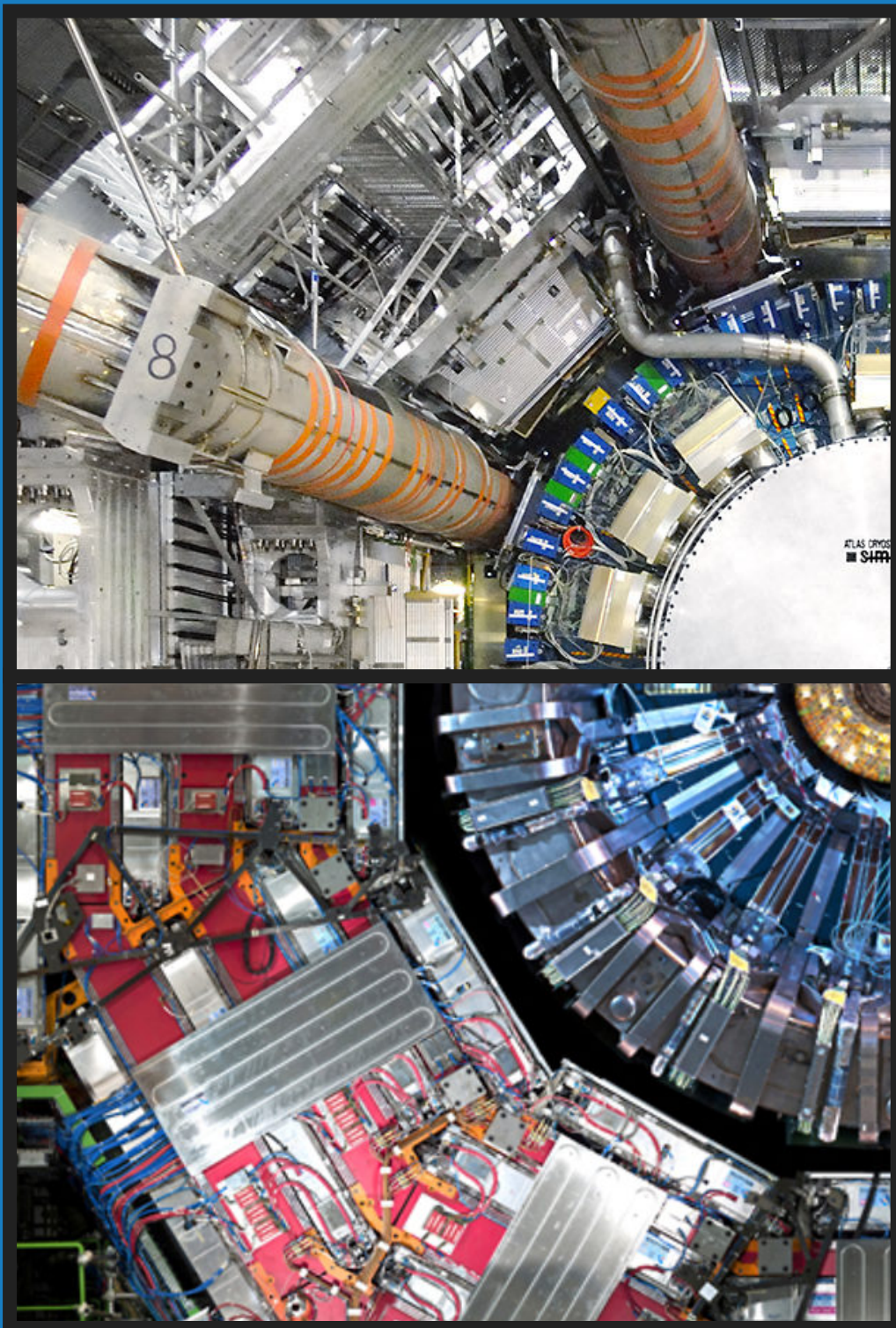
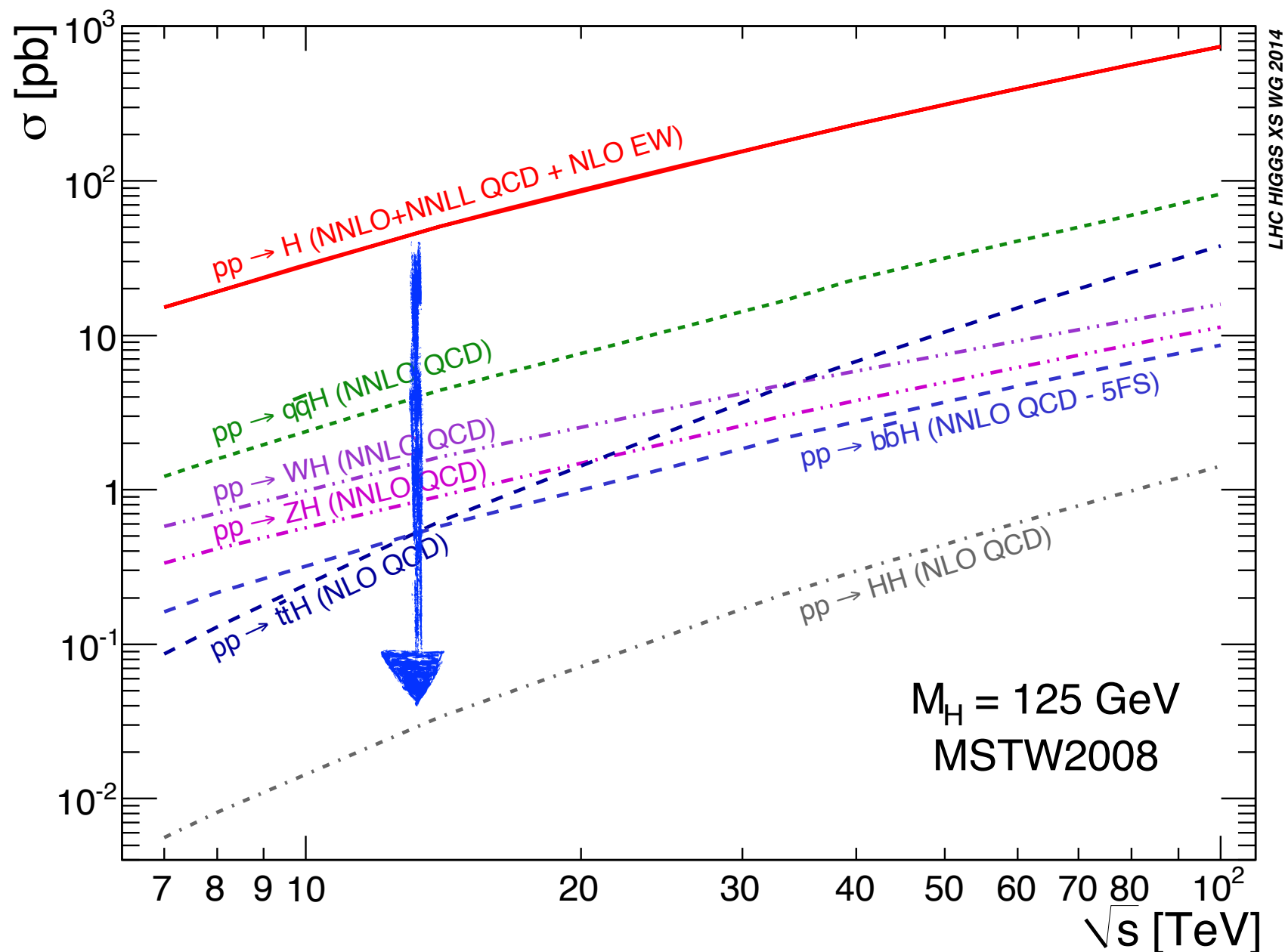




# SEARCHING FOR HIGGS PAIR PRODUCTION AT THE LHC

Elizabeth Brost (BNL)

# Higgs Boson Pair Production at the LHC



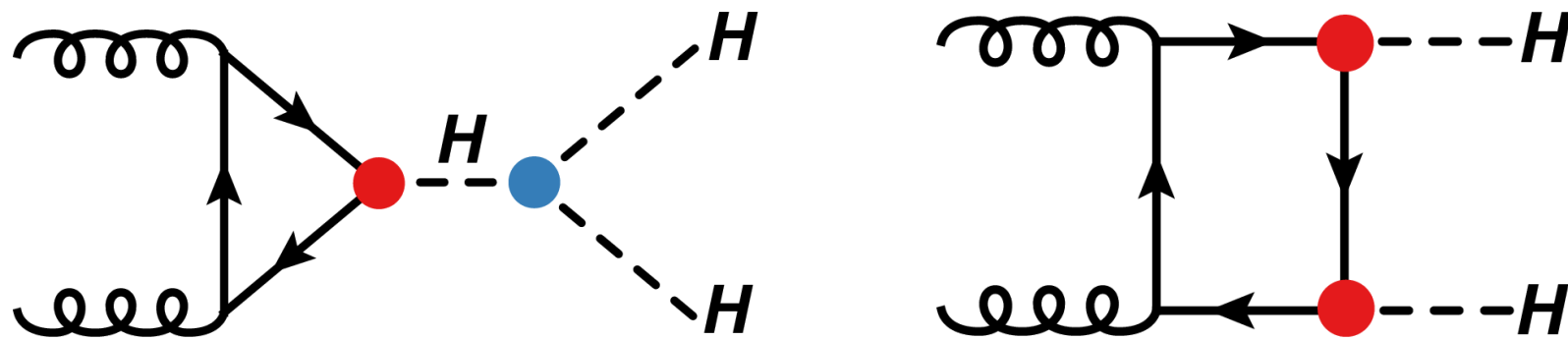
Higgs pair production is **less than 0.1%** of the total Higgs production at the LHC

**Huge spoiler: not observable in the current dataset**



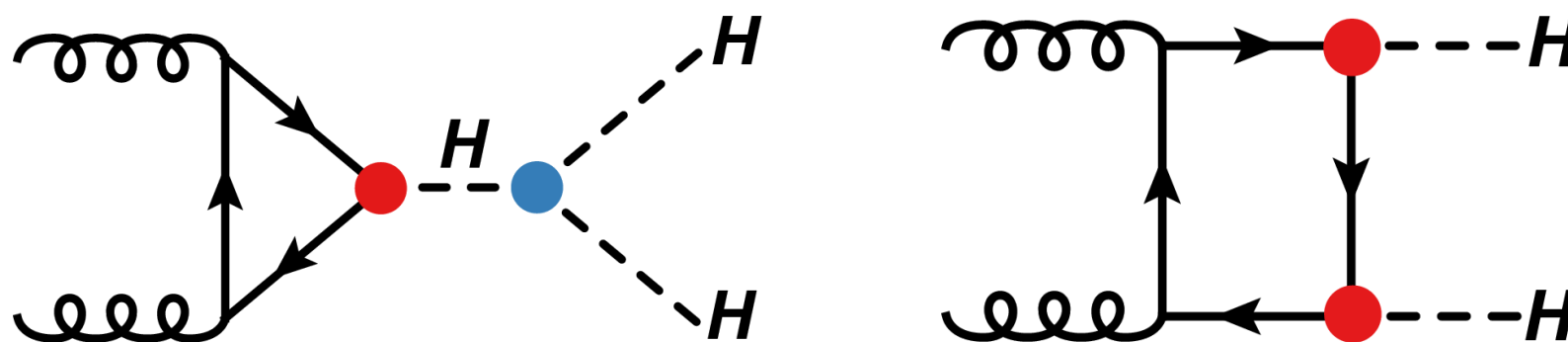
# SM Higgs Pair Production

- ▶ **Standard Model:** small!  $\sigma(HH) = 31.05 \text{ fb @ } 13 \text{ TeV}$
- ▶ + destructive interference between processes involving **Higgs self-coupling** and box-diagram with two  **$t\bar{t}H$**  vertices

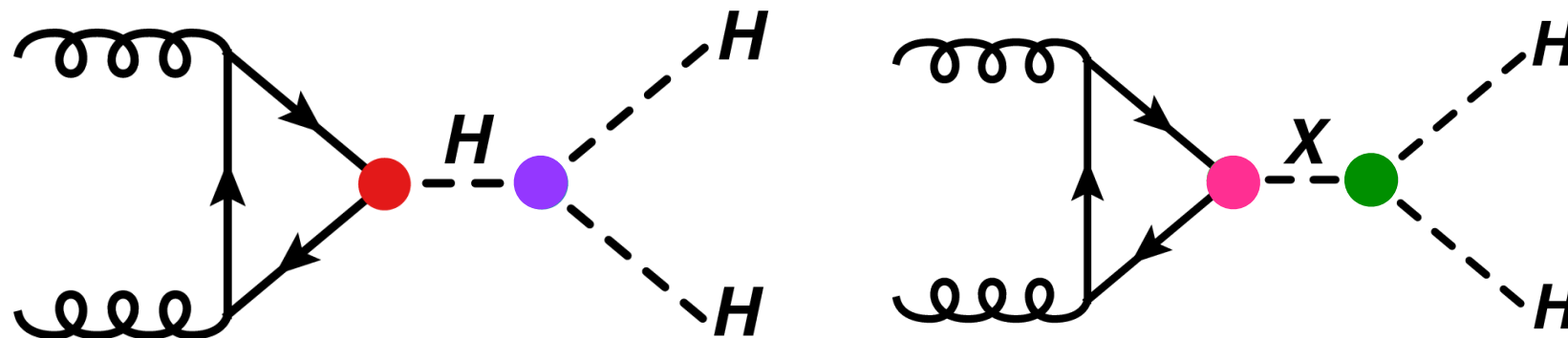


# SM and BSM Higgs Pair Production

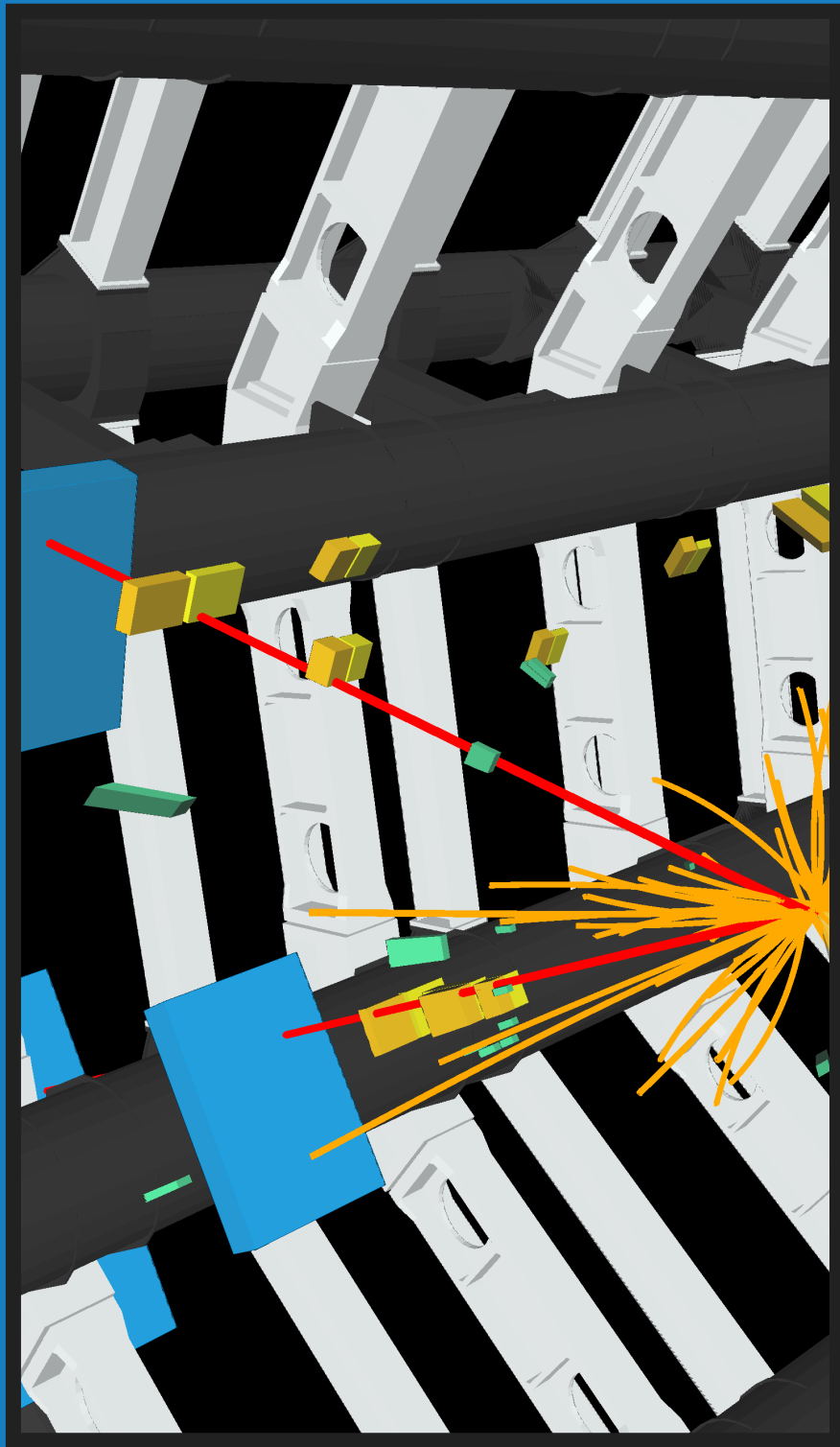
- ▶ **Standard Model:** small!  $\sigma(HH) = 31.05 \text{ fb @ 13 TeV}$ 
  - ▶ + destructive interference between processes involving **Higgs self-coupling** and box-diagram with two **ttH** vertices



- ▶ **Beyond the Standard Model:** possible enhancements?
  - ▶ **top quark Yukawa enhancements?** **enhanced self-coupling?** **resonant production** via a heavy scalar?





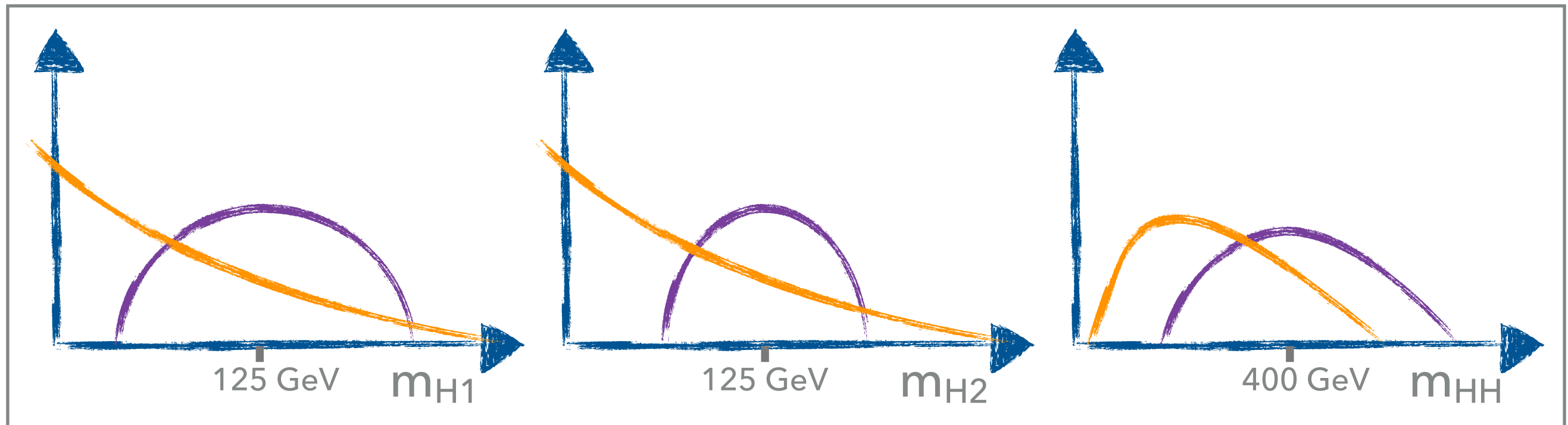


# HOW TO SEARCH FOR HIGGS PAIR PRODUCTION

# Object and Event Reconstruction

The Higgs masses,  $m_{H1}$  and  $m_{H2}$ , and the four-body mass,  $m_{HH}$  can be used to discriminate between **signal** and **background**:

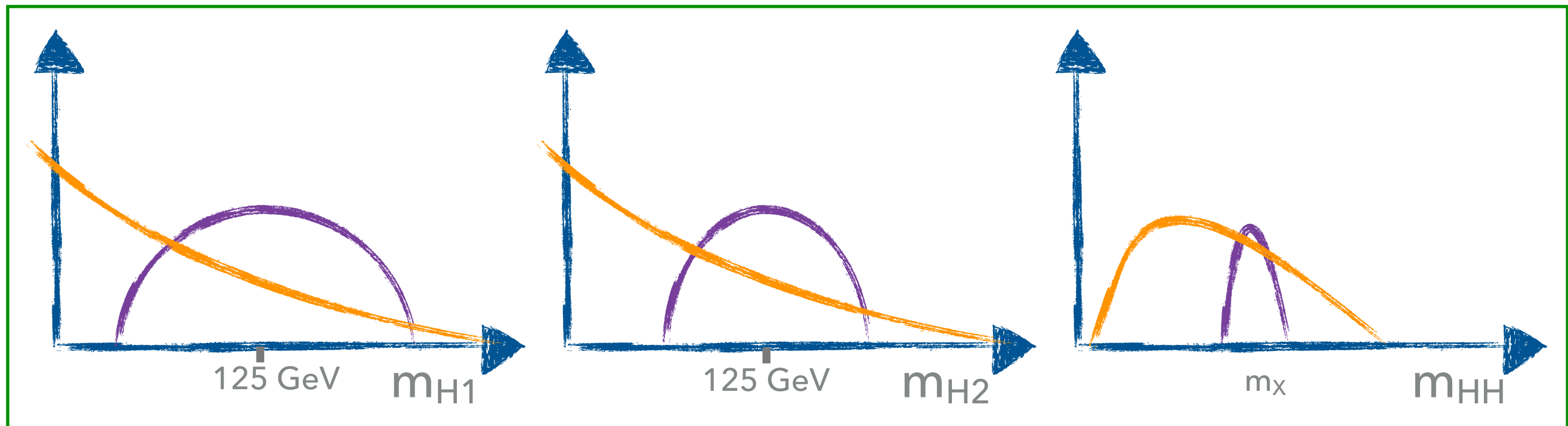
## SM HH production



# Object and Event Reconstruction

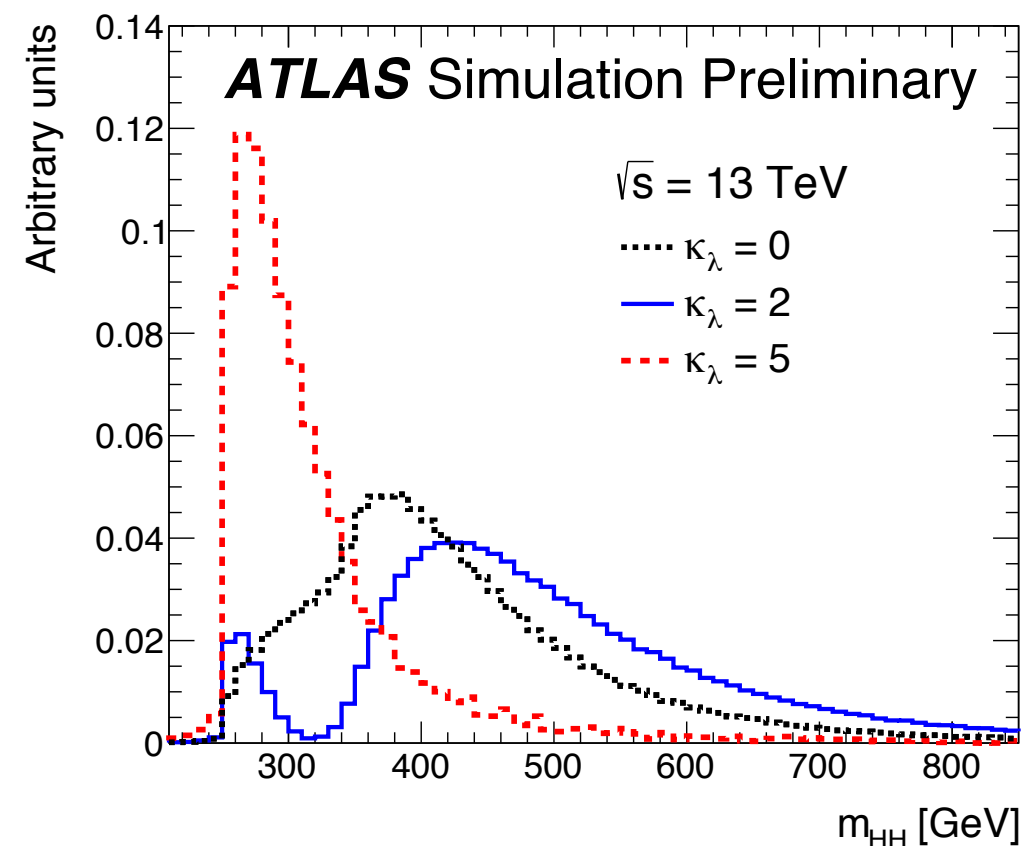
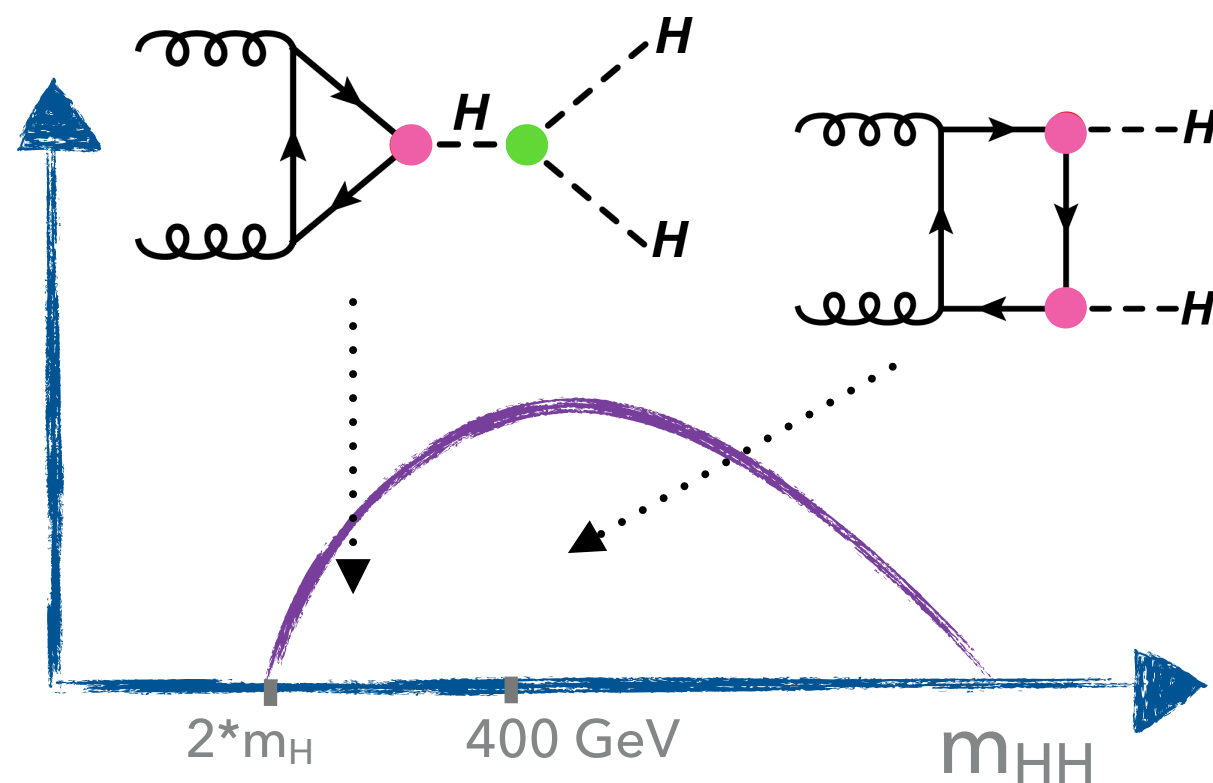
The Higgs masses,  $m_{H1}$  and  $m_{H2}$ , and the four-body mass,  $m_{HH}$  can be used to discriminate between **signal** and **background**:

## BSM HH production



# SM Higgs Pair Production Processes

Different processes contribute to the  $m_{HH}$  spectrum at different masses:



- ▶ At  $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{SM} = 0$ , the only contributions are from the box diagram
- ▶ Maximal destructive interference at  $\kappa_\lambda = 2$
- ▶ At  $\kappa_\lambda \geq 5$ , the triangle diagram dominates

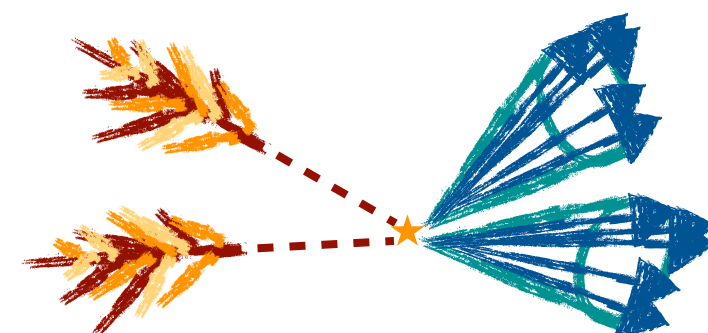


# How to Search for Higgs Pair Production

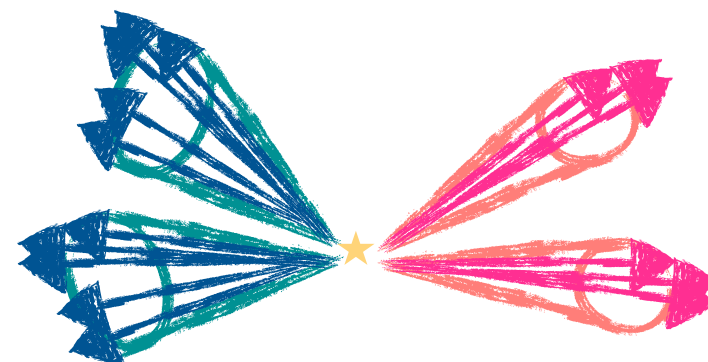
**BR(HH → XXYY)**

|                | bb    | WW   | gg | $\tau\tau$ | cc | ZZ | $\gamma\gamma$ | $Z\gamma$ | $\mu\mu$ |
|----------------|-------|------|----|------------|----|----|----------------|-----------|----------|
| bb             | 33%   |      |    |            |    |    |                |           |          |
| WW             | 25%   | 4.6% |    |            |    |    |                |           |          |
| gg             |       |      |    |            |    |    |                |           |          |
| $\tau\tau$     | 7.4%  |      |    |            |    |    |                |           |          |
| cc             |       |      |    |            |    |    |                |           |          |
| ZZ             | 3.1%  |      |    |            |    |    |                |           |          |
| $\gamma\gamma$ | 0.26% | 0.1% |    |            |    |    |                |           |          |
| $Z\gamma$      |       |      |    |            |    |    |                |           |          |
| $\mu\mu$       |       |      |    |            |    |    |                |           |          |

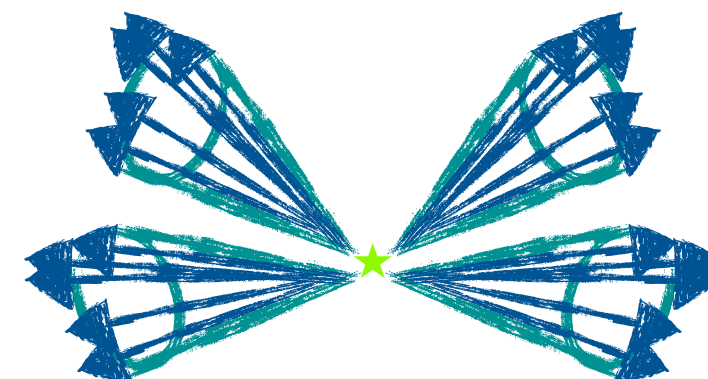
HH →  $\gamma\gamma bb$



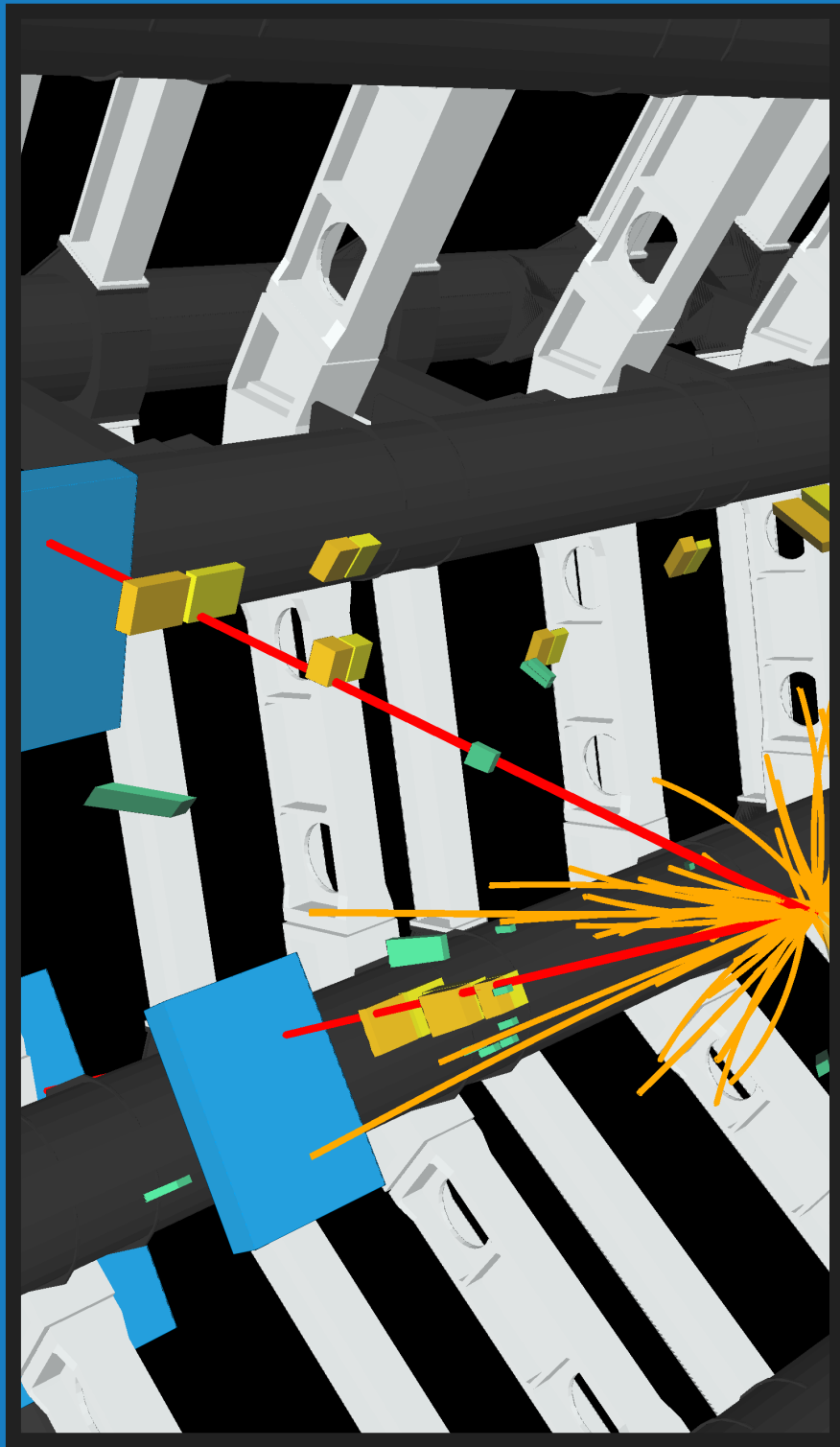
HH → bb $\tau\tau$



HH → bbbb

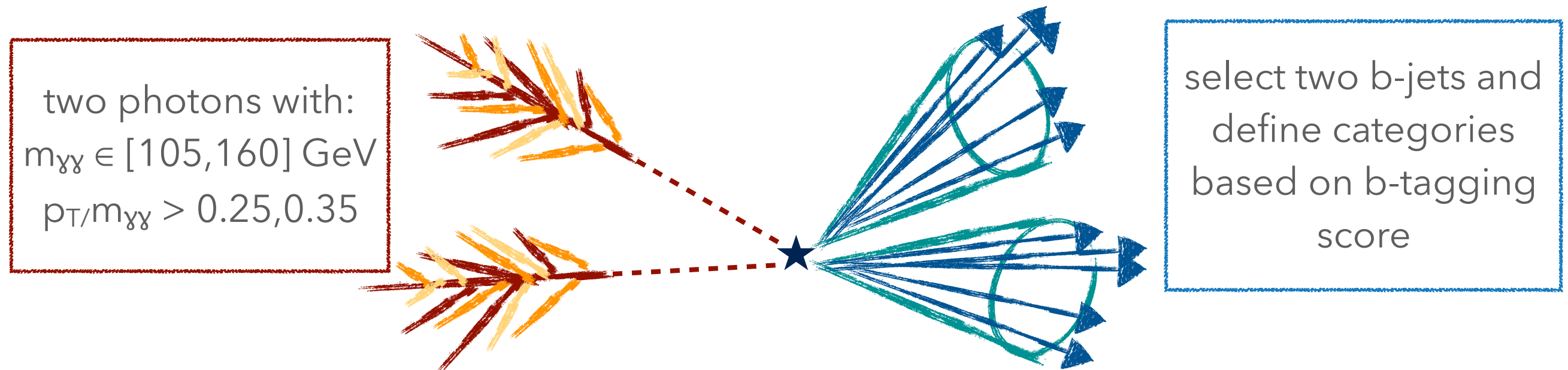


I will present details of ATLAS searches in the three most sensitive channels, and then compare the ATLAS and CMS combinations



ATLAS

$HH \rightarrow \gamma\gamma bb$

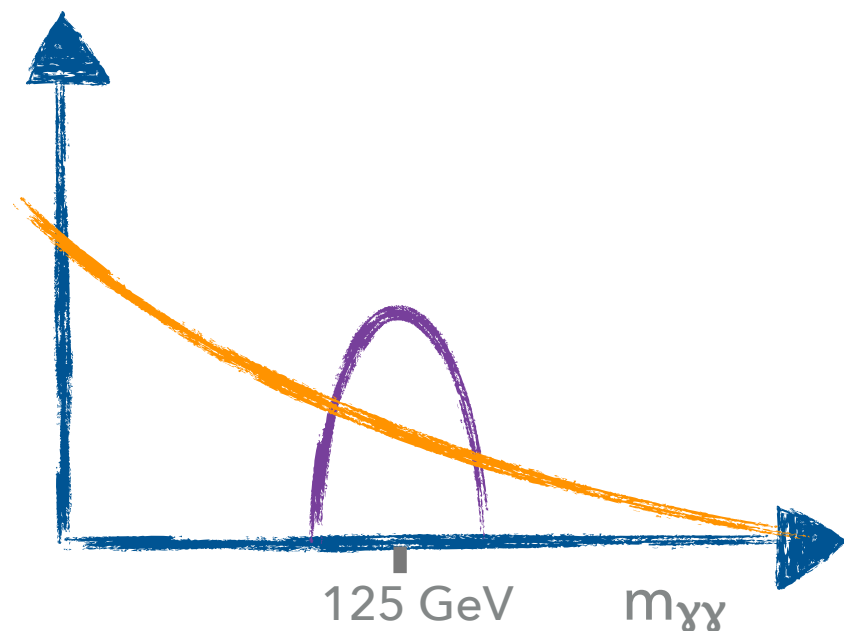


- ▶ require two b-tagged jets, with  $|\eta| < 2.5$ ,  $p_T > 25 \text{ GeV}$ :
  - ▶ **if:** two jets pass loose b-tagging: **2 b-tag category (most sensitive)**
  - ▶ **else if:** one jet passes tight b-tagging: 1 b-tag category (use BDT to choose 2nd jet)
  - ▶ **else:** 0 b-tag control region

# How do we search for $HH \rightarrow \gamma\gamma bb$ ?

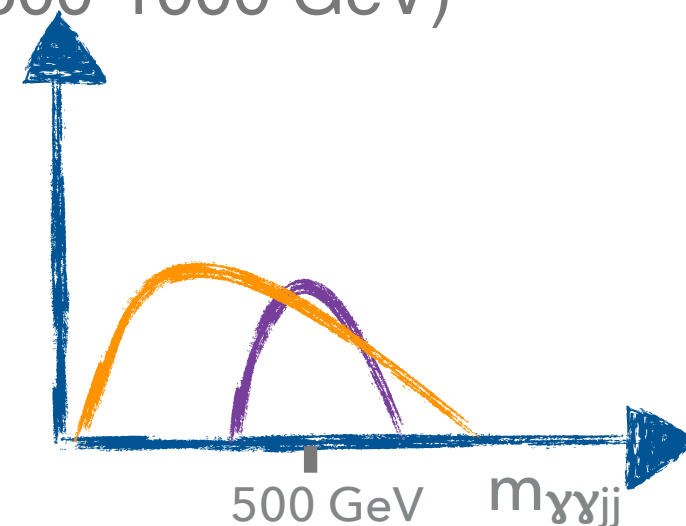
## non-resonant search

- Cut on  $m_{bb}$ , fit the data in  $m_{\gamma\gamma}$ 
  - **signal**: Double-sided Crystal Ball
  - **background**: exponential



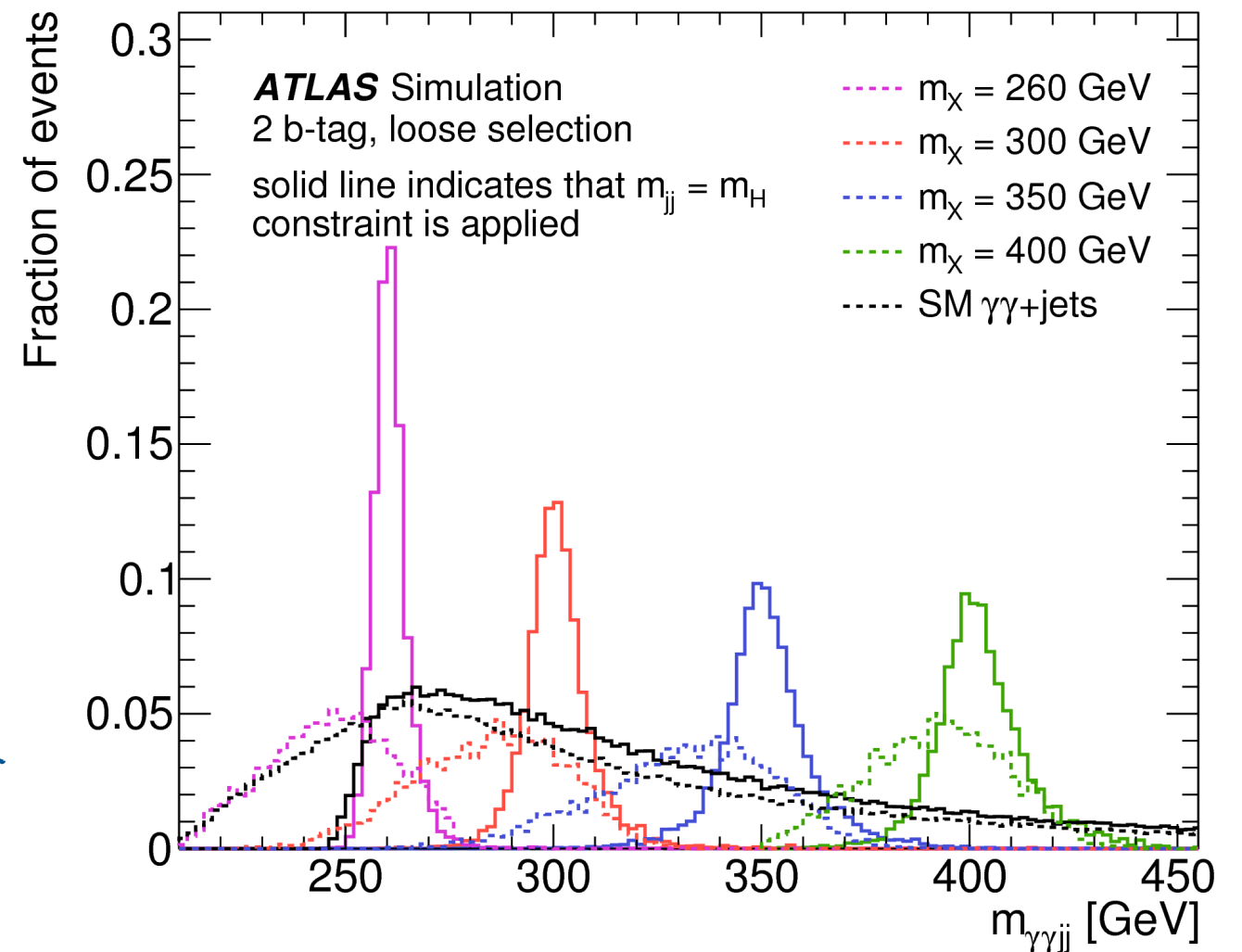
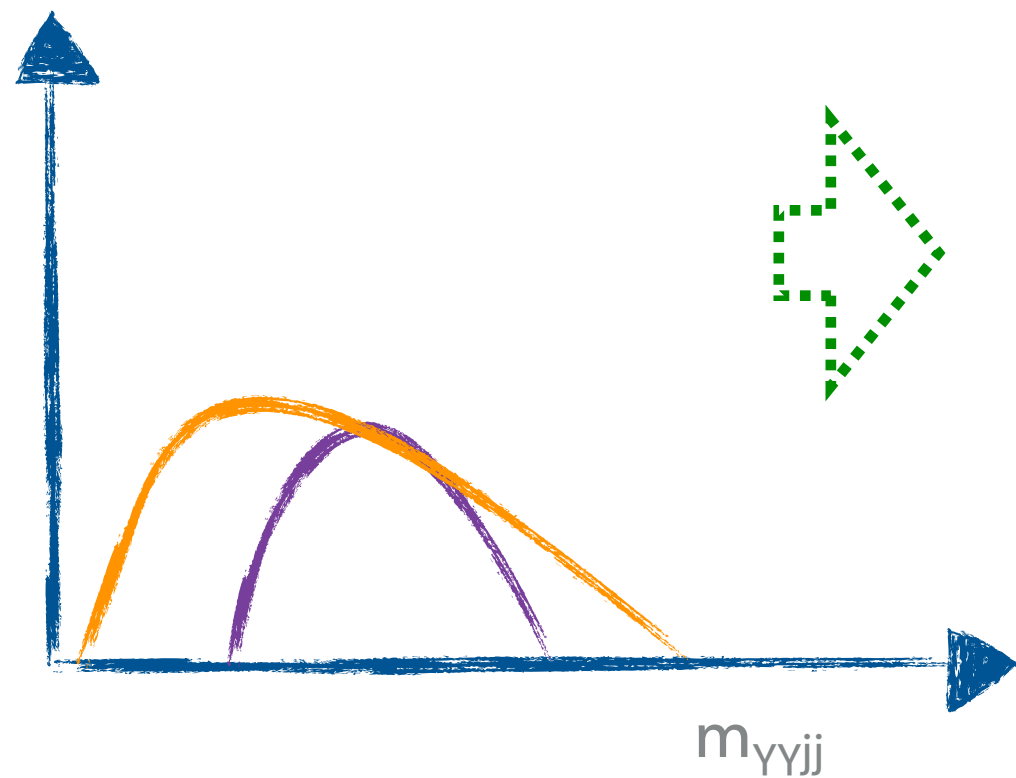
## resonant search

- Cut on  $m_{bb}$  and  $m_{\gamma\gamma}$ , fit the data in  $m_{\gamma\gamma jj}$ 
  - **signal**: Gaussian with exponential tails
  - **background**: Novosibirsk for low masses (260-500 GeV), exponential for high masses (500-1000 GeV)



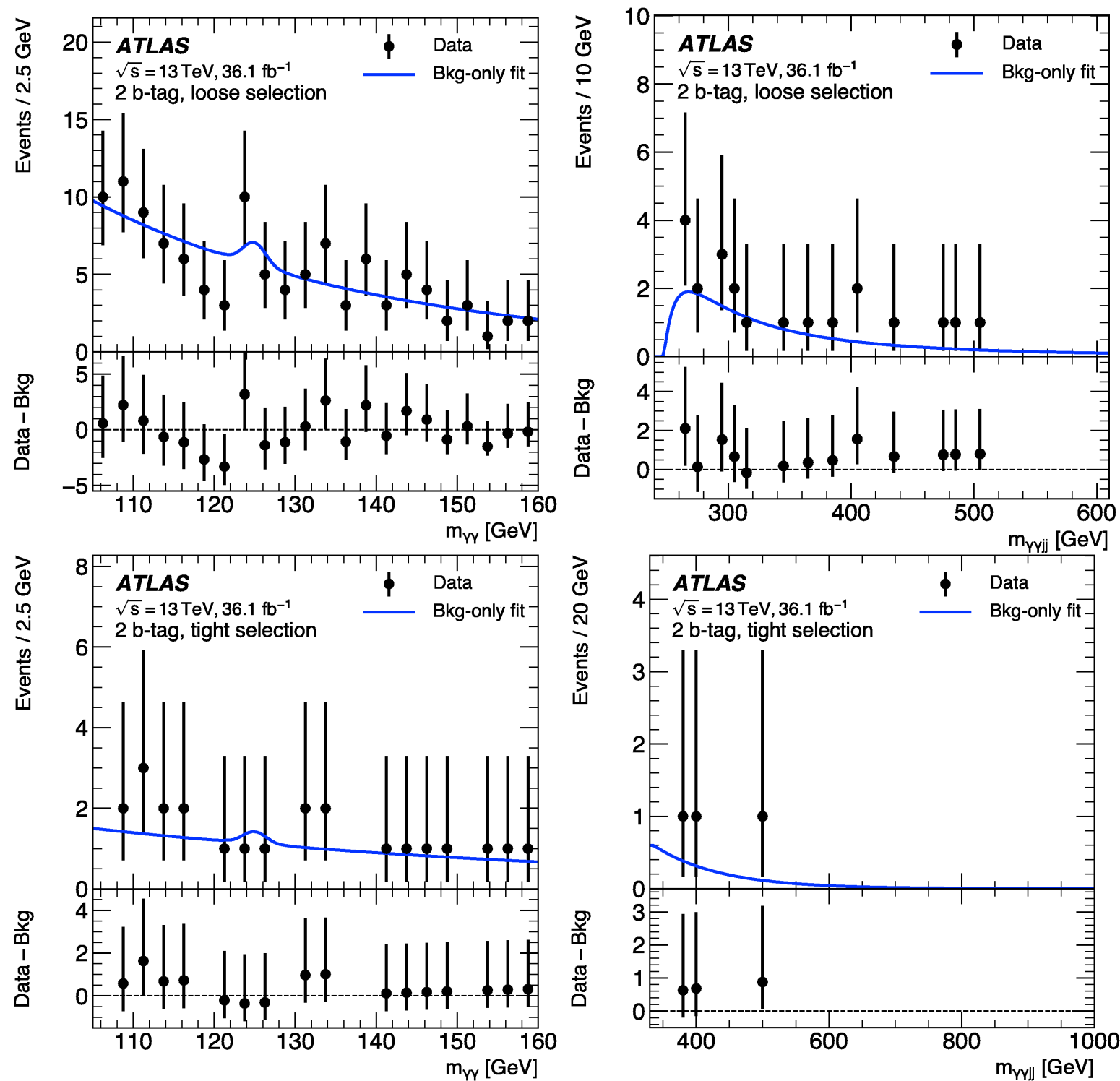
# $\gamma\gamma b\bar{b}$ : Resonant Modeling

Scale the dijet mass to 125 GeV for both **signal** and **background**:



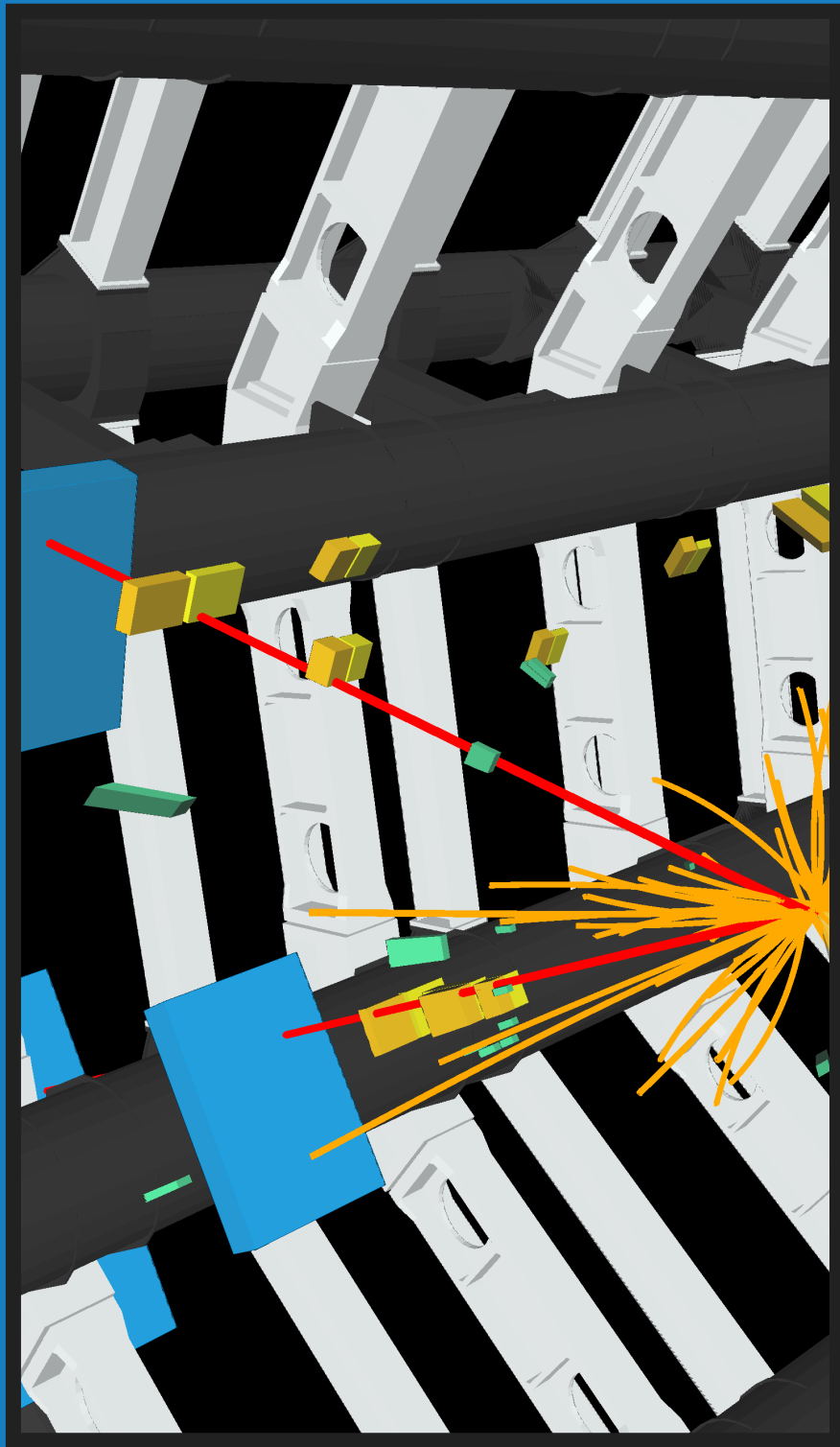
This improves the signal resolution and accuracy

# $\chi\chi b\bar{b}$ : Comparison of Data to Background-only Fit



- Fit 1- and 2 b-tag categories in data simultaneously
- No significant excess observed → set limits

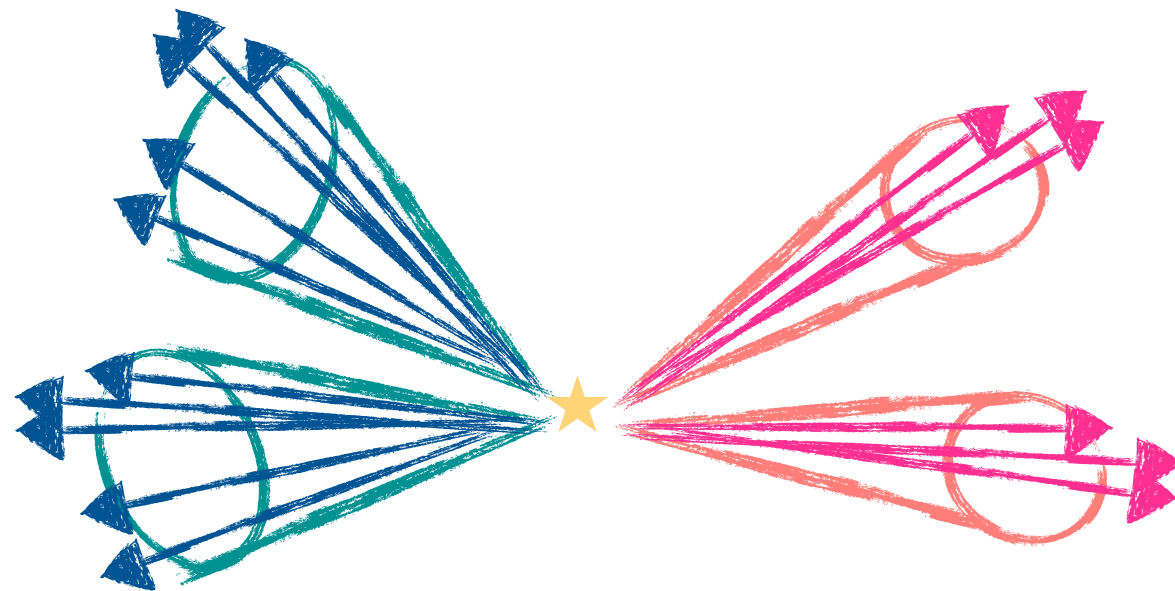




ATLAS

$HH \rightarrow bb\tau\tau$

two b-jets with:  
loose b-tag,  
 $p_T > 45, 20 \text{ GeV}$



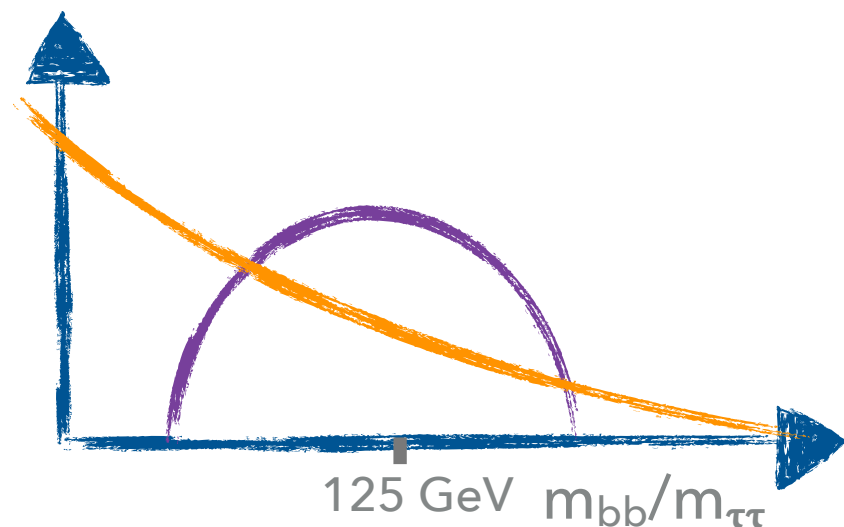
select two taus (or  
one light lepton and  
one tau) with  
opposite sign and  
 $m_{\tau\tau}^{\text{MMC}} > 60 \text{ GeV}$

two selections: lep+had, had+had – based on the tau decays

# How do we search for $HH \rightarrow bb\tau\tau$ ?

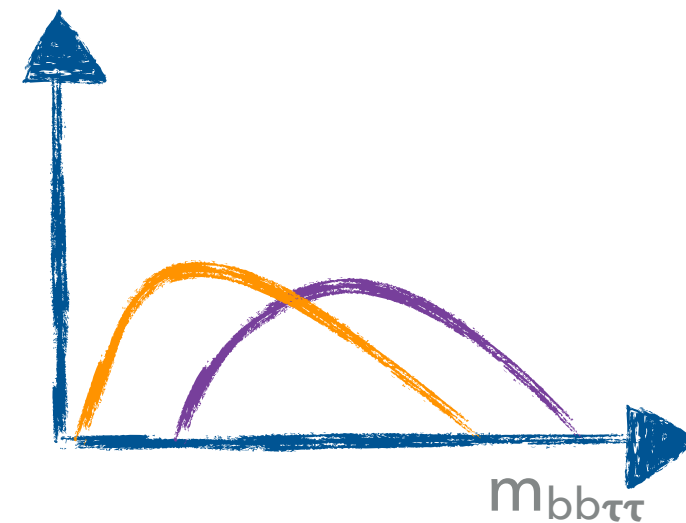
## non-resonant search

- Train a BDT on SM  $HH$  signal, and on signal with varied self-coupling ( $\kappa_\lambda = 20$ )
- Simultaneous fit of 3 BDT distributions (one had+had, two lep+had- based on the triggers used)



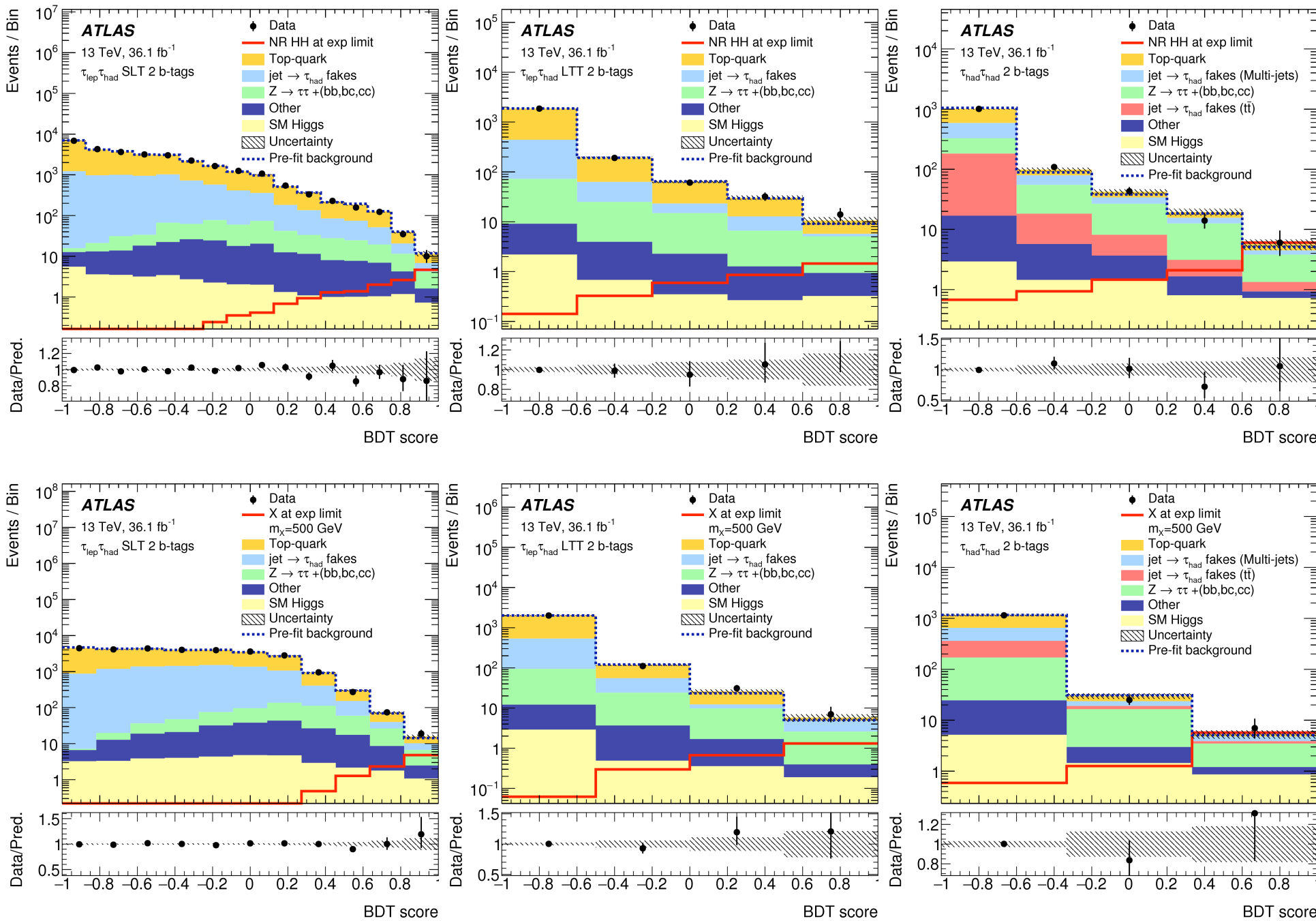
## resonant search

- Train a dedicated BDT for each mass point
- Fit the 3 BDT results for each mass point



# bb $\tau\tau$ : Comparison of Data to BDT Output

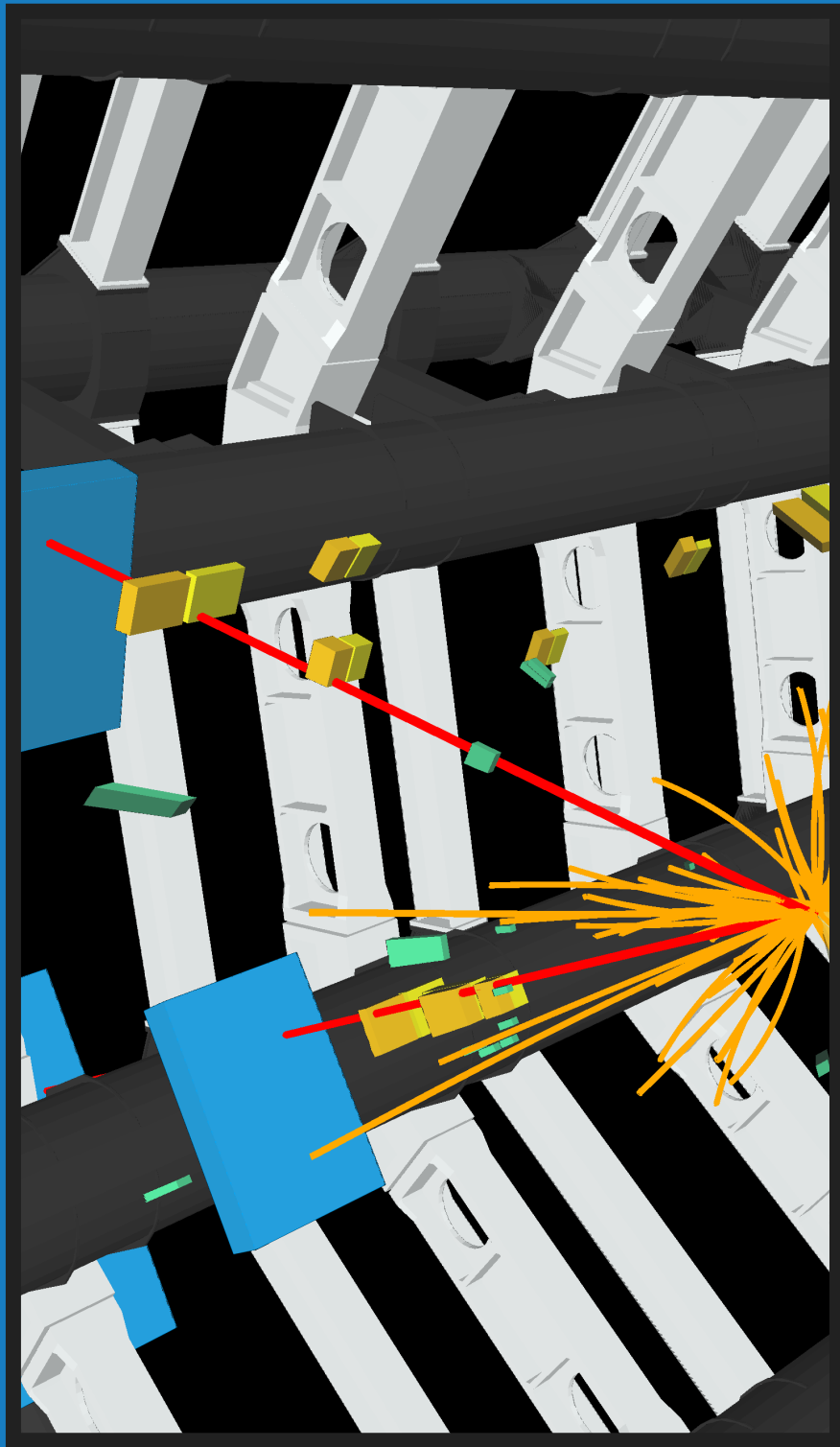
## SM HH signal



► Simultaneous fit of three categories (lep+had SLT, LTT and had+had)

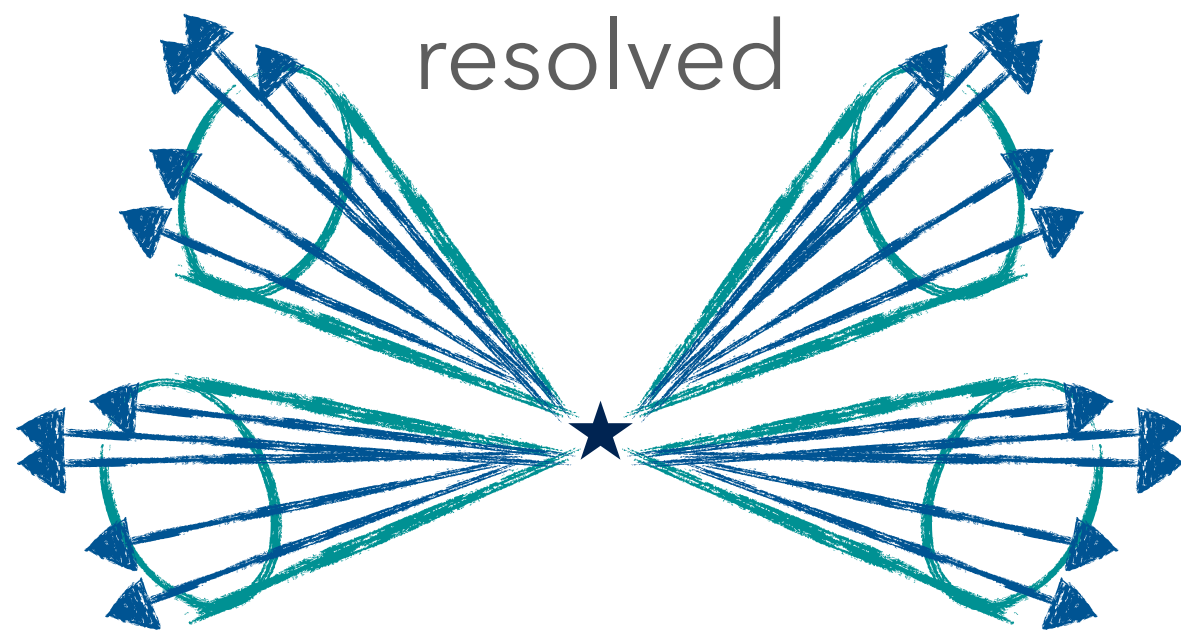
► No significant excess observed  $\rightarrow$  set limits

## resonant HH signal (500 GeV)

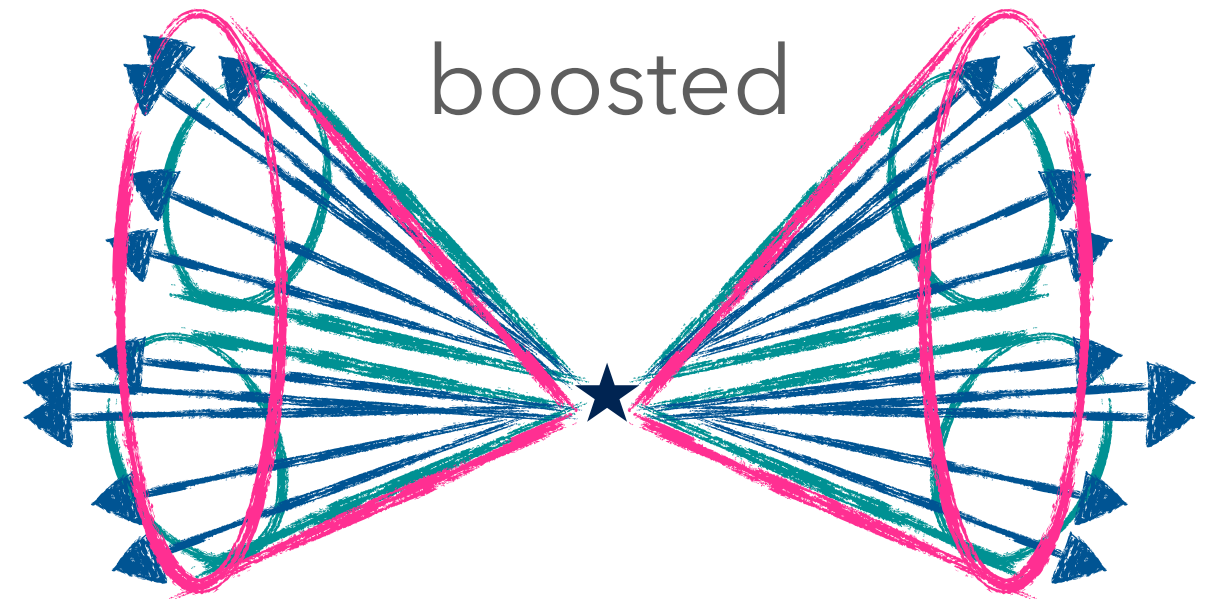


ATLAS

$HH \rightarrow b\bar{b}b\bar{b}$



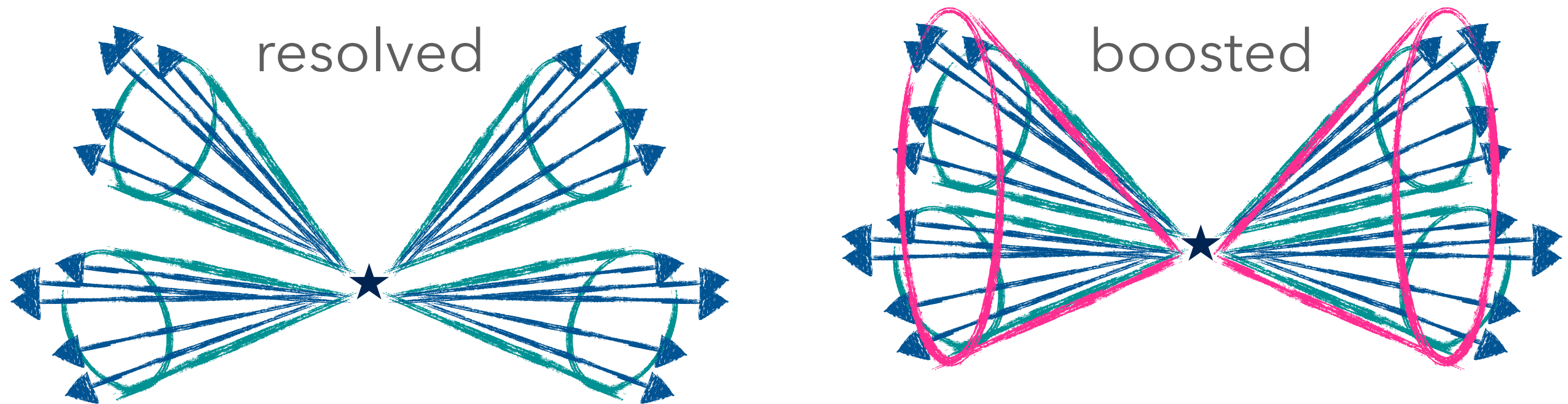
$\geq 4$  b-tagged jets,  
 $p_T > 40$  GeV



$\geq 2$  large-R (1.0) jets  
( $\geq 1$  (R=0.2)  
b-tagged jet in each)

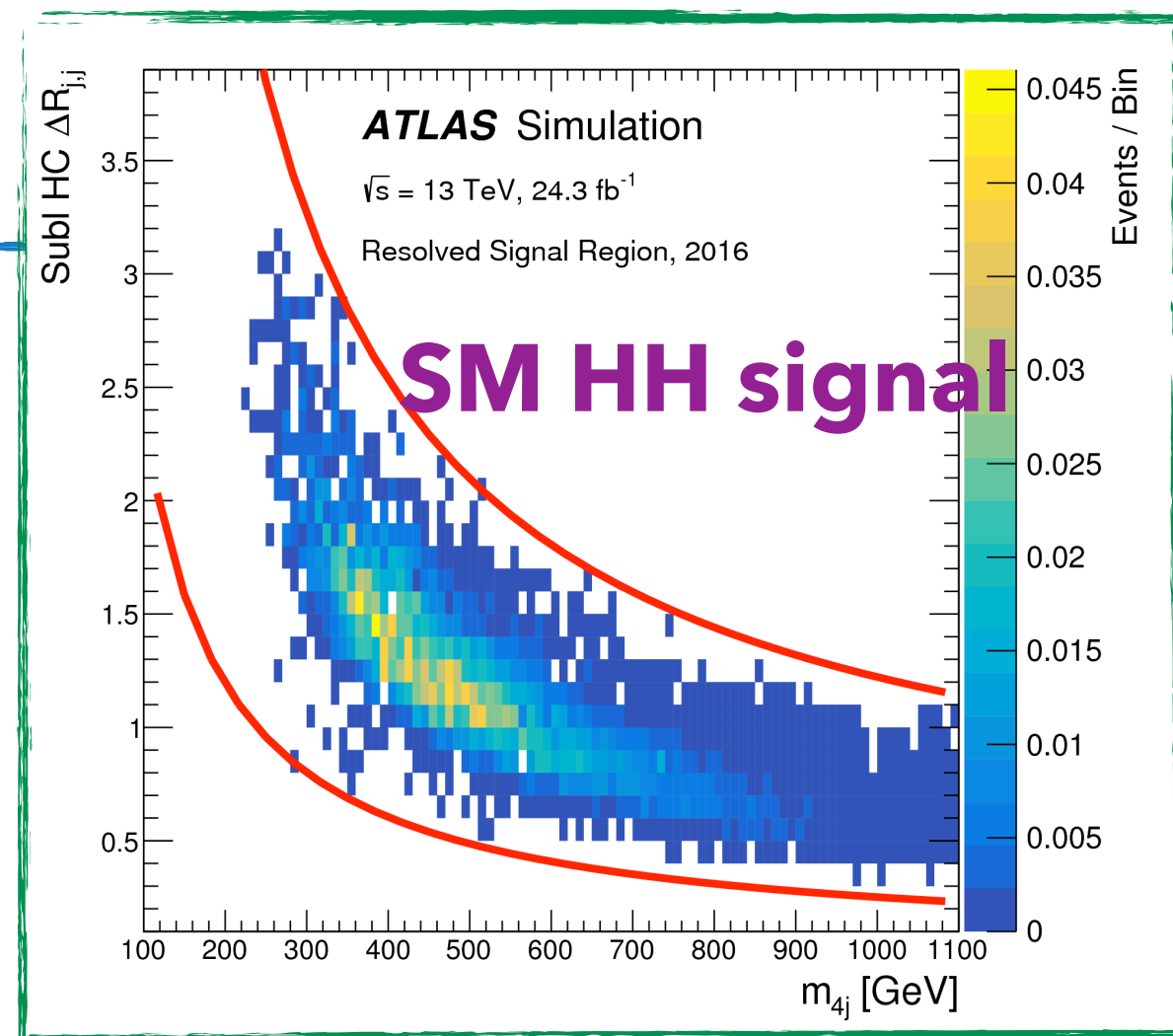
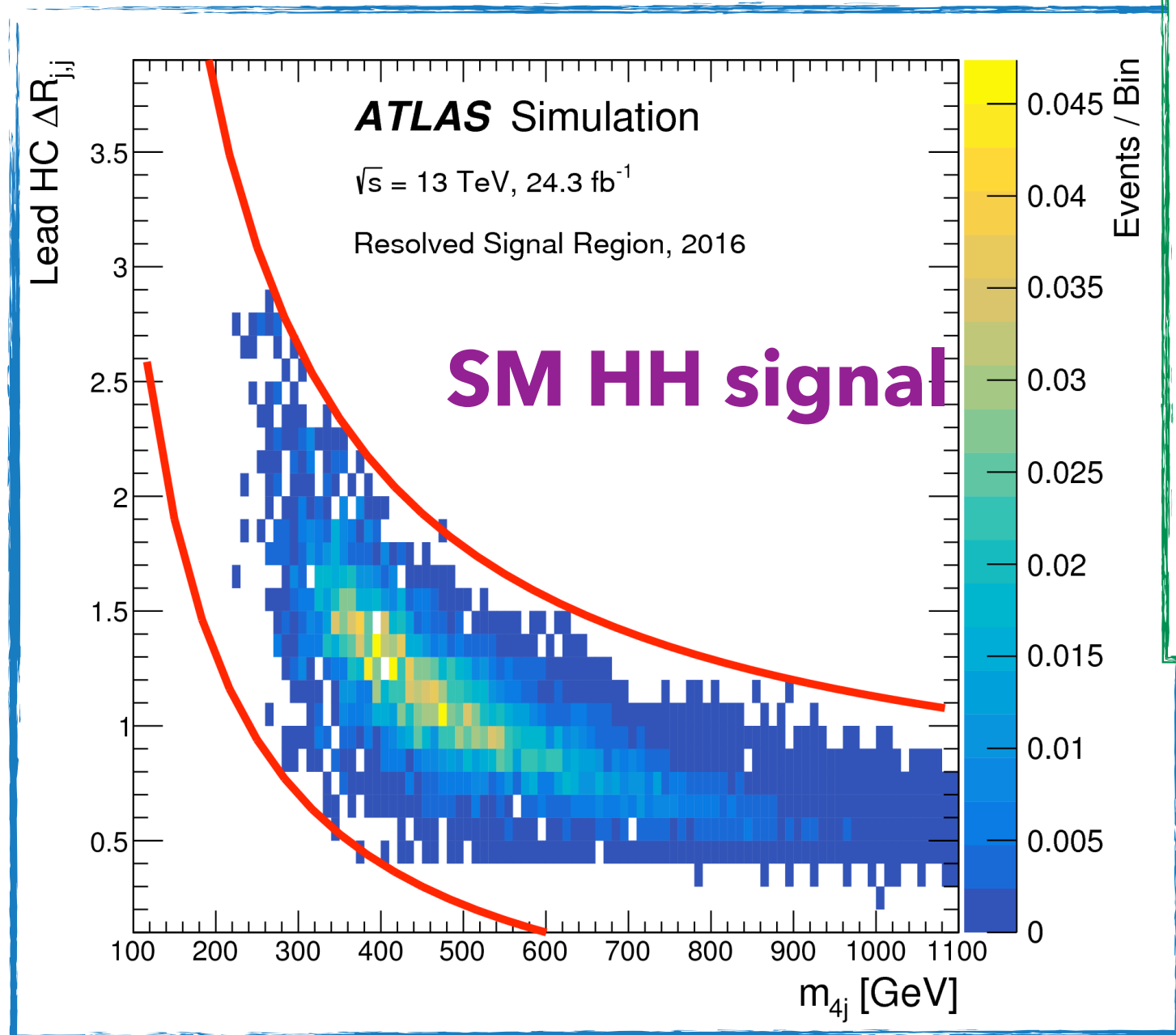


# bbbb: Event Reconstruction



- ▶ Resolved: angle between the two jets depends on the Lorentz boost, and thus the four-jet mass
  - ▶ four-jet-mass dependent cuts on  $\Delta R(j,j)$  to reconstruct the two Higgs candidates
- ▶ Boosted: signal eff. depends on four-jet mass (2b cat. most efficient at high mass)

# bbbb: Event Reconstruction



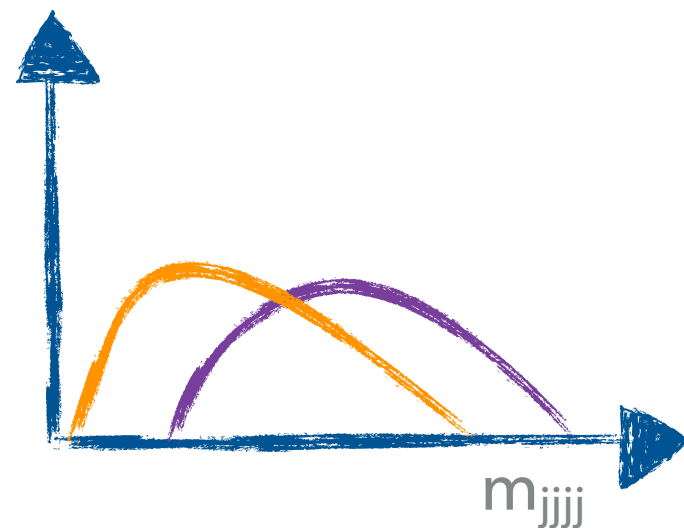
# How do we search for $HH \rightarrow bbbb$ ?

## non-resonant search

- use resolved selection only
- unlike the other di-Higgs searches, the discriminant variable in the search is  $m_{jjjj}$ 
  - scale  $m_{jj}$  to  $m_H$  when reconstructing the four-body mass
- **main backgrounds:**
  - QCD multijet (95%)
  - $t\bar{t}$  (5%)

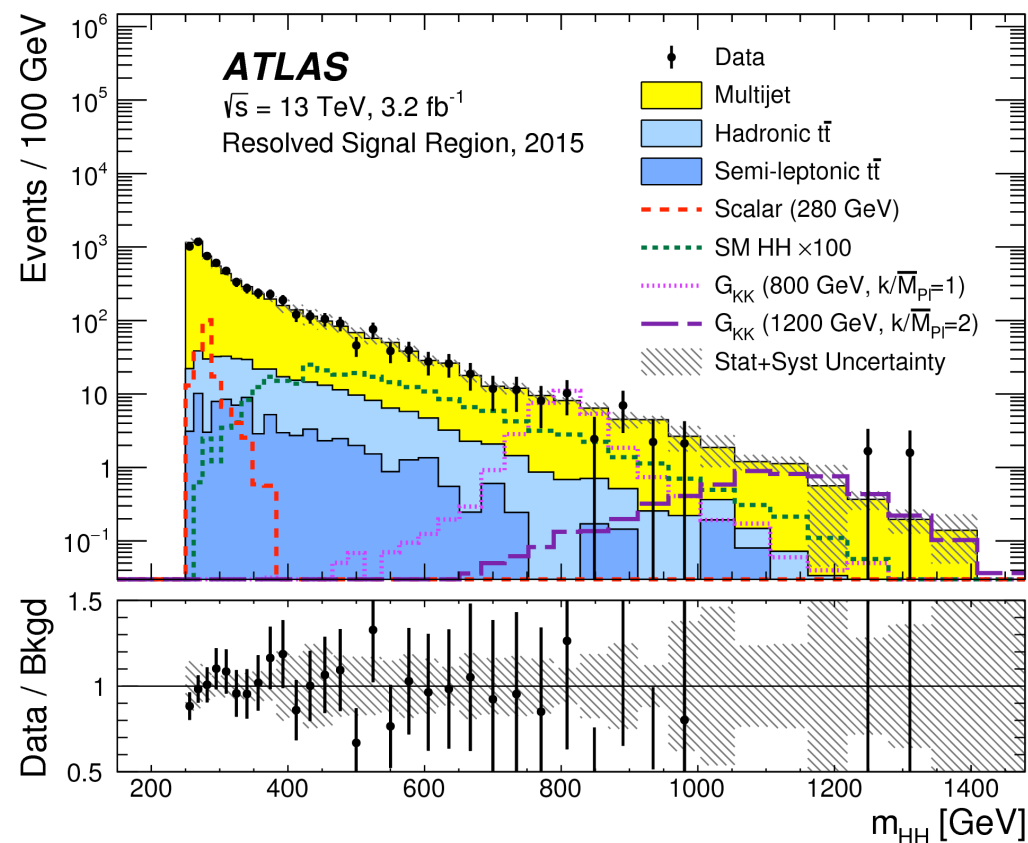
## resonant search

- resolved:
  - target  $m_X$  from 260-1400 GeV
- boosted:
  - target  $m_X$  from 800-3000 GeV

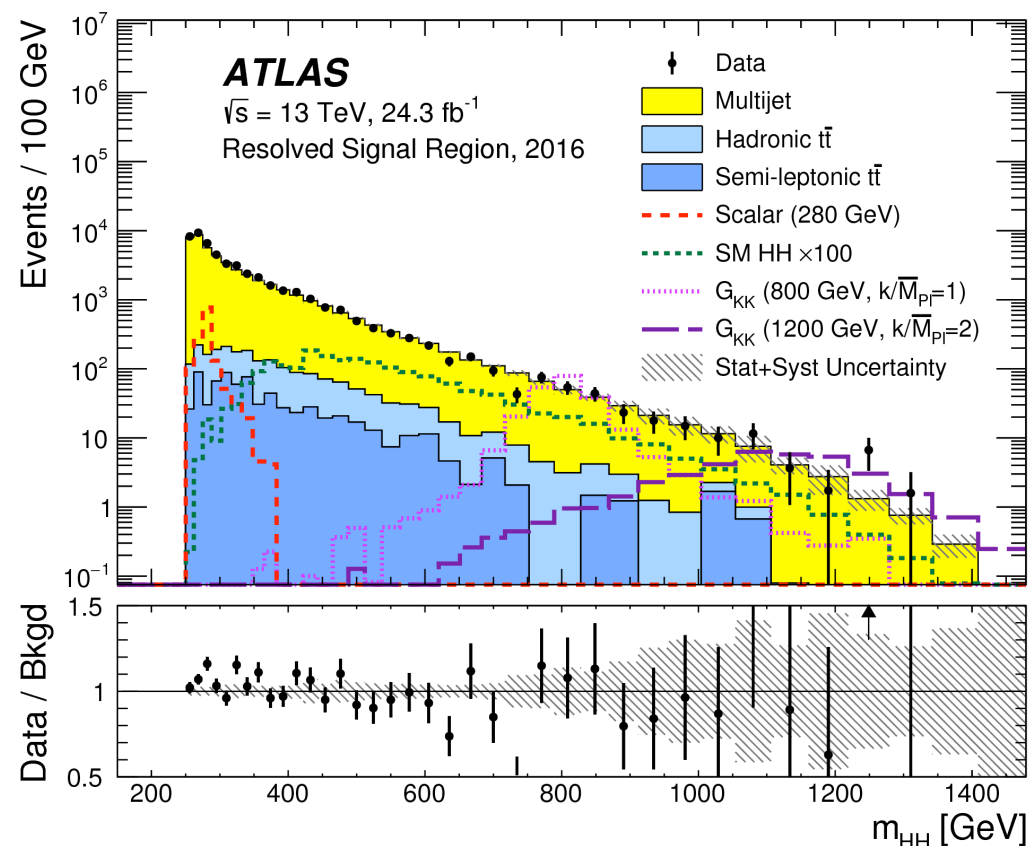


# bbbb: Comparison of Data to Background Model

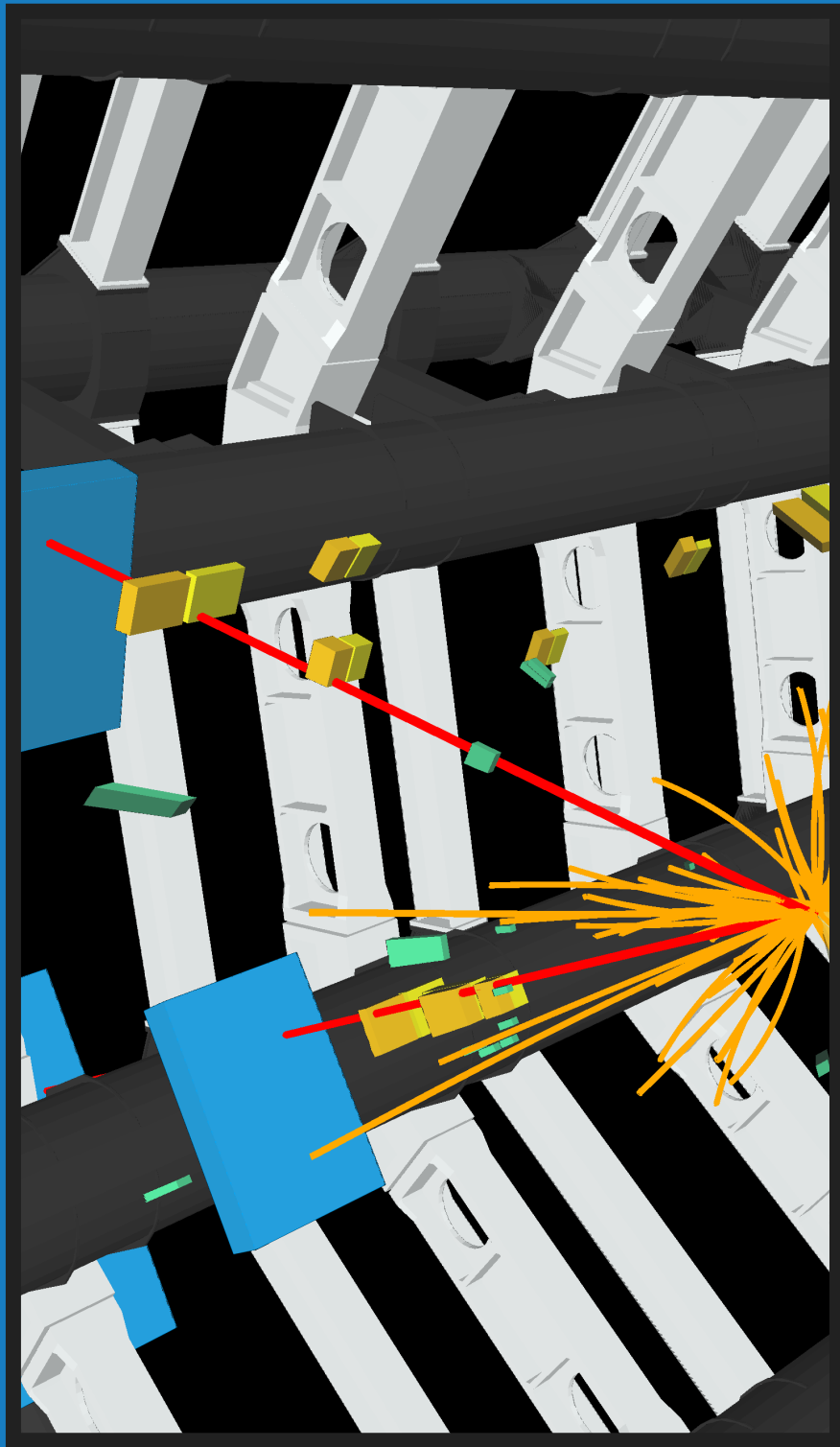
2015



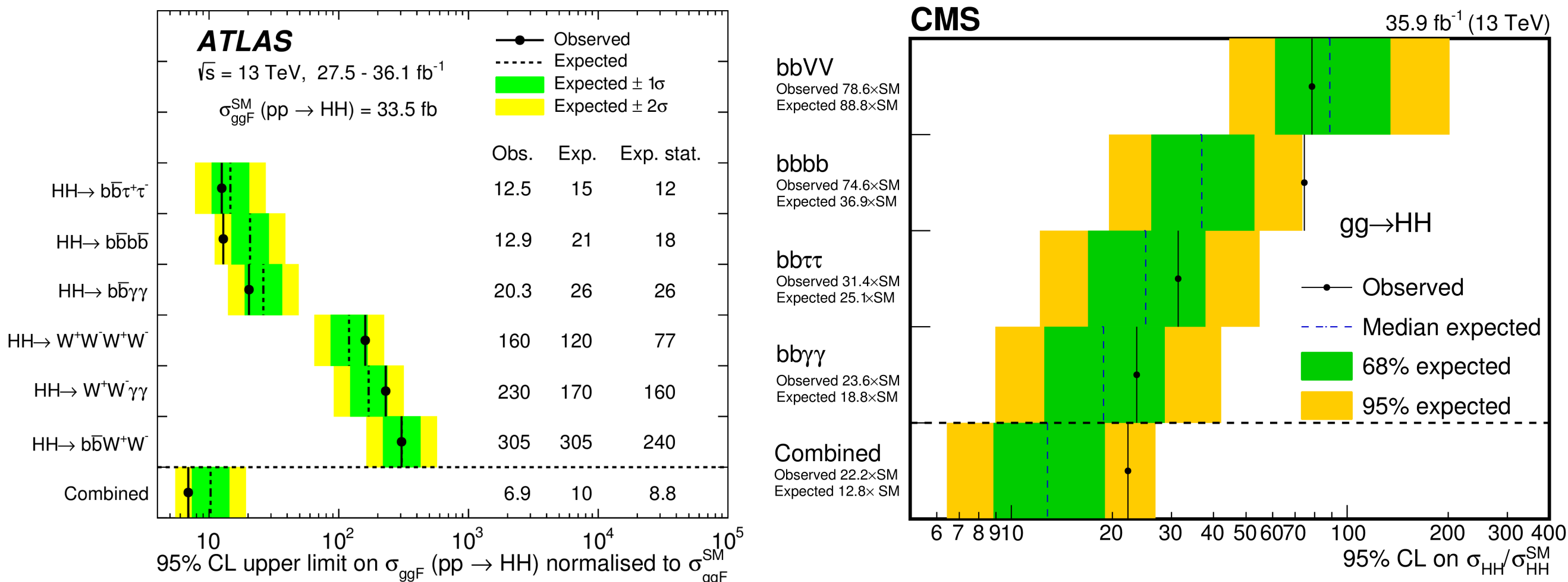
2016



- ▶ Profile likelihood fit to 2015+2016 data simultaneously (resolved) and 2-, 3-, and 4-tag signal regions (boosted)
- ▶ No significant excess observed → set limits



# ATLAS AND CMS HH RESULTS

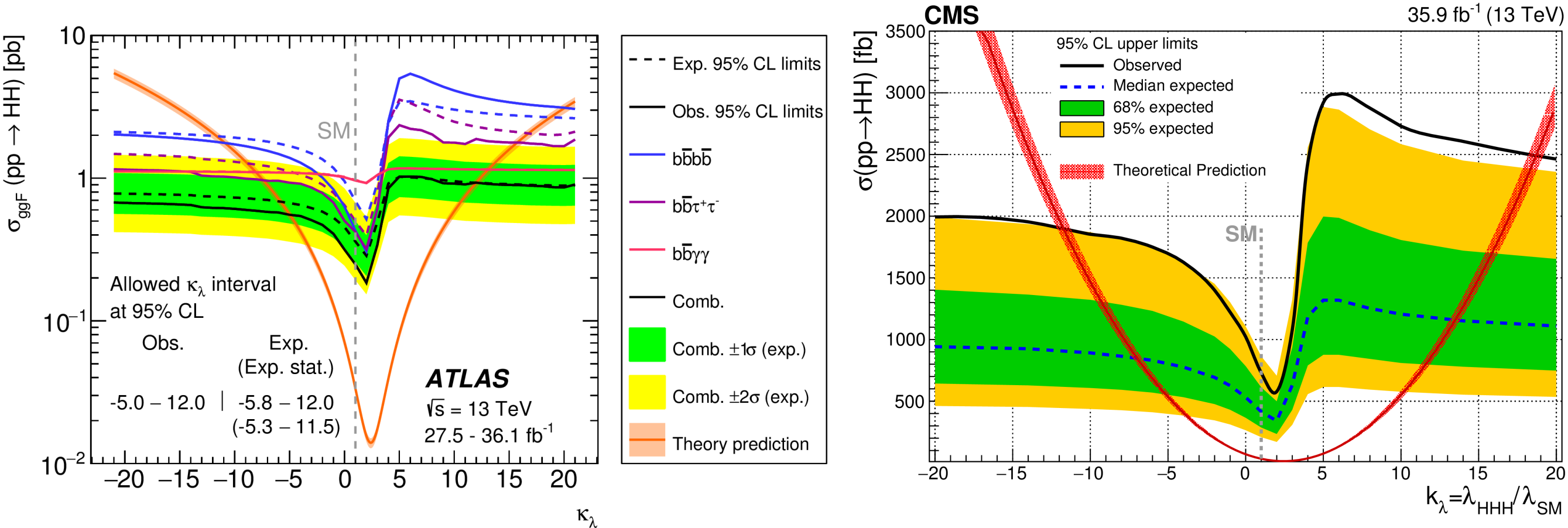


|                                               | ATLAS                      |                                              | CMS                        |                                              |
|-----------------------------------------------|----------------------------|----------------------------------------------|----------------------------|----------------------------------------------|
|                                               | observed                   | expected                                     | observed                   | expected                                     |
| $\text{HH} \rightarrow \gamma\gamma\text{bb}$ | $20.4^*\sigma_{\text{SM}}$ | $26.3^*\sigma_{\text{SM}}$                   | $23.6^*\sigma_{\text{SM}}$ | <b><math>18.8^*\sigma_{\text{SM}}</math></b> |
| $\text{HH} \rightarrow \text{bb}\tau\tau$     | $12.6^*\sigma_{\text{SM}}$ | <b><math>14.6^*\sigma_{\text{SM}}</math></b> | $31.4^*\sigma_{\text{SM}}$ | $25.1^*\sigma_{\text{SM}}$                   |
| $\text{HH} \rightarrow \text{bbbb}$           | $12.9^*\sigma_{\text{SM}}$ | <b><math>20.7^*\sigma_{\text{SM}}</math></b> | $74.6^*\sigma_{\text{SM}}$ | $36.9^*\sigma_{\text{SM}}$                   |
| combination                                   | $6.7^*\sigma_{\text{SM}}$  | <b><math>10.4^*\sigma_{\text{SM}}</math></b> | $22.2^*\sigma_{\text{SM}}$ | $12.8^*\sigma_{\text{SM}}$                   |



# Limits on the Higgs Self-Coupling

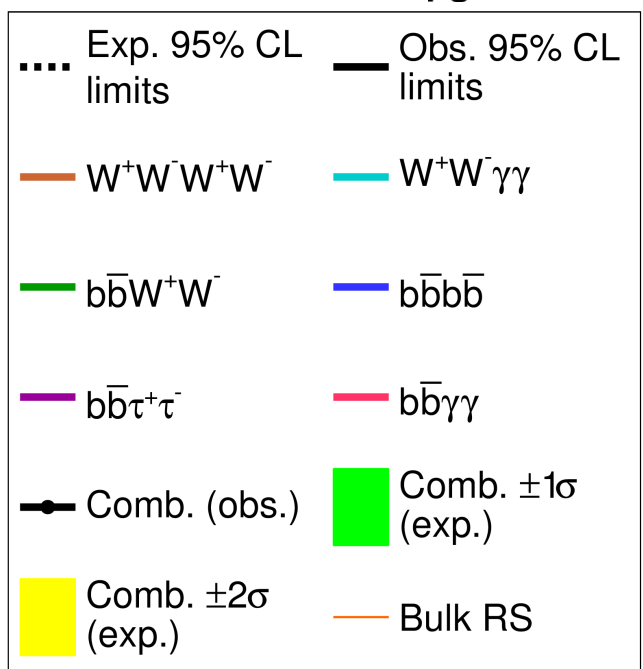
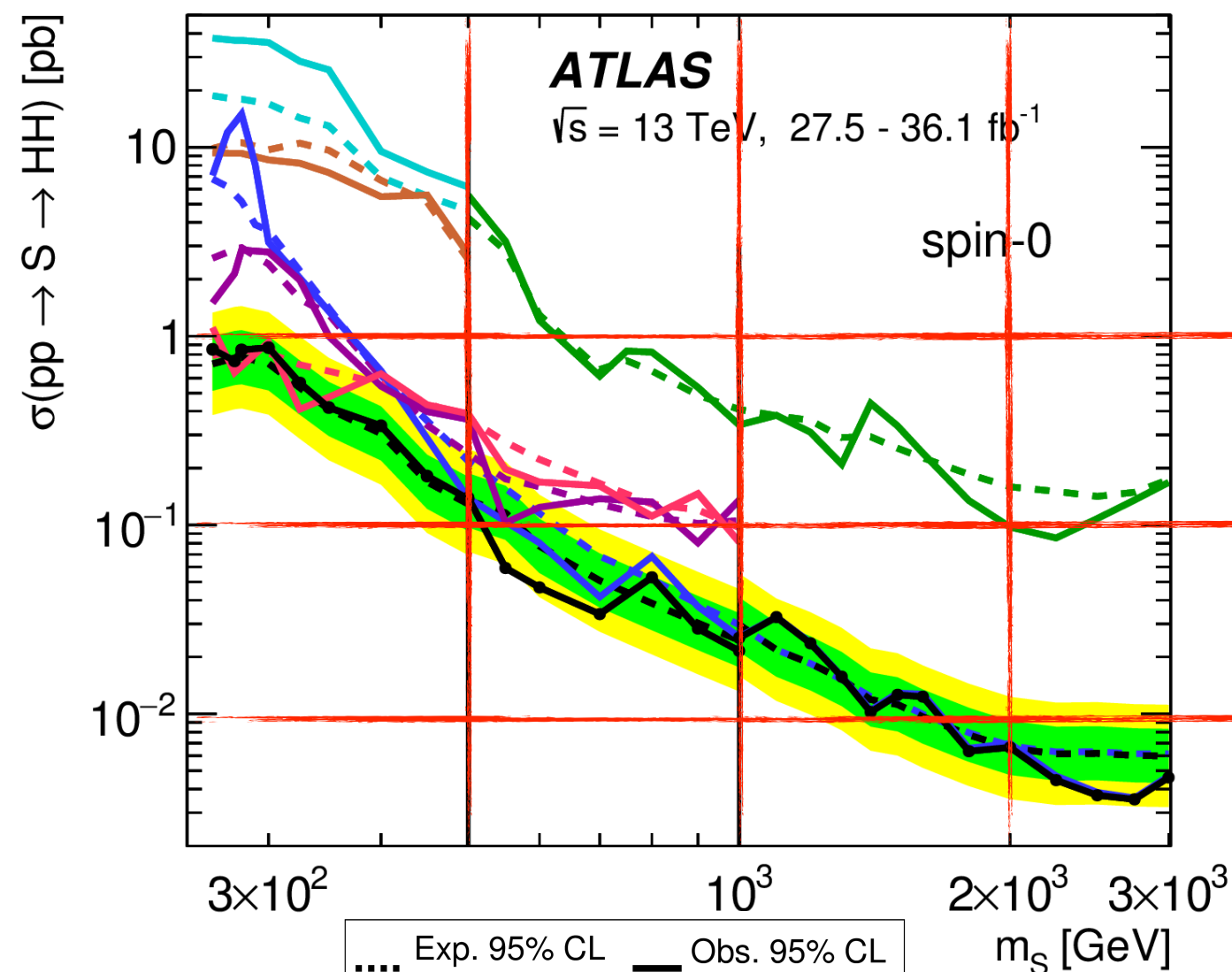
ATLAS: [submitted to Phys. Lett. B](#)  
CMS: [Phys. Rev. Lett. 122 \(2019\) 121803](#)



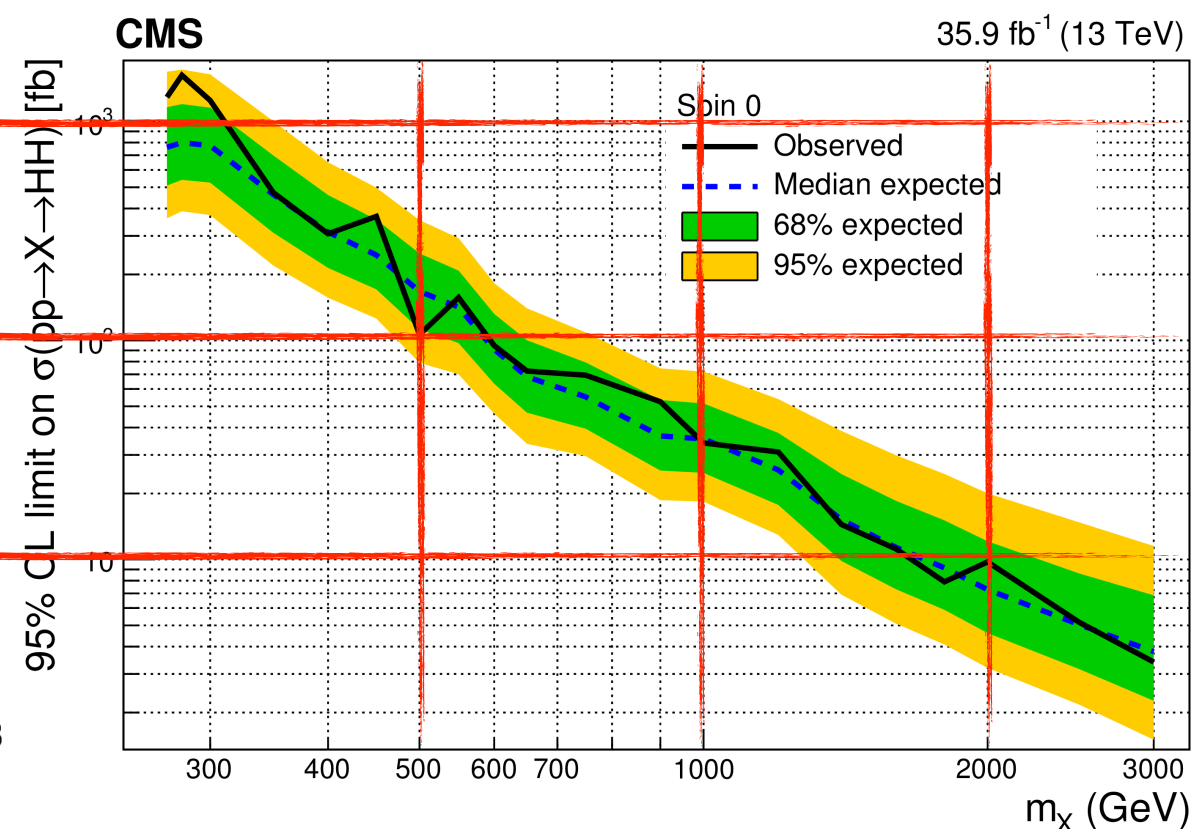
| ATLAS                          |                                                        | CMS                             |                                |
|--------------------------------|--------------------------------------------------------|---------------------------------|--------------------------------|
| observed                       | expected                                               | observed                        | expected                       |
| $-5.0 < \kappa_\lambda < 12.1$ | <b><math>-5.8 &lt; \kappa_\lambda &lt; 12.0</math></b> | $-11.8 < \kappa_\lambda < 18.8$ | $-7.1 < \kappa_\lambda < 13.6$ |

# Resonant Limits: $\sigma(S) \cdot \text{BR}(S \rightarrow \text{HH})$

ATLAS: [submitted to Phys. Lett. B](#)  
CMS: [Phys. Rev. Lett. 122 \(2019\) 121803](#)



vertical red lines at 500, 1000, 2000 GeV



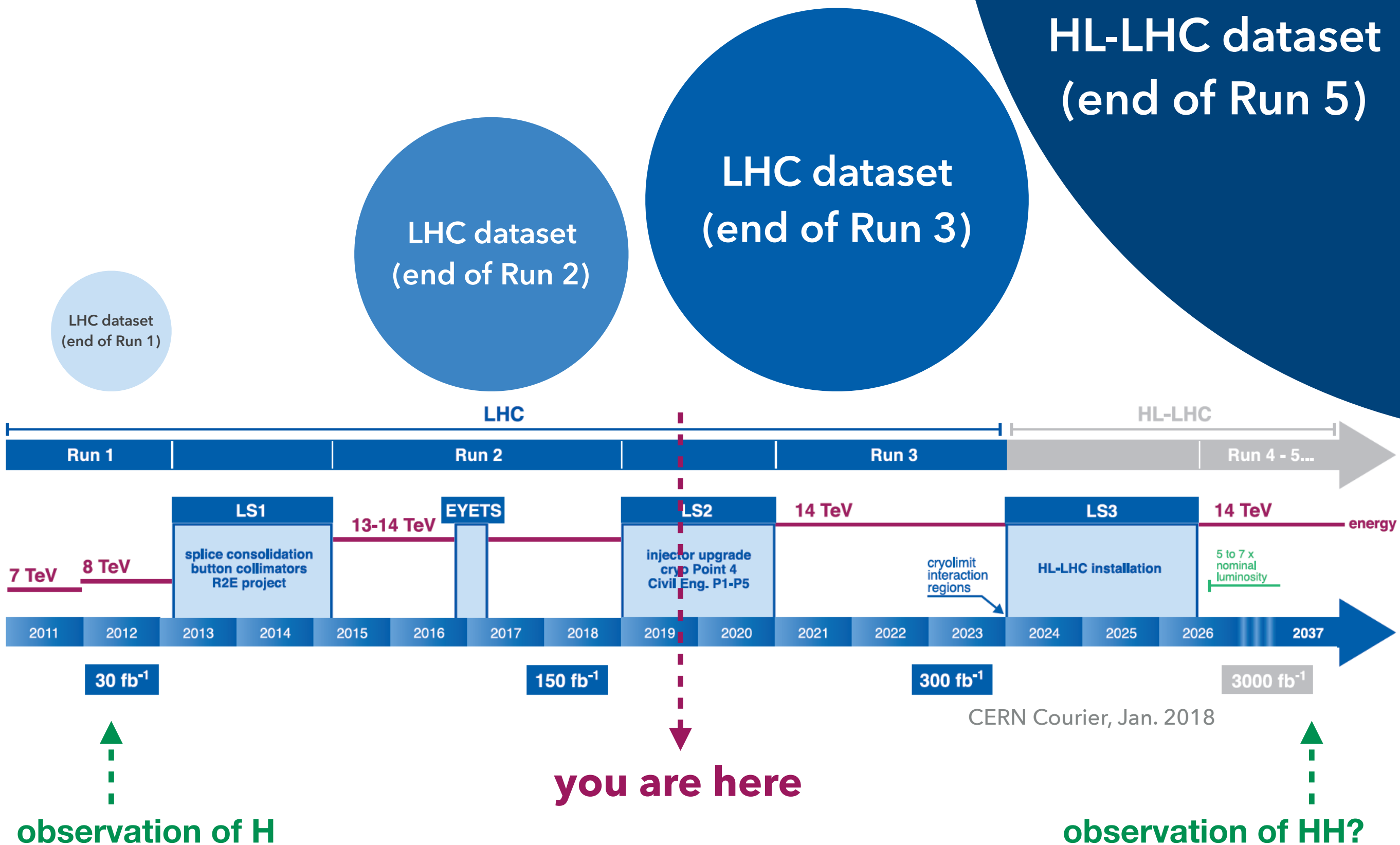
ATLAS and CMS resonant HH results are very similar across the mass range  $\sim 280 - 3000 \text{ GeV}$

# Conclusions

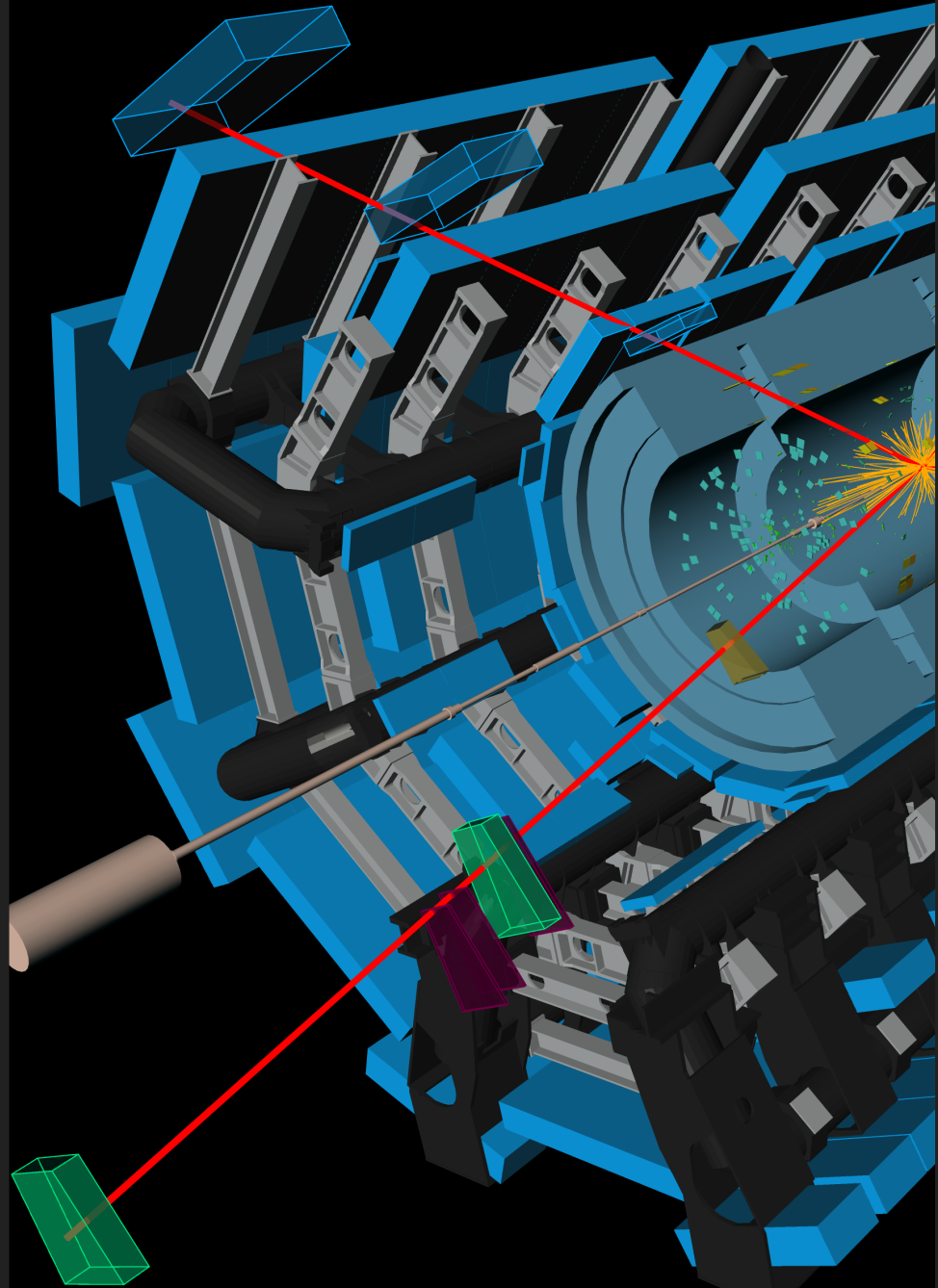
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- ▶ Studying electroweak symmetry breaking is one of the long-term goals of the LHC
- ▶ Measuring the Higgs self-coupling is one of the final open points in our suite of measurements of the properties of the Higgs boson— and it is nearly within our reach (at the HL-LHC?)
- ▶ Keeping up with our current rate of progress will require novel experimental techniques and data-collection methods!

# LHC Data Collection



Run: 338220  
Event: 2718372349  
2017-10-15 00:50:49 CEST



# BACKUP SLIDES

# $\gamma\gamma b\bar{b}$ : Details on Monte Carlo samples

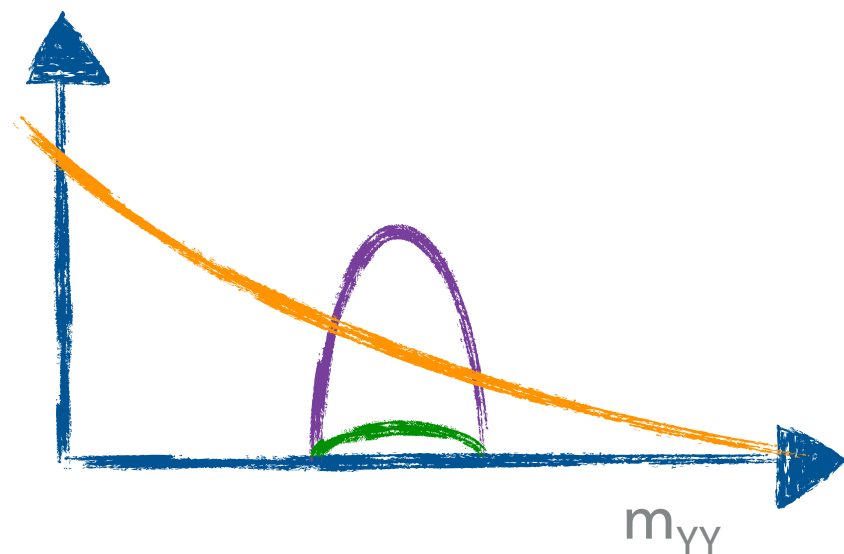
| Process                   | Generator                      | Showering | PDF set      | $\sigma$ [fb] | Order of calculation of $\sigma$ | Simulation |
|---------------------------|--------------------------------|-----------|--------------|---------------|----------------------------------|------------|
| Non-resonant SM $HH$      | MADGRAPH5_aMC@NLO              | Herwig++  | CT10 NLO     | 33.41         | NNLO+NNLL                        | Fast       |
| Non-resonant BSM $HH$     | MADGRAPH5_aMC@NLO              | PYTHIA 8  | NNPDF 2.3 LO | -             | LO                               | Fast       |
| Resonant BSM $HH$         | MADGRAPH5_aMC@NLO              | Herwig++  | CT10 NLO     | -             | NLO                              | Fast       |
| $\gamma\gamma$ plus jets  | SHERPA                         | SHERPA    | CT10 NLO     | -             | LO                               | Fast       |
| $ggH$                     | POWHEG-Box NNLOPS (r3080) [60] | PYTHIA 8  | PDF4LHC15    | 48520         | N <sup>3</sup> LO(QCD)+NLO(EW)   | Full       |
| VBF                       | POWHEG-Box (r3052) [61]        | PYTHIA    | PDF4LHC15    | 3780          | NNLO(QCD)+NLO(EW)                | Full       |
| $WH$                      | POWHEG-Box (r3133) [62]        | PYTHIA    | PDF4LHC15    | 1370          | NNLO(QCD)+NLO(EW)                | Full       |
| $q\bar{q} \rightarrow ZH$ | POWHEG-Box (r3133) [62]        | PYTHIA 8  | PDF4LHC15    | 760           | NNLO(QCD)+NLO(EW)                | Full       |
| $t\bar{t}H$               | MADGRAPH5_aMC@NLO              | PYTHIA 8  | NNPDF3.0     | 510           | NLO(QCD)+NLO(EW)                 | Full       |
| $gg \rightarrow ZH$       | POWHEG-Box (r3133)             | PYTHIA 8  | PDF4LHC15    | 120           | NLO+NLL(QCD)                     | Full       |
| $b\bar{b}H$               | MADGRAPH5_aMC@NLO              | PYTHIA    | CT10 NLO     | 490           | NNLO(5FS)+NLO(4FS)               | Full       |
| t-channel $tH$            | MADGRAPH5_aMC@NLO              | PYTHIA 8  | CT10 NLO     | 70            | LO(4FS)                          | Full       |
| $W$ -associated $tH$      | MADGRAPH5_aMC@NLO              | Herwig++  | CT10 NLO     | 20            | NLO(5FS)                         | Full       |



# $\gamma\gamma$ bb: Backgrounds

## non-resonant search

- SM Higgs  $\rightarrow \gamma\gamma$ 
  - ggF, VBF, WH, ZH, ttH, bbH, tH
  - shape and normalization from MC
- $\gamma\gamma(+\gamma j + j\gamma + jj) + \text{jets}$ 
  - use MC model to choose a background fit function only



## resonant search

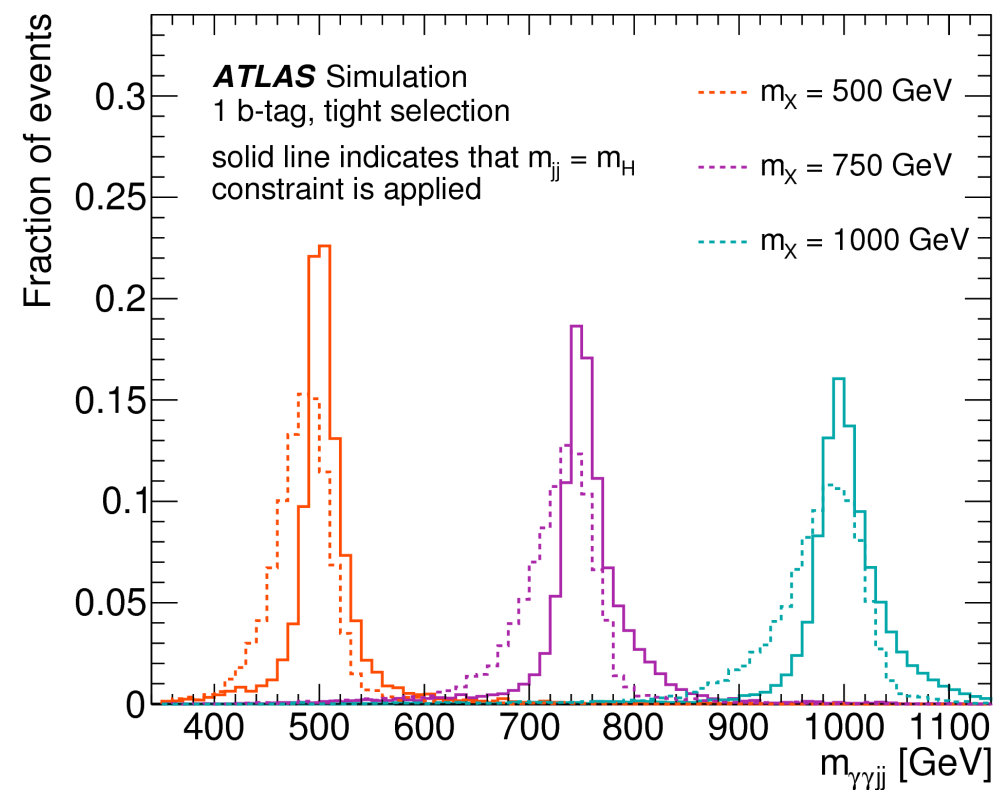
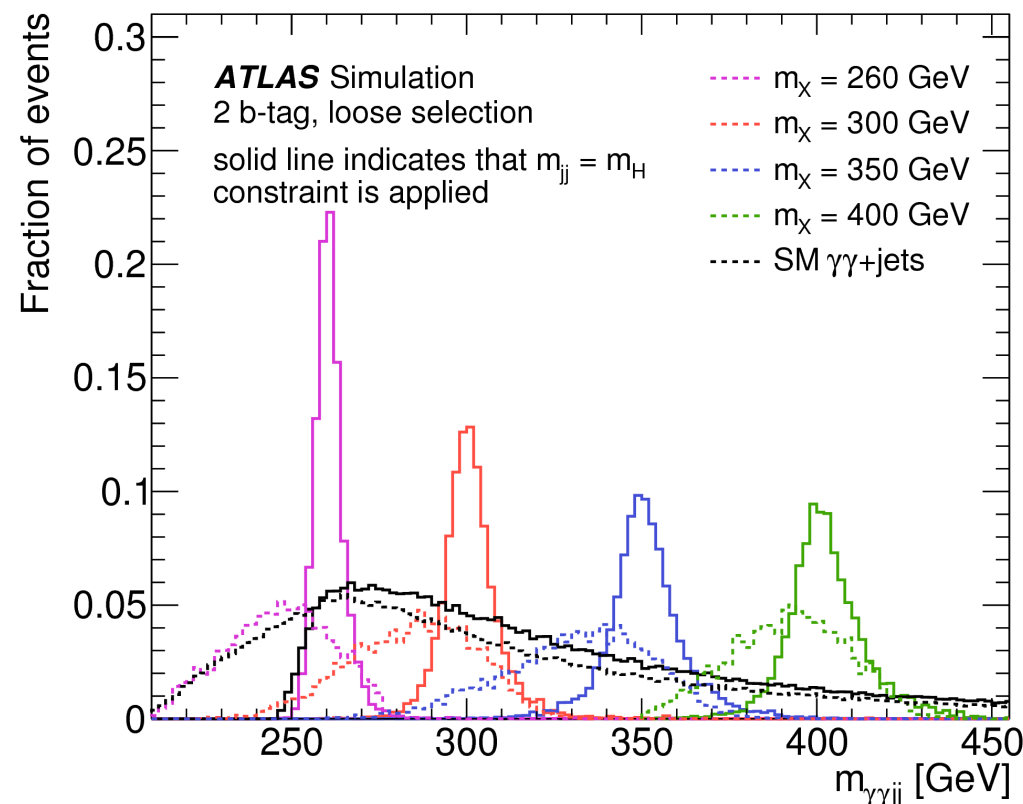
- SM Higgs  $\rightarrow \gamma\gamma$  and SM di-Higgs  $\rightarrow \gamma\gamma$ bb
  - shape and normalization from MC
- $\gamma\gamma + \text{jets}$ 
  - use MC model to choose a background fit function only



# $\gamma\gamma b\bar{b}$ : Resonant Signal Modeling

- ▶ resonant signal is modeled with a Gaussian with exponential tails - simultaneous fit to all mass points
- ▶ constrain  $m_{jj} = m_H$  in the resonant search, to improve four-body mass resolution

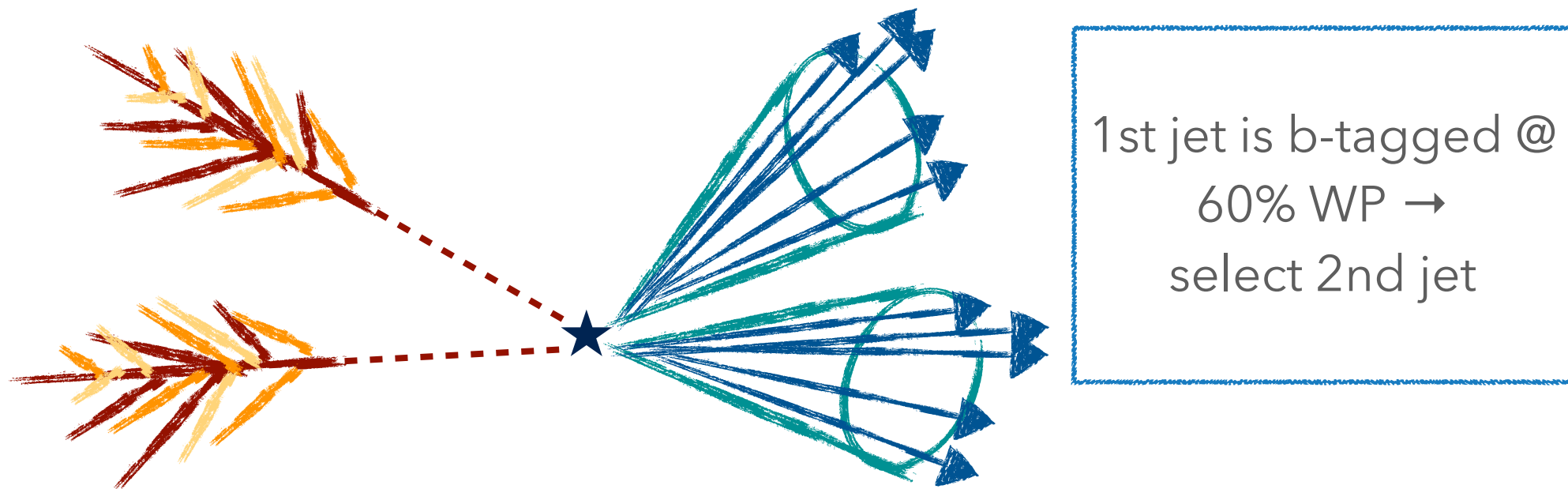
loose selection



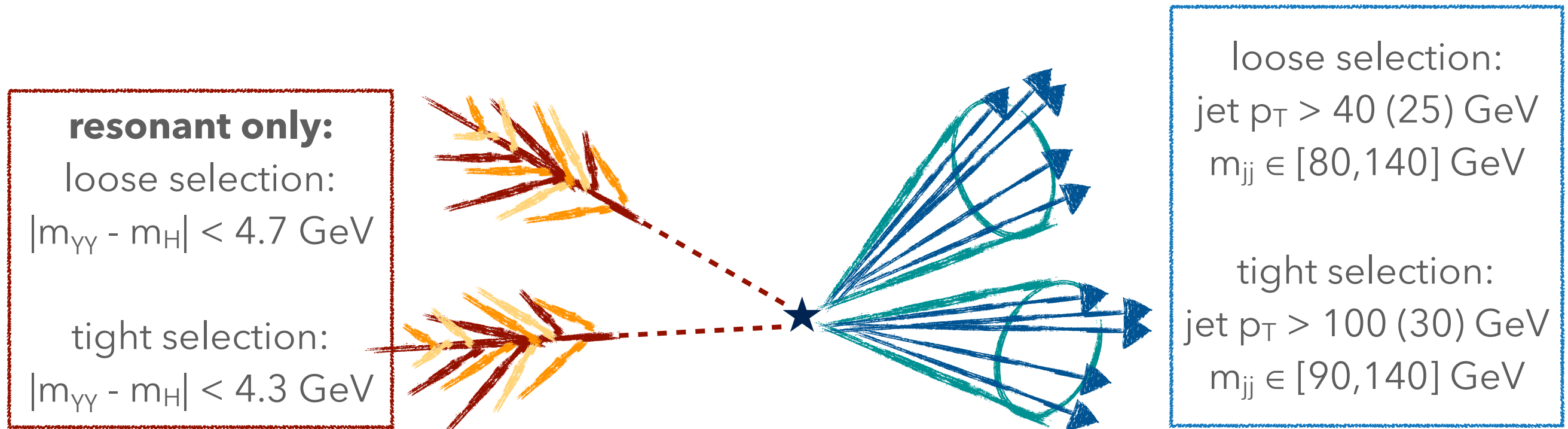
tight selection

# $\gamma\gamma b\bar{b}$ : 1 b-tag BDT

- ▶ Train BDT on correct and incorrect second jet selections, in signal and background MC (background has no correct choice!)
- ▶ Variables considered: jet  $p_T$ , di-jet  $p_T$ , di-jet mass, jet  $\eta$ , di-jet  $\eta$ , di-jet  $\Delta\eta$ , passes 77%/85% WP, ranking from best to worst in:  $p_T$ , best match to  $m_H$ , di-jet  $p_T$

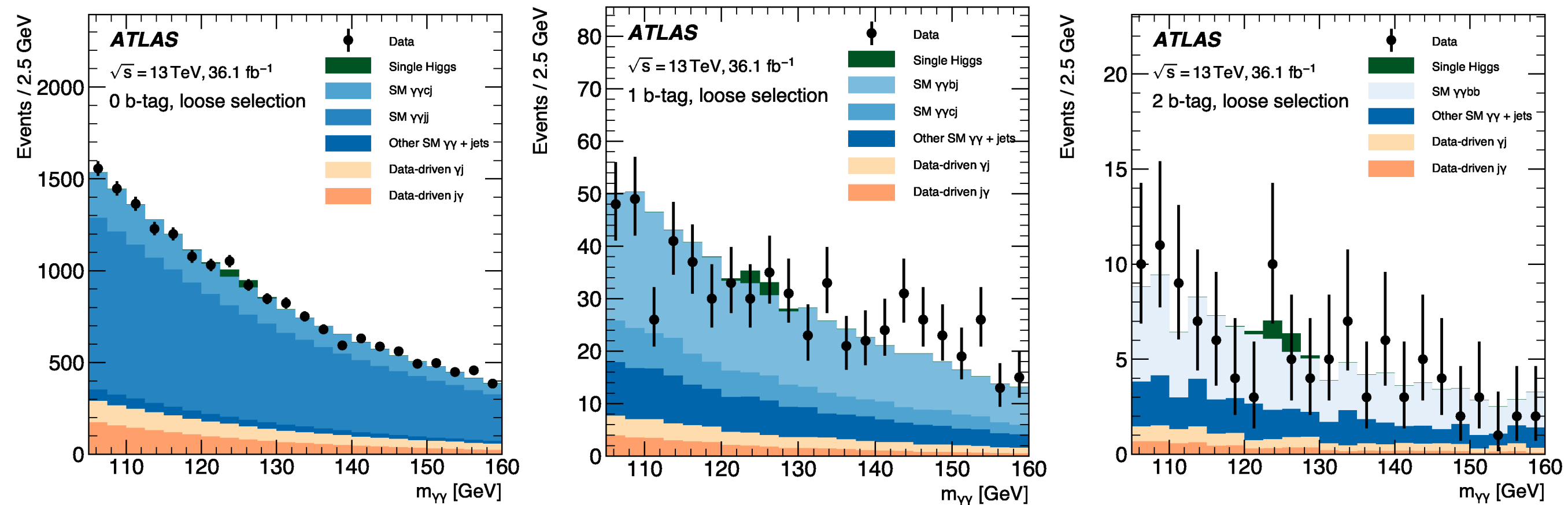


# $\gamma\gamma b\bar{b}$ : Event Selection

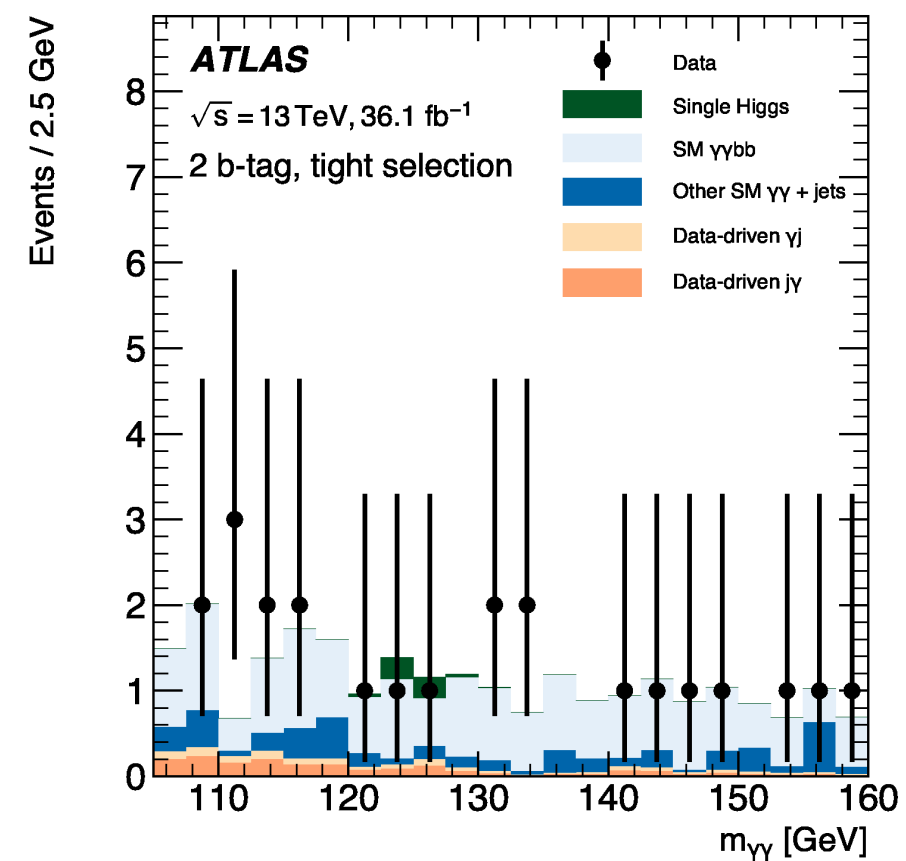
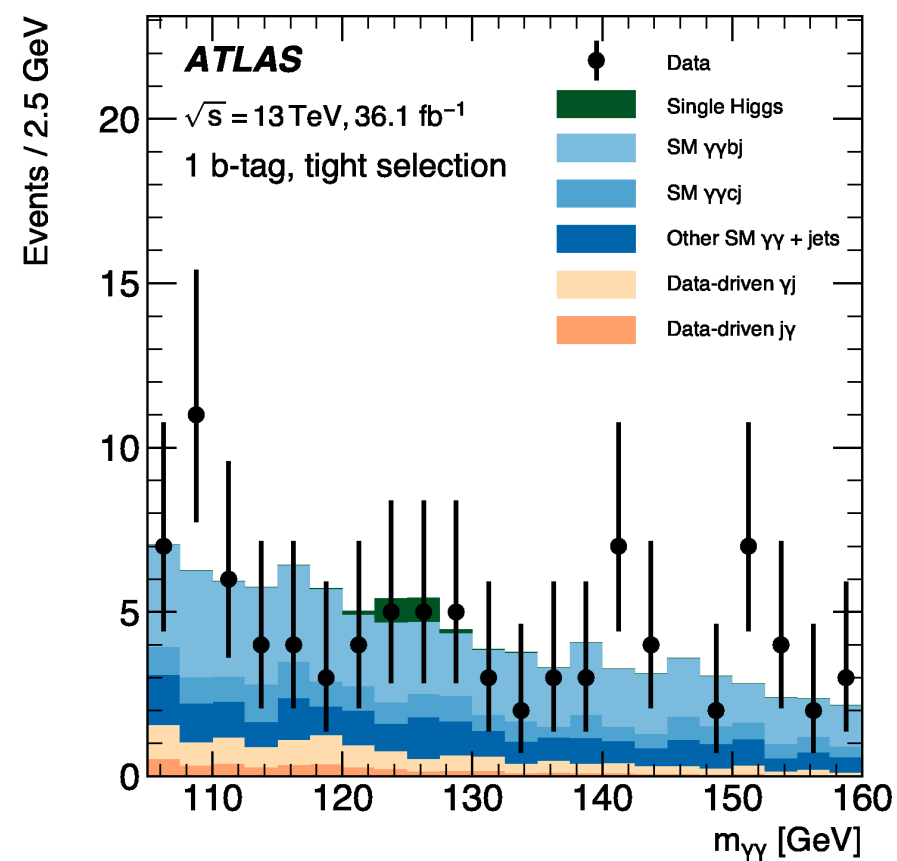
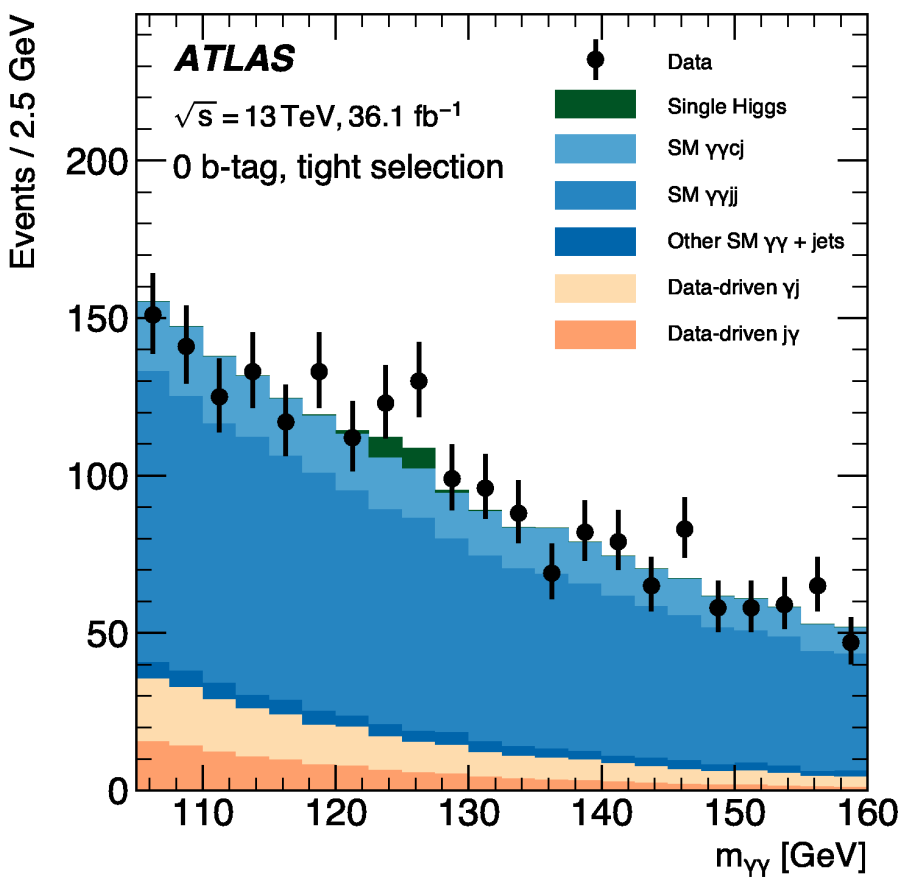


- ▶ define two non-orthogonal selections:
  - ▶ “loose” jet selection for  $260 < m_X < 500 \text{ GeV}$ , and setting limit on self-coupling
  - ▶ “tight” jet selection for  $500 < m_X < 1000 \text{ GeV}$ , and non-resonant search

# $\gamma\gamma b\bar{b}$ : Continuum Background Modeling, Non-Resonant Search

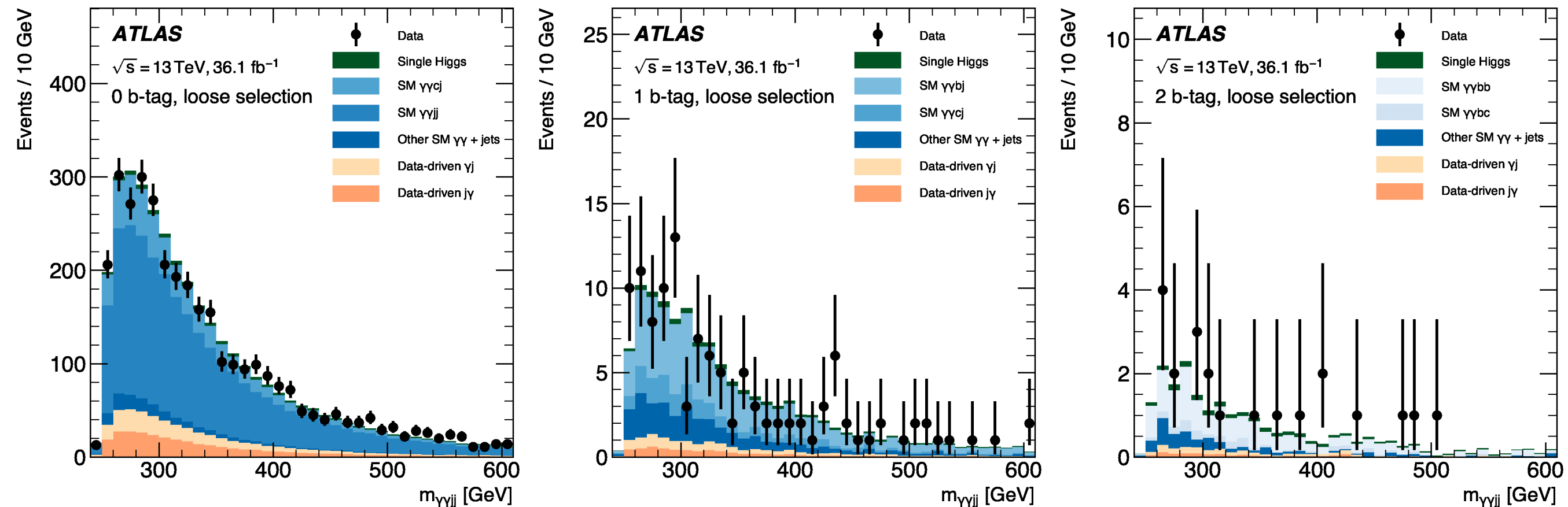


# $\gamma\gamma b\bar{b}$ : Continuum Background Modeling, Non-Resonant Search

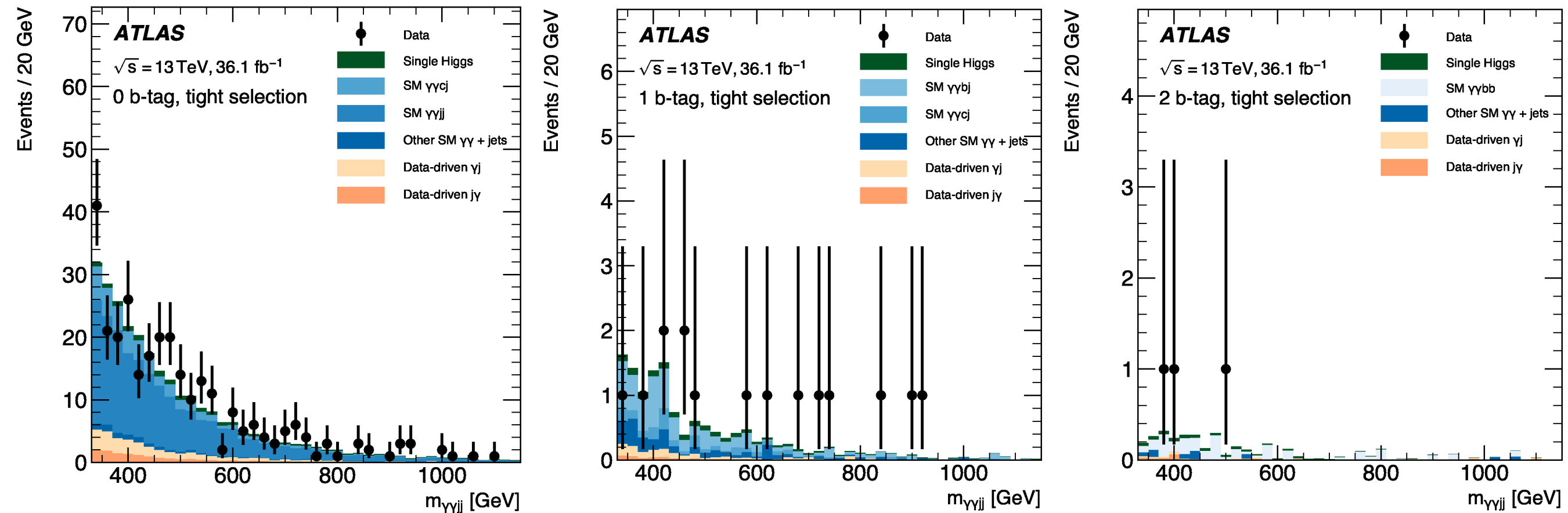




# $\gamma\gamma b\bar{b}$ : Continuum Background Modeling, Resonant Search



# $\gamma\gamma b\bar{b}$ : Continuum Background Modeling, Resonant Search



# γγbb Search is stats-limited, but...

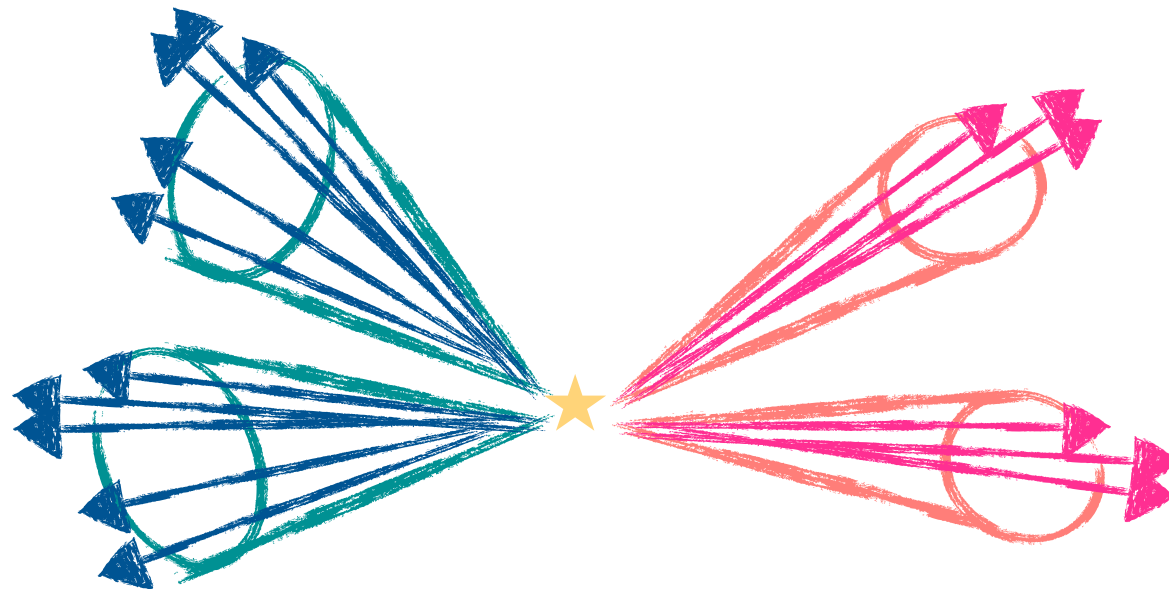
- ▶ largest systematic uncertainties from: **photon ID**, **JES/JER**, **flavor-tagging**

| Source of systematic uncertainty |                   | % effect relative to nominal in the 2-tag (1-tag) category |        |                 |         |                             |        |                 |        |
|----------------------------------|-------------------|------------------------------------------------------------|--------|-----------------|---------|-----------------------------|--------|-----------------|--------|
|                                  |                   | Non-resonant analysis                                      |        |                 |         | Resonant analysis: BSM $HH$ |        |                 |        |
|                                  |                   | SM $HH$ signal                                             |        | Single- $H$ bkg |         | Loose selection             |        | Tight selection |        |
| Luminosity                       |                   | ±2.1                                                       | (±2.1) | ±2.1            | (± 2.1) | ±2.1                        | (±2.1) | ±2.1            | (±2.1) |
| Trigger                          |                   | ±0.4                                                       | (±0.4) | ±0.4            | (± 0.4) | ±0.4                        | (±0.4) | ±0.4            | (±0.4) |
| Pile-up modelling                |                   | ±3.2                                                       | (±1.3) | ±2.0            | (± 0.8) | ±4.0                        | (±4.2) | ±4.0            | (±3.8) |
| Photon                           | identification    | ±2.5                                                       | (±2.4) | ±1.7            | (± 1.8) | ±2.6                        | (±2.6) | ±2.5            | (±2.5) |
|                                  | isolation         | ±0.8                                                       | (±0.8) | ±0.8            | (± 0.8) | ±0.8                        | (±0.8) | ±0.9            | (±0.9) |
|                                  | energy resolution | -                                                          |        | -               |         | ±1.0                        | (±1.3) | ±1.8            | (±1.2) |
|                                  | energy scale      | -                                                          |        | -               |         | ±0.9                        | (±3.0) | ±0.9            | (±2.4) |
| Jet                              | energy resolution | ±1.5                                                       | (±2.2) | ±2.9            | (± 6.4) | ±7.5                        | (±8.5) | ±6.4            | (±6.4) |
|                                  | energy scale      | ±2.9                                                       | (±2.7) | ±7.8            | (± 5.6) | ±3.0                        | (±3.3) | ±2.3            | (±3.4) |
| Flavour tagging                  | $b$ -jets         | ±2.4                                                       | (±2.5) | ±2.3            | (± 1.4) | ±3.4                        | (±2.6) | ±2.5            | (±2.6) |
|                                  | $c$ -jets         | ±0.1                                                       | (±1.0) | ±1.8            | (±11.6) | -                           |        | -               |        |
|                                  | light-jets        | <0.1                                                       | (±5.0) | ±1.6            | (± 2.2) | -                           |        | -               |        |
| Theory                           | PDF+ $\alpha_s$   | ±2.3                                                       | (±2.3) | ±3.1            | (± 3.3) | n/a                         |        | n/a             |        |
|                                  | Scale             | +4.3                                                       | (+4.3) | +4.9            | (+ 5.3) | n/a                         |        | n/a             |        |
|                                  |                   | -6.0                                                       | (-6.0) | +7.0            | (+ 8.0) | n/a                         |        | n/a             |        |
|                                  | EFT               | ±5.0                                                       | (±5.0) | n/a             |         | n/a                         |        | n/a             |        |

# $\gamma\gamma$ bb: Final Event Yields

|                                  | 1-tag             |                   | 2-tag             |                   |
|----------------------------------|-------------------|-------------------|-------------------|-------------------|
|                                  | Loose selection   | Tight selection   | Loose selection   | Tight selection   |
| Continuum background             | 117.5 $\pm$ 4.7   | 15.7 $\pm$ 1.6    | 21.0 $\pm$ 2.0    | 3.74 $\pm$ 0.78   |
| SM single-Higgs-boson background | 5.51 $\pm$ 0.10   | 2.20 $\pm$ 0.05   | 1.63 $\pm$ 0.04   | 0.56 $\pm$ 0.02   |
| Total background                 | 123.0 $\pm$ 4.7   | 17.9 $\pm$ 1.6    | 22.6 $\pm$ 2.0    | 4.30 $\pm$ 0.79   |
| SM Higgs boson pair signal       | 0.219 $\pm$ 0.006 | 0.120 $\pm$ 0.004 | 0.305 $\pm$ 0.007 | 0.175 $\pm$ 0.005 |
| Data                             | 125               | 19                | 21                | 3                 |

# bb $\tau\tau$ : BDT Variables



- ▶ **lep+had** SLT resonant:  $m_{HH}$ ,  $m_{bb}$ ,  $m_{\tau\tau}^{\text{MMC}}$ ,  $\Delta R(\tau, \tau)$ ,  $\Delta R(b, b)$ , MET, MET centrality, transverse W mass,  $\Delta\phi(H, H)$ ,  $\Delta p_T(\ell, \tau_{\text{had-vis}})$ , subleading b-jet  $p_T$
- ▶ **lep+had** SLT non-resonant, LTT:  $m_{HH}$ ,  $m_{bb}$ ,  $m_{\tau\tau}^{\text{MMC}}$ ,  $\Delta R(\tau, \tau)$ ,  $\Delta R(b, b)$ , transverse W mass
- ▶ **had+had**:  $m_{HH}$ ,  $m_{bb}$ ,  $m_{\tau\tau}^{\text{MMC}}$ ,  $\Delta R(\tau, \tau)$ ,  $\Delta R(b, b)$ , MET centrality

# HH $\rightarrow$ bb $\tau\tau$ Backgrounds

## had+had channel

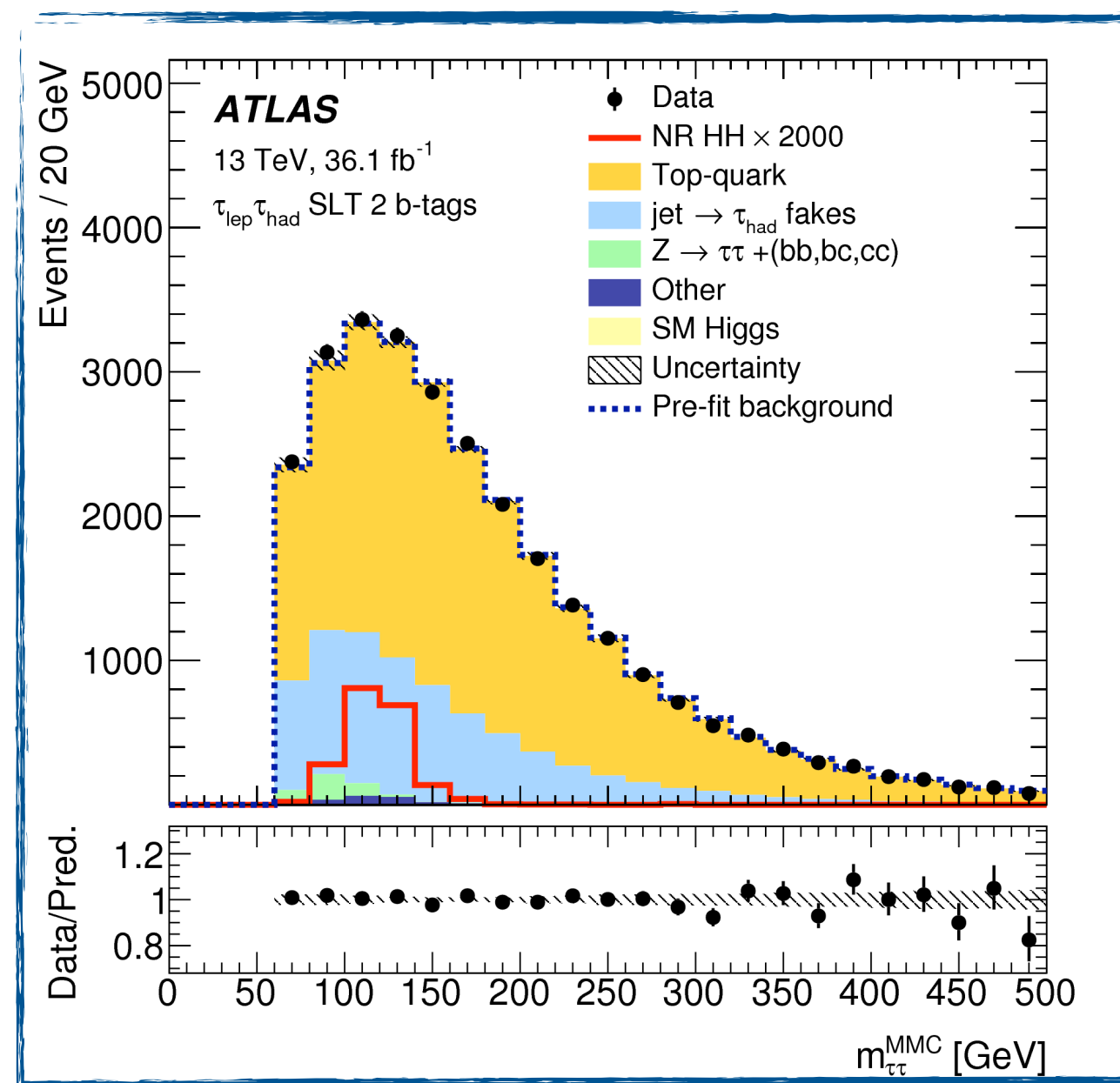
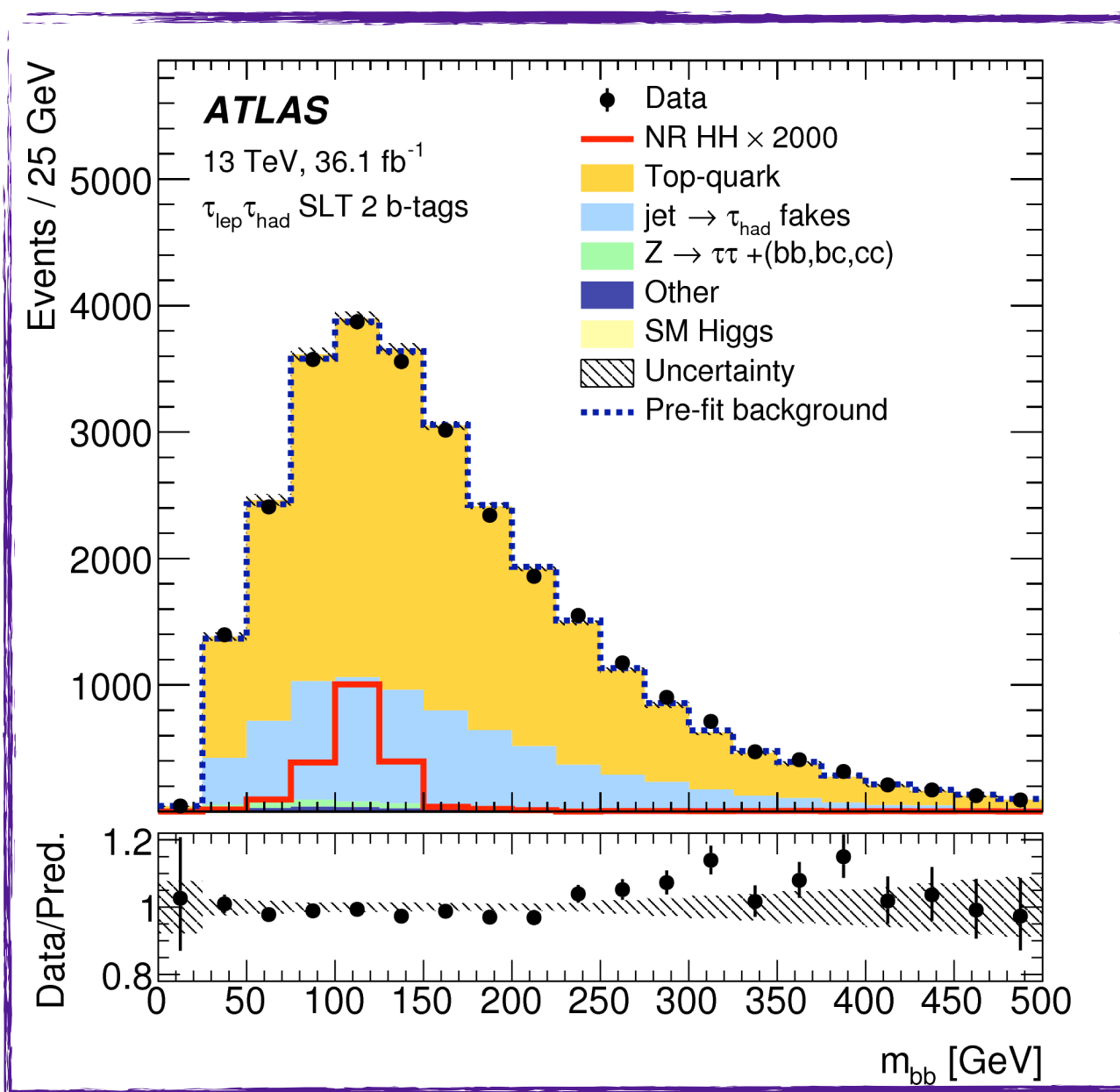
- ttbar (two real taus): 42%
- fake taus: 25% - estimated with data-driven ABCD\* method
- Z+jets: 15%
- ttbar with fake taus: 15% - correct MC with fake rates from data
- other small backgrounds from MC

|                            |                            |
|----------------------------|----------------------------|
| A: OS + 2<br>signal taus   | B: SS + 2<br>signal taus   |
| C: OS + >1<br>anti-ID taus | D: SS + >1<br>anti-ID taus |

## lep+had channel

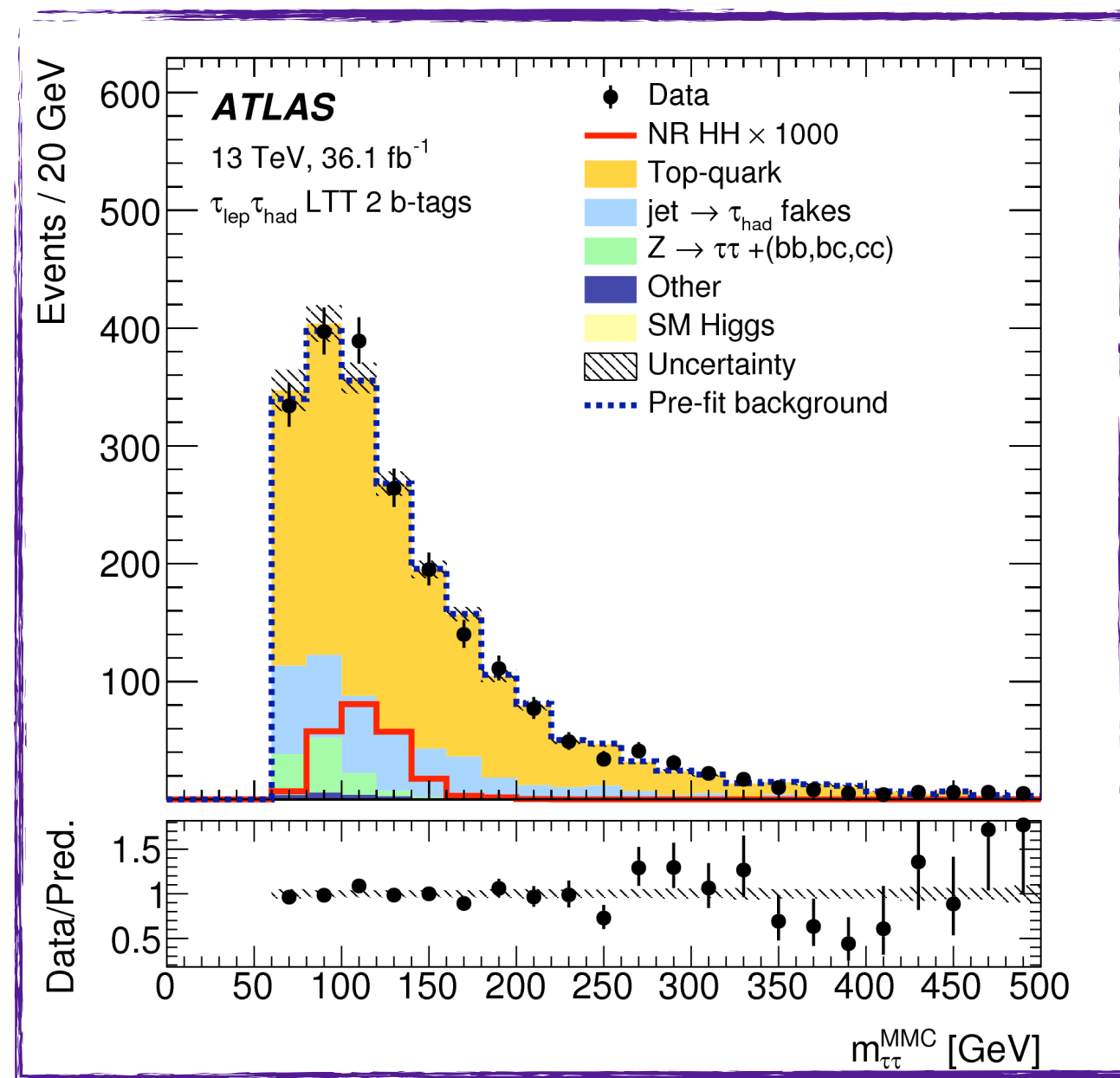
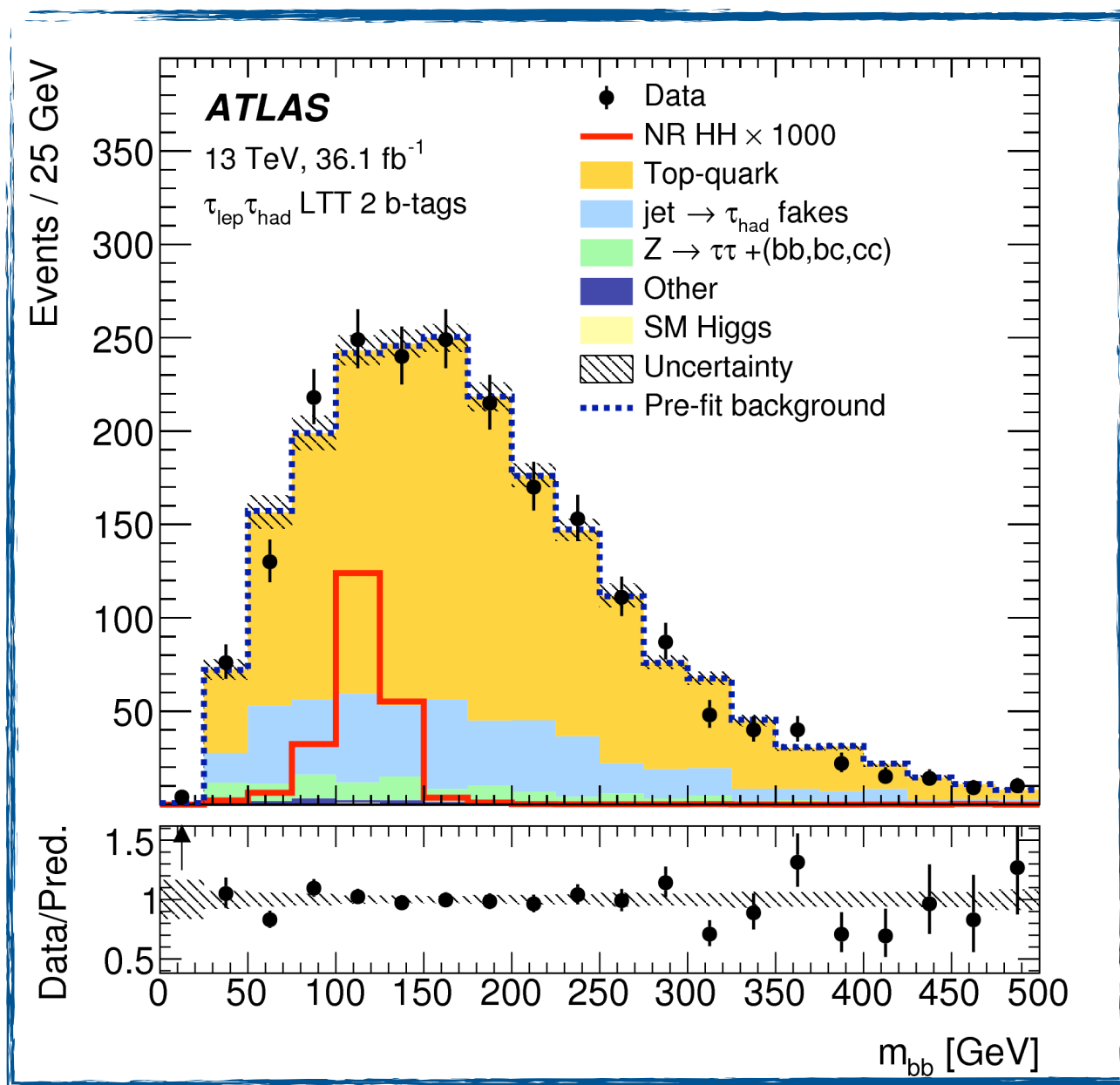
- ttbar (two real taus): 62%
- fake taus from ttbar, W+jets, QCD: 31% estimated with a combined fake factor method
- other backgrounds (Z+jets, W+jets, single top, diboson) from MC: 7%

# $bb\tau$ : lep+had SLT observables

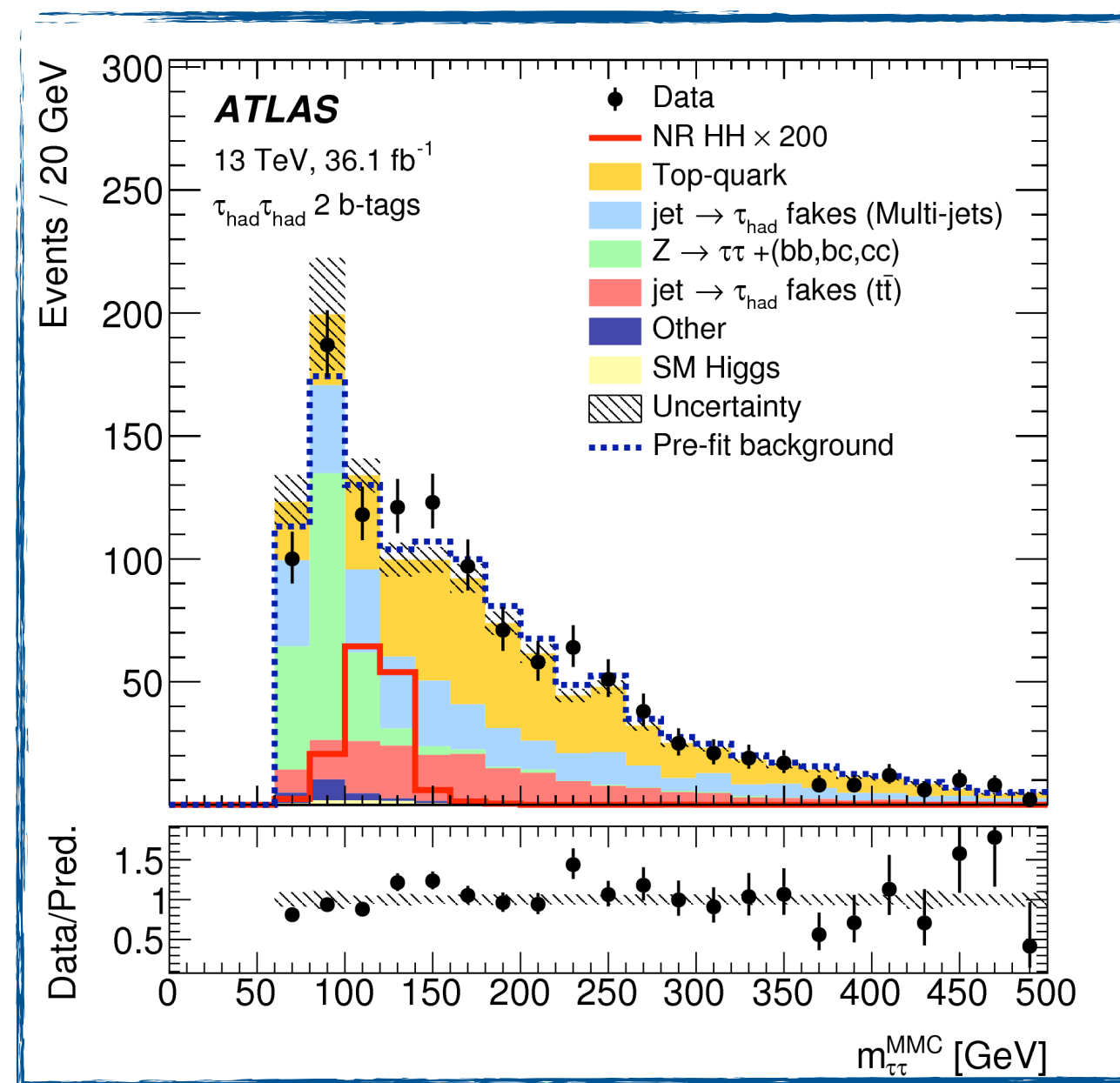
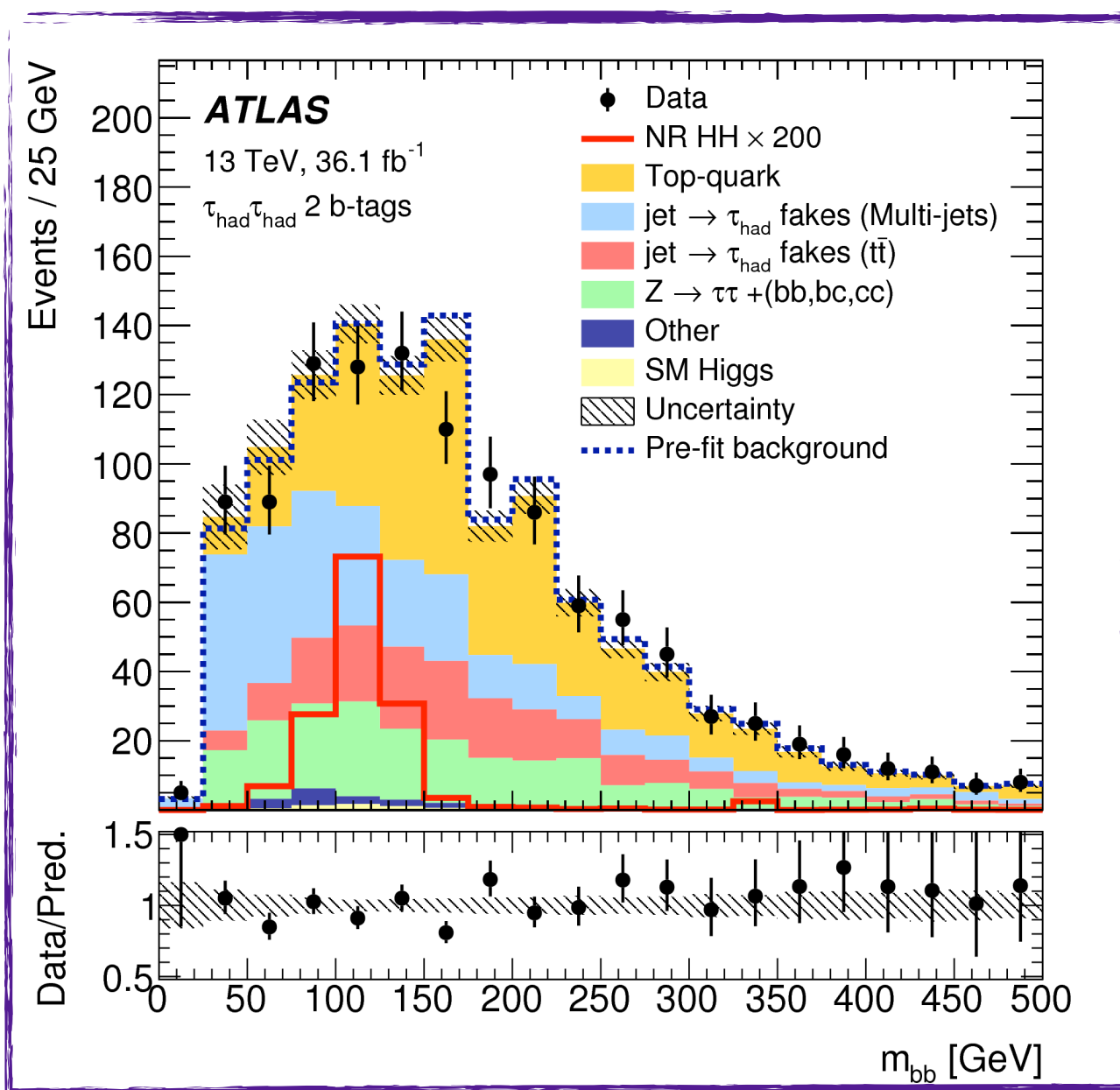




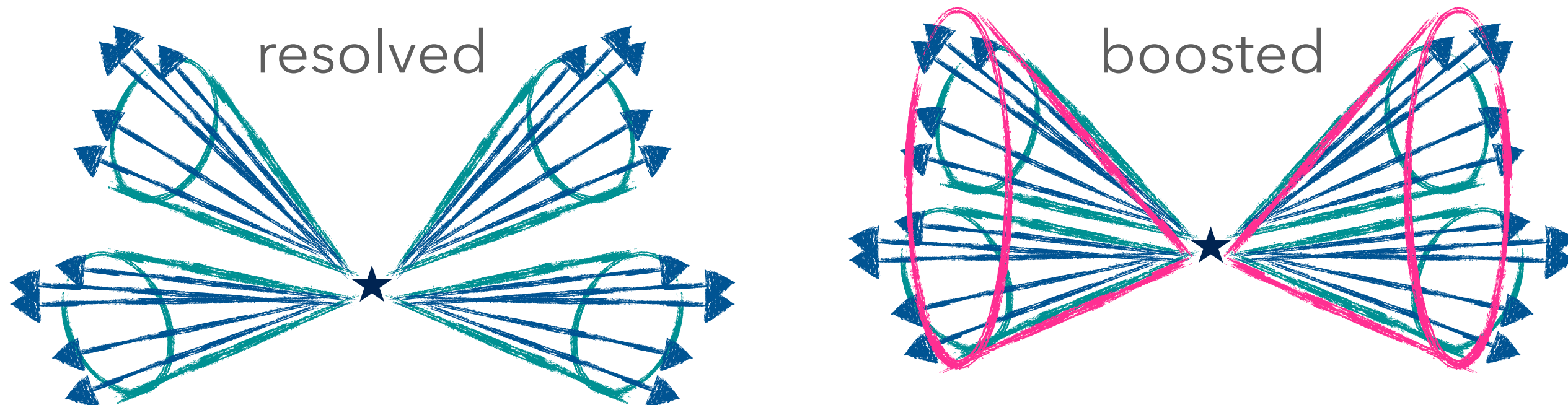
# bb $\tau$ : lep+had LTT observables



# bb $\tau\tau$ : had+had observables



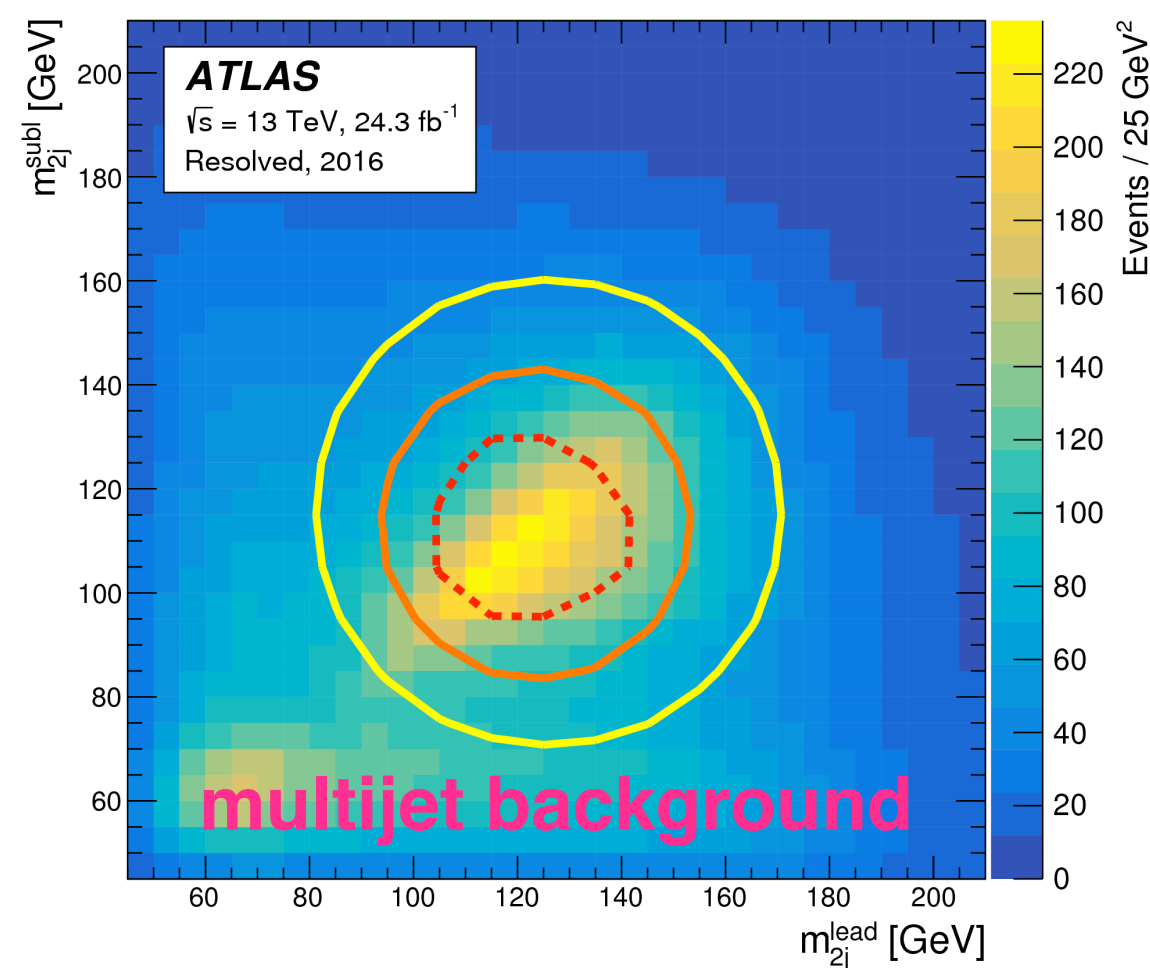
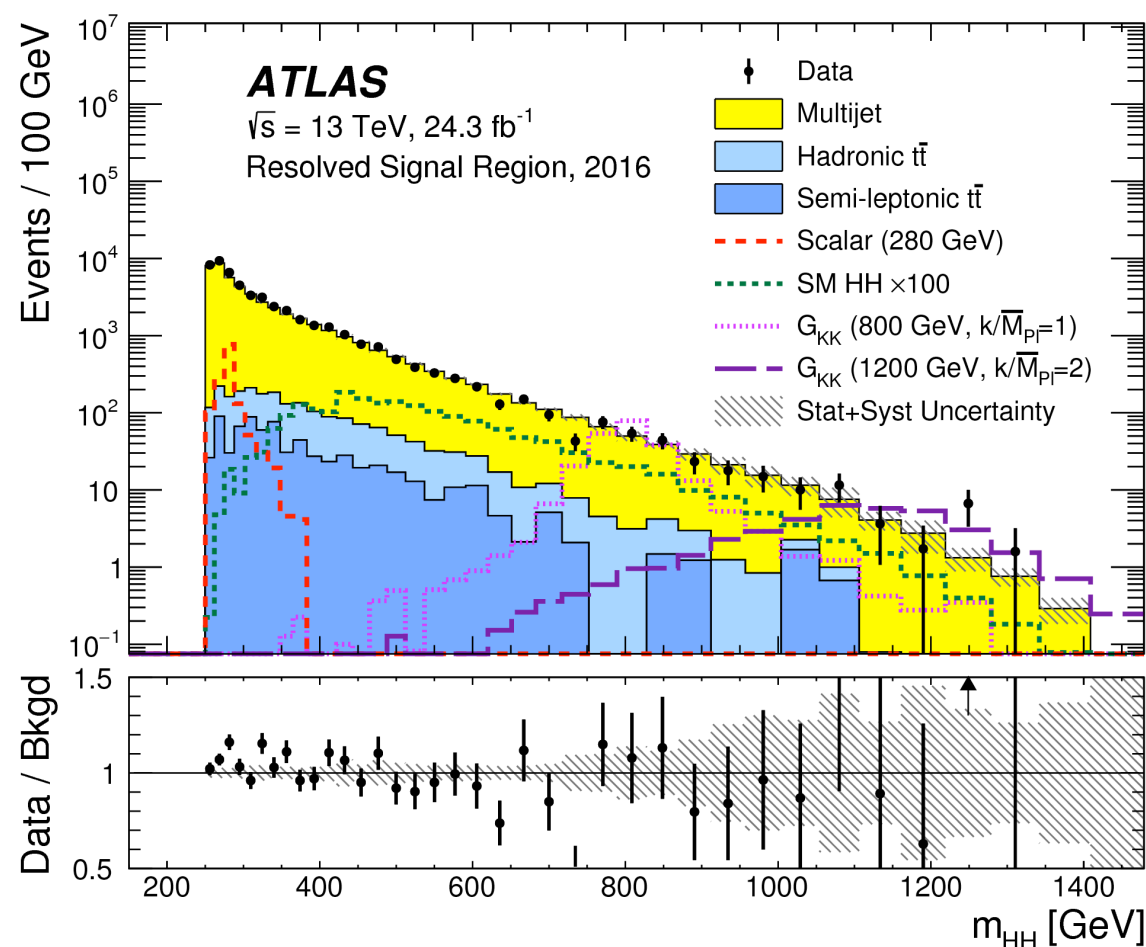
# bbbb: Event Selection



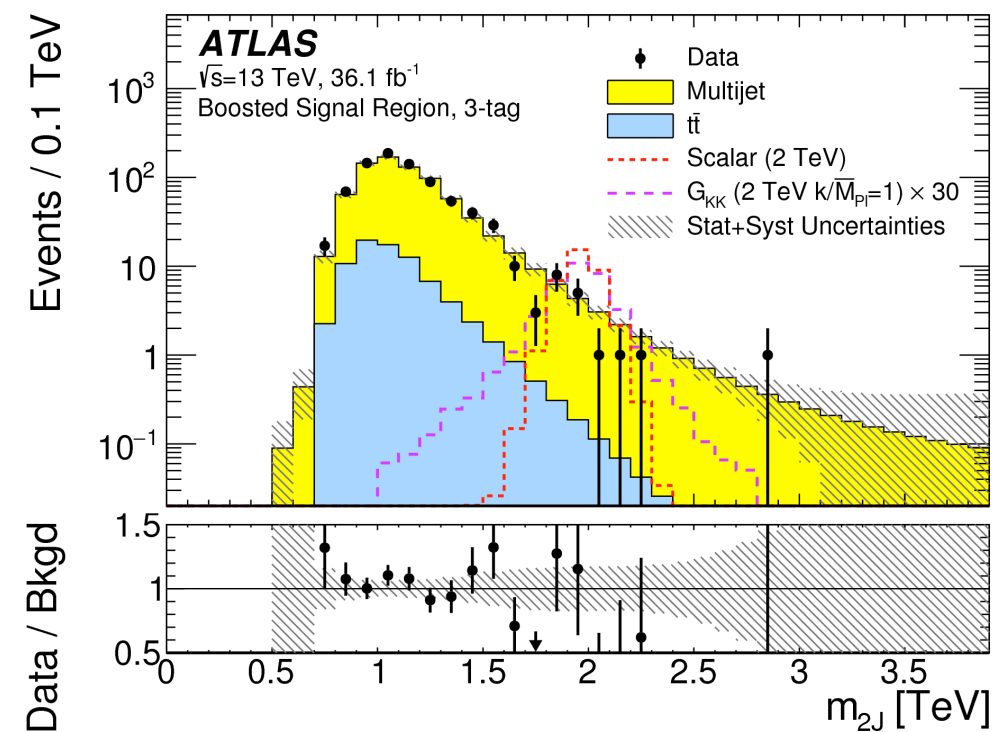
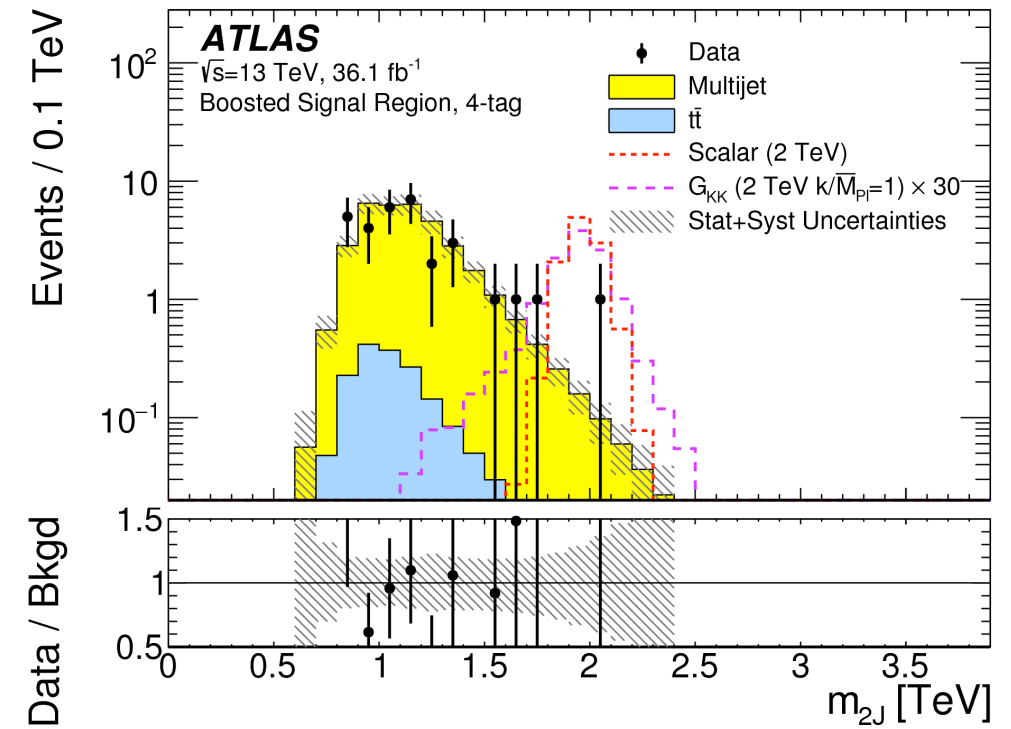
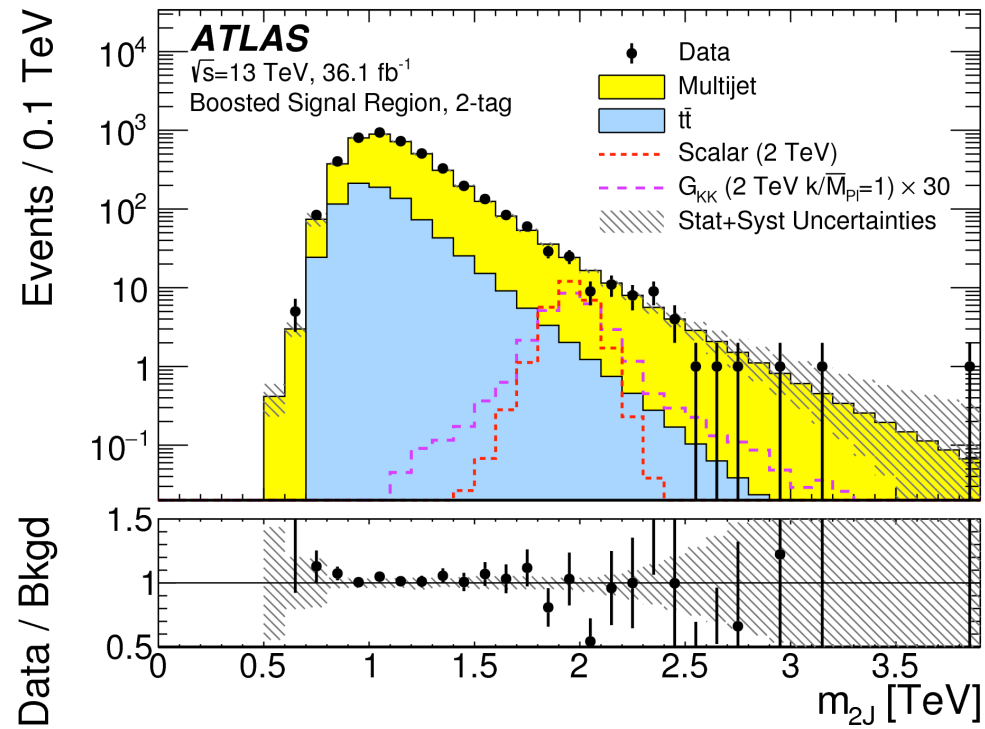
- ▶ Resolved: additional cuts on  $p_T$  of the Higgs candidates,  $\Delta\eta$  between the Higgs candidates, and a top veto  
 $(X_{Wt} = \sqrt{(m_W - 80 \text{ GeV} / 0.1 m_W)^2 + (m_t - 173 \text{ GeV} / 0.1 m_t)^2} > 1.5)$
- ▶ Resolved and boosted: Signal and control regions are defined in a ring around the Higgs mass in a 2D  $(m_{jj1}, m_{jj2})$  plane – background is data-driven

# bbbb Background Modeling

- ▶ resolved: ~95% of background is from multi-jet events (data-driven)
  - ▶ Define **signal**, **control**, and **sideband** regions in 2-tag selection
  - ▶ Multi-jet background is estimated in sidebands and reweighted to correct for differences between 2- and 4-tag selections
- ▶ Similar method in boosted analysis using  $N_{\text{btags}}$

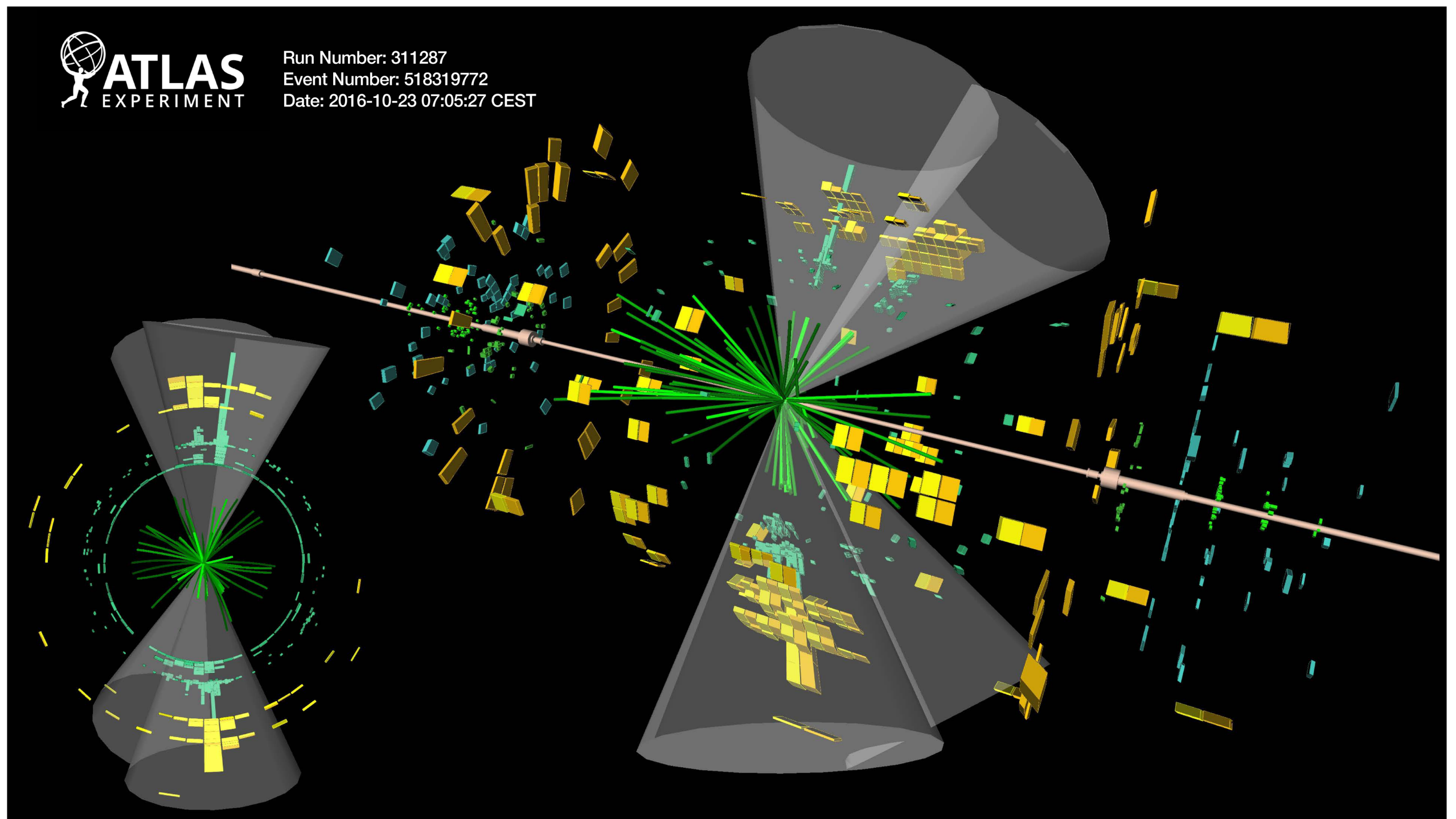


# bbbb: boosted signal regions



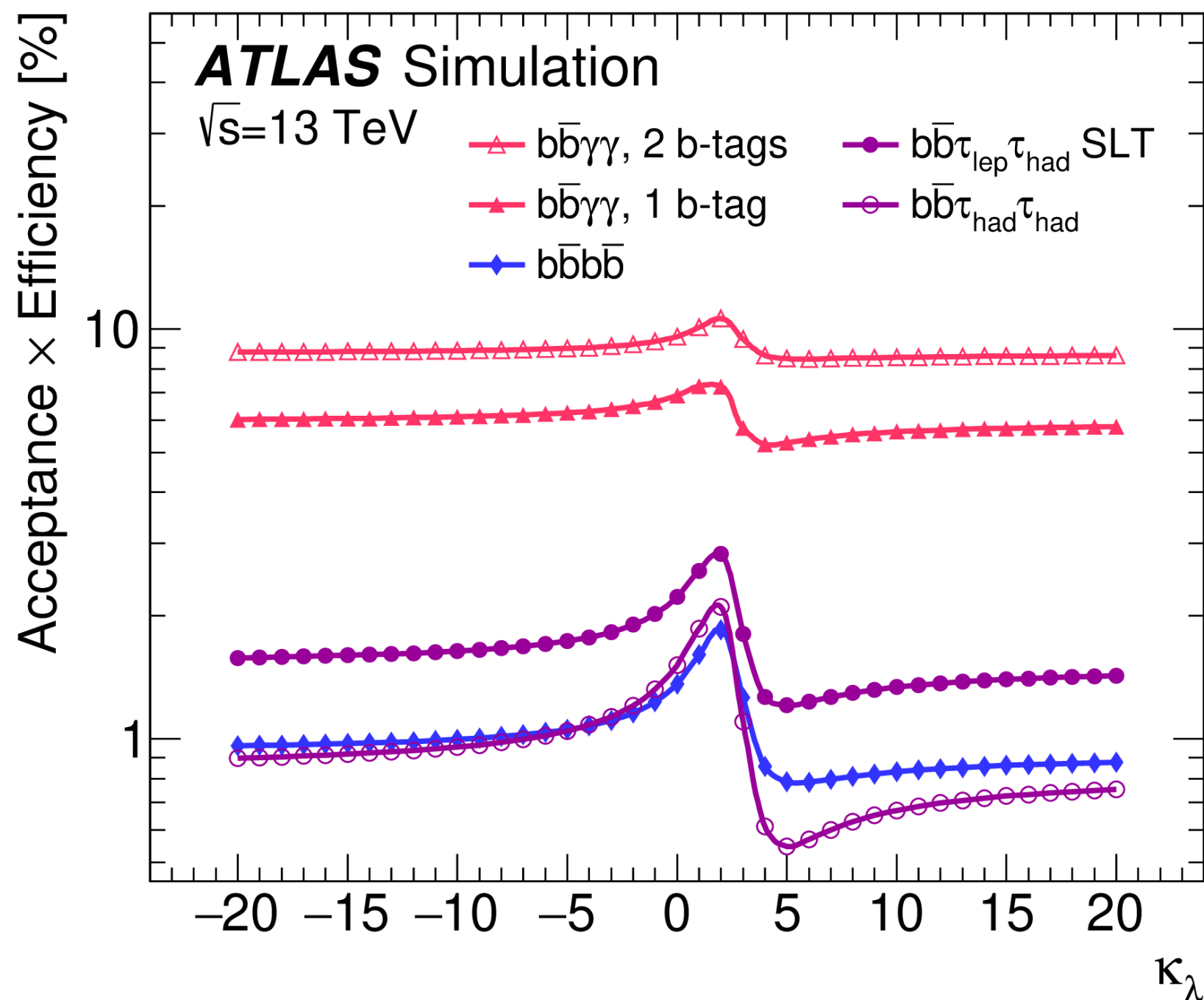


# bbbb event display: resolved selection



# Non-Resonant Limits: Higgs Self-Coupling

acceptance\*efficiency curves for each channel





- ▶ ATLAS combination of  $b\bar{b}b\bar{b}$ ,  $\gamma\gamma b\bar{b}$ , and  $b\bar{b}\tau\tau$  gives  $3.5\sigma$  significance in the HL-LHC dataset ( $3000 \text{ fb}^{-1}$ )
  - ▶ ATLAS+CMS combination:  $4.5\sigma$
- ▶ ATLAS self-coupling limit:  $0.4 < \kappa_\lambda < 1.7$ 
  - ▶ ATLAS+CMS combination:  $0.57 < \kappa_\lambda < 1.5$

