jets with $p_T > 30$ GeV and $|\eta| < 2.8$
$\Delta\phi(\text{jet}, \vec{p}_T^{\,\text{miss}}) > 0.4$

- Signal regions (SRs) defined in missing transverse momentum (MET)
  - Inclusive (IM) for model independent results
  - Exclusive (EM), combined for model specific interpretation
- Combined fit of CRs and SRs
- **No significant excess above SM backgrounds**

➡ constraints on new physics

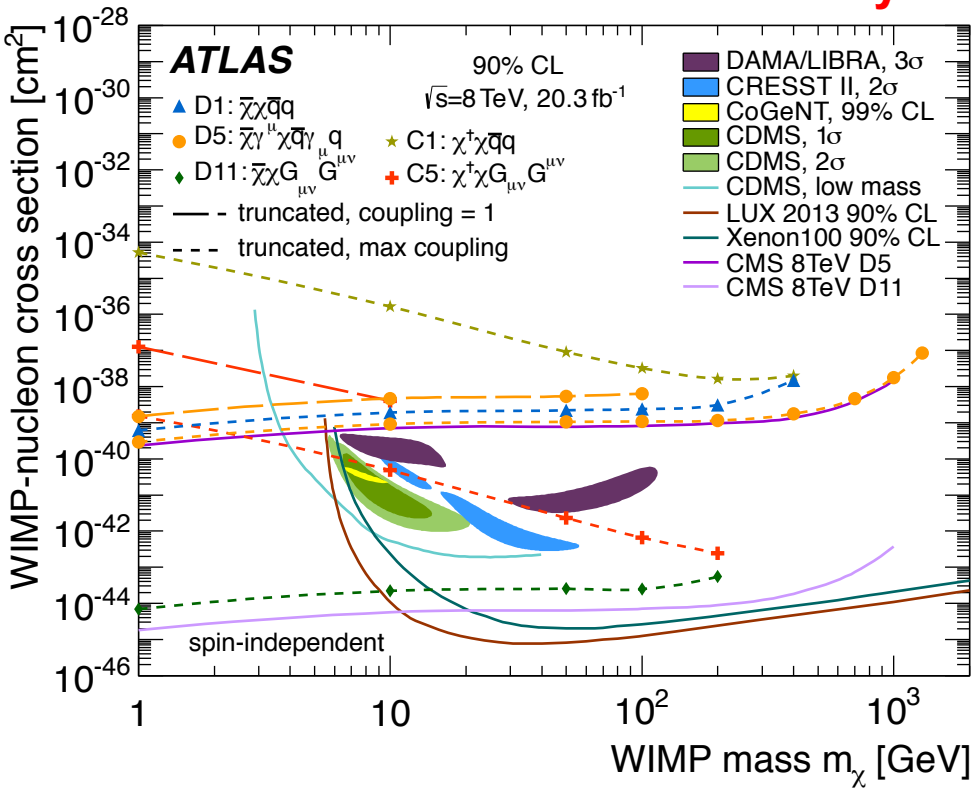
Signal channel	$\langle\sigma\rangle^{95}_{obs}$ [fb]
IM1	553
IM2	308
IM3	196
IM4	153
IM5	61
IM6	23
IM7	19

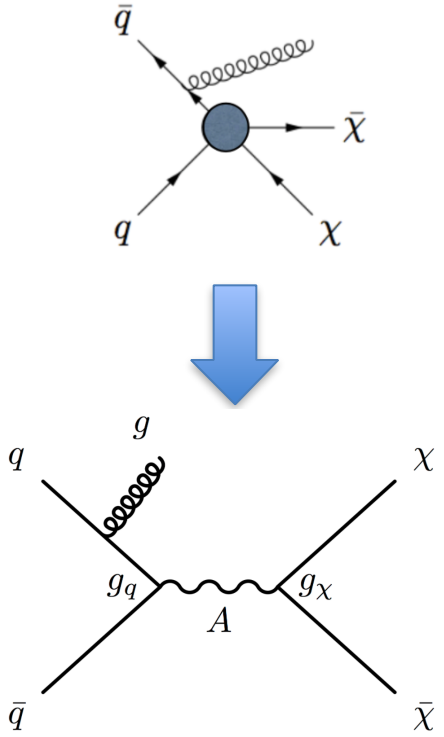
Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
E_T^{miss} (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

arXiv:1604.07773

Monojets - Interpretation

Run-1 - For illustration only!

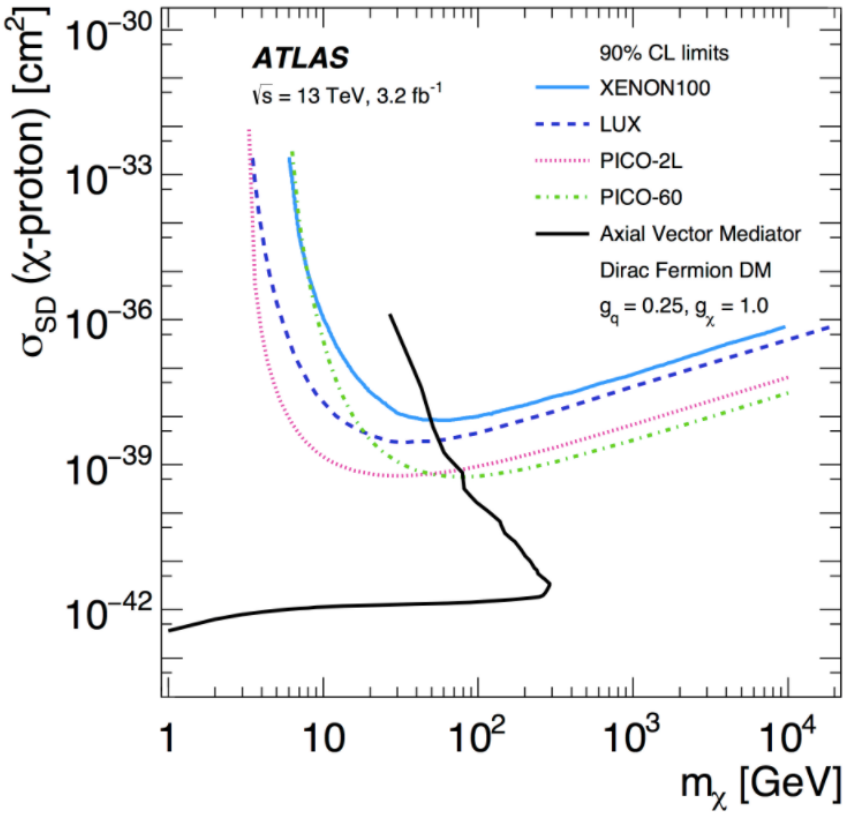


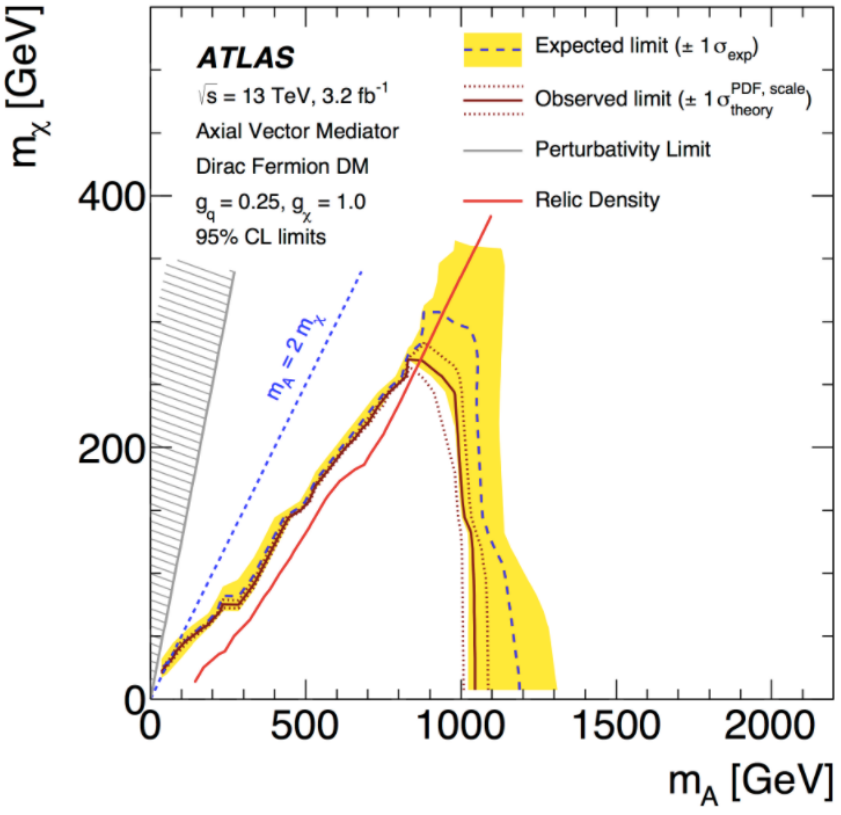


arXiv:1502.01518

- Attempt to stay as model-independent as possible -> In **LHC Run-1** use of Effective Field Theory (EFT) approach (similar to direct detection experiments)
  - But: high momentum transfer possible at LHC - validity is limited and range of validity depends on model characteristics beyond the EFT
- **Move to simplified models including massive mediator where available**

Monojets - Run-2 Interpretation



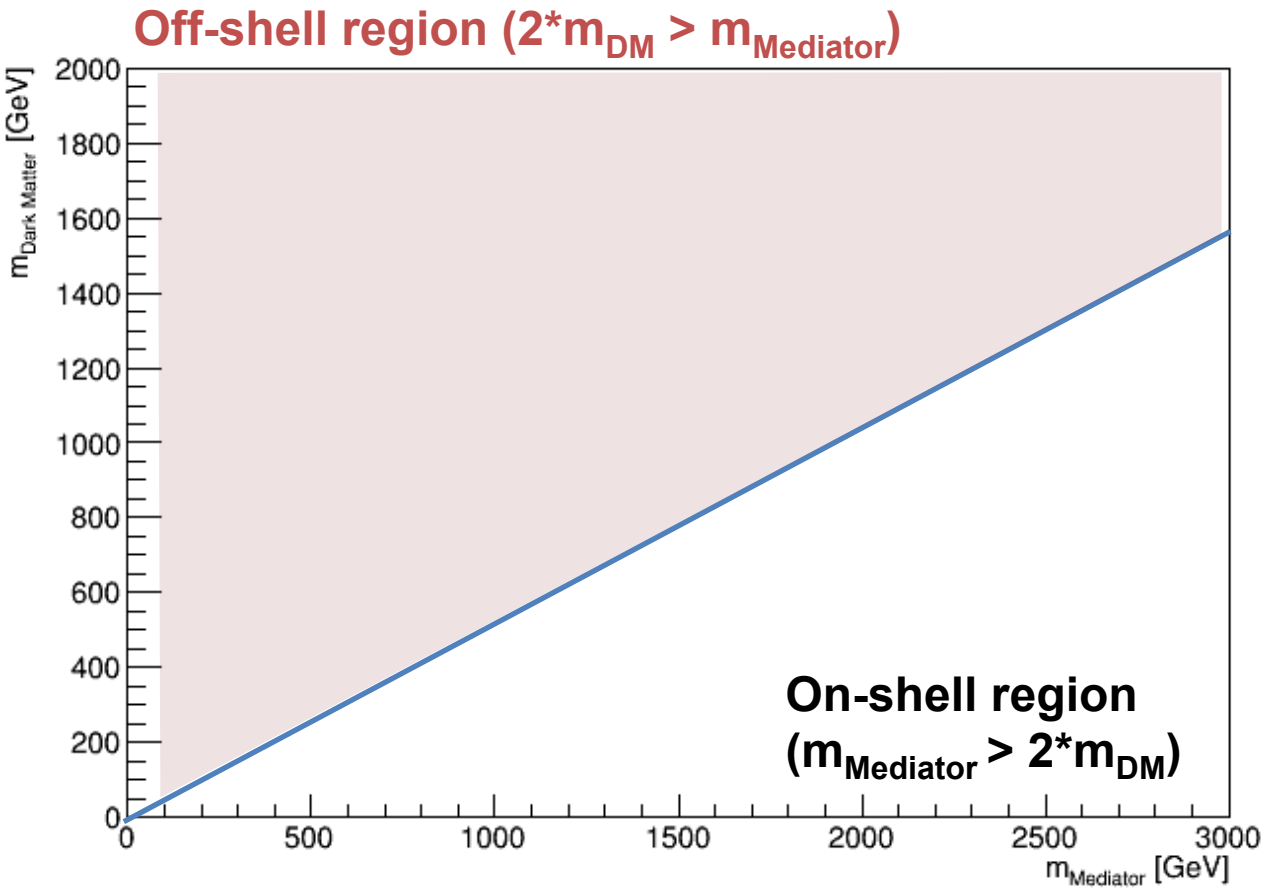


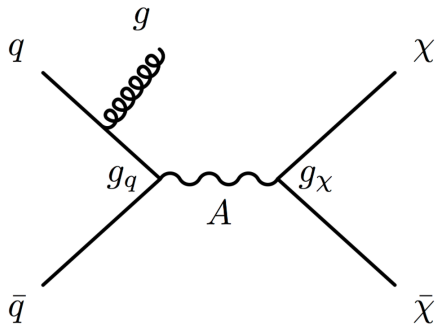
arXiv:1604.07773

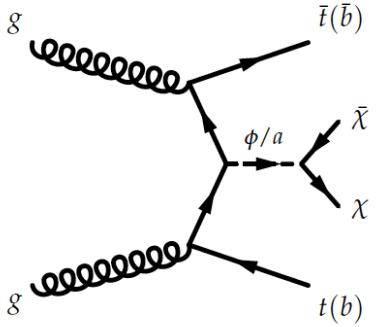
- Collider results retain unique access to low DM masses
- **Model dependency now explicit**
  - Constraints often presented in plane of DM and mediator mass (right)

(Not necessarily both interpretations (left and right figure) provided by any given analysis, guidelines for translation can be found in ATLAS/CMS DM report arXiv:1507.00966)

Types of Dark Matter searches

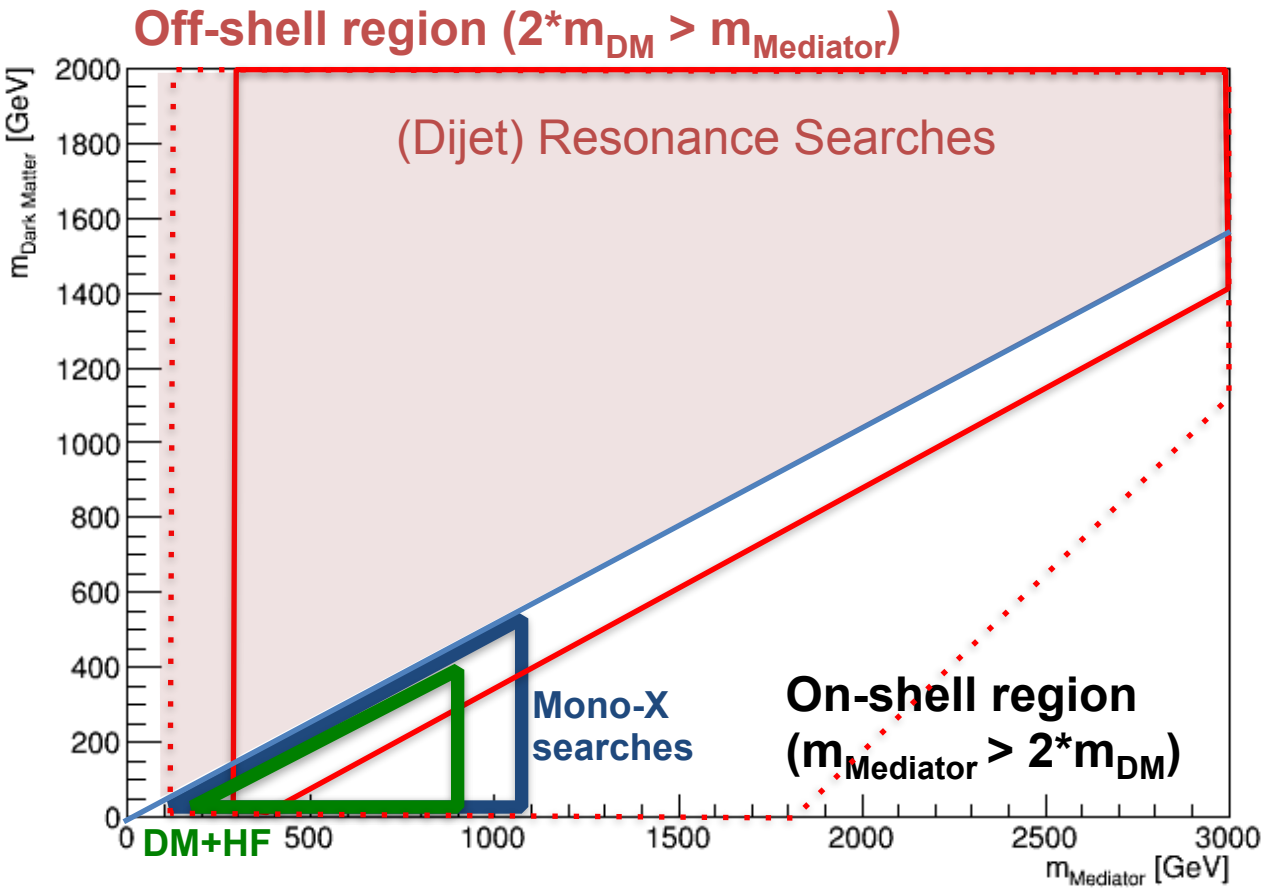


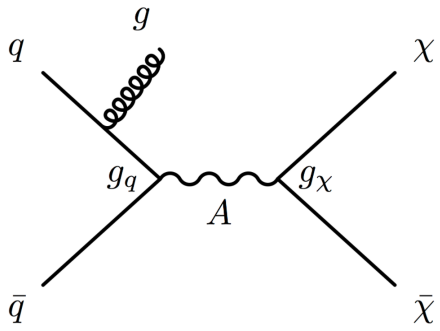


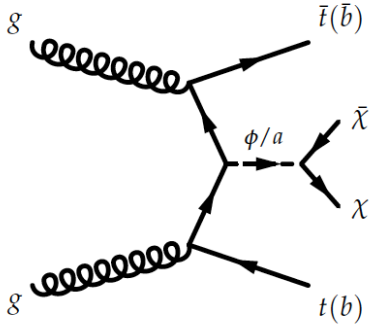


- In addition to Mono-X and heavy flavor + DM searches, due to explicit coupling of mediator to quarks, sensitivity from e.g. dijet resonance searches

Types of Dark Matter searches

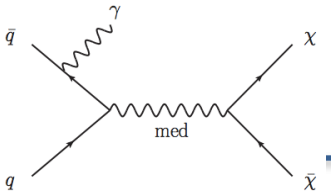






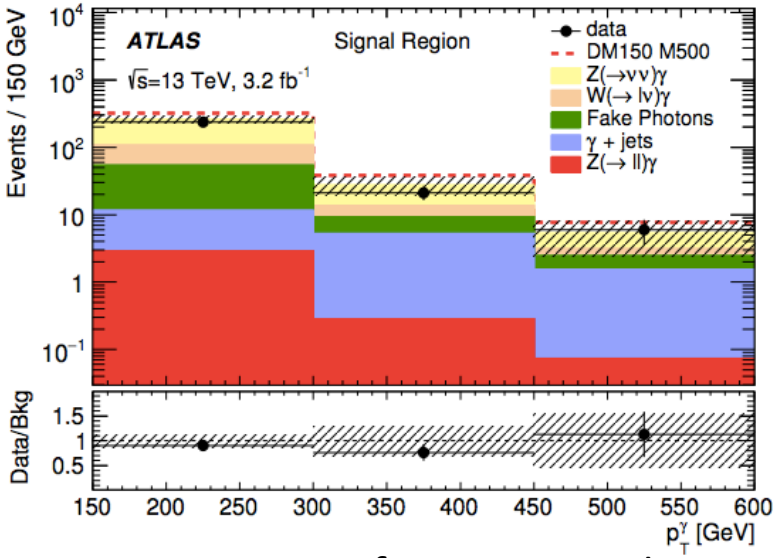
- In addition to Mono-X and heavy flavor + DM searches, due to explicit coupling of mediator to quarks, sensitivity from e.g. dijet resonance searches
- **Let's discuss the other searches to build real versions of this mockup**

Monophoton analysis

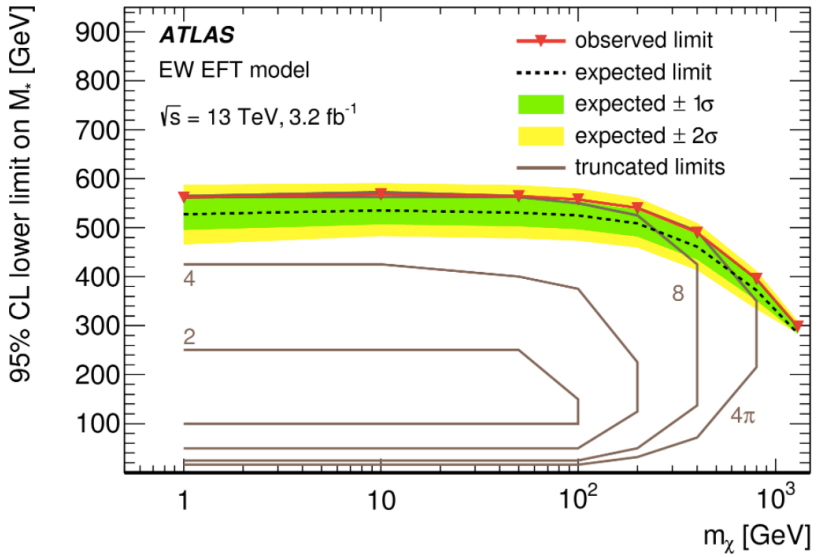


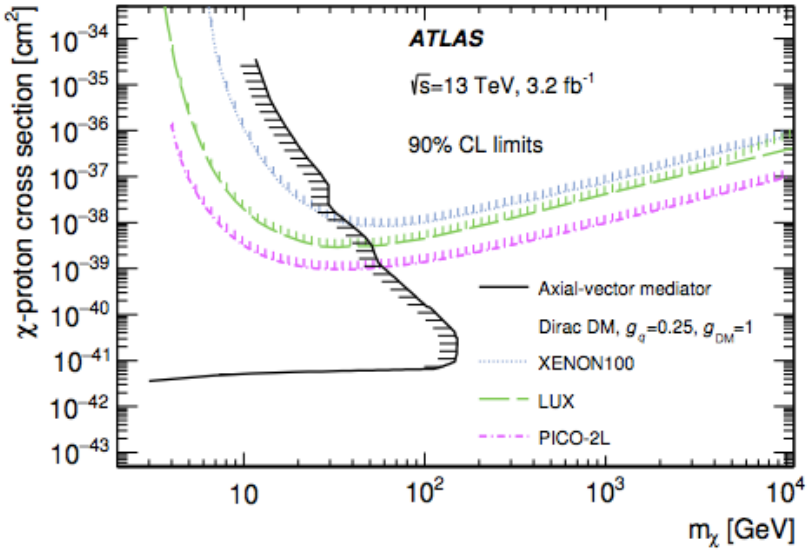
- Events with isolated photon (pT > 150 GeV) and MET > 150 GeV selected
  - Lepton veto, at maximum one jet
- Main backgrounds are data driven
- Fake photons from electrons via “Z->eγ”
- Fake photons from jets using ABCD method

- No excess above SM expectation observed



EFT for γγ-χχ coupling

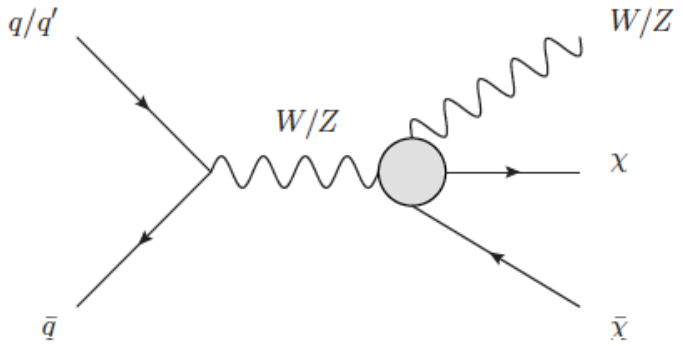




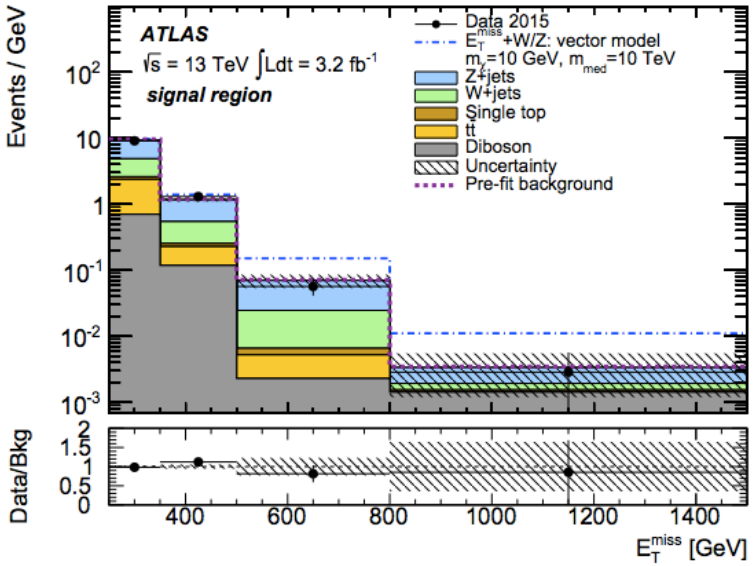
arXiv:1604.01306

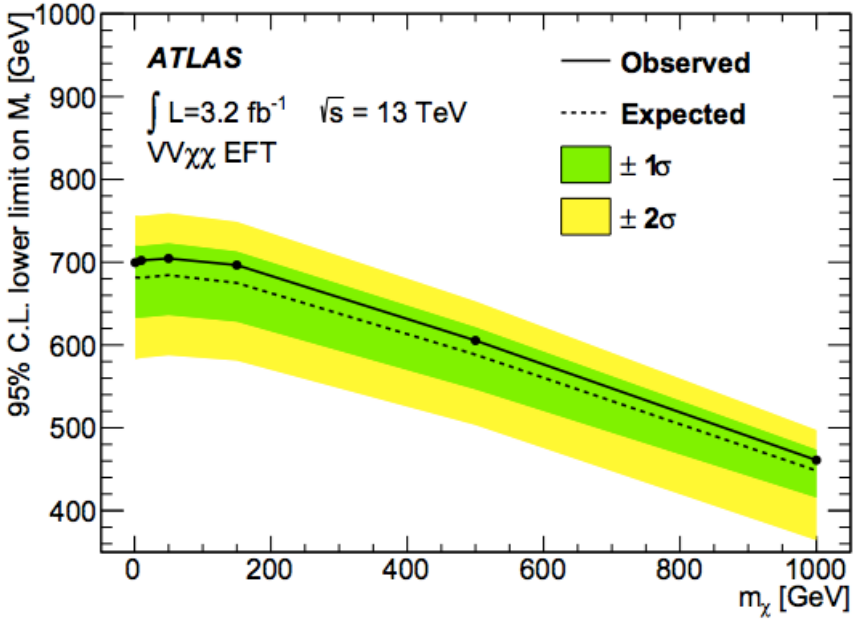
Mono-W/Z -> large-R jet

- What if there is no strongly interacting mediator?
- Select events with MET > 300 GeV and boosted, hadronically decaying W/Z (pT > 200 GeV)
  - Not reconstructed as two individual jets, but as one “merged” large radius jet
- Dominant background Z->νν
  - constrained via Z->μμ
- No excess above SM observed
  - interpret results in simplified models, but also EFT for W/Z and DM interaction



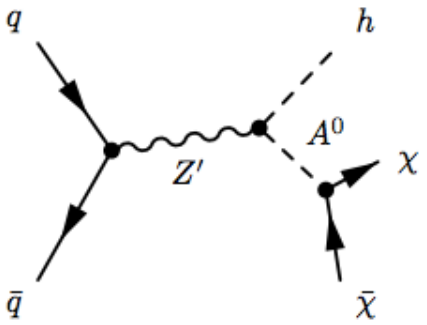
arXiv:1608.02372





Mono-Higgs -> γγ

- Search for h+MET with h->γγ, interpreted in context of a number of models, e.g.
  - Type-II two-Higgs-doublet model (shown here)
  - Heavy scalar model with H → hχχ (EFT)
- Events split into four categories
  - High MET significance, high $p_{\gamma\gamma}$
  - High MET significance, low $p_{\gamma\gamma}$
  - Intermediate MET significance
  - The rest



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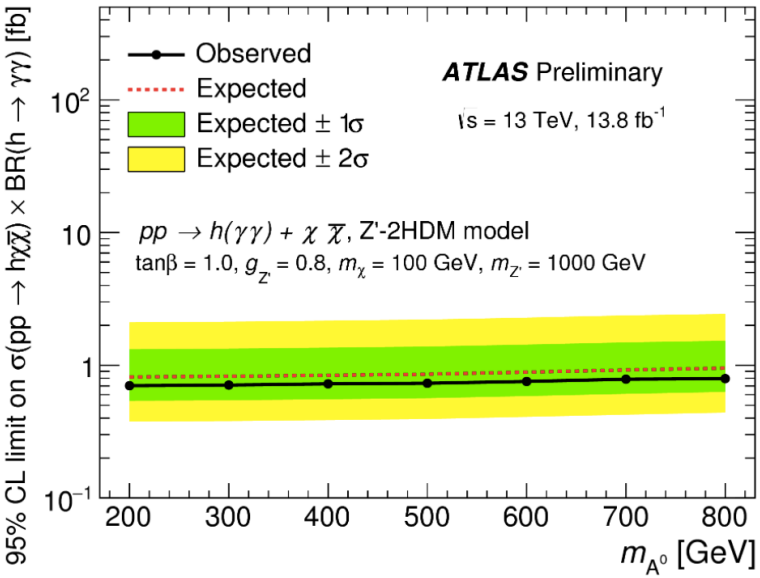
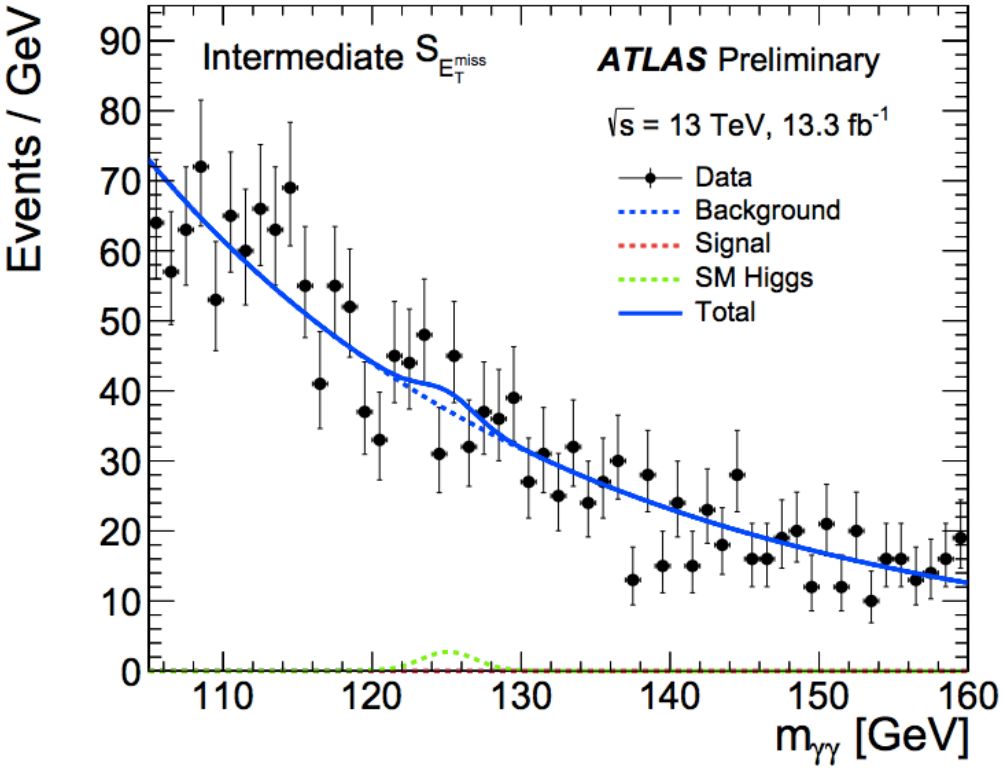
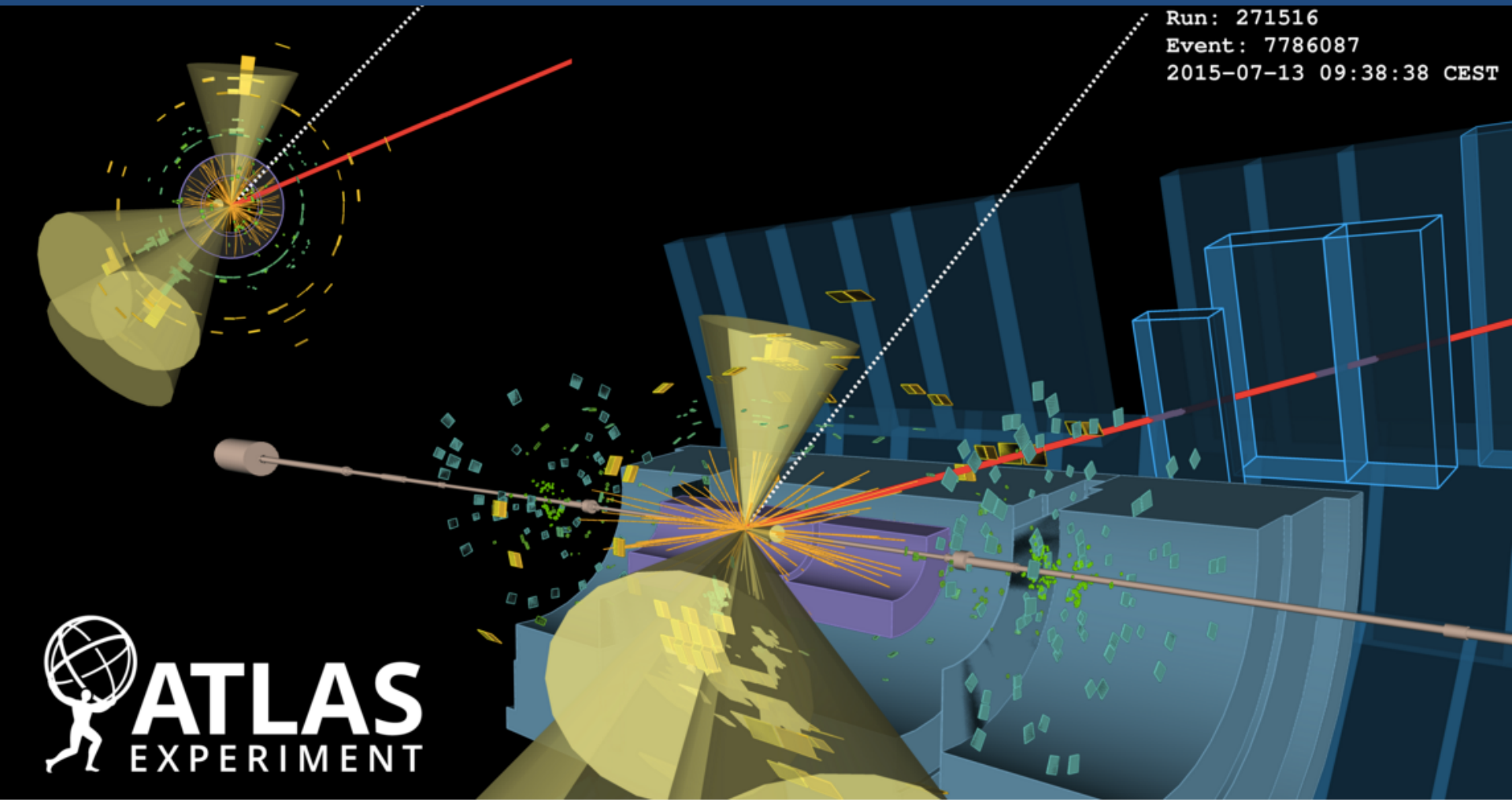




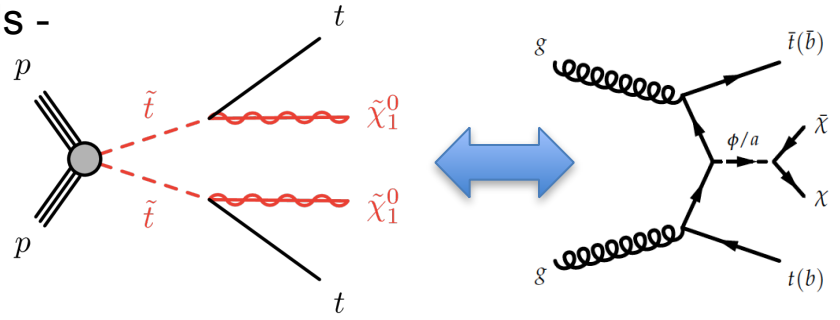
Dark Matter plus Heavy Flavor Quarks



Two top quark candidates with missing transverse momentum of 470 GeV

DM + Heavy Flavor

- Searches for Supersymmetric partners of e.g. top quarks include dedicated signal regions for DM+ttbar
- Sensitivity comparable between decay channels - exemplarily showing 1-lepton analysis
  - Slight excess in one signal region (3.3 σ)
    - expected somewhere considering number of analyses/signal regions being looked at



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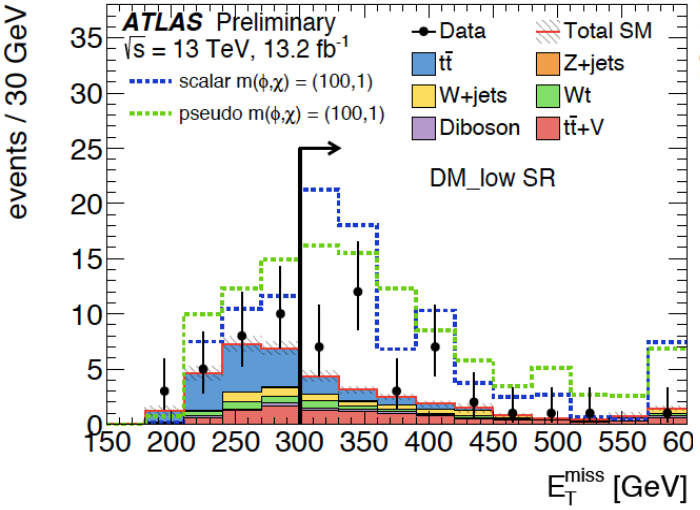
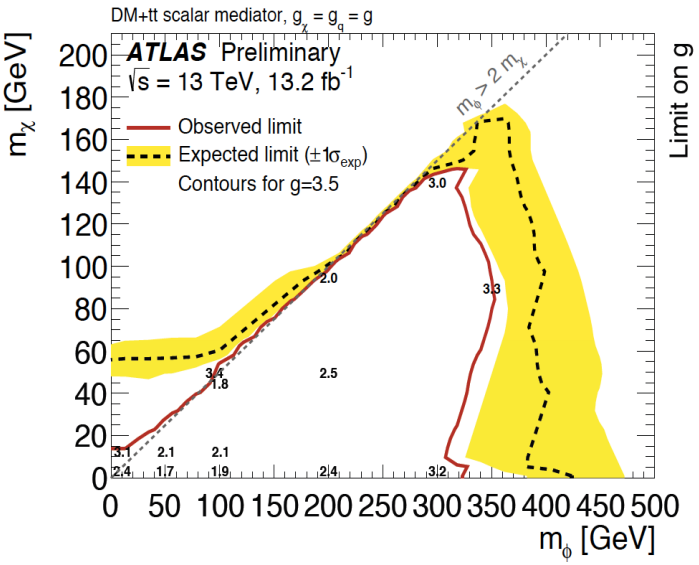
ATLAS-CONF-2016-050

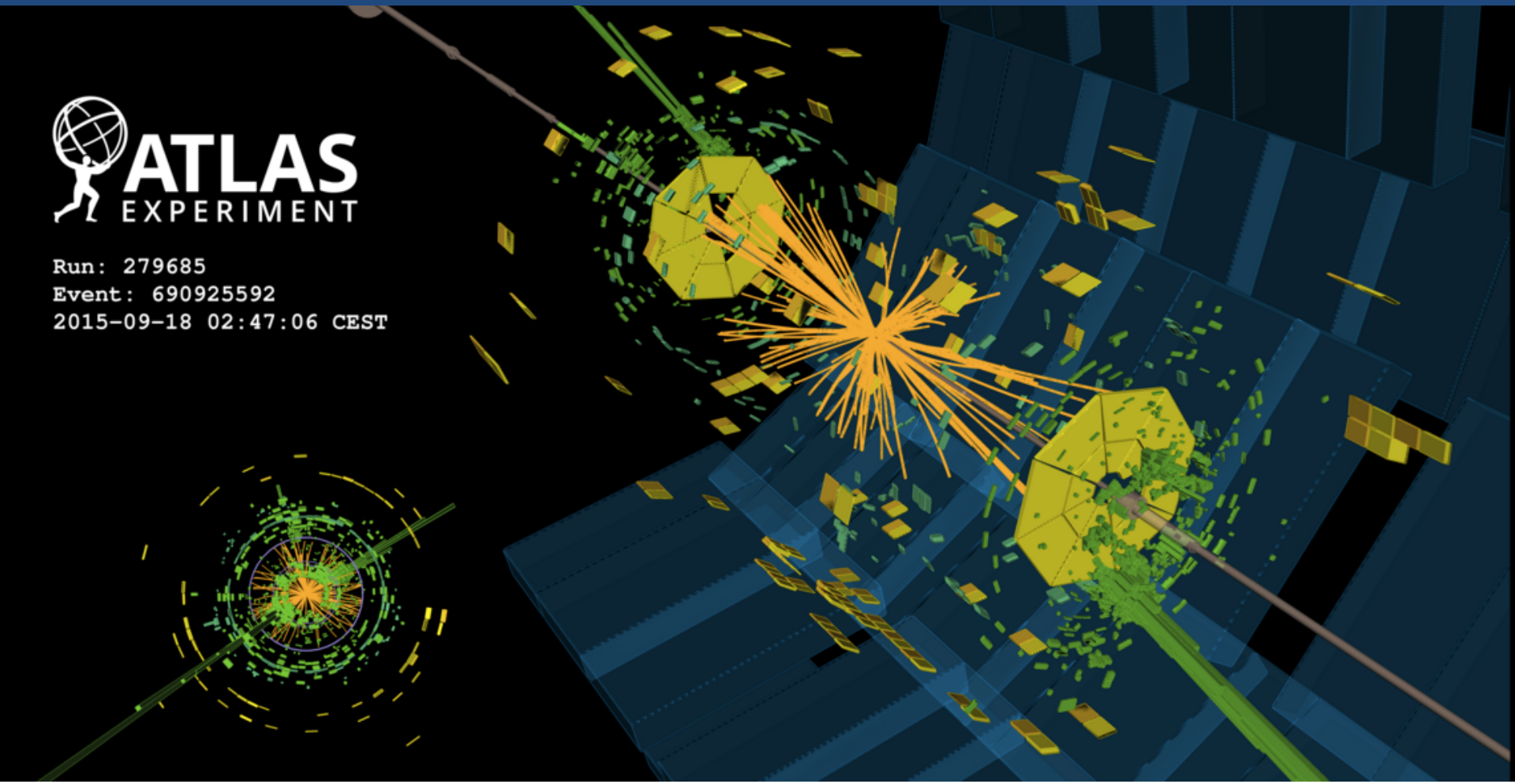
ATLAS-CONF-2016-077

Signal region	DM_low	DM_high
Observed	35	21
Total background	17 ± 2	15 ± 2
$t\bar{t}$	4.2 ± 1.3	3.3 ± 0.8
W+jets	3.1 ± 1.5	3.4 ± 1.4
Single top	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t}+V$	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t}+W/Z$ NF	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.0004 (3.3)	0.09 (1.3)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	28.3	15.6





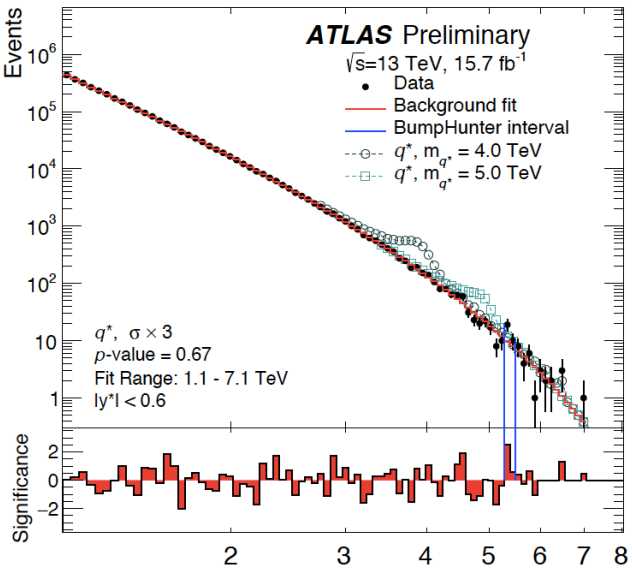
Resonance Searches and Dark Matter



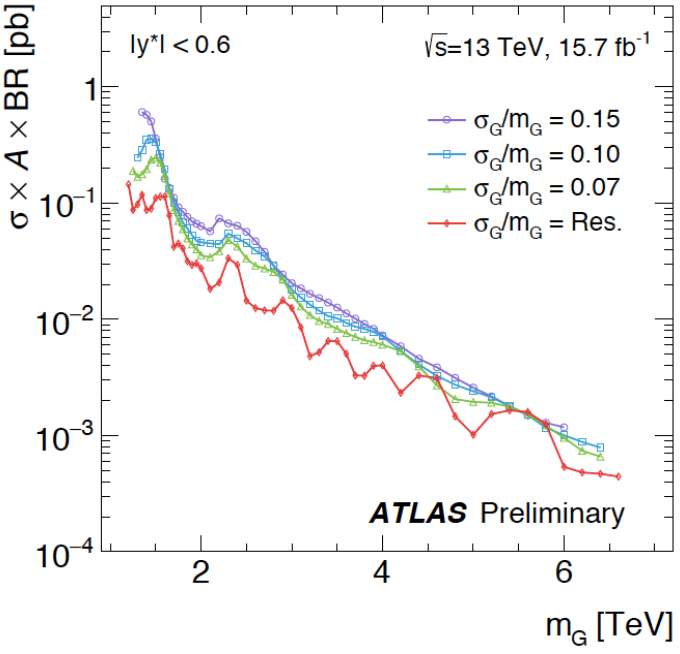
Event with dijet system with a mass of 8.8 TeV

Hints at DM in dijet events?

- DM mediator coupling to quarks in principle allows for sensitivity in dijet resonance searches
  - Constrain parts of the phase space in addition to other searches - discovery of a new resonance on its own would hardly be evidence for Dark Matter
- ATLAS dijet searches provide constraints on generic resonances of variable width -> interpret as mediator in DM model



Background obtained from fitting functional form to data

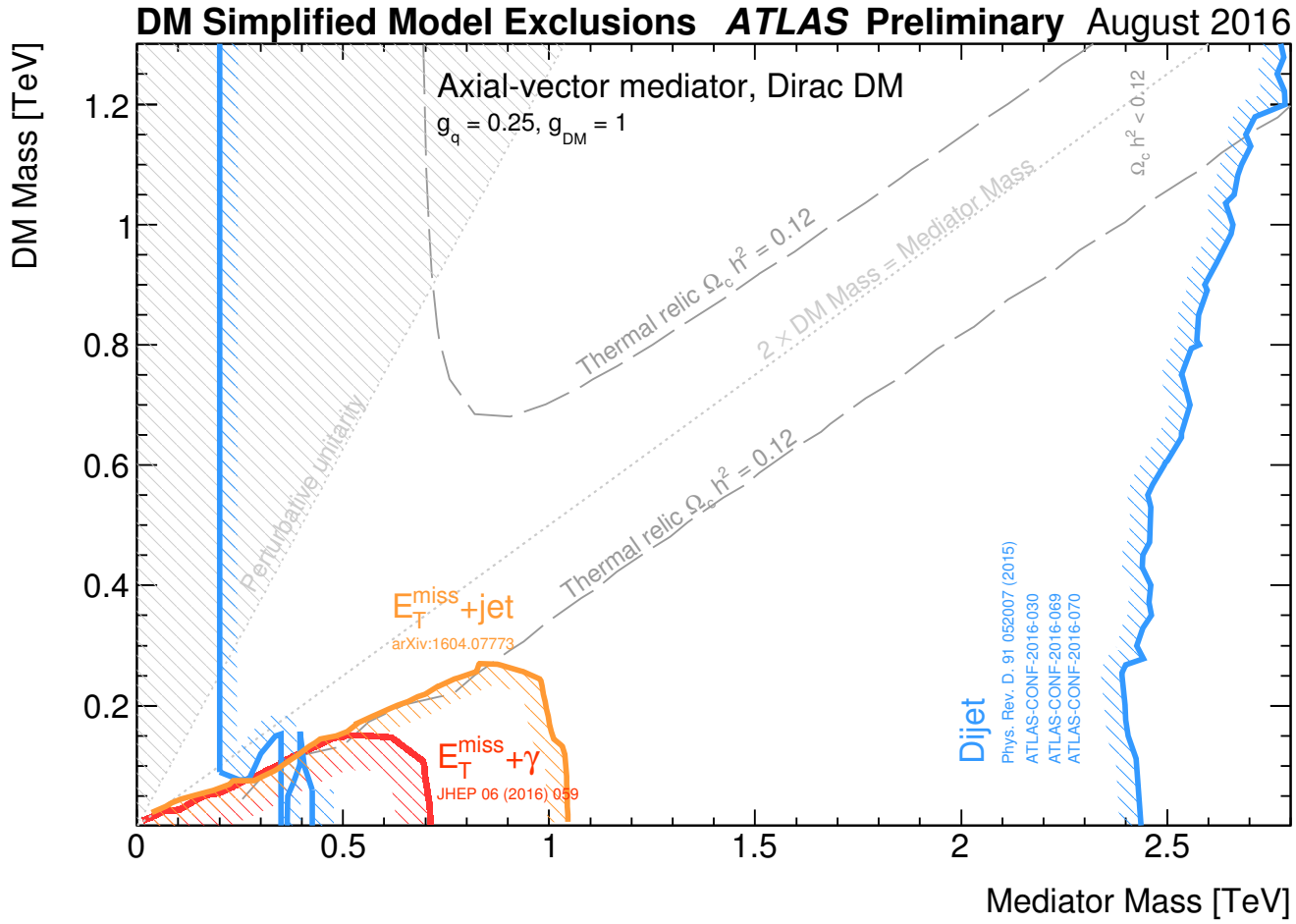


- Likewise, coupling to leptons would open up dilepton searches*
- Details on these searches can be found in general ATLAS Exotics talk

* no ATLAS reinterpretation done yet, Z' results provide rough indication

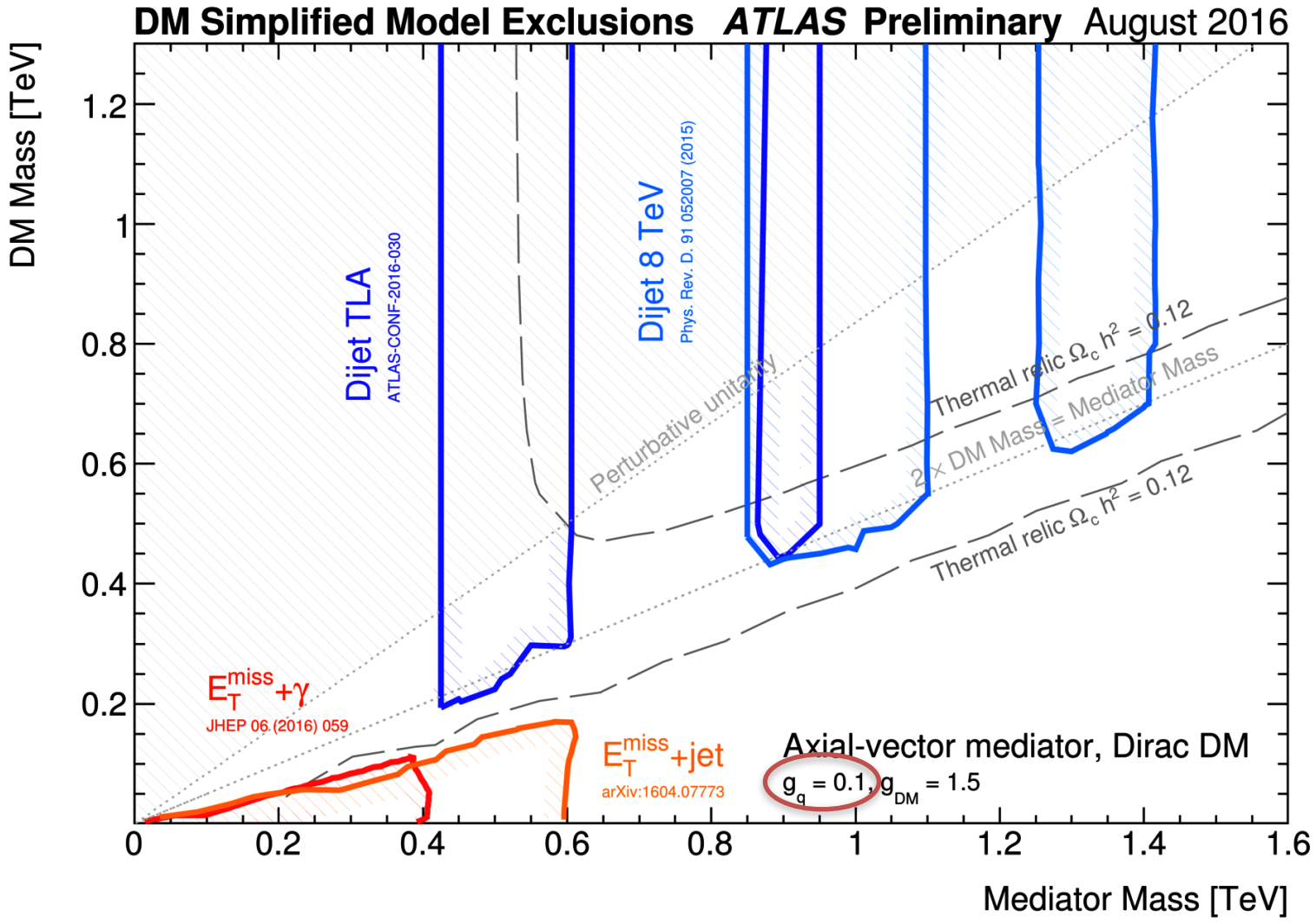
ATLAS-CONF-2016-069

Putting everything together

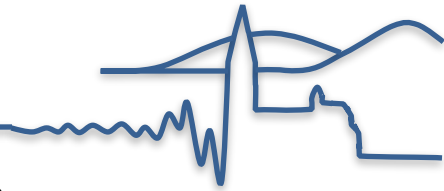


- No evidence for physics beyond the Standard Model found in any channel
- Choice of $g_q = 0.25$ for simplified models a bit “optimistic”?
  - Large part of phase space closed by resonance searches

Putting everything together



Summary and Outlook



- LHC and ATLAS showed great performance in 2015 and 2016

- Dark Matter sector is a very active field
- **Collider searches can provide valuable input to the search for Dark Matter, especially at low masses**

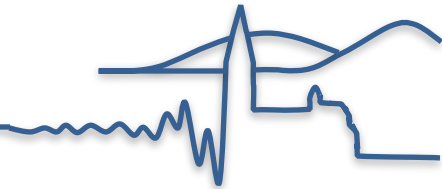
- Move to simplified models (required at LHC) limits model independent interpretation* but necessary
  - also opens up new avenues, e.g. reinterpretation of resonance searches to constrain DM models

- **No evidence for physics beyond the Standard Model found so far** ☹
  - Dark Matter "evidence" at colliders also would not be unambiguous - large difference between "collider stable" and galactic time scales

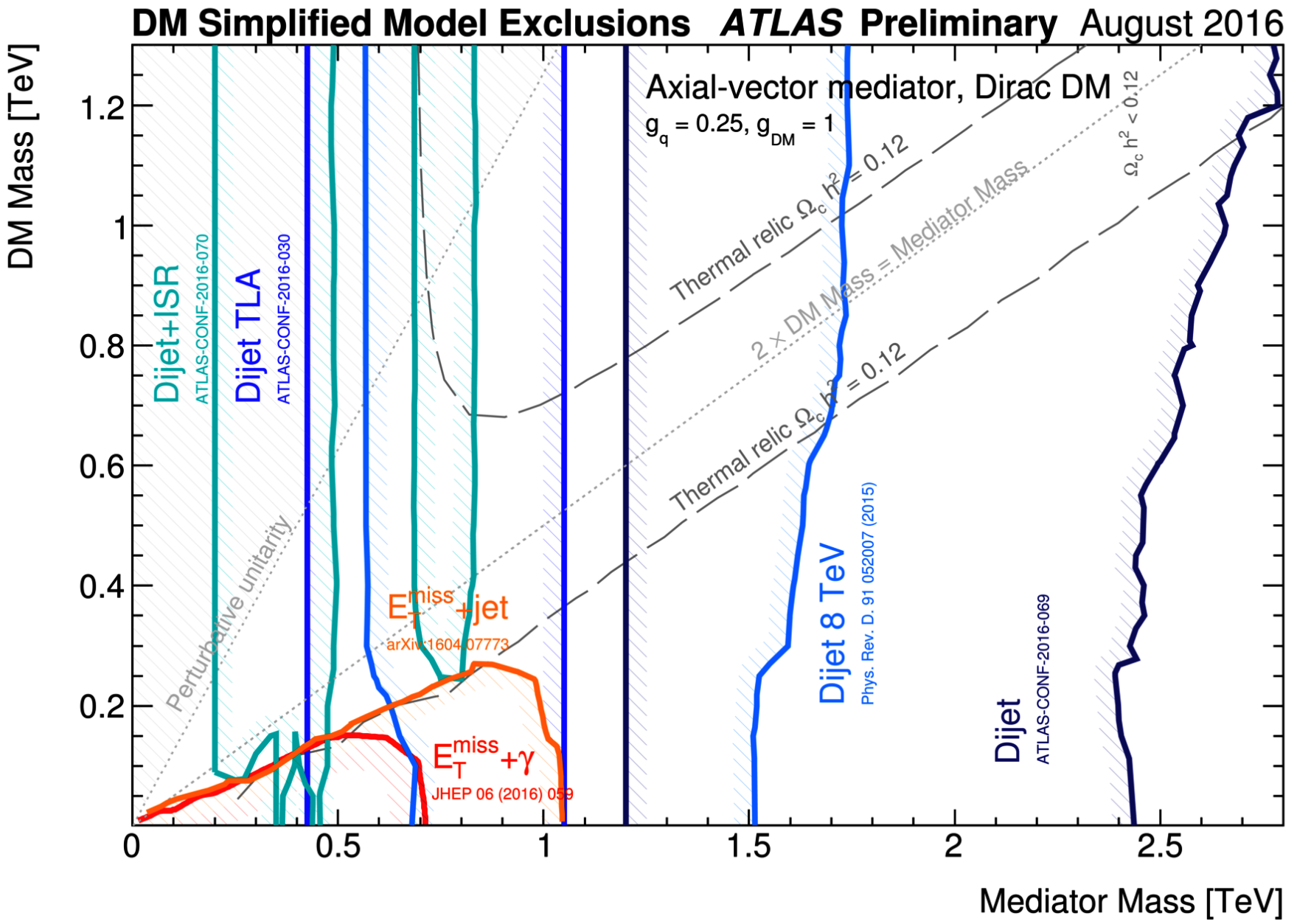
- 3 to 10 times more data already recorded and mostly analyzed - **stay tuned!**

* which technically never was there @colliders

Backup

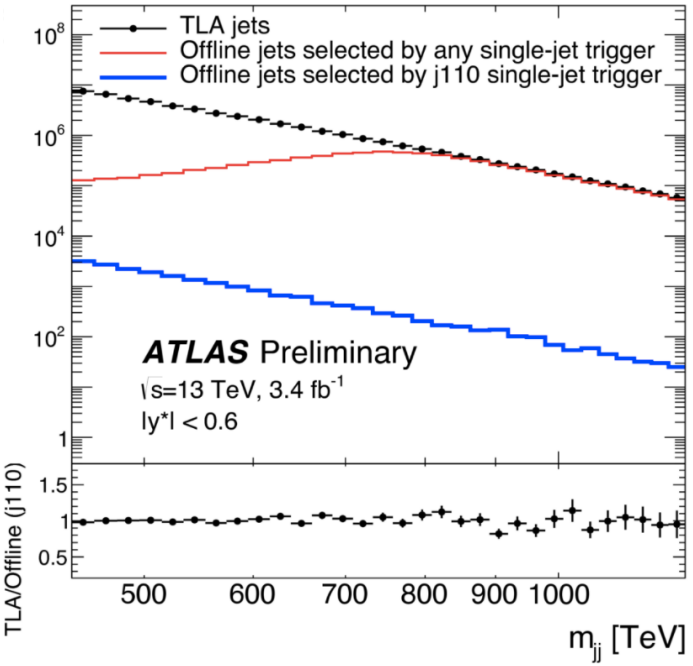


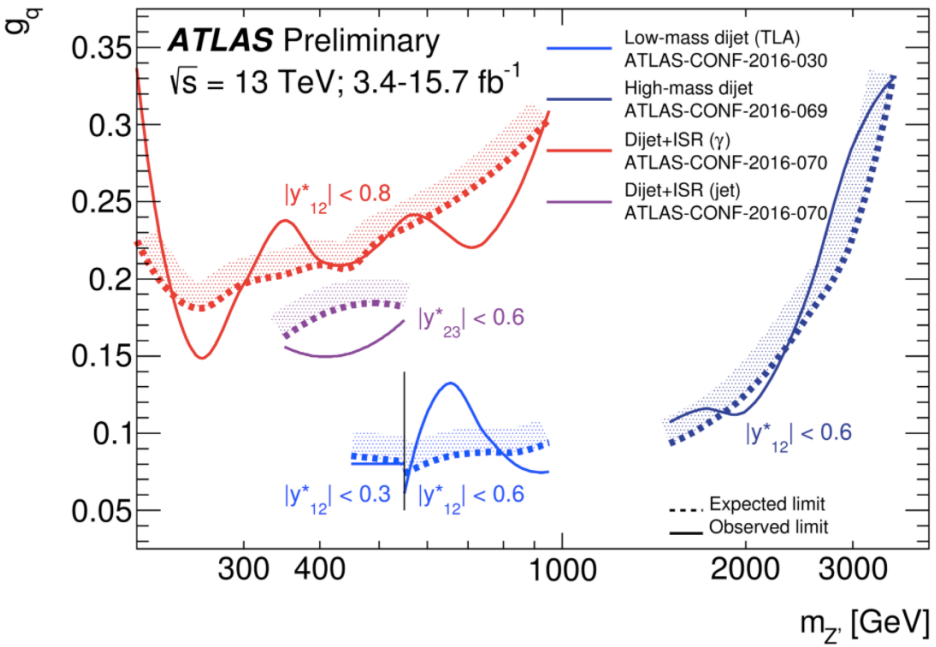
- All relevant current ATLAS results can be found at:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults


DM Simplified Model Exclusions ATLAS Preliminary August 2016
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_{DM} = 1$
Thermal relic $\Omega_c h^2 = 0.12$
2 × DM Mass = Mediator Mass
Thermal relic $\Omega_c h^2 = 0.12$
$\Omega_c h^2 < 0.12$
Perturbative unitarity
Dijet+ISR
ATLAS-CONF-2016-070
Dijet TLA
ATLAS-CONF-2016-030
E_T^{miss}+jet
arXiv:1604.07773
E_T^{miss}+γ
JHEP 06 (2016) 059
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Dijet
ATLAS-CONF-2016-069
DM Mass [TeV]
Mediator Mass [TeV]
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2
2.5

Low Mass Dijet Resonances?

- In DM context, also interested in low mass resonances with low coupling to quarks
  - Not accessible by default dijet search due to data acquisition bandwidth constraints
- ATLAS implemented additional data stream for minimal event information (jets only) bypassing high level trigger

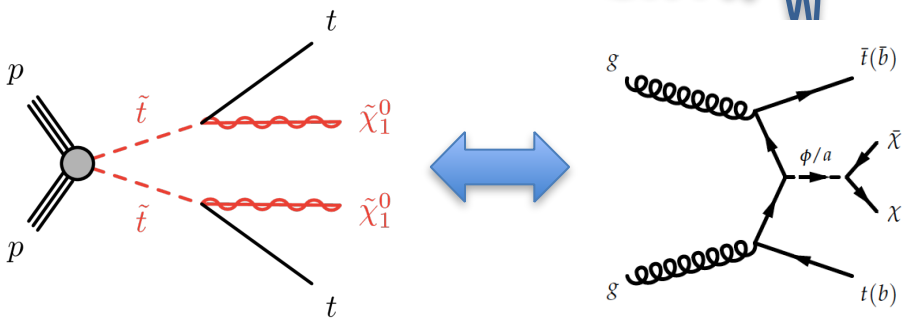




- Additionally look at events where dijet system is balanced against high momentum initial state radiation
  - Allows events to pass trigger thresholds for “normal” data acquisition

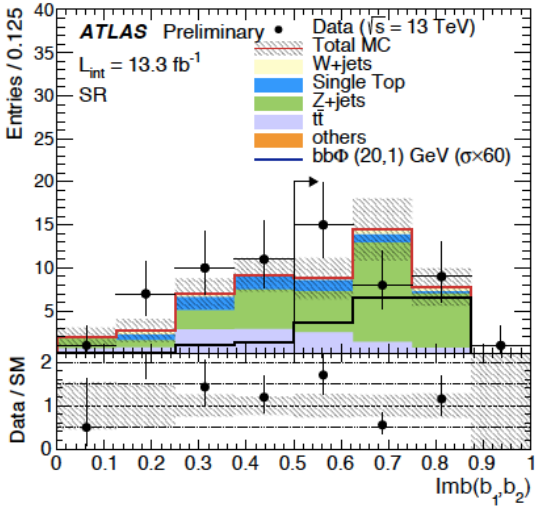
DM + Heavy Flavor

- Searches also conducted in "SUSY-like" final states of DM + bb/ttbar

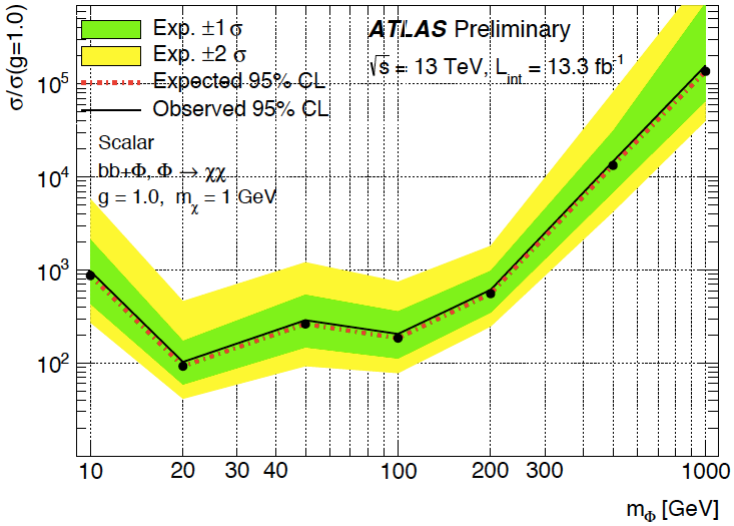


- bb-type analysis selects events with
  - 2 b-jets, using a 60% signal efficiency working point
  - MET > 150 GeV and no significant third jet (p_T > 60 GeV)
- Separate signal from background by requiring large angular separation of all jets and the two b-tagged jets plus a momentum imbalance

$$Imb(b_1, b_2) = \frac{p_T(b_1) - p_T(b_2)}{p_T(b_1) + p_T(b_2)} > 0.5$$



Signal channel	$\langle \epsilon\sigma \rangle^{95}_{obs}$ [fb]
SR	1.38



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