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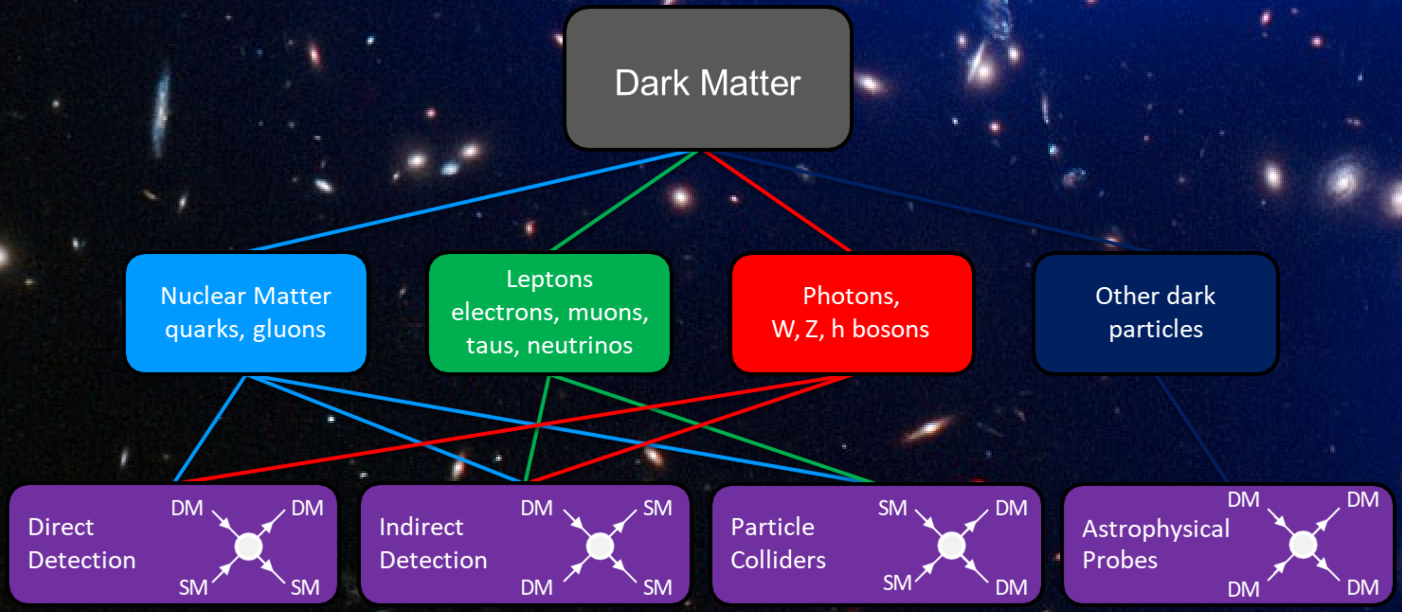
Recent Higgs to Dark Photon search combination and Dark Higgs search results from ATLAS

Qibin LIU on behalf on the ATLAS Collaboration

The Dark Matter

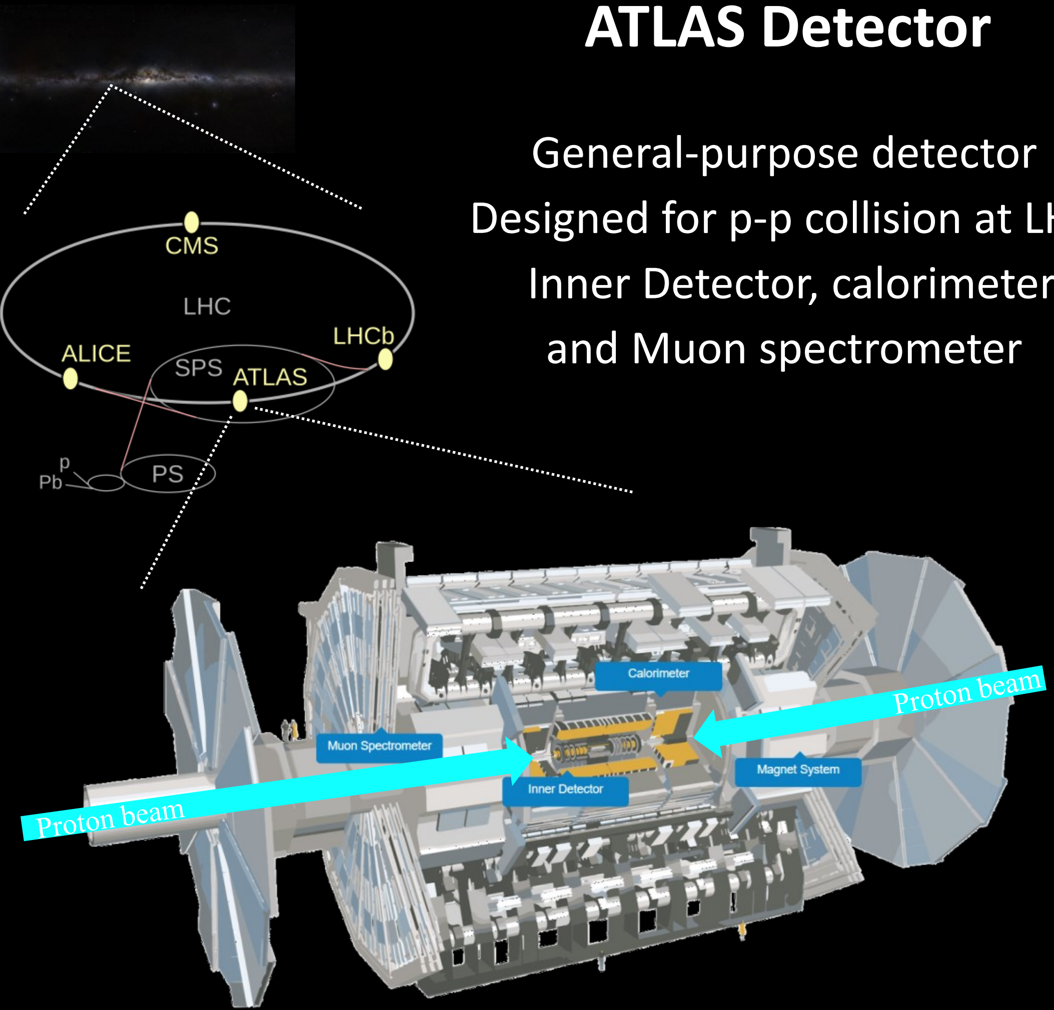
- Existence of dark matter (DM) supported by many pieces of evidence
  - Galaxy rotation , gravity lensing, bullet cluster, cosmic microwave background, contradictions in MOND, so on
- DM makes up most of our universe – its nature remains largely unknown
- In quest to search for any possible interaction of DM beyond gravity
  - Major effort in nowadays study for new physics



1305.1605

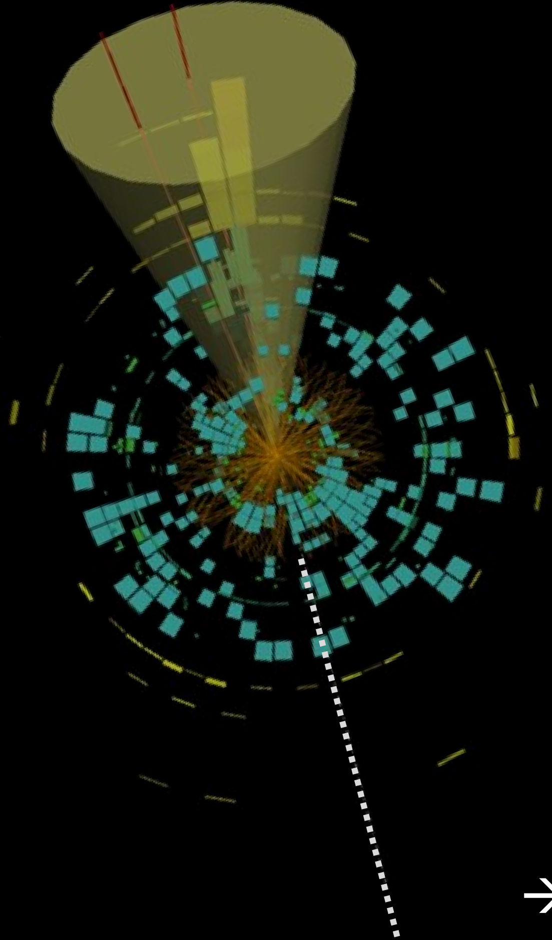
MACS J0152.5-2852

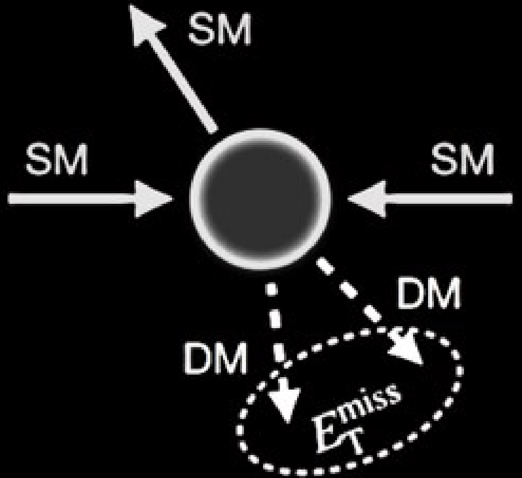
Dark Matter Searches at ATLAS



ATLAS Detector

General-purpose detector
Designed for p-p collision at LHC
Inner Detector, calorimeters
and Muon spectrometer





Detection of Dark Matter

DM invisible from detector: E_T^{miss}
→ Detect from recoil of visible particles
→ Detect from resonance or unusual signature
If nothing detected: exclusion limit is set

Combination of searches for Higgs boson decays into a photon and a massless dark photon using pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

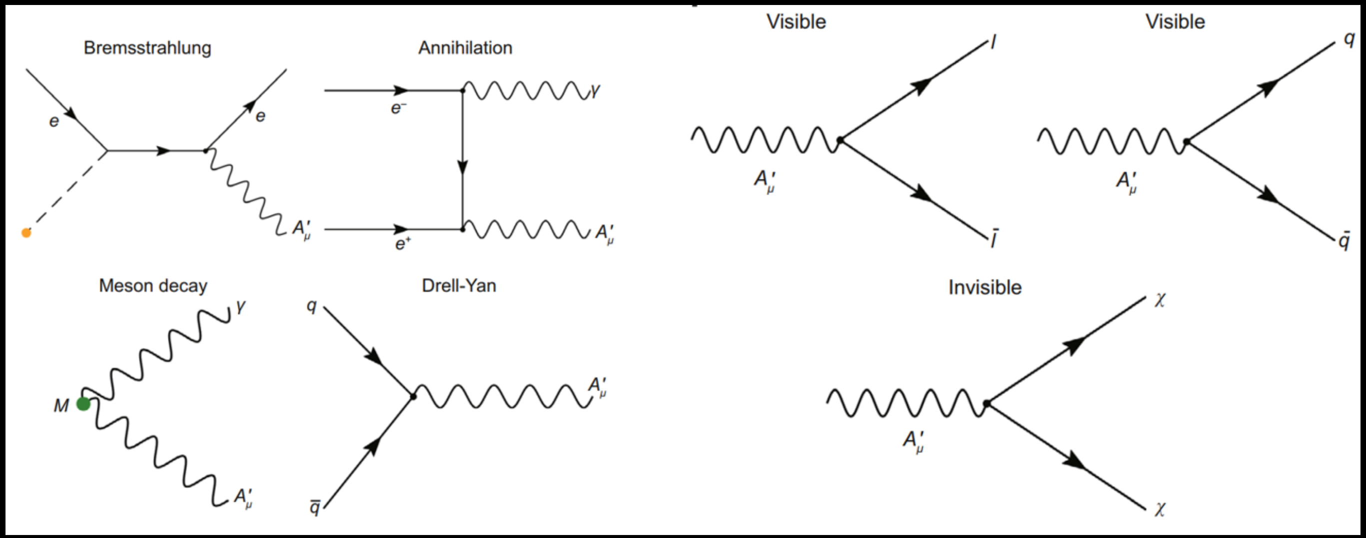
JHEP 08 (2024) 153

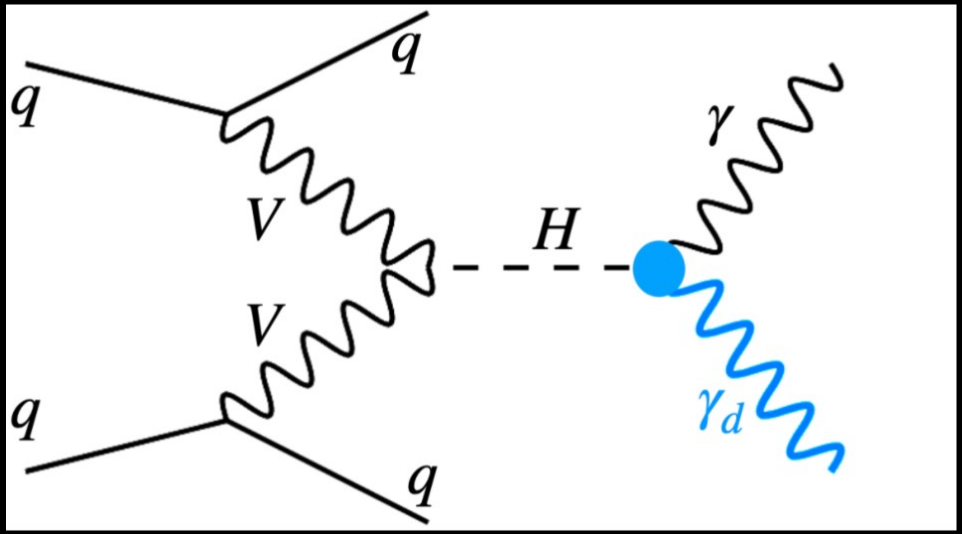
Dark Photon

- U(1) extension to SM and focus on kinetic mixing of dark gauge boson (dark photon) with SM
  - Allowing massless gauge boson and other mass mechanism besides Higgs mechanism

$$L = L_{\rm sm} + \varepsilon F^{\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

- Widely studied by direct detection and fixed target experiments
- Collider experiments provide unique channel to search for dark photon: through Higgs coupling

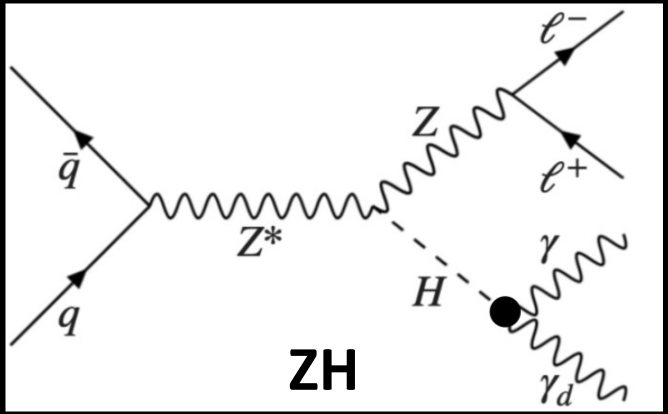


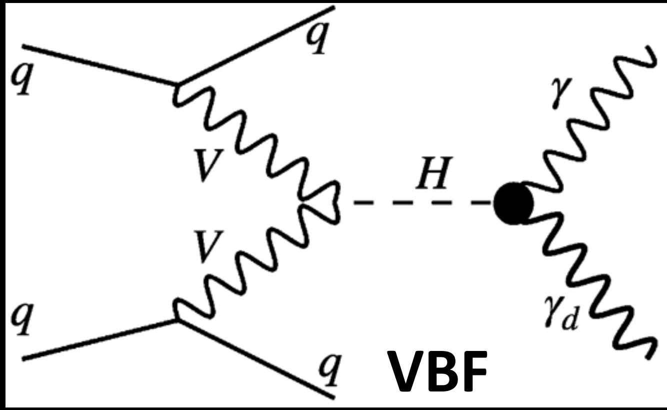


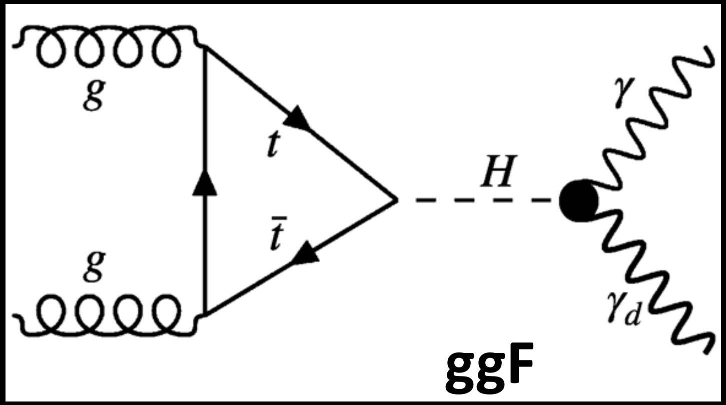
Dark Photon Searches at ATLAS

- 3 latest ATLAS searches for massless dark photon with Higgs coupling

	Main Production Mode	Ref.
ZH Analysis	ZH	**JHEP 07 (2023) 133**
VBF Analysis	VBF	**Eur. Phys. J. C 82 (2022) 105**
Mono-γ Recast	ggF	**ATL-PHYS-PUB-2023-003**

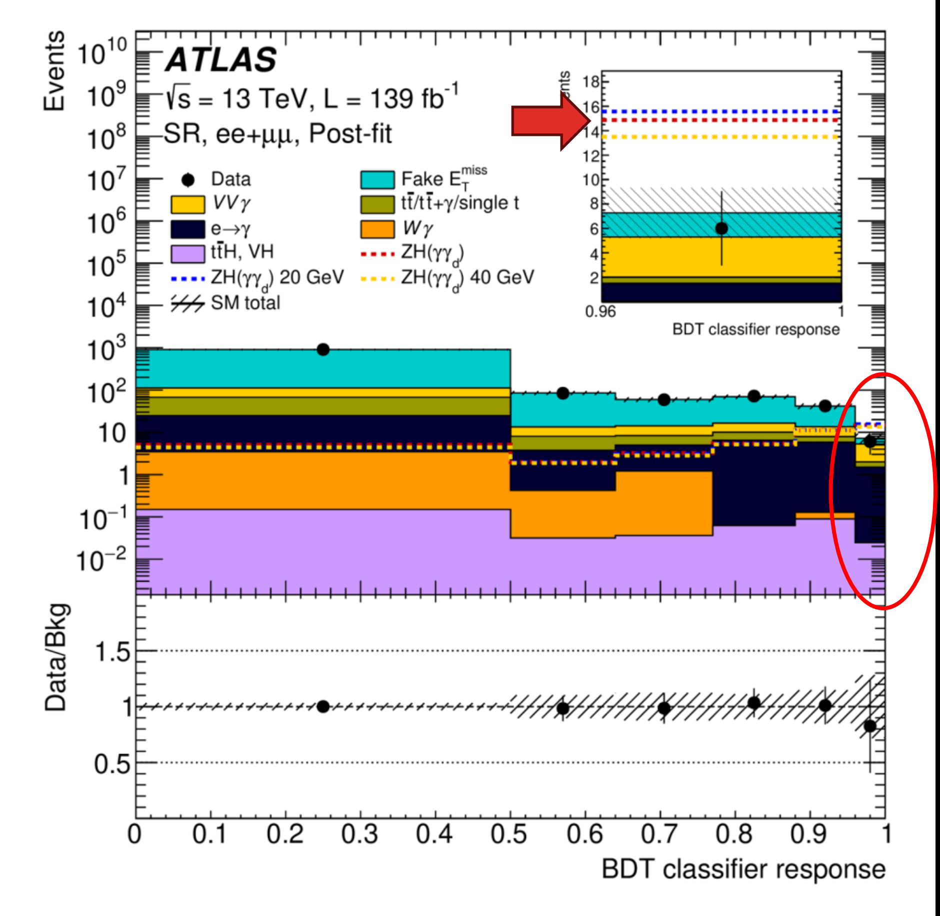


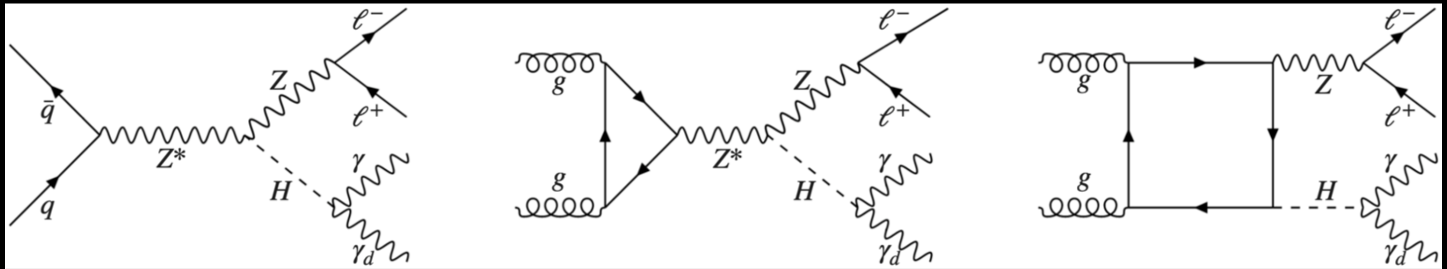




Dark Photon Signature in ZH Analysis

JHEP 07 (2023) 133





Topo: 1 photon (25GeV), **2 lep (Z mass window)**, <=2 jets, MET (60GeV)

Main background from leptonically VVγ and fake MET

Fake MET estimated by data-driven; syst in leading rank

BDT enhance S/B combining **MET significance**, mT, m_ll, pTgam, so on

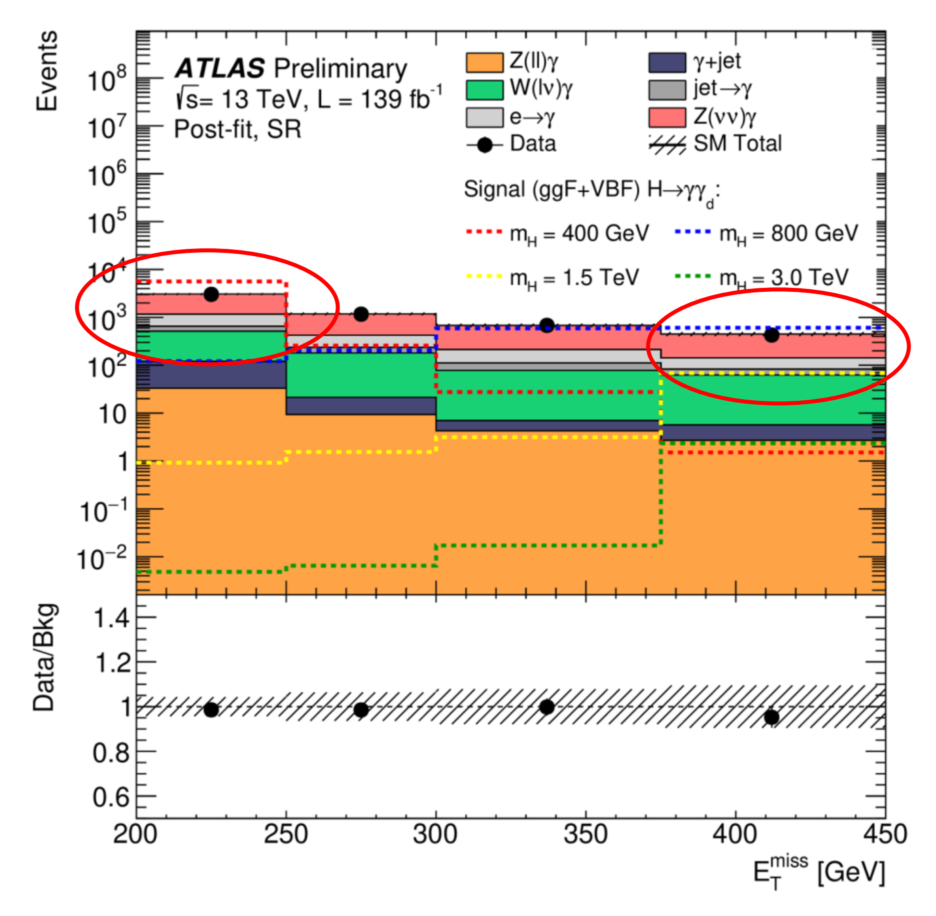
VVγ estimated with MC and controlled using dedicated CR

Good sensitivity for SM H to dark photon while still statistical limited

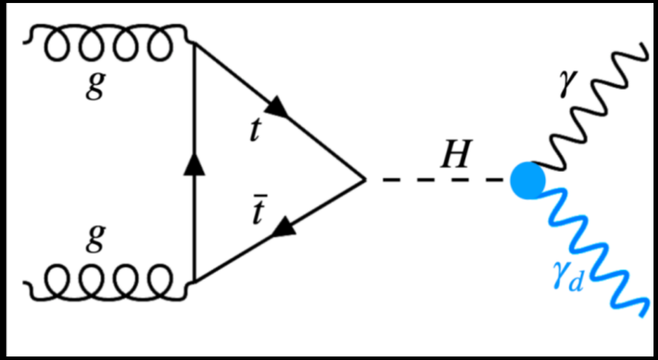
Observed(expected) 95% CL limit: BR(H→γγd)=2.3%(2.8%)

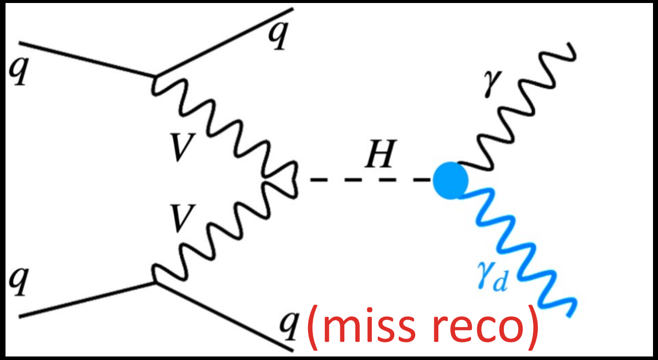
Dark Photon Signature in Mono-photon Recast

ATL-PHYS-PUB-2023-003



Mono- γ (γ+MET) recast





Topology: **>=1 photon, no lepton, <=1 jet (30GeV)**, MET (200GeV)

Photon trigger at relatively high ET (g140)

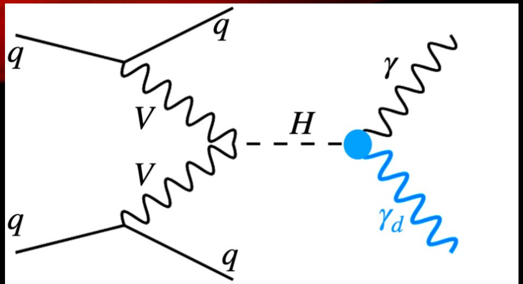
Main background from Z(vv)γ, W(ll)γ, γ+jets and e/j fake photon

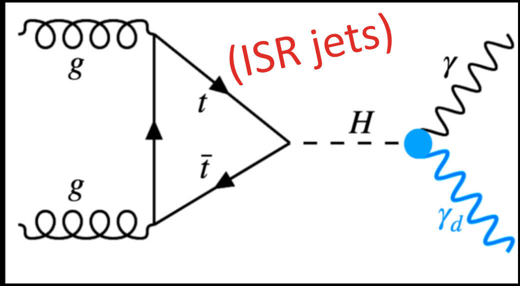
Real photon: Z(vv)γ dominated. Esti. from MC and control w/ CR

Fake photon from data-driven and related syst leading rank

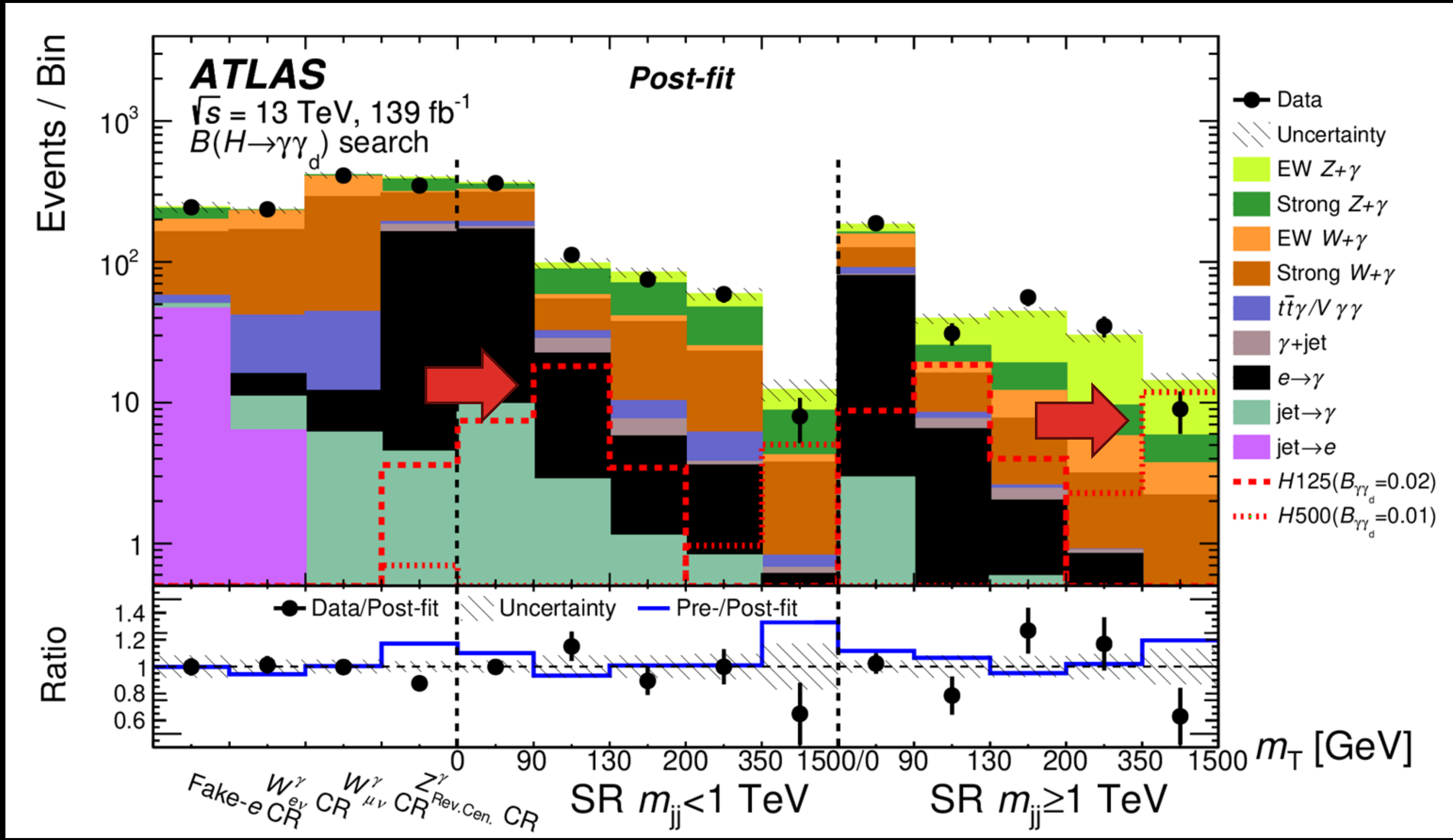
Good sensitivity in BSM heavy Higgs to dark photon up to mH 3TeV

Dark Photon Signature in VBF channel





Eur. Phys. J. C 82 (2022) 105



Topo: **1 photon, no lepton, >=2 jet**, MET(trig)

Main bkg from Wγ, Zγ and fake photon

Strong/EW-induced Vγ controlled with CRs

Fake photon related uncertainty dominates

Good sensitivity in both SM and BSM Higgs

Dark Photon Combination

- Orthogonal analysis channels allows maximize the sensitivity though stat. combination
- Negligible little overlap due to different definition of object (e.g. EMTopo/Pflow jet, JVT, …)

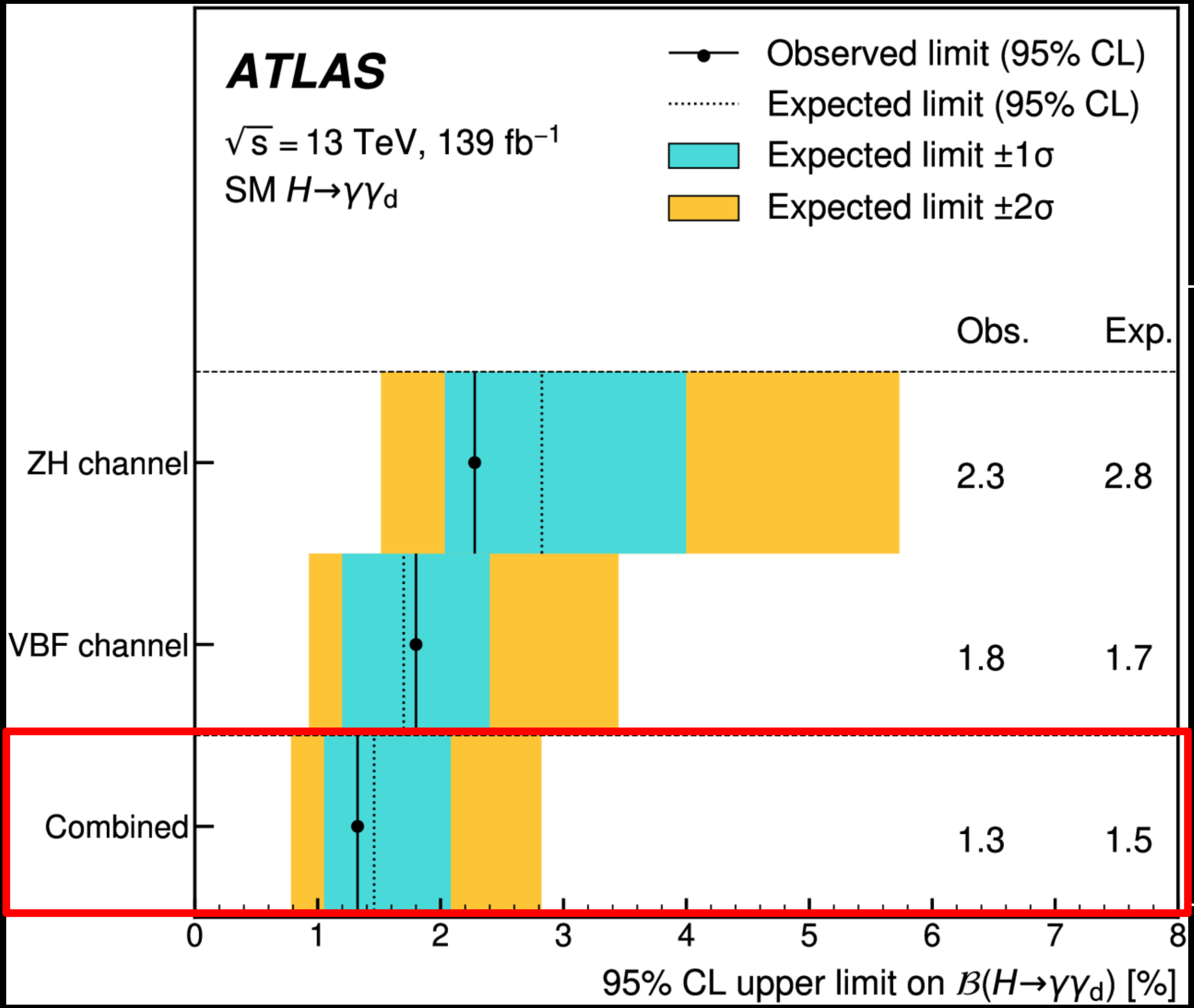
	Main Production Mode	SM Higgs?	BSM Higgs?
ZH Analysis	ZH	Y	N
VBF Analysis	VBF	Y	Y
Mono-γ Recast	ggF	N	Y

Channels	ZH
Trigger by	Lepton(s)
Photons	1
E_T^γ [GeV]	> 25
E_T^{miss} [GeV]	> 60
Jets	≤ 2
Leptons	2, $m_{\ell\ell} \in (76, 116)$GeV
Discriminant	BDT score and 1 CR

Channels	VBF
Trigger by	E_T^{miss}
Photons	1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$
E_T^{miss} [GeV]	> 150
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$, $\lvert\Delta\phi_{j_1 j_2}\rvert < 2$
Leptons	0 (e, μ)
Discriminant	m_{jj} and m_T in SR and 4 CRs

Channels	γ+MET
Trigger by	Photon
Photons	≥ 1
E_T^γ [GeV]	> 150
E_T^{miss} [GeV]	> 200
Jets	≤ 1
Leptons	0 (e, μ, τ)
Discriminant	E_T^{miss}

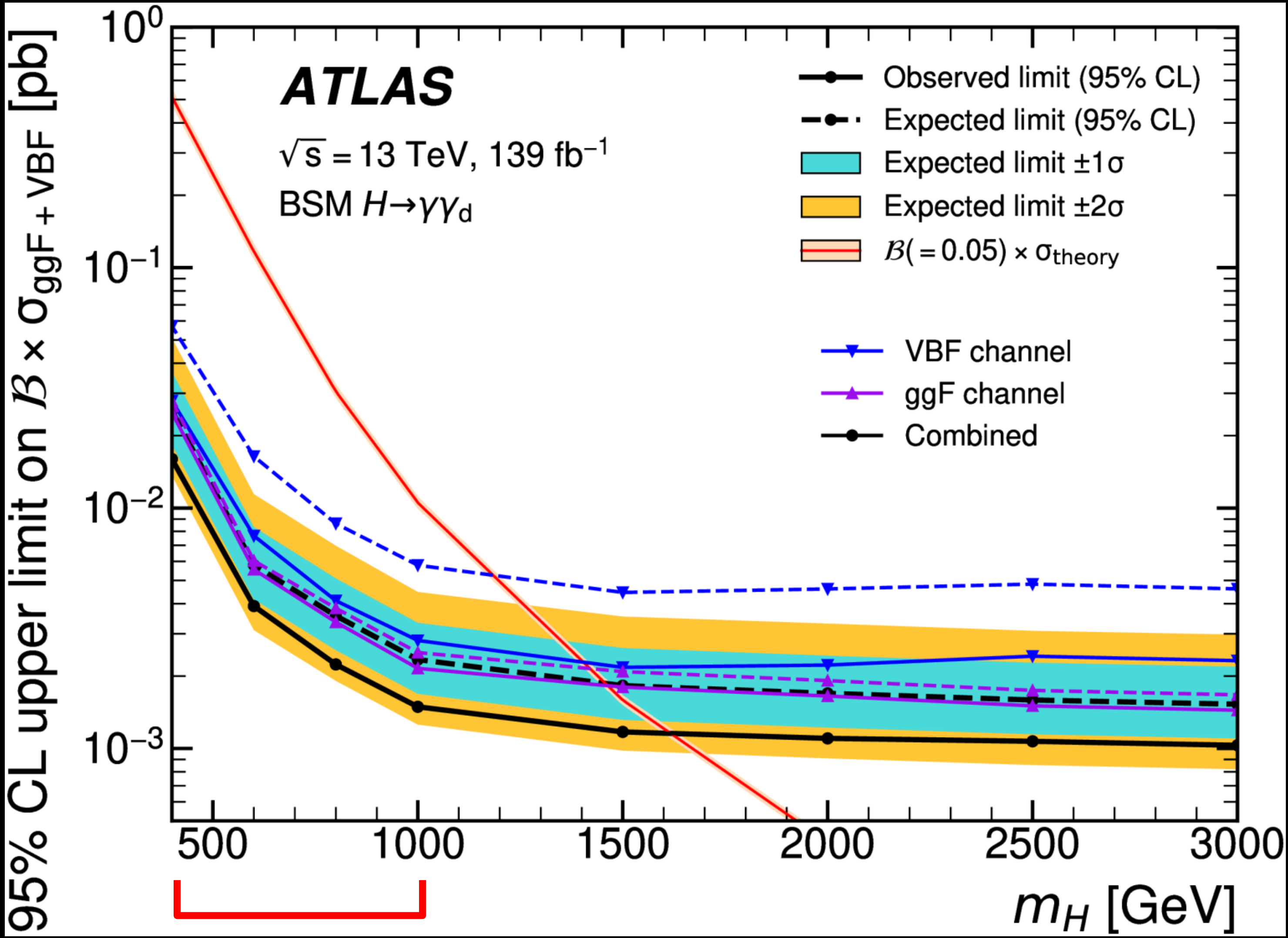
Latest ATLAS constraint on Dark Photon



Current best constraint!

CMS
4.6 (3.6) %
3.5 (2.8) %
2.9 (2.1) %

Latest ATLAS constraint on Dark Photon



Previously Probed

Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final state using collisions at $\sqrt{s}$=13TeV with the ATLAS detector

ATLAS-CONF-2024-004

2407.10549

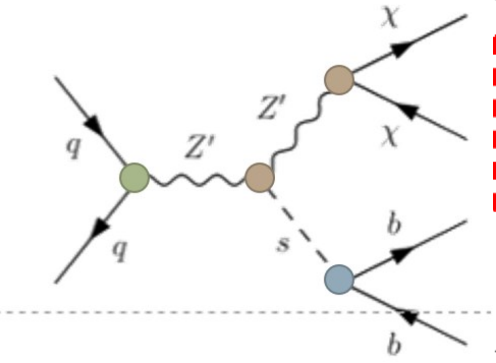
[1] JHEP 04 (2017) 143
[2] PLANCK2018

Higgs Mechanism in Dark Sector

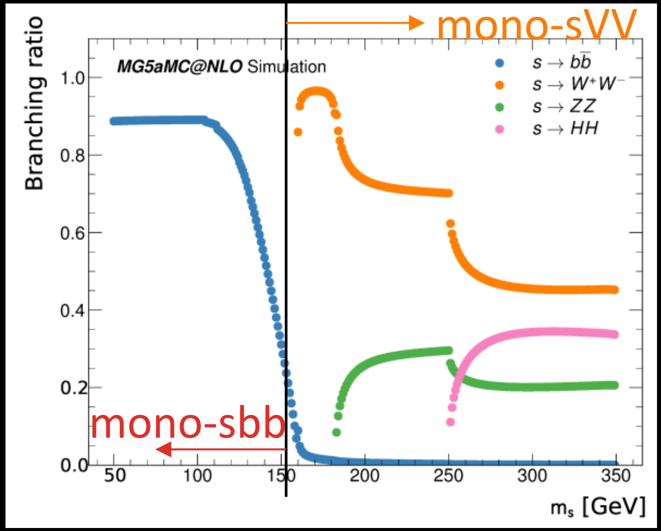
- Explain the mass of DM with Higgs mechanism in dark sector: spontaneously broken U(1)' gauge symmetry
- **Majorana** DM χ interacts with SM via spin-1 mediator Z' and a singlet s under $U(1)'$
- Mixing of dark Higgs s and SM Higgs h : detectable decay as $s \to b\bar{b}$, $s \to VV$ depending on mass
- New annihilation channel to SM open up ($\chi\chi \to ss \to SM$): prevent **DM Relic Density (Ωh^2)** over-production
- 4 parameters of interest and new scan method with Ωh^2 fix at 0.12 (assuming all DM from this mechanism) [2]
  - First time directly require Ωh^2 condition in collider DM search

$$\mathcal{L}_\chi = -g_q Z'^{\mu}\bar{q}\gamma_\mu q$$

$$\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^{\mu}\bar{\chi}\gamma^5\gamma_\mu\chi - g_\chi \frac{m_\chi}{m_{Z'}} s\bar{\chi}\chi + 2\, g_\chi\, Z'^{\mu} Z'_\mu \left(g_\chi\, s^2 + m_{Z'} s\right)$$



Parameter	Explain
m_s	mass of Dark Higgs
m_χ	mass of DM
$m_{Z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: q<->Z' fixed 0.25 as benchmark
θ	mixing angle of SM Higgs<->dark Higgs fixed according to [I]



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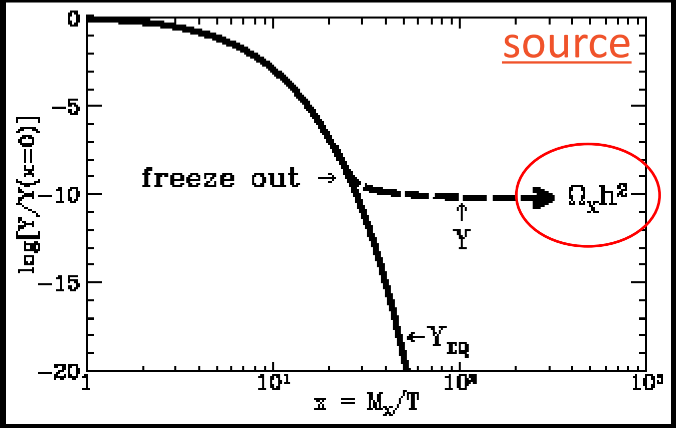
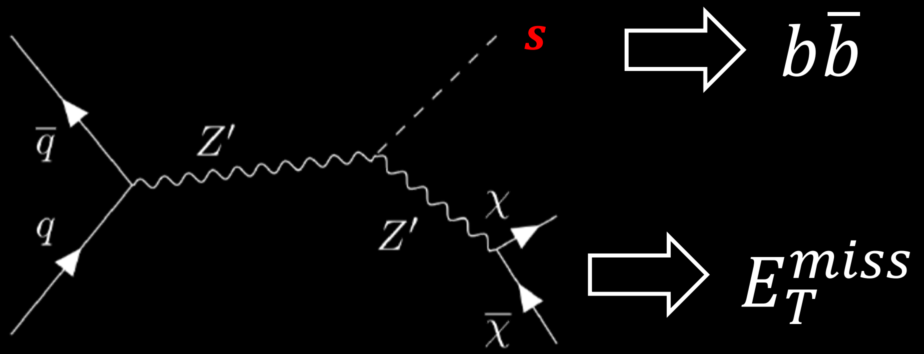
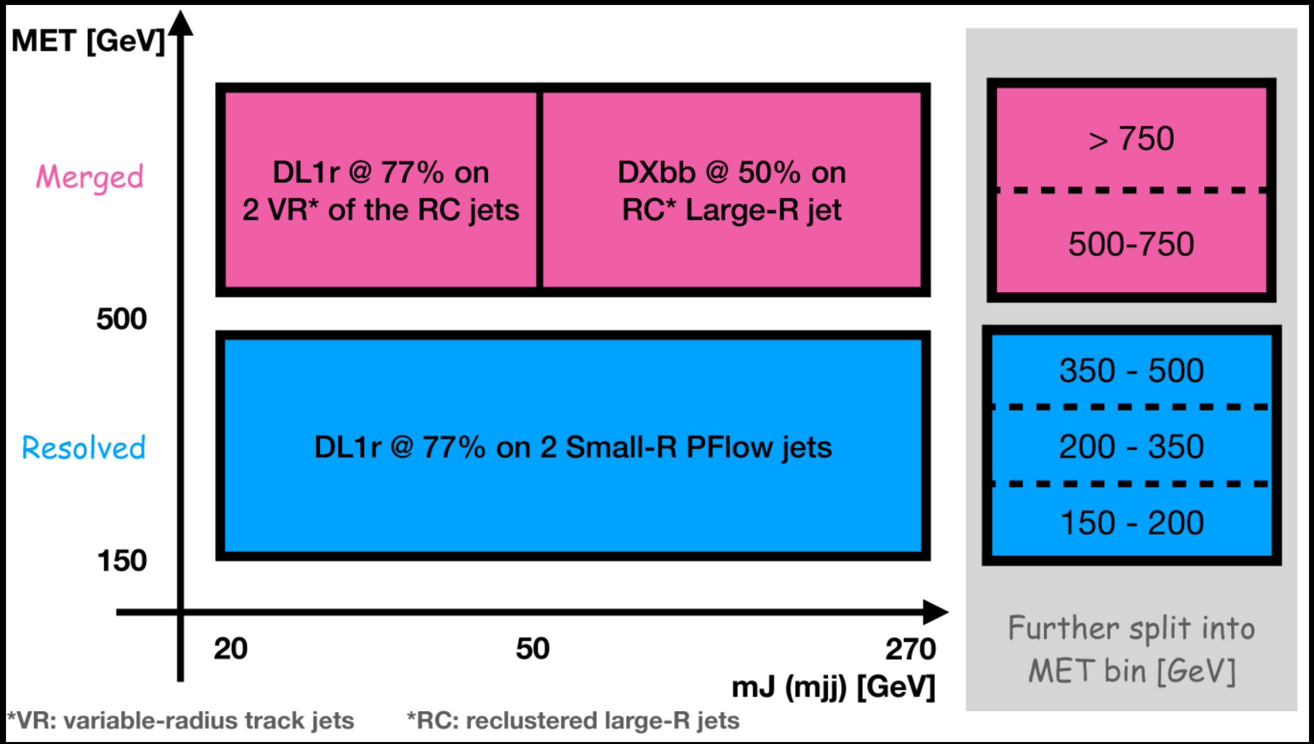
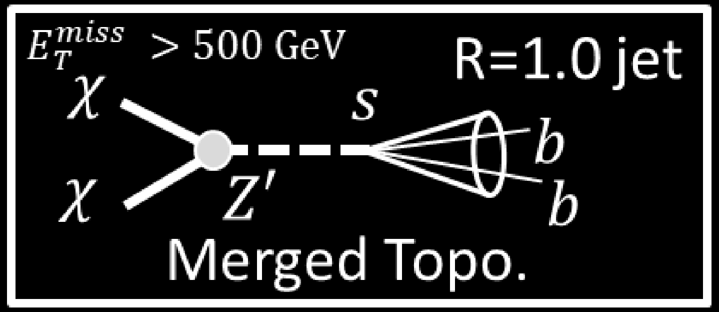


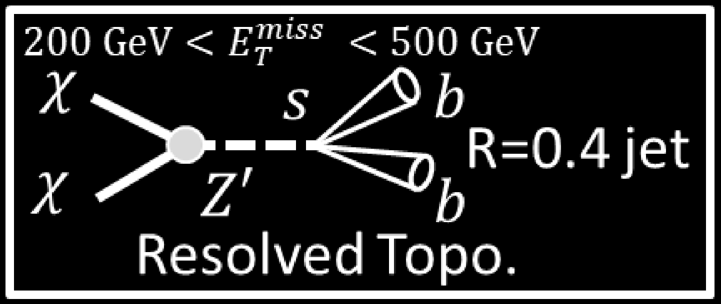
Overview of Mono-S(bb) Analysis

- Search for dark Higgs boson with $b\bar{b} + E_T^{miss}$ signature
- Probe E_T^{miss} down to 200 GeV and m_{bb} down to 30 GeV
- Resolved/boosted topology reconstructed depending on MET









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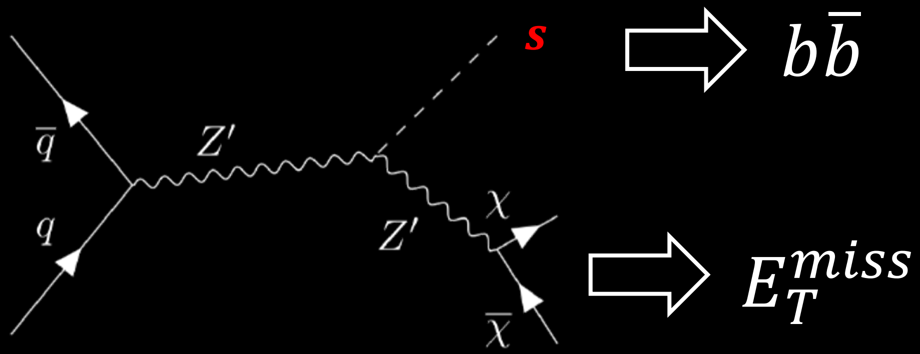
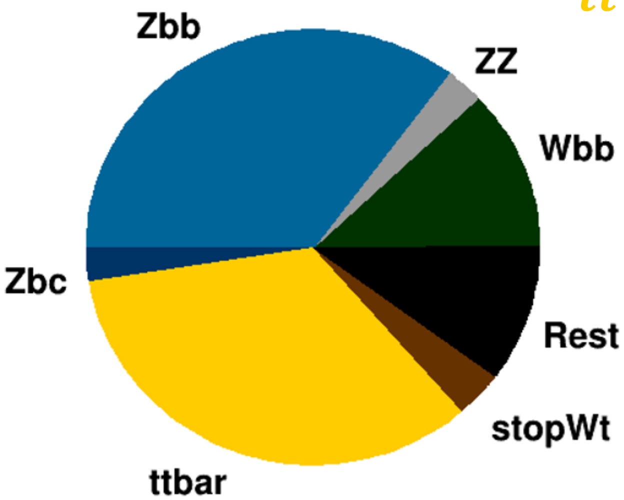
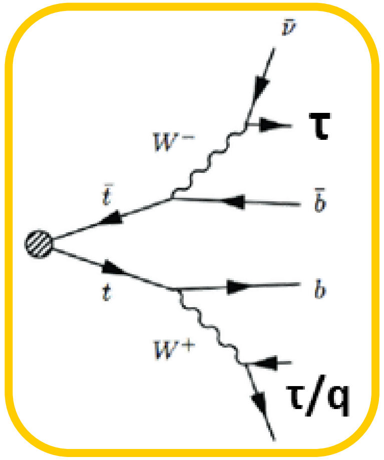
- Probe E_T^{miss} down to 200 GeV and m_{bb} down to 30 GeV
- Resolved/boosted topology reconstructed depending on MET
- Background from W+jets, ttbar (τ not vetoed) and Z+jets ($Z\nu\nu + b\bar{b}$)
  - Different composition in MET regions
  - Estimated from MC and normalization fitted to data in 1-muon and 2-lepton control region



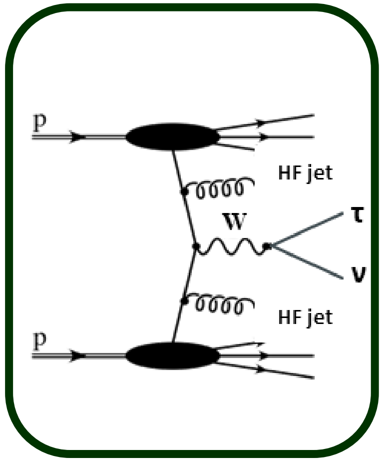
150GeV<MET<200GeV



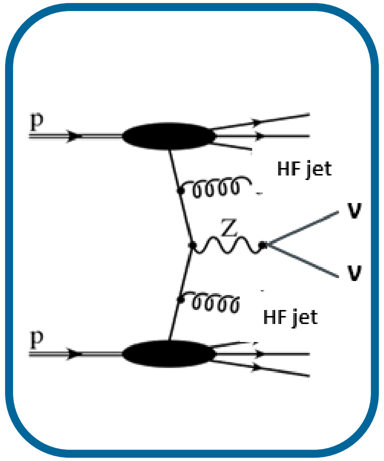
$t\bar{t} \rightarrow bbW(\tau\nu)W(\tau\nu/qq)$



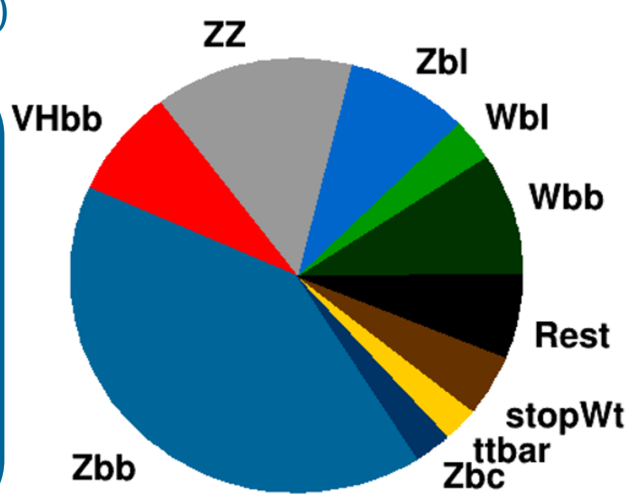
$W(\tau\nu) + jets(b\bar{b})$



$Z(\nu\nu) + jets(b\bar{b})$



MET>750GeV



Analysis Selections

Cut	Resolved	Merged
Trigger	0/1-lepton: lowest unprescaled $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers 2-lepton: lowest unprescaled single-lepton triggers	
Lepton multiplicity	0-lepton: veto on baseline electrons, muons 1-lepton: exactly one signal μ 2-lepton: 2 baseline e or μ, exactly 2 signal e or μ with opposite sign	
Z mass window	2-lepton only: $\lvert m_Z - m_{\ell\ell} \rvert < 10$ GeV	
τ vetoes	veto on baseline τ leptons & extended τ-veto	
$\min_{j\in\{1,2,3\}} \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j)$	$> 20°$	
Jet multiplicity	$2 \leq N^{\mathrm{central}}_{\mathrm{small-R\ jets}} \leq 4$	$N^{\mathrm{central}}_{\mathrm{large-R\ jets}} \geq 1$
b-tag multiplicity	$N^{b-\mathrm{tagged}}_{\mathrm{small-R\ jets}} = 2$	leading large-R jet D_{Xbb}-tagged (m_J>50GeV) $N^{b-\mathrm{tagged}}_{\mathrm{asso.VRTrk.jets}} = 2$ (m_J<50GeV)
Non-associated b-jet veto	-	$N^{b-\mathrm{tagged}}_{\mathrm{non-asso.VRTrk.jets}} = 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	0-lepton: $\mathcal{S} > 12$ 1-lepton: $\mathcal{S}_{\mathrm{lep.invis.}} > 12$ 2-lepton: $\mathcal{S}_{\mathrm{lep.invis.}} > 12$ & $\mathcal{S} < 5$	—
Top-mass proxy	$m_{\mathrm{T}}^{b,\mathrm{min}} > 170$ GeV $m_{\mathrm{T}}^{b,\mathrm{max}} > 200$ GeV	—
$E_{\mathrm{T}}^{\mathrm{miss}}$ and $S(b\bar{b})$ recoil	$0.7 < E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}(jj) < 1.3$	$0.7 < E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}(J) < 1.3$
Boosted decay	-	$2m_J/p_{\mathrm{T}}(J) < 0.6$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$150 < E_{\mathrm{T}}^{\mathrm{miss}} < 500$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV

Lepton trigger used in CR

QCD veto

B-tagging strategy

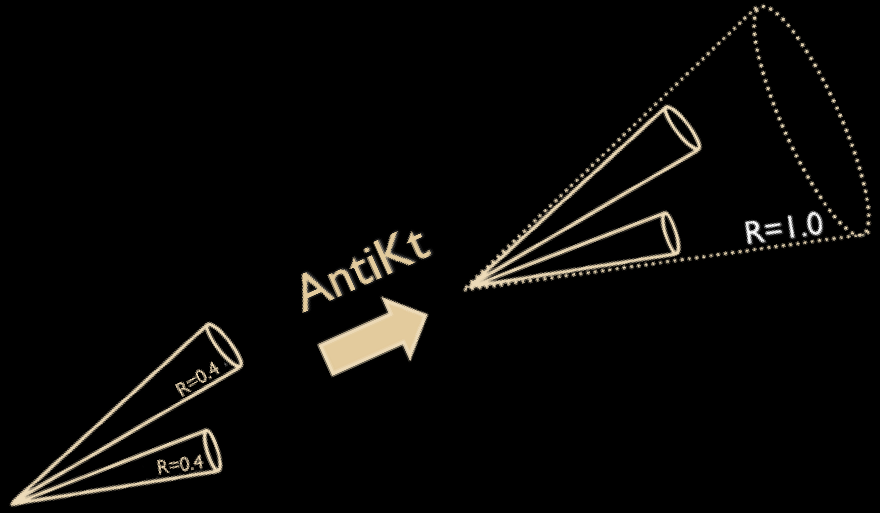
Top veto

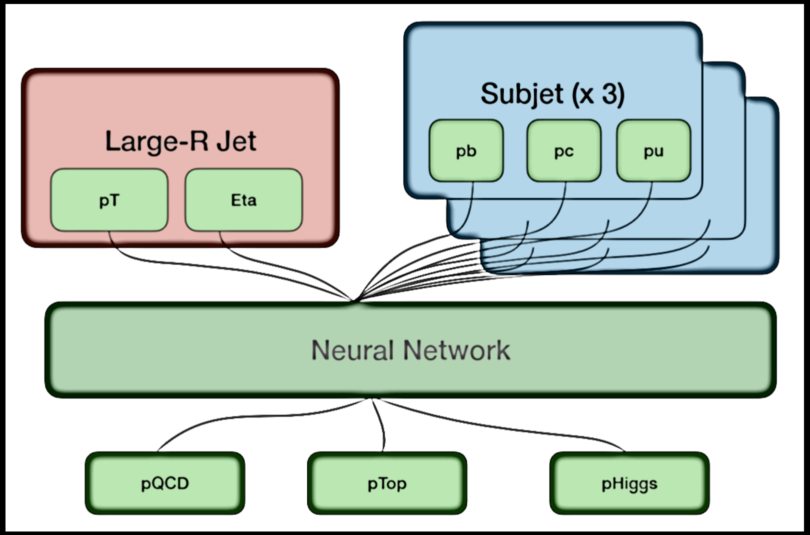
Optimized for back-back topo.

Signal topology with varying mass

Novel Analysis Techniques in Merged Region

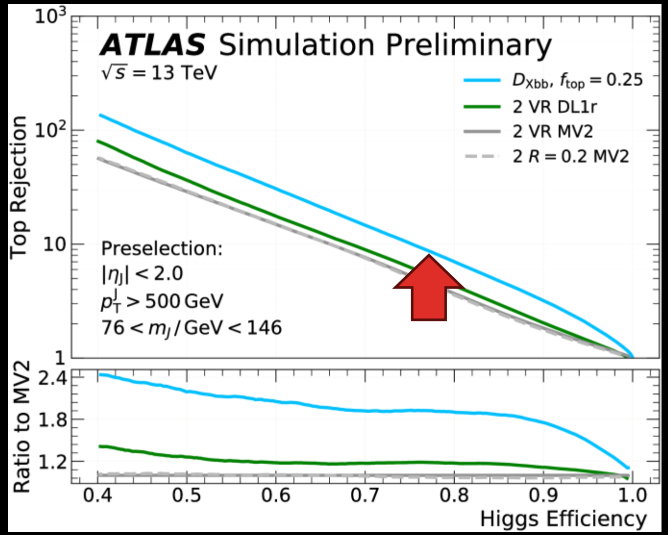
- **Reclustering(RC) jet extends the search range for scalar mass down to 20GeV**
  - Jet reconstruction at low mass is challenging standard large-R jet is NOT supported for mJ below 50GeV
  - Jet mass well-defined: calculated from calibrated input jets and systematic uncertainty propagated
- **Combining Large-R jet kinematics and sub-jet information with machine learning: *DXbb tagger***
  - High efficiency discriminating Hbb v.s. Top/QCD and mass-agnostic design applicable in a wide mass range
  - Calibrated using Zbb (signal jet efficiency) and semi-leptonic ttbar (background jet efficiency)





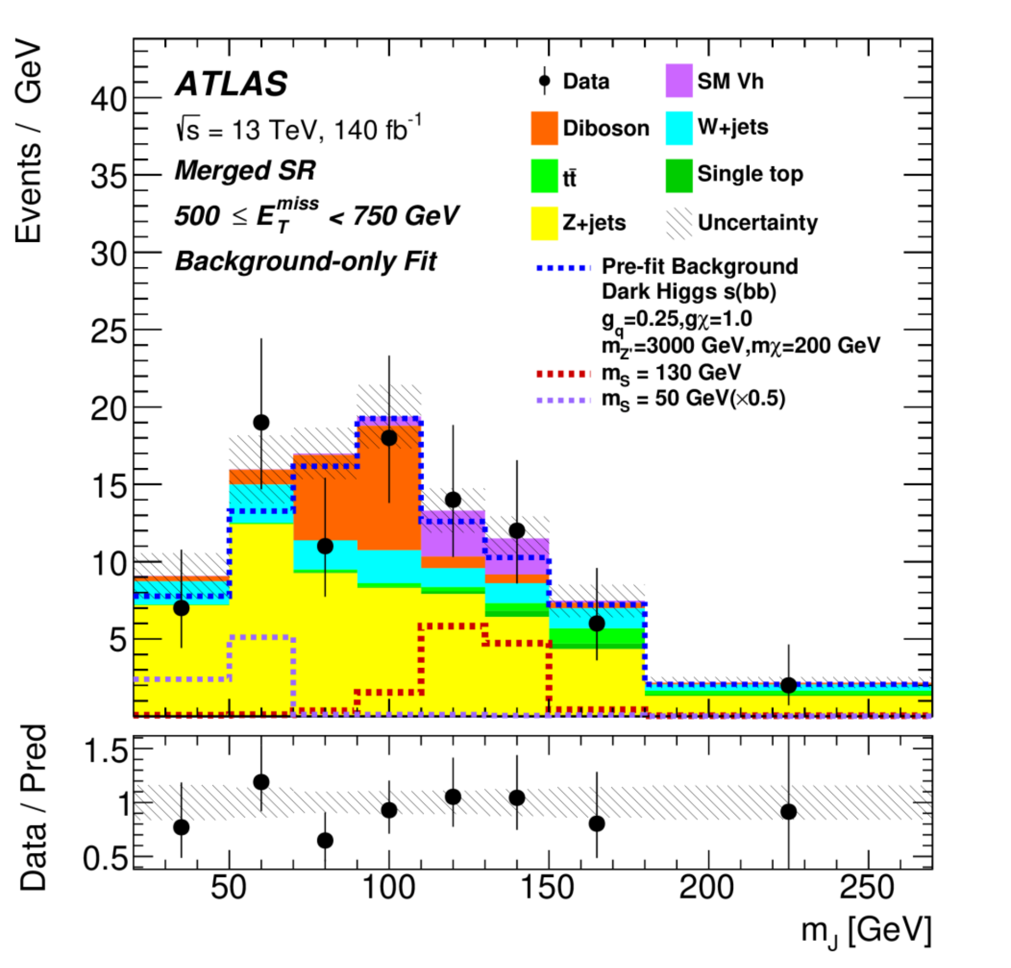
ATLAS Boosted Xbb jet tagging (*DXbb*)

ATL-PHYS-PUB-2020-019



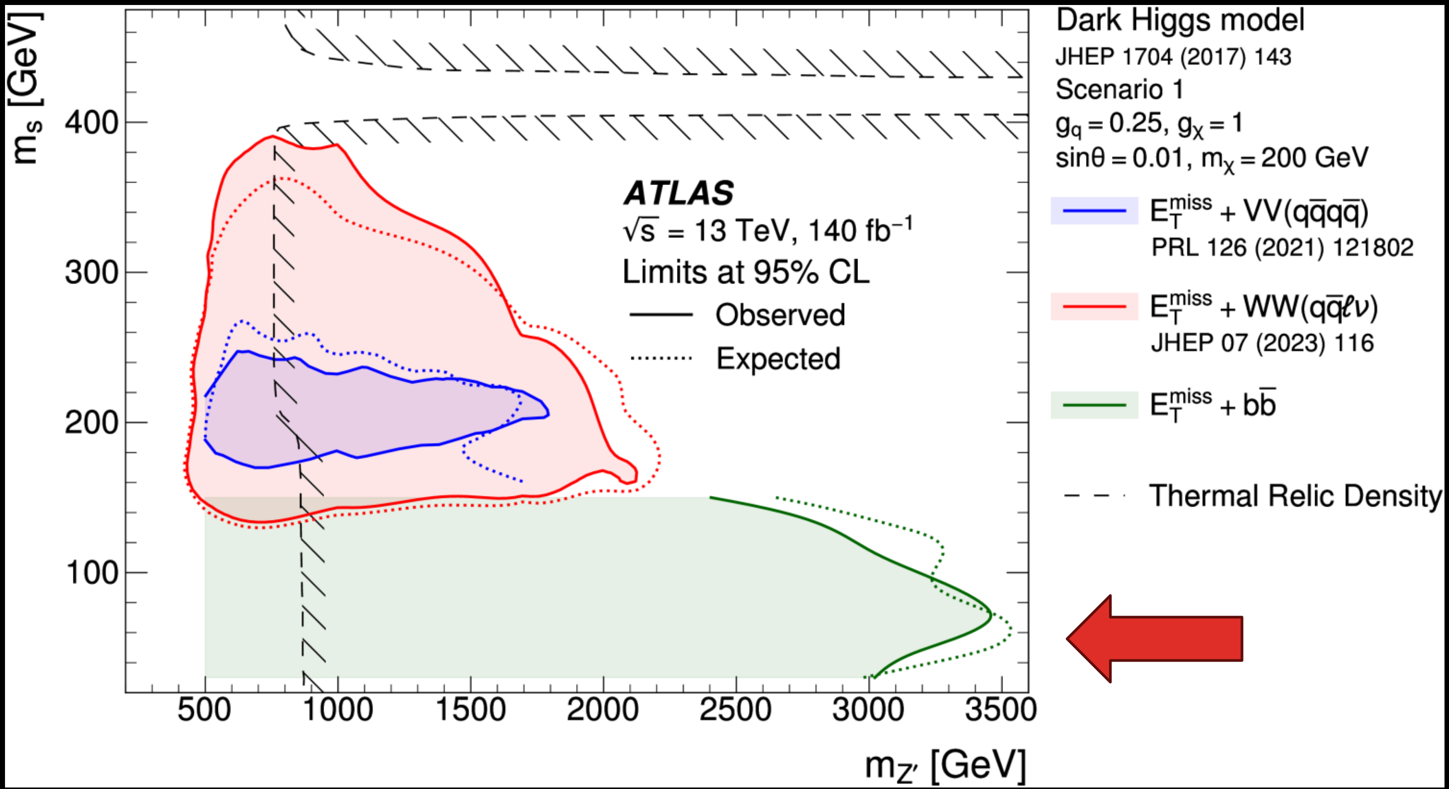
***DXbb* v.s. 2 single-b jets tagging**

Results & Latest Collider Constrain on Dark Higgs



No significant derivation from SM

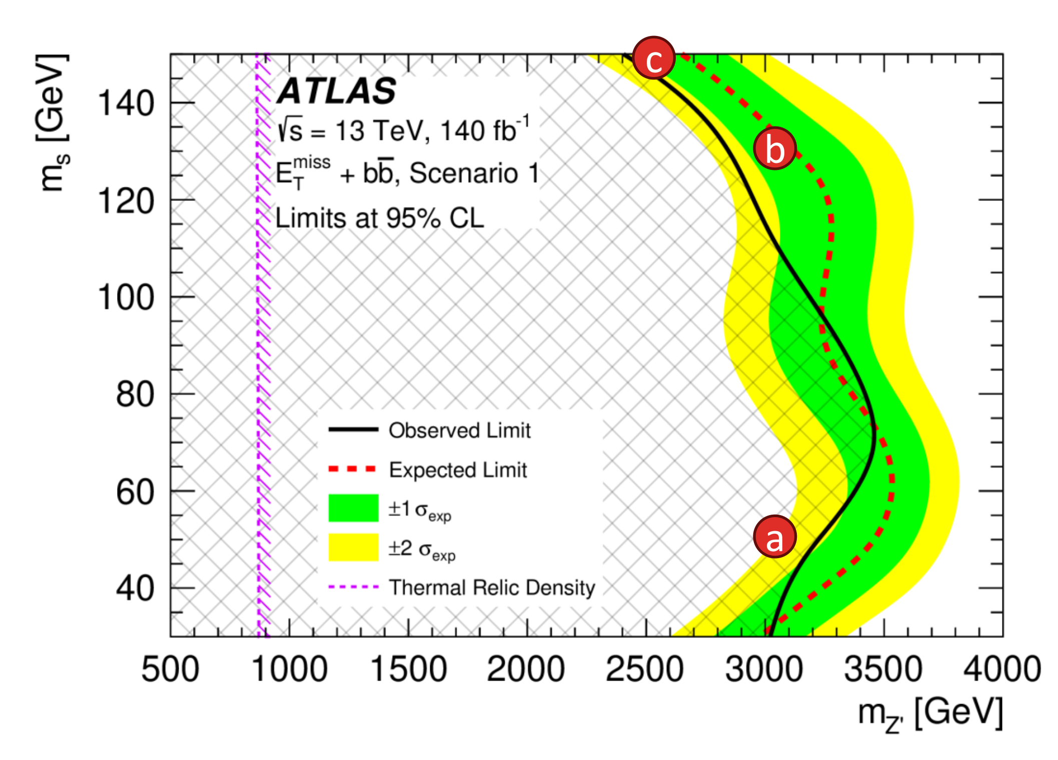
Benchmark setup of dark Higgs model (g_χ=1, m_χ=200GeV)



Excluded dark Higgs m_S < 150 GeV and $m_{Z'}$ up to 3.5 TeV
Complete mass scan from 400GeV to 30GeV

Impact of Systematic Uncertainty

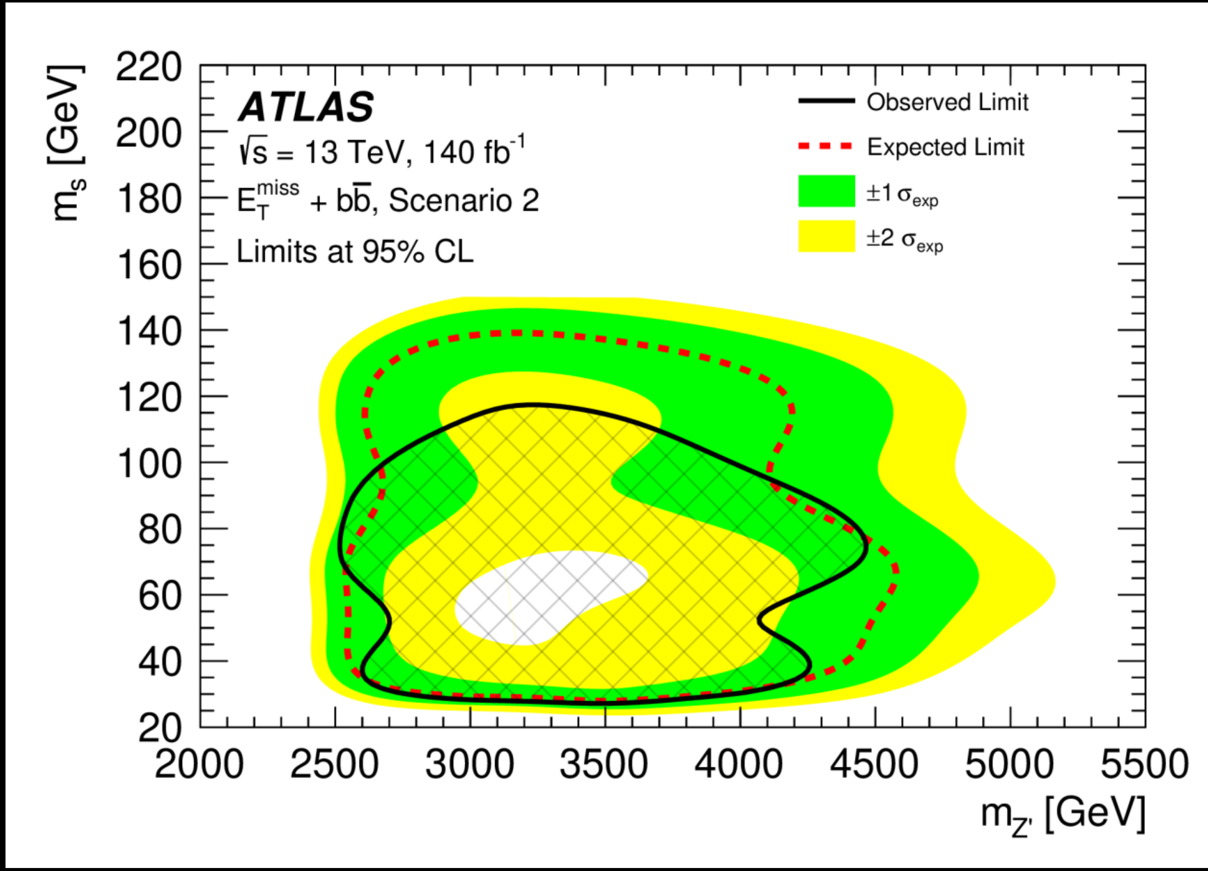
Selected Signals		
	m_S [GeV]	mZ' [GeV]
a	50	3000
b	130	3000
c	150	2500



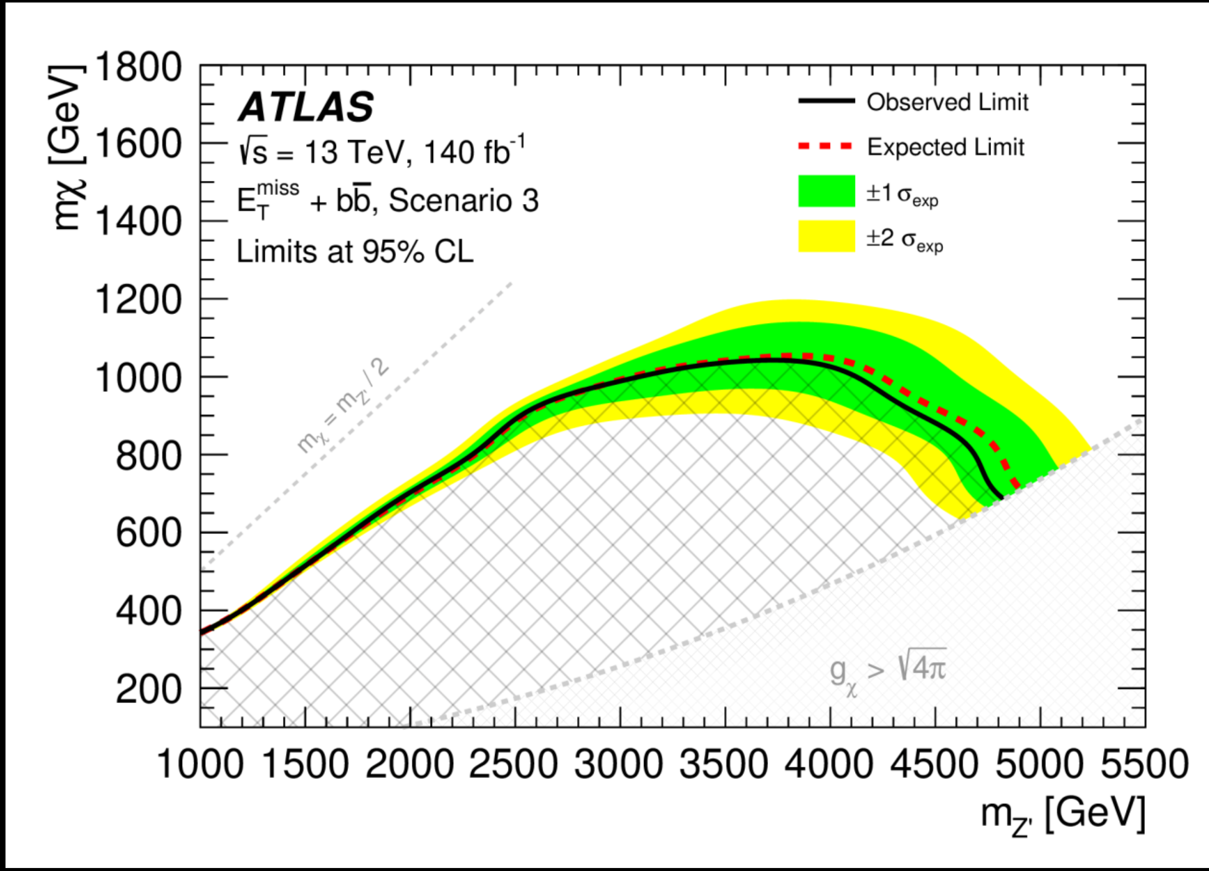
Source of uncertainty	Fraction of total uncertainty [%] (a)	(b)	(c)
Signal modeling	0	1	0
Z+jets normalization	41	11	11
W+jets normalization	8	13	13
$t\bar{t}$ normalization	1	7	8
Z+jets theory	16	24	25
W+jets theory	8	12	9
$t\bar{t}$ theory	3	8	11
Other background theory	10	16	22
MC statistics	15	17	18
Flavor tagging	18	47	37
Jet energy	3	7	11
Other experimental	2	4	3
Total systematic uncertainty	57	66	63
Data statistical uncertainty	82	75	77
Total uncertainty	100	100	100

Latest Collider Constrain on Dark Higgs

Relic density compatible setup ($\Omega h^2 = 0.12$)



Scenario2 (m_χ = 900GeV)
Excluded $m_{Z'}$ up to 4.1 TeV



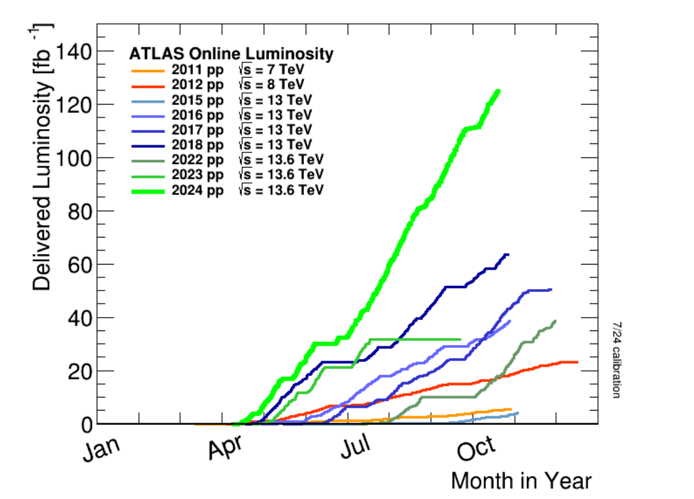
Scenario3 (m_S = 70GeV)
Excluded $m_{Z'}$ up to perturbative limit

Science Bulletin 69 (2024) 3005
2407.10549

Summary

- **Recent combination of dark Photon and search for dark Higgs at ATLAS reported**
- **Combination of dark Photon searches with VBF+MET, ZH and mono-photon signatures**
  - Best collider constraint from LHC on SM Higgs decay to photon and dark photon
  - Strongest exclusion of BSM Higgs coupled to dark photon: mass up to 1.5TeV
- **Search for Dark Higgs in bb+MET final states using full Run2 data**
  - Coherent relic density with cosmology and complete the scan of scalar mass in 30-400GeV
  - Enabled by novel ML-based mass-agnostic Xbb tagging and low mass boosted jet
- **Still a lot to fully understand the DM but progressing + promising!**

ATLAS Luminosity

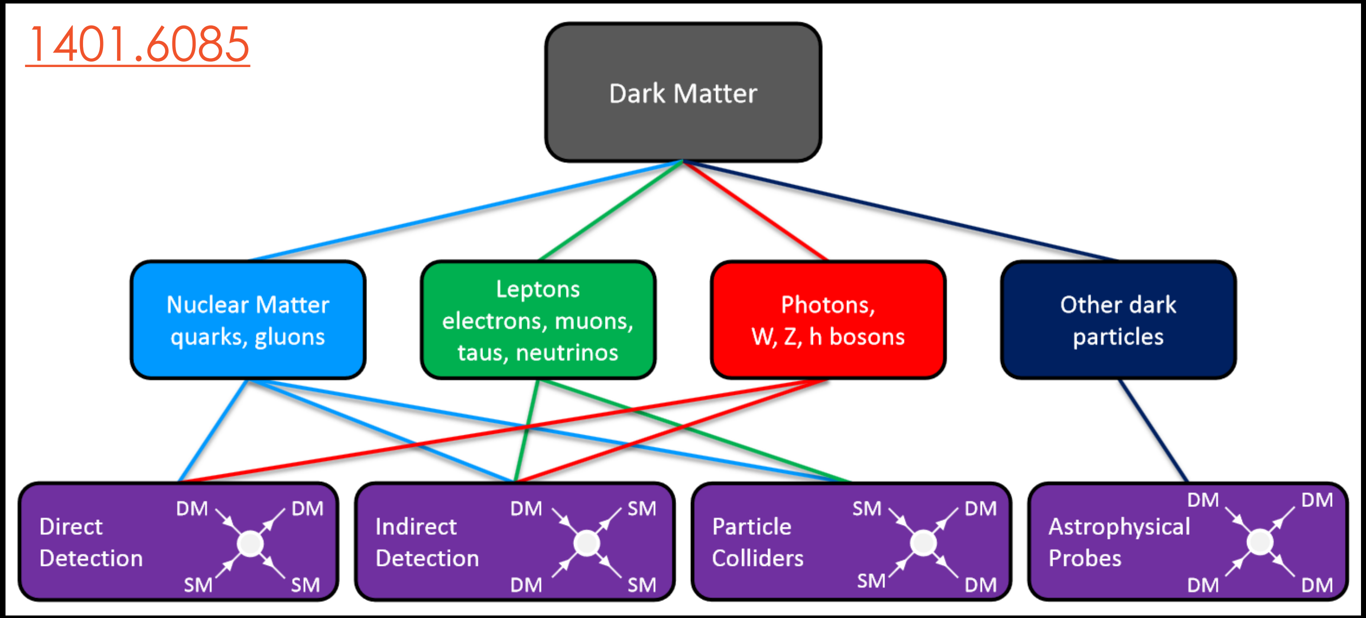


Stay Tuned!

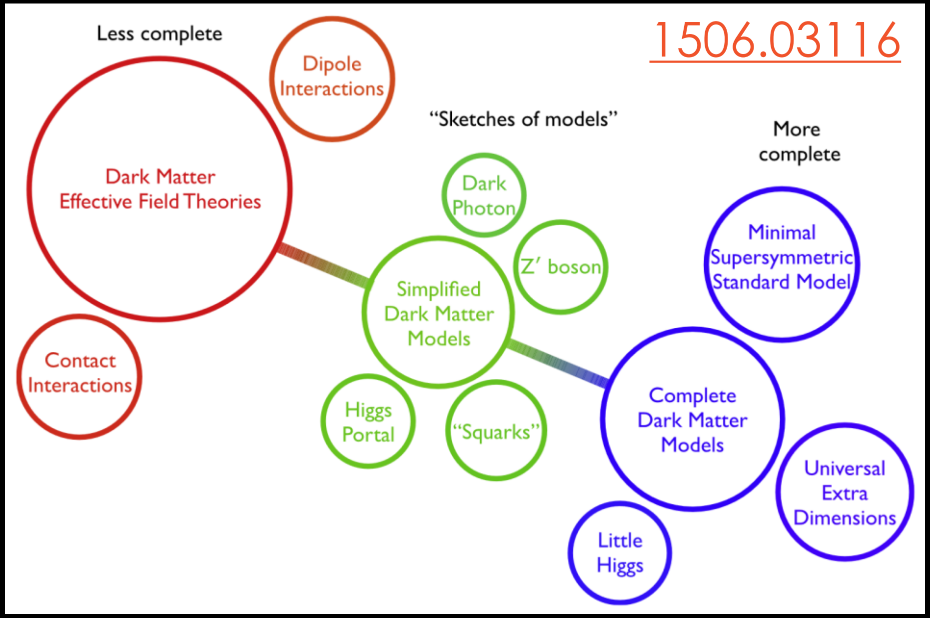
More the luminosity, Less the dark!

BACKUP

DM Interaction

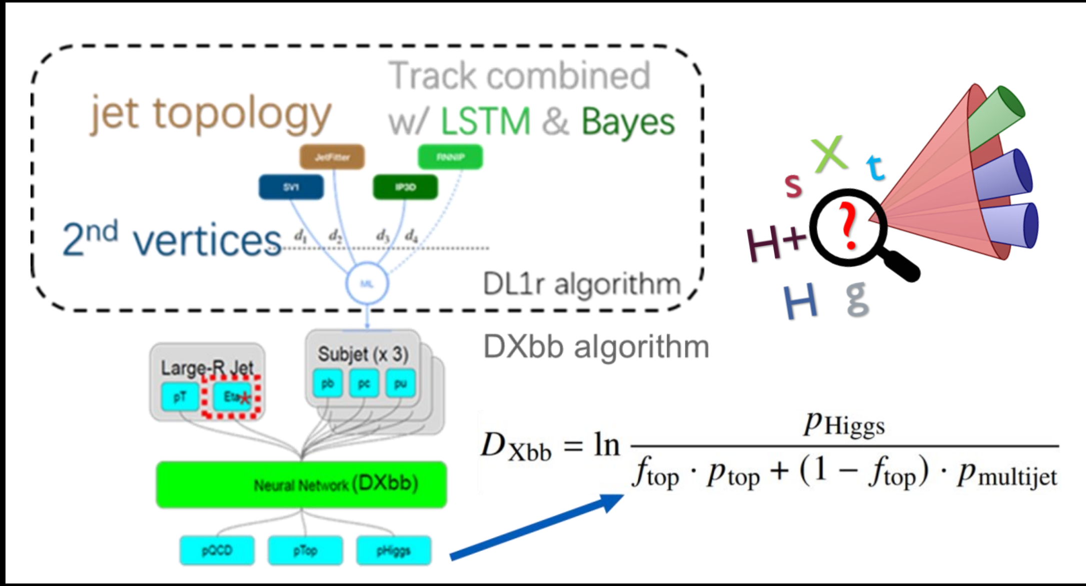


DM Theory

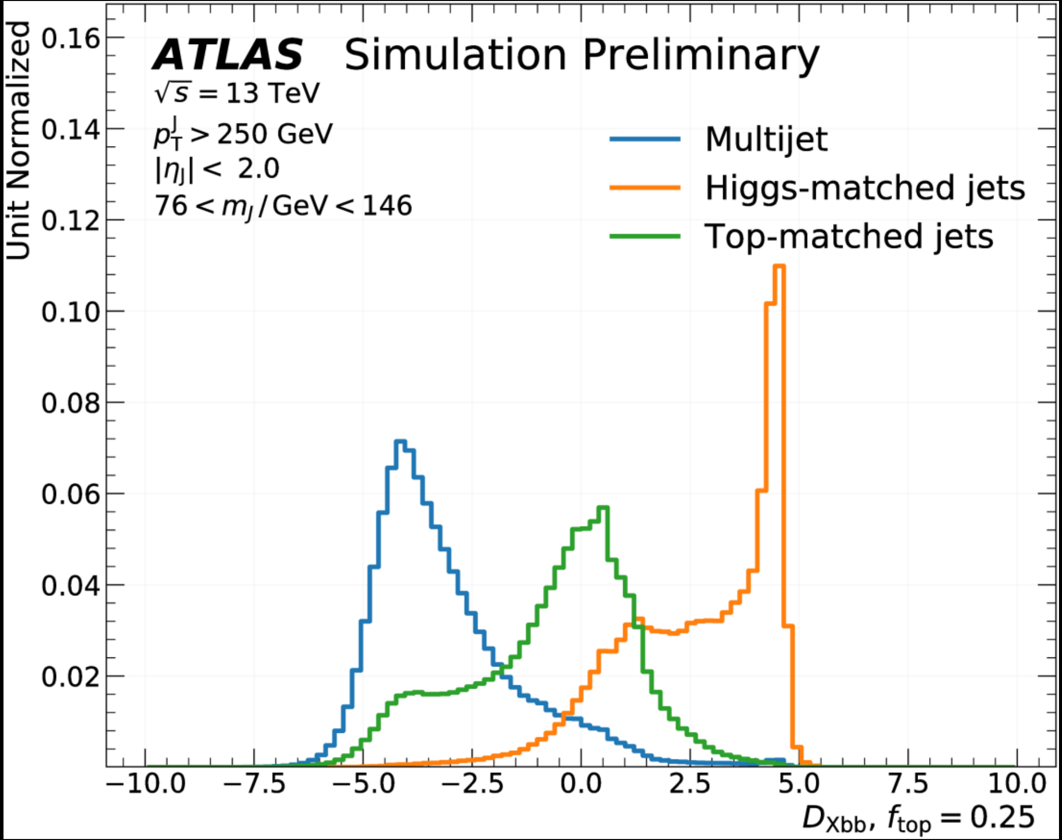


Boosted Xbb tagger in ATLAS

DXbb tagger [ATL-PHYS-PUB-2020-019]
Deep Neural Network based Xbb tagging
Hbb(mass-agnostic) v.s. QCD v.s. Top



$$D_{\mathrm{Xbb}} = \ln \frac{p_{\mathrm{Higgs}}}{f_{\mathrm{top}} \cdot p_{\mathrm{top}} + (1 - f_{\mathrm{top}}) \cdot p_{\mathrm{multijet}}}$$



Updated! GN2X tagger [ATL-PHYS-PUB-2023-021]
Transformer based Xbb tagging
(New analyses coming soon!)

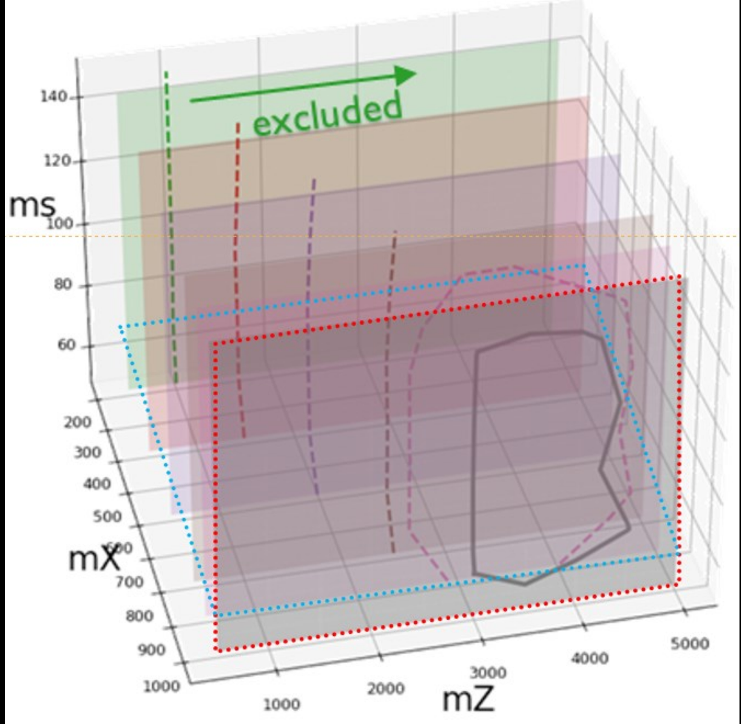
Dark Higgs

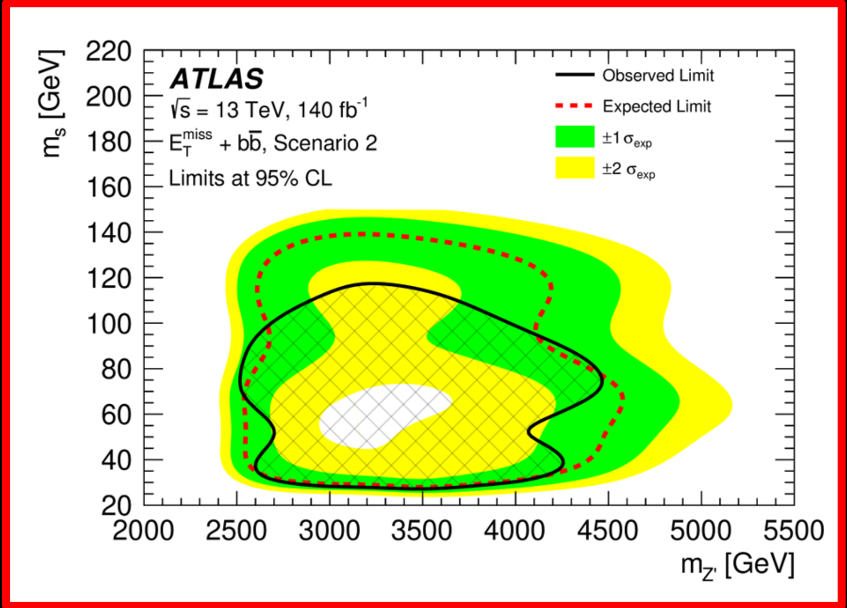
Relic-coherent 3-D Parameter Space

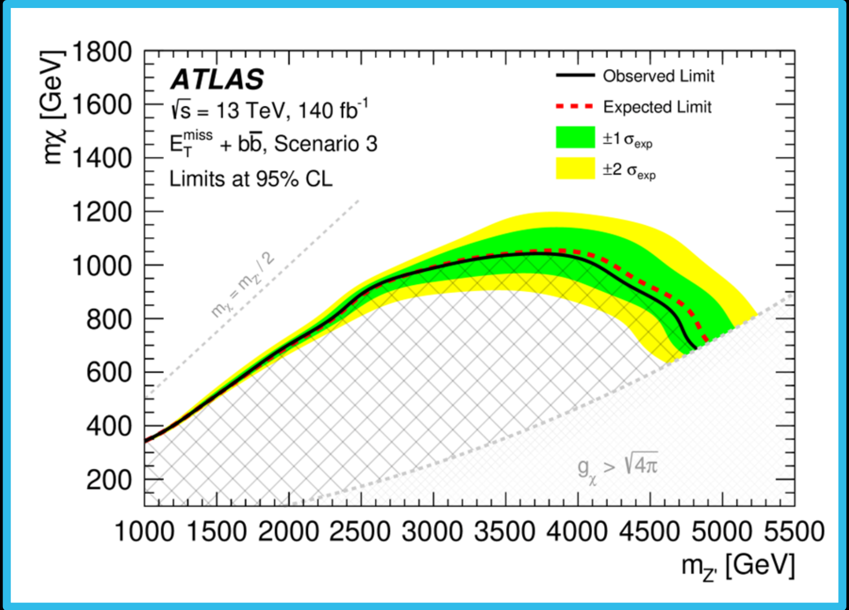
How <u>relic density</u> used to reduce parameter space of DM model

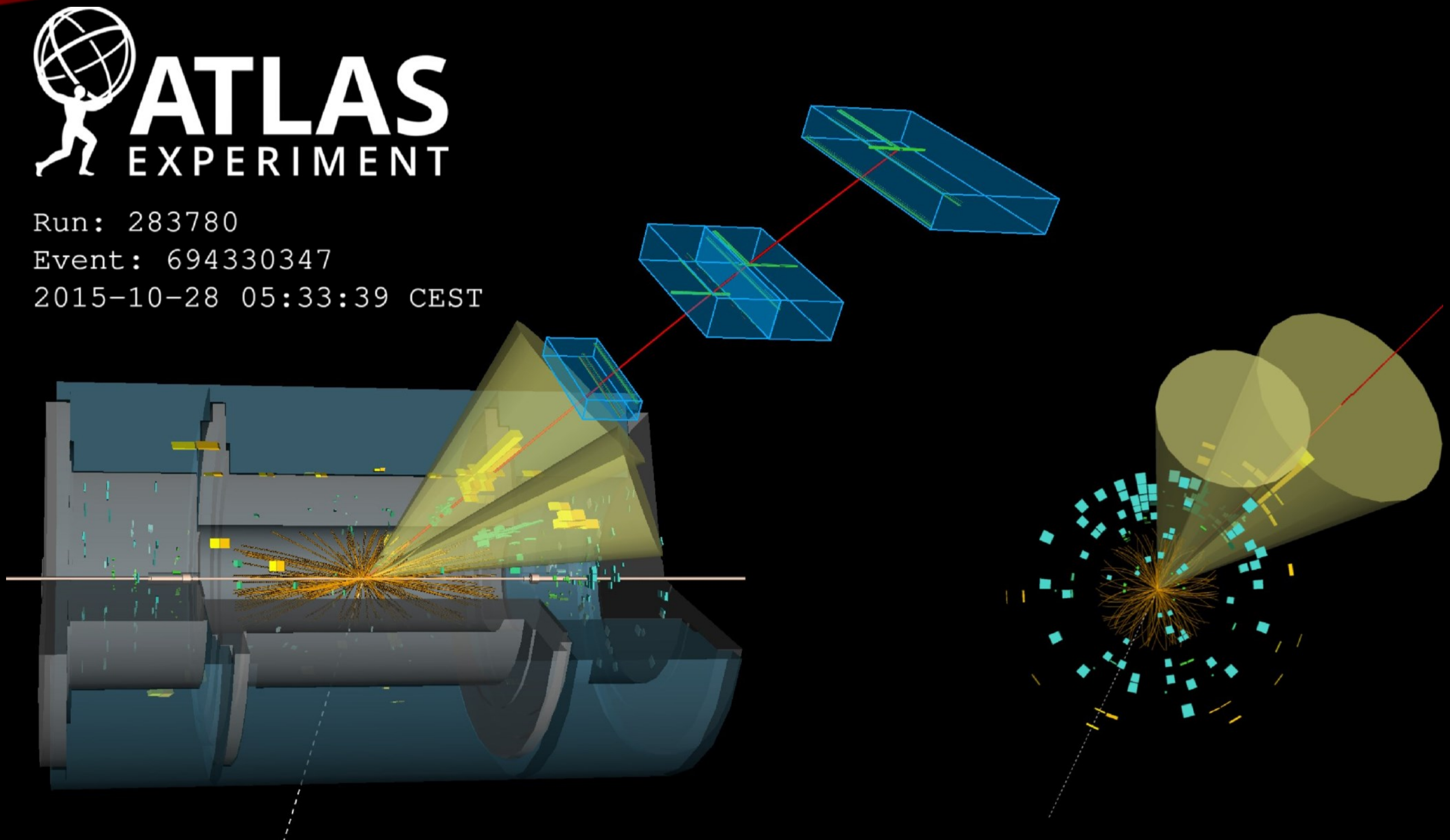
Reco Analysis Result

Set the final exclusion limit





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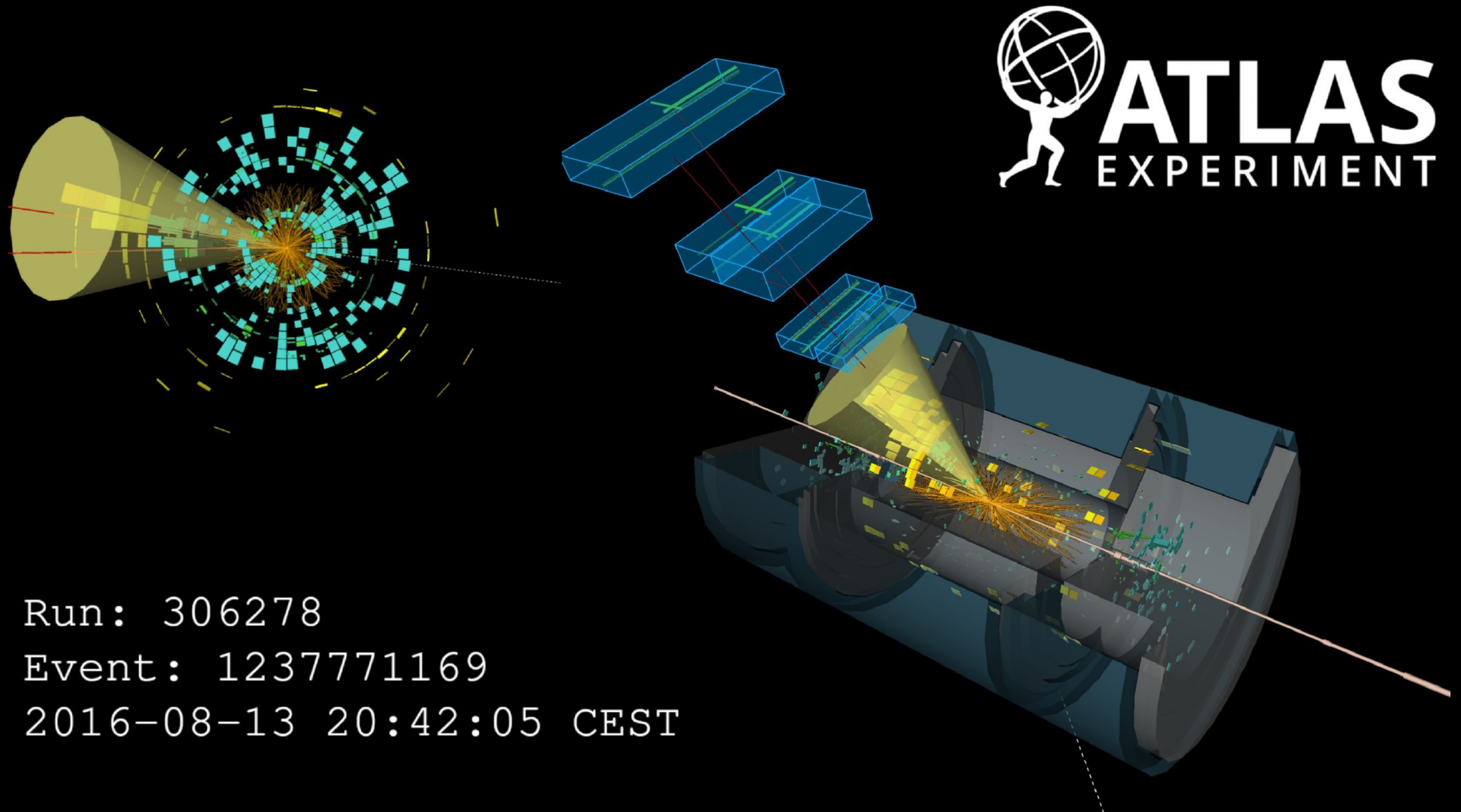
2015-10-28 05:33:39 CEST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EXPERIMENT
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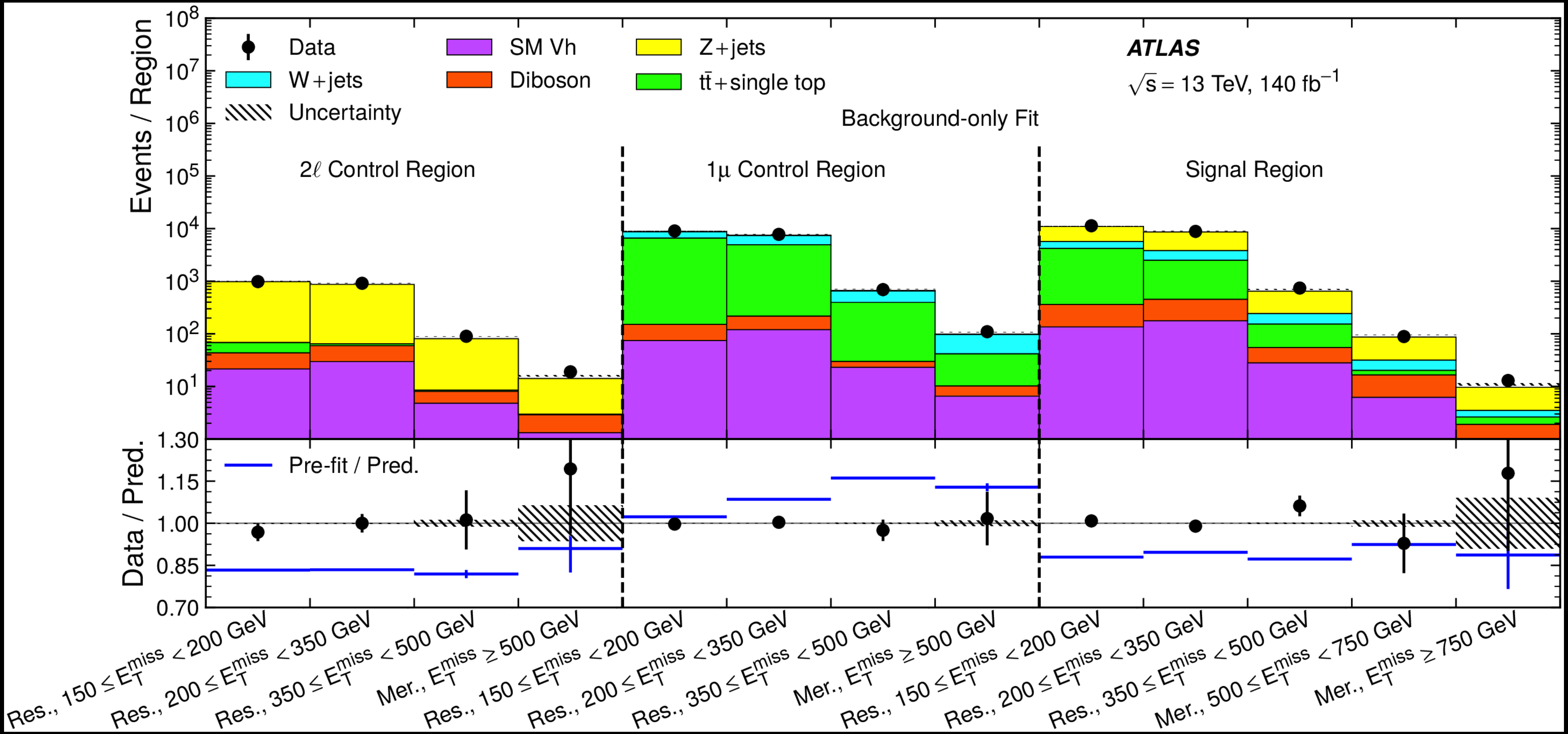
Event: 1237771169
2016-08-13 20:42:05 CEST

Mono-S(bb) Analysis: Post-fit



Summary of Selection of Dark Photon Search

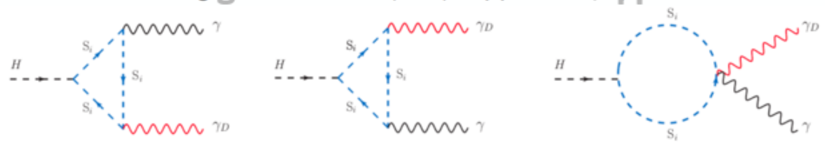
Channels	VBF	ZH	ggF
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Lepton(s)	Photon
Photons	$= 1$, $C_\gamma > 0.4$	$= 1$	≥ 1
E_{T}^{γ} [GeV]	$\in (15, \max(110, 0.733 \times m_{\mathrm{T}}))$	> 25	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$	≤ 2	≤ 1
	$\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$		
Leptons	$= 0$ $(e,\ \mu)$	$= 2$, SFOC	$= 0$ $(e,\ \mu,\ \tau)$
		$m_{\ell\ell} \in (76, 116)$ GeV	
Disc. variables	m_{jj} and m_{T} in SR and 4 CRs	BDT score and 1 CR	$E_{\mathrm{T}}^{\mathrm{miss}}$
Reference	[34]	[35]	[36]
Processes considered in the combination	VBF, ggF	ZH	ggF, VBF
Combination scenario	SM, BSM	SM	BSM

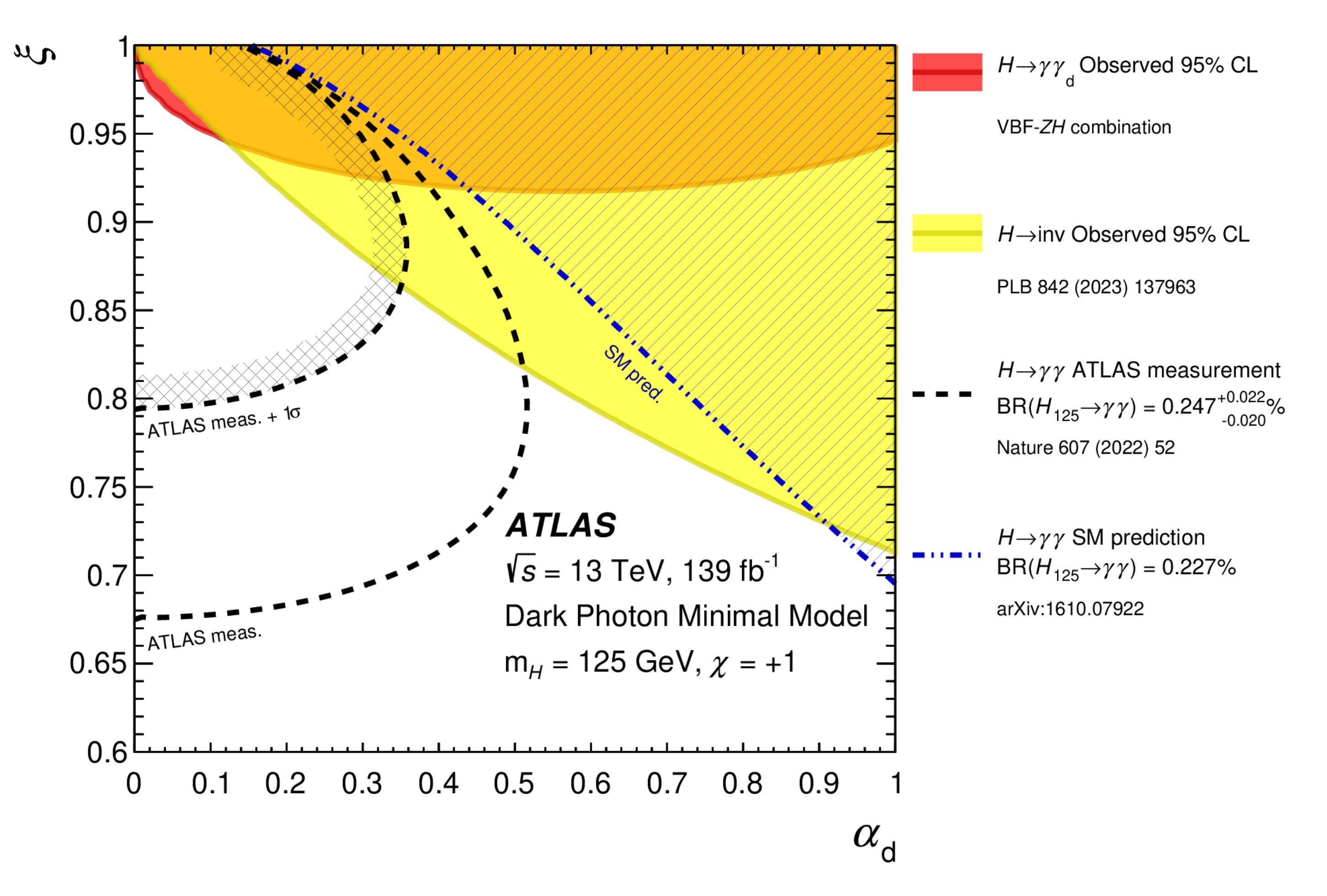
Minimal Model for Dark Photon

$$\mathcal{L} \sim \mu \cdot H^{\dagger} S_L S_R + h.c. \xrightarrow{\text{EWSB}} \mathcal{L}_S^0 = \partial_\mu \hat{S}^{\dagger} \partial^\mu \hat{S} - \hat{S}^{\dagger} M_S^2 \hat{S}$$

μ:mass parameter SL:SU(2)L doublet SR:SU(2)R singlet

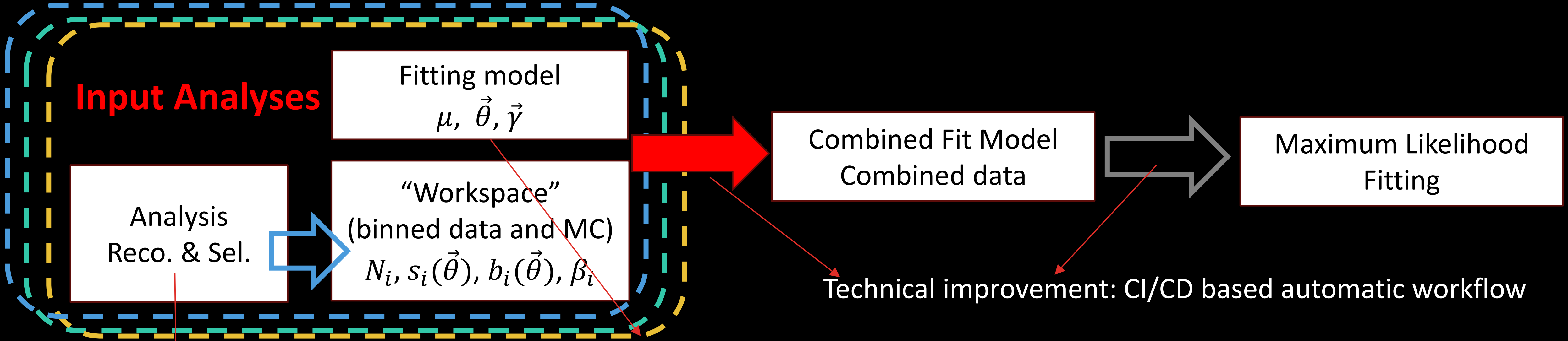
Diagrams contribute to H→γγd





Statistical Combination

$$L(\mu,\vec{\theta},\vec{\gamma}) = \prod_{i\in bins} \mathrm{Pois}\left(N_i \mid \mu s_i(\vec{\theta}) + \gamma_i b_i(\vec{\theta}) \right) \times \prod_{\theta\in\vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i\in bins} Gauss\left(\beta_i \mid \gamma_i\beta_i, \sqrt{\gamma_i\beta_i} \right)$$



Technical improvement: CI/CD based automatic workflow

Recast method for analysis preservation/reuse

● means correlated, ◐ means partially correlated.

	VBF	ZH	ggH(monophoton)
LUMI	●	●	●
PRW	●	●	●
JES	◐	◐	◐
JER	○	○	○
JVT	◐	◐	◐
EG Resolution and scale	◐	◐	◐
EL ISO/RECO efficiency	●	●	●
EL ID efficiency	●	●	●
MET	◐	◐	◐
MUON ISO/RECO efficiency	●	●	●
MUON ID/MS/SAGITTA/SCALE	●	●	●
Flavor tagging	●	●	●
MC Stat	○	○	○

Systematic uncertainty correlation carefully handled: Correlate only when from same source and recipe and no obvious pull/constraint in different phase spaces

Dark Photon Signature with SM Higgs Coupling

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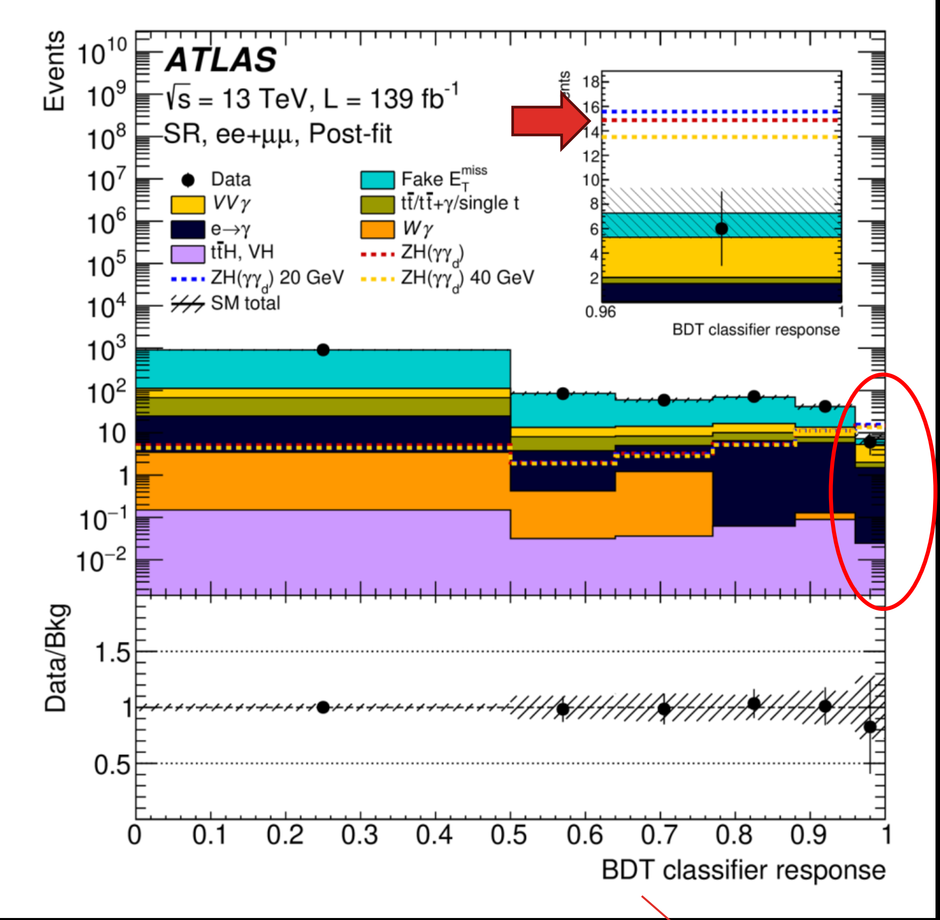
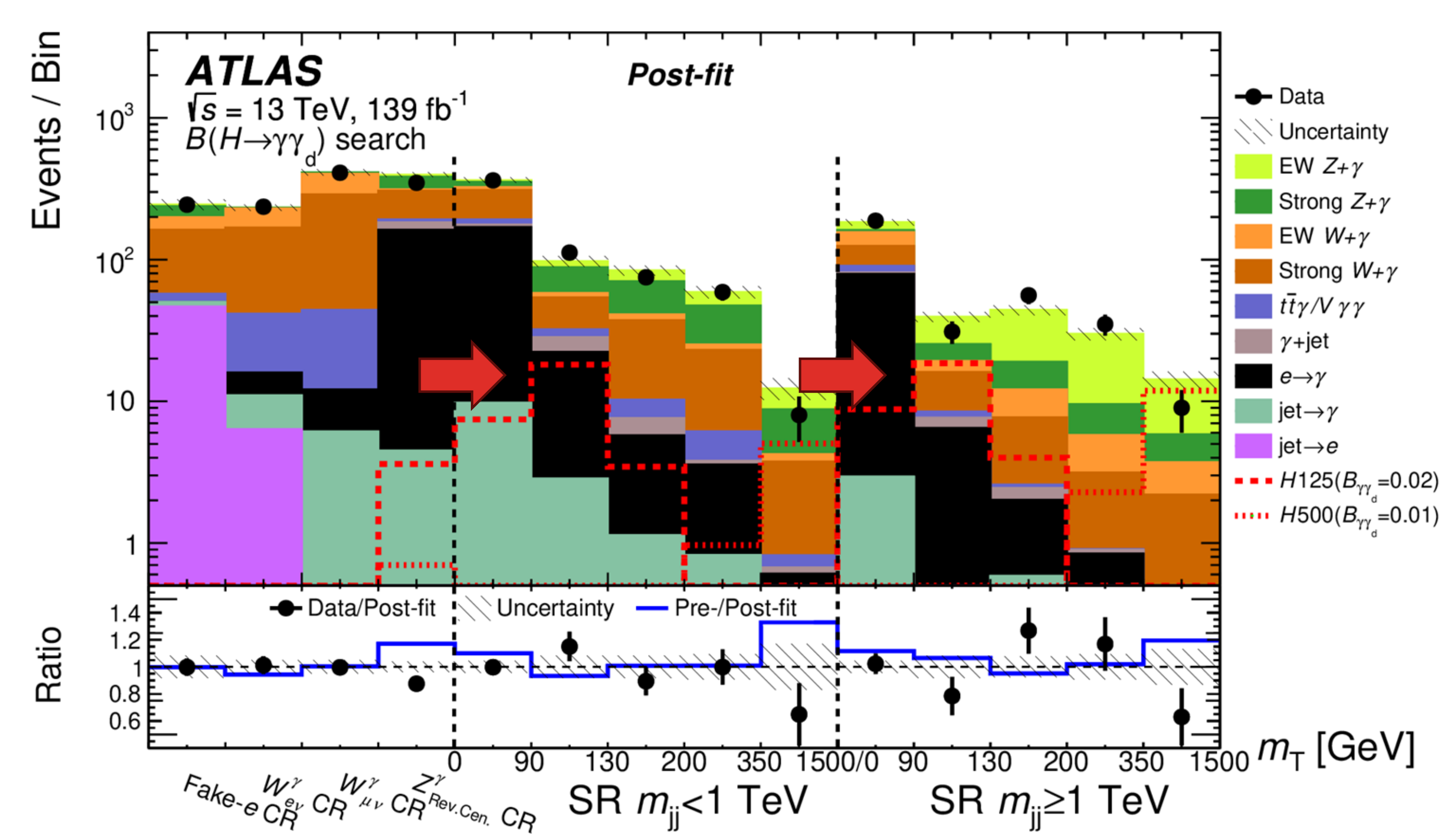


Eur. Phys. J. C 82 (2022) 105



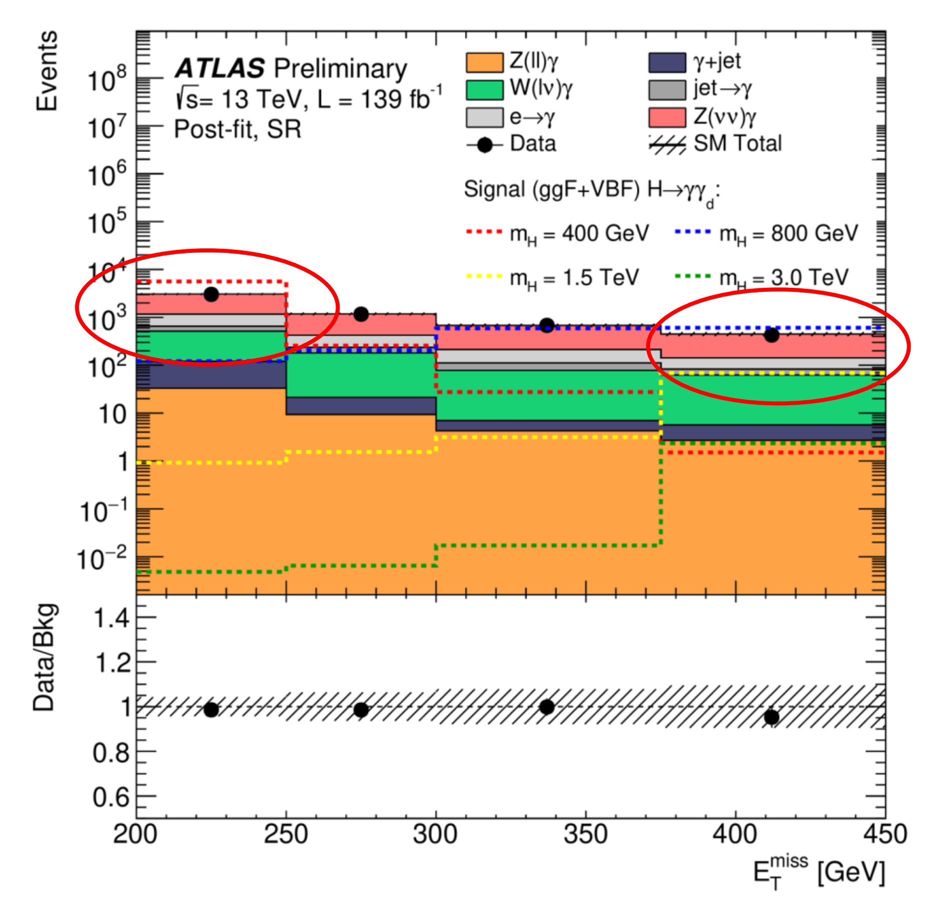
ZH channel

Combine 6 obs. MET significance, mT, …

VBF channel

Dark Photon Signature with BSM Higgs Coupling

ATL-PHYS-PUB-2023-003



Mono- γ (γ+MET) recast

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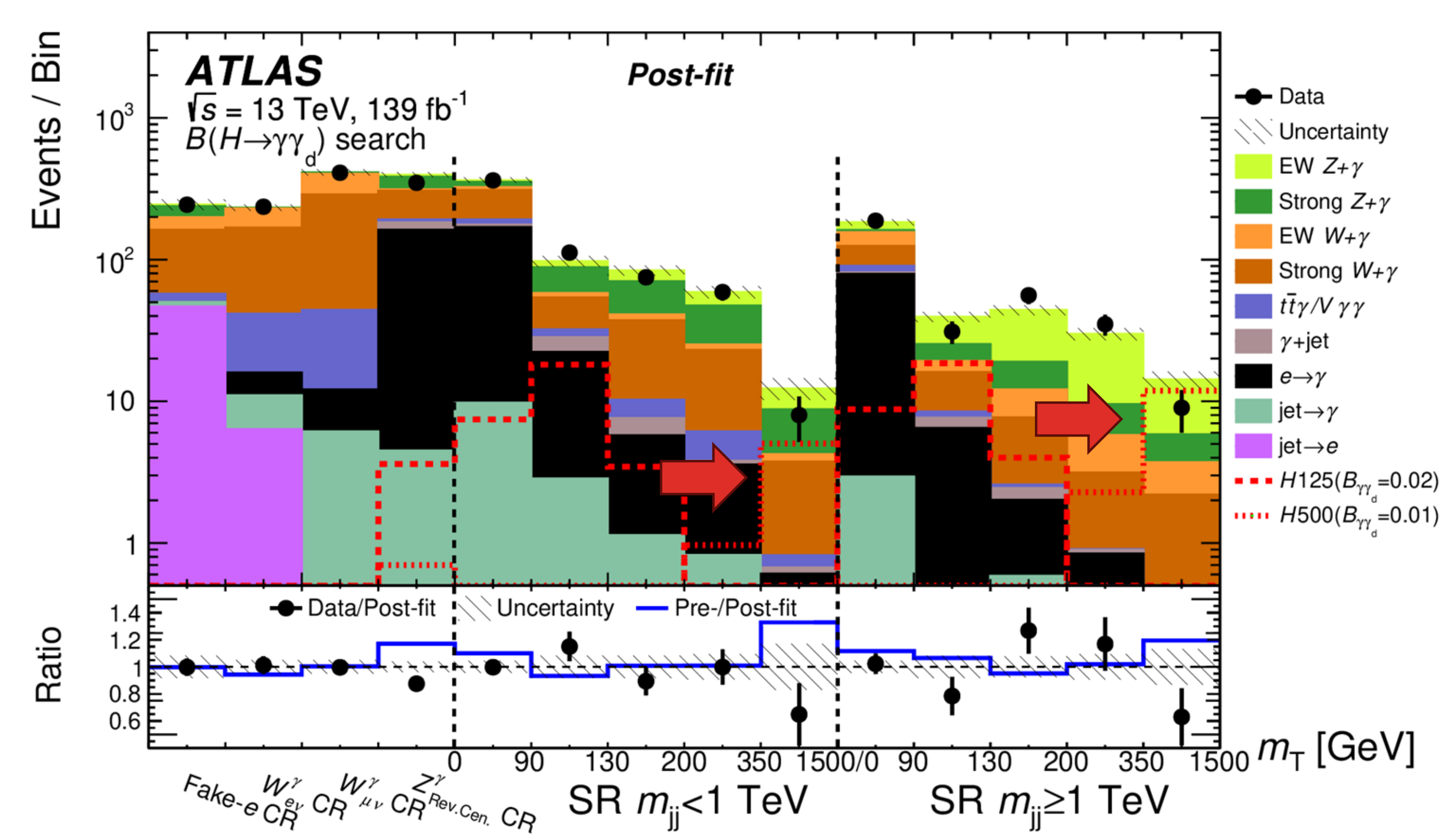

VBF channel

Dark Photon Combination: Uncertainty

SM Higgs

Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$[%]
Theory uncertainties	49
Signal modelling	2.2
Background modelling	47
Experimental uncertainties	63
Luminosity, pile-up	< 0.1
Jets, $E_{\text{T}}^{\text{miss}}$	40
Electrons, muons	11
Fake background	35
MC statistical uncertainty	36
Systematic uncertainties	75
Statistical uncertainty	66
Total uncertainty	100

BSM Higgs

Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$ [%]				
m_H [GeV]	400	800	1000	2000	3000
Theory uncertainties	30	27	28	40	35
Signal modelling	2.2	4.6	5.2	6.9	2.0
Background modelling	30	27	27	38	34
Experimental uncertainties	64	51	45	37	41
Luminosity, pile-up	4.6	2.6	2.9	2.8	2.3
Jets, $E_{\text{T}}^{\text{miss}}$	22	12	11	13	14
Electrons, muons	20	23	18	13	14
Fake background	52	41	35	25	29
MC statistical uncertainty	20	17	19	19	23
Statistical uncertainty	75	84	87	85	86
Systematic uncertainties	67	55	49	53	52
Total uncertainty	100	100	100	100	100

Dark Photon Combination: Acceptance

BSM Higgs

m_H [GeV]	$200 \leq E_T^{miss} < 250$ GeV ggF [%]	VBF [%]	$250 \leq E_T^{miss} < 300$ GeV ggF [%]	VBF [%]	$350 \leq E_T^{miss} < 375$ GeV ggF [%]	VBF [%]	$E_T^{miss} \geq 375$ GeV ggF [%]	VBF [%]
400	8.15	4.30	0.35	0.49	0.04	0.05	<0.01	<0.01
600	9.05	4.95	18.9	9.10	7.74	5.44	0.35	0.53
800	3.21	1.96	5.33	3.27	15.4	9.39	15.6	10.5
1000	1.63	1.24	2.50	1.72	5.92	4.01	29.4	21.2
1500	0.50	0.38	0.73	0.69	1.65	1.33	33.3	30.0
2000	0.22	0.21	0.35	0.33	0.67	0.69	32.7	34.3
2500	0.10	0.09	0.16	0.18	0.35	0.41	29.6	38.0
3000	0.04	0.08	0.08	0.11	0.19	0.29	28.9	39.6