

# Status and plan of $HH \rightarrow 4b$

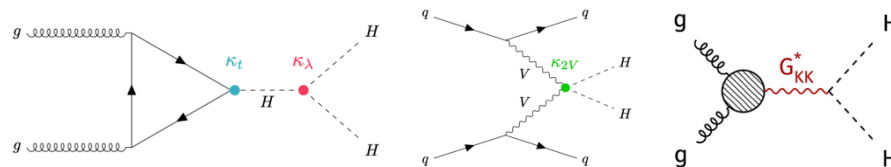
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Liaoshan Shi (SYSU)

2026年8月21日  
H+HH 课题交流研讨会



# Analysis scope



- Run2 + partial Run3 (2022-2023/2024)
- Docs: <https://atlas-hh-bbbb.docs.cern.ch/>
- Initially several components were developed within a single HH→4b analysis effort.
- Split off into two analyses mainly due to the timeline of Xbb tagger.
  - Resolved [ANA-HIGP-2024-39](#) (Stage: 2<sup>nd</sup> EB meeting)
    - Glance author list also preserves boosted authors until the split off. INT note keeps track of only the authors contributing to resolved.
  - Boosted [ANA-HIGP-2025-19](#) (Stage: pre-EB)
    - Inherited the boosted author list and evolve on top of it.

|     | Resolved    | Boosted                       |
|-----|-------------|-------------------------------|
| ggF | $k_\lambda$ | $k_\lambda$                   |
| VBF | $k_{2V}$    | $k_{2V}$ , EFT                |
|     |             | Resonant<br>(Scalar/graviton) |

*\* New in this round*

# Current organization

## Resolved

- Analysis contacts:
  - Sebastien Rettie
  - **Liaoshan Shi (SYSU)**
- INT note editors:
  - **Yizhou Cai (NJU)**
  - Malin Horstmann
- Paper editors:
  - Marco Valente
  - **Lei Zhang (NJU)**

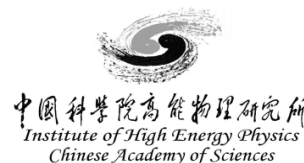
## Common

- Easyjet framework bbbb contact:
  - **Yizhou Cai (NJU)**

## Boosted

- Analysis contacts:
  - Dilia Maria Portillo Quintero
  - Hava Rhian Schwartz
- INT note editors:
  - **Zonghuan Duan (NJU)**
  - Nikita Pond

Institutions involved in HH→4b:



# HH → 4b as a driver of b-jet trigger CP work

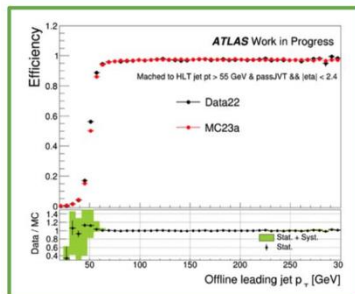
- Pure b-jet final state → the only handle for triggering
- Main user of b-jet triggers → motivated person power to push forward the CP work
- Analysis operates on trigger turn-on to gain acceptance at low mHH → complicated turn-on region SF measurement

HLT\_j75c\_020jvt\_j50c\_020jvt\_j25c\_020jvt\_j20c\_020jvt\_SHARED\_2j20c\_020jvt\_bgn177\_pf\_ff\_presel2c20XX2c20b85\_L1J45p0ETA21\_3J15p0ETA25

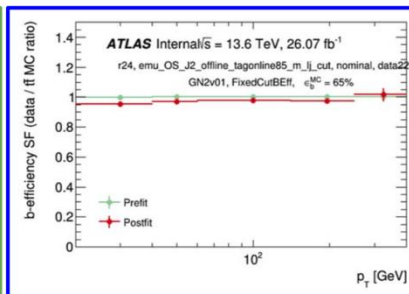
HLT: 4 central jets

HLT: 2 b-tagged jets

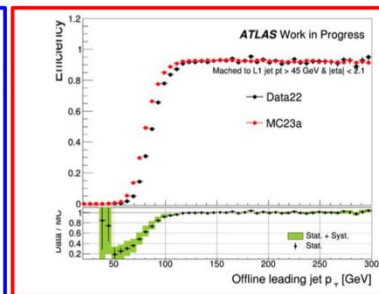
L1: 3 central jets



HLT jet → offline jet



HLT b-jet → offline b-jet



L1 jet → offline jet

# HH→4b as a driver of b-jet trigger CP work

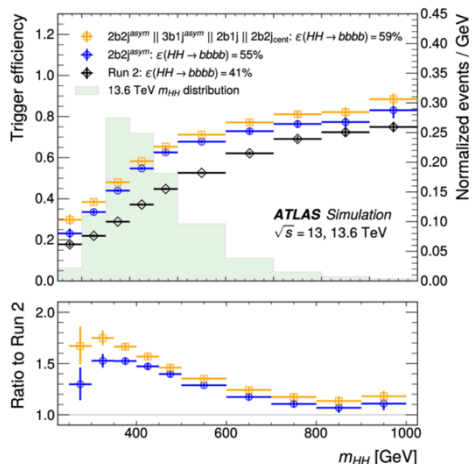
- b-jet trigger development driven by HH→4b physics

## Resolved:

2b1j+2b2j (Run2) → asym 2b2j (Run3)

signal eff 41%→59% and smoother background

Used in  
ongoing  
analysis

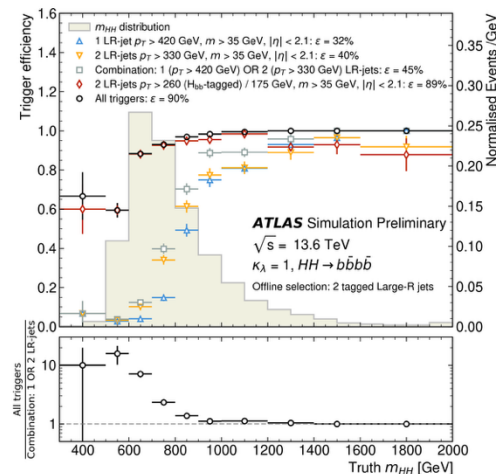


Commissioning and validation (Liaoshan + b-jet trigger team)  
Checked the impact on analysis (Zonghuan)

## Boosted:

single LRJ → double LRJ → Xbb trigger

signal eff 32% → 45% → 90%



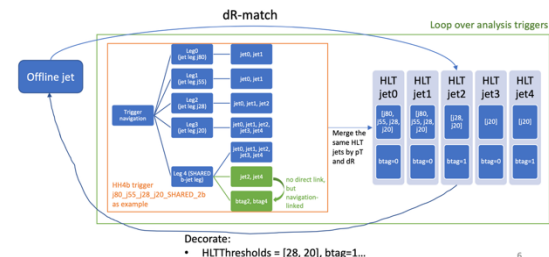
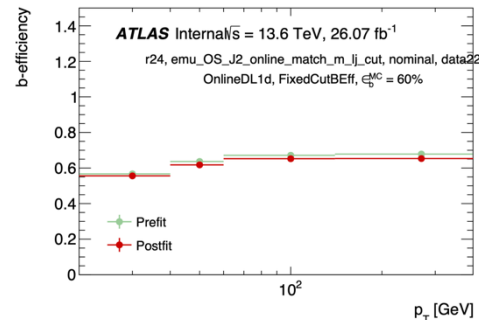
For full  
Run3  
analysis

(Yizhou, Liaoshan + b-jet trigger team)

## HH→4b as a driver of b-jet trigger CP work

- Trigger b-tagging efficiency/SF measurement and analysis tool development

- Measure the trigger b-tagging SFs in R25 for both Run2 and Run3 all WPs (**bb $\tau\tau$  team + AQP students from 4b team**)
- New approach to accommodate offline pseudo-continuous b-tagging (**Liaoshan + bb $\tau\tau$  team**)
- b-jet trigger matching strategy and corresponding tools (**Liaoshan**)
- Develop CP tools to apply the SFs (**Liaoshan + many**)



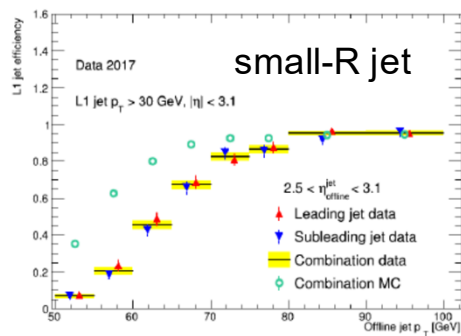
Could be improved in the future:

- Need a faster workflow to estimate trigger b-tagging efficiency and SFs, could be lower precision.
- Current workflow requires too much FTE. Analysis blocked without SFs, but the impact from trigger b-tagging SFs is anticipated small due to high b-jet multiplicity in the signal.

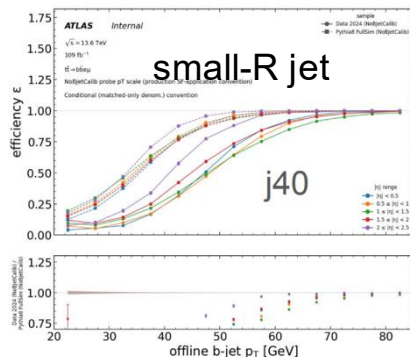
# HH→4b as a driver of b-jet trigger CP work

## ● Trigger jet efficiency turn-on measurement

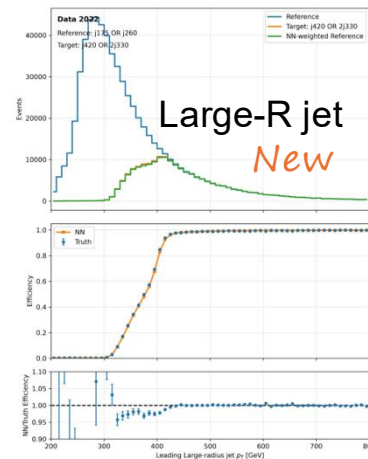
- Phase-space dependent. Jet trigger group doesn't provide SFs.
- L1 SFs have large impact to the HH signal and can't be ignored



AnalysisTop-based framework  
and 2022+2023 SFs (Ab, TJ)  
Run 2 SFs (Khuram + Hideki)



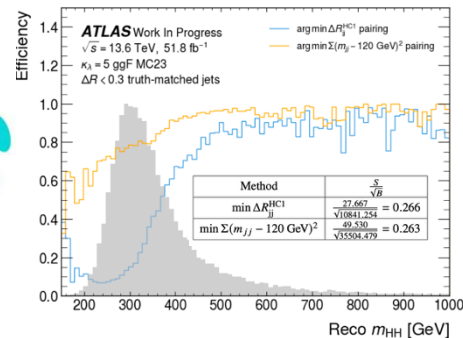
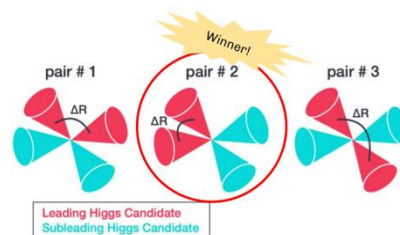
Easyjet-based framework  
and 2024 SFs (Nikita, Liaoshan)



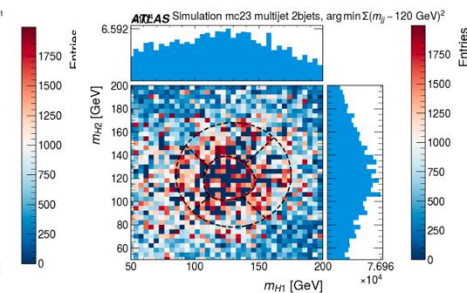
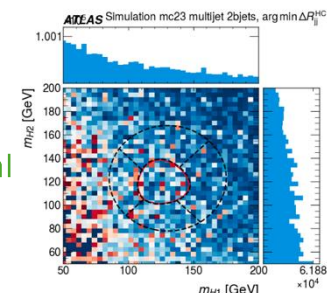
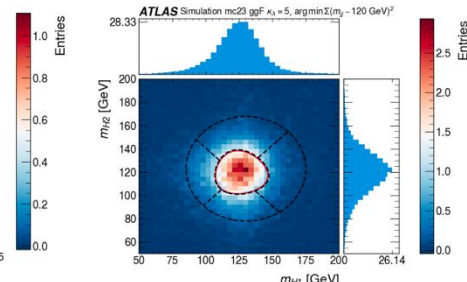
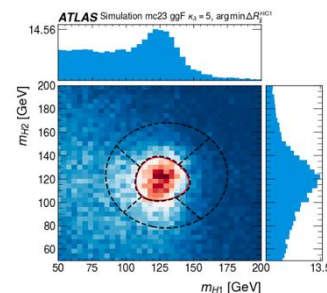
LRJ SFs (Kunlin)  
NN-based calibration (Pritha, Aurelio, Liaoshan)

- 2024 SFs were the main blocker for resolved HH→4b to explore 2024 data. Now feasible.
- NN-based calibration may be able to measure more complicated trigger combinations.

# Higgs Candidate Pairing



- Same as previous analysis:  $\min\_dR$ 
  - Sub-optimal in low- $m_{HH}$  region, limited the improvement from trigger acceptance.
- Several methods investigated. No single method is better than  $\min\_dR$ :
  - Background sculpting
  - Low accuracy in some phase space
- Also tested CMS method:
  - Include multiple pairing methods as input features in signal classifier → didn't see an improvement
- To be improved in next round
  - ML-based pairing
  - Better use pairing information in SR definition and signal classification



# Background estimation

## Resolved ggF

*New in this round*

- GP+NFlows, using only 4b data in the training

- Gaussian Process (GP) interpolates background yields from CR → SR
- Flows conditioned on ( $m_{H1}$ ,  $m_{H2}$ ) to predict features

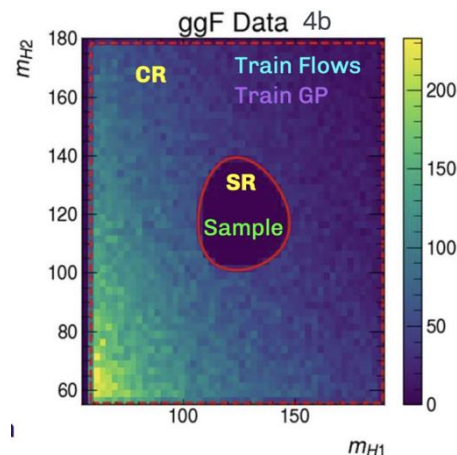
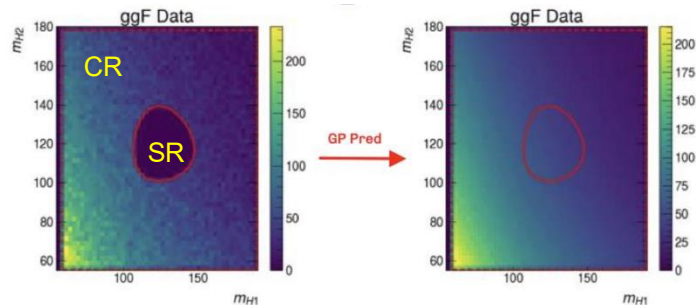
$$p(\vec{x}, m_{h1}, m_{h2}) = p(\vec{x} | m_{h1}, m_{h2}) p(m_{h1}, m_{h2})$$

(Also condition on year)      Flow      GP

- Yizhou played a key role in the optimisation

- Alternative methods investigated

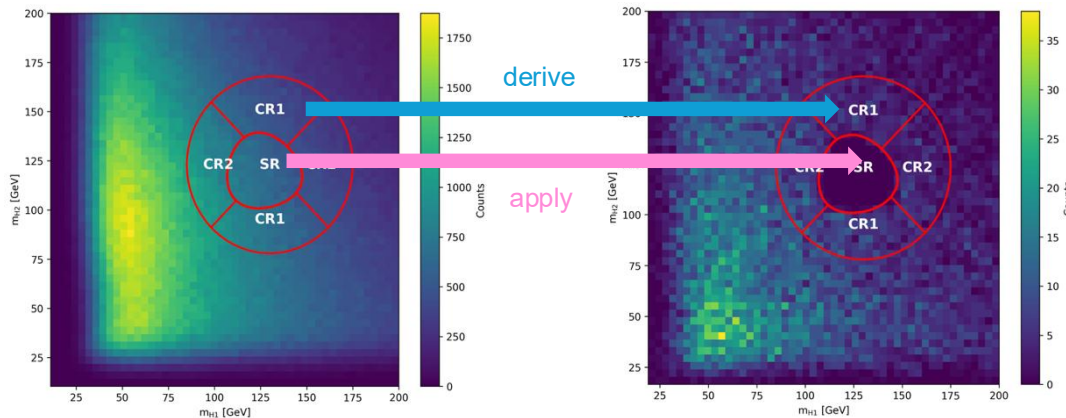
- NN reweighting, Optimal transport (Zonghuan)



# Background estimation

## Resolved VBF

- NN multi-dimensional reweighting
  - Train NN in CR1 to reweight 2b to 4b
  - Evaluate NN in SR
  - Train an alternative NN in CR2 to derive systematics
- Also used in previous round of ggF analysis

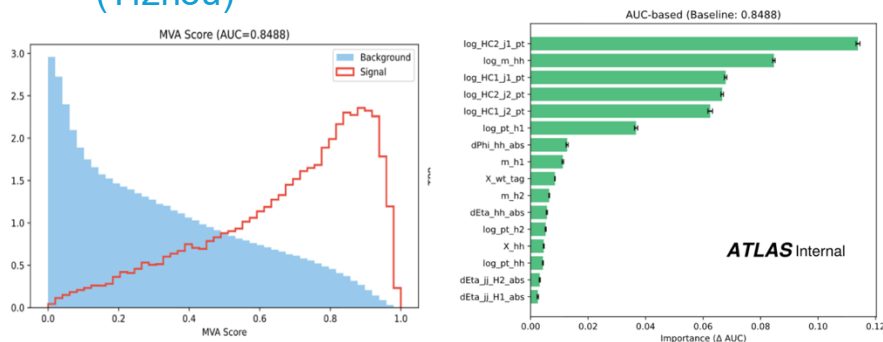


# Signal classifiers

## ggF (DNN) *New in this round*

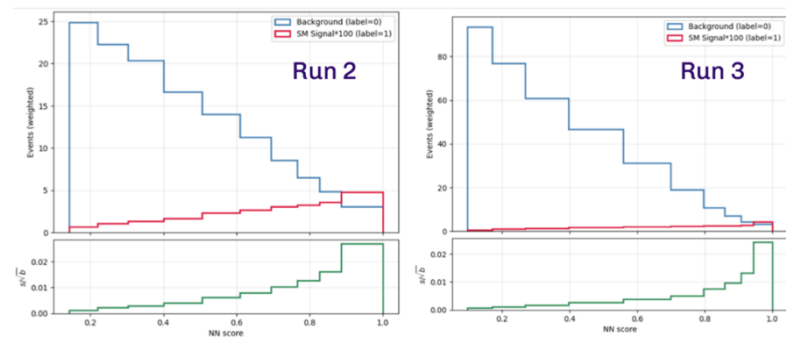
- Background from GP + Nflows
- Signal  $k_l=\{-1, 0, 1, 2.5, 5, 10\}$ ,  $k_l=0$  weighted by 2
- Final discriminant  $\log(p_S/p_B)$
- Drop events below -1

(Yizhou)



## VBF

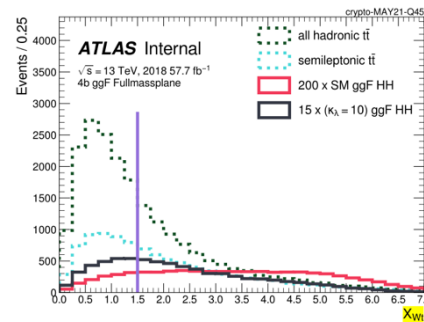
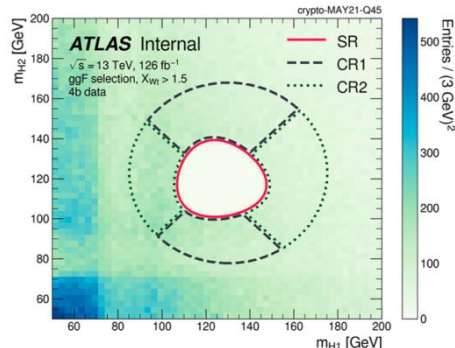
- Background from reweighting
- Signal  $k_{2V}=\{0, 1\}$ ,  $k_{2V}=1$  weighted by 10
- Final discriminant is NN output score
- Separate networks for Run 2 and Run 3
- Drop first bin



NSBI was explored but not used in this round.

# Xwt cut

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4 \text{ GeV}}{0.1m_W}\right)^2 + \left(\frac{m_t - 172.5 \text{ GeV}}{0.1m_t}\right)^2}.$$

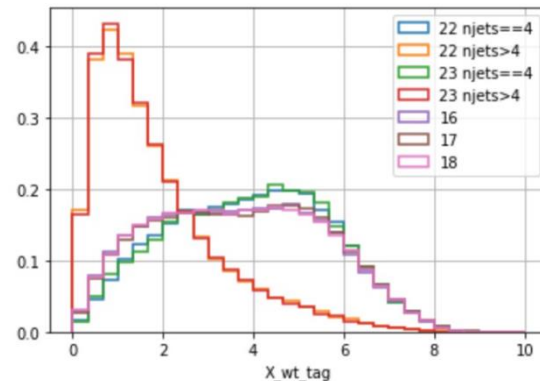


Xwt cut in Run 2 analysis

- Top-veto cut from Run 2 analysis no longer optimal for Run 3.

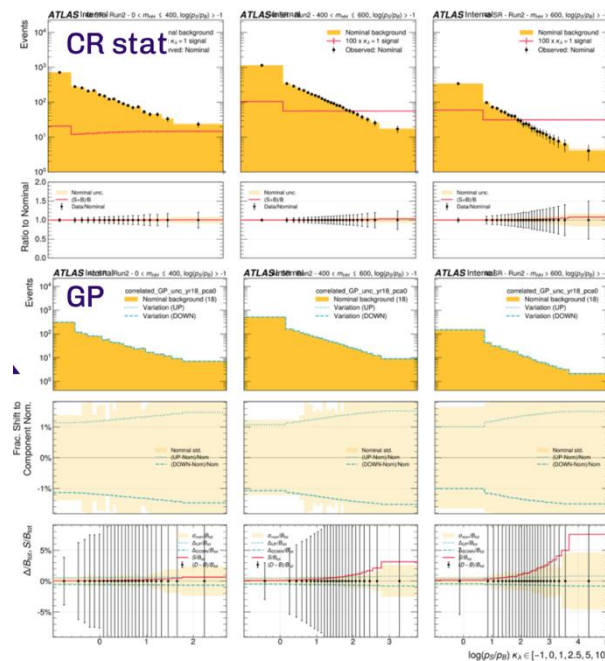
- Better b-tagging reject c-jet from W decay → lower top background
- Xwt cut causes strips affecting background smoothness.
- Run 3 trigger accepts signal with higher jet-multiplicity and more bkg-like Xwt values
- MVA uses Xwt directly as input feature

- Remove Xwt cut improves the sensitivity.



# ggF Background Modelling Systematics

- **Flows CR statistical uncertainty**
  - Draw 20 pseudo datasets from nominal prediction in CR
  - Repeat entire procedure on each dataset and take variance
- **GP uncertainty**
  - From PCA on GP covariance matrix
- **Non-closure systematics (dominant)**

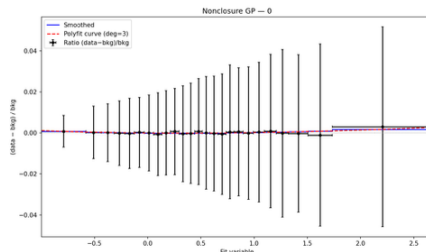


# ggF Background Modelling Systematics

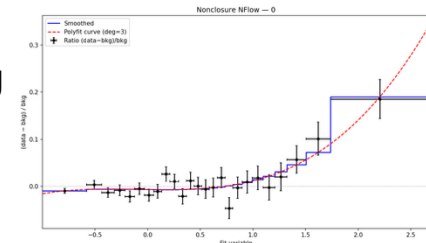
## ● Non-closure systematics (dominant)

- Repeat background estimation procedure in 2b and compare to data to derive non-closure from
  - GP mismodeling
  - flow mismodeling
  - CR→SR interpolation
- Add non-closure as systematical NPs. Test in 3b data to verify closure.

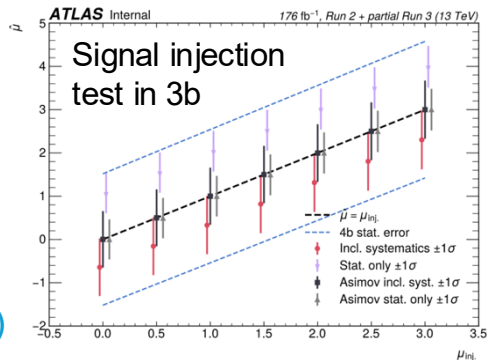
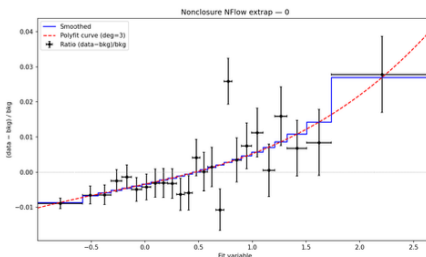
GP mismodeling



Flow mismodeling



CR→SR interpolation

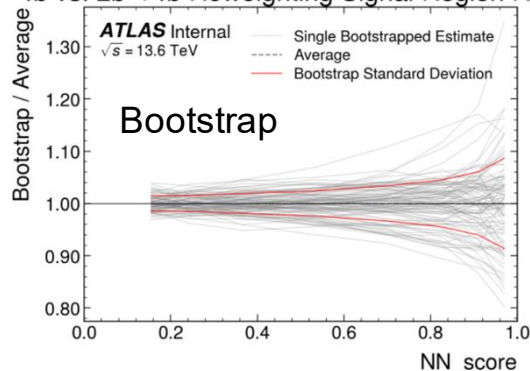


(Yizhou, Khanh, Xingyang)

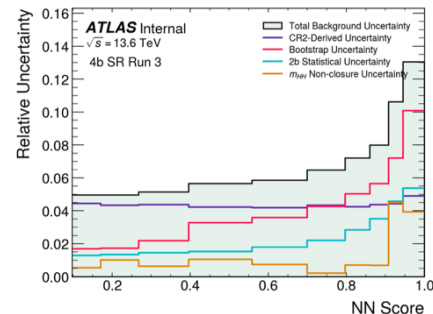
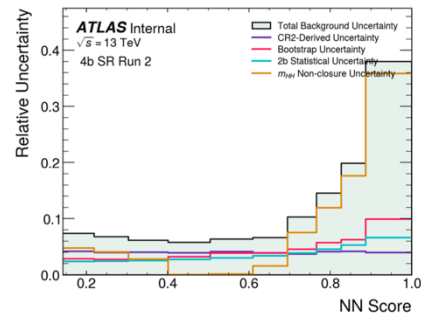
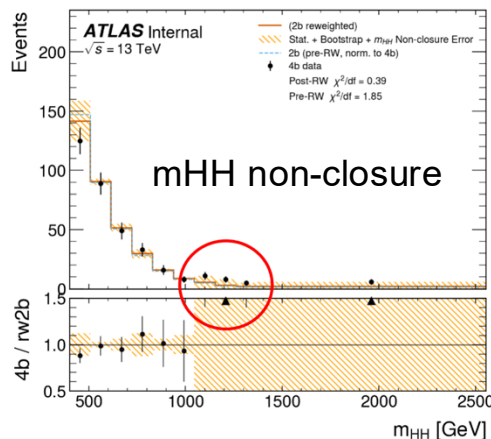
# VBF Background Modelling Systematics

- Stat uncertainty in 2b background template
- Bootstrap uncertainty for limited training stats
- Alternative CR uncertainty
- mHH non-closure

4b vs. 2b→4b Reweighting Signal Region Run 3



4b vs. 2b→4b Reweighting CR1 Run 2



# Resolved ggF sensitivity

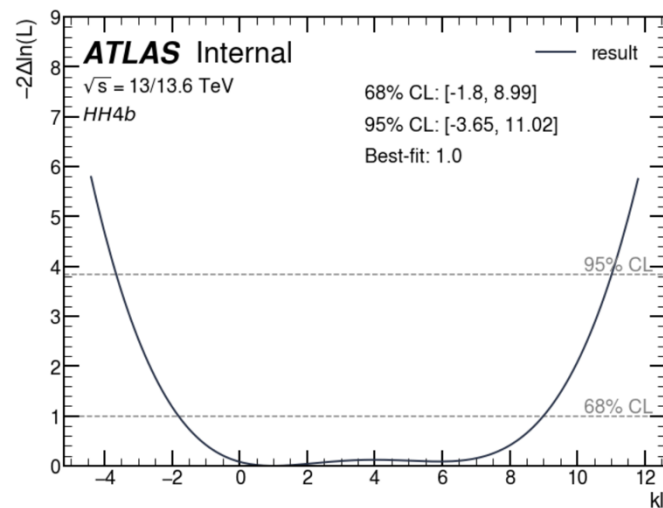
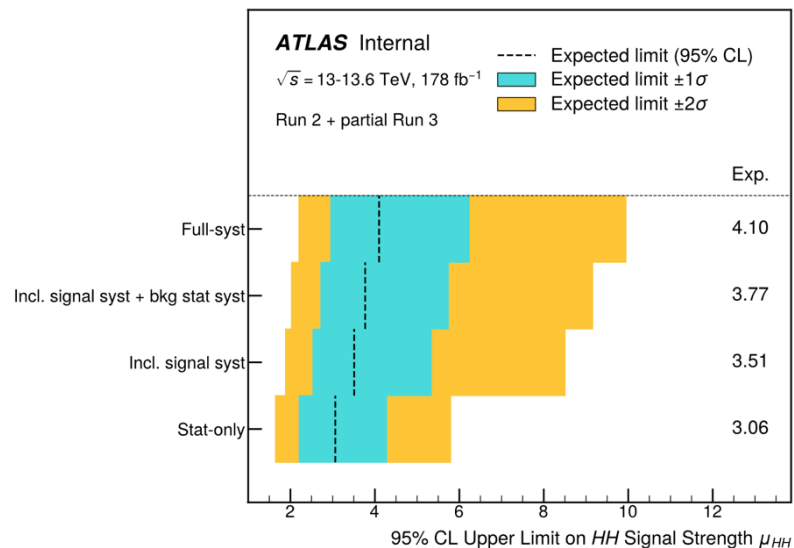
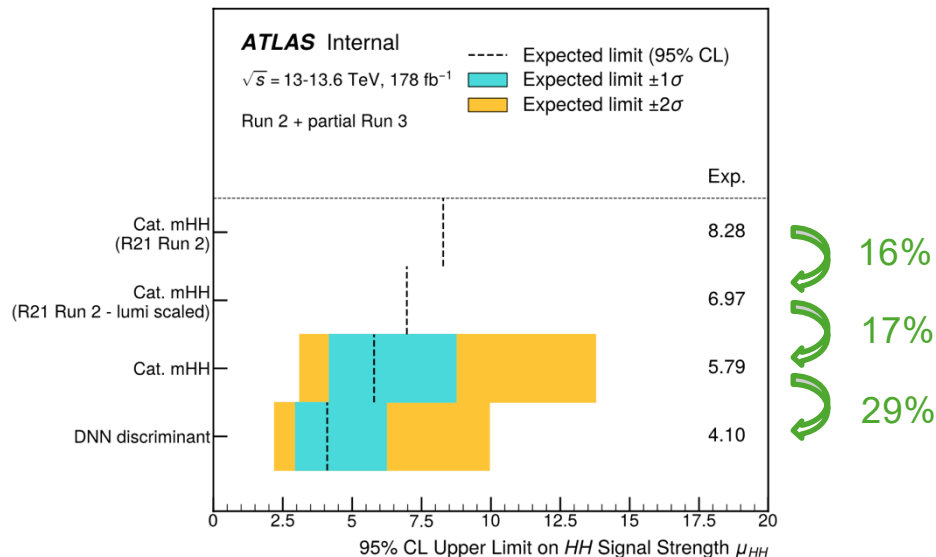
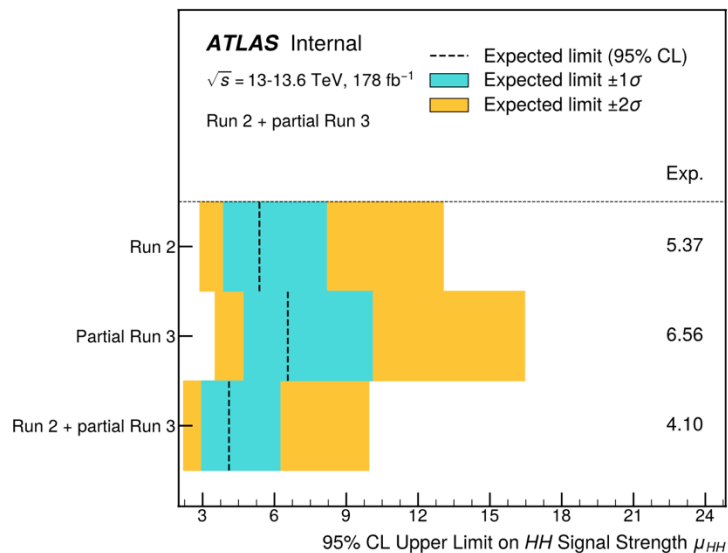
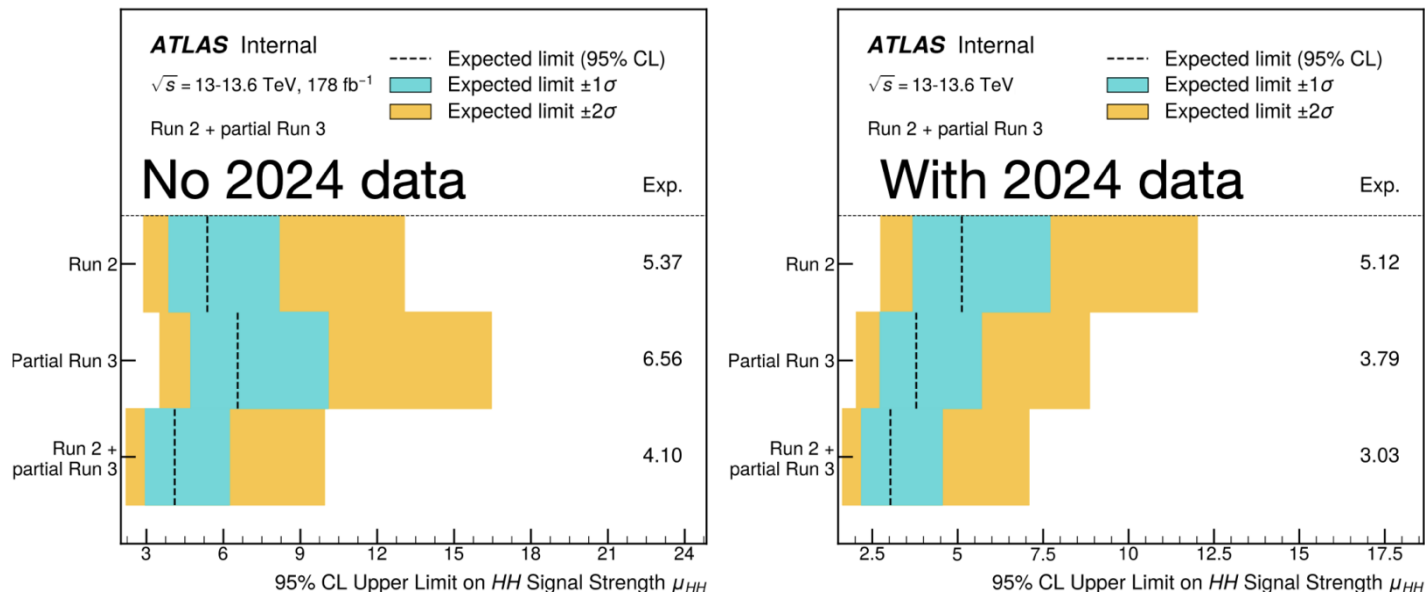


Figure 125: Constraint on  $\kappa_\lambda$  in the ggF analysis.

# Resolved ggF sensitivity

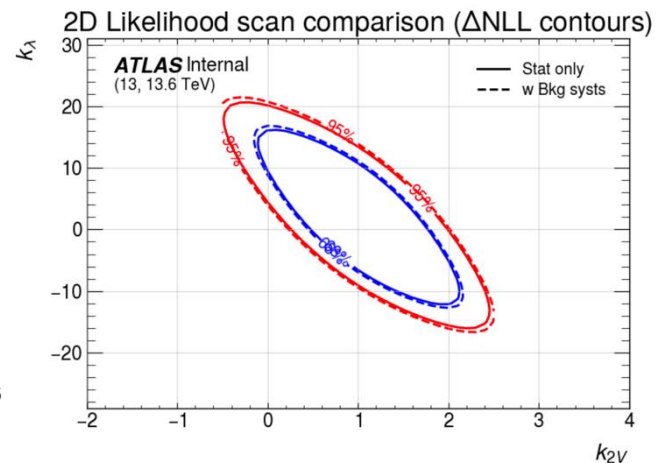
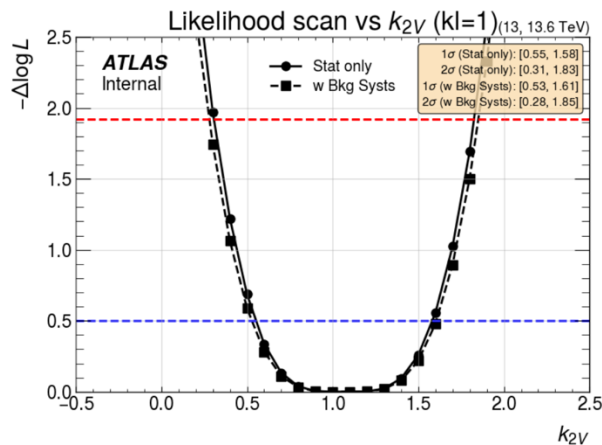
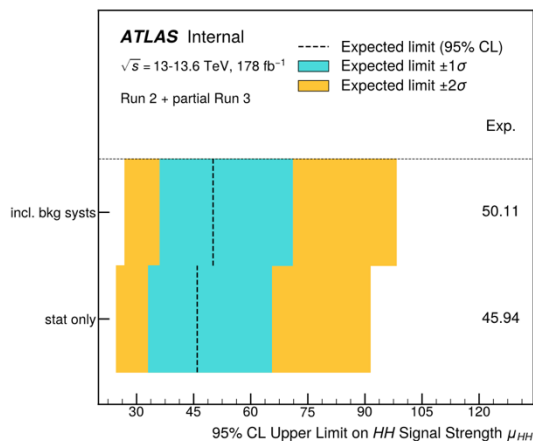


# Resolved ggF sensitivity with 2024 data

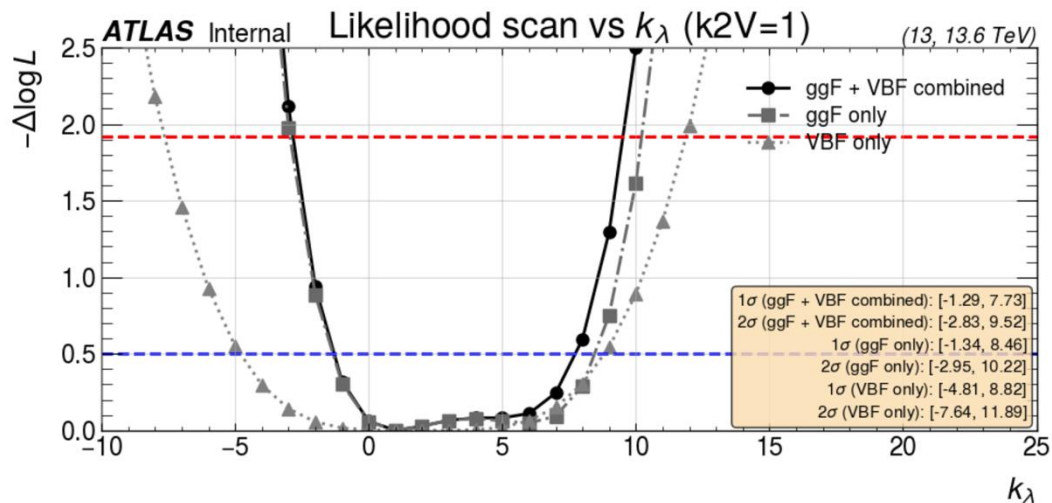
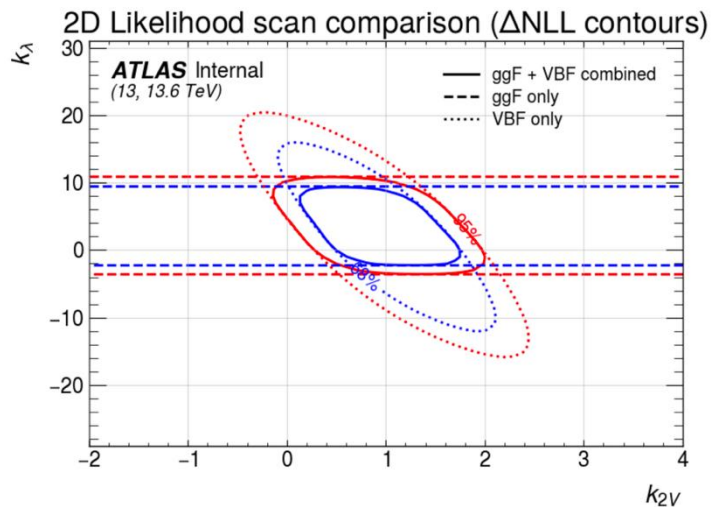


- Trigger SFs and signal systematics not included in 2024.

# Resolved VBF sensitivity



# Resolved combined sensitivity



# Plan forward

- Resolved channel target mid September for unblinding request
  - Inclusion of 2024 data to be decided
- Boosted channel still working on GN3X calibration and trigger SF measurement.
- Resolved + boosted orthogonality and combination:
  - Shared frameworks and ntuples ensure feasibility to veto each other.
  - If resolved publishes first, do not apply boosted veto in resolved results
  - Apply orthogonality cut and perform combination in the second publication. Channel priority will be decided based on combined sensitivity.