SM

Searches for dark matter → with the ATLAS EXPERIMENT at the LHC

Tae Min Hong

on behalf of the ATLAS Collaboration

University of Pittsburgh

Pennsylvania, United States

17 July 2023

XII Int'l Conf. on New Frontiers in Phys. (ICNFP), Κολυμβάρι, Κρήτη

https://indico.cern.ch/event/1199102/

Literature on dark matter

I scoured titles on arXiv.org

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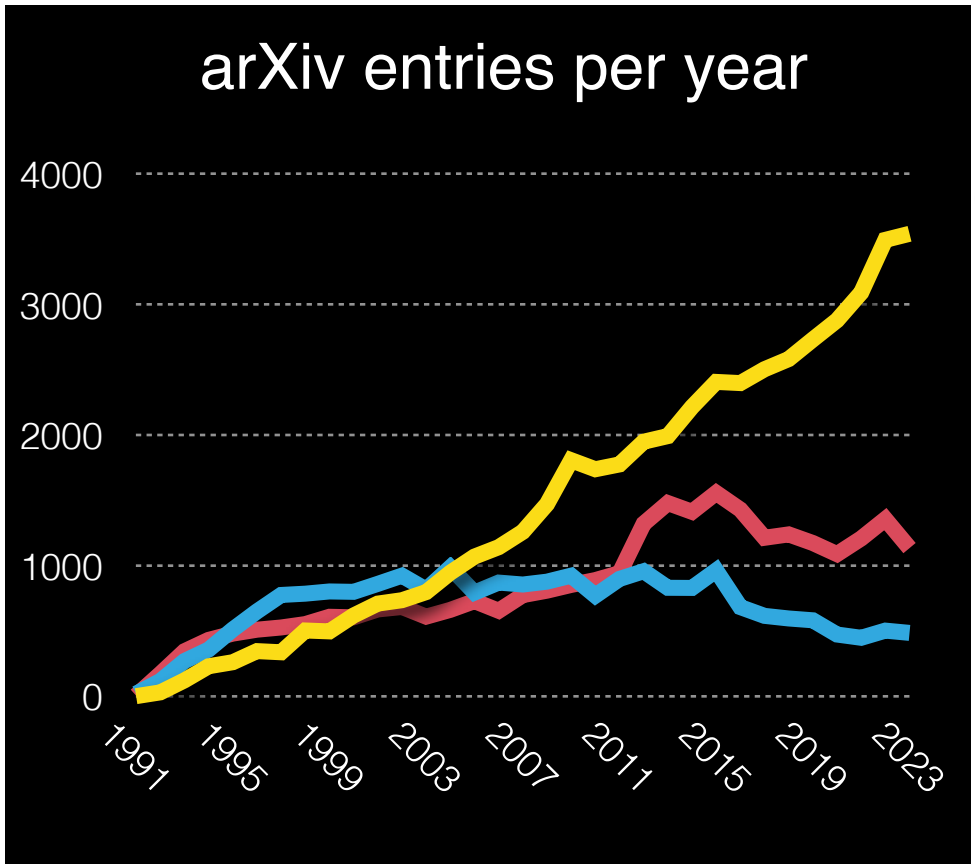
Zwicky

Rubin

1933 ... 1962 ...



DM
DARK MATTER

Higgs

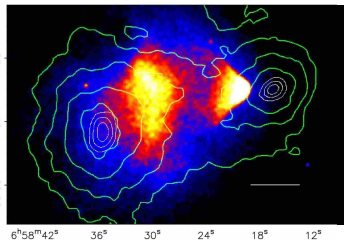
SUSY
SUPERSYMMETRY

Scaled up 2023 since ½ way

Dark matter papers see continued growth

Higgs

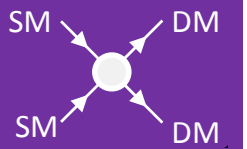
SUSY



DM & collider theories

Wide range of ideas from effective to complete

Particle Colliders



Clowe et al., Astrophys. J. 648 (2006) 109-113

Snowmass 2013, Ch. 4, [1401.6085]

Abdallah et al., Phys. Dark Univ. 9-10 (2015) 8-23

Less complete — Sketches of models — More complete

Dark Matter Effective Field Theories

Dipole Interactions

Contact Interactions

Simplified Dark Matter Models

Dark Photon

Z′ boson

Higgs Portal

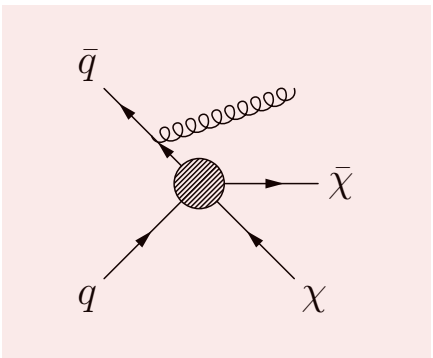
"Squarks"

Complete Dark Matter Models

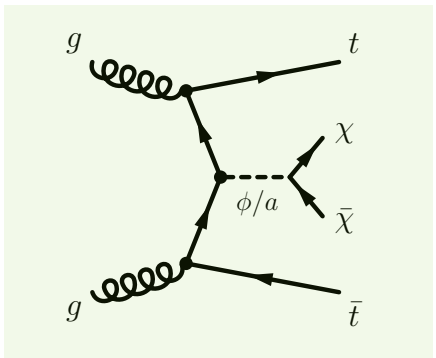
Minimal Supersymmetric Standard Model

Universal Extra Dimensions

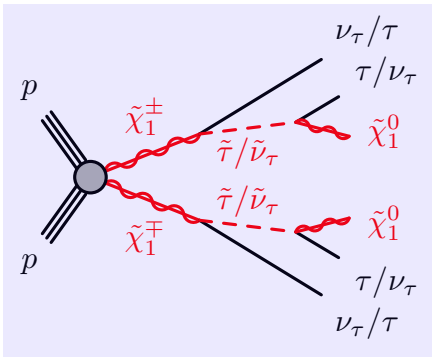
Little Higgs



mono-jet



mediator



decay chain

This talk

Outline

10+ papers, so only a taste of new results

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Pittsburgh

Intro

- Models, LHC, ATLAS EXPERIMENT, MET

Sketches of models → More complete

This talk

- DM via scalars : VBF H, ZH, $t\bar{t}\phi$
- DM via methods : dark sector jets, single t, anomaly ML
- DM in SUSY : 2 tau, 1 e/μ lepton + jets, 2-3 e/μ leptons

Related ATLAS talks, posters

•	July 14	S. Bansal	New symmetries in the Higgs sector	: High-, low-mass scalars, H_{125} to light scalars
•	July 18	S. Ezzarqtouni	Combo of ATLAS DM searches	: Direct & assoc. prod., via mediator
•	July 11	A. Rodriguez Vera	New phenomena	: Lepto-q, vector-like q, DM via unconven. / long-lived
•	July 13	R. Zhang	Active Learning in DM search	: Z_{dark} to 4 leptons in preserved data w/ Panda & iDDS
•	July 18	A. Cheng	Unsupervised ML for anomaly	: One b-jet + one (b-jet / e / μ)
•	July 20	E. Torro Pastor	Challenging & Long-lived	: Fractional charge, long-lived
•	July 11	E. Antipov	Strong SUSY production	: Gluino, squark - stop / sbottom, RPC / RPV w/o MET
•	July 20	Y. Cai	Electroweak SUSY production	: Sleptons, charginos, neutralinos

upcoming

Simplified models

Features of mediator

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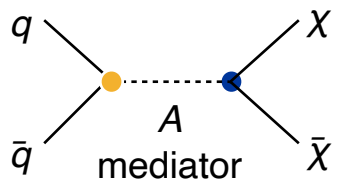
Table of characteristics

Property	Spin 0	Spin 1
Charge Q	0	
Mass m	?	
Mediator is similar to	H, ϕ Escudero et al, JCAP 12 (2016) 029	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_t \gg m_u$	$Q_b = Q_d$
Channels in this talk	VBF H, ZH, $t\bar{t}H/\phi$ (p.11 - 14)	dark QCD, top, anomaly (p.15 - 18)

complementary probes

Lagrangian terms

$g_q\, \bar{q} q A$	$g_\chi\, \bar{\chi} \chi A$
matter-mediator	DM-mediator



Counting parameters

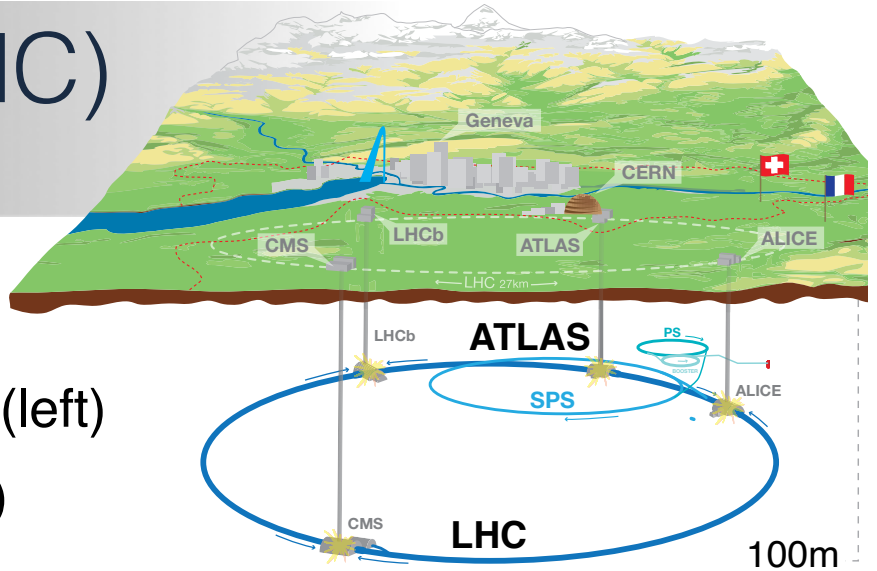
g_q	m_q	m_A	g_χ	m_χ	m_A
❶	known	❷	❸	❹	-

same

Caveat emptor
2d exclusion plot necessarily assumes 2 other parameters

Large Hadron Collider (LHC)

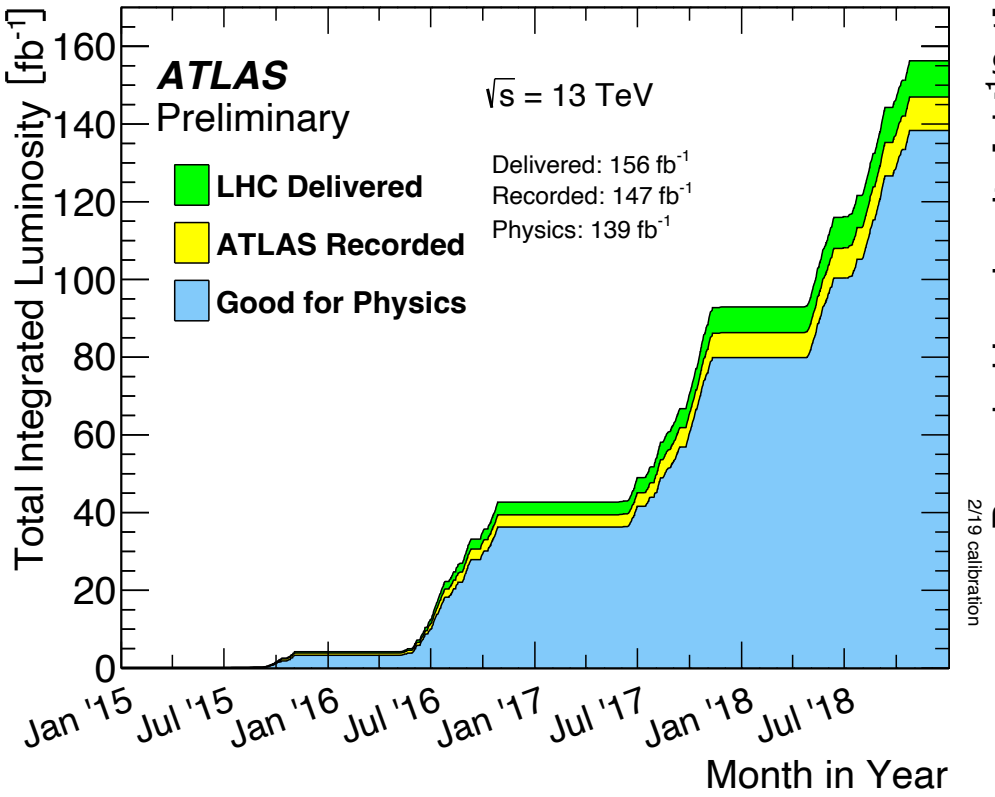
Collide protons at √s = 13 TeV since 2015



Data

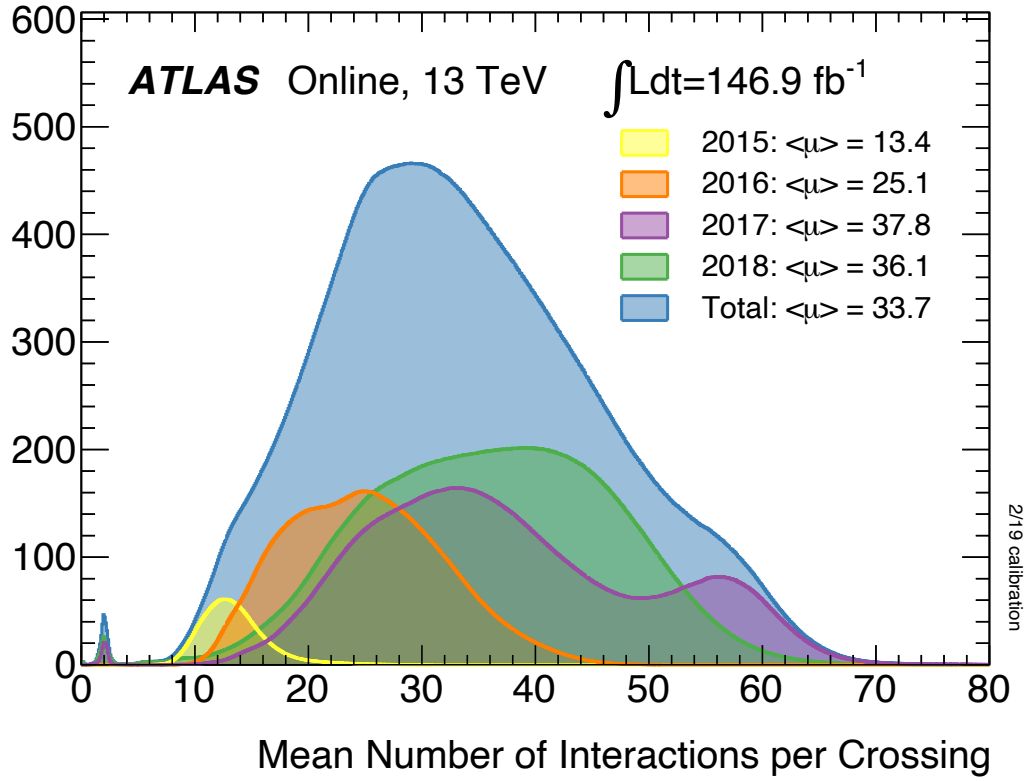
- Following results use the entire 13 TeV sample (left)
- ~ 30 simultaneous collisions per crossing (right)

Integrated luminosity



https://cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Pileup distribution



https://cds.cern.ch/images/OPEN-PHO-CHART-2014-006-1

DM production at LHC

Leaves MET (E_T^{miss}, Missing E_T) transverse to the collision axis

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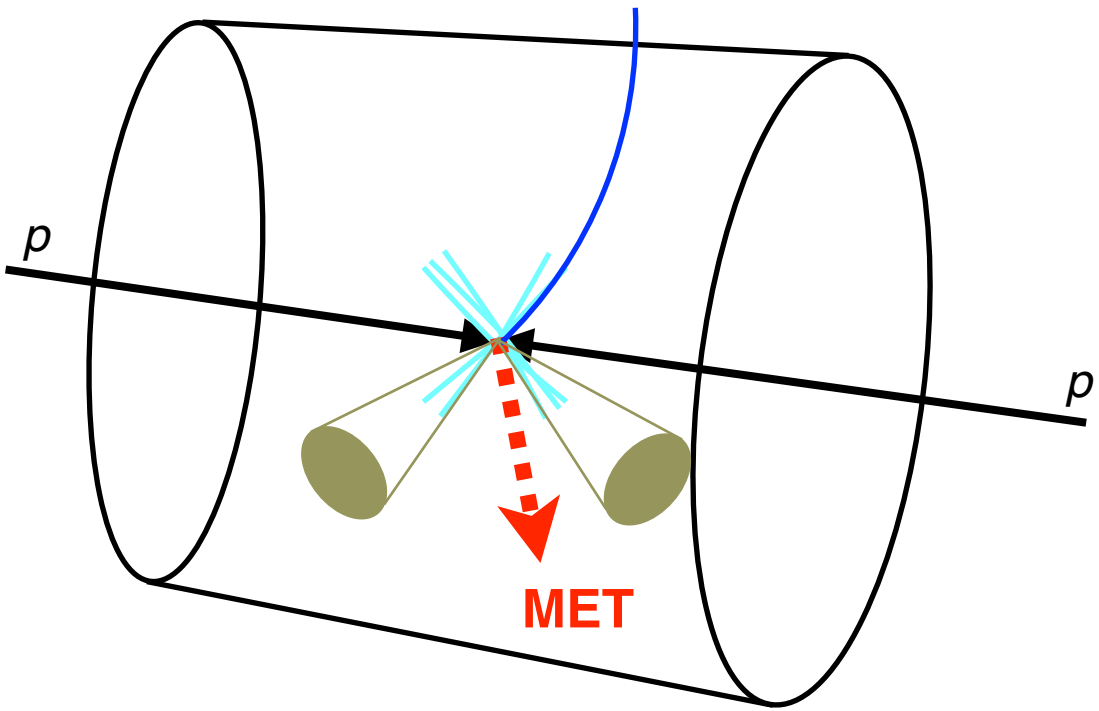
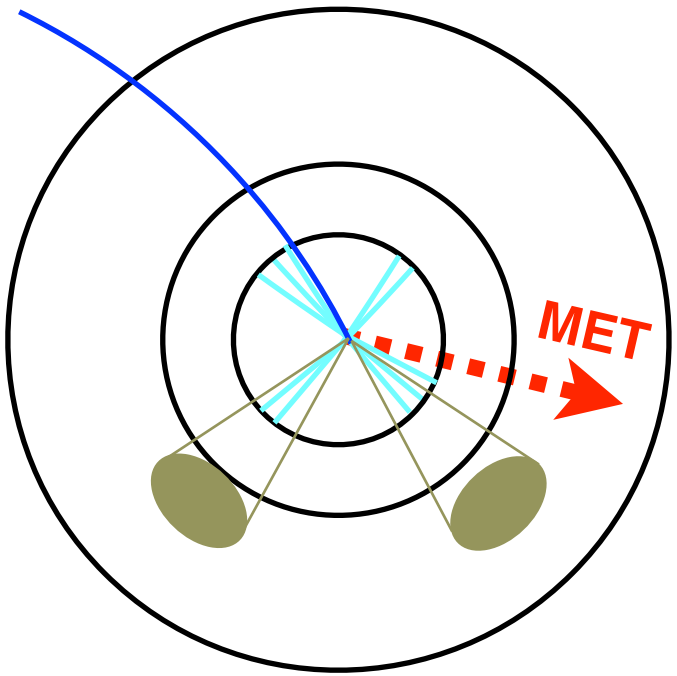
Direct production: pp → DM + recoil
MET

Momentum conservation
Hadronic jet , MET, lepton, photon

Perspective side view



Transverse x-y view



ATLAS experiment

Many upgrades from Run-1 to Run-2 (also for Run-3, HL-LHC)

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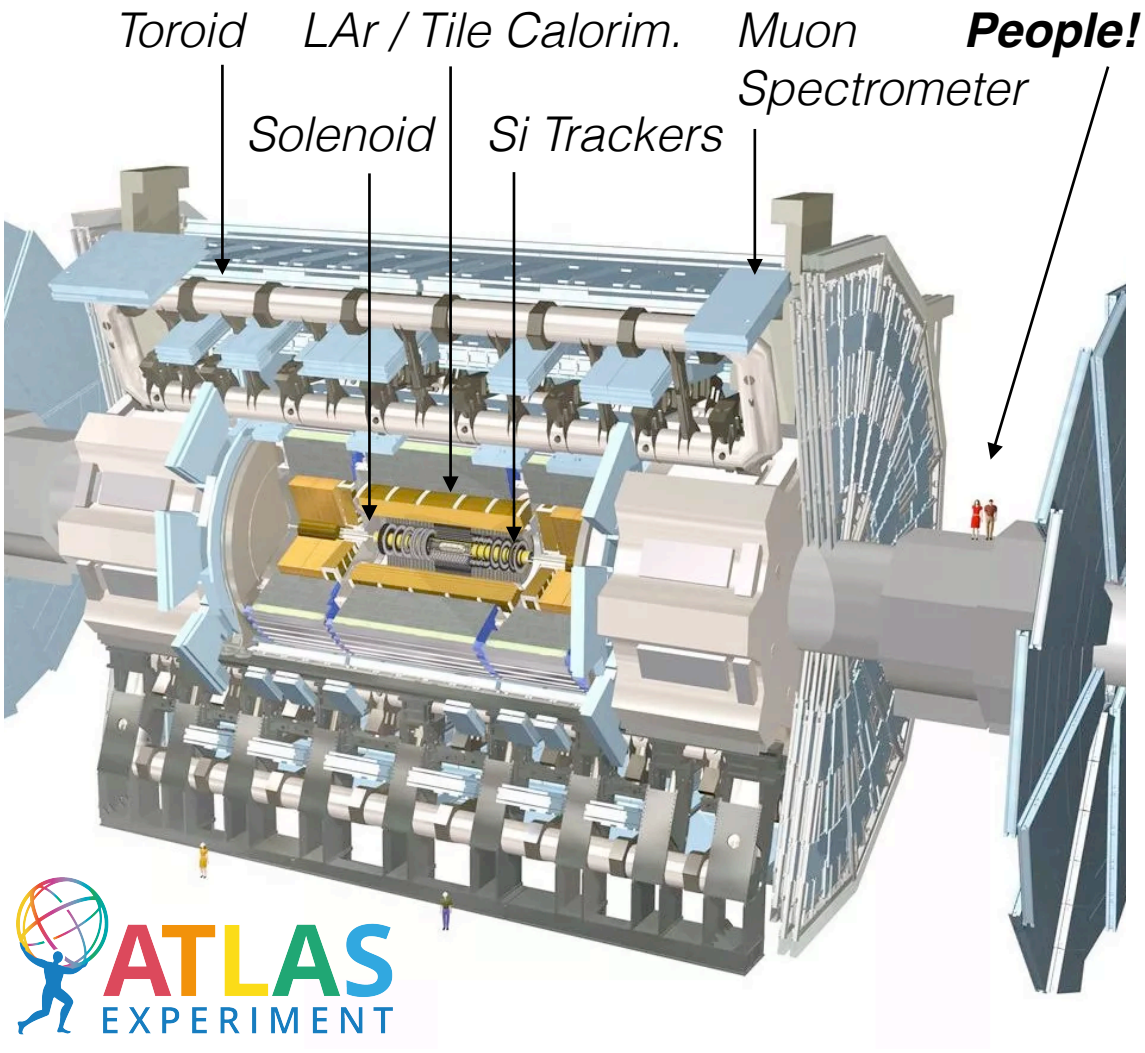
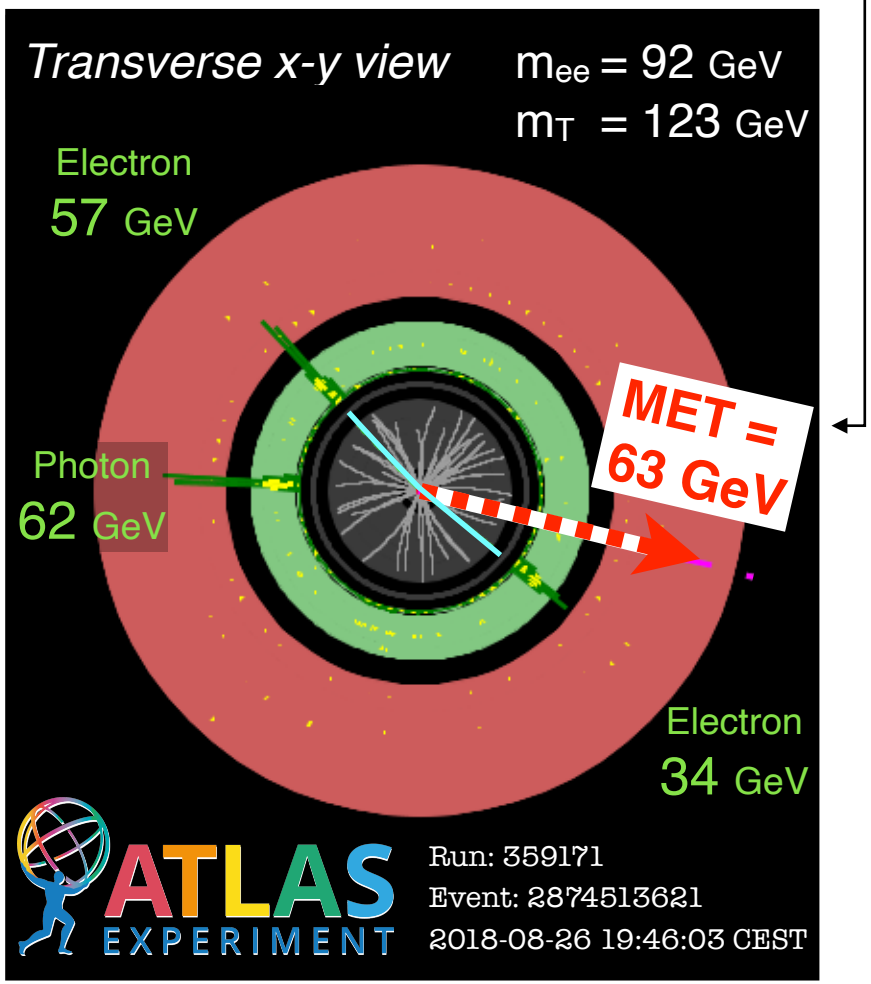
Detector



Event display with photon

$Z_{ee}H$, $H \rightarrow \gamma\gamma_{dark}$



ATLAS, J. Instrum. 3 (2008) S08003

http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-13

ATLAS experiment

Trigger, Data acquisition, Computing

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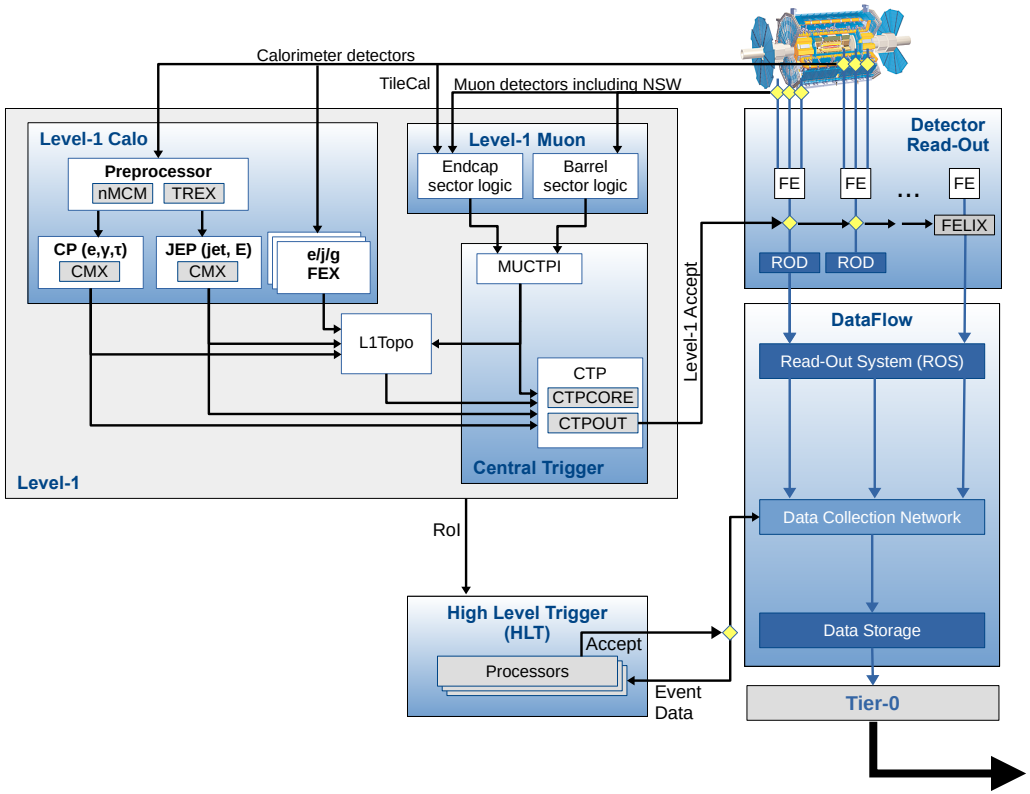
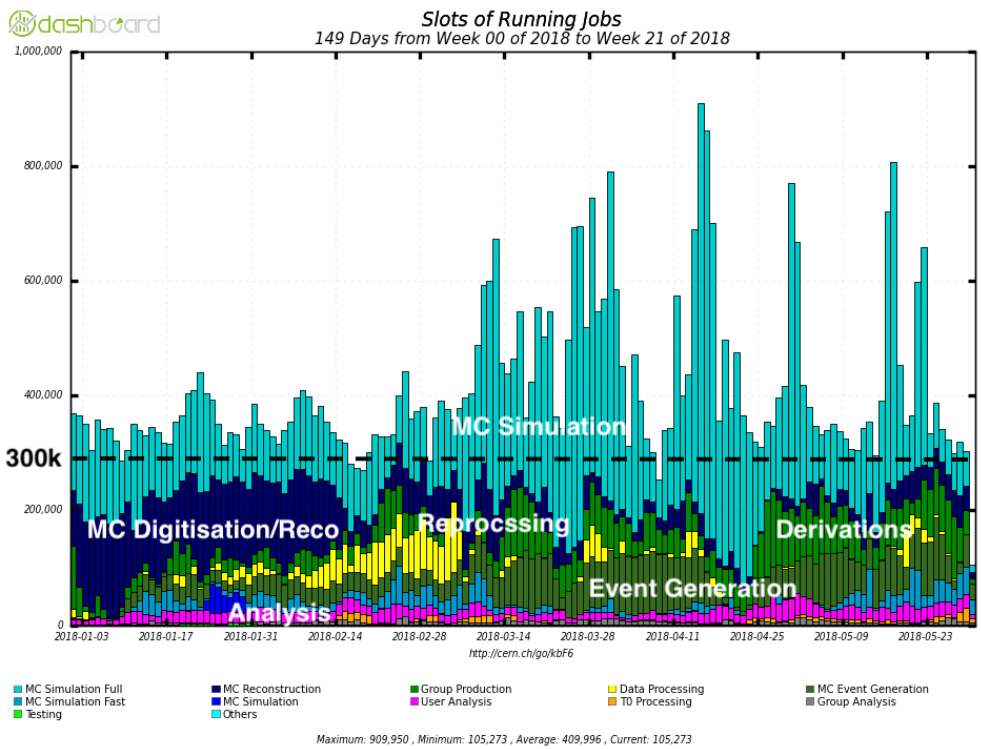
TDAQ

Upgraded L1Calo hardware, MET trigger algorithms, etc.



Computing

Simul. 10B events / yr using 300k CPU



https://cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsDAQ

EPJ Web Conf. 214 (2019) 03010

General feature: MET (Missing E_T)

DM escapes leaving momentum imbalance in the transverse plane

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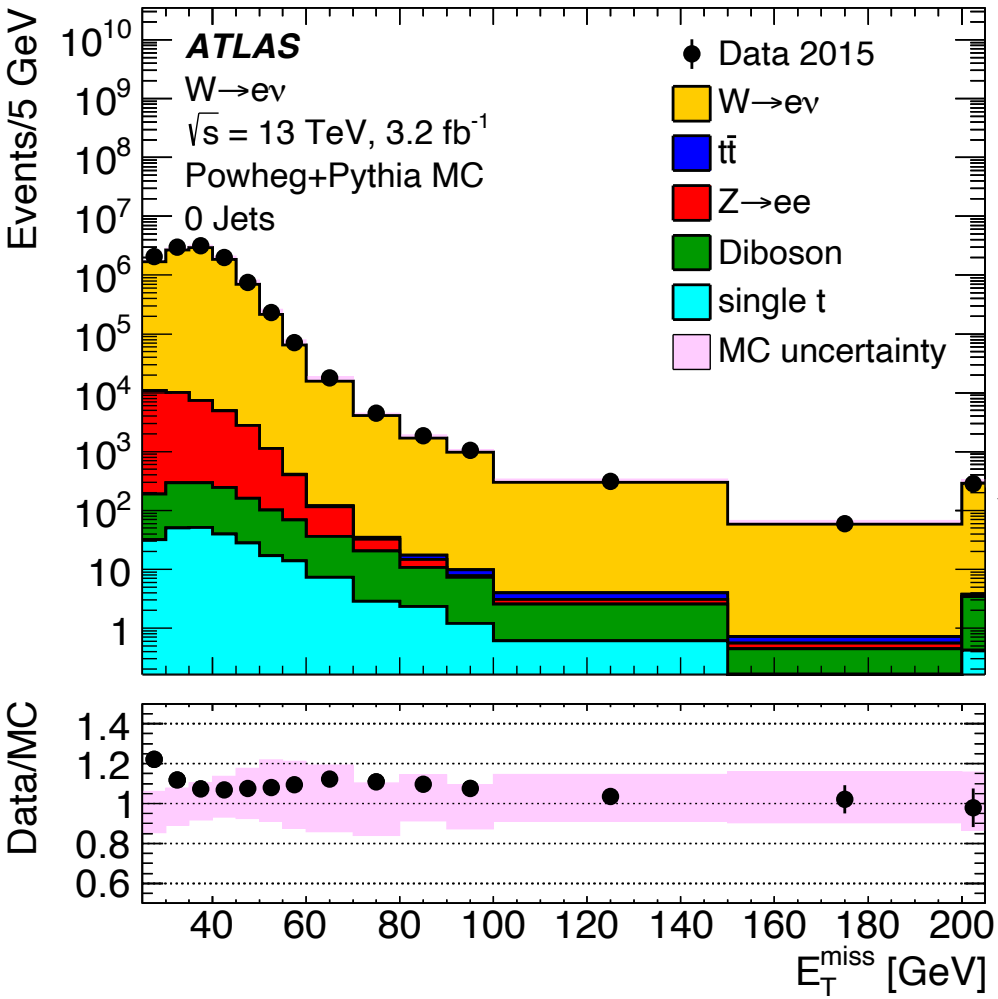
MET distribution of W_{ev}

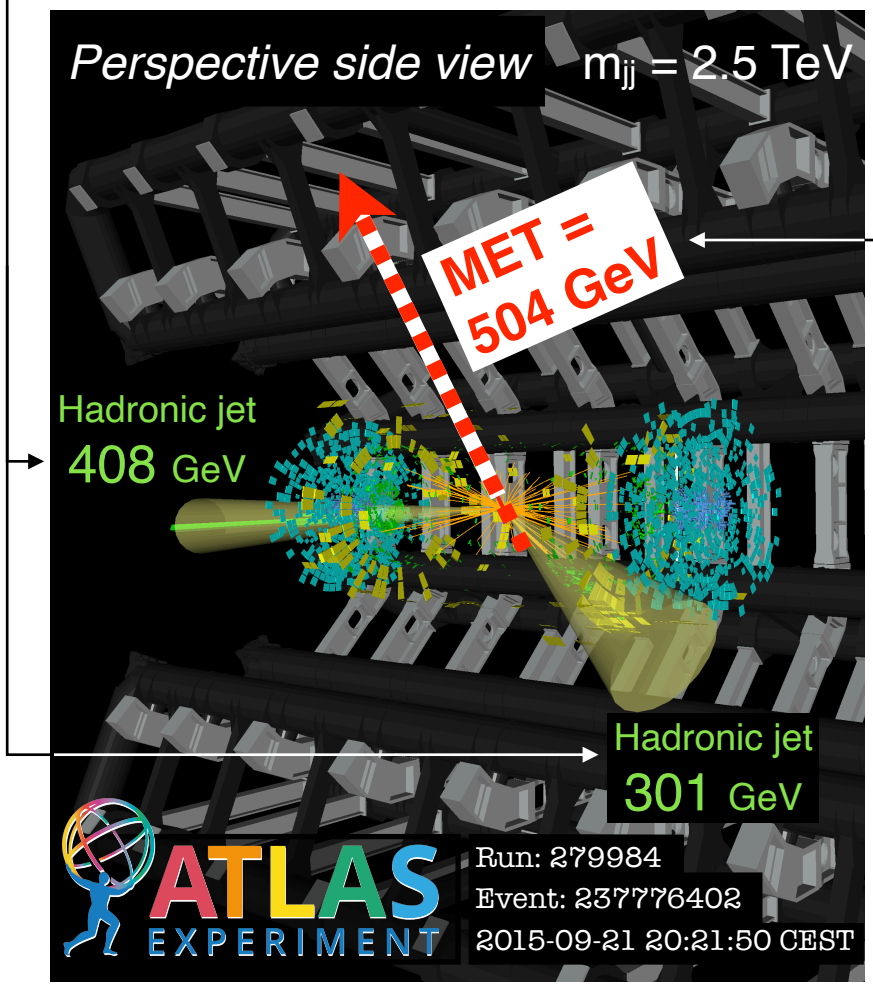
Nice description of core + tail



ATLAS, Eur. Phys. J. C 78 (2018) 903

Event display with VBF jets

VBF $H \rightarrow$ *XX*, *veto W, Z*



https://atlas.cern/updates/briefing/invisible-Higgs-search

Dark matter via scalars: H_{125}, ϕ

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Overview

- Search is challenging like precision measurement
- Assume σ_{H125} for Higgs, σ fits allow $B_{inv} \approx O(10\%)$

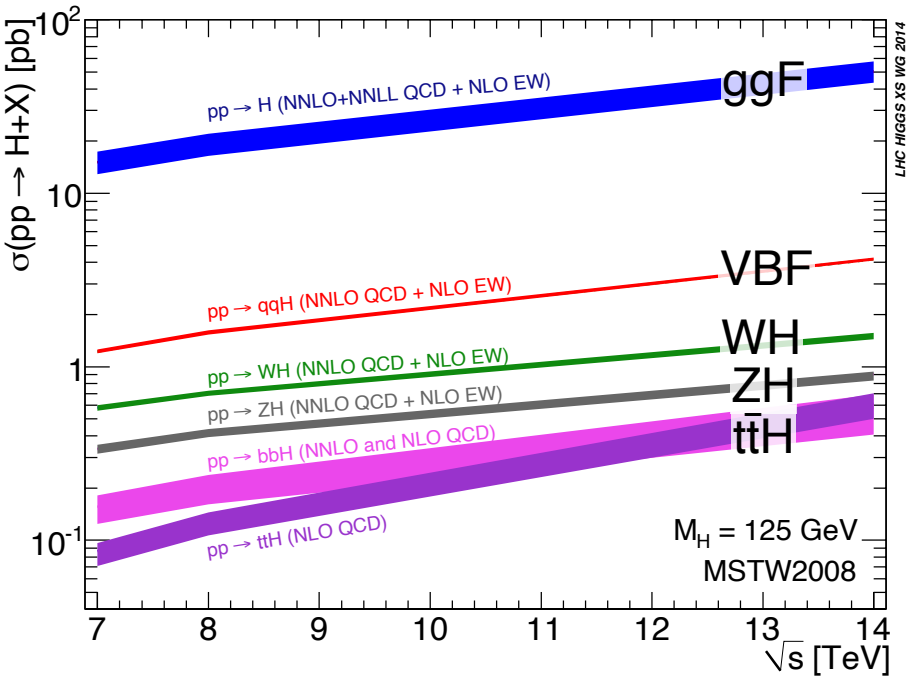
ATLAS, Nature 607 (2022) 52-59

Challenges

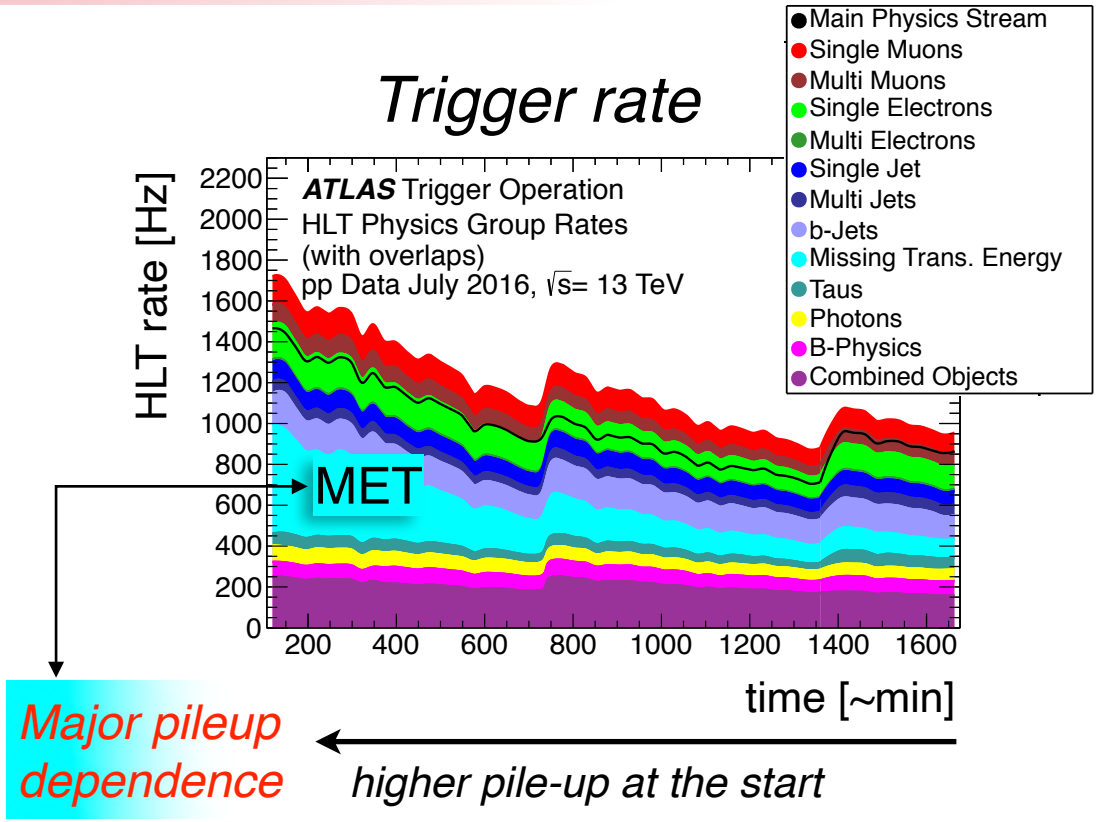
- Need recoil, no ggF H_{125}: use VBF, VH, $t\bar{t}H$ (left)
- Orders-of-mag. dominant QCD process: large MET, but trigger has pileup dependence (right)

ATLAS, J. High Energy Phys. 08 (2020) 80

H_{125} cross section



Trigger rate

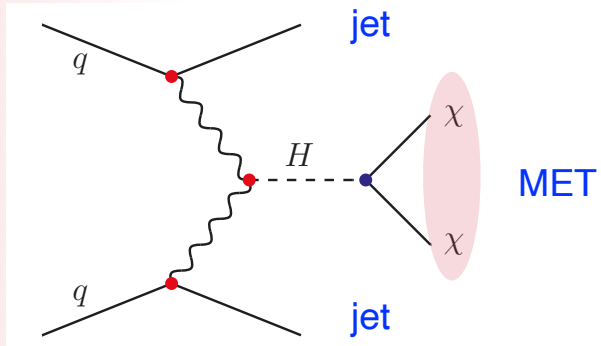


https://cern.ch/twiki/bin/view/LHCPhysics/LHCHWGCrossSectionsFigures http://cern.ch/twiki/pub/AtlasPublic/TriggerOperationPublicResults

DM pair in H_{125} decays: VBF

J. High Energy Phys. 08 (2022) 104 / EXOT-2020-11

Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb^{-1} of proton-proton data recorded by the ATLAS experiment

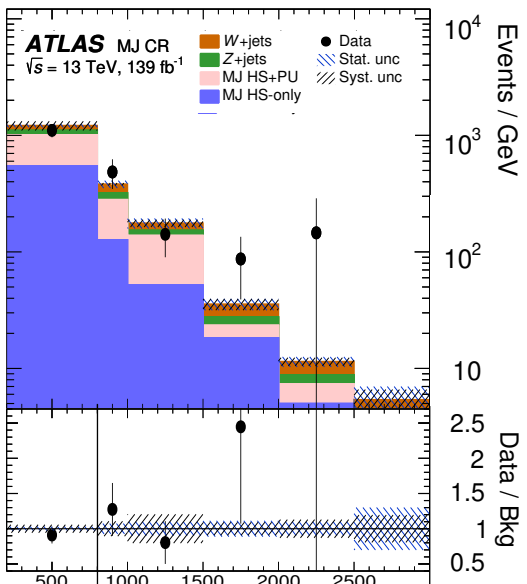


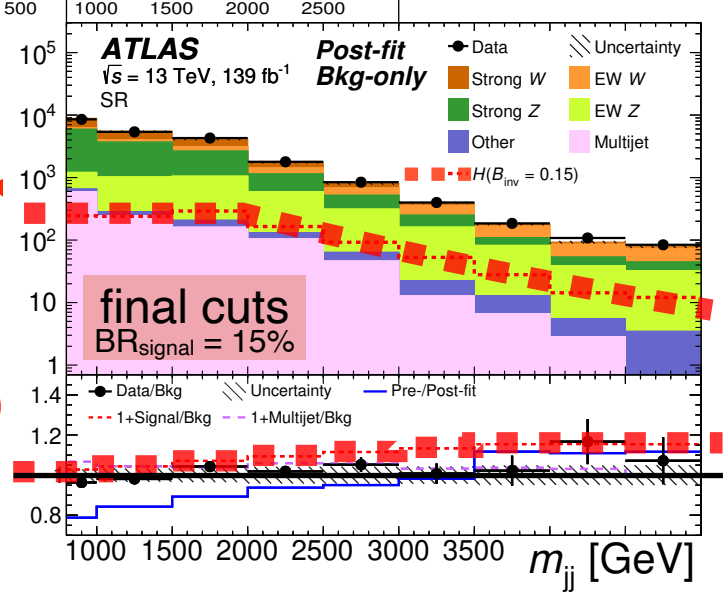
Summary

- Background est.
  - $Z_{\nu\bar{\nu}}$, est. w/ $Z_{\ell\ell}$ & $W_{\ell\nu}$
  - QCD multijet CR ⟶
- Analysis
  - Trig. MET > 160 GeV
  - High m_{jj} (binned fit)

Results

	(%)
• Errors on $\hat{\mu}$	5.2
• stat	2.9
• multijet	2.1
• 95% CL limits	
• BR_{inv} on H_{125}	14.5 (10.3)
• Combination	10.7 (7.7) exp'd





- Higgs portal Doujadi et al., Phys. Rep. 842 ('20) 1-180
  - scalar DM : $\sigma_{WIMP} \sim m_\chi^{-2} \cdot \Gamma_{inv}$
  - fermion DM : $\sigma_{WIMP} \sim$ const $\cdot \Gamma_{inv}$

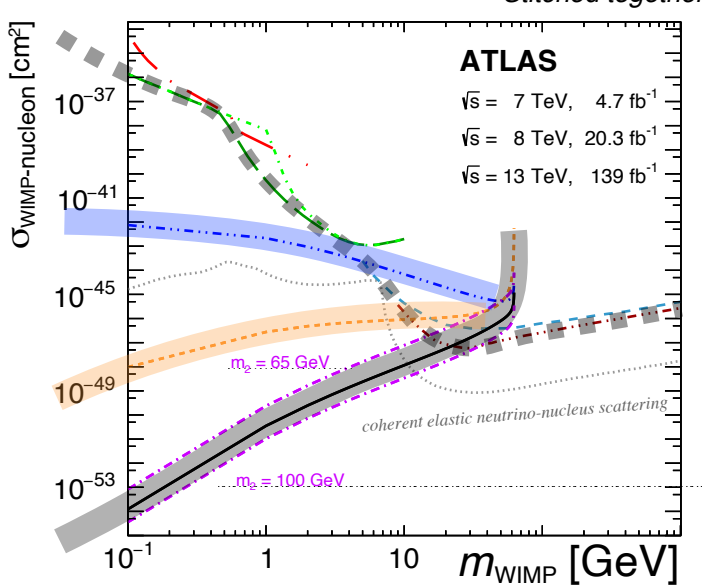
ATLAS, Phys. Lett. B 842 (2023) 137963 / HIGG-2021-05

$B_{H \to inv} < 0.093$

All limits at 90% CL

Higgs Portal WIMP:
- Scalar
- Majorana
- Vector$_{EFT}$
- Vector$_{UV\ model,\ \alpha = 0.2}$

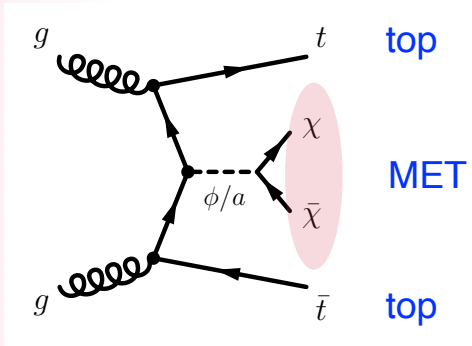
Other experiments:
- Xenon1T-Mig
- DS50-MigNQ
- DS50-MigQF
- PandaX-4T
- LUX-ZEPLIN
- *Stitched together*



DM pair in ϕ, H decays: $t\bar{t}\phi$, $t\bar{t}H$

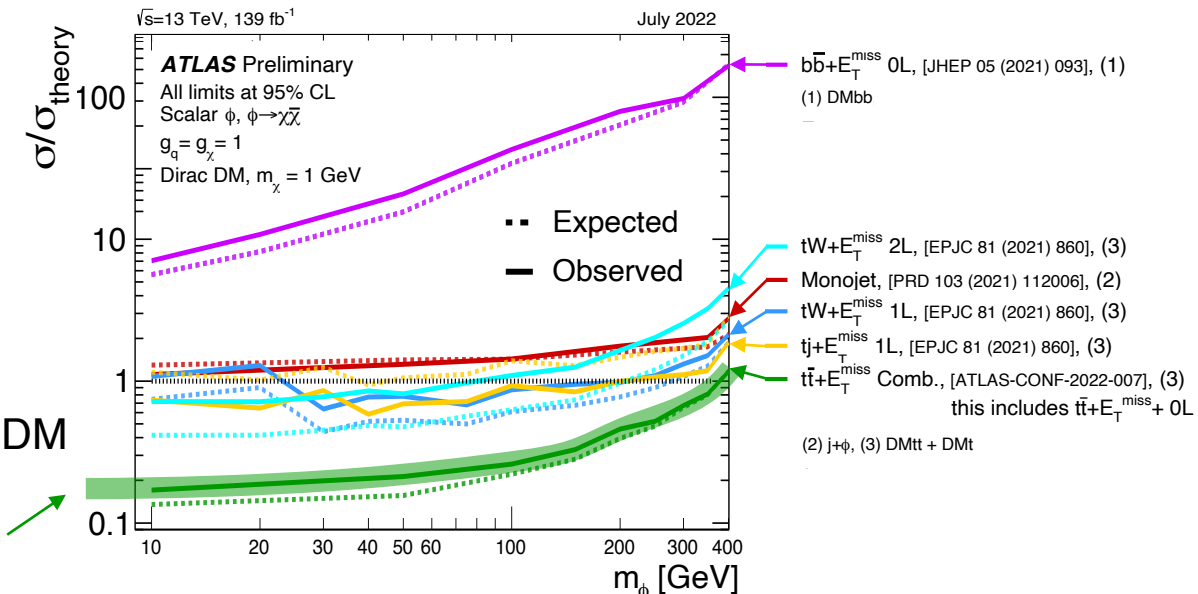
Eur. Phys. J. C 83 (2023) 503 / SUSY-2019-12

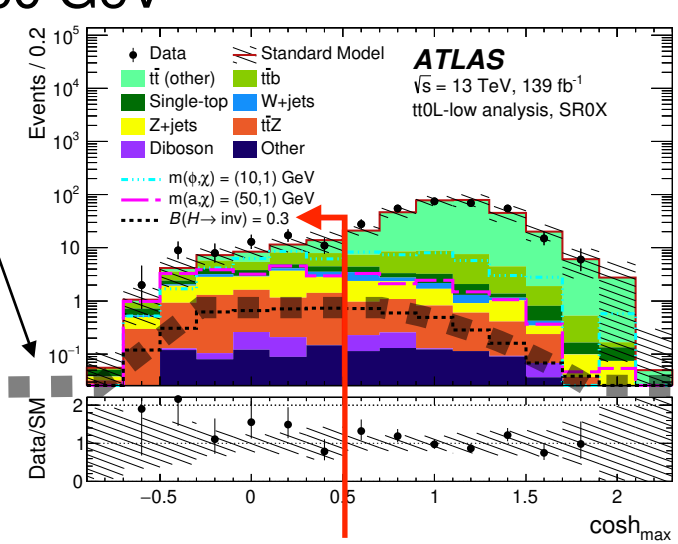
Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV *pp* collision data with two top quarks and missing transverse momentum in the final state

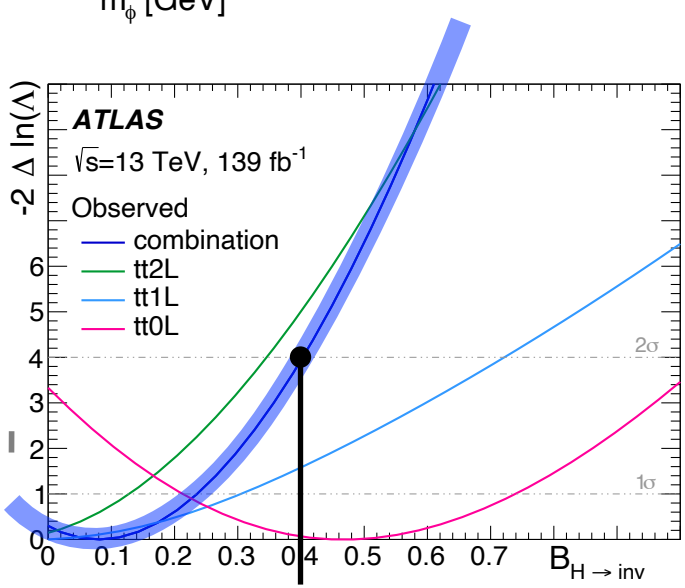


Summary

- Yukawa-type coupling to 3rd gen
- Lepton channels
  - 2ℓ : JHEP 04 (2021) 165
  - 1ℓ : JHEP 04 (2021) 174
  - 0ℓ, MET>250 : EPJC 80 (2020) 737, no DM
  - 0ℓ, MET>160 : This work
  - DM comb'n : ATL-PHYS-PUB-2022-036 (2022)
- Analysis of 0 lep, MET > 160 GeV
  - Compute χ^2
  - $\cosh_{max}$, pseudo-top reco. var.







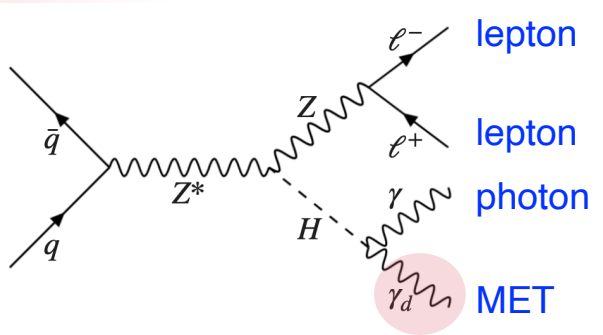
Results

- Tightest bound on spin-0
- Also BR_{inv} limit on H_{125}
  - 38% (30% exp'd)

Dark γ in H_{125} decays: ZH

[2212.09649] (2022) / HDBS-2019-13 subm. to JHEP

Search for dark photons from Higgs boson decays via ZH production with a photon plus missing transverse momentum signature from *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

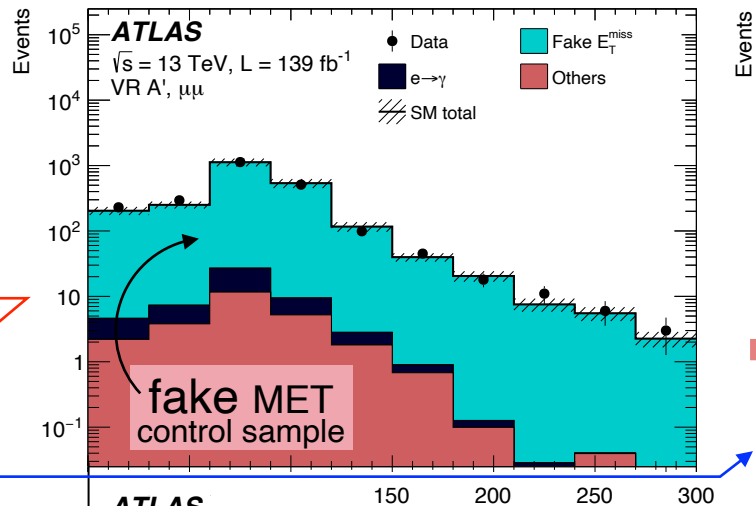


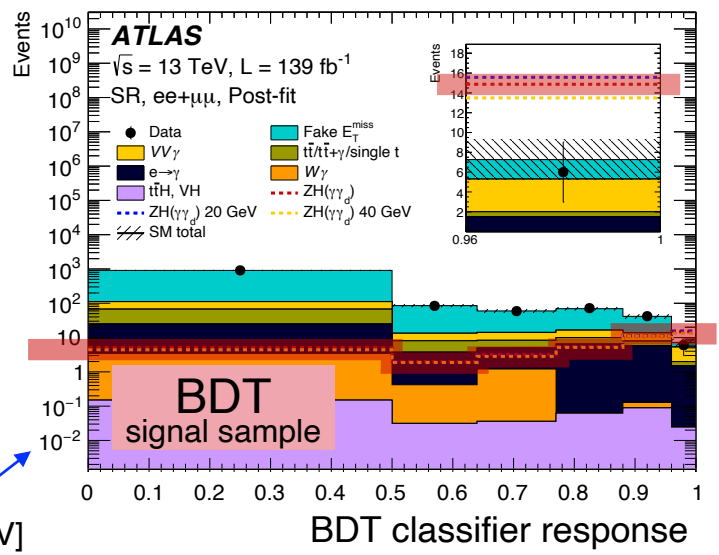
Summary

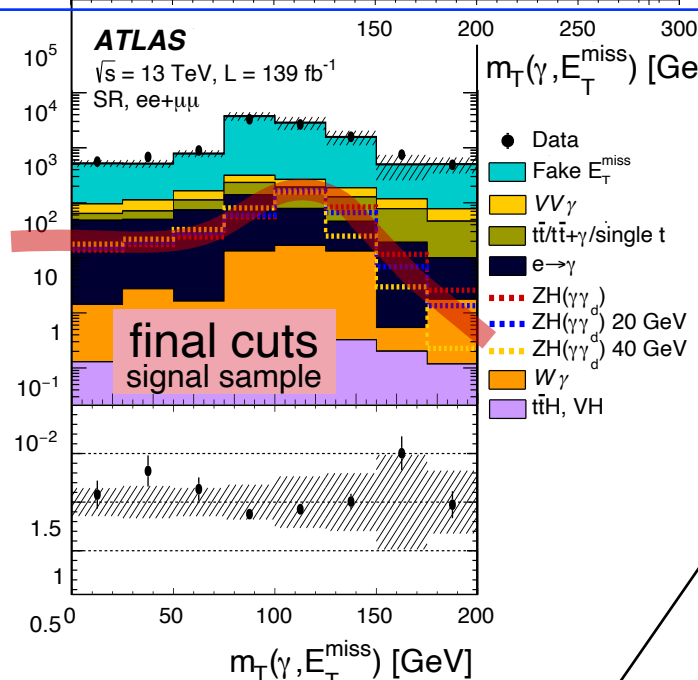
- Background est.
  - MET_{fake} from Z w/ mismeas. jet → γ
- Analysis
  - Transv. mass m_T
  - BDT bins

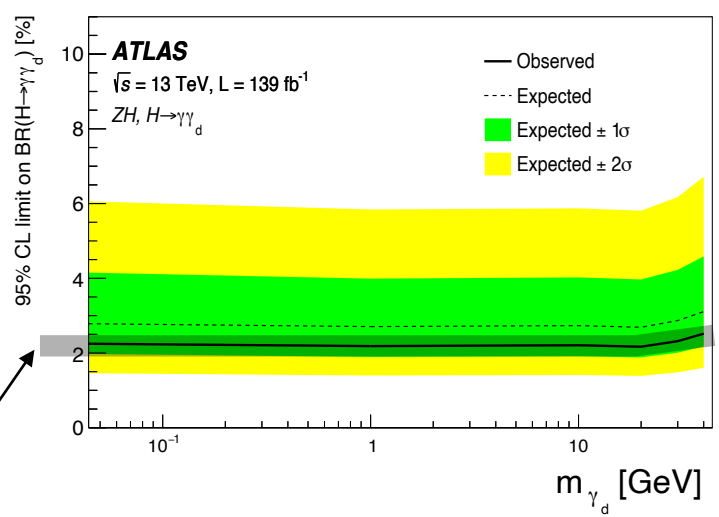
Results

	(%)
• Errors on N_{SM}	28
• MET_{fake} shape	18
• data stat	16
• 95% CL limits	
• $BR_{dark\ massless\ \gamma}$	2.3 (2.8) exp'd
• Massive γ interpretation	









Dark matter via various methods

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Overview

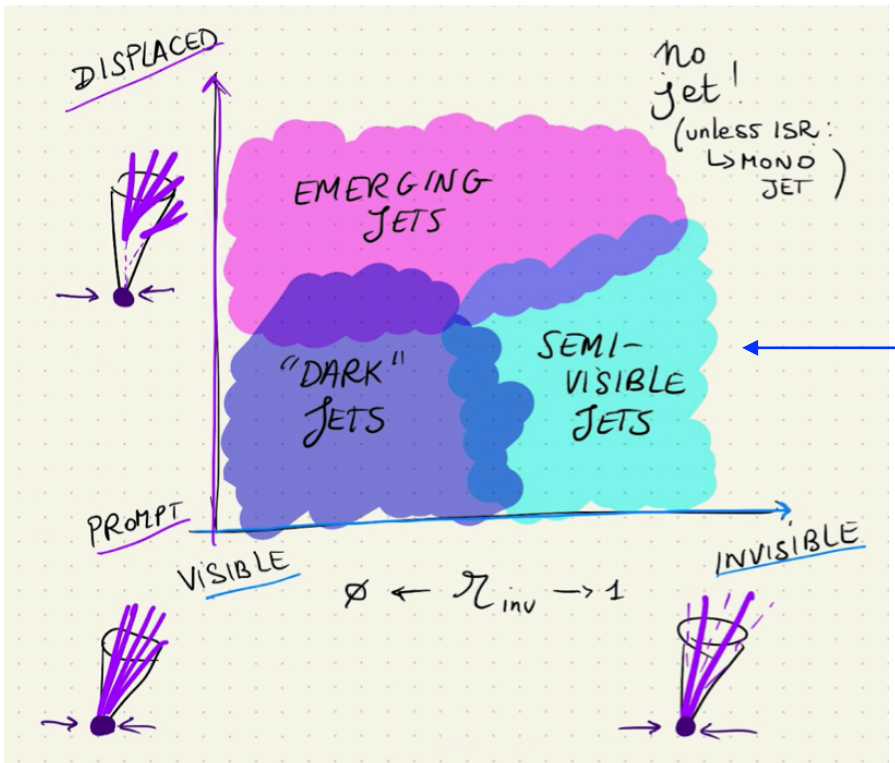
- Anomaly detection
- Single top + DM
- Dark QCD with varying visibility (left, right)

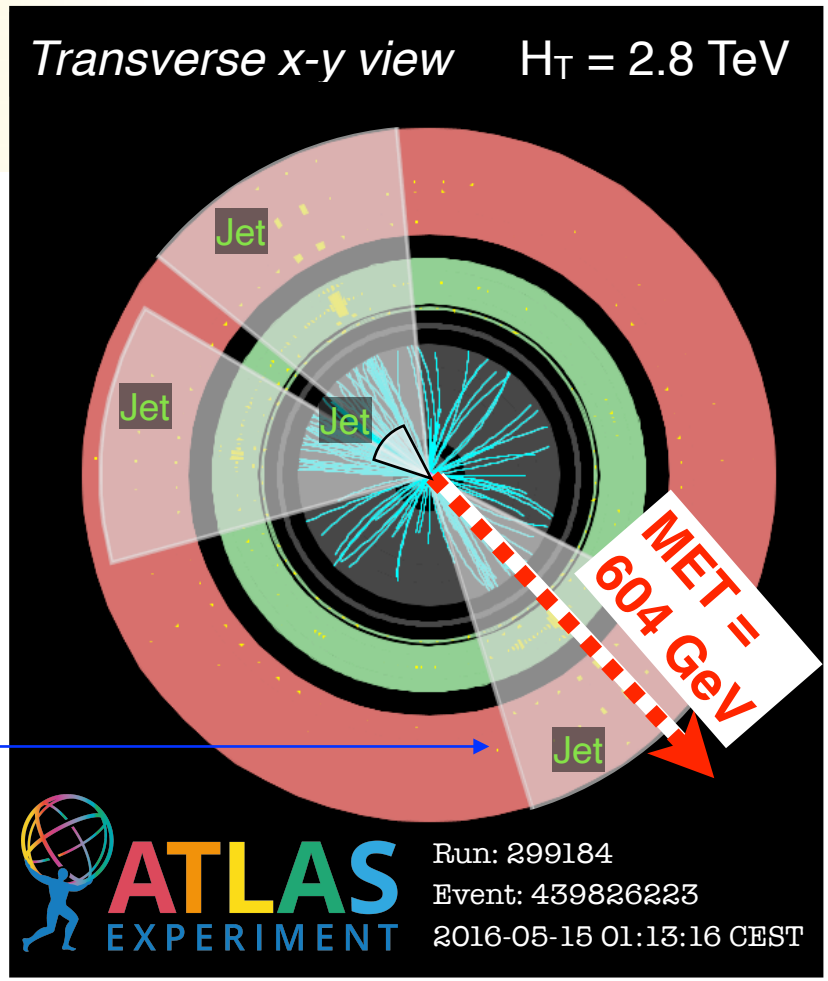
Dark QCD

- Vary invisible frac.
- Semi-visible jet aligns with MET

Event display with jets

Semi-visible jet aligned with MET





By C. Doglioni after discussion with K. Pedro, C. Fallon

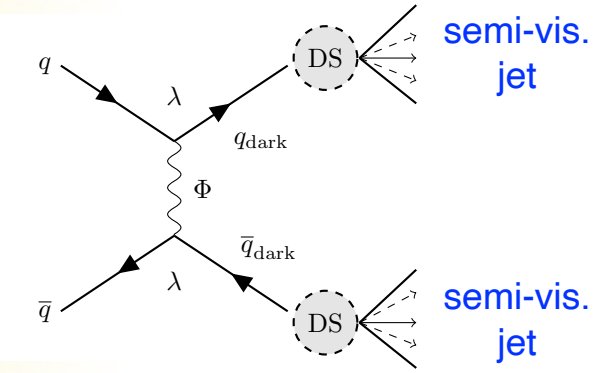
https://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2022-37

Dark hadrons in semi-visible jets

[2305.18037] (2022) / EXOT-2022-37 subm. to PLB

Search for non-res. prod'n of semi-vis. jets using Run 2 data in ATLAS

- Relevant theory paper by Cohen, Lisanti, Lou & Mishra-Sharma, *LHC searches for dark sector showers*, J. High Energy Phys. 196 (2017)

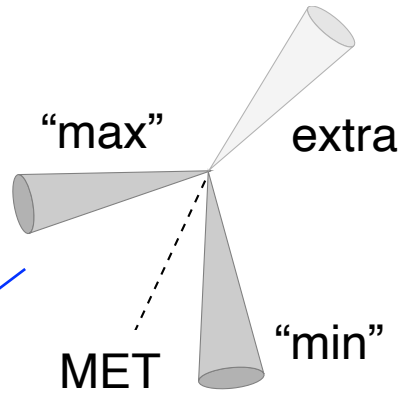


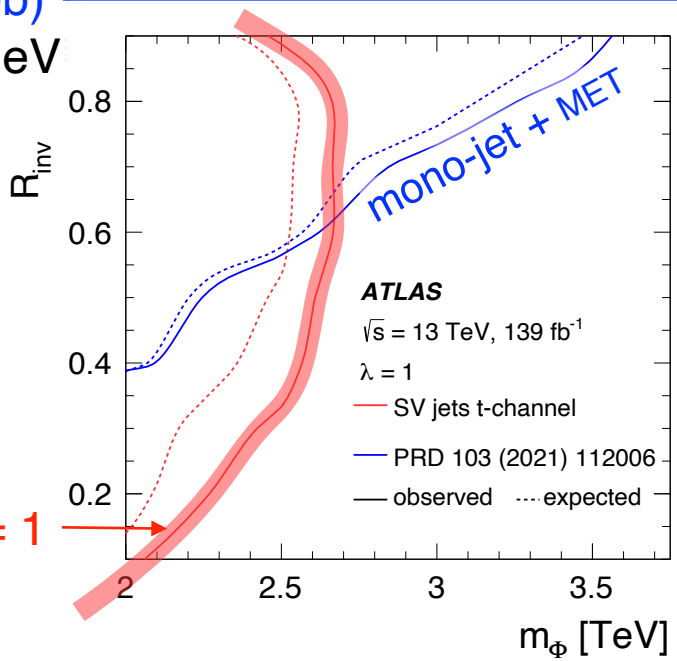
Summary

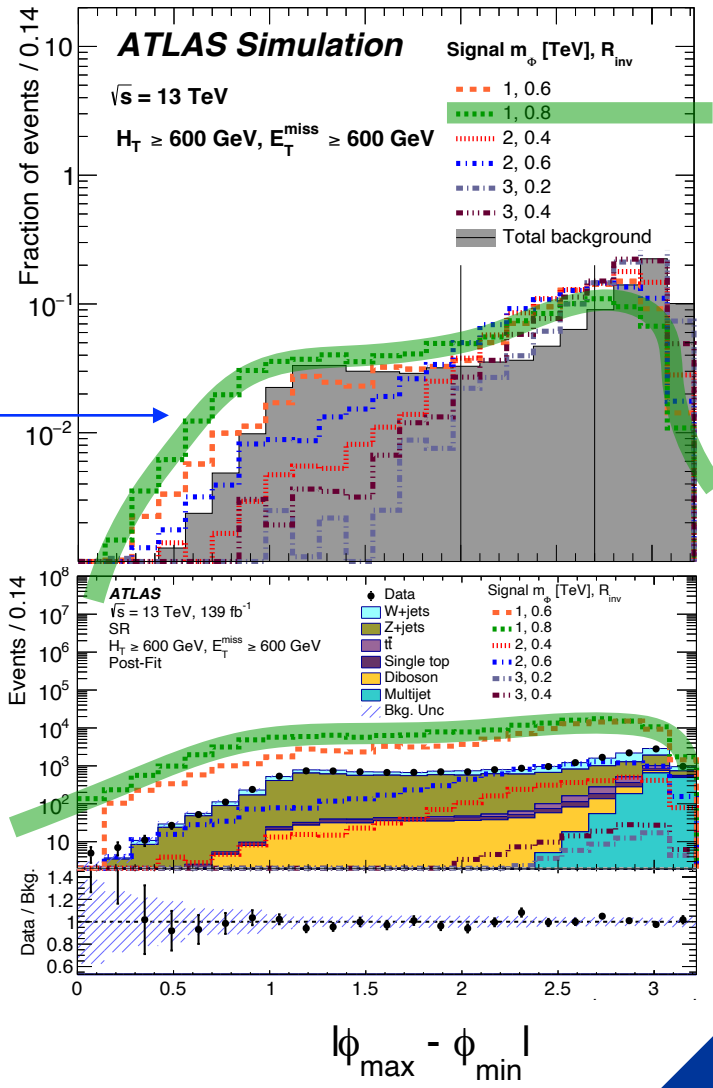
- Signal - MADGRAPH + PYTHIA8
  - $m_{dark\ had.}$=10 GeV, m_Φ=O(1) TeV, vary R_{inv} = inv. frac. in jets
- Analysis
  - Bin in p_T^{bal} v. $\Delta\phi_{jj}$ (not b-to-b)
  - 2+ jets > 250, extra > 30 GeV
  - Trig + MET > 200 GeV

Results

- Sample size
  - 17k, mostly W+jet, Z+jet
- 95% CL limits
  - Exclude $m_\Phi \gtrsim 2$ TeV for $\lambda = 1$



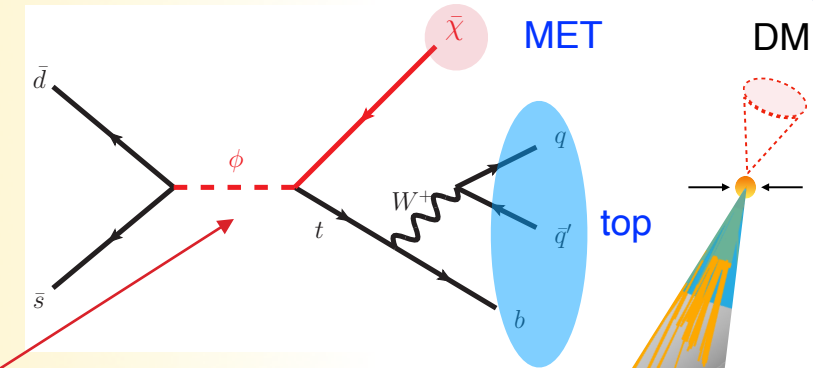




DM produced w/ single top

ATLAS-CONF-2022-036 (2022)

Search for invisible particles produced in association with single top quarks in proton-proton collisions at √s = 13 TeV with ATLAS



Summary

- Signal models
  - Vector-like quark $T \rightarrow t Z_{vv}$
  - Non-resonant $\phi \rightarrow t \chi$
  - Resonant $u \rightarrow t V_{XX}$
- Analysis
  - Trig + MET > 250 GeV
  - BDT w/ xgBoost

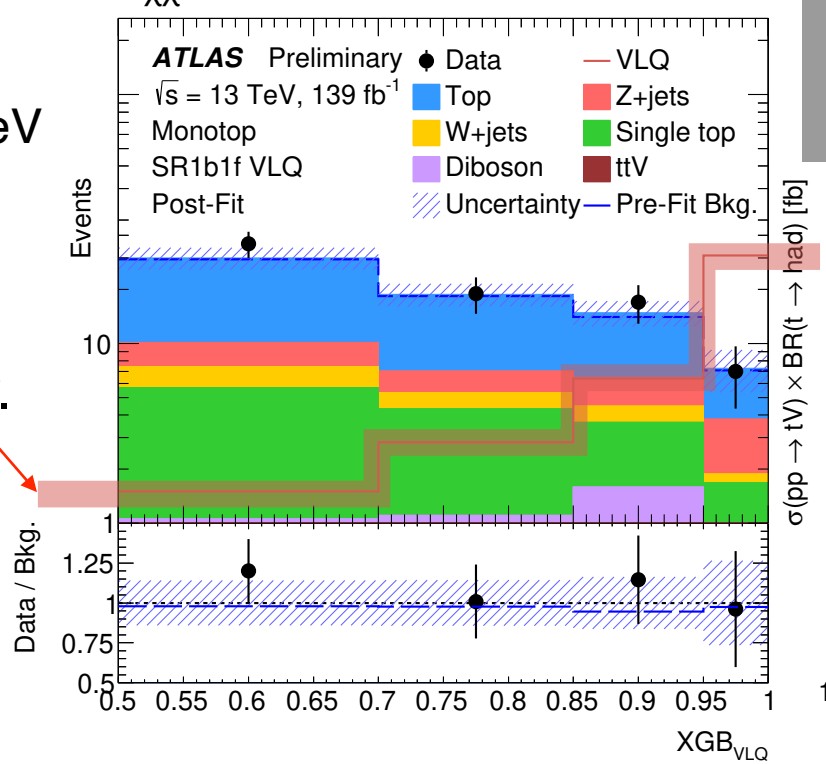
Results

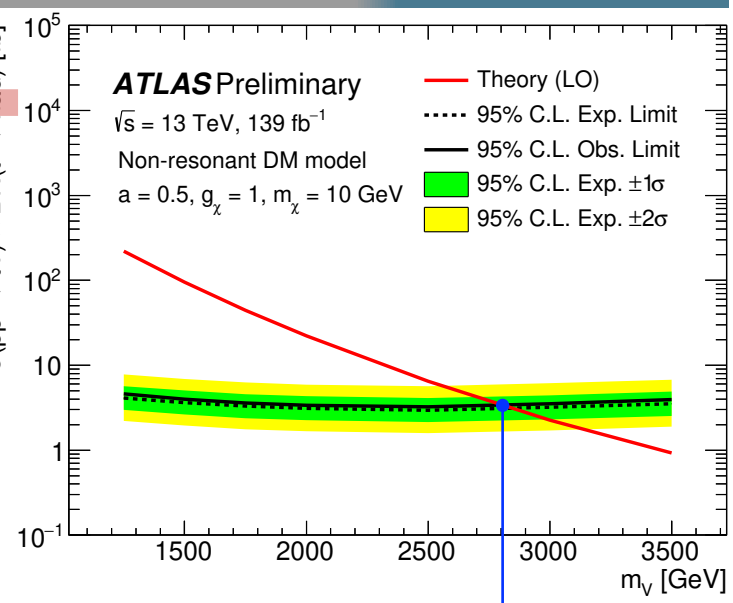
- 95% CL limits — Prev.
  - $m_T < 2.2$ TeV — 1.7
  - $m_\phi < 5.0$ TeV — 3.5
  - $m_V < 2.8$ TeV — 1.9

ATLAS, JHEP 05 (2019) 041
CMS, JHEP 05 (2022) 093

Event display for
boosted top w/ 3-prongs →

ATLAS, JHEP 10 (2020) 61
/ EXOT-2018-48

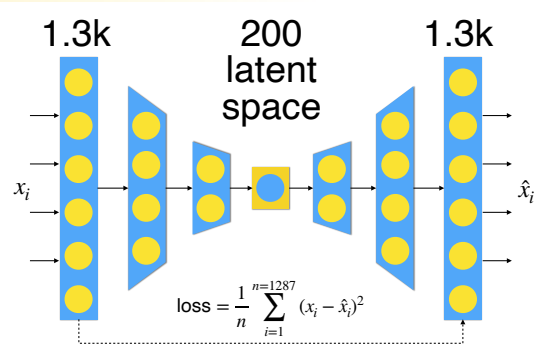




DM produced via anomaly

[2307.01612] (2023) / EXOT-2022-07 subm. to PRL

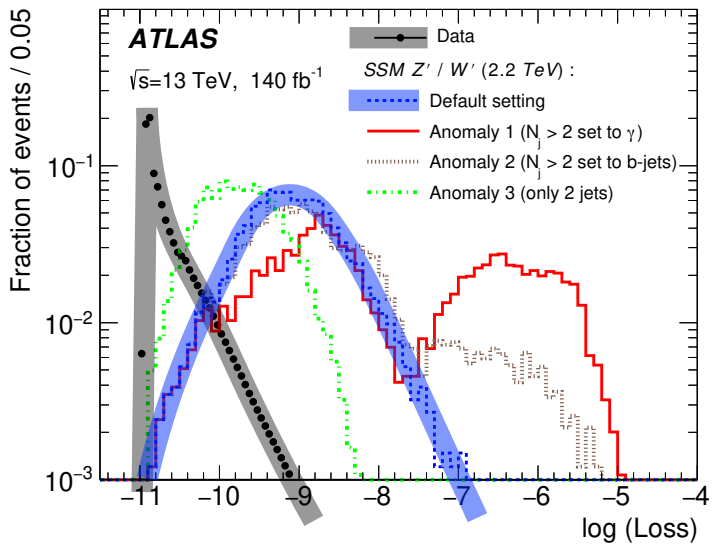
Search for new phenomena in two-body invariant mass distributions using unsupervised machine learning for anomaly detection at $\sqrt{s} = 13$ TeV with the ATLAS detector



- Output trained to approx. input
- Autoencoder to learn SM

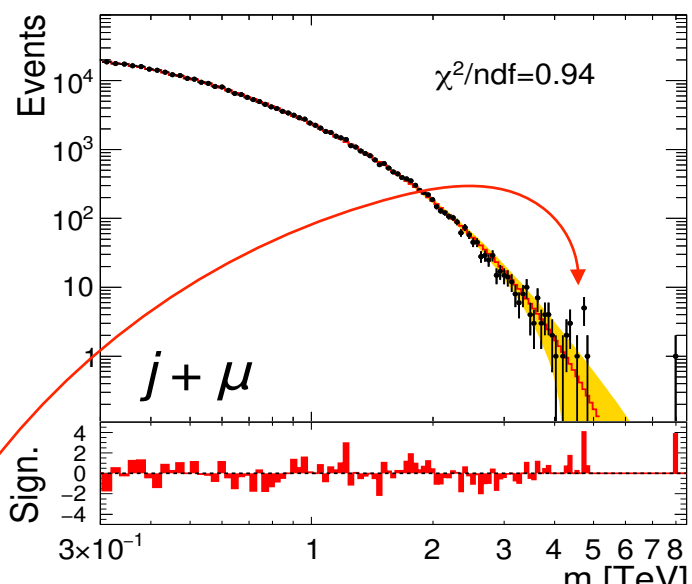
Summary

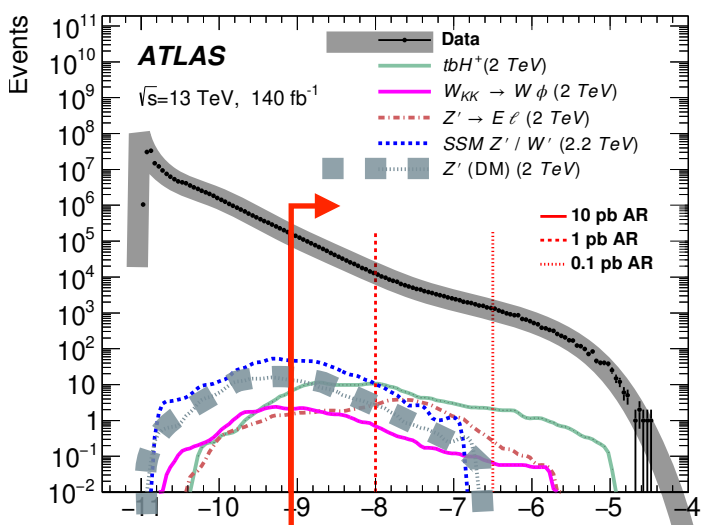
- Teach SM w/o signal model
  - Train w/ data, validate w/ MC
- Analysis
  - Lep. trig, use BumpHunter 9 m_{j+x}
  - 1.3k inputs to a.e., exclude 9 m_{j+x}
  - Cut log(Loss), then look at 9 m_{j+x}
- "Loss function" ~ input-output distance
  - Peaks low for SM
  - Peaks high for BSM or appear as bump



Results

- 5 benchmark BSM
  - tbH$^+$, H$^+$ → tb
  - W_{KK}, W+radion
  - Z' → Eℓ, E → Zℓ
  - W' → WZ' → ℓνqq̄
  - DM Z' → qq̄
- BumpHunter 2.9σ
  - $m_{j\mu}$ = 4.8 TeV, 10 pb AR





Dark matter via supersymmetry

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Overview

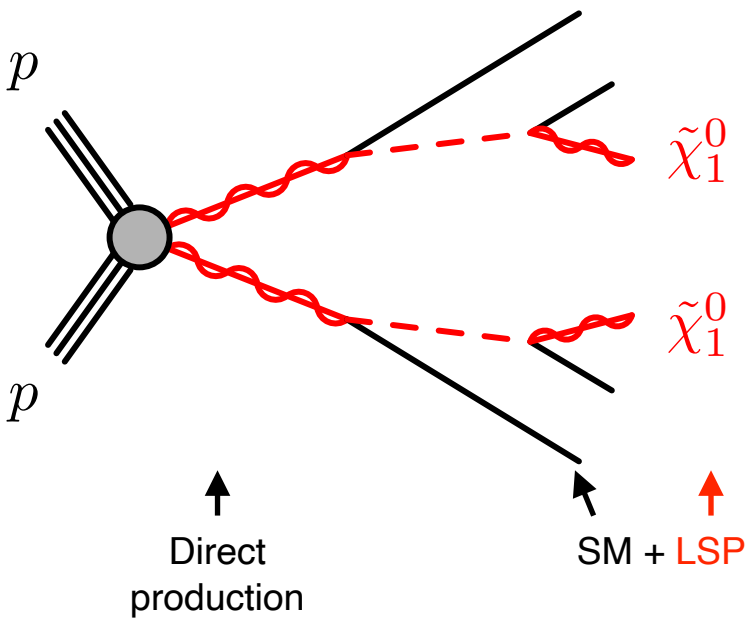
- SUSY produced → SM + LSP
- Direct vs. indirect production
  E-weak vs. strong production
- (higgsino wino bino) =
  (charginos neutralinos)

Challenges

- Huge param. space, so simplify with tan β etc., but shrinking with results
- Can expand R-parity, baryon #
- R-parity conserved, violated

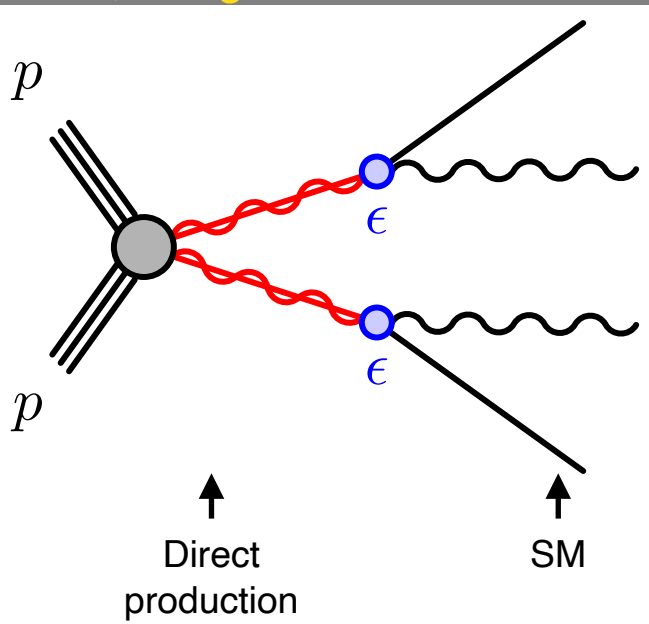
R-parity conserving

LSP = DM candidate

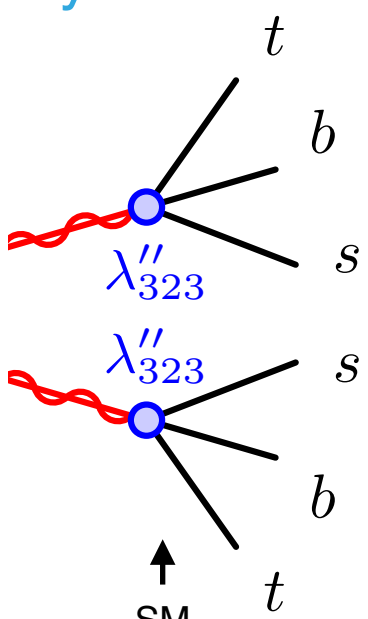


R-parity violate

No LSP, but gravitino / axino = DM



Baryon # violate

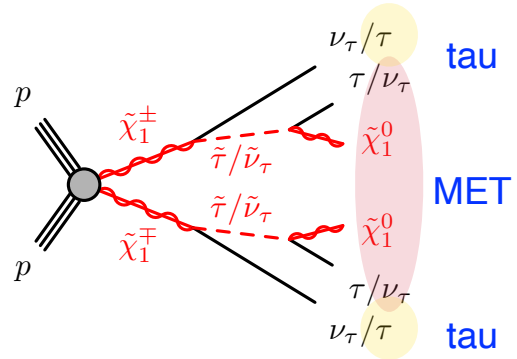


This talk

DM LSP in direct: 2 tau

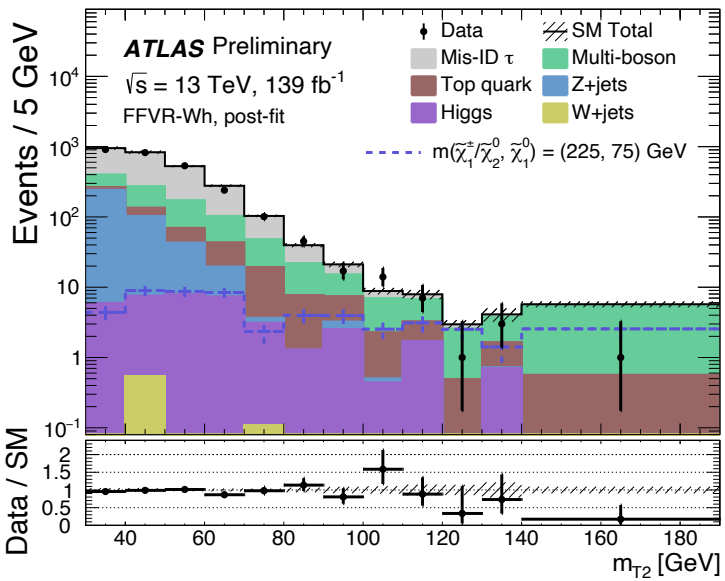
ATLAS-CONF-2023-029 (2023)

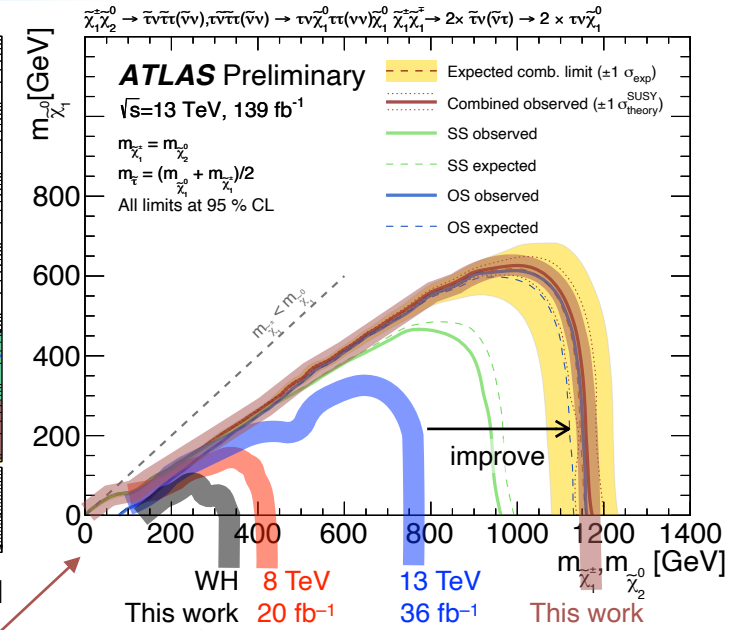
Search for electroweak SUSY production in final states with two τ-leptons in √s = 13 TeV pp collisions with the ATLAS detector

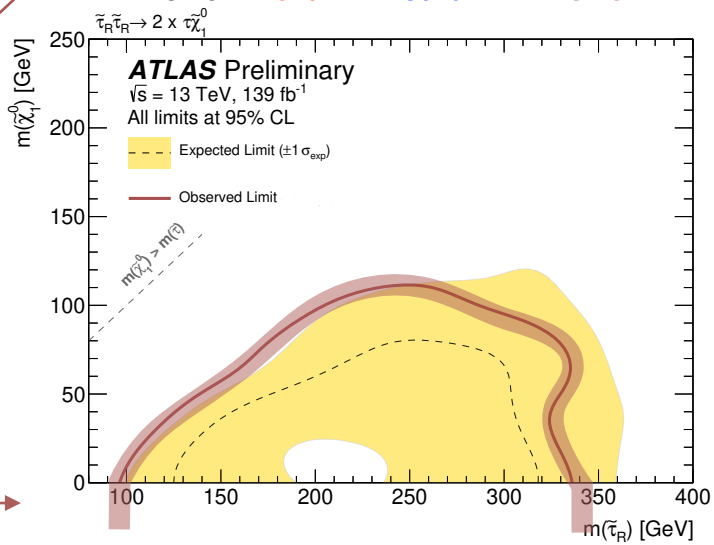


Summary

- Signal
  - Bino-like LSP with wino-like C1 / N2 (see)
  - WH+2 LSP (not shown)
  - $\sigma_{\tilde{\tau}L} \gtrsim 2 \cdot \sigma_{\tilde{\tau}R}$
    Fuks et al., JHEP 1401 (2014) 168
- Background est.
  - τ mis-id validate
- Cuts
  - m_{T2} to detect kinematic endpoint
  - Trig: asym. di-tau (+MET for high-mass)
  - For WH, use $m_{lep,had} \sim m_H$







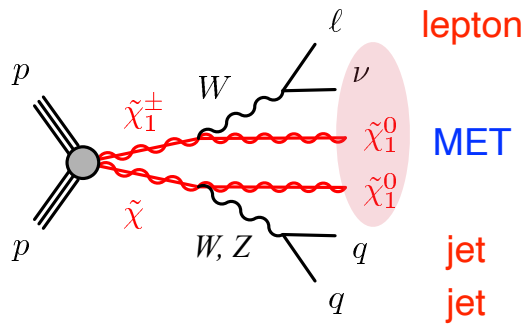
Results

- Chargino excludes 1.2 TeV, indp't WH excludes 300 GeV
- First limit on $\tilde{\tau}_R$

DM LSP in direct: 1 lepton + jets

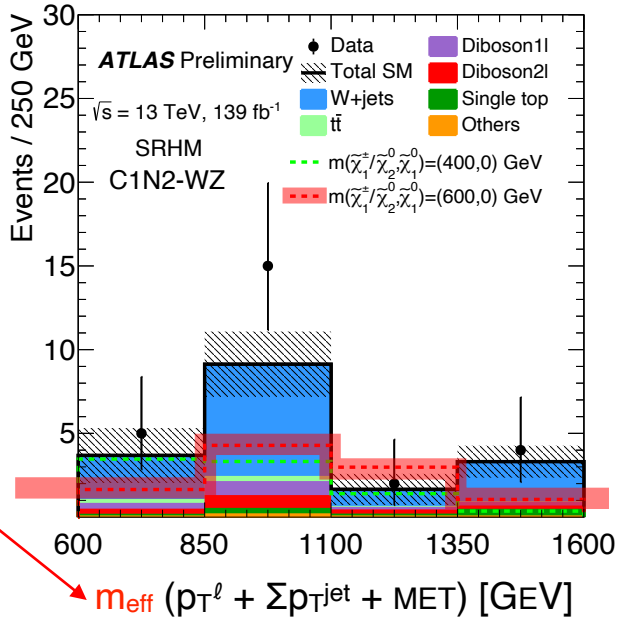
ATLAS-CONF-2022-059 (2022)

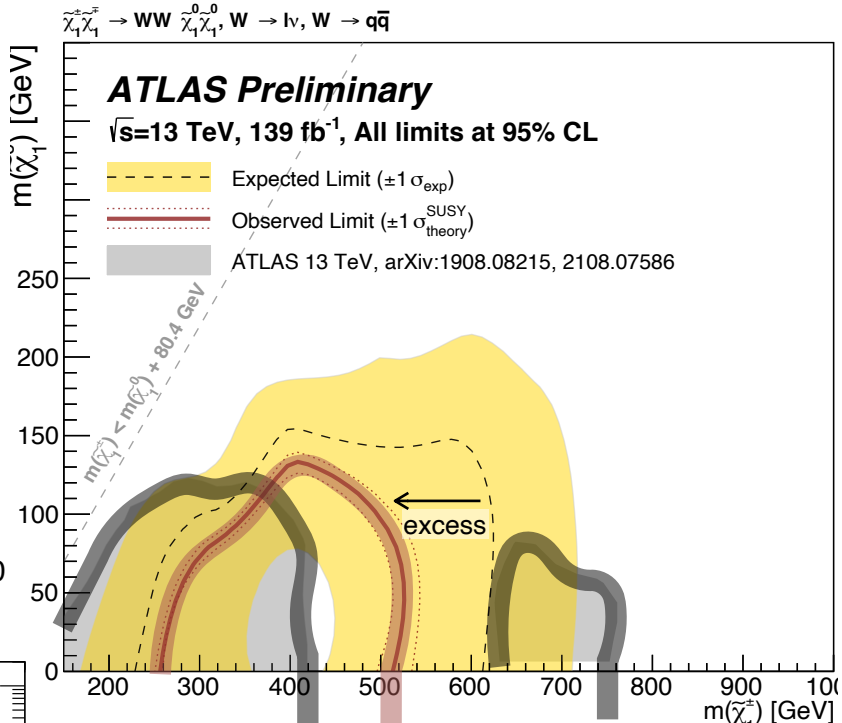
Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum and in *pp* collisions at 13 TeV with the ATLAS detector



Summary

- Background est.
  - W + jets (50 - 75%)
- Analysis
  - m_{jj}, m_T, S_{MET}, Final sample m_{eff}





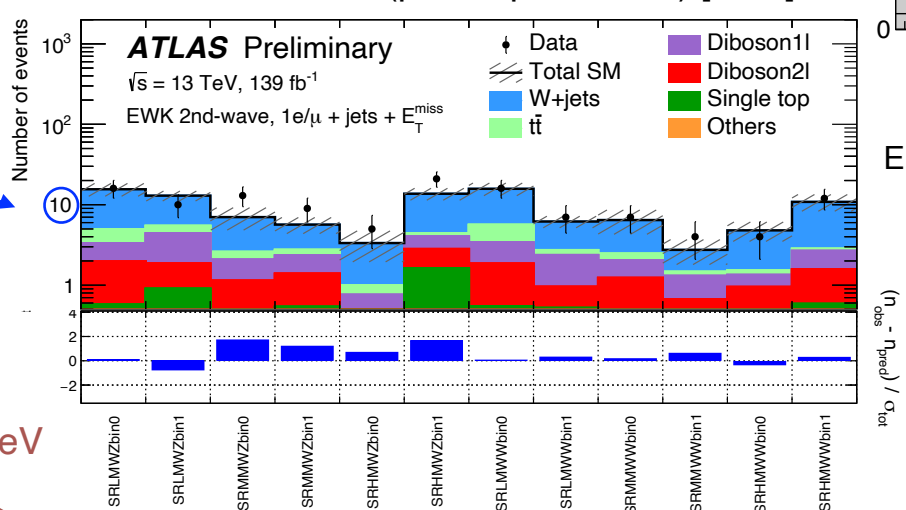
2 lep + MET
EPJC 80 (2020) 123

Boosted bosons
PRD 104 (2021) 112010

This work
important orthogonal final state

Results

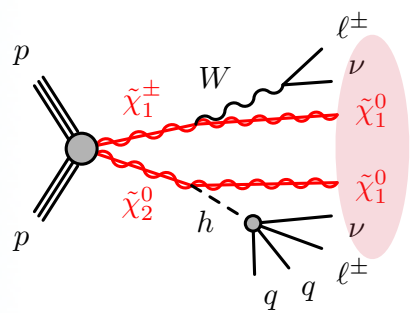
- Yield
  - O(10)
- Errors
  - Stats, JES
- 95% CL limits
  - $m_{\chi 1\pm} > 500$ GeV



DM LSP in direct: 2 SS or 3 lep.

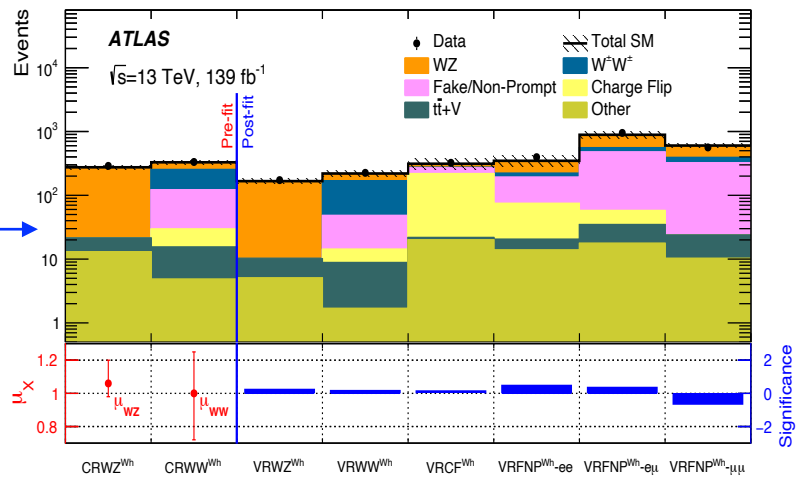
ATLAS-CONF-2022-042 (2022)

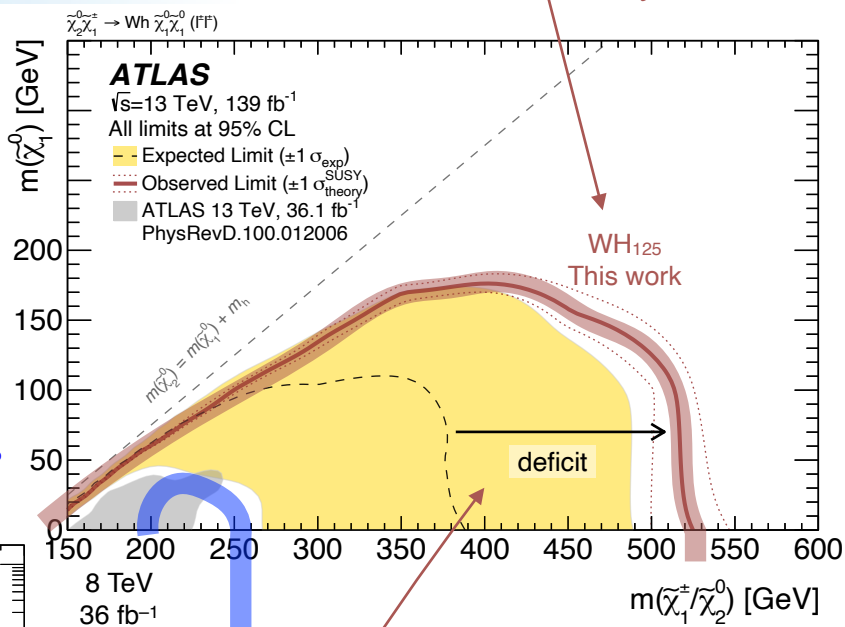
Search for direct production of winos and higgsinos in events with two same-charge leptons or three leptons in *pp* collision data at $\sqrt{s}$ =13 TeV with the ATLAS detector



Summary

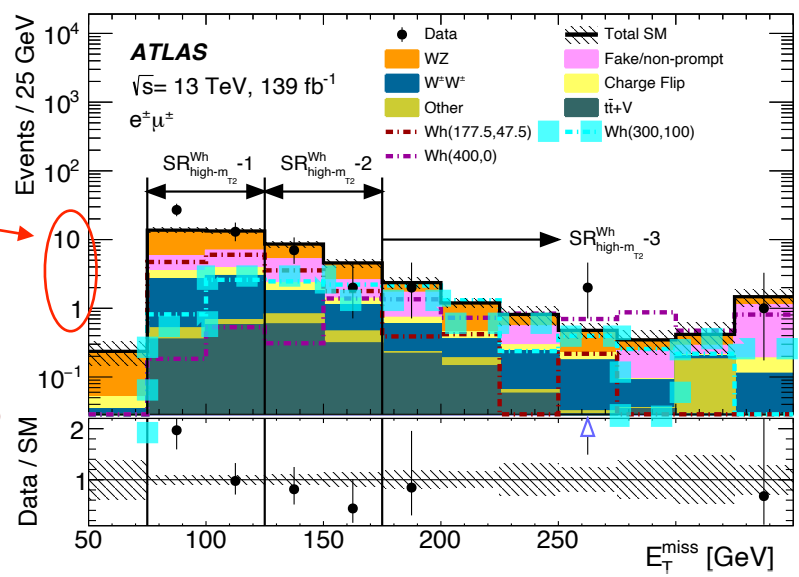
- Background
  - Di-boson CR
- Analysis
  - Trig. dilep or MET > 250





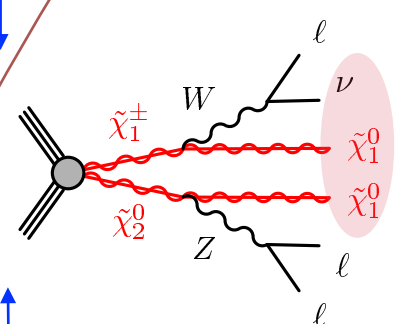
Results

- Error RPC
  - Stats
  - Fake / Non-Pr
- 95% CL limits
  - $m_{\tilde{W}}$ > 525, WH_{125}
  - $m_{\tilde{W}}$ > 250, WZ GeV

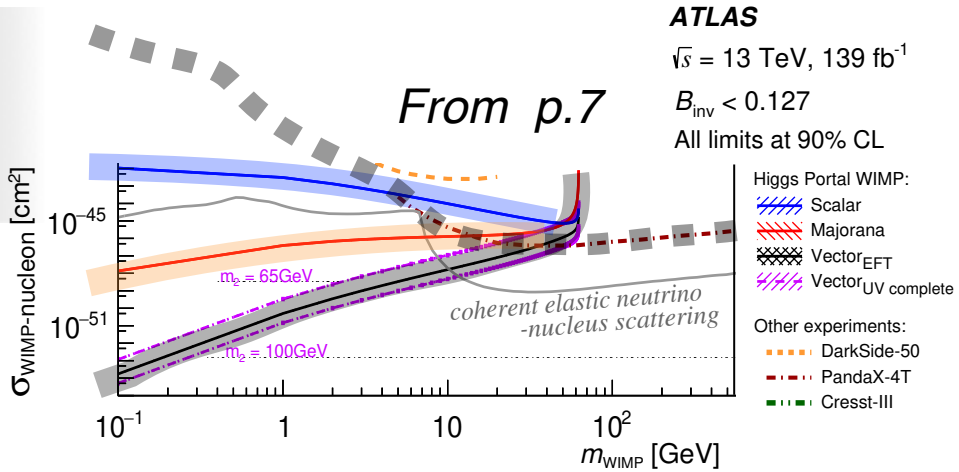


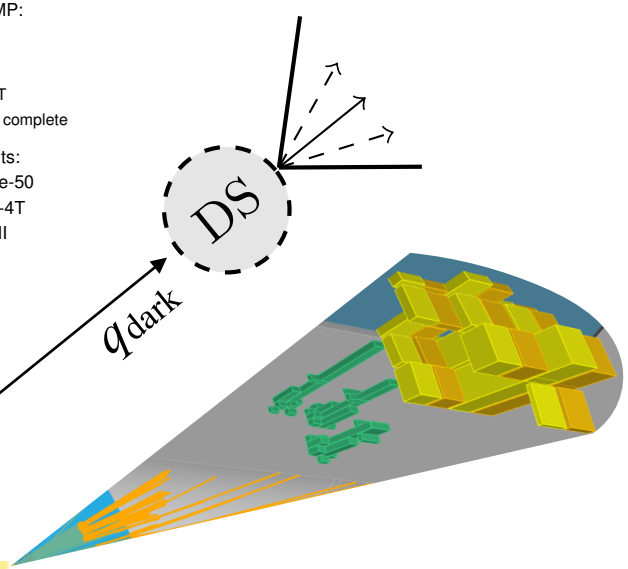
handful events in the tail

WZ (This work), orthog. to Wh



Summary





This talk

- DM via scalars : VBF H, ZH, $t\bar{t}\phi$
- DM via methods : dark sector jets, single t, anomaly ML
- DM in SUSY : 2 tau, 1 e/μ lepton + jets, 2-3 e/μ leptons

Conclusions

- Novel approaches: simplified model, unsupervised, full model
- Like Minoans, ATLAS is always leaping to produce the best results!

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Extra

Theory on theories on DM

Nice schematic

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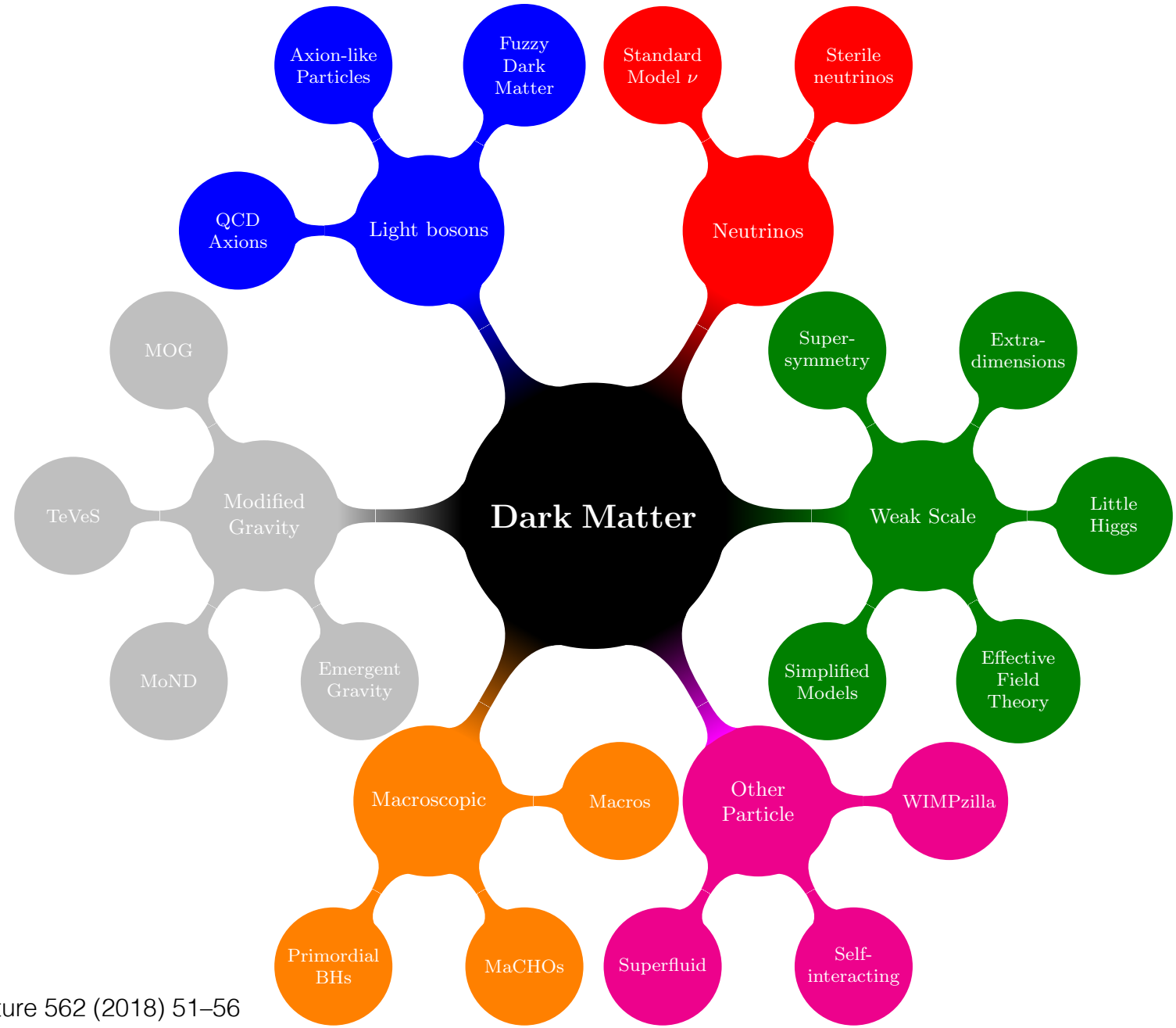

Bertone & Tait, Nature 562 (2018) 51–56

Dark matter at the LHC

Complementarity in approaches

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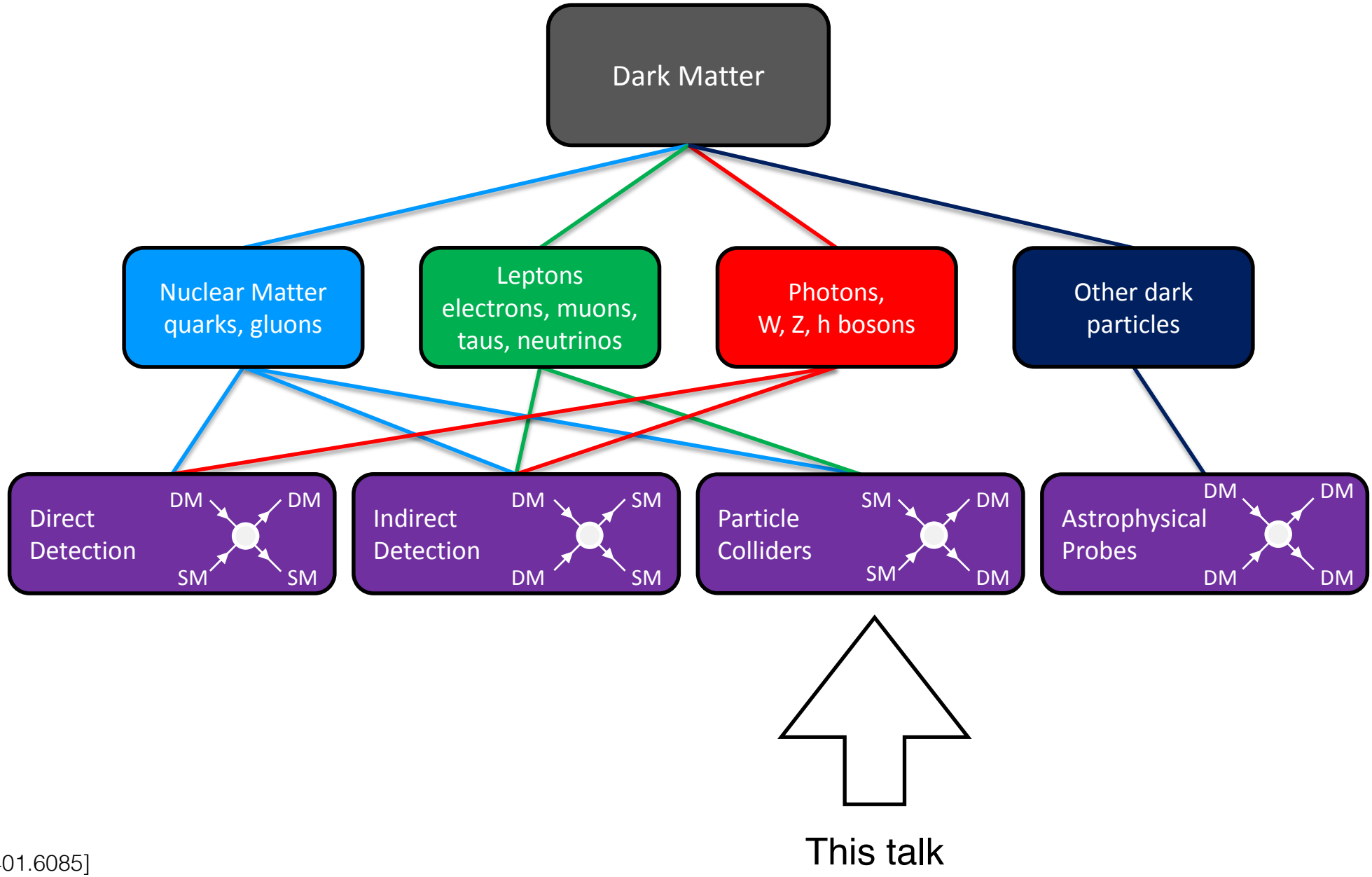

[1401.6085]

Dark matter summary plots

ATL-PHYS-PUB-2022-036, for s-chan., 2HDM+a, Dark Higgs models

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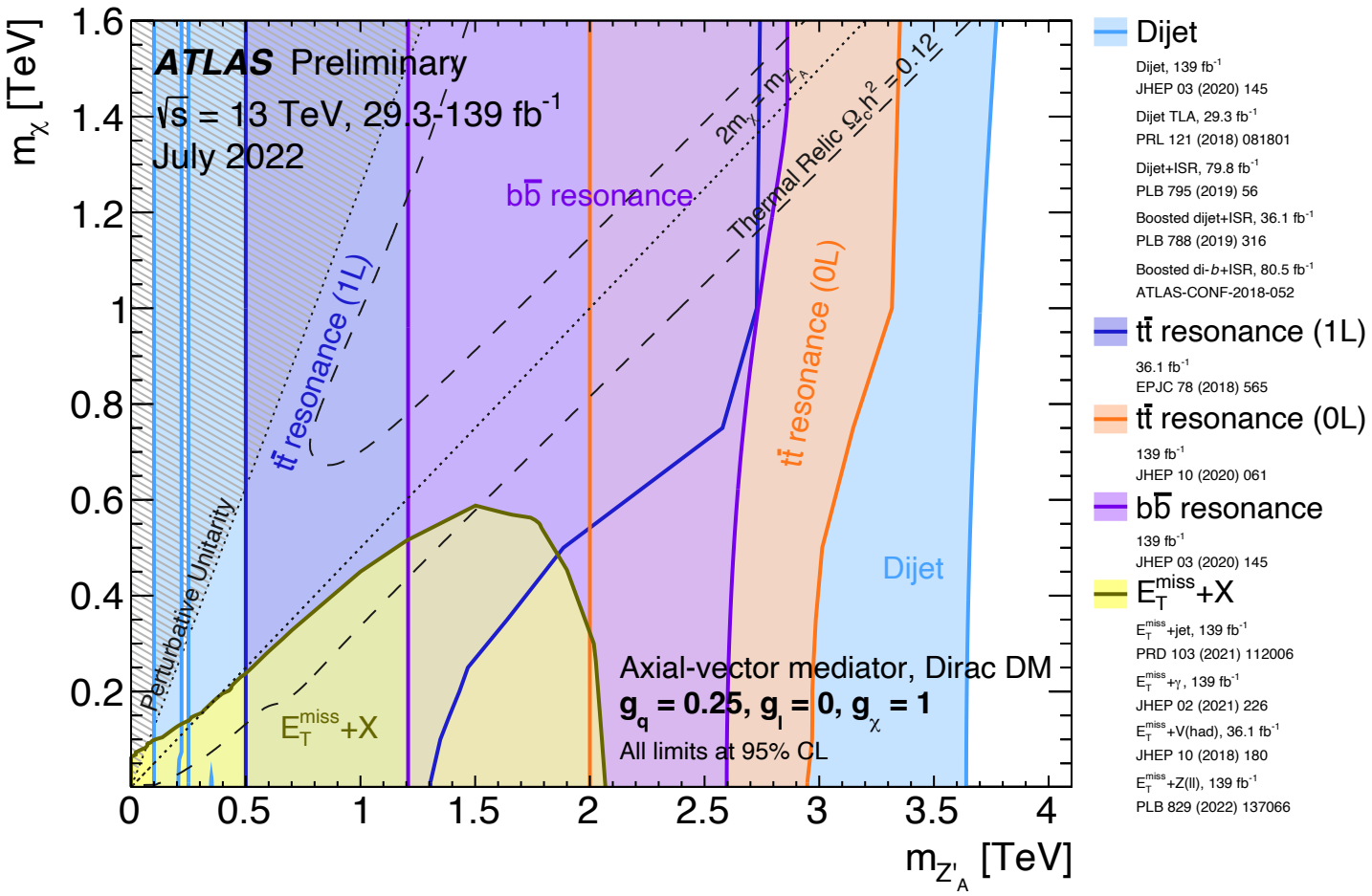

Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for leptophobic axial-vector mediator simplified models. Each shaded region represents the union of the exclusion contours of the individual analyses listed in the legend, where more than one result contributes. The exclusions are computed for a DM coupling $g_\chi = 1$, quark coupling $g_q = 0.25$, universal to all flavours, and no coupling to leptons. Dashed curves labelled "thermal relic" correspond to combinations of DM and mediator mass values that are consistent with a DM density of $\Omega h^2 = 0.12$ and a standard thermal history, as computed in MadDM [Phys. Dark Univ. 26 (2019) 100377, AIP Conf. Proc. 1743 (2016) 1, 060001]. Between the two curves, annihilation processes described by the simplified model deplete Ωh^2 to below 0.12. A dotted line indicates the kinematic threshold where the mediator can decay on-shell into DM. Excluded regions that are in tension with the perturbative unitary considerations of [JHEP 02 (2016) 016] are indicated by shading in the upper left corner. The reinterpretation procedure for the TLA analysis follows the procedure recommended by ATLAS in Appendix A of [Phys. Rev. D 91 (2015) 052007], while the high-mass dijet and dijet+ISR analyses are reinterpreted following [Phys. Lett. B 769 (2017) 520].

Dark matter summary plots

ATL-PHYS-PUB-2022-036, for s-chan., 2HDM+a, Dark Higgs models

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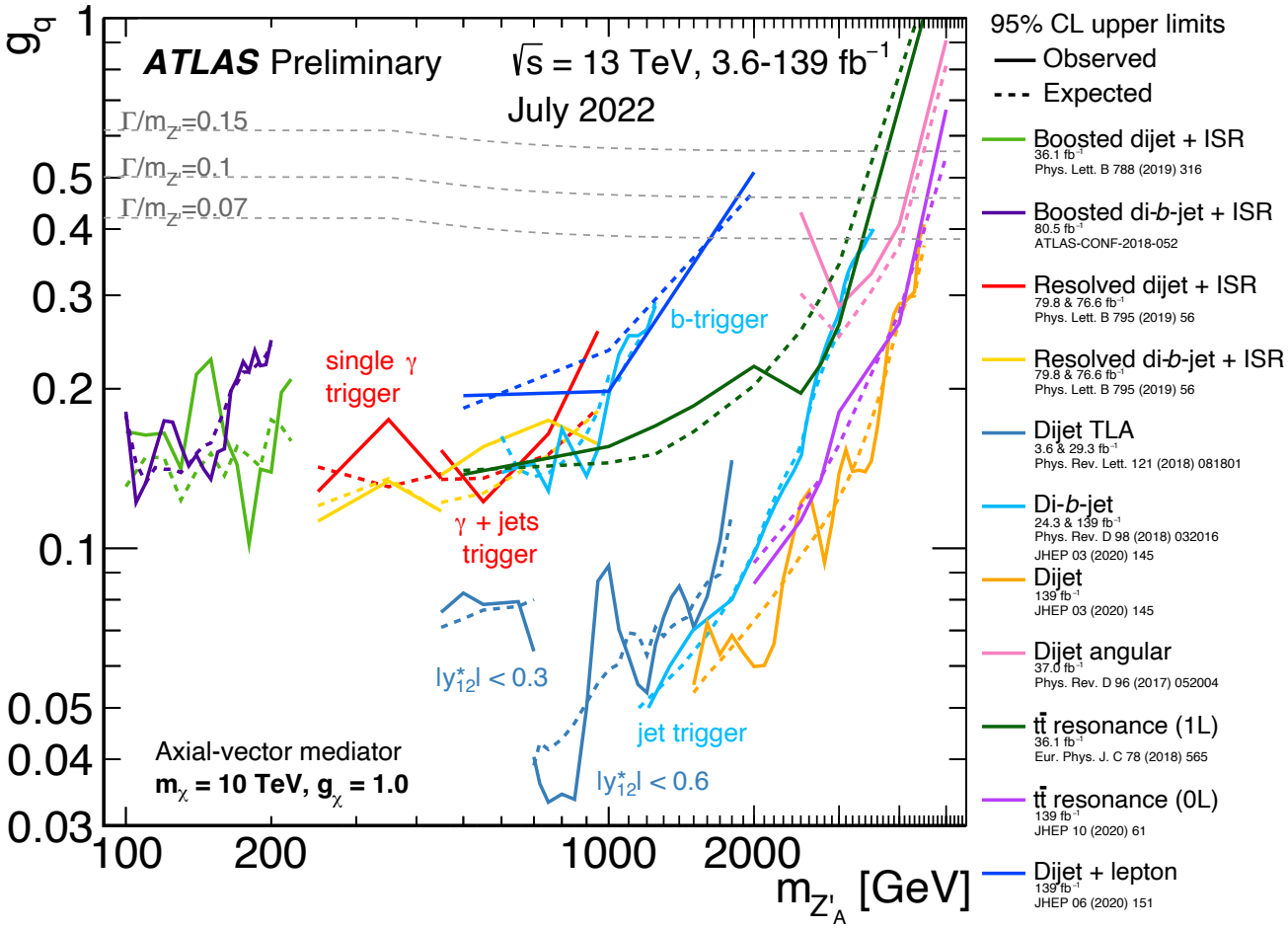

Hadronic resonance search contours for 95% CL upper limits on the coupling g_q as a function of the resonance mass $m_{Z'A}$ for the leptophilic axial-vector mediator simplified model. The expected limits from each search are indicated by dotted lines. The TLA dijet analysis has two parts, employing different datasets with different selections in the rapidity difference y* as indicated. The dijet+ISR (γ) analysis also has two parts, each using a different trigger strategy, and each further studied in inclusive and b-tagged channels. Two lines are also shown for the di-b-jet search. These are from separate analyses, one which used b-jet triggers and provides the limit at lower mass, and one which used inclusive jet triggers and provides the high mass limit. Coupling values above the solid lines are excluded, as long as the signals are narrow enough to be detected using these searches. The TLA dijet search with $|y^*| < 0.6$ is sensitive up to $\Gamma/m_{Z'} = 7\%$, the TLA dijet with $|y^*| < 0.3$ and dijet + ISR searches are sensitive up to $\Gamma/m_{Z'} = 10\%$, and the dijet and di-b-jet searches are sensitive up to $\Gamma/m_{Z'} = 15\%$. The dijet angular analysis is sensitive up to $\Gamma/m_{Z'} = 50\%$. No limitation in sensitivity arises from large width resonances in the $t\bar{t}$ resonance analysis. Benchmark width lines are indicated in the canvas. $\Gamma/m_{Z'} = 50\%$ lies beyond the canvas borders.

Abstract

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The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If Dark Matter interacts weakly with the Standard Model (SM) it could be produced at the LHC. The ATLAS Collaboration has developed a broad search program for DM candidates in final states with large missing transverse momentum produced in association with other SM particles (light and heavy quarks, photons, Z and H bosons, as well as additional heavy scalar particles) and searches where the Higgs boson provides a portal to Dark Matter, leading to invisible Higgs decays. The results of recent searches on 13 TeV pp data from the LHC, their interplay and interpretation will be presented.