Stronger together to search for new heavy resonances in ATLAS

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Resonance search

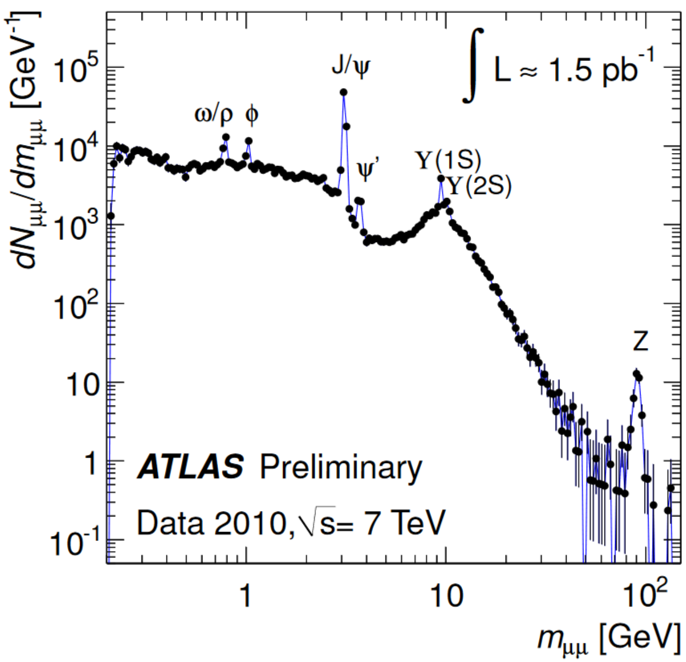
- An unstable particle creates a resonance peak in the mass spectrum.
  - ➢ The branching ratio is proportional to coupling strengths to decaying particles.

$$f(E) = \frac{k}{(E^2 - M^2)^2 + M^2\Gamma^2}$$

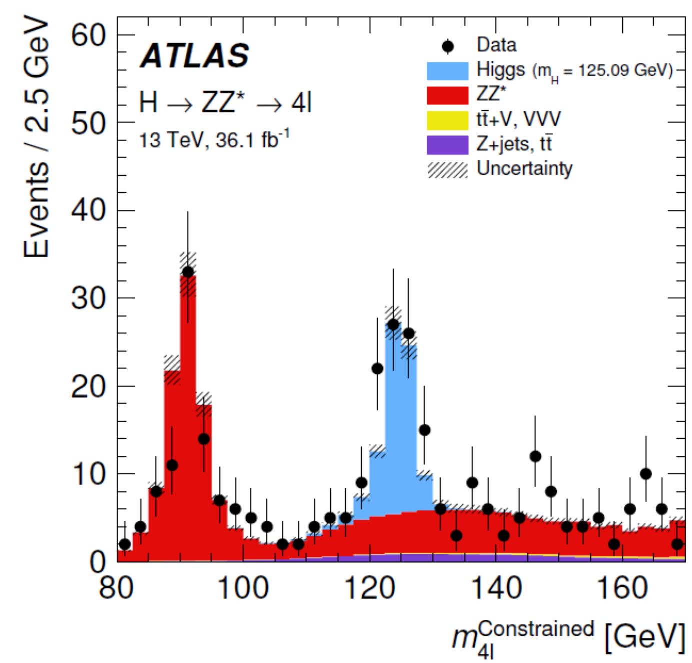
- Search for new resonance is a standard way to find a new particle.
  - ➢ Higgs boson was discovered in 2012.

We aim to discover heavy mass resonance created by a new BSM (Beyond the Standard Model) particle.

Di-muon invariant mass

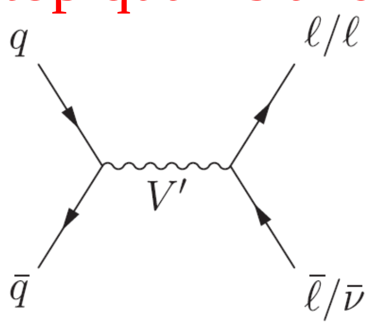


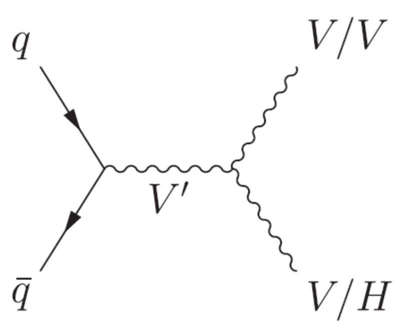
4ℓ invariant mass in H→ZZ

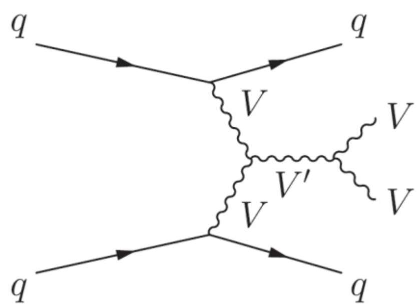


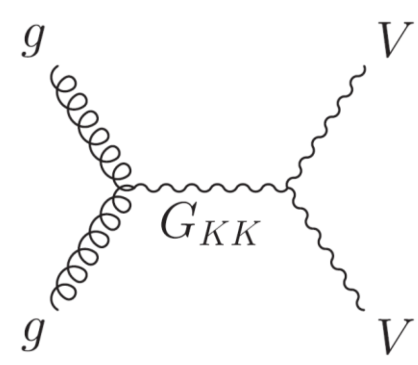
Heavy resonance in BSM

- There are many candidates of BSM that creates heavy resonances for example:
  - Extended gauge sectors in Grand Unified Theories (GUT)
  - Randall-Sundrum model with warped extra dimension
  - Extended Higgs sectors (as two Higgs doublet model)
  - Composite Higgs bosons
- The new heavy resonance search is one of the most important tasks in the ATLAS program.
- Our team is focusing on the search of resonances decaying to leptons, top quarks and di-bosons.





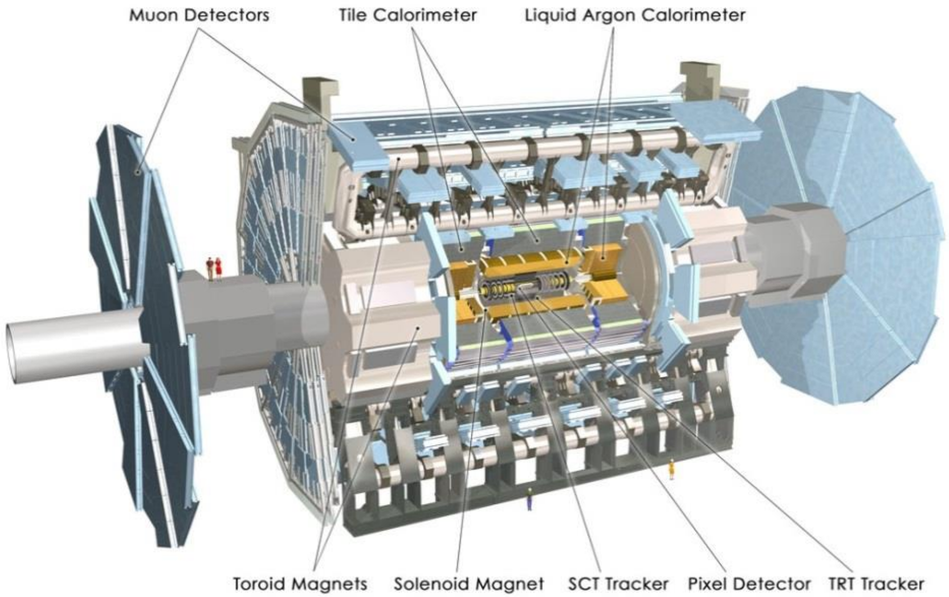




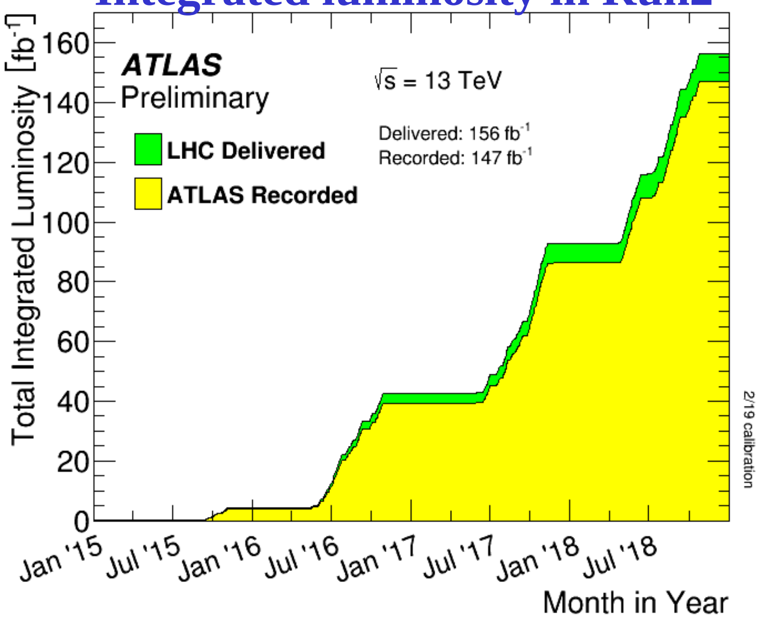
ATLAS Run2 with 13 TeV

- ATLAS is the experiment using LHC to study Higgs couplings and search for BSM particles.
  - ➢ ATLAS discovered Higgs boson in 2012.
- ATLAS took 147 fb^{-1} of data with 13 TeV in 2015-2018 (Run 2).

Our team intensively participated in the searches for new heavy resonance by using large statistics taken in Run2.



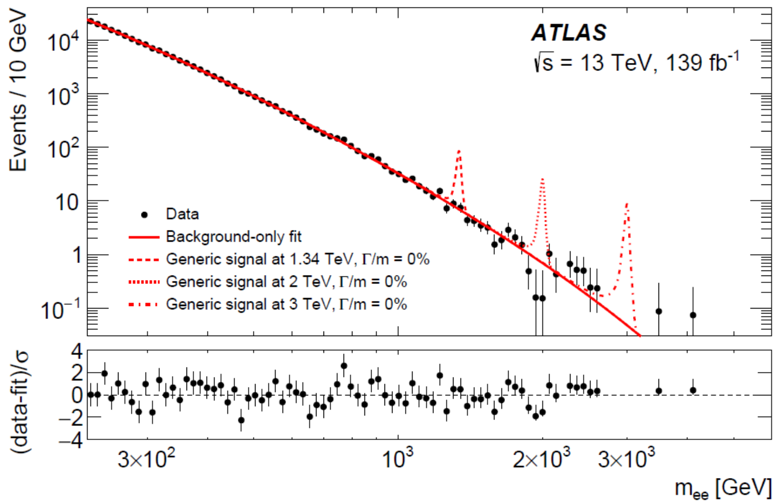
Integrated luminosity in Run2

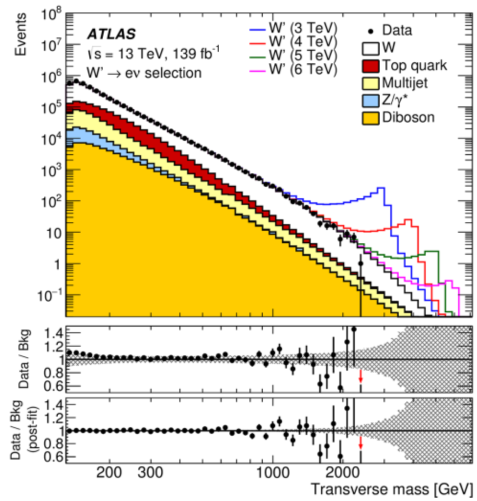


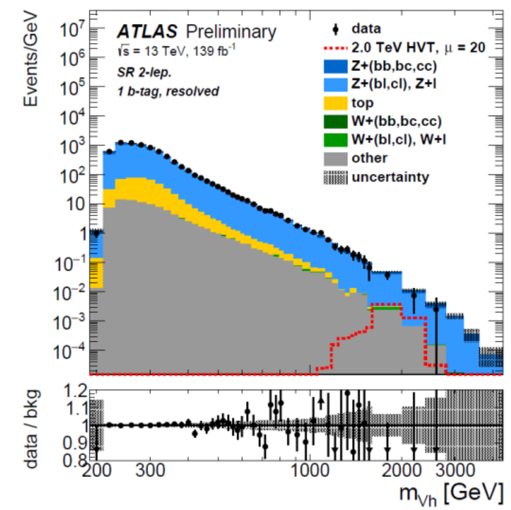
Heavy resonance search in ATLAS

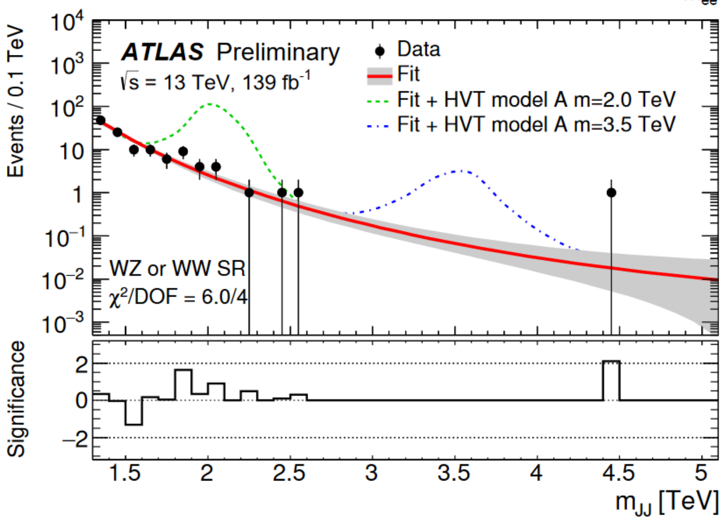
No new resonance peak has been observed in any analysis modes so far.

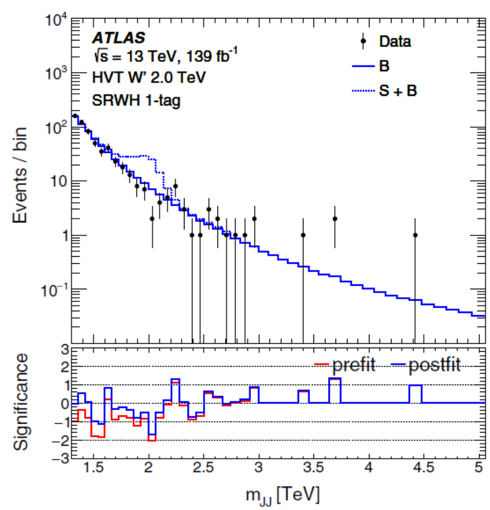
→ The results are consistent with SM.

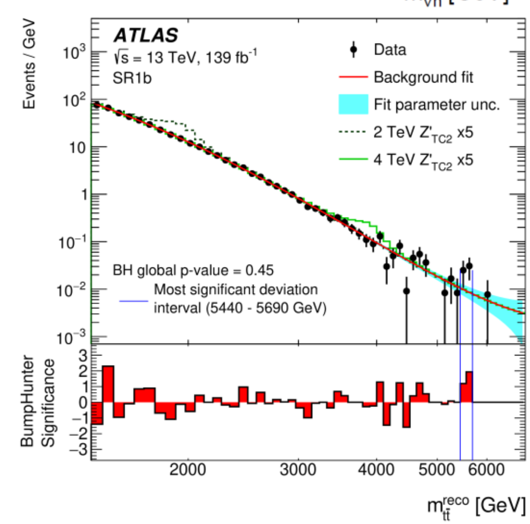






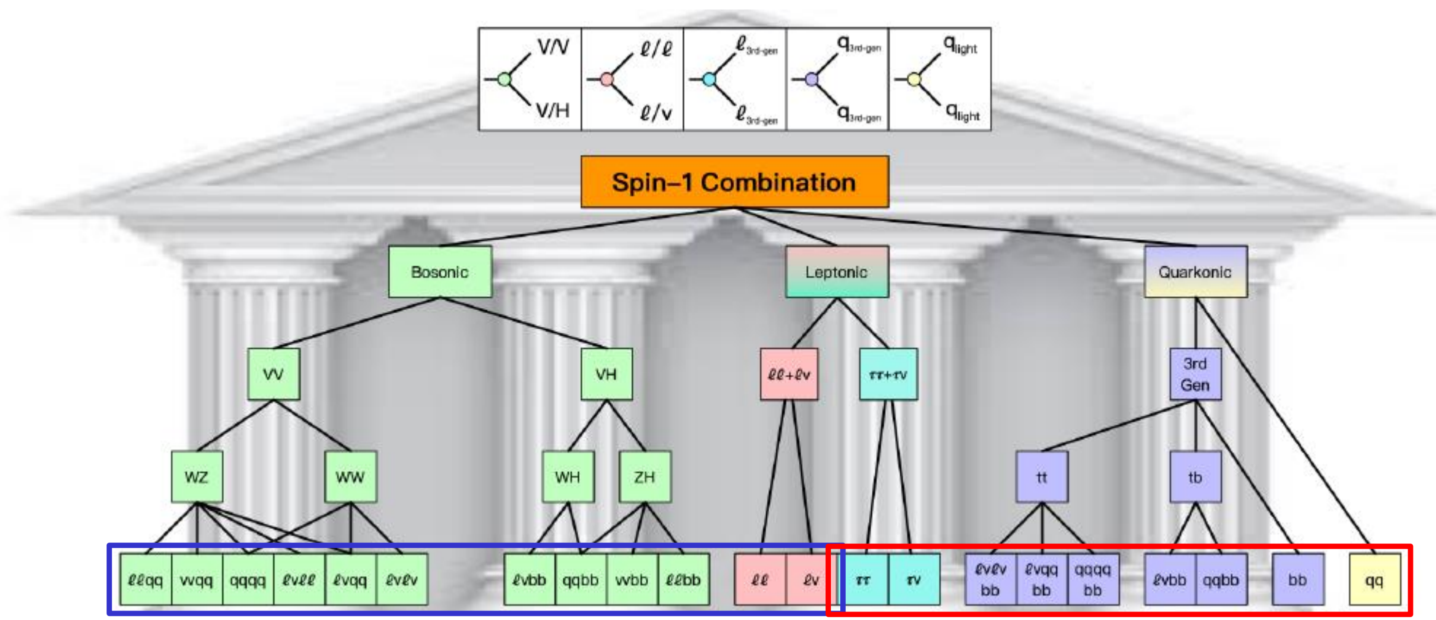






Combination analysis

- The sensitivity to the new heavy particle can be improved, combining the analysis results on different final states.
- Combination analysis was performed with $\ell\nu$, $\ell\ell$, VV and VH final states by using dataset of 36 fb^{-1} taken in 2015 and 2016.
- This project aims to improve the combination analysis by using a full Run2 dataset of 139 fb^{-1}, adding the final states of a top quark and tau.



Previous combination **For new combination**

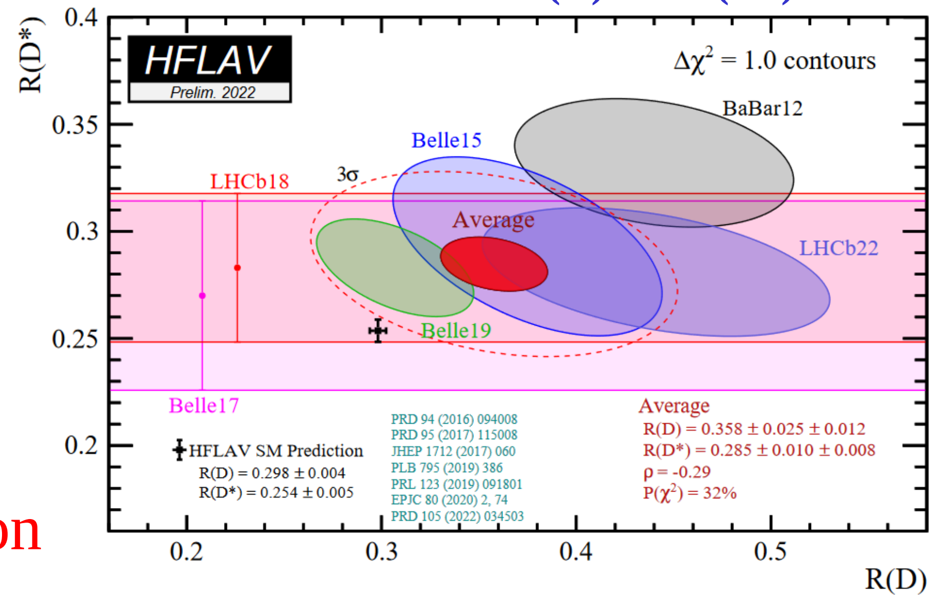
Flavor anomalies in 3rd generation

- Departures from lepton flavor universality were observed in semi-taunic decays of B mesons by Babar, Belle and LHCb [here].

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

Measurement of R(D) v.s. R(D*)



- 3.2σ discrepancy from SM prediction
- Existence of a new heavy boson strongly coupling to the third generation is one of the possibility.

This gives us strong motivation to include the final states with a top and tau into the combination analysis.

Heavy vector triplet model

- Heavy Vector Triplet (HVT) model provides a phenomenological framework with new heavy gauge bosons and their couplings to SM particles (JHEP09 (2014) 060).
  - New heavy gauge bosons: $W'^{\pm}$, Z'
  - Couplings to SM particles: g_q, g_ℓ, g_H

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -\boxed{g_q}\mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - \boxed{g_\ell}\mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - \boxed{g_H}\left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.}\right)$$

- The masses of $W'^{\pm}/Z'$ are assumed to be degenerated in this analysis.
- Several benchmark situations can be considered, based on HVT model.
  - Model-A: Dominated by fermion coupling (g_H=-0.56, g_q = g_ℓ= -0.55)
  - Model-B: strongly coupling to WZ or ZZ (g_H=-2.9, g_q = g_ℓ= 0.14)
  - Model-C: only vector boson fusion process (g_H=1, g_q = g_ℓ= 0)

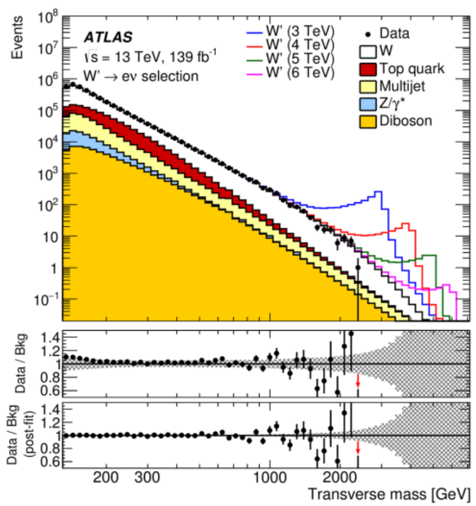
The combination analysis aims to put the limits on masses of new heavy gauge bosons and their couplings (g_H, g_f, g_ℓ) in HVT framework.

Combination methodology (1)

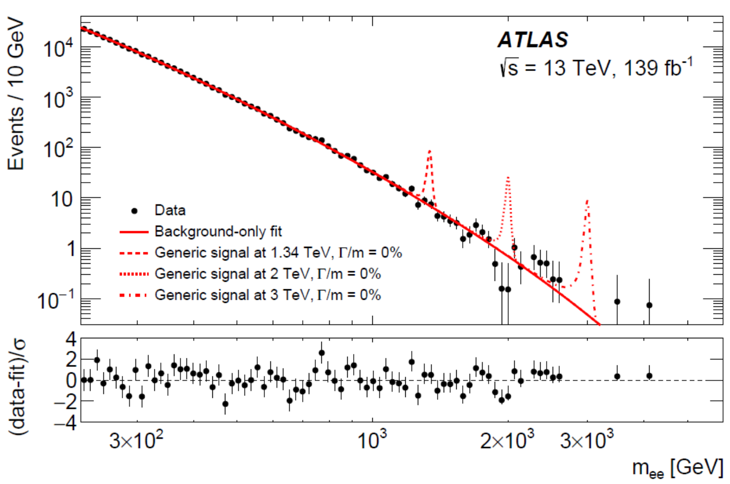
1. Prepare discriminant variables after event selection for each final state.

- For example, transverse mass for W’ and di-lepton mass for Z’
- “Acceptance × Efficiency” is calculated to evaluate the original number of events.

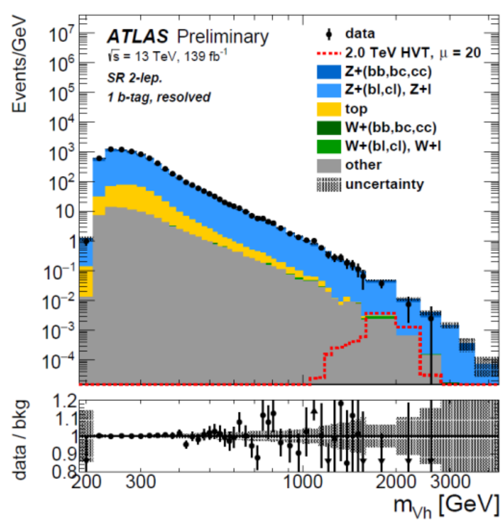
m_T in W’→eν_e



Di-electron mass in Z’→ee



VH invariant mass



Combination methodology (2)

2. Evaluate systematic uncertainties on the signal and background for each final state.

3. Fitting to MC samples of HVT model with the maximum likelihood method.

- 1D fitting for upper limits on (σ x $\mathscr{B}$)

$$\mathcal{T} = -2\ln\frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}}(\hat{\mu}))}$$

- 2D fitting on coupling strengths

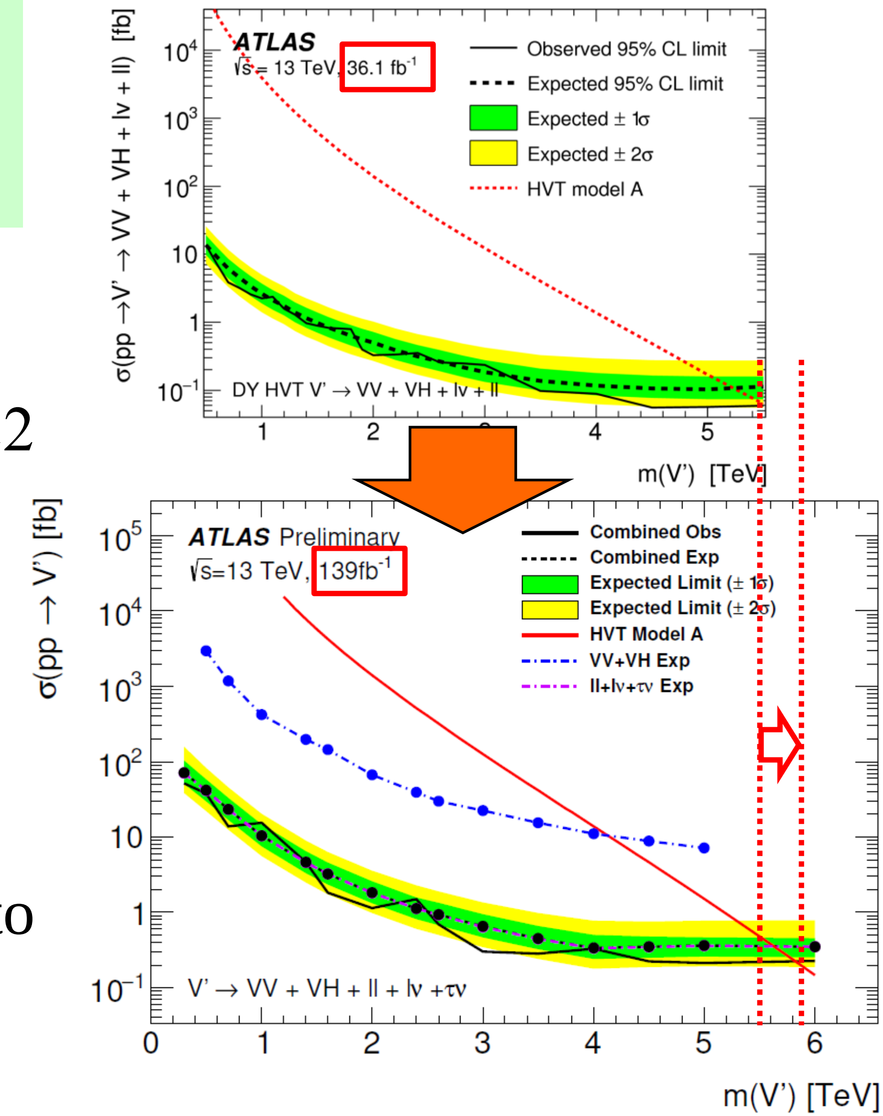
$$\mathcal{T}' = -2\ln\frac{L(\vec{g}, \hat{\hat{\boldsymbol{\theta}}}(\vec{g}))}{L(\hat{\vec{g}}, \hat{\boldsymbol{\theta}}(\hat{\vec{g}}))}$$

$$L = \prod_c \prod_i \mathrm{Pois}(n_{ci}^{\mathrm{obs}} | n_{ci}^{\mathrm{sig}}(\mu, \vec{\theta}) + n_{ci}^{\mathrm{bkg}}(\vec{\theta})) \prod_k f_k(\theta_k)$$

4. Evaluate the upper limits on (σ x $\mathscr{B}$) and coupling strengths in the HVT framework.

Mass limits

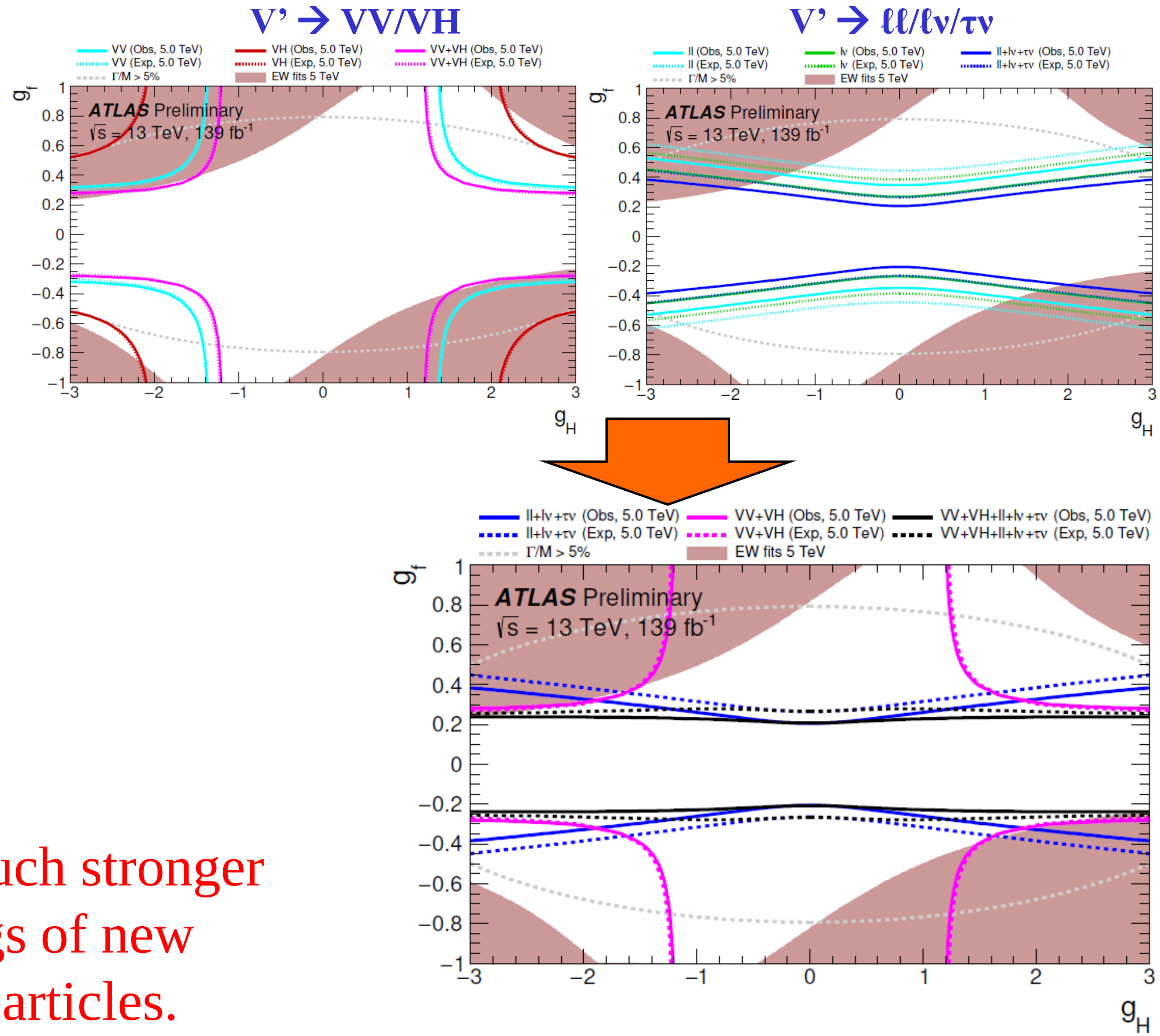
- The partial combination results are obtained in 2019 [ATL-PHYS-PUB-2019-031] with ℓℓ and ℓν, and in 2022 [ATLAS-CONF-2022-028] with ℓℓ, ℓν, VV, VH and τν.
  - ➢ VV(qqqq, ννqq, ℓνqq, ℓℓqq, ℓνℓℓ), VH (qqbb, ννbb, ℓνbb, ℓℓbb)
- Combination analysis improves the mass limit significantly with respect to those with an individual final state.
- The mass limit was extended by 0.3 TeV from the previous analysis with 36 fb^{-1}.



Channel	HVT-A Exclusion Limit		HVT-B Exclusion Limit	
	Observed [TeV]	Expected [TeV]	Observed [TeV]	Expected [TeV]
VV	4.2	4.0	4.3	4.2
VH	3.6	3.6	3.9	3.9
$VV+VH$	4.2	4.2	4.5	4.4
$\ell\ell+\ell\nu+\tau\nu$	5.8	5.6	3.2	2.7
$VV+VH+\ell\ell+\ell\nu+\tau\nu$	5.8	5.6	4.5	4.4

Limits on couplings (g_H v.s. g_f)

[ATLAS-CONF-2022-028]

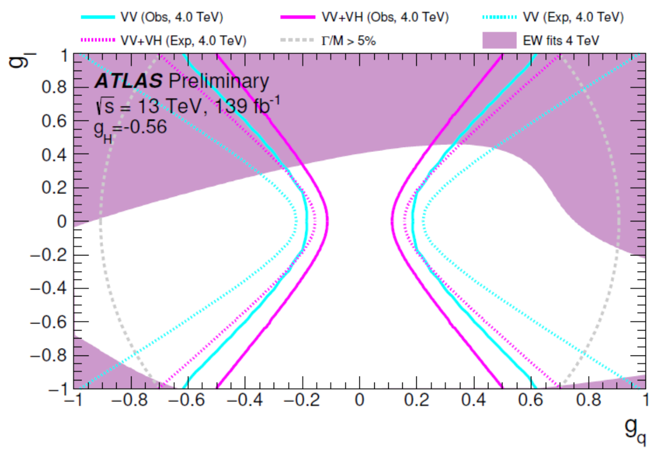


Combination gives much stronger constraint on couplings of new heavy bosons to SM particles.

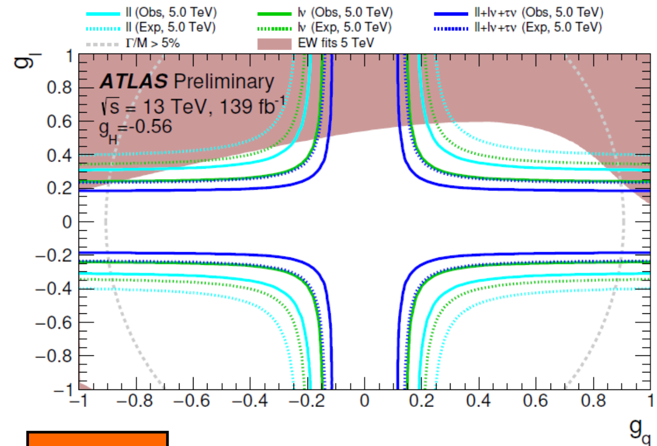
Limits on couplings (g_q v.s. g_f)

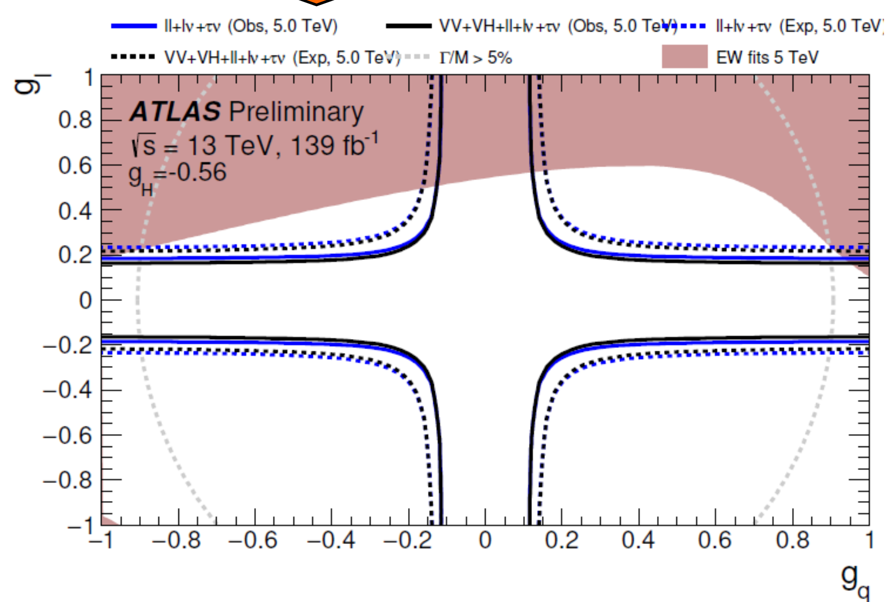
[ATLAS-CONF-2022-028]

V' → VV/VH



V' → ℓℓ/ℓν/τν



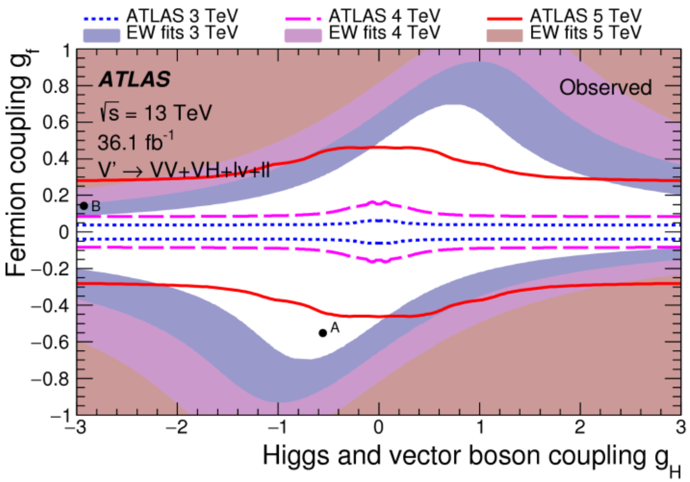


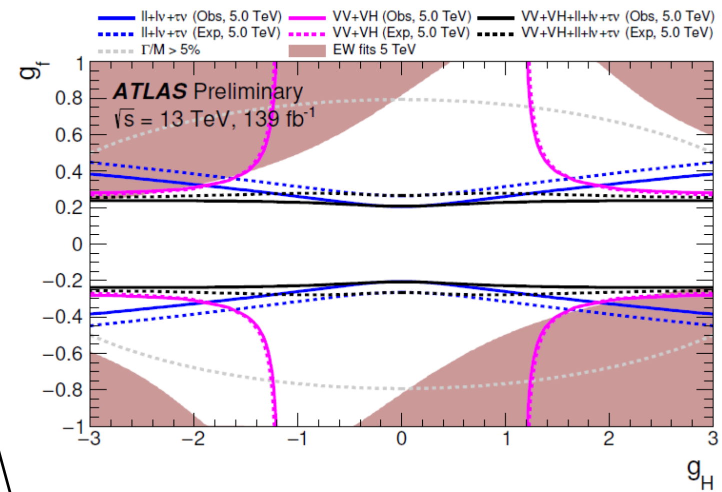
Combination gives much stronger constraint on couplings of new heavy bosons to SM particles.

Limits on couplings (36 v.s. 139 fb^{-1})

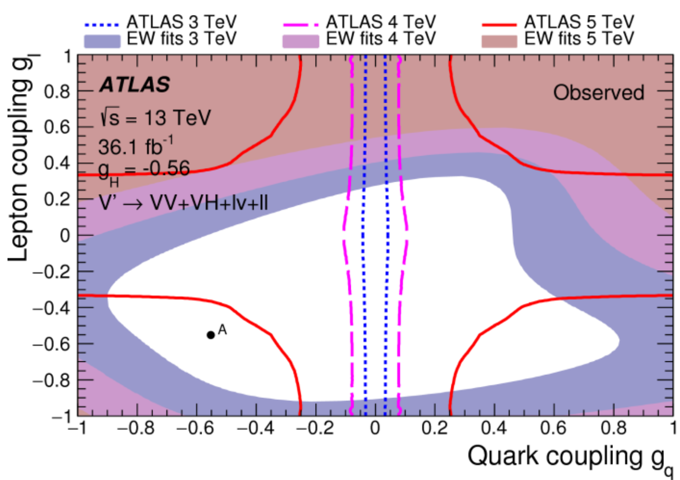
Stronger constraints on the couplings are obtained, compared to the previous combination with 36 fb^{-1}.

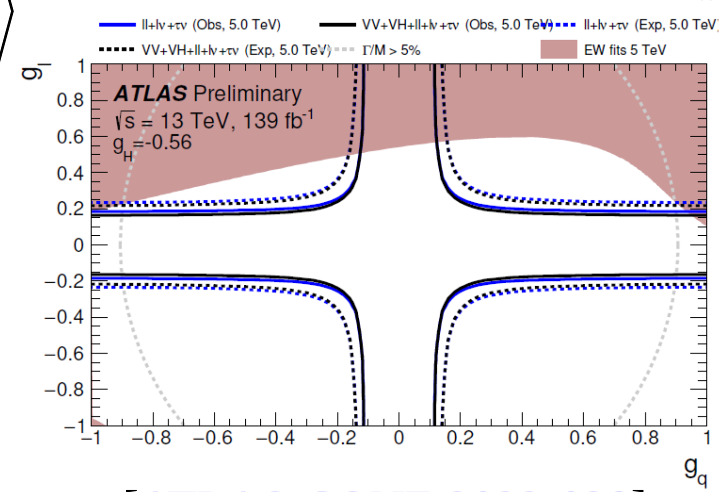
(g_H v.s. g_f)





(g_q v.s. g_f)



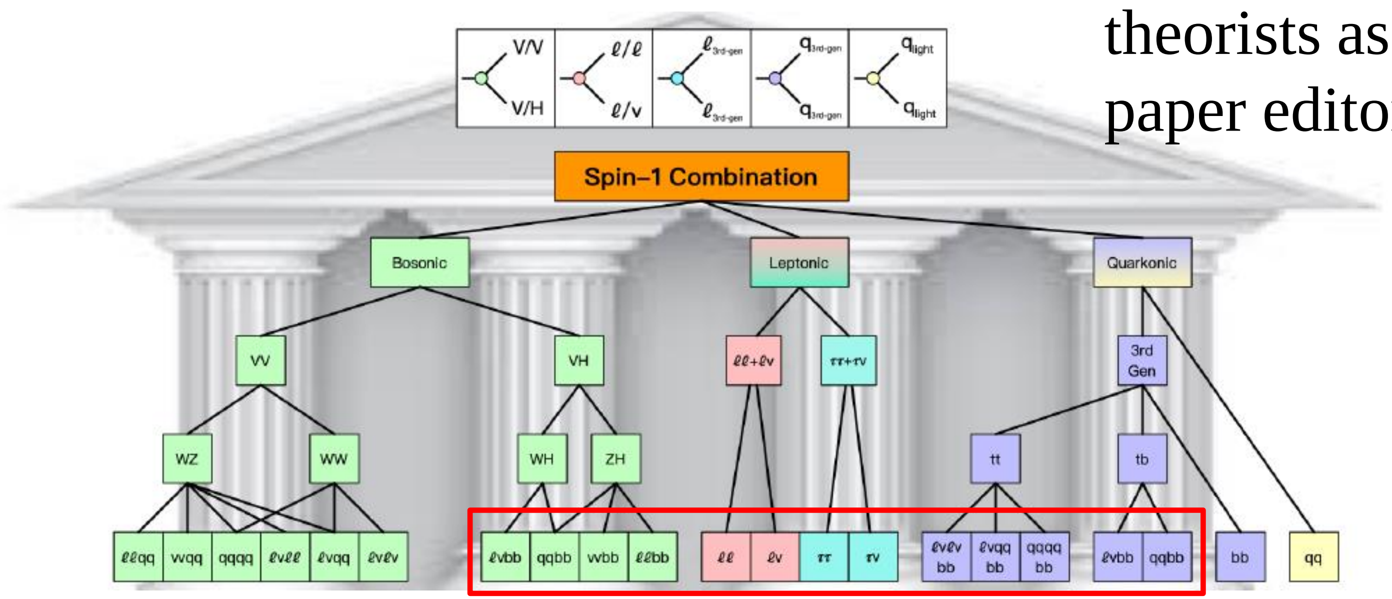


[Phys. Rev. D98, 052008 (2018)]

[ATLAS-CONF-2022-028]

Team of this project

Final states	Institute	Person
ℓℓ	LAPP	T. Berger-Hryn’ova
ℓν	KEK	Y. Takubo, K. Nagano
VH	LPNHE	R. Camacho Toro
tt, tb	LPC	S. Calvet, J. Donini
	Tokyo	K. Terashi



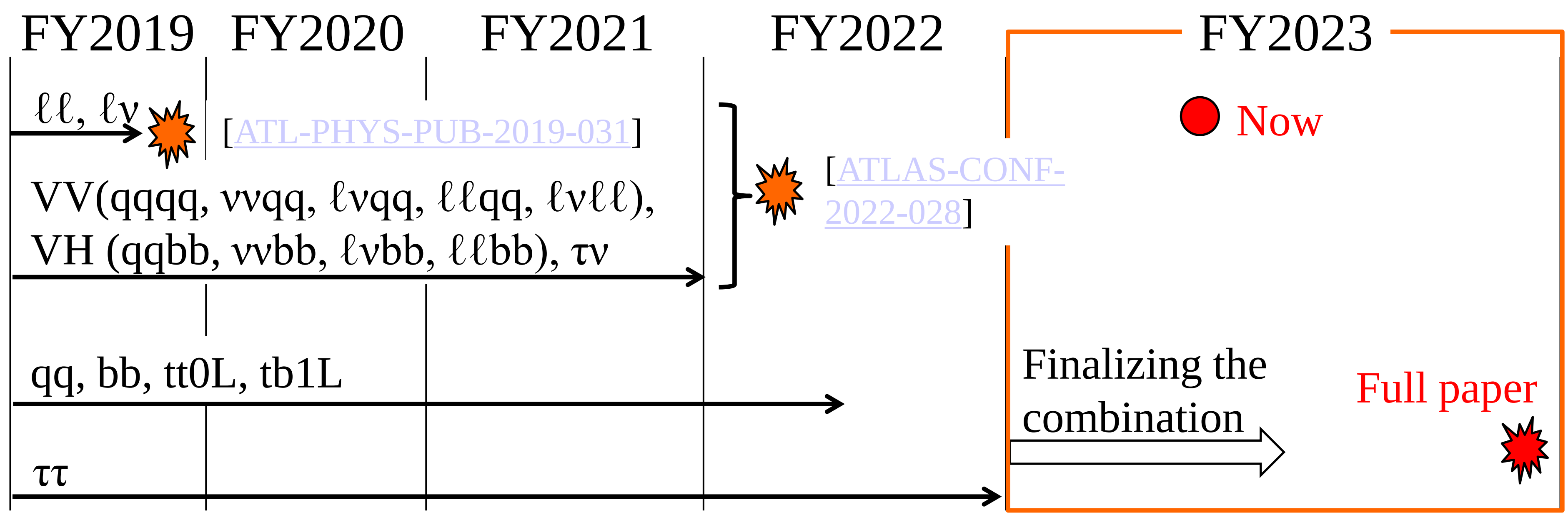
Covered by our team

- This project consists of experts in the analyses of the different final states.
- More than a half of the final states are covered by our team.
- Koji has been the analysis contact in 2019-2021 and Tetiana is a contact with theorists as well as one of the paper editors for this analysis.

Schedule of our project

- Our project started in 2019 and the original plan was to finalize the analyses until 2022.
- But, our project was significantly delayed by covid-19 due to no possibility to work at their institutes and hold in-person meetings.

→ We request to extend our project until the end of 2023 fiscal year to finalize our analyses and publish the results.



Research exchange

- Thanks to support by TYL-FJPPL (3k Euro/260k Yen), we could perform research exchange in 2022 fiscal year.
  - Tanya: KEK/Tokyo U. (Nov. 27 to Dec. 2)
  - Yosuke: LAPP/CERN (Mar. 8-20)
- We worked for our analysis together in person, gave seminar, and held informal meetings.

Visit Belle-II detector

Discussion with Japanese BQ

Discussion in snow mountain at Annecy

Summary & Conclusion

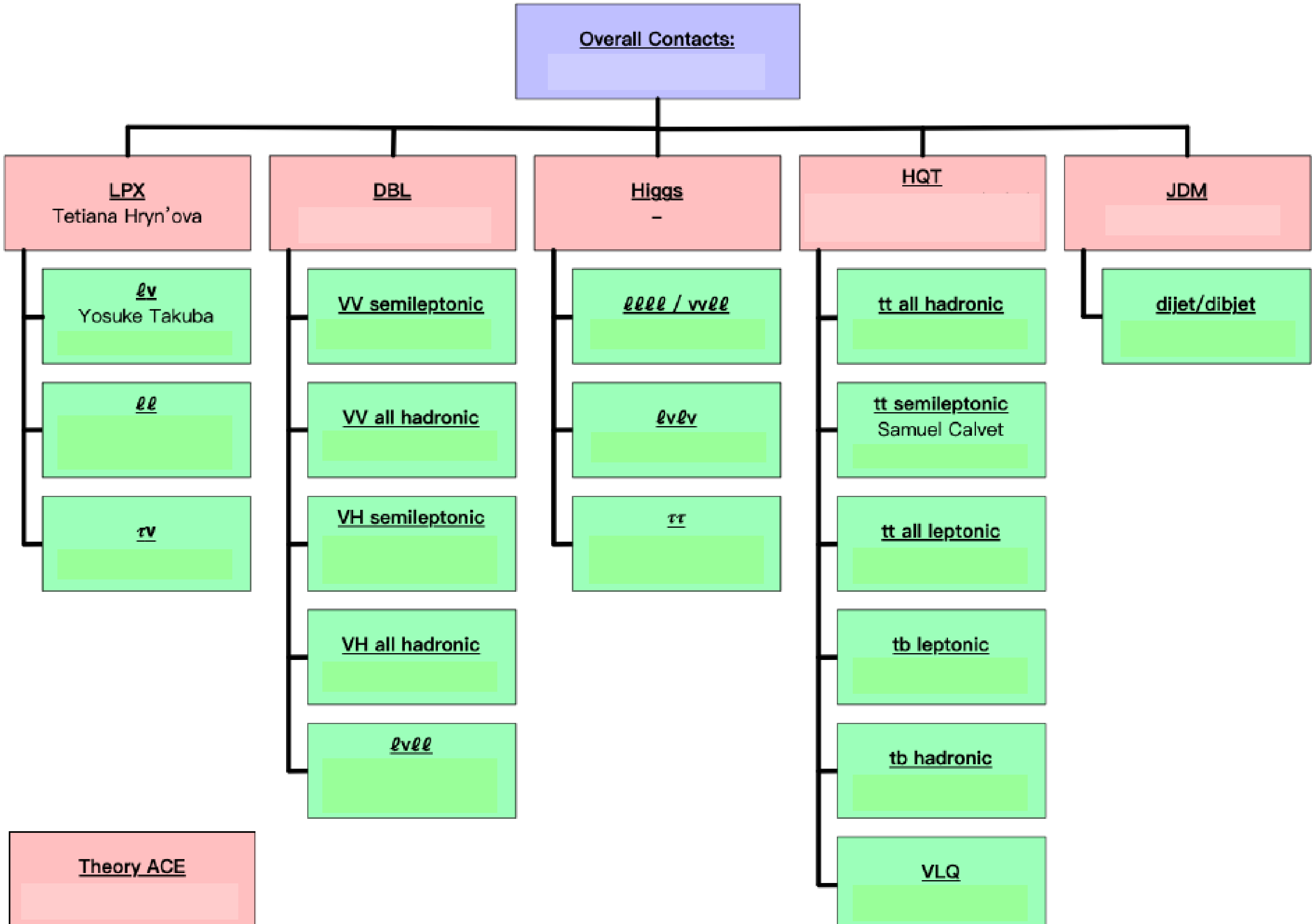
- The heavy resonance search is one of the most important physics program to explore new BSM particles at ATLAS.
- The combination analysis can give much stronger constraints on the masses and couplings of new particles, compared to separated analyses.
- Our project is to perform the combination analysis based on HVT framework by using a full ATLAS Run2 dataset (139 fb^{-1}) and improve the previous results with dataset of 36 fb^{-1}.
  - More final states, especially those with a top quark and tau.
- Our team unites people who take a leading role in each analysis group, and the collaboration will maximize our contribution to the combination analysis.
- The partial combination results were published in 2019 [ATL-PHYS-PUB-2019-031] and 2022 [ATLAS-CONF-2022-028], and the analysis will be finalized in 2023.

Backup

Analysis channels for 139 fb^{-1}

Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.	Ref
$WW/WZ \to qqqq$	0	Veto	≥2J	-	m_{VV}	[10]
$WZ \to \nu\nu qq$	0	Yes	≥1J	0	m_{VV}	[11]
$WZ \to \ell\nu qq$	1e, 1μ	Yes	≥2j, ≥1J	0, 1, 2	m_{VV}	[11]
$WZ \to \ell\ell qq$	2e, 2μ	-	≥2j, ≥1J	0	m_{VV}	[11]
$WZ \to \ell\nu\ell\ell$	3 $\subset$ (e, μ)	Yes	-	0	m_{VV}	[12]
$WH \to qqbb$	0	Veto	≥2J	1, 2	m_{VH}	[13]
$ZH \to \nu\nu bb$	0	Yes	≥2j, ≥1J	1, 2	m_{VH}	[15]
$WH \to \ell\nu bb$	1e, 1μ	Yes	≥2j, ≥1J	1, 2	m_{VH}	[14]
$ZH \to \ell\ell bb$	2e, 2μ	Veto	≥2j, ≥1J	1, 2	m_{VH}	[15]
$\ell\nu$	1e, 1μ	Yes	-	-	m_T	[17]
$\tau\nu$	1τ	Yes	-	-	m_T	[18]
$\ell\ell$	≥2e, ≥2μ	-	-	-	$m_{\ell\ell}$	[16]

Heavy resonance combination group



Systematic uncertainties for 36 fb^{-1} (1)

TABLE IV. Lepton systematic uncertainties. The abbreviations S and B stand for signal and background, respectively, and "Negl." denotes uncertainties that are negligible. Each uncertainty is considered as correlated between the channels listed.

Source	$\ell\nu qq$	$\ell\ell qq$	$\ell\ell\nu\nu$	$\ell\nu\ell\nu$	$\ell\nu\ell\ell$	$\ell\ell\ell\ell$	$\ell\nu bb$	$\ell\ell bb$	$\ell\nu$	$\ell\ell$
Electron trigger	S + B	S + B	S + B	S + B	Negl.	S + B	S + B	S + B	Negl.	Negl.
Electron reconstruction	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	Negl.
Electron identification	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	S + B
Electron isolation	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	S + B
Electron energy scale	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Electron energy resolution	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	S + B
Muon trigger	S + B	S + B	S + B	S + B	Negl.	S + B	S + B	S + B	S + B	Negl.
Muon reconstruction	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Muon isolation	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	S + B
Muon momentum scale	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	Negl.	Negl.
Muon momentum resolution	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B

TABLE V. $E_{\mathrm{T}}^{\mathrm{miss}}$ systematic uncertainties. The abbreviations S and B stand for signal and background, respectively, while the symbol $\cdots$ denotes uncertainties that are not applicable. Each uncertainty is considered as correlated between the channels listed.

Source	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell\nu\nu$	$\ell\nu\ell\nu$	$\ell\nu\ell\ell$	$\nu\nu bb$	$\ell\nu bb$	$\ell\nu$
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	S + B	S + B	S + B	$\cdots$	$\cdots$	S + B	S + B	$\cdots$
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term scale	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B

Systematic uncertainties for 36 fb^{-1} (2)

TABLE VI. Small-R jet systematic uncertainties. The abbreviations S and B stand for signal and background, respectively, and "Negl." denotes uncertainties that are negligible. Each uncertainty is considered as correlated between the channels listed.

Source	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$	$\ell\ell\nu\nu$	$\ell\nu\ell\nu$	$\ell\nu\ell\ell$	$qqbb$	$\nu\nu bb$	$\ell\nu bb$	$\ell\nu$
Small-R jet energy scale	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Small-R jet energy resolution	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Small-R jet flavor	S + B	S + B	S + B	S + B	S + B	Negl.	S + B	S + B	S + B	S + B
Small-R jet pileup	S + B	S + B	S + B	S + B	S + B	Negl.	S + B	S + B	S + B	S + B
Small-R jet punchthrough	S + B	S + B	S + B	S + B	S + B	Negl.	S + B	S + B	S + B	S + B
Small-R jet JVT	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B	S + B

TABLE VII. Large-R jet systematic uncertainties. The abbreviations S and B stand for signal and background, respectively. Each uncertainty is considered as correlated between the channels listed.

Source	$qqqq$	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$	$qqbb$	$\nu\nu bb$	$\ell\nu bb$	$\ell\ell bb$
Large-R jet D_2 scale	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Large-R jet D_2 resolution	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Large-R jet scale	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Large-R jet resolution	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Large-R jet mass scale	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B
Large-R jet mass resolution	S	S + B	S + B	S + B	S + B	S + B	S + B	S + B

Systematic uncertainties for 36 fb^{-1} (3)

TABLE VIII. Flavor-tagging systematic uncertainties. The abbreviations S and B stand for signal and background, respectively. Each uncertainty is considered as correlated between the channels listed.

Source	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$	$\ell\ell\nu\nu$	$\ell\nu\ell\nu$	$\ell\nu\ell\ell$	$qqbb$	$\nu\nu bb$	$\ell\nu bb$	$\ell\ell bb$
b tagging	S + B	S + B	S + B	B	B	B	S + B	S + B	S + B	S + B
c tagging	S + B	S + B	S + B	B	B	B	S + B	S + B	S + B	S + B
Light-q tagging	S + B	S + B	S + B	B	B	B	S + B	S + B	S + B	S + B
Tagging extrapolation	S + B	S + B	S + B	B	B	B	S + B	S + B	S + B	S + B

Systematic uncertainties for 36 fb^{-1} (4)

TABLE IX. Theoretical systematic uncertainties. The abbreviation B stands for background, while the symbol $\cdots$ denotes uncertainties that are not applicable, "Negl." denotes uncertainties that are negligible, and "Corr" marks whether the uncertainty is correlated between the channels listed. The abbreviation F means that this parameter was left to float in the background control region for that channel. The systematic uncertainties in the background modeling for the fully hadronic analysis $qqqq$ are embedded in the fit function used to model the background.

Source	Corr	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$	$\ell\ell\nu\nu$	$\ell\nu\ell\nu$	$\ell\nu\ell\ell$	$qqbb$	$\nu\nu bb$	$\ell\nu bb$	$\ell\ell bb$	$\ell\nu$	$\ell\ell$
DY PDF variation	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B
DY PDF choice	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B
DY PDF scale	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	Negl.	B
DY α_S	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B
DY EW corrections	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B
DY photon induced	Yes	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B
Top cross section	No	B	F	F	B	B	$\cdots$	B	B	B	B	B	Negl.
Top extrapolation	No	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	$\cdots$
Top modeling	No	B	B	B	B	B	$\cdots$	$\cdots$	B	B	B	Negl.	Negl.
Diboson cross section	No	B	B	B	B	B	$\cdots$	B	B	B	B	Negl.	Negl.
Diboson extrapolation	No	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	$\cdots$
Multijet cross section	No	$\cdots$	B	$\cdots$	$\cdots$	$\cdots$	B	B	$\cdots$	B	$\cdots$	$\cdots$	$\cdots$
Multijet modeling	No	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	$\cdots$	B	$\cdots$	B	B
$Z+$jets cross section	No	F	B	F	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B	B	$\cdots$	$\cdots$
$Z+$jets modeling	No	B	B	B	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B	B	$\cdots$	$\cdots$
$W+$jets cross section	No	B	F	B	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B	B	$\cdots$	$\cdots$
$W+$jets modeling	No	B	B	B	$\cdots$	$\cdots$	$\cdots$	$\cdots$	B	B	B	$\cdots$	$\cdots$