Stronger together to search for new heavy resonances in ATLAS

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Resonance search

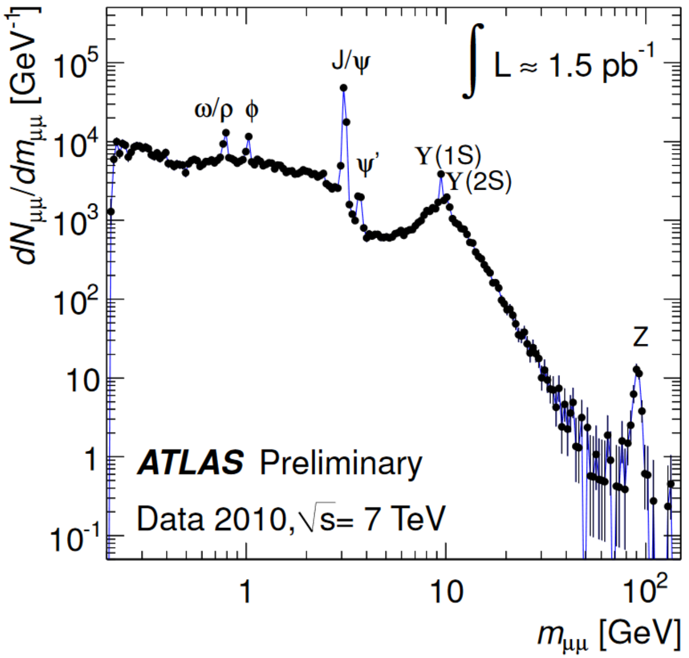
- An unstable particle creates a resonance peak in the mass spectrum.
  - The branching ratio is proportional to coupling strengths to decaying particles.

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

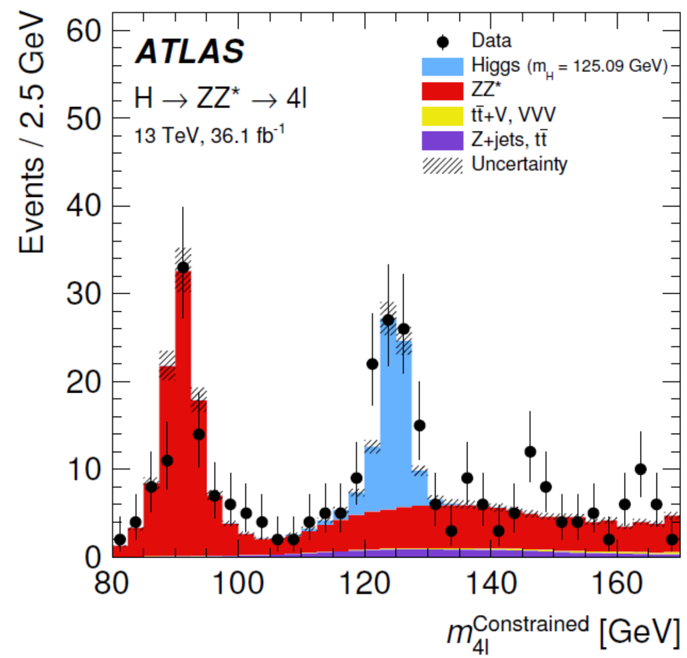
- Search for new resonance is standard way to find a new particle.
  - Higgs boson was discovered in 2012.

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

Di-muon invariant mass

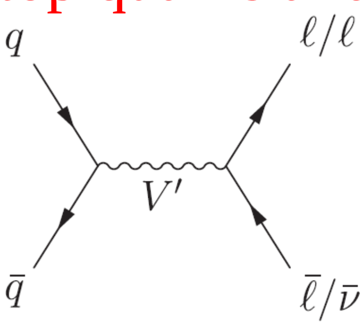


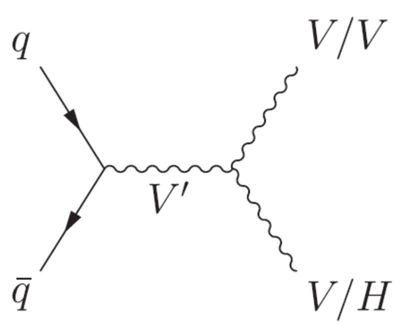
4ℓ invariant mass in H→ZZ

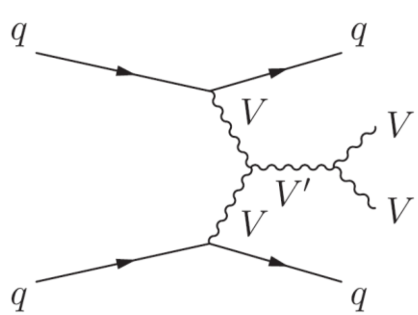


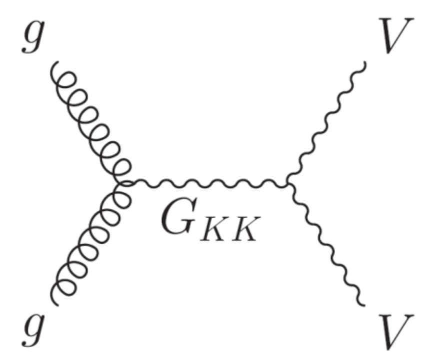
Heavy resonance in BSM

- 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.







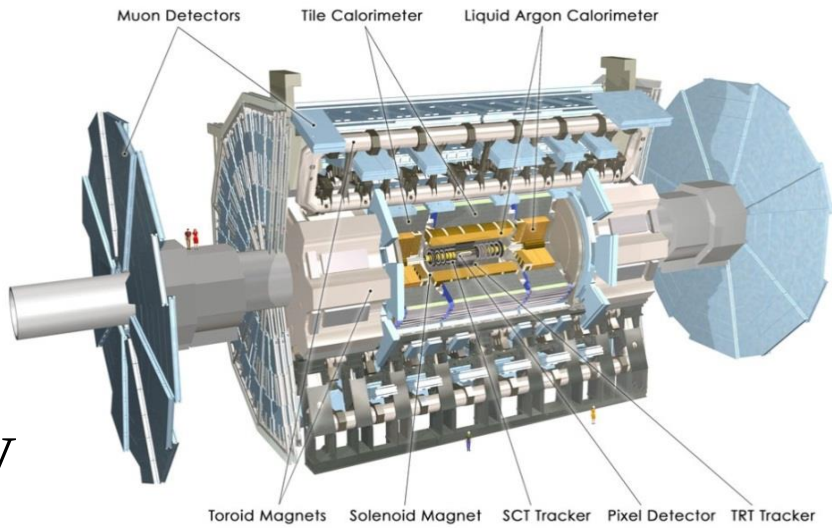


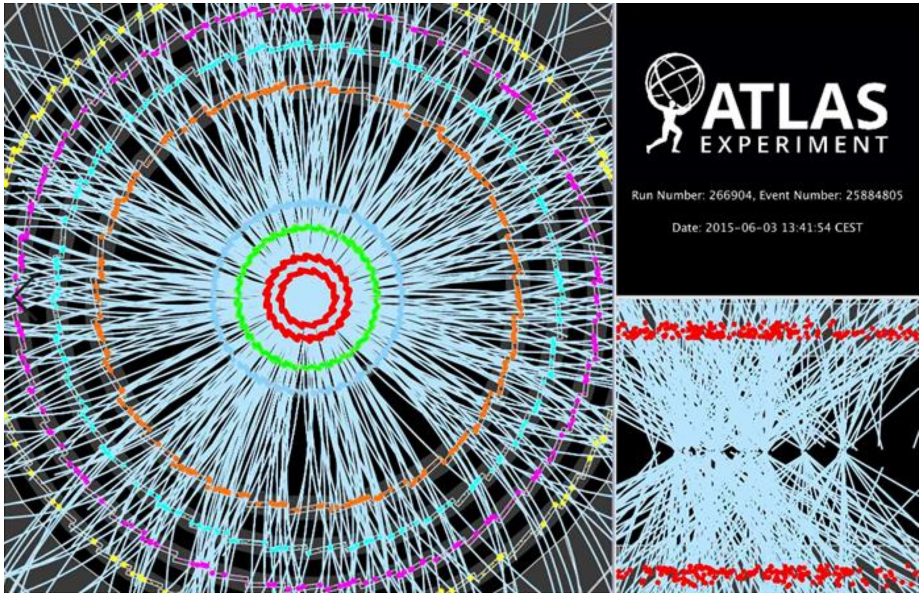
ATLAS Run2 with 13 TeV (1)

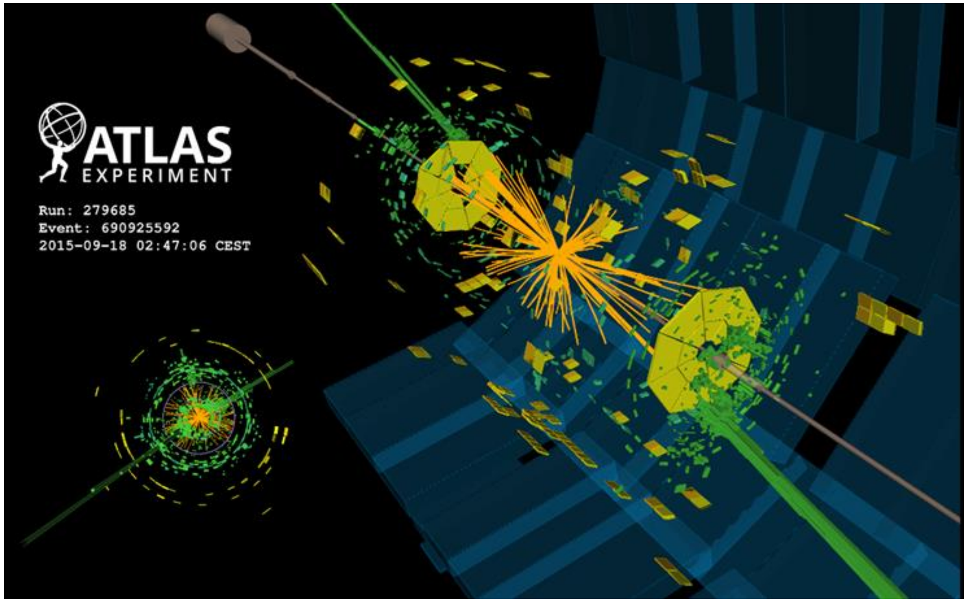
- The pp LHC colliding energy was increased from 8 TeV to 13 TeV after Long-Shutdown 1 (2013-14).

  → **Much better sensitivity to new heavy particles!**

- ATLAS started data-taking with 13 TeV colliding energy in 2015 (Run2).





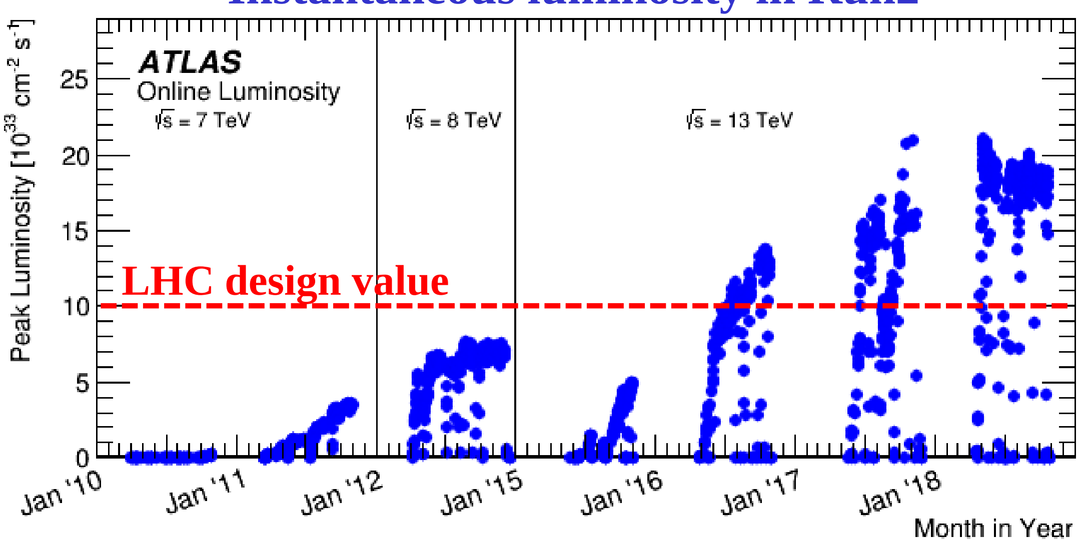


ATLAS Run2 with 13 TeV (2)

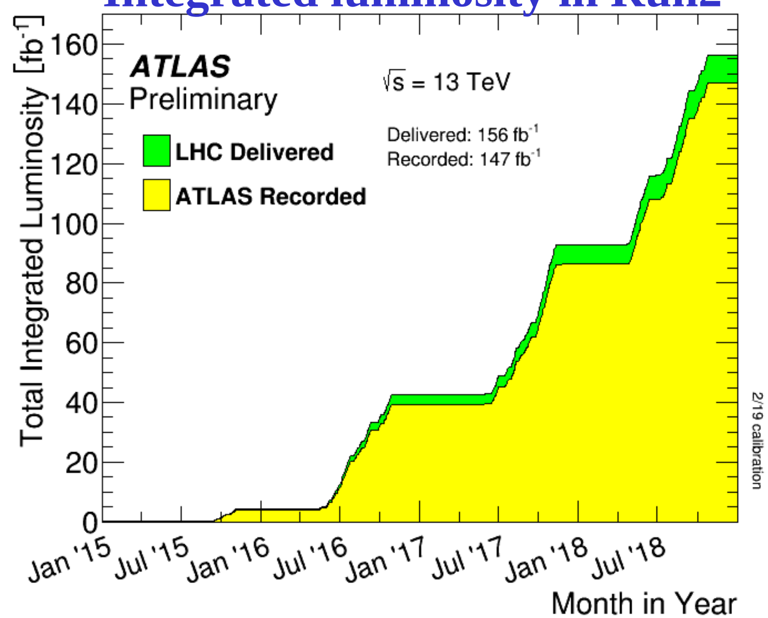
- ATLAS finished Run2 data-taking on December 2018.
- The instantaneous luminosity reached 2 times larger than LHC design value in Run2 (LHC design value: 1.0 x 10^{34} $cm^{-2}s^{-1}$)
- ATLAS took data of 147 fb^{-1} with 13 TeV.

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

Instantaneous luminosity in Run2



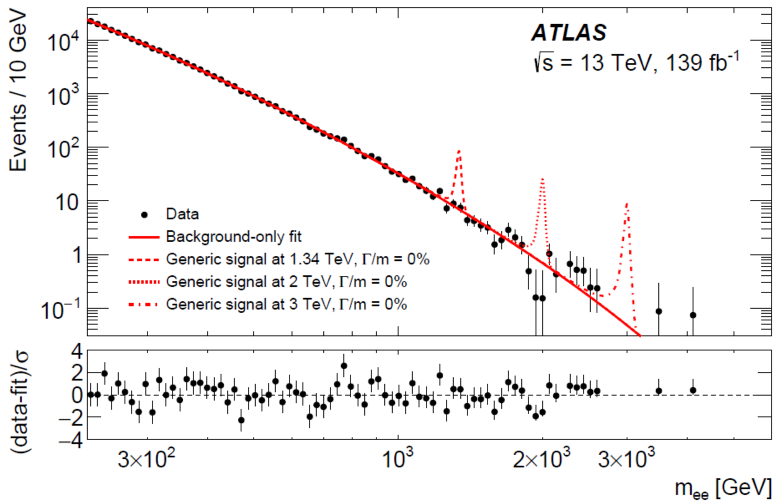
Integrated luminosity in Run2

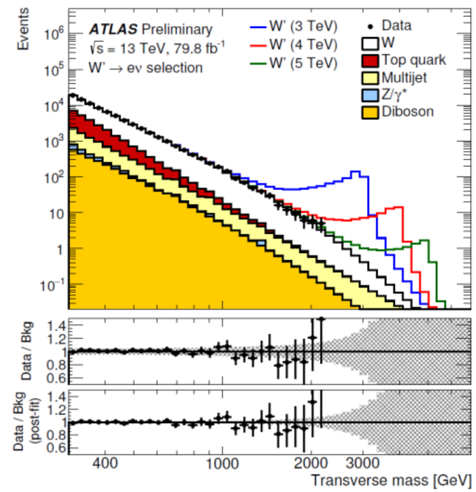


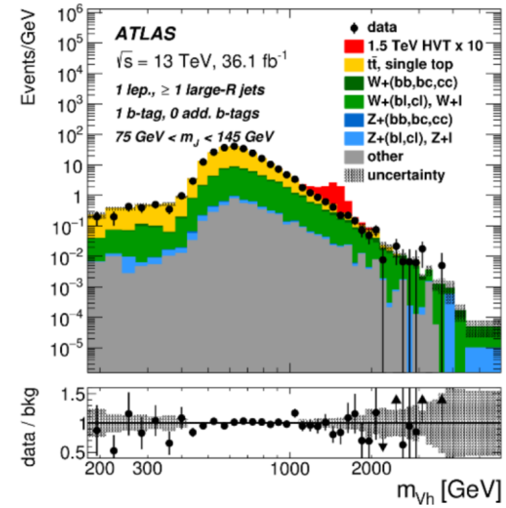
Heavy resonance search in ATLAS

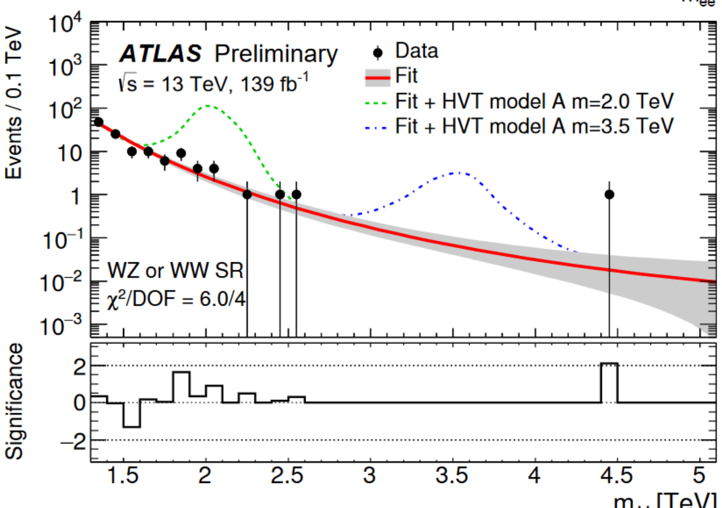
No new resonance peak has been observed in any analysis modes so far.

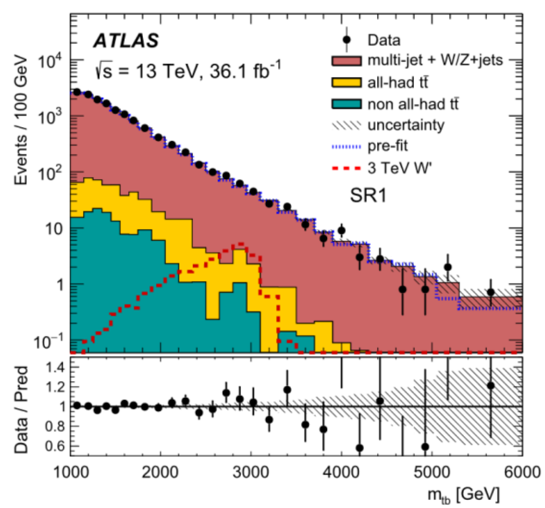
→ The results are consistent with SM.

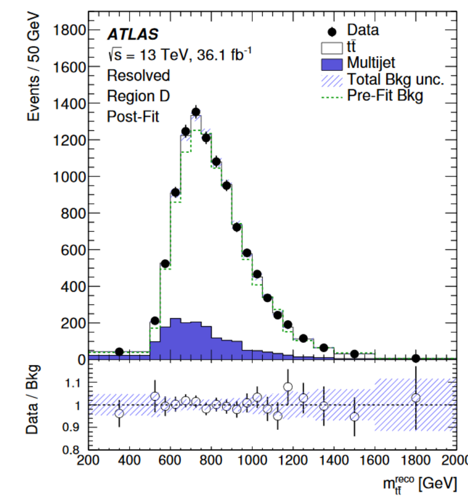






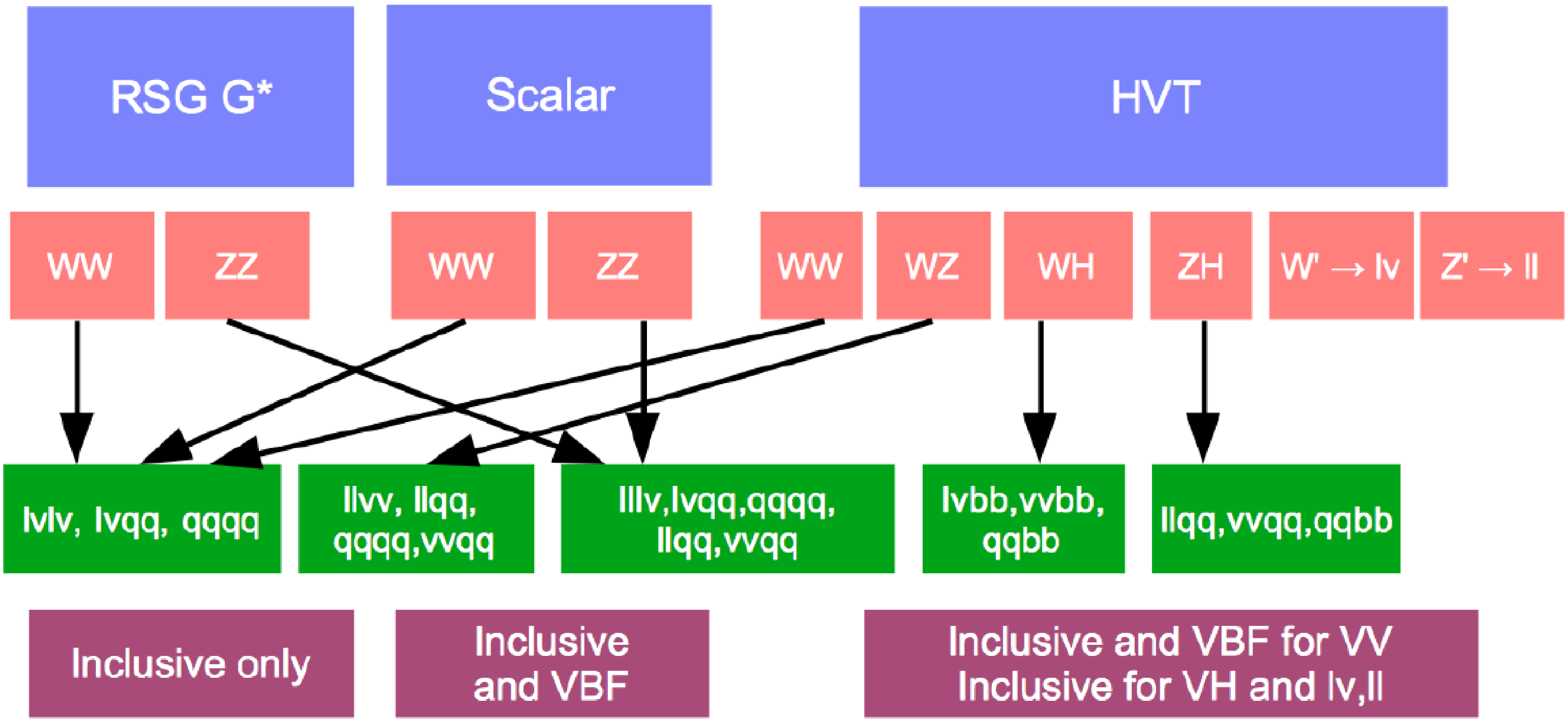






Previous combination study

- The new heavy particle can decay into several final states.
- The analysis results of each final state were combined by using dataset of 36 fb^{-1} taken in 2015 and 2016.



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

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

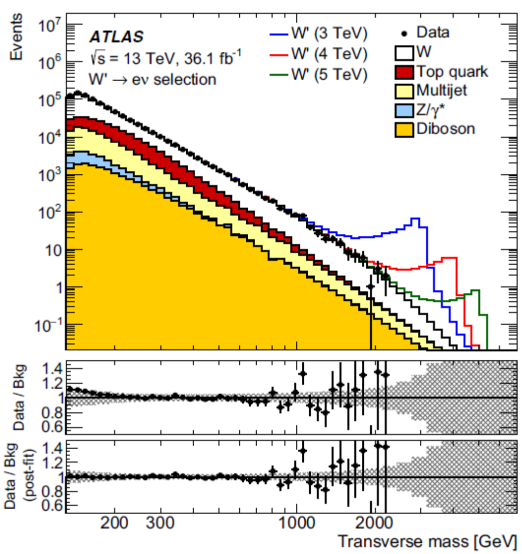
- The masses of $W'^{\pm}/Z'$ are assumed to be degenerated in this analysis.
- Several benchmark situations can be considered, based on HVT model.
  - Model-A: Dominated by fermion coupling (g_H=-0.56, g_q = g_ℓ= -0.55)
  - Model-B: strongly coupling to WZ or ZZ (g_H=-2.9, g_q = g_ℓ= 0.14)
  - Model-C: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

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

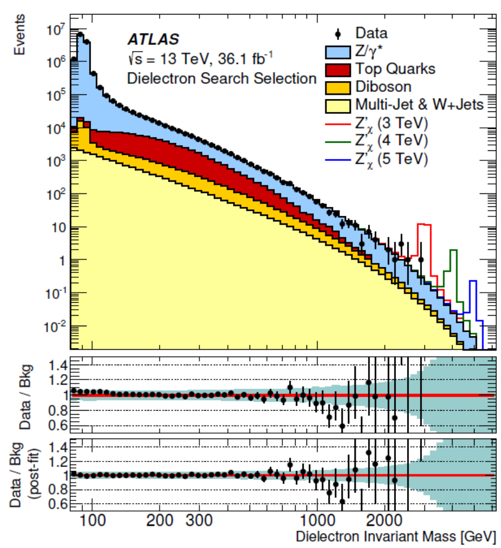
Combination methodology (1)

1. Prepare discriminant variables after event selection for each final state.
   - For example, transverse mass for W’ and di-lepton mass for Z’
   - Mass cut was applied to ignore interference effects.
   - “Acceptance x Efficiency” was calculated to evaluate the original number of events.

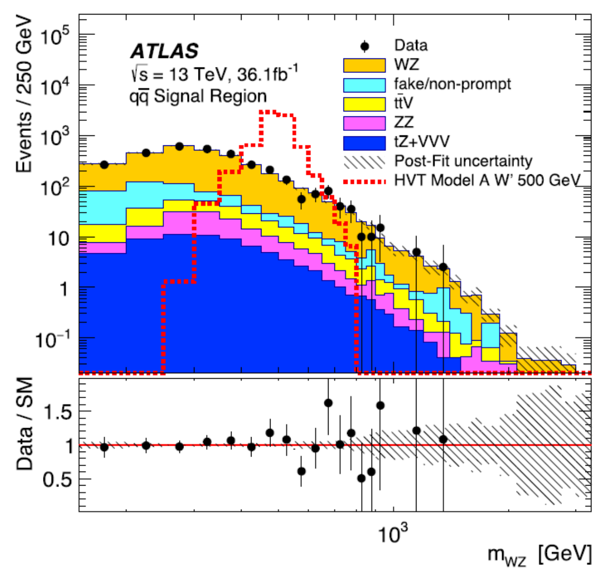
m_T in $W' \to e\nu_e$



Di-electron mass in $Z' \to ee$



WZ invariant mass



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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

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

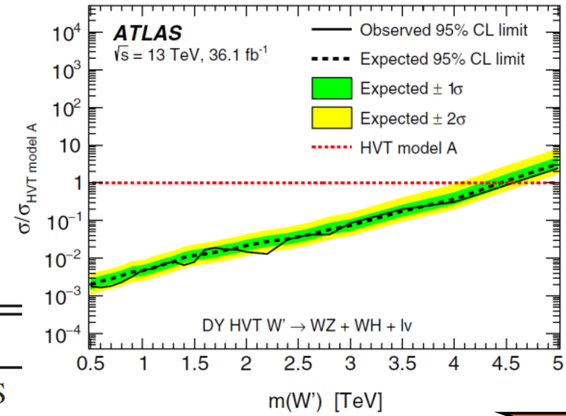
$$L = \prod_c \prod_i \mathrm{Pois}(n_{ci}^{\mathrm{obs}} | n_{ci}^{\mathrm{sig}}(\mu,\vec{\theta}) + n_{ci}^{\mathrm{bkg}}(\vec{\theta})) \prod_k f_k(\theta_k)$$

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

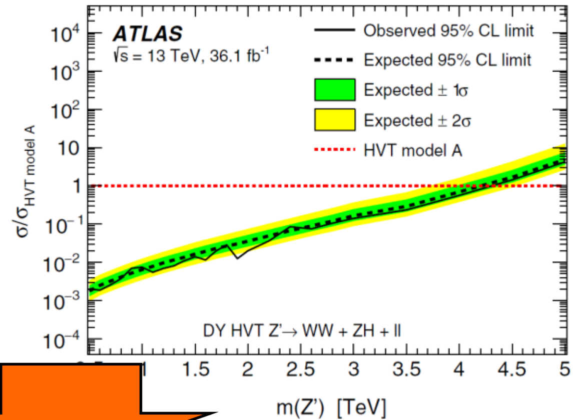
Combined results with 36 fb^{-1}(1)

Phys. Rev. D98, 052008 (2018)

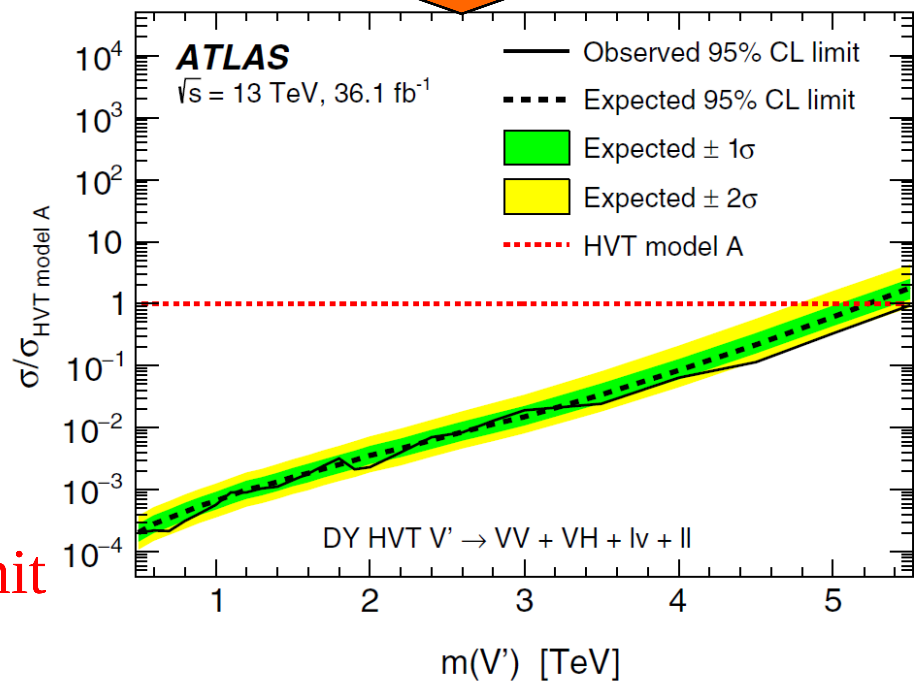
W' → WZ/WH/ℓν



Z' → WW/ZH/ℓℓ



	Lower limits on resonance mass (TeV)					
	HVT model A		HVT model B		Bulk RS	
Channel	Obs	Exp	Obs	Exp	Obs	Exp
WW	2.9	3.1	3.6	3.5	1.7	1.9
WZ	3.6	3.6	3.9	3.9	...	...
ZZ	...	...	...	...	1.5	1.7
VV	3.7	3.7	4.0	3.9	2.3	2.2
WH	2.6	2.8	2.8	3.1	...	...
ZH	2.7	2.5	2.8	2.8	...	...
VH	2.8	3.1	3.0	3.4	...	...
$\ell\nu$	4.6	4.6	...	...	...	...
$\ell\ell$	4.5	4.4	...	...	...	...
$\ell\nu/\ell\ell$	5.0	5.0	...	...	...	...
VV/VH	4.3	4.3	4.5	4.4	...	...
$VV/VH/\ell\nu/\ell\ell$	5.5	5.3	...	...	...	...

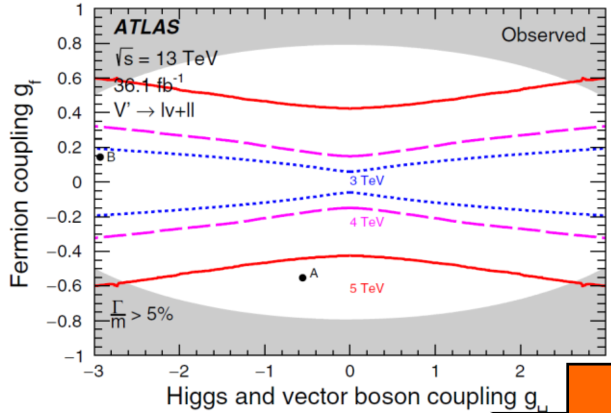


Combination improved the mass limit of a new heavy boson significantly.

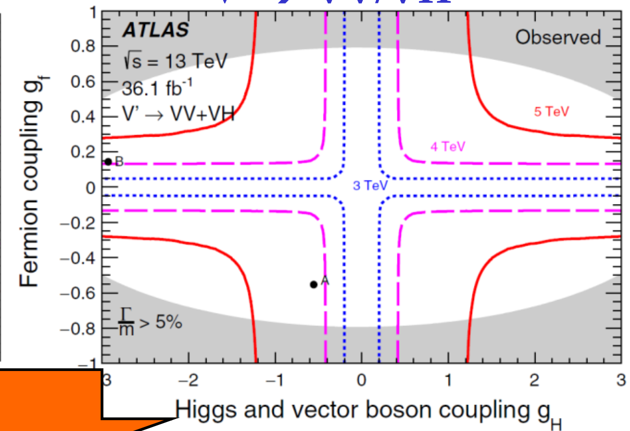
Combined results with 36 fb^{-1}(2)

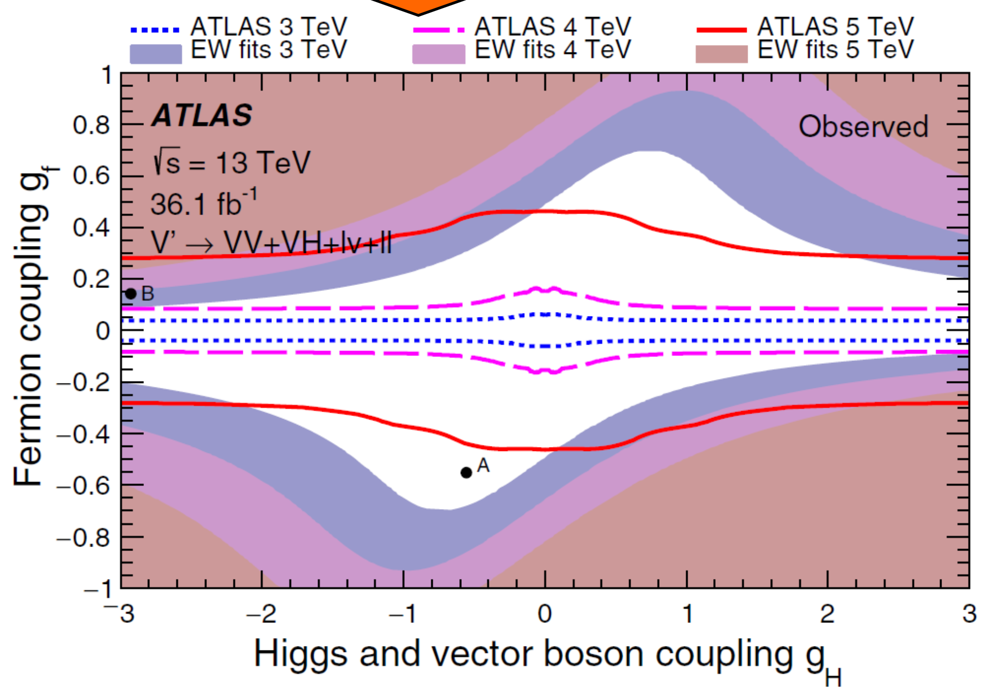
Phys. Rev. D98, 052008 (2018)

V' → ℓν/ℓℓ



V' → VV/VH





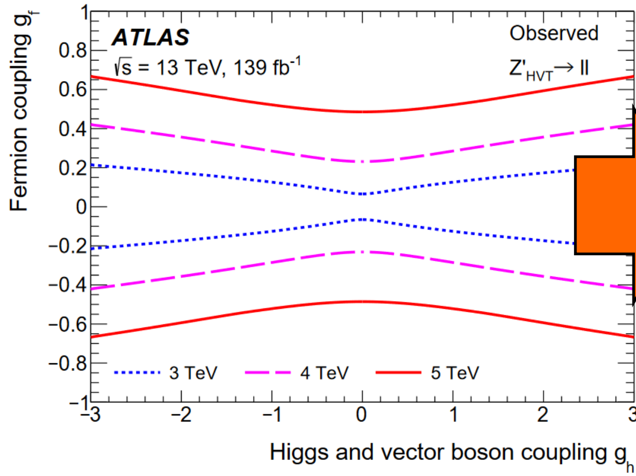
Combination gave much stronger constraint on couplings of new heavy bosons to SM particles.

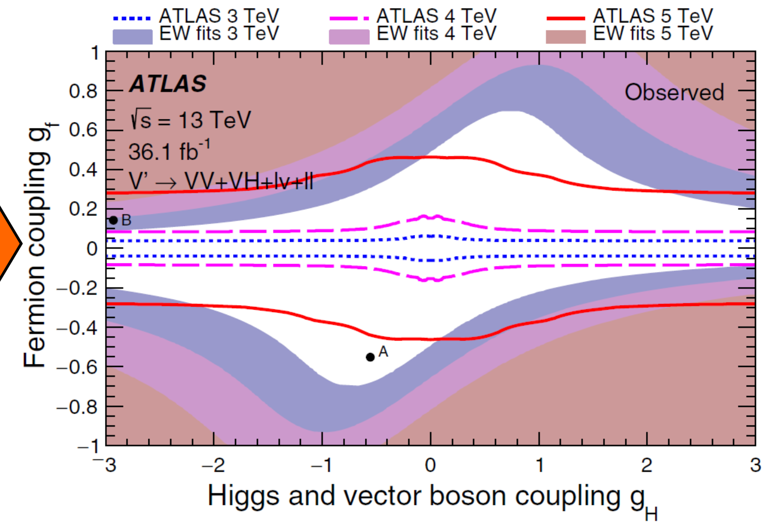
Big advantage of combination analysis

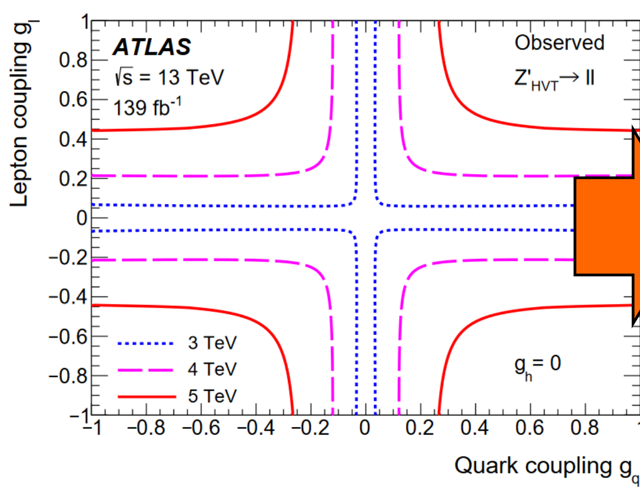
The combination with 36 fb^{-1} gave stronger constraint than Z' only results with 139 fb^{-1}.

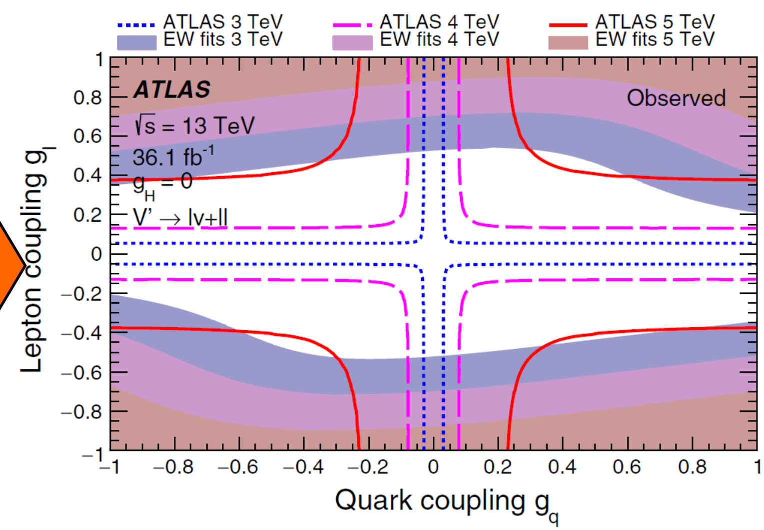
Z' only with 139 fb^{-1}

Combination with 36.1 fb^{-1}



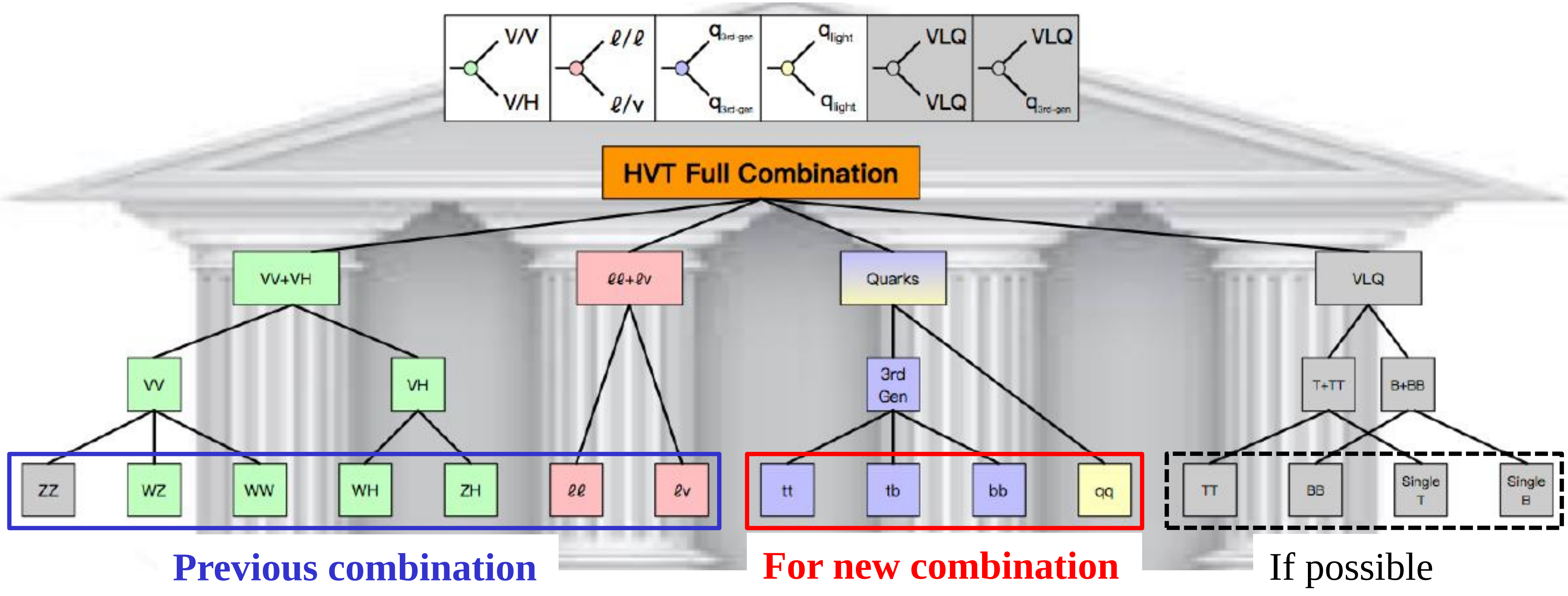






Grand combination

- The combination analysis will be performed by using a full Run2 dataset of 149 fb^{-1} (only 36 fb^{-1} for the previous combination).
- The final states, especially those with a top quark and tau, are added.
- It will give much stronger constraint on new boson masses and their couplings in HVT framework.



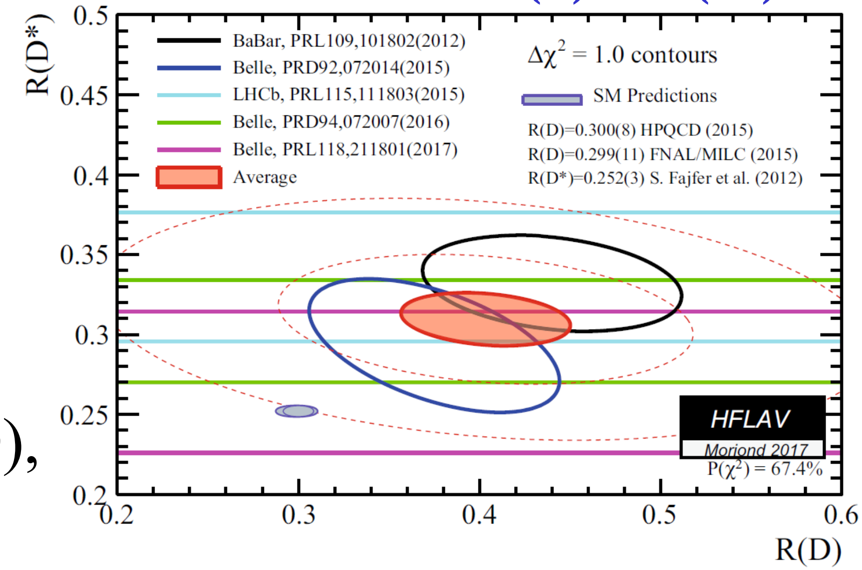
Flavor anomalies in 3rd generation

- Departures from lepton flavor universality was observed in semi-taunic decays of B mesons in particular by Babar, Belle and LHCb.
  - Eur. Phys. J. C (2017) 77, 895

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

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

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



- Exceed SM prediction by 2.2 σ in R(D), 3.4 σ in R(D*) → **3.9 σ in total**

- 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.

Our team for grand combination

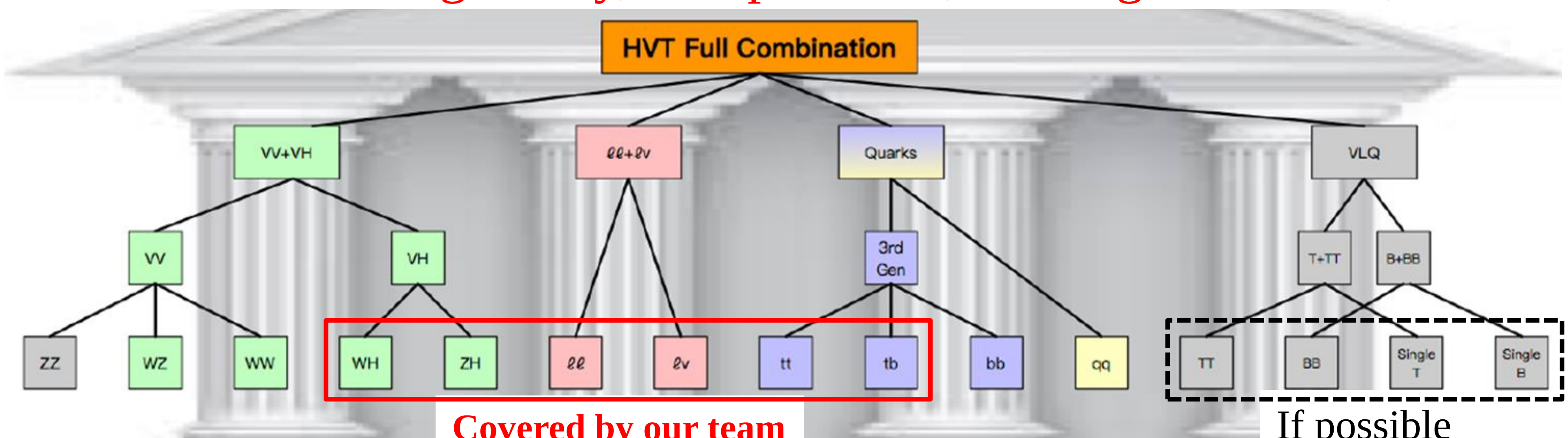
Final states	Institute	Person
$\ell\ell$	LAPP	T. Berger-Hryn'ova, P. Falke, Students
$\ell\nu$	KEK	Y. Takubo, K. Nagano
VH	LPNHE	R. Camacho Toro
tt, tb	LPC	S. Calvet, J. Donini
	Tokyo	K. Terashi, Students

Worked together for previous combination.

Collab. btw. students also can be promoted.

New collaboration

2019-2020 is an important period to materialize this combination with studies on orthogonality, interpretation, new signal models, etc..



Summary & Conclusion

- ATLAS collected data of 149 fb^{-1} with 13 TeV pp colliding energy in Run2.
- The heavy resonance search is one of the most important tasks in ATLAS program to explore new BSM particles.
- The combination study was performed by using dataset of 36 fb^{-1}, based on HVT framework and gave much stronger constraints on the masses and couplings of new particles, compared to separated analyses.
- The next target is combination analysis with a full Run2 dataset, including 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.
- 2019-2020 is an important period for this combination, and the support from TYL/FJPPL will strengthen our unity.

Backup

Analysis channels for 36 fb^{-1}

TABLE III. Summary of analysis channels, diboson states they are sensitive to, and their experimental signatures. The selection reflects requirements specific to each channel. Additional jets (not included in the "Jets" column) are required to define VBF categories. The notation j represents small-R jets, and J represents large-R jets. Leptons are either electrons or muons. The notation $1e$, 1μ means that the signature is either $1e$ or 1μ, whereas $1e + 1\mu$ means $1e$ and 1μ. A veto is imposed on E_T^{miss} in some channels to guarantee orthogonality between final-state channels. The symbol $\cdots$ signifies that no requirement is imposed on a given signature.

		Selection					
Channel	Diboson state	Leptons	E_T^{miss}	Jets	b-tags	VBF categories	Ref.
$qqqq$	$WW/WZ/ZZ$	0	Veto	2J	⋯	⋯	[9]
$\nu\nu qq$	WZ/ZZ	0	Yes	1J	⋯	Yes	[13]
$\ell\nu qq$	WW/WZ	$1e, 1\mu$	Yes	2j, 1J	⋯	Yes	[10]
$\ell\ell qq$	WZ/ZZ	$2e, 2\mu$	⋯	2j, 1J	⋯	Yes	[13]
$\ell\ell\nu\nu$	ZZ	$2e, 2\mu$	Yes	⋯	0	Yes	[14]
$\ell\nu\ell\nu$	WW	$1e + 1\mu$	Yes	⋯	0	Yes	[12]
$\ell\nu\ell\ell$	WZ	$3e$, $2e + 1\mu$, $1e + 2\mu$, 3μ	Yes	⋯	0	Yes	[11]
$\ell\ell\ell\ell$	ZZ	$4e$, $2e + 2\mu$, 4μ	⋯	⋯	⋯	Yes	[14]
$qqbb$	WH/ZH	0	Veto	2J	1, 2	⋯	[15]
$\nu\nu bb$	ZH	0	Yes	2j, 1J	1, 2	⋯	[16]
$\ell\nu bb$	WH	$1e, 1\mu$	Yes	2j, 1J	1, 2	⋯	[16]
$\ell\ell bb$	ZH	$2e, 2\mu$	Veto	2j, 1J	1, 2	⋯	[16]
$\ell\nu$	⋯	$1e, 1\mu$	Yes	⋯	⋯	⋯	[17]
$\ell\ell$	⋯	$2e, 2\mu$	⋯	⋯	⋯	⋯	[18]

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 ⋯ 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	⋯	⋯	S + B	S + B	⋯
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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	$\cdots$	$\cdots$