DM searches at LHC/ATLAS

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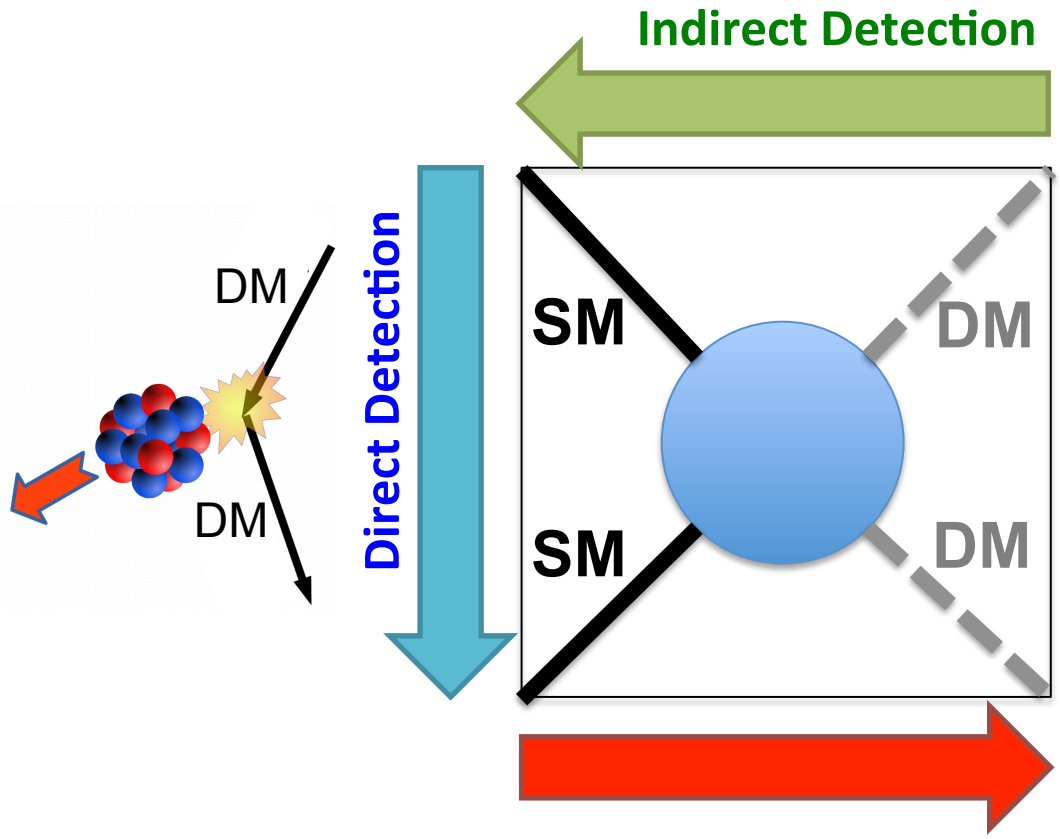
Revealing the history of the universe with
underground particle and nuclear research 2016

Outline

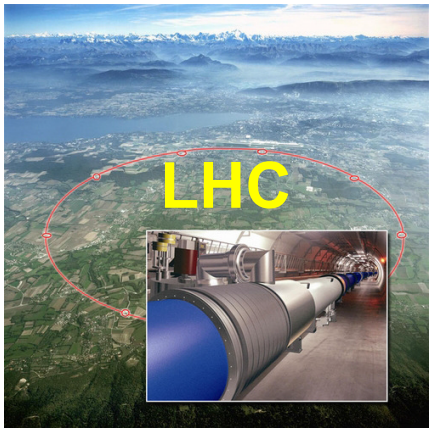
- DM Collider searches & results from Run-1
- Analysis approach for LHC Run-2
- LHC & ATLAS
- Results from Run-2
  - mono-X searches
  - di-jet searches
- Summary

The 3rd direction in DM searches

- LHC provides complementary approach in DM hunting



Complementary also in kinematics coverage

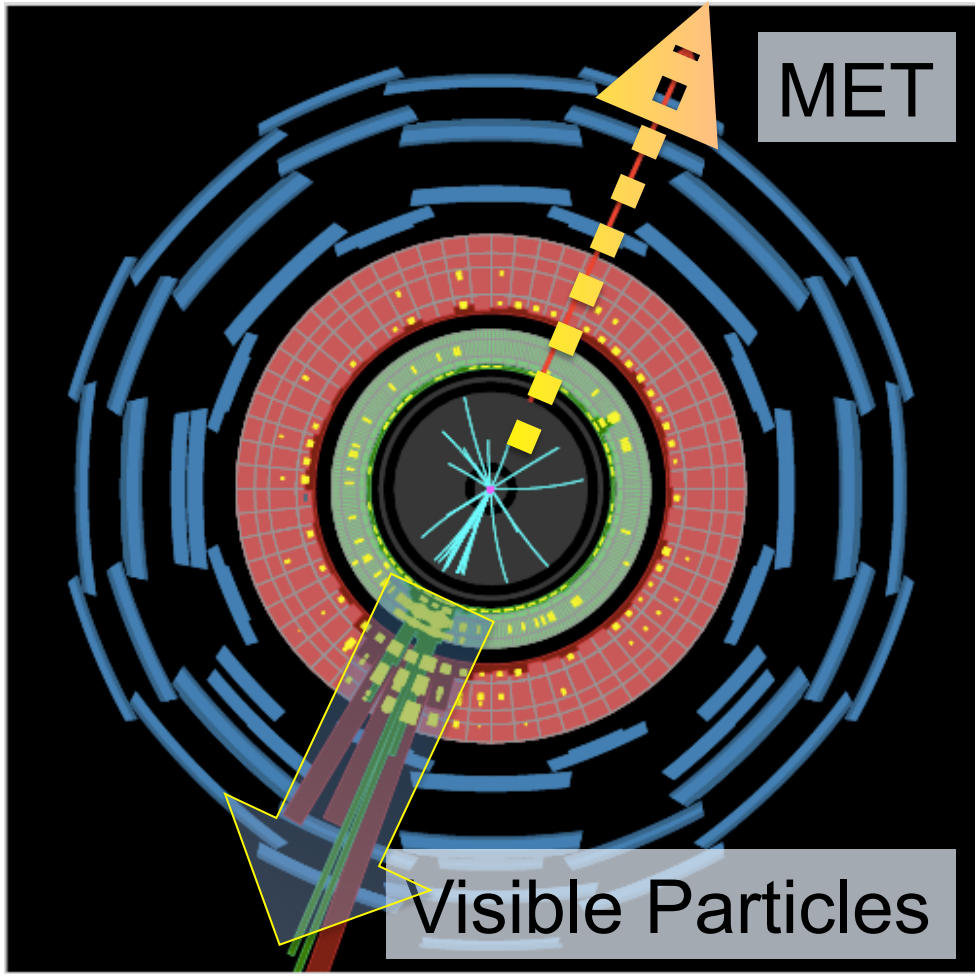


Advantages of knowing the initial state particle species/energies

Collider signature

Momentum Conservation :

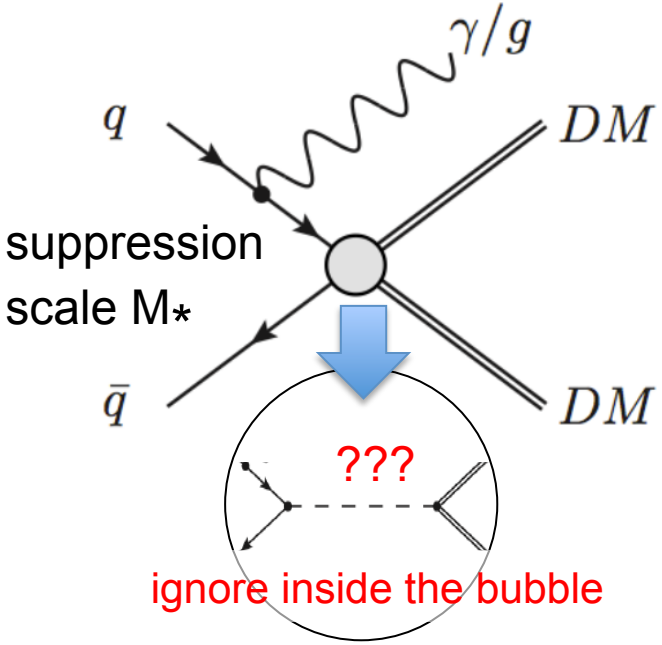
Missing Transverse Energy (MET = DM) ⟷ High pT visible object(s)



highest pT (~970 GeV) single-jet event observed in the ATLAS 13 TeV data

DM models at LHC (in Run-1)

- Effective Field Theory (EFT) : provides simple framework to compare collider and non-collider experiments

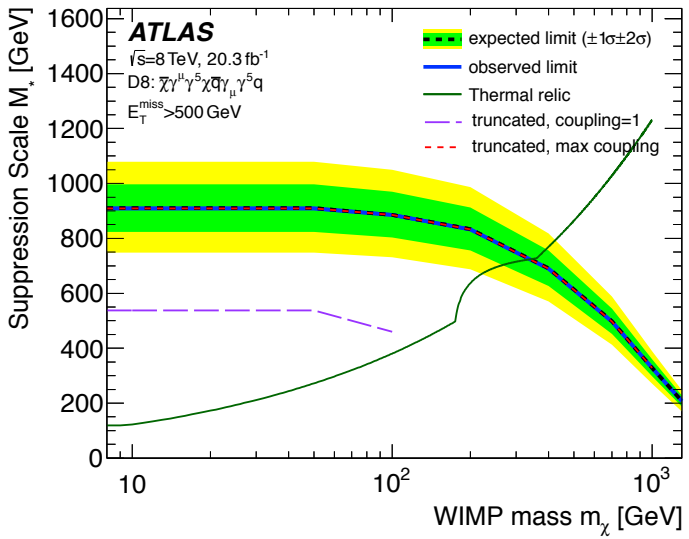


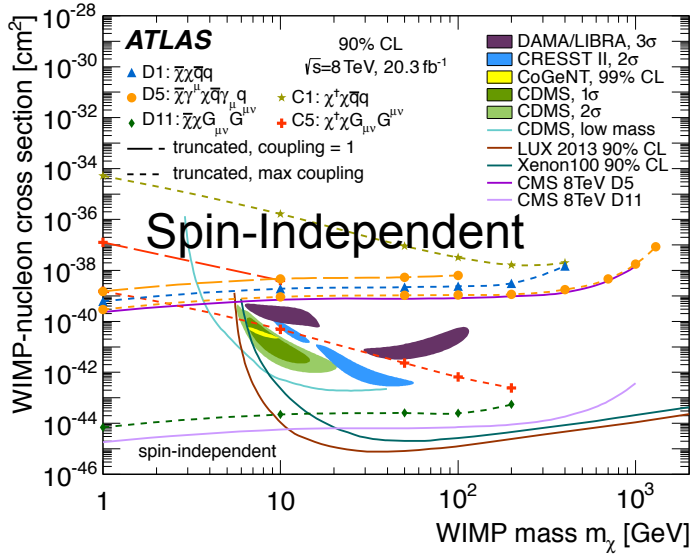
Eur. Phys. J. C75 (2015) 299

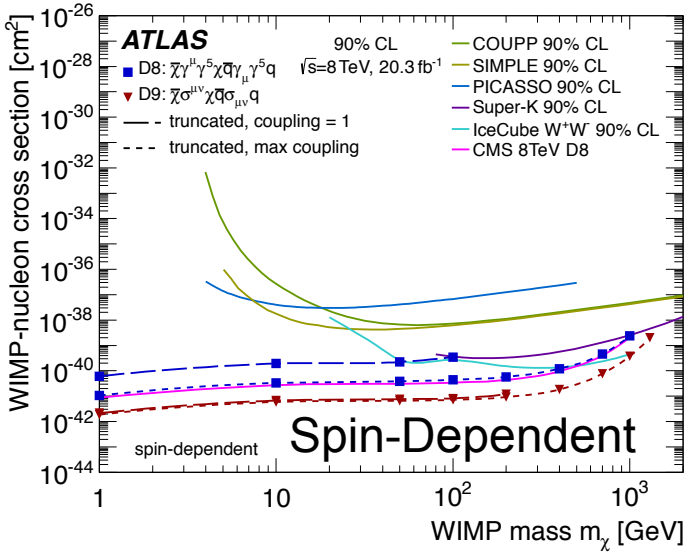
	Name	Initial state	Type	Operator
Scalar	C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
	C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
Dirac Fermion	D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
	D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
	D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
	D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
	D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

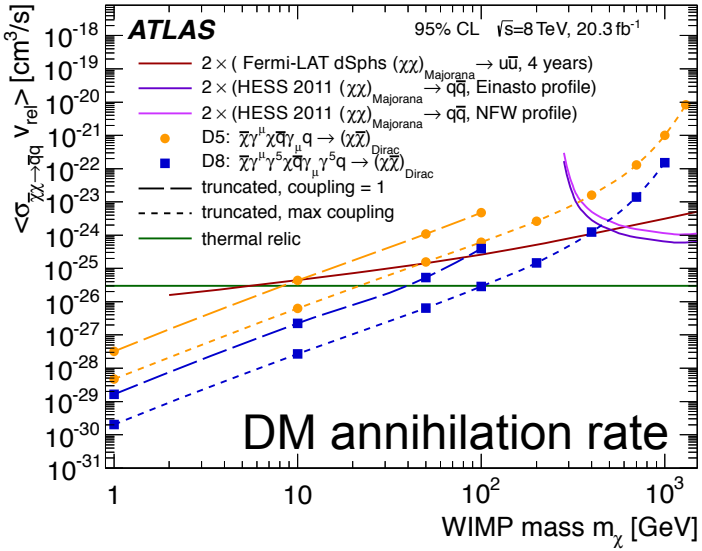
- Limited validity : assumption $m_{mediator} \gg Q(interaction)$ (Fermi constant like couplings)
- Frequently used during Run-1 8TeV (2010-2012), often criticized
- Migrating to "simplified model" from the end of Run-1

8TeV Results (EFT limits vs. Non-collider WIMP searches)









truncation (use small Q events only) to check the EFT validity

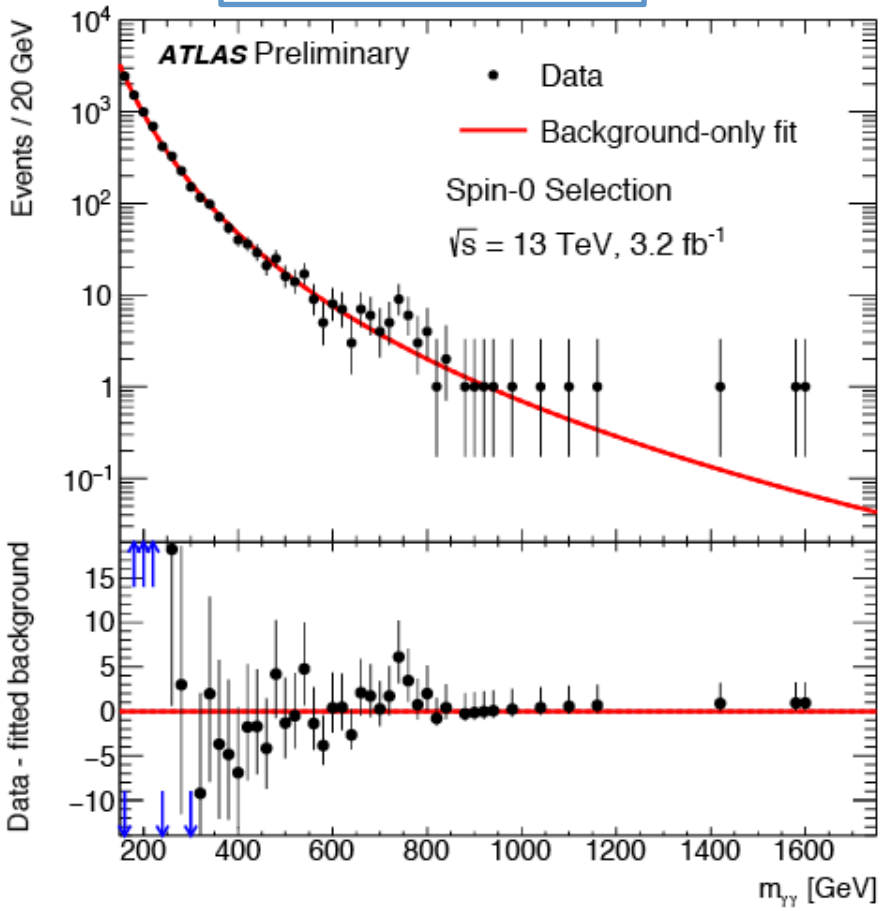
Eur. Phys. J. C75 (2015) 299

Collider searches insensitive to WIMP mass (when lighter than MET, jet cuts)
Limit keeps constant below a few GeV → Complementary to non-collider exp.

DM and the 750 GeV resonance

SPin-0 analysis

ATLAS-CONF-2016-018



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

- Local (Global) Z=3.9 (2.0) σ
- 6% width Γ_X~45GeV

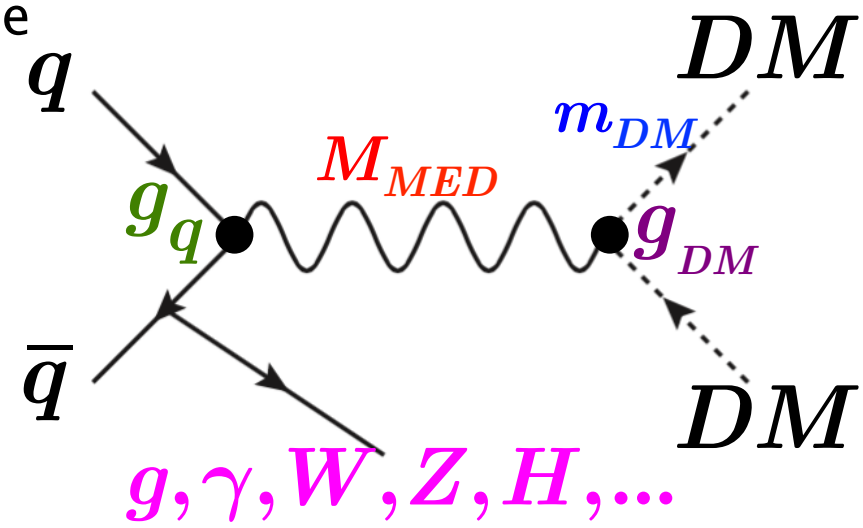
- Large local significances observed in both ATLAS and CMS around 750 GeV
- "to be confirmed" with higher luminosity in 2016
- ATLAS prefers large width approximation (~45GeV), while CMS prefers narrow width (<1 GeV) where detector intrinsic resolution is ~10 GeV
- IF ATLAS is correct, particle X(750 GeV) may decay into invisibles → possible connection to DM

DM searches in LHC Run-2

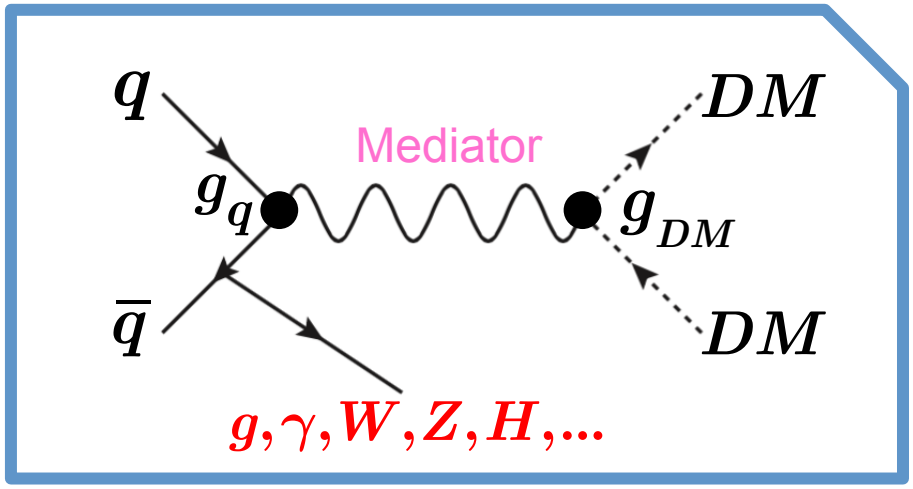
Simplified Models

- General framework valid at high (any) Q^2
- Recommendations
  - DM@LHC14 (arXiv:1506.03116)
  - LHCDMWG (arXiv:1603.04156, arXiv:1507.00966)
- Mediator particle connects the SM quarks to DM particles
- Model depends on four parameters (m_{DM}, M_{MED}, g_q, g_{DM})
- Results shown in m_{DM} vs. M_{MED} plane

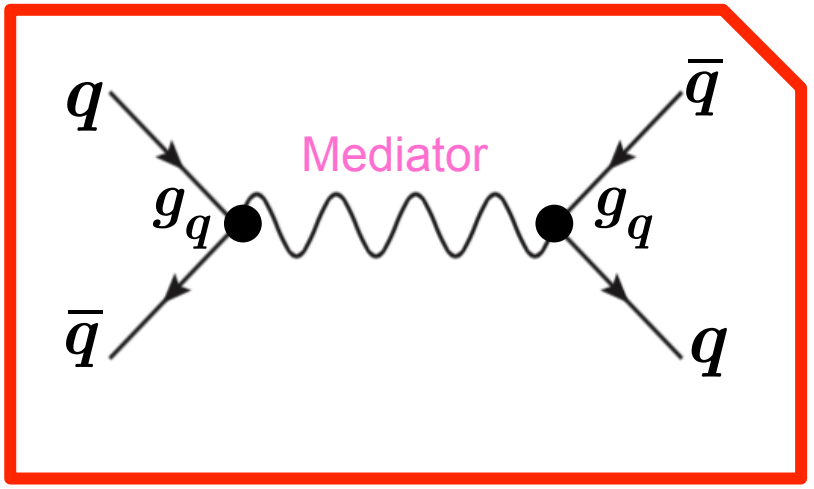
Mediator Type	g_{DM}	g_q
Vector	1	0.25
Axial-Vector	1	0.25
Scalar	1	1
Pseudo Scalar	1	1



DM searches at LHC



Mono-X + MET



Di-Jets

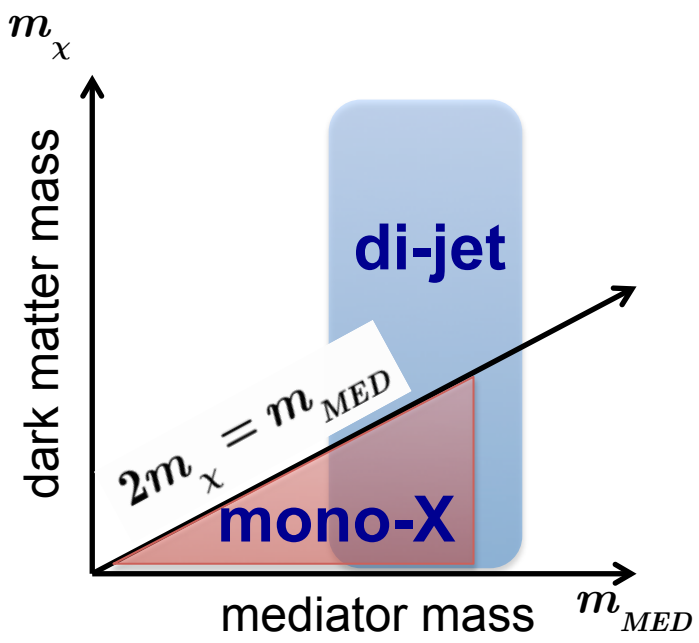
- Mediator couples to DM with g_{DM}, to SM quarks with g_q
- DM cannot be reconstructed in detector

  → Look for accompanying signature (mono-X)
- Mediator can also decay into quark (Jet) pairs

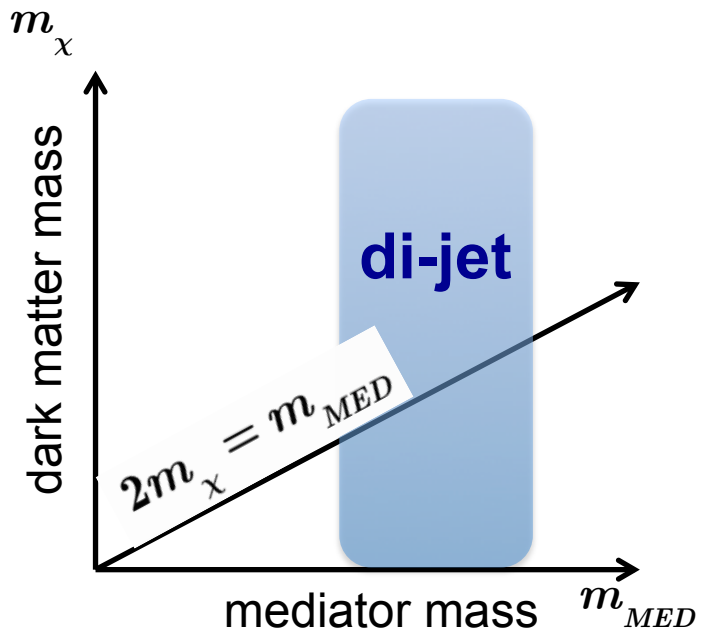
  → Di-jet resonance signature

DM searches at LHC

- Simplified models separate the couplings to DM and SM
  → possibilities for more complex interpretations
- Complementarity between search channels
  e.g. **mono-X** and **di-jet** arXiv:1503.05916



Large couplings to DM

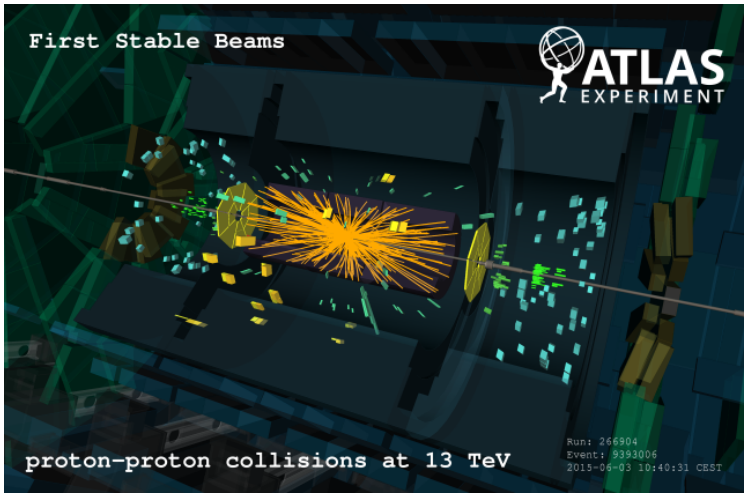


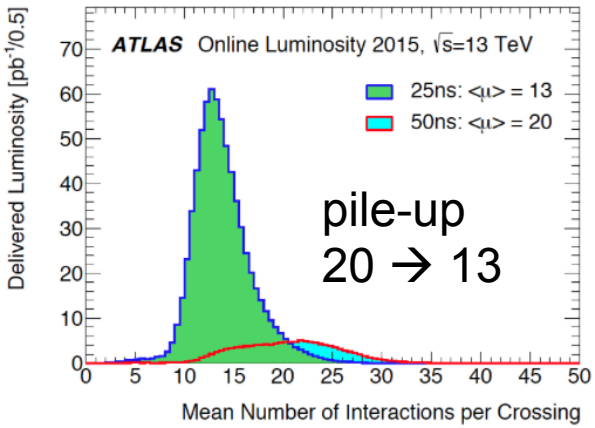
Small couplings to DM

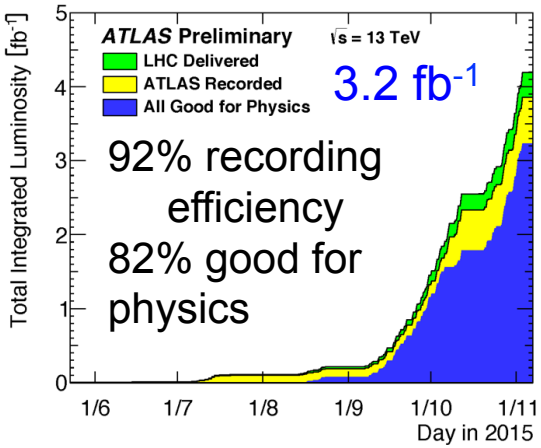
LHC
&
ATLAS

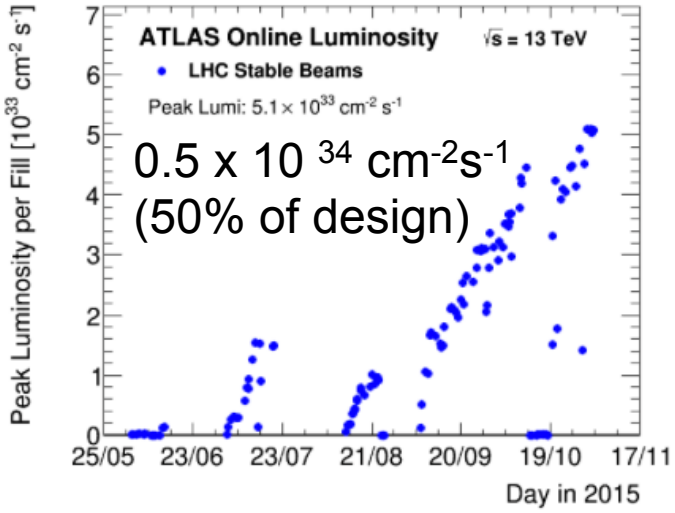
2015 LHC is back in business (Run-2)

13 TeV collisions

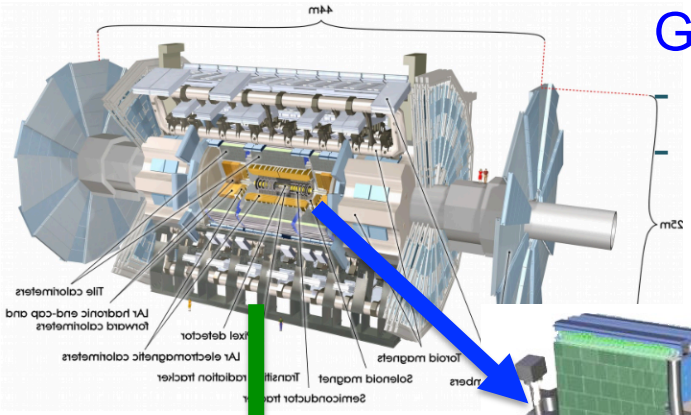








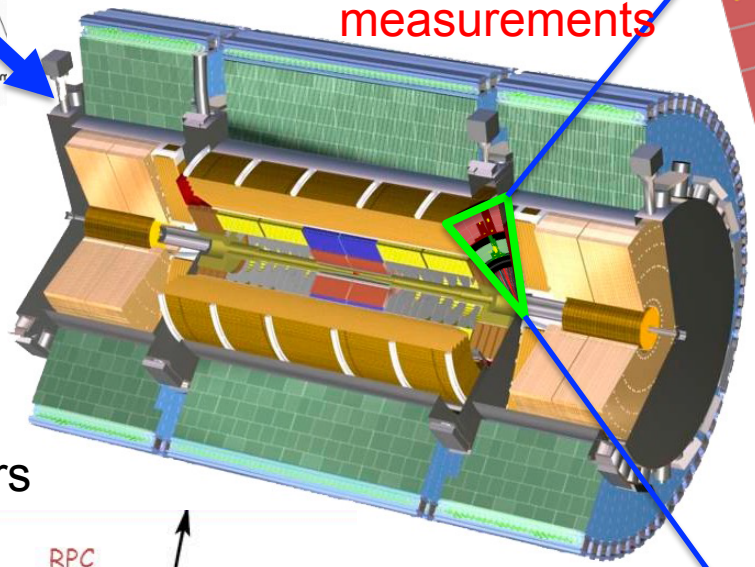
ATLAS detector

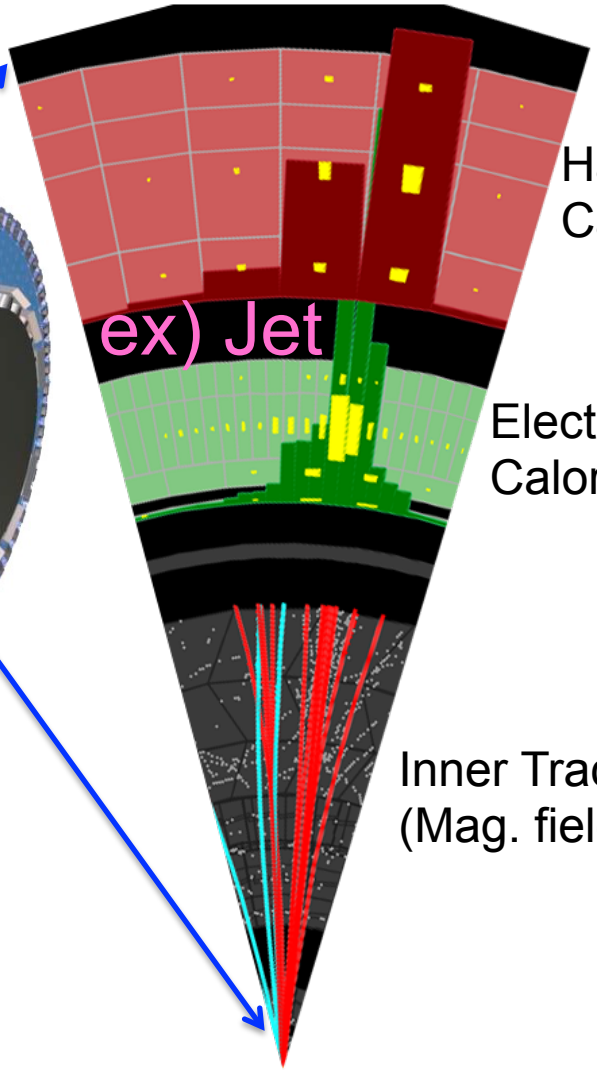


General purpose detector

- excellent tracking in central region & muon spectrometer
- good energy measurements with fine segmented calorimeters

electron, photon, hadrons, jet measurements



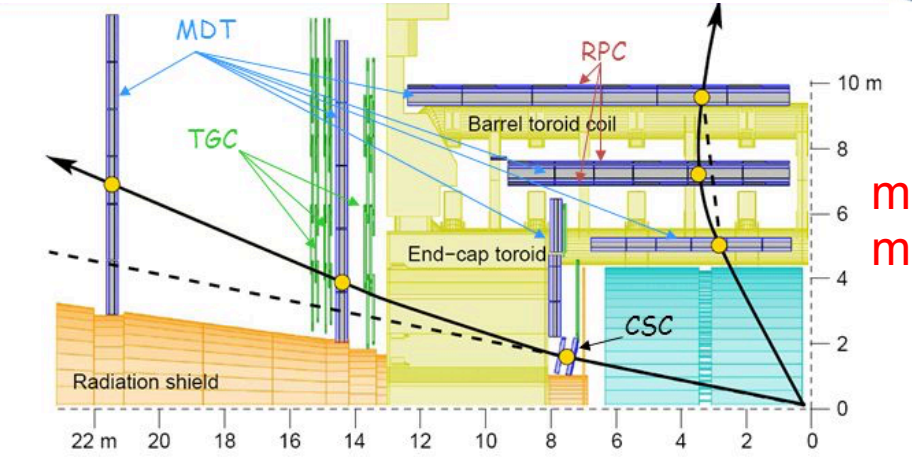


Hadron Calorimeter

Electromagnetic Calorimeter

Inner Tracker (Mag. field = 2T)

Muon Spectrometers

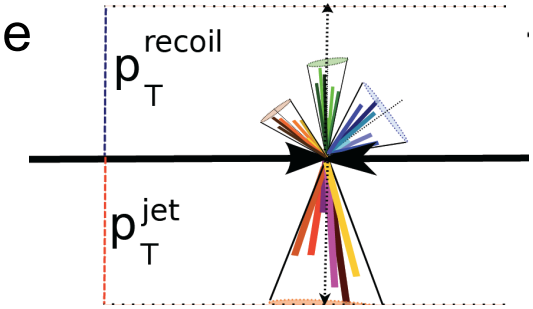


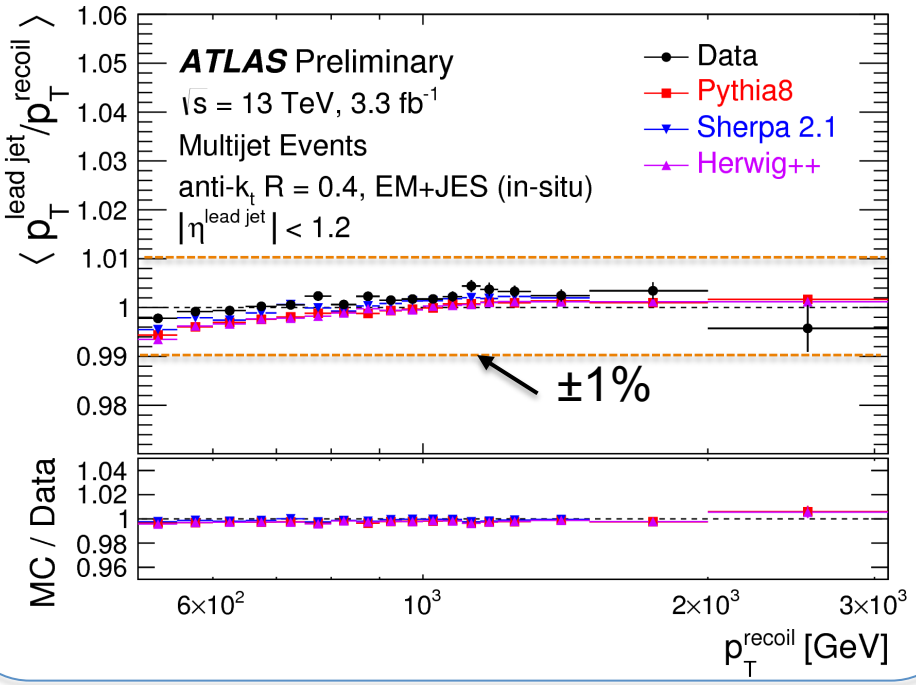
muon measurements

Performance for TeV signature

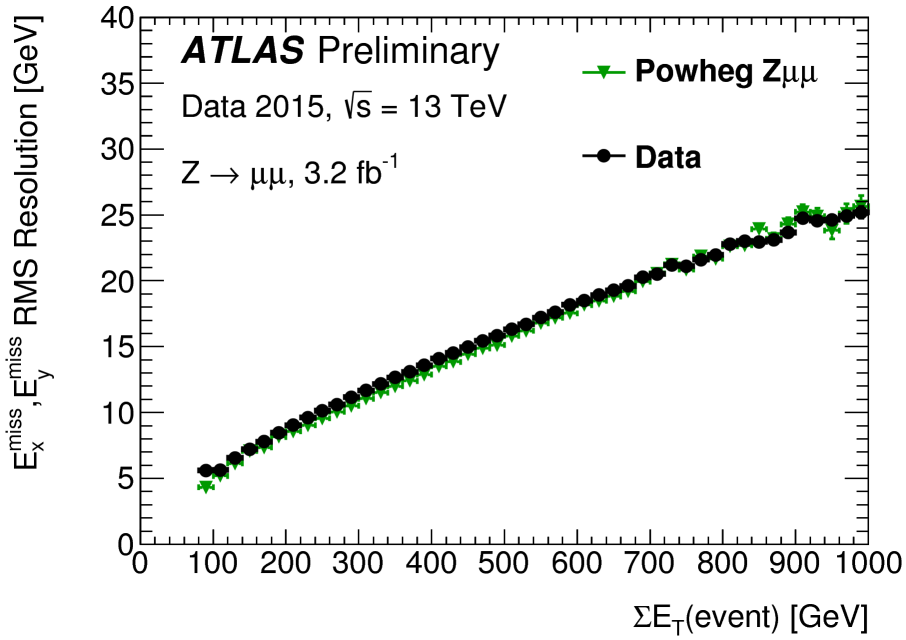
Reconstruction of Jet, MET, High-pT objects (boosted) important to explore TeV region

Jet Calibration is well understood up to multi-TeV scale





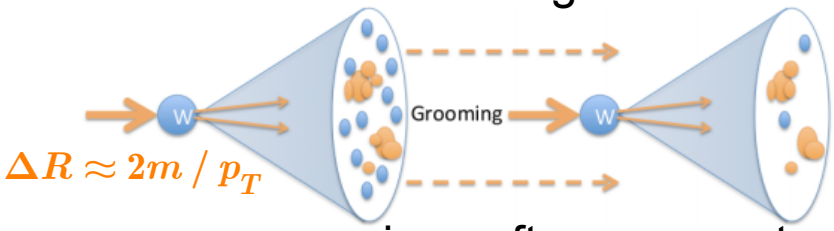
Missing ET is well understood
Intrinsic MET resolution estimated with Z→ μμ events



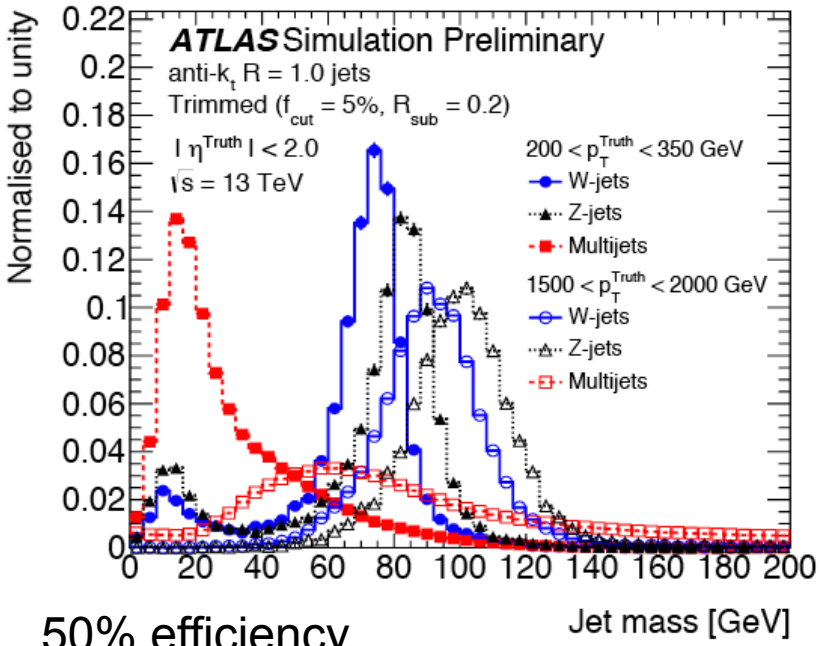
Performance for TeV signature (cont'd)

Boosted W/Z tagging

Reconstructed as large radius JET



- removing soft component
- identifying two sub-jets

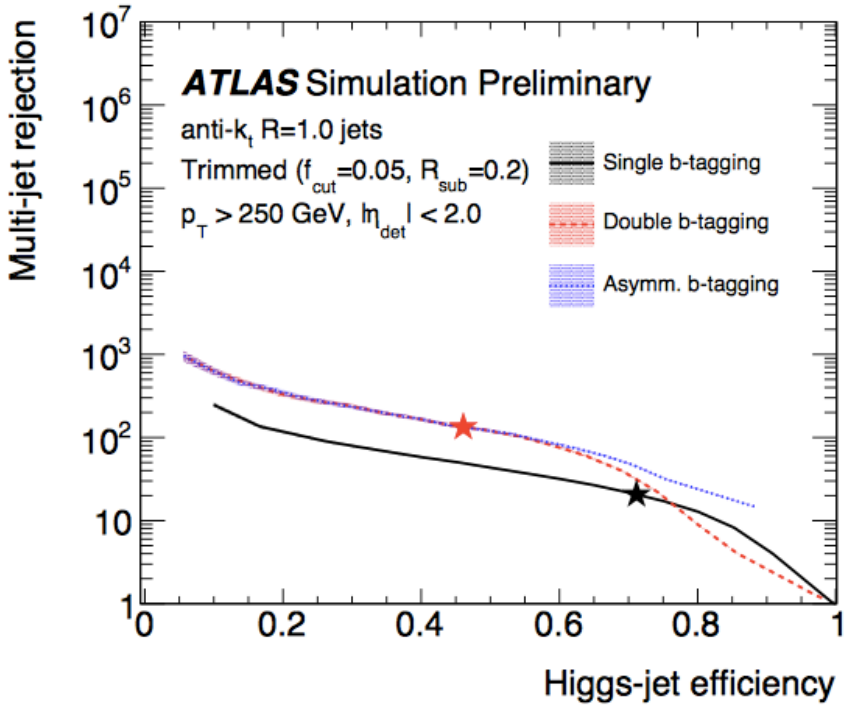


ATLAS-PHYS-PUB-2015-033

50% efficiency
~50 BG rejection factor (p_T>200GeV)

Boosted H tagging

Double b-tagging, jet-mass, sub-structure

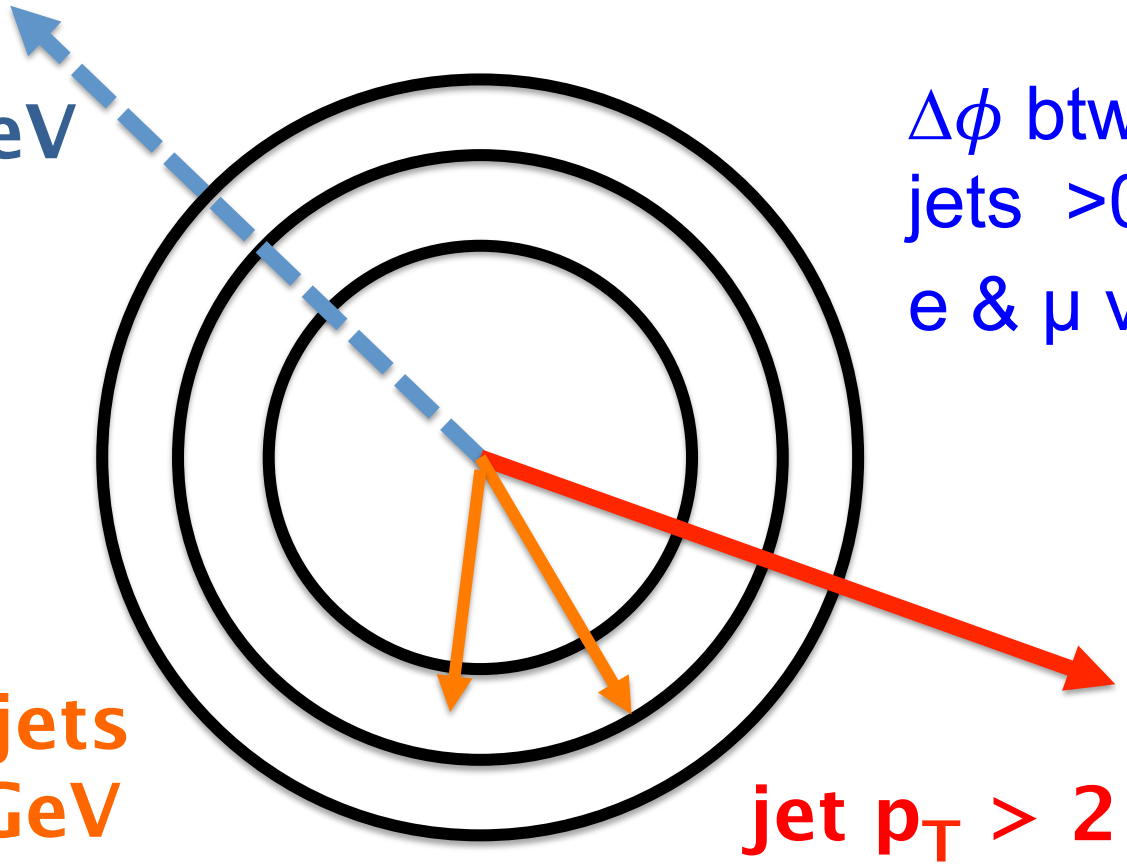


loose selection
40% efficiency
~250 rejection for inclusive multi-jets
~70 rejection for hadronic top

DM production
Mono-Jet + MET

Mono-Jet + MET

Signal Region



MET > 250 GeV

$\Delta\phi$ btw MET & jets >0.4

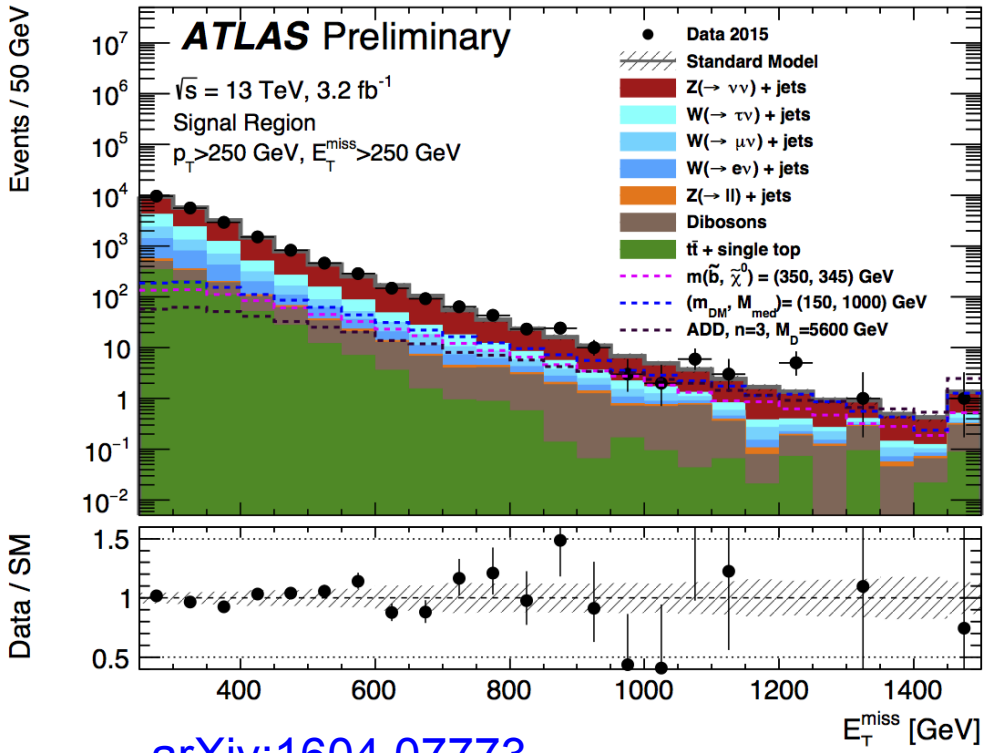
e & μ veto

allow up to 3 jets with p_T > 30 GeV

jet p_T > 250 GeV
|eta|<2.4

Mono-jet searches (13 TeV)

Most sensitive mono-X +MET channel with large stats (α_{QCD} large)



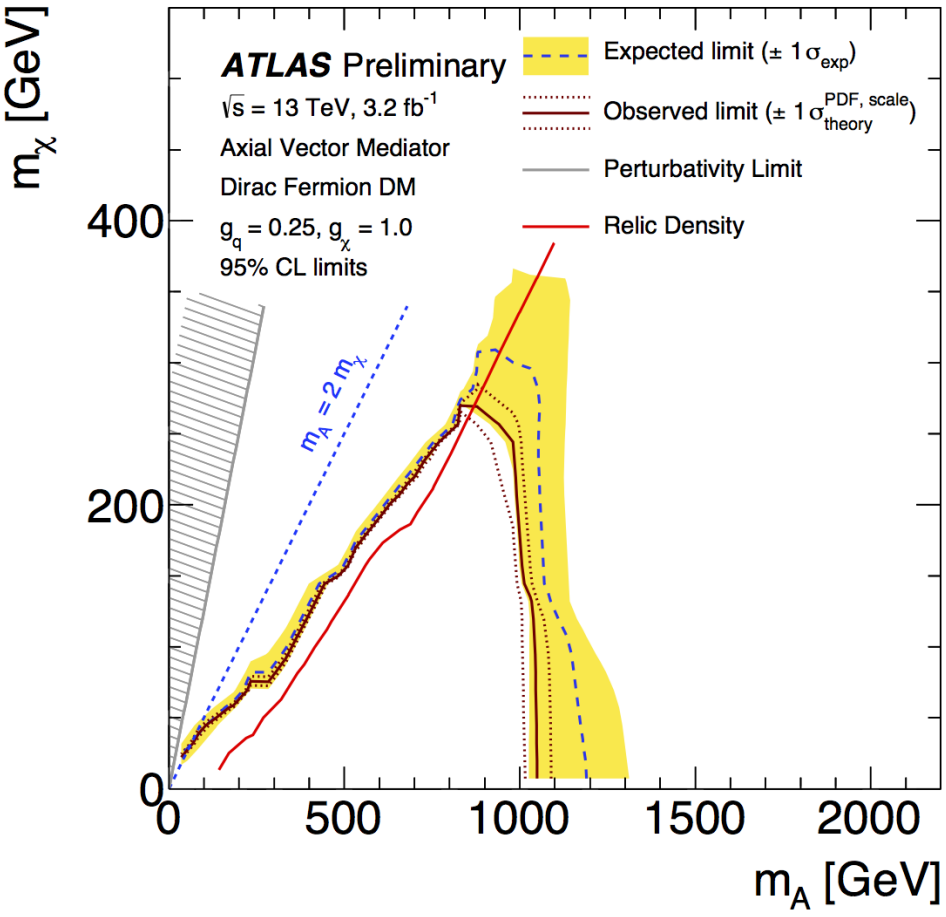
arXiv:1604.07773

- Background
  - hard to model MET
  - use Z→ℓℓ, W→ℓν to model main Z→νν bkgs
  - detector effects, non-collision bkgs (estimates data driven)
- Results (no excess)
  - 21447 events observed
  - 21730 ± 940 bkgs events expected

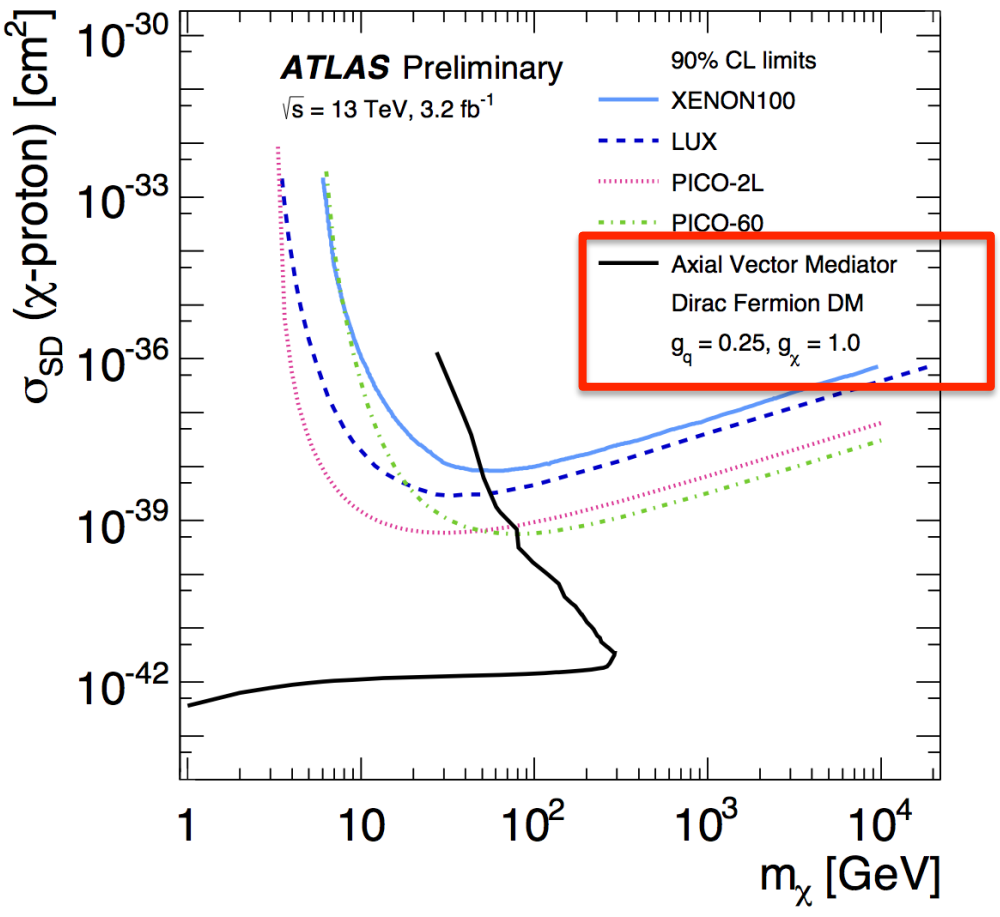
  → limit setting

Mono-jet interpretation (13 TeV)

Limits as a function of DM & mediator mass



Comparison w.r.t. non-collider results



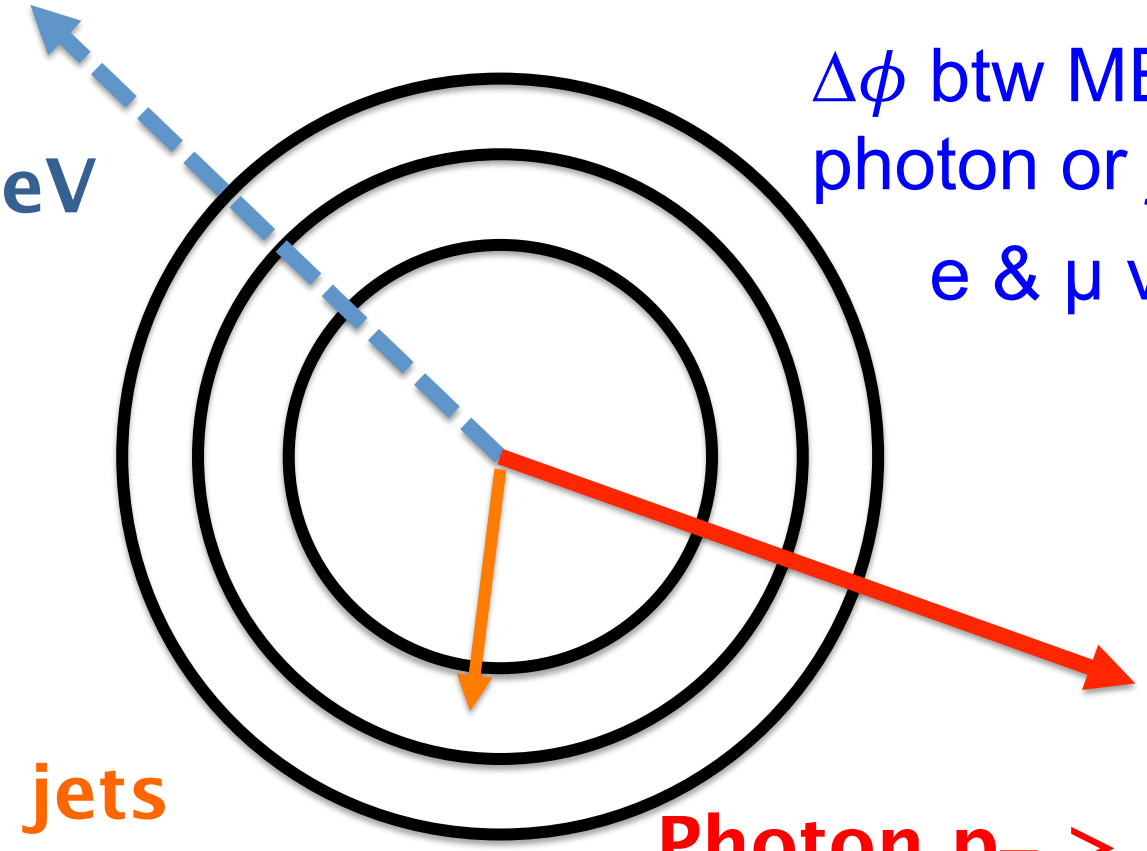
Constraints on DM simplified model :
Axial vector mediator (fixed couplings)
Mediator mass below 1TeV excluded (for 250GeV DM)

WIMP-proton cross section above 10^{-42} cm^2 excluded
(for DM mass < 10 GeV)

DM Productions beyond Mono-Jet

Mono-photon + MET

Signal Region



MET > 150 GeV

$\Delta\phi$ btw MET & photon or jets >0.4

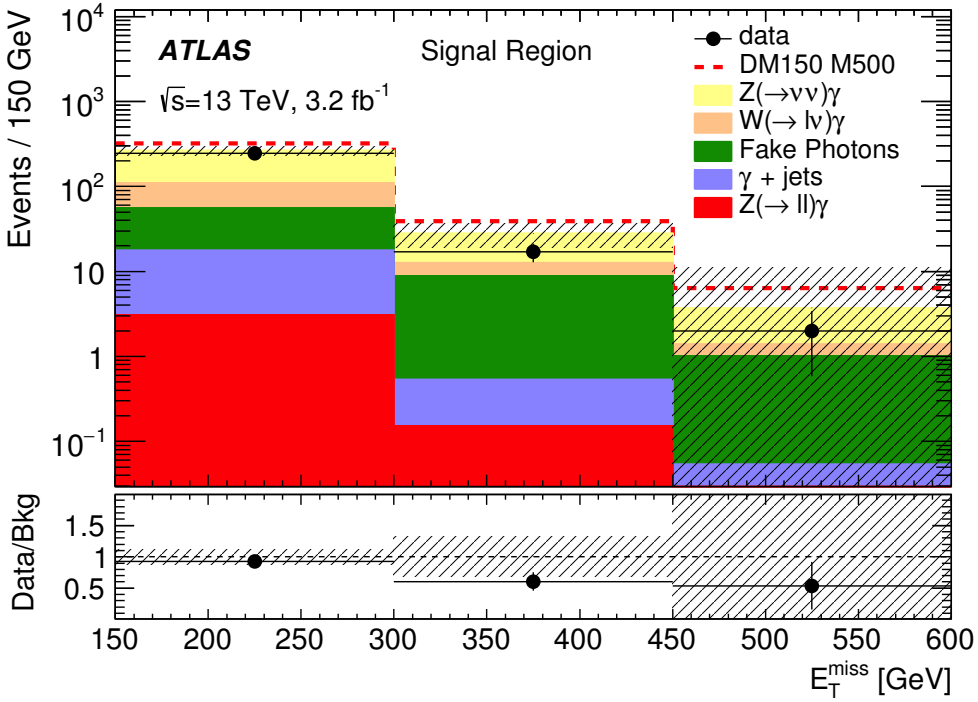
e & μ veto

allow up to 1 jets with p_T > 30 GeV

Photon p_T > 150 GeV
|eta|<2.37
tight ID & isolation

Mono-photon searches (13 TeV)

$\alpha_{EM} << \alpha_{QCD}$ ➔lower statistics than mono-jet
relatively low mass Signal region



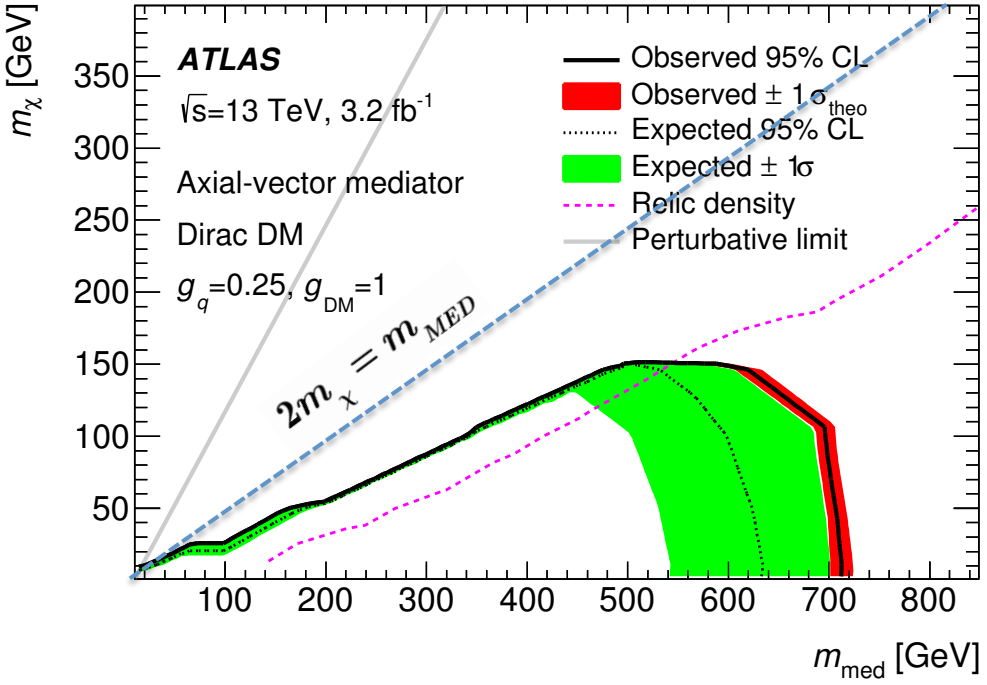
arXiv:1604.01306

- Background (control region)
  - Z(→νν)+γ (2e, 2μ CR)
  - W(→ℓν)+γ (1μ CR)
  - γ+jets (γ+jets lower MET CR)
- Results (no excess)
  - 264 observed events
  - 295±34 BG events expected

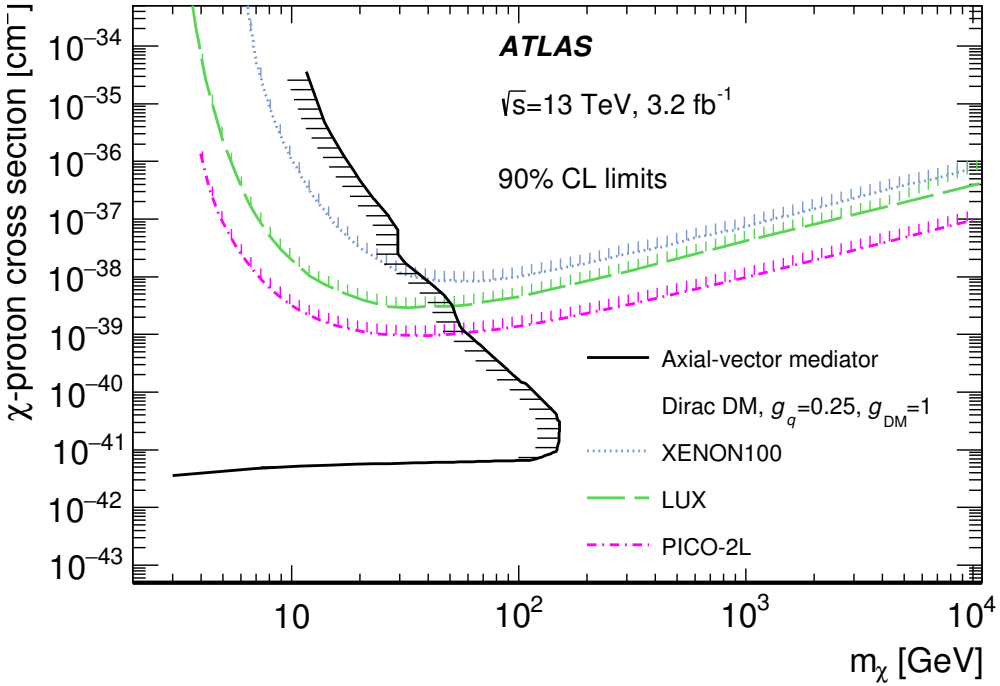
SM BG consistent → Limit setting

Mono-photon interpretation (13 TeV)

Limits as a function of DM & mediator mass



Comparison against non-collider results



Constraints on DM simplified model :
Axial vector mediator (fixed couplings)
Mediator mass below 0.7 TeV excluded
(for 100GeV DM)

WIMP-proton cross section above
~ 10^{-41} cm^2 excluded
(for DM mass < 150GeV)

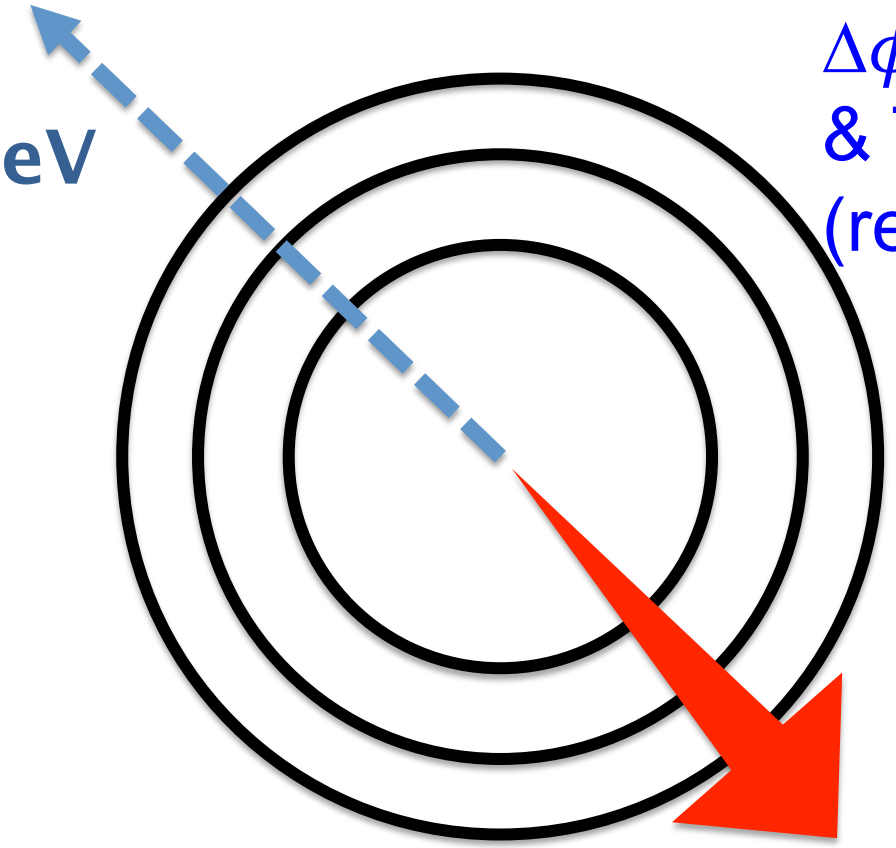
Mono-W/Z + MET

Signal Region

Trk MET > 30GeV

$\Delta\phi$ btw MET
& Trk MET < pi/2
(reduce fake MET)

MET > 250 GeV

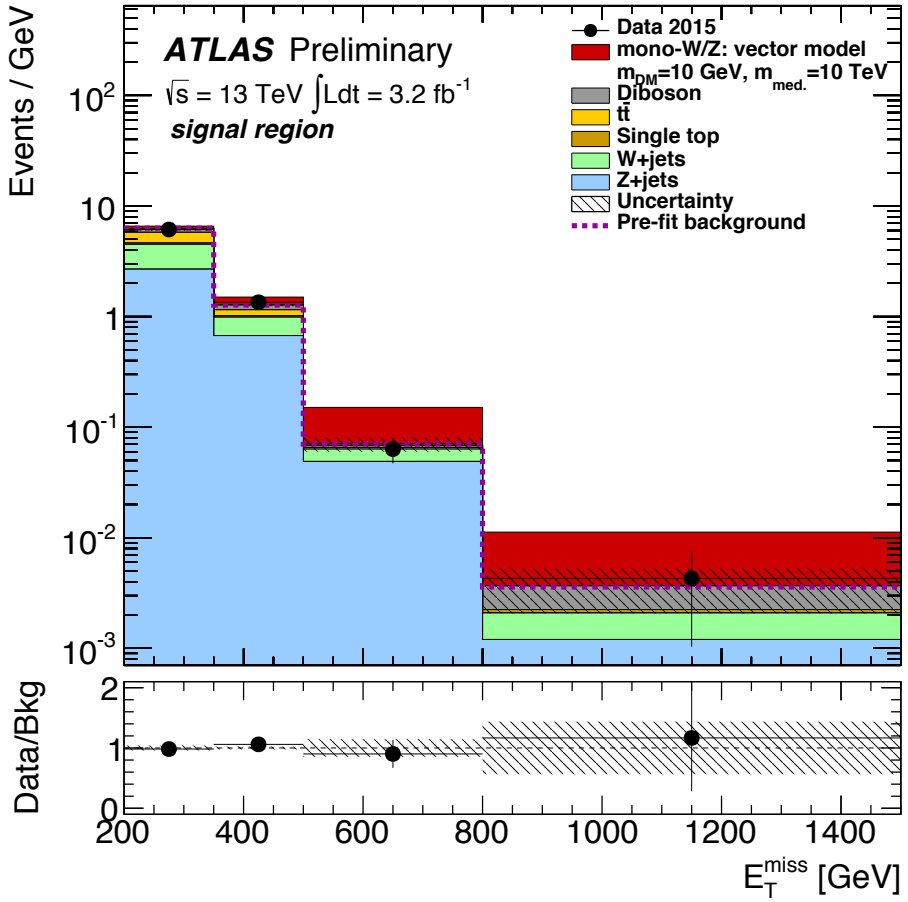


e & μ veto

Large radius Jet (W/Z)

Mono-Z/W searches (13 TeV)

Search for Dark Matter associating with hadronically decaying W/Z

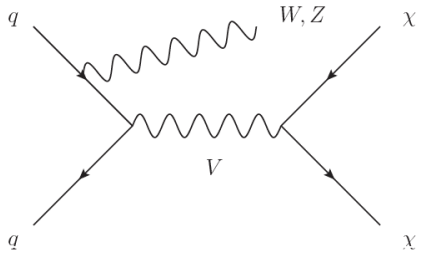


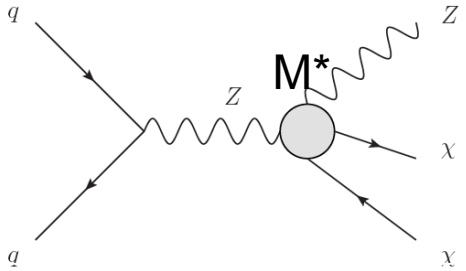
ATLAS-CONF-2015-080

- Background (CR)
  - Z+jets (2 muon)
  - W+jets (1 muon & no b-jet)
  - ttbar (1 muon & 1 b-jet)
  - simultaneous fit with 3 normalization factors
- largest systematics from modeling of large radius jet (~10%)
- No excess observed → Limit

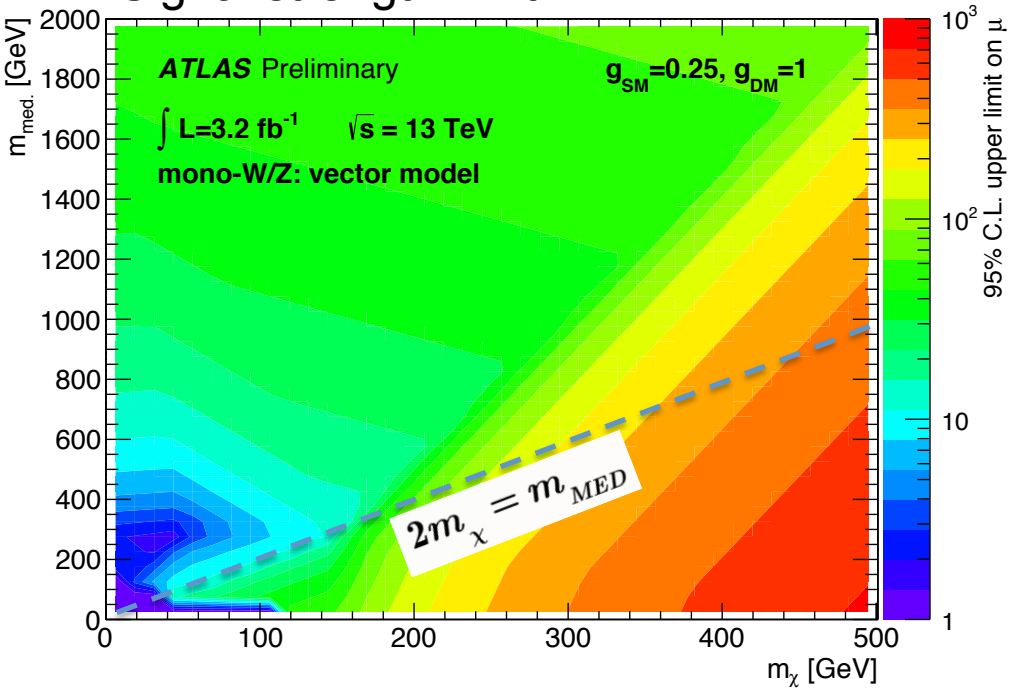
Process	events
Z+jets	519 ± 31
W+jets	326 ± 22
$t\bar{t}$ and single-top	217 ± 18
Diboson	88 ± 12
Total Background	1150 ± 30
Data	1143

mono-Z/W interpretation (13 TeV)



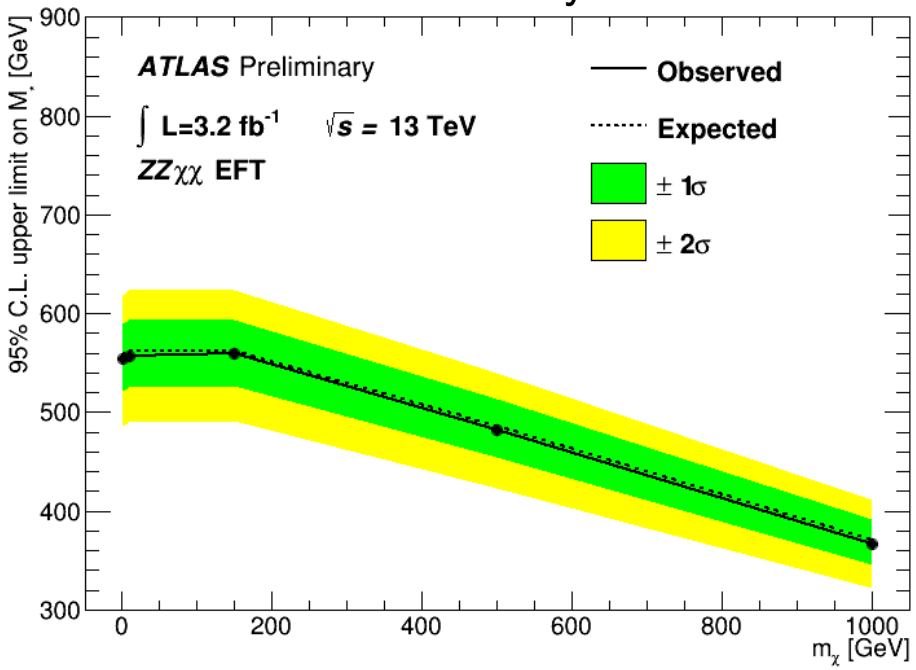


Simplified model (vector mediator)
Signal strength limit



ATLAS-CONF-2015-080

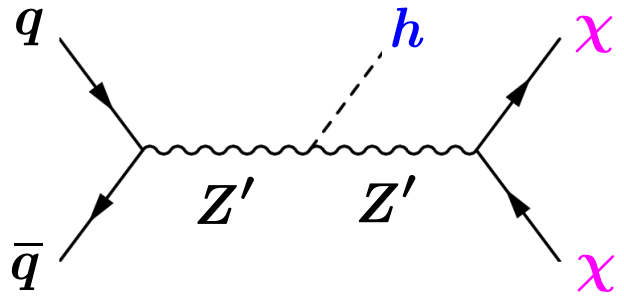
Interpreted with $ZZ\chi\chi$ EFT
model where DM directly interact with Z



8TeV 20.3 fb^{-1} so far had stronger constraints on D5 (M*=1800 GeV)
Phys. Rev. Lett 112, 041802 (2014)

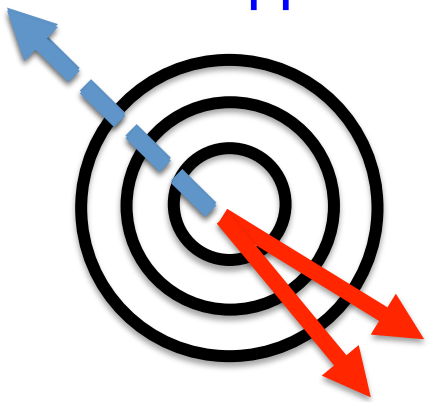
Mono-Higgs searches (13 TeV)

- look into models where Higgs couples to Dark Sector



Looked into three H final states

H→γγ

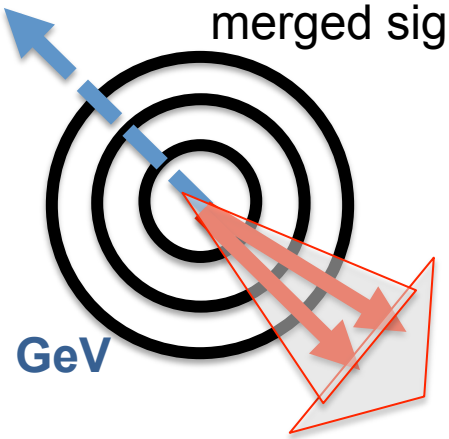


At least **2 photons**
(tight ID, isolated)
105 GeV < $m_{\gamma\gamma}$ < 160 GeV

Other requirements on $p_T^{\gamma\gamma}$, MET

H→bb

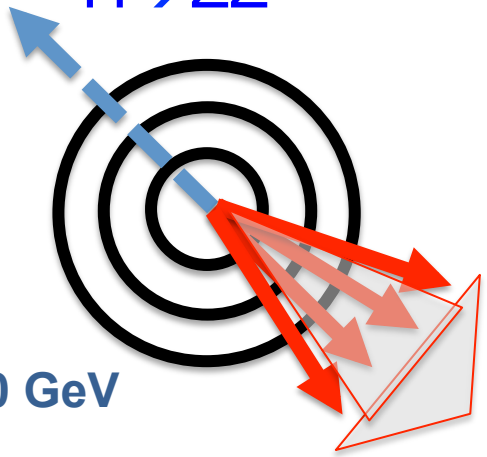
merged signal



One large-radius jet
(associated with 2-trk jets)

Resolved signal region
for MET < 500 GeV
(requiring 2 jets)

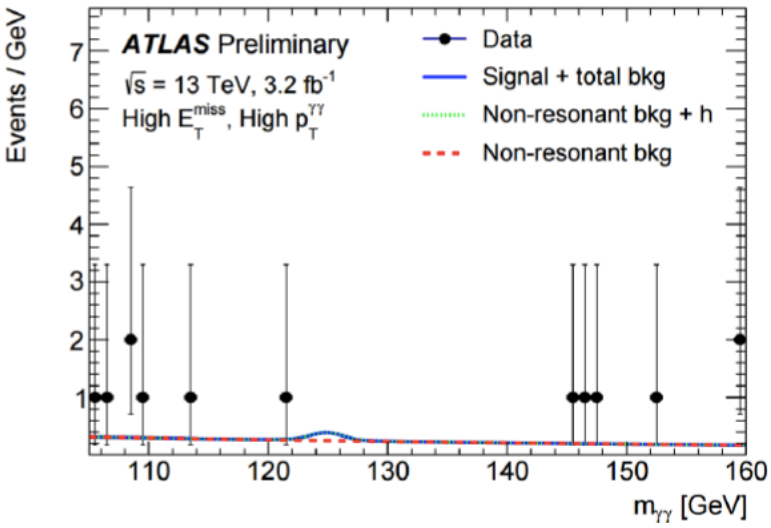
H→ZZ

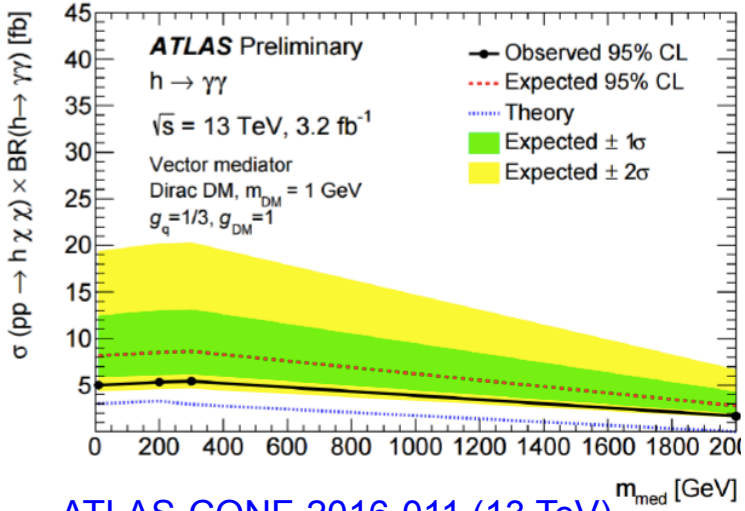


Require 4 leptons
110 < m_{4l} < 140 GeV

Mono-Higgs searches (13 TeV)

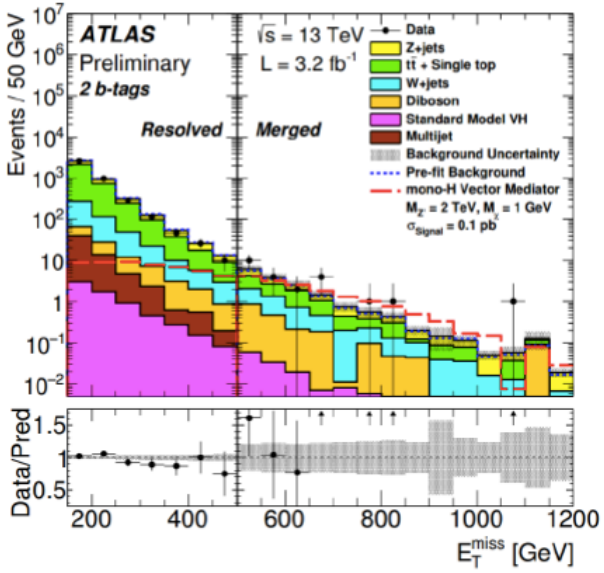
H→γγ

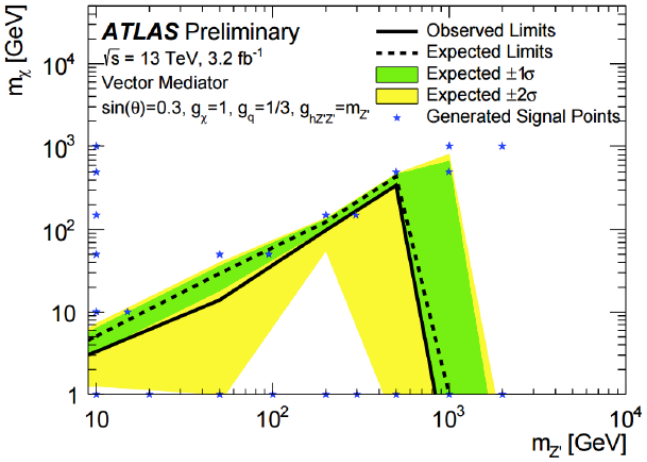




ATLAS-CONF-2016-011 (13 TeV)
Phys. Rev. Lett. 115, 131801 (8 TeV)

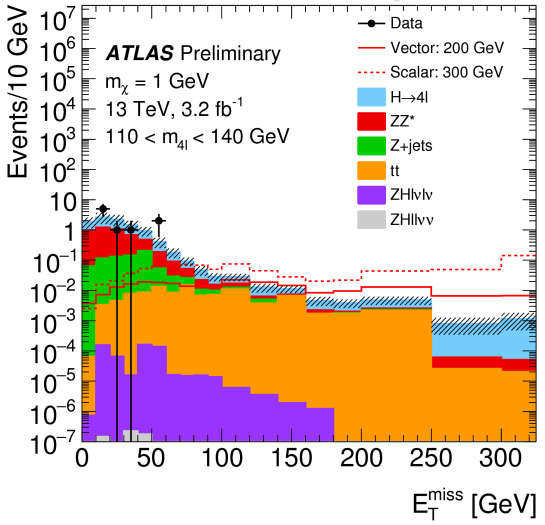
H→bb

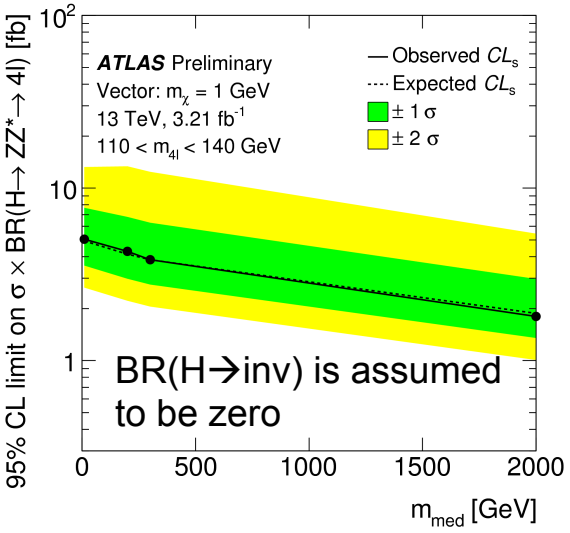




ATLAS-CONF-2016-019 (13 TeV)
Phys. Rev. D 93, 072007 (8 TeV)

H→ZZ→4lep





ATLAS-CONF-2015-059 (13 TeV)

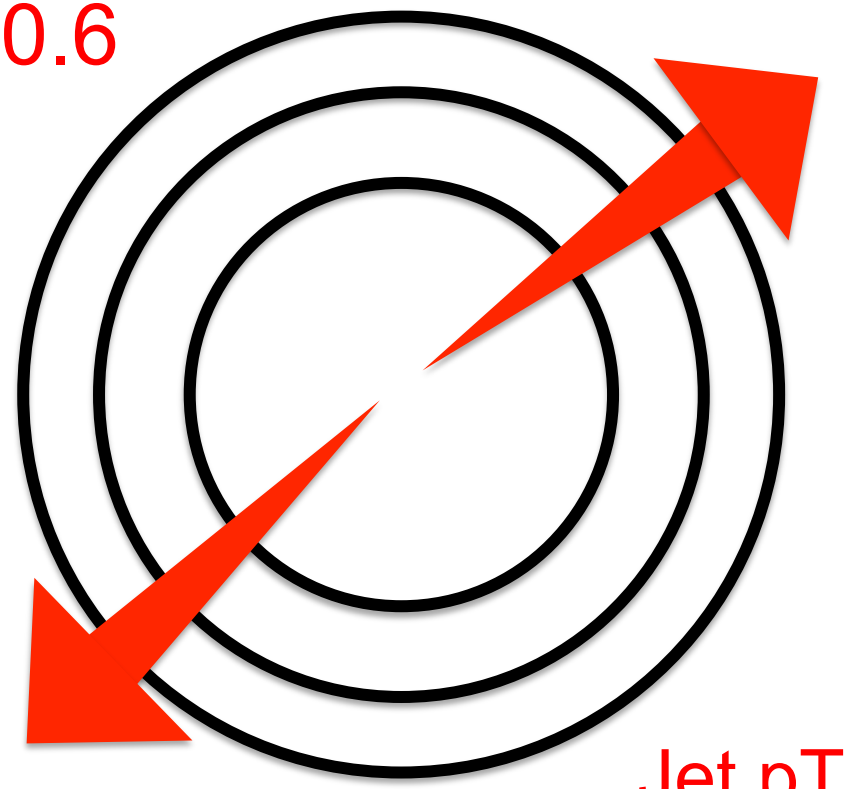
DM Searches via Di-jet production

Di-jet searches

Signal Region

$|y^*| = \sqrt{(y_1 - y_2)} < 0.6$

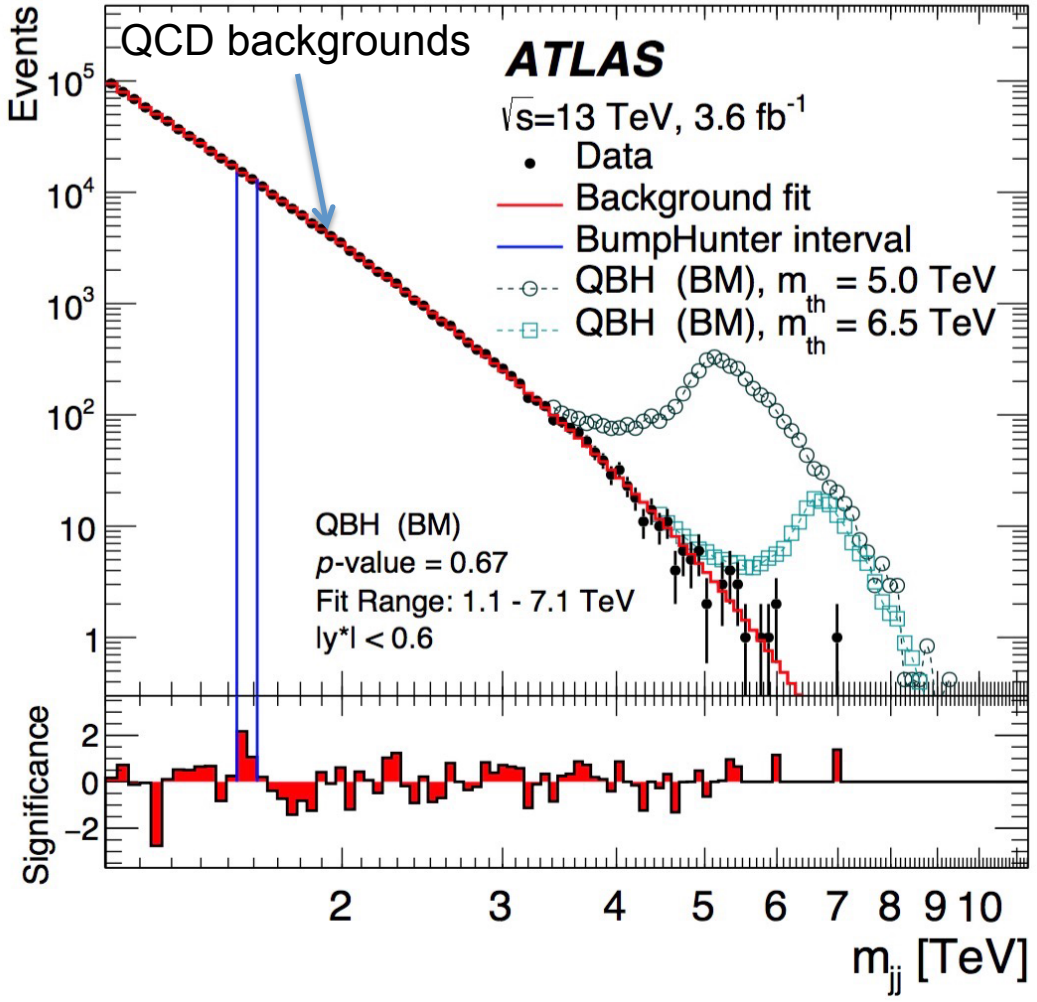
$m_{jj} > 1.1$ TeV



Jet pT > 450 GeV

Di-jet searches (13 TeV)

Resonant Analysis



Phys. Lett. B 754 (2016) 302

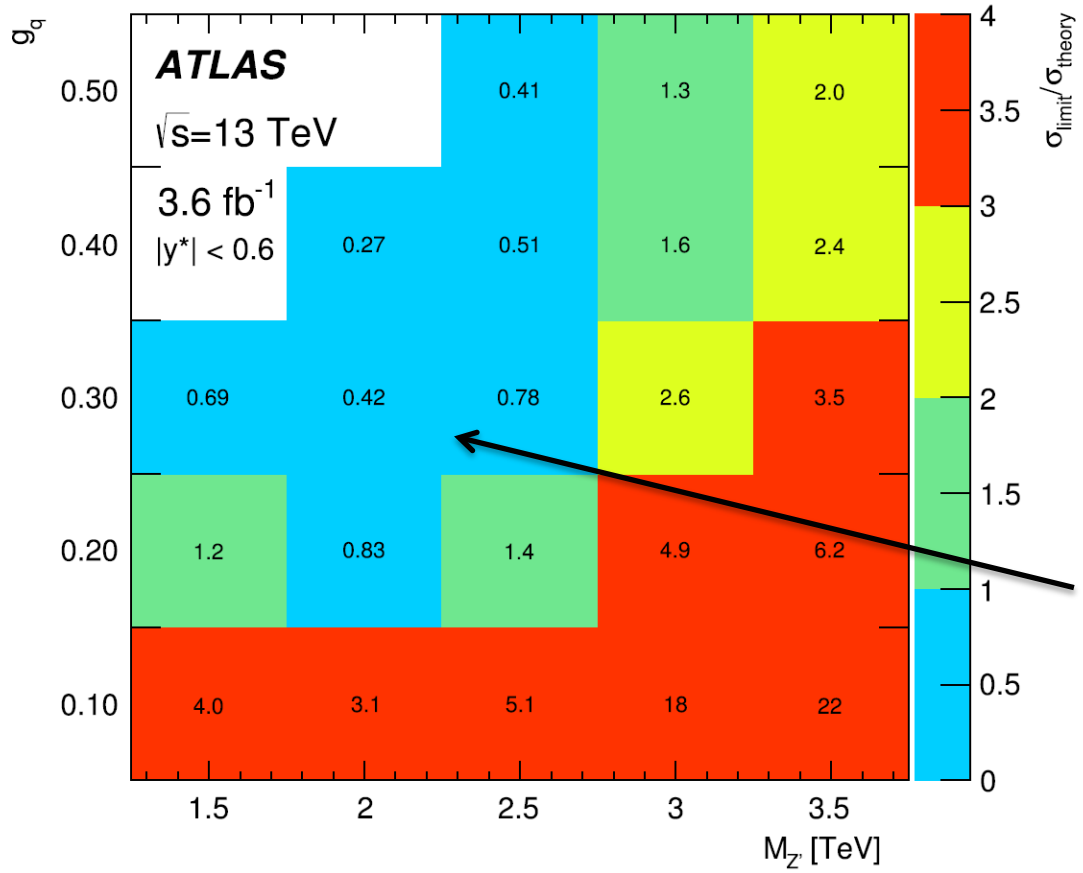
- Look for resonance qq, qg and gg
- Most sensitive benchmark search among BSM channels
- Data driven background fit
  - Fit smooth spectrum

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

  - empirical function
- Excess findings in m_{jj} distribution
  - Bumphunter
  - Tailhunter

No Significant Excess observed

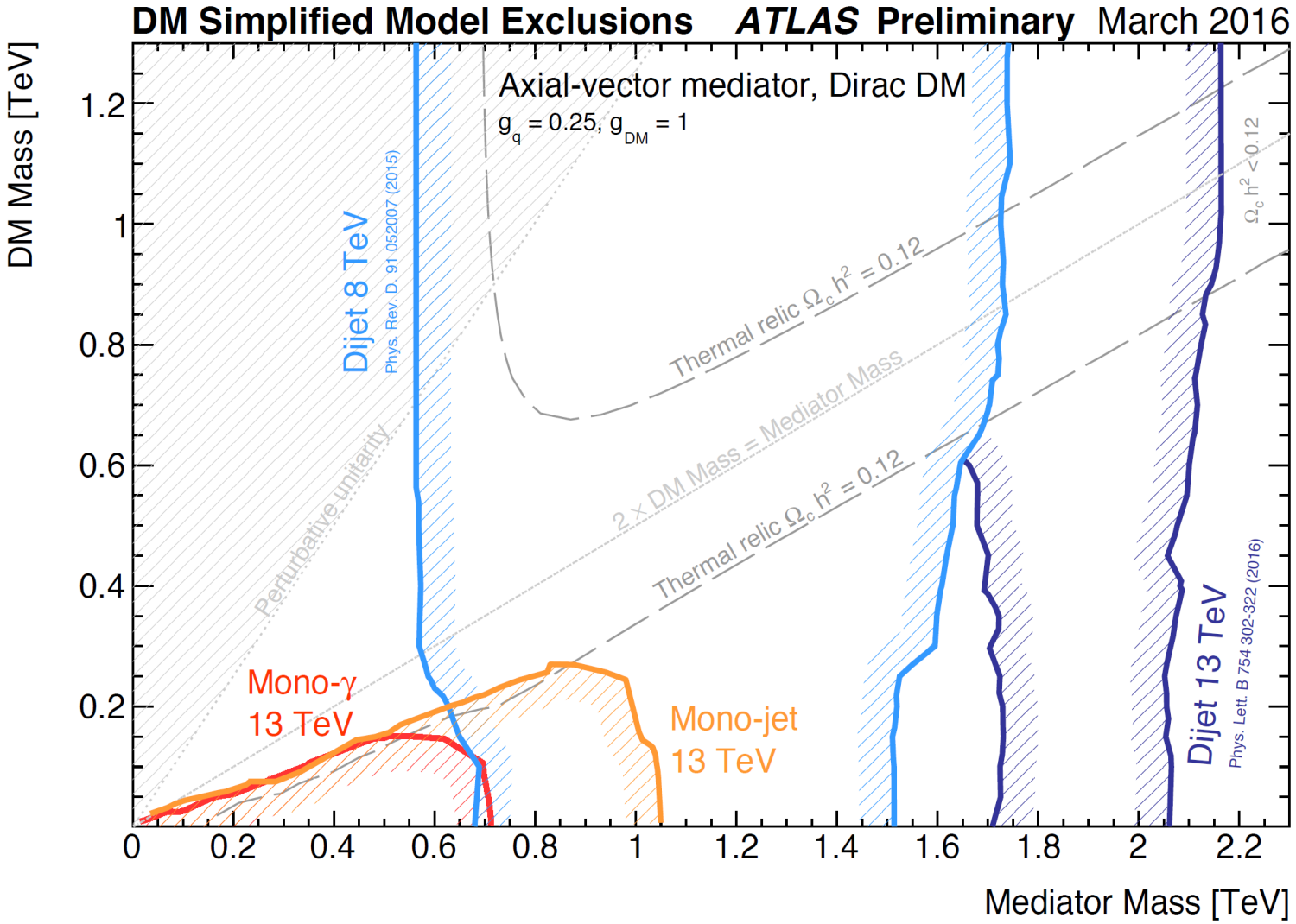
Di-jet interpretation (13 TeV)



light blue areas are excluded by 95%C.L.

- Limits on extra Z'- gauge boson
  - leptophobic model
  - limits on g_q coupling for different Z' masses

Di-jet simplified model results



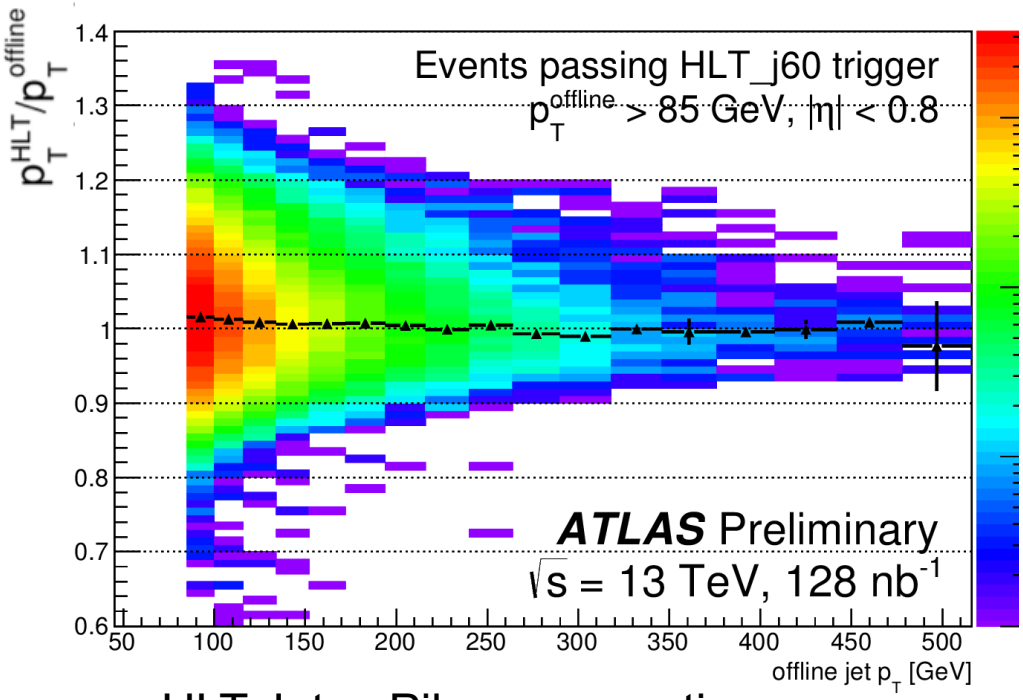
- Complementary among the search channels
- With assumed couplings (g_q=0.25, g_{DM}=1) , above regions are excluded

Low mass di-jet events

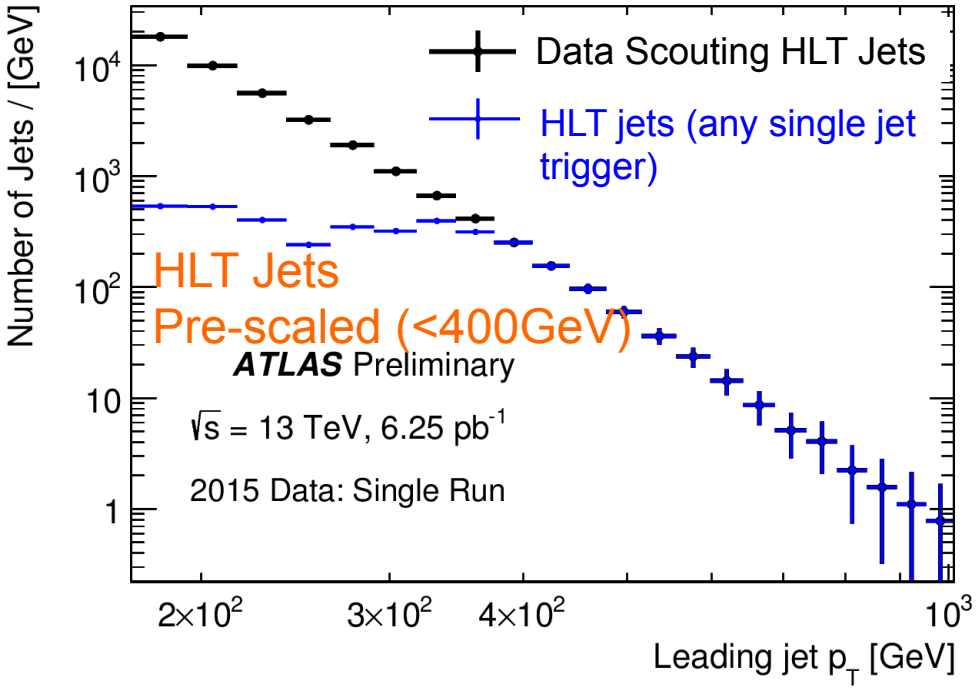
- DM/mediator may still hide in low mass with small couplings
- Low mass search → limited readout bandwidth and storage space

➔ Online data scouting (Trigger level analysis) to reduce event size and increase recorded events

- Important implementation for Run-2 (all four LHC experiments)



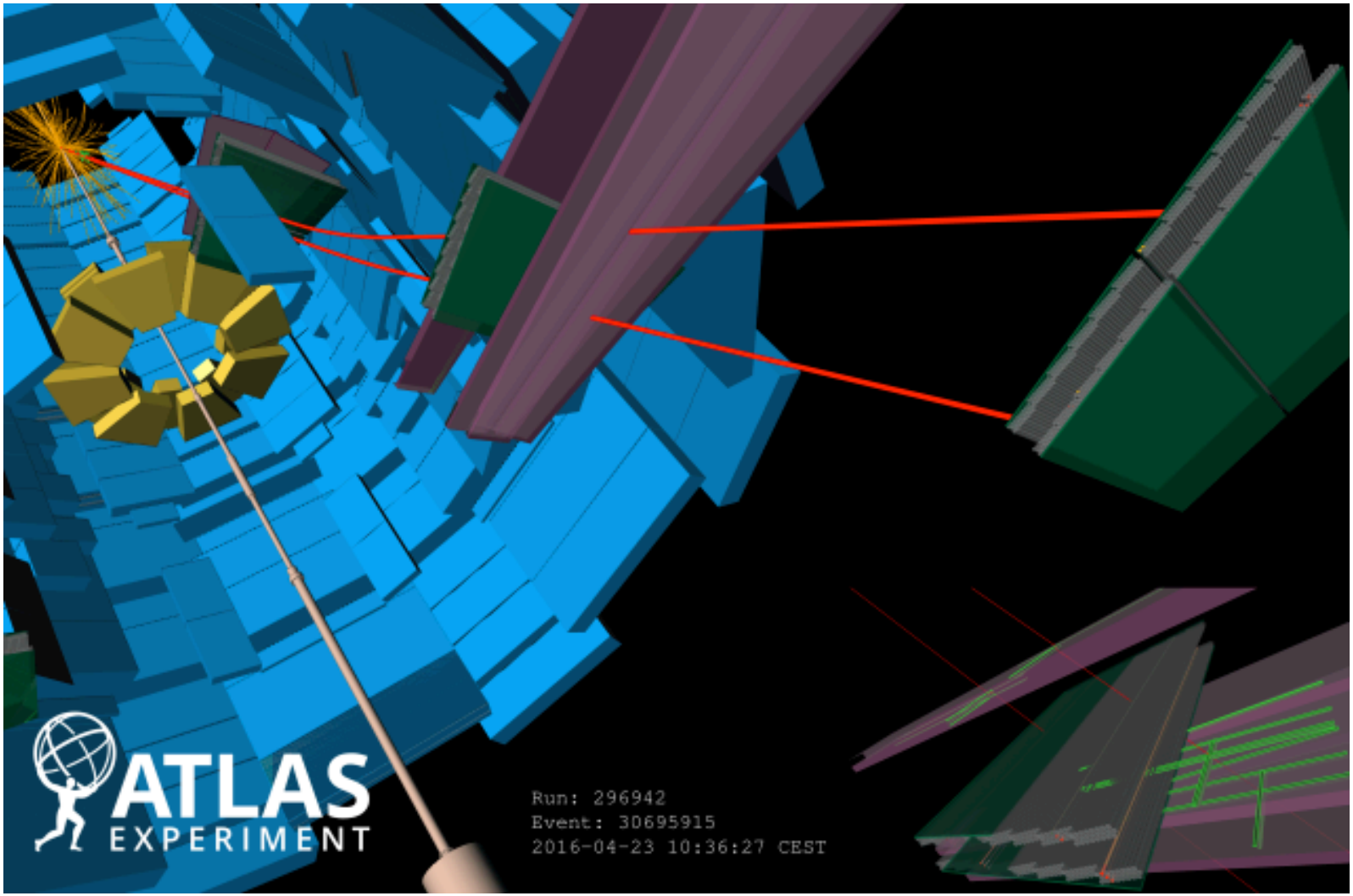
HLT Jets : Pile up correction
Jet Energy Scale applied



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults#Jet_Trigger_and_Data_Scouting_Pe

2016 Collisions has Just Started (May 6th)

ATLAS Events at 13 TeV - First 2016 Stable Beams



10% of the design luminosity → will be 100%

Conclusion

- LHC/ATLAS Run-2 started (2015, 3.2 fb^{-1})
- DM searches had new interesting results
- Searches extended in channels, parameter spaces, now uniformly interpreted via 'simplified model'
- Comparison with DD/ID experiments became valid

- LHC DM searches are complementary to non-collider searches
- LHC has just restarted operation for 2016

  expecting much higher integrated luminosity in 2016 (~25 fb^{-1} is expected)
- More exciting results are around the corner, stay tuned