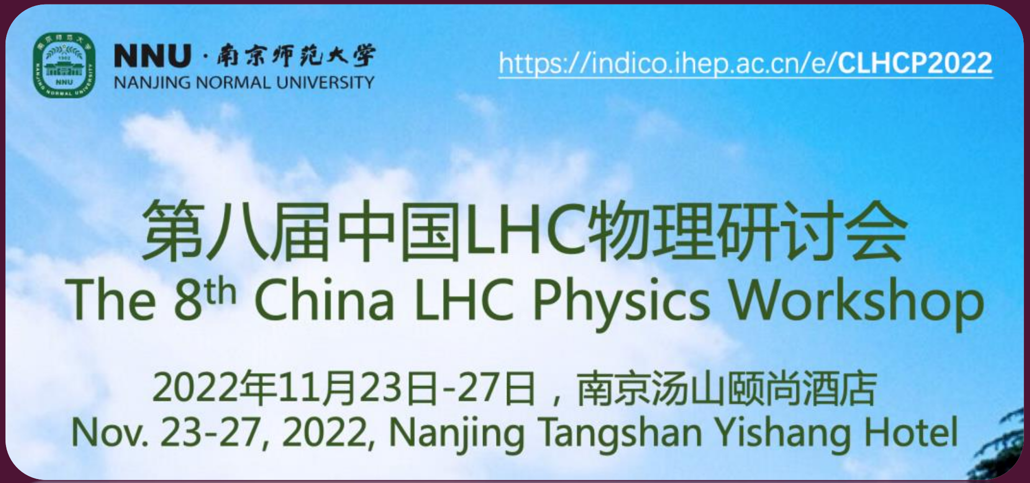
Search for Dark Matter Produced in Association with a Dark Higgs Boson Decaying to two b quarks at ATLAS and the potential to utilize the novel DXbb tagger

Qibin LIU [TDLI. & Shanghai JiaoTong University]

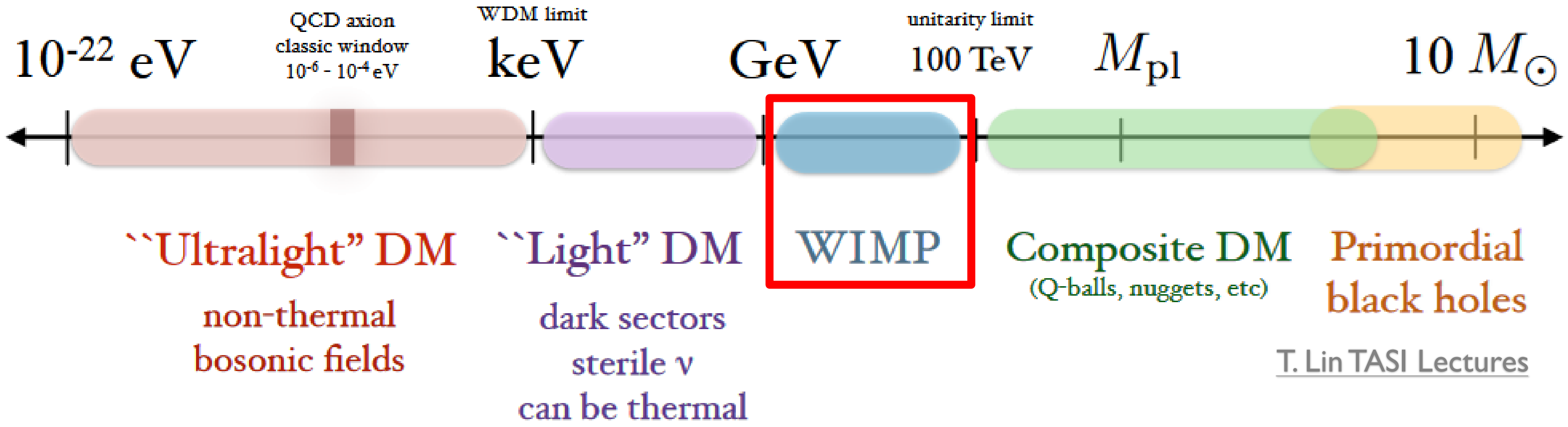
李政道研究所
Tsung-Dao Lee Institute



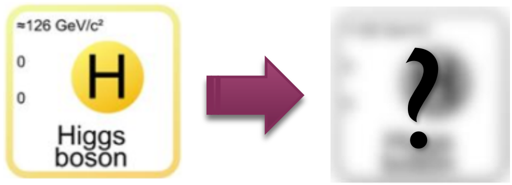
Supervisor: Shu LI

Introduction

- Evidence from cosmology observation support the existence of Dark Matter (DM)
- Weakly Interacting Massive Particle (WIMP) draws wide interests across a wide range of DM mass assumption
- Dark Higgs model with similar structure as SM Higgs proposed and popularly studied in ATLAS
- Dedicated analysis for Dark Higgs Boson decaying into 2 b quarks being studied utilizing advanced methods
- New techniques well tested and promising for future : DXbb tagger



T. Lin TASI Lectures

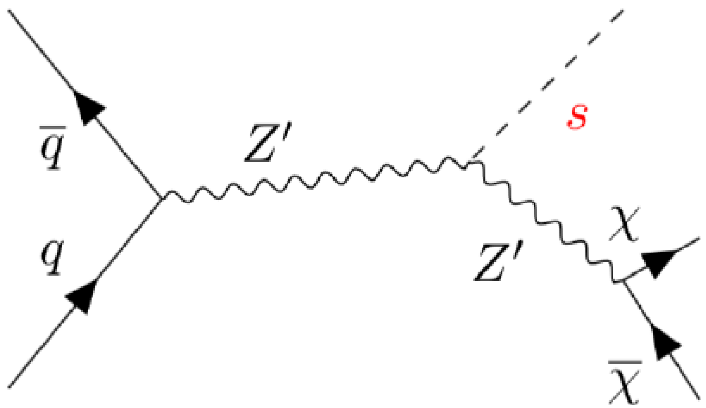


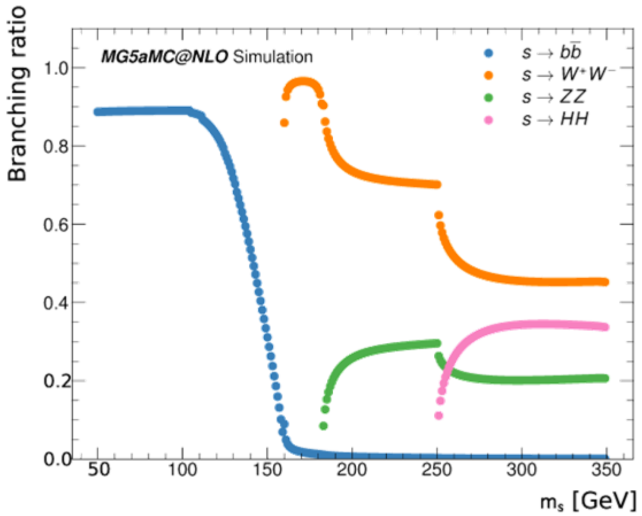
Dark Higgs Model

- Spontaneously broken U(1)' gauge symmetry introduced in WIMP framework to account for the mass in dark sector
- Scalar particle **s** called dark Higgs boson [1] and the vector boson Z' , forming a two-mediator DM(2MDM) model [2]

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

- Mixing between dark Higgs and SM Higgs leads to detectable products e.g. s→bb, s→VV depending on the scalar mass
- New annihilation channel to SM opened up (χχ→ss→...) and relax the constraint from cosmological observation
  - Resolve the over-production issue of DM prediction



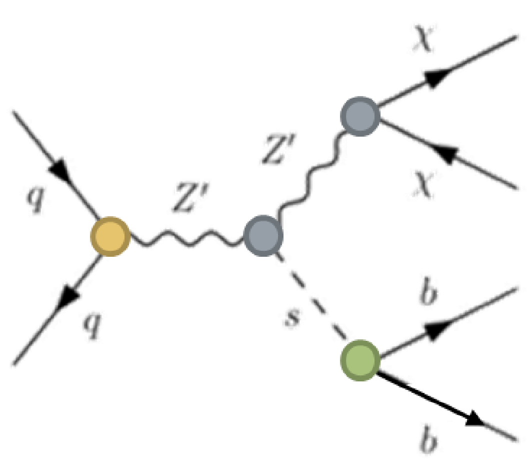


ATL-PHYS-PUB-2019-032

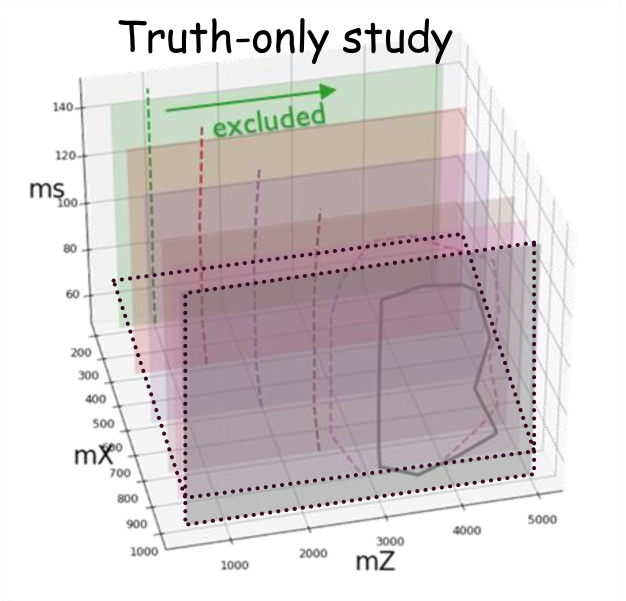
[1]: 1701.08780
[2]: 1606.07609

Signal Parameter Space

- Explore all the 4 important parameters (mS, mχ, mZ' and gχ), especially at low mass
- Extra constraint from cosmology: Ωh^2
  - Reflects the property of DM evolution and thermal equilibrium
  - DM hypothesis should predict compatible Ωh2 with obs. like Plank 2018
- 3 signal interpretations enable the search in a 3D parameter space (mS-mZ'-mX)

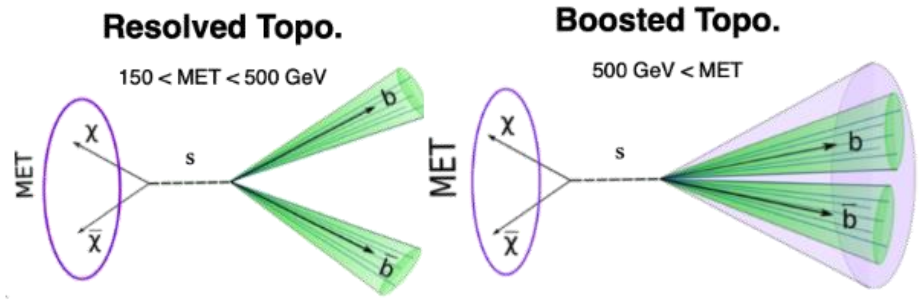


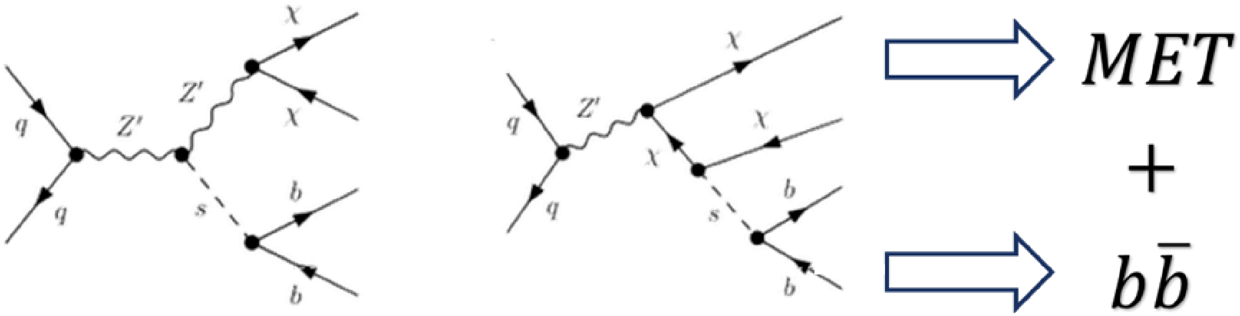
Parameter	Explain
m_s	mass of dark higgs
m_χ	mass of DM
$m_{Z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: q<->Z' fixed 0.25 as benchmark
θ	mixing angle of SM Higgs<->dark Higgs fixed according to [1]



MonoS(→bb) Analysis

- Search for low mass dark Higgs w/ b-quark pair and high MET signature using **ATLAS full Run2 data**
- Events triggered with large MET : MET>150GeV required in analysis
- Analysis strategies optimized according to the event topology
  - Resolved and merged regions defined based on MET and different selections/methods applied
- New techniques to analyze challenging boosted jet with varying mass
  - Jet reconstruction w/ reclustering technique (**RC jet**)
  - Jet tagging w/ ML-based mass-agnostic tagger (**DXbb**)

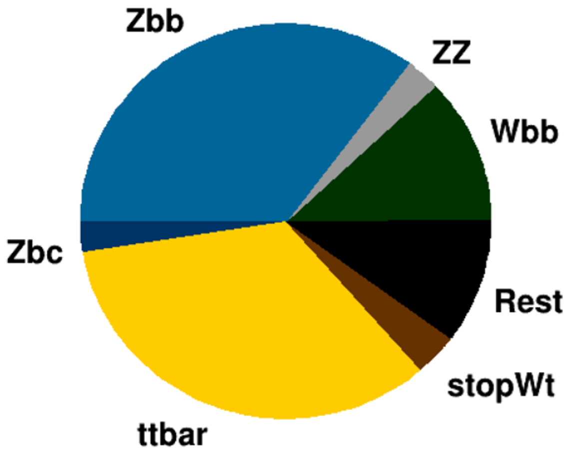




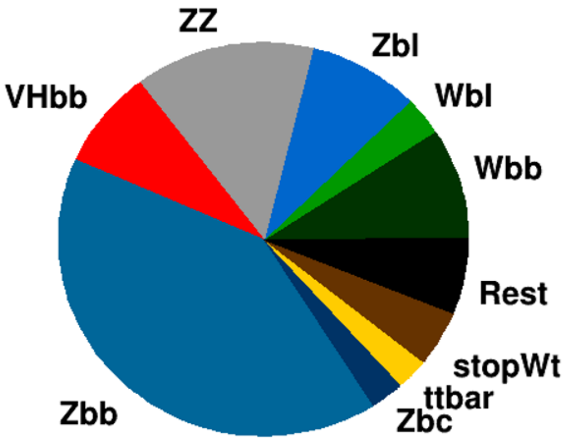
MET/GeV	[150,200)	[200,350)	[350,500)	[500,750)	[750,+∞)
Recon. Object	Two Small-Radius Jets			One Large-Radius jet (RC)	
Common Sel.	0.7<MET/pT_jj<1.3, Δϕ(j,MET)>20°, N_lep==0				
Special Sel.	$m_T^{b,min} > 170GeV, m_T^{b,max} > 200GeV$ MET_significance>12			2mJ/pT_J<0.6	
B-tagging	N_tagged_Jet==2			Tagging on large-R jet(DXbb, etc)	
Fitting variable	Dijet mass			Large-R jet mass	

Main Background and Control regions

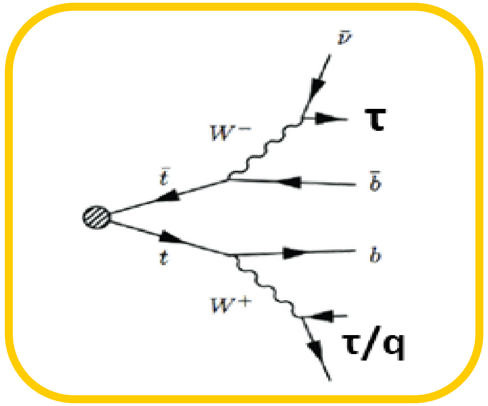
- Dominant background :
  - $t\bar{t} \rightarrow bWbW, W + HF \rightarrow l\nu + HF$:lepton is not identified/captured
  - $Z + HF \rightarrow \nu\nu + HF$: mimic the $bb + MET$ signature
- Changing fraction at different MET range
- Control region (CR) designed to control the yield with data:
  - One-muon region for $t\bar{t}$ and $W + jets$
  - Two-lepton region for $Z + jets$

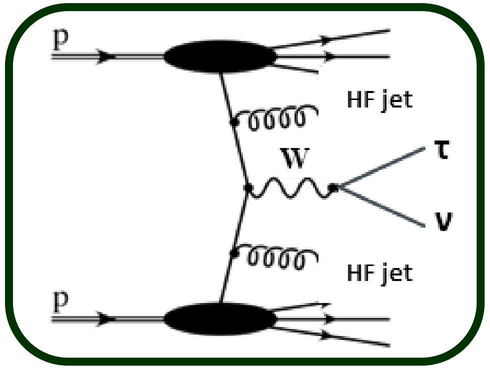


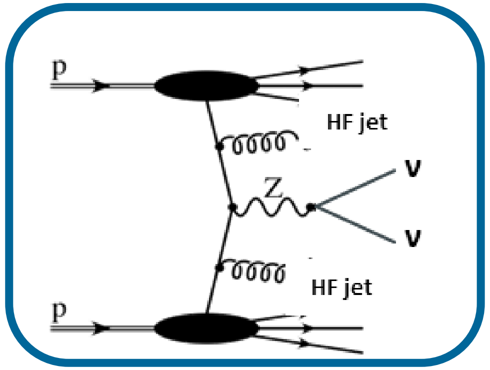
150GeV<MET<200GeV



750GeV<MET

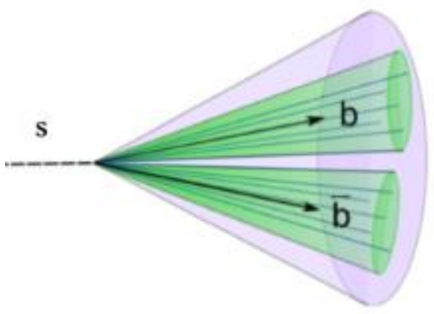




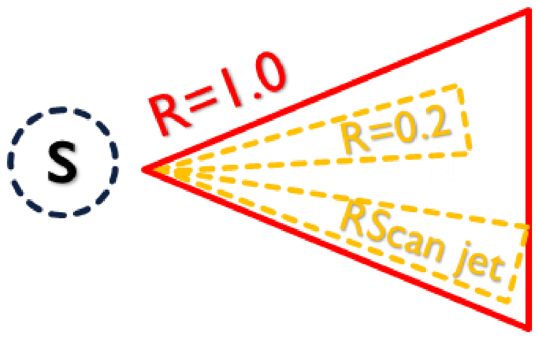


Reconstruction of highly boosted events

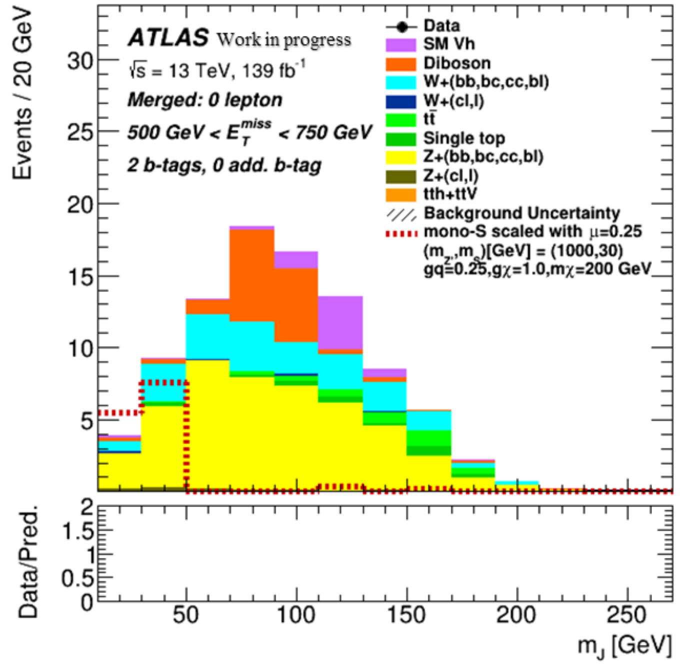
- Merged region with high MET has better sensitivity since small backgrounds but **challenging**
- **Jet reconstruction and tagging: two b-jets get highly boosted and merged**
- ➢ Limited support for low mass jet reconstruction → worse sensitivity at lower signal mS
- ➢ Reclustering jet studied: jet first clustered with R=0.2 and then reclustered with AntiKt R=1.0 algorithm
- ➢ Comparable performance at high mass while lowest mass boundary extend to 20GeV



Boosted S→bb

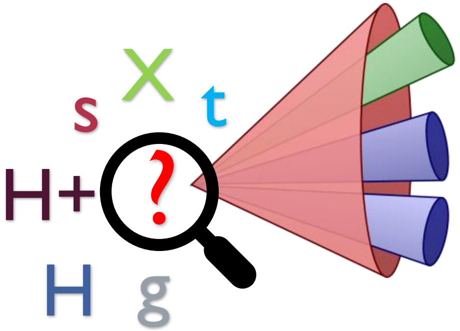


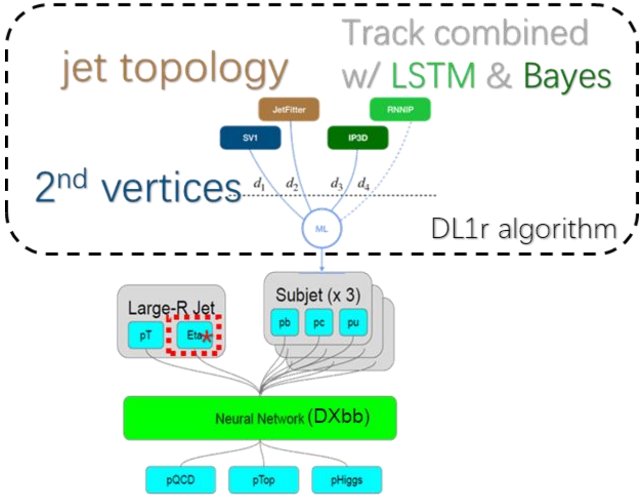
Reclustering Large-R Jet

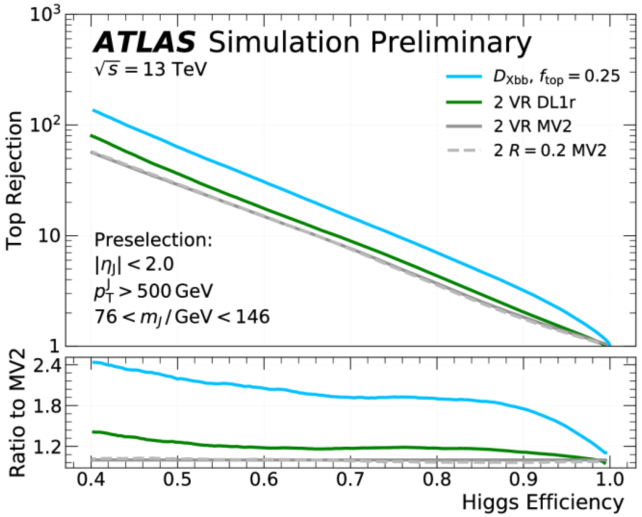


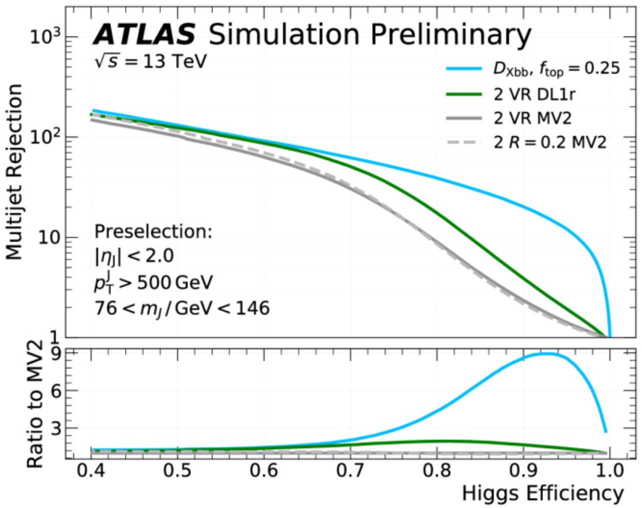
Boosted X→bb Tagging

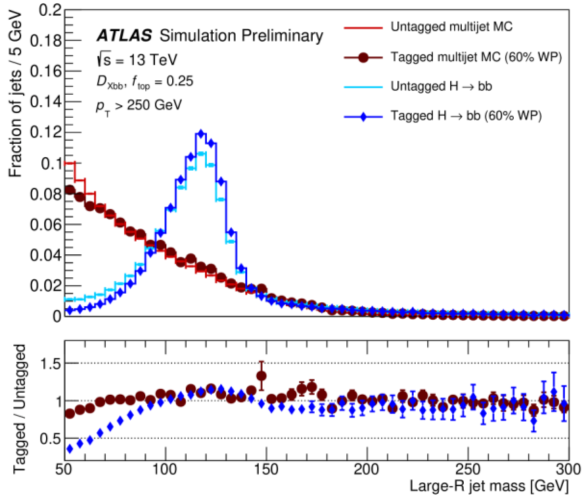
- B-tagging of highly boosted jet is another challenge → merged b-jets and complex composition
- Deep machine learning based tagger dealing with the challenge of boosted X→bb tagging
  - Output combining 3 probabilities being H/Top/QCD jet: $D = \ln\left(\frac{p_H}{(1-f_{top})p_{QCD} + f_{top}p_{top}}\right)$
- Better classification performance than tagging the 2b separately
- Good mass agnostic feature → no dependance on mass: really "X"→bb





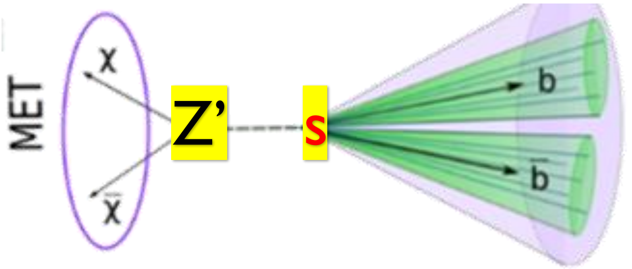


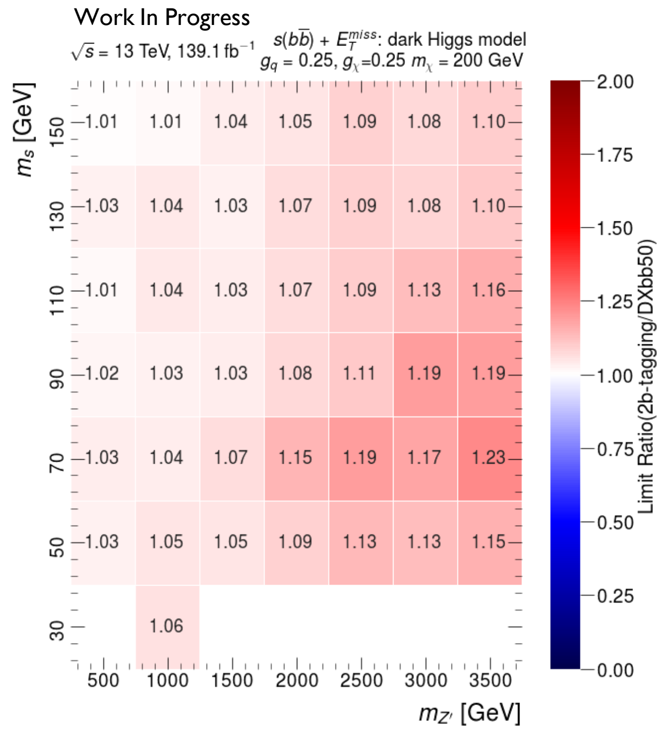




Sensitivity Study of Tagging methods

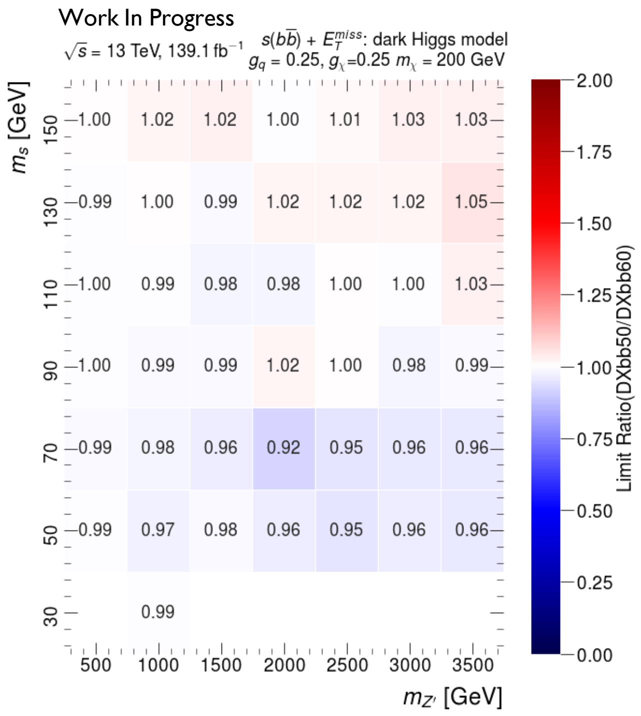
- Different large-R jet tagging studied for the merged region: targeting best signal sensitivity (smallest limit)
  - DXbb tagging v.s. 2b tagging (conventional method: counting b-tagged subjet)
- DXbb shows better sensitivity (lower limit) for all the signal points
  - Especially for the high mZ'(thus high pT) and low mass → highly boosted region
- Different DXbb WPs compared: DXbb 50WP chosen as analysis baseline





\`DXbb\` wins

"2b-tagging wins



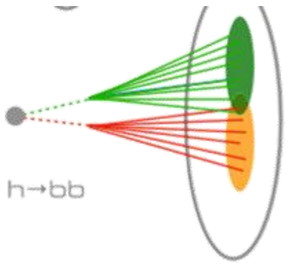
\`DXbb 60WP\` wins

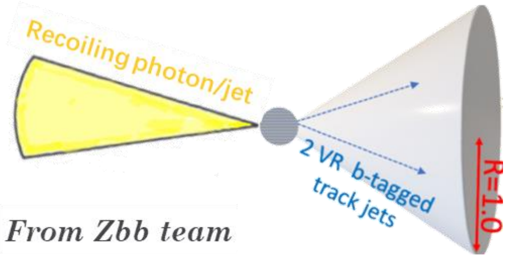
\`DXbb 50WP\` wins

Calibration of DXbb tagger and Application to MonoSbb

- Tagging method developed based on MC simulation must be fully calibrated to account for the data/MC difference
- Several dedicated calibrations developed in ATLAS and the scale factor (efficiency correction of data to MC) available
- Dominant processes being tagged of monoSbb analysis got correction from either calibration or constraints from data

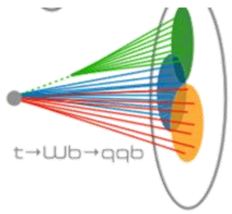
2b final states (from particle decay)
e.g. Signal, VHbb, VV

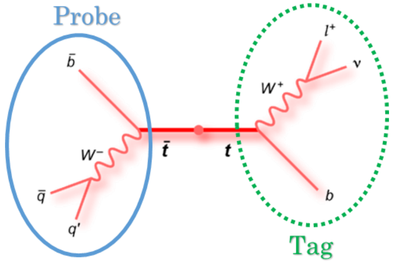




$Z \rightarrow bb$ calibration

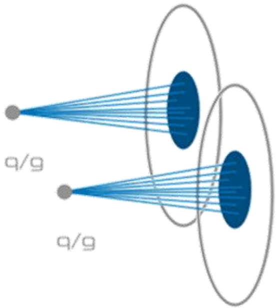
1b final states
e.g. ttbar, single top, V+jets (bc/bl)

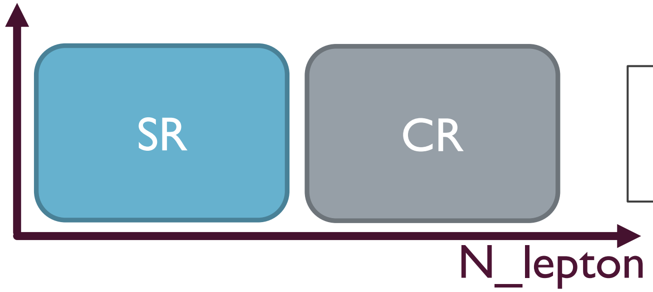




Semi-leptonic ttbar calibration

2b final states (from QCD)
e.g. V+jets (bb)

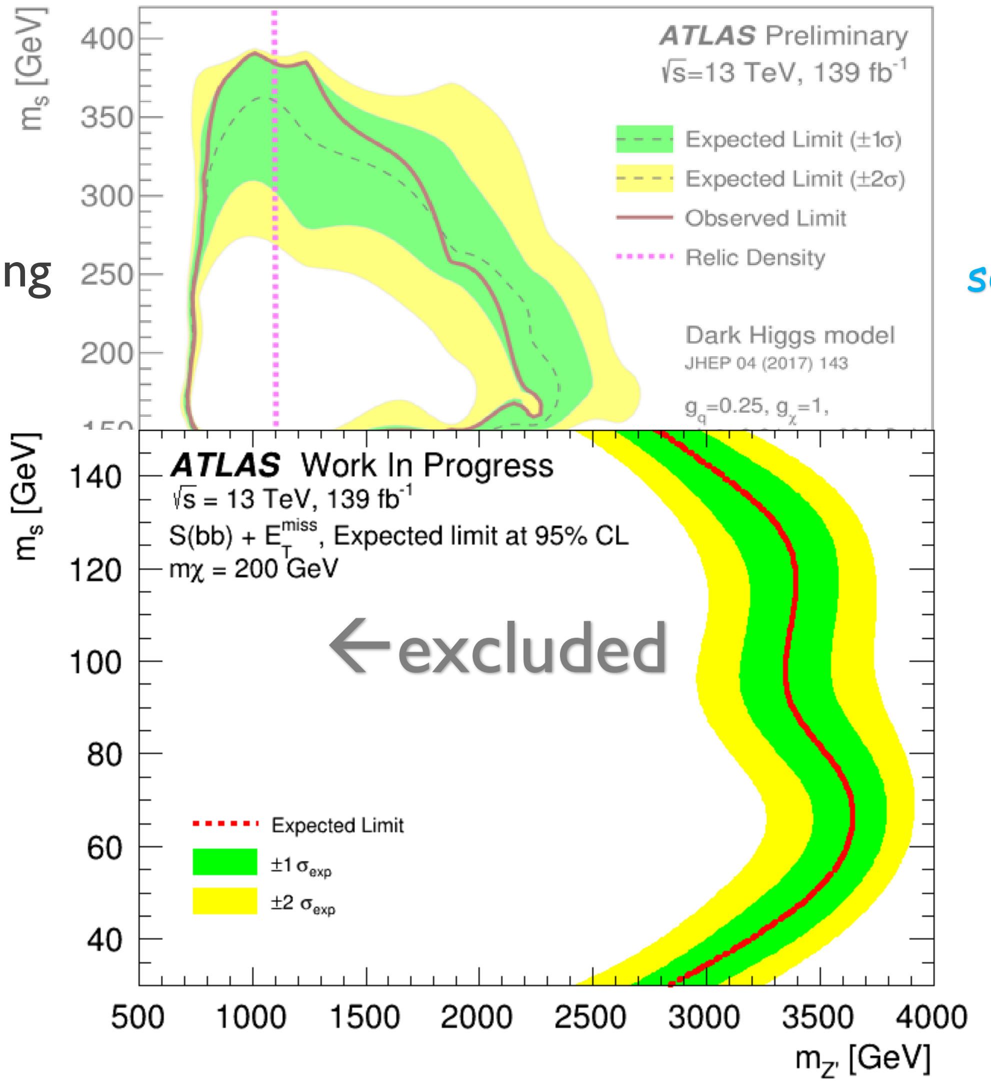




Constrained by data
(corrected with fitting)

Statistical Study and Results

- Signal strength and normalization of dominant background extracted simultaneously with fitting
- Exclusion limit at 95% C.L. set on signal model
- Complement of the sister analysis (s→WW)
- At fixed mχ =200GeV and gχ=1.0, dark Higgs signal expected to be excluded with 30GeV<mS<150GeV and mZ'<3TeV
- Most sensitive for signal with mS~70GeV and excluded mZ' up to 3.5TeV

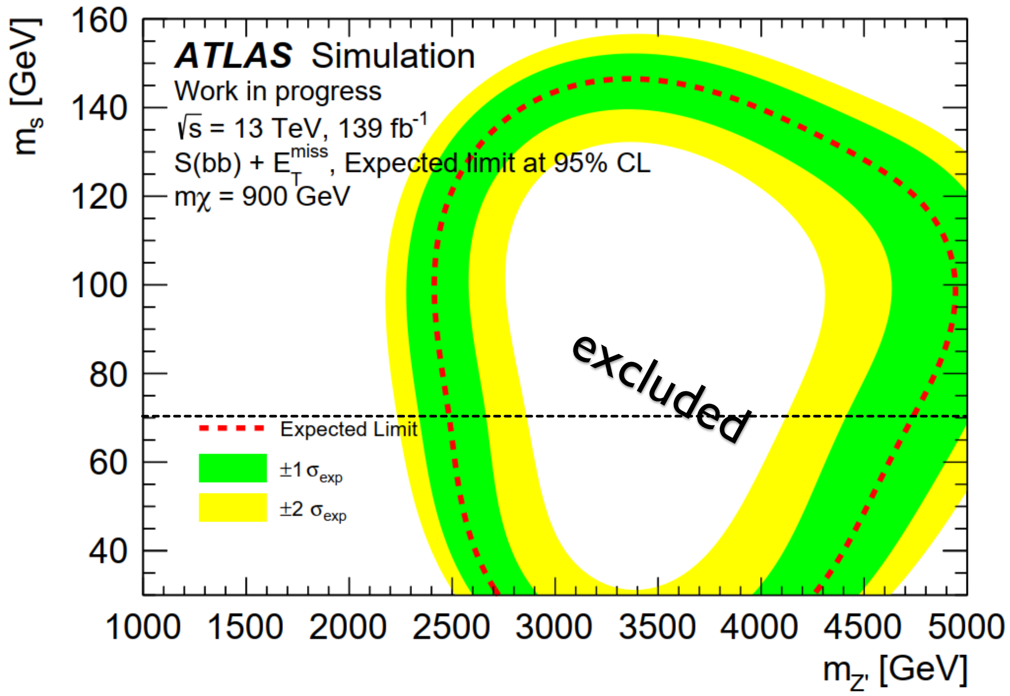


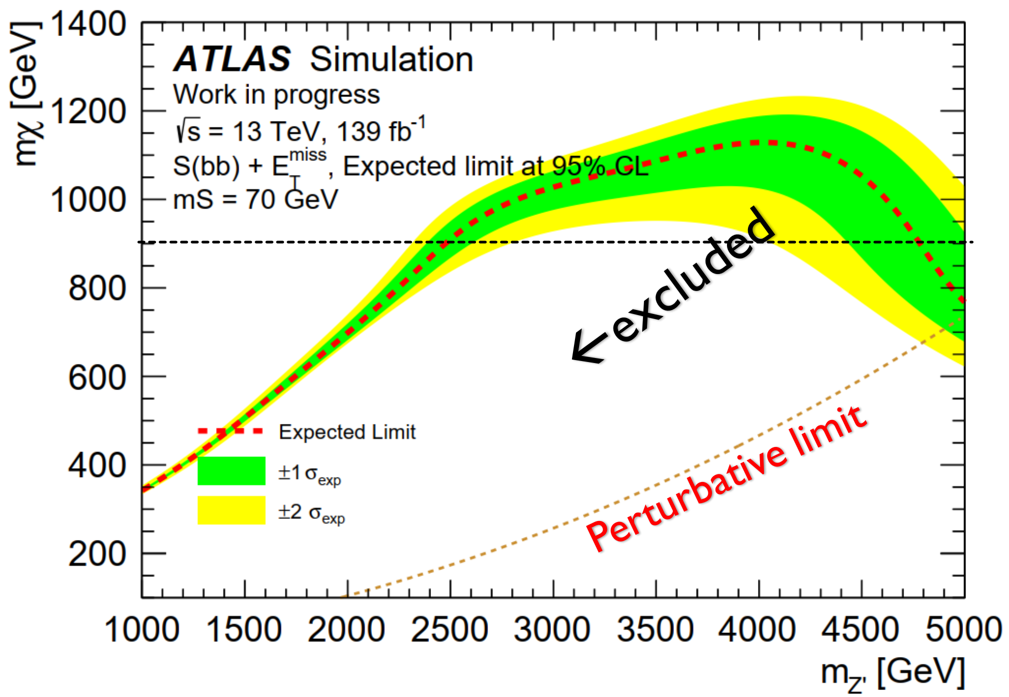
← sister analysis search for s to WW

← MonoSbb

Statistical Study and Results

- Freeze-out relic density observation from cosmology constrains the value of gχ
- Exclusion limit at 95% C.L. set for dark Higgs to probe the mS-mZ'-mχ parameter space w.r.t relic density
- mZ' around 3~4TeV is excluded with mχ =900GeV and mS<140GeV
- mχ is excluded up to 1TeV at mS=70GeV and mZ' around 3~4TeV





Summary and Outlook

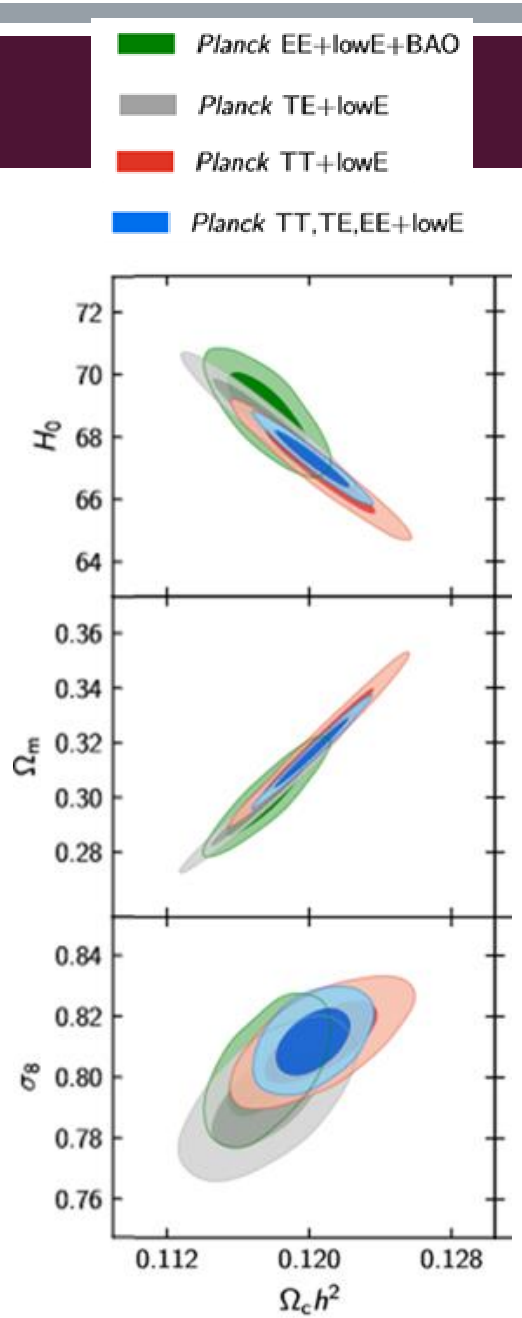
- Dark Higgs model as one candidate for WIMP explains the mass origin in dark sector and searched in ATLAS
- Dedicated MonoSbb analysis established focusing on dark Higgs decaying into 2b quarks with extended parameters setup especially emphasizing the relic density constraint
- Advanced techniques including reclustering large-R jet and deep learning based DXbb tagger applied
- Preliminary results expected to exclude dark Higgs model of mZ' up to 3TeV and mS between 30-150 GeV as well as other limits on 3D parameter space
- Significant sensitivity improvement from DXbb tagger and promising application in the future for highly boosted jets

Thanks!

BACKUPS

Ωh^2 observation and constrain on gX

- Freeze-out relic density of dark matter(DM) Ωh^2
  - A cosmological variable reflects the property of DM evolution mechanism dating back from Big Bang
- Ωh^2 can be obtained from observation
  - Planck 2018 observed Ωh^2=0.1200 $\pm$ 0.0012
- Ωh^2 can also be calculated from theory
  - Universe expansion and cooling slow down the DM interaction
  - $Y \equiv n_{DM}/s$ stop decreasing and finally converge to Ωh^2
  - Theory calculation
- A good model should give compatible Ωh^2
  - Ωh^2 > observation: Over-produced
  - Ωh^2 < observation: Needs supplement contribution from other DM model
- In the Dark Higgs model case:
  - Imply a constrain on { mZ, mX, gX, mS }

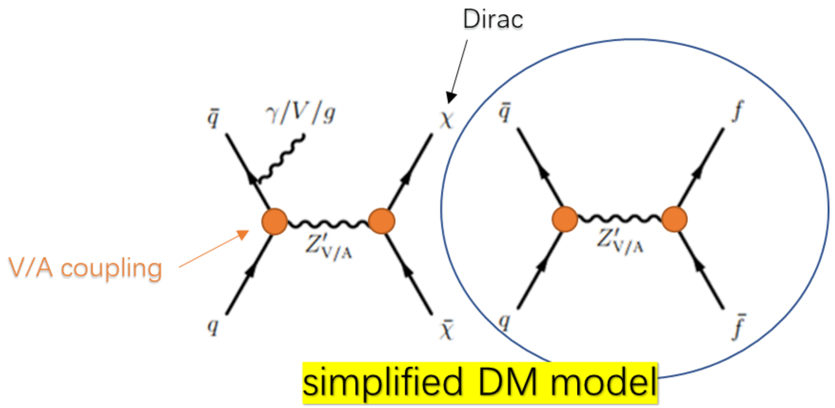


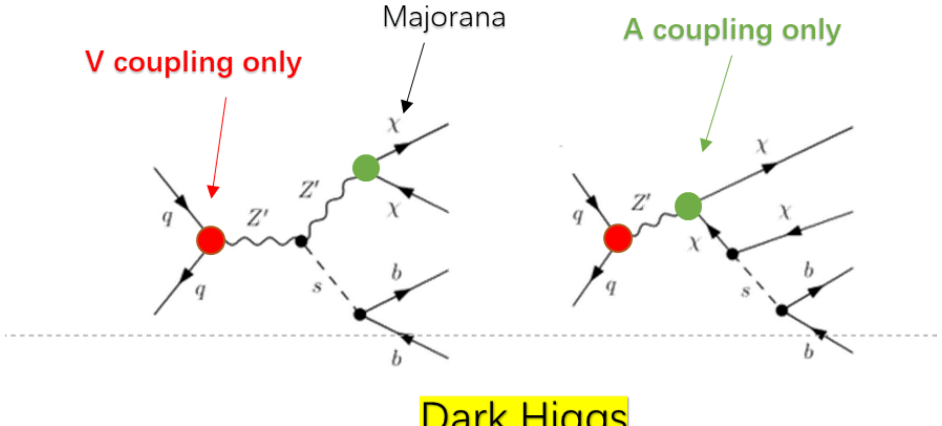
Comparing with other DM model in ATLAS

- In ATLAS EXOT summary plot, only Dirac DM for vector/axia-vector mediator is considered for simplified DM model
- In Dirac DM+mediator model, most region has been excluded in the latest summary plot

➢ "The coupling combination that we consider is not only theoretically more motivated but also less constrained by non-LHC experiments, which is why we prefer it."

➢ If really want to compare with Dirac DM case, the cross-section should times 0.5 as a rough estimation => thus existing search will have lower exclusion power





Uncertainty List

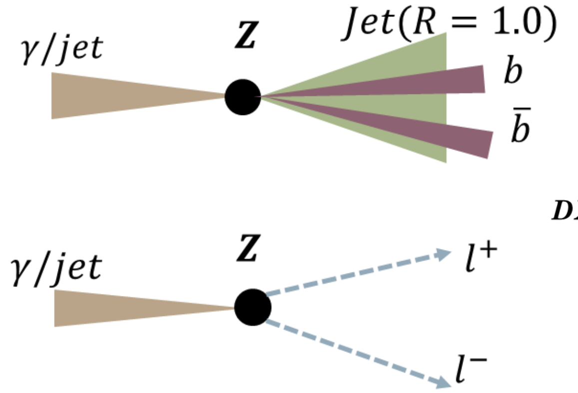
Objects	Systematics
Luminosity	1.7% as priori
Pileup	PRW_DATASF
Small-R(0.4) jet	JES, JER, JVT, fJVT
	DL1r tagging
Small-R(0.2) jet	JES, JER propagated to RC
VR Track jet	DL1r tagging
RC large-R jet	Xbbv3 tagging
	RC-LCTopo matching
ET-miss	trigger efficiency
	track-based soft term
	track-in-jets scale unc.
Lepton	ID/Iso/Trigger of Elec/Muon/Tau

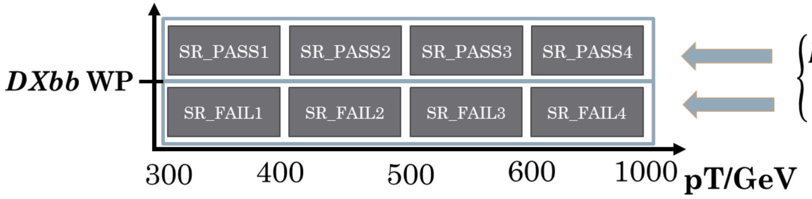
Group	Processes included	uncer. treatment
X → bb like	VHbb, VZ, monoSbb signal	Zbb calibration applied
1b	ttbar, single top, V+bc, V+bl	ttbar calibration applied
Non-res 2b	V+bb	Constrained by Merged Regions

Process	Sources
ttbar	ME, PS, PDF, Scale, ISR, FSR
single top	ME, PS, PDF, Scale, ISR, FSR
V+jets	ME (vs MG), PS(CKKW+QSF), PDF, Scale
Diboson	ME (vs PP), PS, PDF, Scale
VHbb	PS, PDF, Scale
ttH, ttV	(negligible)
monoSbb signal	PDF, Scale (monoHbb approach)

Calibration of DXbb

$$SF = \frac{\varepsilon^{\text{data}}}{\varepsilon^{\text{MC}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{data}}_{\text{total}}}}{\frac{N^{\text{MC}}_{\text{passed}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{MC}}_{\text{passed}}}}{\frac{N^{\text{data}}_{\text{total}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\mu_{\text{post-tag}}}{\mu_{\text{pre-tag}}}$$



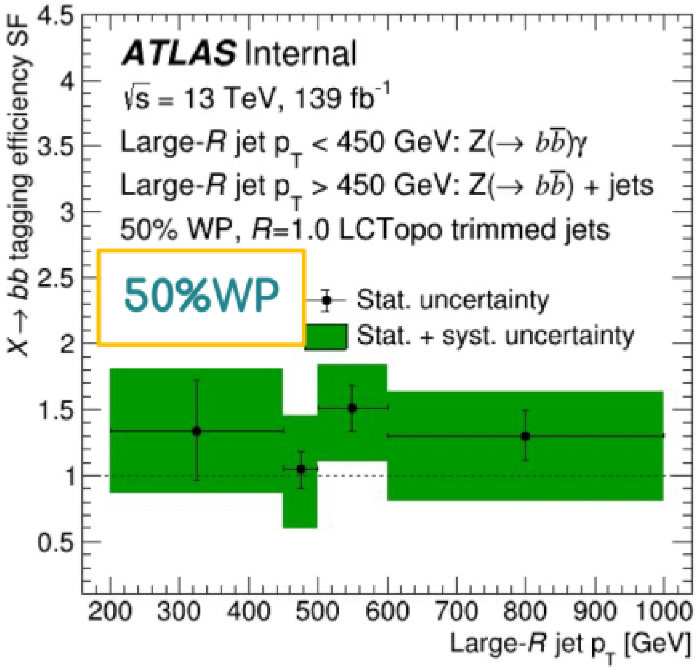


$$SF \equiv \frac{\epsilon^{data}}{\epsilon^{MC}}$$

$$\begin{cases} D_{pass} = NF * SF * S_{pass} + B_{pass} \\ D_{fail} = NF * SF' * S_{fail} + B_{fail} \end{cases}$$

$$SF' \equiv \frac{1 - \epsilon^{MC} * SF}{1 - \epsilon^{MC}}$$

Zbb calib.



Ttbar calib.