Search for doubly resonant beyond the Standard Model process with one Higgs boson and one scalar resonance in the $b\bar{b}\gamma\gamma$ final state in the ATLAS experiment at the LHC

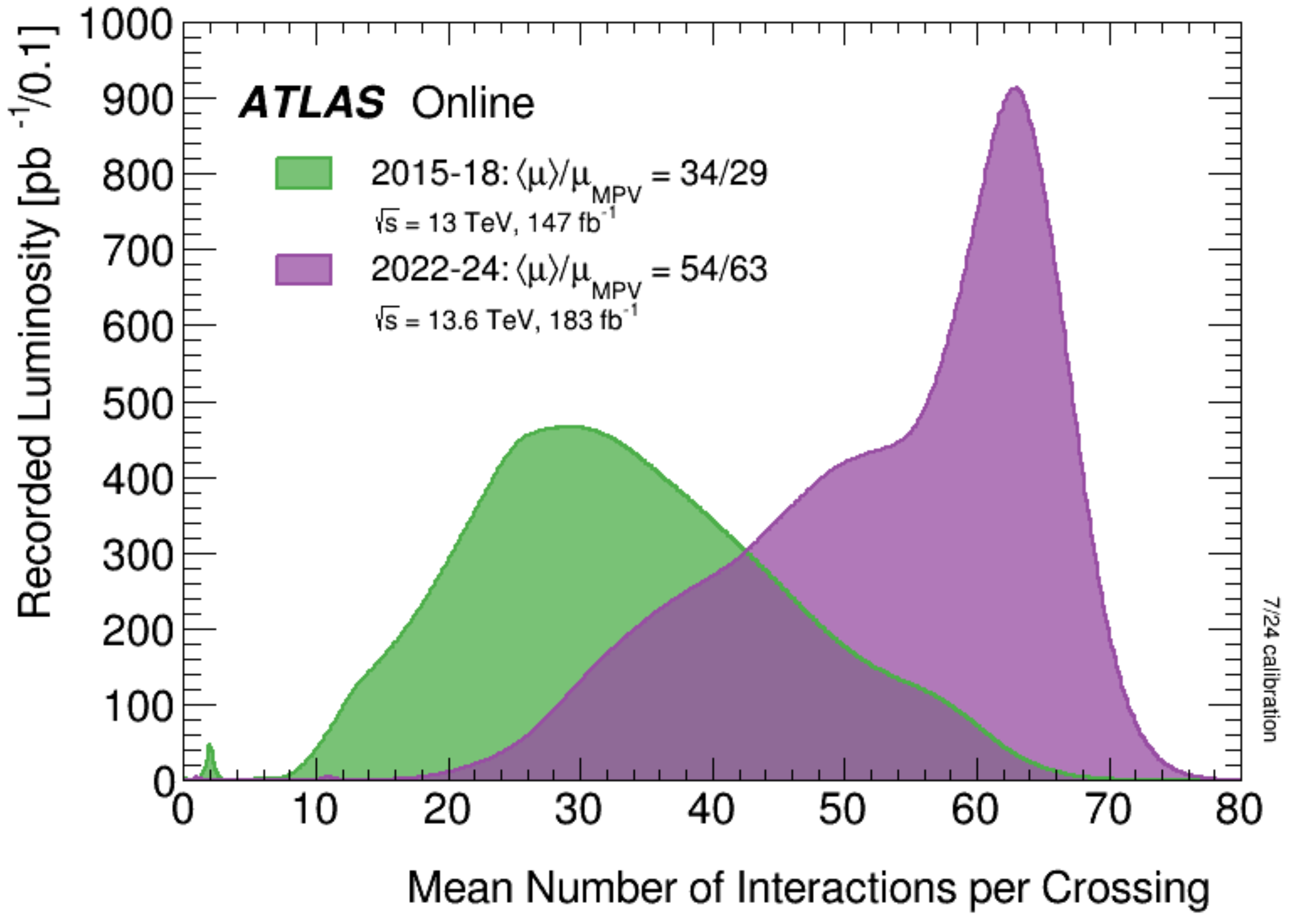
CPPM Seminar

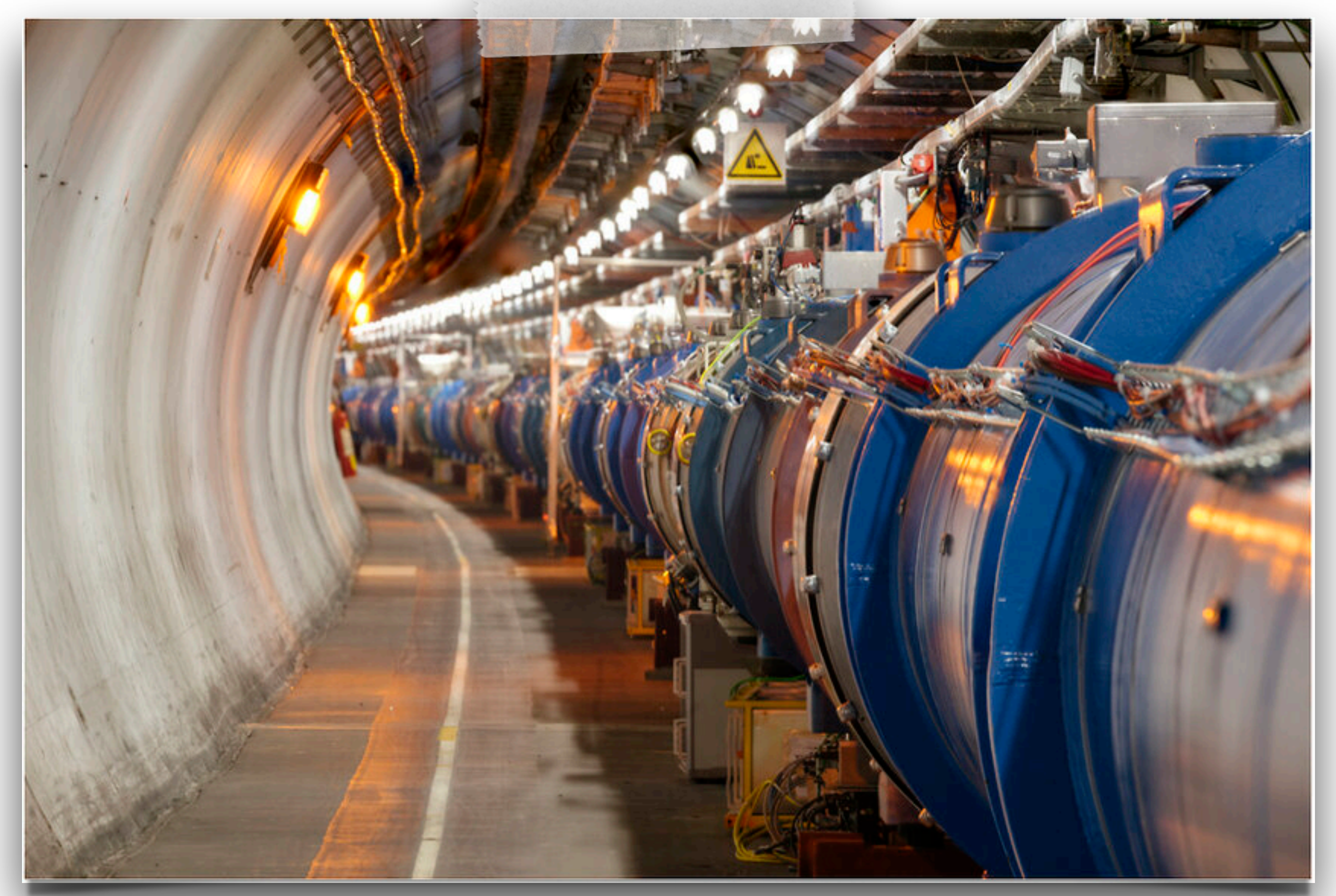
Grigorii Tolkachev

Supervisors: Emmanuel Monnier and Timothée Theveneaux-Pelzer

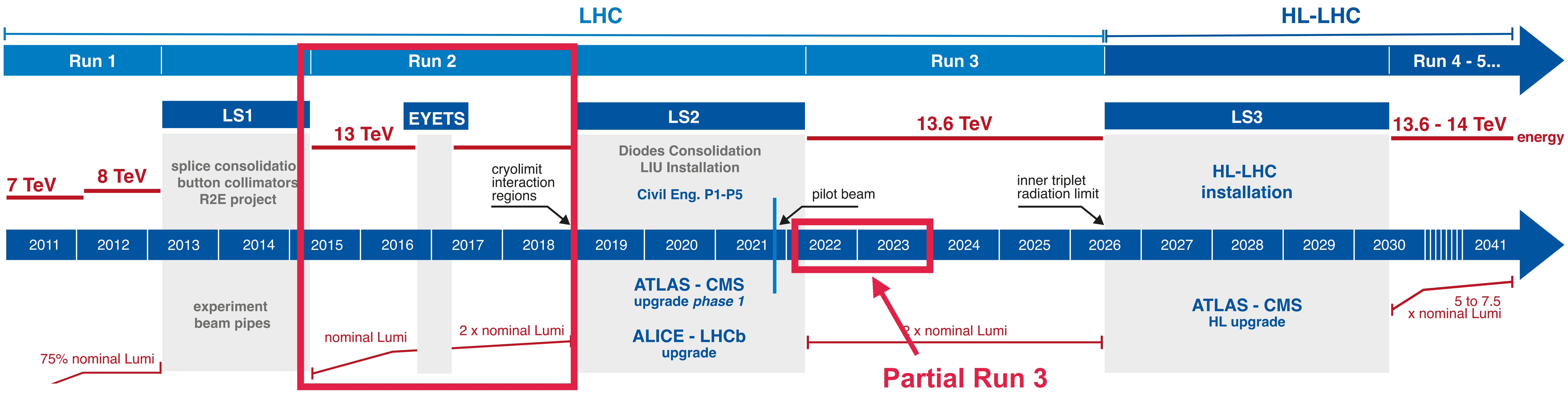
24.04.2025

The Large Hadron Collider





- The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator
- Proton-proton and heavy ion collisions, proton-protons at centre-of-mass energies of 7, 8, 13, now 13.6 TeV

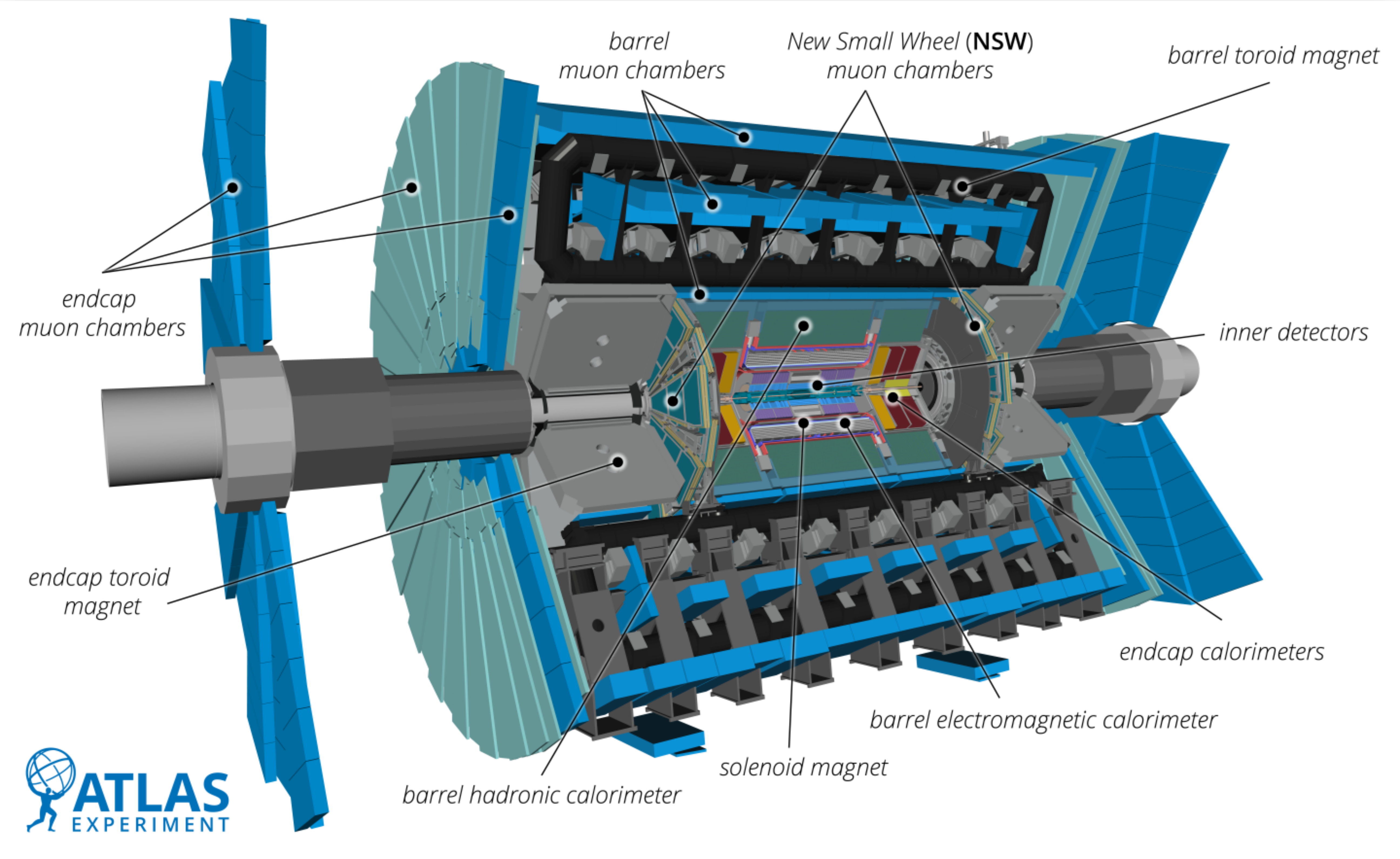


The ATLAS experiment

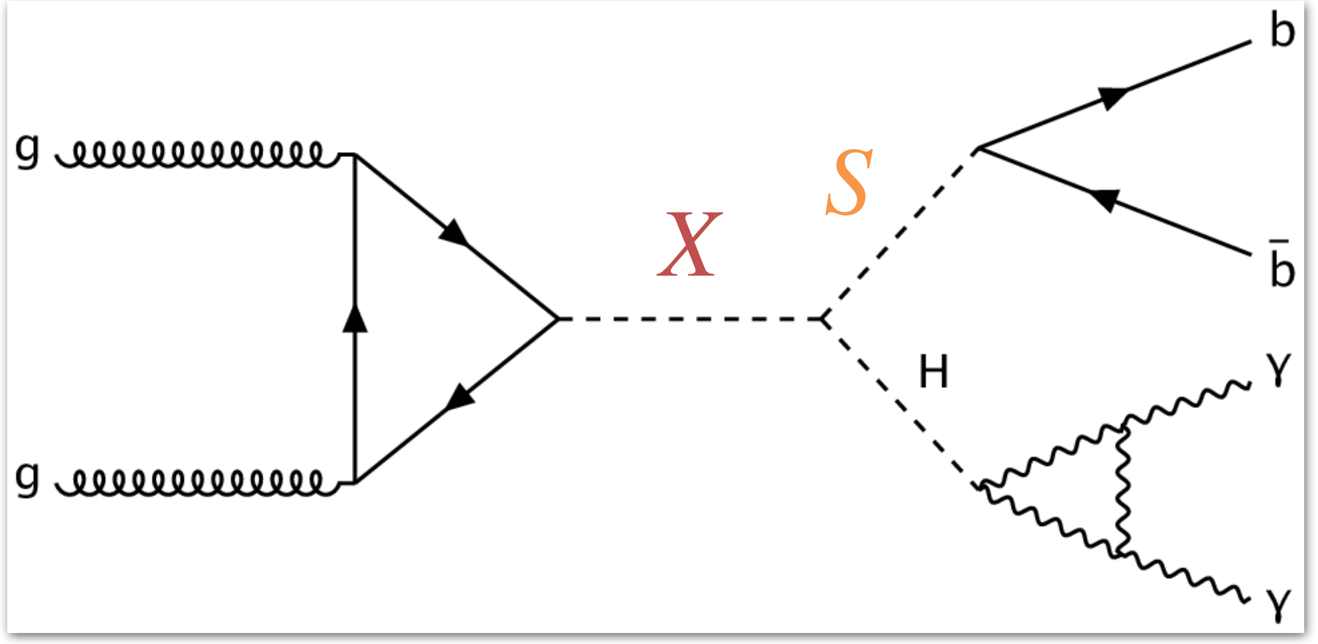
ATLAS is a multipurpose detector designed to study Higgs boson physics, perform precision measurements to test deviations from the Standard Model, and search for Beyond Standard Model particles, particularly in the Higgs sector

The ATLAS detector is composed by subsystems:

- Tracker
- Electromagnetic and hadronic calorimeters
- Muon spectrometer
- Magnet system
  (Central solenoid and toroid)

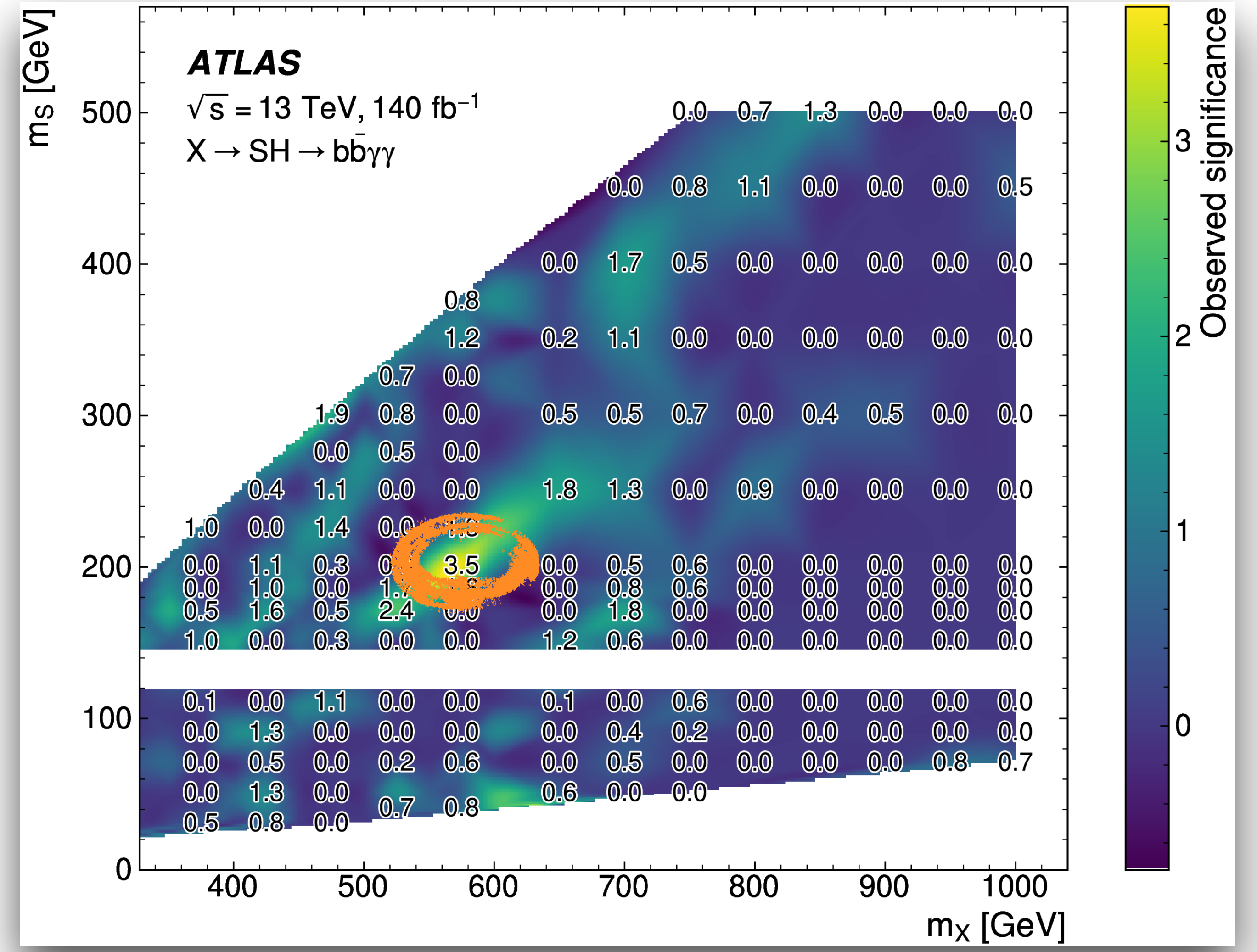


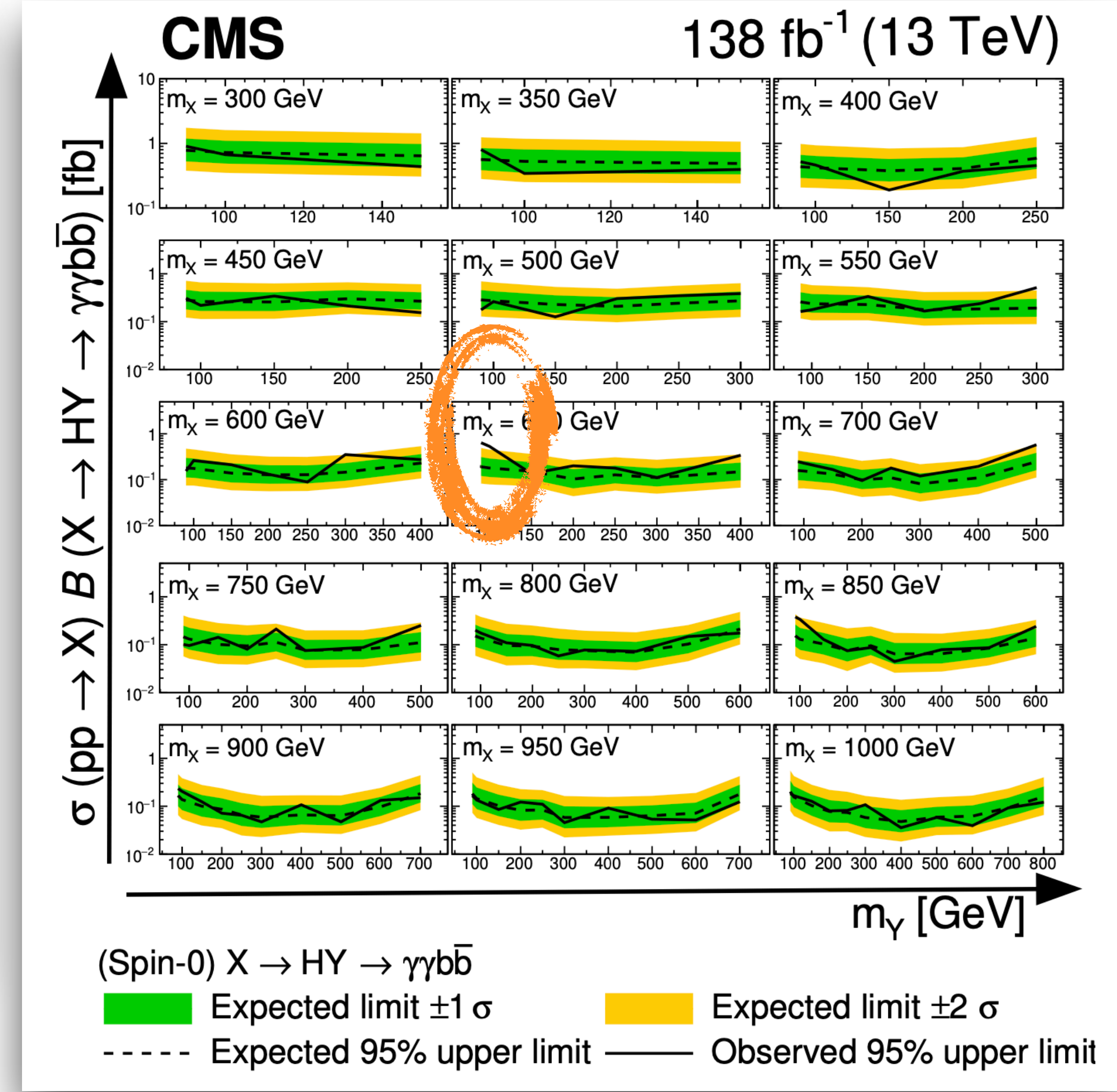
Introduction & Motivation



Introduction

- Many theoretical BSM (TRSM, 2HDM, NMSSM, …) models predict the existence of new scalar particles in the Higgs sector, denoted as X and S, which could be produced in proton-proton collisions in association with a Higgs boson in process $pp \to X \to SH$
- Model-independent search. Set limits on production cross-section times BR using the narrow width approximation





Motivation

- In Run 2 we have two excesses:
  - ATLAS: $m_X, m_S = (575, 200)$ GeV, local (global) significance of 3.5 (2.0) σ [JHEP 2411 (2024) 047]
  - CMS: $m_X, m_S = (650, 90)$ GeV, local (global) significance of 3.8 (2.8) σ [JHEP 05 (2024) 316]

Goal:

- Follow-up on the excess seen in the Run 2 data using Run 2 + partial Run 3
- We follow a similar strategy as for Run 2 paper, with several improvements

- Maxime's thesis
- Run 2 + partial run 3 results recently submitted for publication: arXiv:2510.02857
- Public results: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGP-2024-34/

Data and Monte Carlo Simulations (MC)

Data

- 140 fb^{-1} of $\sqrt{s}$ = 13 TeV Run 2, data 2015 - 2018
- 58.6 fb^{-1} of $\sqrt{s}$ = 13.6 TeV Run 3 data, 2022 - 2023

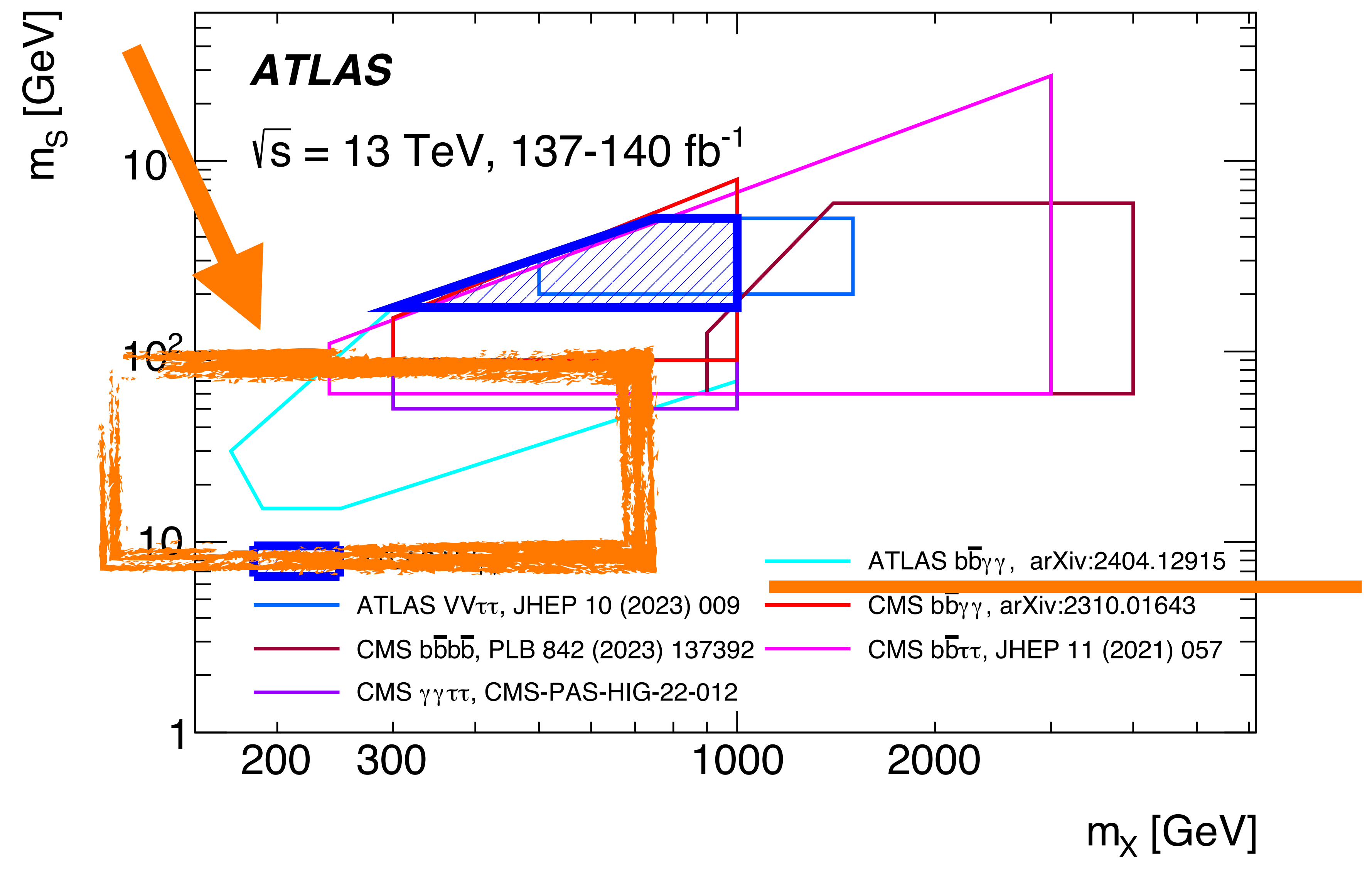
Signal MC 160 generated signal mass points

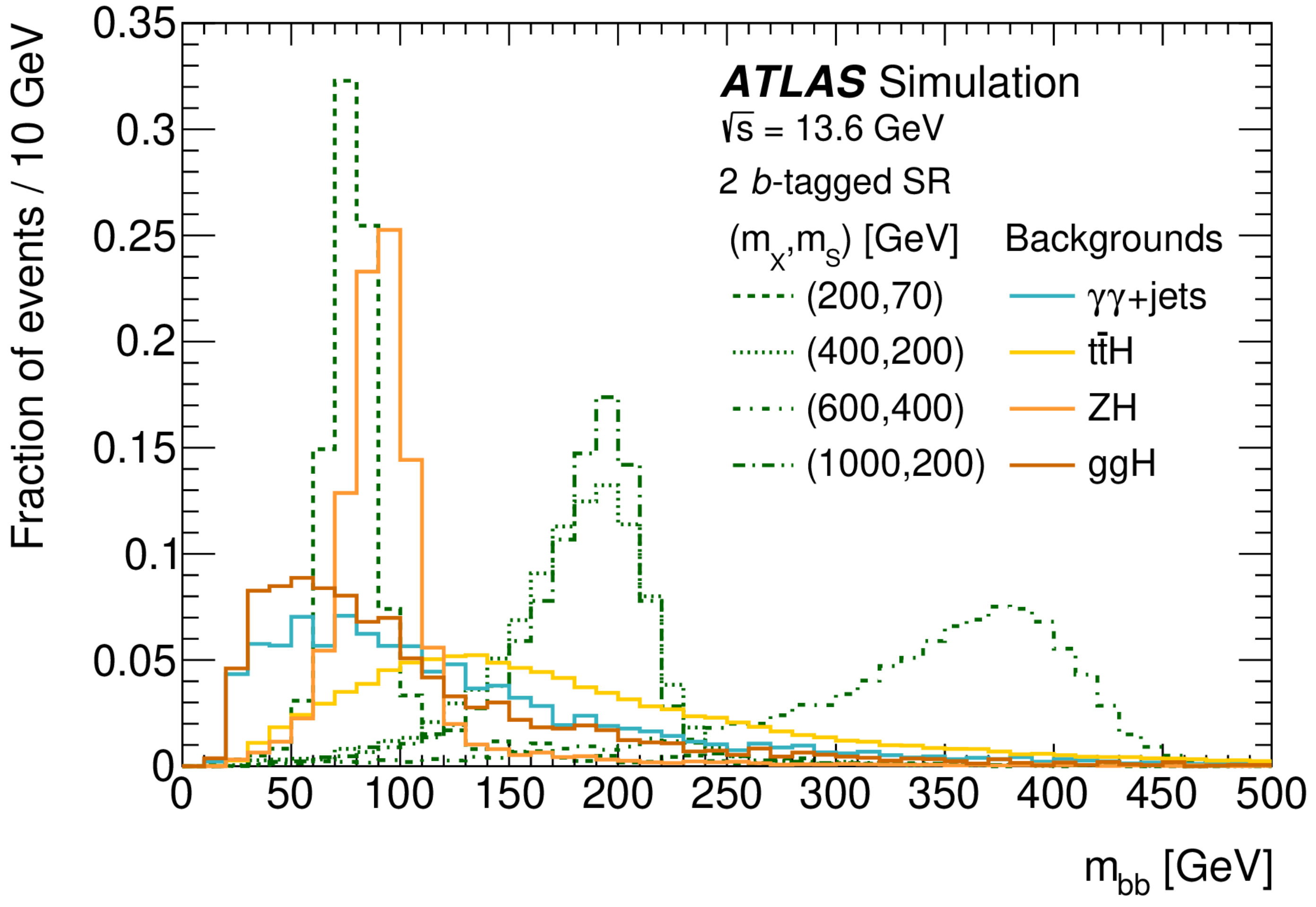
- LO Pythia8 + EvTGen2.1 NNPDF 2.3 LO (ME) + A14 NNPDF23LOtune (PS)
- Mass Grid: $170 \leq m_X \leq 1000, 15 \leq m_s \leq 500$ GeV

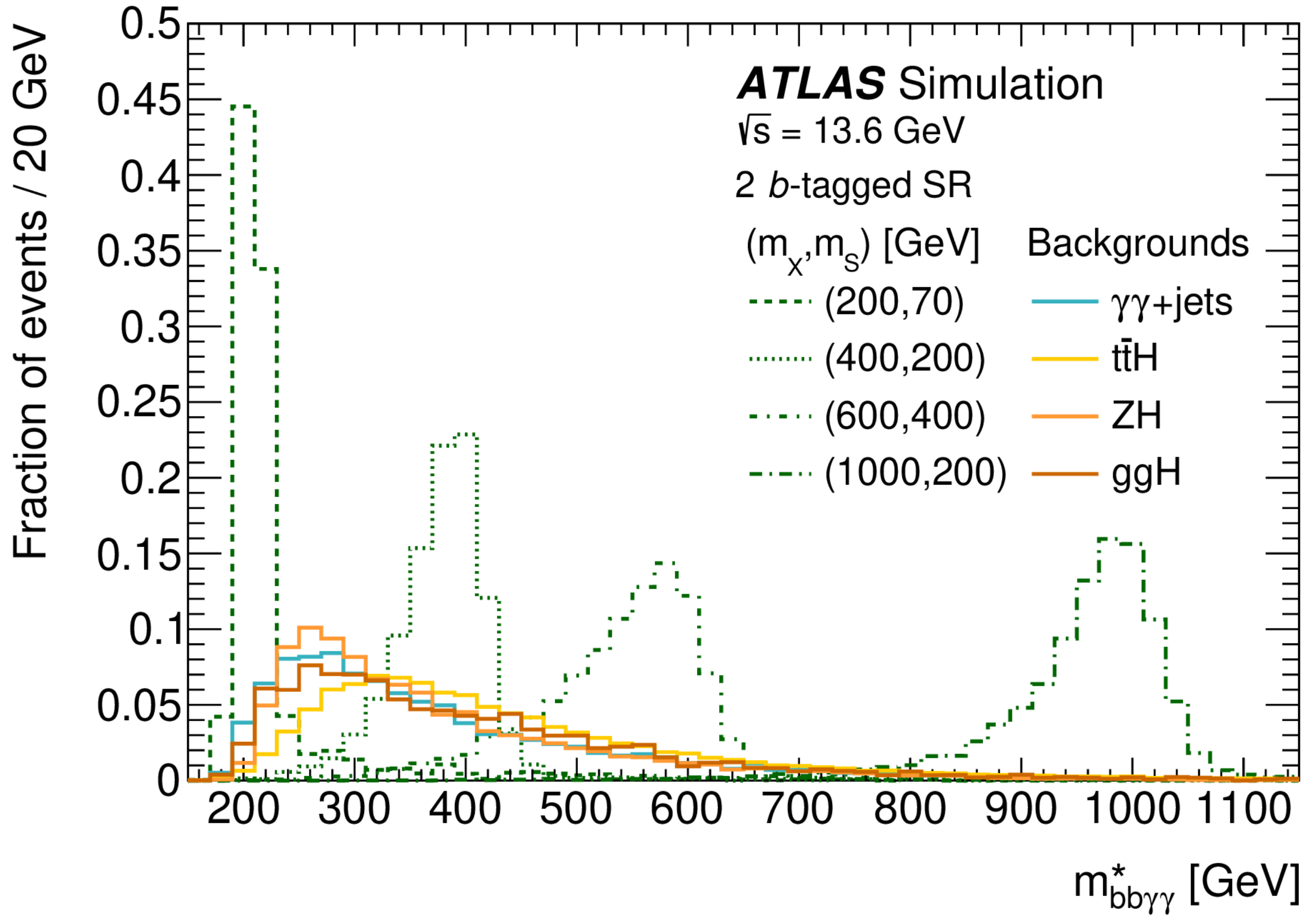
Background MC

- Single- and di-Higgs processes: ggFH, VBFH, ttH, bbH, VH, tHjb, tHbj, tHW, ggFHH and VBFHH
- Continuum QCD: $\gamma\gamma$+jets, tt$\gamma\gamma$, Z$\gamma\gamma$

Only $bb\gamma\gamma$ probes the low mass







Pre-selection

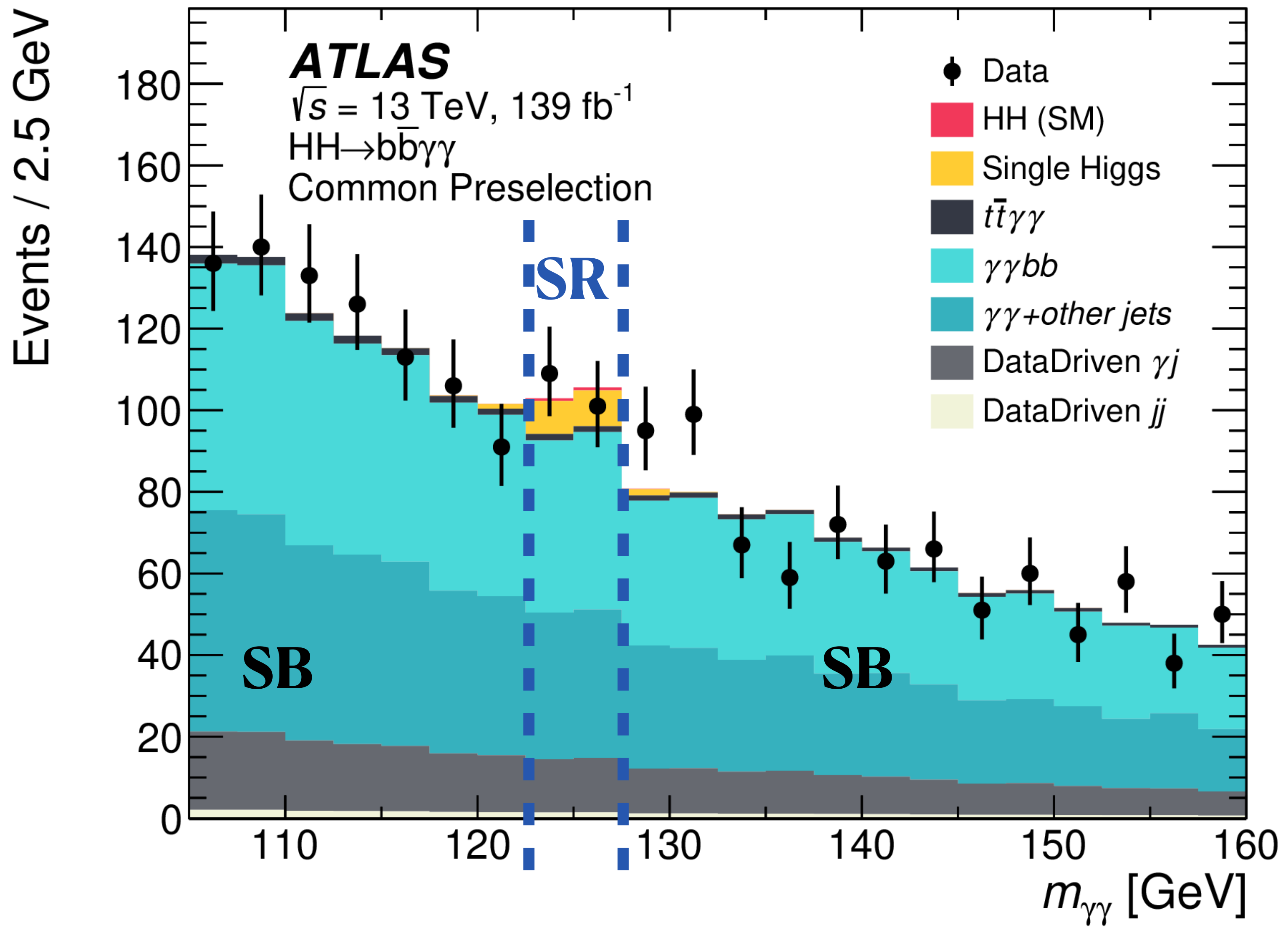
s

- At least 2 tight and isolated photons
- $p_T/m_{\gamma\gamma} > 0.35\ (0.25)$ for leading (sub-leading) photon
- $105 \leq m_{\gamma\gamma} \leq 160$
- At least 2 jets
- Exactly 0 leptons
- Less then 6 central jets ($|\eta| < 2.5$) — ttH rejection
- Exactly two (resolved) or one (merged) b-tagged jet

S is very boosted ($m_S/m_X < 0.09$)

Selection	m_X = 190GeV, m_S = 15GeV
Event cleaning and filtering	99.50 (+0.01, -0.01)
Pass trigger	53.42 (+0.07, -0.07)
2 loose photons	47.00 (+0.07, -0.07)
Trigger match	46.90 (+0.07, -0.07)
2 tight ID photons	40.54 (+0.07, -0.07)
2 tight + ISO photons	35.06 (+0.07, -0.07)
Rel. p_T cuts	32.24 (+0.07, -0.07)
$m_{\gamma\gamma} \in [105, 160]$ GeV	32.21 (+0.07, -0.07)
N_{lepton} == 0	32.12 (+0.07, -0.07)
At least 2 central jets	15.40 (+0.05, -0.05)
Less than 6 central jets	15.31 (+0.05, -0.05)
Exactly 2 b-jets (GN2 WP85%)	0.70 (+0.01, -0.01)
Exactly 1 b-jet (GN2 WP85%)	9.66 (+0.04, -0.04)
Final yield 2 b-jets	0.99
Final yield 1 b-jet	12.7

Analysis strategy

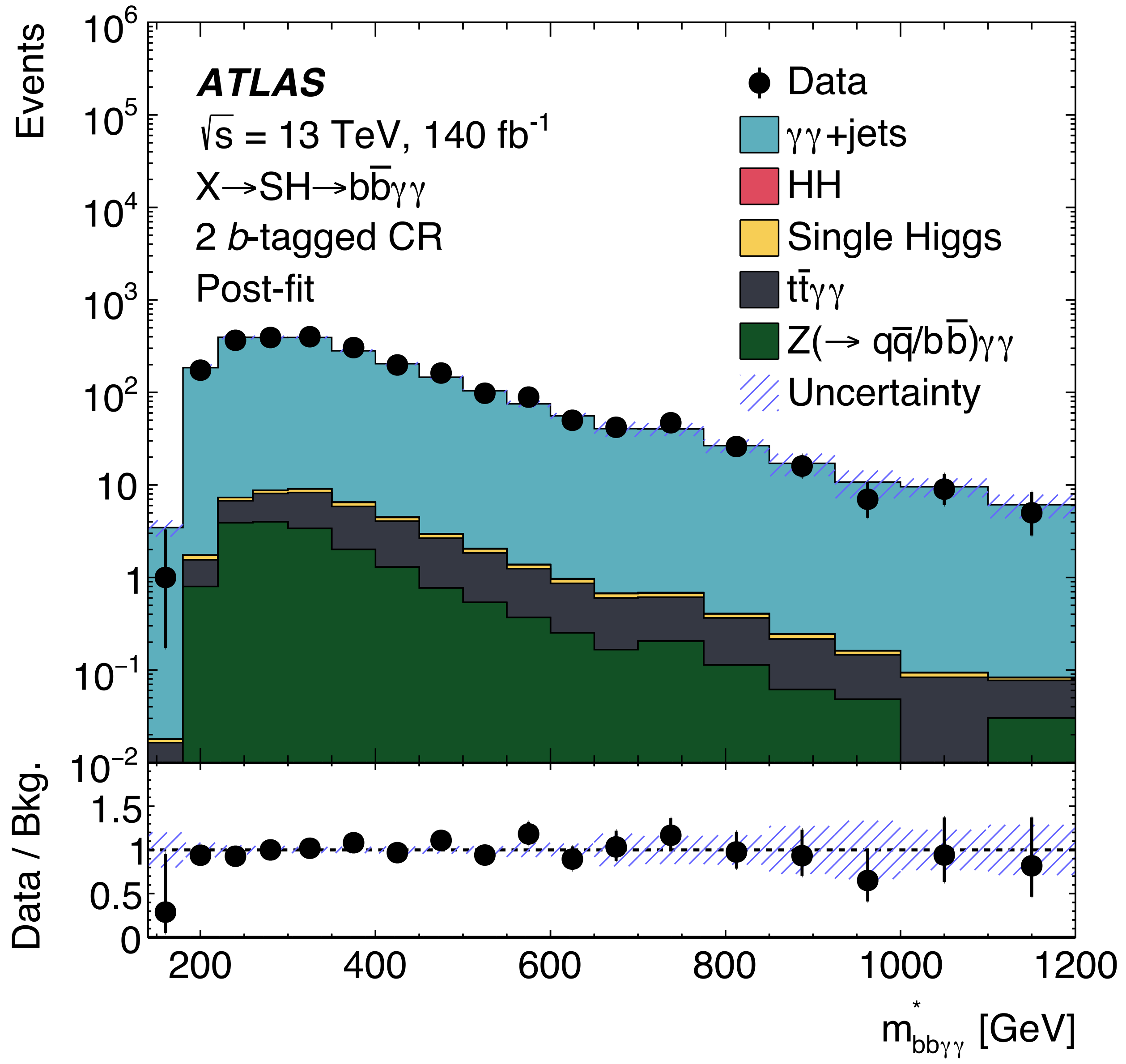


- SR is optimized to maximize the signal-to-background ratio. SB is used to extract background correction (1D fit and norm factor for $\gamma\gamma$+ jets)
- Background correction based on 1D fit $m^*_{bb\gamma\gamma}$ or $m^*_{b\gamma\gamma}$ to improve Data/MC agreement
- Bin optimization: exactly 1 background event in highest PNN score bin, 2 background event in the second to last bin …
- Train PNN for signal extraction in SR
- Fit combining SR and SB
- Estimate upper limits on the signal strength, significance for **360 mass points (160 generated + 200 interpolated)**

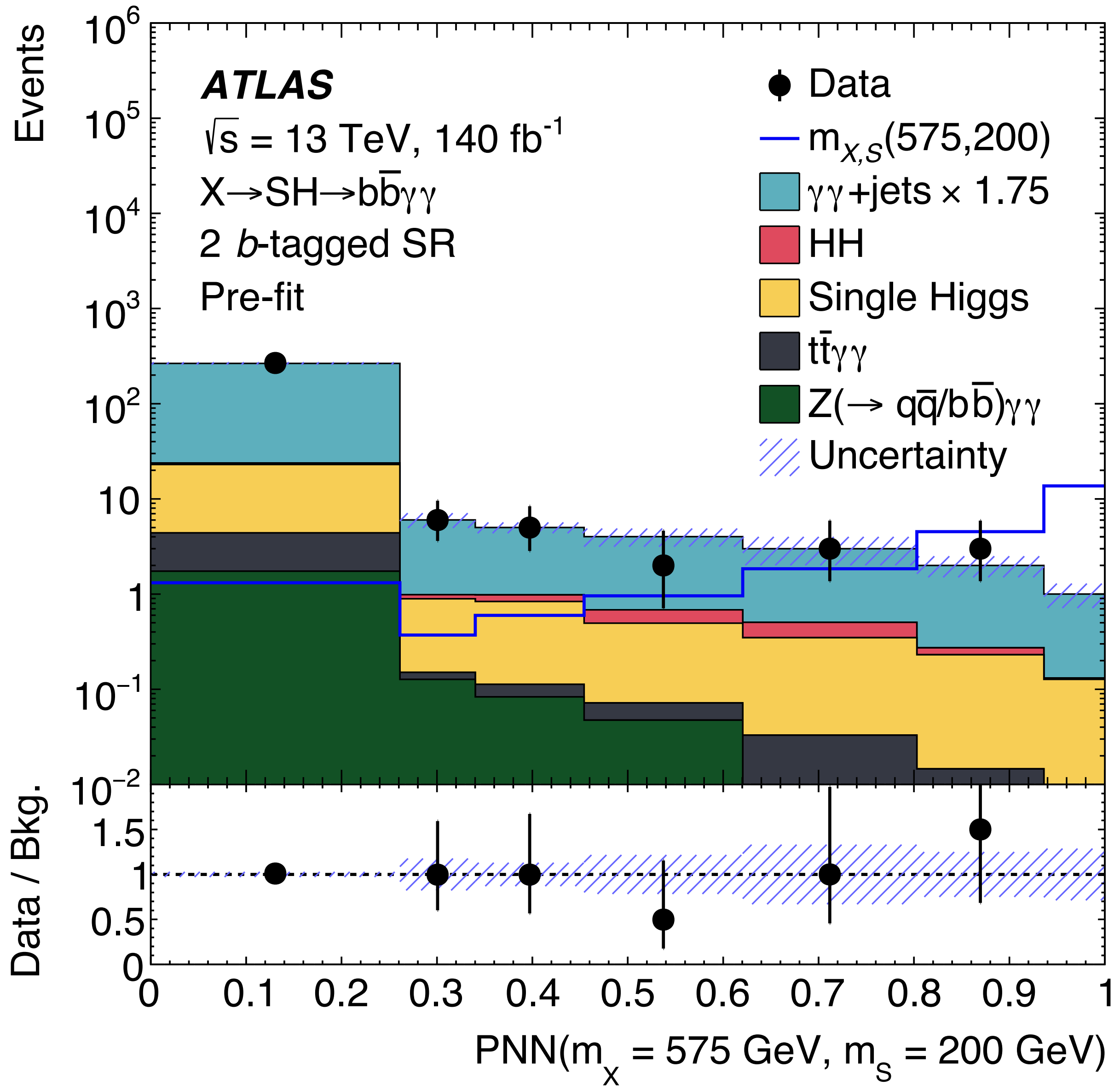
Parameterised Neural Network (PNN)

- PNN takes as input both the event features **x** and a parameter vector **θ** enabling a smooth interpolation across the mass space.
- 4 separate PNNs for resolved, merged regions and Run 2/3
- A Input features:
  - Two parameters (m_X, m_S)
  - **Resolved:** m_{bb}, $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{\gamma\gamma} - 125\ \text{GeV})$
  - **Merged:** p_T of b-jet, $m^*_{b\gamma\gamma} = m_{b\gamma\gamma} - (m_{\gamma\gamma} - 125\ \text{GeV})$
- Trained on all generated signal points and a subset of backgrounds

SB: $m_{\gamma\gamma} < 122.5$ **or** $m_{\gamma\gamma} > 127.5$ **GeV**



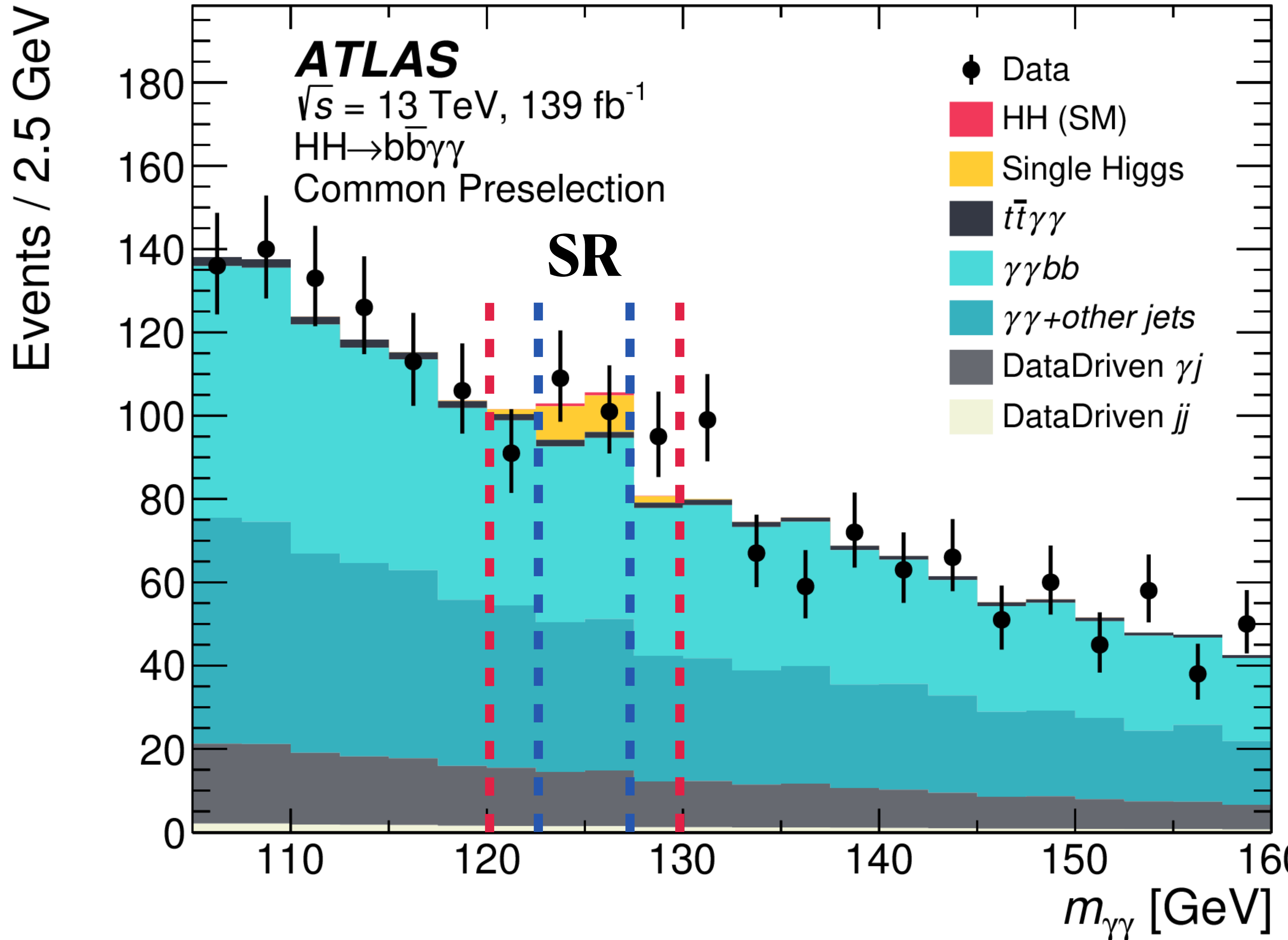
SR: $m_{\gamma\gamma} \in [122.5, 127.5]$ **GeV**



Studying the impact the $m_{\gamma\gamma}$ window

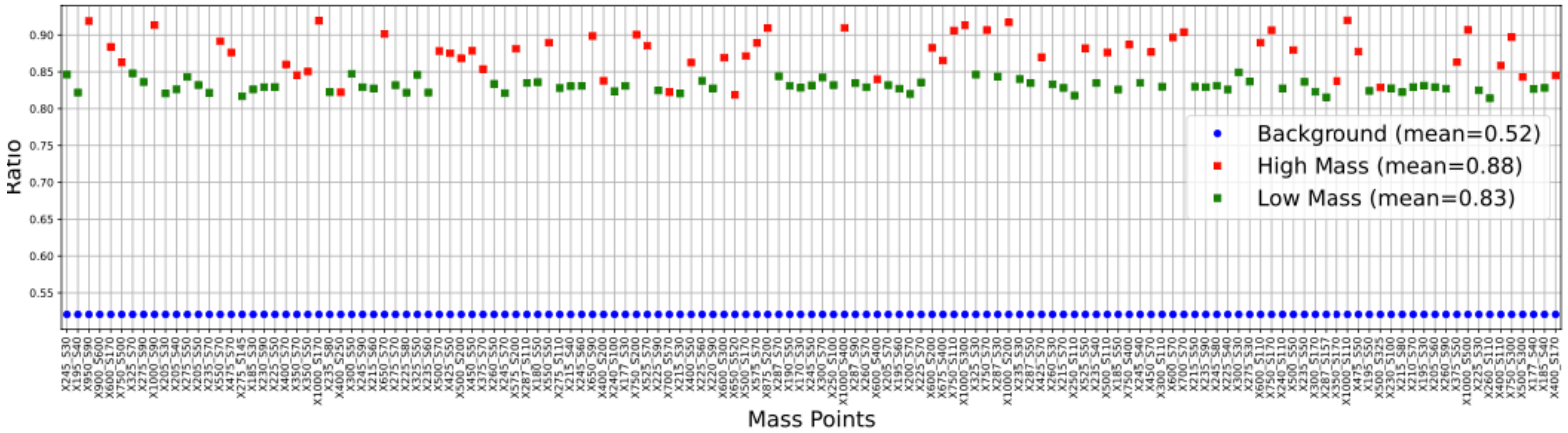
Tightening SR:

$m_{\gamma\gamma} \in [120,\ 130] \rightarrow [122.5,\ 127.5]$

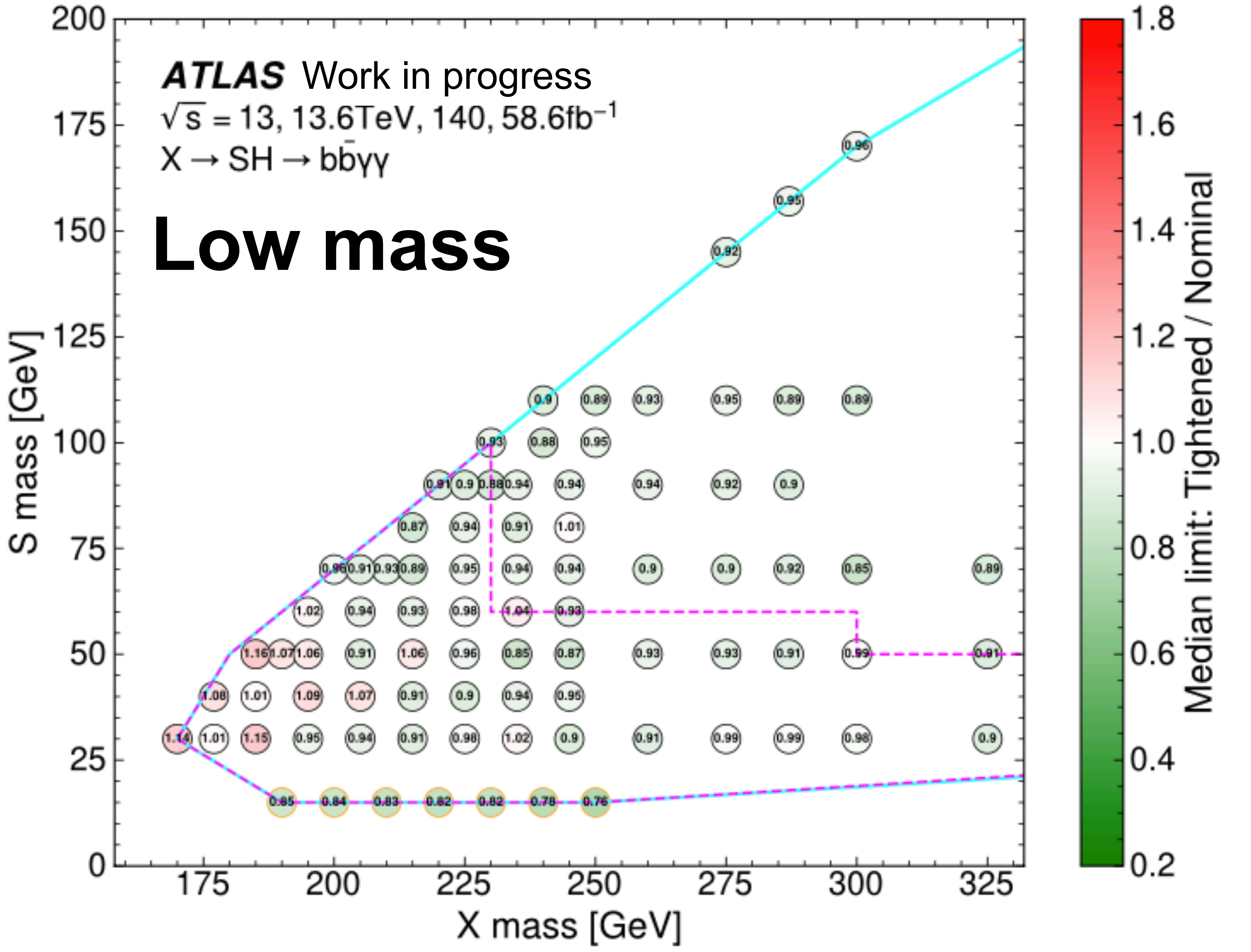


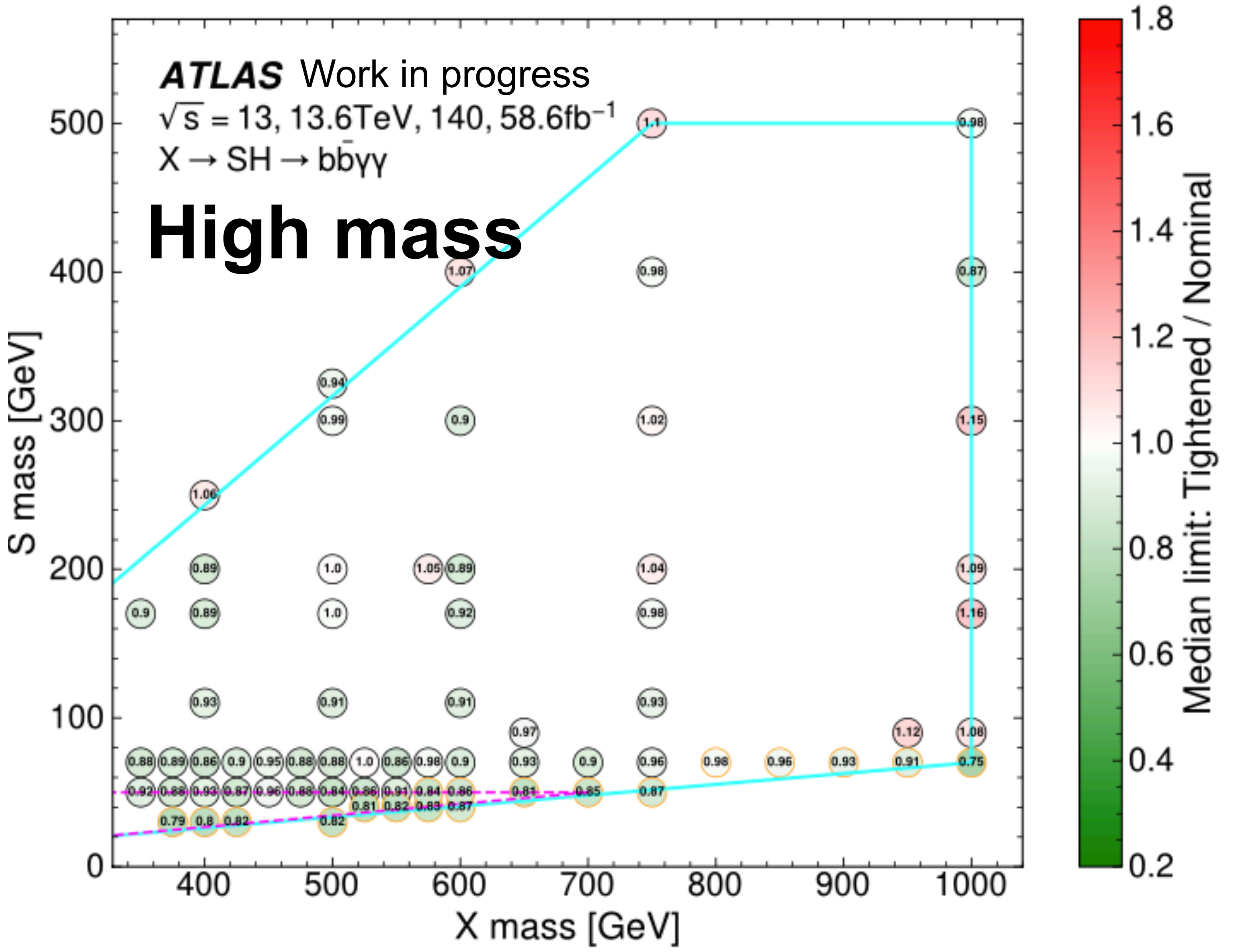
- With tightened mass window we cut ~ 50% background and up 17% signal in SR
- Limit ratio less than 1 for majority of mass points, indicates that expected limits for tightened SR are less compered to SR with $m_{\gamma\gamma} \in [120,130]$ GeV
- **Decided to use** $m_{\gamma\gamma} \in [122.5,\ 127.5]$ GeV

Signal and background yields ratio

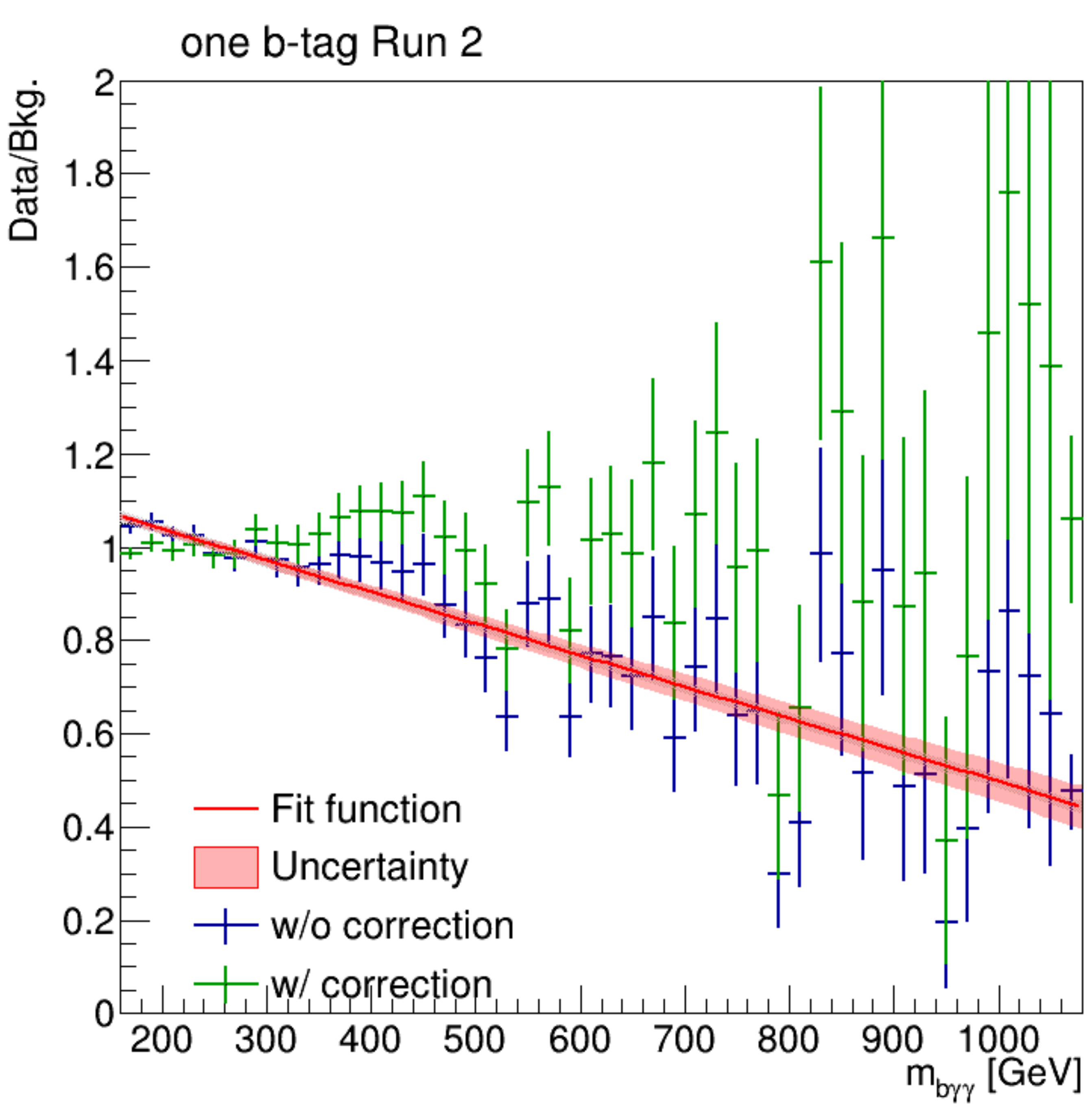


Ratio of expected limits on signal strength



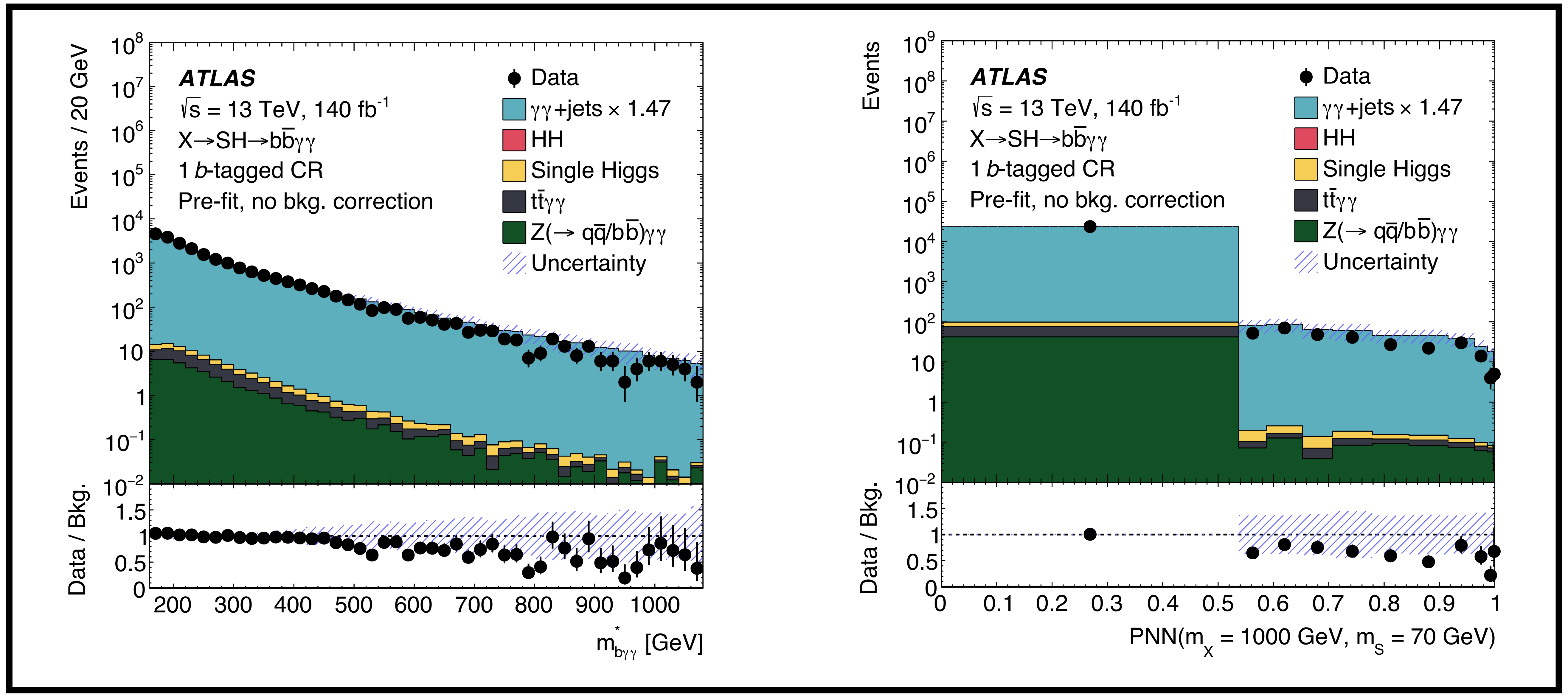


Background correction

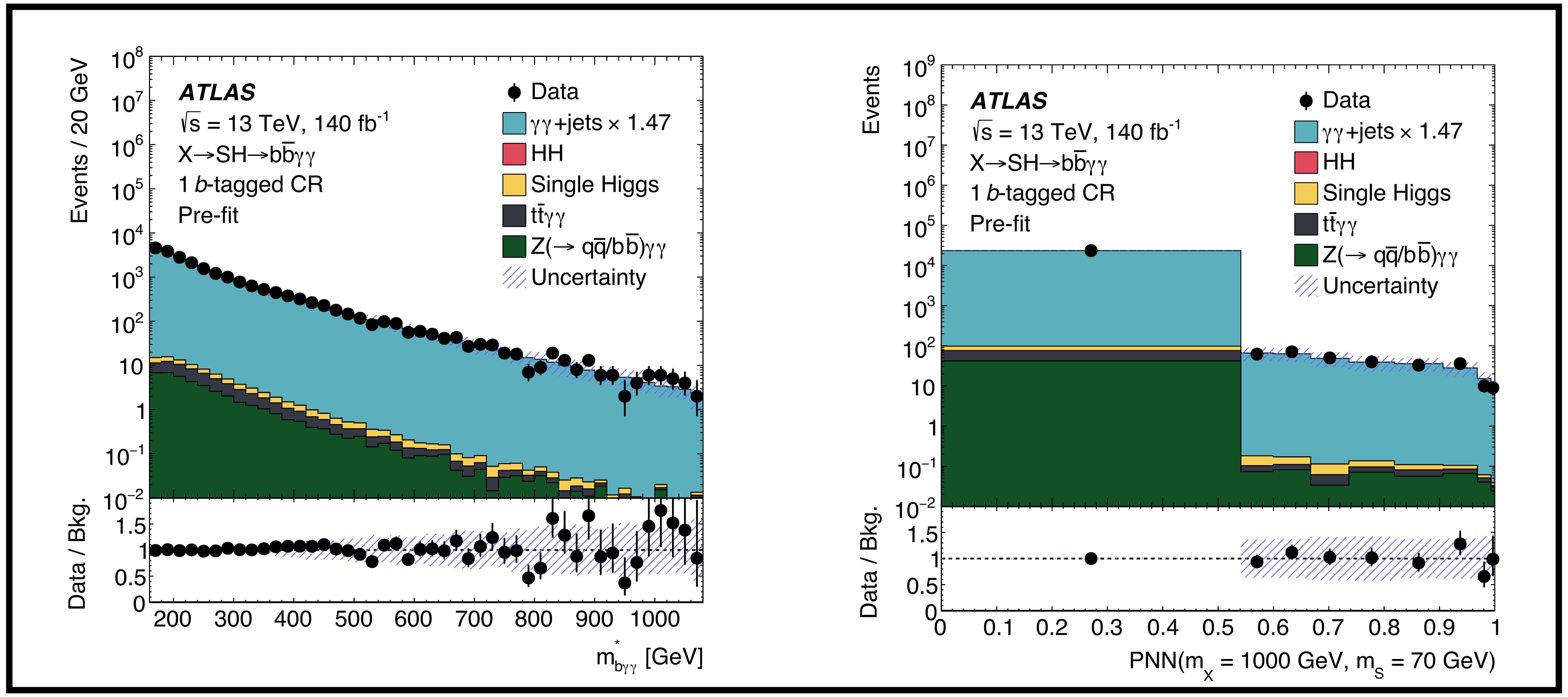


- Large Data/MC disagreement in PNN due to disagreement in $m^*_{b\gamma\gamma}$ or $m^*_{bb\gamma\gamma}$
- Applying an event-by-event correction to background based on a 1D linear fit of Data/MC vs. $m^*_{b\gamma\gamma}$ or $m^*_{bb\gamma\gamma}$ improves agreement in this variable
- Include uncertainty on the correction

SB without correction



SB with correction



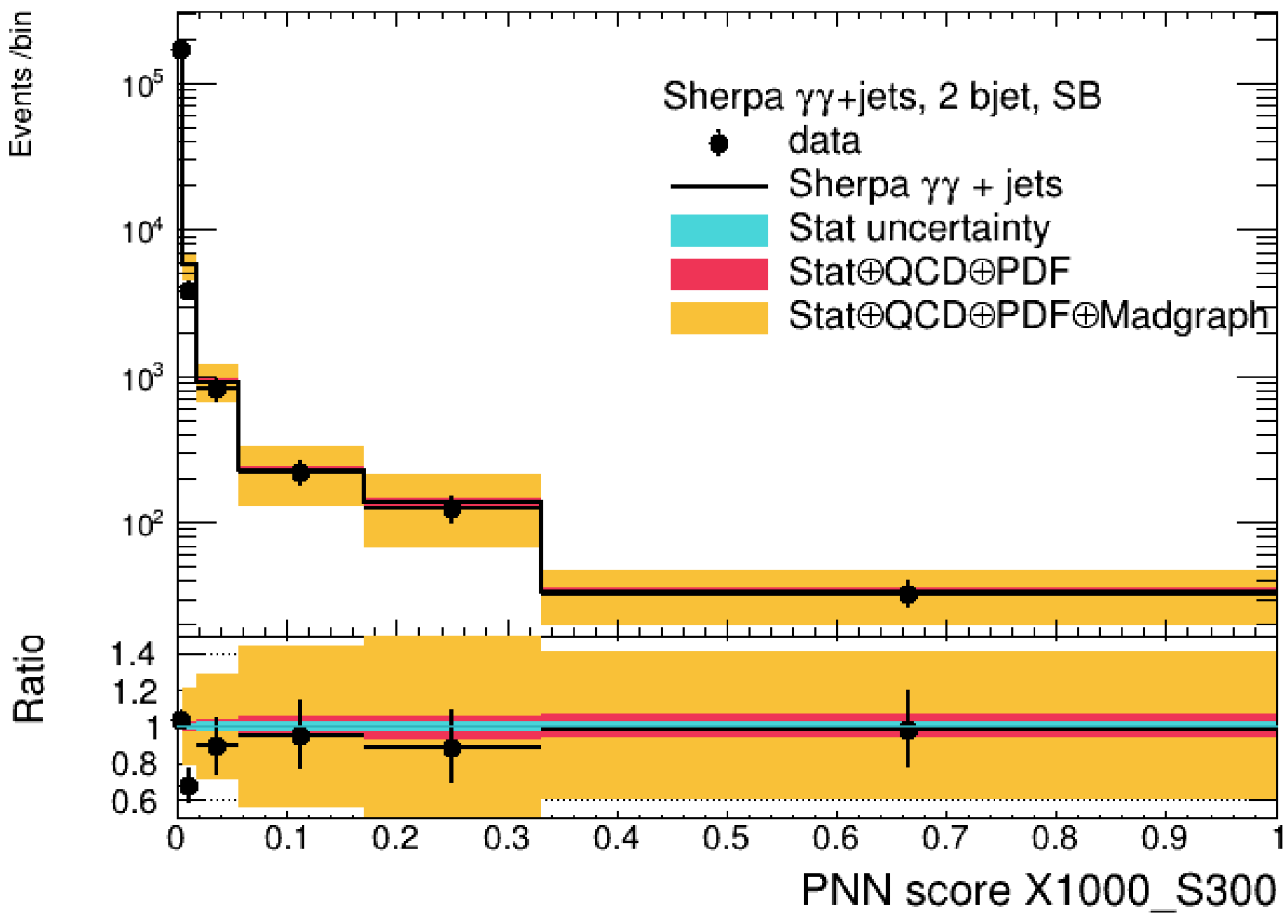
Systematics

Experimental (following CP recommendations)

- Pile-up modeling, luminosity, diphoton trigger efficiency
- Photon: energy scale, energy resolution, ID and isolation efficiencies
- Jet: energy scale, energy resolution, JVT efficiency, tagging efficiencies
- Muon efficiency corrections, Muon momentum calibrations
- Missing E_T soft term scale

Theoretical systematics

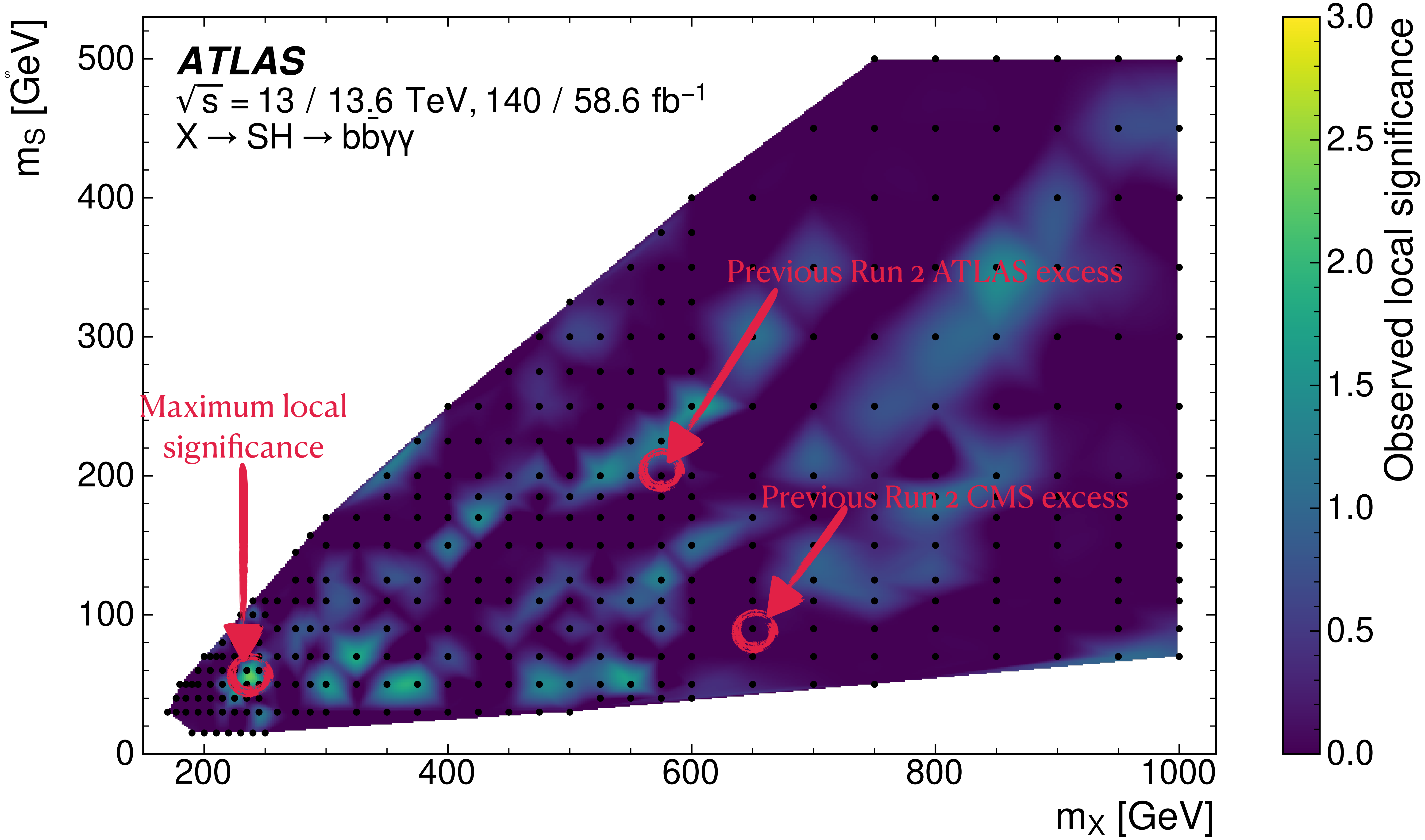
- $\gamma\gamma$-modeling (compare Sherpa and MadGraph)
- QCD Scale, PDF and α_s uncertainties
- In single H processes with heavy flavour at LO (VBFH, WH, ggFH) a global 100% normalisation uncertainty is used
- BR uncertainties for $H \to \gamma\gamma$ and $H \to bb$
- Parton showering uncertainties for signal (10%) and single H processes (from alternative Pythia/Herwig samples)
- Uncertainty on the interpolation for interpolated signals
- Uncertainty on the background correction



Correlation strategy

- Flavour, EG and Background correction NPs are de-correlated between Run 2 and 3
- The rest are correlated

Signal significance

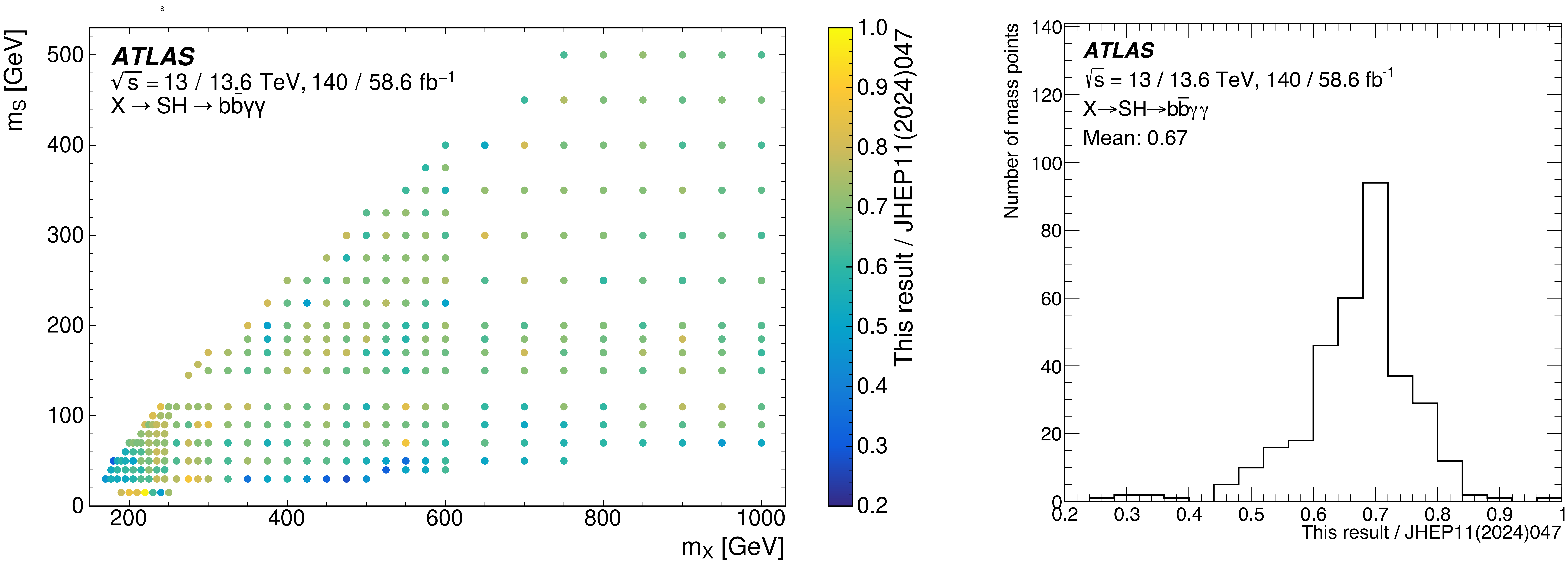


- Added $m_S = 125$ GeV hypothesis, for 23 m_X mass points
- These are new mass points which are interpolated
- Not included in Run 2 $X \rightarrow SH$ paper, because it was (incorrectly) seen as less sensitive than Run 2 $X \rightarrow HH$ analysis

- The largest excess with respect to the background only hypothesis ~2.0 σ is observed for $m_X,\ m_S = (235,\ 60)$ GeV
- Do not see excesses observed by ATLAS $m_X,\ m_S = (575,\ 200)$ GeV and CMS $m_X,\ m_S = (650,\ 90)$ GeV in Run 2
- Many mass points with local 0σ, because they have 0 data event in the highest PNN score bins

Comparison to Run 2 paper

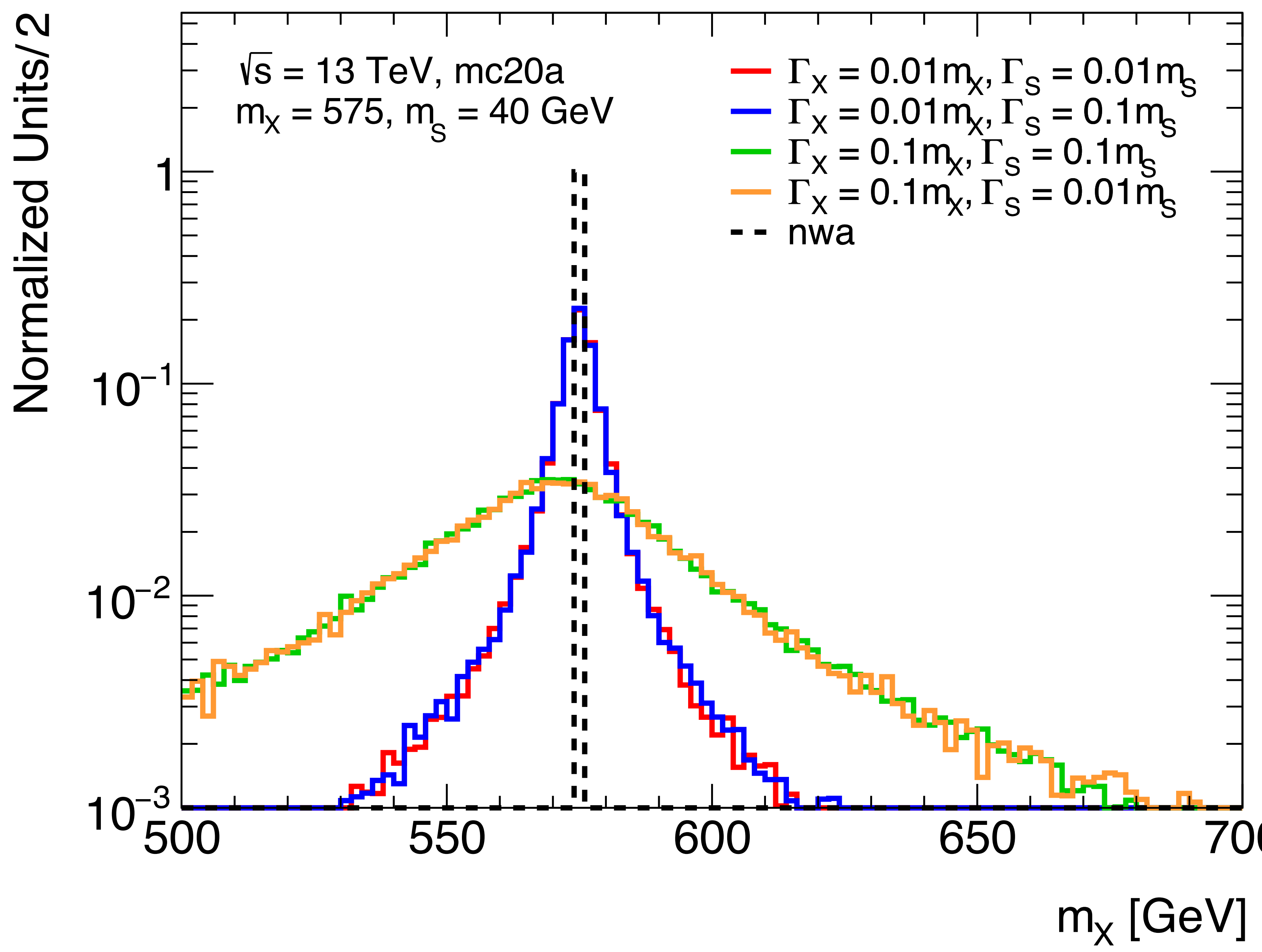
Ratio of expected limits at 95% CL on the production cross section times branching ratio to $bb\gamma\gamma$



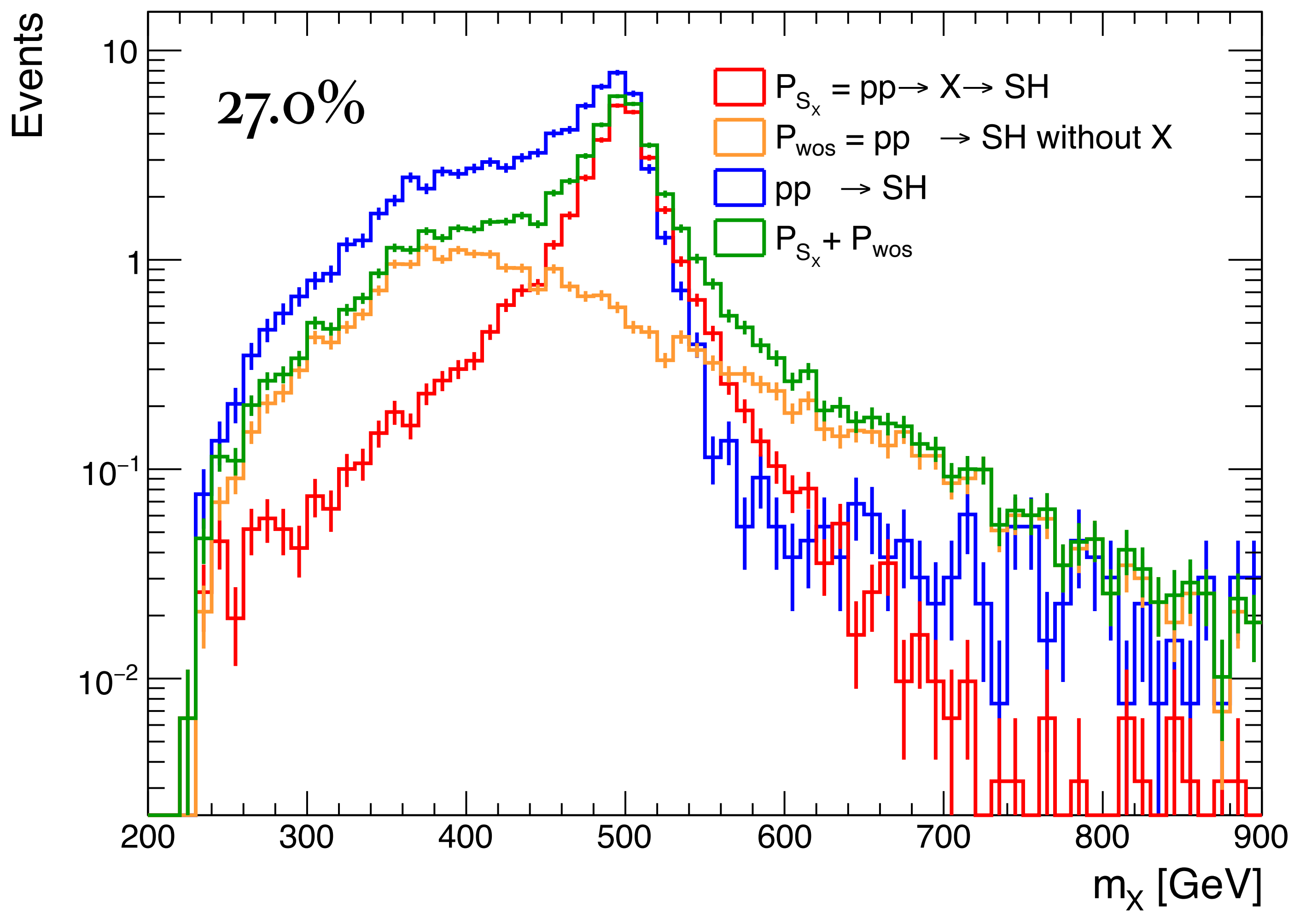
- Distribution of ratios across all tested mass points, illustrating the overall improvement in sensitivity

Wide width study

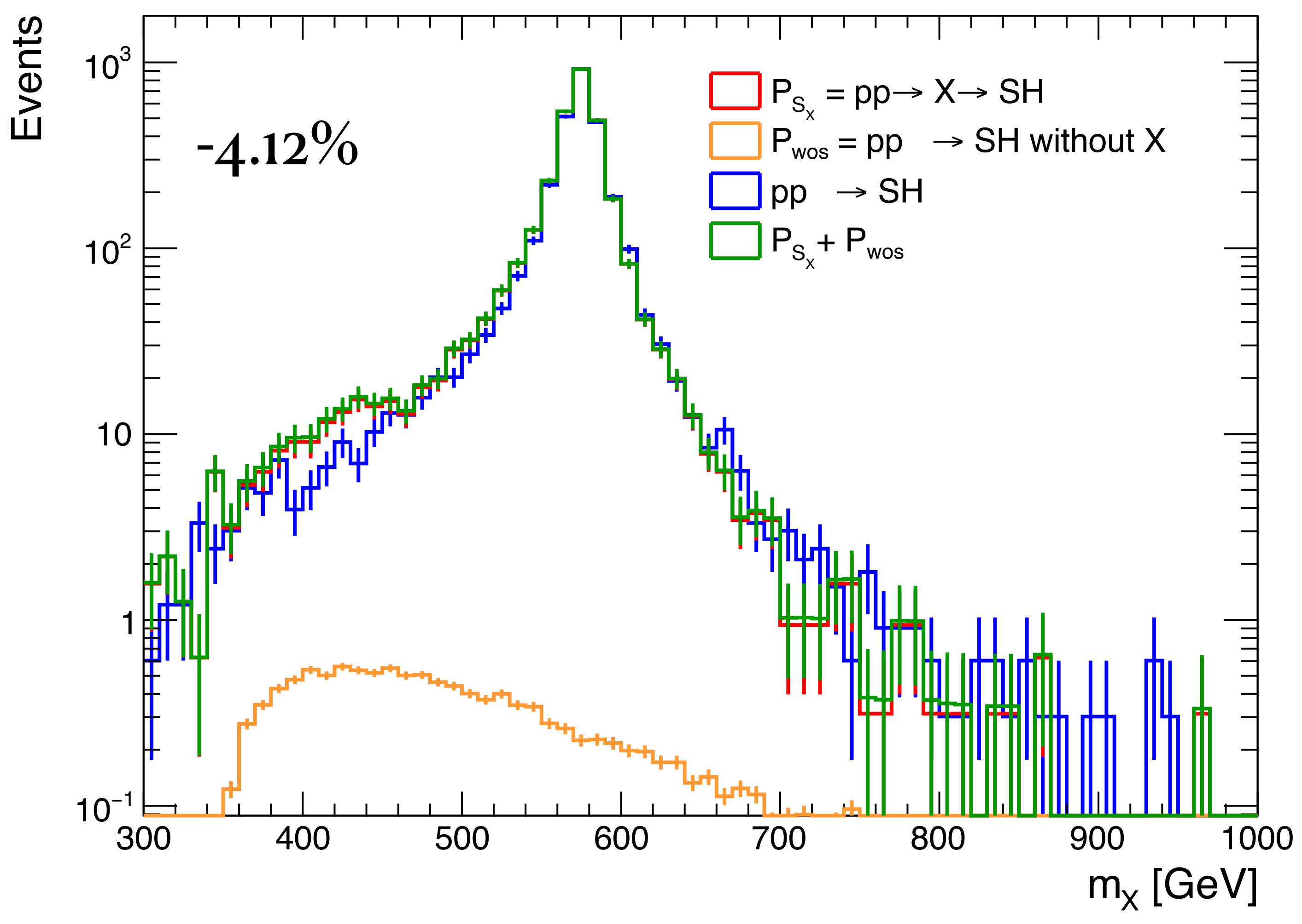
- Preliminary study was done by master student from CPPM
- As expected, we are less sensitive when using wide widths
- If we want go beyond NWA we have to check Interference effects arXiv:2409.06651
- What is the min and max width we can use?
- How widths affect Interference?
- Check Two-Real-Singlet Model (TRSM) BPs to see what we can have arXiv:1908.08554

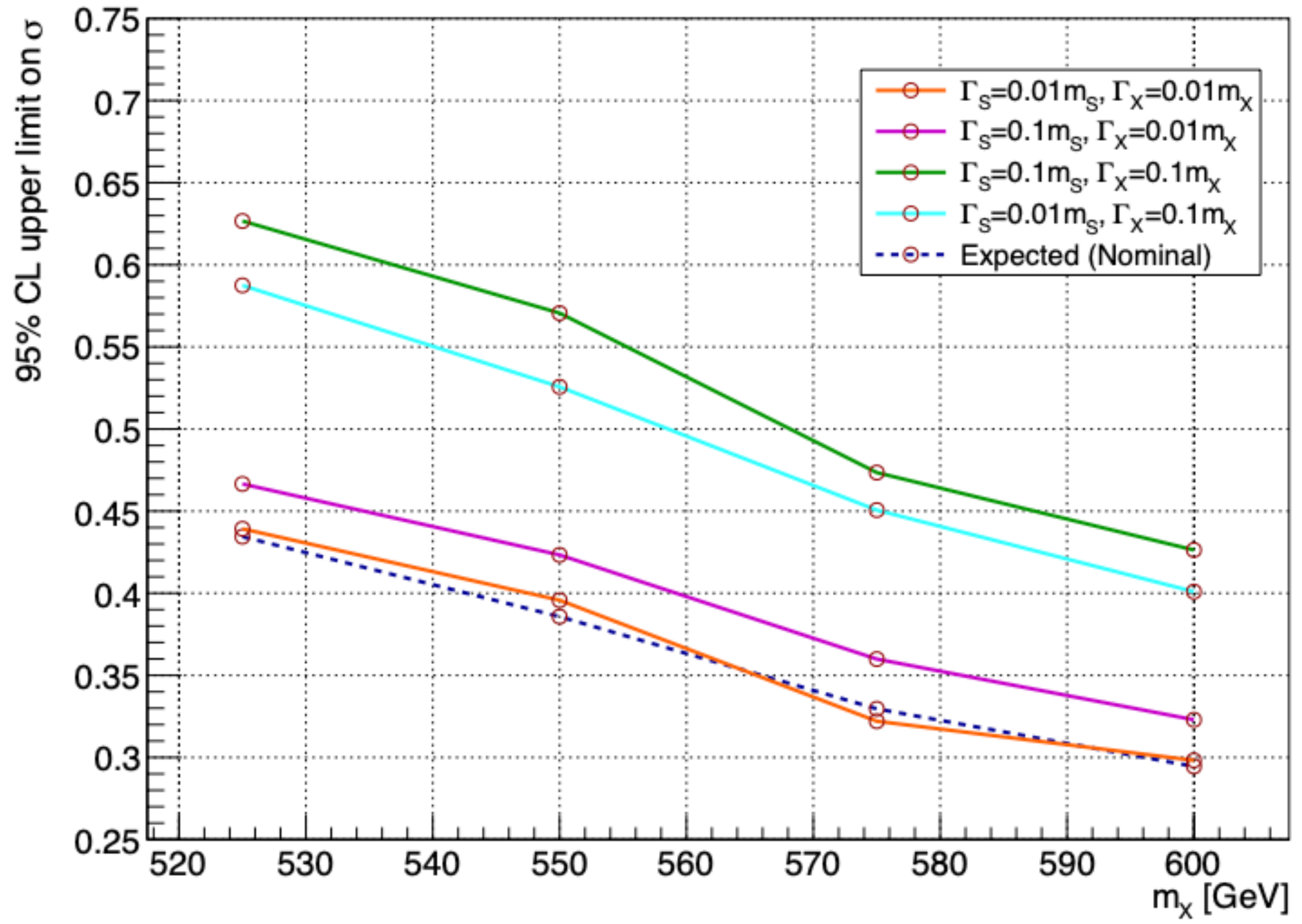


TRSM BP5 m_X = 500, m_S = 100, GeV



TRSM BP3 m_X = 575, m_S = 175, GeV





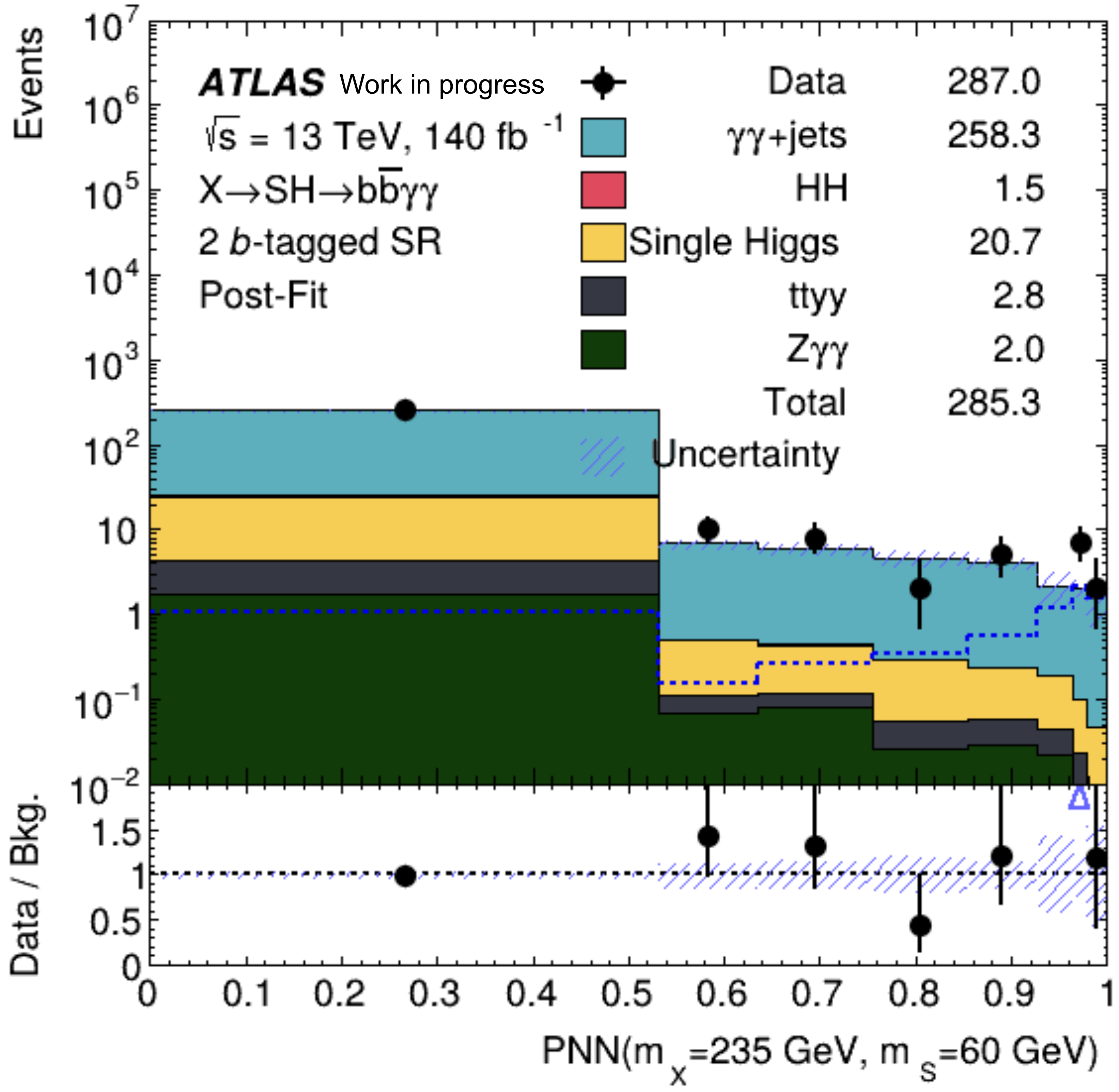
- BP5 exhibits large interference (at truth level) but has a very small xs
  Need to check at reco level.

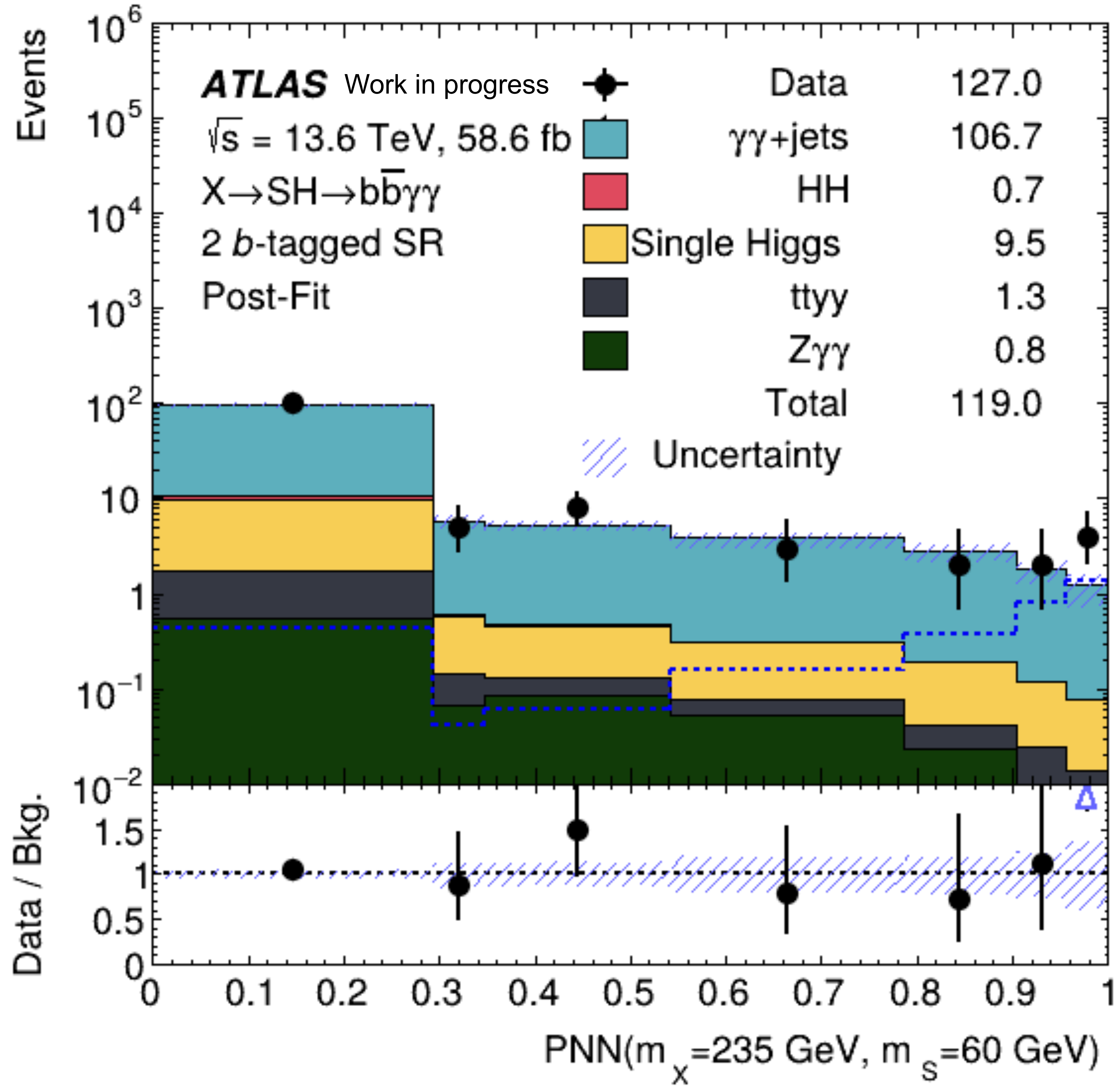
Conclusion

- Search for $X \to SH \to bb\gamma\gamma$ following up on excesses from previous Run 2 searches
- Including partial Run 3 data, the new b-tagging GN2v01 algorithm and several improvements that provide better sensitivity across most mass points
- Significant improvement in expected limits compared to previous Run 2 searches $X \to (S/H)H \to bb\gamma\gamma$
- ATLAS and CMS excesses were not confirmed
- Maximum local significance of ~2.0σ for $m_X,\ m_S = (235,\ 60)$ GeV
- We are working on HEPdata and paper for journal
- Work on the wide width is in progress. Going to calculate the theoretical cross-section for TRSM

Backup

New excess: m_X, $m_S = (235, 60)$ GeV





	Significance
Run 2	1.5
Run 3	1.6
Run 2 + Run3	2.0

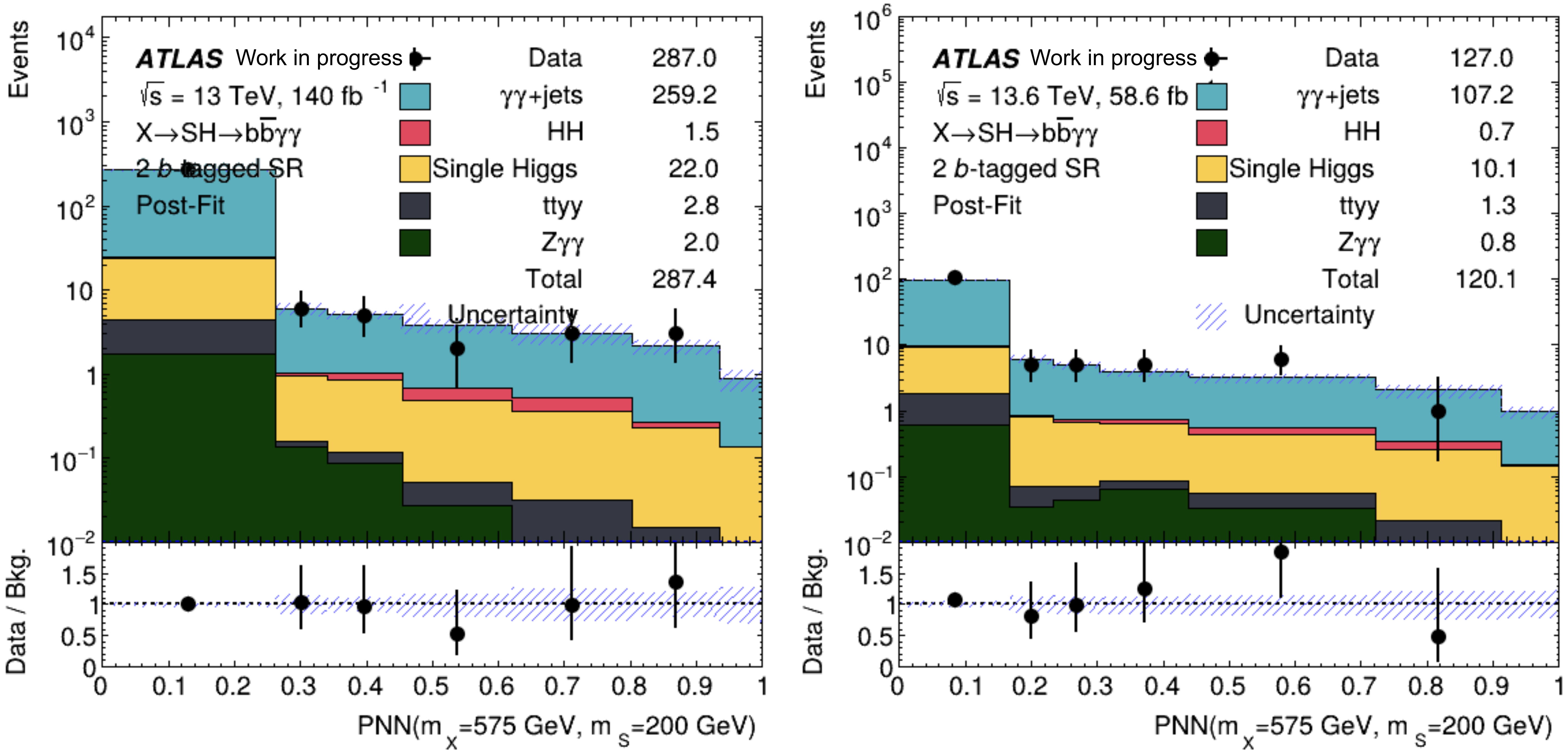
- Good agreement between Data / Background except
  - Run 2: 2nd highest PNN score bin with ~ 7 data events
  - Run 3: 1st highest PNN score bin with ~ 4 data events

The Run 2 ATLAS excess: $m_X, m_S = (575, 200)$ GeV

- 0 data events in the highest PNN score bin for Run 2 and Run 3 → best fit $\mu = 0$
- Good agreement with background in other bins

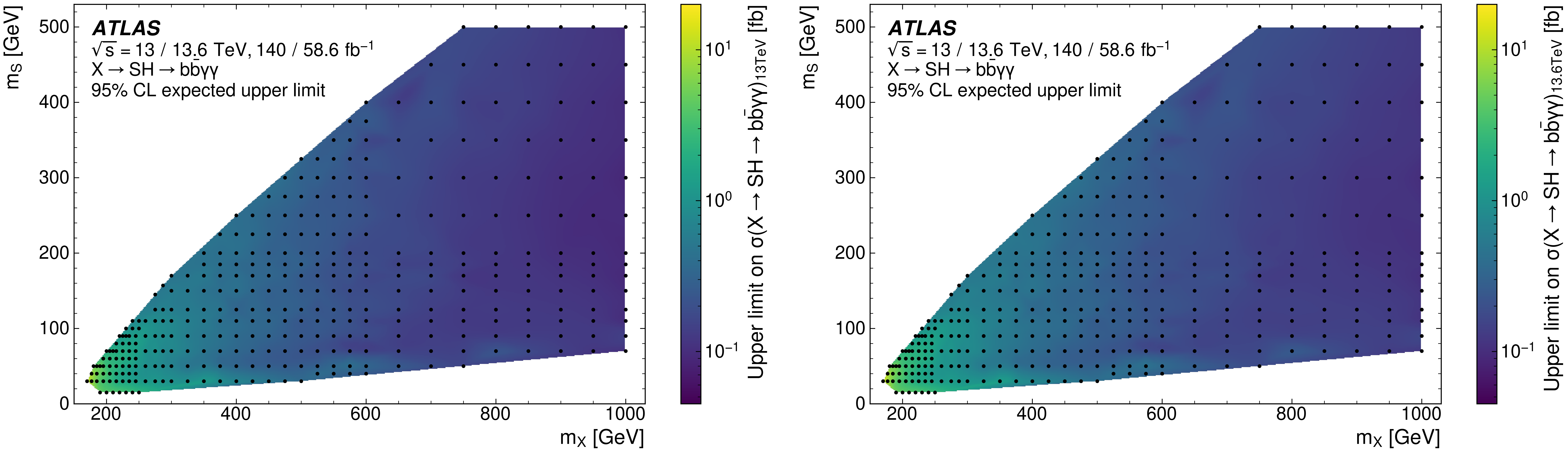
Event migration for the Run 2 results:

- 6 events were in the highest PNN-score bin in the previous analysis
- 1 event does not pass the pre-selection anymore (one photon is now reconstructed as an electron).
- 2 events do not pass the 2-btag selection (DL1r → GN2).
- 1 event does not pass the tightened $m_{\gamma\gamma}$ selection
- 2 events migrated from the last PNN-score bin to the second-to-last bin



Expected limits

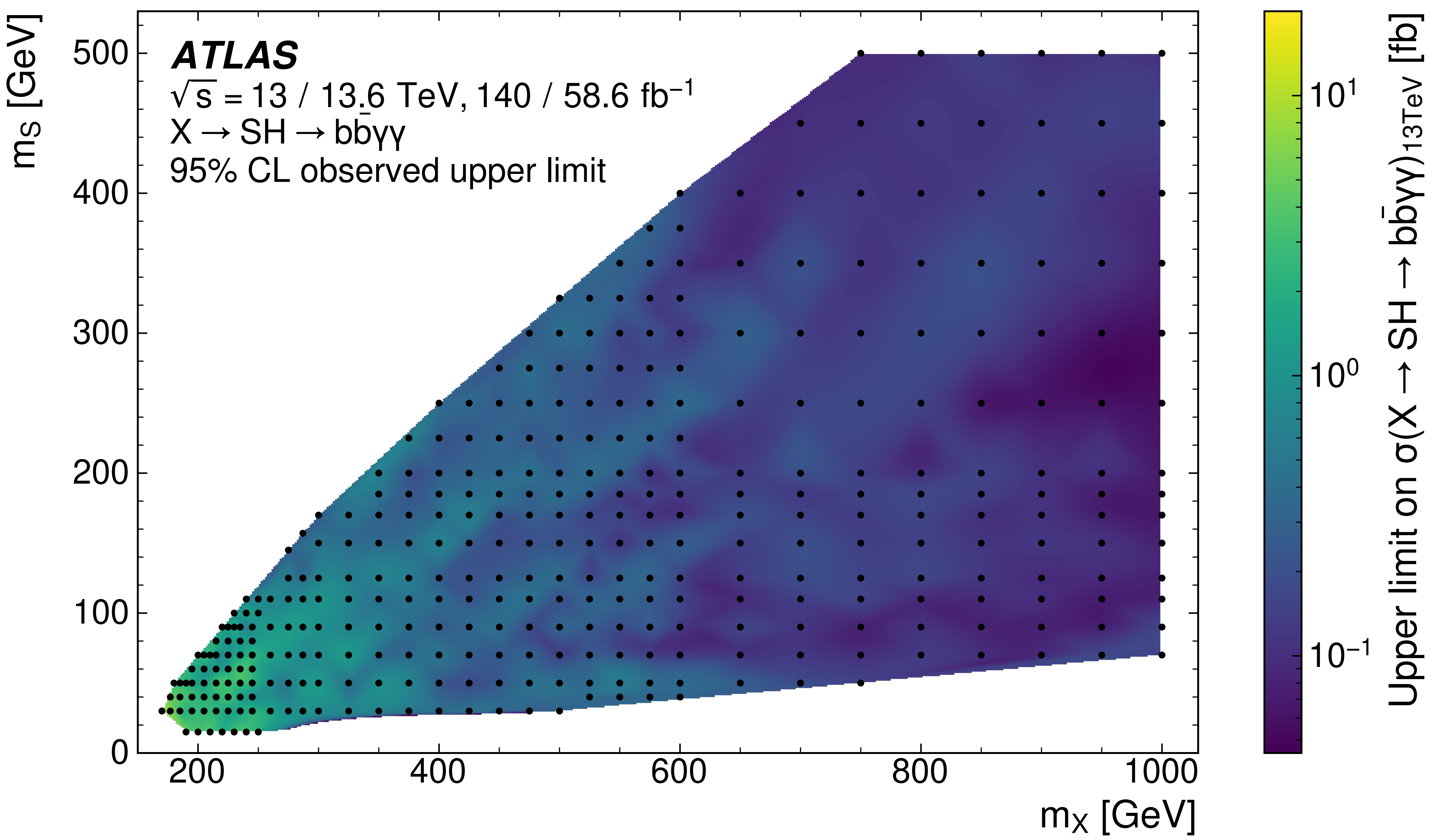
Expected limits at 95% CL on the production cross section times branching ratio to $bb\gamma\gamma$

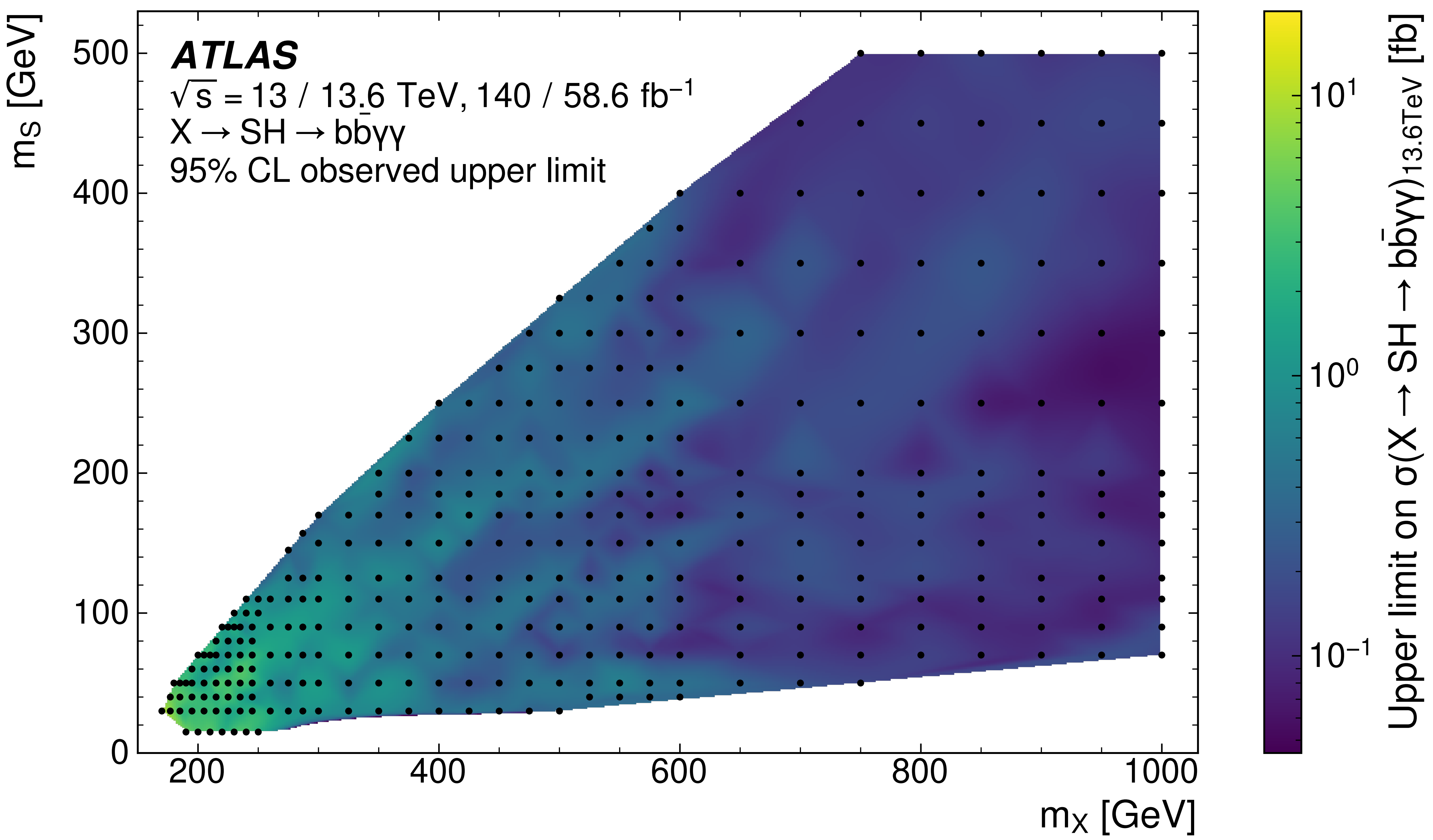


- limits on σ_{13TeV} and $\sigma_{13p6TeV}$ are simply related by the $\sigma_{13p6TeV}/\sigma_{13TeV}$ ratio predicted by Pythia8
- Limits range from 0.09 to 11.4 fb for σ_{13TeV} and from 0.10 to 12.4 for $\sigma_{13.6TeV}$
- Best sensitivity in the high mass region due to a better signal efficiency

Observed limits

Observed limits at 95% CL on the production cross section times branching ratio to $bb\gamma\gamma$



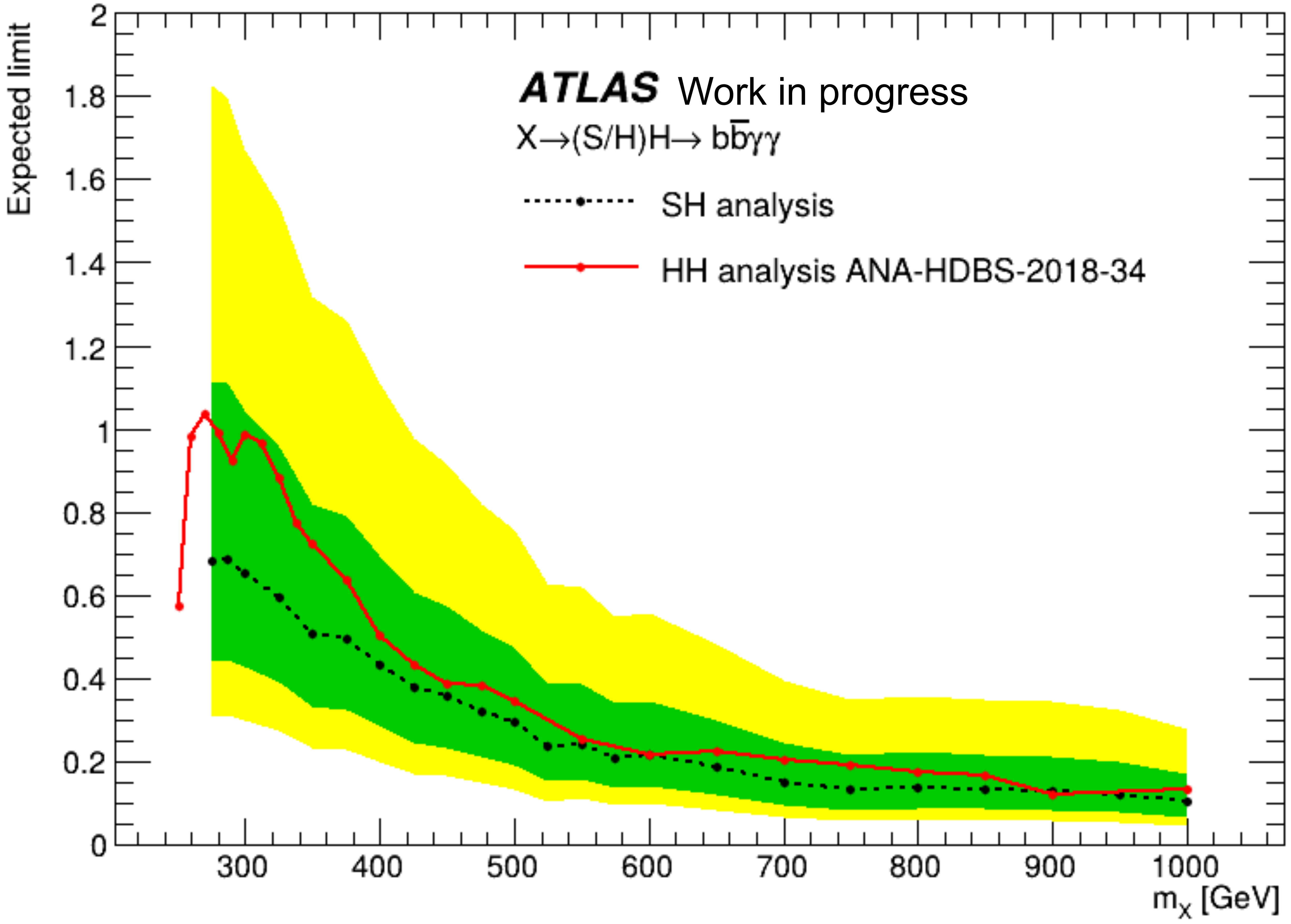


- limits on σ_{13TeV} and $\sigma_{13p6TeV}$ are simply related by the $\sigma_{13p6TeV}/\sigma_{13TeV}$ ratio predicted by Pythia8
- Limits range from 0.06 to 9.0 fb or σ_{13TeV} and from 0.06 to 9.8 for $\sigma_{13.6TeV}$
- Similar trend as the expected limits - Better in the high mass region due to a better signal efficiency
- The same for m_S = 125 GeV as for expected limits - They have limits compatible with neighboring mass points

Comparison to Run 2 paper $m_S = 125$ GeV

Expected limits at 95% CL on the production cross section times branching ratio to $bb\gamma\gamma$

s



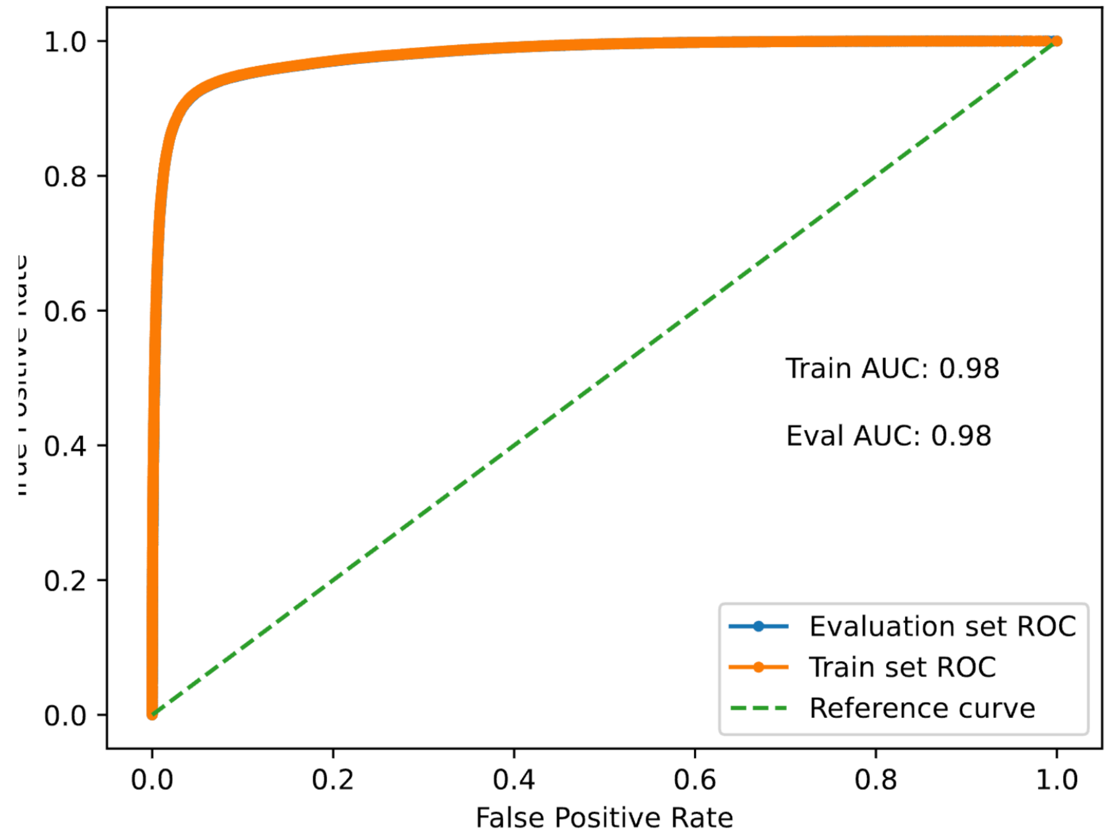
- New result shows better sensitivity compared to HH results

Parameterised neural network

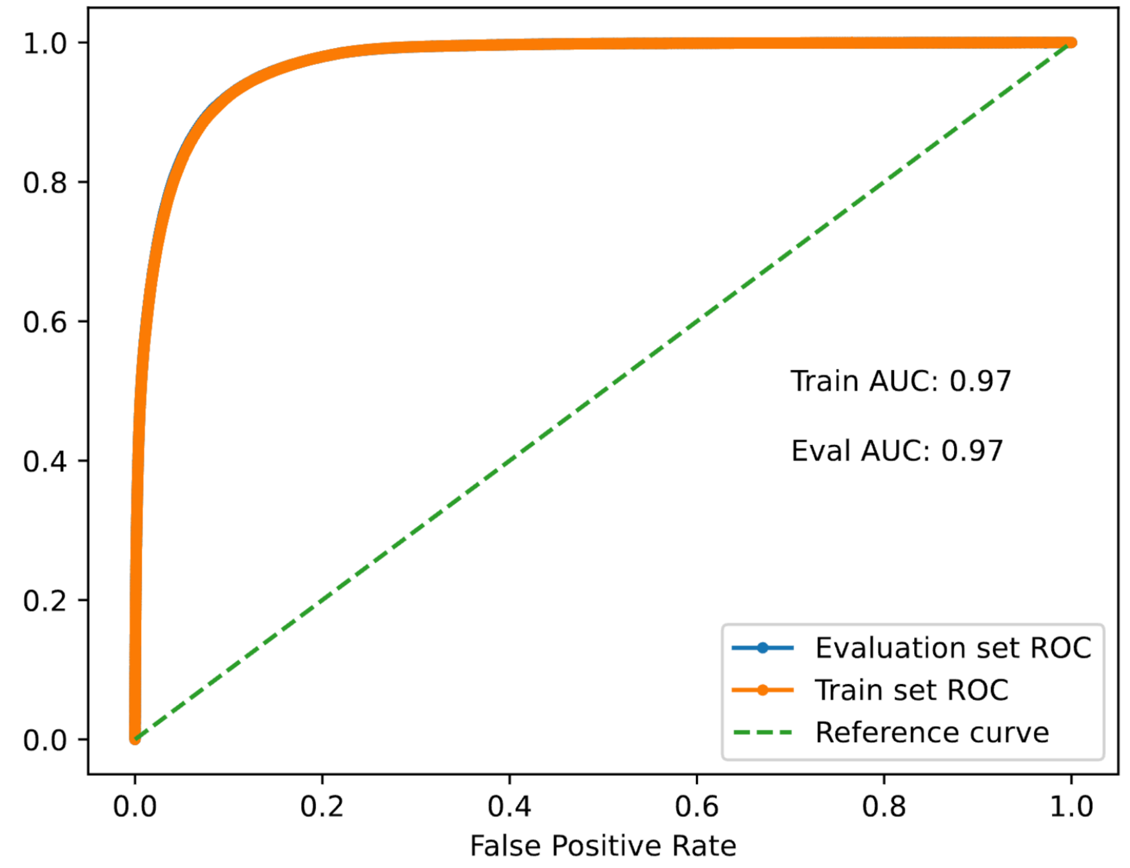
- PNNs are trained with a set of training variables (x) that are used to discriminate signal and background and a set of parameters ($\theta = m_X, m_S$)
- 4 different PNNs int total: separate PNN for resolved and merged region, and for Run2 and Run3
- Input features:
  - Two parameters (m_X, m_S)
  - **Resolved:** m_{bb}, $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{\gamma\gamma} - 125$ GeV)
  - **Merged:** p_T of b-jet, $m^*_{b\gamma\gamma} = m_{b\gamma\gamma} - (m_{\gamma\gamma} - 125$ GeV)
- Low number of training variables allows to use Lorenz transformation for the interpolation
- Both the resolved and merged are parametrised on m_X, m_S while for the previous analysis the merged PNN was only parametrised on m_X. That gives improvement of the AUC (0.94 -> 0.97)
- Trained on all generated signal points and a subset of backgrounds
- Cross validation setup:
  - 3 folds, trained on events with: event number %3= n-1 with = 1, 2, 3
  - Trained for 2000 epochs

Parameter	Range	Sampling Mode
Number of hidden layers	[1-6]	1
Dropout rate (per-layer)	[0, 0.2]	0.05
Learning rate	[0.0001 - 0.1]	Log

Run 2 resolved PNN - CV 2



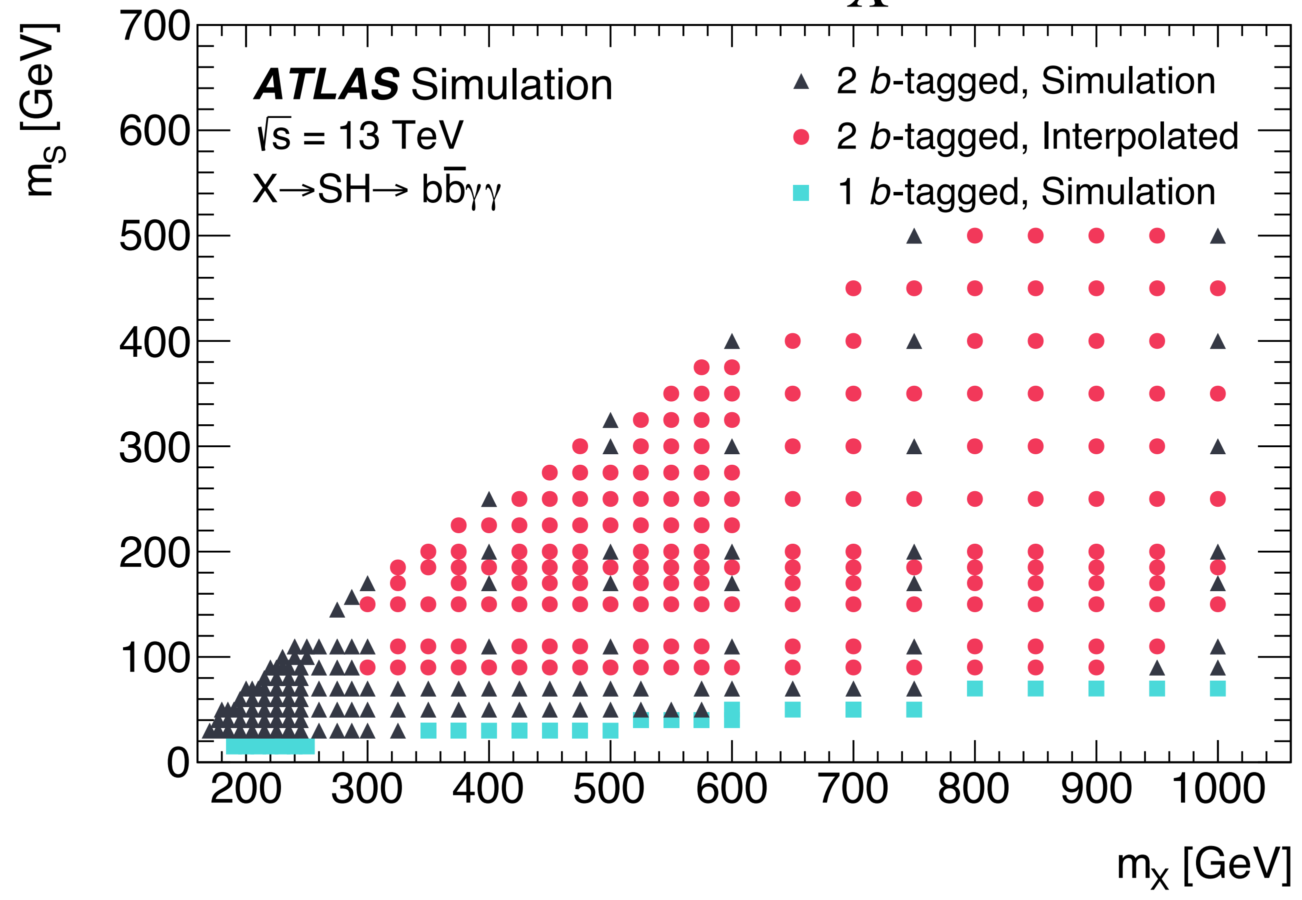
Run 2 merged PNN - CV 2



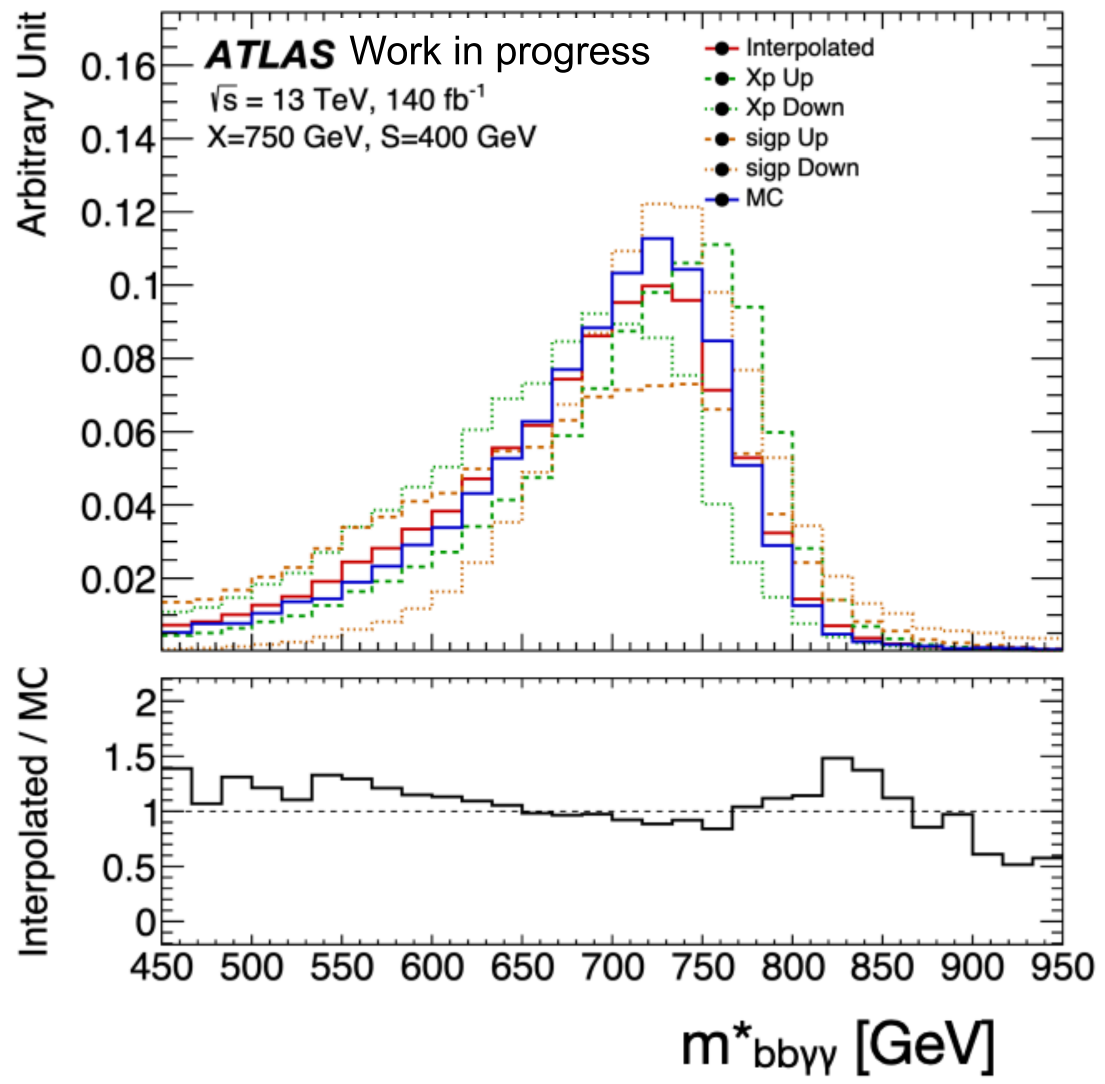
	CV1	CV 2	CV 3
Train set	Fold 1	Fold 2	Fold 3
Evaluation set	Fold 2	Fold 3	Fold 1
Private test set	Fold 3	Fold 1	Fold 2

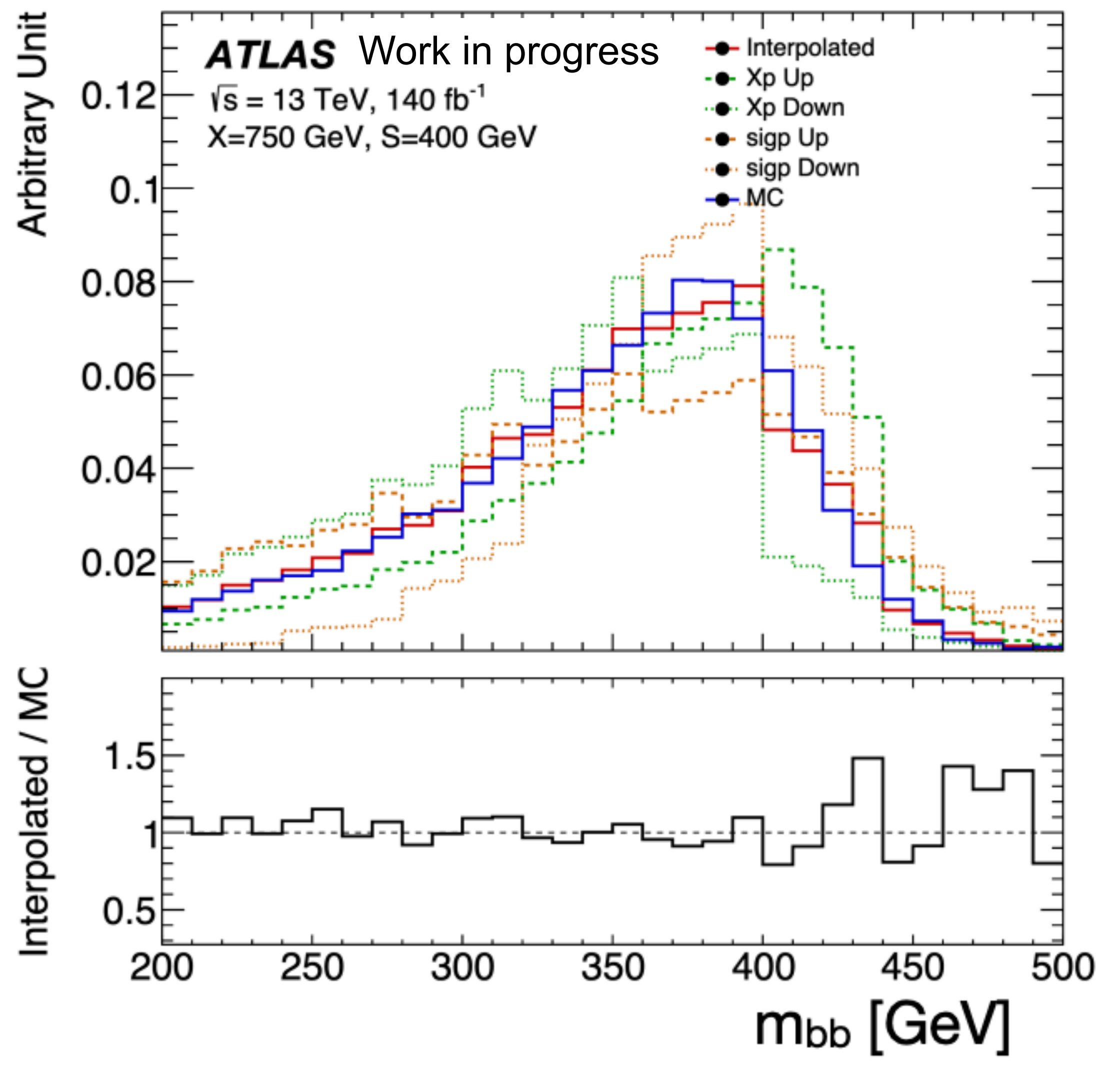
Signal interpolation

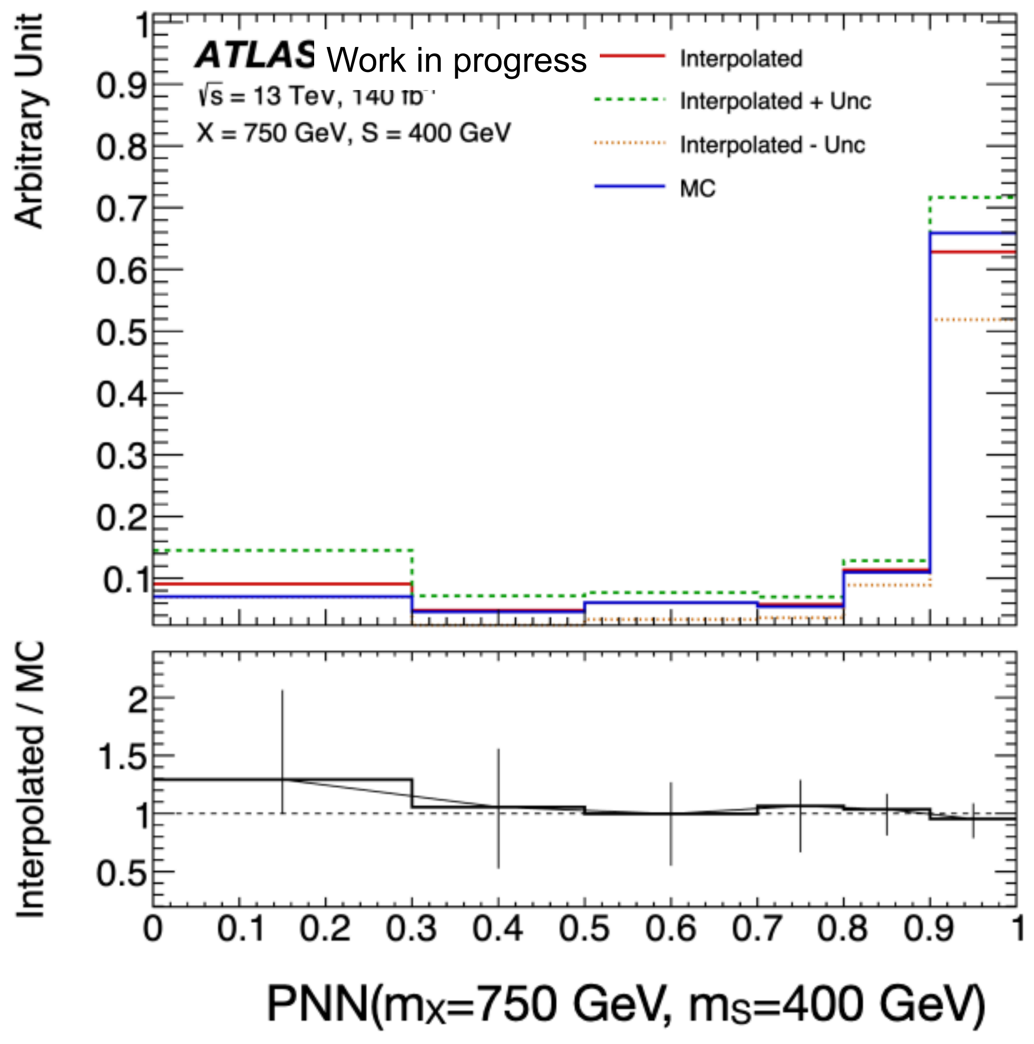
177(200) interpolated mass points in $m_X \geq 300$ GeV and



- **Resolution weighting:** Measure mass resolution of m_{bb} for all MC mass points. Interpolate using Delaunay triangulation. Apply weights to reproduce mass resolution. Same for signal yield.
- **Rescaling:** The kinematics of an interpolated mass point are emulated from generated mass point by scaling the rest-frame four vectors of H and S.
- Deriving uncertainty by varying fit parameters. Signal yield systematics interpolation
- $$R_p = \frac{|\vec{p}_S^X|(m_X^{target}, m_S^{target})}{|\vec{p}_S^X|(m_X^{init}, m_S^{init})}, \; |\vec{p}_S^X| = \frac{[(m_X^2 - (m_h + m_S)^2)(m_X^2 - (m_h - m_S)^2]^{1/2}}{2m_X}$$
- After interpolation use interpolated m_{bb} and $m^*_{bb\gamma\gamma}$ to obtain PNN score



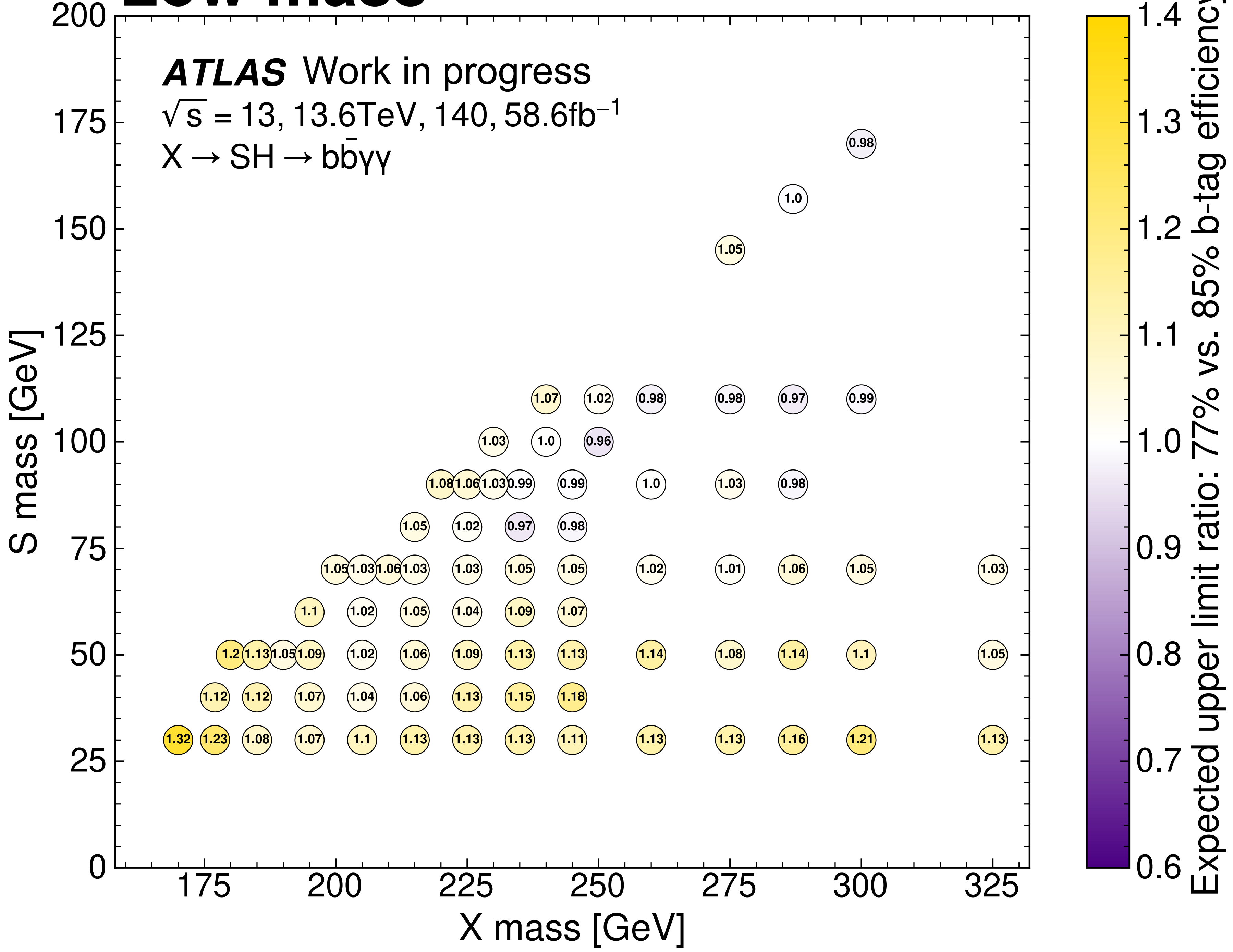




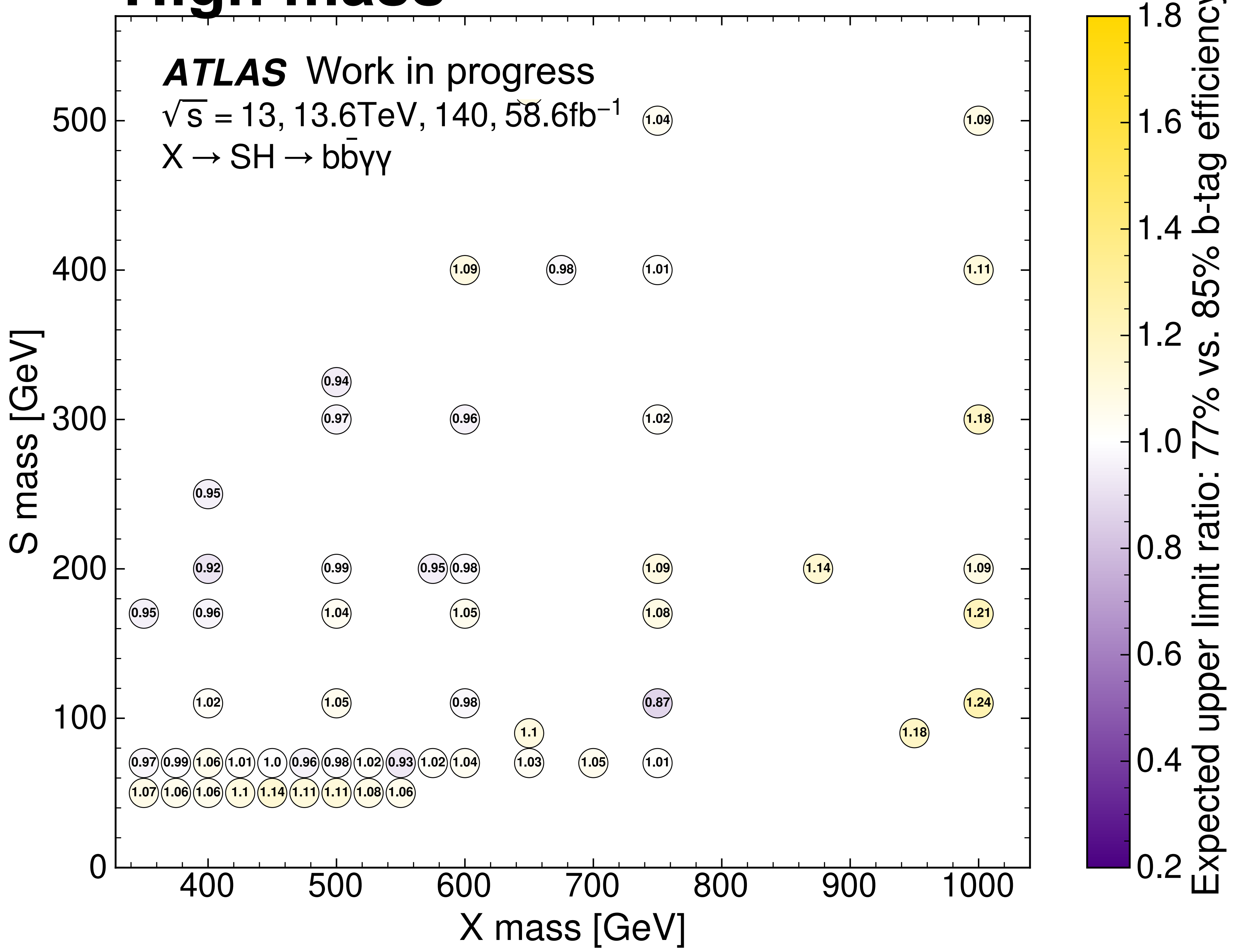
Comparison of expected limits for 77% and 85% btag WP

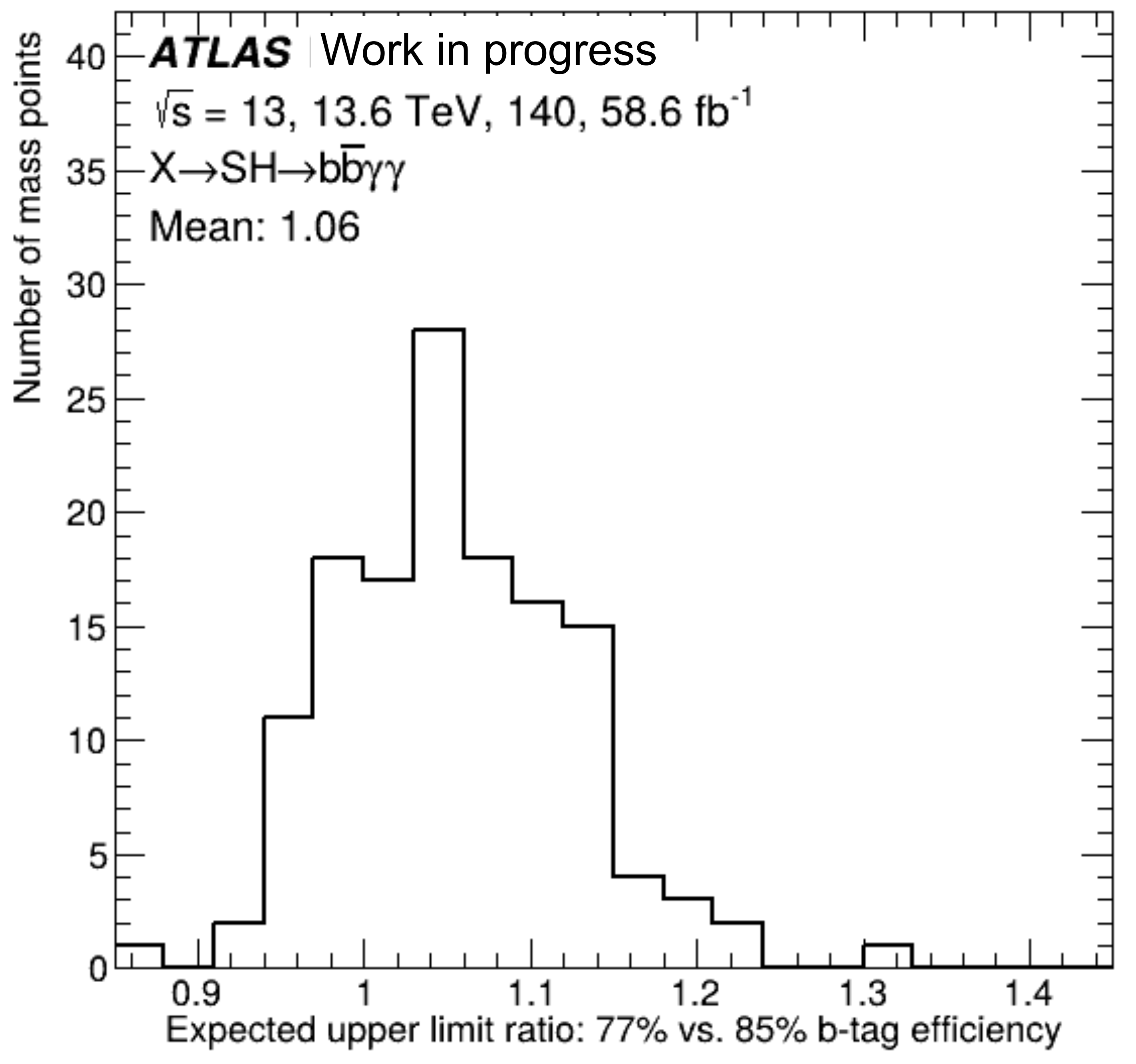
Ratio of expected limits at 95% CL on the production cross section times branching ratio to $bb\gamma\gamma$

Low mass



High mass





- The ratio is more than 1 for most mass points, indicating that using a 85% b-tagging efficiency working point instead of a 77% working point decreases the expected limits.
- **Decided to use 85% b-tagging efficiency WP**

Object selection

Photons

- ID: Tight ID with $|\eta| < 1.3$ or $1.52 < |\eta| < 2.37$
- Isolation: FixedCutLoosem, topoEtCone20 < $0.065 p_T$ and ptcone20 < $0.05 p_T$

Jets

- PFlow jets +JVT applied
- $p_T > 25$ GeV
- b-tagging: GN2v01 85% WP

+ Overlap removal

For background suppression - vetoing leptons

Electrons:

- $|\eta| < 2.47$ and $p_T > 10$ GeV + MediumLH ID + Loose_VarRad Iso

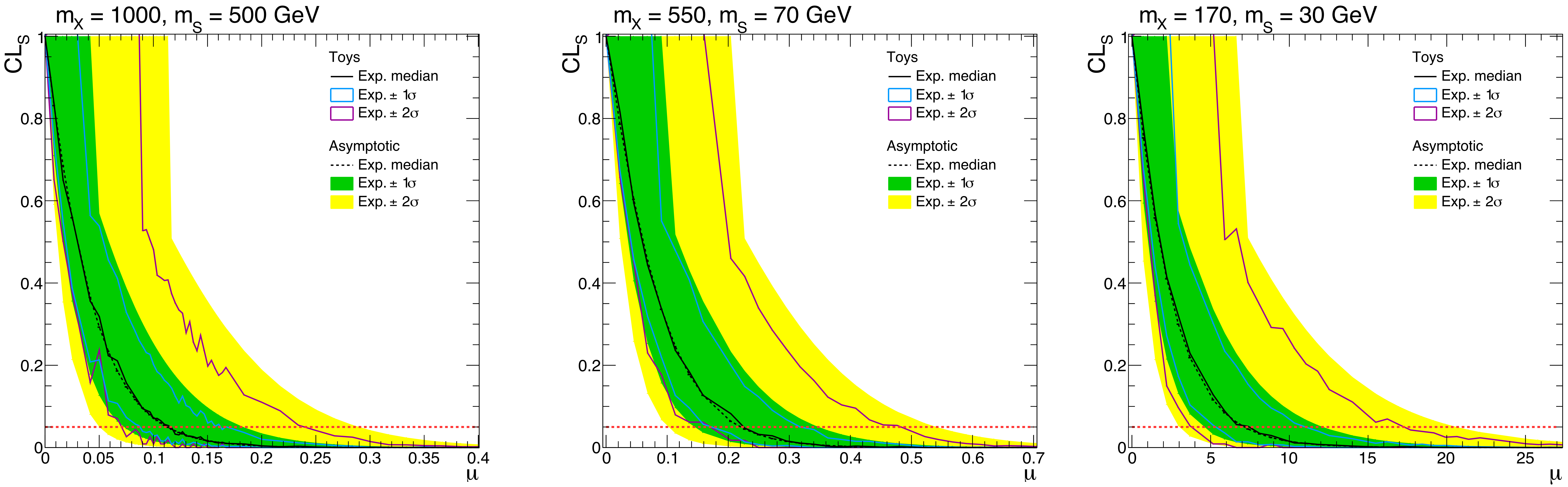
Muons:

- $|\eta| < 2.7$ and $p_T > 10$ GeV + Medium ID PflowLoose_VarRad Iso

Matched to the primary vertex via requirements:

- $|z0| \sin\theta < 0.5$ mm for electrons and muons and $|d0| \sigma_{d0} < 5\ (3)$ for electrons (muons)

Asymptotic and Toys comparison

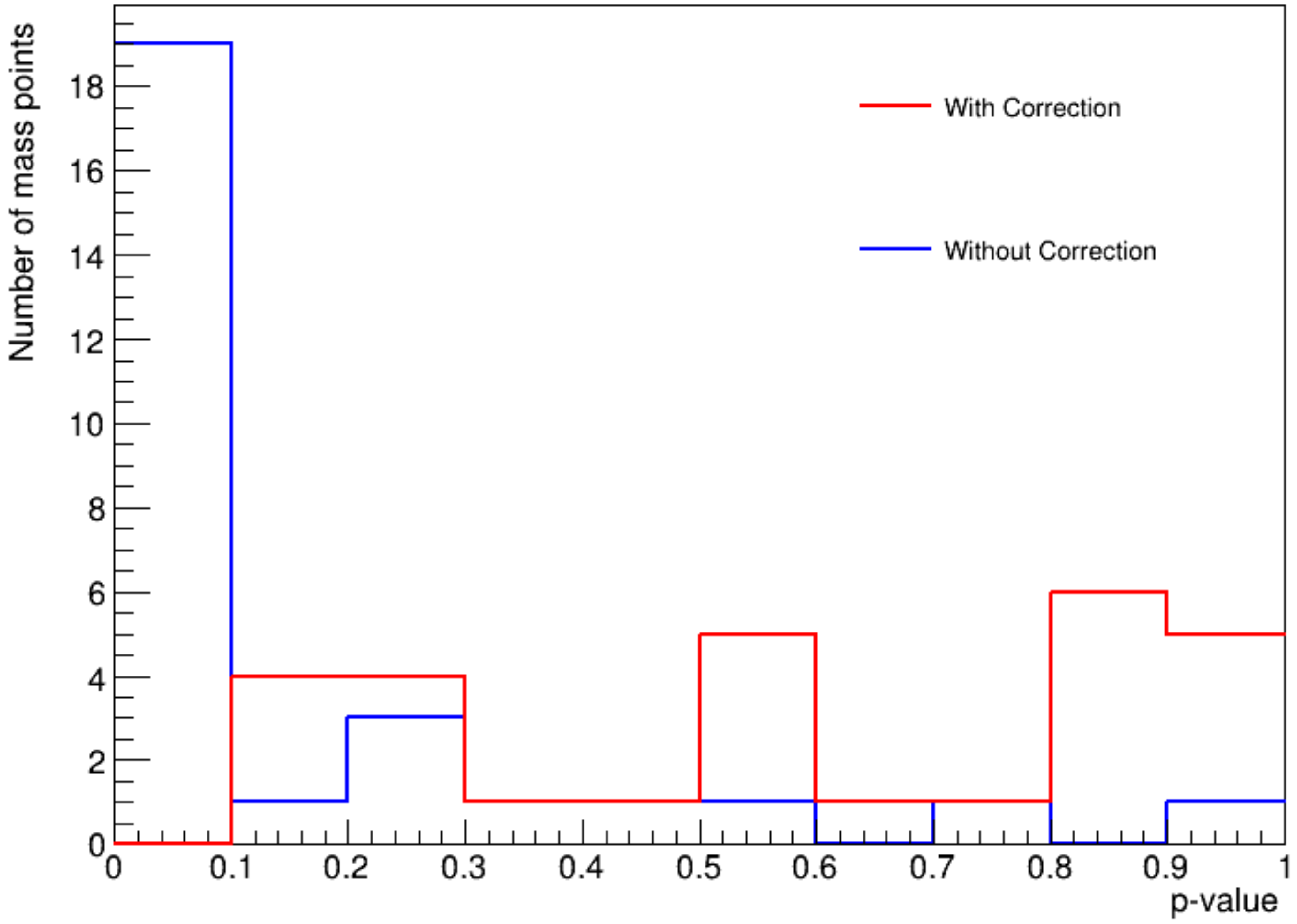


(m_X, m_S) [GeV]	Asymptotic [fb]	Toys [fb]	Rel. difference [%]
(170, 30)	7.129 ± 0.419	7.374 ± 0.737	3.45 ± 12.15
(550, 70)	0.220 ± 0.016	0.224 ± 0.020	2.06 ± 11.61
(1000, 500)	0.114 ± 0.003	0.115 ± 0.0017	1.47 ± 3.28

- It is observed that the asymptotic limits agree with the corresponding results obtained with toys within a maximum relative difference of 3.45%. Hence, the asymptotic approximation is considered reliable at the level of 3.45% for the $SH \to b\bar{b}\gamma\gamma$ analysis.

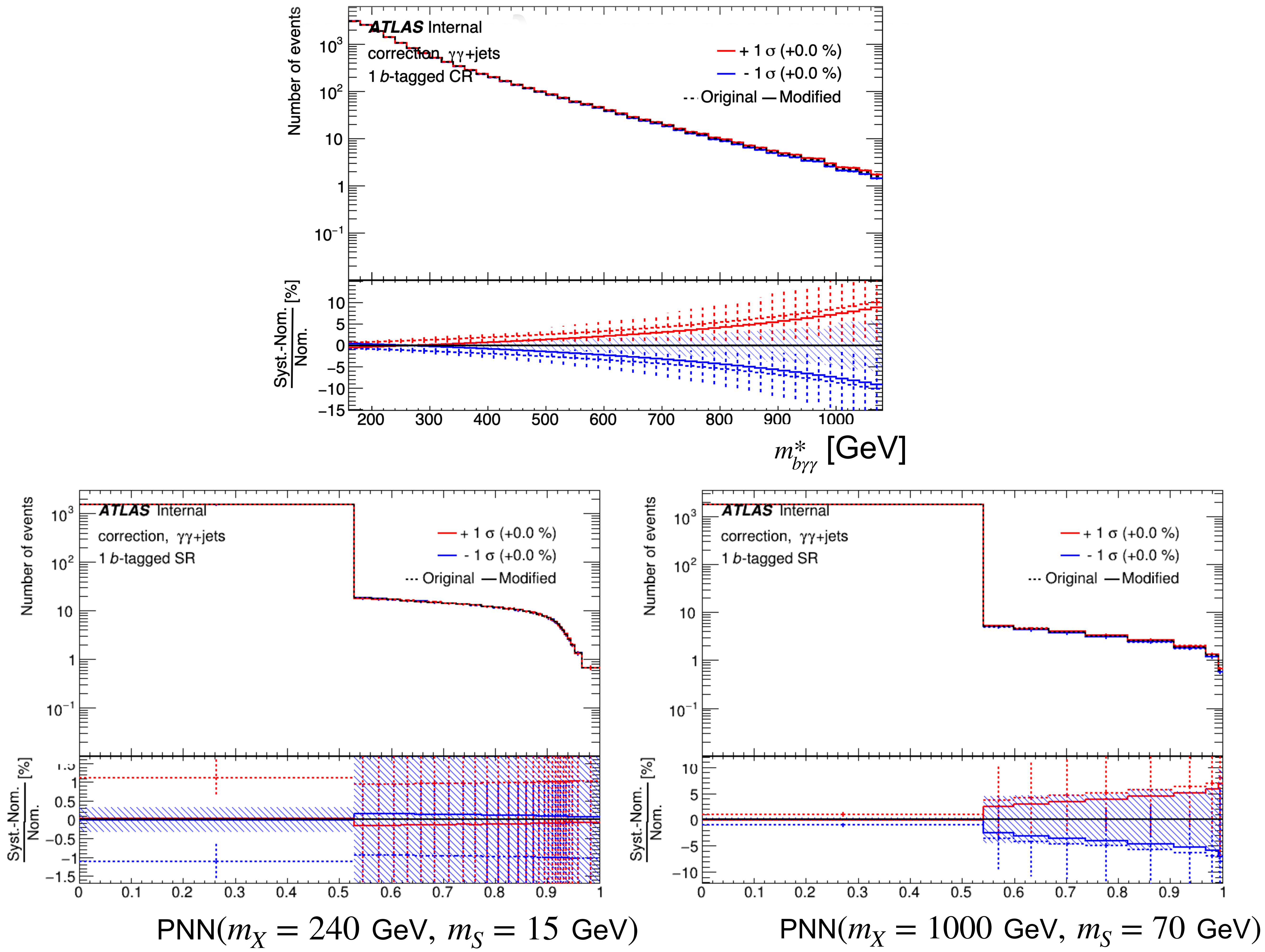
Background correction

p-value of PNN score for all mass points from one-btag region Run 2



- The correction improves the Data/MC agreement across all mass points.

Uncertainty on the correction



- Have higher uncertainty for PNN with hight m_X mass as expected