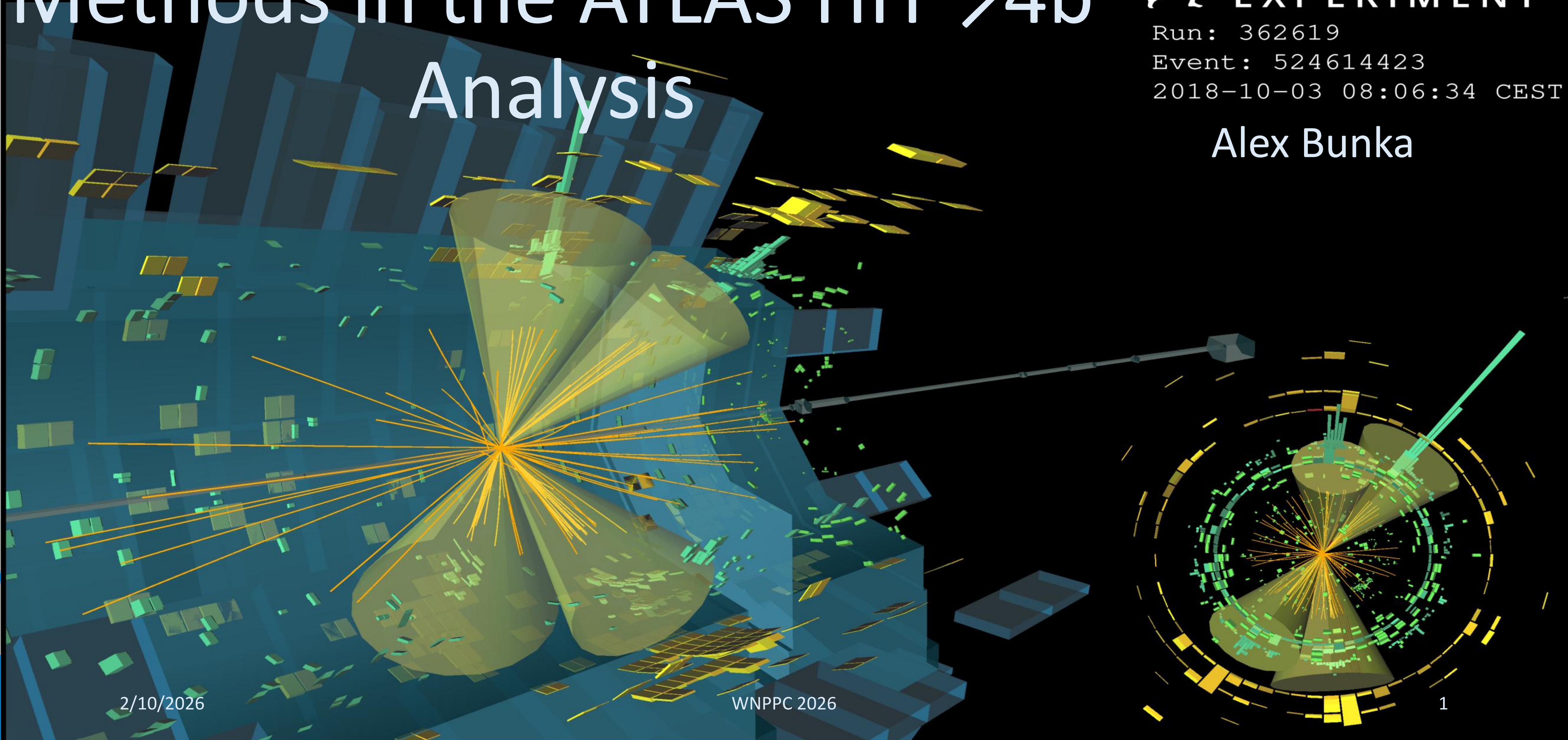
New Background Uncertainty Methods in the ATLAS HH→4b Analysis

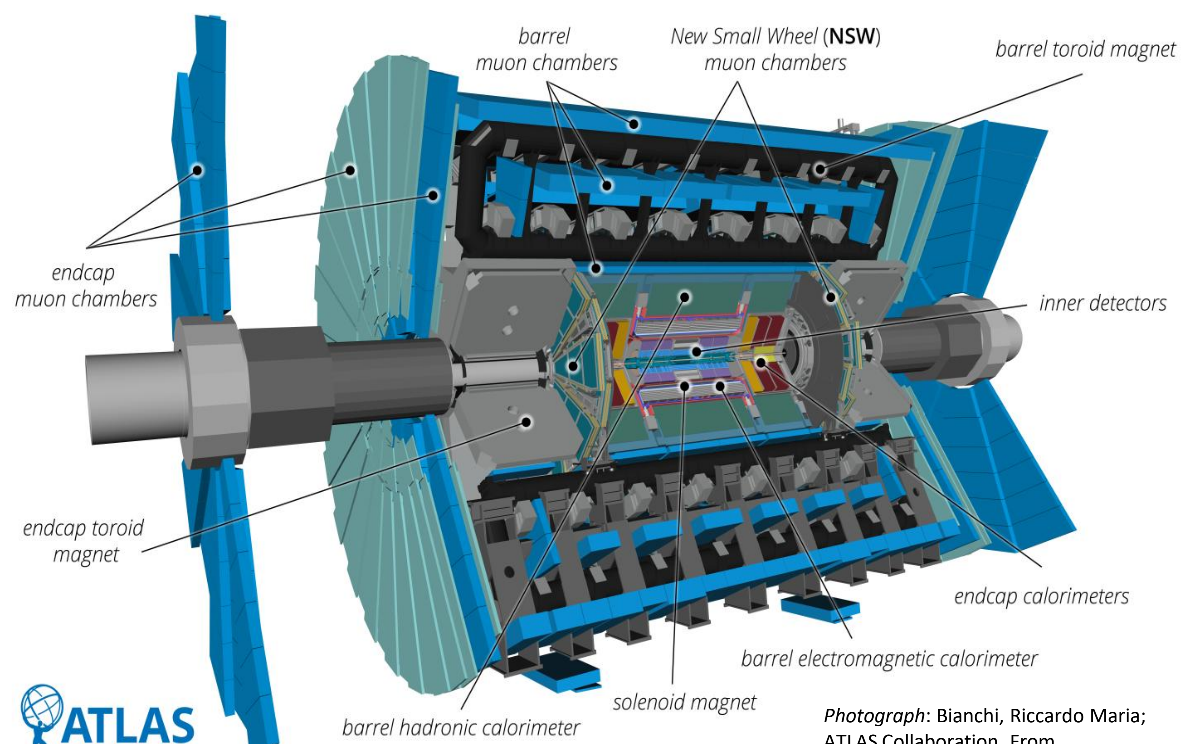
Image Credit



Alex Bunka

ATLAS and the LHC

- LHC is a 27km proton collider
  - Located near Geneva, Switzerland
  - Highest energy particle collisions ever achieved
- ATLAS is the largest general purpose particle detector ever built
  - 25m diameter, 44m length
  - Measures position, momentum and energy of billions of particles every second!



Photograph: Bianchi, Riccardo Maria; ATLAS Collaboration. From https://cds.cern.ch/record/2837191

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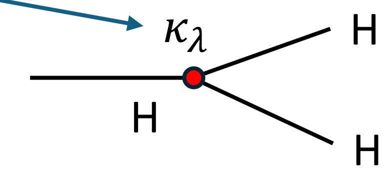
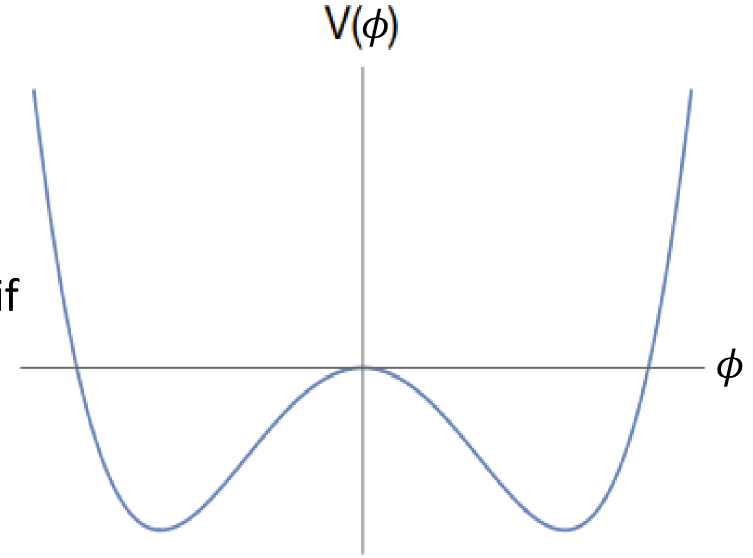
The Higgs Boson

$$V = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2\nu} h^3 + \ldots$$

$$\lambda_{hhh}^{SM} = \frac{m_h^2}{2\nu}, \kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$$



This is the general form after electroweak symmetry breaking, but if $\kappa_\lambda \neq 1$, it's different!



- First theorized in 1964, elementary particles gain mass by interacting with the Higgs field
  - Higgs potential includes Higgs boson mass, Higgs field, h^3 term predicts 3 Higgs coupled together
- Discovered by ATLAS and CMS (another LHC experiment) in 2012
  - Many accurate measurements of different properties, not enough data to extricate trilinear Higgs coupling

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https://doi.org/10.1103/PhysRevLett.13.508 Higgs theory paper!
https://doi.org/10.1016/j.physletb.2012.08.020 Higgs discovery paper (ATLAS)!

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Motivation: HH->4b

- Triangle diagram has dependence on κ_λ, the HHH coupling strength.
- Box and triangle diagrams interfere destructively – harder to isolate!
- Insights to Electroweak Symmetry Breaking and BSM physics!

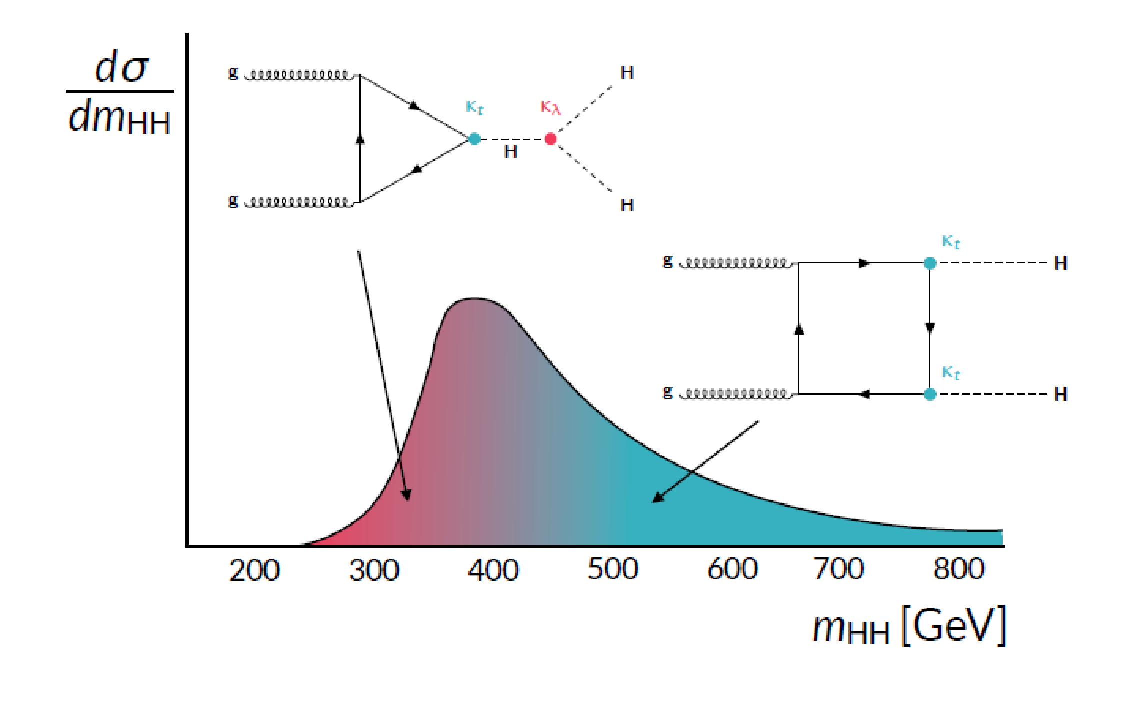

Figure from:
The ATLAS Collaboration, Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector, Phys. Rev. D 108, 052003 (2023)
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.052003

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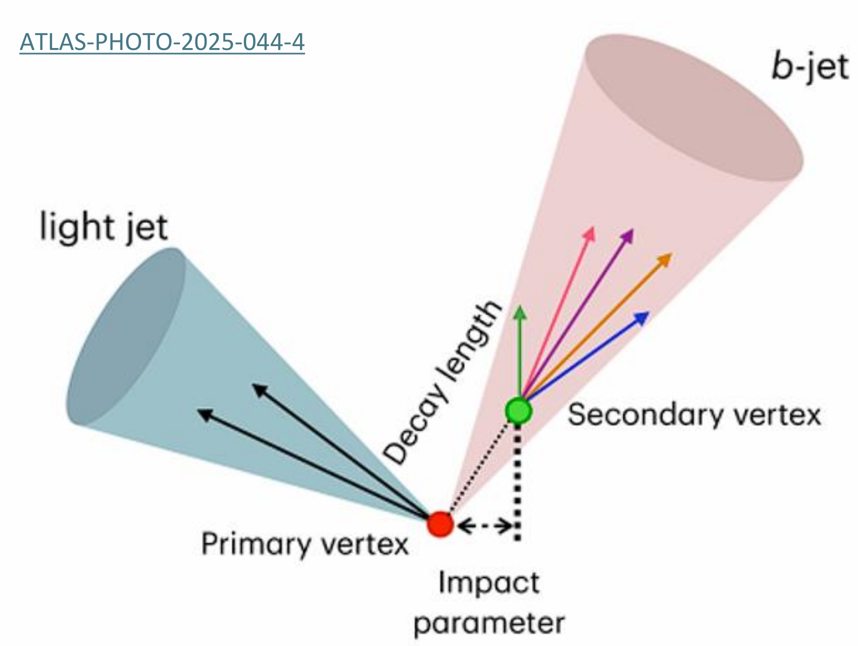
Branching Ratios and B Tagging

- Higgs Bosons decay quickly, with many different decay channels
  - The most common decay is to a pair of bottom quarks, $H \rightarrow bb$, at 58%. ~1/3 of HH pairs decay to 4b
- 4b final state is the most common! But it has the most background
  - B quarks show up as particle jets, and the ATLAS detector sees a lot of jets from many different sources
- Data is sorted by the number of b quark jets. Jets are b tagged based on different features, primarily the long lifetime of b quark hadrons



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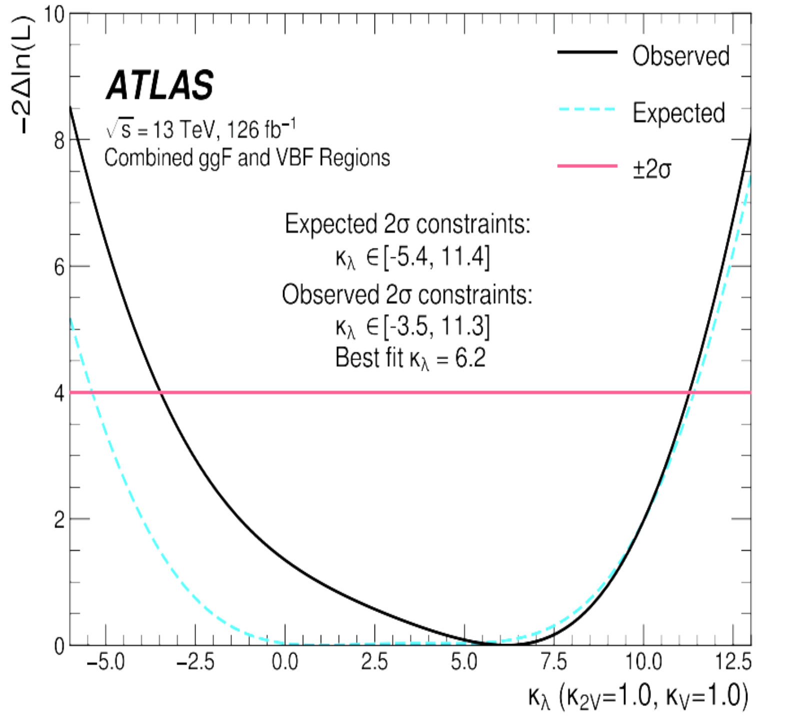
Previous Results



(a)

Source of Uncertainty	$\Delta\mu/\mu$
Theory uncertainties	
Theory uncertainty in signal cross-section	−9.0%
All other theory uncertainties	−1.4%
Background modeling uncertainties	
Bootstrap uncertainty	−7.1%
CR to SR extrapolation uncertainty	−7.5%
3b1f nonclosure uncertainty	−2.0%

- Run 2 analysis, 2023:
  - Broad κ_λ constraints, -3 $\longrightarrow$11!
  - No evidence of signal
- Total background uncertainty was the largest in the analysis, which greatly hinders the final results.

Improve uncertainty,
Improve limit!

Figures and results from:
The ATLAS Collaboration, Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at √s =13 TeV with the ATLAS detector, Phys. Rev. D 108, 052003 (2023)
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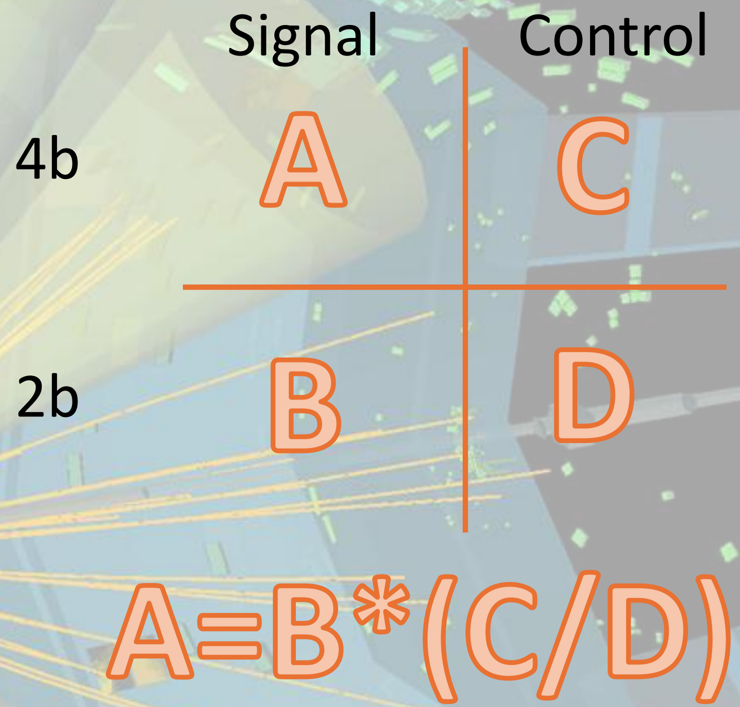
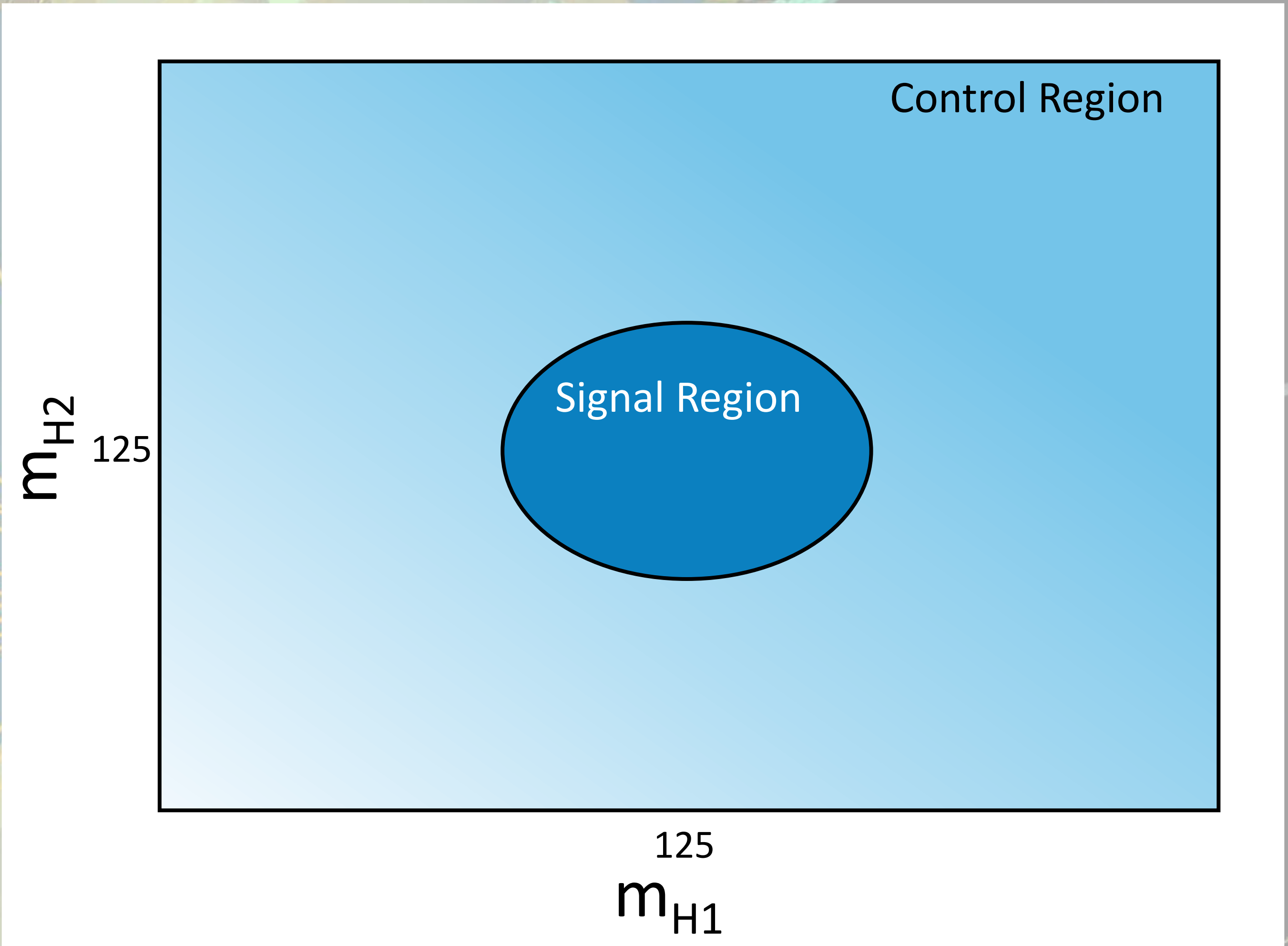
Past Methods

- The background is primarily multijet events
  - Very complicated QCD calculations are difficult to model accurately
- Previously: 2b to 4b ABCD
  - Learn the relationship between 2b and 4b backgrounds in a control region
  - Apply to the 2b signal region to estimate the 4b SR
- Sources of background uncertainties
  - Uncertainty – stdev of 100 reweighting functions, statistical uncertainty in 2b, 3b-4b non closure…
- What can we do to improve this?



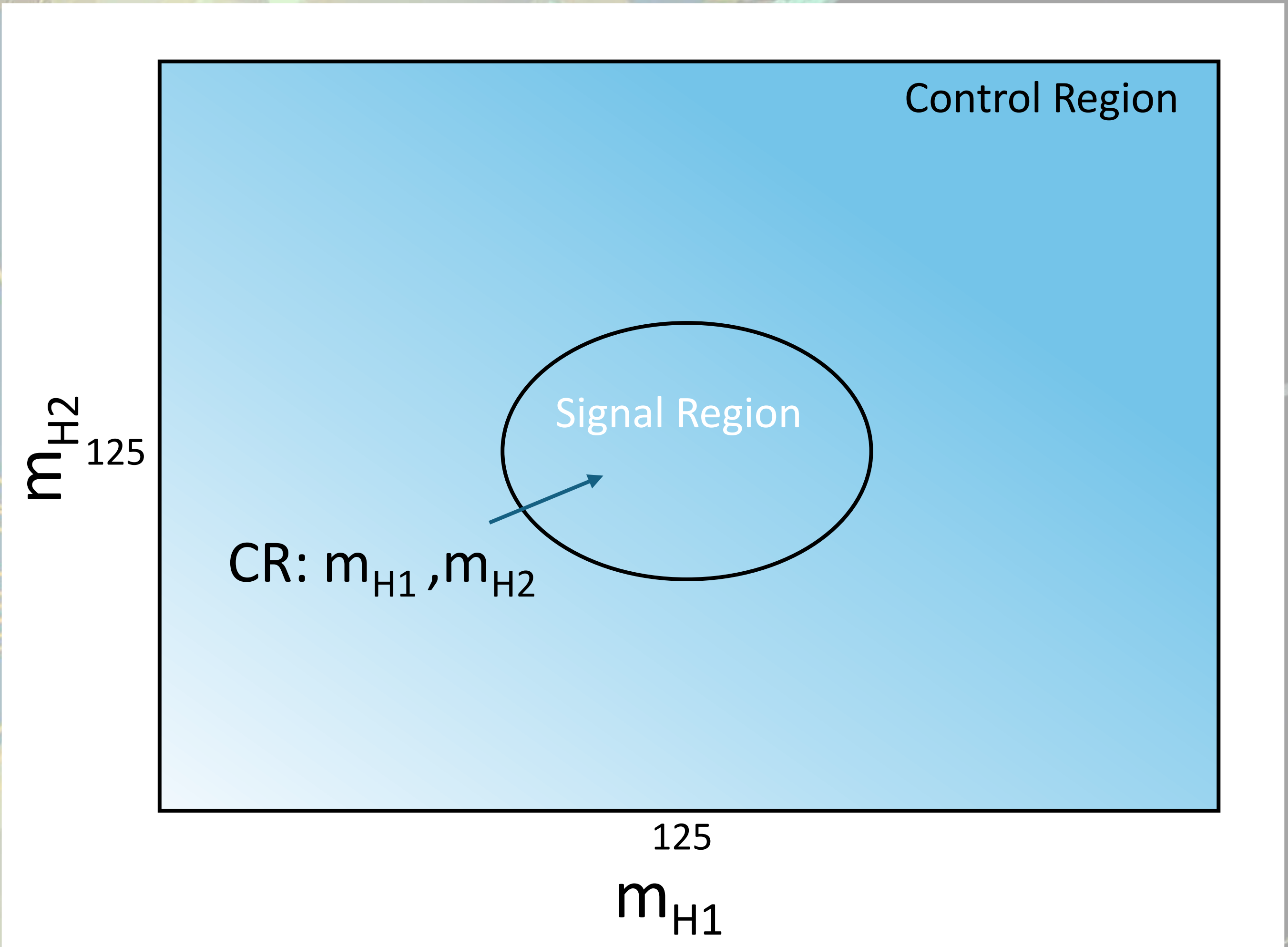
New Background Methods

- **We know the control region, but the signal region is blinded.**
- Higgs mass is 125 GeV, so the signal region is an ellipse centered around (x, y) = (125, 125).
- Outside of this ellipse is the control region.



New Background Methods

- **Fit the 2d histogram of masses to smoothly fill in the signal region, which gives m_{H1} & m_{H2} for the signal.**
- Learn how to "move" between different m_{H1}, m_{H2} points in the control region
- Interpolate from the control region to the signal region



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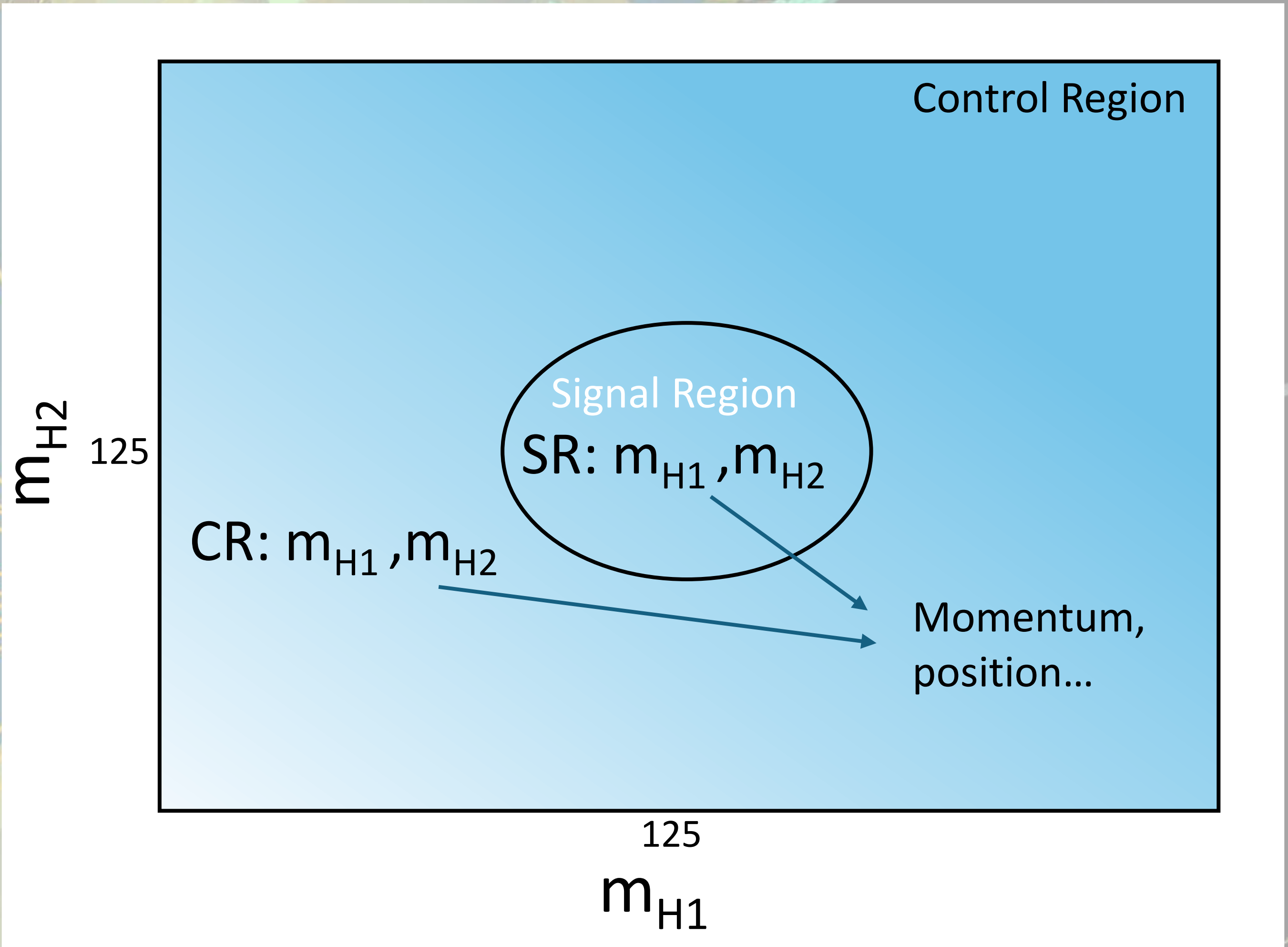
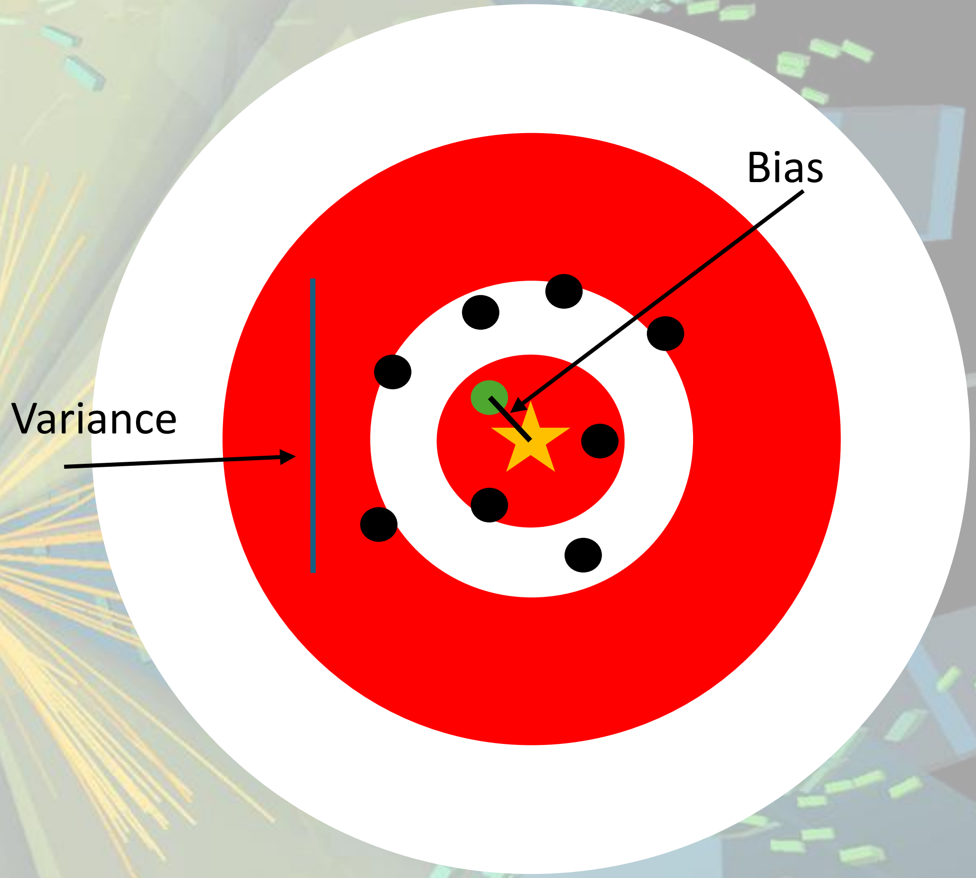
New Background Methods

- **Use a generative model to morph these first simple variables into other physics features**
- Start in the signal region, and find the relationship between the mass plane and other physics distributions
- Apply this relationship to the signal region mass plane from the previous step



Why Use 3b for Uncertainty?

- The statistics of 4b are limited
  - Roughly ten times more data passes 3b requirements than 4b
  - If we randomly downsample the 3b data, we have similar statistical effects with ten versions to show variations
  - Majority of 3b data is 4b that failed one b-tag
- 4b is blinded
  - We cannot look at the 4b signal region data until we have all the background modelling complete
  - Can't risk biasing our analysis work!



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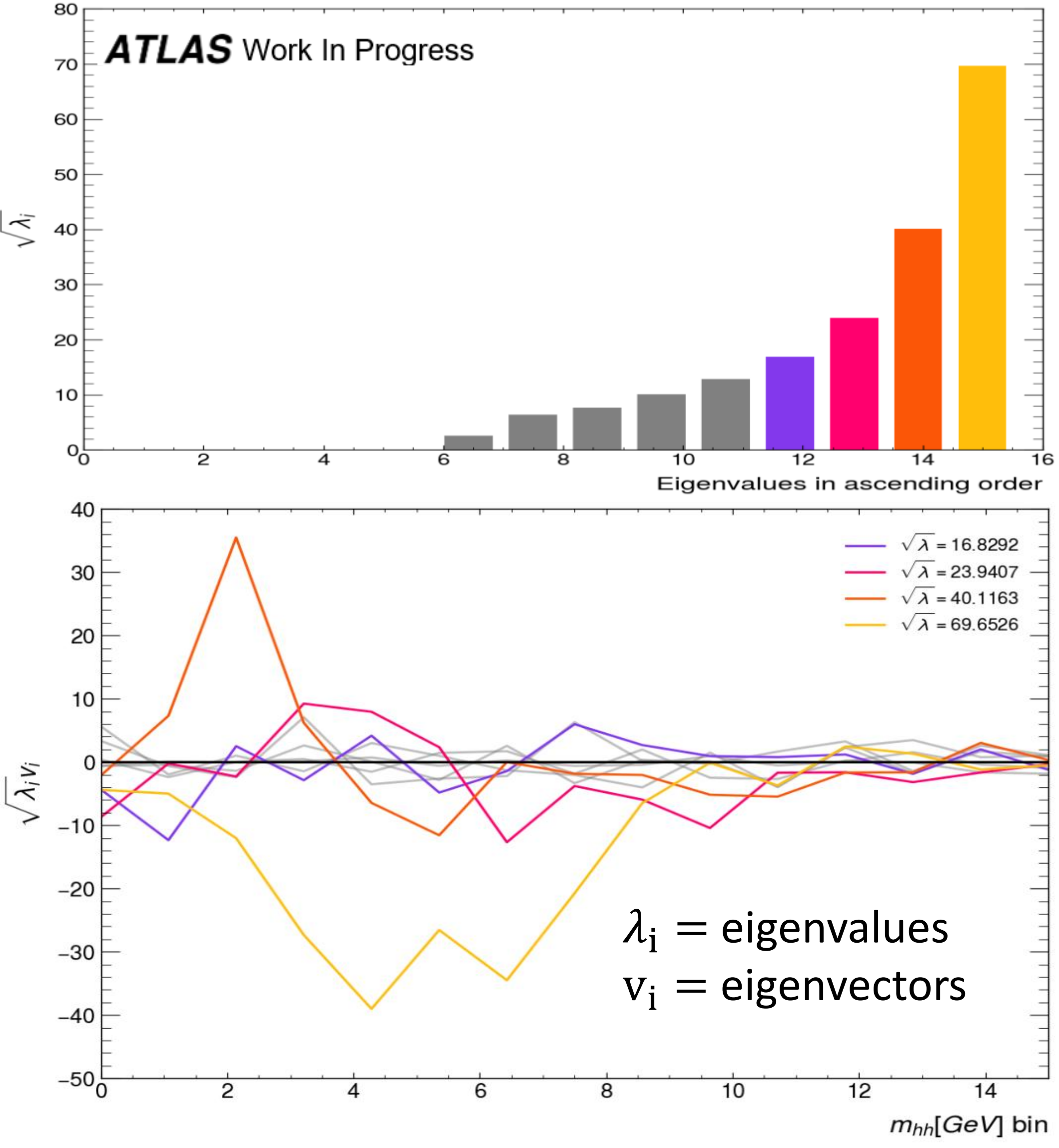
Background Uncertainty: 3b Predictions



- Use 3b data for the systematics, $N_{3b} = 10N_{4b}$, create 10 subsets.
- Train a background estimate from each of the subsets (call these replicas).
- Principle Component Analysis on the average of the replicas.
  - Solve an eigenvalue problem:
  - Eigenvectors are variations in shape, eigenvalues are the magnitude of the changes.

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Uncertainty in Two Parts

The Variance Step:

- How much do the individual replicas differ from their average?
- Unconstrained fit of each replica vs average, then iteratively add EVs.
- Continue till pulls are uncorrelated.

The Bias Step:

- How much does the average differ from data?
- Use EVs as nuisance parameters, constrained from variance step.
- Unconstrain NPs until the fit is good.

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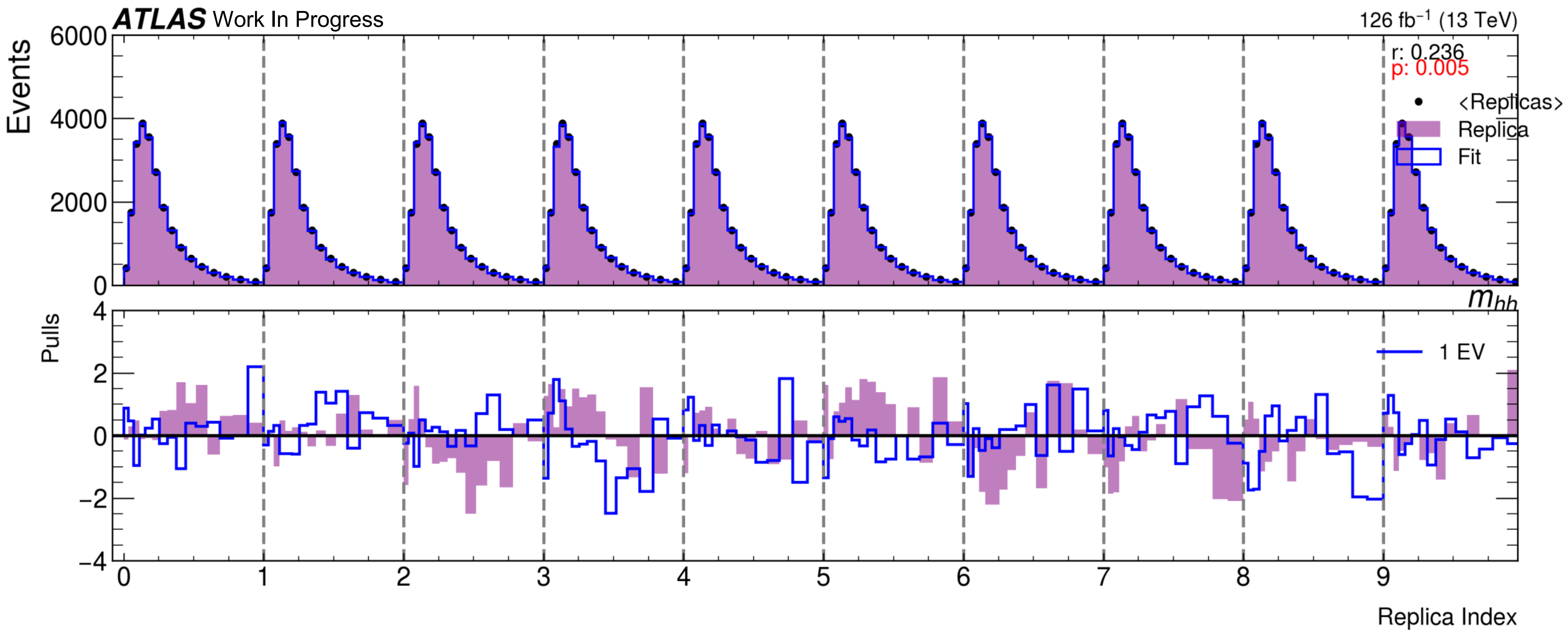
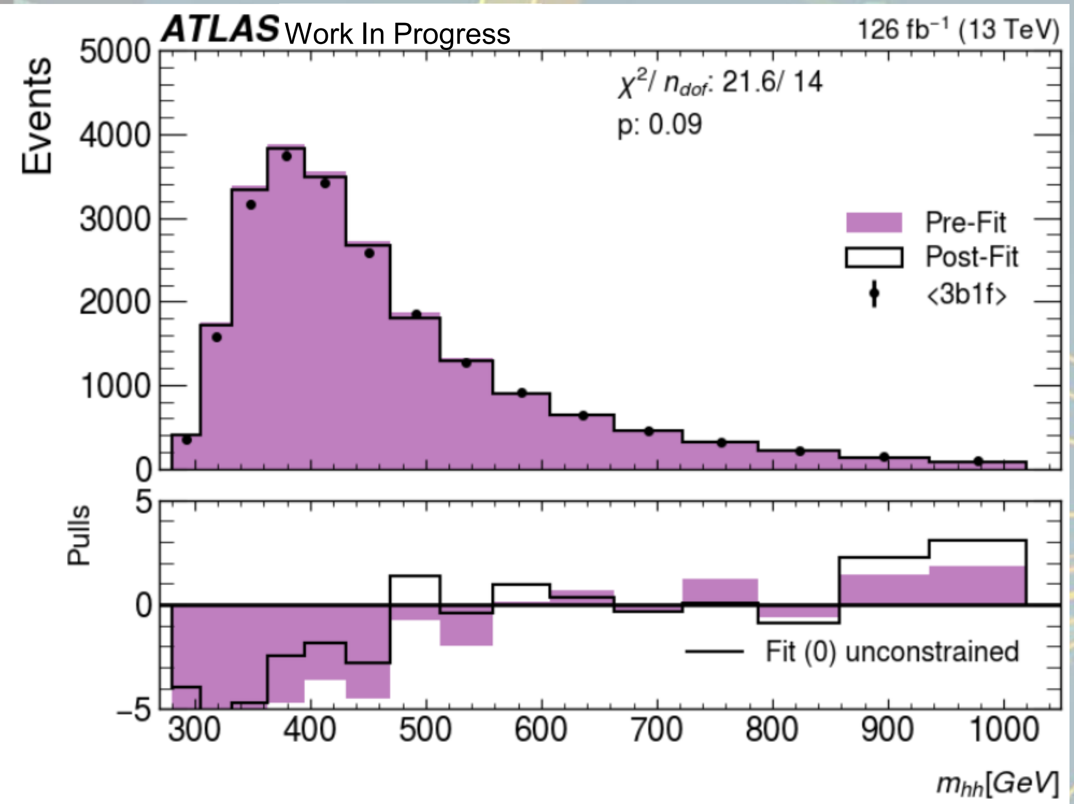
Variance: Fitting Against Average



The Bias Step

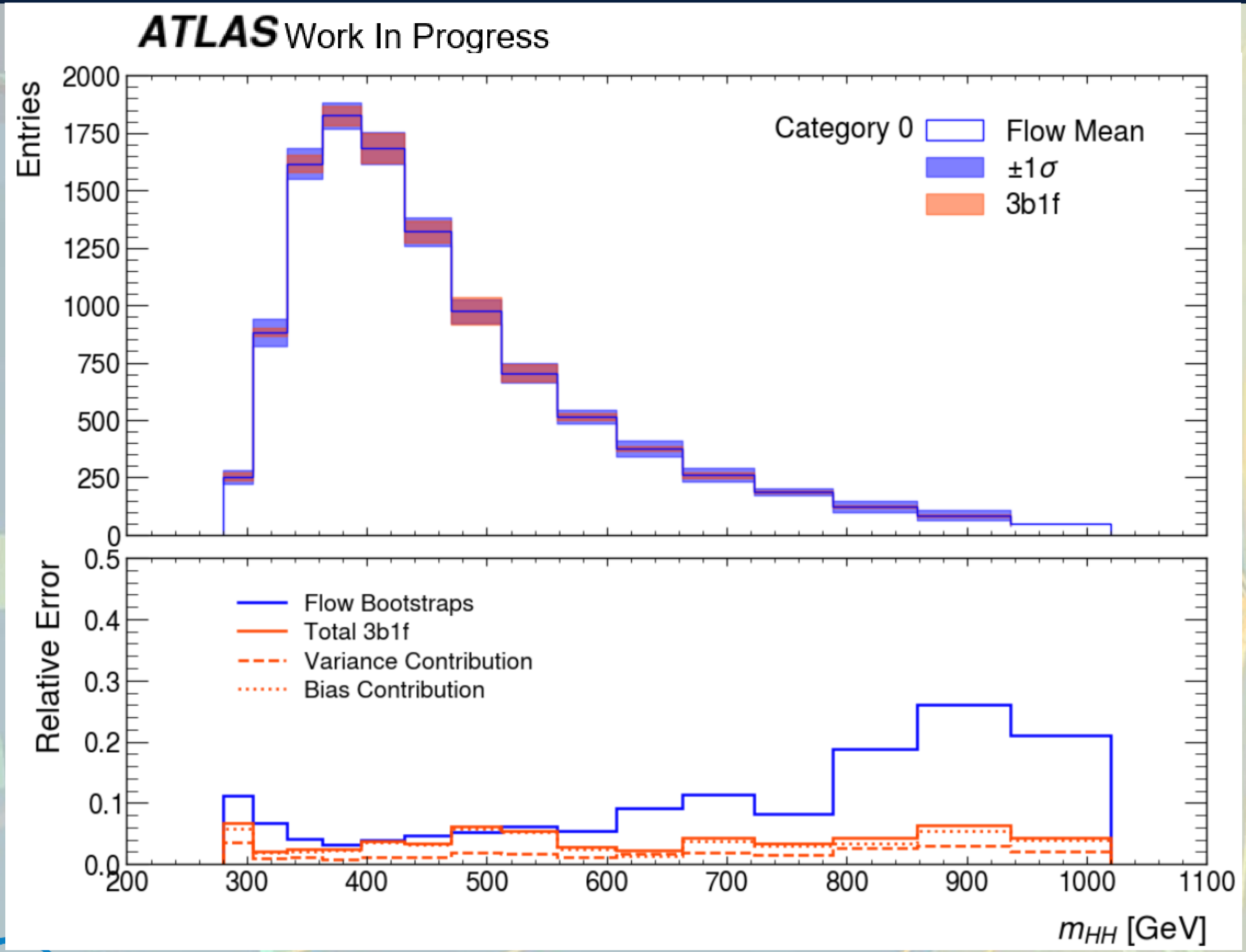
- Compare the average of the replicas to real 3b data
- Use EVs as nuisance parameters, constrained from variance step
  - If the lowest correlation was after 6 fits, we have 6 EVs to use
- Unconstrain NPs until the fit is good
  - Different statistical methods tested: Chi2, F-test…
- Loosened fit value and variance uncertainty (from before) combined for final uncertainty

Bias: Fitting Against Data



- Typically achieve closure (p>0.05) with 0 or 1 NP
  - Does not change with different stats methods
- The bias step contributes more to the final uncertainty than the variance
  - Even though it converges in fewer fit steps, the fit value is much larger

Total Uncertainty



- Red lines are the uncertainties from each step, and combined
- Blue is the stdev of 25 trainings
- Uncertainty less than or equal to that of older methods
- Reduced background uncertainty will greatly improve our analysis power!

Summary

- The HH->4b analysis is important to investigate the behaviour of the Higgs Boson and study BSM physics.
- The power of this analysis can be limited by large uncertainties, and improvements are needed keep up with the increase in data.
- Many updates have been made to the background prediction and uncertainty.
- The variance/bias method works to produce a reasonable background uncertainty.
  - Smaller than earlier methods, looks to cover the required range.
- Ideally, this will be used in both the partial Run 3 and full Run 3 analyses.

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Thank You!

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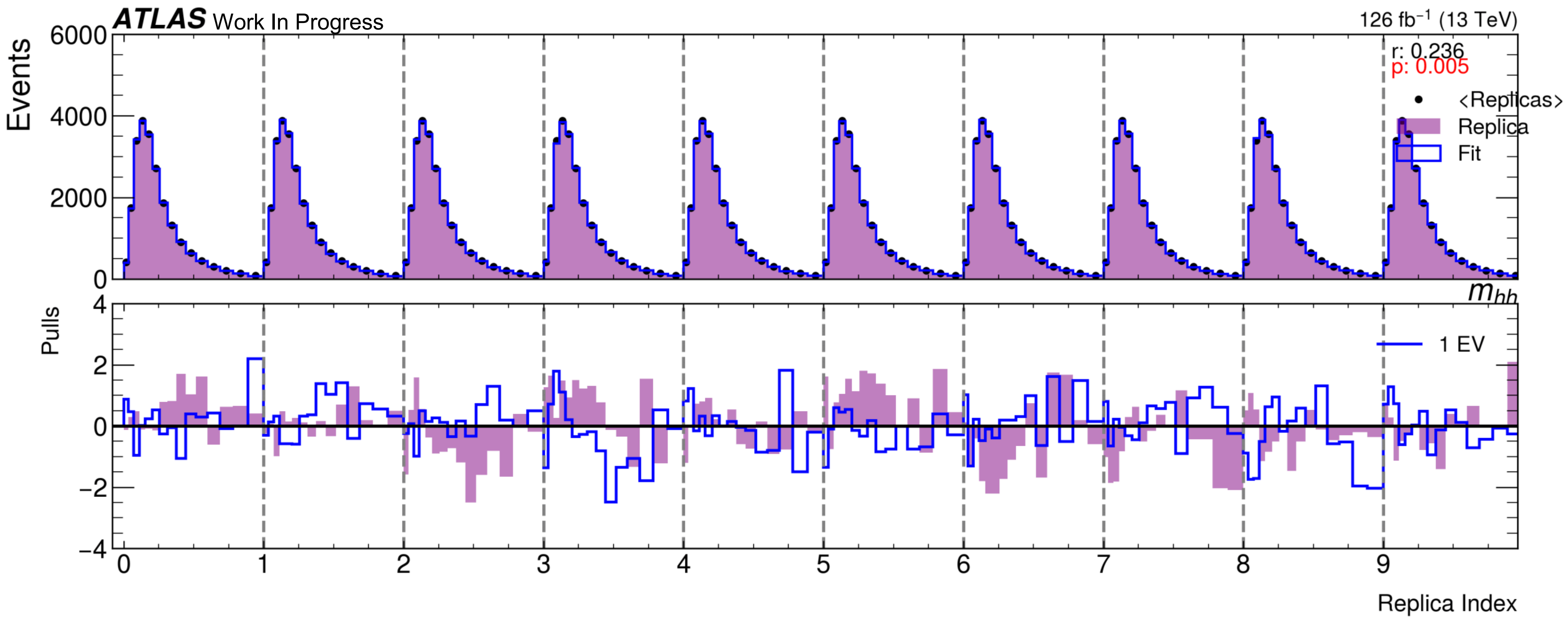
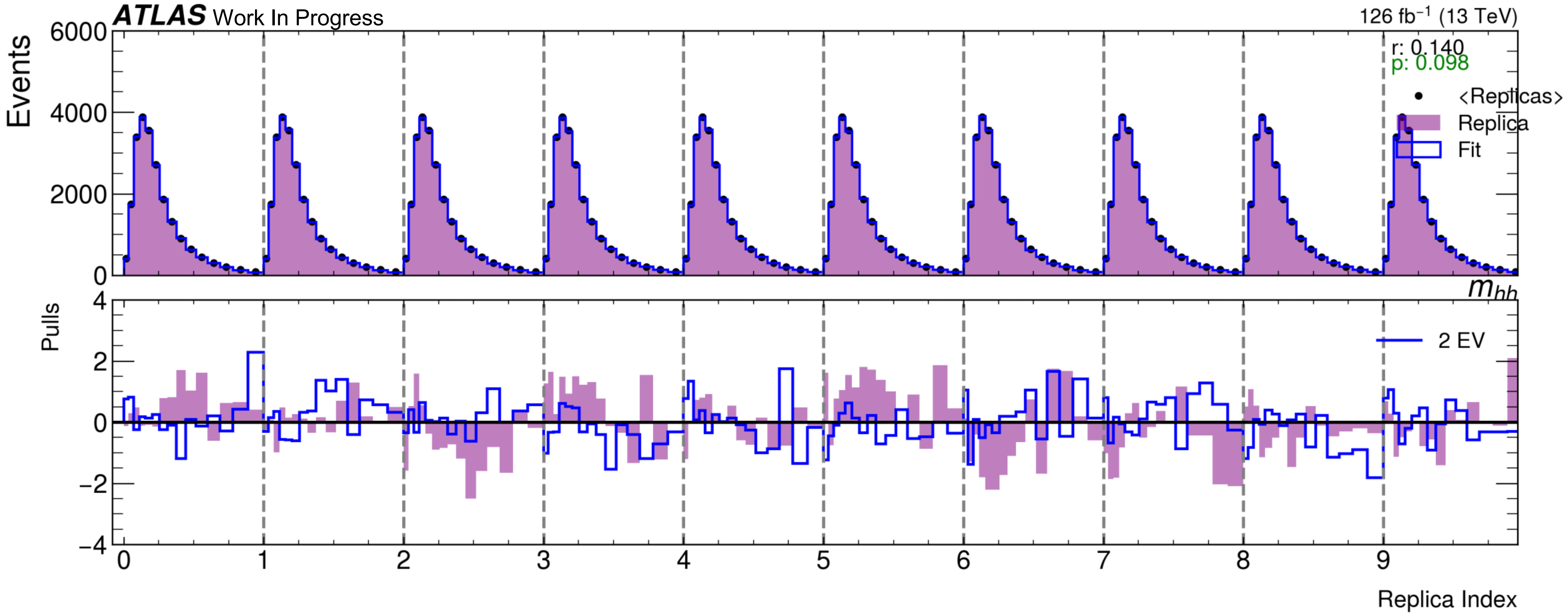
mhh Variance Steps



mhh Variance Steps



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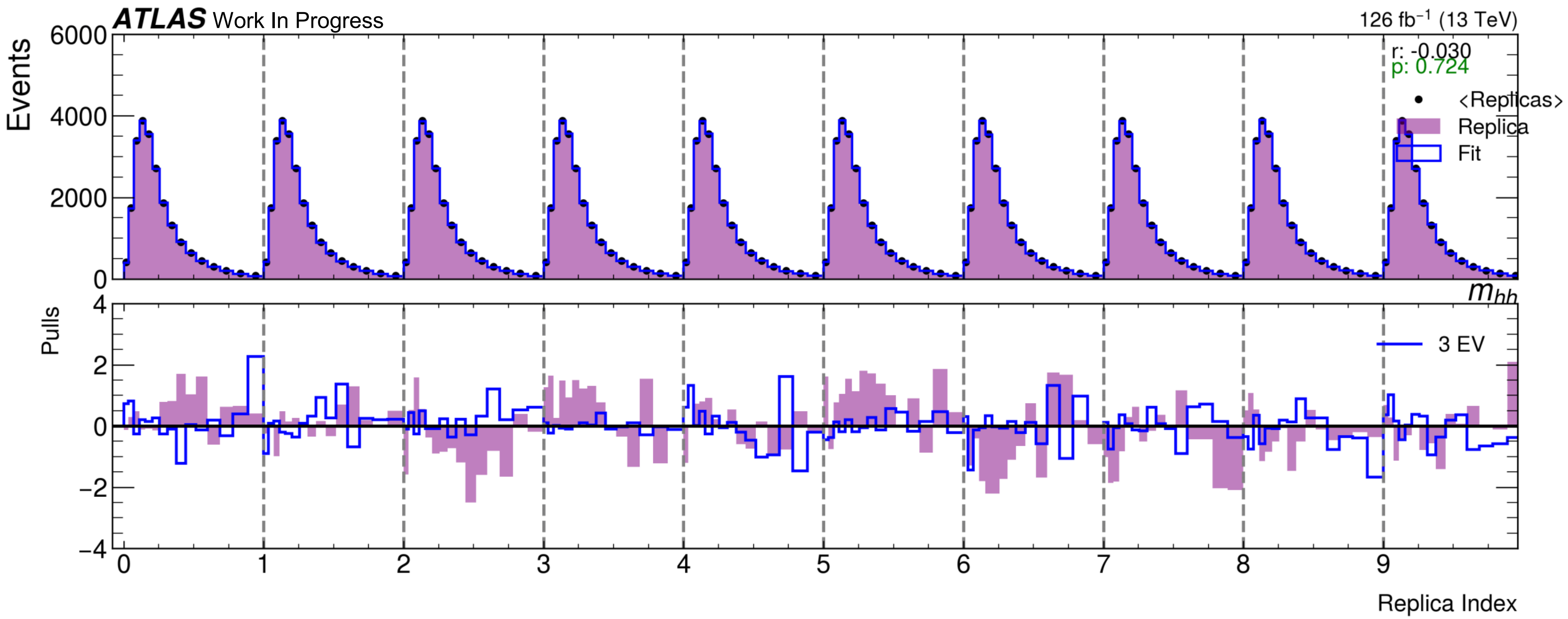

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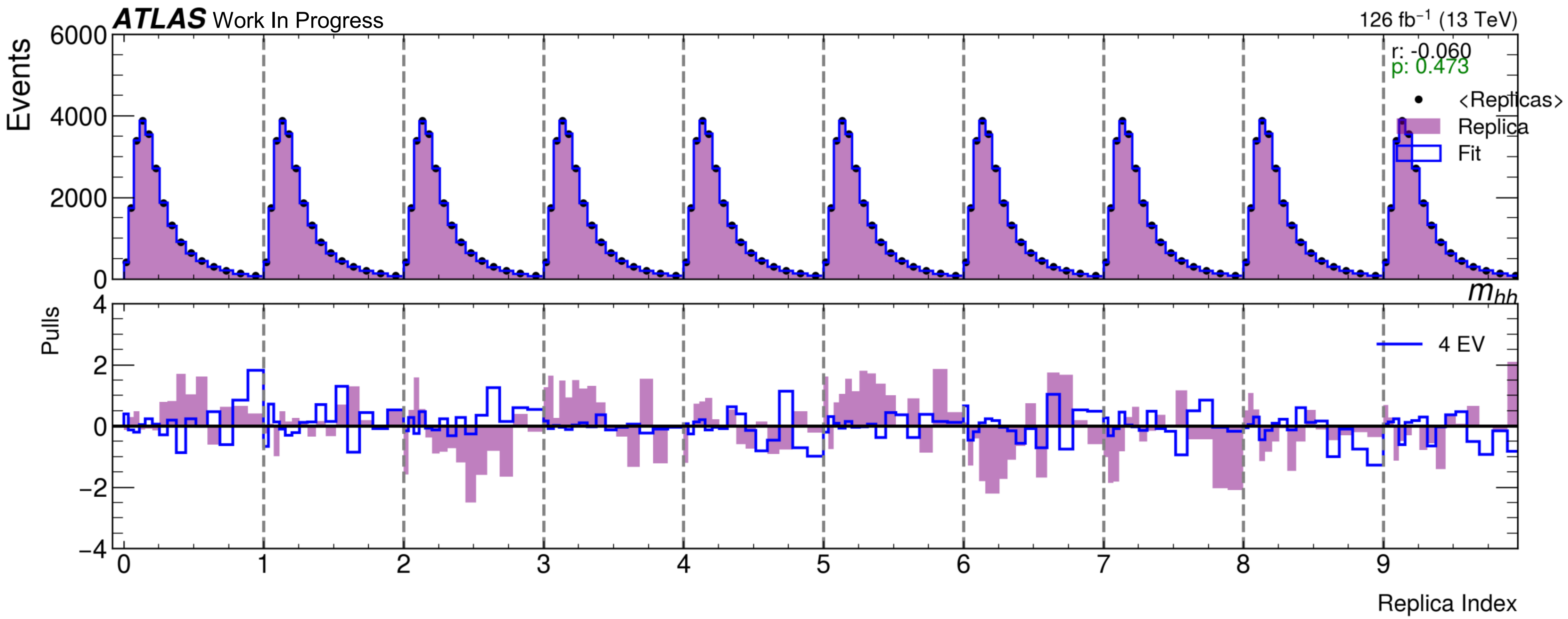

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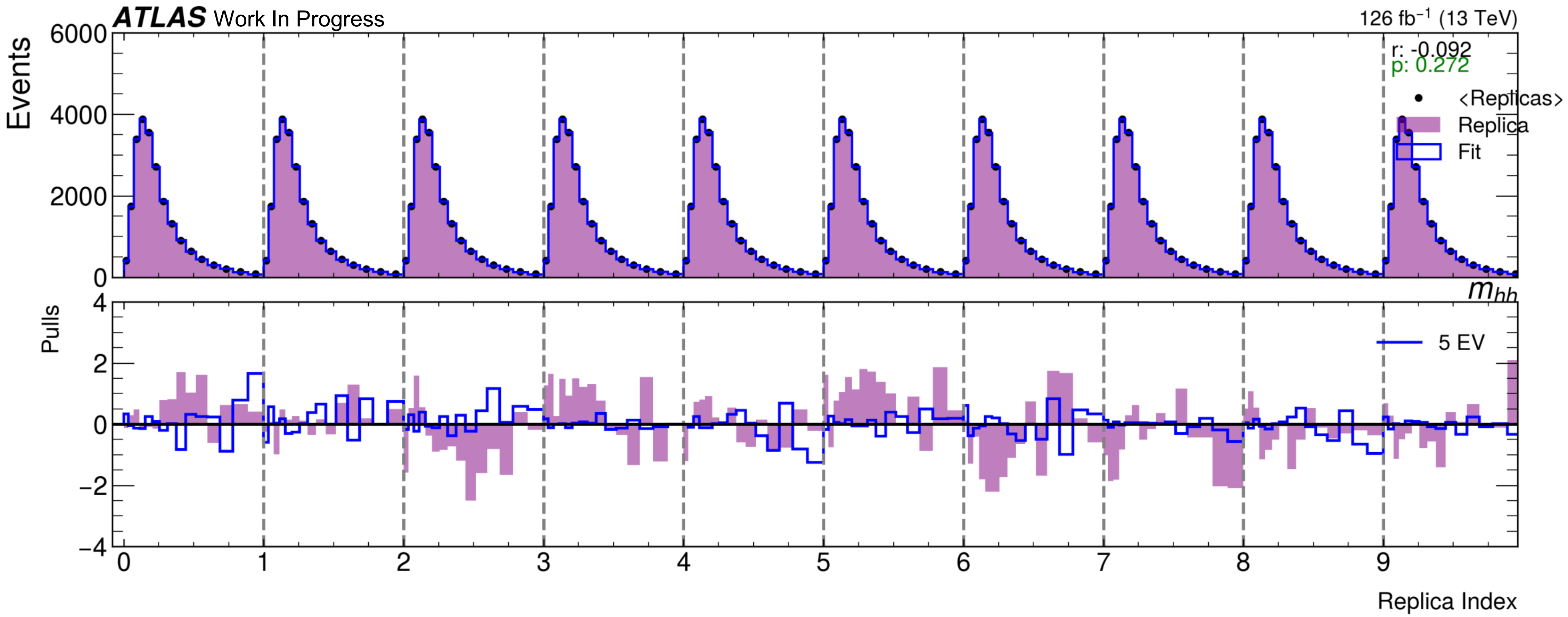

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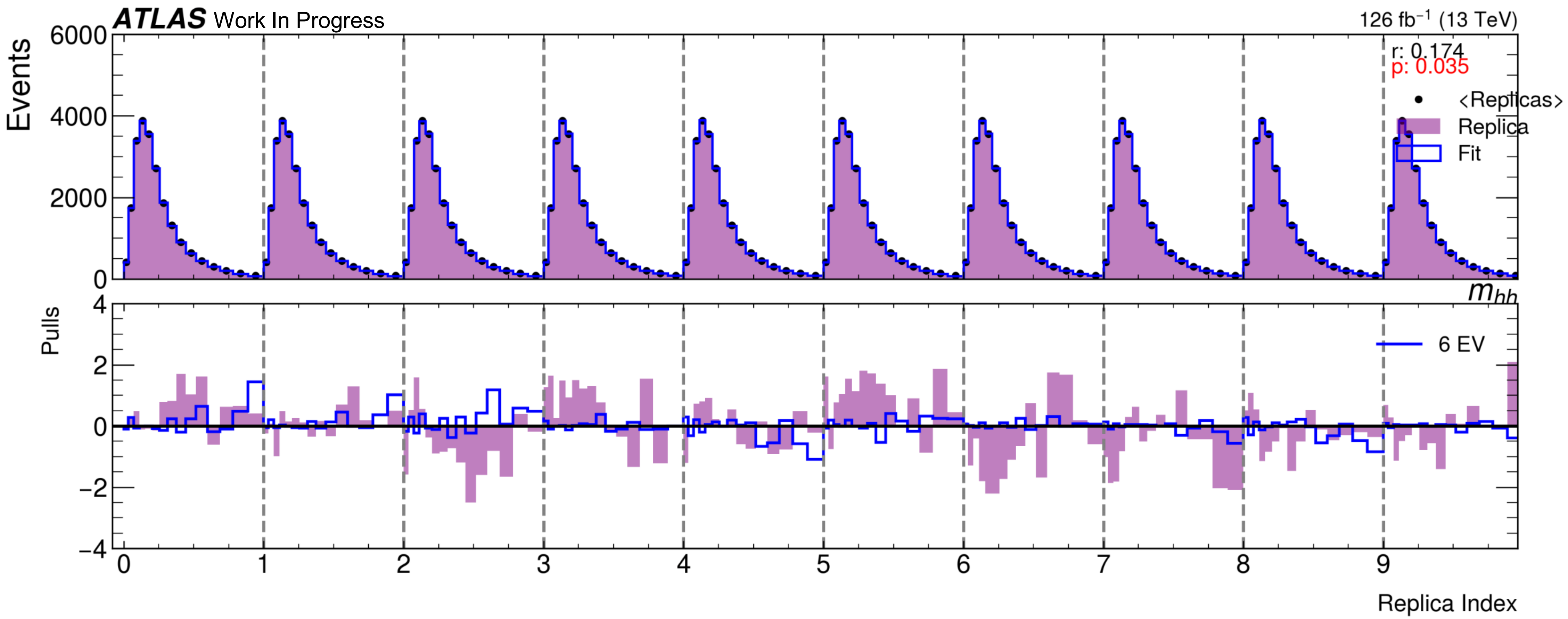

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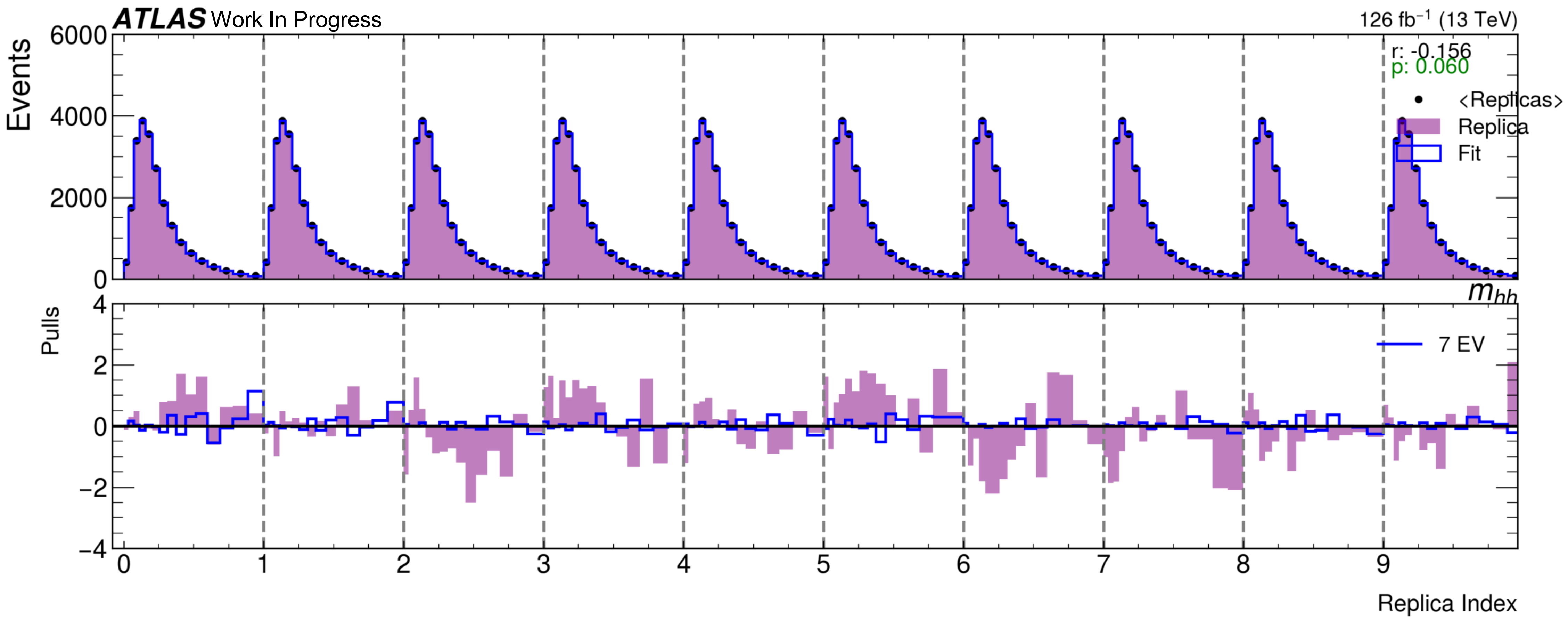

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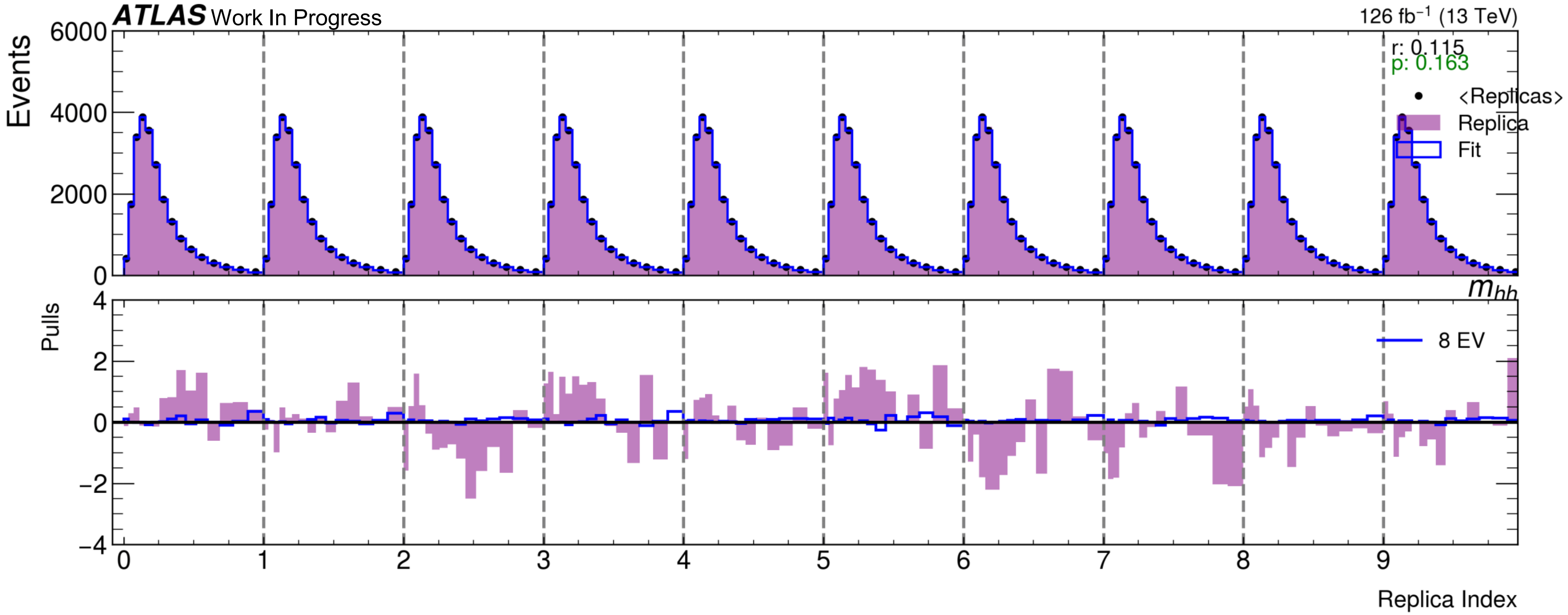

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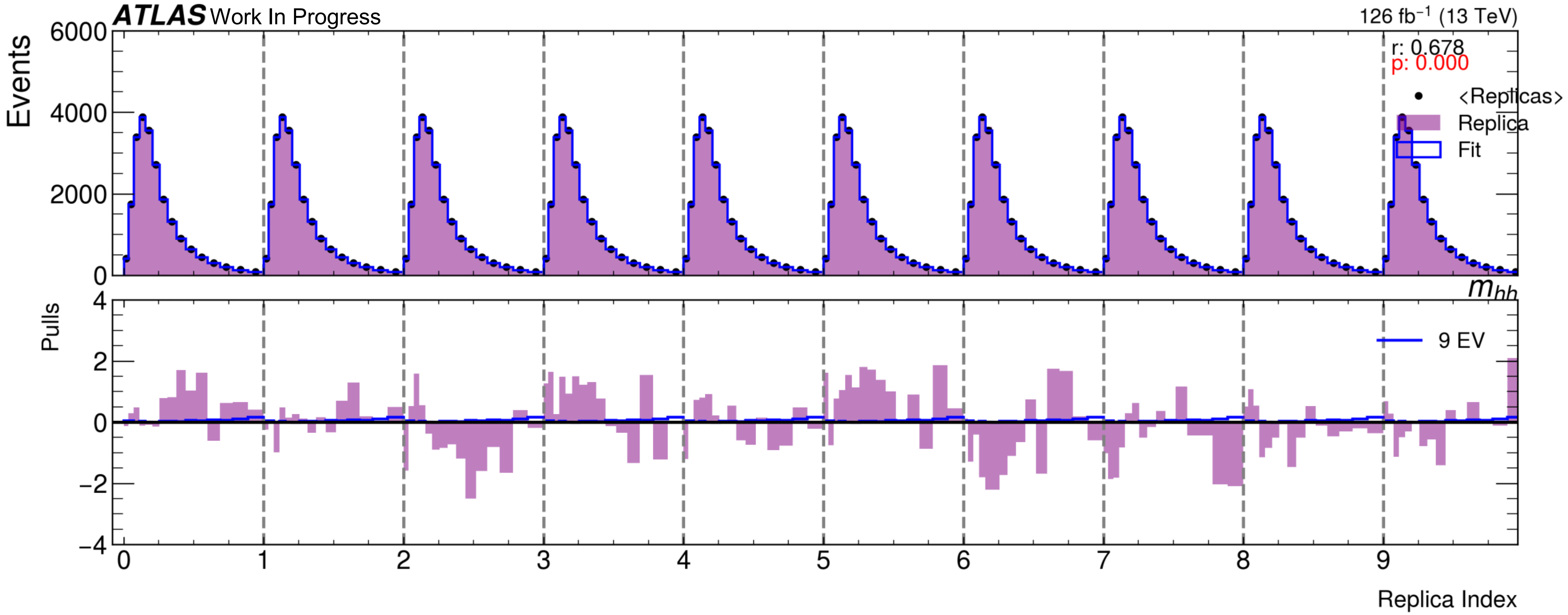

mhh Variance Steps