DARK MATTER SEARCH ON THE MONO-HIGGS ($H\rightarrow bb$) IN ATLAS EXPERIMENT

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ON BEHALF OF ATLAS COLLABORATION

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31-07-2018

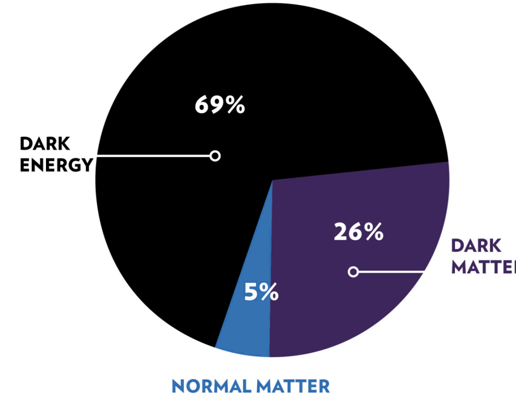
THE DARK MATTER QUESTION

Evidence of Dark Matter (DM) → Cosmological Observations

- Galaxy rotation curves, X-ray observation of galaxy collisions, Gravitational lensing, etc..

There is no evidence yet for non-gravitational interactions between DM and Standard Model (SM) particles.

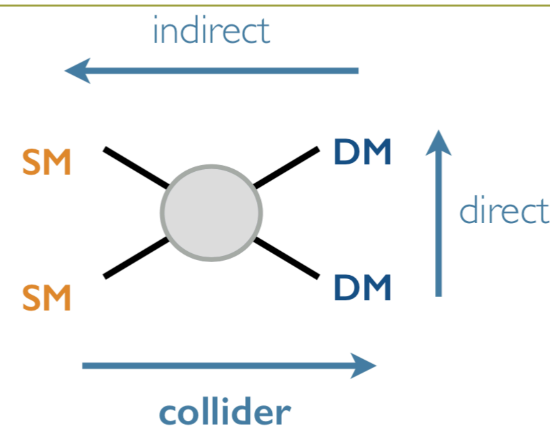
No viable DM candidate within SM



Dark Matter Searches

What do we know about DM*?

- How much: $\Omega h^2 \sim 0.12$
- Cold (Non-relativistic during structure formation)
- Non-baryonic
- Massive
- Electrically neutral (Dark)
- Stable
- Weakly interacting



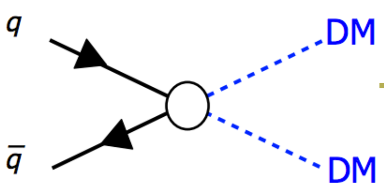
Production at Colliders

- Cannot directly detect DM particles.
- Instead infer production through large amounts of **Missing Energy**

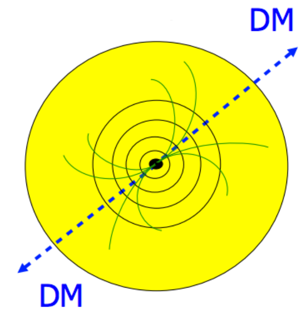
* Assuming DM as WIMP

DARK MATTER PRODUCTION AT LHC: MONO-X INTRODUCTION

The basic diagram of DM production and detection



DM doesn't interact with the detector



In the transverse plane:

2 back-to-back invisible particles

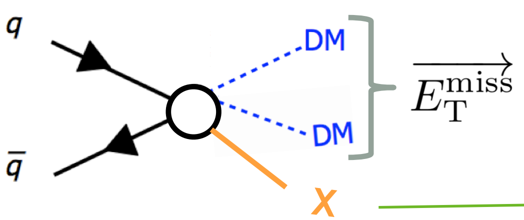
Then…how to trigger a DM event?

The "Mono-X" Topology

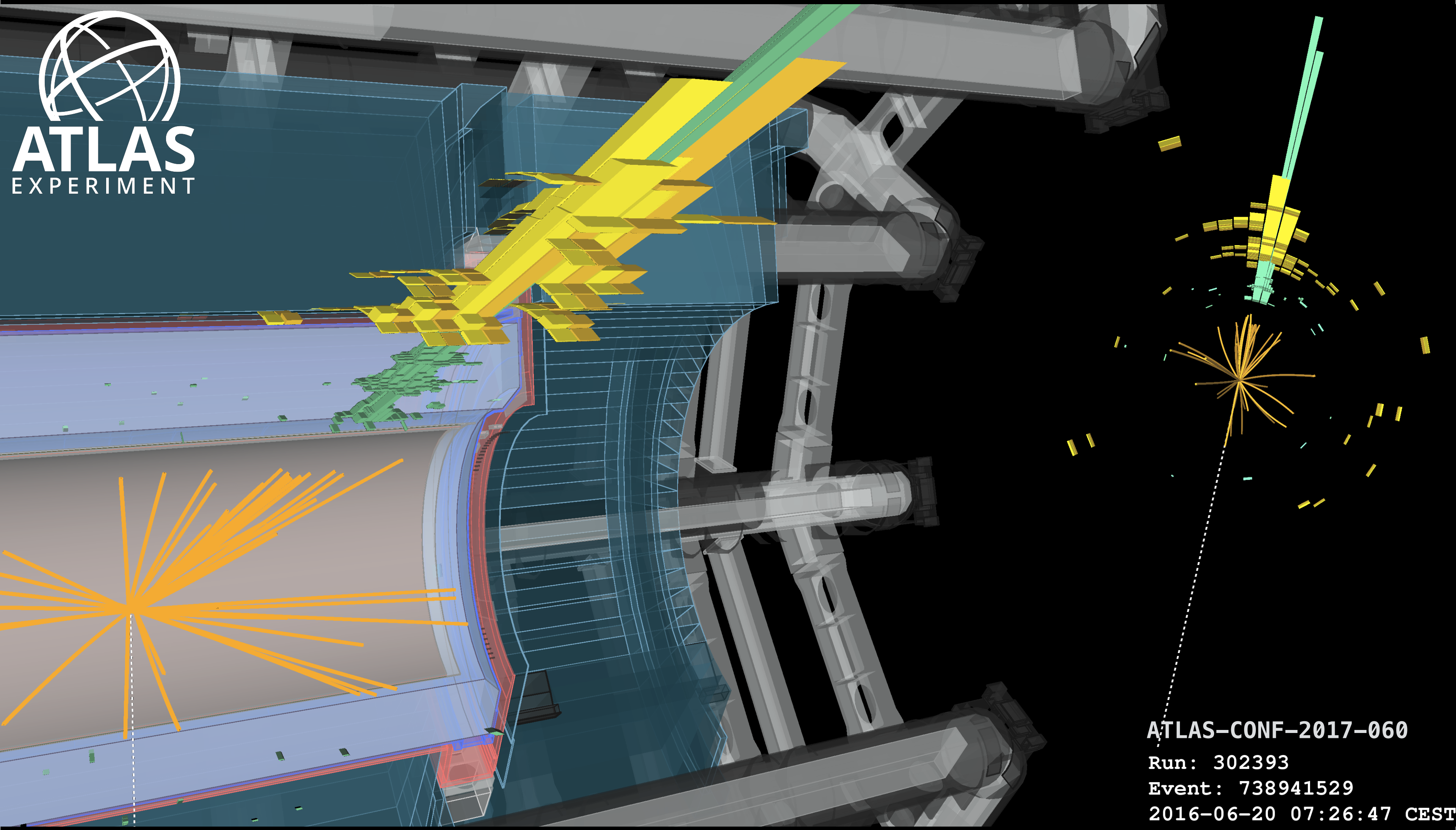
Standard Model (SM) particles ('**X**') recoils against missing transverse momentum

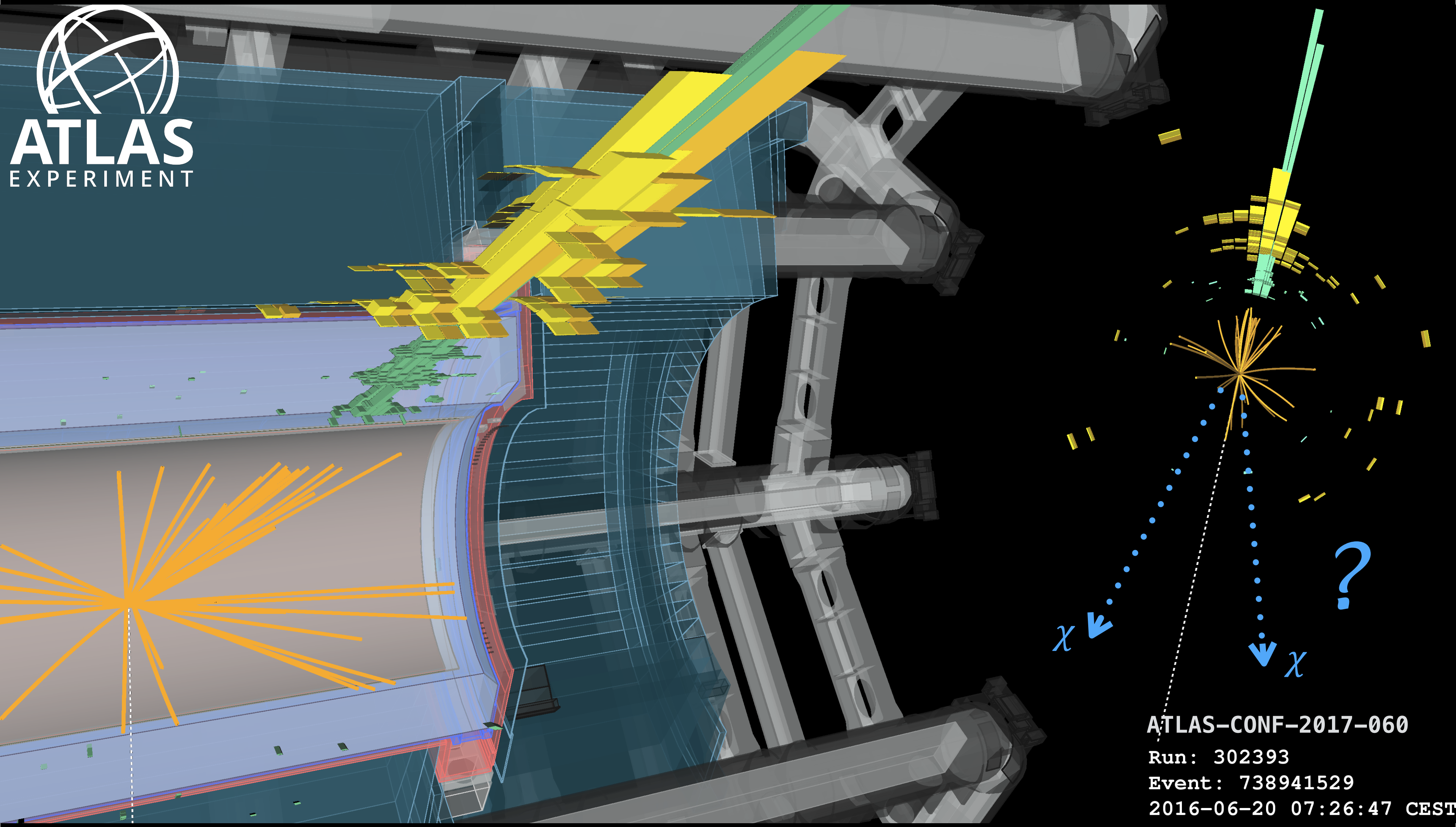
$$pp \rightarrow \not{E}_T + X$$

In the final state we look for…



- Large Missing Transverse Momentum (**MET**)
- Well defined SM particle 'X'


ATLAS
EXPERIMENT
ATLAS-CONF-2017-060
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST


ATLAS EXPERIMENT
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ATLAS-CONF-2017-060
Run: 302393
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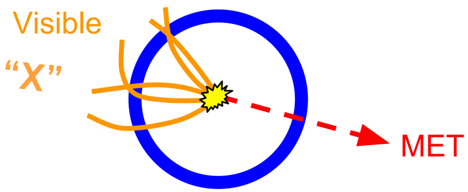
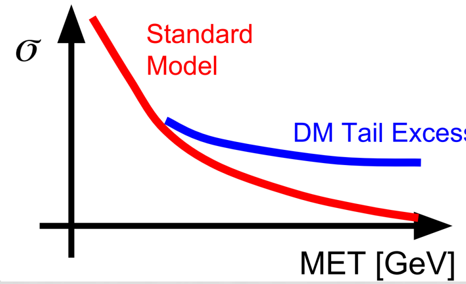
MONO-X SIGNATURES

◇ Searching for excess in energy imbalance on the transverse plane - missing transverse energy/momentum = "**MET**"

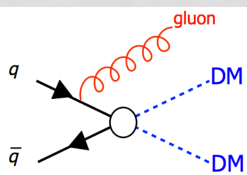
Select - Select events with "X"
- veto other activity

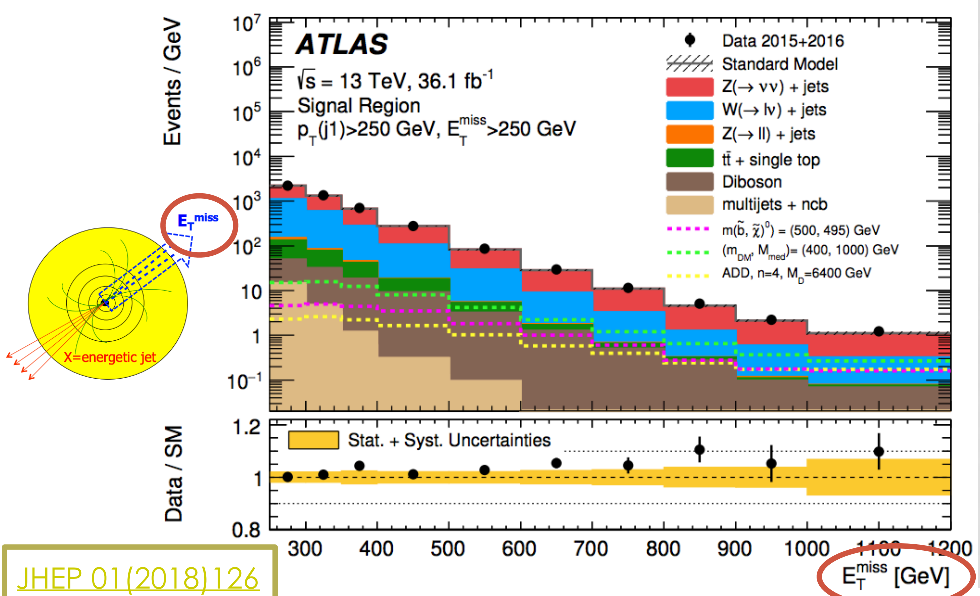


Goal - Search for excess in MET tail



If **'X'** is a radiated ISR gluon:
MONO-jet

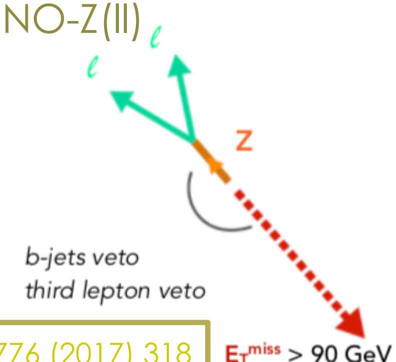




JHEP 01(2018)126

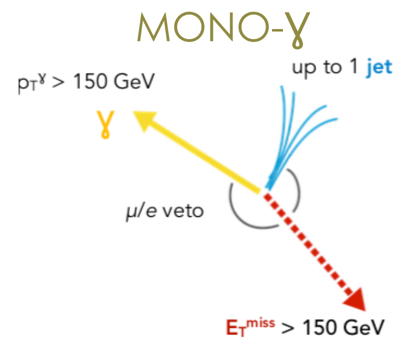
Some members of the mono-X family

MONO-Z(ll)



PLB 776 (2017) 318

MONO-ɣ



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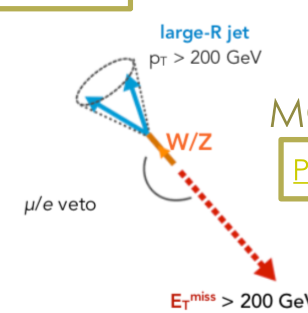

MONO-W/Z(HADRONIC)

Phys. Lett. B 763 (2016) 251

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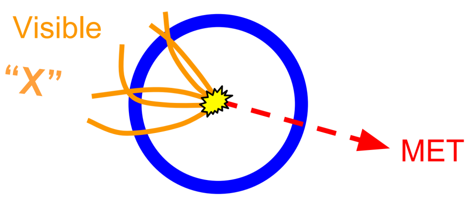
Select - Select events with "X"
- veto other activity



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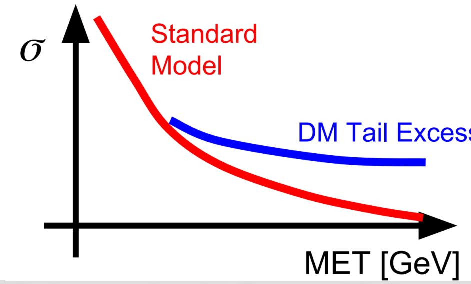

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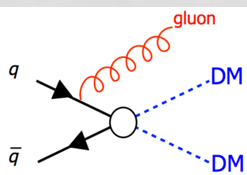

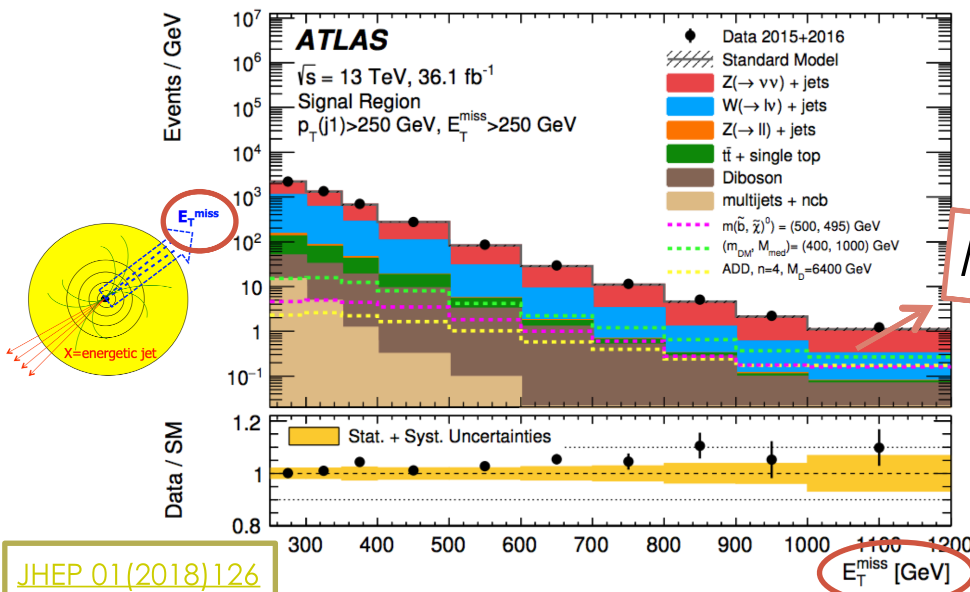

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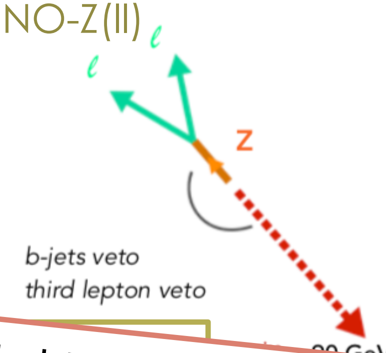

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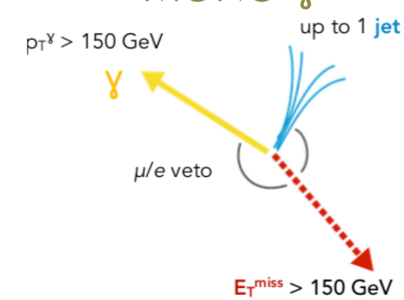

Model Interpretation?

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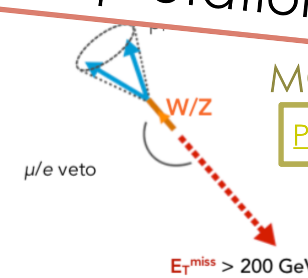

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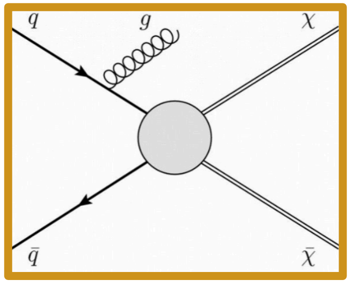
DARK MATTER MODELS

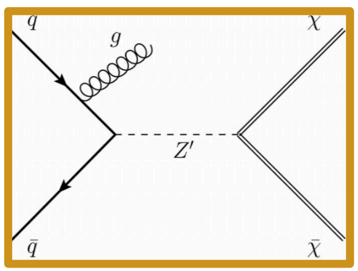
Completeness / Complexity

Effective Field Theories



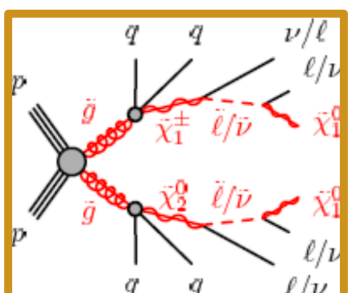
- ◇ Contact interaction assumed between DM and SM

Simplified Models



- ◇ Renormalizable minimal extension of SM
- ◇ Involving ***DM candidate*** + ***Mediator***

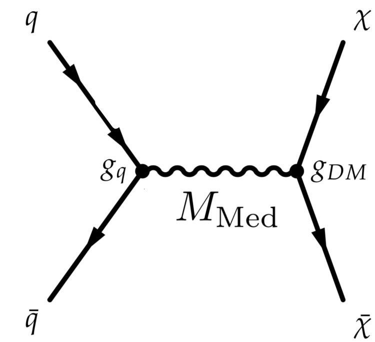
UV complete Model



- ◇ Can explain the hierarchy and other SM problem
- ◇ Naturally provide DM candidate

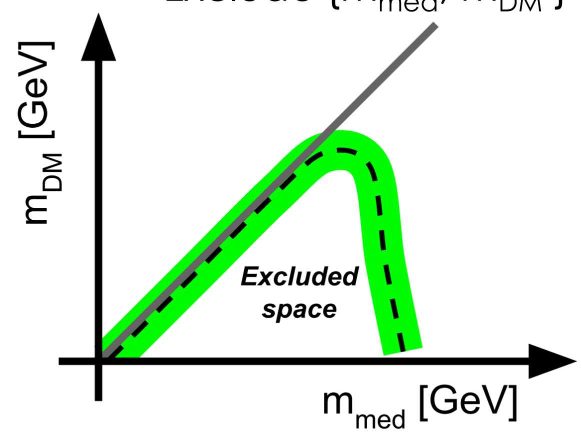
Mostly free parameters:

- ◇ mediator mass (M_{Med})
- ◇ WIMP mass (m_χ)
- ◇ 2 couplings (g_{DM} , g_q)



4-dimensional problem, projecting limits onto a 2-D plane

- Ex.: Choose $\{g_q, g_{DM}\}$
- → Exclude $\{m_{med}, m_{DM}\}$



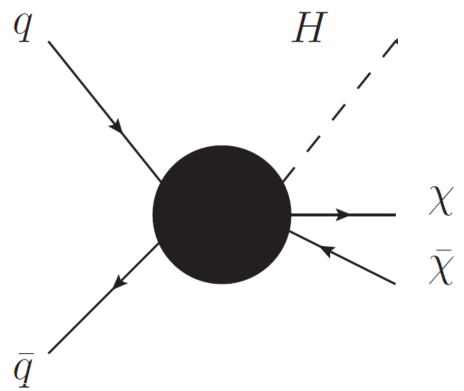
Benchmark models from:
ATLAS-CMS DM forum (1507.00966)
LHC DM Working group (link)

MONO-H MOTIVATION

◇ Higgs boson discovery in run1 provides unique method for probing dark matter at LHC

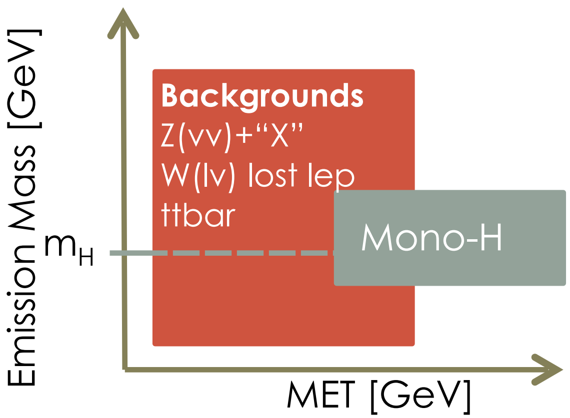
◇ No Initial State Radiation Higgs

- More closely connected to DM production
- Provides direct probe of DM-SM coupling



◇ Signature extended beyond a high MET tail

- The visible part of the event has a characteristic energy/ mass scale.



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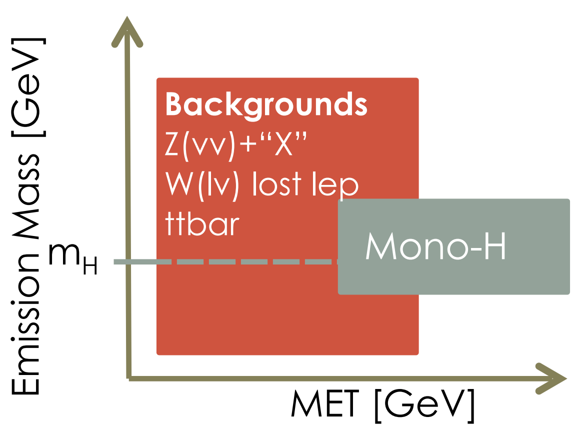
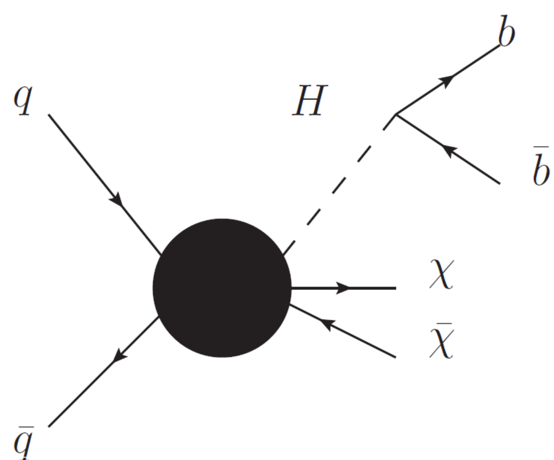
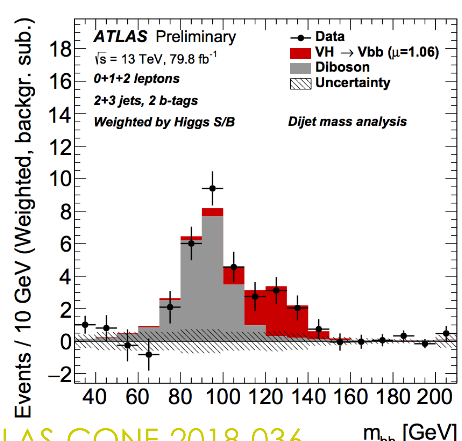




Bonus:
Observation of VH→Vbb

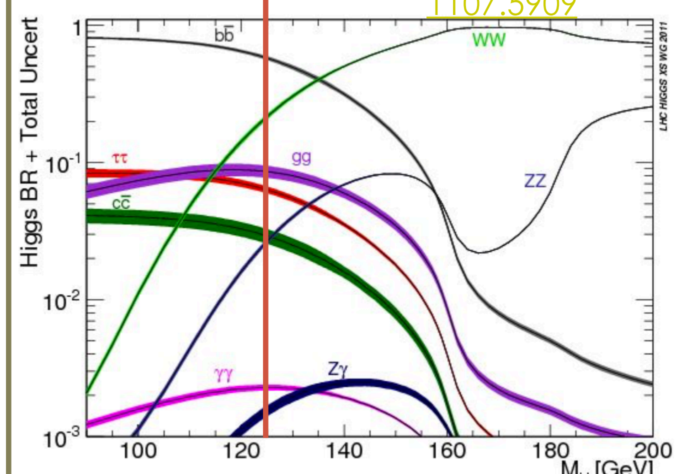


ATLAS-CONF-2018-036

◇ H→bb dominant decay mode

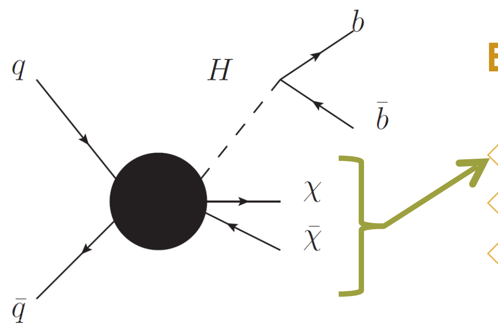
- H(125)→bb branching ratio is ~57%

1107.5909



OVERVIEW OF THE MONO-H STRATEGY

Search for DM produced in association with Higgs→bb. Final state: **MET + H(bb)**



Event selection overview:

- Trigger on high MET
- No leptons (e/μ/τ veto)
- Identify H→bb decay

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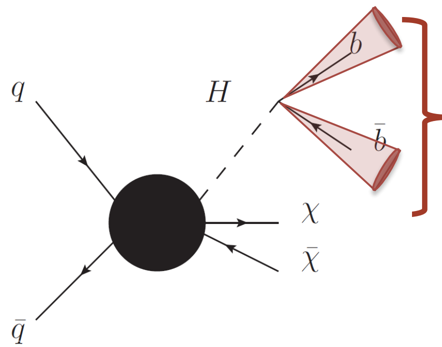

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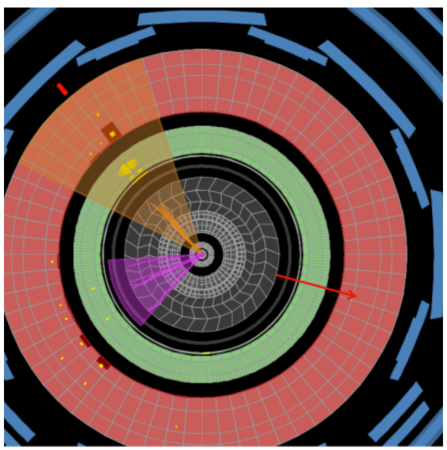
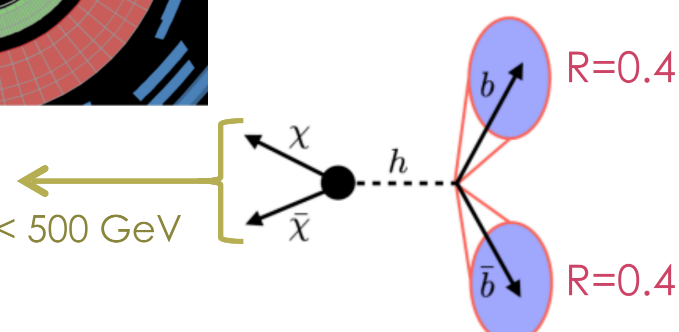
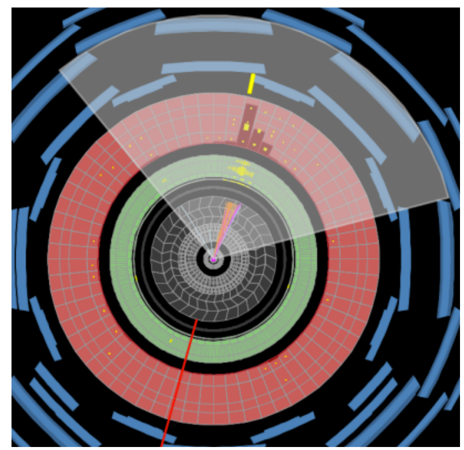
Resolved Regime



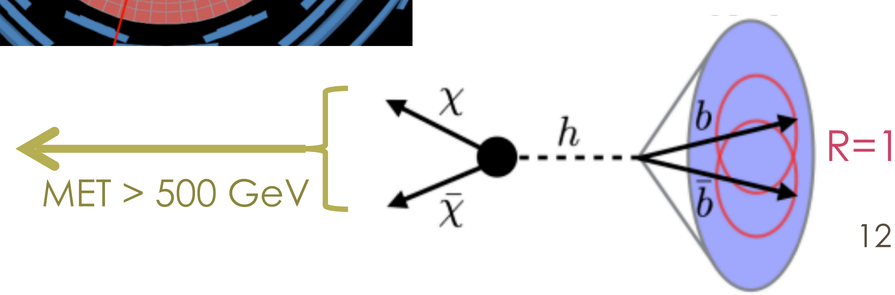
Higgs is reconstructed with a pair of small radius jets (j)



Merged Regime

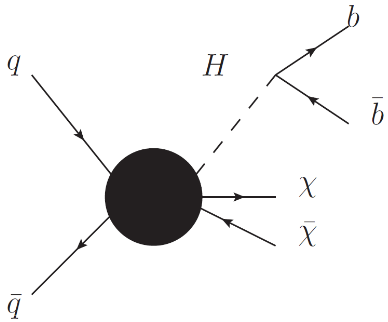


For boosted events, the Higgs is reconstructed with a large radius jet (J) with substructure



MONO-H: BACKGROUNDS AND REGIONS

Search for DM produced in association with Higgs→bb. Final state: **MET + H(bb)**



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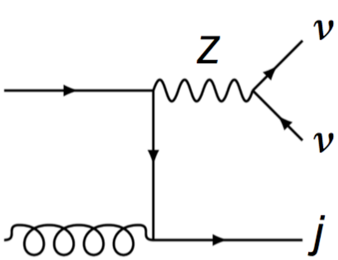
Dominant Backgrounds

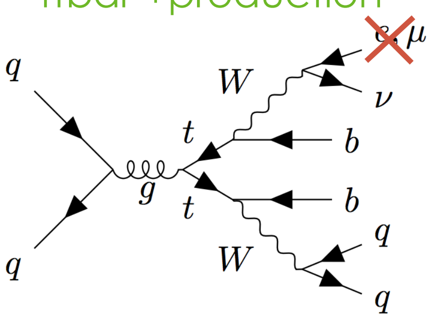
Z→νν+ Jets



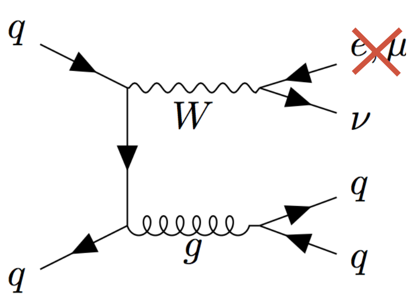
Real MET

→ Real jets

ttbar +production



W→ l(e/μ)ν



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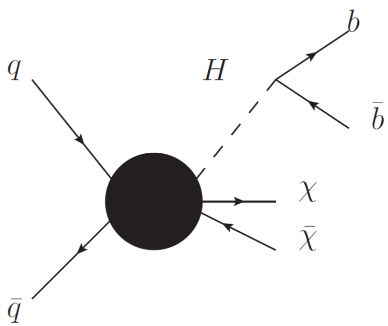

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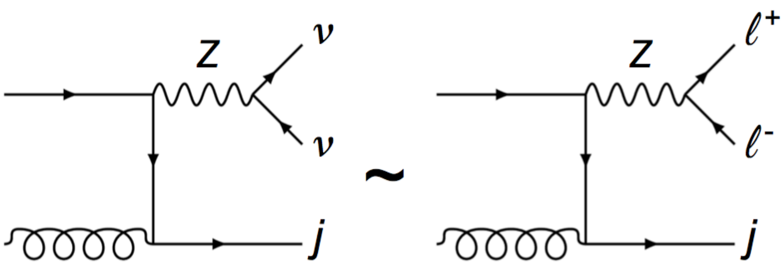

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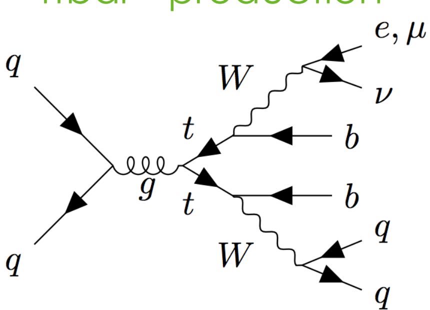

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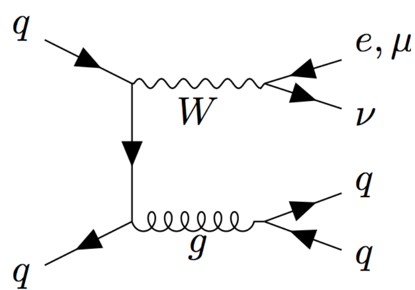
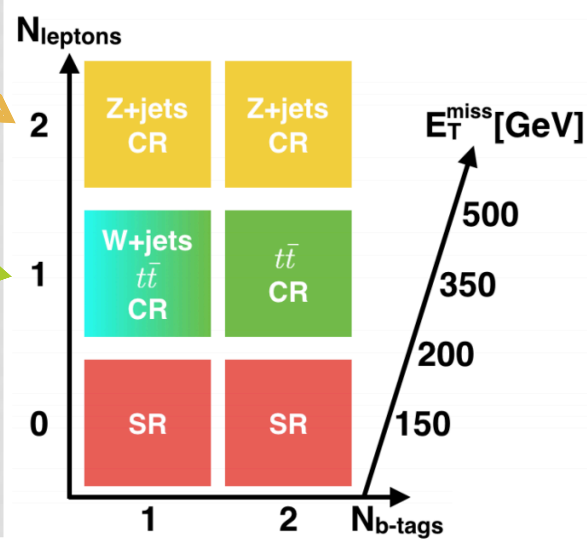


Signal and Control Regions

- 0-lepton Signal Region
- 1-lepton, 2-lepton Control Regions
- Binned in N(b-tags), MET



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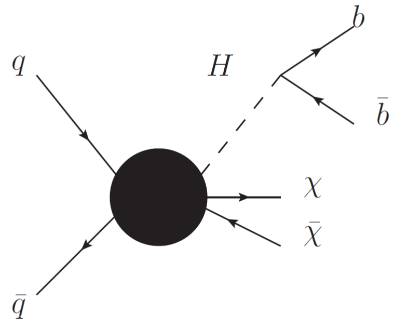

Event selection overview:

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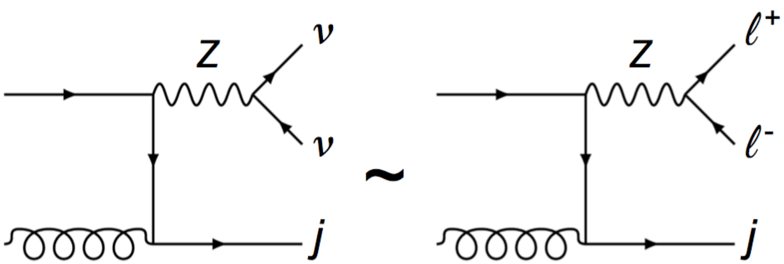
→ Search for bumps in mjj/mJ around 125 GeV

Dominant Backgrounds

Z→νν+ Jets



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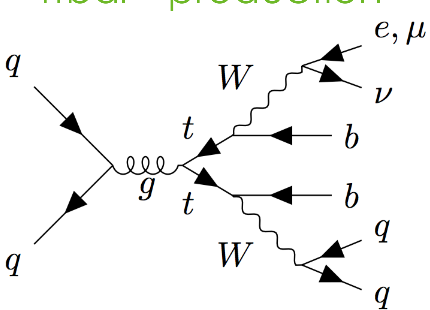

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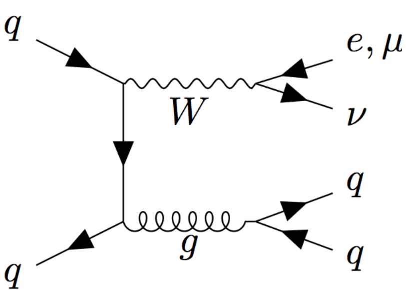

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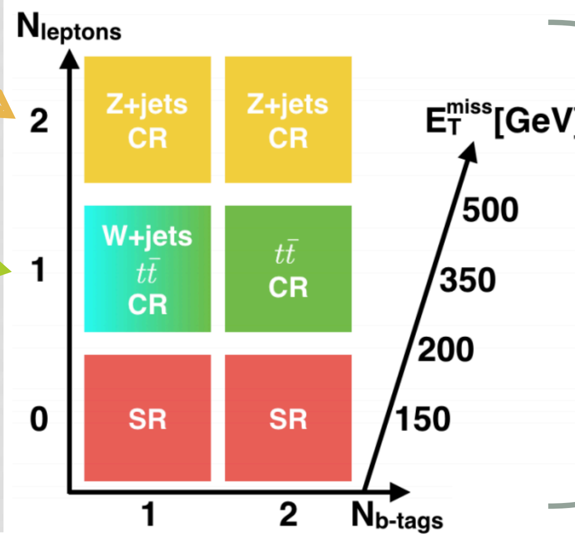
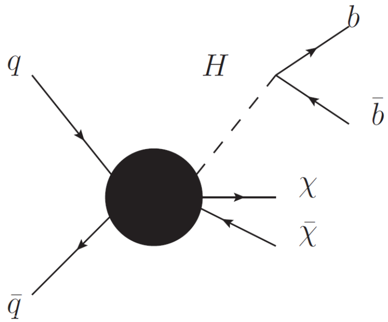


Simultaneous fit to $mH_{candidate}$

MONO-H: INTERPRETATION

Search for DM produced in association with Higgs→bb. Final state: **MET + H(bb)**



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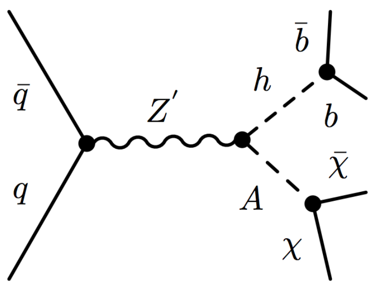
Interpretation of the signal

Z'+2HDM model (Type II)

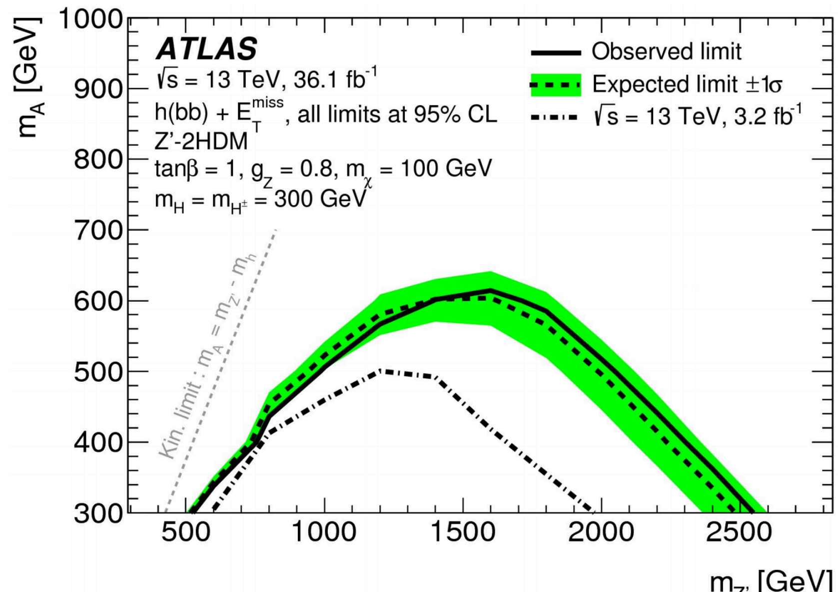


Fixed Parameters

- $m_χ$ = 100 GeV
- tan β = 1.0
- g_{Z0} = 0.8
- $m_H = m_{H\pm}$ = 300 GeV
- BR(A → χχ) = 100%

1402.7074

Since no significant deviation from SM prediction is observed, the results are interpreted as exclusion limits.



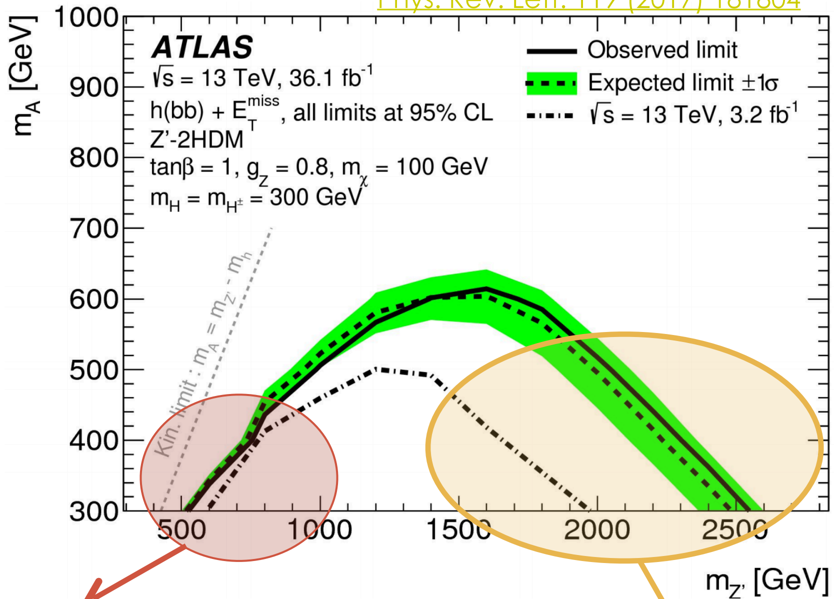
Result using full 2015 + 2016 dataset: 36.1 / fb

Phys. Rev. Lett. 119 (2017) 181804

HOW TO IMPROVE MONO-H ANALYSIS?

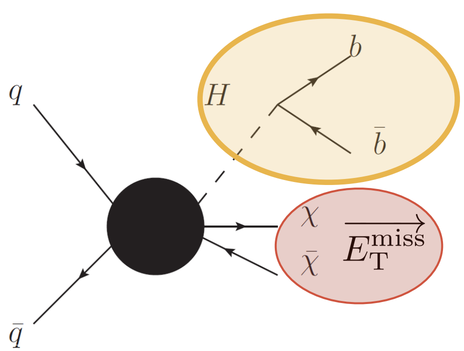
Commissioning and exercising NEW Combined Performance improvements

Phys. Rev. Lett. 119 (2017) 181804



Object based MET Significance

Test the impact of an object-based MET Significance in order to reduce the multi-jet background and/or improve its estimation



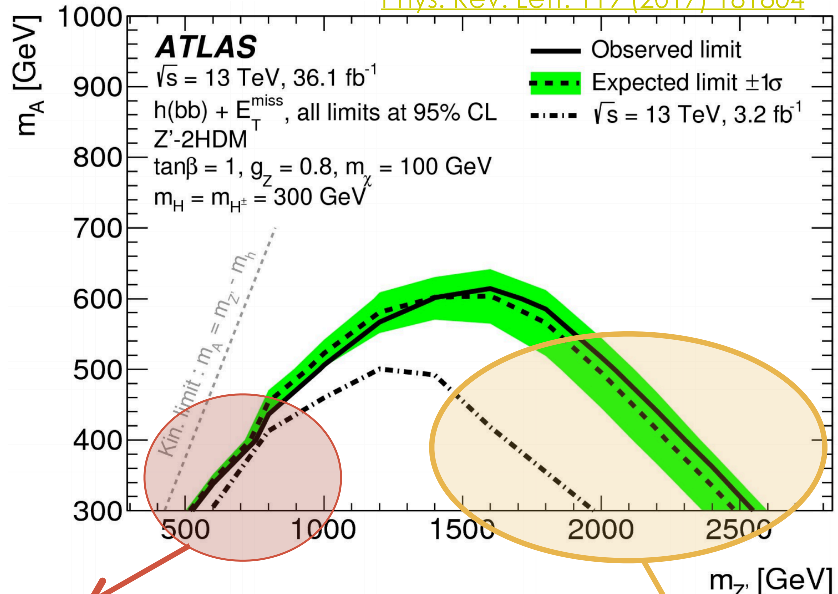
Variable Radius track jets

Establish VR track jets as a technique to increase the sensitivity in boosted topologies with b-tagging.

HOW TO IMPROVE MONO-H ANALYSIS?

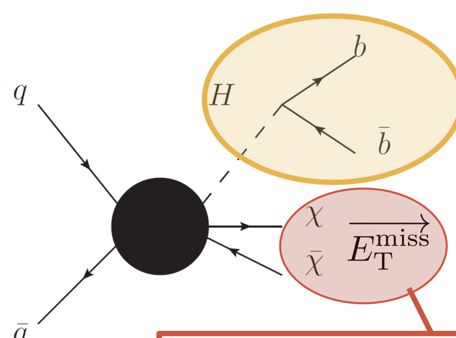
Commissioning and exercising NEW Combined Performance improvements

Phys. Rev. Lett. 119 (2017) 181804



Object based MET Significance

Test the impact of an object-based MET Significance in order to reduce the multi-jet background and/or improve its estimation



Variable Radius track jets

Establish VR track jets as a technique to increase the sensitivity in boosted topologies with b-tagging.

MET performance is critical for dark matter searches

MISSING TRANSVERSE ENERGY RECONSTRUCTION

◇ **Missing Transverse Energy (MET)**

$$\sum_i \vec{p}_i = 0 \quad \Longrightarrow \quad \sum_{\text{observable}} \vec{p}_i + \vec{E}_T^{\text{miss}} = 0 \qquad \vec{E}_T^{\text{miss}} = - \sum_{\text{observable}} \vec{p}_i$$

When something is missing

Two effects could imply an imbalance in the total transverse momentum (MET ≠ 0)

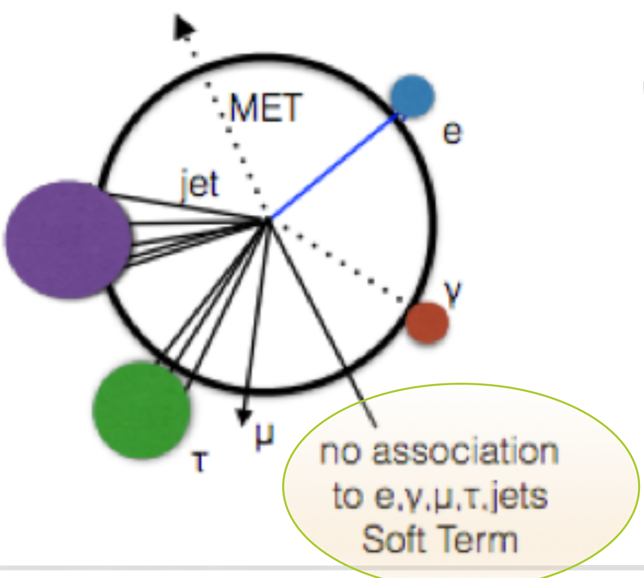
- ◇ **Non-interacting particles** (True MET): SM particles (neutrinos), new physics (Dark Matter, SUSY, etc.)
- ◇ **Fake detection** (Fake MET): Objects misreconstruction, detector effects (dead regions).

Reconstructed Met = Calorimeter Objects + Muons + Soft Terms

Calorimeter Objects: Electrons, Photons, Taus, Jets

Electrons, Photons, Taus, Jets + Muons: Hard Objects

Soft Terms: Every signal which can't be clearly identified/calibrated.



- Track based Soft Term (TST)
- Calorimeter based Soft Term (CST)

OBJECT-BASED MISSING TRANSVERSE MOMENTUM SIGNIFICANCE

- Events in which the reconstructed Missing Transverse Momentum, MET, is either consistent with contributions solely from particle-measurement resolutions and efficiencies or consistent with genuine MET can be distinguished by evaluating the **Met Significance S**.

Object-based MET Significance Definition

ATLAS-CONF-2018-039

- Based on the expected resolutions for all objects that enter the MET reconstruction
- Event by event calculated

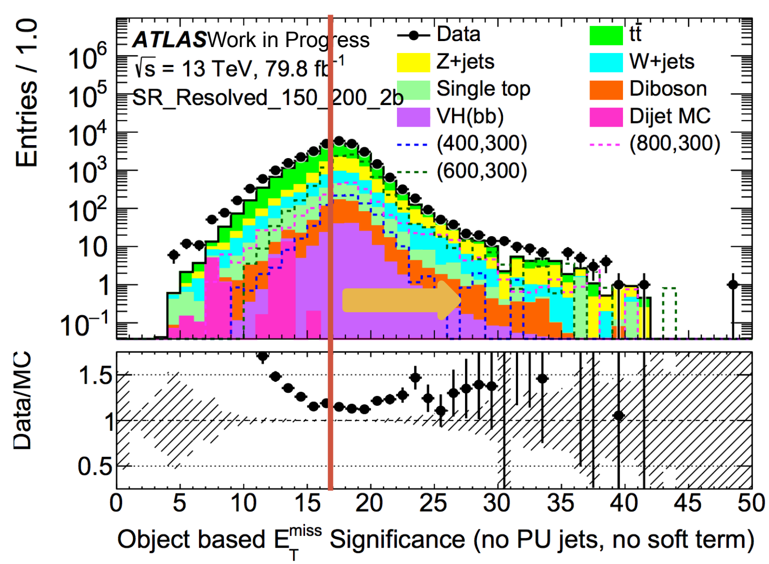
$$\mathcal{S}^2 = 2\ln\left(\frac{\mathcal{L}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})}{\mathcal{L}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|\mathbf{0})}\right) = (\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})^{\mathrm{T}}\left(\sum_i \mathbf{V}_i\right)^{-1}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})$$

Covariance Matrix for each object

This novel definition depends on the multiplicities, types, and kinematics of the objects measured in each event

- The multijet background is originated from pure strong interactions
- Met significance can help to identify and separate multijet background with respect to EW backgrounds and DM signals

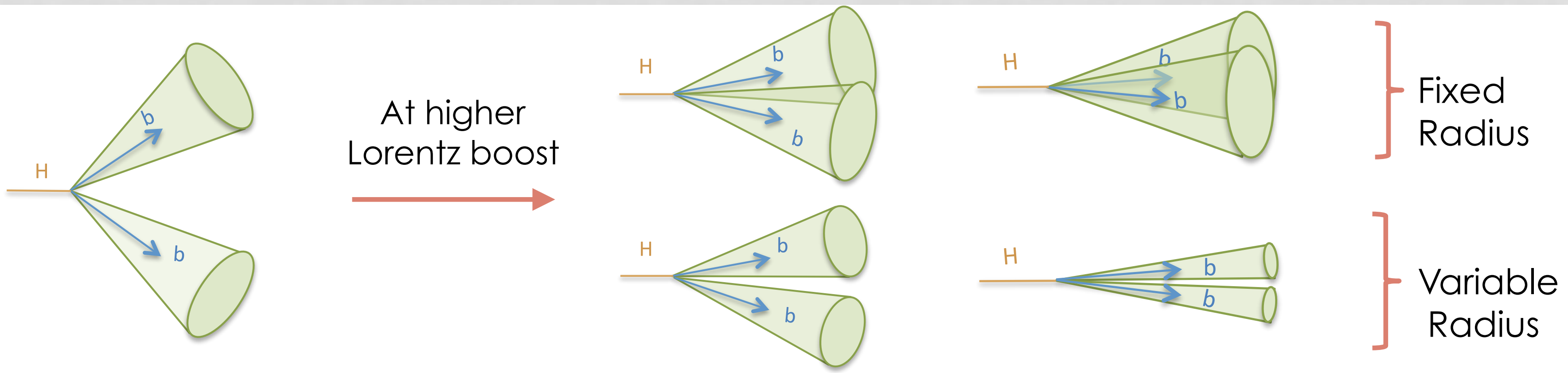
New requirement in resolved selection to suppress multijet background



More than 95% of dijet can be rejected while retaining a signal efficiency ~90%

VARIABLE RADIUS JETS

Merging of Fixed Radius (FR) track jets causes loss of acceptance × efficiency for signals with highly boosted topologies.

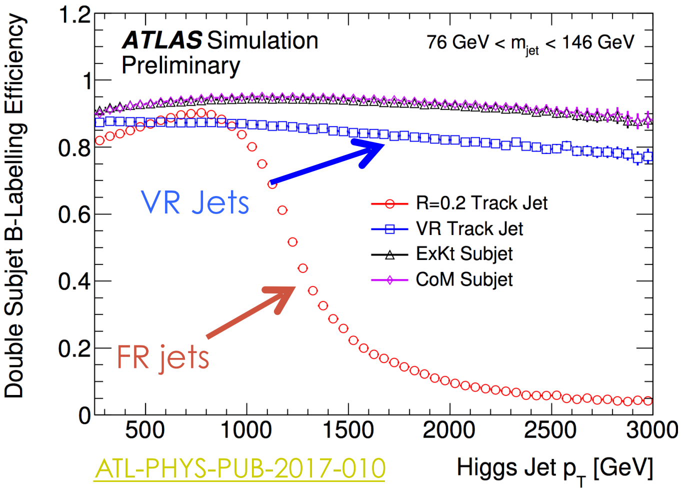


The reconstruction of sub-jets used for b-tagging in the merged regime improves using the VR track jets, resulting in a higher b-tagging efficiency.

VR track-jets

- Used for the first time in analysis!
- anti-kt, R = 0.02-0.4, ρ= 30 GeV

$$R \rightarrow R_{\text{eff}}(p_T) \approx \frac{\rho}{p_T}$$



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VARIABLE RADIUS JETS IN MONO-H

Improve the gain in selection efficiency for large $m_{Z'}$

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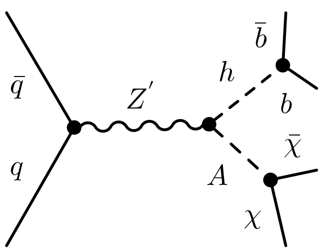

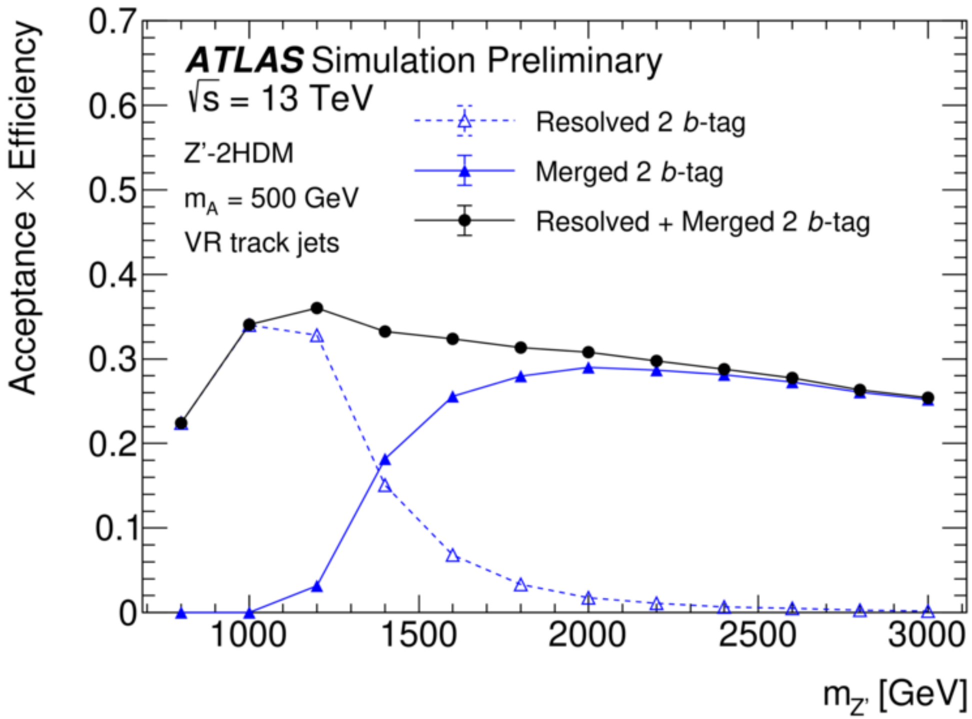

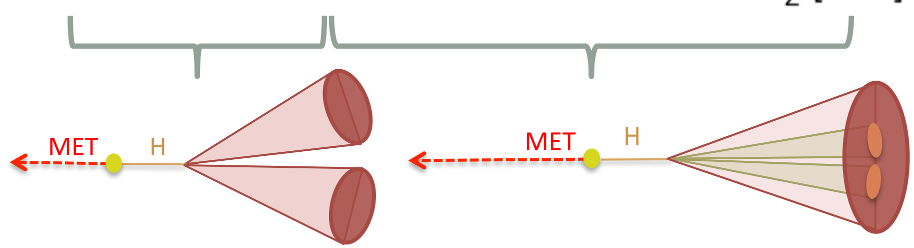

Good complementarity of two regimes

DISTRIBUTIONS AFTER FIT

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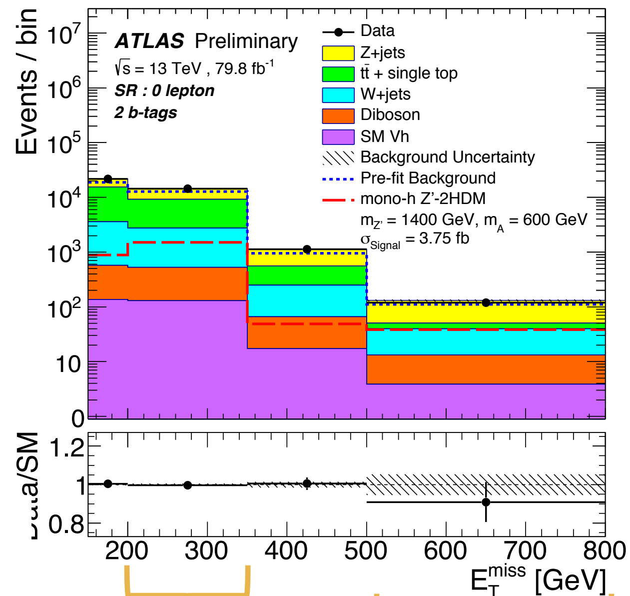

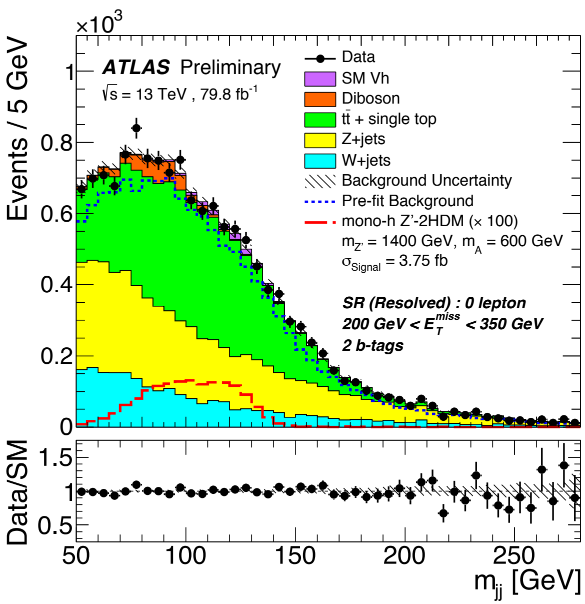

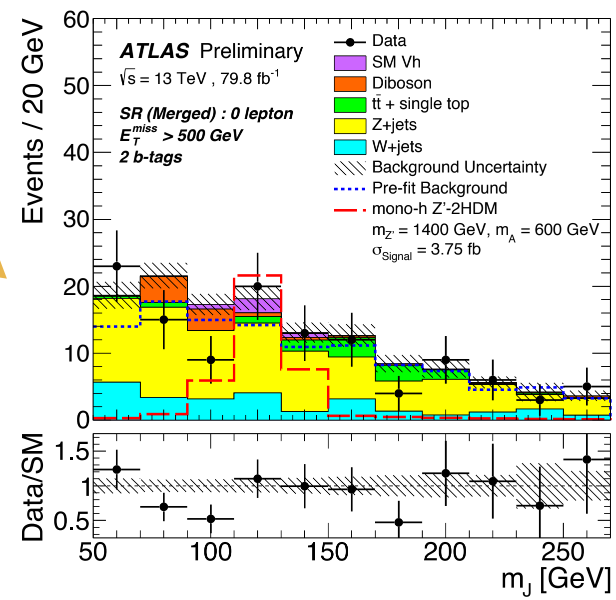

No excess in data observed

⇒ constrain model parameters with exclusion limit contour

EXCLUSION LIMIT

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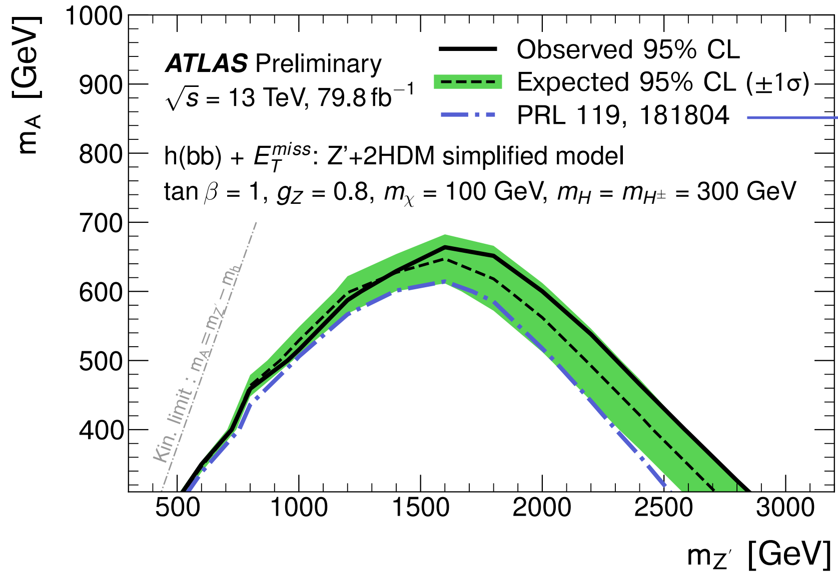
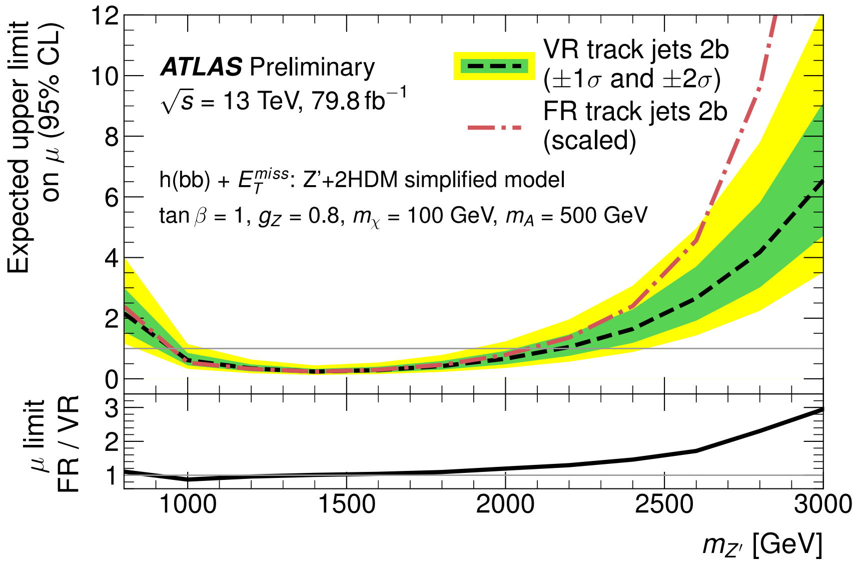
Model parameters excluded at 95%CLS:
mZ’ ≤ 2.8 TeV and
mA ≤ 600 GeV



With FR

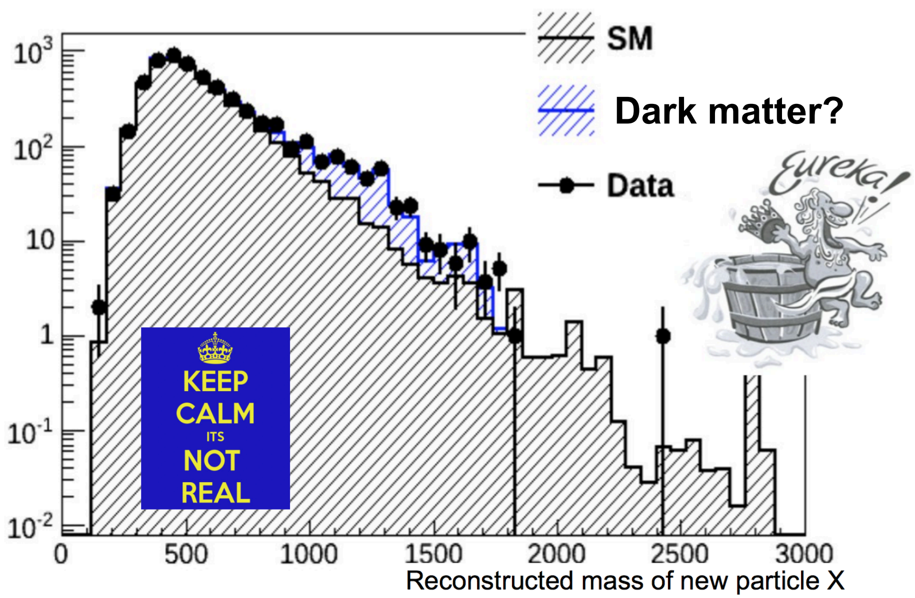
The improvement from using VR track jets



3× improvement driven by VR tracks-jets in boosted region!

CONCLUSIONS

- Broad ATLAS search program to constrain WIMP production at the LHC
- Search for Dark Matter with Higgs boson (→ bb) using 79.8 fb of pp collisions at √s=13TeV
- No significant deviation from Standard Model prediction observed.
- Exclusion contour for Z'+2HDM benchmark model extended up to mZ' ≤ 2.85 TeV for mA=300 GeV
- First time use of VR track jets in ATLAS: helps to maintain double b-tagging efficiency also in highly boosted topologies
- Object based MET significance was validated and commissioned in this analysis. First physics usage.
- More data to analyse…stay tuned for results with full Run-2 dataset!



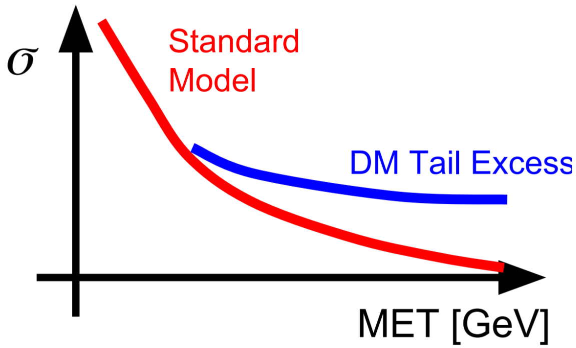
BACKUP SLIDES

MONO-X GENERAL STRATEGY

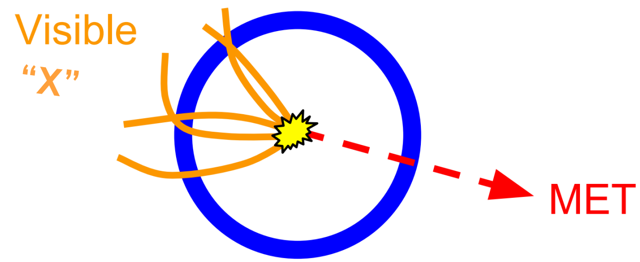
Similar generic strategy followed by Mono-X searches

- Searching for excess in energy imbalance on the transverse plane - missing transverse energy/momentum = "**MET**"

Goal - Search for excess in MET tail

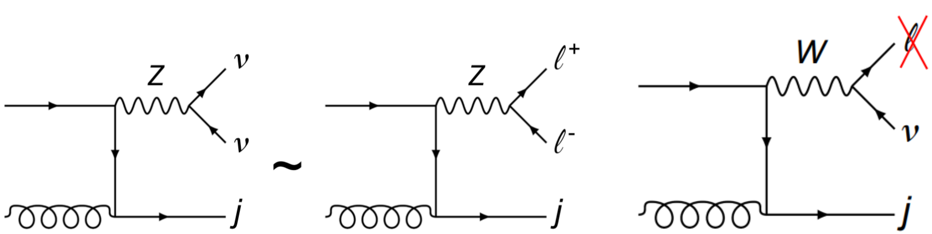


Select - Select events with "X"
- veto other activity



Backgrounds

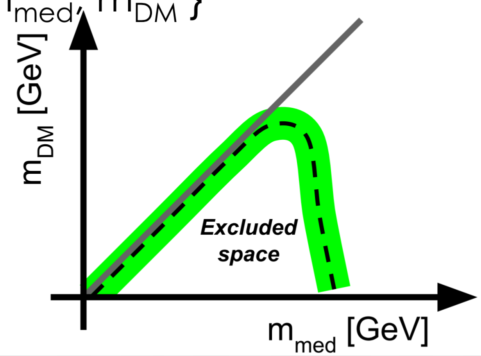
- Z(νν)+"X", W(lν) lost lep, ttbar
- Dedicated CRs to correct MC



Discovery!

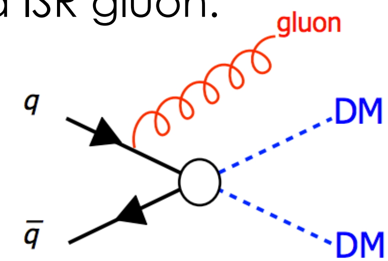
Otherwise, exclude regions of parameter space

- Ex.: Choose $\{g_q, g_{DM}\}$
- → Exclude $\{m_{med}, m_{DM}\}$

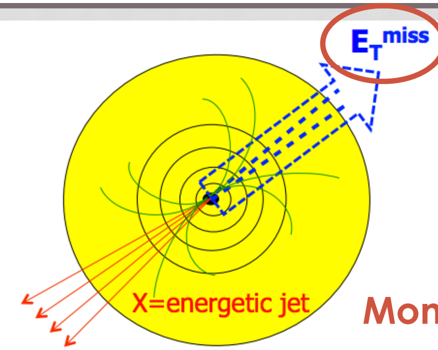


MONO-X SIGNATURES

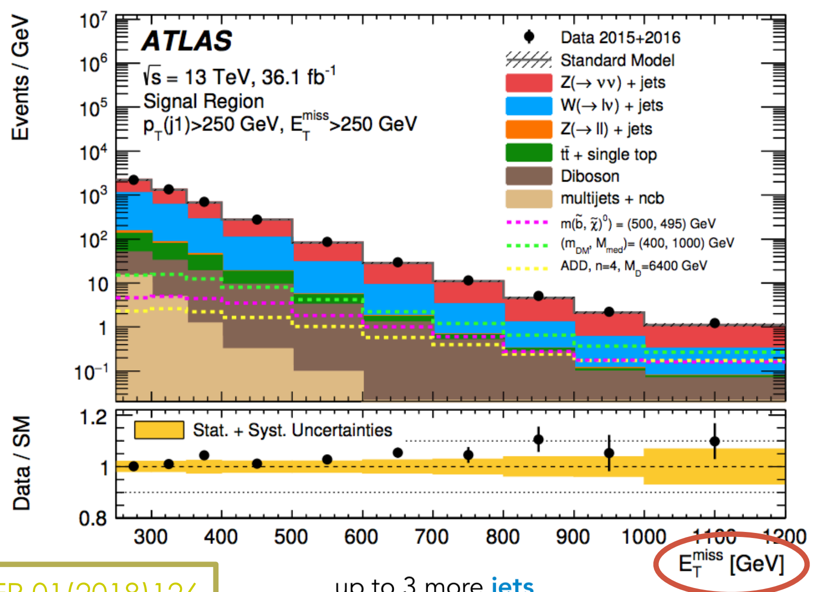
Example: If **'X'** is a radiated ISR gluon:



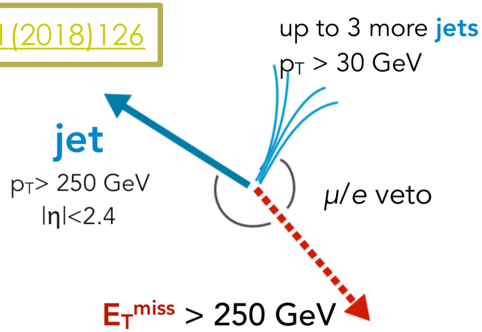
E and P conservation →



Mono-Jet

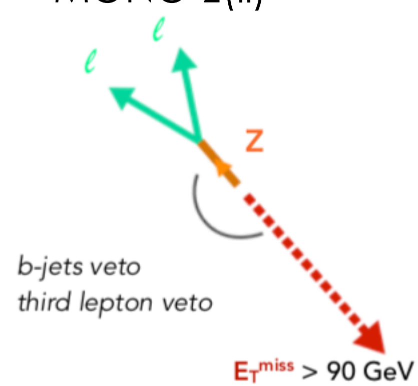


JHEP 01(2018)126



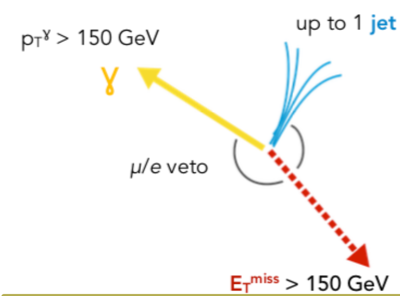
Some members of the mono-X family

MONO-Z(ll)



PLB 776 (2017) 318

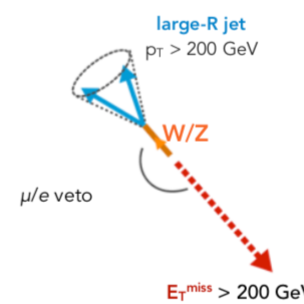
MONO-ɣ



Eur. Phys. J. C 77 (2017) 393

MONO-W/Z(HADRONIC)

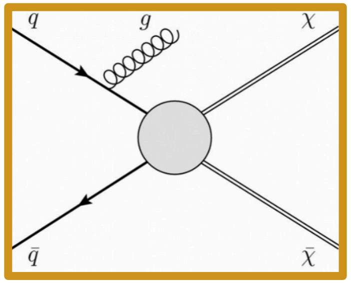
Phys. Lett. B 763 (2016) 251



DARK MATTER MODELS

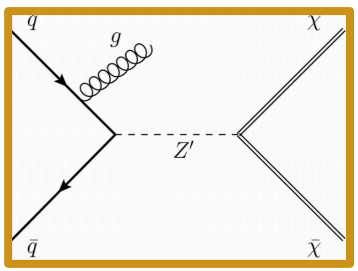
Completeness / Complexity

Effective Field Theories



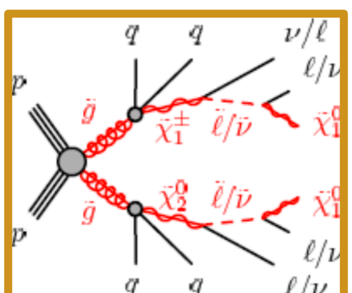
- ◇ Contact interaction assumed between DM and SM

Simplified Models



- ◇ Renormalizable minimal extension of SM
- ◇ Involving ***DM candidate*** + ***Mediator***

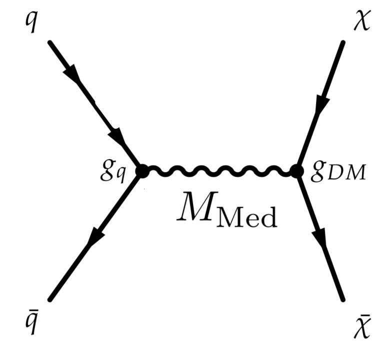
UV complete Model



- ◇ Can explain the hierarchy and other SM problem
- ◇ Naturally provide DM candidate

Mostly free parameters:

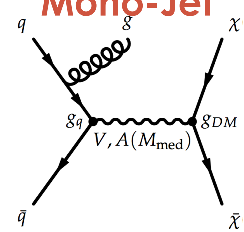
- ◇ mediator mass (M_{Med})
- ◇ WIMP mass (m_χ)
- ◇ 2 couplings (g_{DM} , g_q)



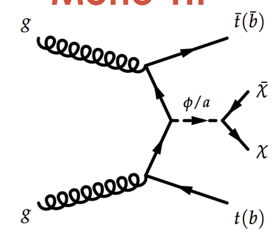
4-dimensional problem, projecting limits onto a 2-D plane

Benchmark models from:
ATLAS-CMS DM forum (1507.00966)
LHC DM Working group (link)

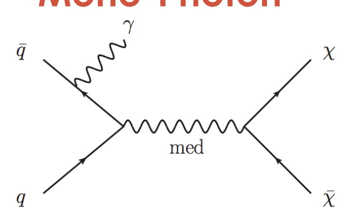
Mono-Jet



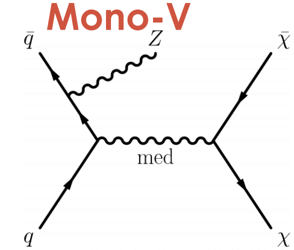
Mono-HF



Mono-Photon



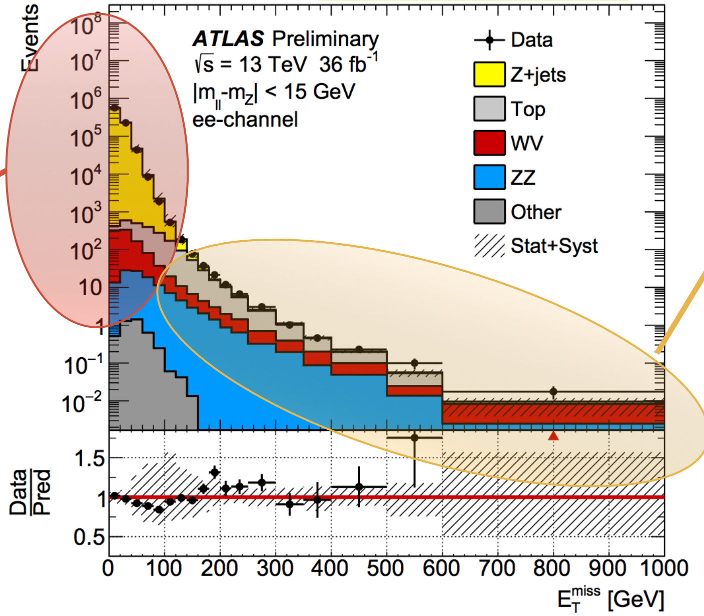
Mono-V



MISSING TRANSVERSE ENERGY PERFORMANCE

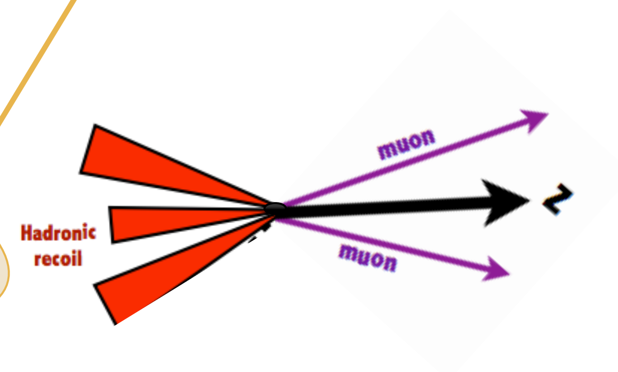
In order to study the performance of the MET, we want to consider a clean process without genuine MET: Z→ leptons + jet

ATLAS-CONF-2018-038



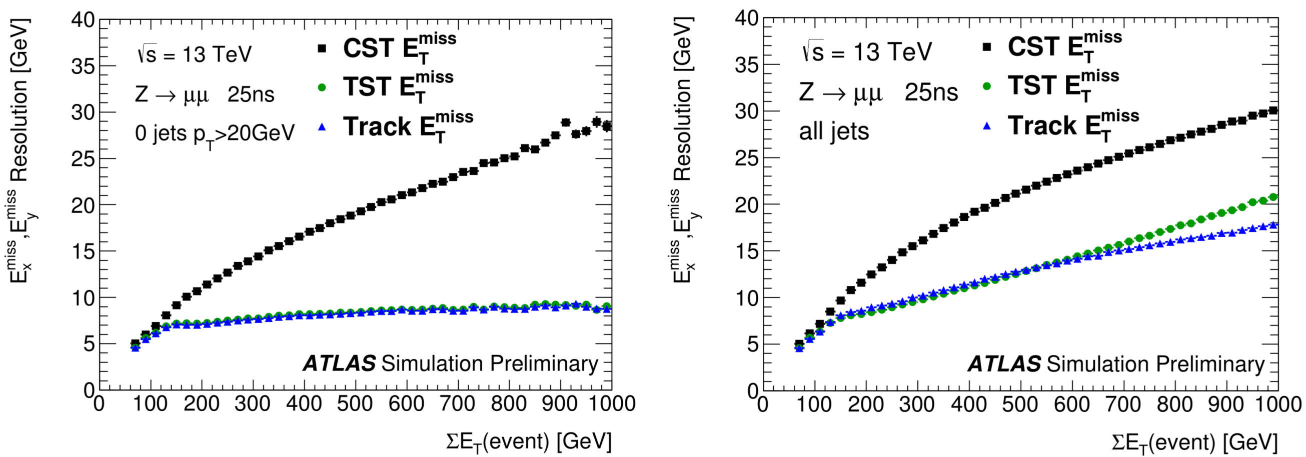
The bulk of the distribution mostly provided by fake MET reconstruction

True MET issued from background processes



ATL-PHYS-PUB-2015-023

MET Resolution



MISSING TRANSVERSE MOMENTUM SIGNIFICANCE

◇ Events in which the reconstructed Missing Transverse Momentum, MET, is either consistent with contributions solely from particle-measurement resolutions and efficiencies or consistent with genuine MET can be distinguished by evaluating the **Met Significance S**.

Event-based MET Significance in ATLAS

$$S = \frac{\text{Met}}{\sqrt{\text{Sumet}}}$$

- Approximation for the MET resolution
- Event based quantity
- Do not take into account directional correlations

Object-based MET Significance Definition

◇ Based on the expected resolutions for all objects that enter the MET reconstruction

◇ Event by event calculated

$$\mathcal{S}^2 = 2\ln\left(\frac{\mathcal{L}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})}{\mathcal{L}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|\mathbf{0})}\right) = (\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})^{\mathrm{T}}\left(\sum_i \mathbf{V}_i\right)^{-1}(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})$$

Covariance Matrix for each object

$$\mathcal{S}^2 = \frac{|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}{\sigma_L^2\left(1-\rho_{LT}^2\right)}$$

Total Variance Longitudinal

$$\sigma_L^2 = \sigma_L^{hard^2} + \sigma_L^{soft^2}$$

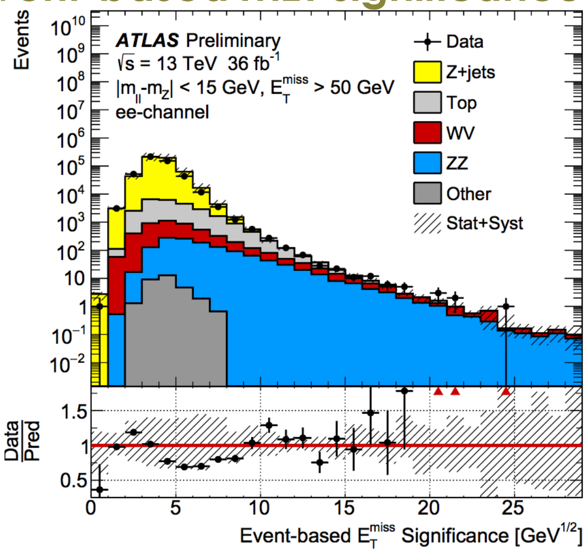
Considers the expected resolutions of "hard" objects

Considers a constant soft term resolution

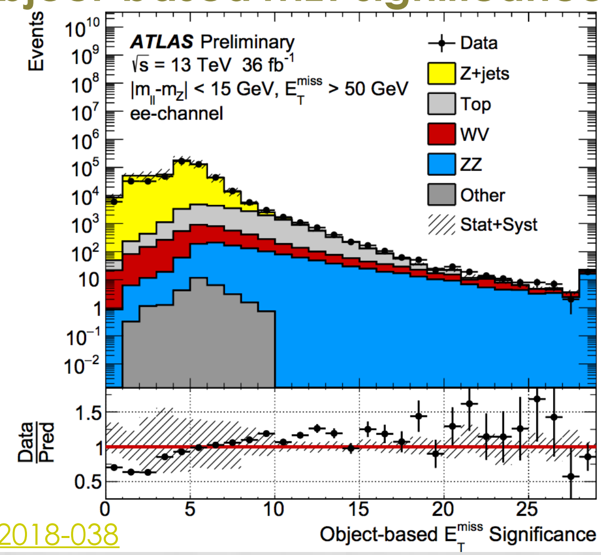
This novel definition depends on the multiplicities, types, and kinematics of the objects measured in each event

EVENT- VRS. OBJECT-BASED MET SIGNIFICANCE

Event-based MET significance

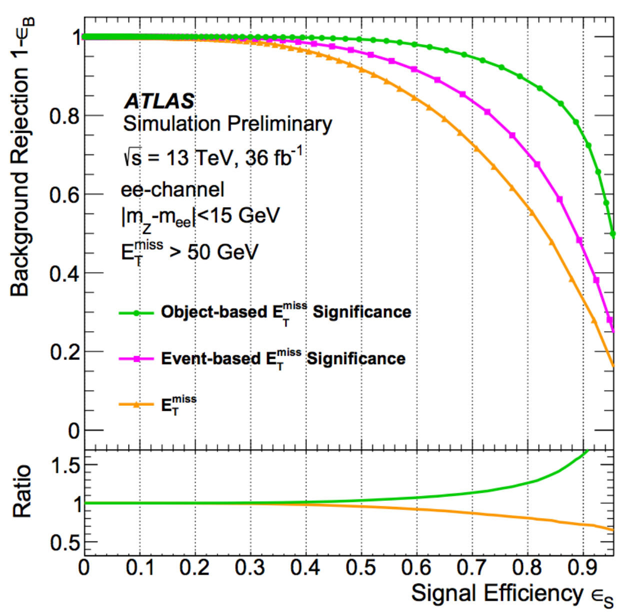


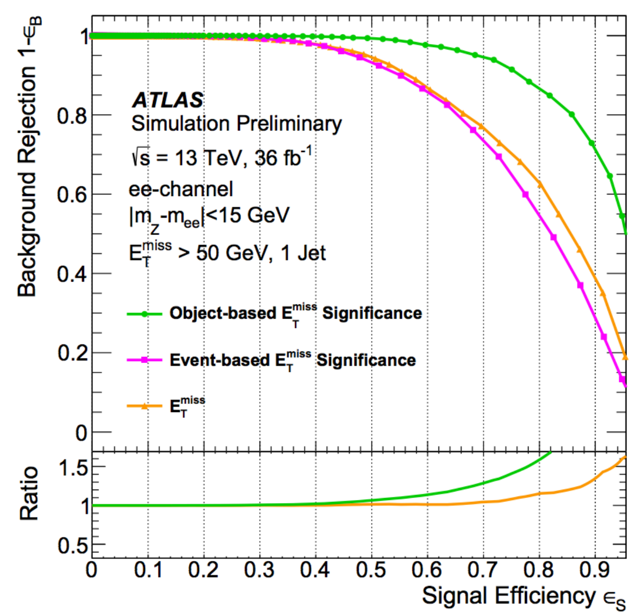
Object-based MET significance



ATLAS-CONF-2018-038

- Comparison of the separation power between
  - Background: Z→ee + jet
  - Signal: ZZ→eeνν+ jet





OBJECT-BASED MET SIGNIFICANCE IN MONO-H ANALYSIS

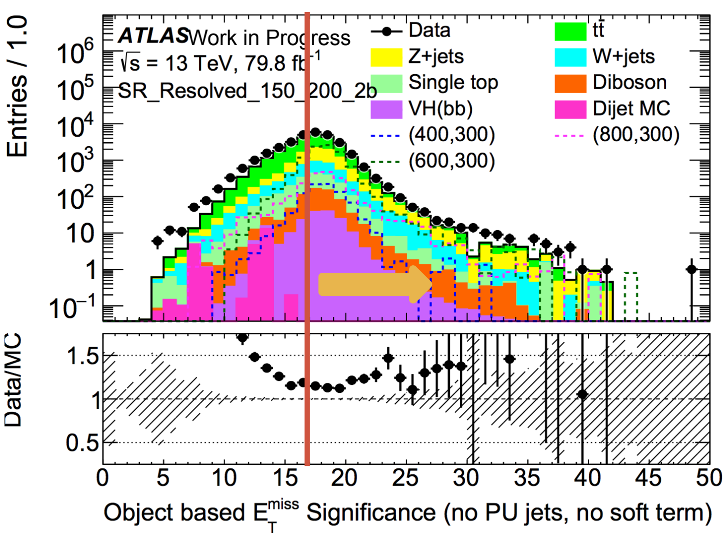
Multijet background

- The multijet background is originated from pure strong interactions
- It introduces fake MET mainly is due to mis-measured jet momenta
- The multijet background is poorly described by MC, requiring a data-driven estimate.

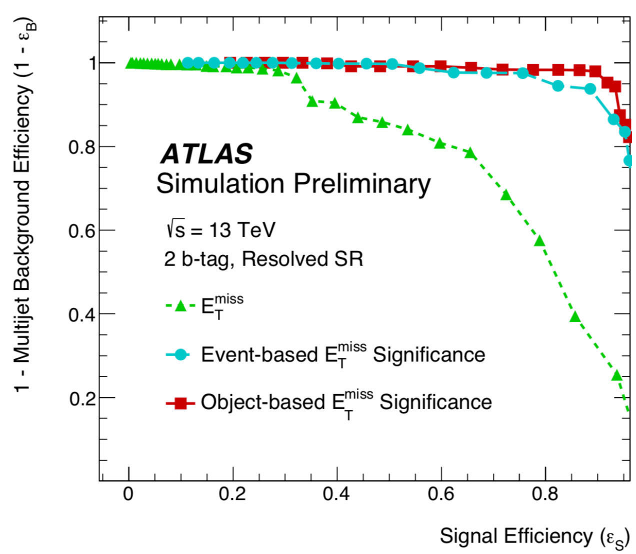
- Met significance can help to identify and separate multijet background with respect to EW backgrounds and DM signals

$$S^2 = \frac{\left|E_T^{miss}\right|^2}{\sigma_L^2\left(1-\rho_{LT}^2\right)}$$

New requirement in resolved selection to suppress multijet background



More than 95% of dijet can be rejected while retaining a signal efficiency ~90%



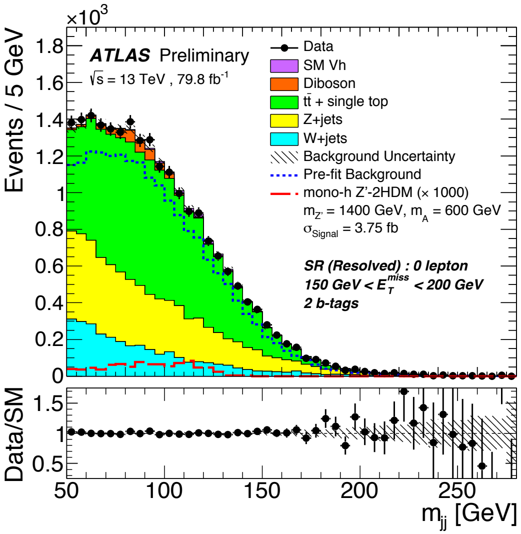
ATLAS-CONF-2018-039

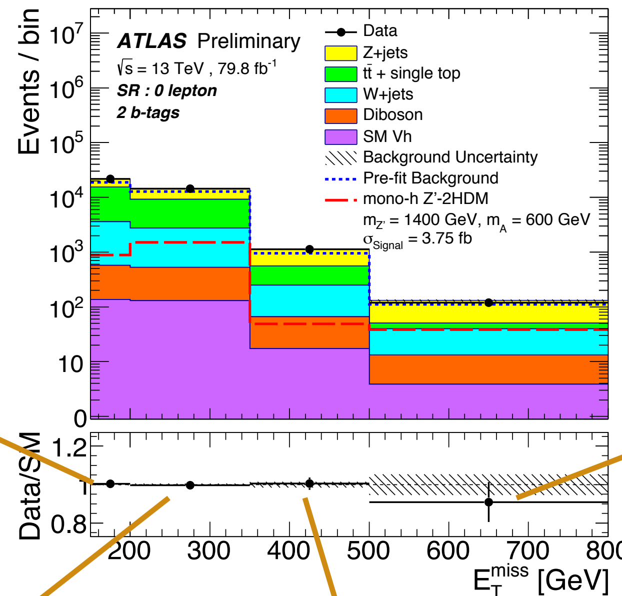
Region
Multijet yield prediction
$150\text{ GeV} < E_T^{miss} < 200\text{ GeV}$
38 ± 17
$200\text{ GeV} < E_T^{miss} < 350\text{ GeV}$
14 ± 22
$350\text{ GeV} < E_T^{miss} < 500\text{ GeV}$
0.1 ± 81

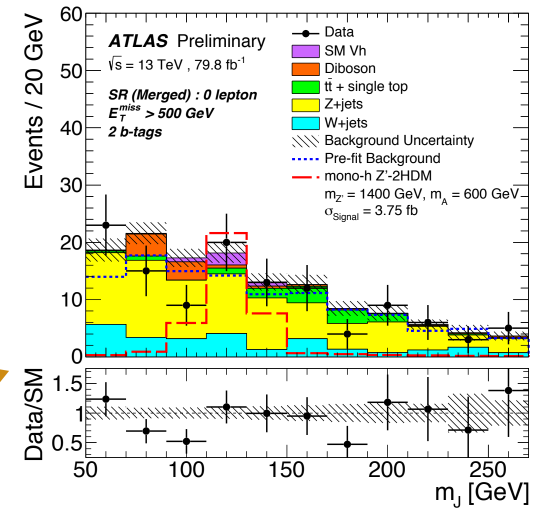
$\Rightarrow$ negligible since smaller than data statistical uncertainty

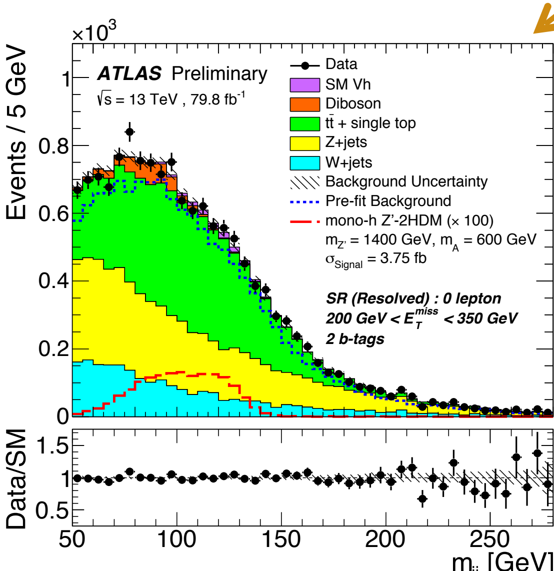
DISTRIBUTIONS AFTER FIT

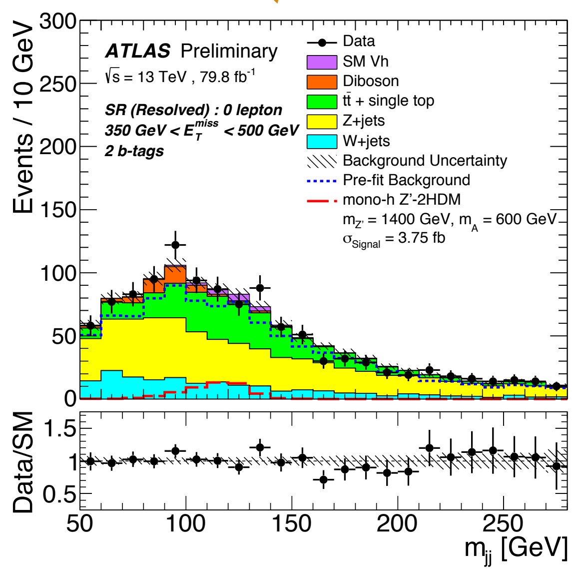
ATLAS-CONF-2018-039









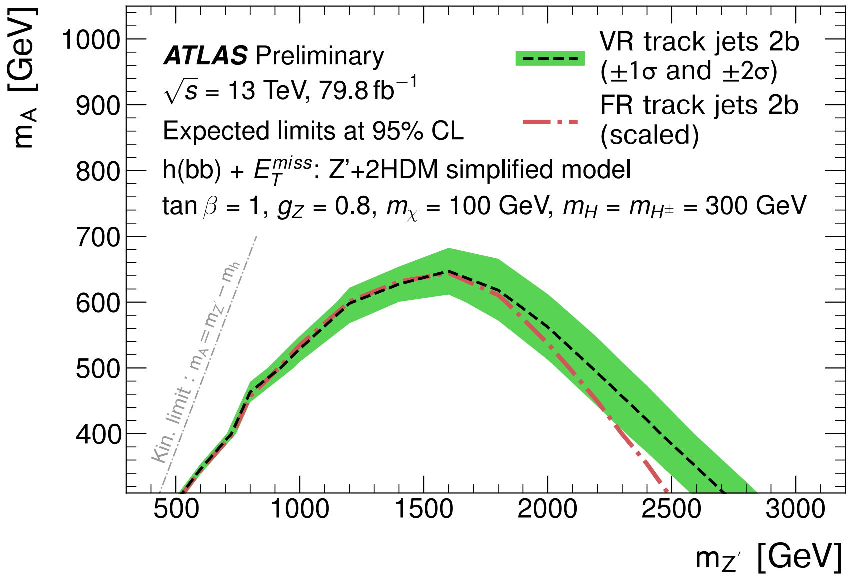


No excess in data observed
⇒ constrain model parameters with exclusion limit contour

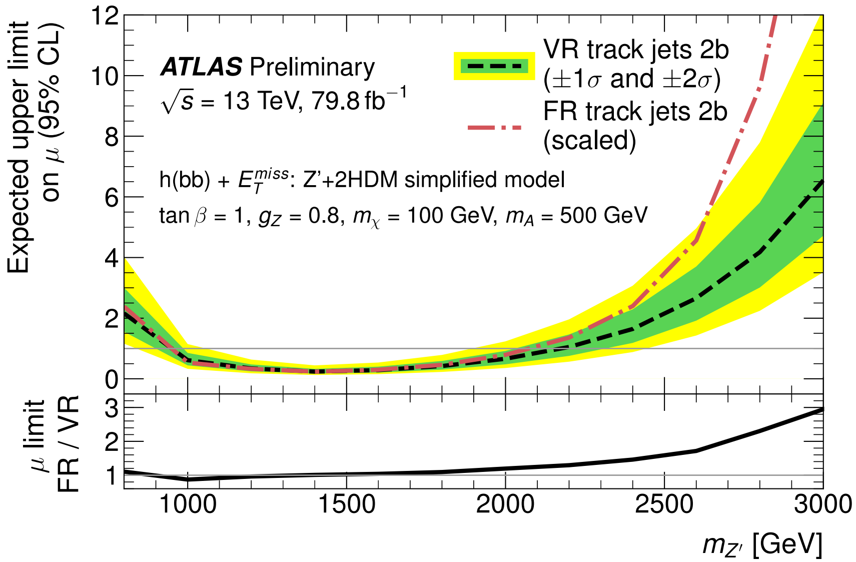
EXCLUSION LIMIT

ATLAS-CONF-2018-039

Model parameters excluded at 95%CLS: mZ' ≤ 2.8 TeV and mA ≤ 600 GeV



The improvement from using VR track jets



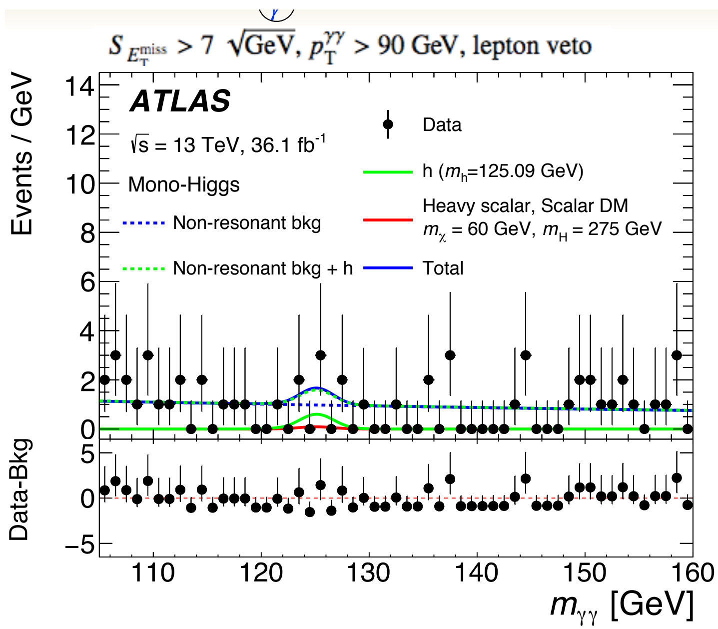
3× improvement driven by VR tracks-jets in boosted region!

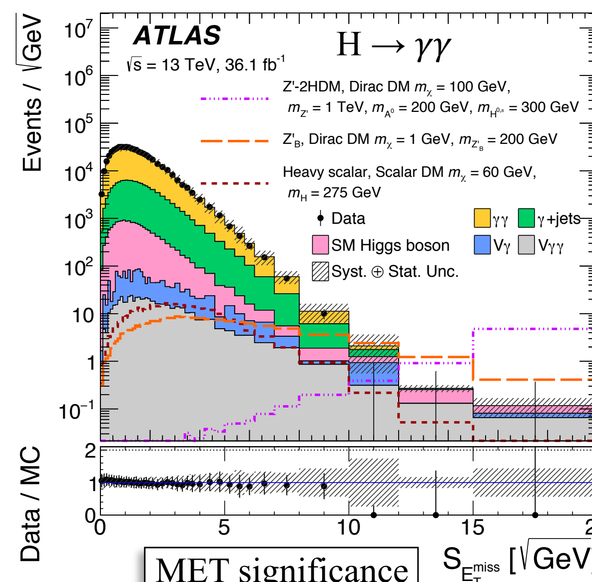
MONO-H WITH H TO PHOTONS OR B QUARKS

Decay	Comments
bb	Highest rate
$\gamma\gamma$	Clean signature

CMS bb and $\gamma\gamma$: EXO-16-012

ATLAS H → $\gamma\gamma$: HIGG-2016-18





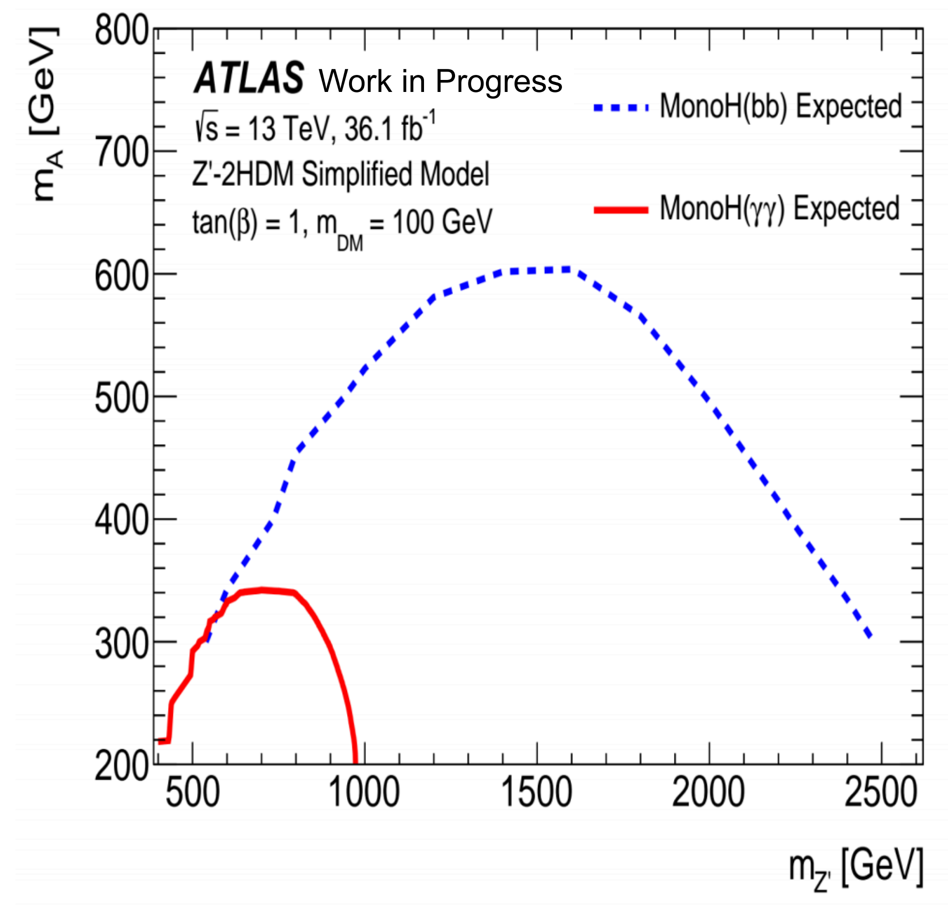
$m_{\gamma\gamma}$

MET significance = MET / $\sqrt{E_T}$ (E_T event E_T including jets & γ)

Clean diphoton mass peak

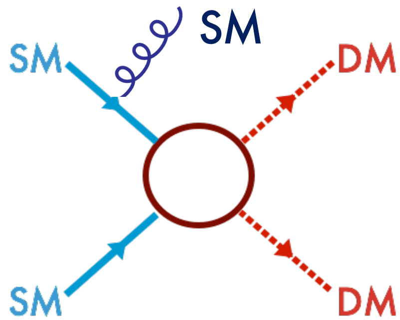
Signal tends to have very high MET

MONO-H WITH H TO PHOTONS OR B QUARKS

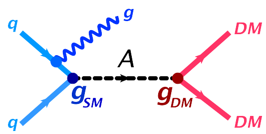


DARK MATTER SEARCHES AT THE LHC

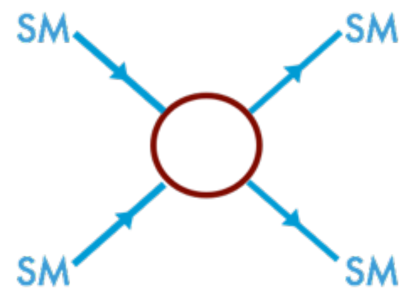
Mono-X



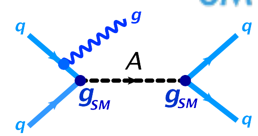
e.g:



Di-X



e.g:



Search for **DM** pairs

- Missing transverse momentum (**MET**) recoiling against a "visible" **X=jet,γ,W,Z,h** from ISR
- SUSY searches involving **MET**

Assume the same particle DM model and search for **mediator decays into SM**

- resonant searches, such as di-jet, di-lepton, ttbar final states

Di-jet

EXOT-2016-21

Classic di-jet search

Rely on single jet triggers

Sensitive to resonance masses in the between 1TeV-2.6 TeV

Di-jet + ISR

ATLAS-CONF-2016-070

Trigger on ISR object to reach lower resonance masses

Sensitive to masses 200GeV-1TeV

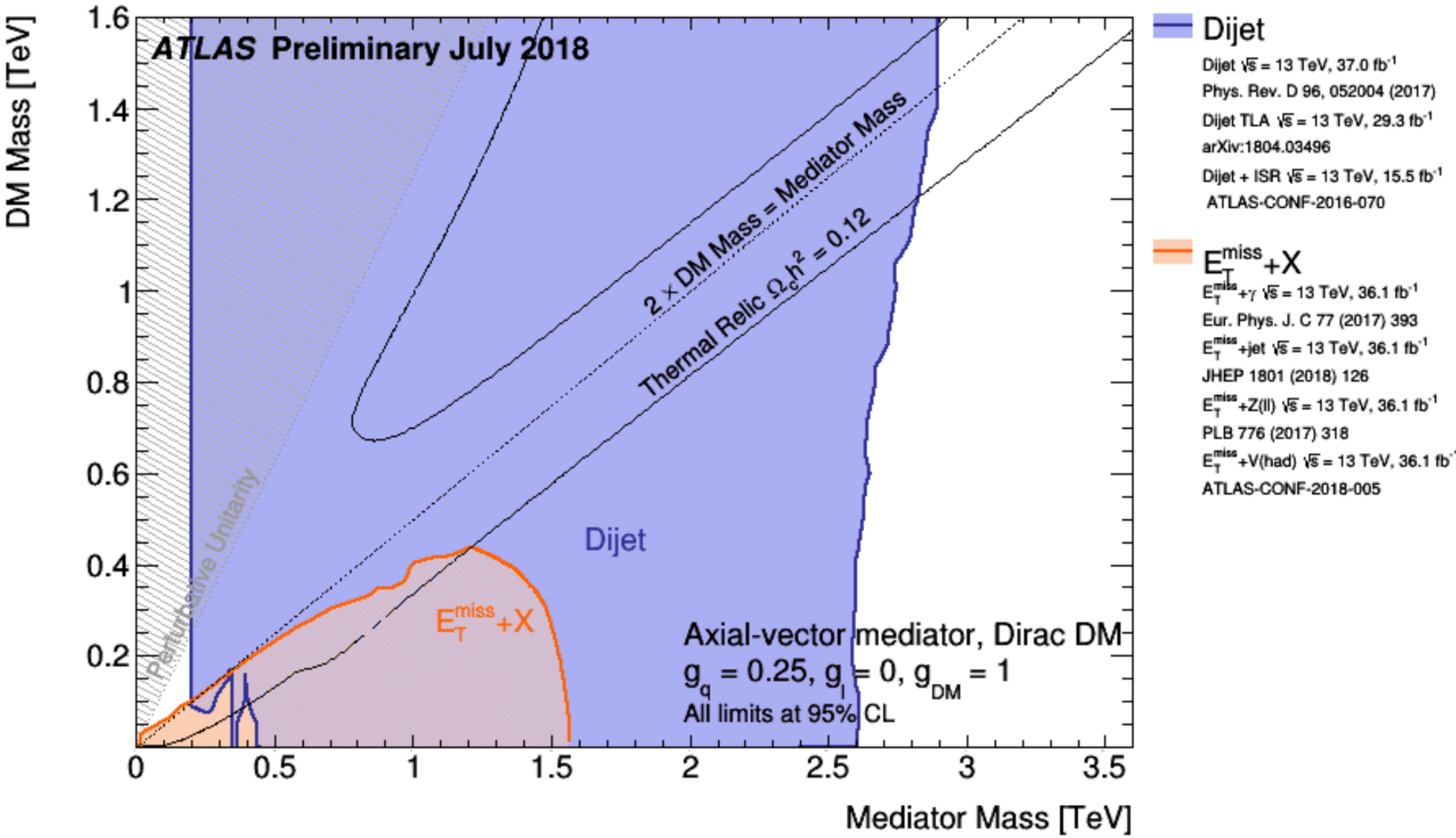
Di-jet at Trigger Level

ATLAS-CONF-2016-030

Overcome single jet trigger prescale limitations by reducing amount of stored information

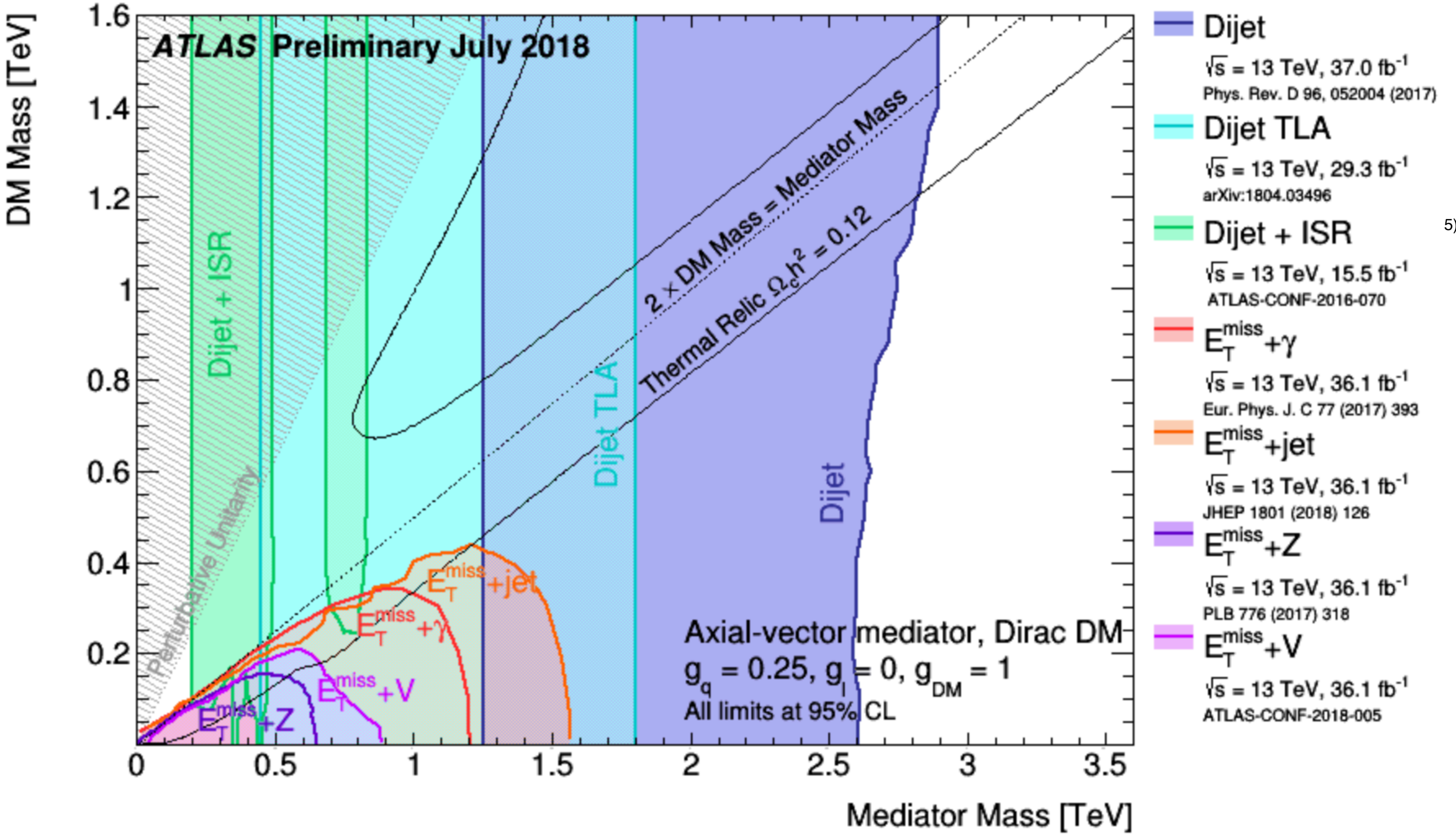
Sensitive to masses 450GeV-1TeV

MONO-X VRS. DI-X



Summary plots from the ATLAS Exotic physics group

MONO-X VRS. DI-X

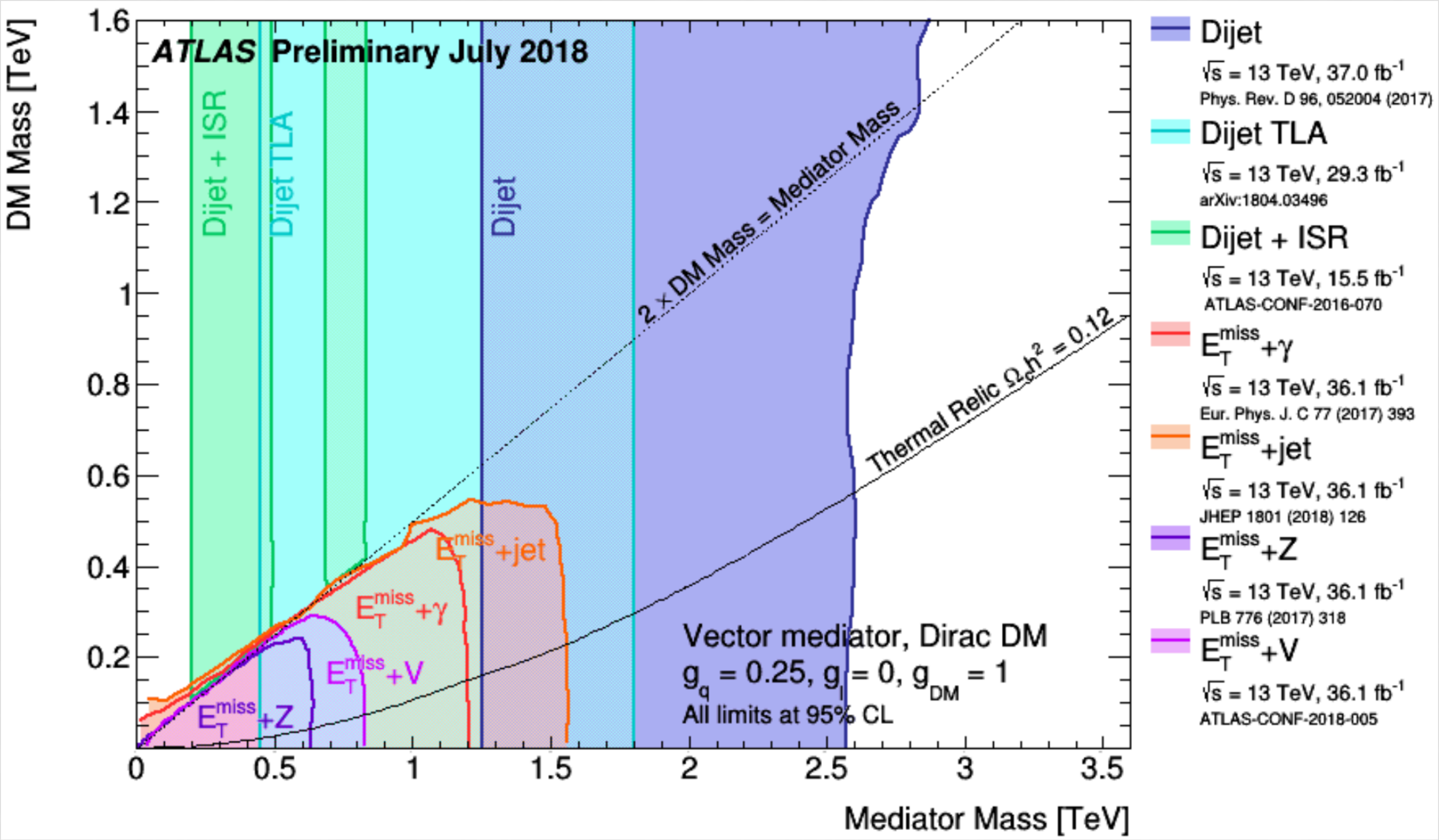


$$g_{DM} = 1.0\,, \quad g_{SM} = 0.25$$

Different coupling choices determine different interplay between Mono-X and Di-X

Summary plots from the ATLAS Exotic physics group

MONO-X VRS. DI-X

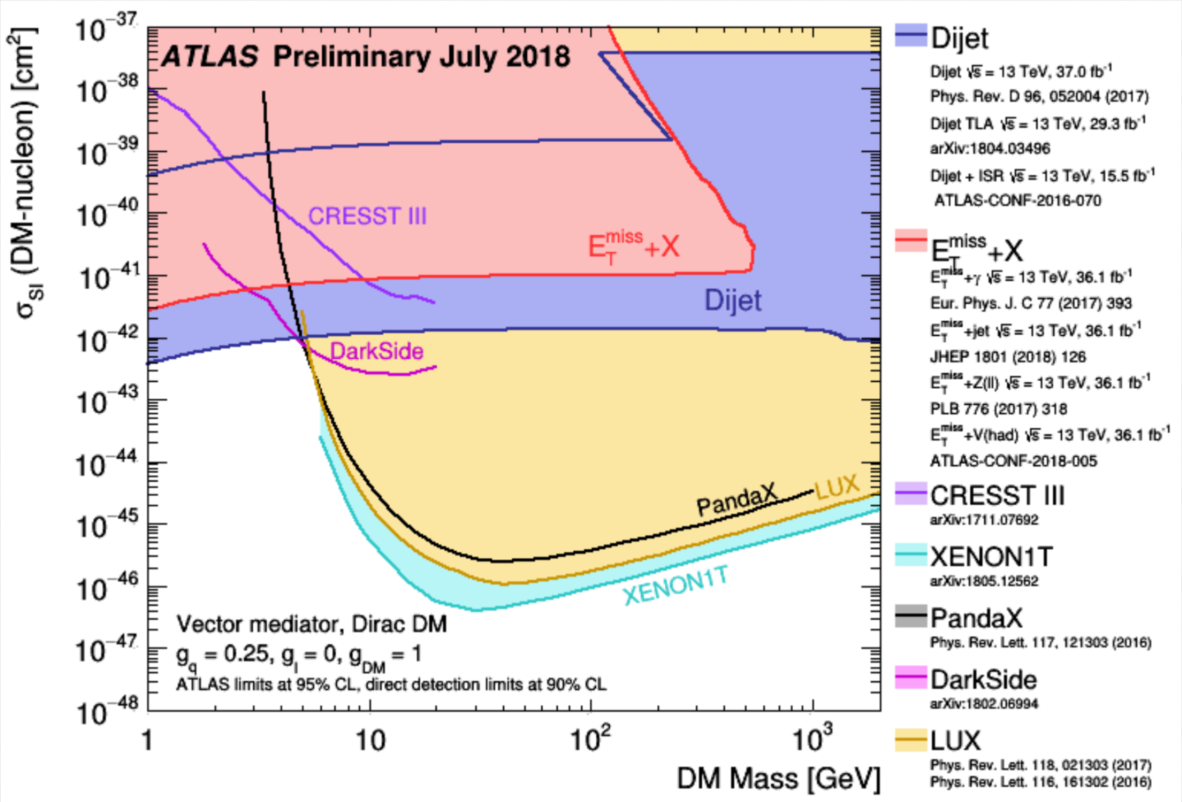


Summary plots from the ATLAS Exotic physics group

ATLAS VS DIRECT DETECTION

ATLAS results translated to direct detection plane (arXiv:1603.04156)

Nice complementarity between ATLAS and direct detection experiments



Summary plots from the ATLAS Exotic physics group

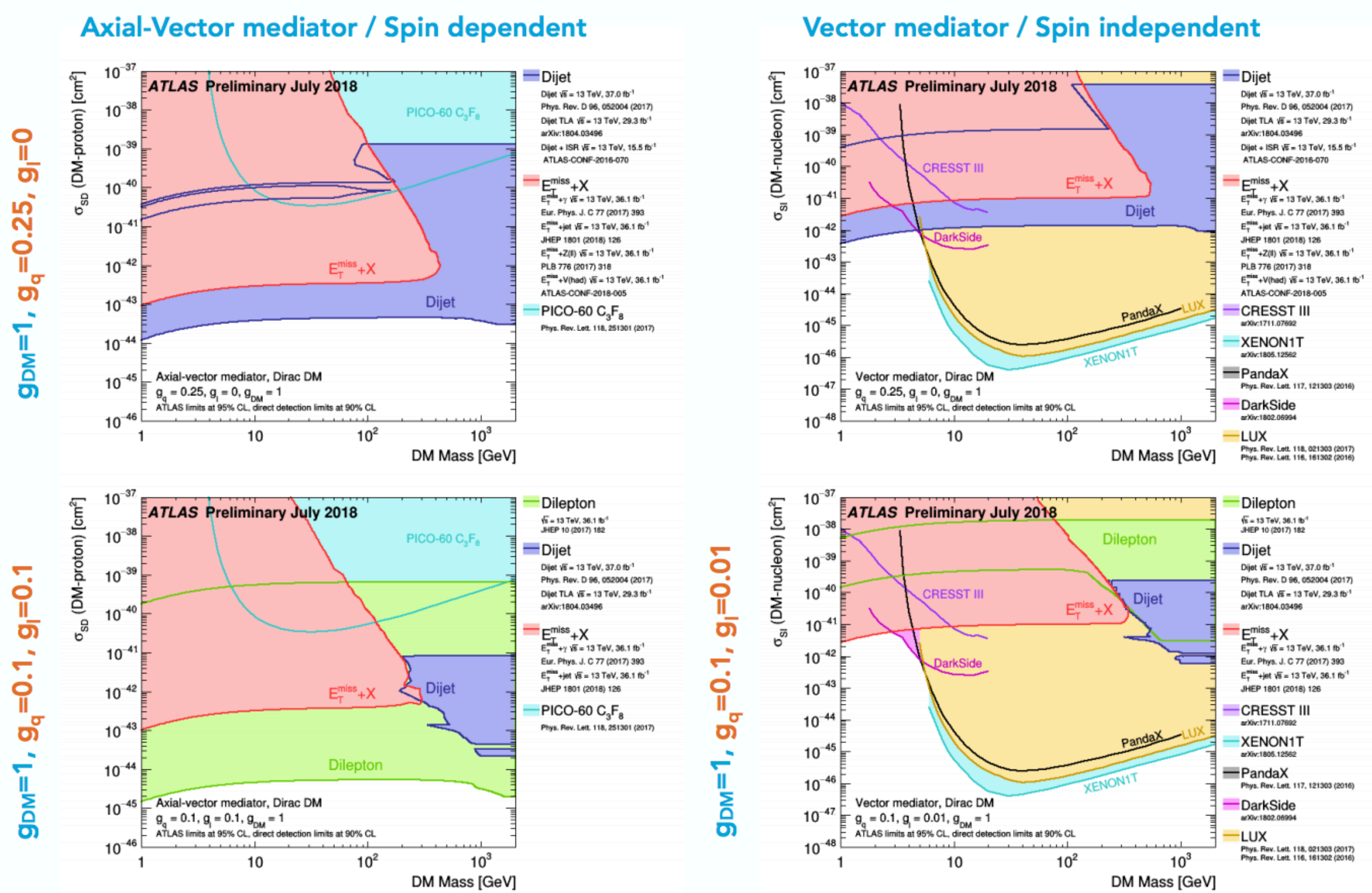
ATLAS VS DIRECT DETECTION

ATLAS results translated to direct detection plane (arXiv:1603.04156)

Nice complementarity between ATLAS and direct detection experiments

Beware !
validity only for this choice of model…

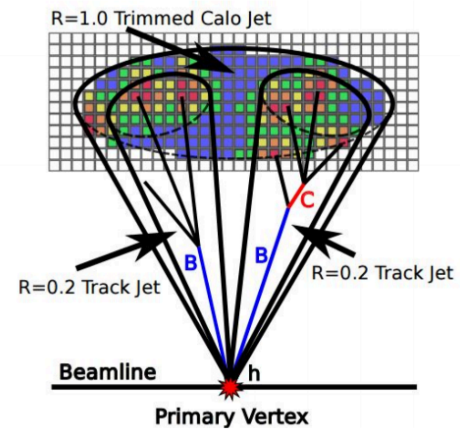
Note: limits at 95% CL for ATLAS, 90% CL for direct detection…



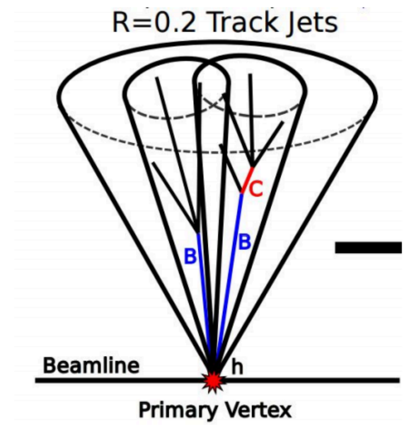
Summary plots from the ATLAS Exotic physics group

VR TRACK JETS

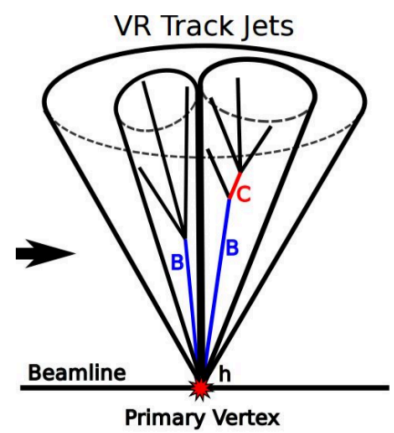
Standard Picture of Higgs Tagging



“I’ve lost my track jets!”



- Canonical *b*-tagging: assumption of a single isolated *B*-hadron
- Mitigate loss of efficiency by redefining how single *b*-tags are obtained
- VR track jets: dynamic cone, $d_{ij} = min\left(p_{\mathrm{T}\,i}^{-2}, p_{\mathrm{T}\,j}^{-2}\right)\Delta R_{ij}^2 / R_{\mathrm{eff}}(p_{\mathrm{T}\,i})^2$, [arxiv 0903.0392]



VARIABLE RADIUS JETS

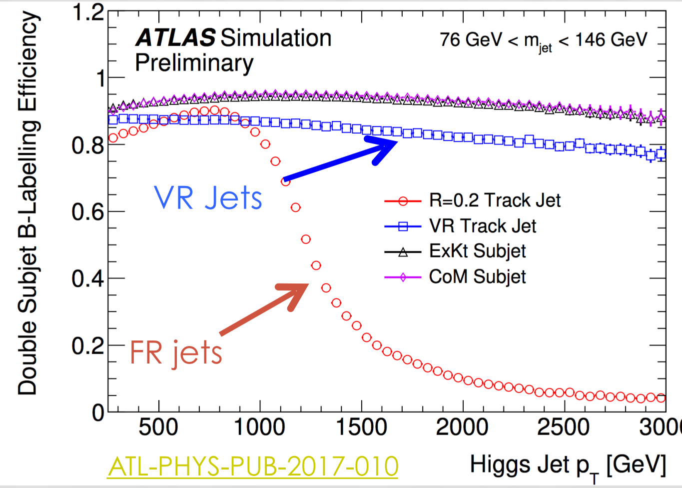
Merging of Fixed Radius (FR) track jets causes loss of acceptance × efficiency for signals with highly boosted topologies.

The reconstruction of sub-jets used for b-tagging in the merged regime improves using the VR track jets, resulting in a higher b-tagging efficiency.

VR track-jets

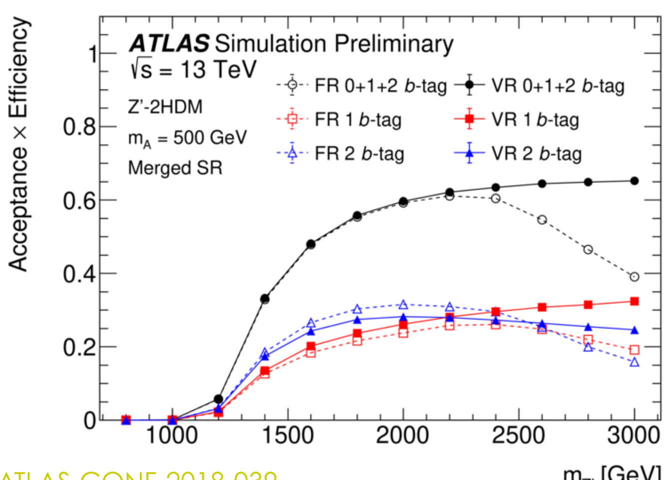
- Used for the first time in analysis!
- anti-kt, R = 0.02-0.4, ρ = 30 GeV

$$R \rightarrow R_{\mathrm{eff}}(p_T) \approx \frac{\rho}{p_T}$$

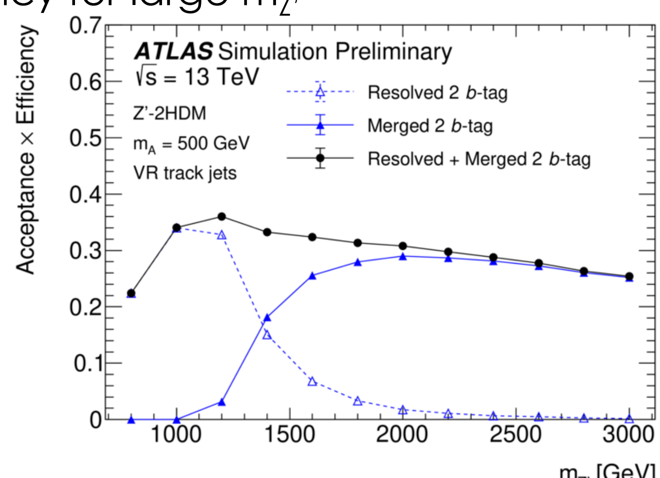


ATL-PHYS-PUB-2017-010

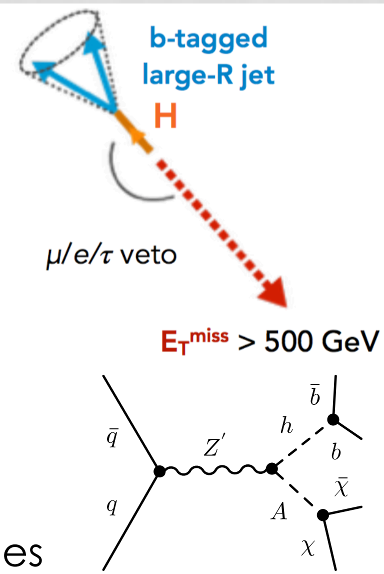
Improve the gain in selection efficiency for large $m_{Z'}$



ATLAS-CONF-2018-039



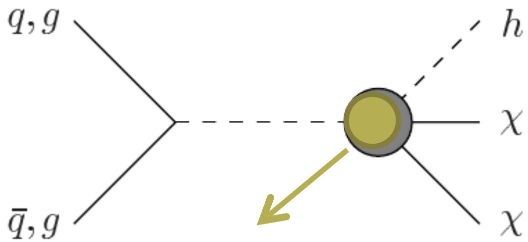
Good complementarity of two regimes



MONO-HIGGS SIGNATURES INTERPRETATIONS

Efective Field Theory framework

Contact operators



$$\lambda|\chi|^2|H|^2$$

$$\frac{1}{\Lambda}\bar{\chi}i\gamma_5\chi|H|^2$$

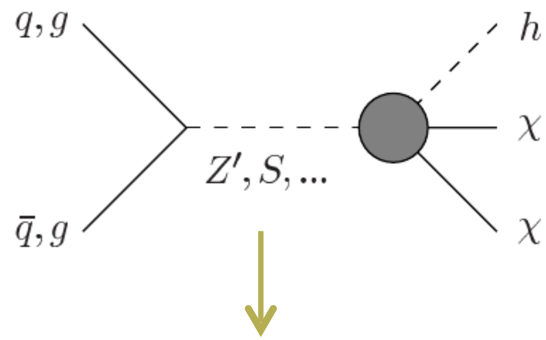
$$\frac{1}{\Lambda^2}\chi^\dagger\partial^\mu\chi H^\dagger D_\mu H$$

$$\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H$$

- Pro
  - Generic interpretation
    - Model independent
- Con
  - Not valid at all momentum transfer

Simplified Models

Minimal number of renormalizable operators

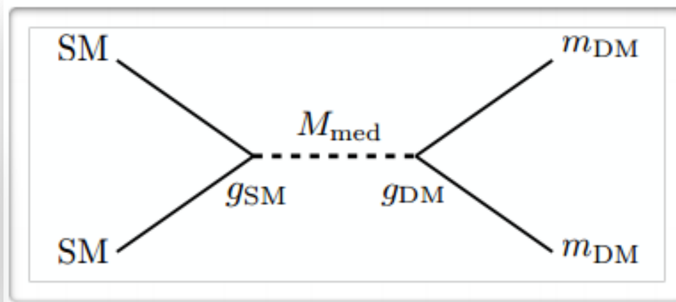


The DM and visible sectors are coupled through a new massive mediator

- Pro
  - UV complete
- Con
  - Less generic (specific number of parameters)
  - Too many exotic models that cannot be reduced to these models.

MONO-HIGGS SIMPLIFIED BENCHMARK MODELS

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar



DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

4-dimensional problem, projecting limits onto a 2-D plane

These Simplified benchmark models were chosen at the LHC Dark Matter forum

MONO-HIGGS SIMPLIFIED BENCHMARK MODELS

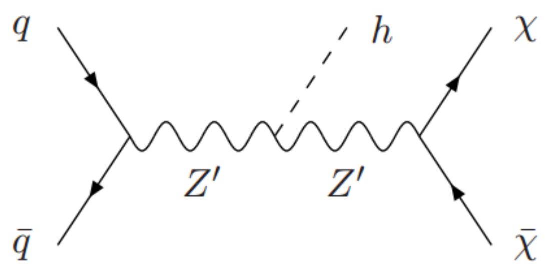
- **Baryonic Z'**

$$g_q \bar{q} \gamma^\mu q Z'_\mu + g_\chi \bar{\chi} \gamma^\mu \chi Z'_\mu$$

After SSB

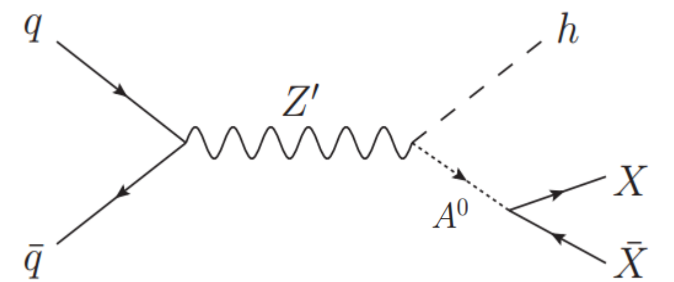
$$-g_{hZ'Z'} h Z'_\mu Z'^\mu$$

$$g_{hZ'Z'} = \frac{m_{Z'}^2 \sin\theta}{v_B}$$



- **Z'-2HDM**

$$-\mathcal{L} \supset y_u Q \tilde{\Phi}_u \bar{u} + y_d Q \Phi_d \bar{d} + y_e L \Phi_d \bar{e} + \text{h.c.}$$



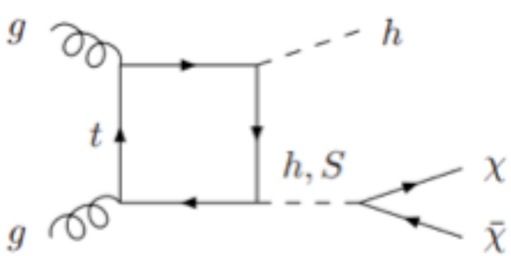
- **Scalar Mediator Model for Mono-H**

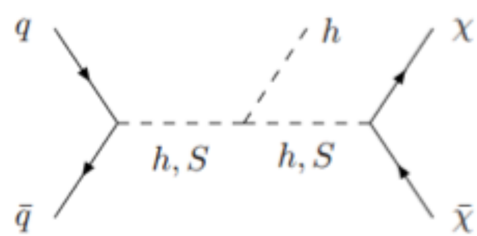
Potential :

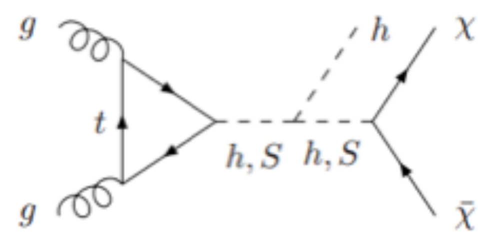
$$V \supset a|H|^2 S + b|H|^2 S^2 + \lambda_h |H|^4$$

After SSB

$$-y_\chi \bar{\chi}\chi(c_\theta S - s_\theta h) - \frac{m_q}{v}\bar{q}q(c_\theta h + s_\theta S)$$

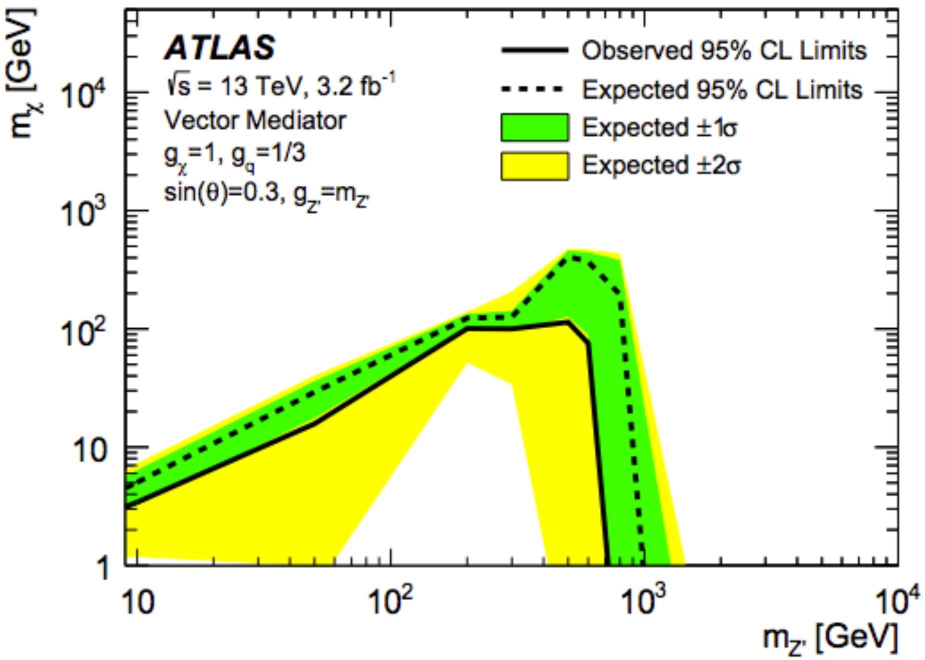




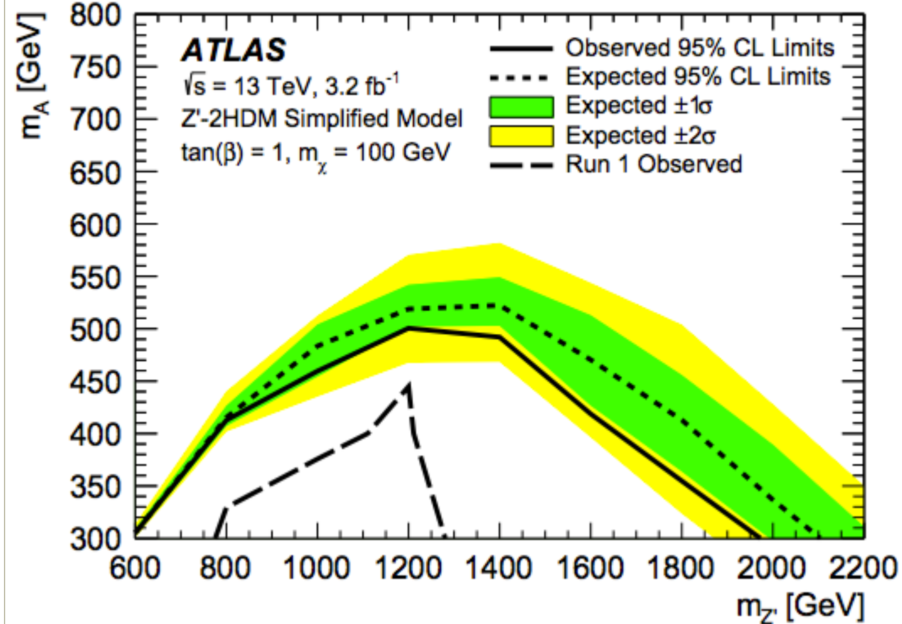


MONO-HIGGS LIMITS ON SIMPLIFIED MODELS

- Baryonic Z'



- Z'-2HDM



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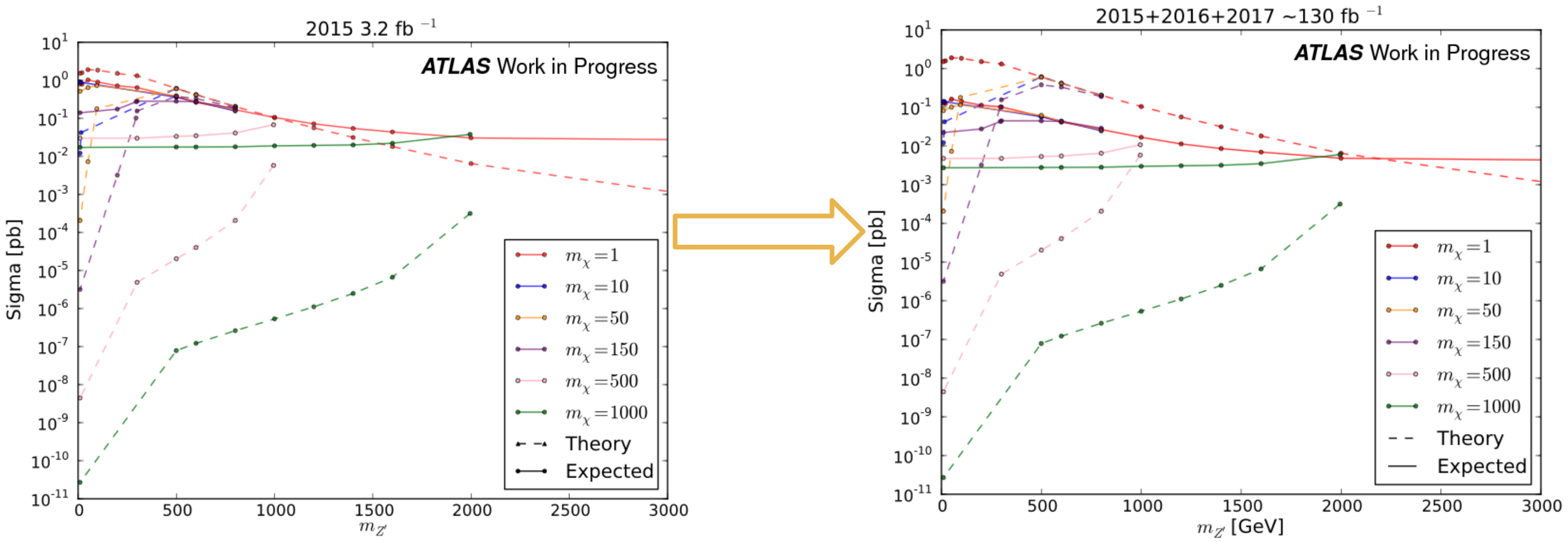
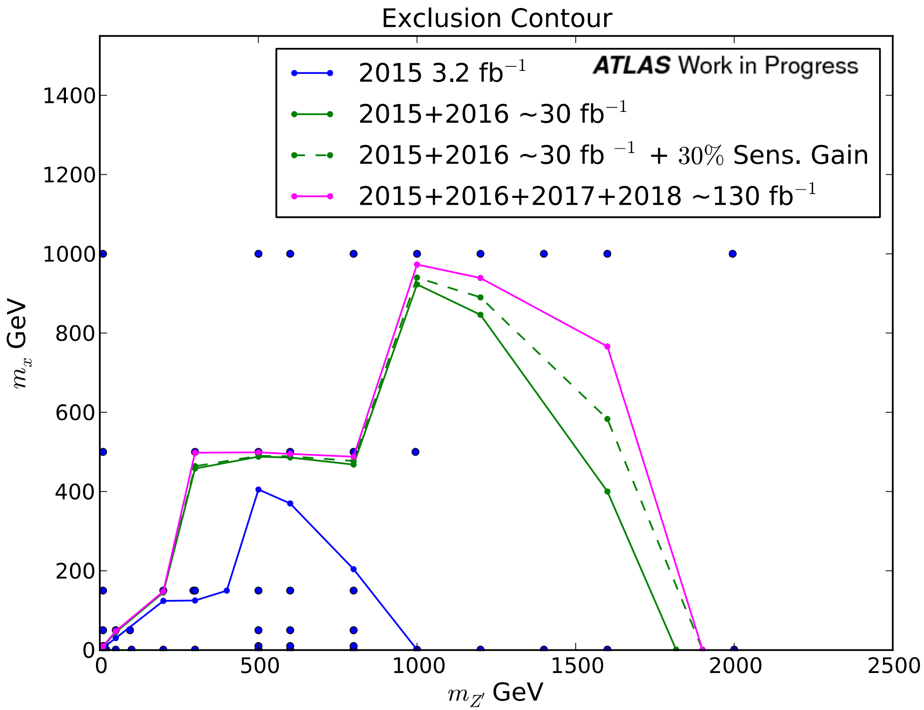
MONO-HIGGS EXPECTED LIMITS ON SIMPLIFIED MODELS

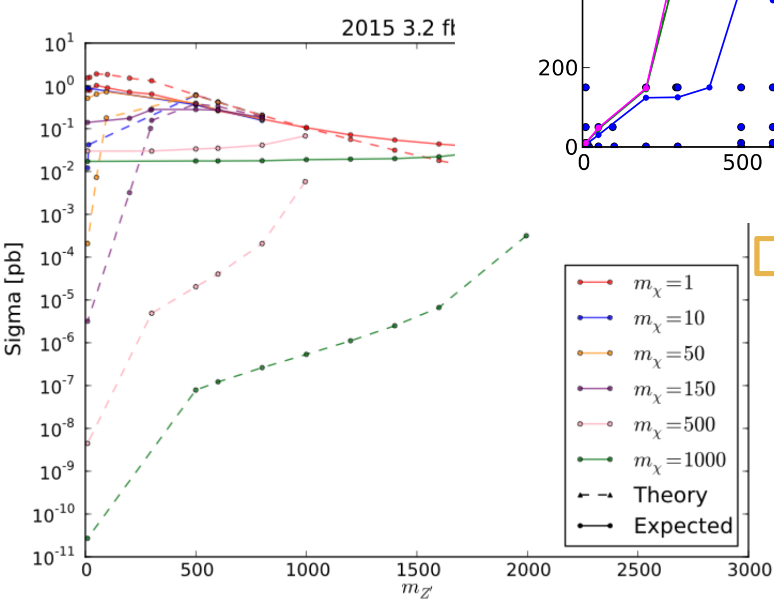
- **Baryonic Z'**

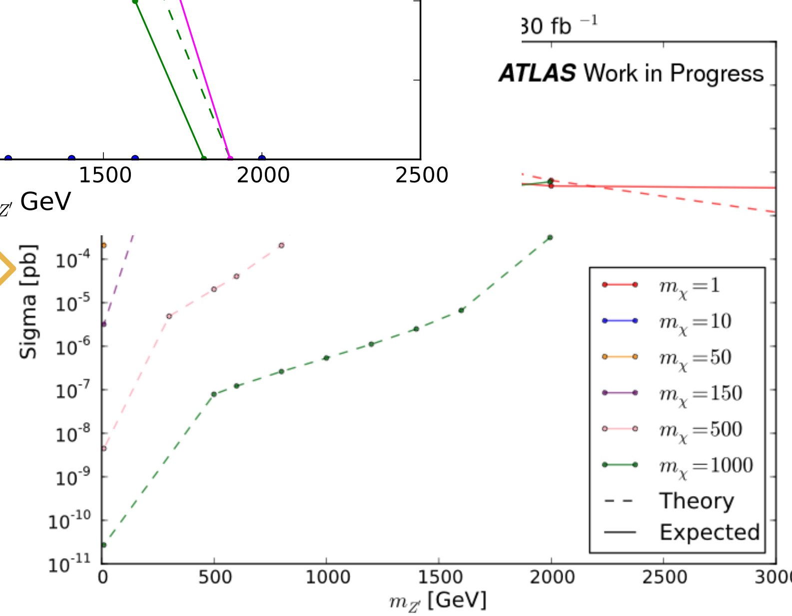


MONO-HIGGS EXPECTED LIMITS ON SIMPLIFIED MODELS

- **Baryonic Z'**



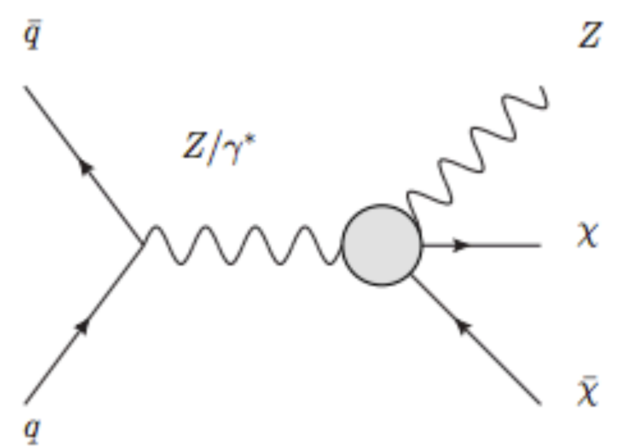




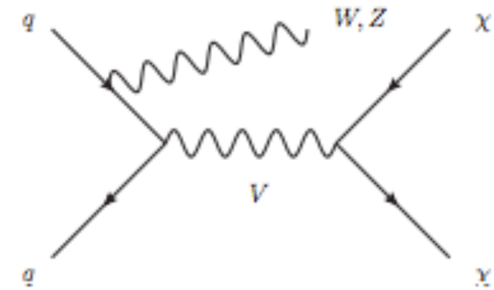
Mono-X channels

- X = Vector Boson or Higgs are covered.
  - Highlights are on 13 TeV analysis (all ATLAS at this moment)
- Mono-photon
  - Low background.
- Mono-Z or mono-W
  - Z can be emitted from mediator in t-channel.
  - Hadronic decay mode → larger cross section
  - Leptonic decay mode → cleaner signature.
- Mono-H
  - No ISR (Initial State Radiation) Higgs.
  - H can be emitted from mediator in s-channel.
  - H -> bb decay mode → larger cross section.
  - H -> γγ decay mode → clean signature.
- VVxx (HHxx) contact interaction is unique.
- Other mono-X:
  - Mono-jet: Andreas Korn's talk.
  - Mono-heavy quark(s): Alberto Zucchetta's talk.

Mono-photon	8 TeV	ATLAS: arXiv:1411.1559[hep-ex] CMS: arXiv:1410.8812
	13 TeV	ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-05/
Mono-Z/W (hadr)	8TeV	ATLAS: arXiv:1309.4017[hep-ex] CMS: CMS PAS EXO-12-055
	13 TeV	ATLAS: ATLAS-CONF-2015-080
Mono-Z(ll)	8 TeV	ATLAS: arXiv: 1404.0051[hep-ex] CMS: arXiv: 1511.09375
Mono-W(lv)	8 TeV	ATLAS: arXiv:1407.7495[hep-ex] CMS: arXiv:1408.2745[hep-ex]
Mono-H(bb)	8 TeV	ATLAS: arXiv:1510.0621[hep-ex]
	13 TeV	ATLAS: ATLAS-CONF-2016-019
Mono-H(gamgam)	8 TeV	ATLAS: arXiv:1506.01081[hep-ex]
	13 TeV	ATLAS: ATLAS-CONF-2016-011



Simplified model parameters in Run2



- Based on the Dark Matter Forum recommendation (arXiv:1507.00966 [hep-ex]).
- Dark matter: Dirac particles.
- Mediator: Vector, Axialvector, Scalar or Pseudoscalar particles.
- Mediator width: minimal width = sum of contributions from DM and quarks lighter than a half of the mediator mass.
- S-channel coupling constants:
  - Coupling to DM: $g_{DM} = 1.0$
  - Coupling to SM: universal to all quarks.
    - Vector and Axialvector: $g_{SM} = 0.25$ (larger values are constrained by dijet searches, also to keep the mediator width narrow).
    - Scalar and Pseudoscalar: $g_{SM} = 1.0$
- T-channel couplings: $g_{DM} = g_{SM} = 0.1 - 7$

Mono-H(bb) Results

NEW

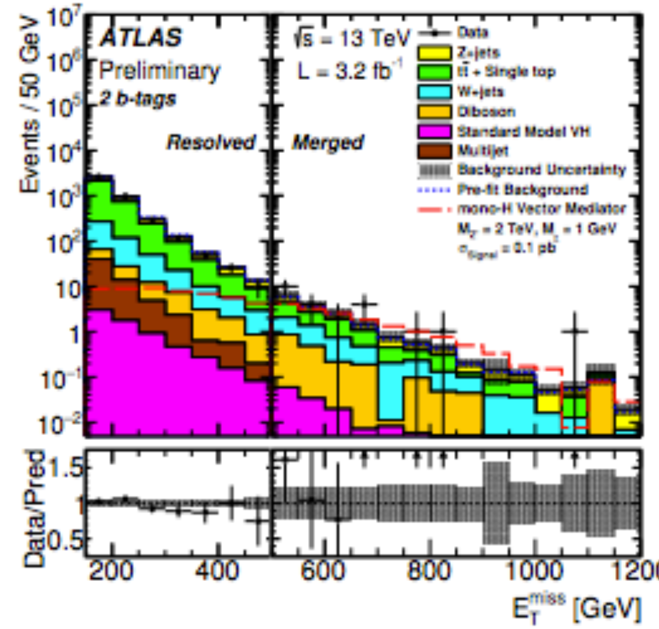
13 TeV

ATLAS

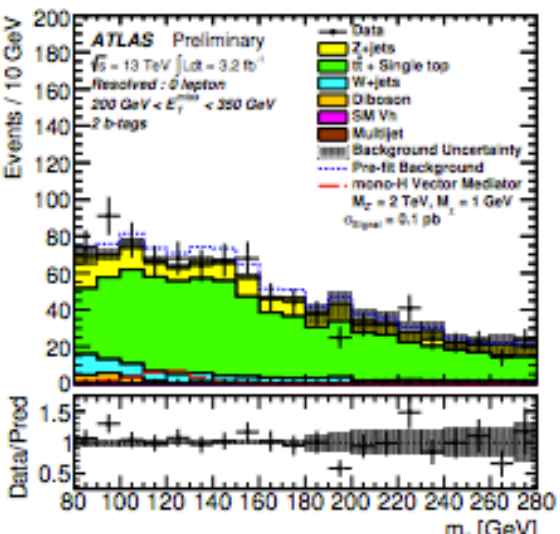
- ATLAS 13 TeV, 3.2 fb^{-1}; 4 signal regions:

E_T^{miss} (GeV)	Resolved 150–200	Resolved 200–350	Resolved 350–500	Merged >500
$Z + jets$	258.52 ± 26.81	171.24 ± 13.13	14.63 ± 1.21	3.80 ± 0.44
$W + jets$	94.78 ± 27.79	70.14 ± 21.67	7.51 ± 2.42	2.48 ± 0.71
$t\bar{t}$ & Single top	1444.38 ± 44.39	656.02 ± 24.51	30.76 ± 1.41	4.83 ± 0.88
Multijet	21.38 ± 9.96	10.89 ± 5.08	0.58 ± 0.27	–
Diboson	17.84 ± 1.62	18.73 ± 0.98	2.53 ± 0.22	1.20 ± 0.12
$SMVh$	2.77 ± 1.30	2.78 ± 1.40	0.46 ± 0.23	0.15 ± 0.08
Tot. Bkg.	1839.68 ± 33.12	929.80 ± 19.63	56.47 ± 2.08	12.47 ± 1.27
Data	1830	942	56	20
Exp. Signal	80.15 ± 7.95	244.53 ± 17.76	160.58 ± 11.56	149.28 ± 33.67

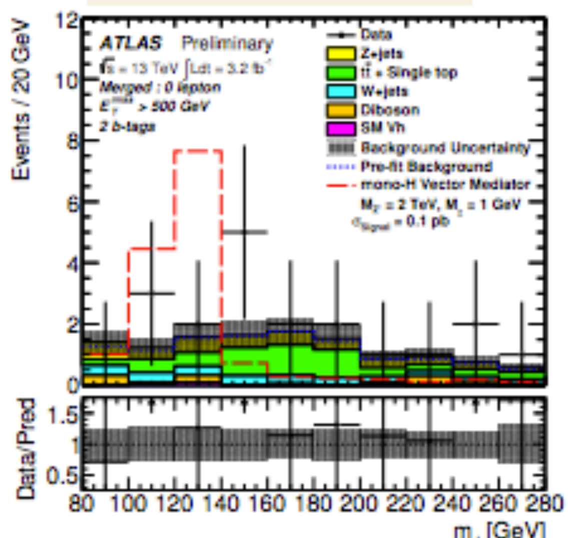
MET



Resolved, 2 b-tag



Merged, 2 b-tag



- Stat error 20.5%
- Systematic error 10.3%
- Main background:
  - Z+jets, W+jets, ttbar
  - Estimated from 1and 2 lepton CR

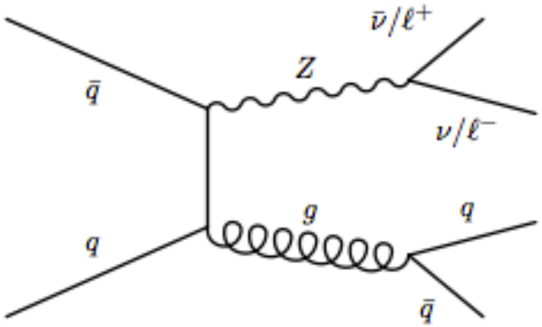
13 TeV

Backup: Mono-H(bb) Event Selection

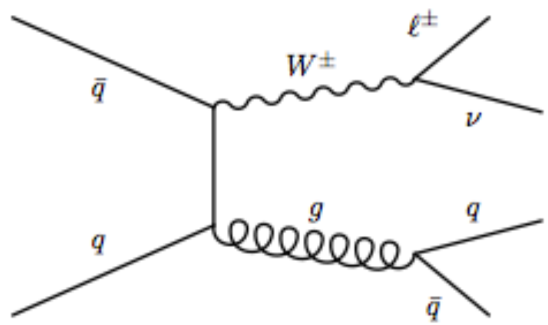
- 13 TeV, 3.2 fb^{-1}, MET trigger.
- MET > 150 GeV, and track based MET: p-MET > 30 GeV
- Lepton veto (no isolated electron or muon with pT>7GeV)
- H candidate:
  - Two small-R jets (j_1 and j_2) in resolved region (MET<500GeV)
    - Leading jet p_T > 45 GeV
  - One large-R jet in merged region (MET>500GeV)
  - 1 or 2 b-tagged jet(s).
- Resolved region : cuts to suppress multi-jets background
  - min[$\Delta\varphi$(MET,jets)] > 20 deg: No jets near MET.
  - $\Delta\varphi$(MET,p-MET) < 90 deg: MET and track MET align.
  - $\Delta\varphi$(MET,Higgs) > 120 deg: MET and H go back-to-back.
  - $\Delta\varphi(j_1,j_2)$ < 140 deg: Two jets are not back-to-back.

Dominant backgrounds are:

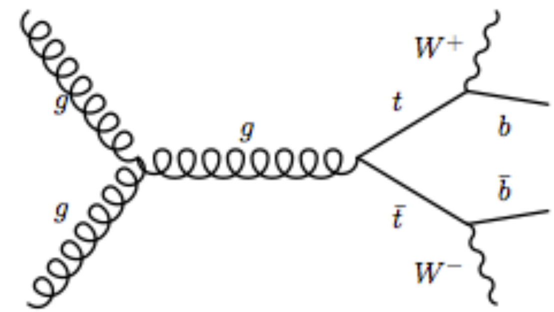
$Z \to \nu\nu$+jets:



$W \to \ell\nu$+jets:



$t\bar{t}$+production:



- Two lepton region to estimate $Z \to \ell\ell$+jets: which is kinematically similar to the desired estimate of $Z \to \nu\nu$+jets
- Single muon region to estimate W+jets and $t\bar{t}$: number of b-tags naturally separates them
- Try to have the control regions close to the signal region

→ Apply similar cuts

- Less dominant backgrounds: single-top, diboson, SM VH $b\bar{b}$, multijet

# of leptons \ # of b-tagged jets	0	1	2
0	CR, Z+jets	SR	SR
1	CR, W+jets	CR, W+jets, $t\bar{t}$	CR, W+jets, $t\bar{t}$
2	CR, Z+jets	CR, Z+jets	CR, Z+jets

OBJECT BASED MET SIGNIFICANCE

The DØ-CMS approach

- How likely is it that this METmeas is TRUE MET, and not simply a result of measurement error or other effects?

This can be evaluated with the log-likelihood ratio of measuring the total observed transverse momentum to the likelihood of the null hypothesis.

$$S(\overrightarrow{E}) \equiv 2ln\left(\frac{\mathcal{L}(\overrightarrow{E} = \sum_i \overrightarrow{E_{T_i}})}{\mathcal{L}(\overrightarrow{E} = 0)}\right)$$

On a event-by-event basis, *S* evaluates the p-value that the observed MET is consistent with a null hypothesis, given the full event composition.

If we assume that …

- The sum of all the truth transverse momentum is equal to zero $\sum \overrightarrow{e_{T_i}} = 0$
- The difference $\overrightarrow{\epsilon_i} = \overrightarrow{E_{T_i}} - \overrightarrow{e_{T_i}}$ has a gaussian probability density function

$$p_i(\overrightarrow{\epsilon_i} \mid \overrightarrow{e_{T_i}}) \equiv P_i(\overrightarrow{\epsilon_i} + \overrightarrow{e_{T_i}} \mid \overrightarrow{e_{T_i}}) = P_i(\overrightarrow{E_{T_i}} \mid \overrightarrow{e_{T_i}}) \sim exp\left[-\frac{1}{2}(\overrightarrow{\epsilon_{T_i}})^{\dagger} V_i^{-1} (\overrightarrow{\epsilon_{T_i}})\right]$$

…the likelihood for two objects is given by:

$$\mathcal{L}(\overrightarrow{E}) = \int P_1(\overrightarrow{E_{T_1}} \mid \overrightarrow{e_{T_1}}) P_2(\overrightarrow{E_{T_2}} \mid \overrightarrow{e_{T_2}})\, \delta\left(\overrightarrow{E} - (\overrightarrow{E_{T_1}} + \overrightarrow{E_{T_2}})\right) d\overrightarrow{E_{T_1}} d\overrightarrow{E_{T_2}}$$

$$\mathcal{L}(\overrightarrow{E}) \sim exp\left[-\frac{1}{2}\left(\overrightarrow{E}\right)^{\dagger}\left(\sum_i V_i\right)^{-1}\left(\overrightarrow{E}\right)\right]$$

DEFINITION OF OBJECT BASED MET SIGNIFICANCE

Covariance Matrix

$$S \sim \left(\sum_i \overrightarrow{E_{T_i}}\right)^{\dagger} \left(\sum_i V_i\right)^{-1} \left(\sum_i \overrightarrow{E_{T_i}}\right)$$

- For each object contributing to the MET, the covariance matrix is rotated into a coordinate system with the x axis parallel to the total Met axis.

$$U_i = \begin{pmatrix} \sigma^2_{E_{T_i}} & 0 \\ 0 & E^2_{T_i}\sigma^2_{\Phi_i} \end{pmatrix} \longrightarrow \mathbf{V} = \sum_i V_i = \begin{pmatrix} \sigma^2_{\parallel} & \sigma^2_{\parallel\perp} \\ \sigma^2_{\parallel\perp} & \sigma^2_{\perp} \end{pmatrix}$$

Where $\sigma^2_{\parallel}$ is the variance in the direction of the Met, $\sigma^2_{\perp}$ is the variance perpendicular to the Met and $\sigma^2_{\parallel\perp} = \rho\,\sigma_{\parallel}\sigma_{\perp}$ is the associated covariance.

Met Significance Simplification

- In this coordinate system, parallel and perpendicular to the total measured Met, the Met Significance can be simplified:

$$S \sim \frac{\left(\sum_i \overrightarrow{E_{T_i}}\right)^2}{\sigma^2_{\parallel}\,(1-\rho^2)}$$

- Where the correlation coefficient is:

$$\rho = \frac{\sigma^2_{\parallel\perp}}{\sqrt{\sigma^2_{\parallel}\,\sigma^2_{\perp}}}$$

NOTE: If $\rho^2 = 1$

In this case the definition becomes:

$$S \sim \frac{\left(\sum_i \overrightarrow{E_{T_i}}\right)^2}{\sigma^2_{\parallel}}$$

For $\rho^2 \geq 0.9$

DEFINITION OF OBJECT BASED MET SIGNIFICANCE

Covariance Matrix

- The significance is defined as the log-likelihood ratio of measuring the total observed transverse momentum to the likelihood of the null hypothesis.

$$S(\overrightarrow{E}) \equiv 2ln\left(\frac{\mathcal{L}(\overrightarrow{E}=\sum_i \overrightarrow{E_{T_i}})}{\mathcal{L}(\overrightarrow{E}=0)}\right)$$

- Assuming gaussian uncertainties distributions:

$$S \sim \left(\sum_i \overrightarrow{E_{T_i}}\right)^{\dagger}\left(\sum_i V_i\right)^{-1}\left(\sum_i \overrightarrow{E_{T_i}}\right)$$

- For each object contributing to the MET, the covariance matrix is calculated as:

$$V^{x,y} = \begin{bmatrix} \sigma_x^2 & \sigma_x\sigma_y \\ \sigma_x\sigma_y & \sigma_y^2 \end{bmatrix}$$

Where the measurements in the x and y components are 100% correlated.

- This matrix is rotated into a coordinate system with the x axis parallel to the total Met axis. Then, the total covariance matrix is calculated as the sum of all the covariance matrices from each object contributing to the Met:

$$\mathbf{V} = \sum_i R(\Phi(\mathrm{Met}))\, V_i^{x,y}\, R(\Phi(\mathrm{Met}))^{-1}$$

DEFINITION OF AN OBJECT BASED MET SIGNIFICANCE

Covariance Matrix

$$\mathbf{V} = \begin{bmatrix} \sigma_{\parallel}^2 & \sigma_{\parallel\perp}^2 \\ \sigma_{\parallel\perp}^2 & \sigma_{\perp}^2 \end{bmatrix}$$

Where $\sigma_{\parallel}^2$ is the variance in the direction of the Met, $\sigma_{\perp}^2$ is the variance perpendicular to the Met and $\sigma_{\parallel\perp}^2 = \rho\,\sigma_{\parallel}\sigma_{\perp}$ is the associated covariance.

Met Significance

- In this coordinate system, parallel and perpendicular to the total measured Met, the Met Significance can be simplified:

$$S \sim \left(\sum_i \overrightarrow{E_{T_i}}\right)^{\dagger} \mathbf{V}^{-1} \left(\sum_{\mathbf{i}} \overrightarrow{E_{T_i}}\right)$$

$$\boxed{S \sim \frac{\left(\sum_i \overrightarrow{E_{T_i}}\right)^2}{\sigma_{\parallel}^2\,(1-\rho^2)}}$$

- Where the correlation coefficient is:

$$\rho = \frac{\sigma_{\parallel\perp}^2}{\sqrt{\sigma_{\parallel}^2\,\sigma_{\perp}^2}}$$

NOTE: If

$$\rho^2 = 1$$

In this case the definition becomes:

$$S \sim \frac{\left(\sum_i \overrightarrow{E_{T_i}}\right)^2}{\sigma_{\parallel}^2}$$

For $\rho^2 \geq 0.9$