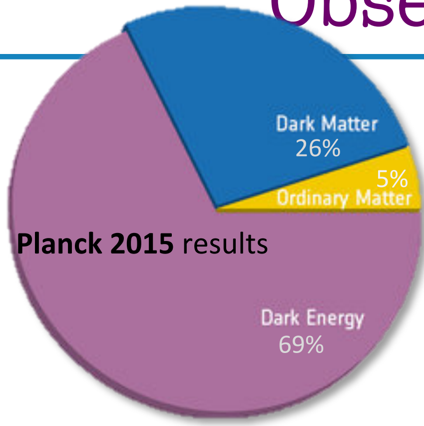
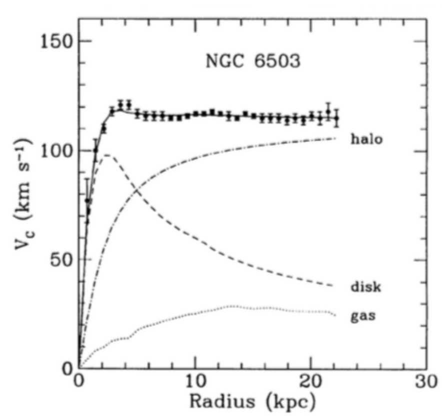
Dark Matter Searches with the ATLAS Detector

Arely Cortes-Gonzalez
(CERN)
On behalf of the **ATLAS Collaboration**

Observational **Evidence** for DM



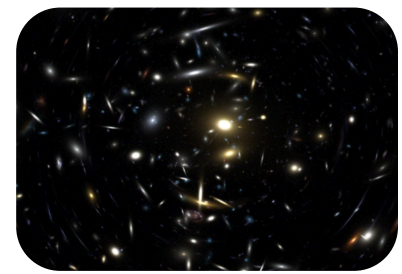
Presence of a **dark matter** component in the universe inferred from the observation of its gravitational interactions.



- **Rotation of stars** around the center of the galaxies is not consistent with the amount of mass *observed*.

- **Collisions of cluster of galaxies**.

← The bullet cluster.



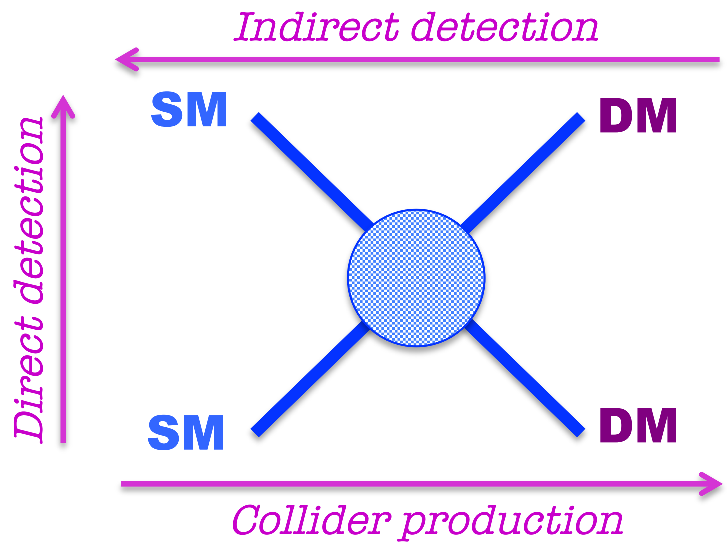
- **Gravitational Lensing**: Large distortion of images of distant galaxies due to gravitational lensing (indication of DM in galaxy clusters).

- **Requirements**:
  - Interacts gravitationally.
  - Cosmologically stable.
  - Electrically Neutral.
  - Massive & weakly interacting.

Candidates?

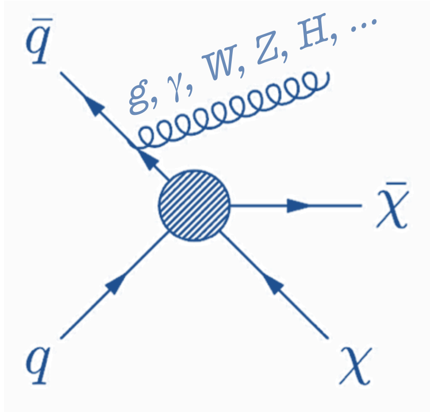
- SUSY particles? E.g. LSP (in R-parity conserving SUSY).
- WIMPs: *Experimental evidence motivates a DM sector composed dominantly of weakly interacting massive particles.*

Dark Matter **Searches**



At colliders like the LHC,
WIMPs can be produced in pairs.

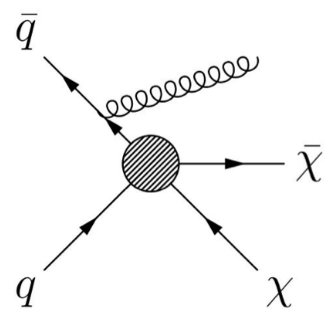
WIMPs escape detection, thus leaving large missing transverse momentum as their signature.



We can tag those events via the presence of an energetic jet, a photon or a boson from ISR.
MET+X topologies.

Effective Field Theories (EFTs) of SM interaction with WIMPs. Effective Lagrangian approach with parameters M* and m_χ. *Theory only applicable when M is much larger than energy scale present in reaction.*

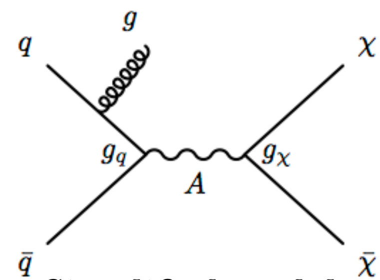
LHC-Run I focus



LHC-Run II focus

Natural solution to **EFT validity**: **simplified models** (with mediator).

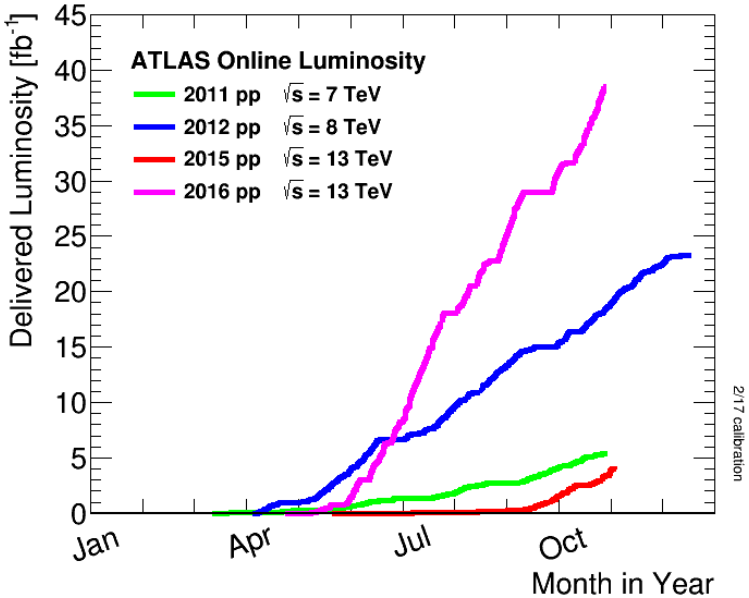
○ Three regimes can be studied: off-shell, resonance, contact interaction.



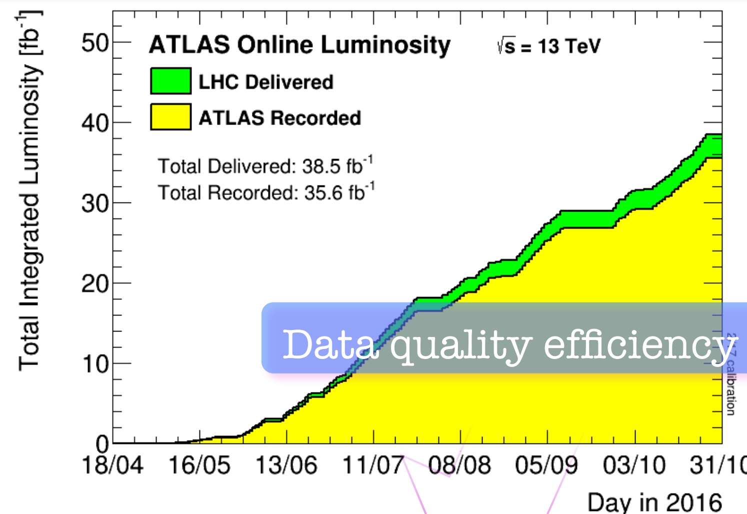
Simplified models

ATLAS **Data**

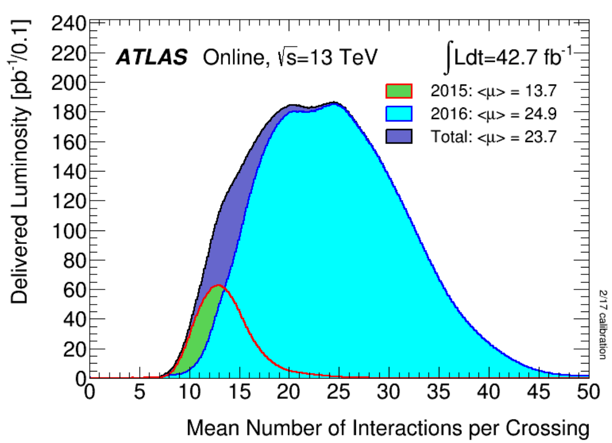
Excellent **performance by the LHC** and high **data taking efficiency** by detectors in the 13 TeV pp collisions period (2015, 2016).

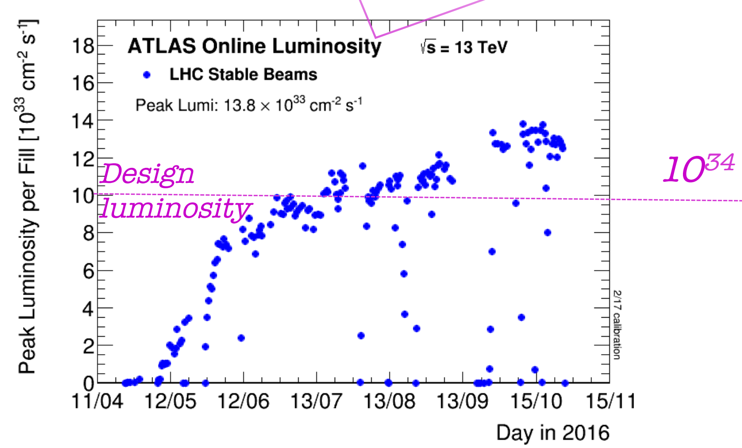


~40 fb^{-1} @ 13 TeV recorded in 2015 and 2016



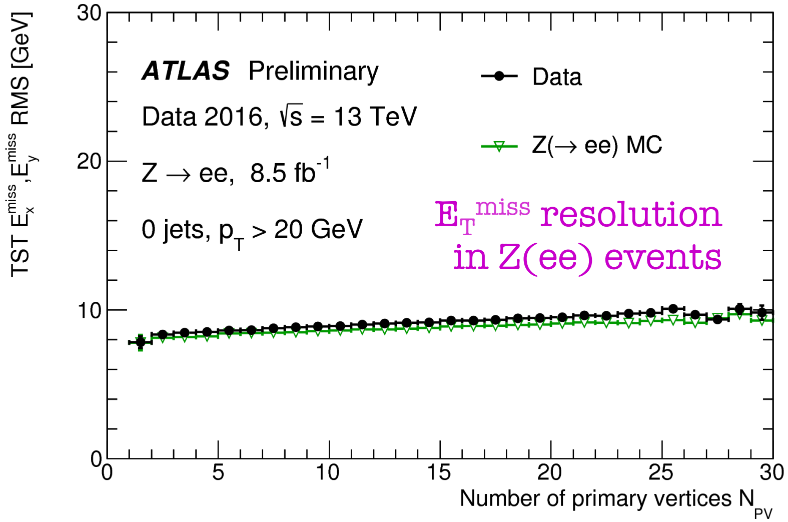
Data quality efficiency 93-95%

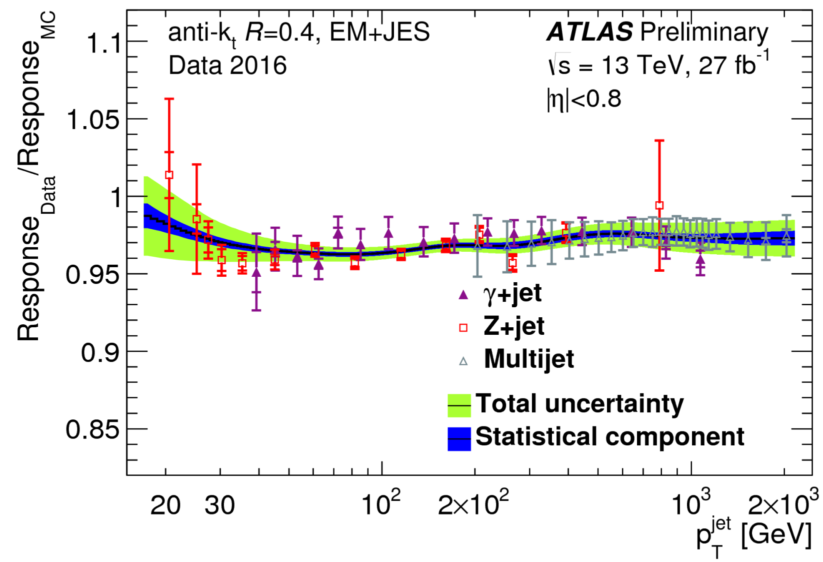


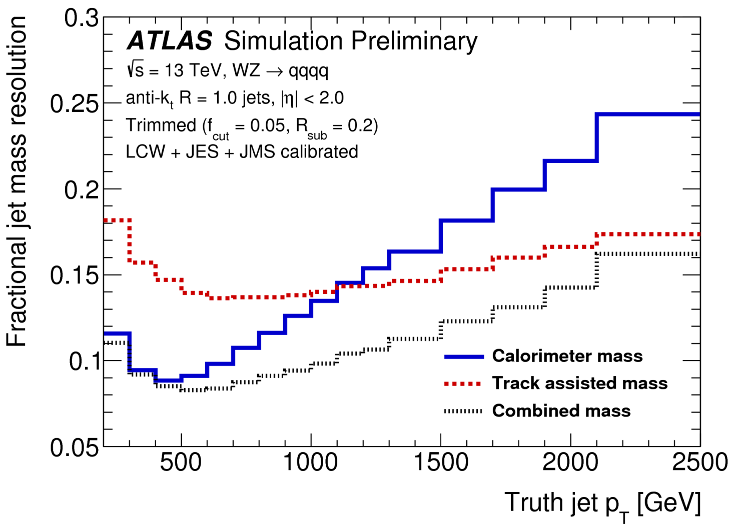


ATLAS **Data**

These analyses rely in a good measurement of missing transverse momenta, and understanding of jet calibration up to multi-TeV scale.



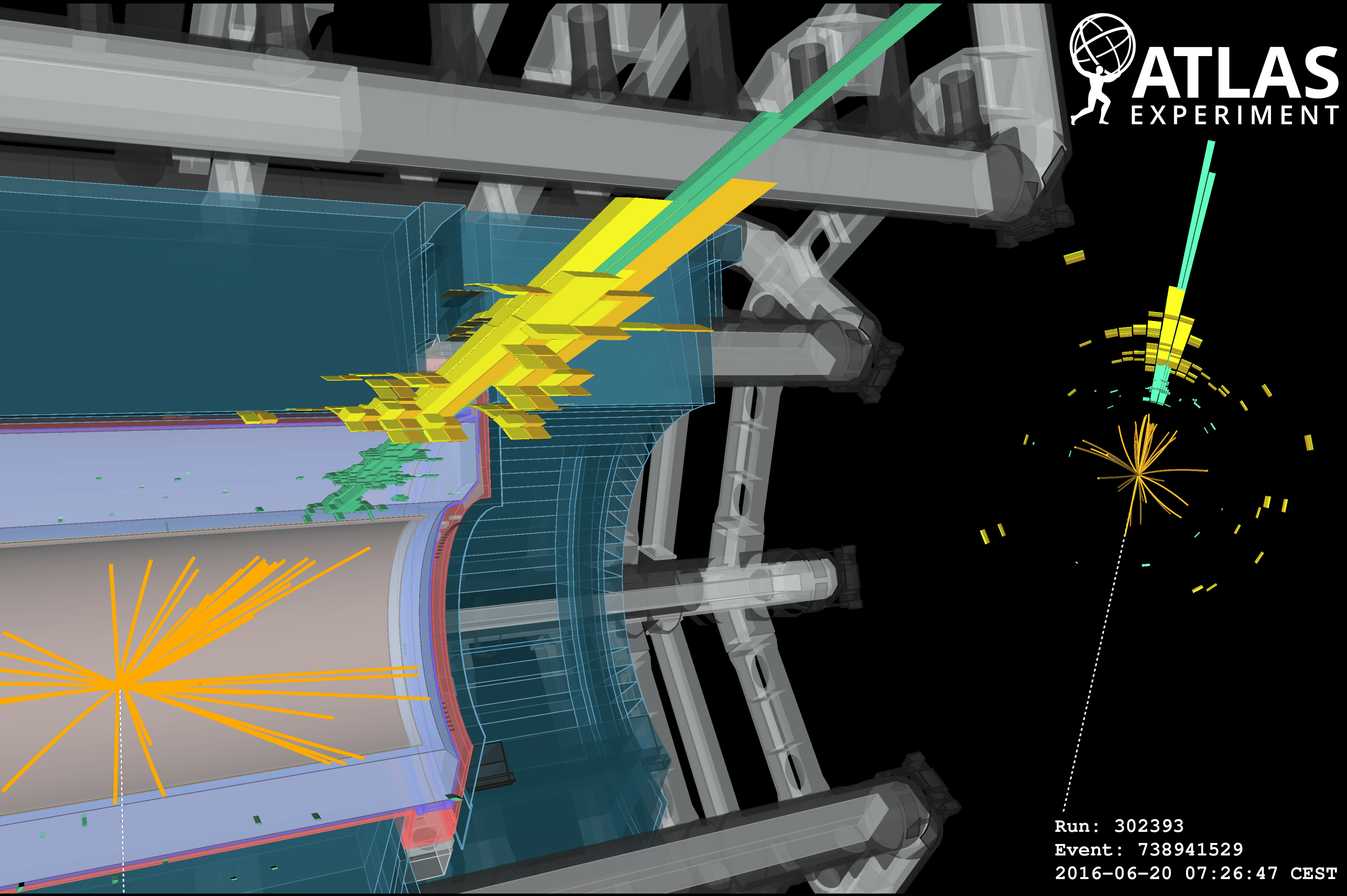




Jet mass improvements

Optimizes **large-R jet mass** computed using combination of calorimeter and tracking information

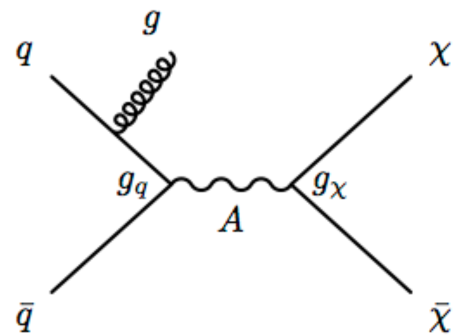
$$m_J \equiv w_{\text{calo}} \times m_{\text{J}}^{\text{calo}} + w_{\text{track}} \times \left(m_{\text{J}}^{\text{track}} \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \right)$$


ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

ATLAS-CONF-2017-060

E_T^{miss} + jets

Benchmark DM model
Axial-vector (s-channel)mediator,
g_{DM} = 1, g_q= 0.25.



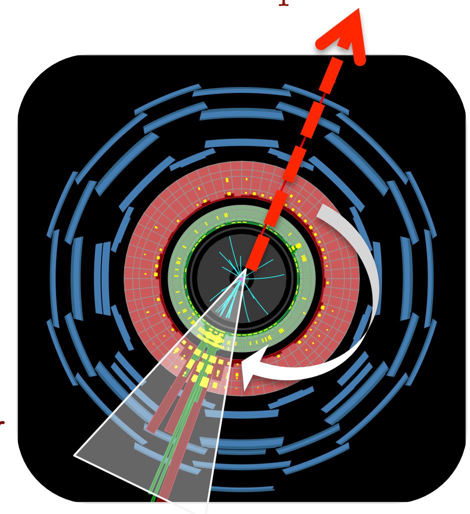
Most sensitive Mono-X channel
"jet" has α_s couplings to initial state quarks.

Selection

Signal region: veto on muons and electrons.

Jet p_T > 250 GeV
$|\eta|$<2.4

E_T^{miss} > 250 GeV



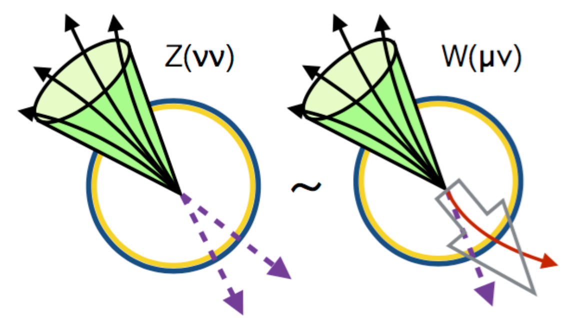
N_{jets} (p_T>30GeV)≤4

$\Delta\phi(E_T^{miss}$, jets) > 0.4

Strategy

- Dominant bkg: **Z(νν)+jets**, followed by W(lν)+jets.
- W/Z bkg modelled at NLO QCD & EW.
  - ***Sherpa NLO(LO) for 1,2(3,4) partons + theory corrections as a function of p_T(W/Z).***
  - [arXiv:1705.04664]
- **V+jets** and **top** bkgs normalized in dedicated CRs.
- DiBosons from MC. NCB and Multijets data driven.

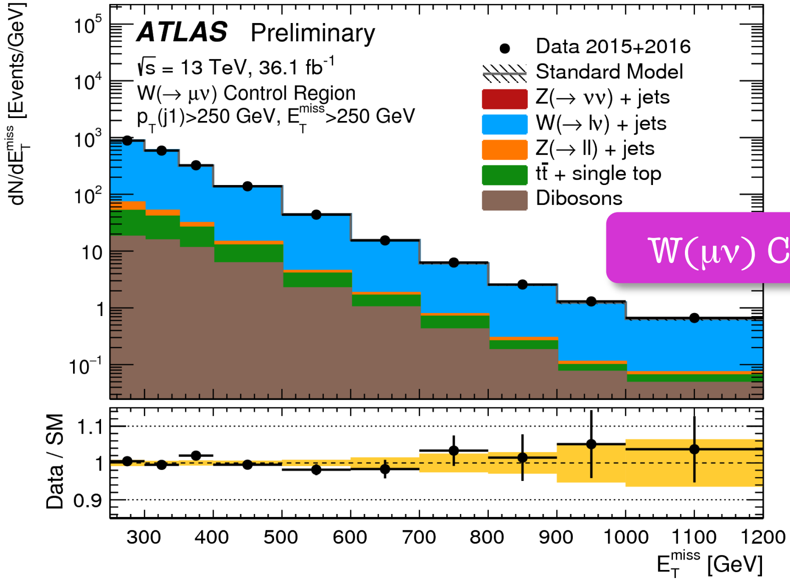
W/Z +jets background
e.g. W(μν) CR used to constrain Z(νν).
Muons treated as invisible:
E_T^{miss} ~boson p_T



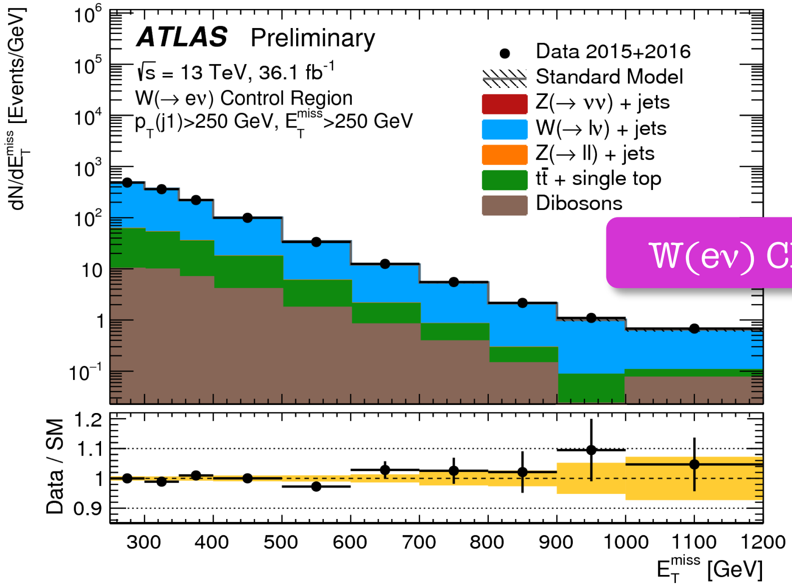
Similarly for Z(ll) CRs.

E_T^{miss} + jets

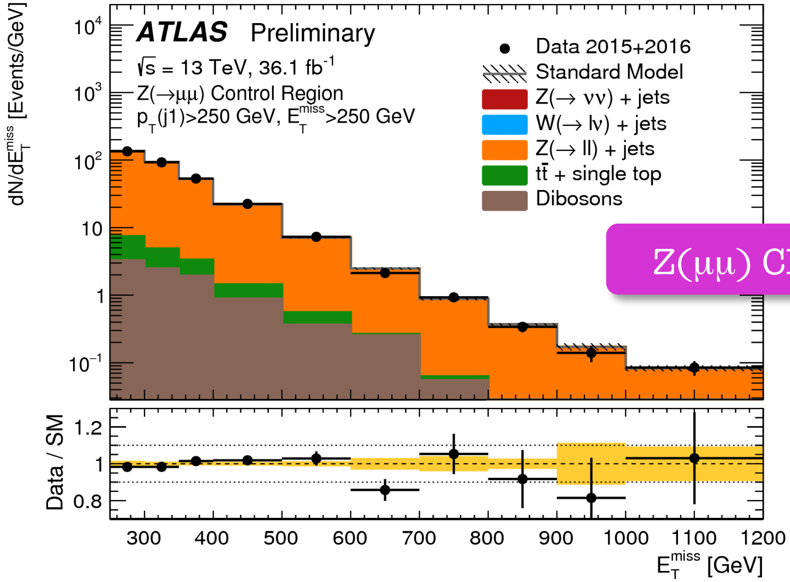
Control Regions



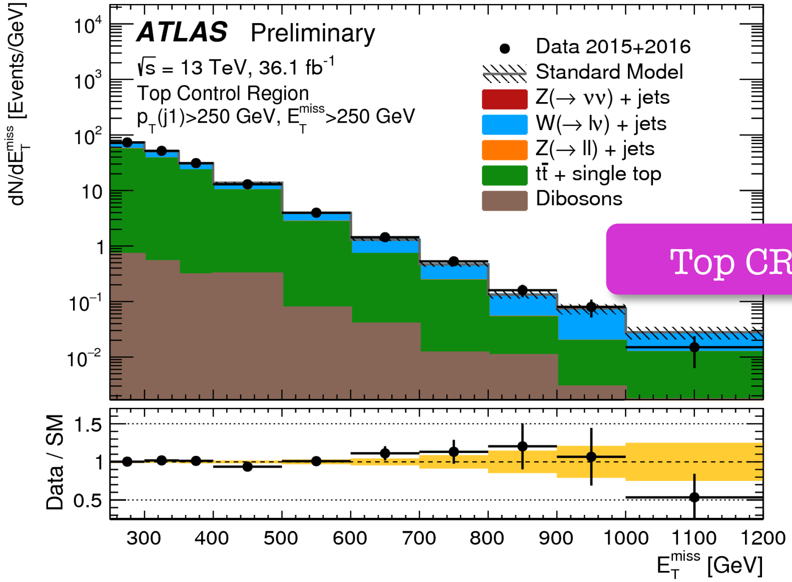
W(μν) CR



W(eν) CR



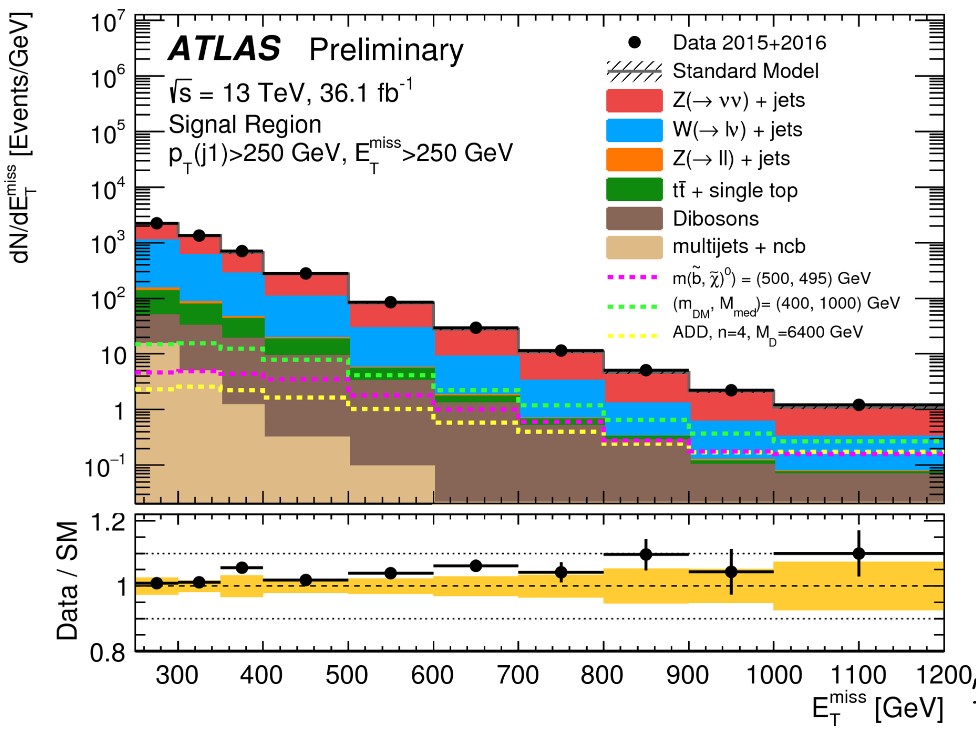
Z(μμ) CR

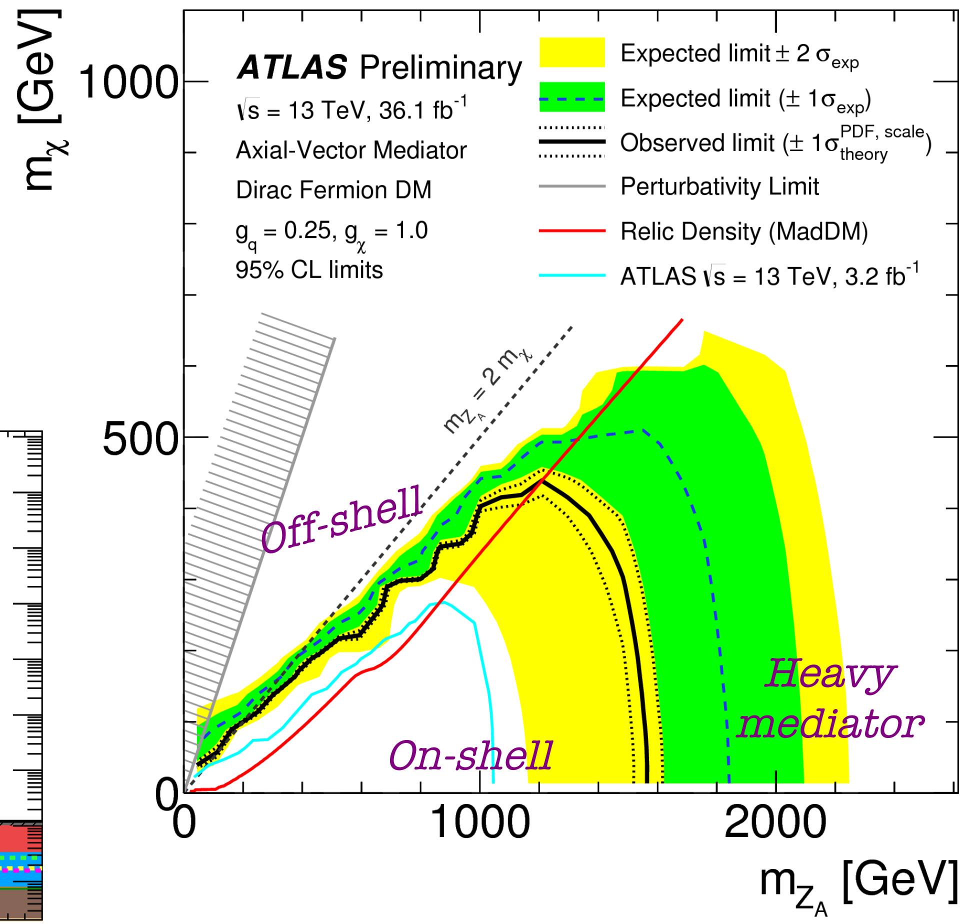


Top CR

E_T^{miss} + jets

- **2-5% background uncertainty in SR.**
- *Theory uncertainty*: 0.7-1% to account for extrapolation between W(lν) and Z(ll) CRs and Z(νν) in the SR.
- *Experimental uncertainties* mainly from jet energy scale and electron/muon efficiency.





Relic density indicates the values for m_Z and m_χ leading to the proper abundance.

Limits on a vector model are also given.

This channel has sensitivity to several SUSY stop/sbottom compressed decay channels and LED.

Z(νν)/Z(ll) ratio

Measure the ratio: σ(E_T^{miss}+jets)/σ(Z→l^+l^-+jets) versus various kinematic variables

VBF + E_T^{miss}

vs. E_T^{miss}, m_{jj}, $\Delta\phi_{jj}$

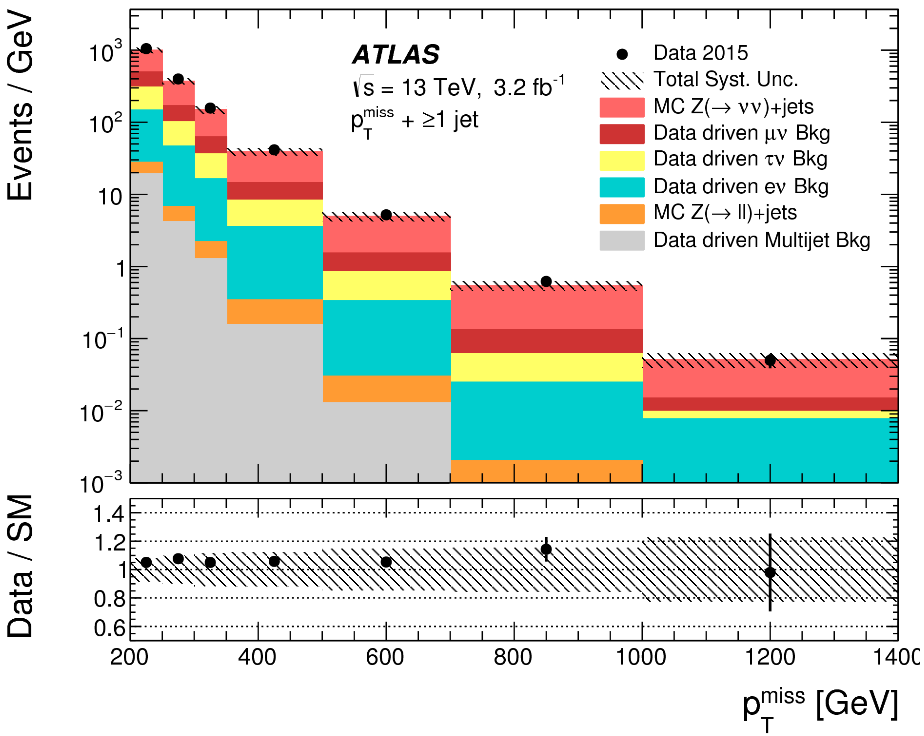
≥ 1 jet+ E_T^{miss}

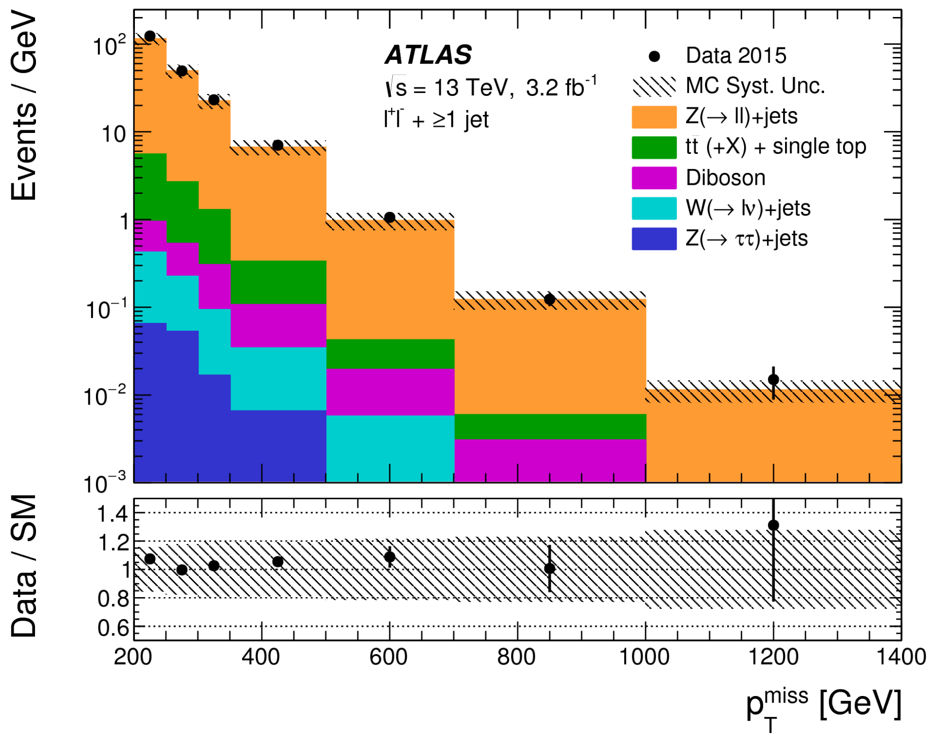
vs. E_T^{miss}

Z(νν)+jets numerator: W-bkgs estimated in W(->eν,μν) CRs. MC used to extrapolate into SR: out-of-acceptance leptons and in-acceptance-leptons.

Z(ll)+jets denominator: other bkgs from MC.

Since SM E_T^{miss}+jets is Z(νν)+jets → *Many uncertainties cancelled out in the ratio.*

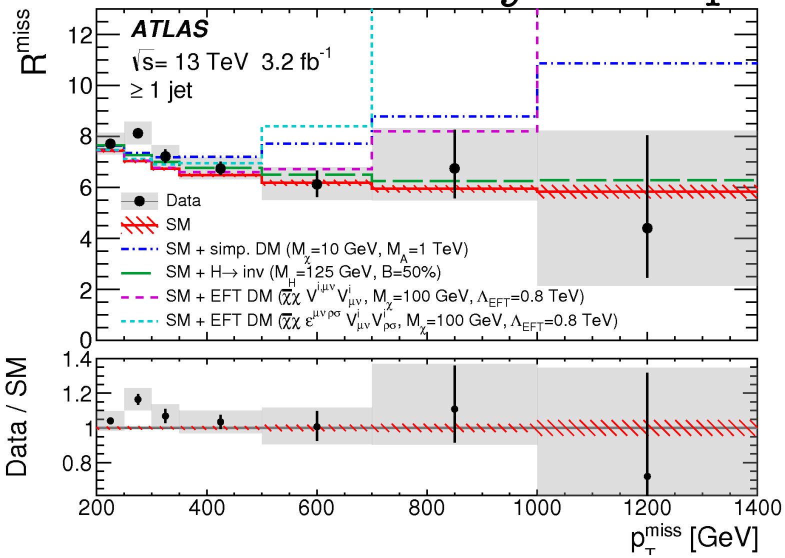


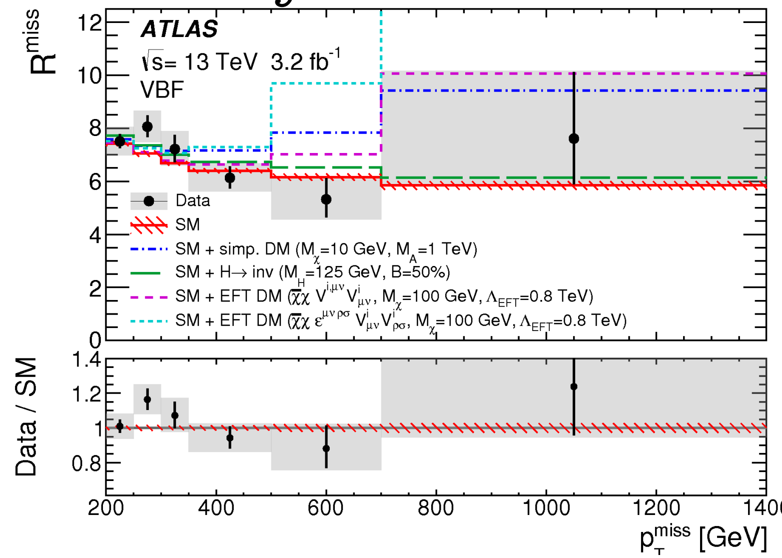


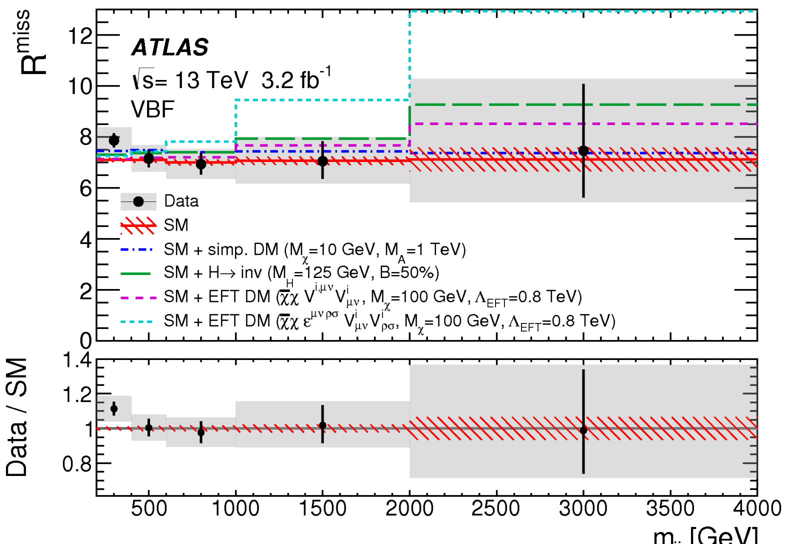
arXiv: 1707.03263

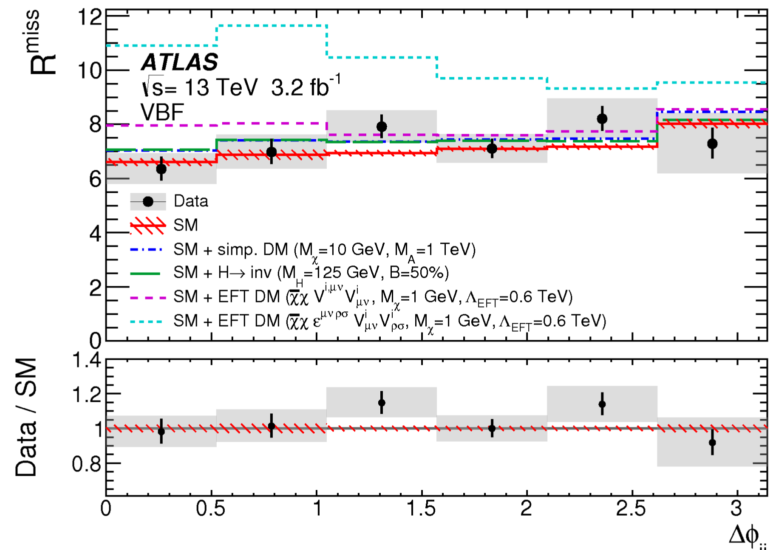
Z(νν)/Z(ll) ratio

The ratio is corrected for detector effects ("unfolded"), so can be easily reinterpreted in terms of any BSM models.









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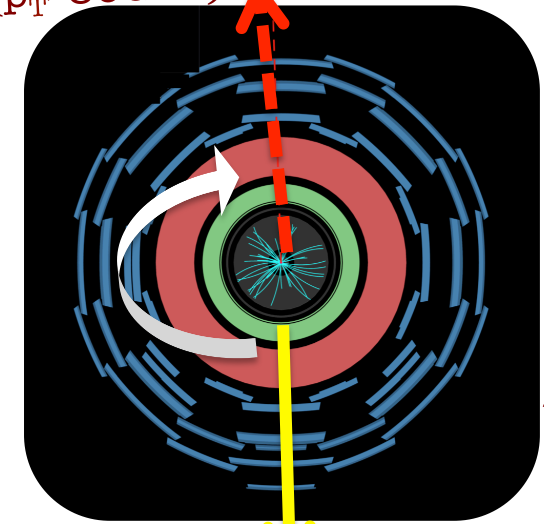
E_T^{miss} + photon

Selection&Strategy

N_{jets} (p_T>30GeV)≤1

E_T^{miss} > 150 GeV



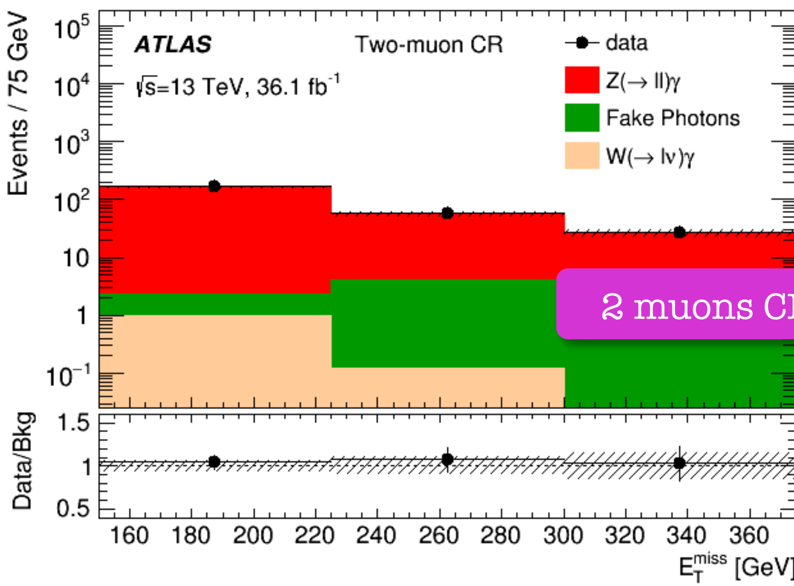
Signal region: veto on muons and electrons.

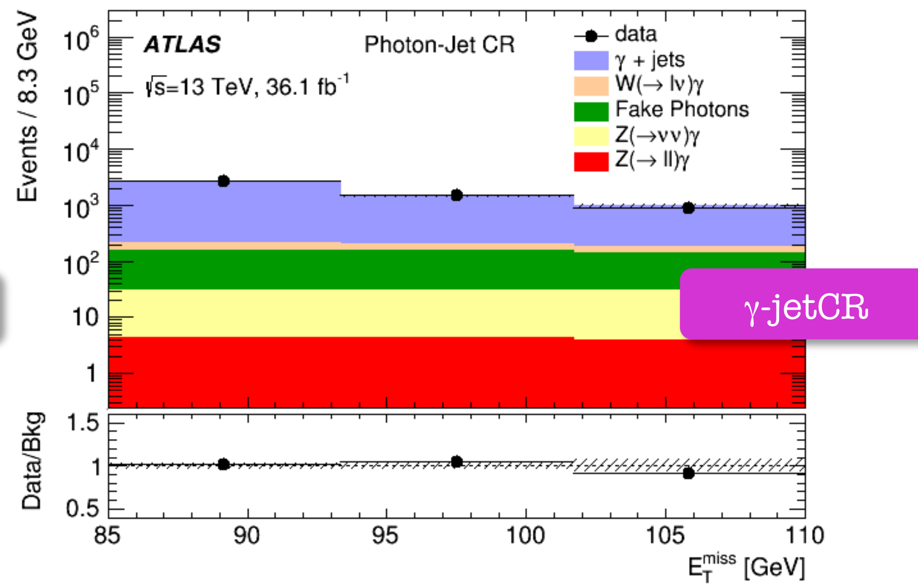
$\Delta\phi(E_T^{miss}, j)$ > 0.4

$\Delta\phi(E_T^{miss}, \gamma)$ > 0.4

Photon E_T > 150 GeV

- Dominant: **Z(νν)+γ** (ISR).
- **V+γ+jets** normalized in dedicated CRs.
  - 3 E_T^{miss}-dependent scale factors: k_Z, k_W, $k_{\gamma jet}$.
  - *Z(νν) normalized in 2μ + 2e CRs.*
- γ+jets bkg from γ+jet CR.





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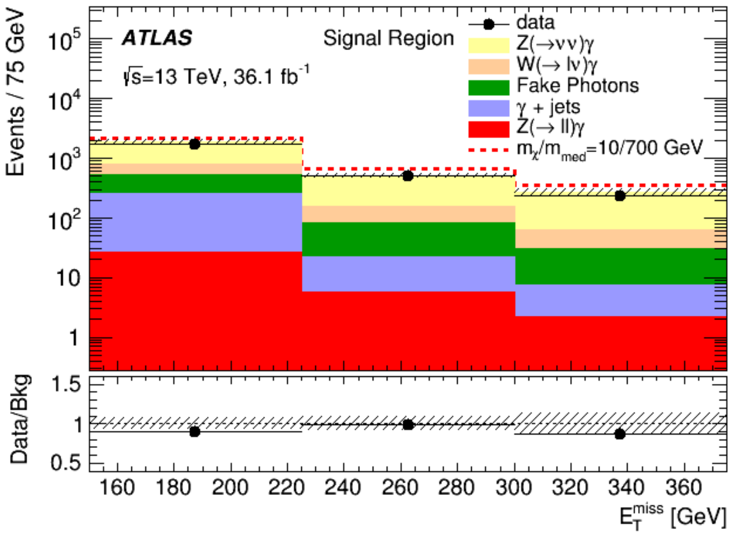
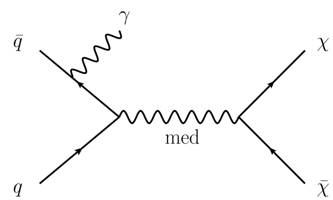
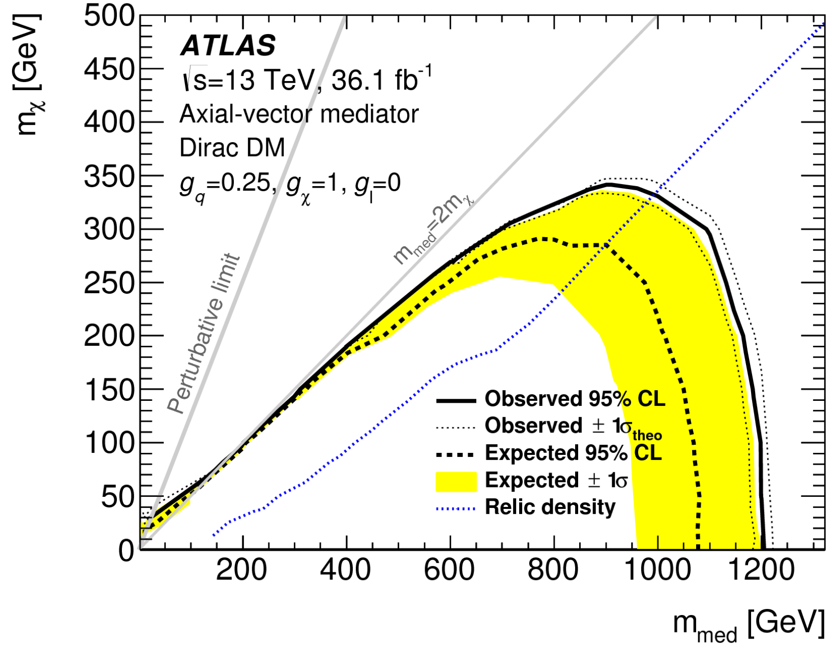
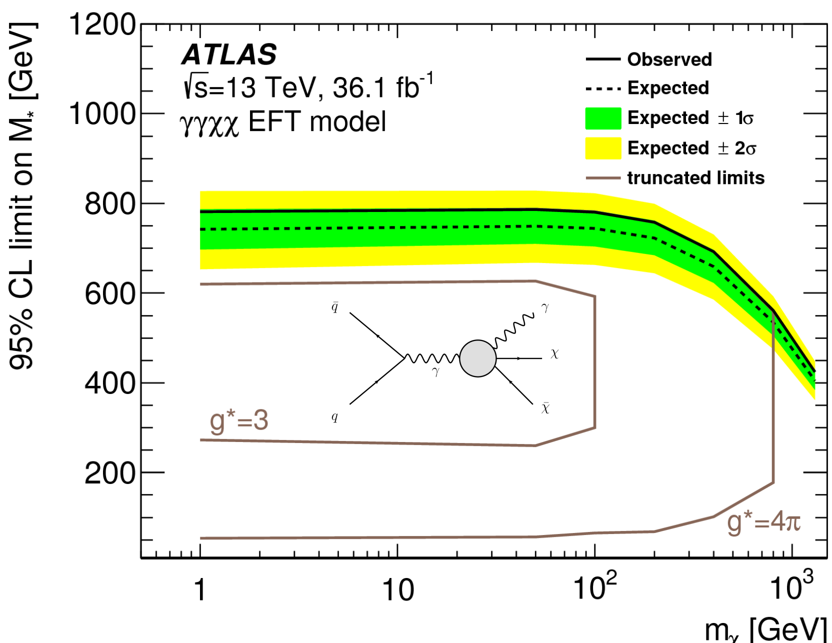
E_T^{miss} + photon





Photon has α_{EM} couplings to initial state quarks.

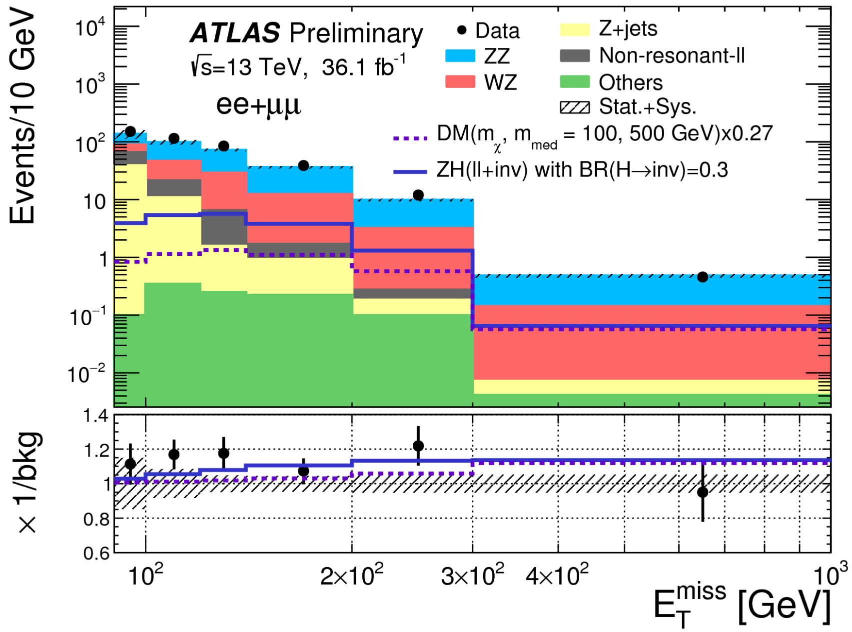




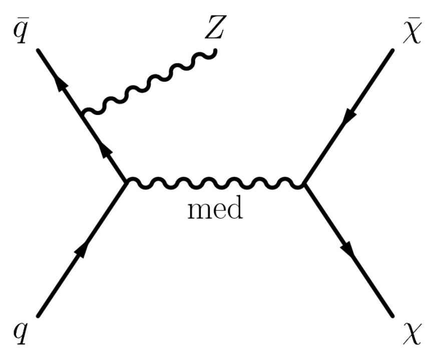
Sensitive to $\gamma\gamma\chi\chi$ EFT. Limits on the effective mass scale M* as a function of m_χ.

Truncation applied to account for the validity of EFT. Assuming $M_{cut} = g^*M^*$, Events having $\sqrt{s} > M_{cut}$ are removed and the limit is recomputed.

E_T^{miss} + Z(ll)



Main uncertainty from ZZ modeling.



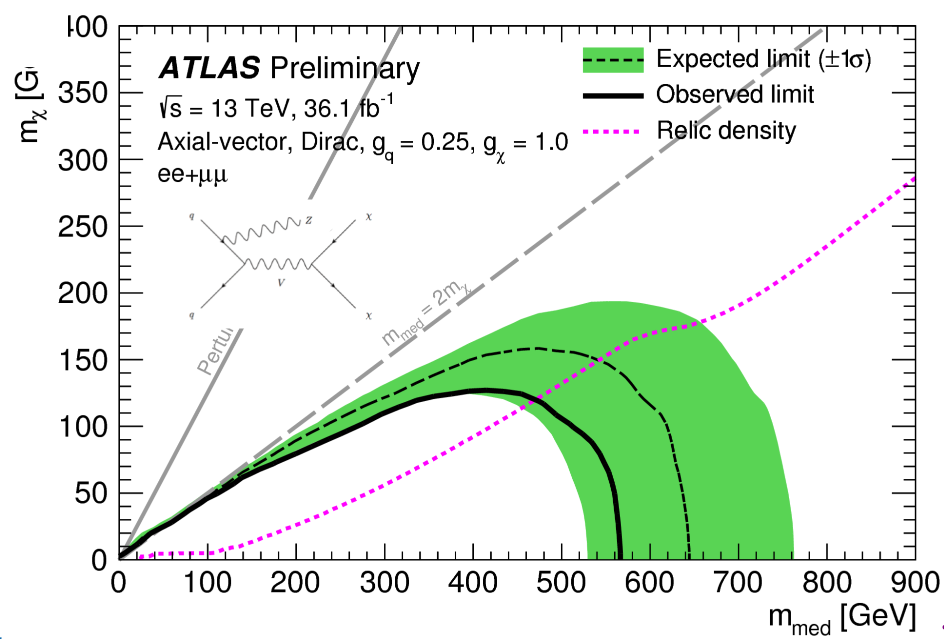
E_T^{miss} +W/Z (jj) search also performed: Phys. Lett. B 763 (2016) 251

Selection & Strategy

$E_T^{miss} > 90$GeV, $E_T^{miss}/H_T > 0.6$, $\Delta\varphi(Z,E_T^{miss}) > 2.7$, 2 leptons ee/μμ (small ΔR_{ll}, near m_Z).

Background strategy:

- **ZZ(llνν)** estimated from MC (irreducible).
- **WZ**: normalized in 3 leptons CR.
- **WW/top**: normalized in eμ CR.
- **Z+jets** (fake E_T^{miss}): "ABCD" method.



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E_T^{miss} + H(bb)

ATLAS EXPERIMENT

Mono-Higgs signal provides direct probe of DM-SM coupling, **H→bb** dominant decay mode.

Selection & Strategy

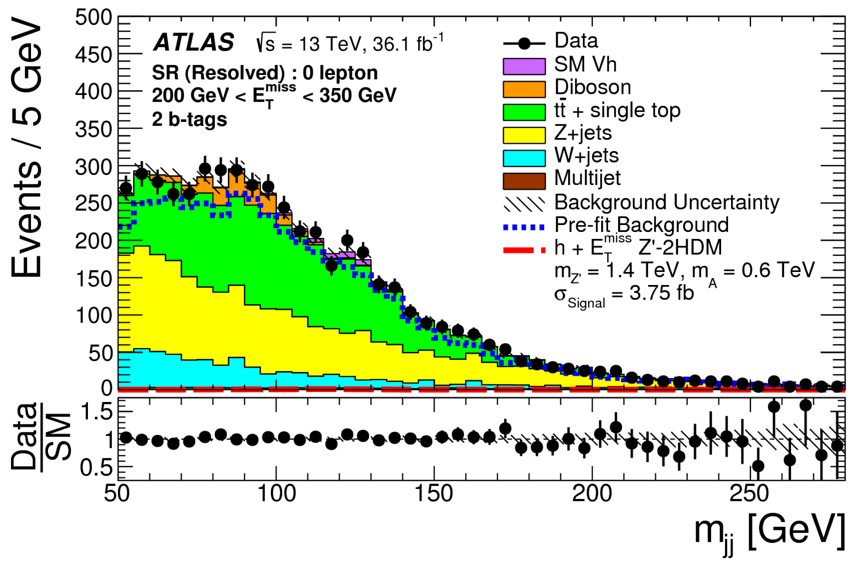
Resolved and **Merged** analyses defined.

Resolved: 150 < E_T^{miss} < 500 GeV (3 bins)
Merged: E_T^{miss} > 500 GeV + h(bb) tagging.

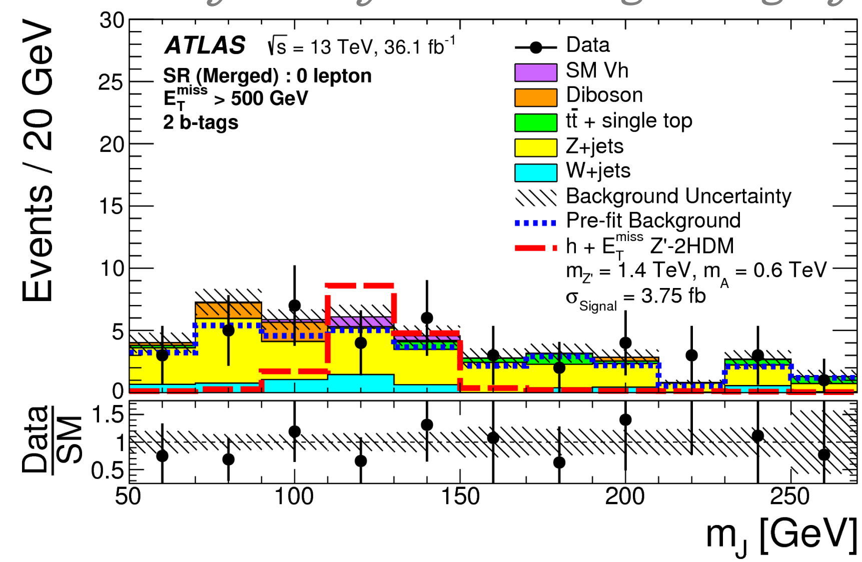
Multiple CR and SR defined by the leptons and N(b-jets) multiplicity, and in several E_T^{miss} regions.

Simultaneous m_{jj}/m_J shape fit in all regions.

Sensitivity mostly from 2 b-tags category.



Resolved region: two distinctive b-jets.



Merged region: boosted Higgs→large-R jet with substructure selection.

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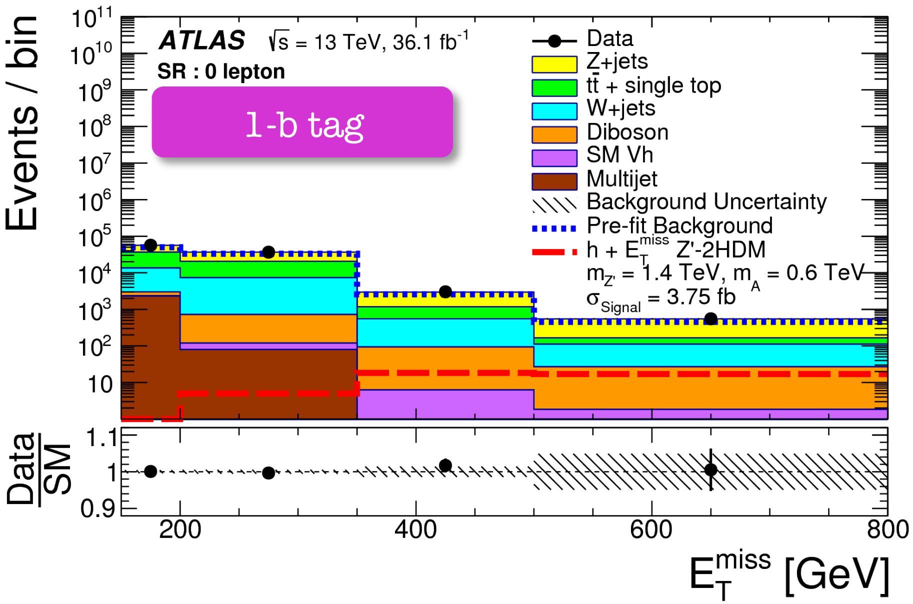
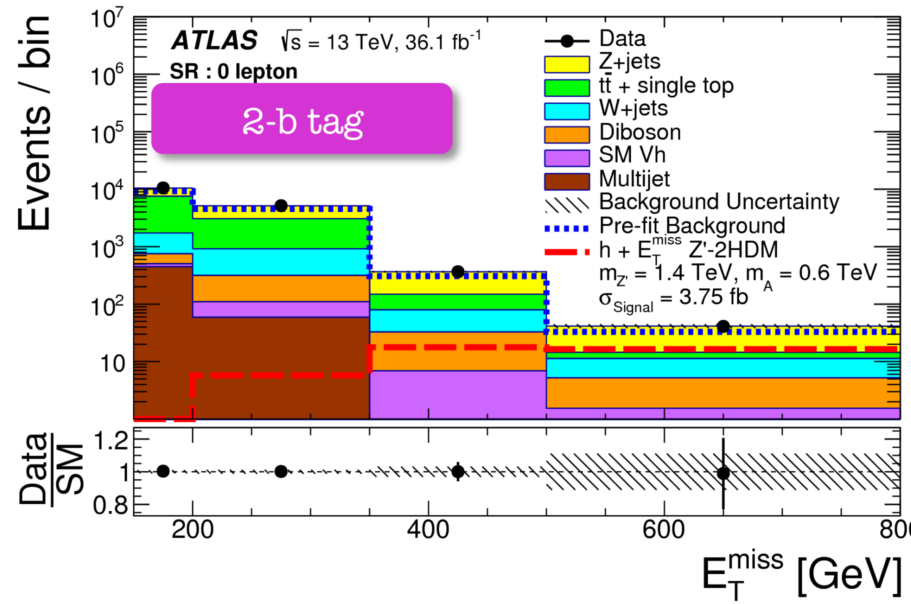
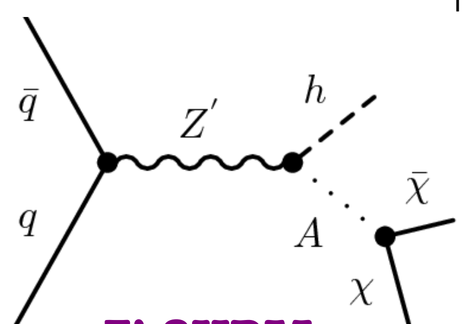
E_T^{miss} + H(bb)

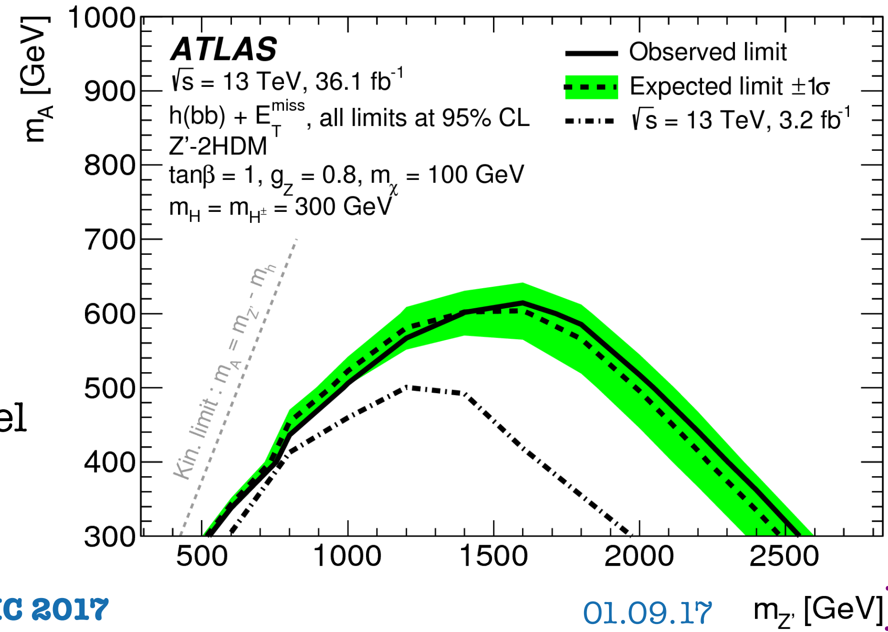






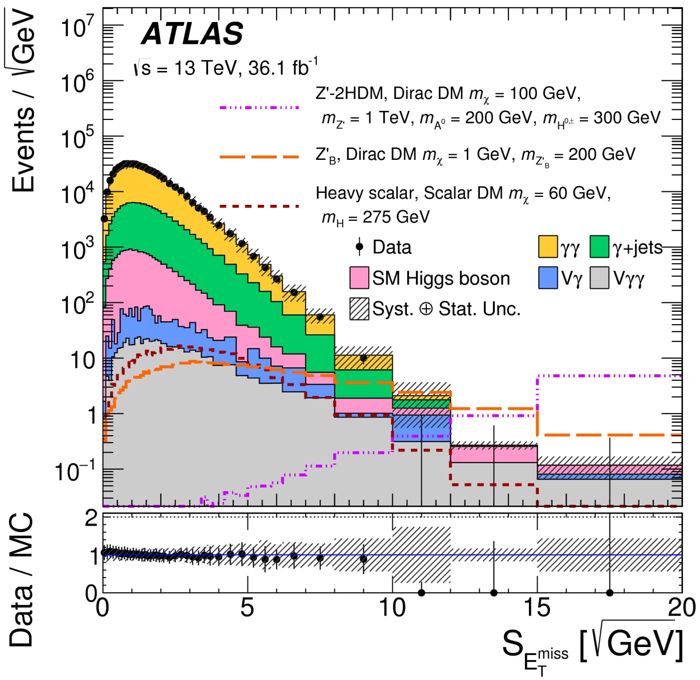
Z'-2HDM

A Z' decays to a Higgs boson h and pseudoscalar A of a two-higgs-doublet model (A decays to a pair of DM χ). Assumes 2HDM for DM coupling.

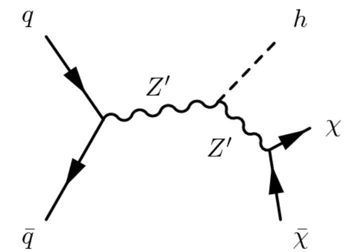


arXiv:1706.03948

E_T^{miss} + H(γγ)

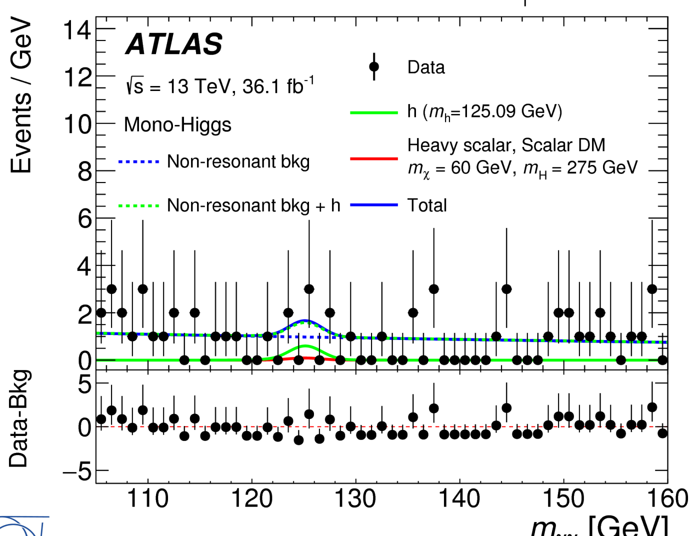


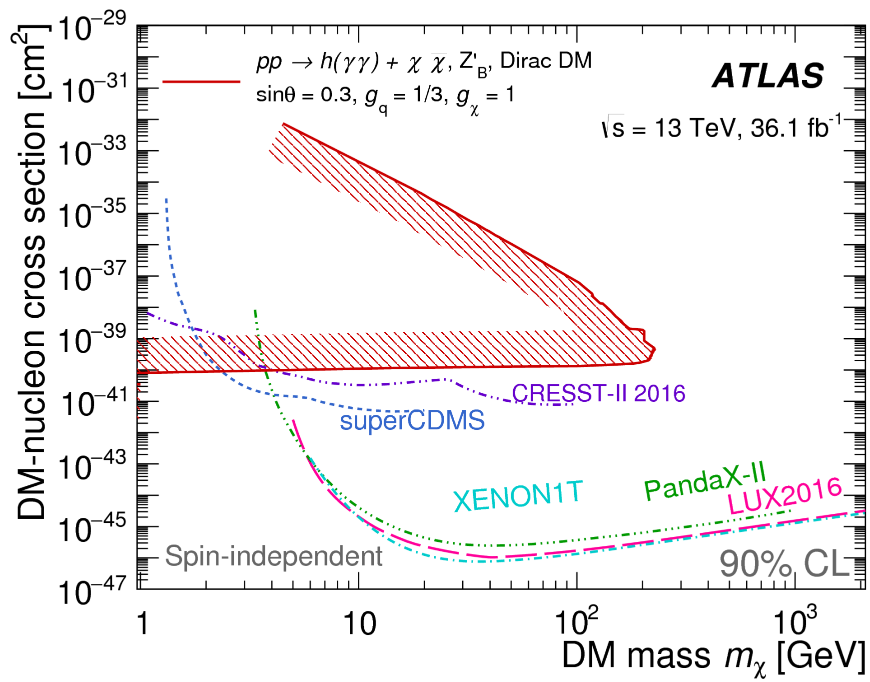
Search for DM in events with E_T^{miss} and H→γγ



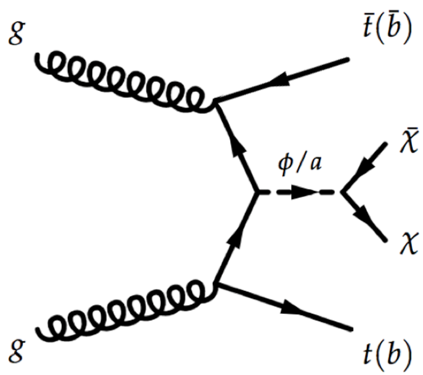
Unbinned maximum-likelihood fit to the observed $m_{\gamma\gamma}$ spectrum used to estimate contributions from different sources.

Z'_B model, DM couples to the SM only via the Z' boson.





MET + HF



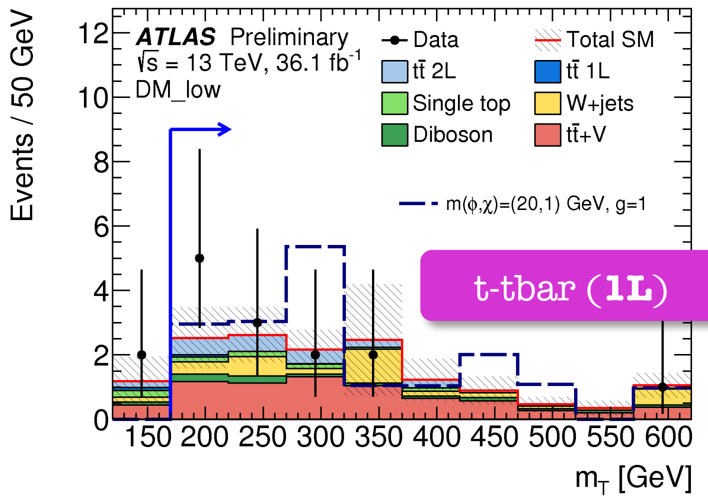
Search performed in different decay channels:

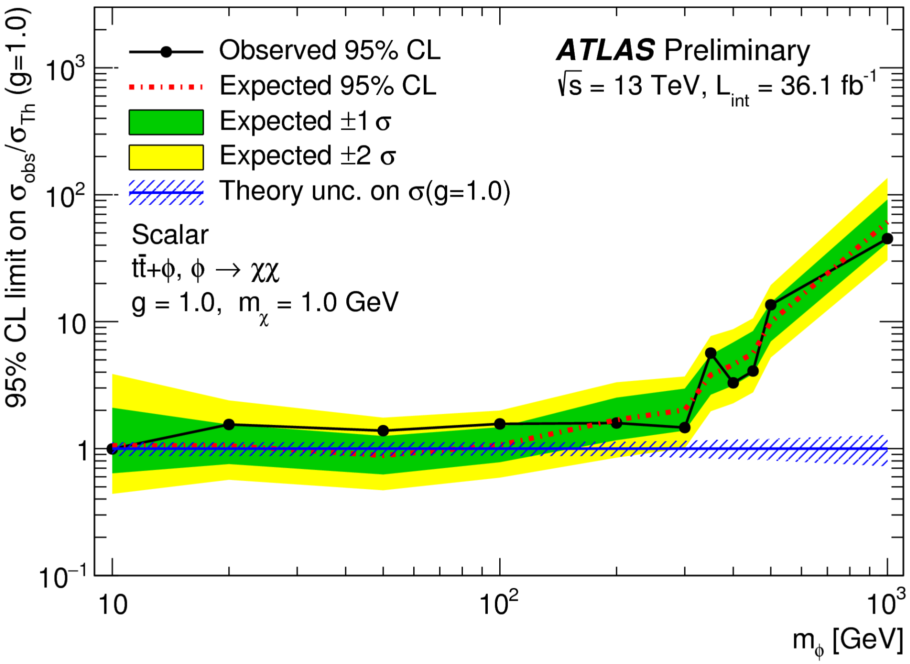
DM + t-tbar:

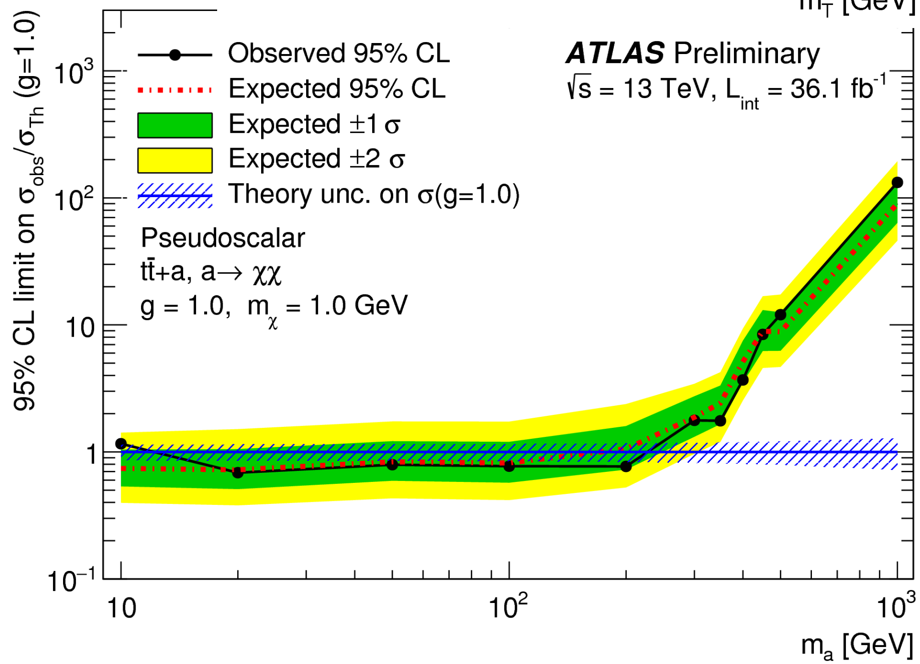
0, 1 and 2 lepton channels

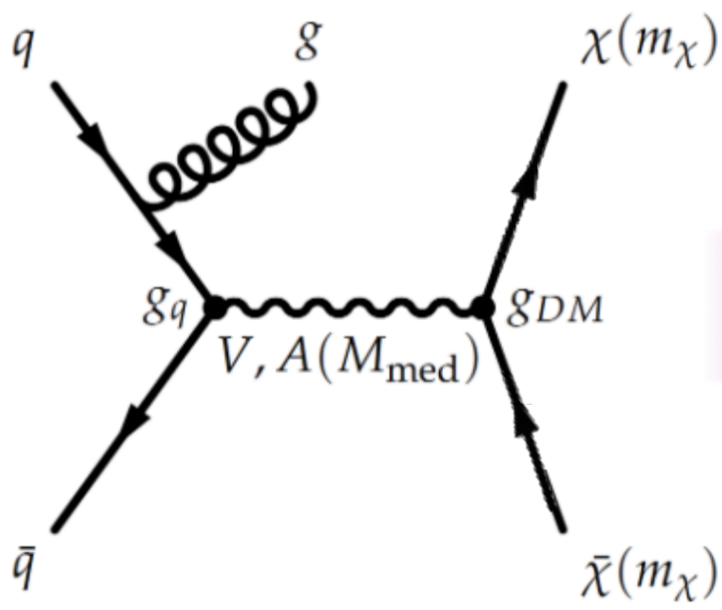
DM + b-bbar

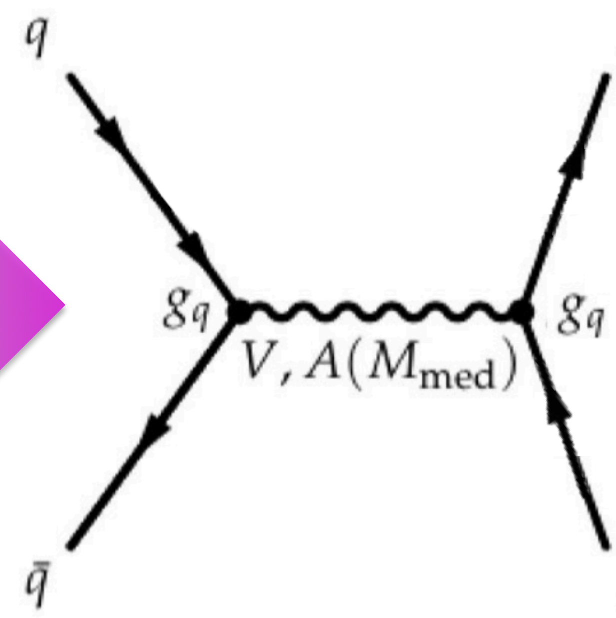
Similar topology as *stop* and *sbottom* searches.



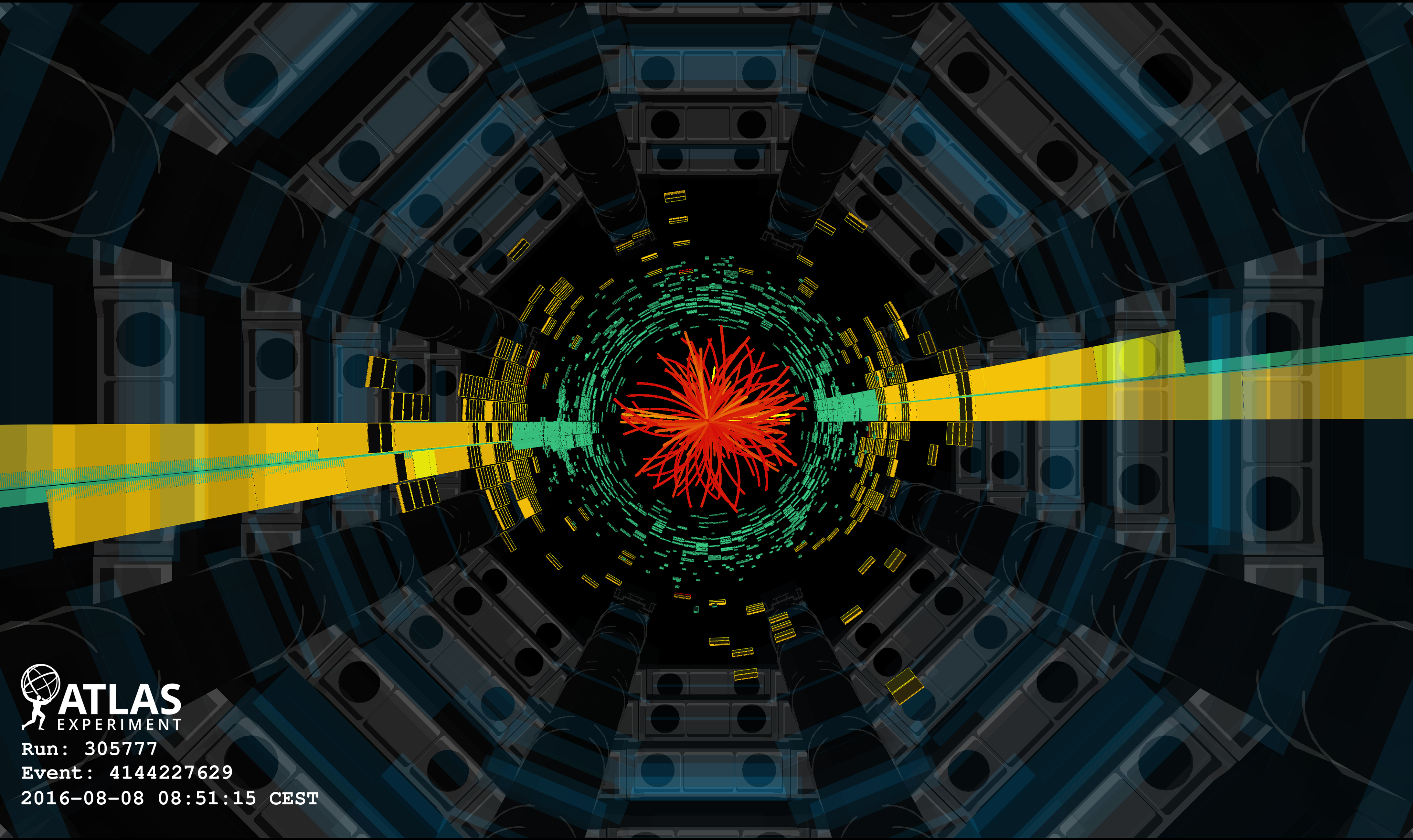








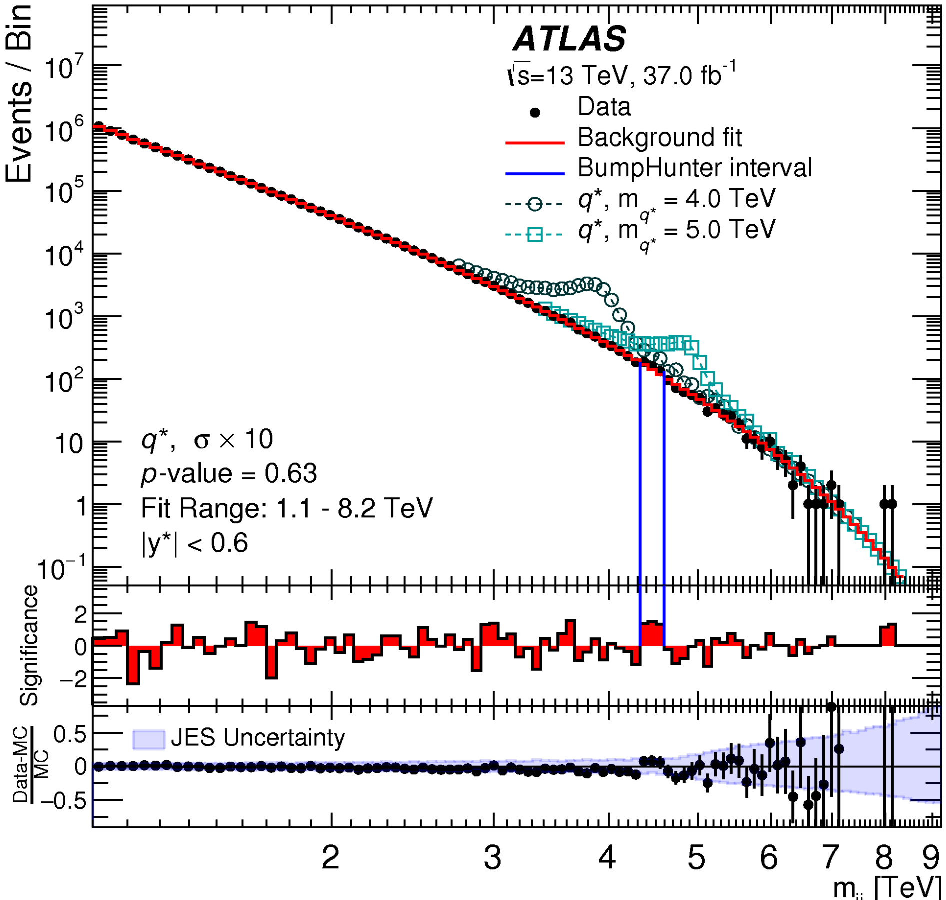
Mediator Searches


ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

Resonance Searches

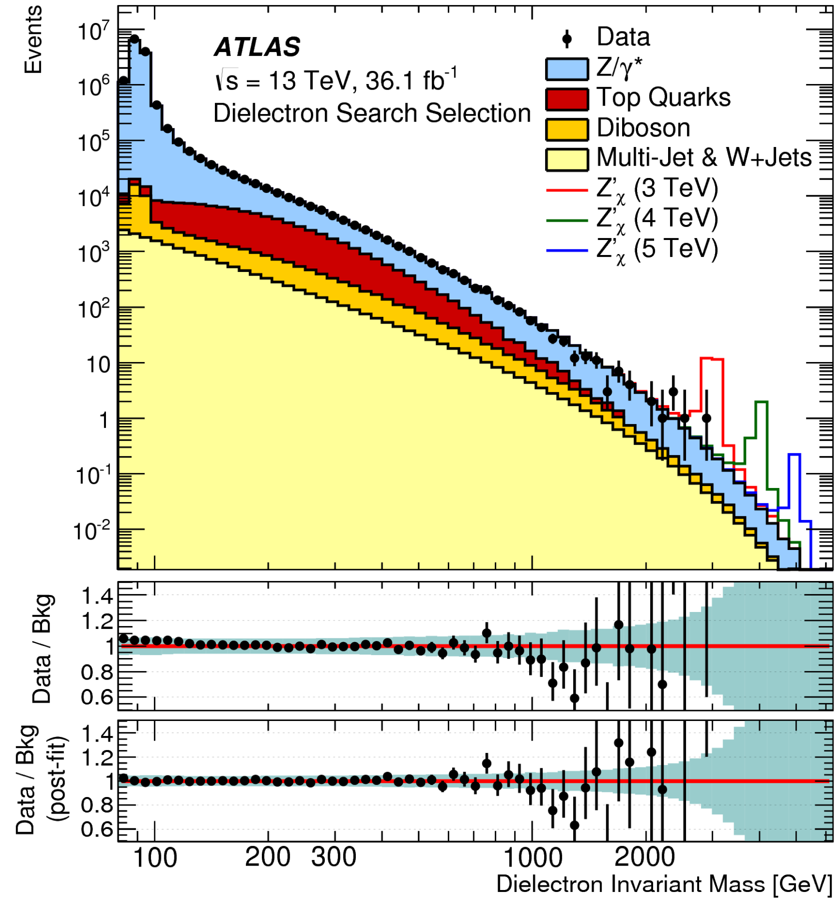
Discussed in more detail in Karol Krizka's talk.

Consider resonance in di-jet and di-lepton events.



Events selected with lowest un-prescaled single jet trigger (p_T> 380 GeV).

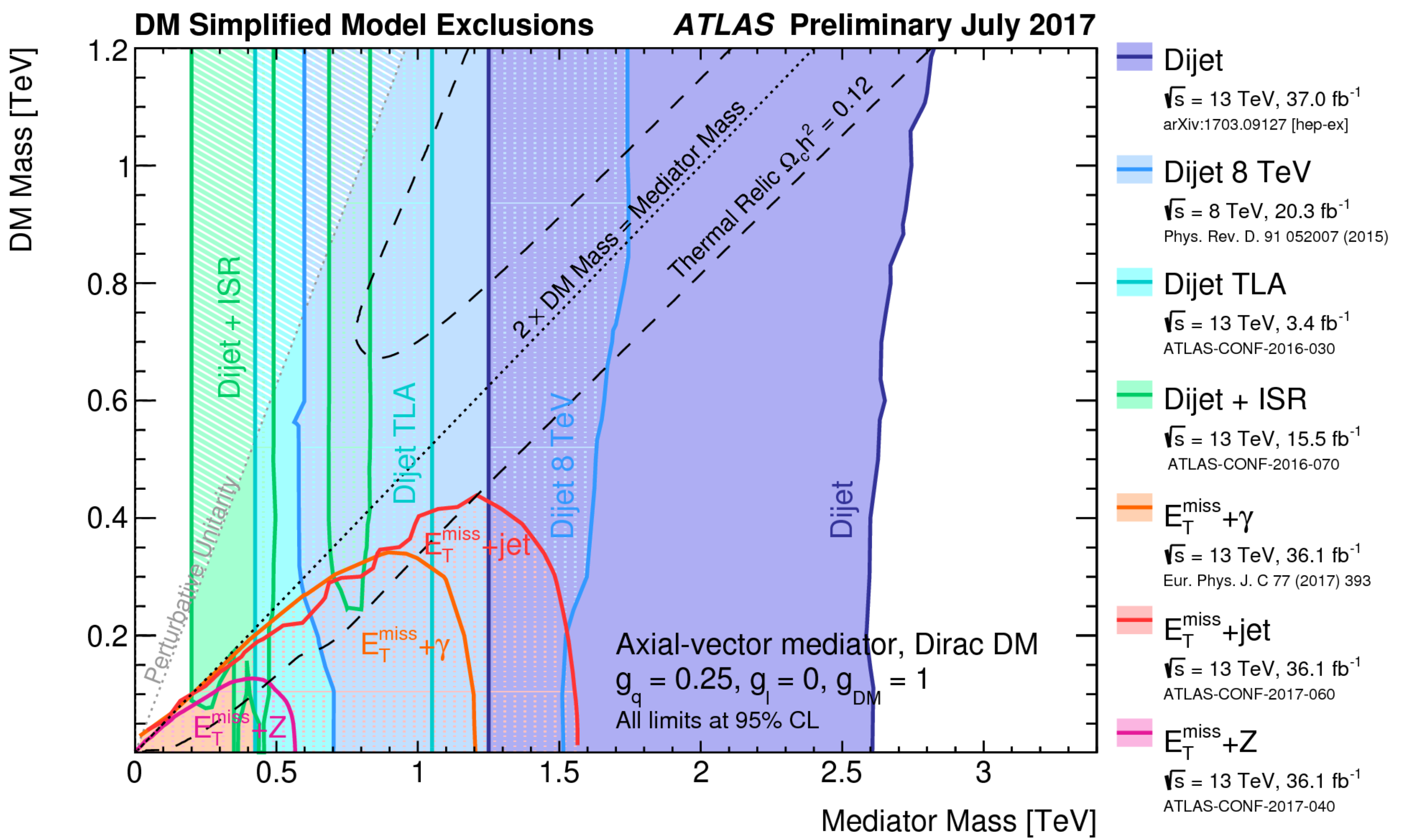
Other strategies used to target the low mass dijet spectrum.



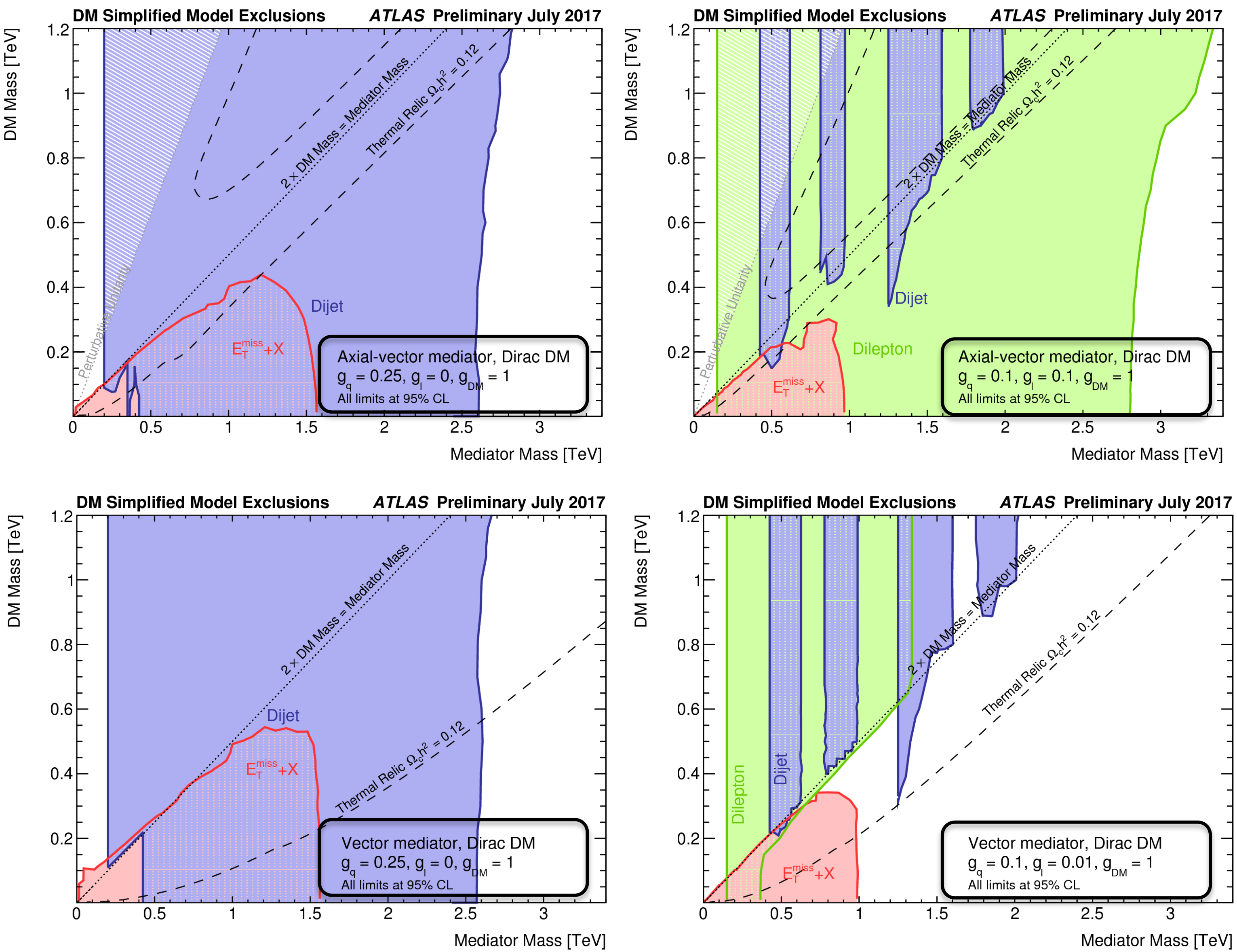
Events selected with 2 same-flavor isolated leptons (*electrons or muons*). Highest $m_{\ell\ell}$ pair (> 80 GeV).

Putting all the pieces together…

Combined Limits



Combined Limits



Dijet

Dijet 8 TeV $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet TLA $\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070

E_T^{miss}+X

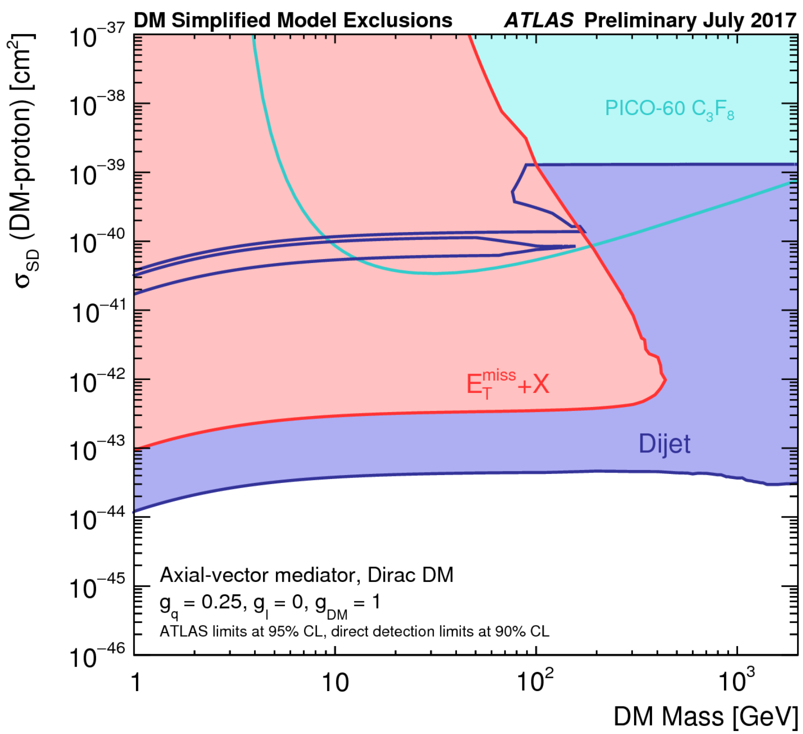
$E_T^{miss}+\gamma$ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060

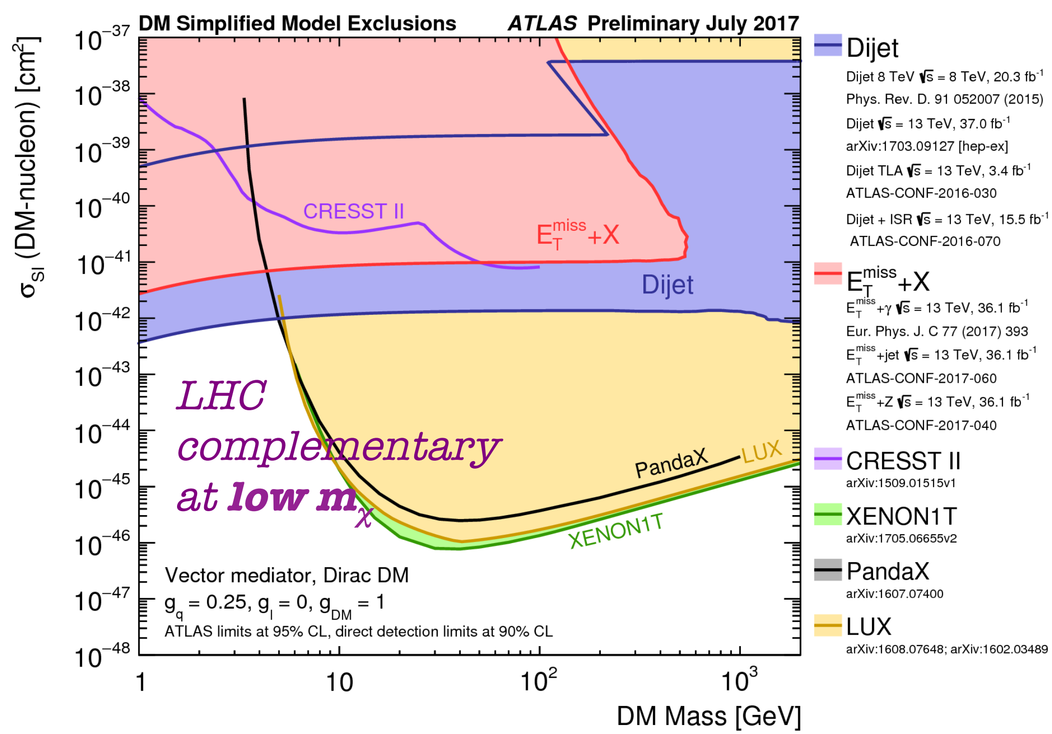
Dilepton

$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
CERN-EP-2017-119

Significant dependence on the **choice of couplings** for the model!

Comparison with **(In) Direct Detection**



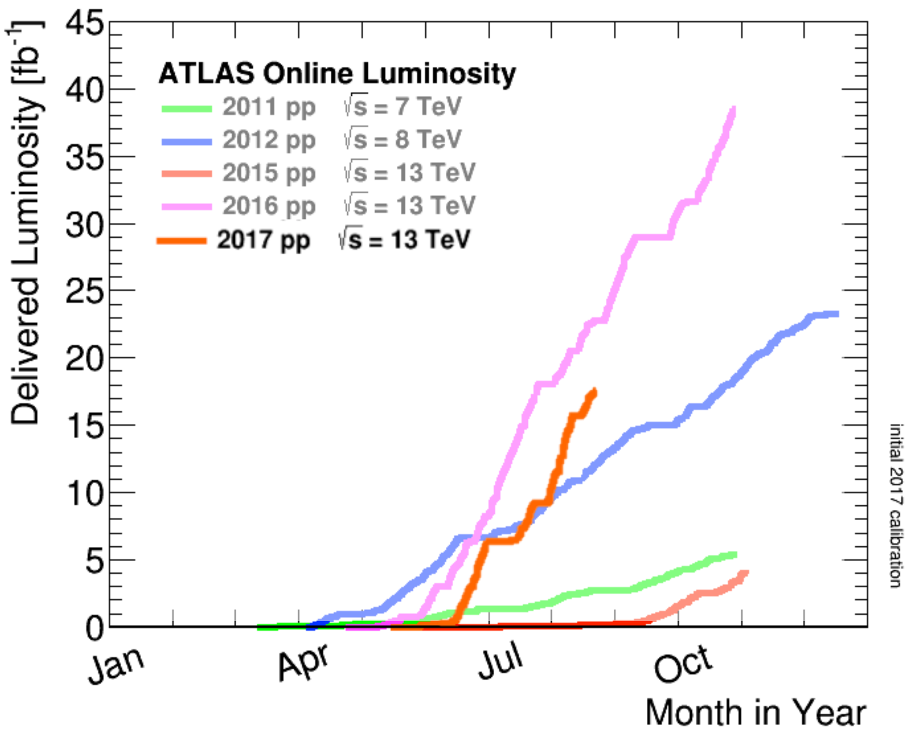


LHC limits also re-interpreted as limits on spin-dependent WIMP-proton (spin-independent WIMP-nucleon) **scattering cross section**.

Comparison with direct and indirect detection experiments in the context of the Z'-like simplified model shows nice complementarity, in particular al low m_χ.

Conclusions

- ATLAS has carried out a broad and very detailed program on DM searches with 13 TeV collisions data.
  - Both searches for invisible DM particles and DM mediators well covered.
  - Searches for DM have an important role in the LHC program, with a large number of final state signatures and techniques being employed.
  - High level of interest to compare to non-LHC experiments: complementarity at low m_{DM} from LHC limits. *Consider caveats for comparison: limits presented for a simplified model, EFT validity questions, …*



LHC is now successfully delivering more data.

New challenges for experiments: Ongoing discussion on new background estimations, theoretical uncertainties, trigger performance, etc

More results to come!

Many thanks!

Bonus Slides

ATLAS Detector

Trigger

Hardware based L1 ~100kHz

Software based HLT ~1kHz

Muons Spectrometer

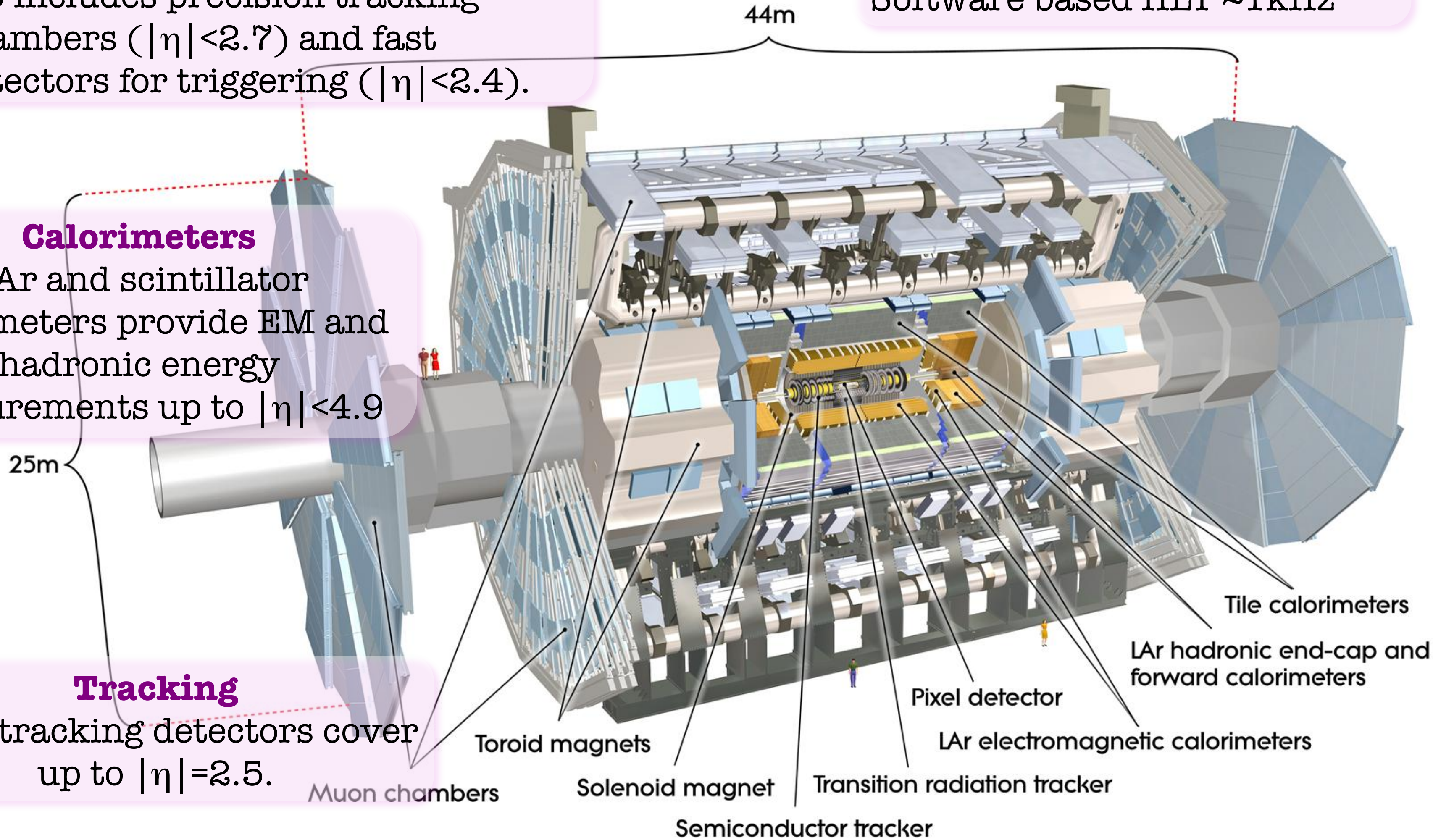
MS includes precision tracking chambers ($|\eta|<2.7$) and fast detectors for triggering ($|\eta|<2.4$).

Calorimeters

LAr and scintillator calorimeters provide EM and hadronic energy measurements up to $|\eta|<4.9$

Tracking

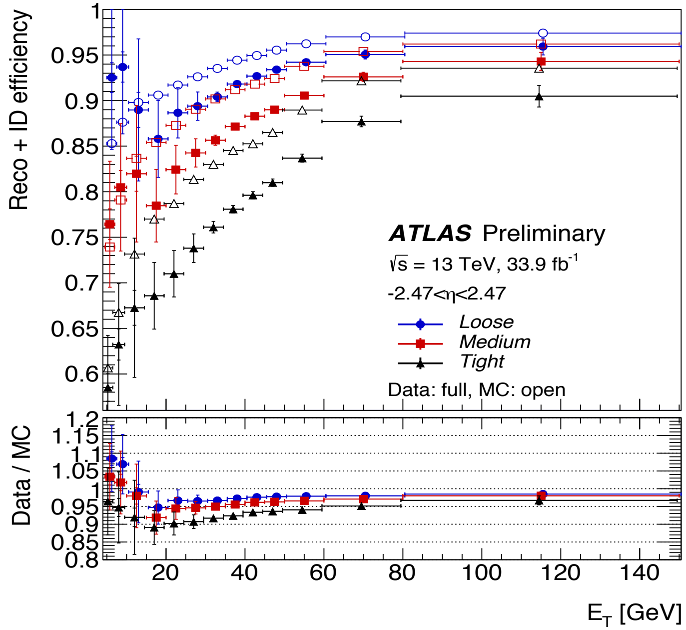
Inner tracking detectors cover up to $|\eta|=2.5$.

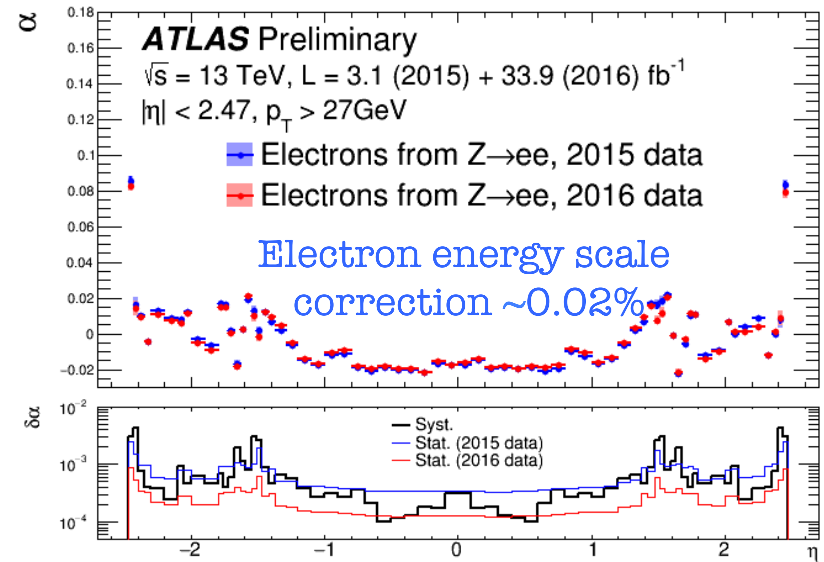


ATLAS-CONF-2016-024
Eur. Phys. J. C. (2016) 76:292

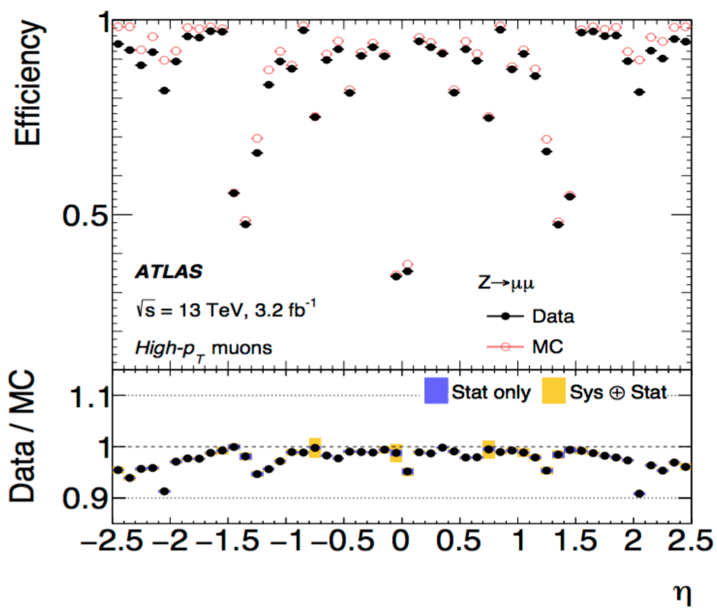
Performance: Leptons

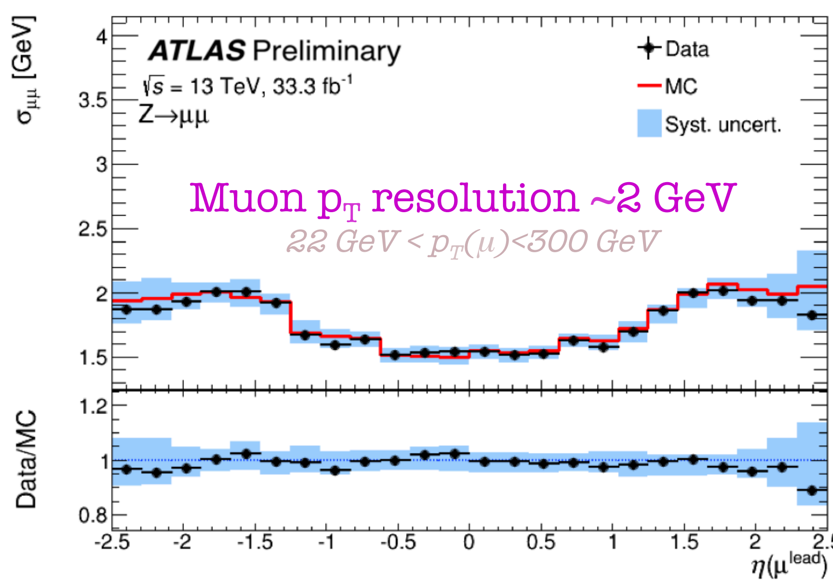
Electrons





Muons





LHC DMWG

arXiv: 1507.00966

arXiv: 1603.04156

All analyses follow the parameter values and limit interpretations as recommended by the LHC-DM WG (aka DM forum).

Simplified Models

Describe the model by a small numbers of free parameters:

- m_{med} (mediator mass),
- m_{DM} (WIMP mass),
- g_{DM}, g_q (couplings).

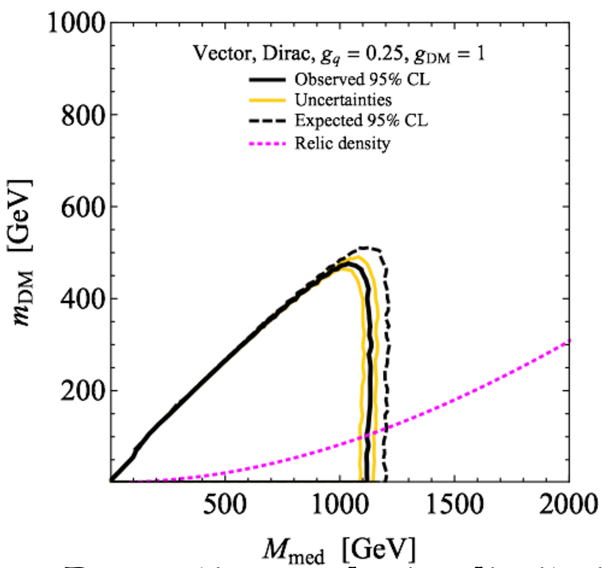
Assuming DM is a Dirac fermion (stable).
Consider different types of mediators (minimal decay width).

Vector mediator: $g_{\rm DM} = 1$ and $g_q = 0.25$.

Axial-vector mediator: $g_{\rm DM} = 1$ and $g_q = 0.25$.

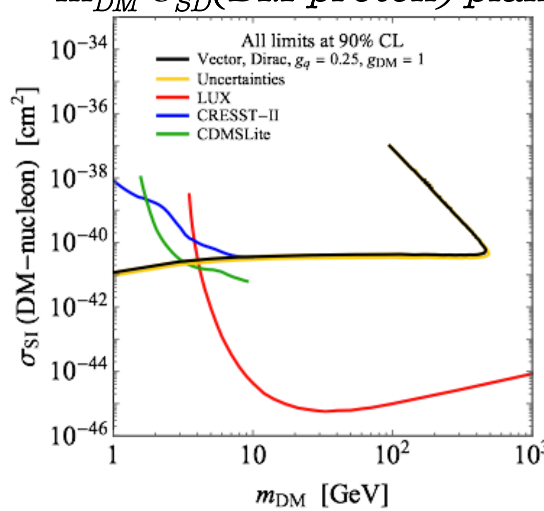
Scalar mediator: $g_q = 1$ and $g_{\rm DM} = 1$.

Pseudo-scalar mediator: $g_q = 1$ and $g_{\rm DM} = 1$.

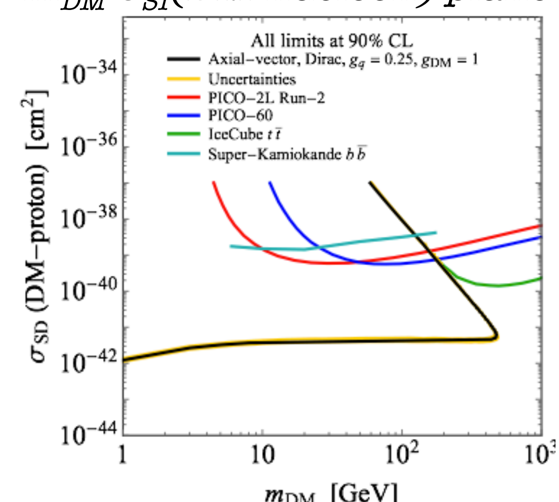


Presenting exclusion limits in the m_{DM}-m_{med} plane...

m_{DM}-σ_{SD}(DM-proton) plane

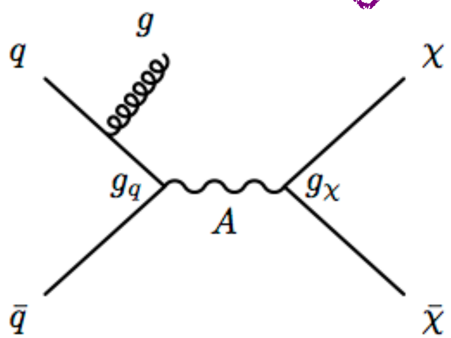


m_{DM}-σ_{SI}(DM-nucleon) plane



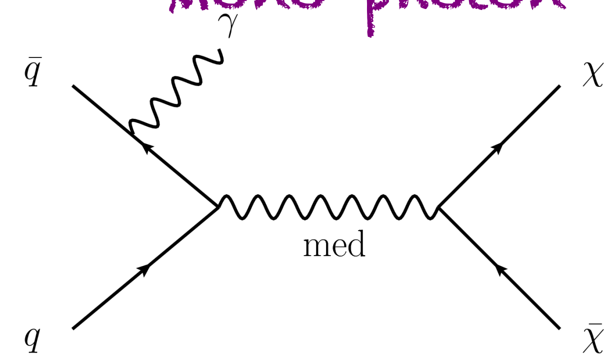
Signal Models

Mono-jet



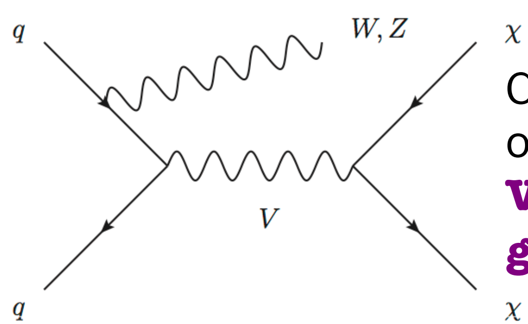
Most sensitive Mono-X channel
"jet" has α_s couplings to initial state quarks.
Axial-vector (s-channel)mediator, **g_{DM} = 1**, **g_q= 0.25**.
Limits also re-interpreted as limits on DM-proton scattering cross section.

Mono-photon



More statistics-limited than mono-jet.
photon has α_{EM} couplings to initial state quarks.
Axial-vector (s-channel) mediator, **g_{DM} = 1**, **g_q= 0.25**.
Limits also re-interpreted as limits on DM-proton scattering cross section.

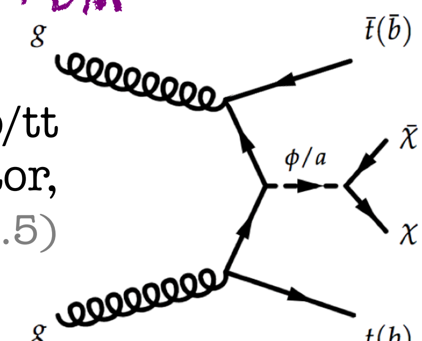
Mono-W/Z



Consider hadronic decays of both W and Z bosons.
Vector mediator,
g_{DM} = 1, **g_q= 0.25**.

HF+DM

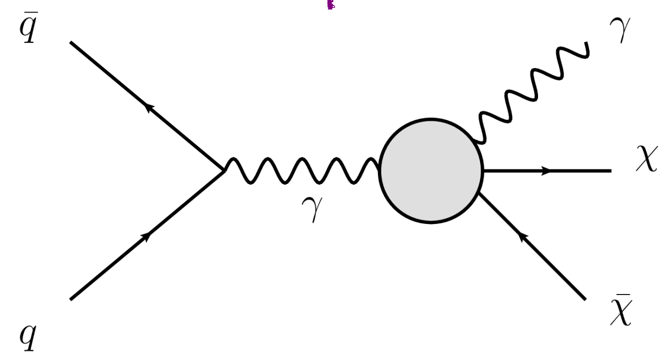
DM+bb/tt
Scalar mediator,
g_{DM} = 1 (g_{DM}=3.5)



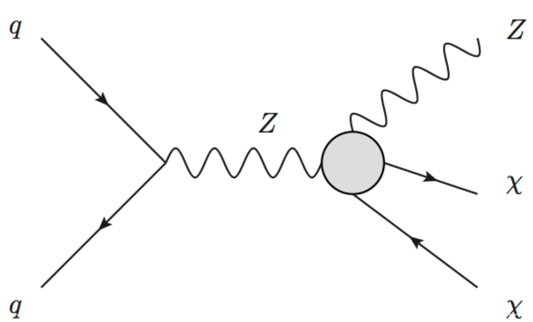
Signal Models

Dimension 7 **EFT** operator with direct couplings between DM and EW bosons; via effective vertex: (no ISR radiation required).
Parameters of the model: EW coupling strengths (k_1, k_2), m_χ and suppression scale Λ.

Mono-photon

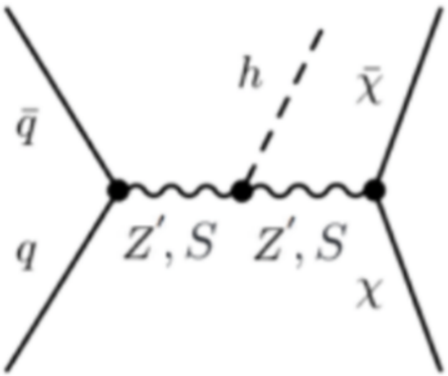


Mono-W/Z



Dark Matter production via **ZZ**$\chi\chi$ vertex in an **EFT** approach (dimension 7).
The strength of the interaction is controlled by the coupling strengths, mass scale M* and m_χ.

Mono-H

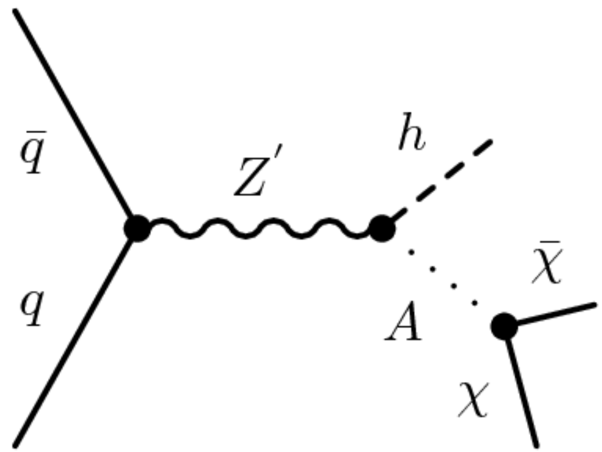


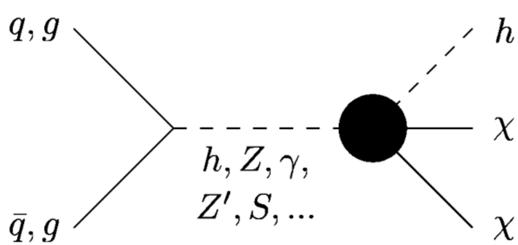
Simplified models: **Vector** or **Scalar** mediators, g_q and g_{DM}.

Vector Z': Requires to introduce baryonic Higgs (additional $\mathbf{g_{hZ'Z'}}$ coupling).
Scalar S: coupling $\mathbf{g_{hSS}}$

2HDM inspired models: **Z'-2HDM**

A Z' decays to a Higgs boson h and pseudoscalar A of a two-higgs-doublet model (A decays to a pair of DM χ). Assumes 2HDM for DM coupling. Two parameters: $g_{Z'}$ (gauge coupling) and the ratio of the up– and down–type vacuum expectation values, tanβ.





EFT models: Consider a number of operators for both scalar and fermionic DM.
Not discussed here.

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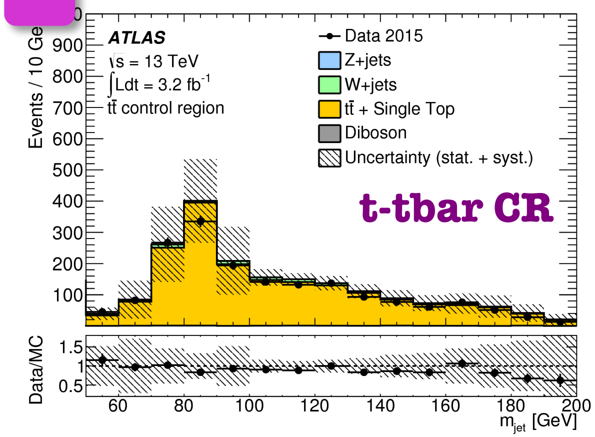
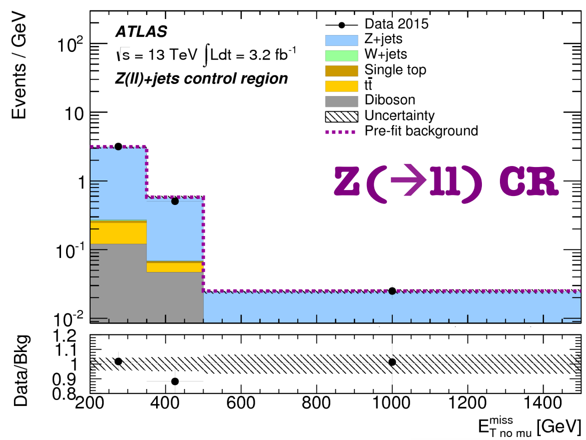
MET + V(had)

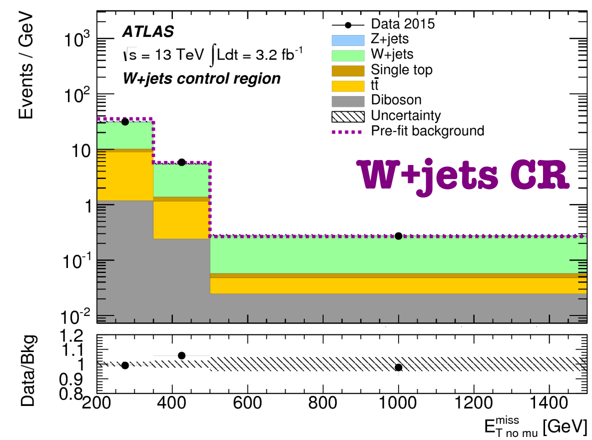
ATLAS EXPERIMENT

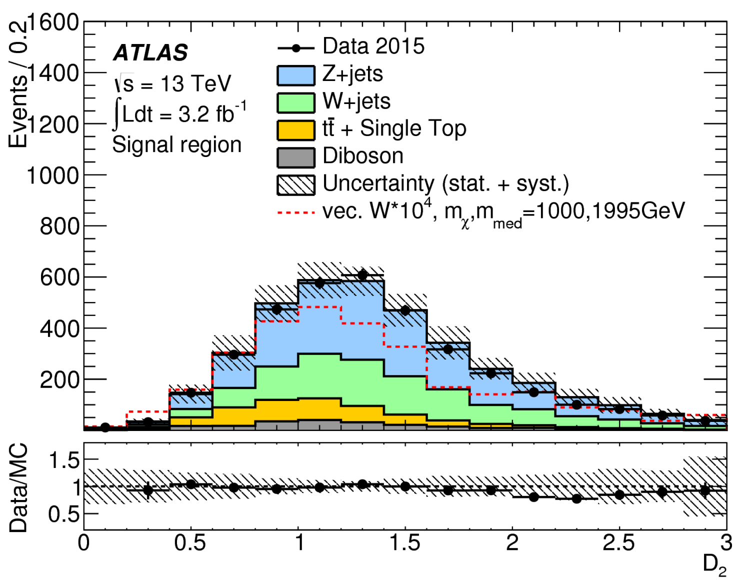
Selection

- **E_T^{miss} > 250 GeV**.
- ≥1 **large-R jet** (R=1.0, p_T > 200 GeV, $|\eta|$ < 2.0)
  - **boson-tagging**: p_T dependent selection based on jet mass and jet substructure.
- p_T^{miss} > 30 GeV,
- $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$,
- $\Delta\phi^{min}(E_T^{miss}, jet^{small\text{-}R})$ >0.6.
- **SR**: veto on muons and electrons (7 GeV).





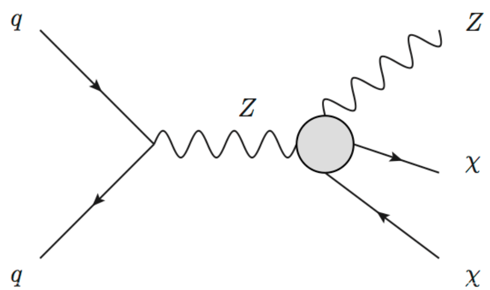


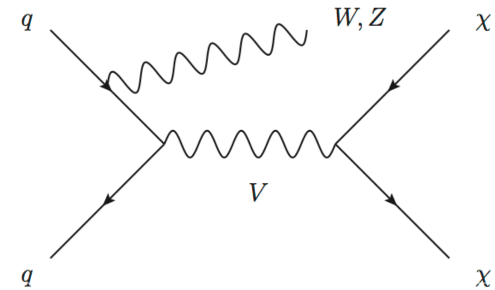


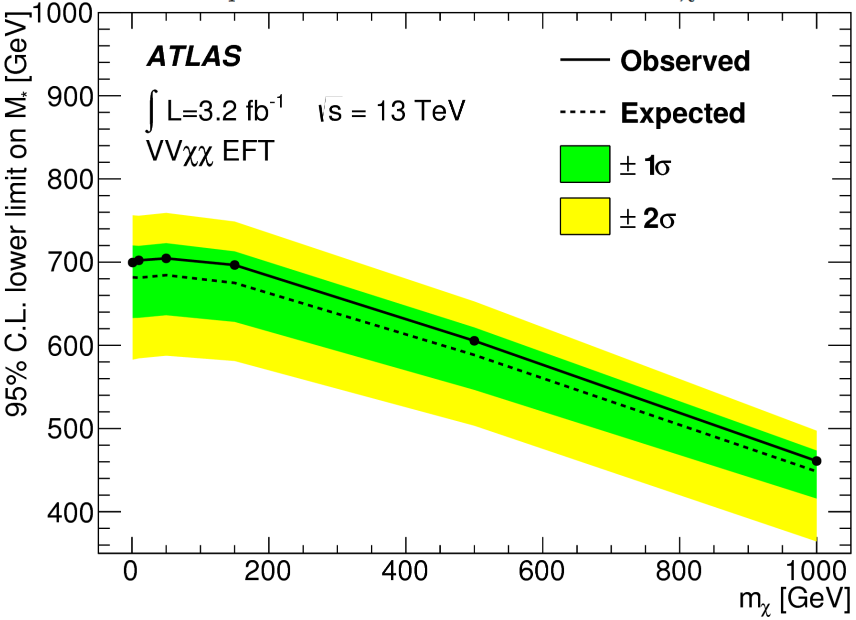
Strategy

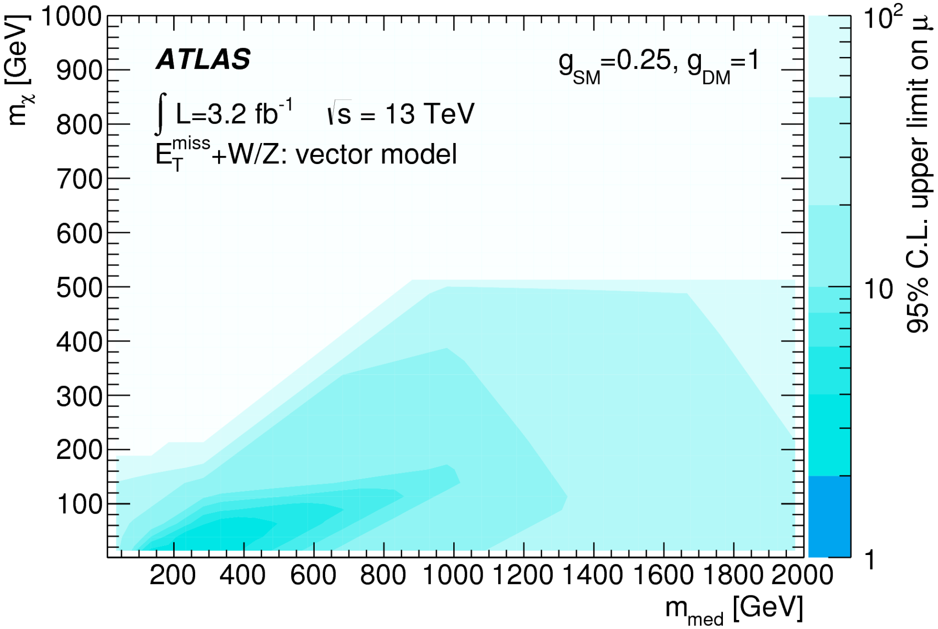
- Dominant bkg: **W/Z+jets**, followed by t-tbar.
- Main bkg normalized in dedicated CRs.
  - 3 normalization factors: k_W, k_Z, k_{ttbar}.
  - Simultaneous *shape fit* of E_T^{miss} distributions.
- Single top and DiBosons from MC.
- Main uncertainties:
  - Modeling of large-R parameters.
  - D2 scale uncert. and mass resolution: 5-10%.

MET + V(had)







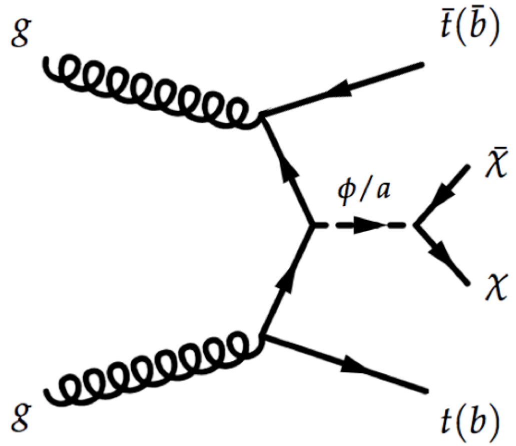


For the ZZχχ EFT, limits are translated into constraints on the mass scale, M★.

Limits on the signal strength μ for the vector-mediated simplified model generated with couplings $\mathbf{g_{SM} = 0.25}$ and $\mathbf{g_{DM} = 1}$.

ATLAS-CONF-2016-086

MET + HF

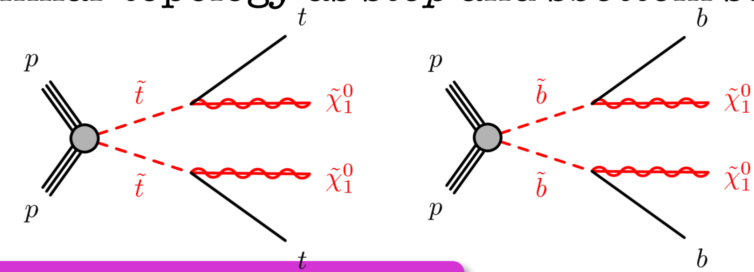


Search performed in different decay channels:

DM + t-tbar: 0, 1 and 2 lepton channels .

DM + b-bbar

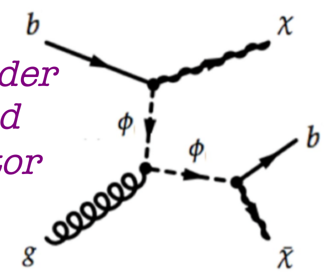
Similar topology as *stop* and *sbottom* searches.

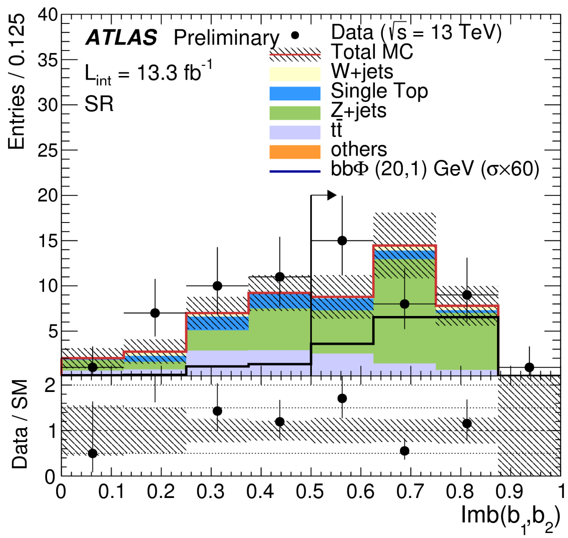


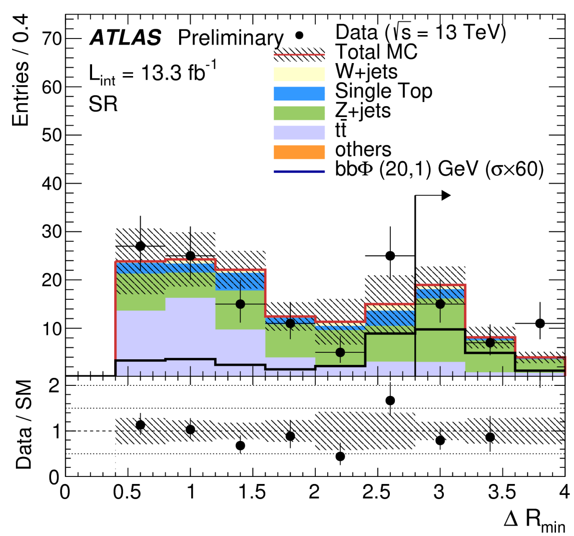
Selection & Strategy

DM+b-bbar: optimized for both low and high mediator masses.

Also can consider color charged scalar mediator models.







One single SR

Two b-tagged jets plus large E_T^{miss}

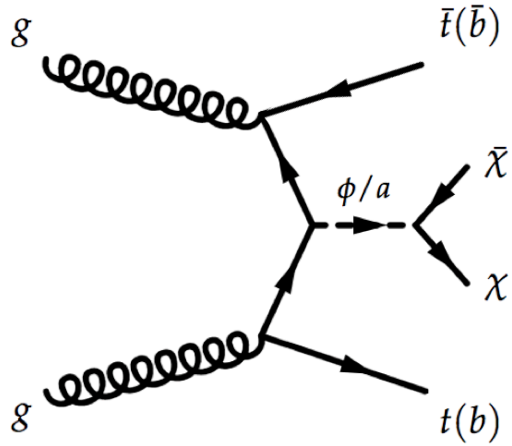
Other discriminants: transverse momentum imbalance, ΔR_{min}.

$Z(\nu\nu)$+b(b) main bkg, followed by t-tbar and single top.

Simultaneous global fit performed in multiple CRs+SR.

ATLAS-CONF-2016-077
ATLAS-CONF-2016-050
ATLAS-CONF-2016-076

MET + HF

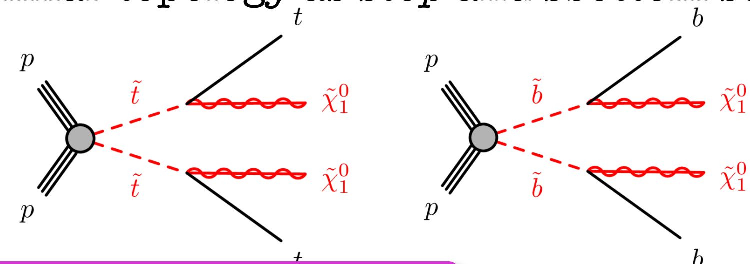


Search performed in different decay channels:

DM + t-tbar: 0, 1 and 2 lepton channels .

DM + b-bbar

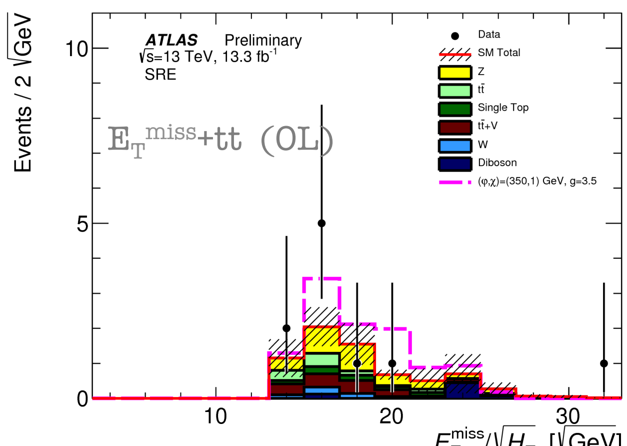
Similar topology as *stop* and *sbottom* searches.



Selection & Strategy

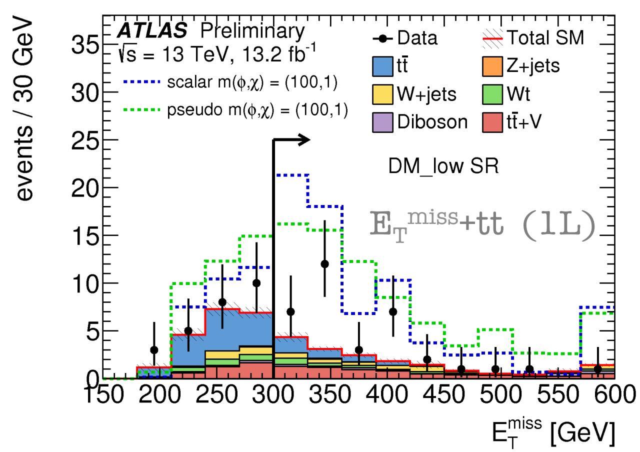
DM+t-tbar: *Same (SUSY) bkg strategy, mostly similar discriminating variables. Define multiple CRs to constrain main backgrounds, and performed a global fit (CRs+SR).*

SRE: optimized for DM (high m_{med}).
2 b-jets, E_T^{miss}>300GeV, ΔR_{bb}>1.5.

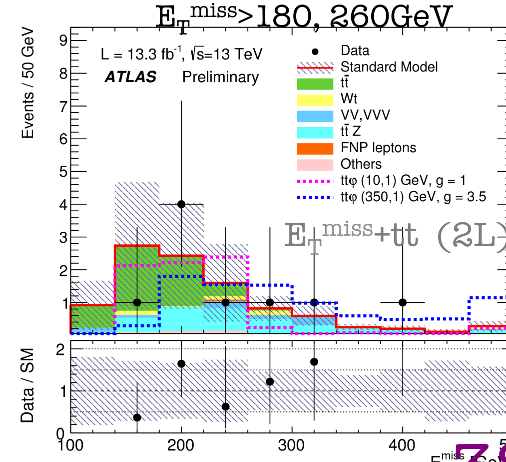


SRs optimized for low & high m_{med}.

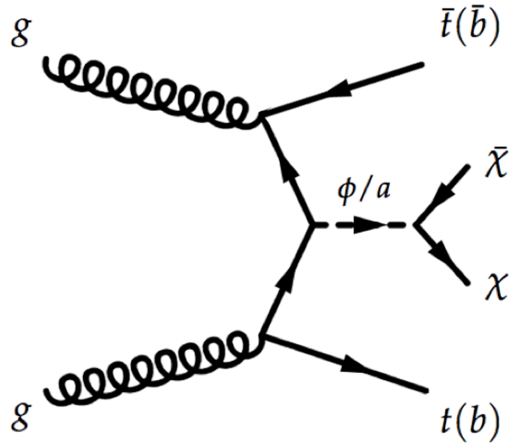
≥1 b-jets, ≥4 jets, E_T^{miss}>300GeV, cut on m_T



≥0 b-jets, m_{T2}(ll)120GeV, E_T^{miss}>180, 260GeV



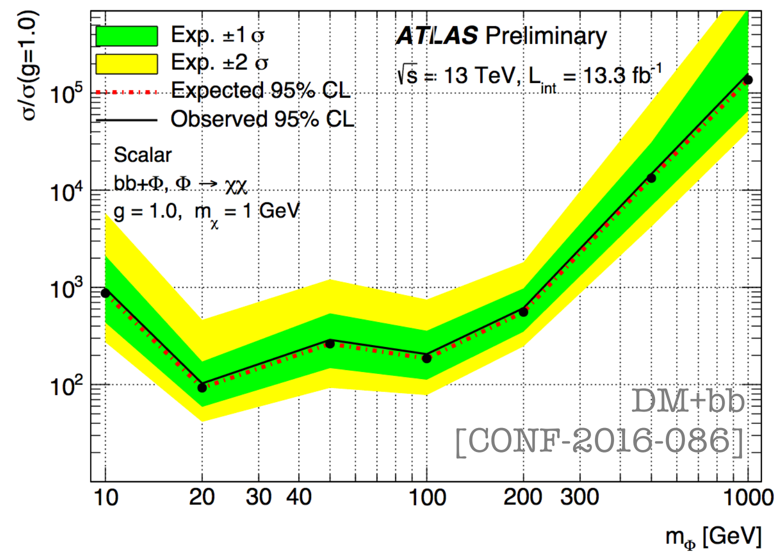
MET + HF



Search performed in different decay channels:

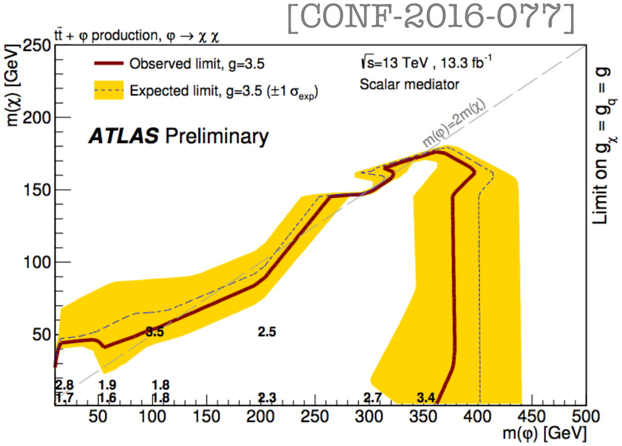
- MET + bb
- MET + tt
  - 0L
  - 1L
  - 2L

Not yet excluding this model for for $g = g_{DM} = g_q = 1$.

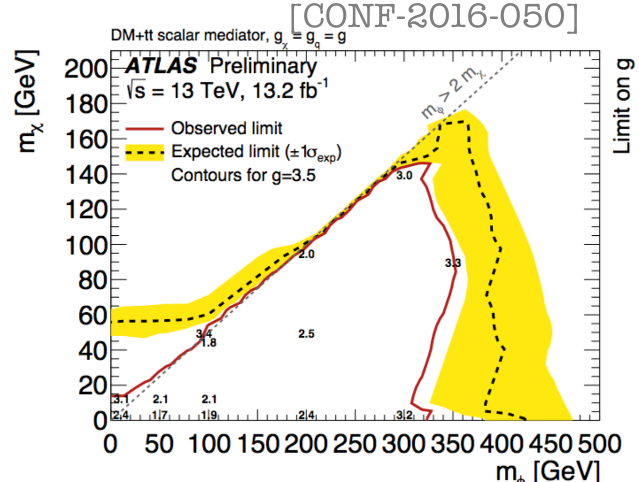


Limits for both scalar and pseudoscalar mediators.

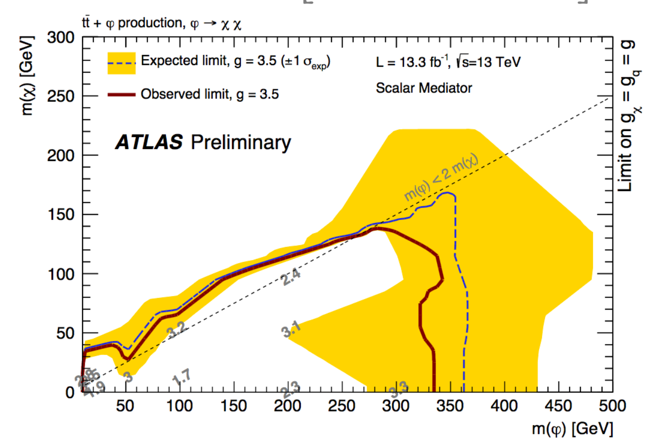
DM+tt (0L)
[CONF-2016-077]



DM+tt (1L)
[CONF-2016-050]



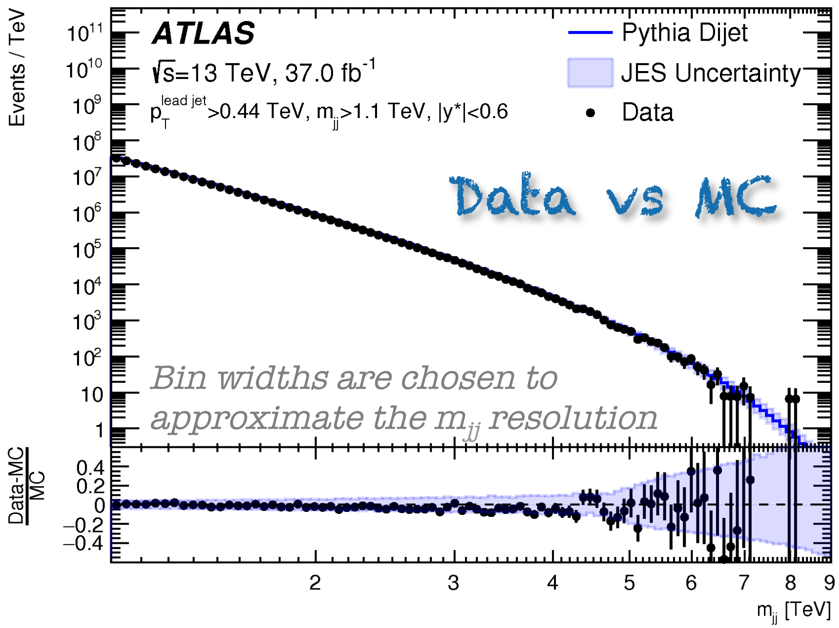
DM+tt (2L)
[CONF-2016-076]



*Limits on DM+tt set for g = **3.5** (no exclusion for g=1).*

arxiv:1703.09127

High mass di-jet



Selection

Events selected with lowest un-prescaled single jet trigger (p_T> 380 GeV).

	p_T^{leading}	$p_T^{\text{subleading}}$	$\lvert y^*\rvert$	$\lvert y_B\rvert$	m_{jj}
Resonance	> 0.44 TeV	> 0.06 TeV	< 0.6	-	> 1.1 TeV
W^*	> 0.44 TeV	> 0.06 TeV	< 1.2	-	> 1.7 TeV
Angular	> 0.44 TeV	> 0.06 TeV	< 1.7	< 1.1	> 2.5 TeV

$|y^*| = |y_1 - y_2|/2$ *Rejects forward peaking t-channel QCD processes.*

Strategy: **Resonance**

$$f(z) = p_1(1-z)^{p_2} z^{p_3} z^{p_4 \log z}$$

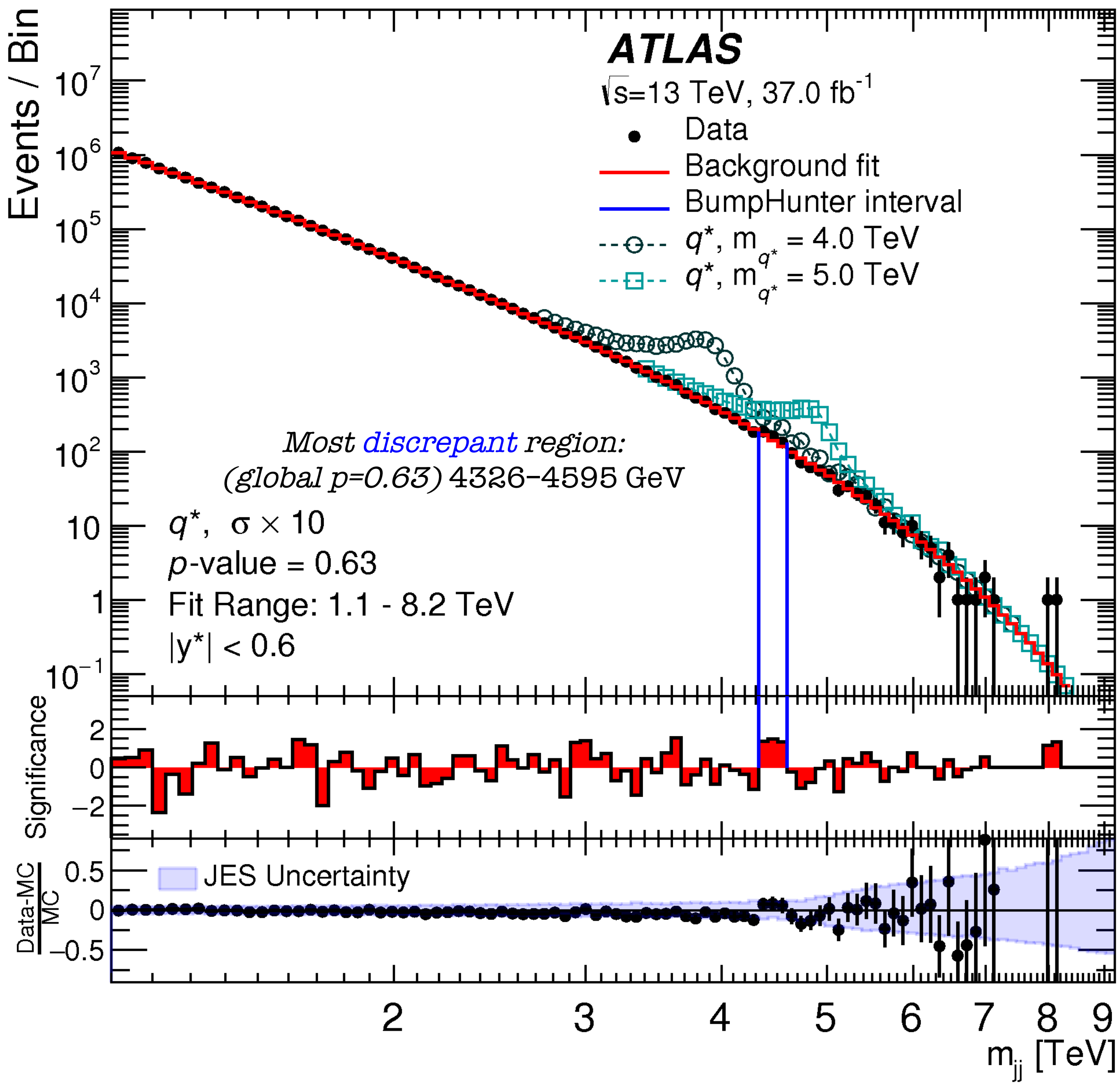
With increasing luminosity and corresponding m_{jj} range extension, a single global fit may not necessarily work.

Sliding Window Fit

NEW

- Perform the f(z) fit in restricted (sliding) ranges (***more flexible!***).
- The limited range allows to use a 3-parameter function.
- Excellent linearity between injected and extracted signal.

High mass di-jet



Selection

Events selected with lowest un-prescaled single jet trigger (p_T> 380 GeV).

$|y^*| = |y_1 - y_2|/2$

Rejects forward peaking t-channel QCD processes.

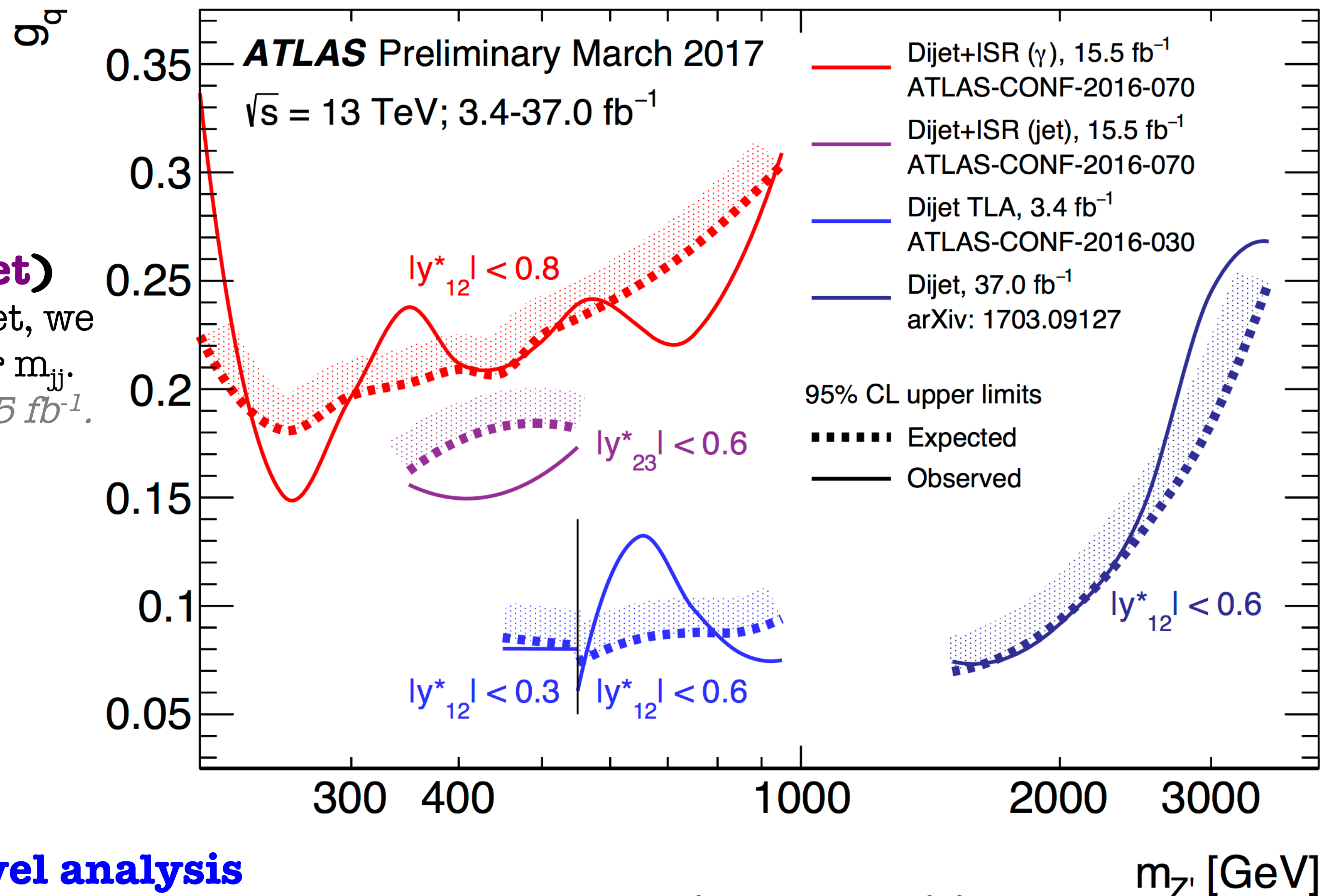
Resonance Search

- **Sliding Window Fit**
  - Perform the f(z) fit in restricted (sliding) ranges (***more flexible!***).
  - Excellent linearity between injected and extracted signal.
- **BumpHunter** algorithm compares the binned m_{jj} of data to the fitted bkg estimate.

Di-jet searches

*Di-Jet searches covering the **low and high mass** regime!*

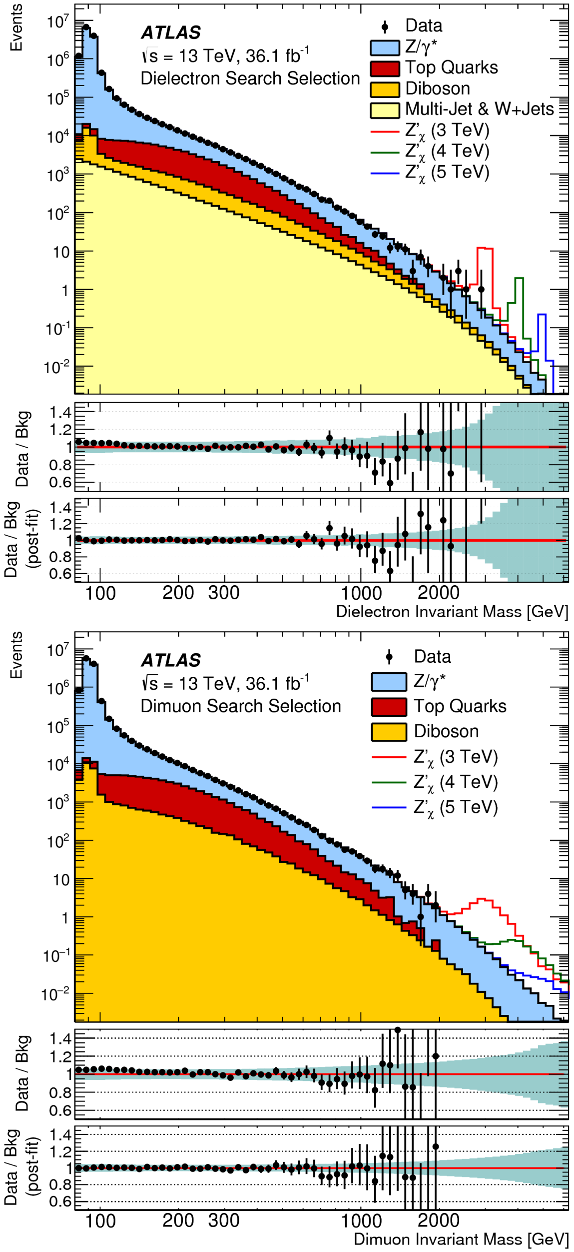
Di-jet + ISR (γ/jet)
Triggering on ISR γ/jet, we can also reach lower m_{jj}.
Last results with 15.5 fb^{-1}.



Trigger level analysis
Strategy: reduce data size/complexity to increase rate of recorded data .
Last results with 3.4 fb^{-1}.

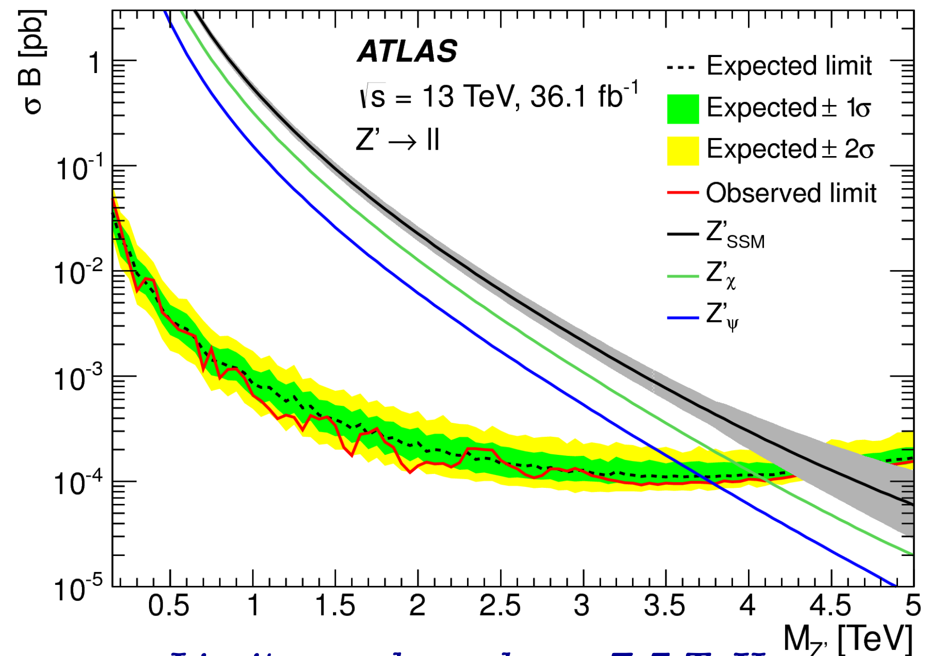
High mass di-jets
Reach at low masses limited by trigger bandwidth and storage.

Di-lepton



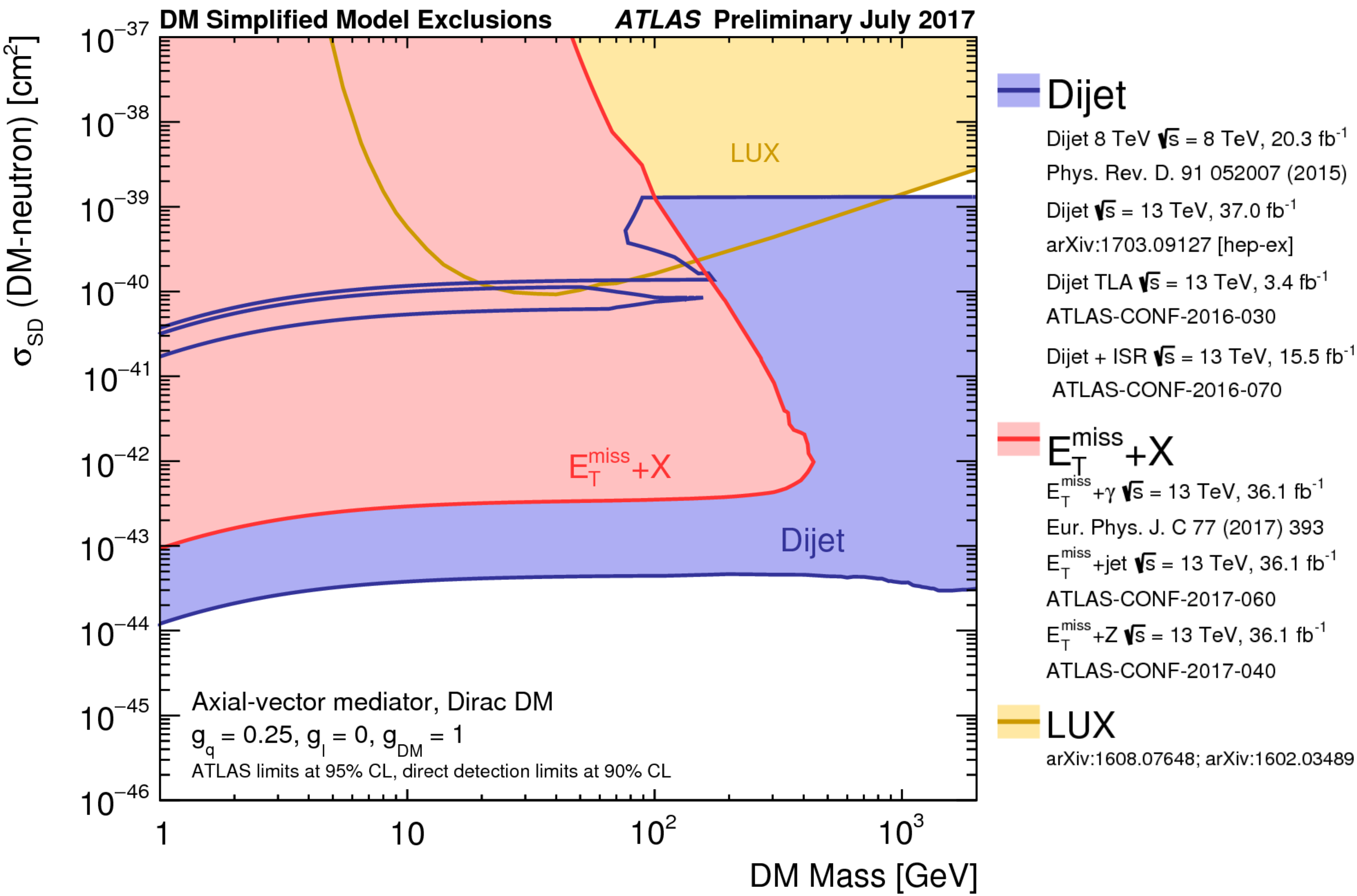
Selection & Strategy

Events selected with 2 same-flavor isolated lepto*ns.*
Highest m_{ll} pair (> 80 GeV).
Main background from **Drell-Yan production**.
DY events are simulated with NLO Powheg generator.
Events yields are corrected with mass dependent rescaling from NLO to NNLO QCD, and NLO EW.



Limits weaken above 3.5 TeV.
Rapidly falling signal x-sections and off-shell low mass signal tail.

Comparison with **Direct Detection**



Z(νν)/Z(ll) ratio

The ratio is corrected for detector effects ("unfolded"), so can be easily reinterpreted in terms of any BSM models.