Dark Matter searches at ATLAS

Giuliano Gustavino

on behalf of the ATLAS collaboration

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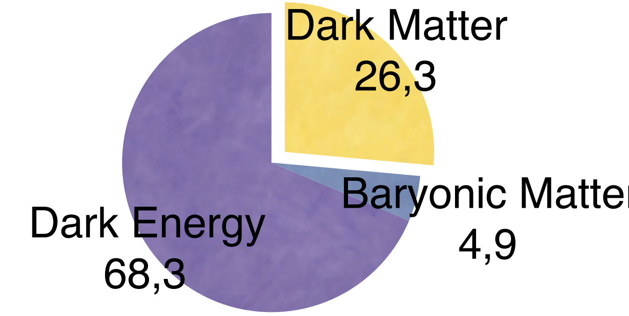
28th Rencontres de Blois

SAPIENZA UNIVERSITÀ DI ROMA

ATLAS EXPERIMENT

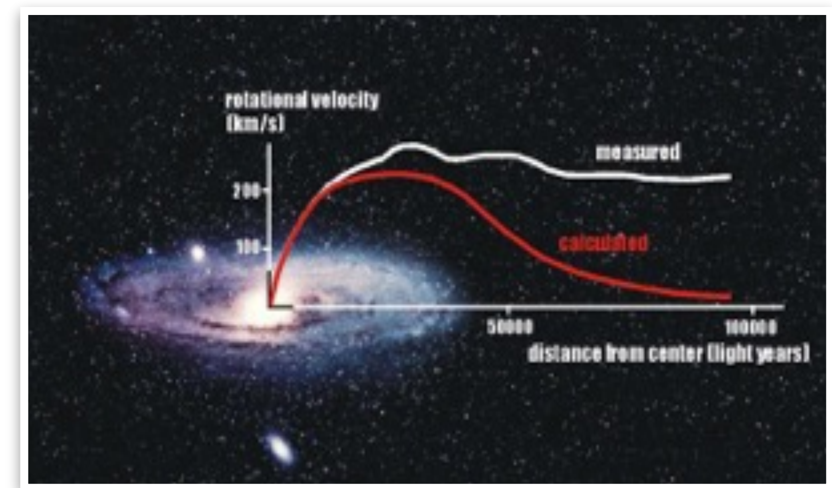
INFN Istituto Nazionale di Fisica Nucleare

The Dark Matter paradigm



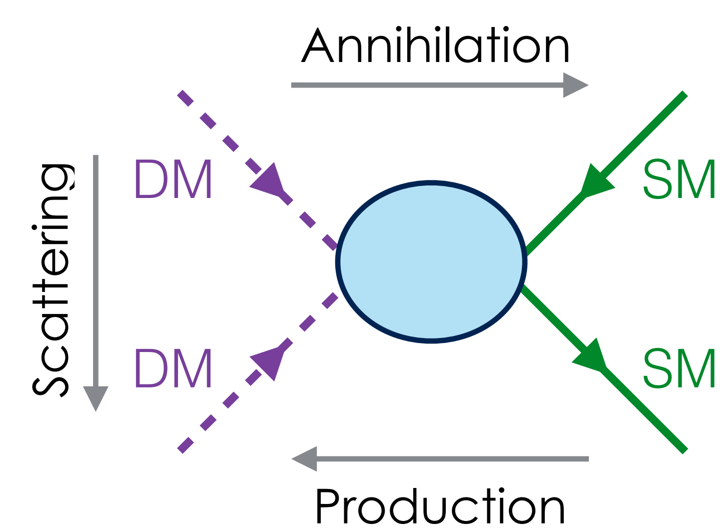
The existence of a Dark Matter (DM) particle is a well-established hypothesis that explains a range of astrophysical and cosmological measurements.

The presence of a non-baryonic component in the universe is inferred from the observation of its gravitational interactions



How can we study the Dark Matter?

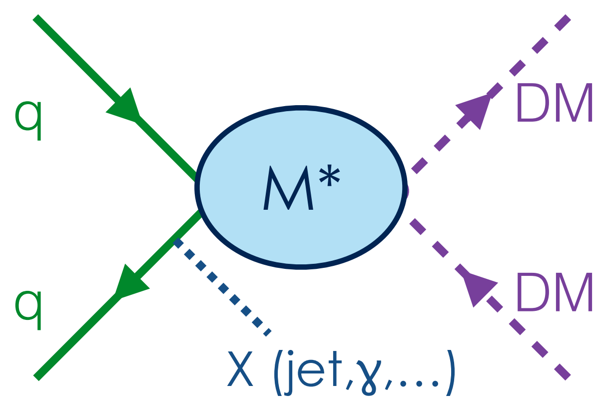
- **direct detection** based on scattering interaction detections (DAMA, LUX etc.)
- **indirect detection** experiments that look for final states given by the DM annihilation (AMS, Ice-Cube etc.)
- Pair **production at LHC** with large missing energy in the detector



The detection of DM candidates in a collider can give complementary results with respect to the other DM detections.

DM search at LHC, in theory

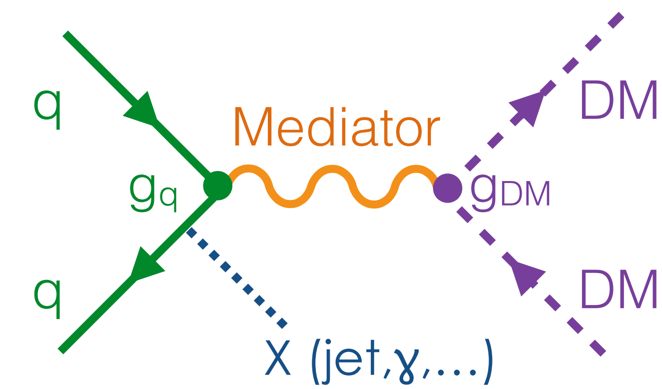
Run1 strategy



Effective Field Theory

simpler but not valid at high Q^2
Several EFT operators were considered (arxiv:1502.01518).

Run2 strategy



Simplified Models

A minimal width mediator (vector, axial-vector, scalar, pseudo-scalar…) couples to SM and DM particles ($\sigma \sim g_q^2 g_{DM}^2$).
4 parameters:
DM & mediator masses, DM & SM couplings

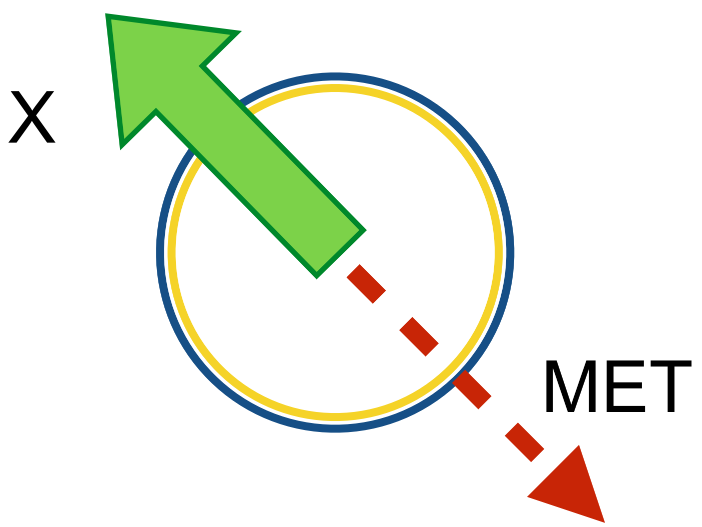
Determined recommended **benchmark models** for LHC Run 2 searches in common accord between ATLAS and CMS (arXiv:1507.00966).

s-channel is considered for the firsts results.

WIMP treated as Dirac fermion for simplicity.

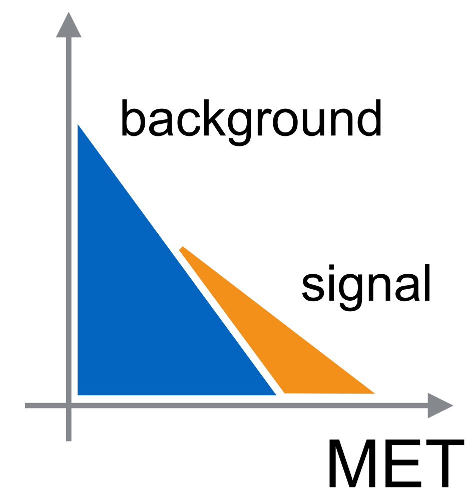
DM search at LHC, in practice

Mono-X signatures

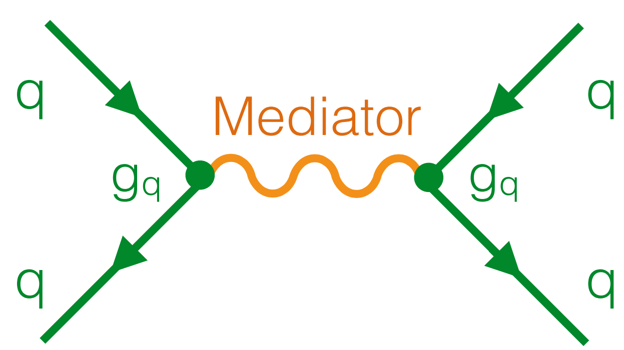


Search for high MET excesses.
General Analysis Strategy:

- Require MET (➡ recoil system p_T)
- Select for X (jet, photon…)
- Veto other objects
- Additional cuts to suppress backgrounds
- Data-driven techniques to estimate background
  ➥ control region with inverted vetoes



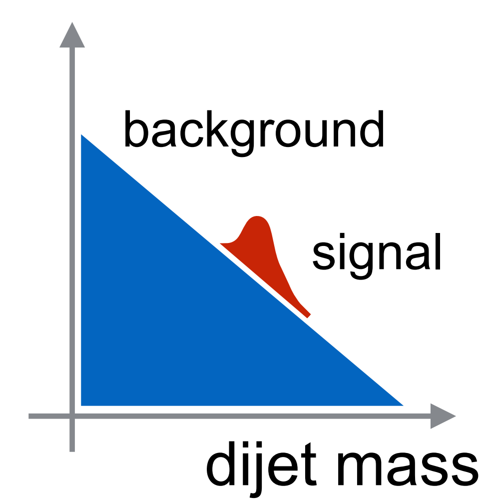
Resonance search



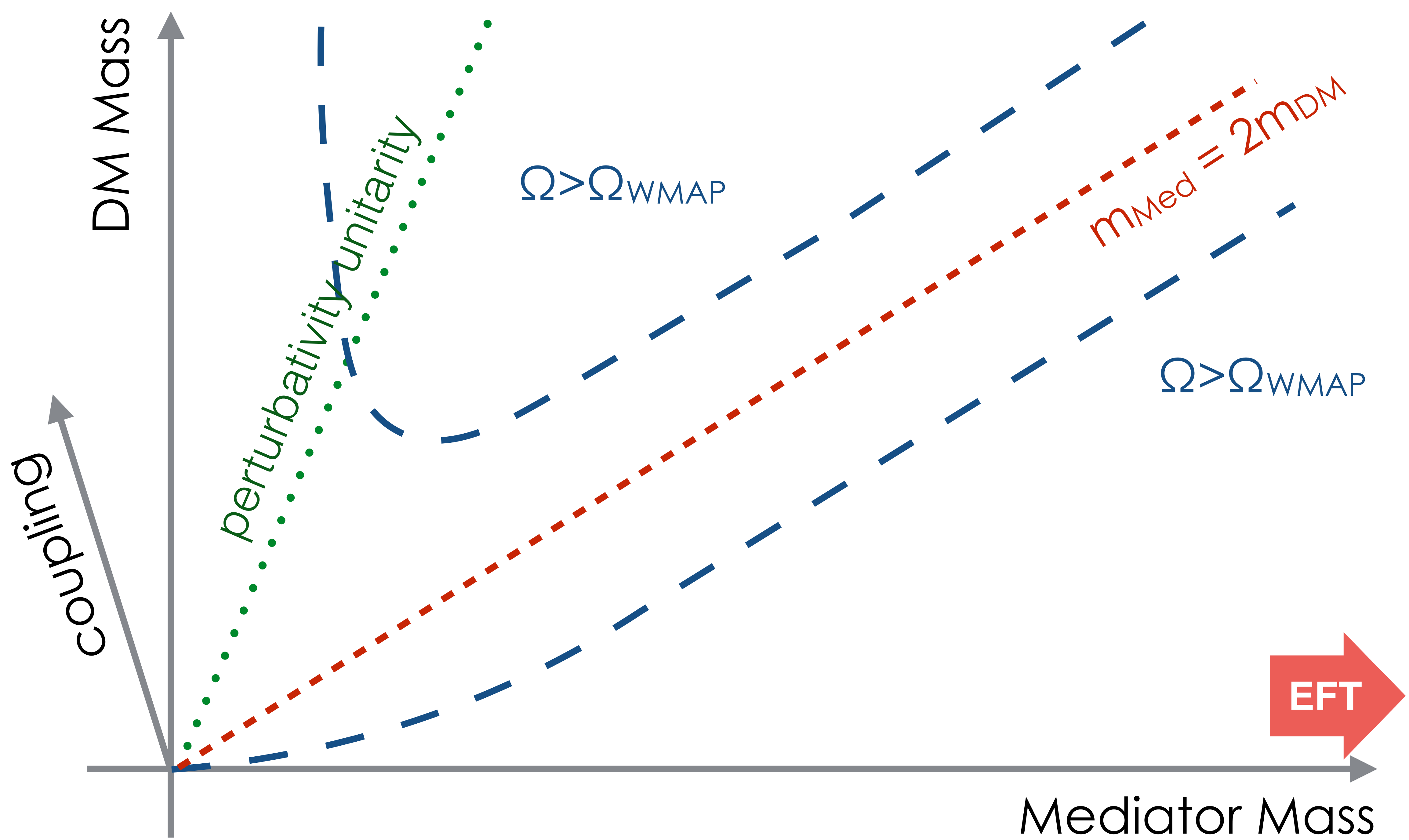
Mediator can decay back to quarks
➡ dijet events ($\sigma \sim g_q^4$).

◆ Probed **high mass** mediator (because the single jet trigger plateau).

◆ Data-scouting could probe **low mass** region (not in this talk).

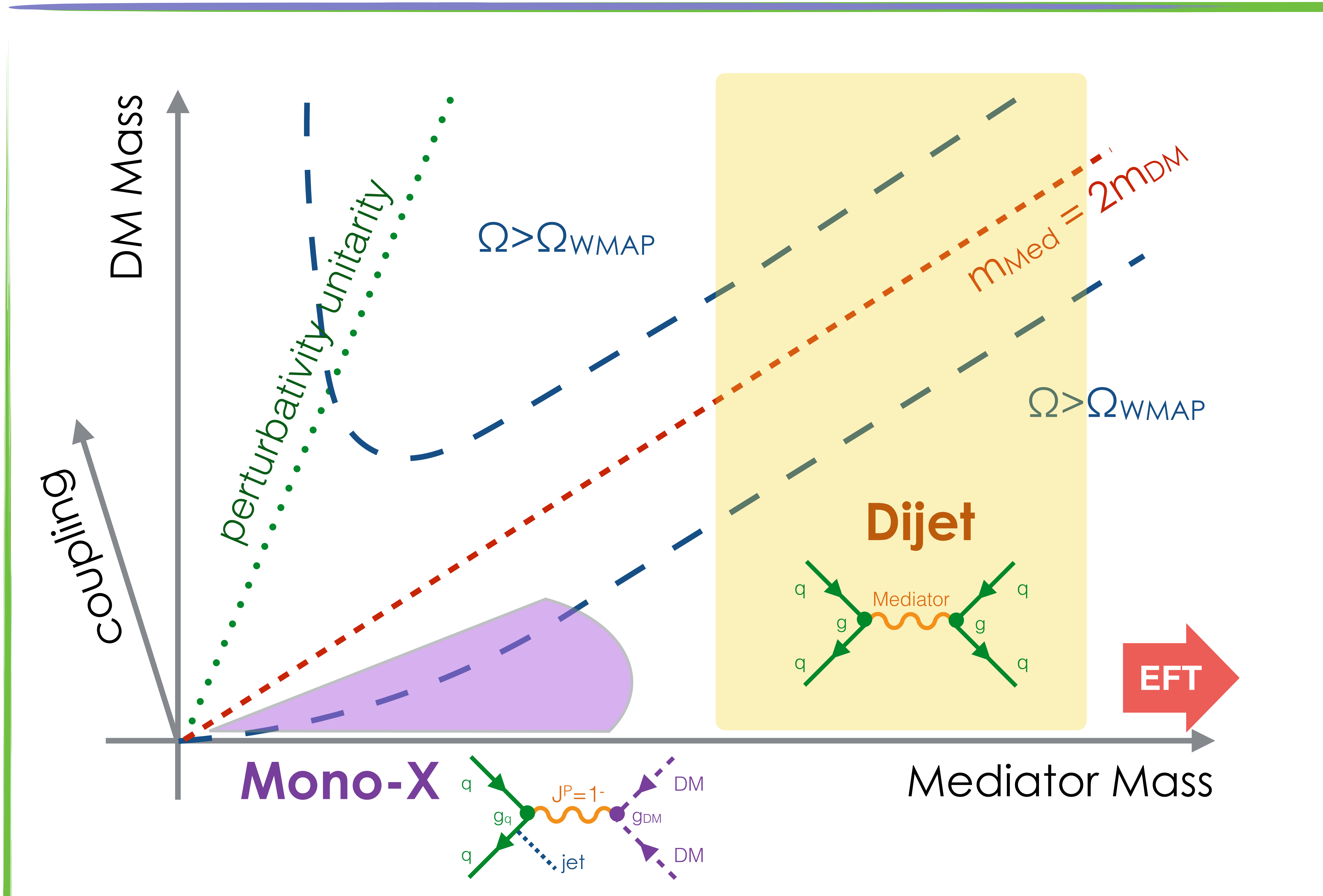


2D Mass plot



DM Mass
coupling
perturbativity
unitarity
Ω>ΩWMAP
$m_{Med} = 2m_{DM}$
Ω>ΩWMAP
EFT
Mediator Mass

2D Mass plot

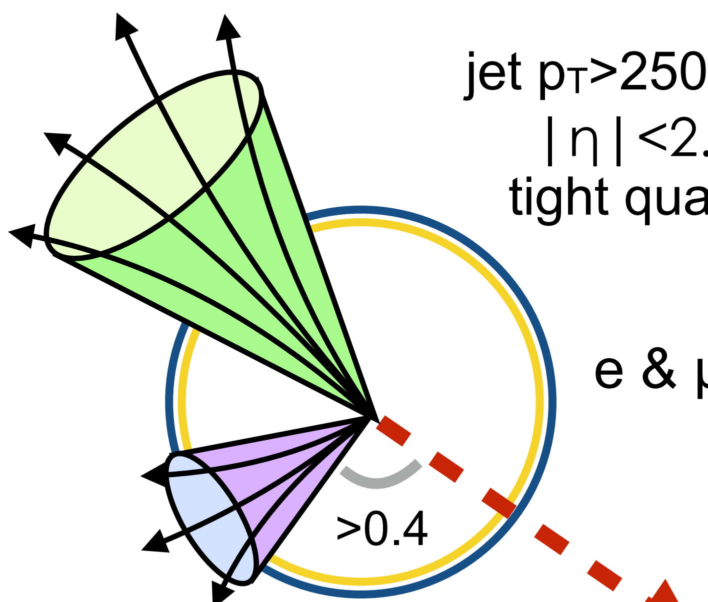


DM Mass
coupling
perturbativity
unitarity
Ω>ΩWMAP
mMed = 2mDM
Ω>ΩWMAP
Dijet
q
Mediator
q
g
g
q
q
EFT
Mono-X
q
JP=1-
DM
gq
gDM
q
jet
DM
Mediator Mass

Mono-jet (arXiv:1604.07773)

SR

MET>70GeV trigger



jet p_T>250GeV,
|η|<2.4,
tight quality

e & μ veto

Up to 3 other jets
(p_T>30GeV)

MET>250 GeV

Z(νν)*, W(μν)	CR1μ
W(τν), W(eν), Zττ	CR1e
Z(μμ)	CR2μ
Z(ee), diboson, top	MC
Multijet and NCB	data

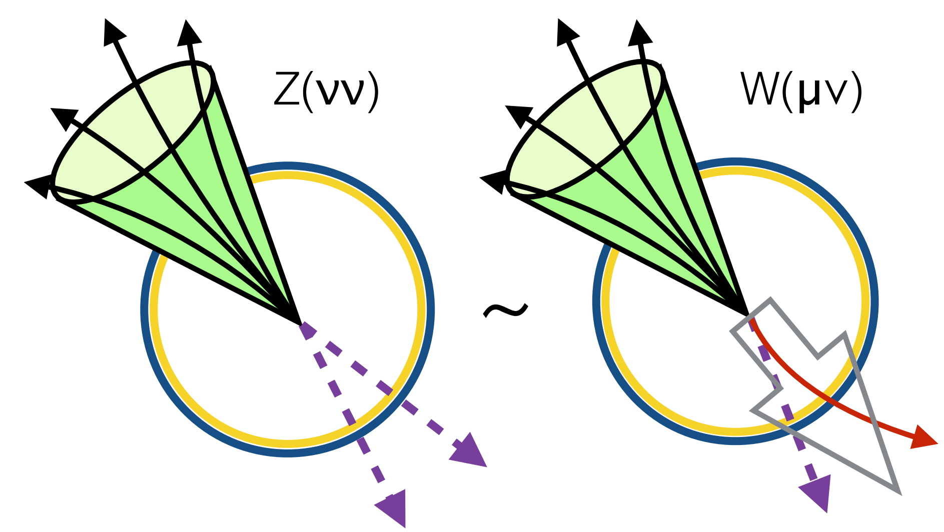
*low statistics in CR2μ

Most sensitive mono-X channel for ISR processes (paying only α_s)

Residual dominant backgrounds given by the **Z(νν)+jets** and **W(τ_{had}ν)+jets** processes

3 control regions are defined (**1μ, 2μ, 1e**) to evaluate the V+jets backgrounds.

MET ~ boson p_T
muons treated as invisibles in the MET calculation



systematic for the W/Z ratio vs p_T and the EW/QCD corrections differences

Mono-jet (fit strategy)

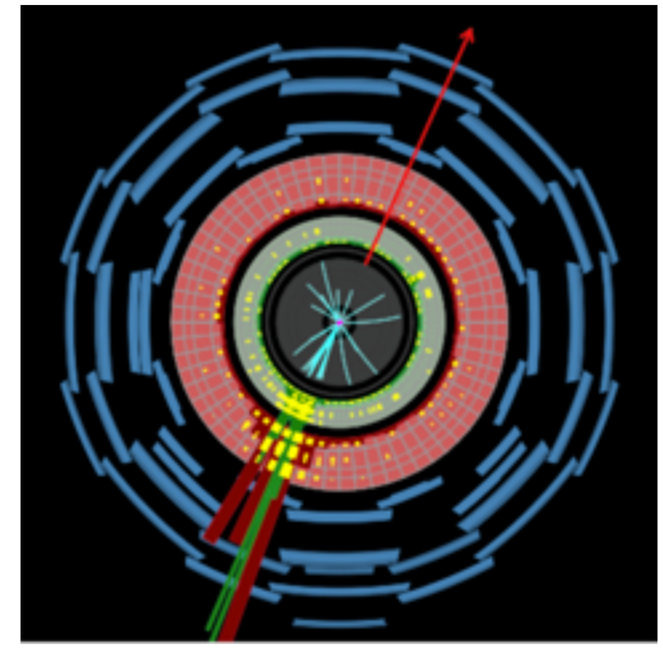
MET binned simultaneous fit is performed:

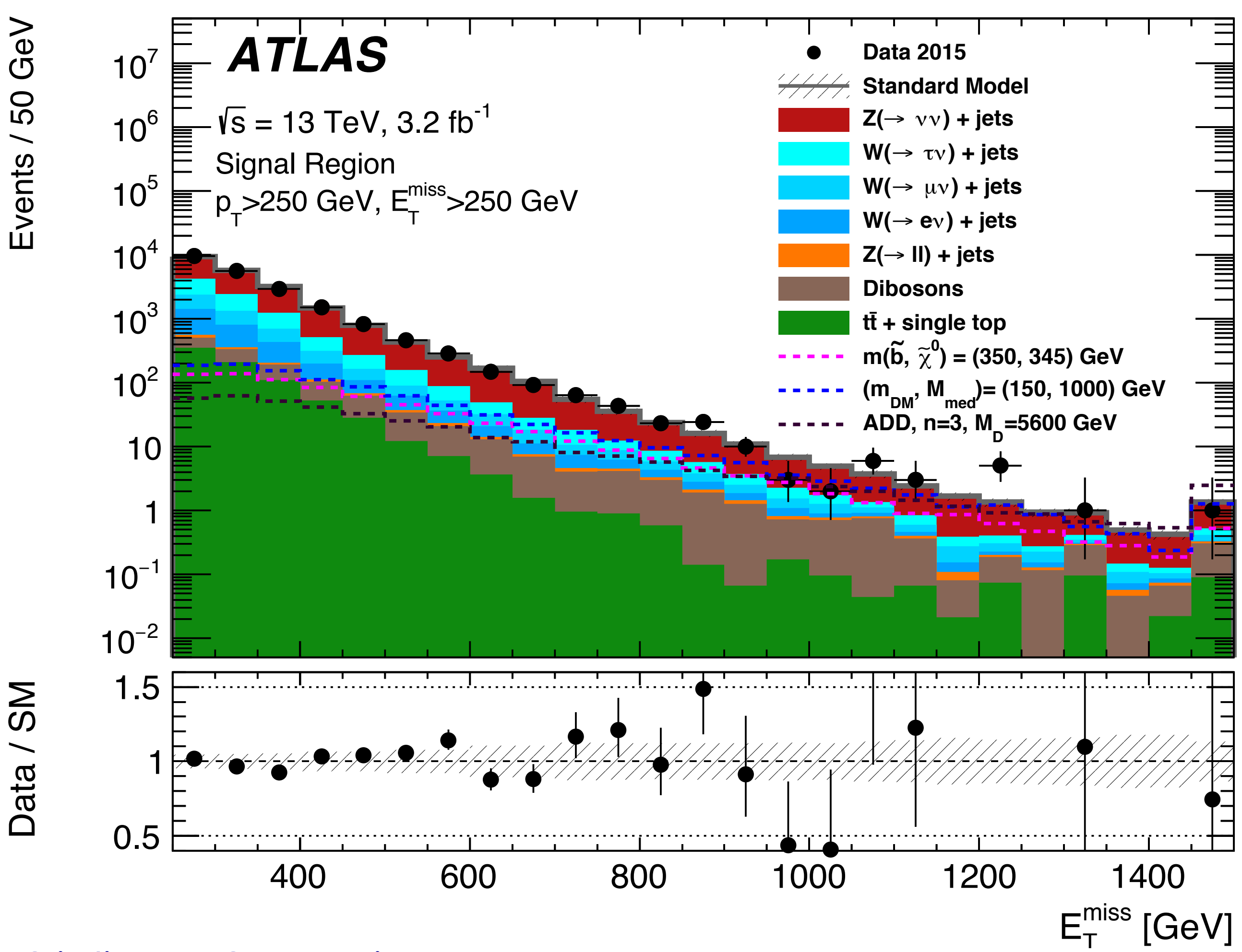
$k1\mu^{(i)}$ x [Z(νν)+jets, W(μν)+jets] + $k1e^{(i)}$ x [W(τν)+jets, W(eν)+jets, Z(ττ)+jets] + $k2\mu^{(i)}$ x [Z(μμ)+jets] + ...

where $i = 1,..,N_{bin}$

MET ϵ [250,300,350,400,500,600,700,∞] GeV

MET = 954 GeV
jet p_T = 973 GeV





Dominant uncertainties (total 4-12%):

- statistical (3-10%),
- top (~3%),
- boson+jet modeling (2-5%)

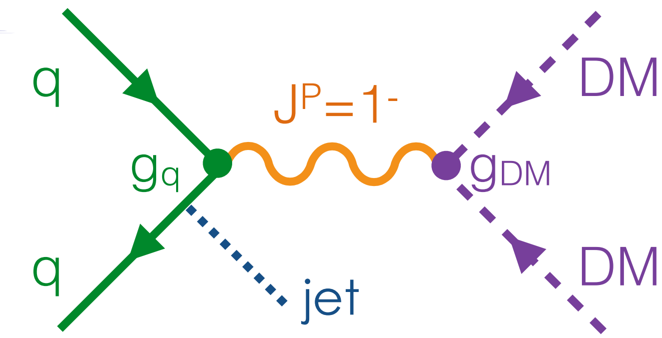
low MET bins ➡ systematics unc. dominates

high MET bins ➡ statistical unc. dominates.

Good agreement is observed between data (21447) and MC expectations (21730 ± 940).

➡ Interpret results as limits

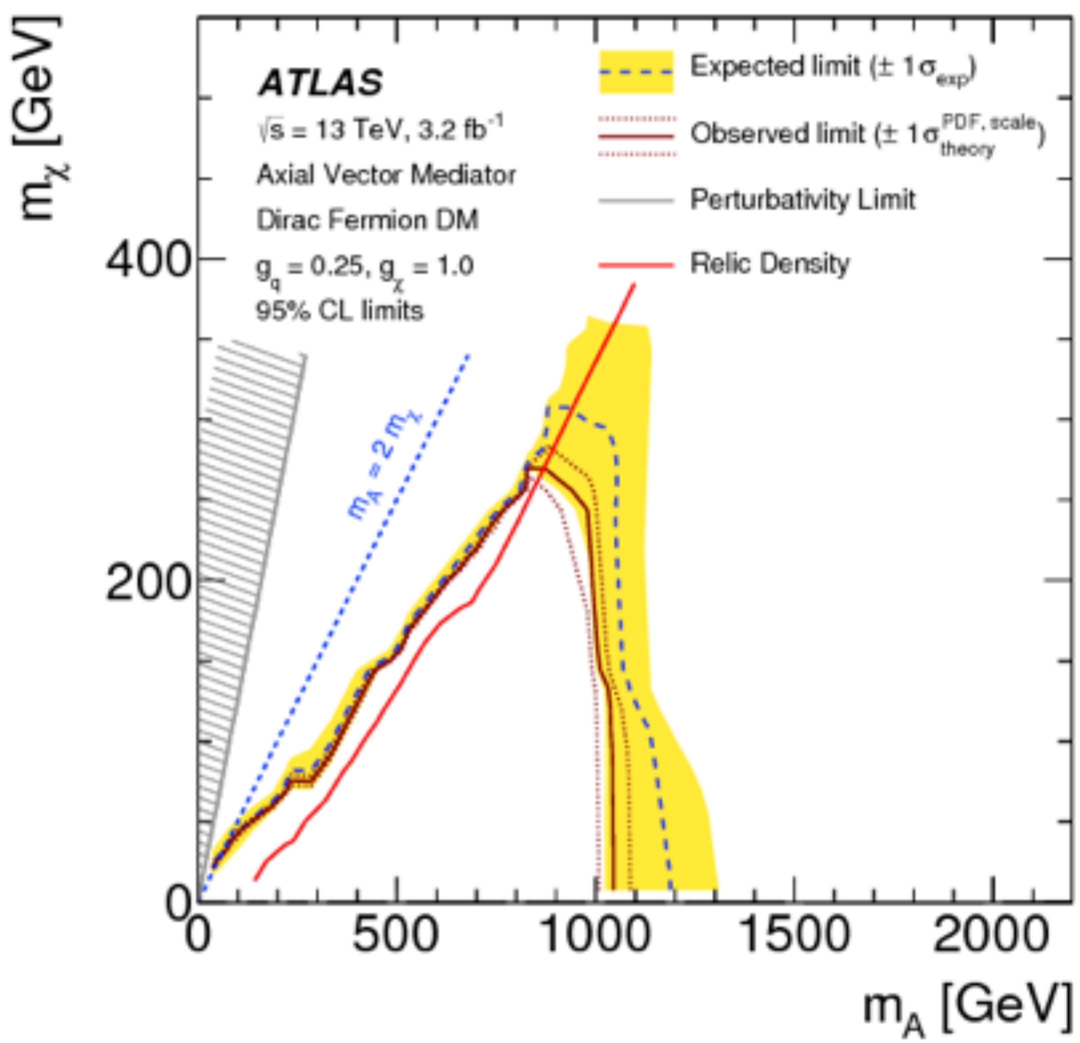
Mono-jet (results)



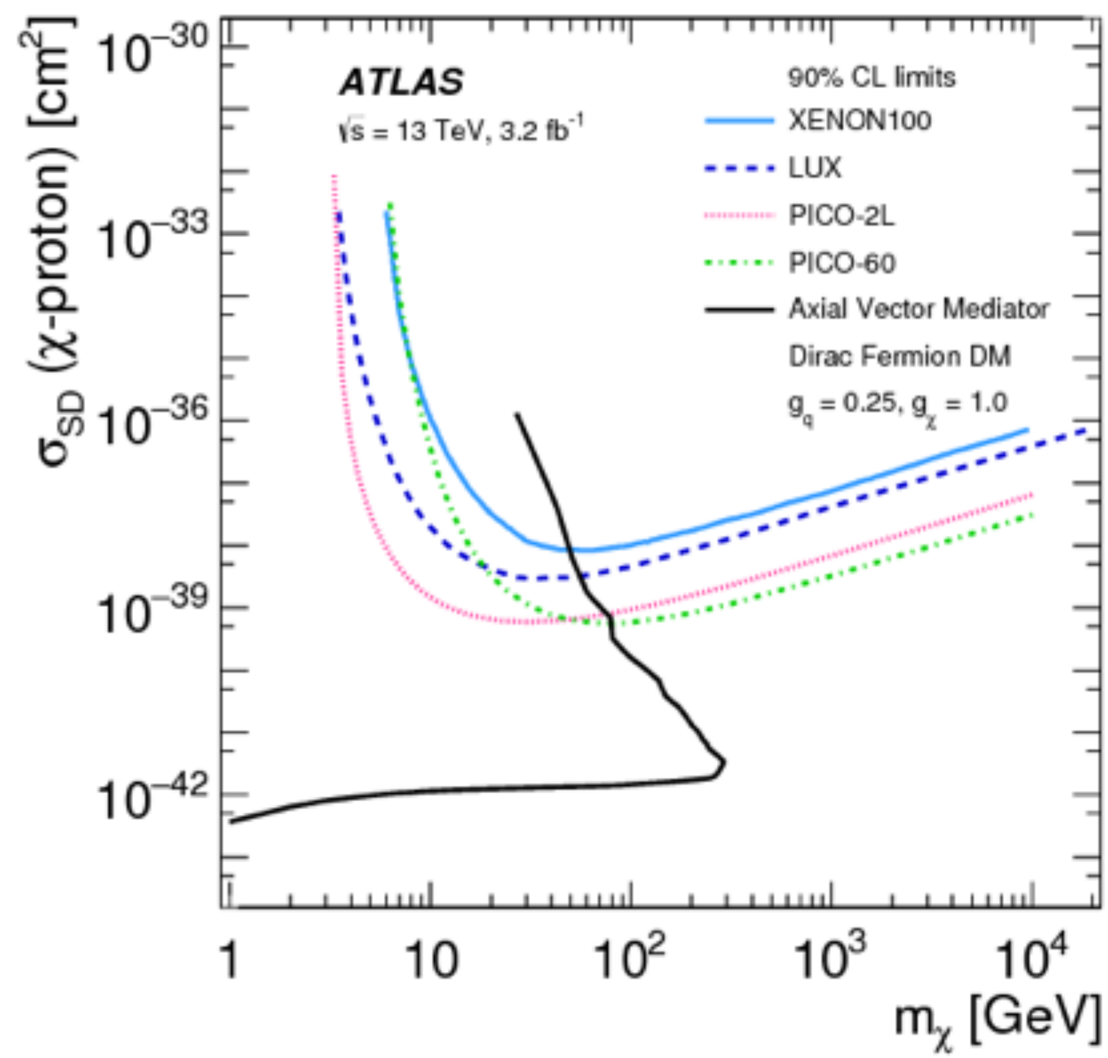
Results interpretation:

axial vector mediator, g_q=0.25, g_{DM}=1

(as recommended by the LHC Dark Matter Working group arXiv:1603.04156)



Contour Limit in the 2D plane DM vs Mediator mass

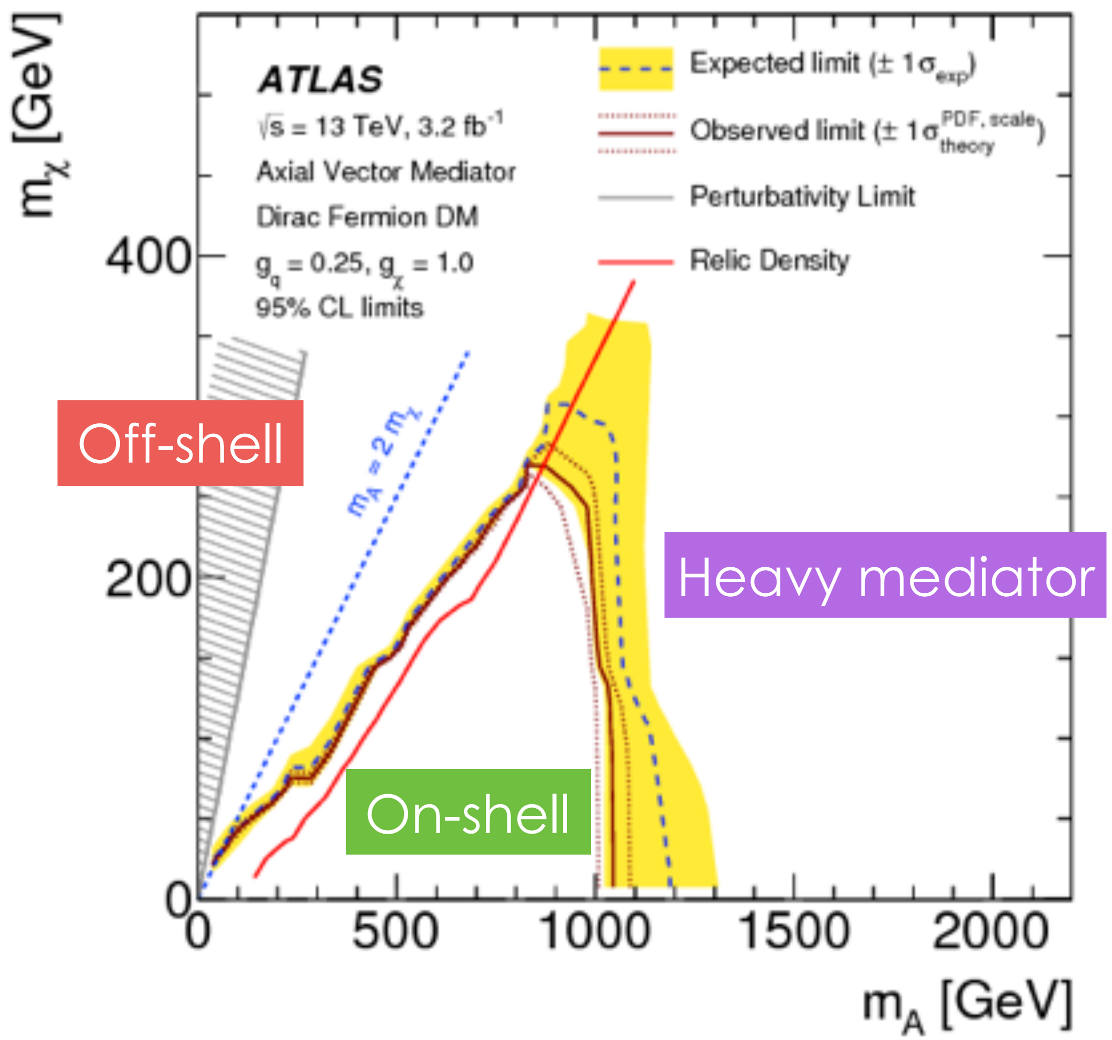


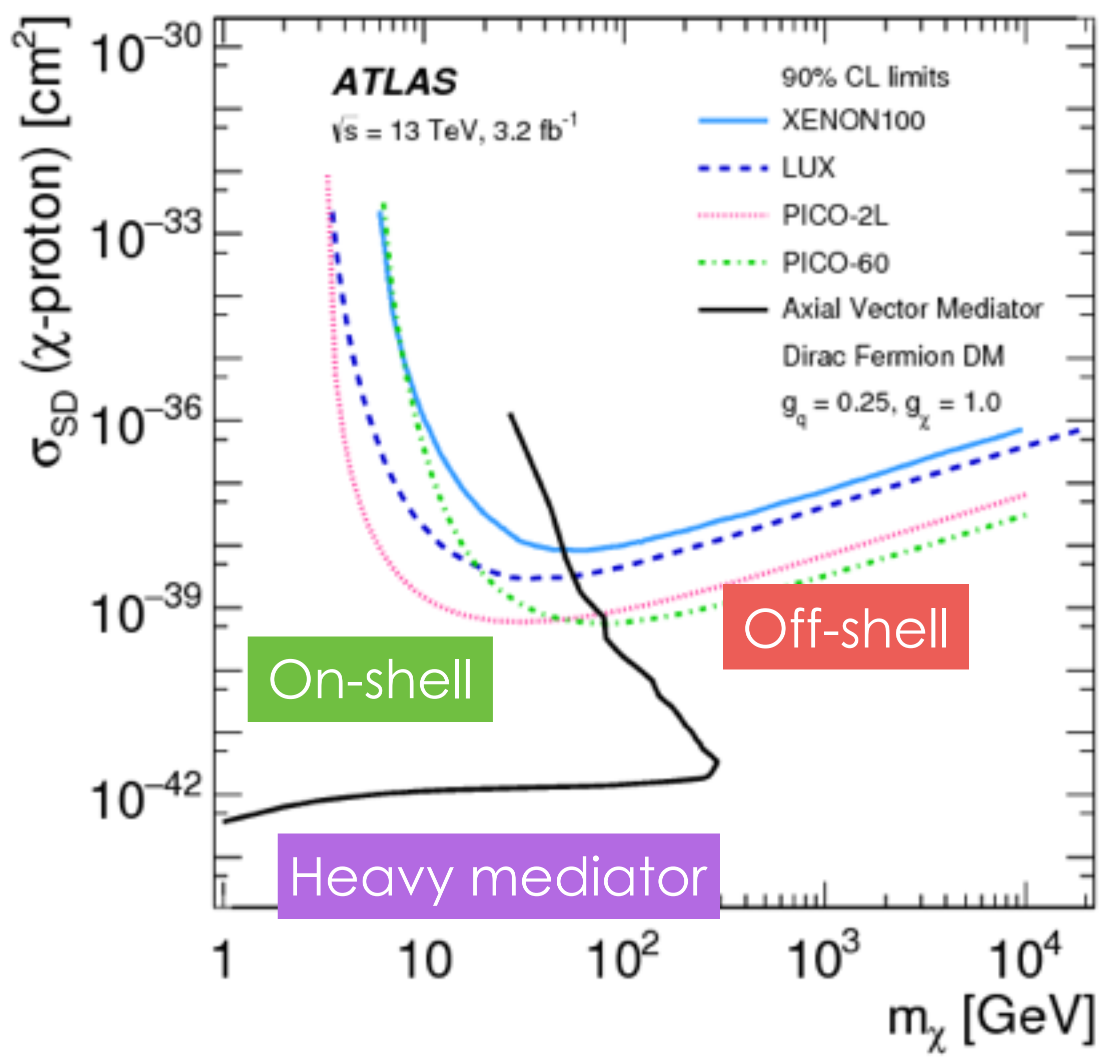
Limit on DM-proton scattering cross-section.

LHC limit gives complementary results wrt direct detection experiments

Mono-jet (results)

On-shell
- high xsecs
- LHC exclusion



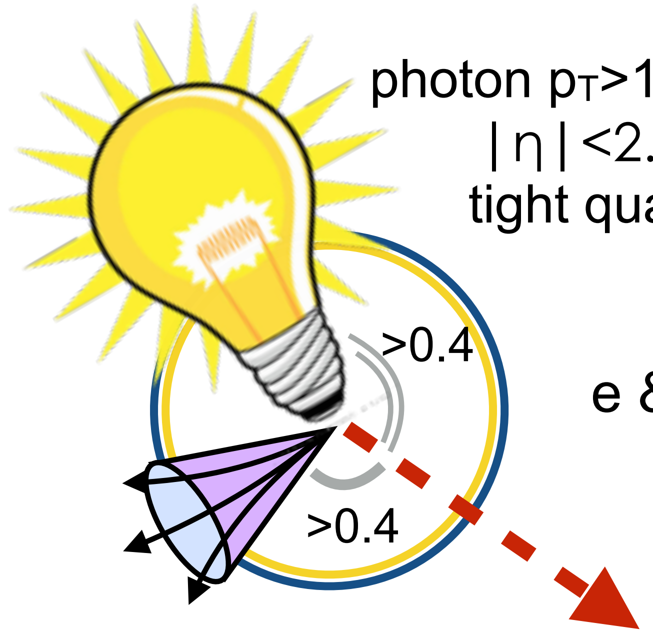


Off-shell
- low xsec
- relic DM underproduced

Heavy mediator
- production suppressed ($\sigma_{SD} \sim M_{med}^{-4}$)
- relic DM overproduced

Mono-photon (arXiv:1604.01306)

Photon p_T>120GeV trigger SR



photon p_T>150GeV, |η|<2.37, tight quality

e & μ veto

An additional jet is permitted (p_T>30GeV)

MET>150 GeV

Lower statistics than mono-jet channel (α_{EM}<<α_s).

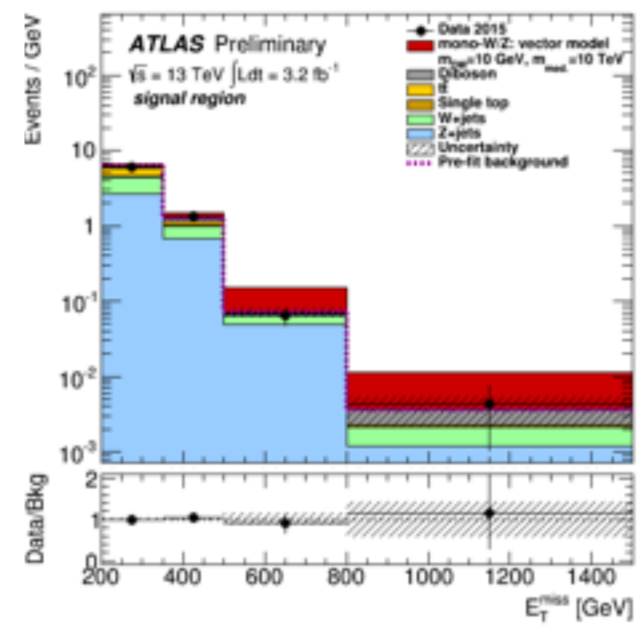
4 control regions to constrain Z/W+γ and γ+jet

Fake γs evaluated from electron and jets.

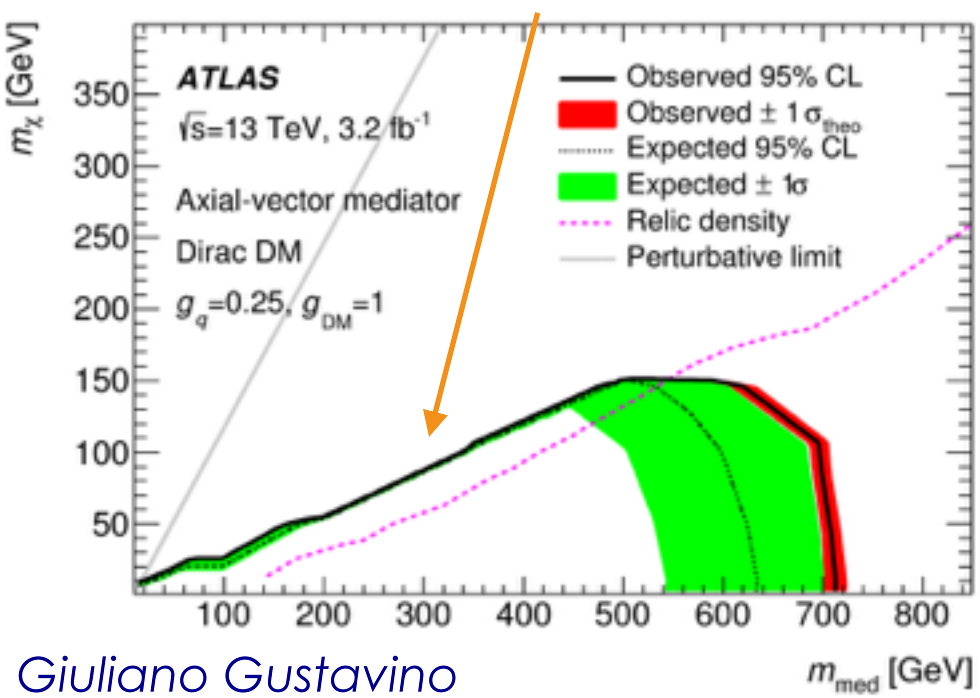
A simultaneous fit between the inclusive MET regions is performed.

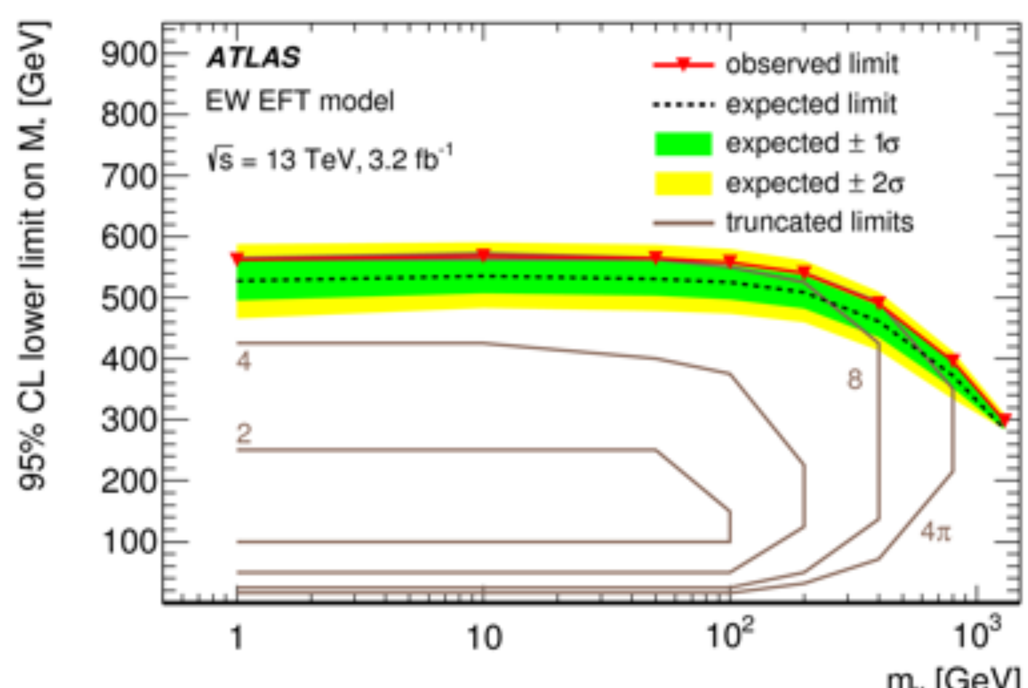
Dominant uncertainties (total 11%):

- statistical unc. in the CRs(9%)
- e→γ fake factor (6%)

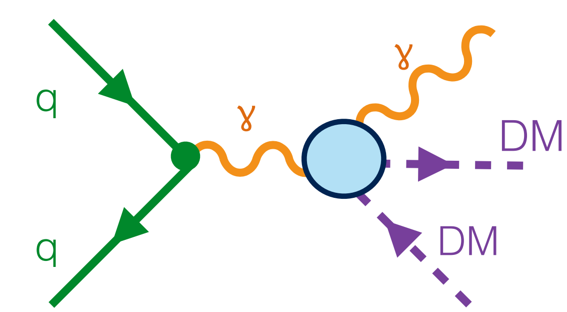


It excludes a subset of the monojet space.



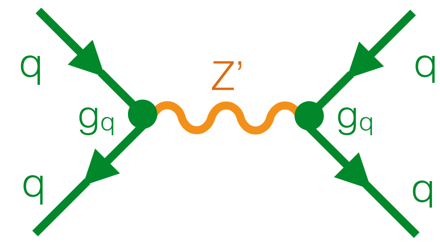


Sensitive to contact interaction of type γγχχ



Dijet (PLB 754 (2016) 302-322)

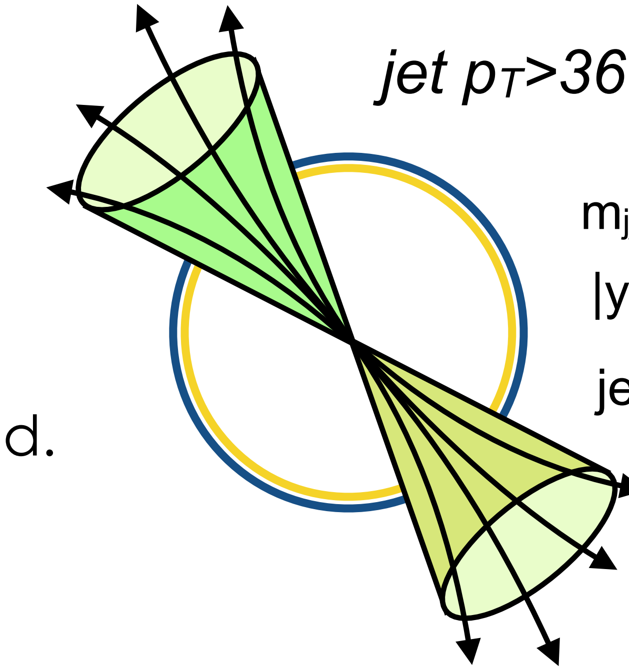
Mediator can decay back to quarks



➡ dijet signatures.

Limited by the single jet trigger threshold (m_{jj} ~1TeV).

A data-driven fit is performed to evaluate the background.



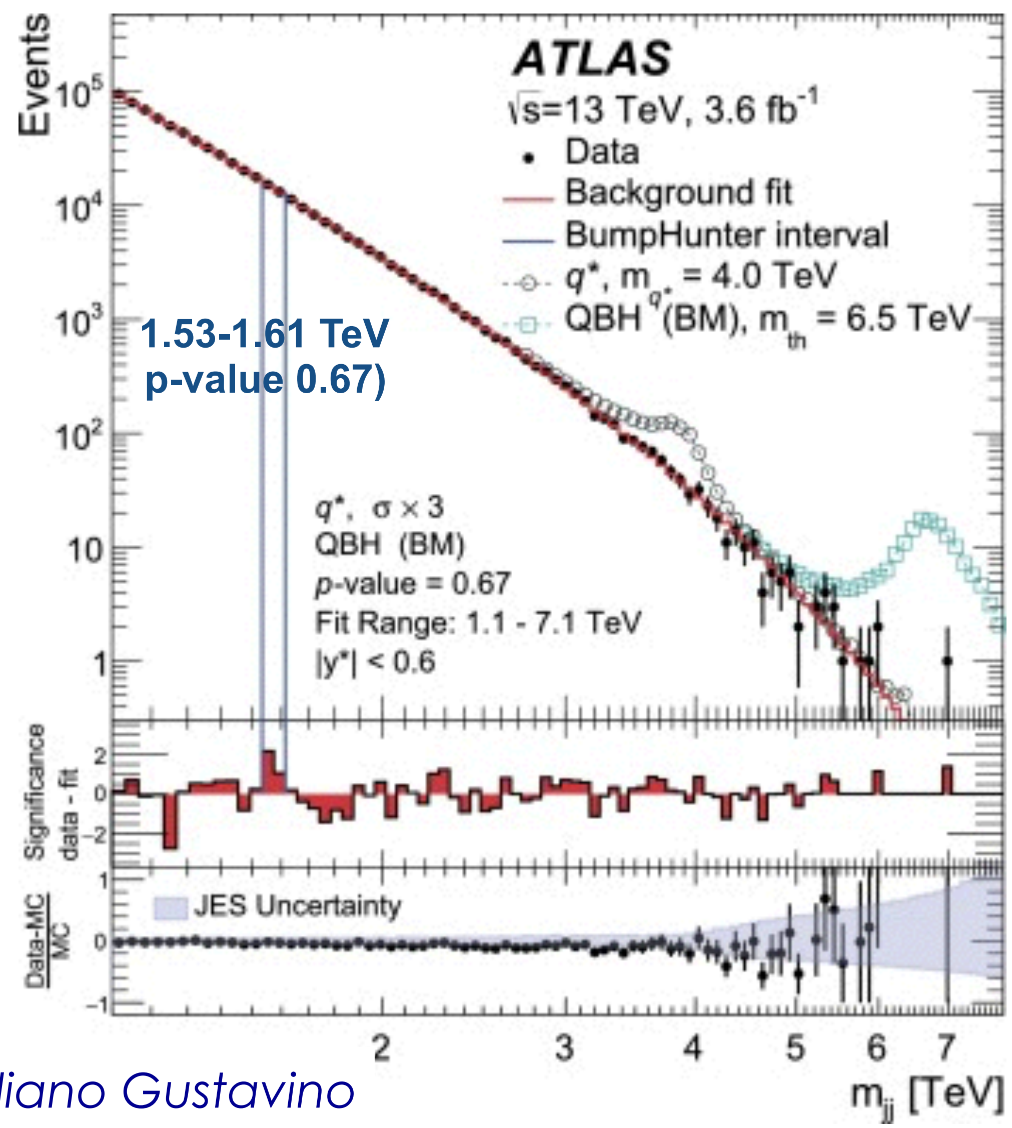
jet p_T>360GeV trigger

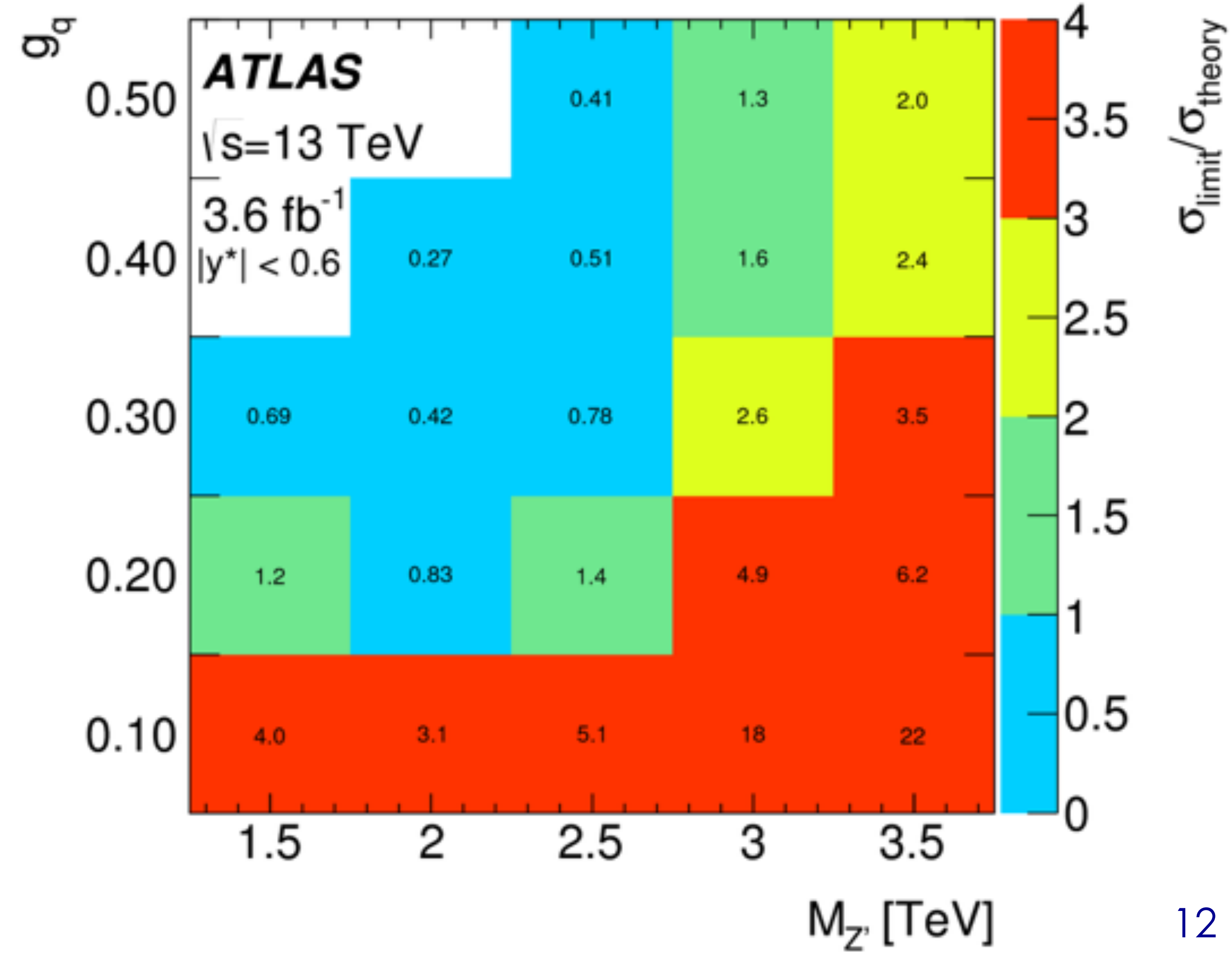
m_{jj}>1.1 TeV

$|y^*| = |y_1 - y_2|/2 < 0.6$

jet p_T > 440,50 GeV

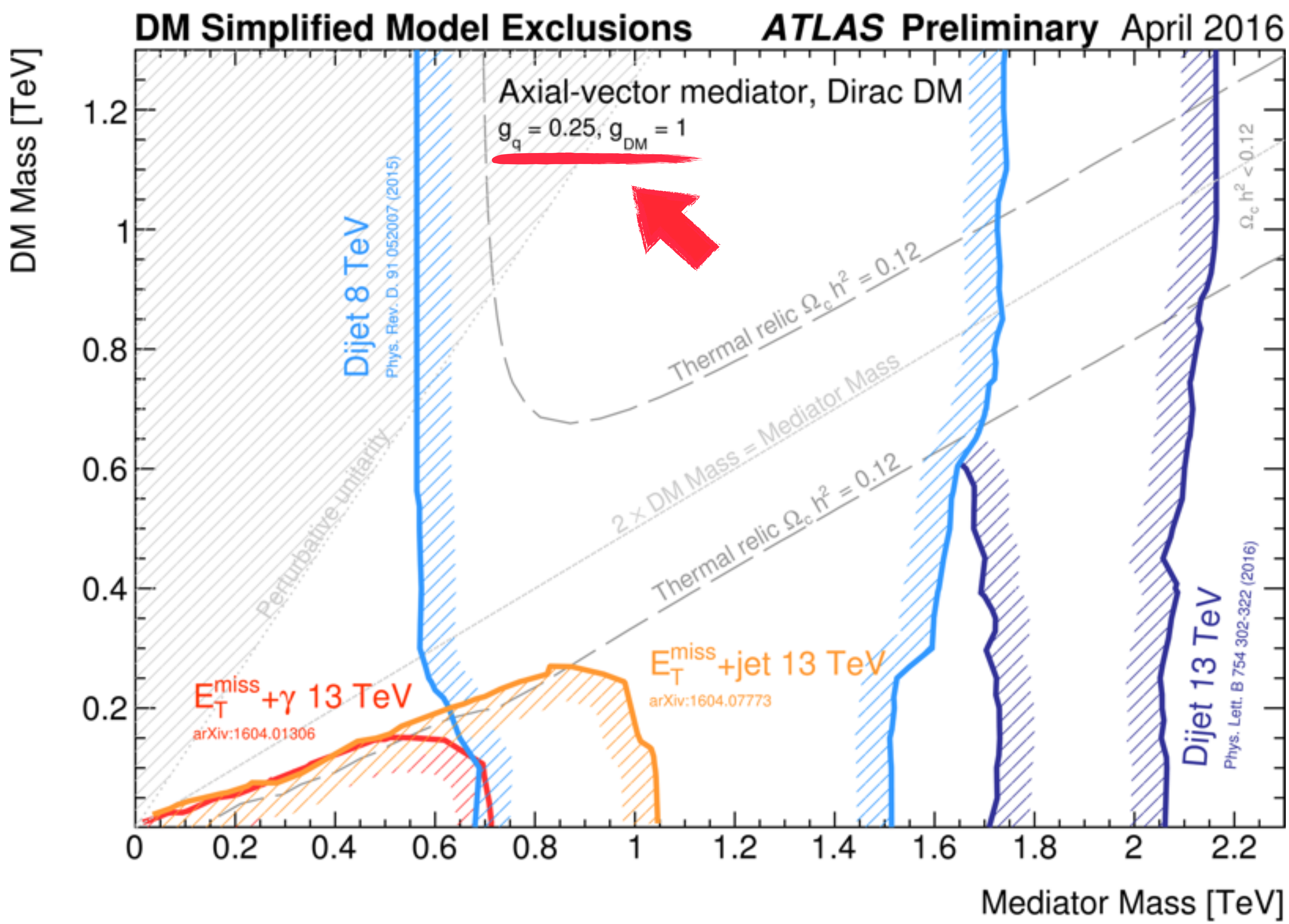
No relevant excesses are observed in the dijet mass distributions





Summary (few)DM LHC results

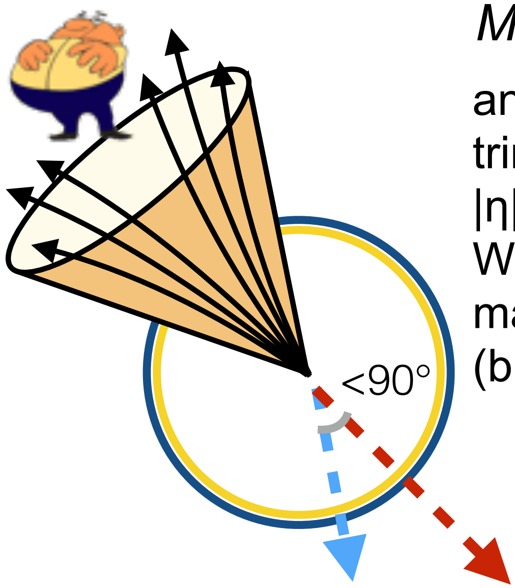
Link plot



Other channels, other models

Mono-W/Z hadronic

ATLAS-CONF-2015-080



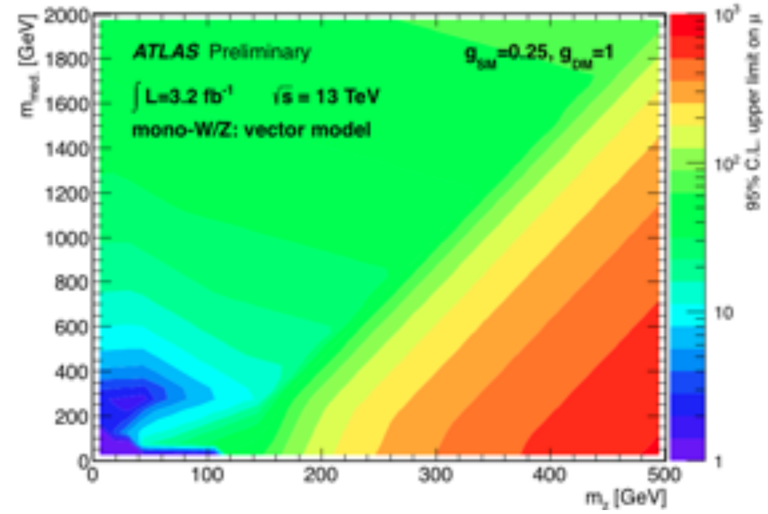
MET>80GeV trigger

anti-k_T R=1.0 jet with trimming, p_T>200GeV, |η|<2, tagging hadronic W/Z decay using jet mass & substructure (bifurcation variable D2)

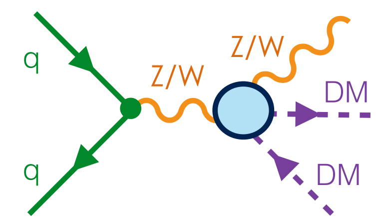
e & μ veto

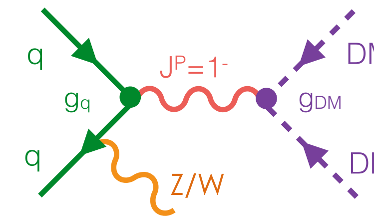
Track MET>30 GeV

MET>250 GeV

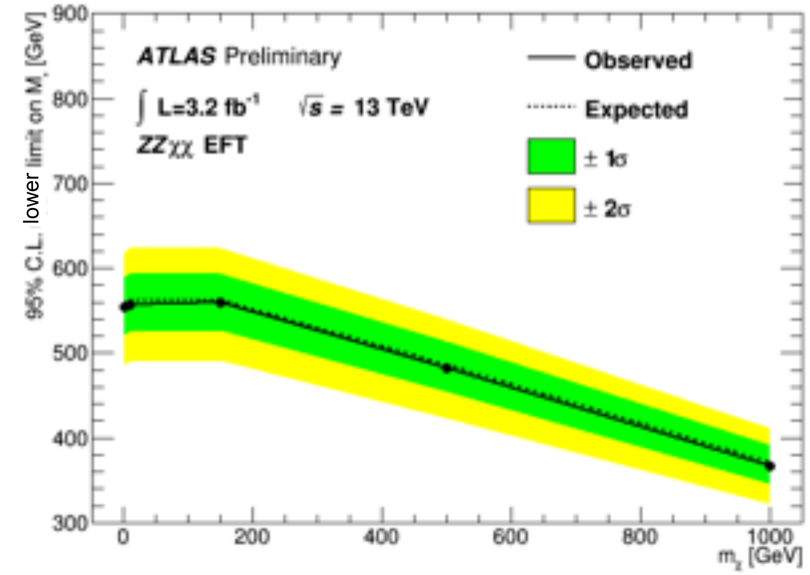


Sensitive to contact interaction of type ZZχχ





less sensitive wrt monojet



Mono-Higgs(bb)

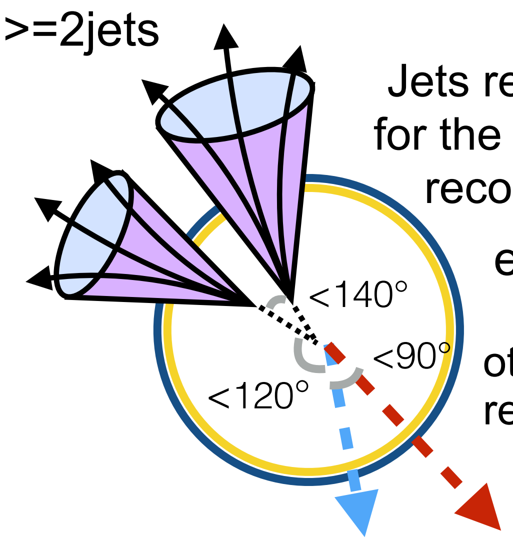
ATLAS-CONF-2016-019

resolved

MET>70GeV trigger

merged

>=2jets



Jets requirements for the higgs boson reconstruction

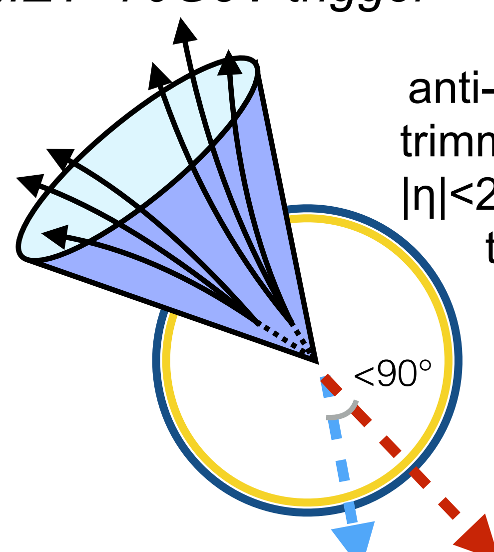
e & μ veto

other cuts to reject mutijet bkg

Track MET>30 GeV

METϵ[150,500] GeV

3 MET sub-regions: [150,200,350,500] GeV

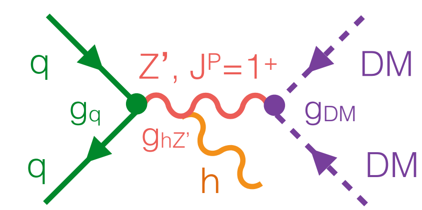


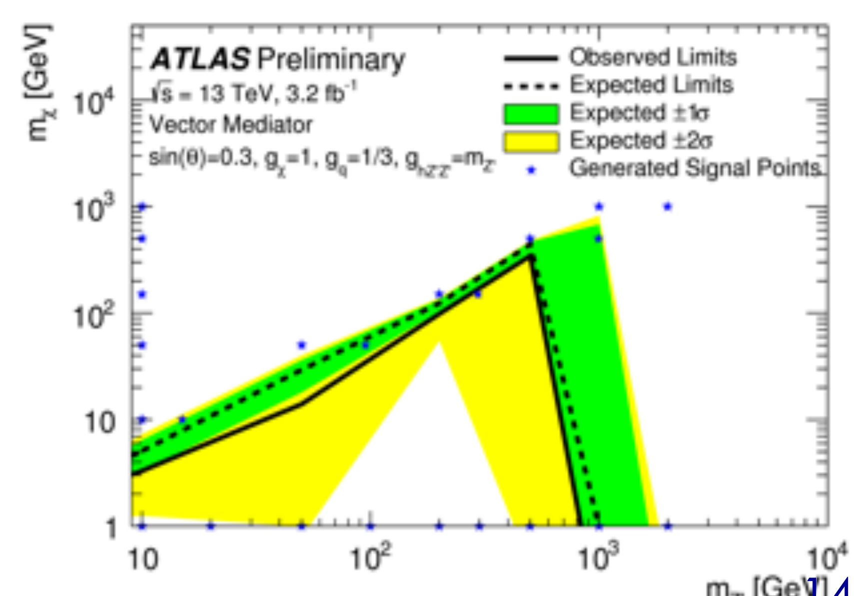
anti-k_T R=1.0 jet with trimming, p_T>200GeV, |η|<2, associated with two track jets

e & μ veto

MET>500 GeV

Track MET>30 GeV

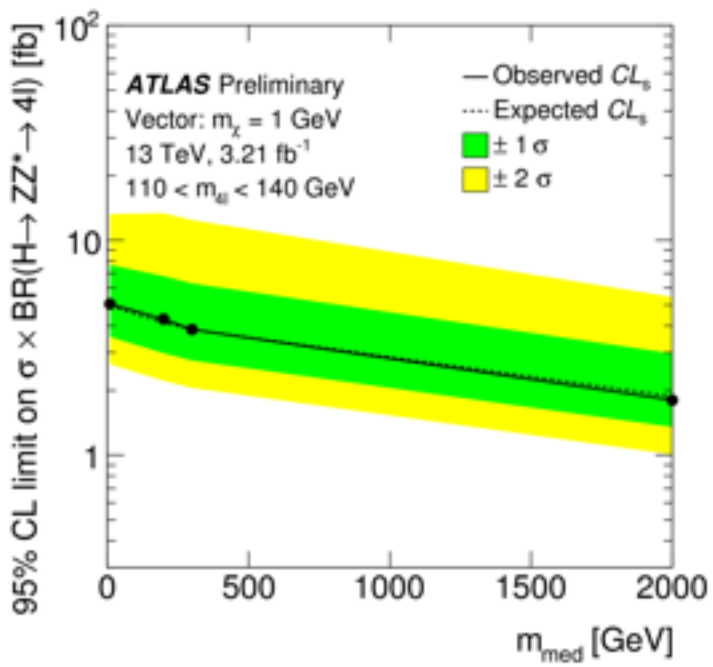




Other mono-X signatures

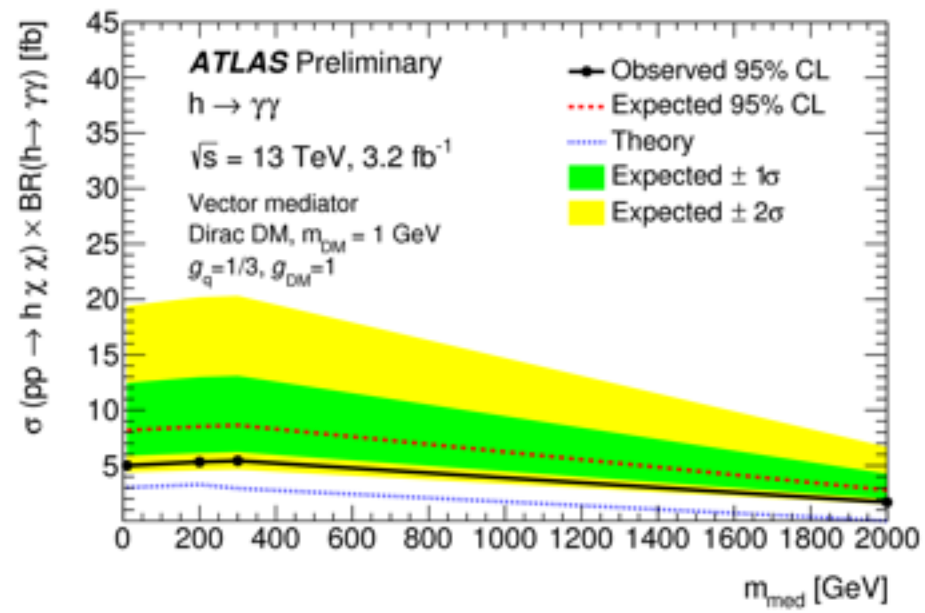
mono-Higgs(4l)

ATLAS-CONF-2015-059



mono-Higgs(γγ)

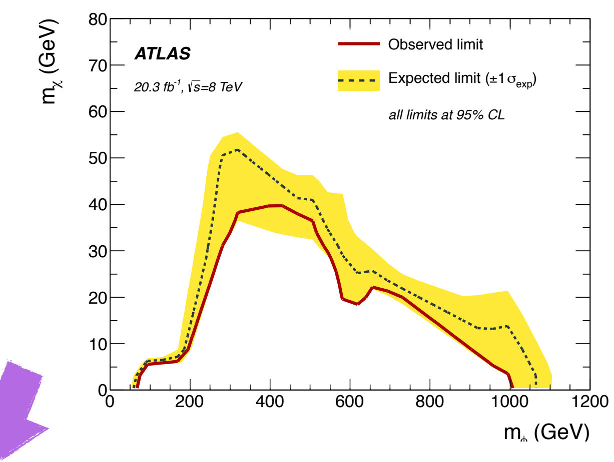
ATLAS-CONF-2016-011

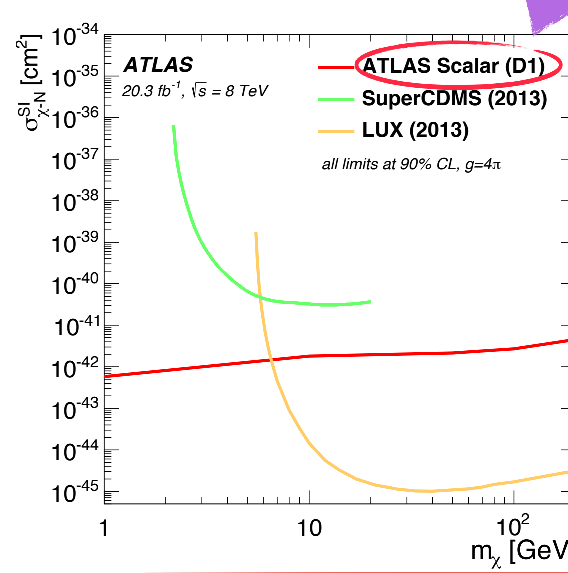


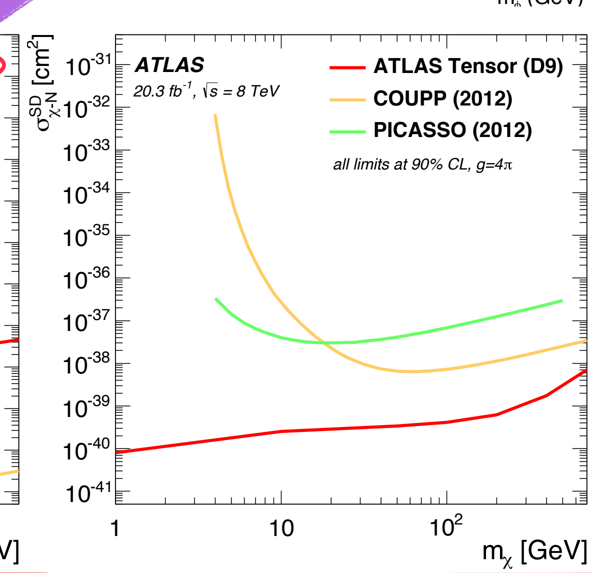
...

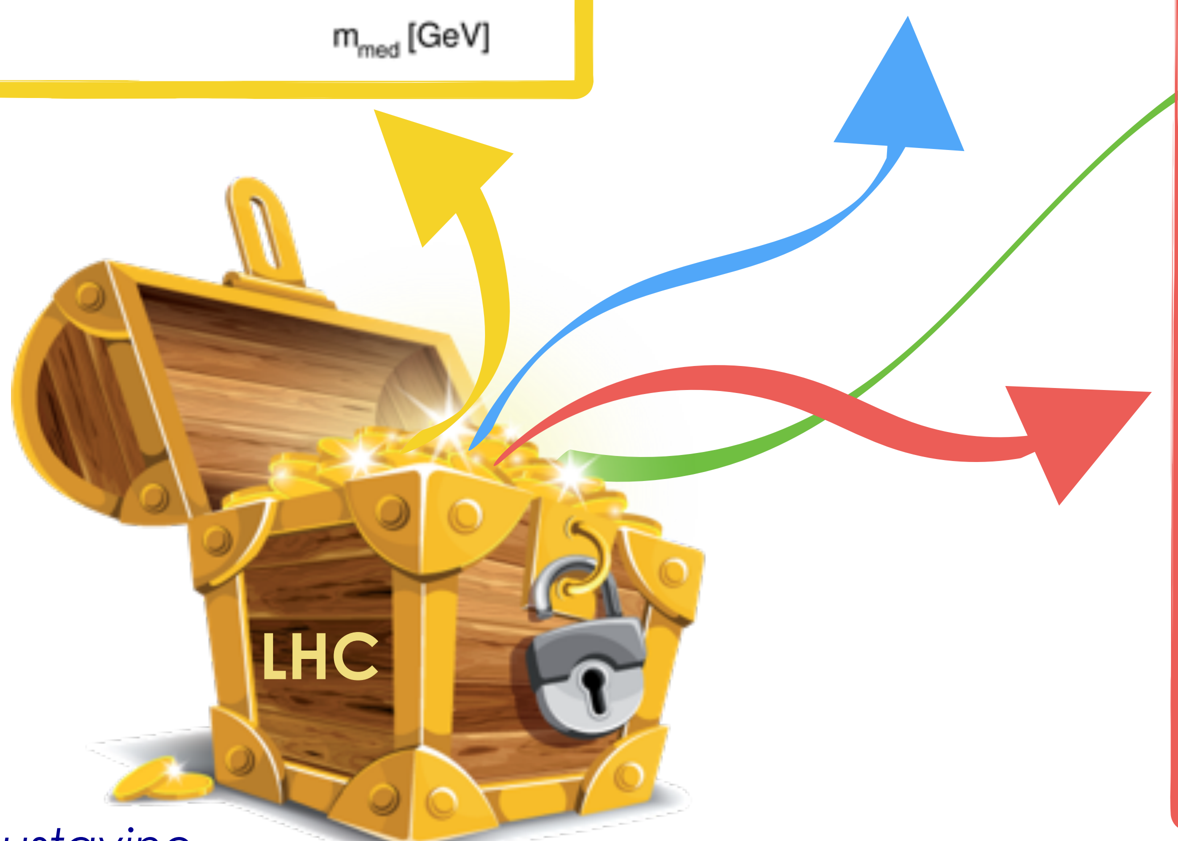
mono-HF (8TeV)

arXiv:1410.4031









Conclusions

Summary

DM searches at 13TeV have just started!

The harmonization between most of the analyses using a common set of simplified models allows to compare easily:

* mono-X and dijet searches;
* collider, direct and indirect detection experiment's results;
* particle physics and cosmological limits.

What next?

The data collection expected in the next year can:

* cover higher MET/jet p_T regimes
* open other scenarios (like pseudo-scalar mediators for monojet);
* reduce the statistical uncertainties;
* improve the sensitivity.

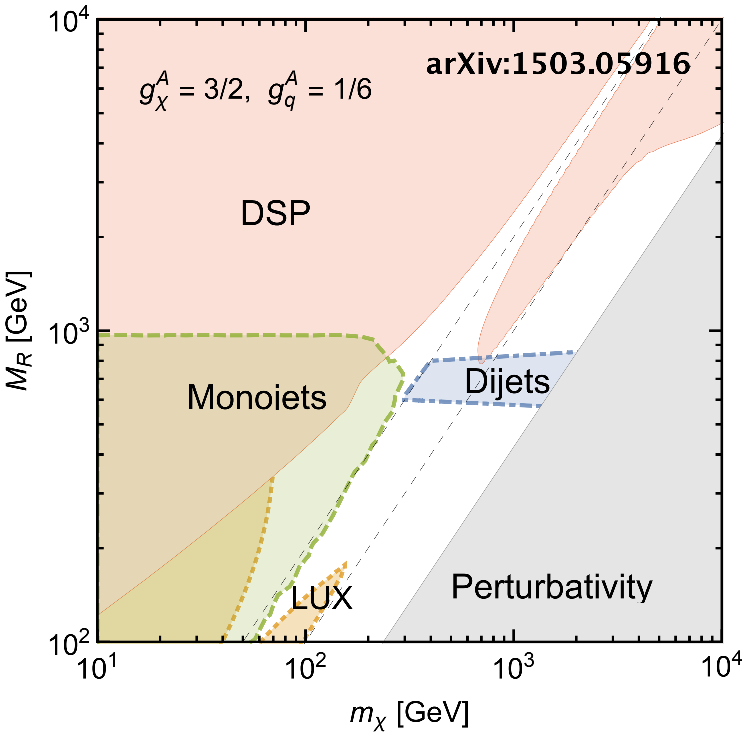
New ideas and new strategies to increase the discovery potential!

Challanges

A wide spectrum of parameters range is still unexplored (don't forget the coupling axis ;))!

Waiting also for new 13TeV results from

* mono-HF that looks for a set of models don't covered by the other mono-X analysis (scalar mediators and t-channels);
* Dijet data scouting could cover also the low mediator mass region quite independently from the DM mass!

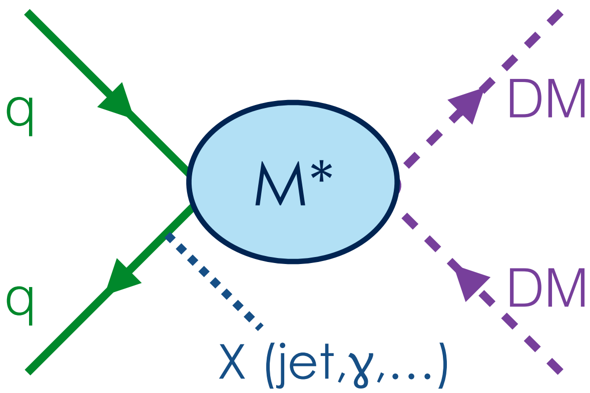


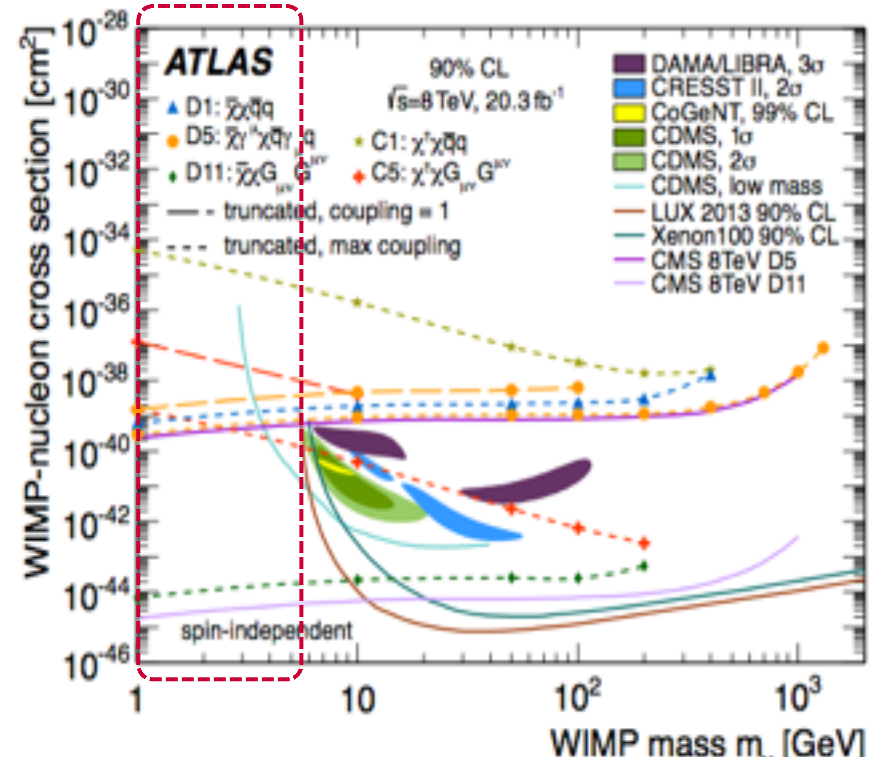
Backup Slides

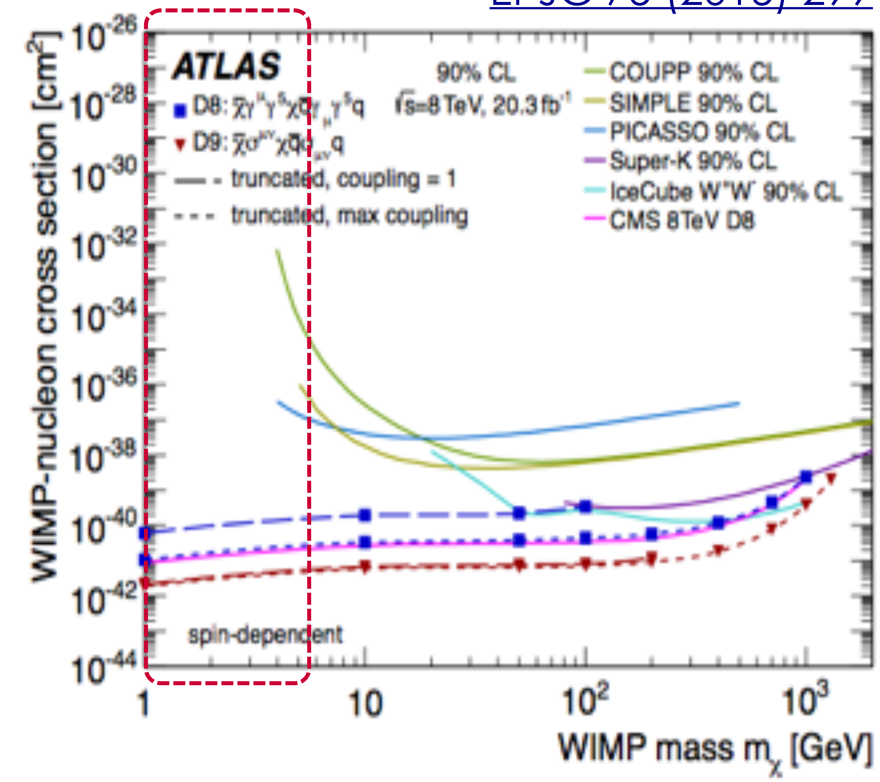
8TeV Monojet results

EPJC 75 (2015) 299

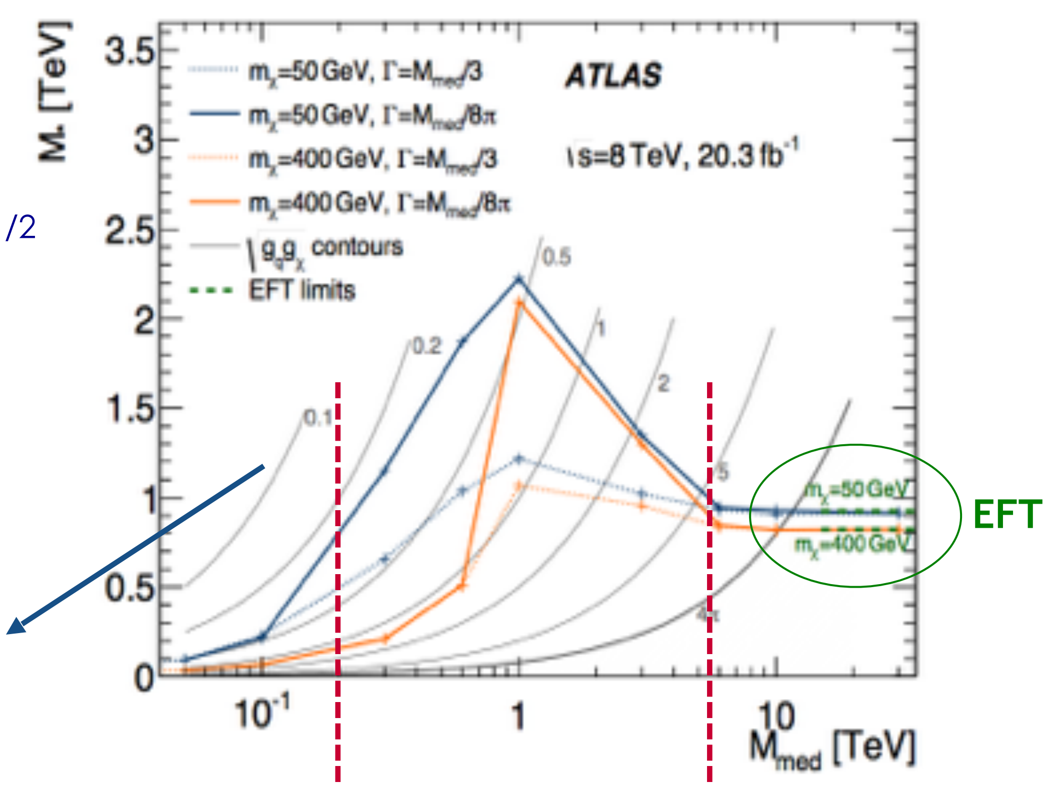
Limit on Spin independent and Spin dependent WIMP-nucleon interaction xsec





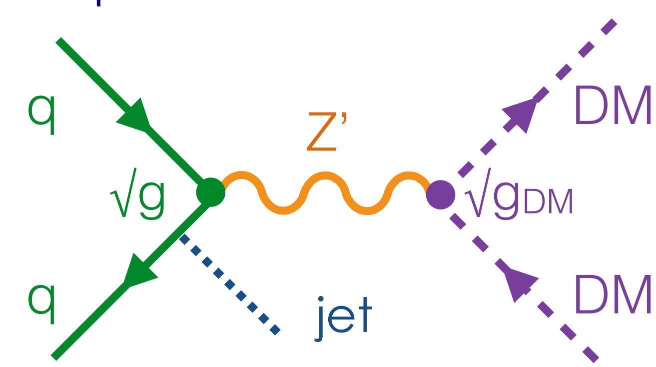


$$M^* = \frac{M_{med}}{(g_{SM} g_{DM})^{1/2}}$$



constant coupling contours

Limits on DM particles which couple to SM quarks via a Z' boson



EFT results optimistics

EFT results pessimistics

limit of high M_{med} is the EFT ($M_{med} >> \sqrt{s}$)

Simiplified Models (axial vector mediator)

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

$$\Gamma^{A}_{\text{min}} = \frac{g_\chi^2 M_{\text{med}}}{12\pi} \beta^3_{DM} \theta(M_{\text{med}} - 2m_\chi) + \sum_q \frac{3 g_q^2 M_{\text{med}}}{12\pi} \beta_q^3 \theta(M_{\text{med}} - 2m_q)$$

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{M_{\text{med}}^2}}$$

Width

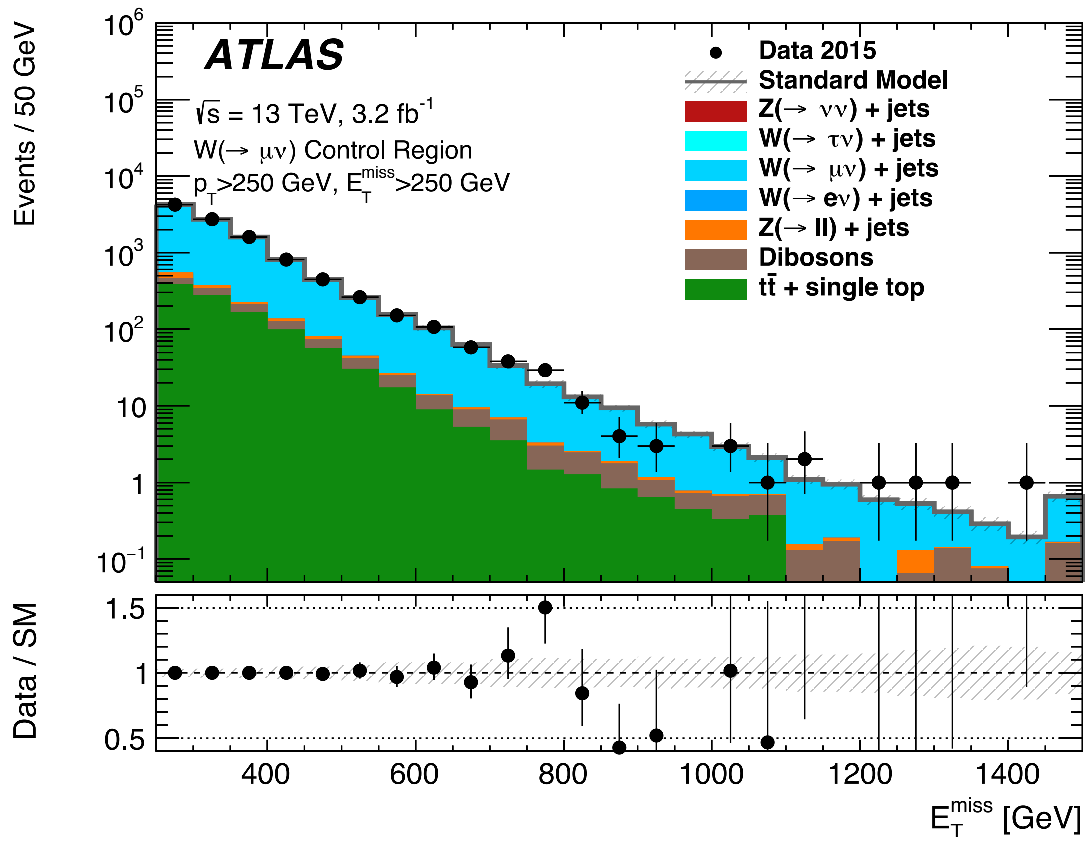
propagator ~ $\frac{1}{Q_{tr}^2 - \mathrm{M}_{\text{med}}^2 + i\mathrm{M}_{\text{med}}\Gamma}$

off-shell $Q_{tr} \gg \mathrm{M}_{\text{med}}$ → $\sigma \propto g_q^2 g_\chi^2$

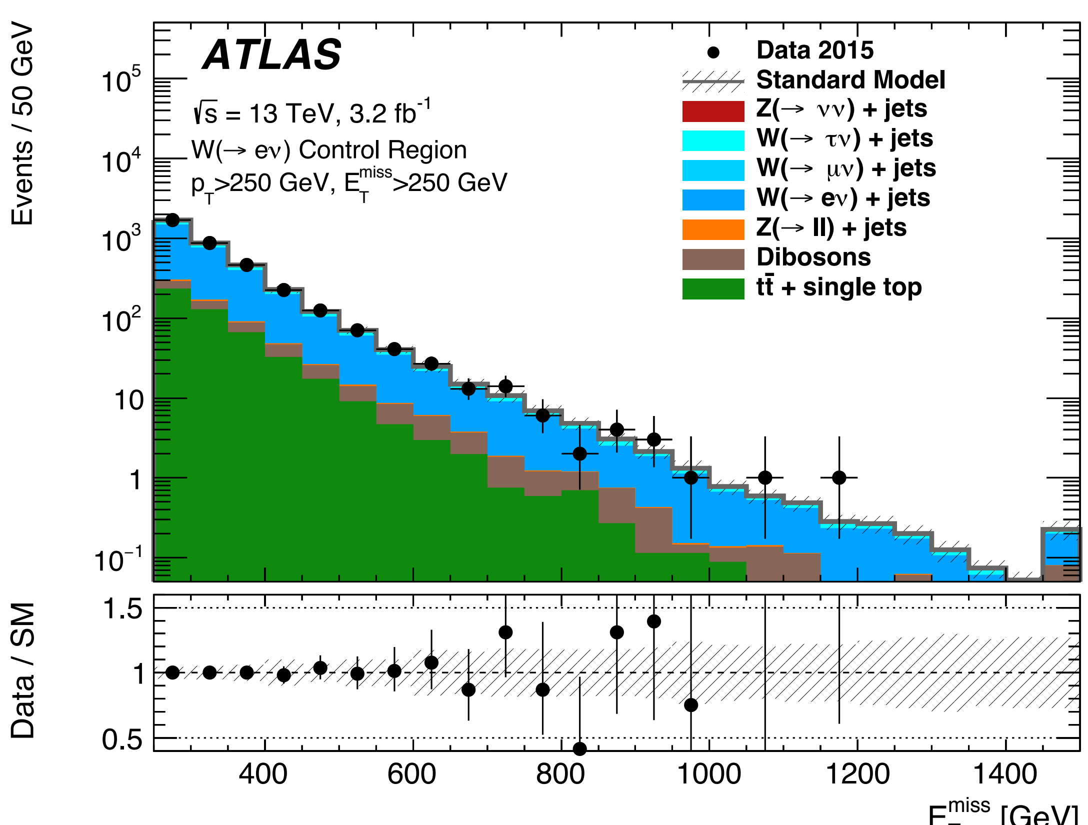
EFT $Q_{tr} \ll \mathrm{M}_{\text{med}}$ → $\sigma \propto g_q^2 g_\chi^2$

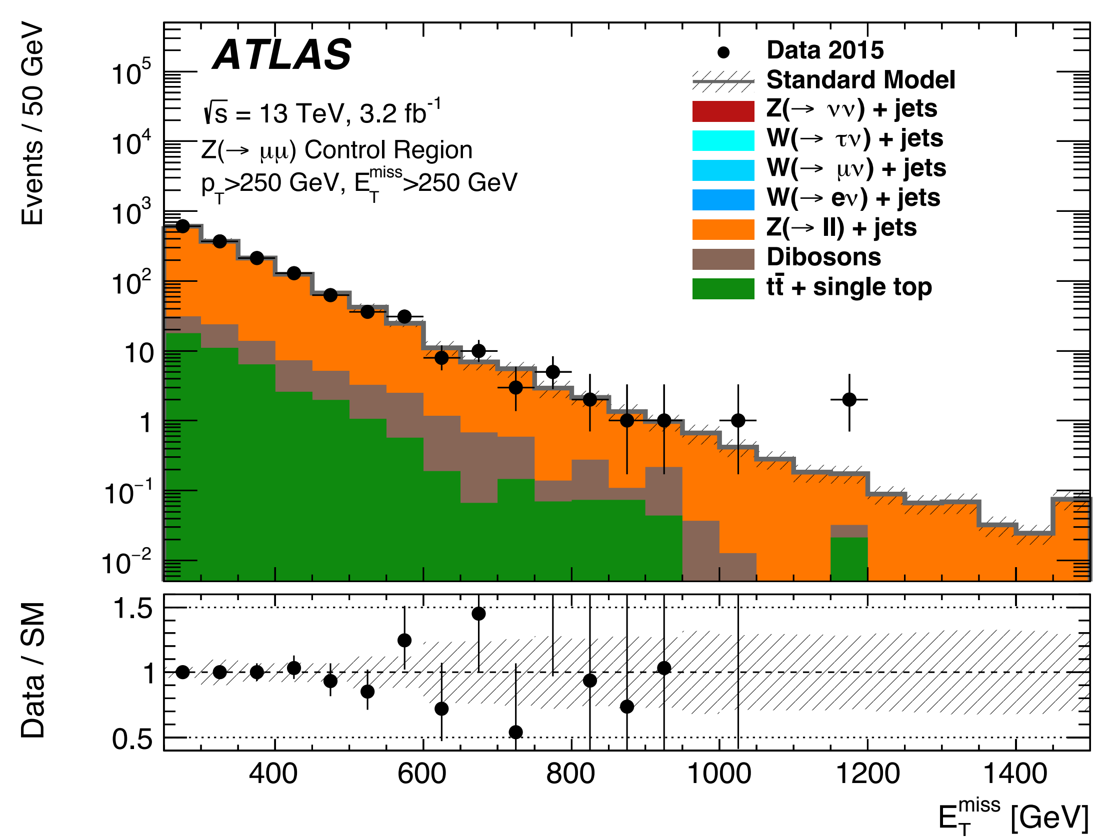
on-shell $Q_{tr} \sim \mathrm{M}_{\text{med}}$ → $\sigma \propto \frac{g_q^2 g_\chi^2}{\Gamma}$

Monojet Control Regions



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





Monojet results

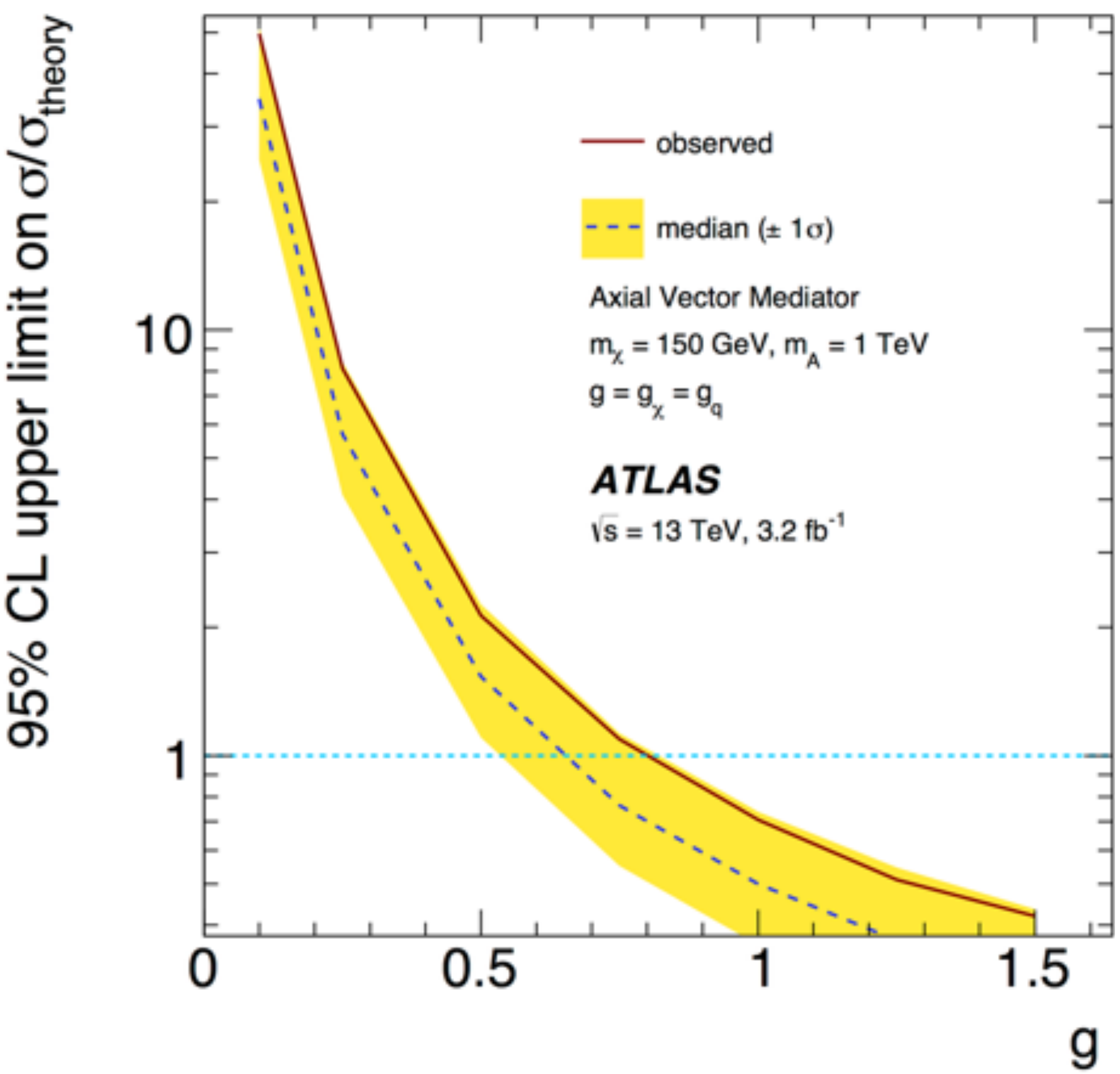
250 GeV < MET < 300 GeV

EM1	SR	$W(\to e\nu)$	$W(\to \mu\nu)$	$Z(\to \mu\mu)$
Observed events (3.2 fb^{-1})	9472	1693	4202	611
SM prediction (post-fit)	9400 ± 410	1693 ± 41	4202 ± 65	611 ± 25
Fitted $W(\to e\nu)$	859 ± 86	1176 ± 70	0.3 ± 0.1	–
Fitted $W(\to \mu\nu)$	930 ± 66	1 ± 0.2	3480 ± 130	0.6 ± 0.1
Fitted $W(\to \tau\nu)$	1910 ± 170	210 ± 13	177 ± 12	0.06 ± 0.03
Fitted $Z(\to ee)$	0.01 ± 0.01	0.3 ± 0.1	–	–
Fitted $Z(\to \mu\mu)$	36 ± 12	$0.05^{+0.04}_{-0.05}$	74 ± 8	579 ± 25
Fitted $Z(\to \tau\tau)$	24 ± 5	16 ± 2	11 ± 4	0.06 ± 0.02
Fitted $Z(\to \nu\nu)$	5050 ± 270	0.8 ± 0.1	0.6 ± 0.1	–
Expected $t\bar{t}$, single top	350 ± 110	235 ± 70	390 ± 120	18 ± 5
Expected dibosons	154 ± 13	54 ± 4	70 ± 7	13 ± 2
Multijets	22 ± 22	–	–	–
NCB	61 ± 61	–	–	–
MC exp. SM events	9620 ± 580	1880 ± 150	4140 ± 260	610 ± 42
Fit input $W(\to e\nu)$	971 ± 74	1329 ± 98	0.3 ± 0.1	–
Fit input $W(\to \mu\nu)$	908 ± 65	1 ± 0.2	3390 ± 190	0.6 ± 0.1
Fit input $W(\to \tau\nu)$	2160 ± 170	238 ± 18	200 ± 14	0.06 ± 0.03
Fit input $Z(\to ee)$	0.01 ± 0.01	0.3 ± 0.1	–	–
Fit input $Z(\to \mu\mu)$	35 ± 12	$0.05^{+0.04}_{-0.05}$	74 ± 9	579 ± 41
Fit input $Z(\to \tau\tau)$	27 ± 5	18 ± 2	13 ± 4	0.07 ± 0.02
Fit input $Z(\to \nu\nu)$	4930 ± 320	0.8 ± 0.1	0.6 ± 0.1	–
Fit input $t\bar{t}$, single top	350 ± 110	235 ± 72	390 ± 120	18 ± 5
Fit input dibosons	154 ± 14	54 ± 5	70 ± 7	13 ± 2
Multijets	22 ± 22	–	–	–
NCB	61 ± 61	–	–	–

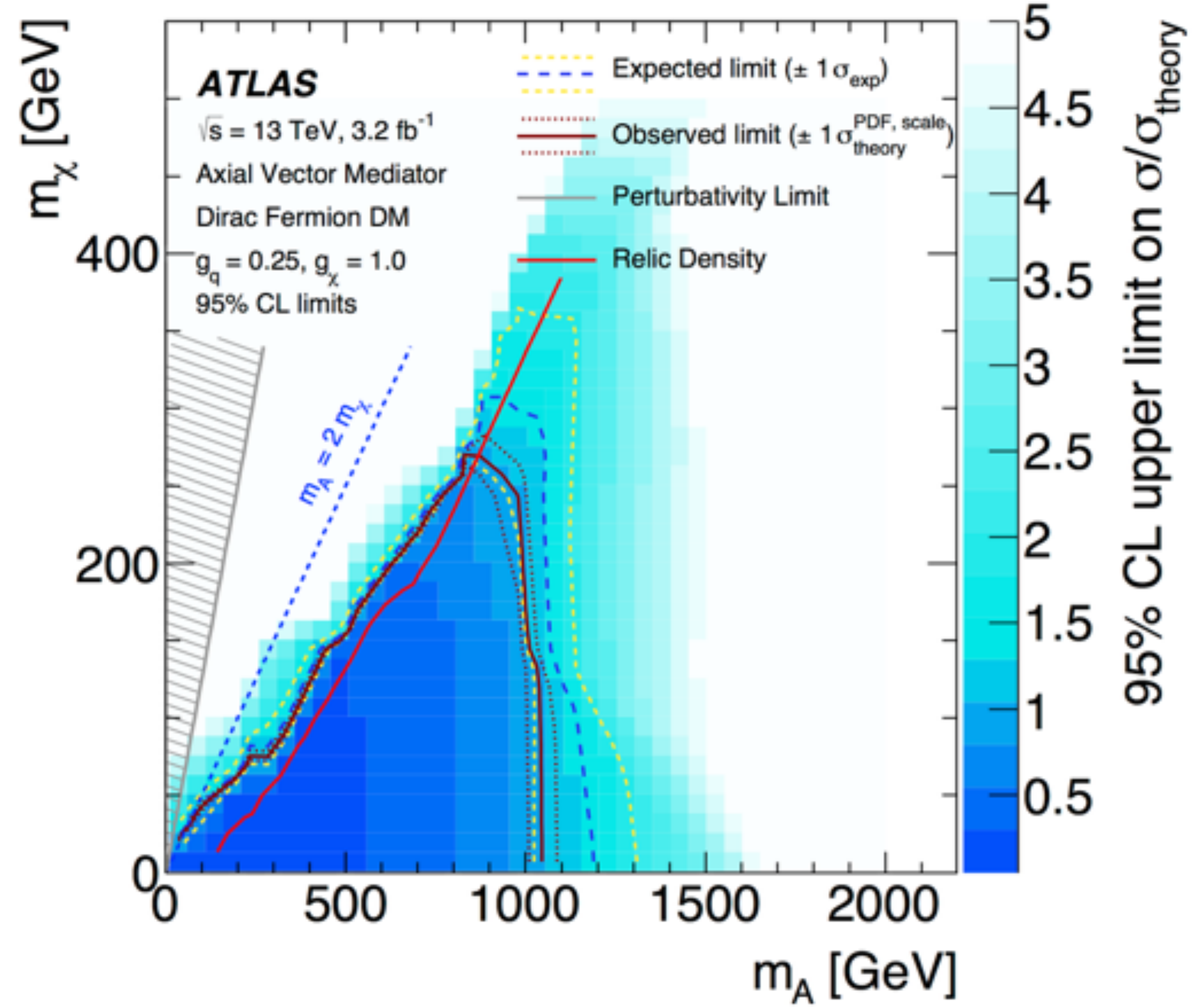
MET > 700 GeV

EM7	SR	$W(\to e\nu)$	$W(\to \mu\nu)$	$Z(\to \mu\mu)$
Observed events (3.2 fb^{-1})	185	32	95	15
SM prediction (post-fit)	166 ± 20	32 ± 6	95 ± 10	15 ± 4
Fitted $W(\to e\nu)$	7 ± 2	21 ± 5	–	–
Fitted $W(\to \mu\nu)$	11 ± 2	0.05 ± 0.01	71 ± 11	0.01 ± 0
Fitted $W(\to \tau\nu)$	19 ± 4	5 ± 1	5 ± 1	0.01 ± 0
Fitted $Z(\to ee)$	–	–	–	–
Fitted $Z(\to \mu\mu)$	2 ± 1	–	1.1 ± 0.3	14 ± 4
Fitted $Z(\to \tau\tau)$	0.2 ± 0.1	0.16 ± 0.04	0.17 ± 0.04	0.02 ± 0.01
Fitted $Z(\to \nu\nu)$	109 ± 18	0.05 ± 0.01	0.01 ± 0	–
Expected $t\bar{t}$, single top	3 ± 1	3 ± 1	9 ± 4	0.4 ± 0.2
Expected dibosons	15 ± 2	3.5 ± 0.3	9 ± 2	1 ± 0.3
Multijets	0.4 ± 0.4	–	–	–
NCB	–	–	–	–
MC exp. SM events	186 ± 15	34 ± 3	106 ± 9	13 ± 1
Fit input $W(\to e\nu)$	8 ± 1	23 ± 2	–	–
Fit input $W(\to \mu\nu)$	12 ± 2	0.06 ± 0.01	81 ± 7	0.01 ± 0
Fit input $W(\to \tau\nu)$	21 ± 2	5 ± 0.4	5 ± 1	0.01 ± 0
Fit input $Z(\to ee)$	–	–	–	–
Fit input $Z(\to \mu\mu)$	1.5 ± 0.4	–	0.9 ± 0.1	11 ± 1
Fit input $Z(\to \tau\tau)$	0.22 ± 0.03	0.18 ± 0.01	0.19 ± 0.02	0.02 ± 0
Fit input $Z(\to \nu\nu)$	125 ± 12	0.06 ± 0.01	0.01 ± 0	–
Fit input $t\bar{t}$, single top	3 ± 1	3 ± 1	9 ± 4	0.4 ± 0.2
Fit input dibosons	15 ± 2	3.5 ± 0.3	9 ± 2	1 ± 0.3
Multijets	0.4 ± 0.4	–	–	–
NCB	–	–	–	–

Monojet Limits



Mono-jet limits with fixed mediator & DM mass and variable coupling

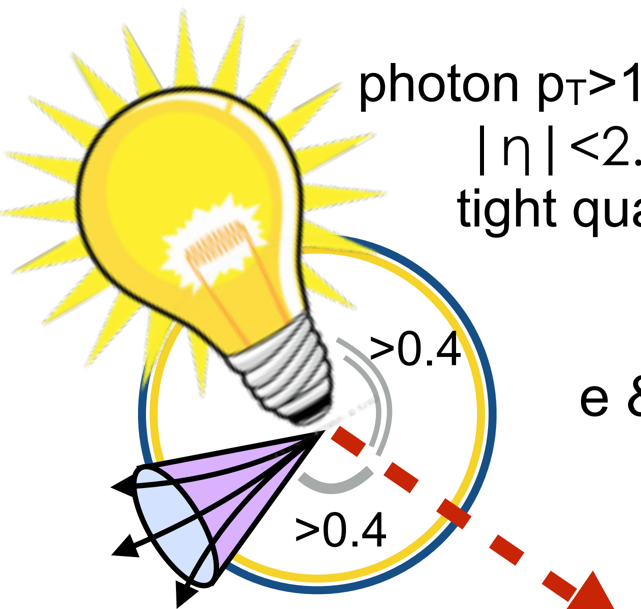


Contour Limit in the 3D plot with DM vs Mediator mass vs μ UL @95%

Mono-photon (arXiv:1604.01306)

Photon p_T>120GeV trigger SR

photon p_T>150GeV, |η|<2.37, tight quality



e & μ veto

An additional jet is permitted (p_T>30GeV)

MET>150 GeV

4 control regions are defined:

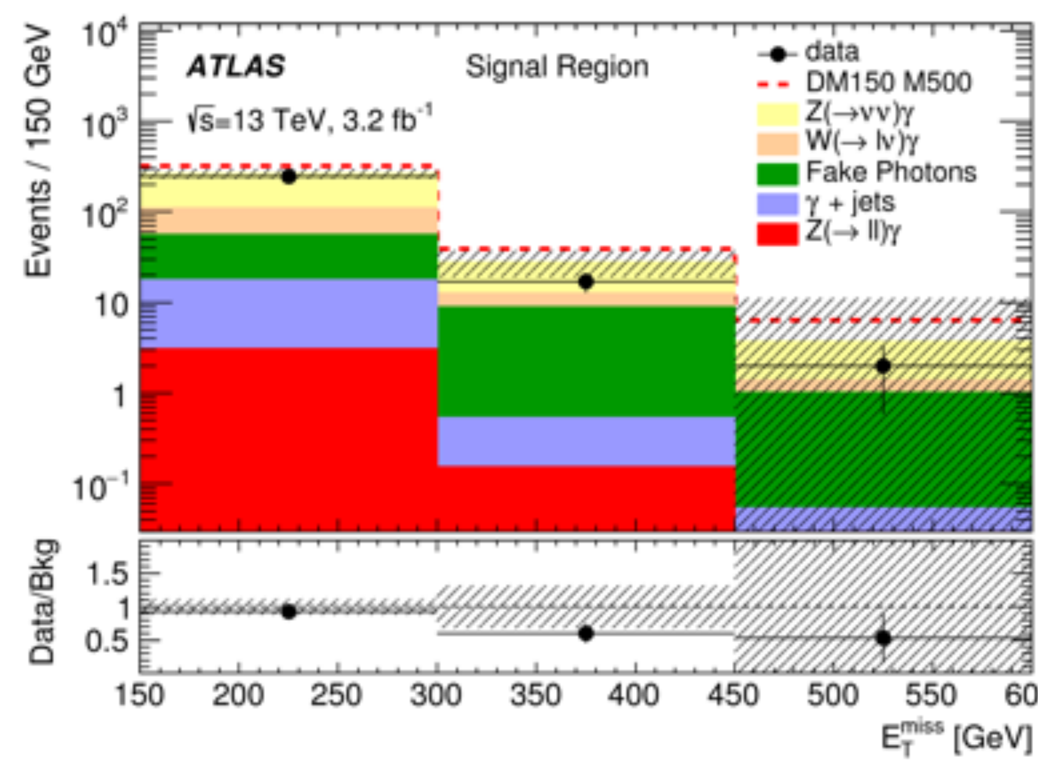
- 2μ and 2e CRs ➡ Z+γ
- 1μ CR ➡ W+γ
- γ+jet CR (85 < MET < 110 GeV, Δϕ(MET,γ)<3.0) ➡ γ+jet
- fake γs evaluated from
  - electrons using e→γ misID factor in ee vs eγ events,
  - jets with an ABCD method using photon quality & isolation.

A simultaneous fit between the inclusive regions is performed.

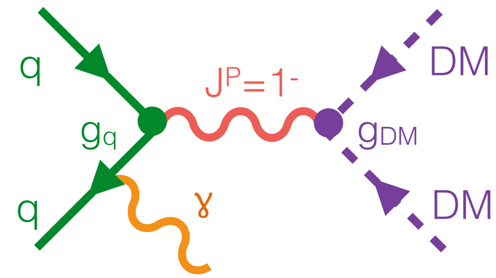
Dominant uncertainties (total 11%):

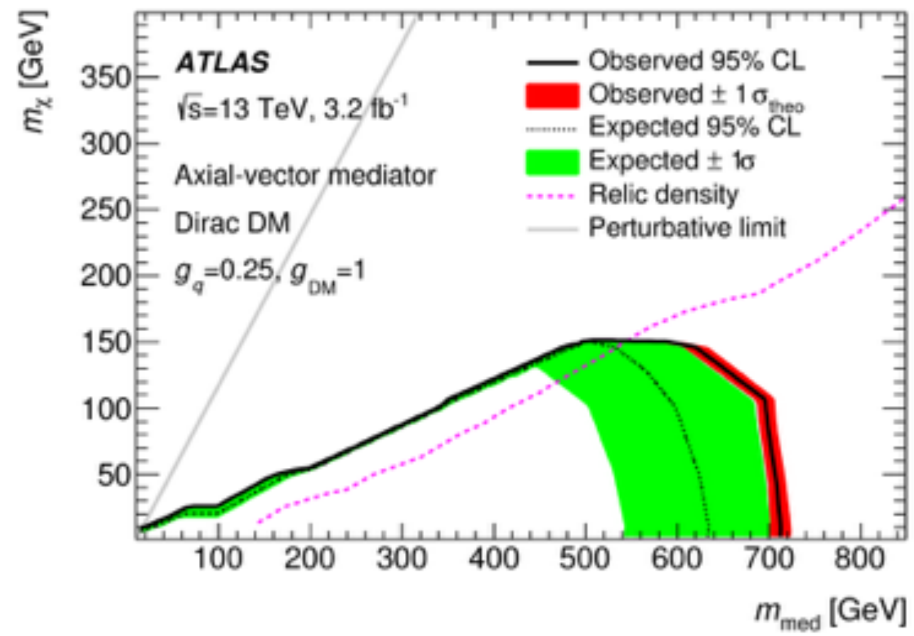
- statistical unc. in the CRs(9%)
- e→γ fake factor (6%)

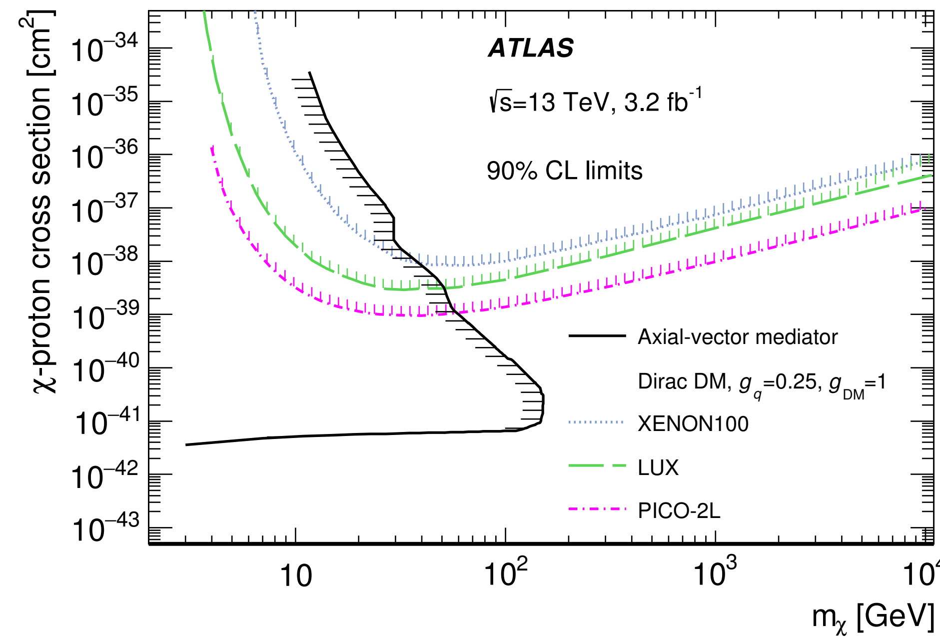
	SR	1muCR	2muCR	2eleCR	PhJetCR
Observed events	264	145	29	20	214
Fitted Background	295±34	145±12	27±4	23±3	214±15
$Z(\to\nu\nu)\gamma$	171±29	0.15±0.03	0.00±0.00	0.00±0.00	8.6±1.4
$W(\to\ell\nu)\gamma$	58±9	119±17	0.14±0.04	0.11±0.03	22±4
$Z(\to\ell\ell)\gamma$	3.3±0.6	7.9±1.3	26±4	20±3	1.2±0.2
$\gamma+$jets	15±4	0.7±0.5	0.00±0.00	0.03±0.03	166±17
Fake photons from electrons	22±18	1.7±1.5	0.05±0.05	0.00±0.00	5.8±5.1
Fake photons from jets	26±12	16±11	1.1±0.8	2.5±1.3	9.9±3.1
Pre-fit background	249±29	105±14	23±2	19±2	209±50



Mono-photon (results)

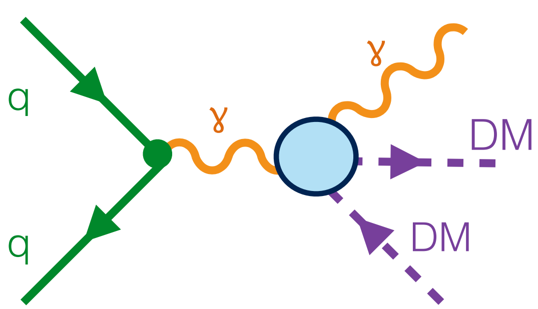




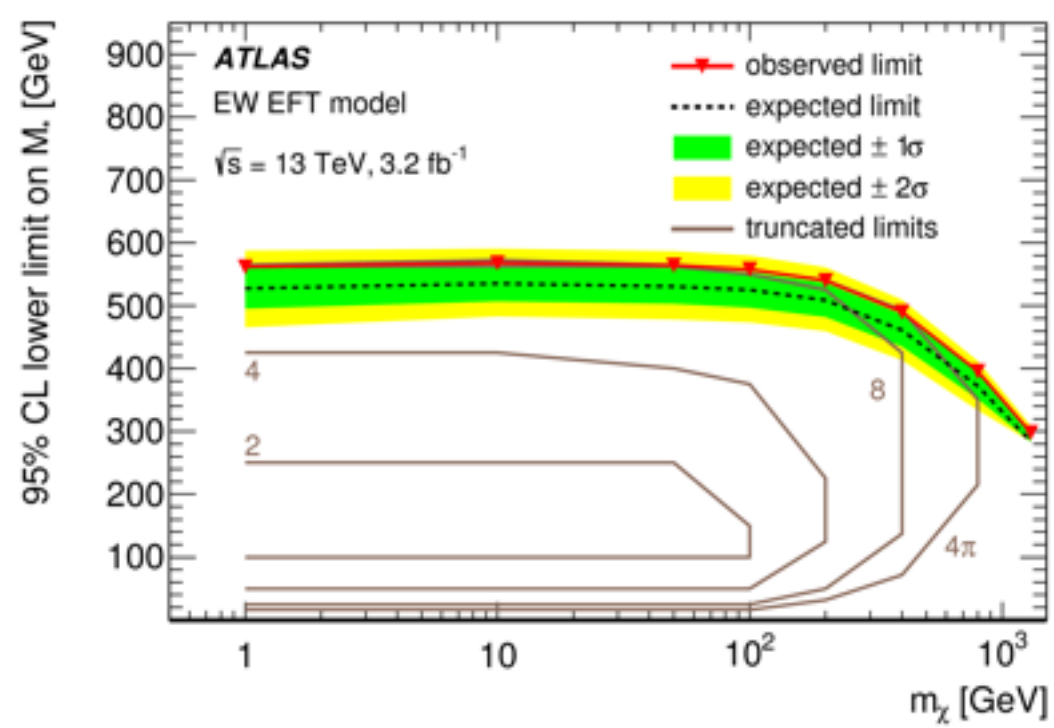


Results interpreted in the same simplified model used in monojet:

it excludes a subset of the monojet space.



Limit on the suppression scale M* for the EFT model with a contact interaction of type $\gamma\gamma\chi\chi$ as a function of the DM mass.



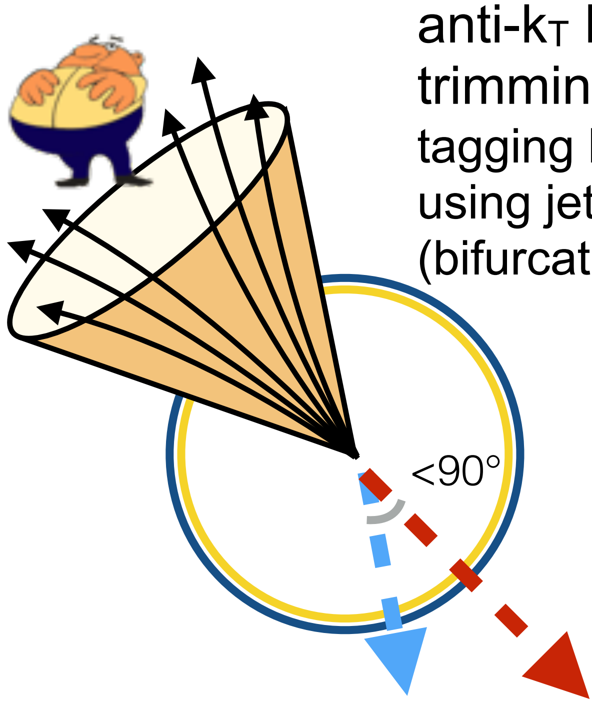
The EFT is not always valid, so a truncation procedure is applied:
events having a centre-of-mass energy larger than $M_{CUT}=g^*M_*$ are removed and the limit is recomputed.

Mono-W/Z hadronic (ATLAS-CONF-2015-080)

SR

MET>80GeV trigger

anti-k_T R=1.0 jet with trimming, p_T>200GeV, |η|<2, tagging hadronic W/Z decay using jet mass & substructure (bifurcation variable D2)



e & μ veto

MET>250 GeV

Track MET>30 GeV

3 control regions are defined:

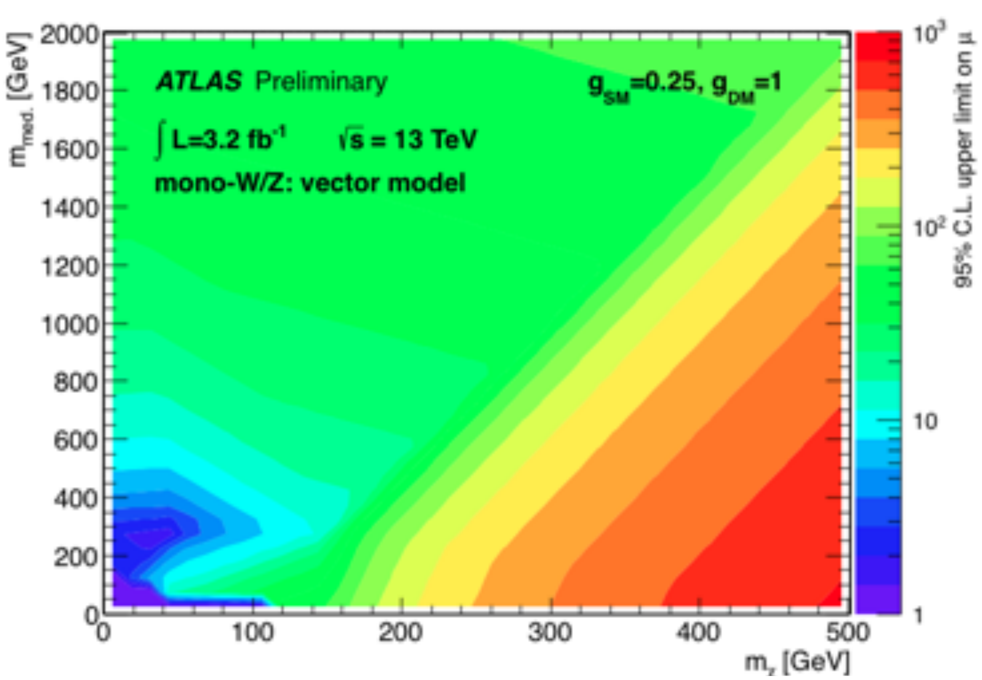
- 2μ CR ➡ Z+jets,
- 1μ & no b-jet CR ➡ W+jets,
- 1μ & >= 1b-jet CR ➡ ttbar.

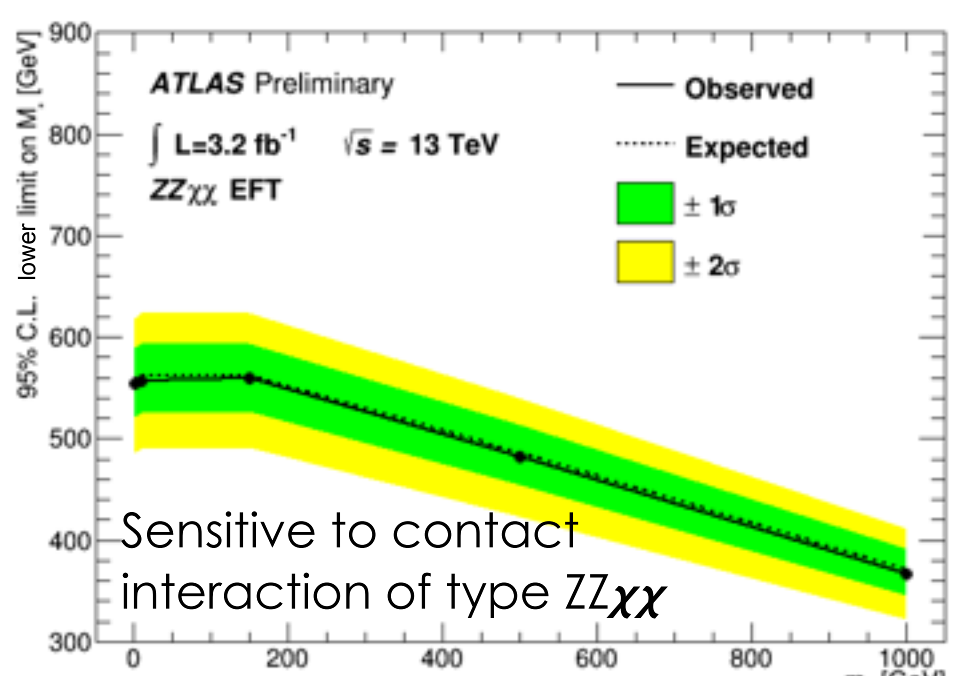
Diboson and single top from MC.

A (track)MET shape fit is performed in the (CRs)SR.

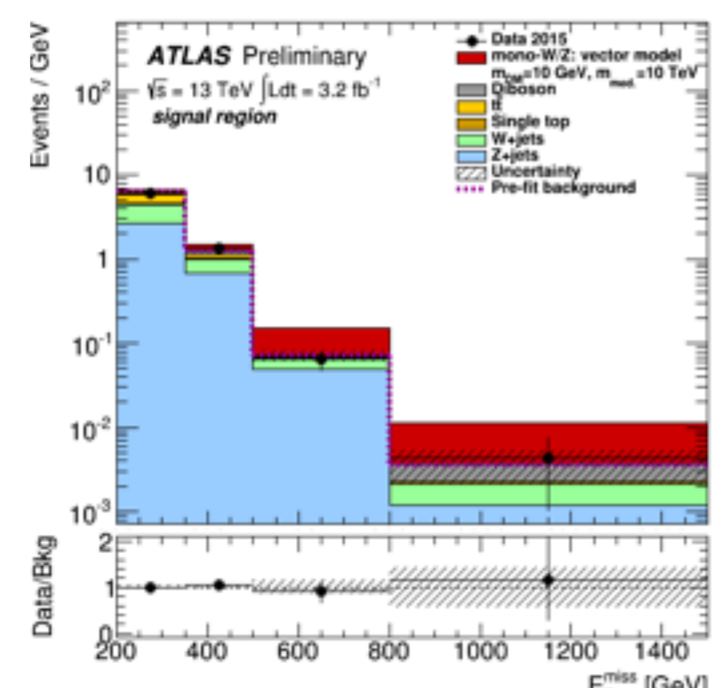
The main systematics are given by the modeling of large-R parameters (D2 variable and mass) with a 5-10% of the total background.

1143 events are observed in agreement with the expectations 1150+/-30.

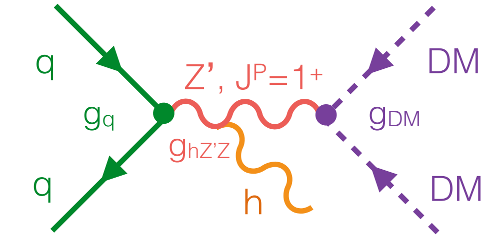




Sensitive to contact interaction of type $ZZ\chi\chi$

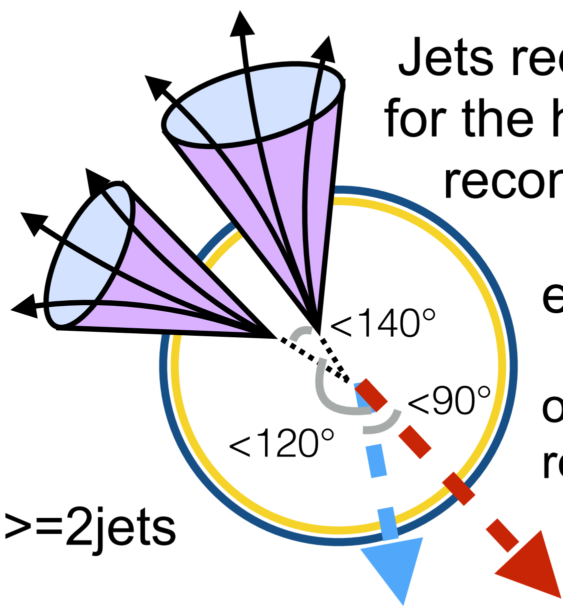


Mono-Higgs($b\bar{b}$) (ATLAS-CONF-2016-019)



SR

resolved



Jets requirements for the higgs boson reconstruction

e & μ

other cuts to reject mutijet bkg

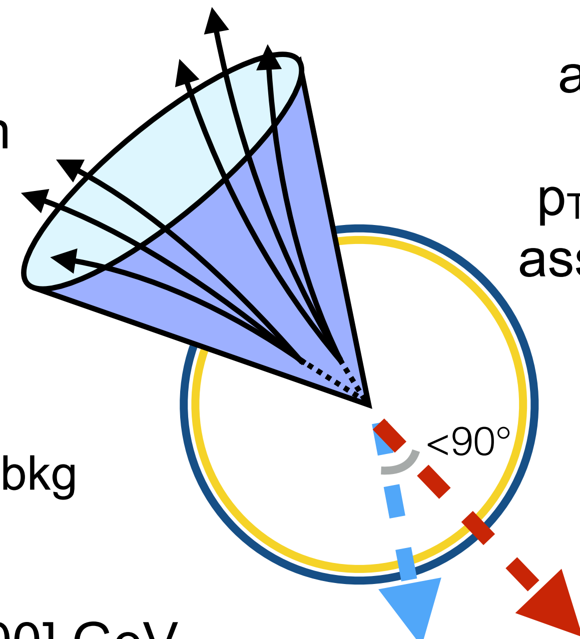
>=2jets

Track MET>30 GeV

MET∈[150,500] GeV

3 MET sub-regions: [150,200,350,500] GeV

merged *MET>70GeV trigger*



anti-k_T R=1.0 jet with trimming, p_T>200GeV, |η|<2, associated with two track jets

e & μ

MET>500 GeV

Track MET>30 GeV

2 signal regions: resolved & merged.

3 categories: 0,1,2 b-tags.

2 control regions:

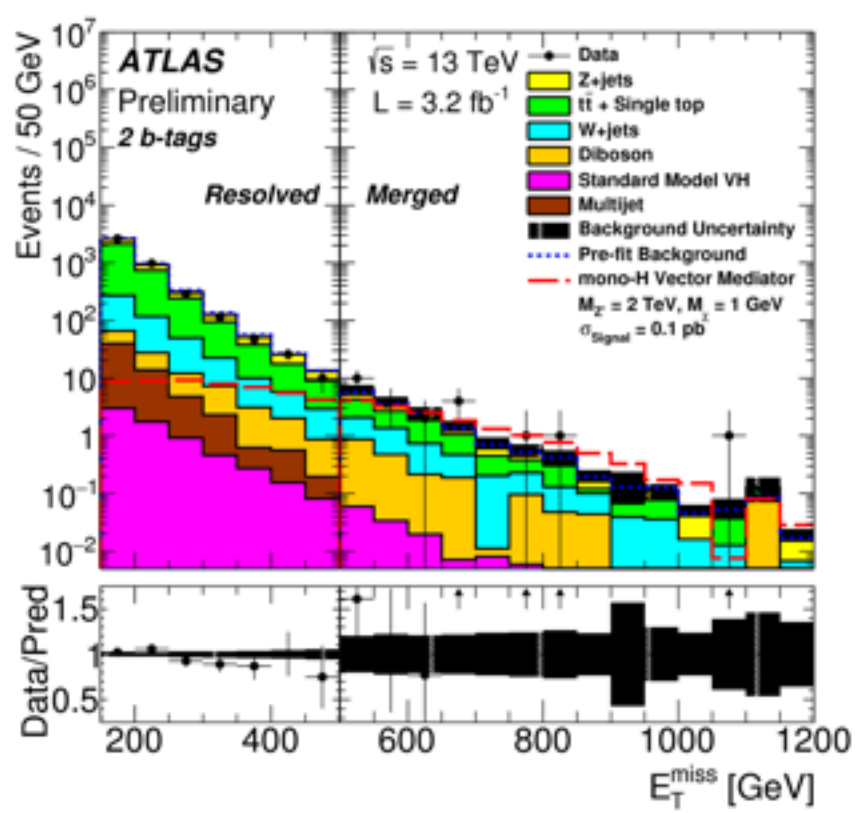
- 2l CR ➡ Z+jets
- 1μ CR ➡ W+jets & ttbar

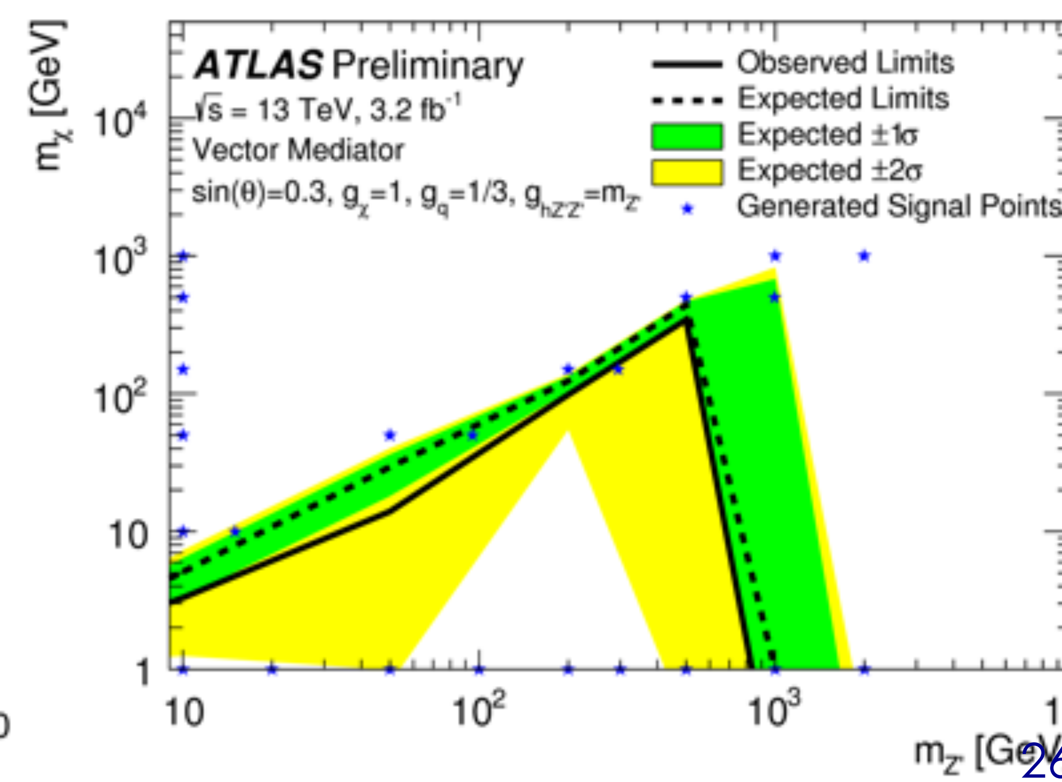
A simultaneous shape fit to the jet mass distribution is performed.

Main exp. systematic uncertainties arise from:

- b-tagging efficiency;
- jet mass/energy calibrations.

No significant excess of events are observed.





Mono-HF (arXiv:1410.4031)

8TeV analysis

Selections based on:

MET, lepton or muon-[b]jet triggers;
cuts on # & p_T (b-)jets, MET, $\Delta\phi$, razor, topness…

4 signal regions:

b+DM, bb+DM, tt(had)+DM, tt(semi-lep)+DM

Control regions:

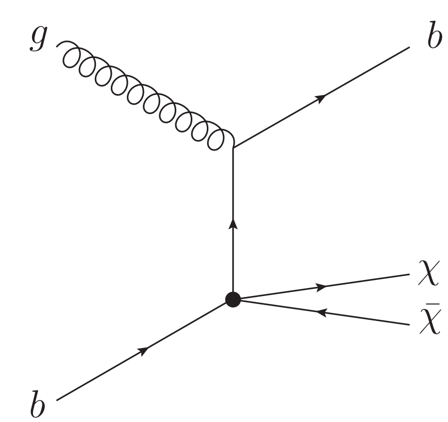
Z/γ+jets CR ➡ Z(νν)+jet in b and bb+DM SRs

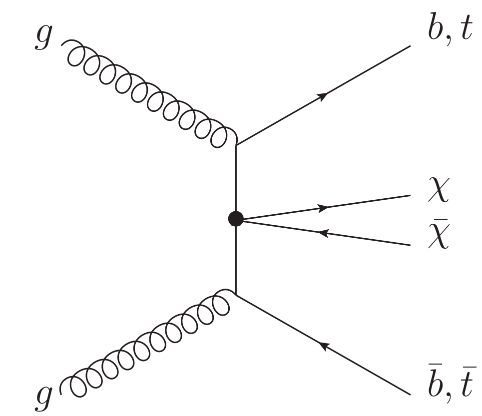
semileptonic CRs ➡ ttbar in tt+DM SR

Tot. Bkg. Unc :

9%,12%,14%,14% (stat, flavor tag, top p_T…)

Sensitivity to scalar interactions effective assuming that the lagrangian **minimally violates flavor** (EFT operators ∝ $\sum m_q$)





Bottom Flavoured Dark Matter model (**b-FDM**) with m_{DM}~35 GeV to explain the Galactic Center excess