# High $p_T$ Physics at the LHC
# Lecture 4:
# Higgs Physics and Advanced Topics

## Warwick Week 2026

**Eleni Skorda, 16 April 2025**

# Lecture Outline

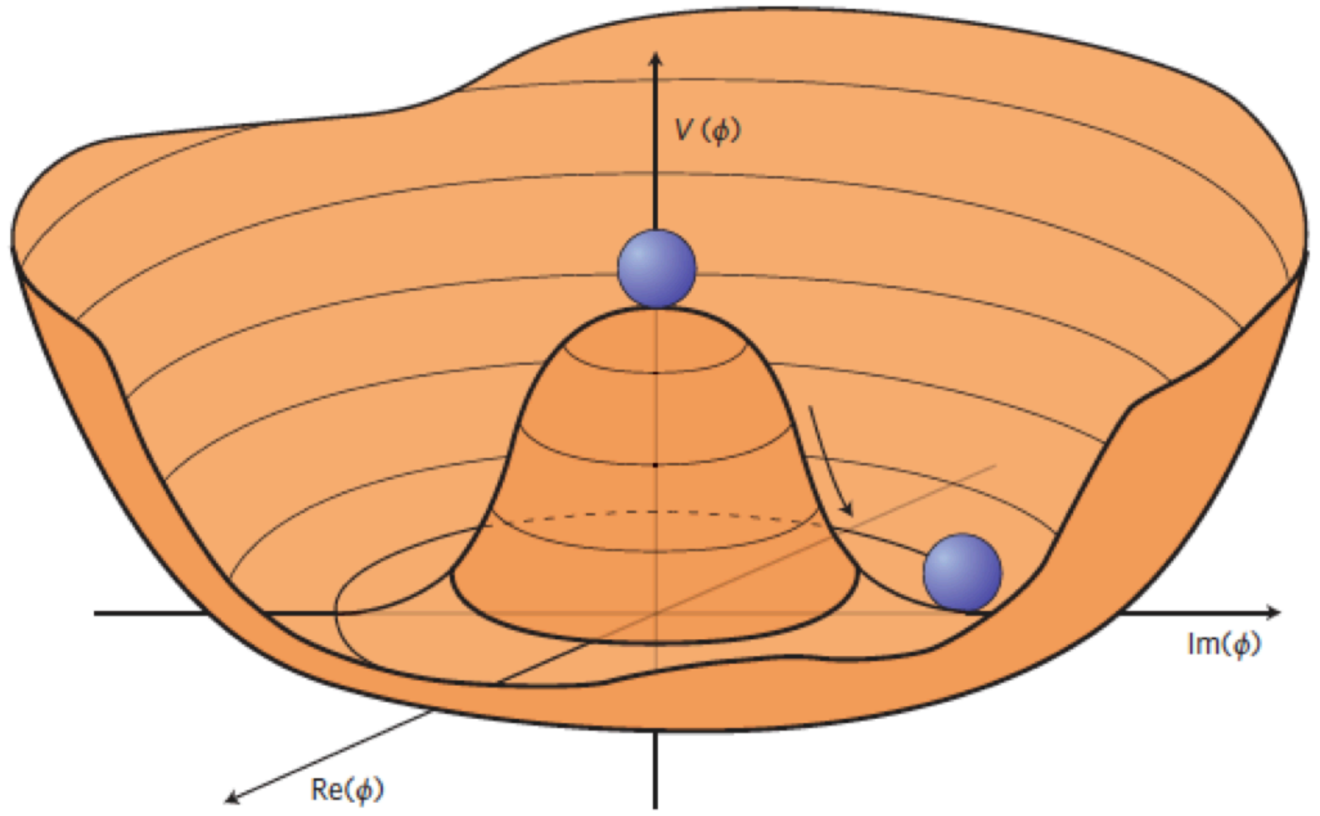
- Slightly different approach in this lecture...
  - Our understanding of the (125 GeV) Higgs boson is still developing rapidly
  - This lecture will review the current state of the art and will be more “technical”
  - Along the way, there will be several interludes to discuss more advanced experimental techniques
- Outline of Lecture
  - Introduction to the Higgs boson
  - Review of main production and decays modes for $m_H$ = 125 GeV
  - Summary of selected recent experimental results
  - Several interludes on event reconstruction techniques

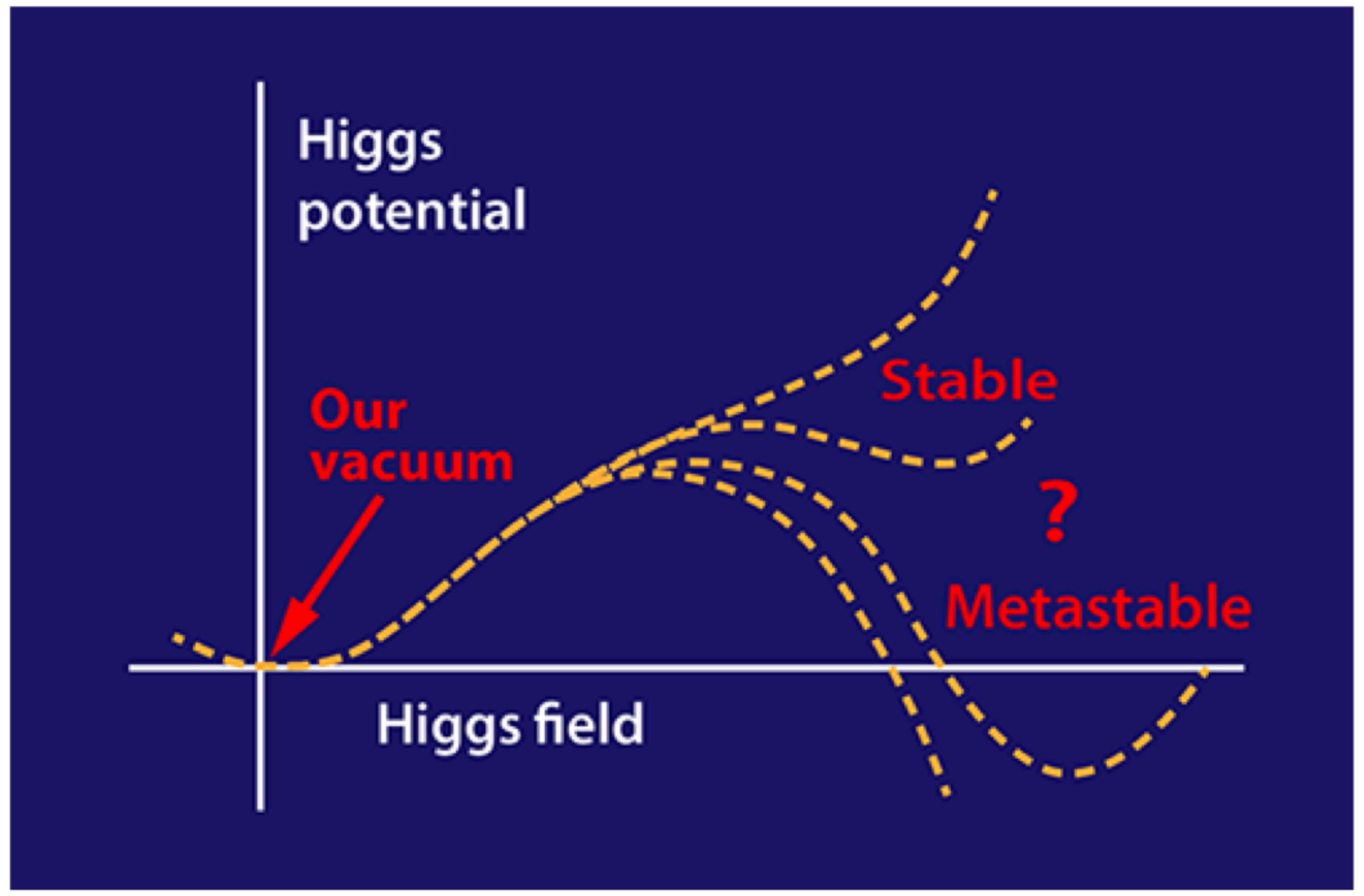
# The Higgs mechanism - quick reminder

- $\mathscr{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi^\dagger \phi)$
- $V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2, \qquad \lambda, \mu \in \mathbb{R}$
- The choice of λ and μ determines the shape of the potential. Finite minimum: λ > 0, but no restriction for $\mu^2$.
- $\mu^2 > 0 \;\Rightarrow$ one minimum at $\phi = 0$, while
- $\mu^2 < 0 \;\Rightarrow$ local maximum at $\phi = 0$
- Symmetry is broken when we choose the ground state:

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

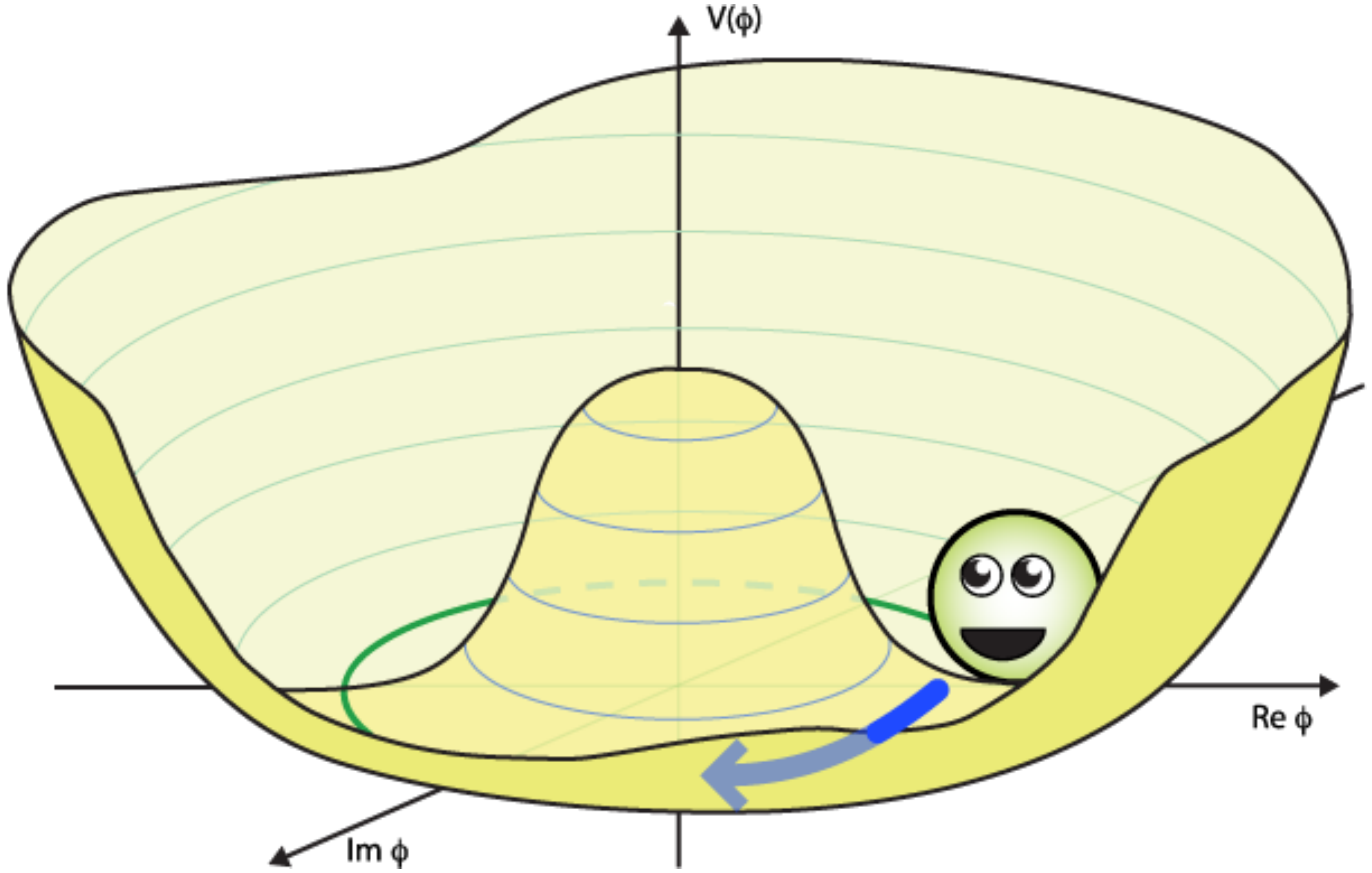
- $m_H = \sqrt{2\lambda v^2}$ , free parameter





# The Brout-Englert-Higgs Mechanism

- Introduce a complex scalar SU(2) doublet $\phi$ to the SM (4 d.o.f.)
- If potential V ($\phi$) has a non-zero VEV, the EW symmetry is spontaneously broken
- Leads to Goldstone bosons (3 d.o.f.) which mix with W ± and Z fields
- Provides gauge invariant mass terms (and long. pol.) to the W± and Z
- Predicts the fourth d.o.f. should manifest as a scalar “Higgs” boson!



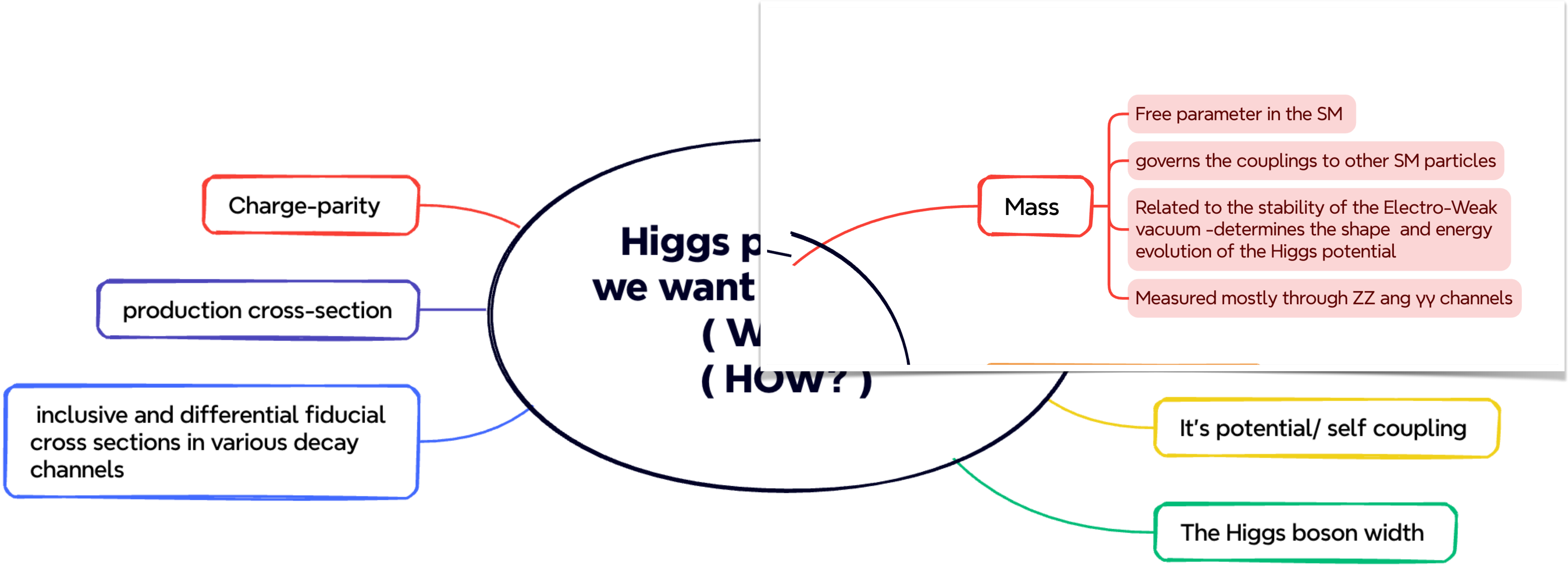
In **2012** a particle with a mass of 125 GeV, consistent with the SM Higgs boson, was discovered by ATLAS and CMS ✓

# Which properties we want to study?

**Higgs properties we want to measure**
**( WHY? )**
**( HOW? )**

- Charge-parity
- production cross-section
- inclusive and differential fiducial cross sections in various decay channels
- Mass
- Yukawa Couplings to fermions/bosons
- It's potential/ self coupling
- The Higgs boson width

# Which properties we want to study?



Higgs p
we want
( W
( HOW? )

Charge-parity

production cross-section

inclusive and differential fiducial cross sections in various decay channels

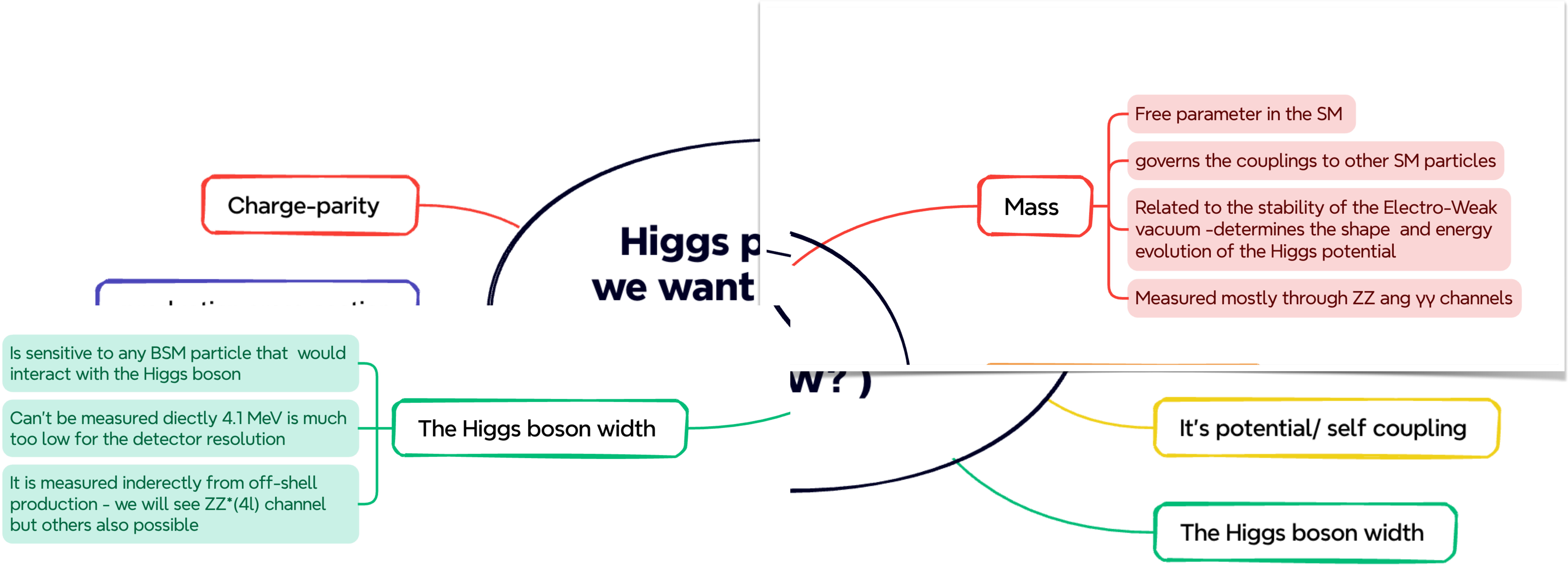
Mass

- Free parameter in the SM
- governs the couplings to other SM particles
- Related to the stability of the Electro-Weak vacuum -determines the shape and energy evolution of the Higgs potential
- Measured mostly through ZZ ang γγ channels

It's potential/ self coupling

The Higgs boson width

# Which properties we want to study?



Charge-parity

Higgs p
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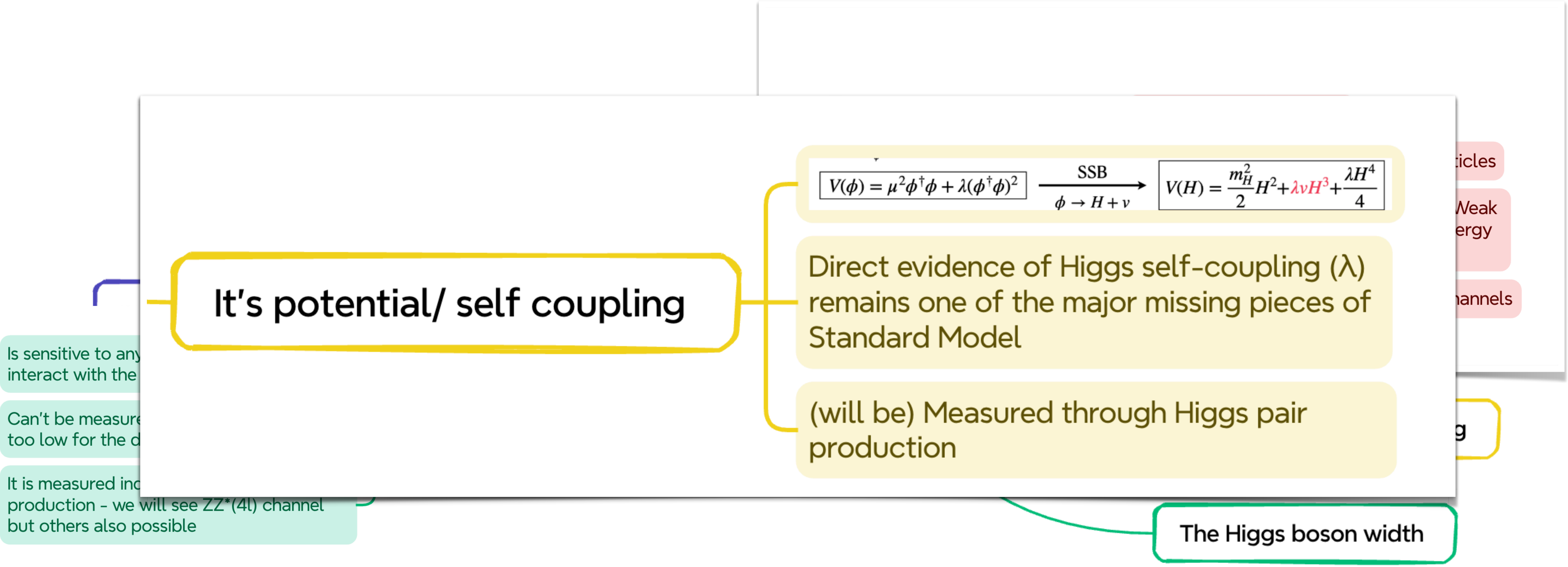
It's potential/ self coupling

The Higgs boson width

The Higgs boson width

- Is sensitive to any BSM particle that would interact with the Higgs boson
- Can't be measured diectly 4.1 MeV is much too low for the detector resolution
- It is measured inderectly from off-shell production - we will see ZZ*(4l) channel but others also possible

# Which properties we want to study?



It's potential/ self coupling

$$\boxed{V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2} \xrightarrow[\phi \to H + v]{\text{SSB}} \boxed{V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{\lambda H^4}{4}}$$

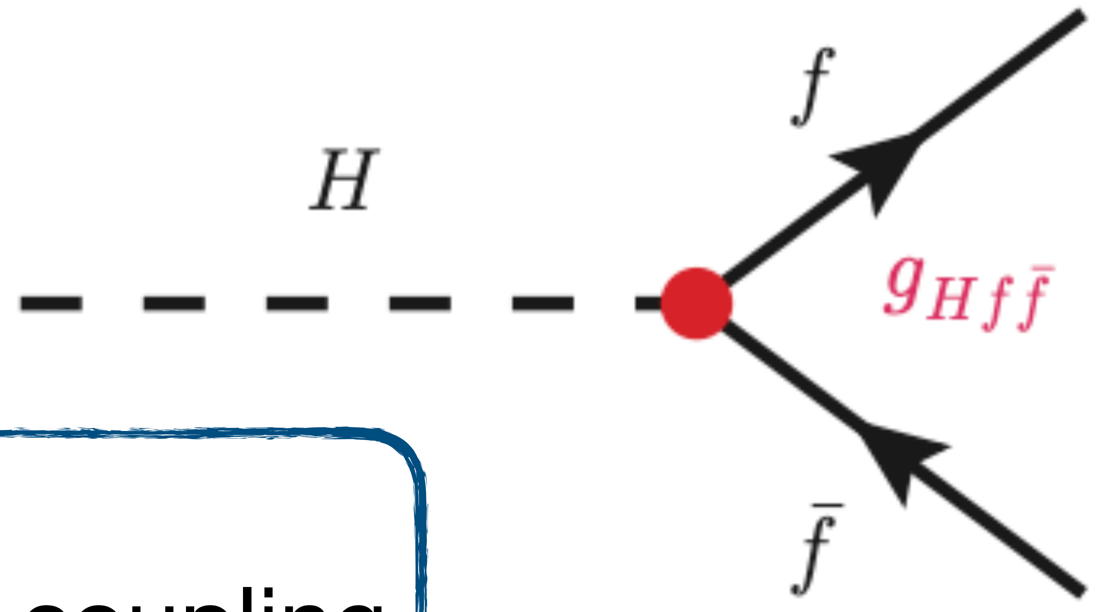
Direct evidence of Higgs self-coupling (λ) remains one of the major missing pieces of Standard Model

(will be) Measured through Higgs pair production

# Fermion Masses in the Standard Model

- `Yukawa'' couplings between the Higgs (ϕ) and fermion (ψ) fields are possible:

$$\mathcal{L}_{\text{fermion}} = -\,y_f\left(\bar\psi_L\phi\psi_R + \bar\psi_R\phi^\dagger\psi_L\right)$$



- If V(ϕ) has a non-zero VEV, expansion leads to (h is the physical Higgs field):

$$\mathcal{L}_{\text{fermion}} = -\boxed{\frac{y_f v}{\sqrt{2}}\bar\psi\psi} - \boxed{\frac{y_f}{\sqrt{2}}h\bar\psi\psi \quad \text{Yukawa coupling}}$$

Mass term

Results in Higgs–fermion coupling proportional to the fermion mass ($g_H f\bar f = m_f/V$)

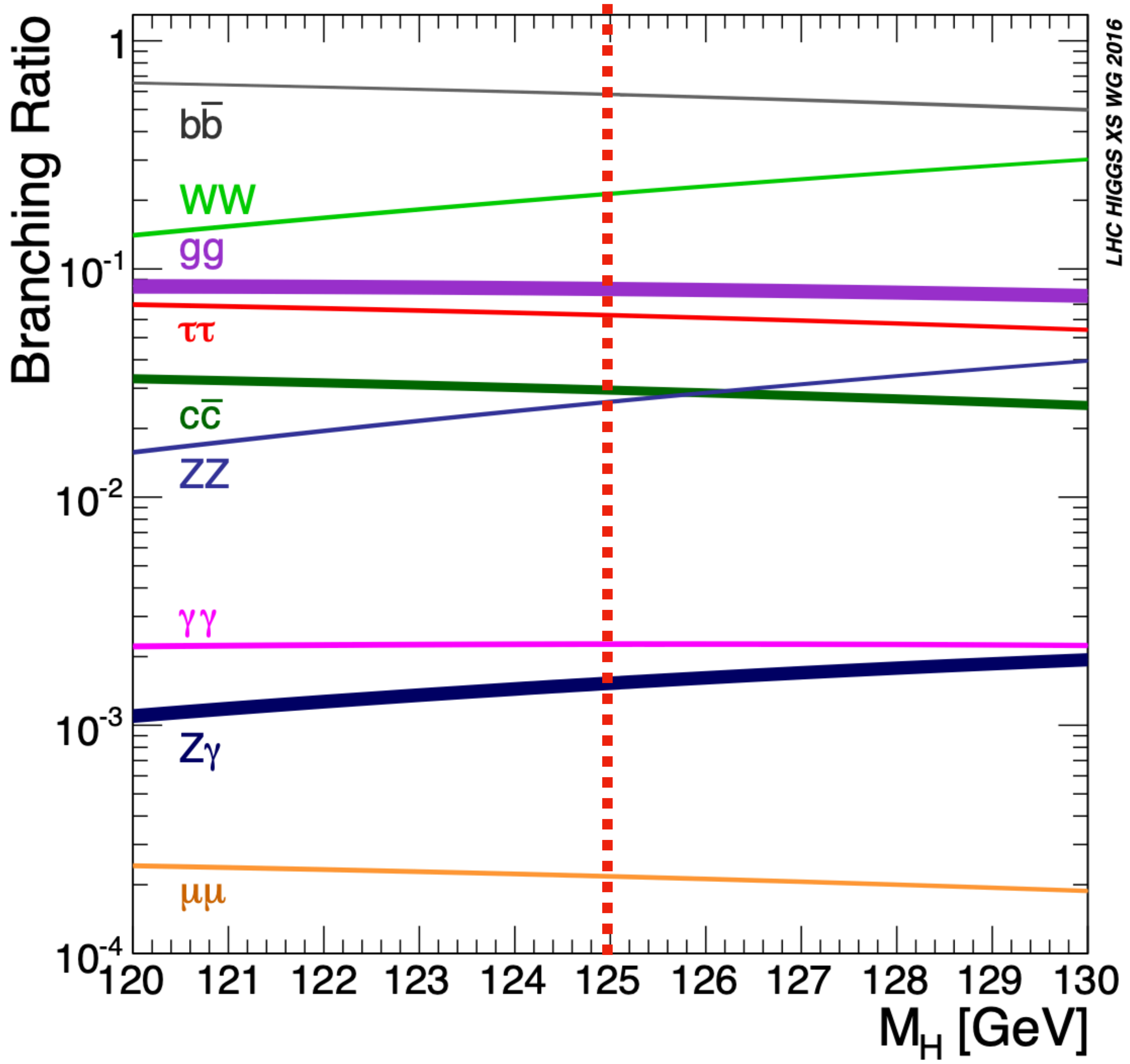
- Gauge invariant fermion mass terms in SM ✓
- $y_f$ “predicted” in SM given knowledge of v and $m_f$ (v ≈ 246 GeV from EW observables) ✓
- Offers no fundamental insight into the observed fermion mass hierarchy ✗

While Yukawa couplings provide concrete predictions for $Hf\bar f$ interactions, they fail to describe the origin the fermion mass hierarchy i.e. why is $m_t/m_e \approx O(10^5)$!?

# Decays of a 125 Higgs boson

Total decay width of SM 125 GeV Higgs boson is around 4 MeV, far below ATLAS/CMS detector resolution!

- $H \to b\bar{b}$ is the most common decay, with $B(H \to b\bar{b}) \approx 58\,\%$
- Decays to fermions ( i.e. $H \to q\bar{q}$, $H \to \ell\ell$ ) directly sensitive to Yukawa couplings $(\Gamma \propto y_f^2)$
- Decays $H \to ZZ^*$ and $H \to WW^*$ probe heart of EWSB (coupling determined by shape of V (ϕ)), for $m_H = 125$ GeV one $W/Z$ is always off-shell
- The decays $H \to \gamma\gamma$ and $H \to gg$ are loop induced, no direct coupling



At $m_H = 125$ GeV, the channels $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ and $H \to \gamma\gamma$ exhibit the most favourable signal to background at the LHC

DOI: 10.23731/CYRM-2017-002, 10.2172/1345634

# Production of a 125 GeV Higgs Boson

Total cross-section at $\sqrt{s} = 13$ TeV is around 55 pb, this is actually not such a small cross-section (given LHC lumi.), over 7M Higgs produced in LHC Run 2!

Higgs production modes at the LHC:

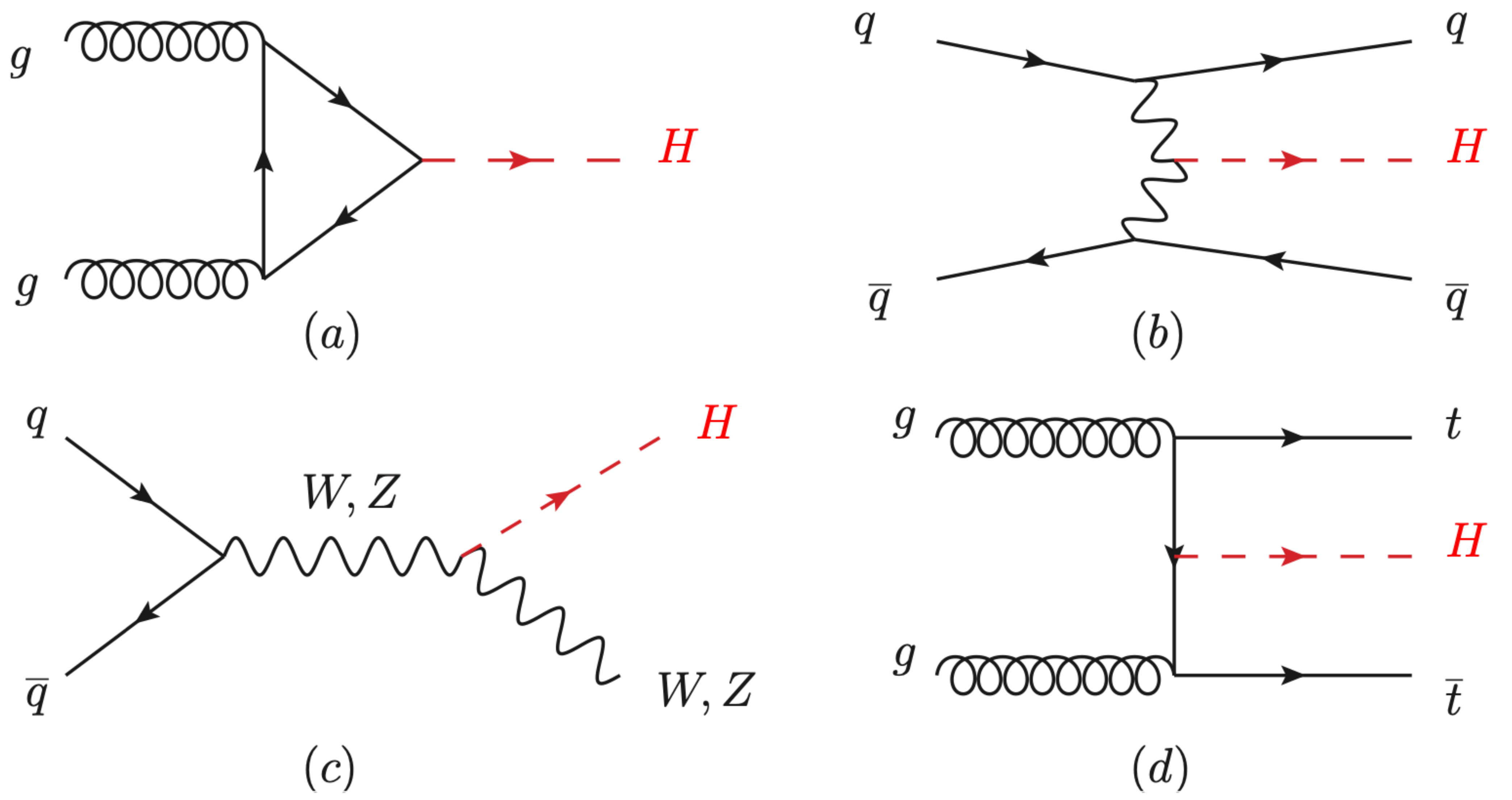
a. Gluon fusion process $gg \to H$ is dominant (≈ 88%)

b. Vector boson fusion (VBF) $q\bar{q} \to Hq\bar{q}$ is the sub-leading process (≈ 7%)

c. Associated production with a W or Z boson "Higgsstrahlung" (≈ 4%)

d. Associated production with $t\bar{t}$ (≈ 1%)

**Modes sensitive to different couplings,** important to study them all. Some channels facilitate the study of experimentally challenging decays e.g. $Z(\ell\ell)H(b\bar{b})$

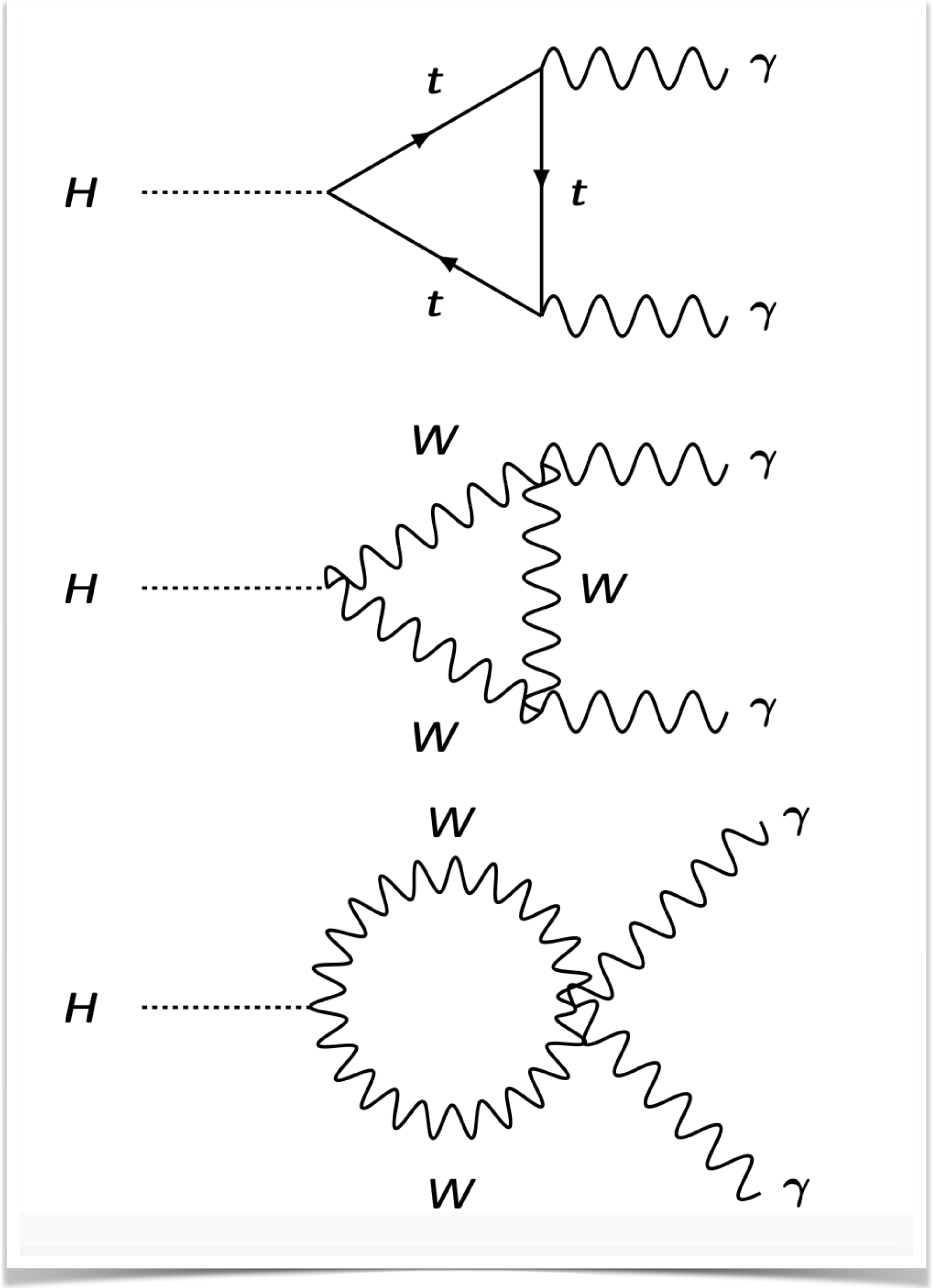


arXiv:1708.00794

# $H \to \gamma\gamma$

# $H \to \gamma\gamma$ decay

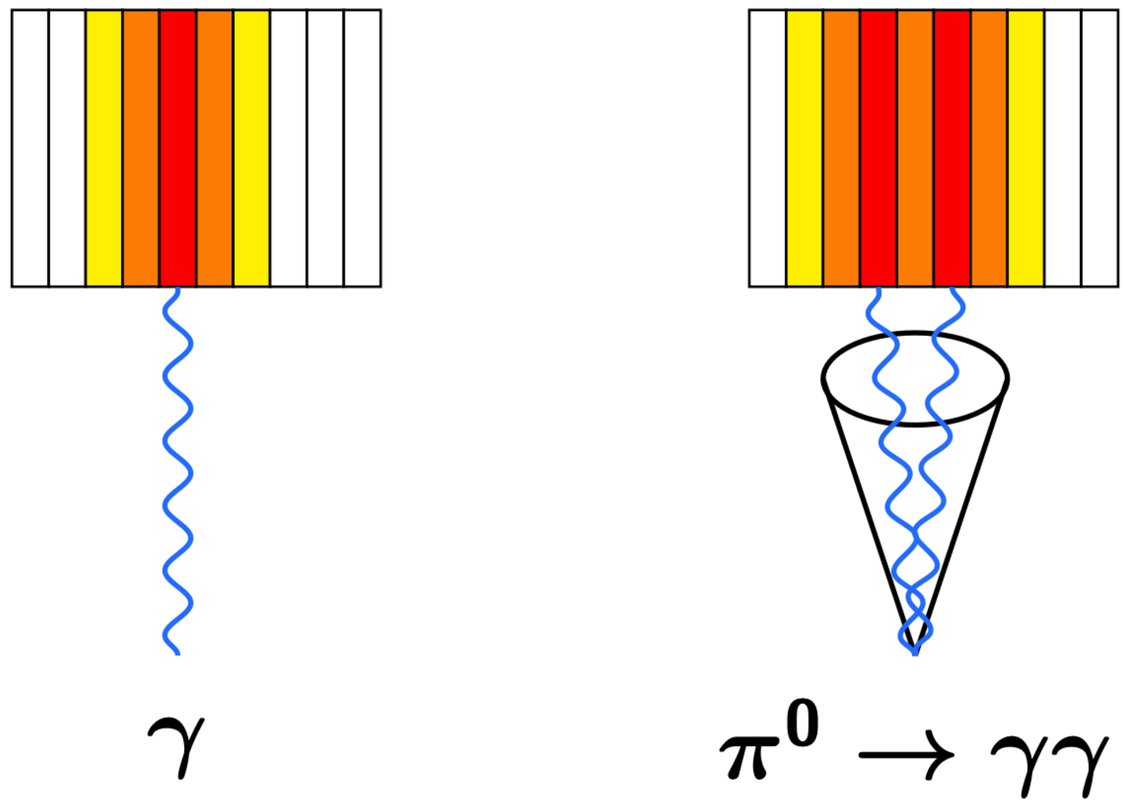
- Decay induced through fermion (mostly top quark) or W boson loop diagrams (with interfering amplitudes)
- Rather low branching fraction $B(H \to \gamma\gamma) \approx 2 \times 10^{-3}$
- Characterised by two high $p_T \approx m_H/2$ photons, isolated from hadronic activity

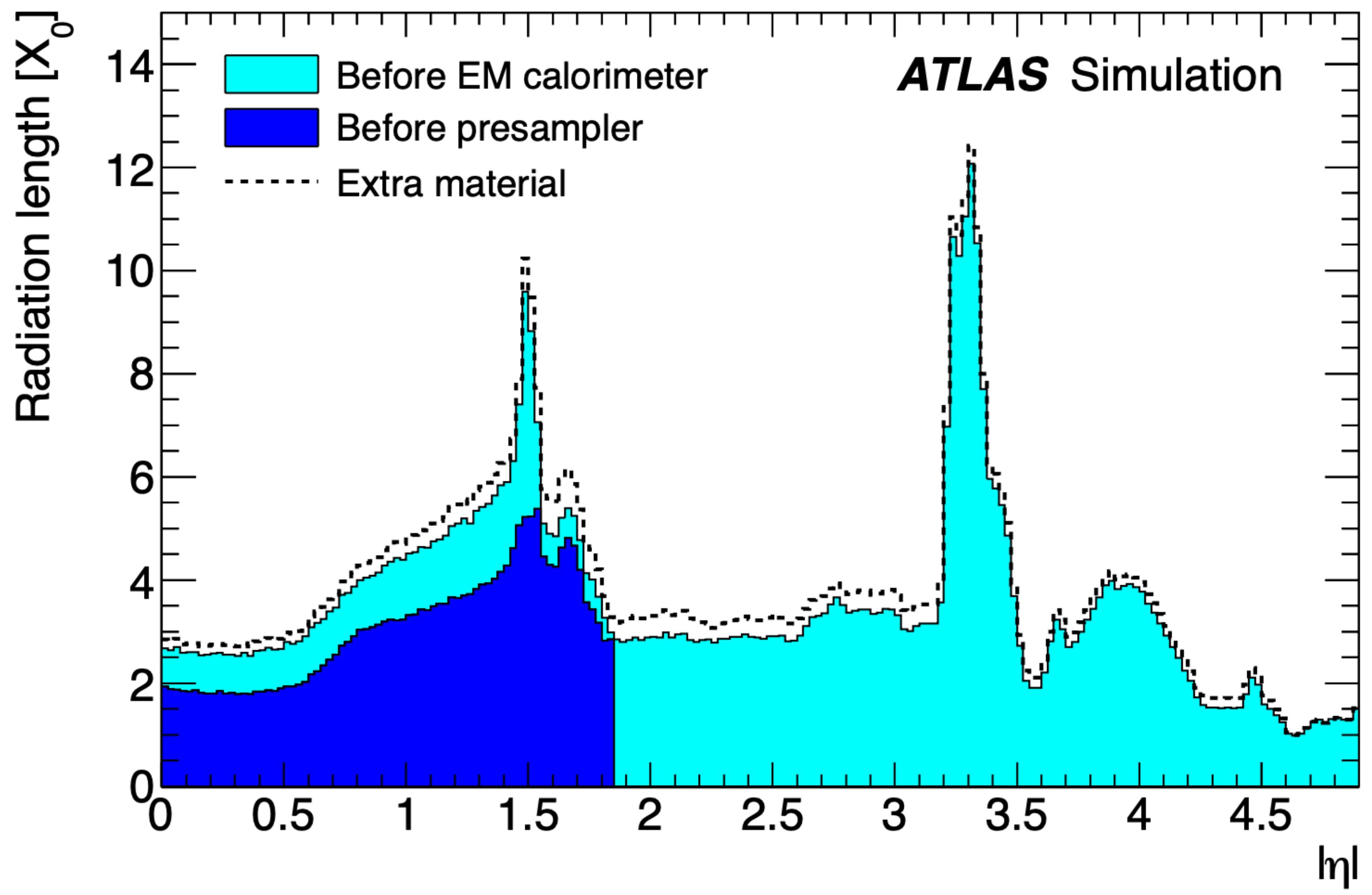


# Photon Reconstruction

**ECal. designed to initiate EM shower of incident photon, energy can be measured and direction inferred based on location of signal calorimeter cells w.r.t. beam spot**

- **Challenge 1: Neutral Hadrons**
  - Jets containing a high fraction of neutral hadrons are the main background to photon reconstruction
  - Primarily caused by $\pi_0 \to \gamma\gamma$ decays (i.e. two photons with a small angular separation)
  - Mitigated by considering the “shape” of the calorimeter signal (single or overlapping photons?)
- **Challenge 2: Material Interactions**
  - Much material (tracking detectors) in front of the EM calorimeter
  - High probability ($\approx$ 30%) that a photon with convert to $\gamma \to e^+e^-$ before reaching the calorimeter
  - Attempt to reconstruct the final state electrons to recover this “inefficiency”

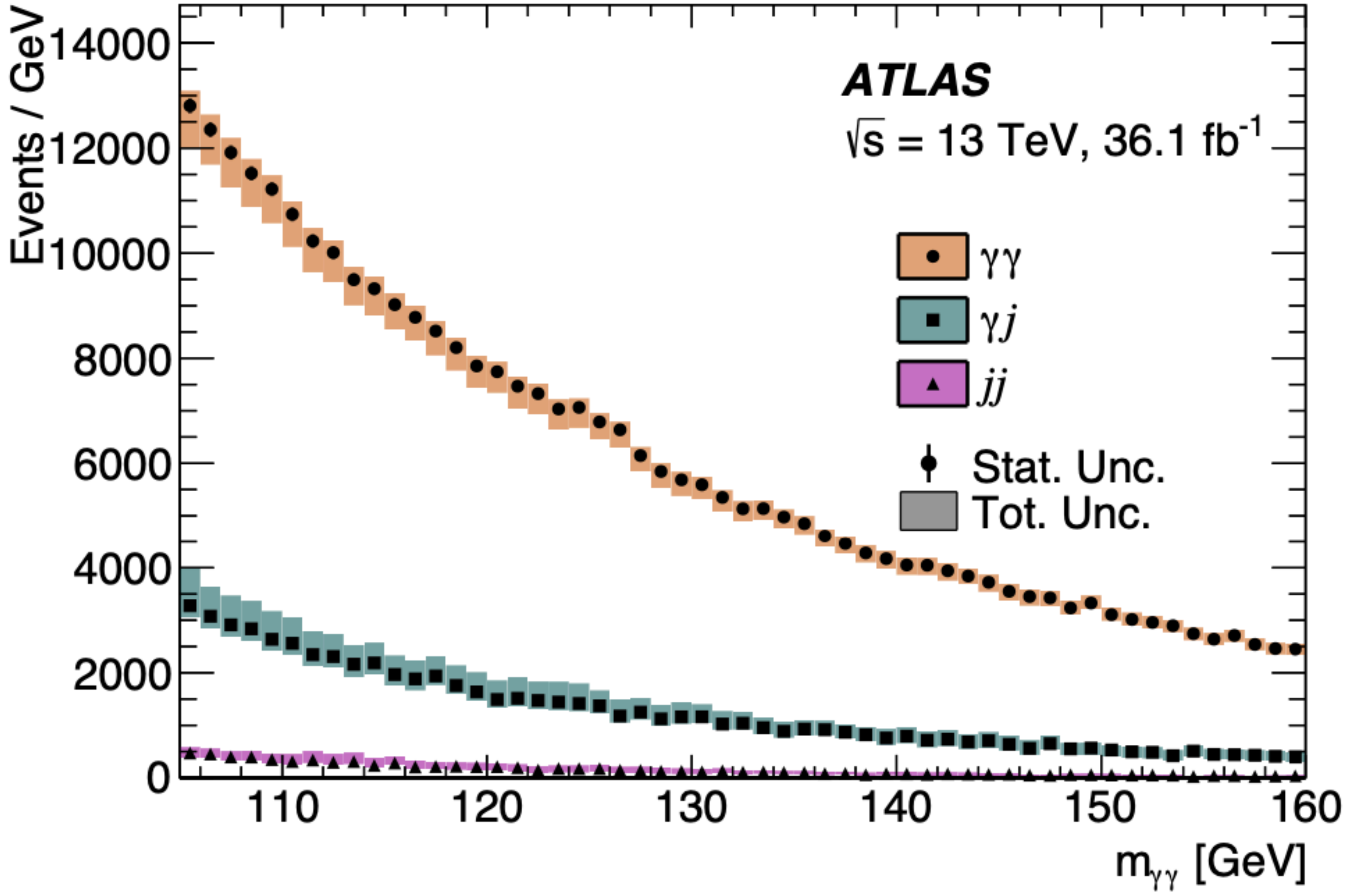




# $H \to \gamma\gamma$ analysis strategy

## Strategy: Look for events containing two isolated high $p_T$ photon candidates

DOI: 10.1103/PhysRevD.98.052005

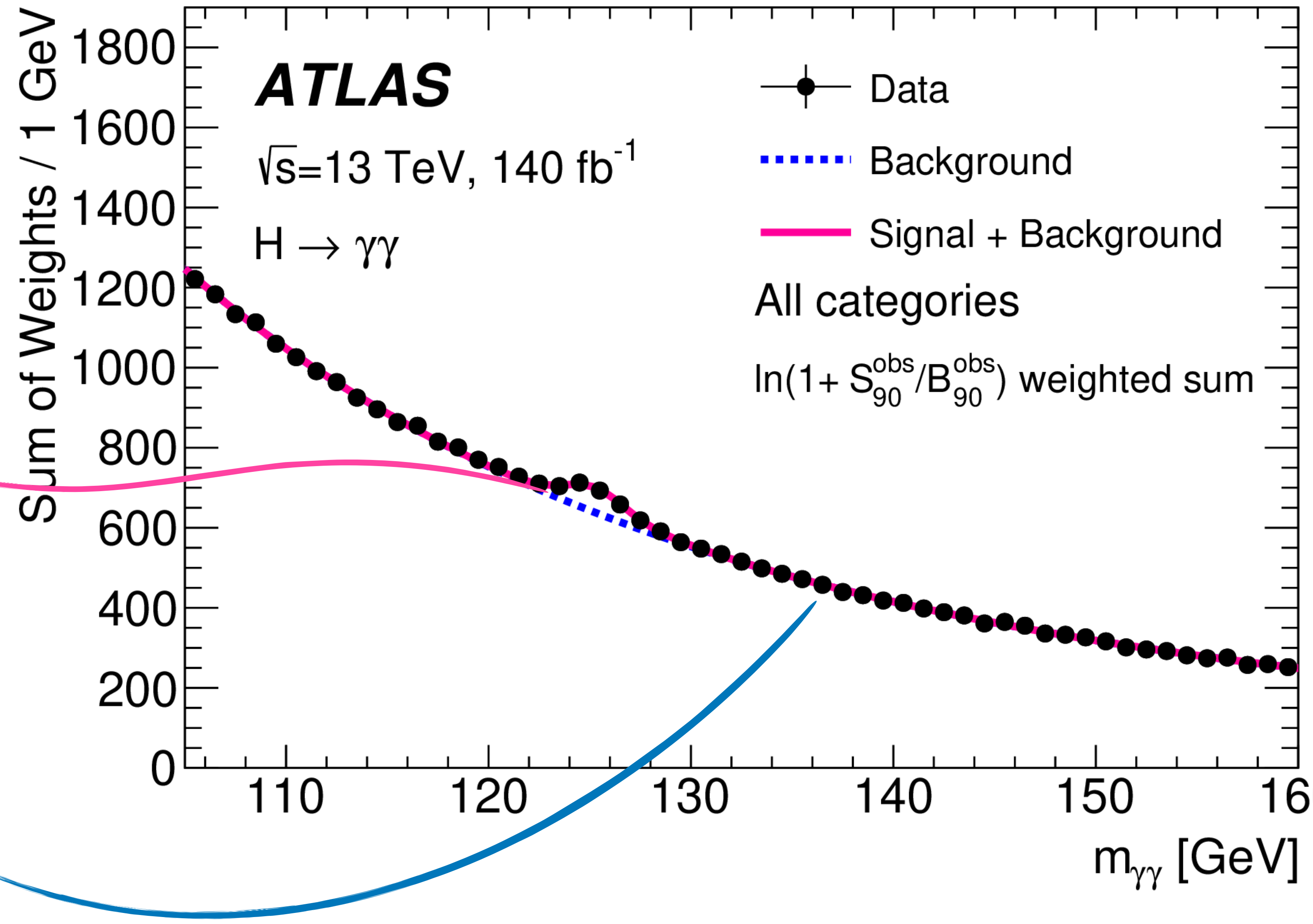


- Dominant "irreducible" background from non-resonant QCD production of two isolated photons
- Residual background due to one or both photons being "fake" from multi-jet production
- Judicious "shower shape" based photon ID selection reduces this to ≈ 20% of total backgound

- Fully reconstructed final state with excellent resolution in $m_{\gamma\gamma}$
- Search for "bump" consistent with $m_{\gamma\gamma}$ resolution (≈ 1.5%) on top of smoothly falling background

Signal = double-sided Crystal Ball function

Background = empirical continuous function of $m_{\gamma\gamma}$, fit in sidebands and extrapolated to Higgs peak region

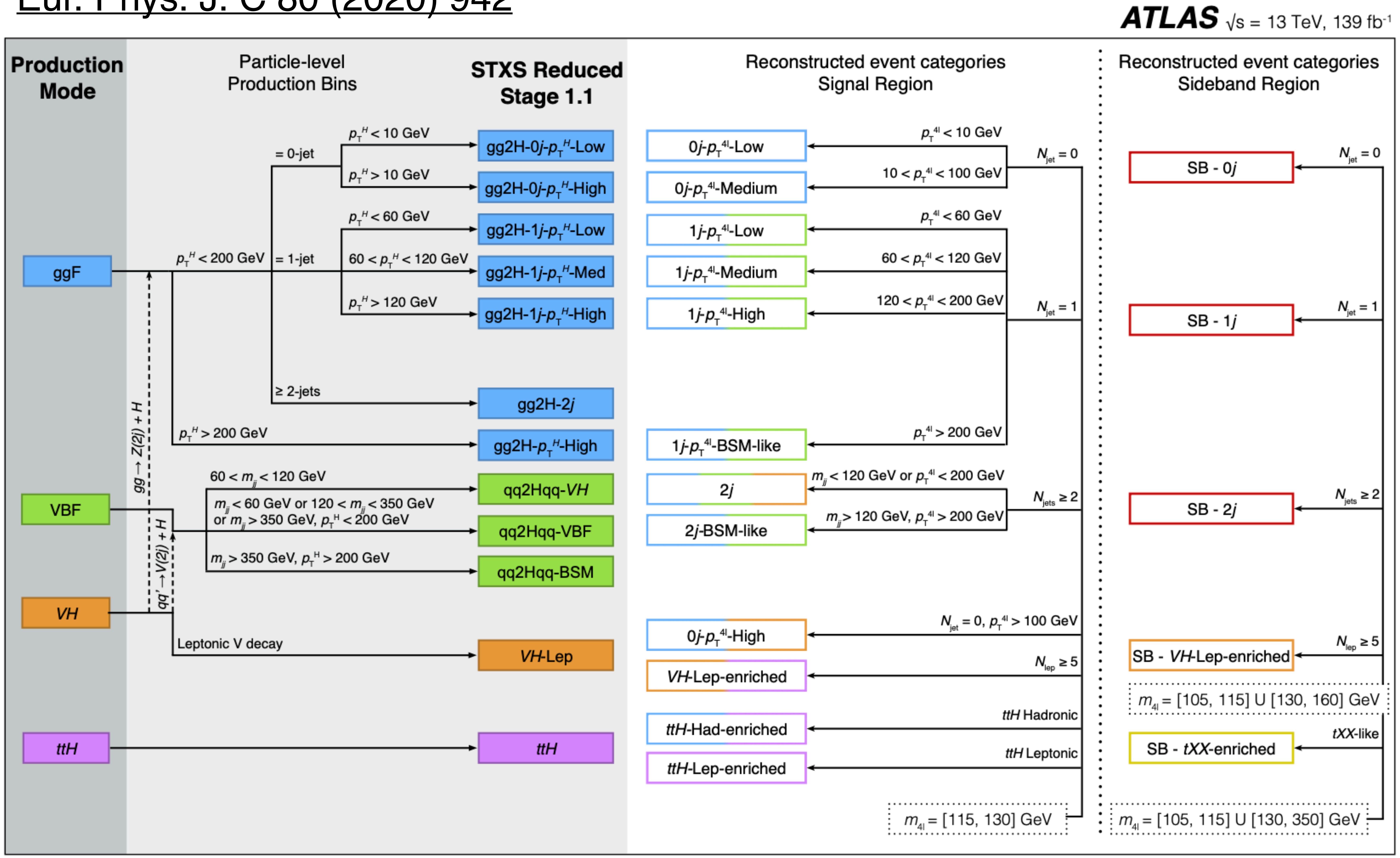


Phys. Lett. B 847 (2023) 138315

# Simplified Template Cross-section (STXS) framework

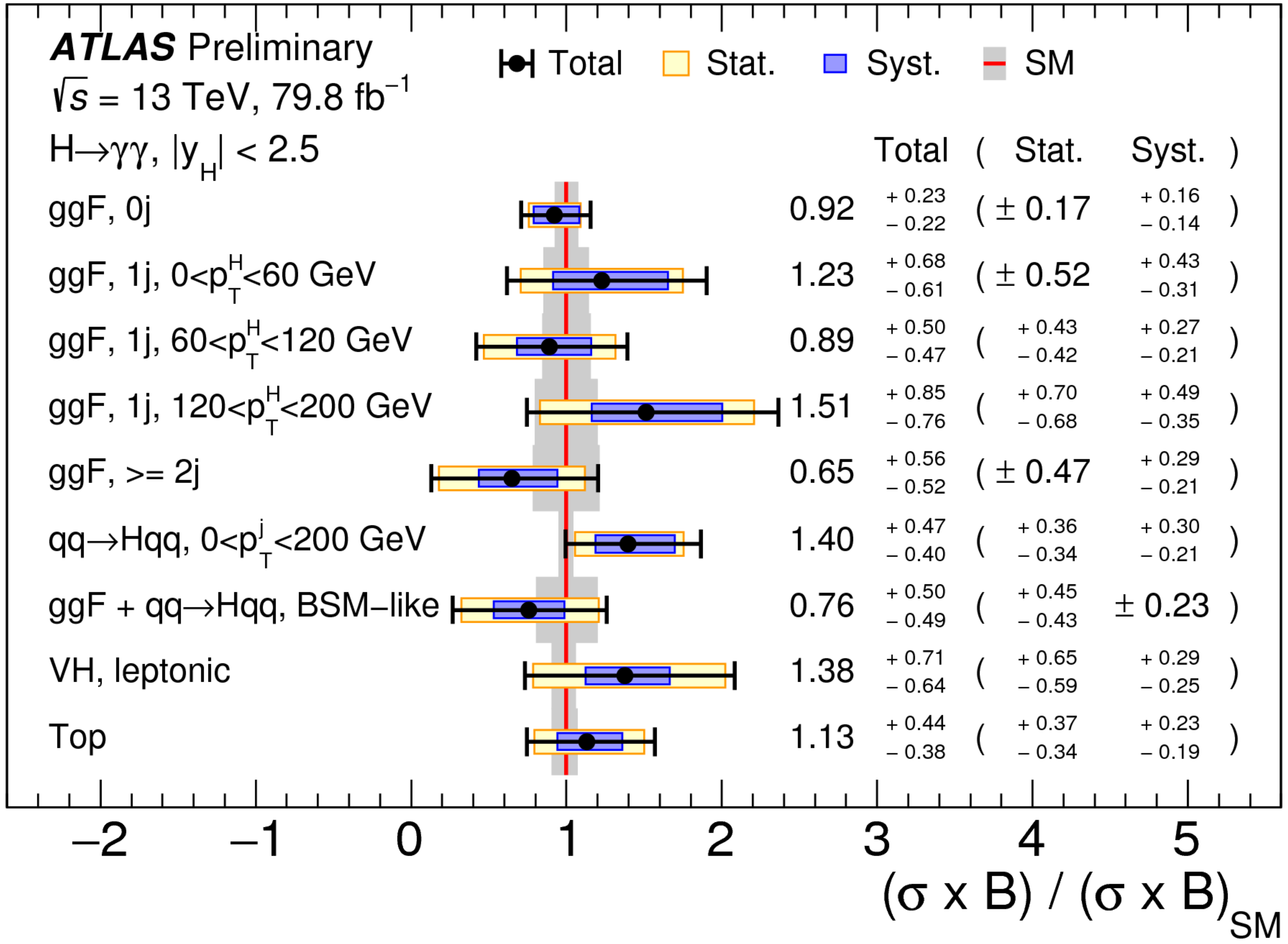
- Measurement strategy detailed in (arXiv:1610.07922)
- Production modes cross sections are measured separately, and each is categorised in bins of truth quantities (eg. $p_T^H$, $N_{\text{jets}}$, $p_T^V$,)
- Cross-section for Higgs production in for various sub-processes for a simplified fiducial volume defined as $|y_H| < 2.5$
- Bins are designed to optimise the signal and BSM sensitivity for a given integrated luminosity, and minimise the theoretical uncertainties
- Theoretical uncertainties kept if they cause migration between categories
- Different stages with various degrees of granularity
- Binning can be chosen depending on each channel's statistics

Eur. Phys. J. C 80 (2020) 942



# Recent production measurement $H \rightarrow \gamma\gamma$

Summary of the measured simplified template cross sections (STXS)



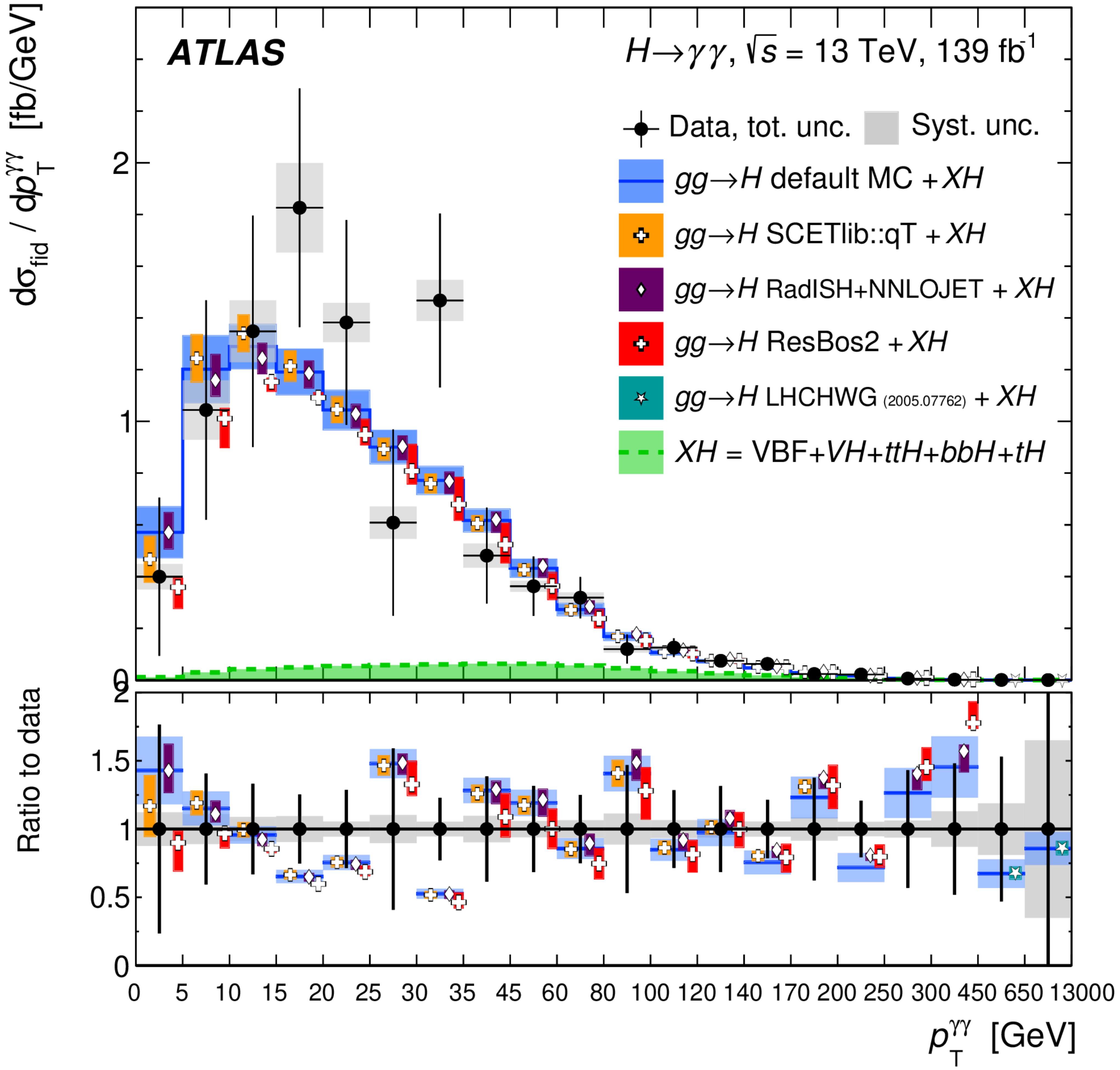
- Wide range of inclusive and differential fiducial (phase space →) cross section measurements

- Global signal strength consistent with SM
$\mu = 1.06 \pm 0.08$ (stat.) ${}^{+0.08}_{-0.07}$ (exp.) ${}^{+0.07}_{-0.06}$ (theo.)

# $H \to \gamma\gamma$ differential cross-sections: $p_T^H$

( JHEP 08 (2022) 027)

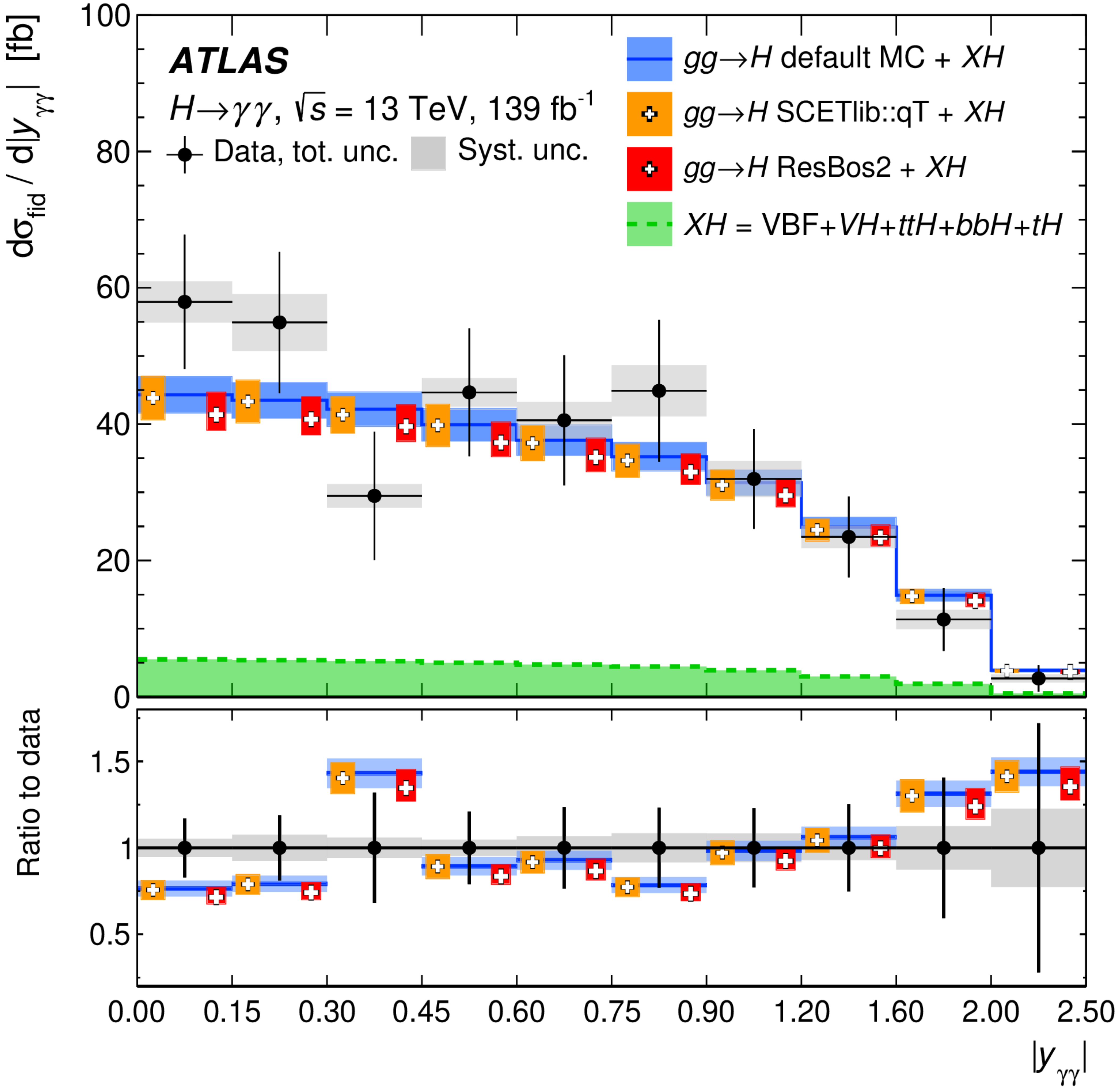
- H → γγ production measurements with $139\ \text{fb}^{-1}$, 13 TeV dataset
- Wide range of inclusive and differential fiducial (phase space →) cross section measurements
- Global signal strength consistent with SM μ = 1.06 ± 0.08 (stat.) +0.08 (exp.)+0.07 (theo.)



# $H \rightarrow \gamma\gamma$ differential cross-sections: $|y_H|$

JHEP 08 (2022) 027

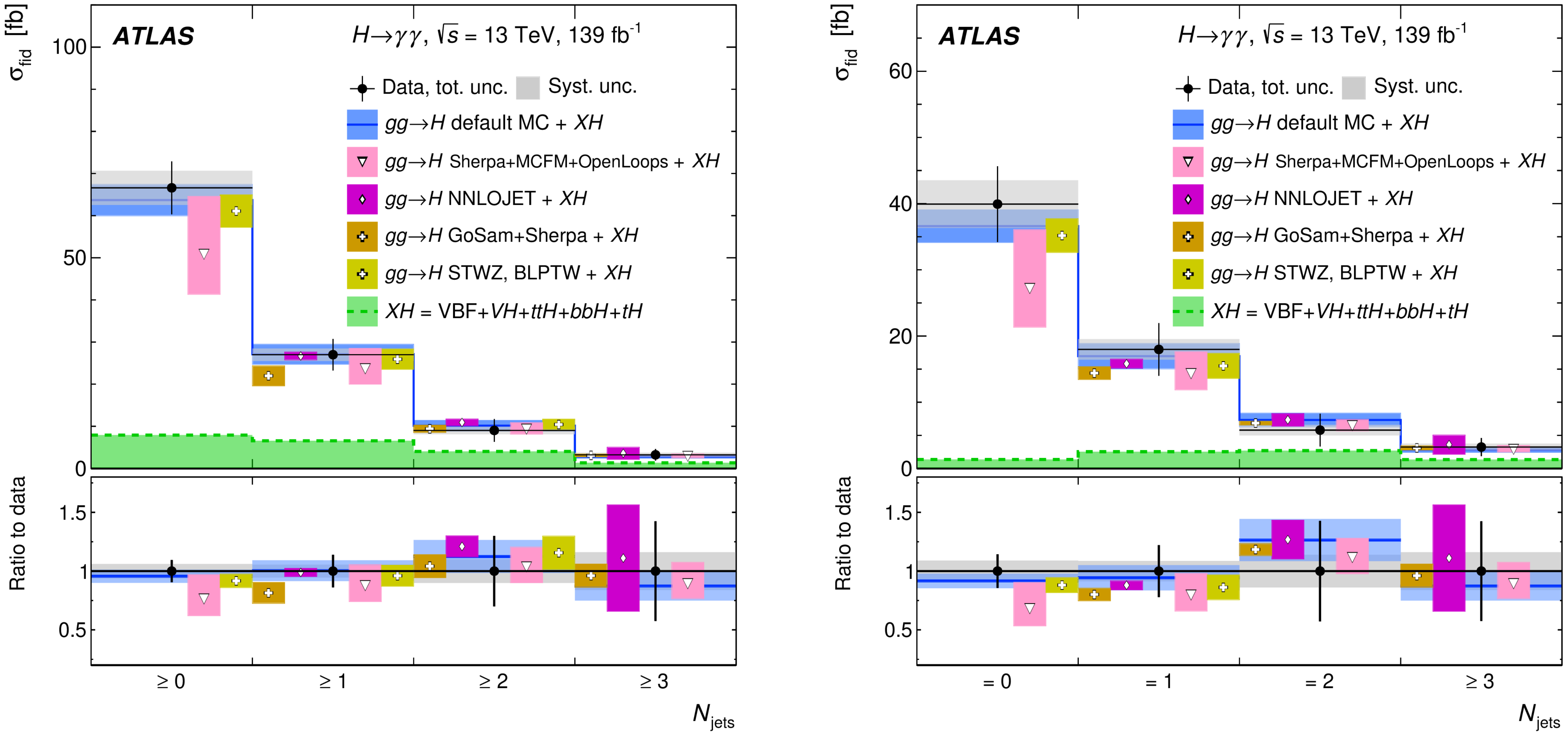
- $\chi^2$ probability for compatibility of data with default SM distribution is 68%
  (POWHEG NNLOPS normalised to YR4 N$^3$LO (QCD) and NLO(EW) cross section)



# $H \to \gamma\gamma$ differential cross-sections: $N_{\text{jets}}$

( JHEP 08 (2022) 027)

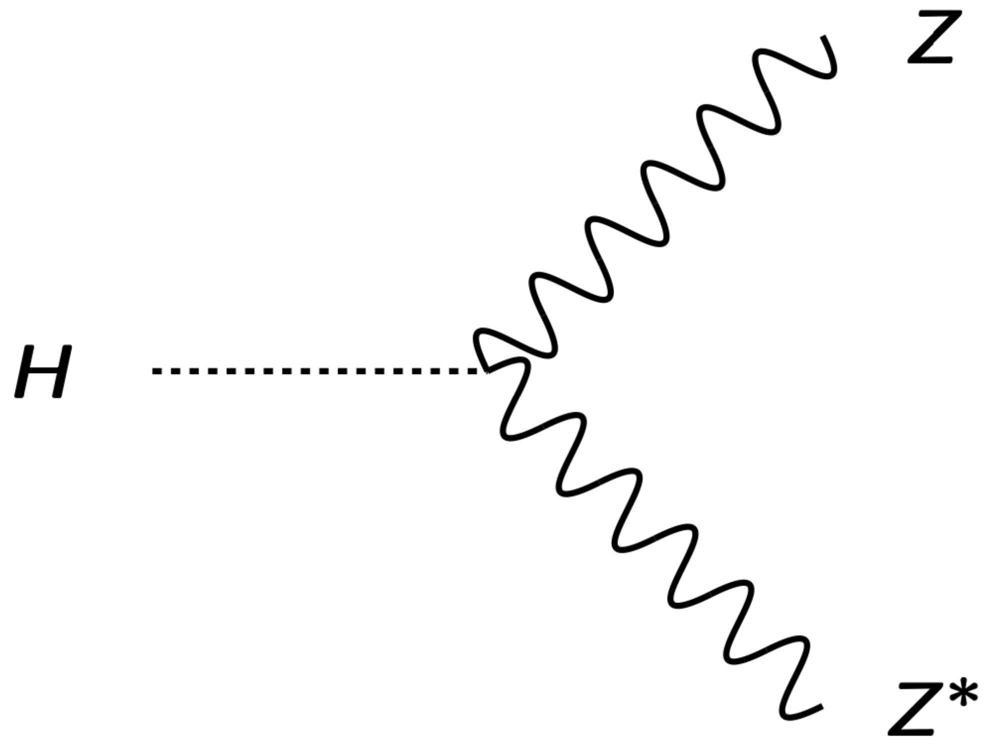
- Particle-level fiducial differential cross-sections times branching ratio
- Multiplicity of associated jets, both inclusive and exclusive bins
- Sensitive to contributions from VH and $t\bar{t}H$ production at high $N_{\text{jets}}$
- $\chi^2$ probability for compatiblity of data with default SM distribution is 96%



# Higgs —> ZZ*

# Higgs to ZZ* decay

- Tree level decay, directly sensitive to $HZZ$ coupling
- Reasonably high branching fraction $B(H \to ZZ^*) \approx 3\,\%$
- Feasibility of experimental study driven by characteristics of Z boson decays
- Most effective channel considers only $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decays
- Reduces branching fraction to $B(H \to ZZ^* \to 4\ell) \approx 10^{-4}$
- Very sensitive to spin / parity properties of Higgs boson given multiple measurable angular distributions



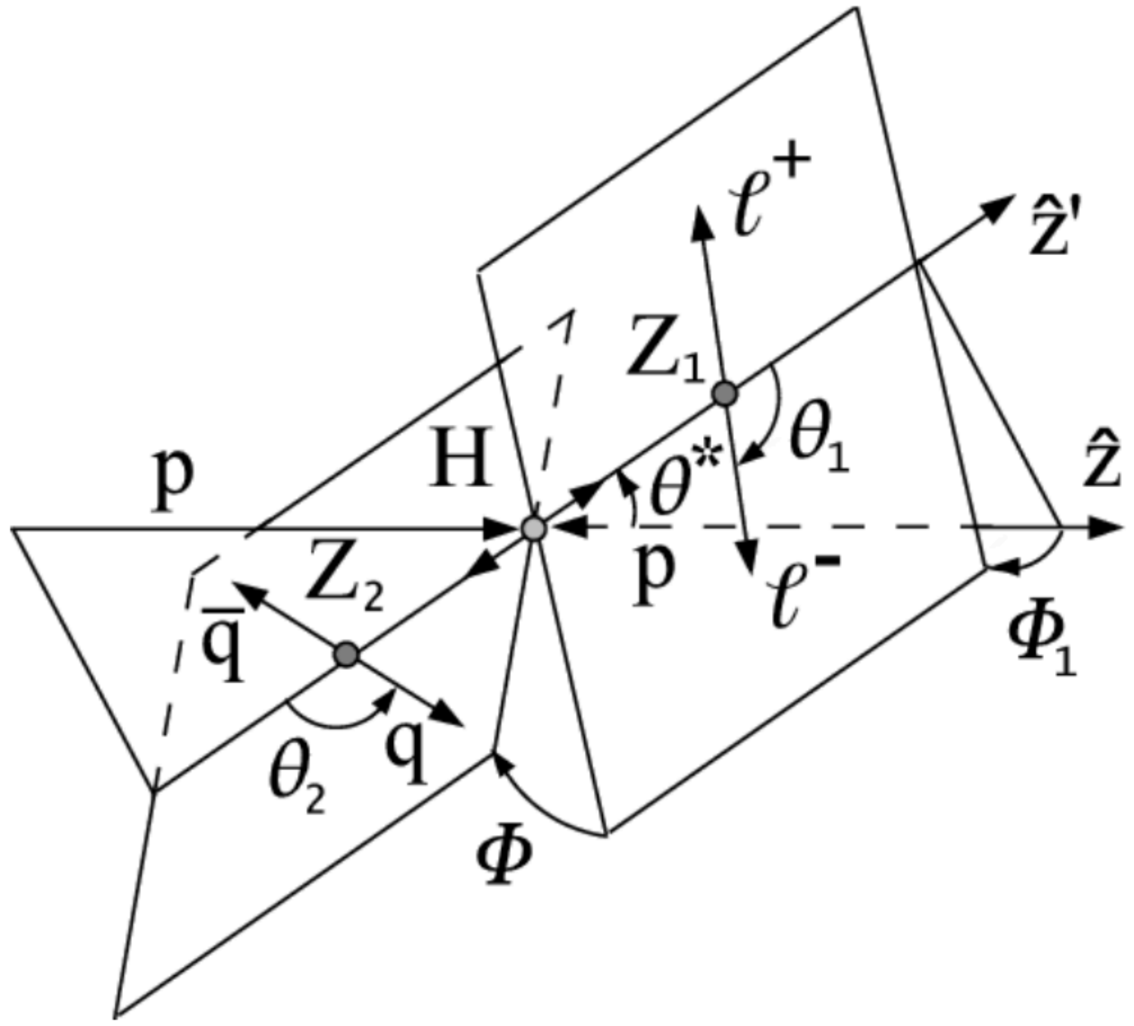
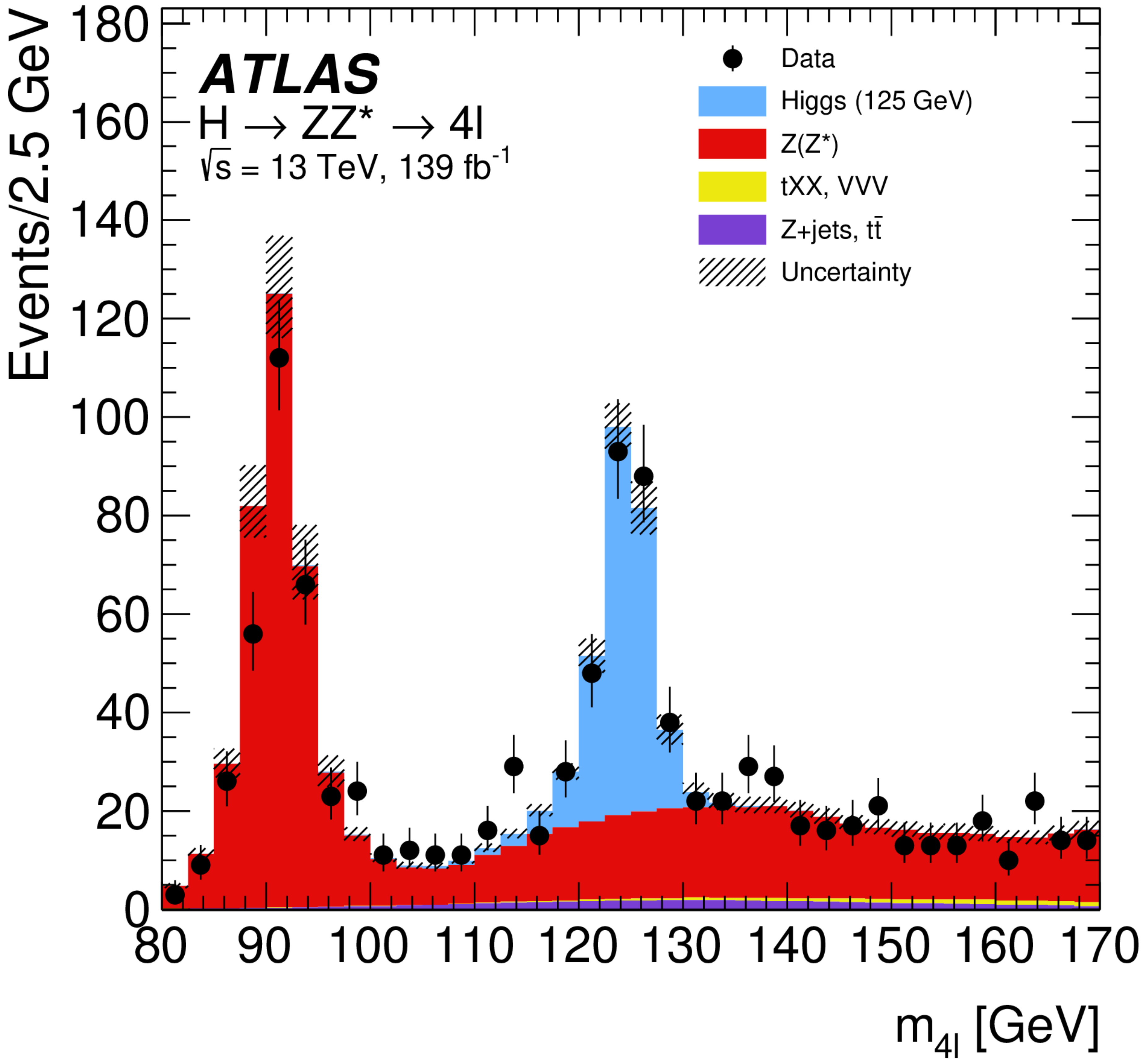
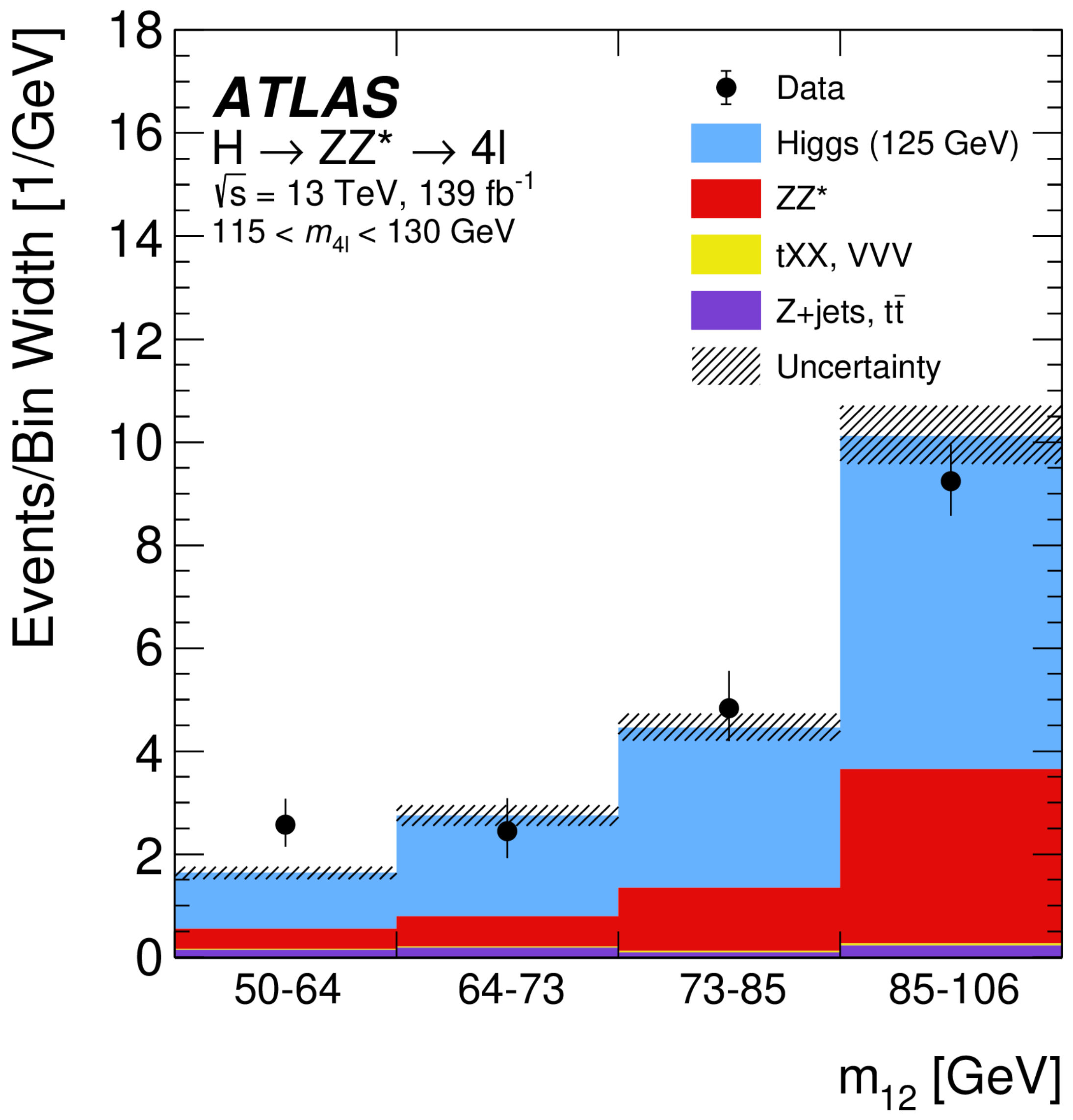


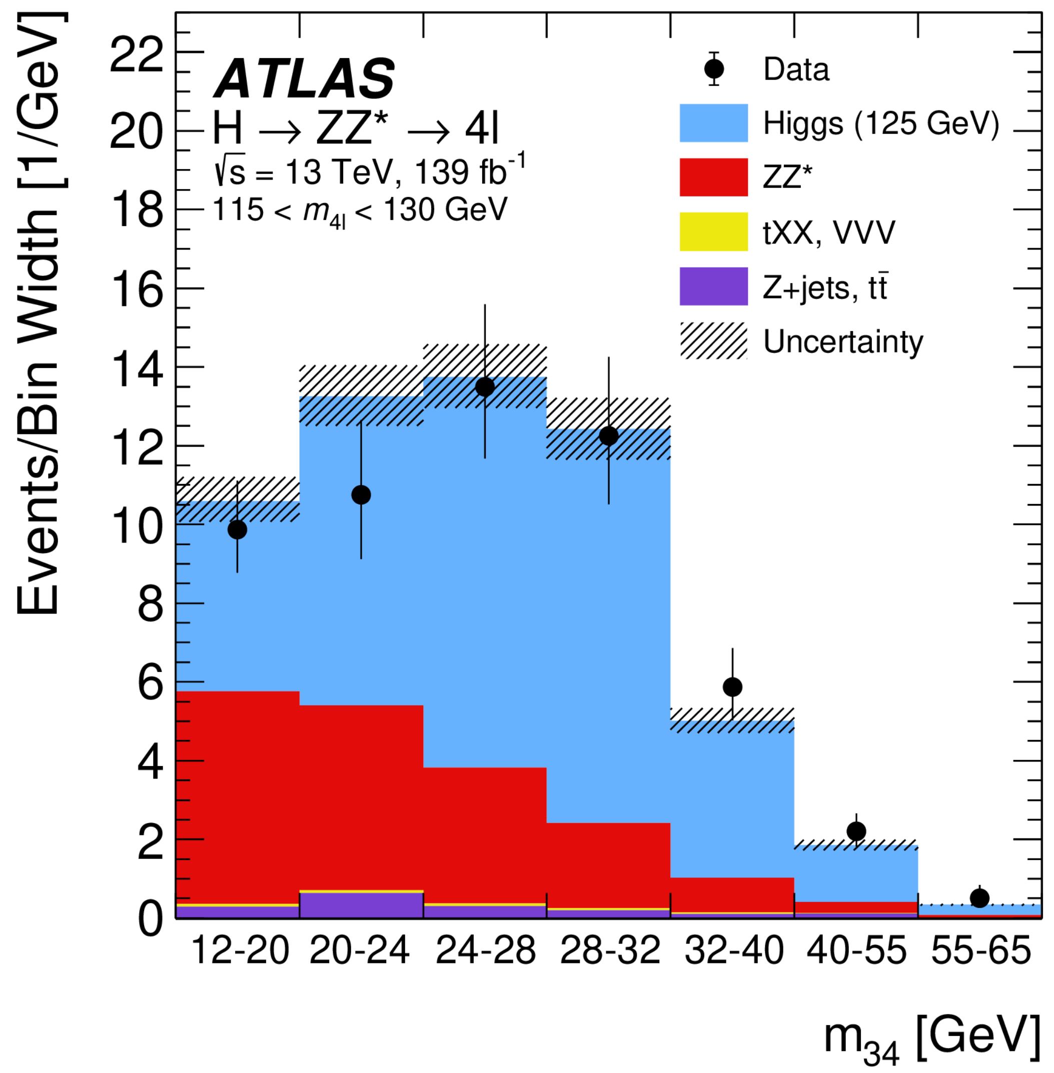
**Figure: CMS-HIG-12-024**

# $H \to ZZ^* \to 4\ell$ analysis strategy (Eur. Phys. J. C 80 (2020) 942)

- Very good resolution in $m_{4\ell}$ and S/B ≈ 1, described as "golden channel"
- Background
  - dominated by "irreducible" non-resonant $Z(Z/\gamma^*)$ production
  - much smaller contributions from $Z+$ jets and $t\bar{t}$

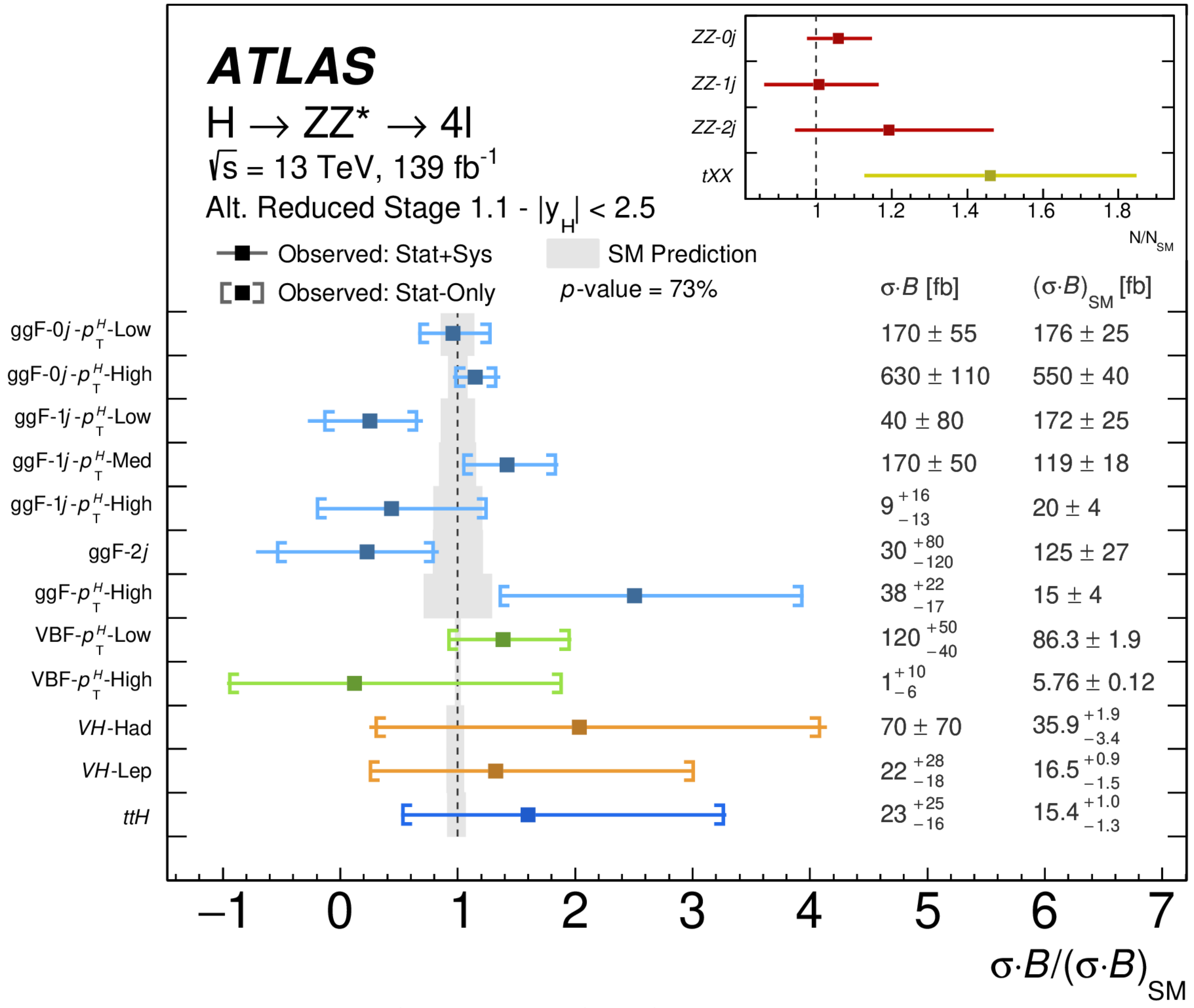






# Latest production measurements with $H \rightarrow ZZ^* \rightarrow 4\ell$

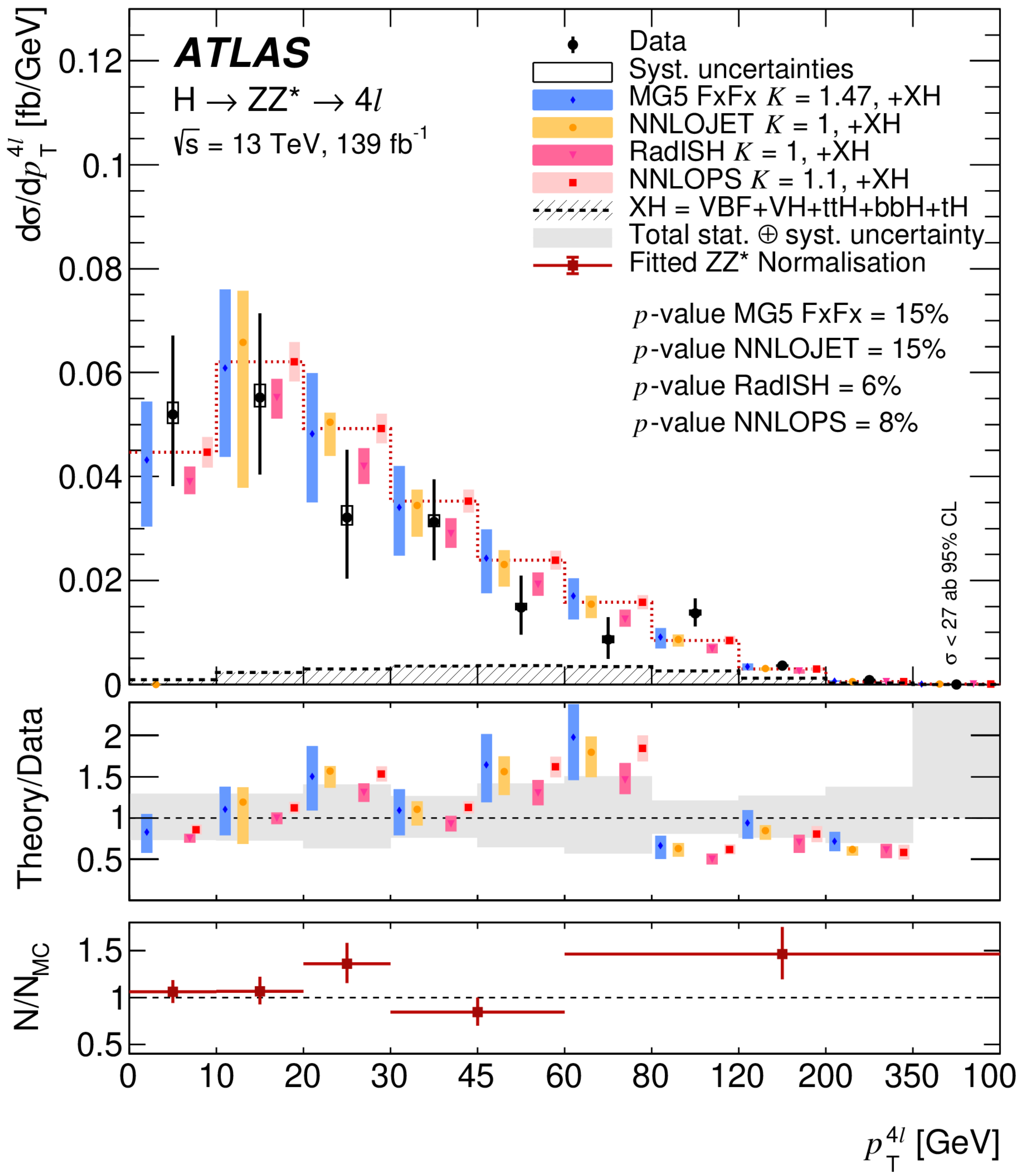
- $H \rightarrow ZZ^* \rightarrow 4\ell$ production measurements updated with 139 $\mathrm{fb}^{-1}$ 13 TeV dataset, global signal strength μ = 1.01 ± 0.08 (stat.) ± 0.04 (exp.) ± 0.05 (theo.)

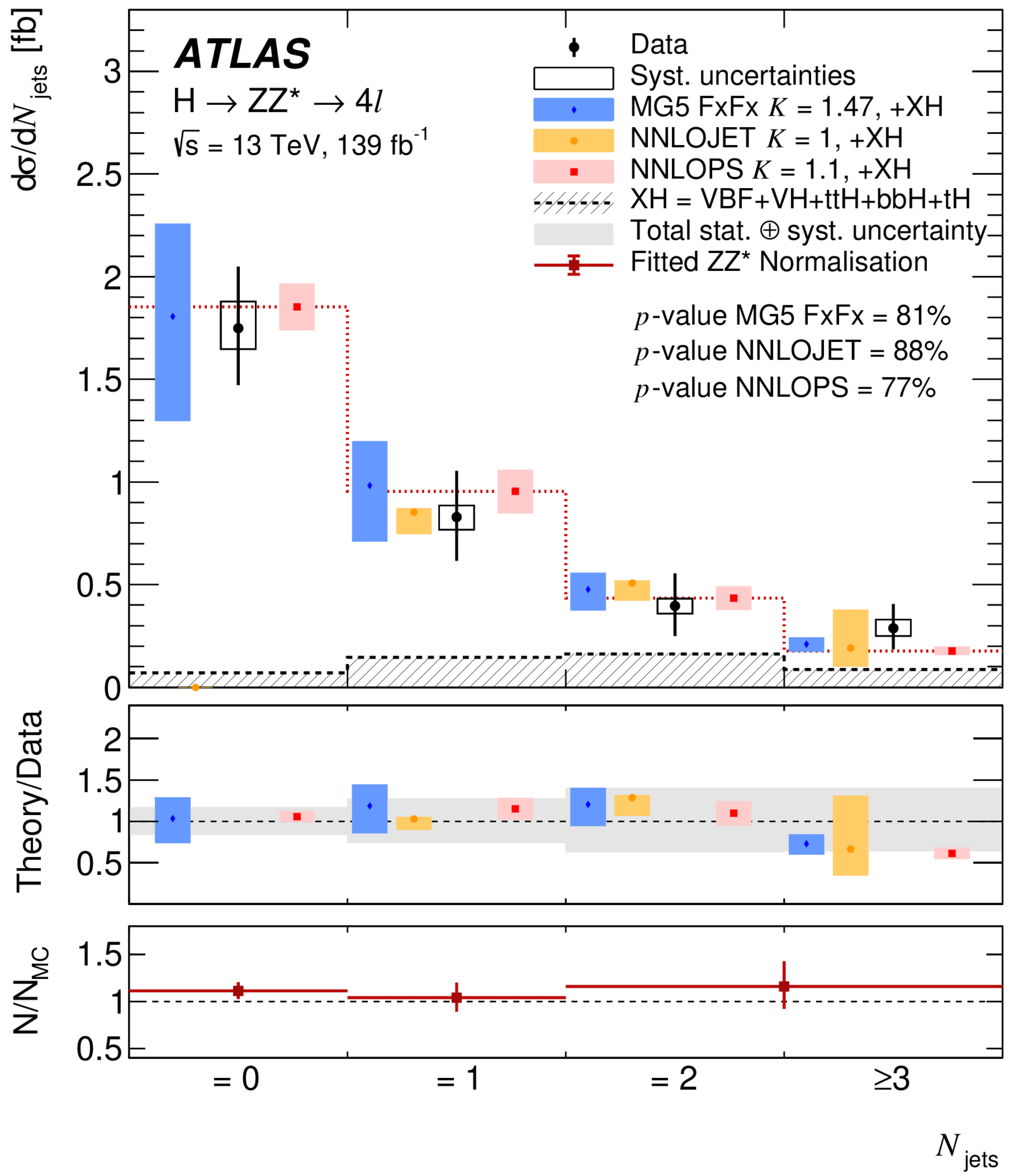


**"Reduced Stage 1.1" STXS (cross-sections)**

# $H \to ZZ^* \to 4\ell$ differential Cross-sections

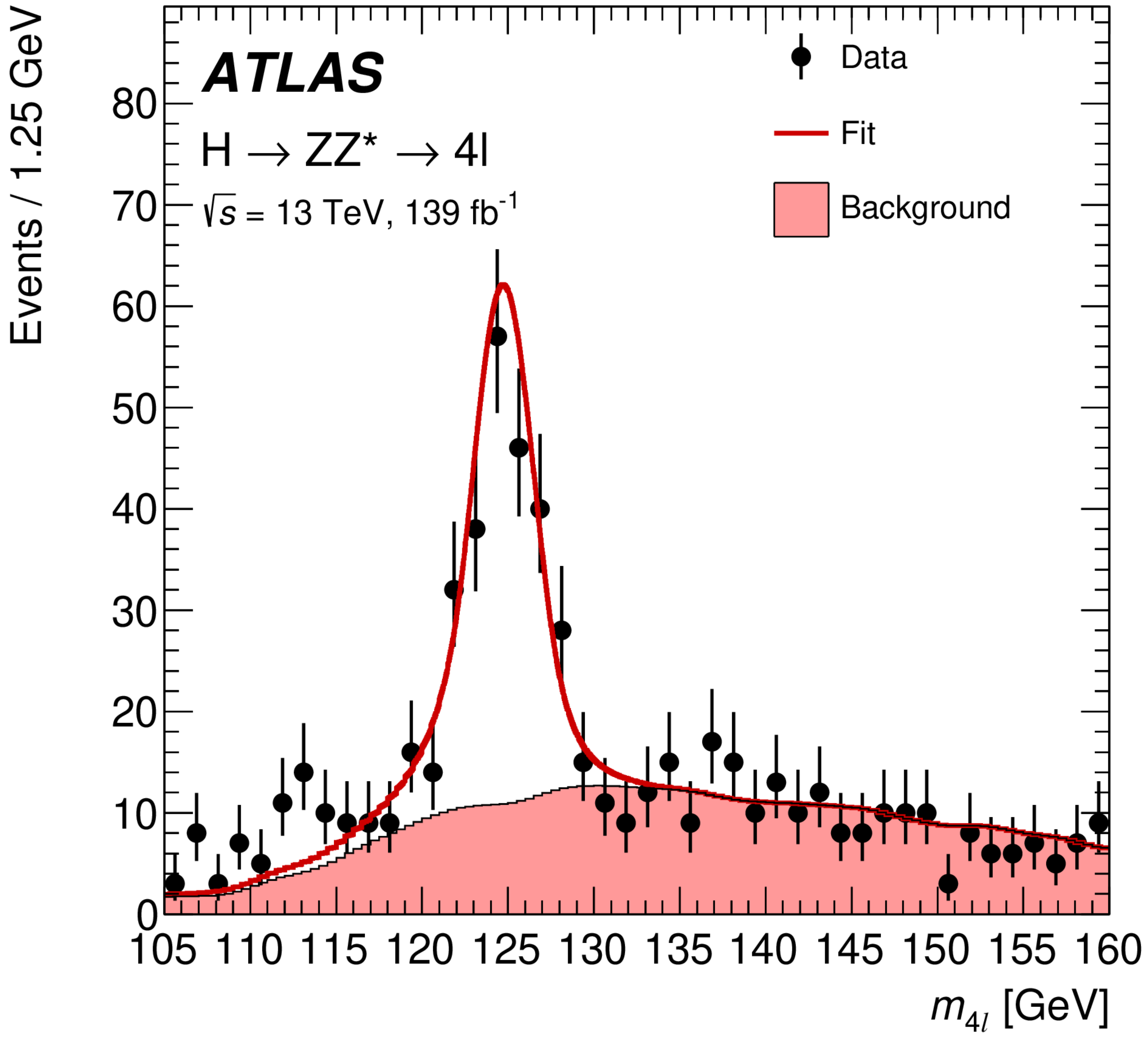
- Differential measurements of $p_T^H$ and associated jet multiplicity
- p-values for compatibility of $p_T^H$ data with predictions reasonably low…

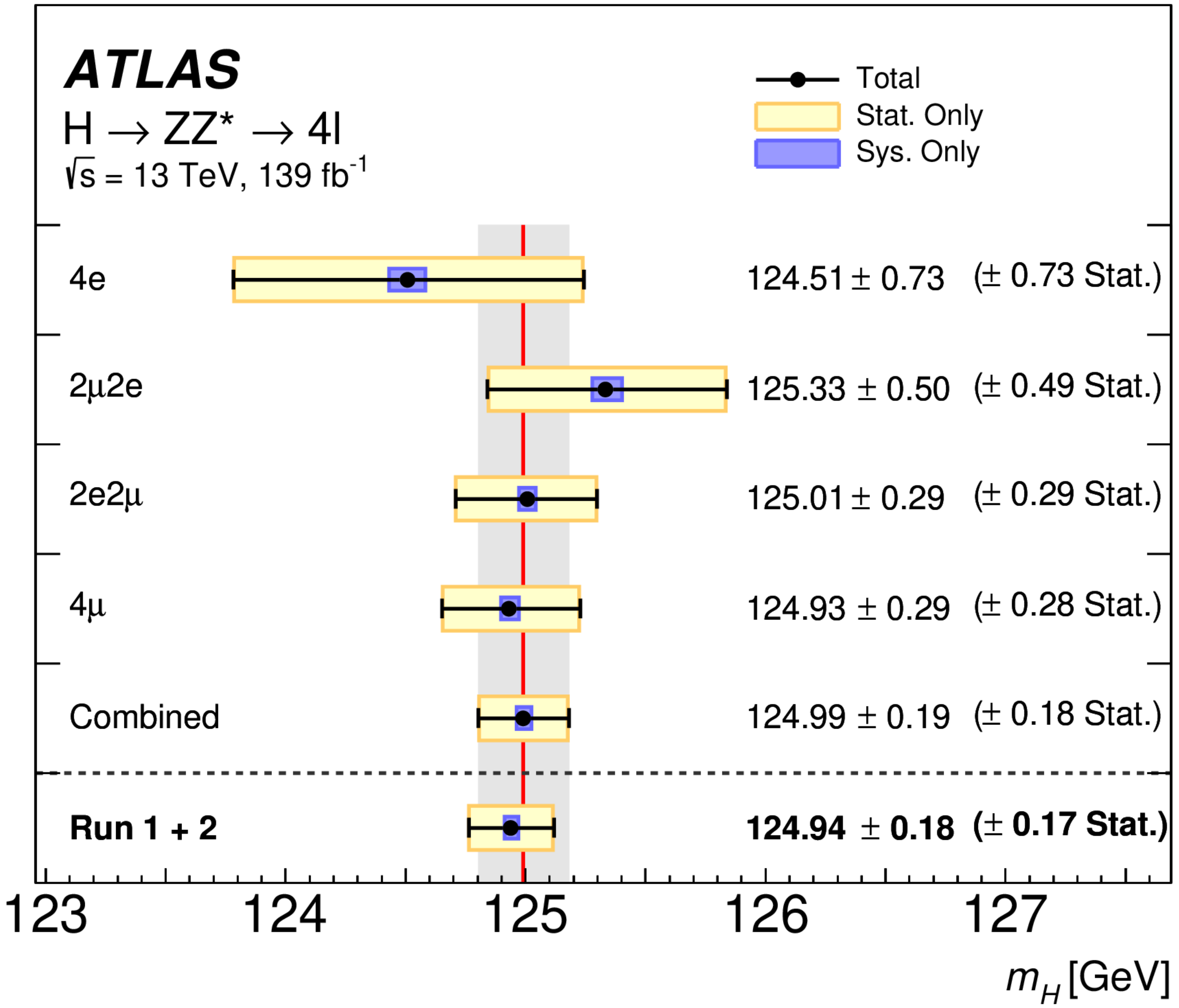




# $H \to ZZ^* \to 4\ell$ $m_H$ measurement

**Phys. Lett. B 843 (2023) 137880**





- Systematic uncertainty dominated by muon momentum scale uncertainty
- $m_H = 124.92 \pm 0.17(\text{stat.}) \pm 0.3(\text{syst})$ GeV (combination)

# Measurement of $\Gamma_H$ from the off-shell production

## Ratio of on/off-shell signal strengths for $gg \to H \to VV^*$ sensitive to $\Gamma_H$

$$\mu_{\text{on-shell}} = \kappa^2_{\text{prod}} \times \kappa^2_{\text{decay}} \times \frac{1}{\kappa_H}, \qquad \kappa_H = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}$$

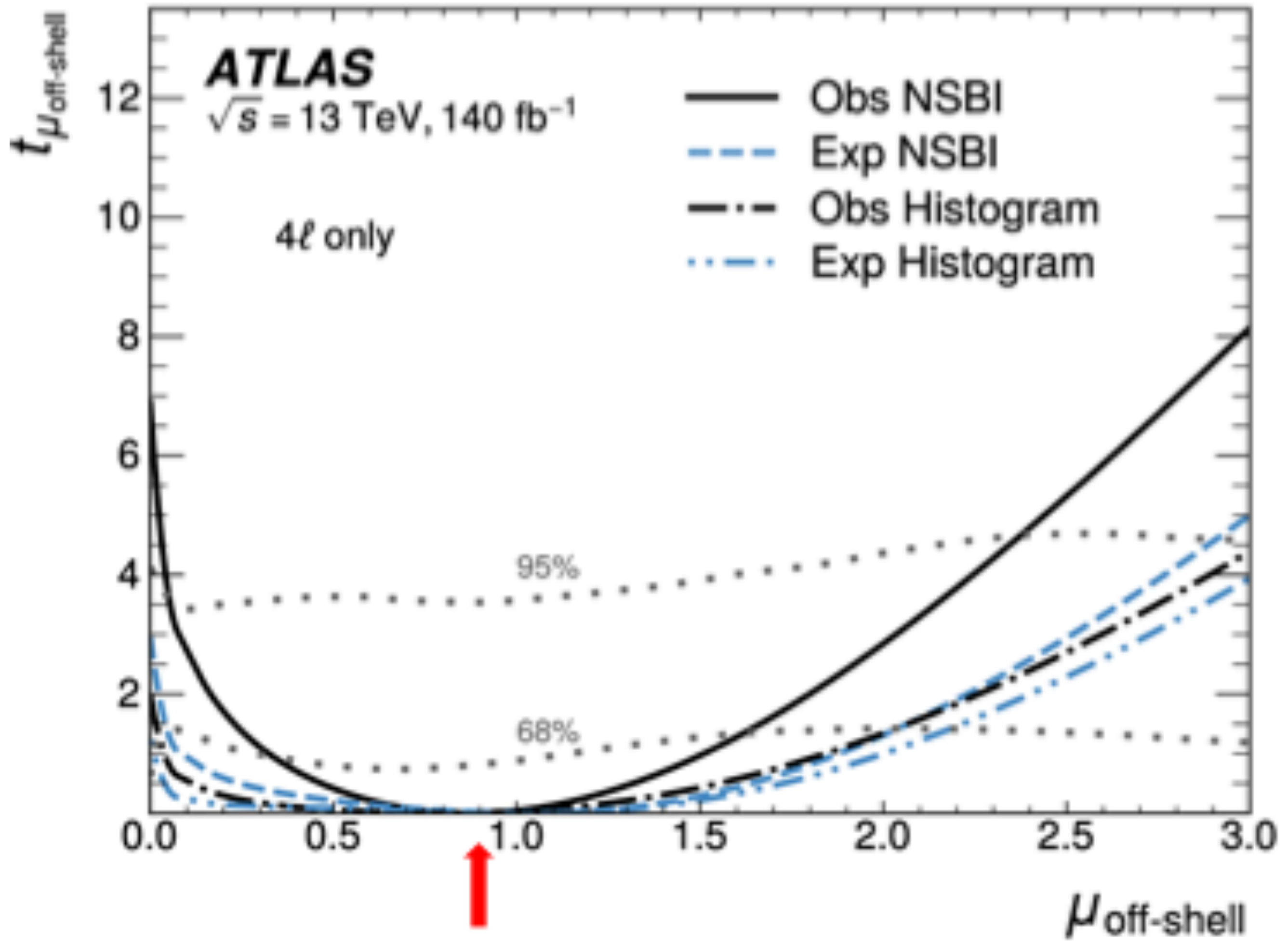
$$\mu_{\text{off-shell}} = \kappa^2_{\text{prod}} \times \kappa^2_{\text{decay}} \qquad \kappa_i = \frac{g_i}{g_i^{\text{SM}}}$$

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \kappa_H \quad (\text{assuming } \kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}})$$

- Theoretical Higgs width: $\Gamma_H = 4.1\ \text{MeV}$, calculated from all possible Higgs decays, hence sensitive to any BSM particle that interacts with the Higgs.
- Not enough resolution to measure $\Gamma_H$ directly at the LHC: indirect measurement in $H \to VV$ $(V = W, Z)$:
- Off-shell $H* \to VV$ slightly enhanced because the vector bosons become on-shell.

# Width measurement in $H \rightarrow ZZ \rightarrow 4\ell$

Likelihood scans for $\mu_{\text{off-shell}}$ :

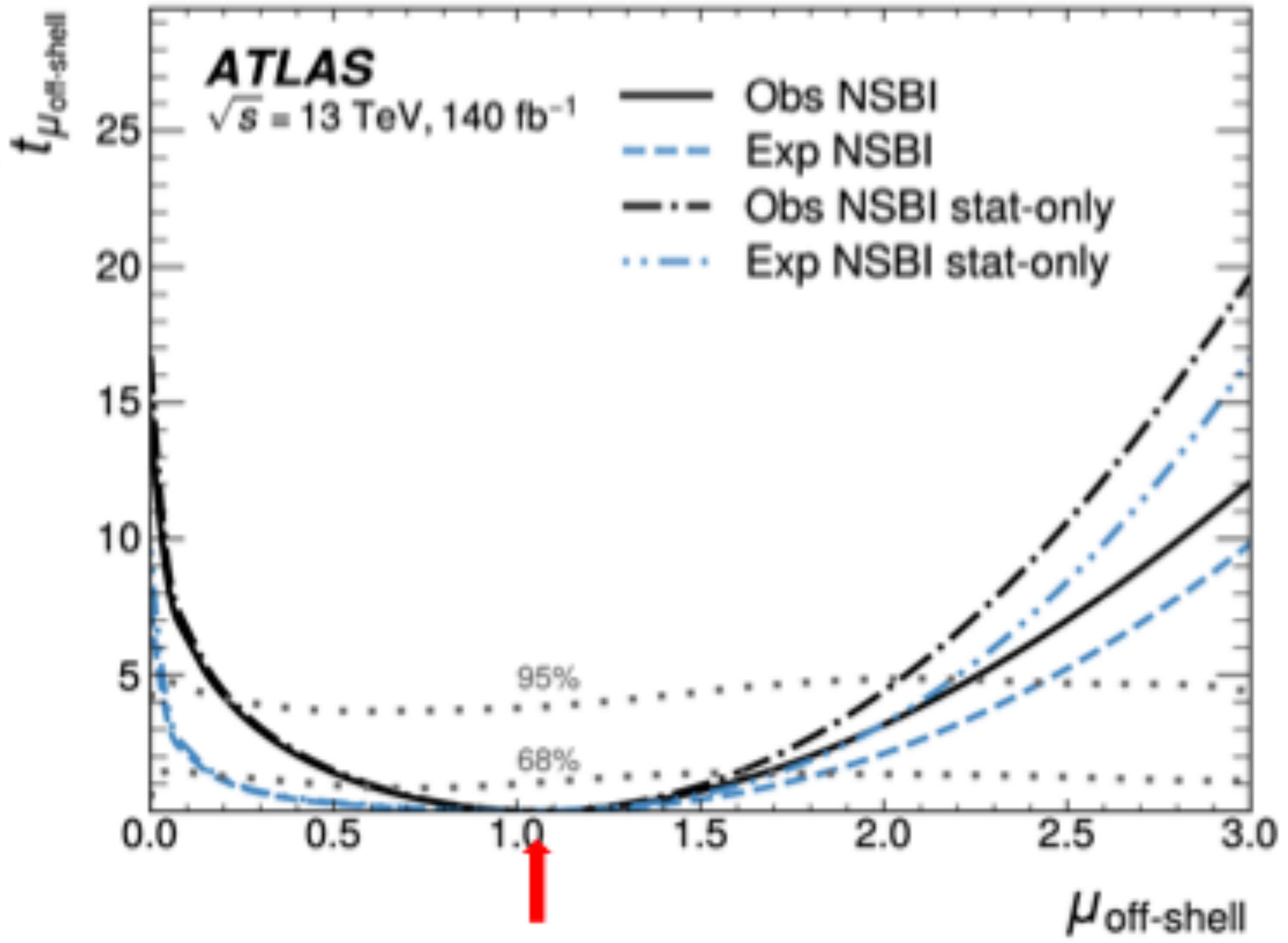


Best-fit: $\mu_{\text{off-shell}} = 0.87^{+0.75}_{-0.54}$
(expected $1.00^{+1.04}_{-0.95}$)

Significance: $2.5\sigma$ (expected $1.3\sigma$)

Compare with previous ATLAS result using **same dataset**:
$\mu_{\text{off-shell}} = 0.79^{+1.21}_{-0.77}$, $0.8\sigma$ significance

Combine with $H \rightarrow ZZ \rightarrow 2\ell 2\nu$
(*Phys. Lett. B* **846** (2023) 138223)



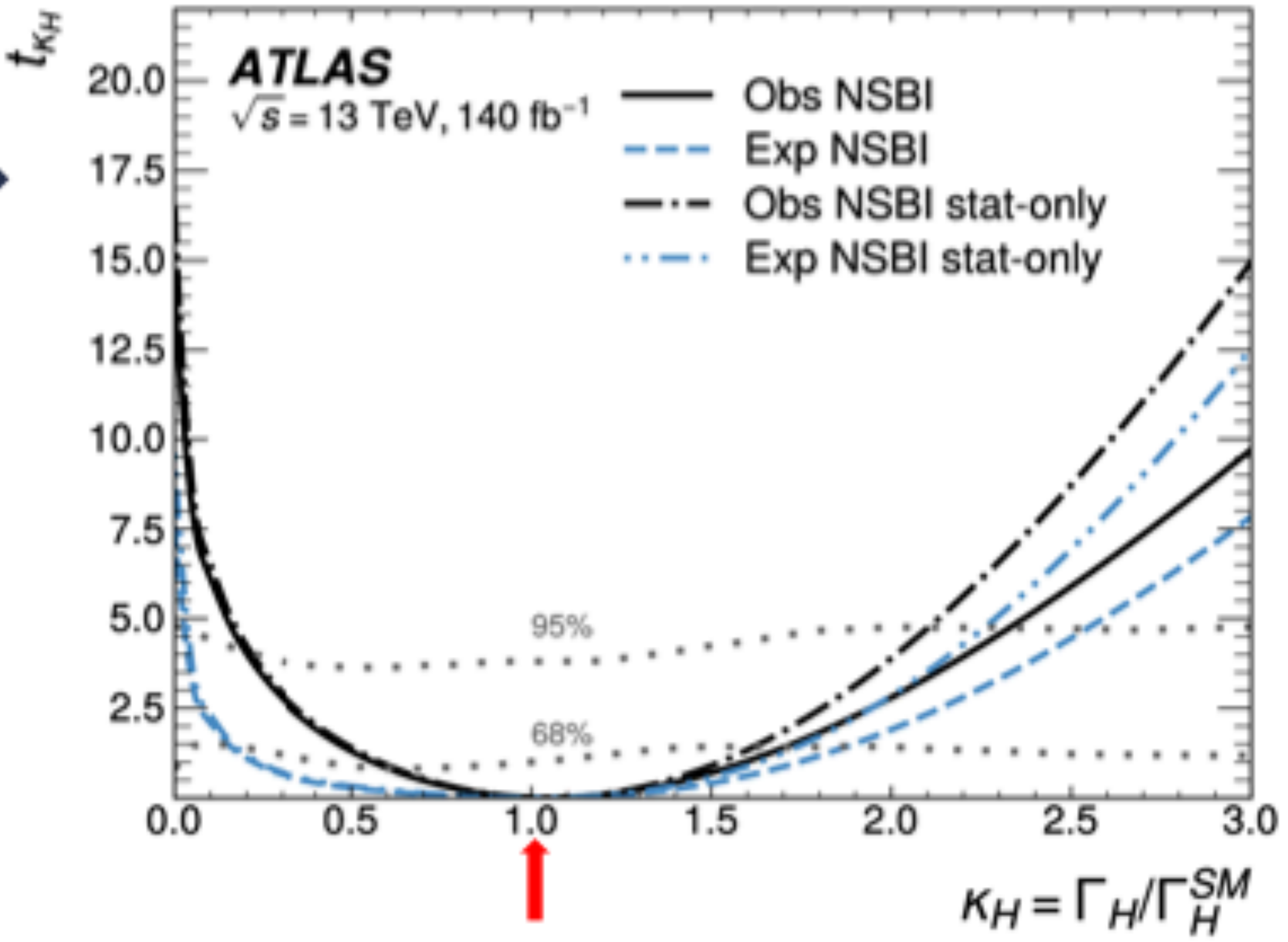
Best-fit: $\mu_{\text{off-shell}} = 1.06^{+0.62}_{-0.45}$
(expected $1.00^{+0.83}_{-0.83}$)

Significance: $3.7\sigma$ (expected $2.4\sigma$)

⇒ Clear evidence for off-shell Higgs production.

Likelihood scan for $\kappa_H$:

Take the ratio with $\mu_{\text{on-shell}}$
(*Eur. Phys. J. C* **80** (2020) 957)



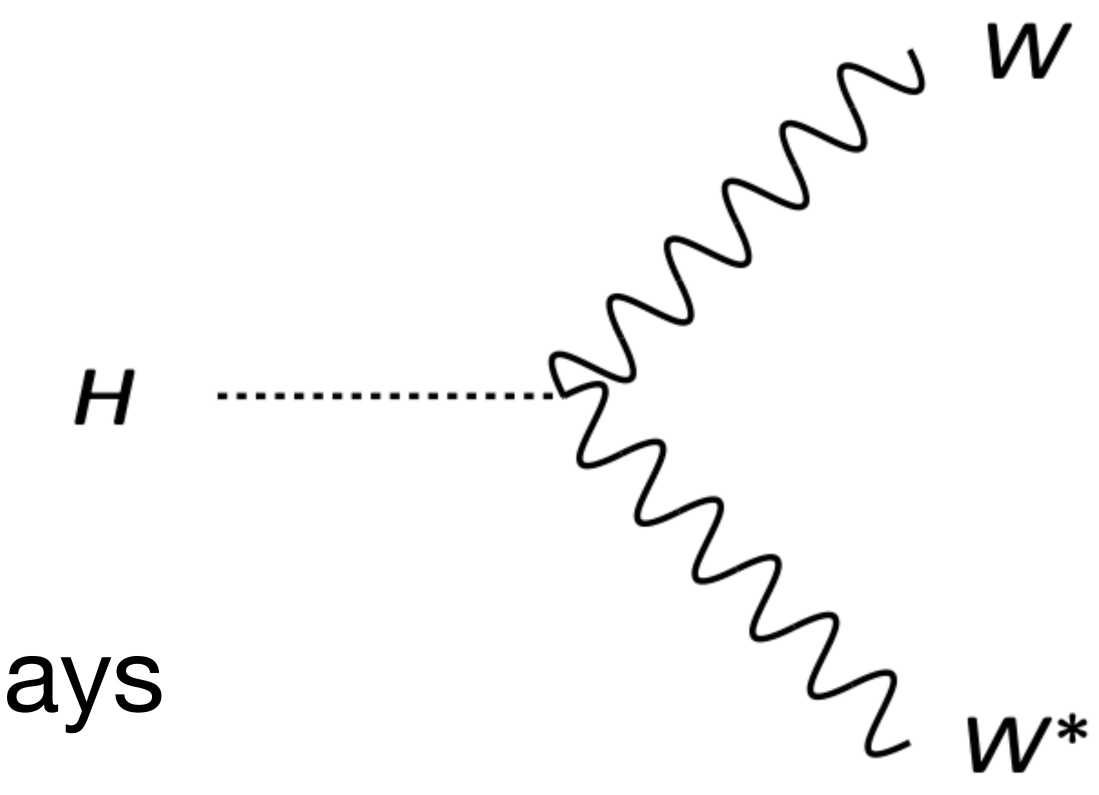
Best-fit: $\Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV
(expected $4.1^{+3.5}_{-3.4}$)

Slide from Elise Le Boulicaut Ennis

# $H \to WW^*$

# $H \to WW^*$

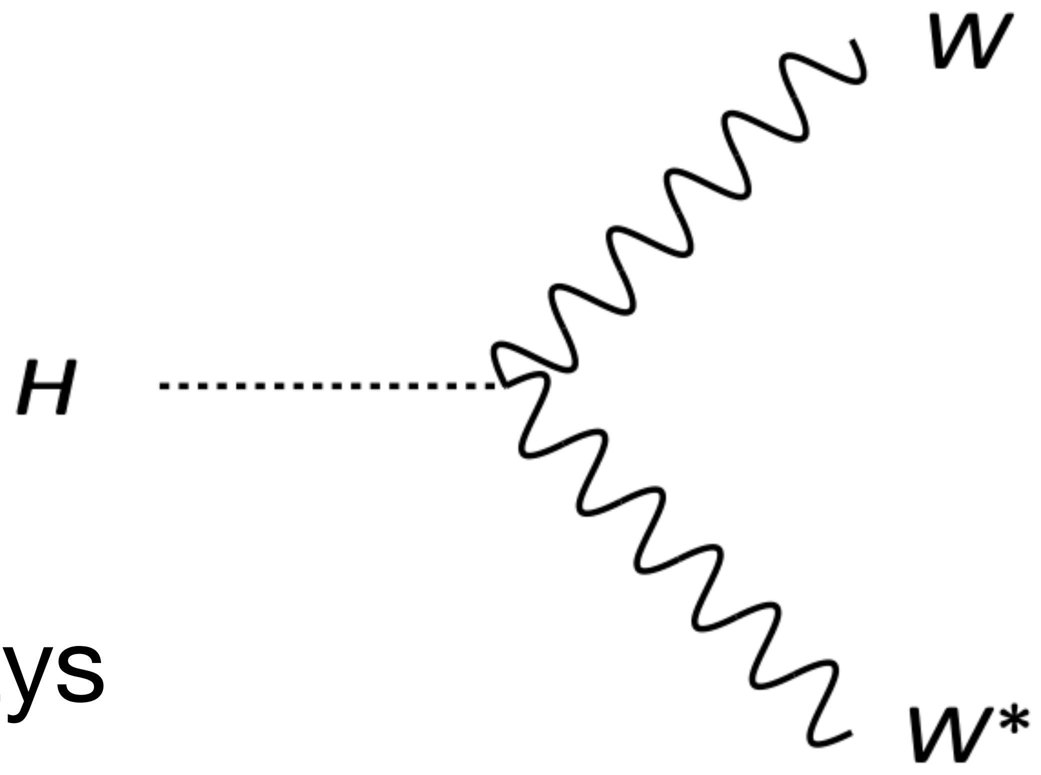
- Tree level decay, directly sensitive to $HWW$ coupling
- Second highest branching fraction for $m_H = 125$ GeV at $B(H \to WW^*) \approx 21\,\%$
- Feasibility of experimental study driven by characteristics of W boson decays

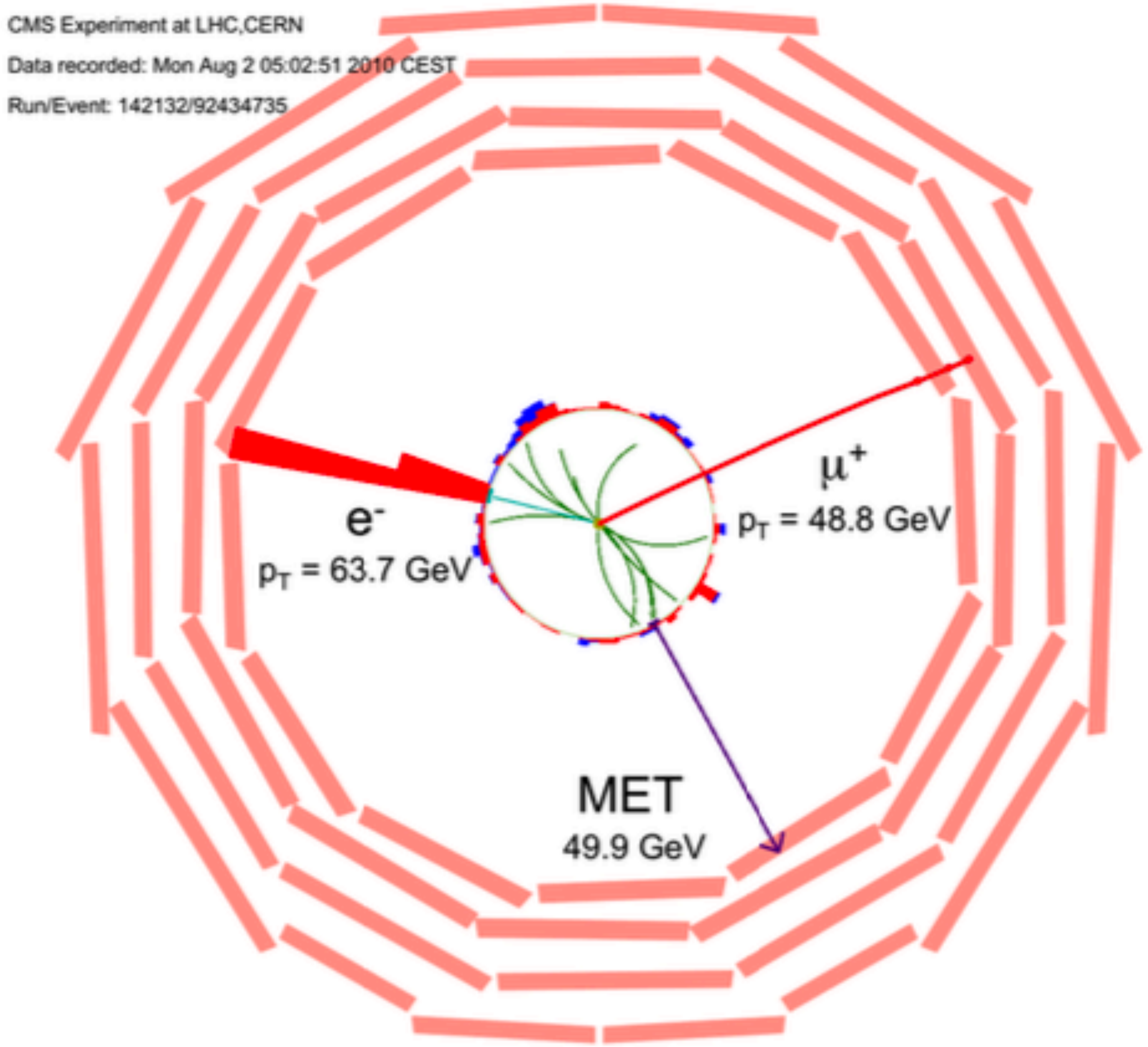


Which decay channels for $W$ bosons?

# $H \rightarrow WW^*$

- Tree level decay, directly sensitive to $HWW$ coupling
- Second highest branching fraction for $m_H = 125$ GeV at $B(H \rightarrow WW^*) \approx 21\,\%$
- Feasibility of experimental study driven by characteristics of W boson decays





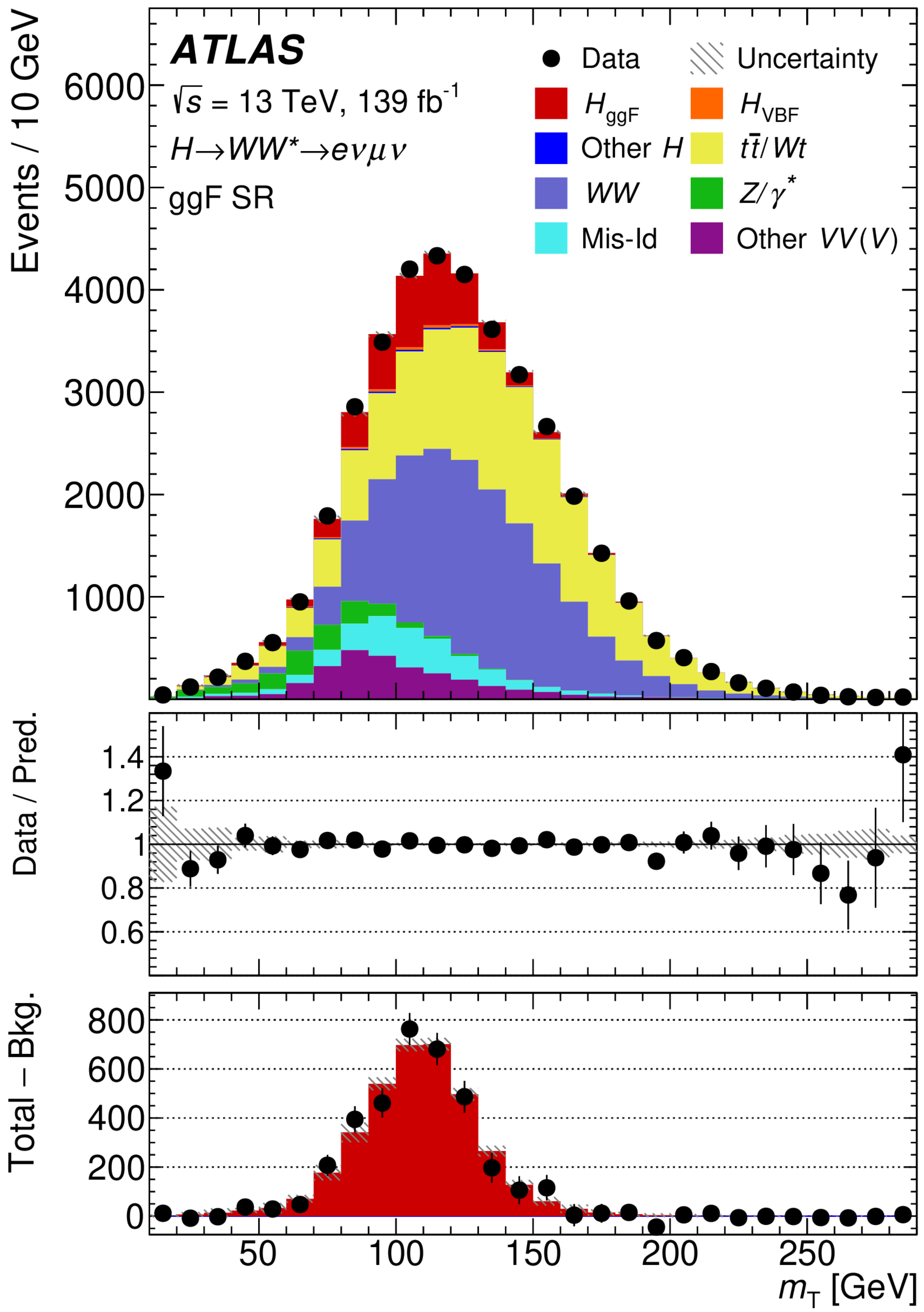
Which decay channels for $W$ bosons?

- Most effective channel considers $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays only
- **Why?** To avoid large backgrounds from $Z \rightarrow e^+e^-, Z \rightarrow \mu^+\mu^-$

Other backgrounds?

# $H \to WW^*$

Phys. Rev. D 108 (2023) 032005

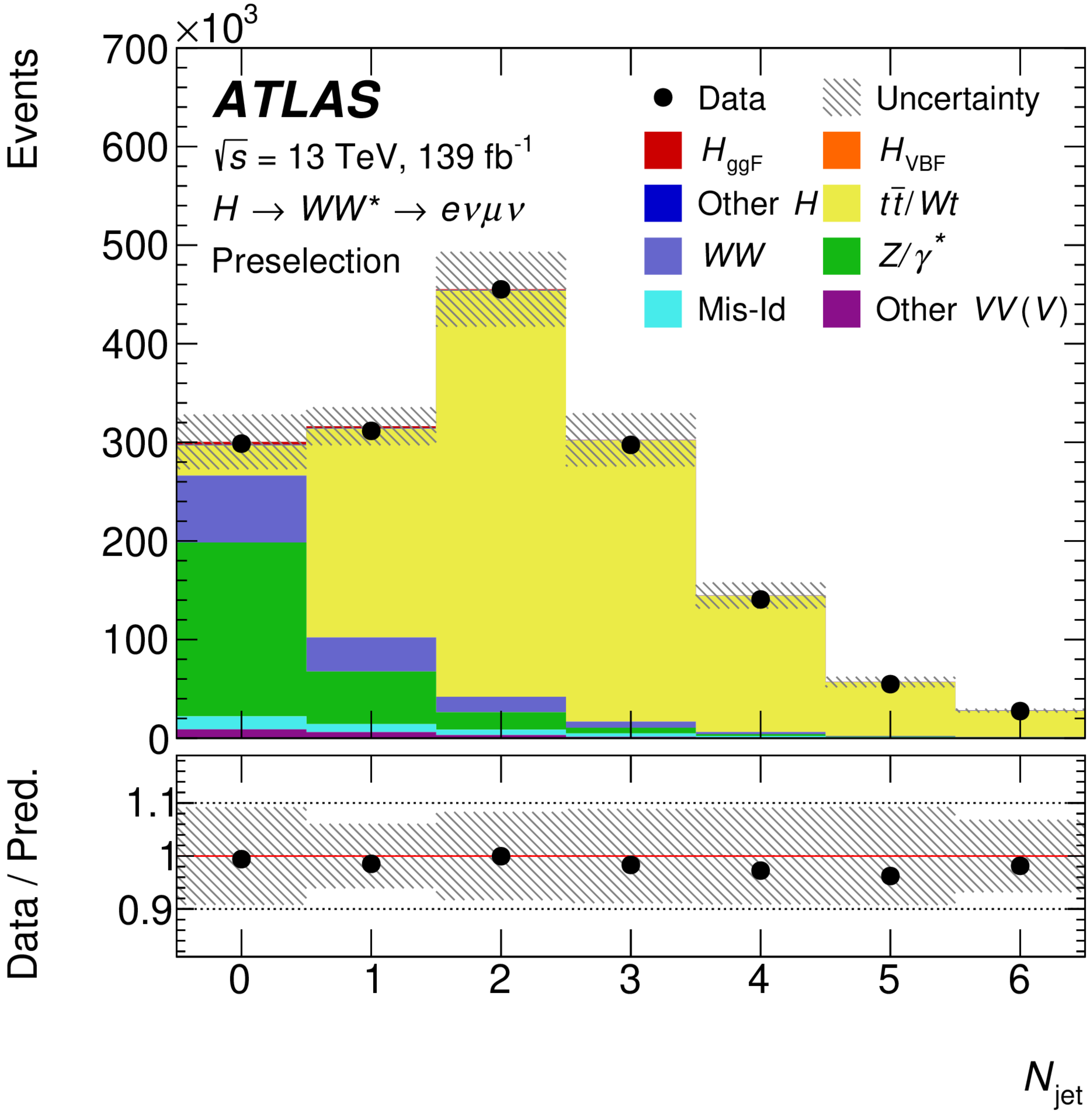


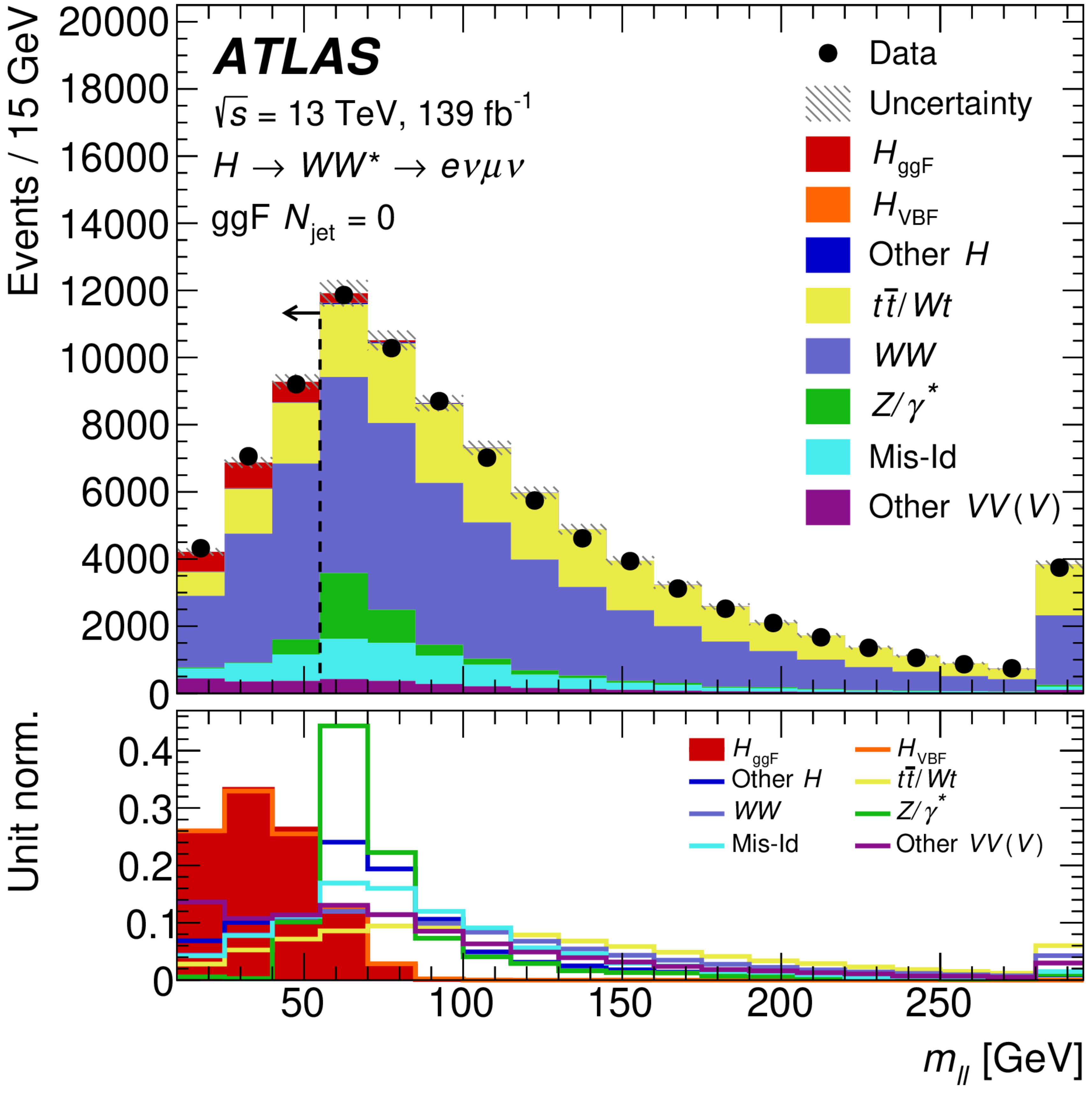
- Target opposite sign $e\mu$ final state, dominant backgrounds $WW$ (≤ 1 jet) and $t\bar{t}$ production (≥ 2 jets)
- Transverse component of di-neutrino system reconstructed as $E_T^{miss}$
- Consider transverse mass ($m_T$) of the $e\mu$ system as signal to background discriminant

← Clear $H \to WW^*$ signal in transverse $e\mu$ mass distribution

# $H \to WW^*$

Phys. Rev. D 108 (2023) 032005

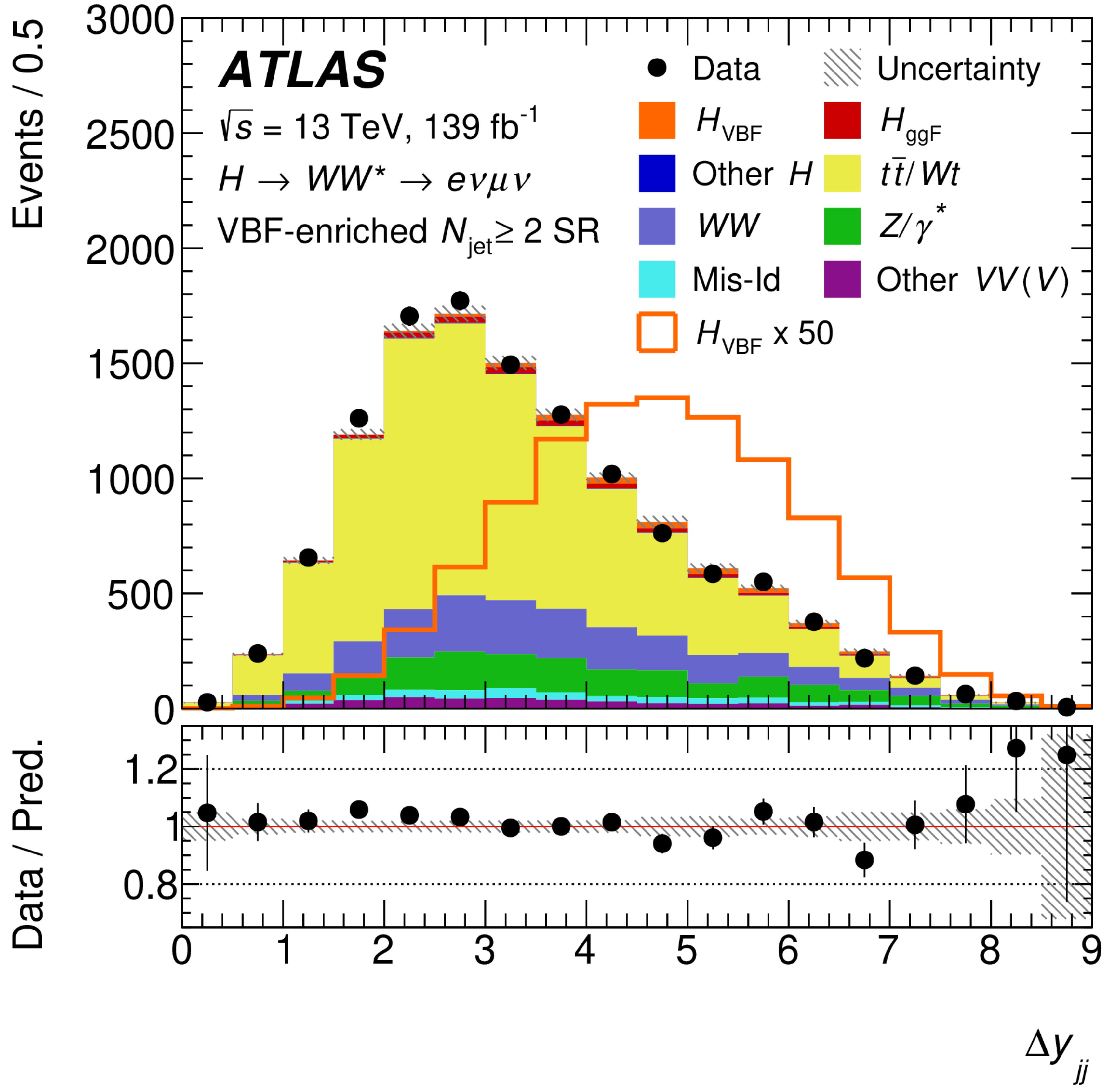


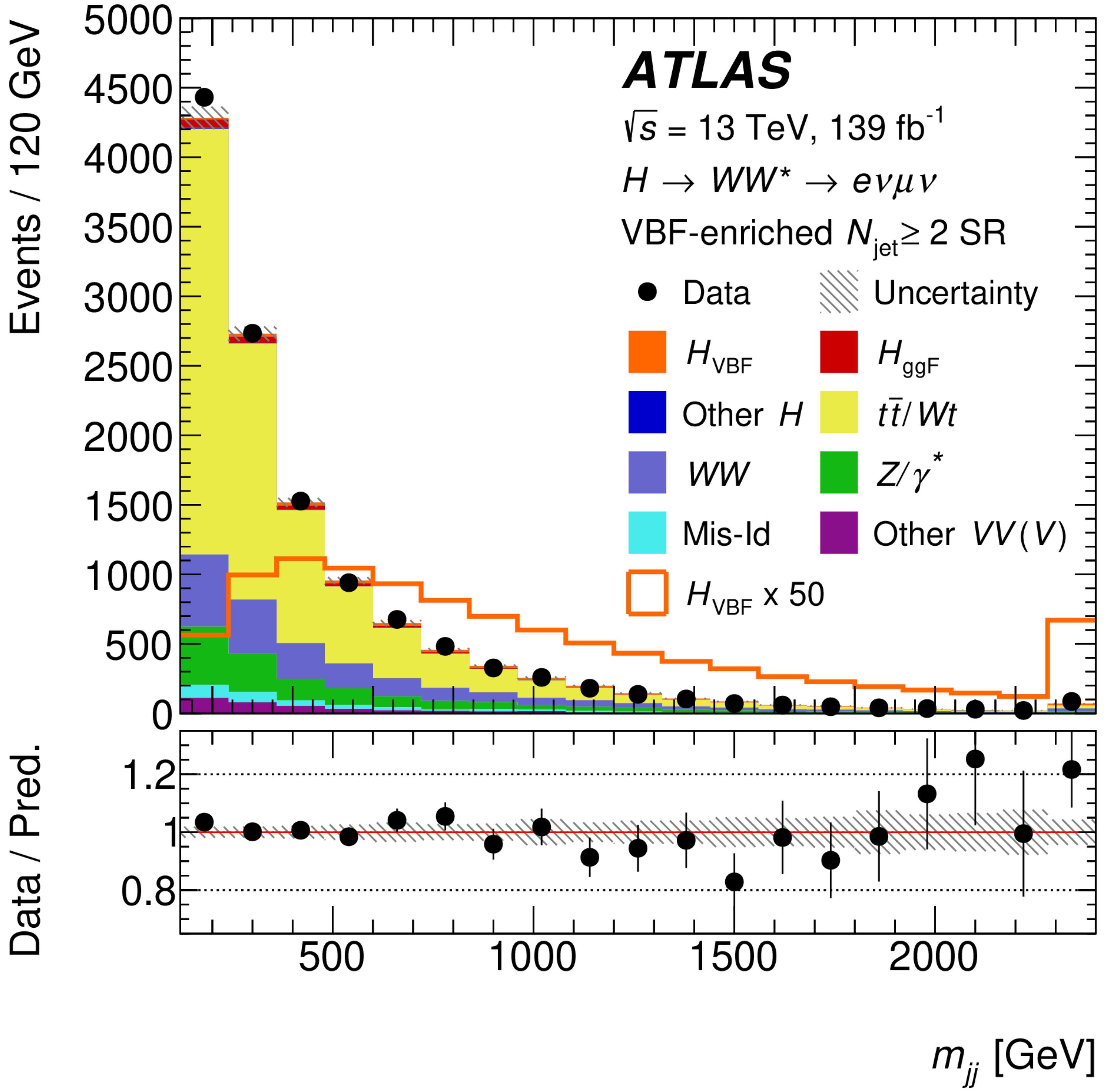


- Categories based on jet multiplicity used to separate $ggH$ and VBF production
- $ggH$-like categories further purified using leptonic variables

# $H \rightarrow WW^*$

Phys. Rev. D 108 (2023) 032005



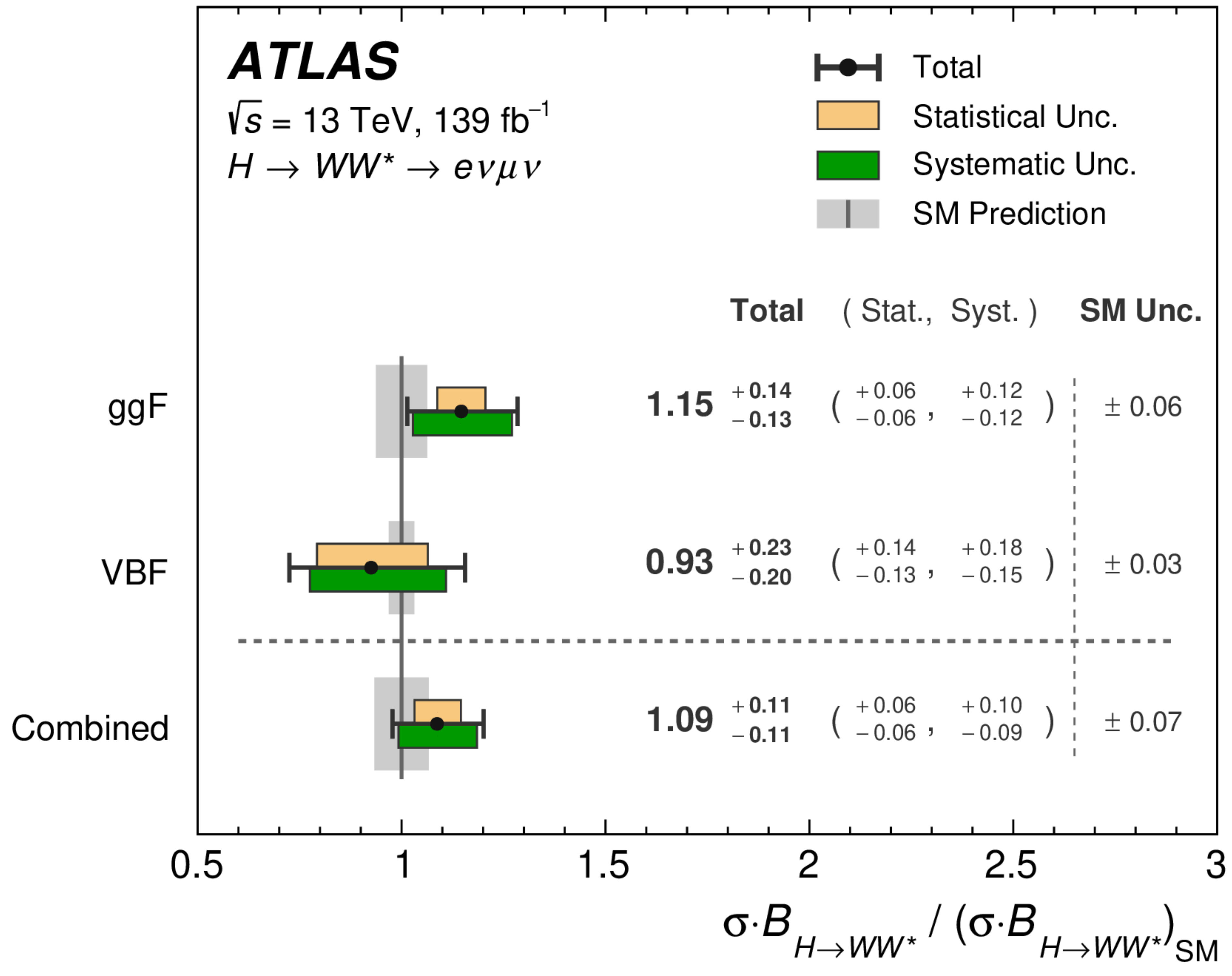


- DNN trained on kinematic variables ($m_{jj}$ , $\Delta y_{jj}$ etc.) used further purify VBF category

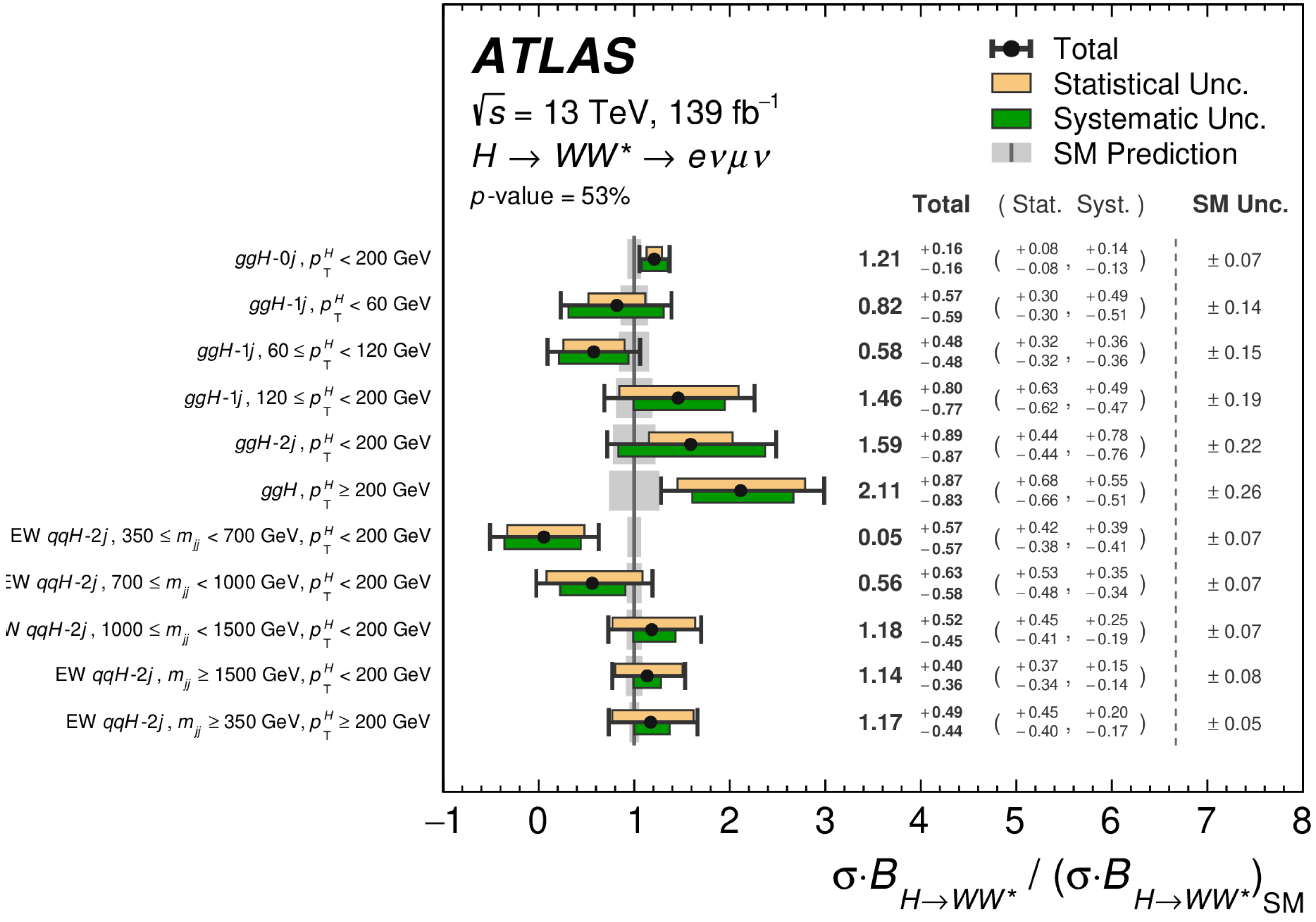
# $H \to WW^*$

Phys. Rev. D 108 (2023) 032005

Cross section for the $ggH$ and VBF processes and their combination, normalised to the corresponding SM prediction

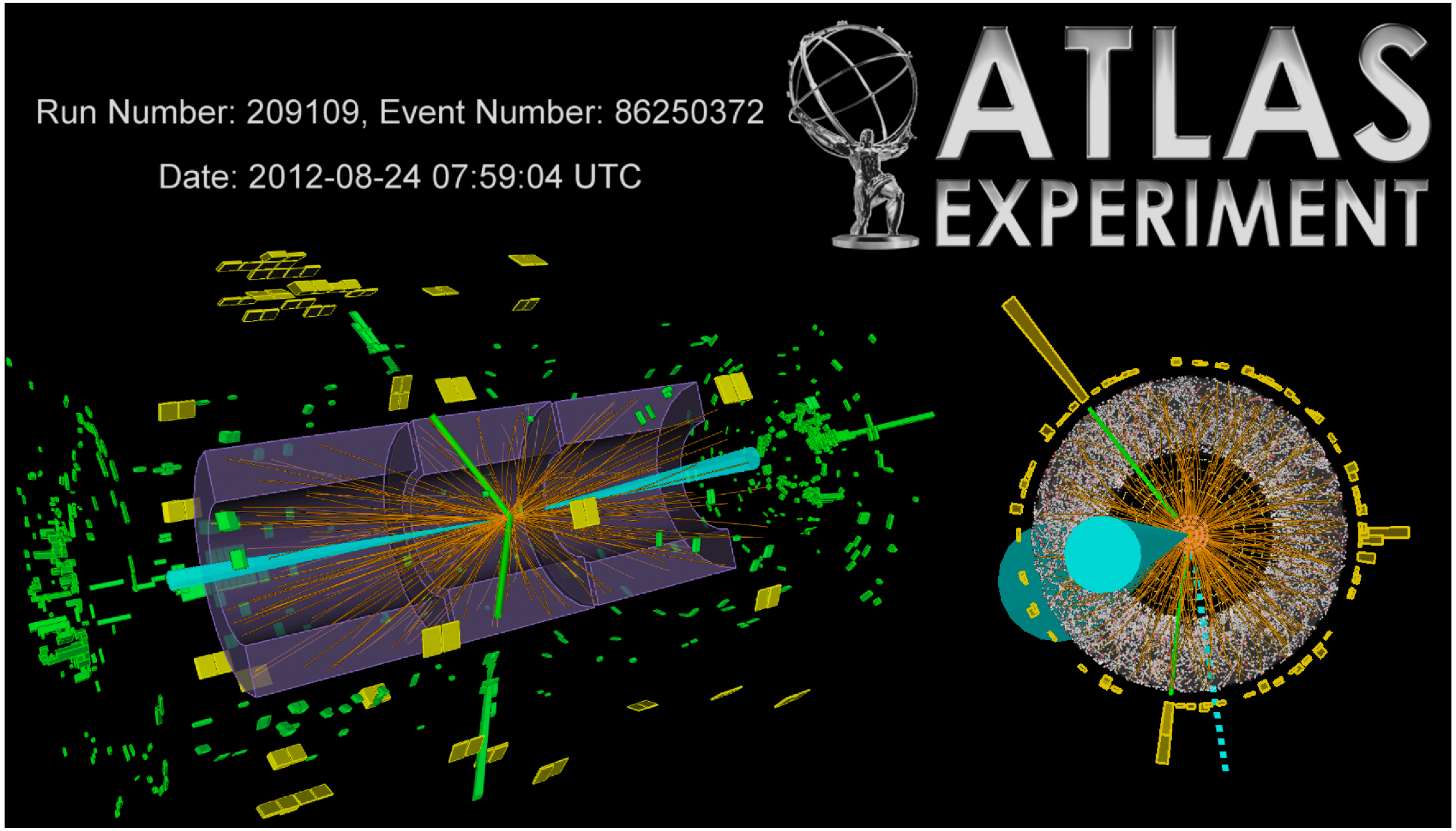


## STXS region measurements

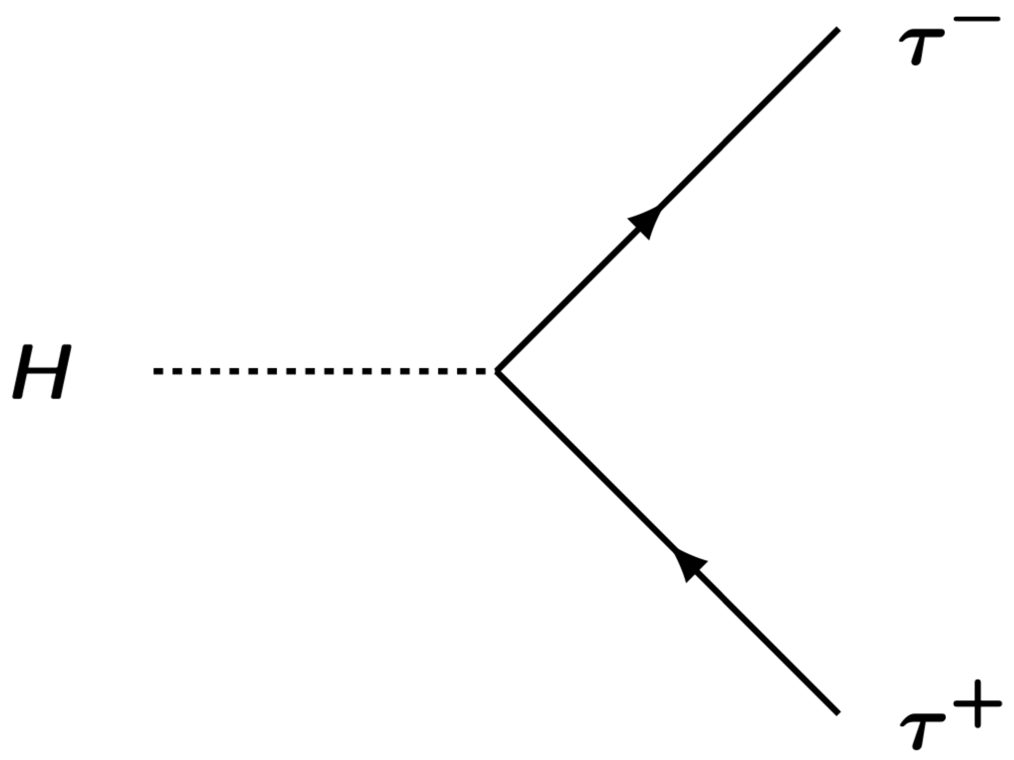


# Higgs -> $\tau\tau$

# $H \rightarrow \tau\tau$ decays



Candidate VBF H → ττ event in 8 TeV data

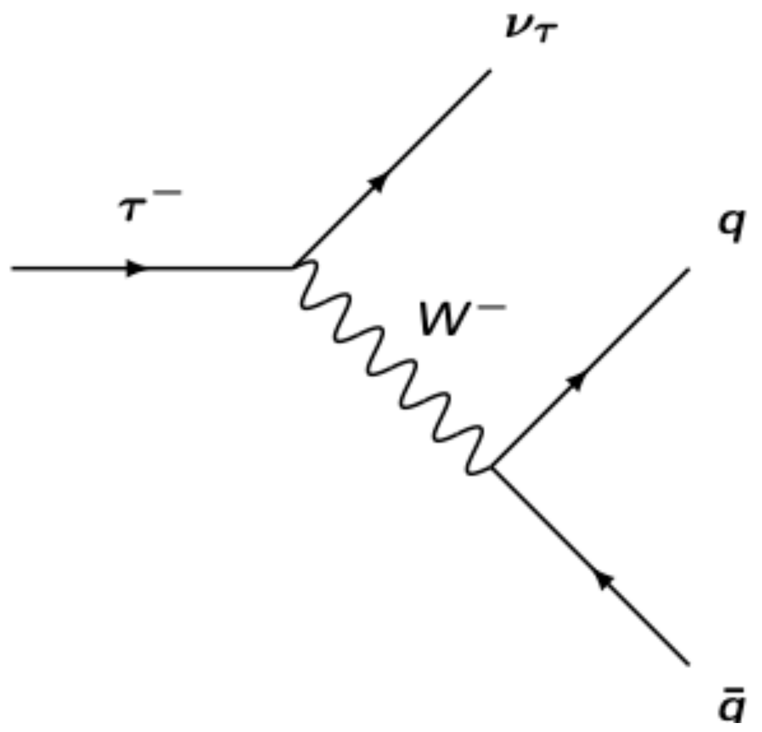


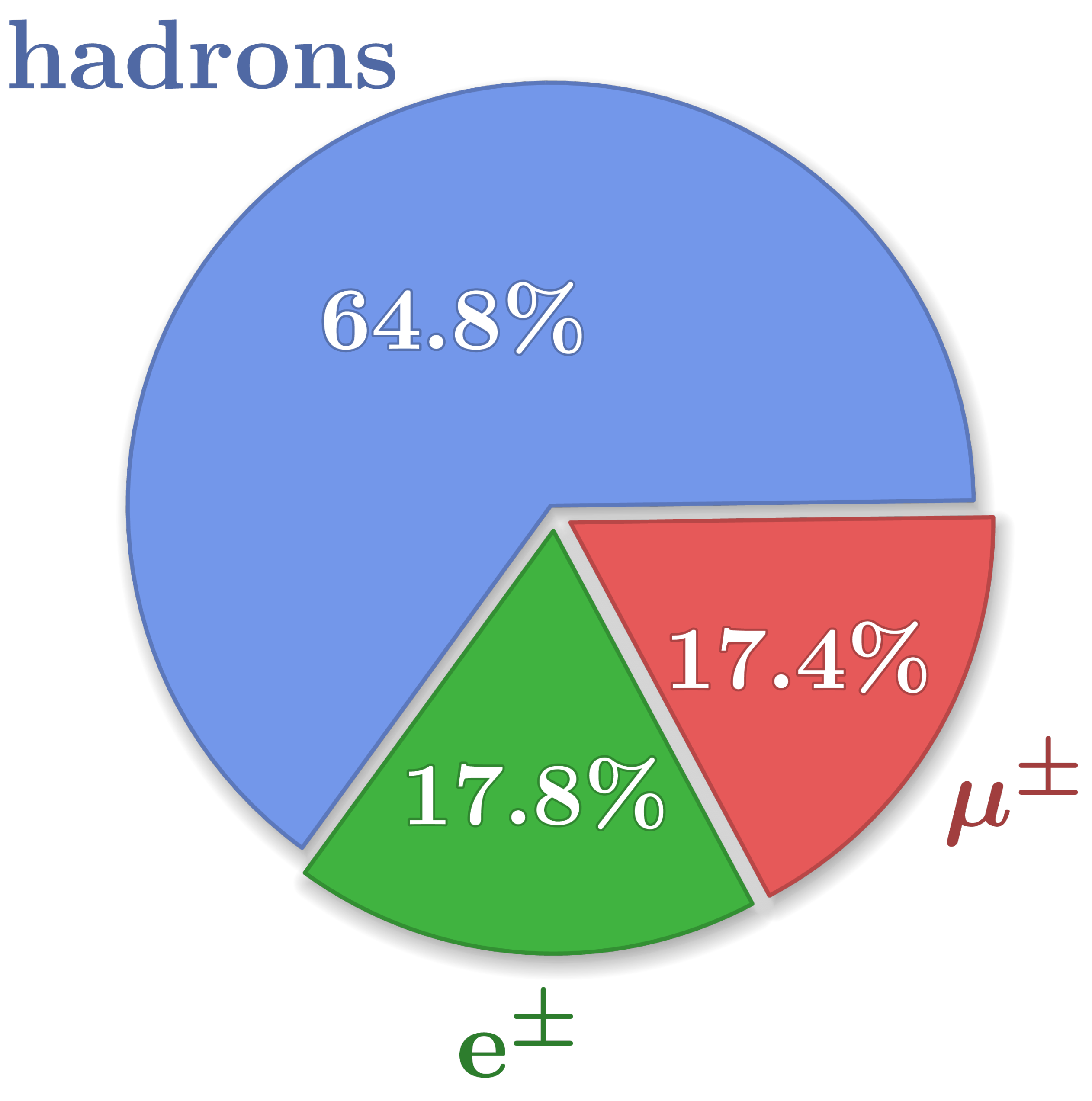
- Tree level decay, directly sensitive to $H\tau\tau$ Yukawa coupling
- Largest leptonic branching fraction for $m_H$ =125GeV at $B(H \rightarrow \tau\tau) \approx 6\,\%$
- Most experimentally accessible channel to study Higgs boson coupling to leptons

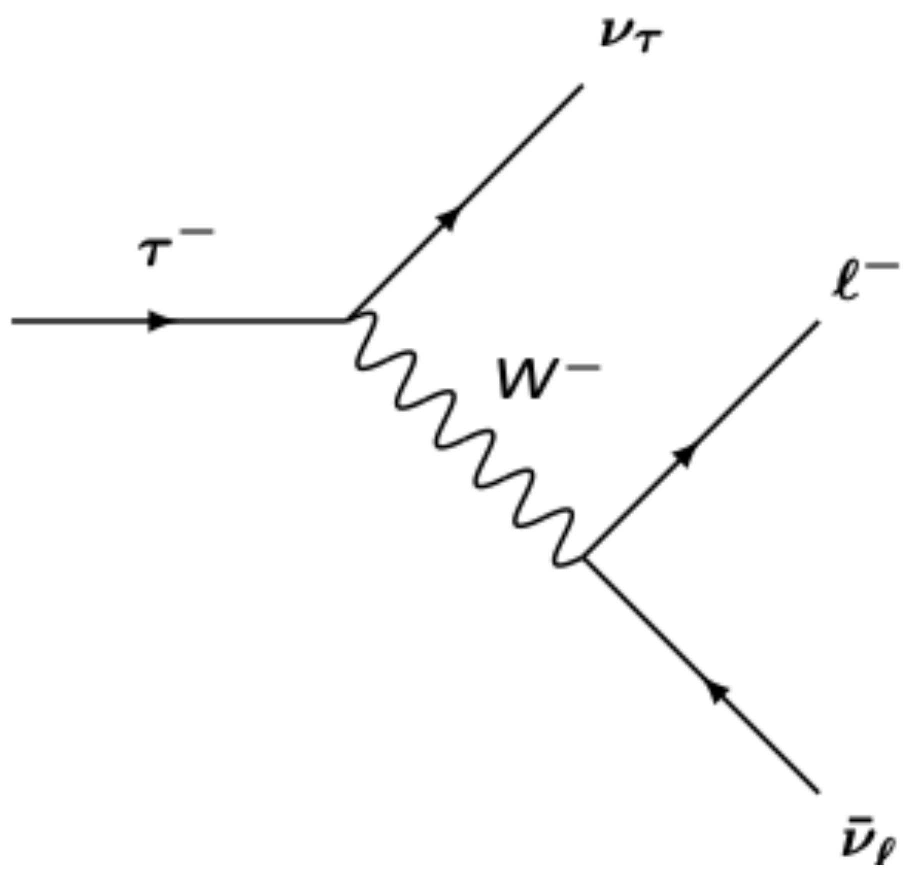
# Small break: $\tau$ decays

Hadronic Decays:

- Neutrino accompanied a system of charged and neutral hadrons, looks like “narrow” hadronic jet
- E.g.
  $B(\tau \to \pi^-\pi^0\nu_\tau) \approx 25\,\%$
  $B(\tau \to \pi^-\nu_\tau) \approx 11\,\%$
  $B(\tau \to \pi^-\pi^+\pi^-\nu_\tau) \approx 9\,\%$
- 1-prong”: exactly one charged particle (inc. e/μ) and any number of neutrals B ≈ 85%
- “3-prong”: exactly three charged particles (hadrons) and any number of neutrals B ≈ 15%







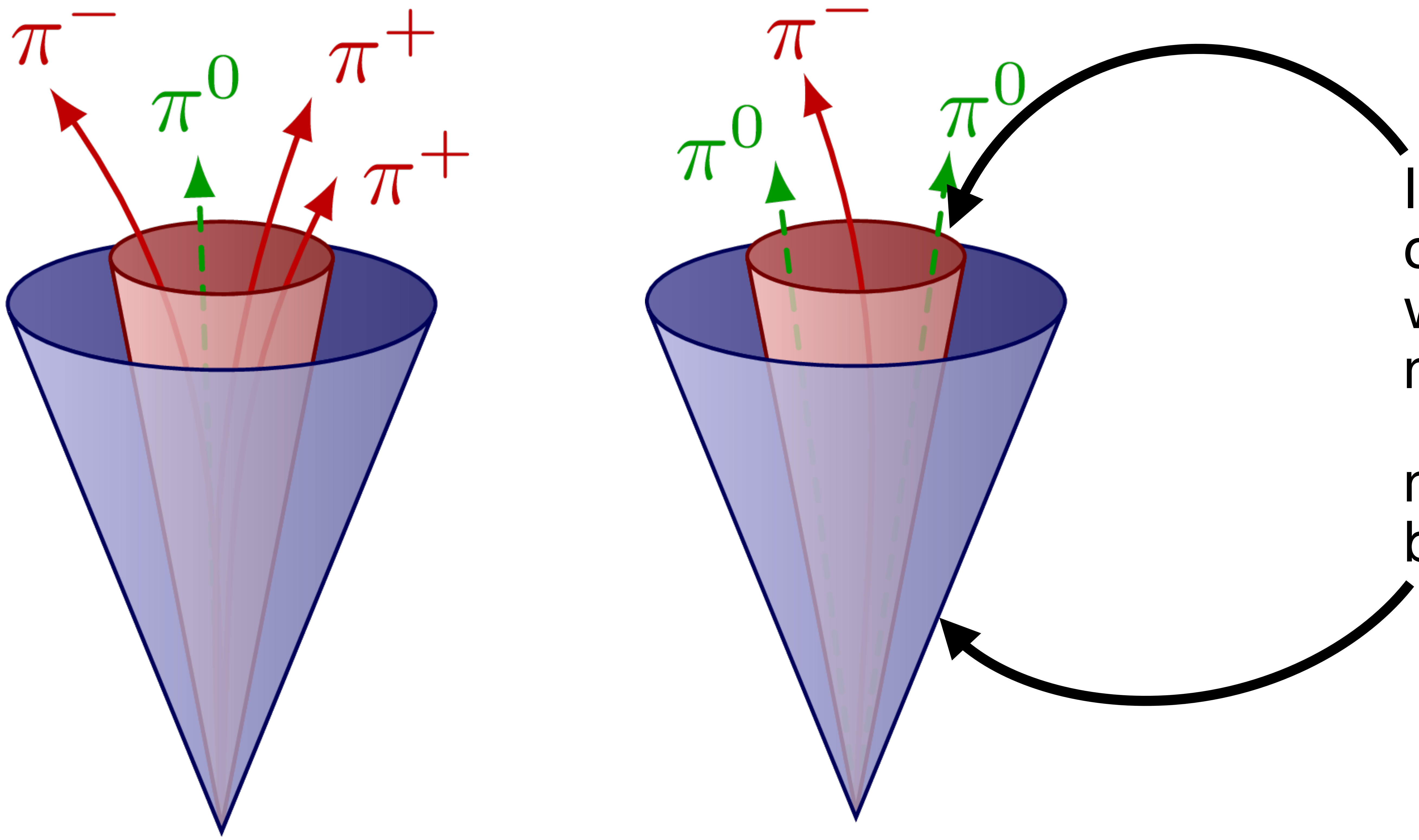
Leptonic Decays:

- Always two neutrinos in the final state, charged leptonis the only “visible” particle
- $B(\tau \to \nu_\tau\bar{\nu}_\ell\ell) \approx 17\,\%\,(\ell = \mu, e)$
- Typically experimentally indistinguishable from isolated e,μ, need more information to identify e.g. Z → τ(lep.)τ(had.)

# Small break: $\tau$ reconstruction

Eur. Phys. J. C 76 (2016) 295

- “1-prong”: exactly one charged particle (inc. e/μ) and any number of neutrals B ≈ 85%
- “3-prong”: exactly three charged particles (hadrons) and any number of neutrals B ≈ 15%

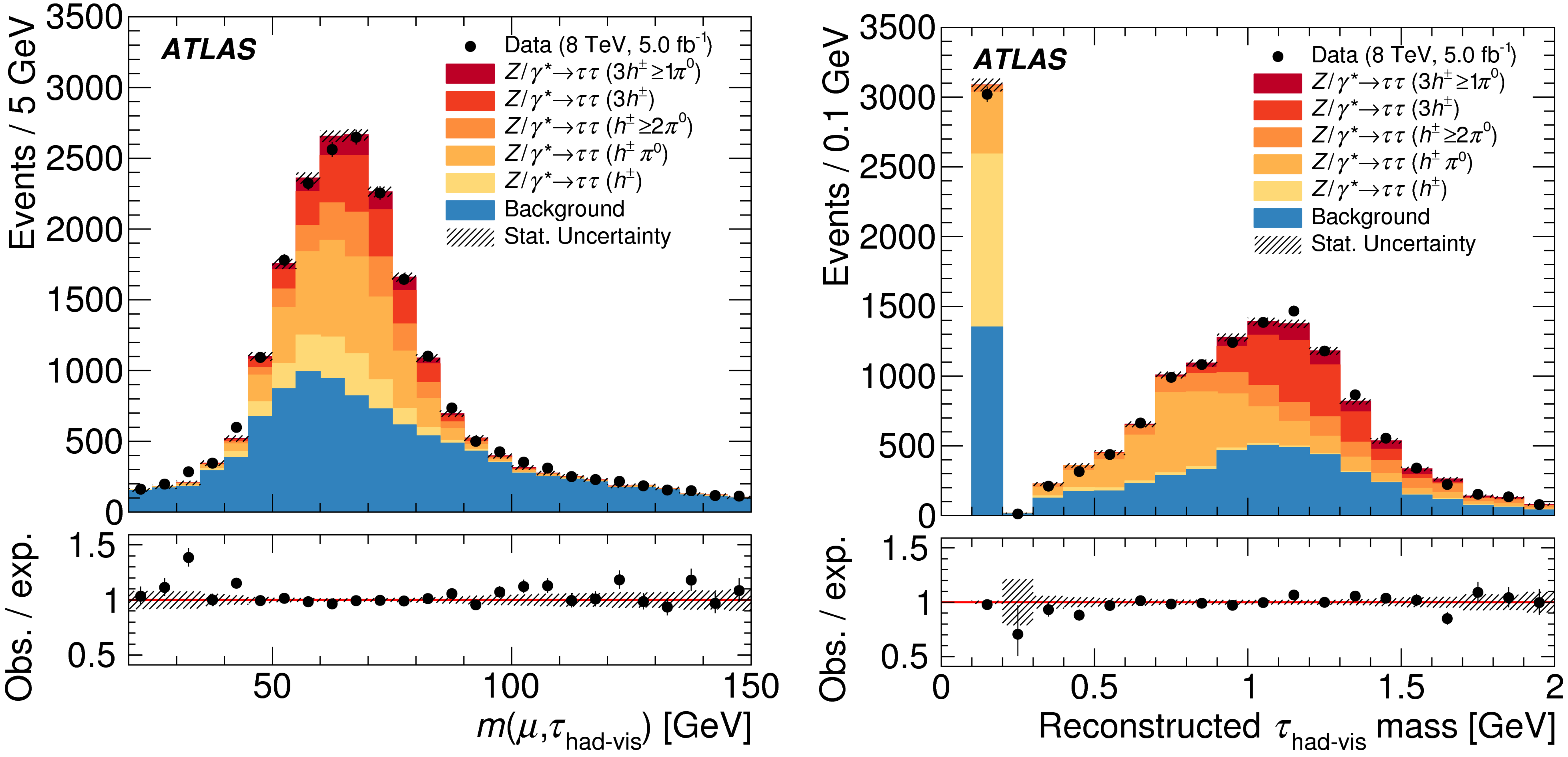


Identify energy deposit in calorimeter, matched to tracks, which is is concentrated within a narrow cone

no further hadronic activity in broader cone

# Small break: $\tau$ reconstruction

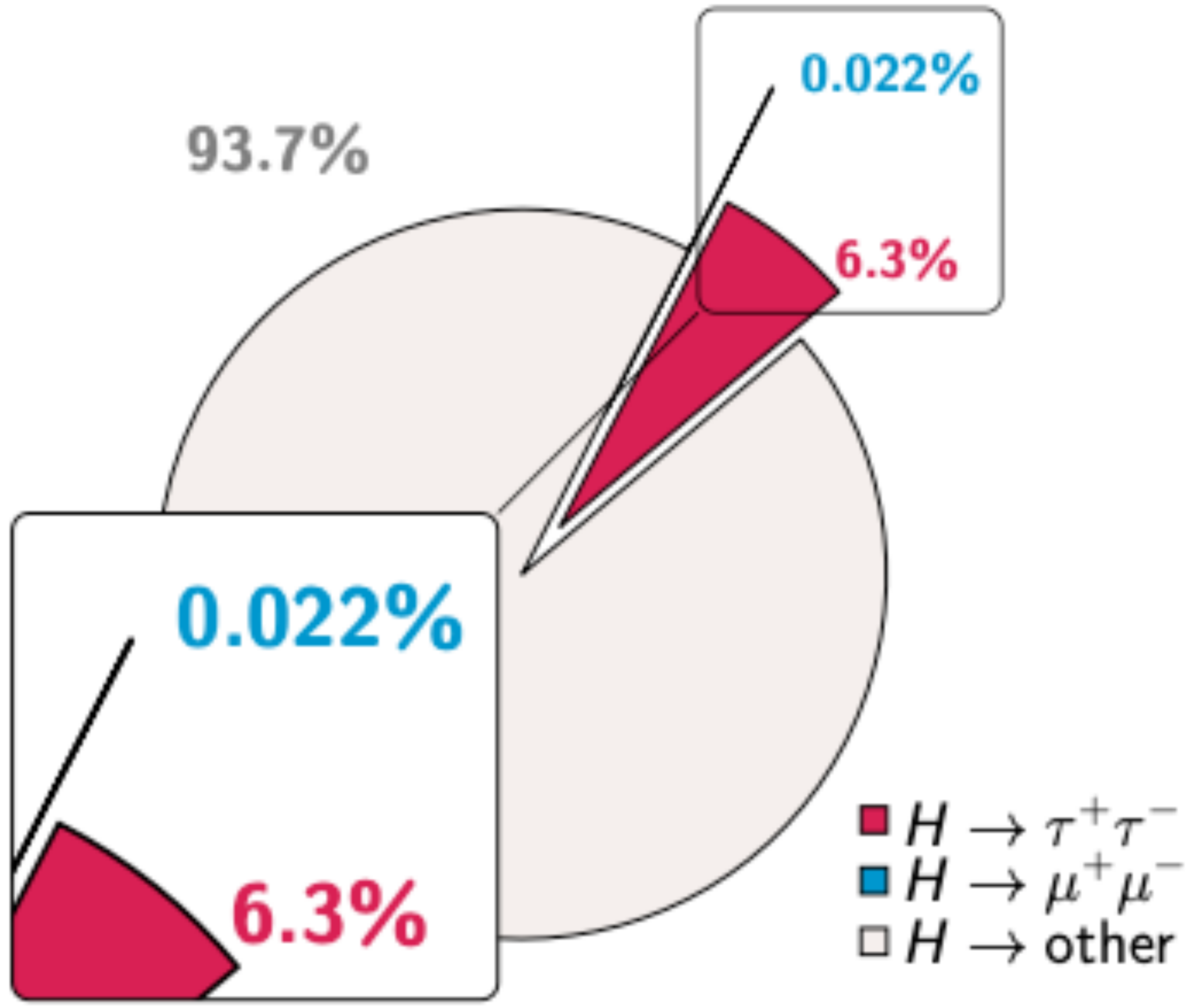
Eur. Phys. J. C 76 (2016) 295



- Reconstruct 4-vector from "visible" decay products,
- $m_{\tau}$, vis $< m_\tau$ due to neutrino
- $Z \to \tau(\mu\nu_\tau)\tau(\nu_\tau$ hadrons$)$ often used as control channel to calibration algorithms

# $H \rightarrow \tau\tau$ production measurement

JHEP 08 (2022) 175



↑ 125 GeV SM Higgs boson branching fractions

High decay rate offers great opportunity to study the Yukawa mechanism in detail

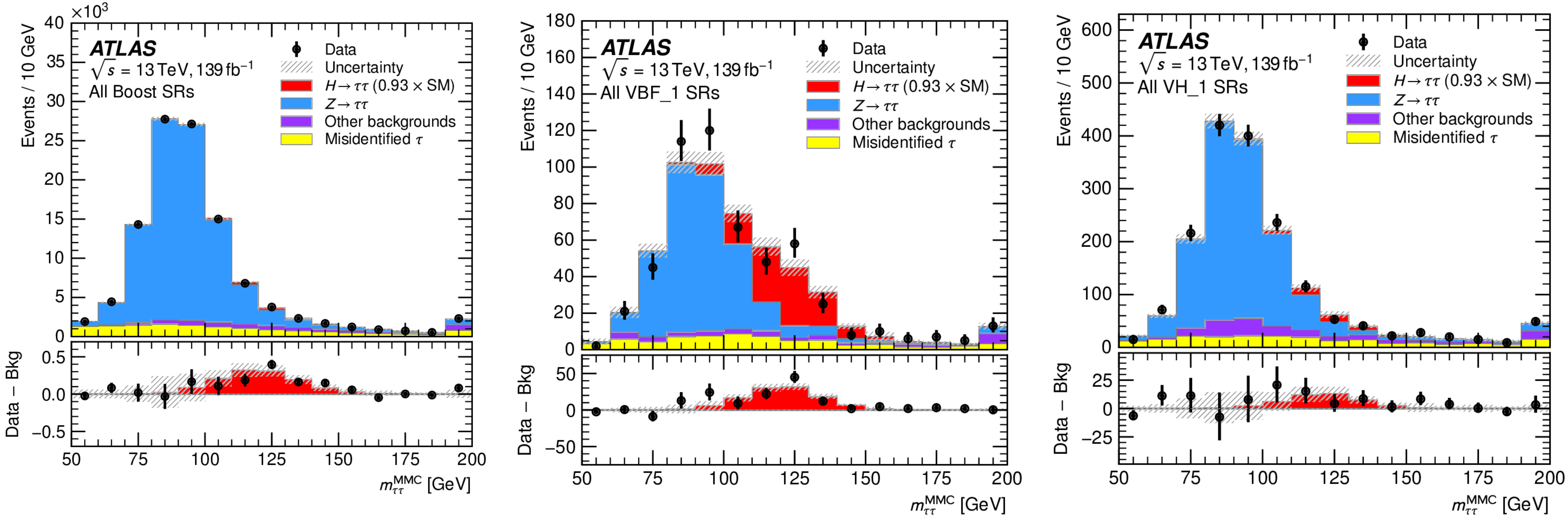
However: Complicated by experimental challenges associated with $\tau$-lepton decay reconstruction

Analysis Strategy

- Three decay channels considered: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{e,\mu}$ and $\tau_e\tau_\mu$
- Mitigate large $Z \rightarrow \tau^+\tau^-$ background with MVA production mode taggers
- Validate $Z \rightarrow \tau^+\tau^-$ modelling with MC using kinematic "embedding" technique
- Use "Missing Mass Calculator" (MMC) algorithm to improve $\tau^+\tau^-$ mass resolution, accounting neutrino energy losses

# $H \rightarrow \tau\tau$ production measurement

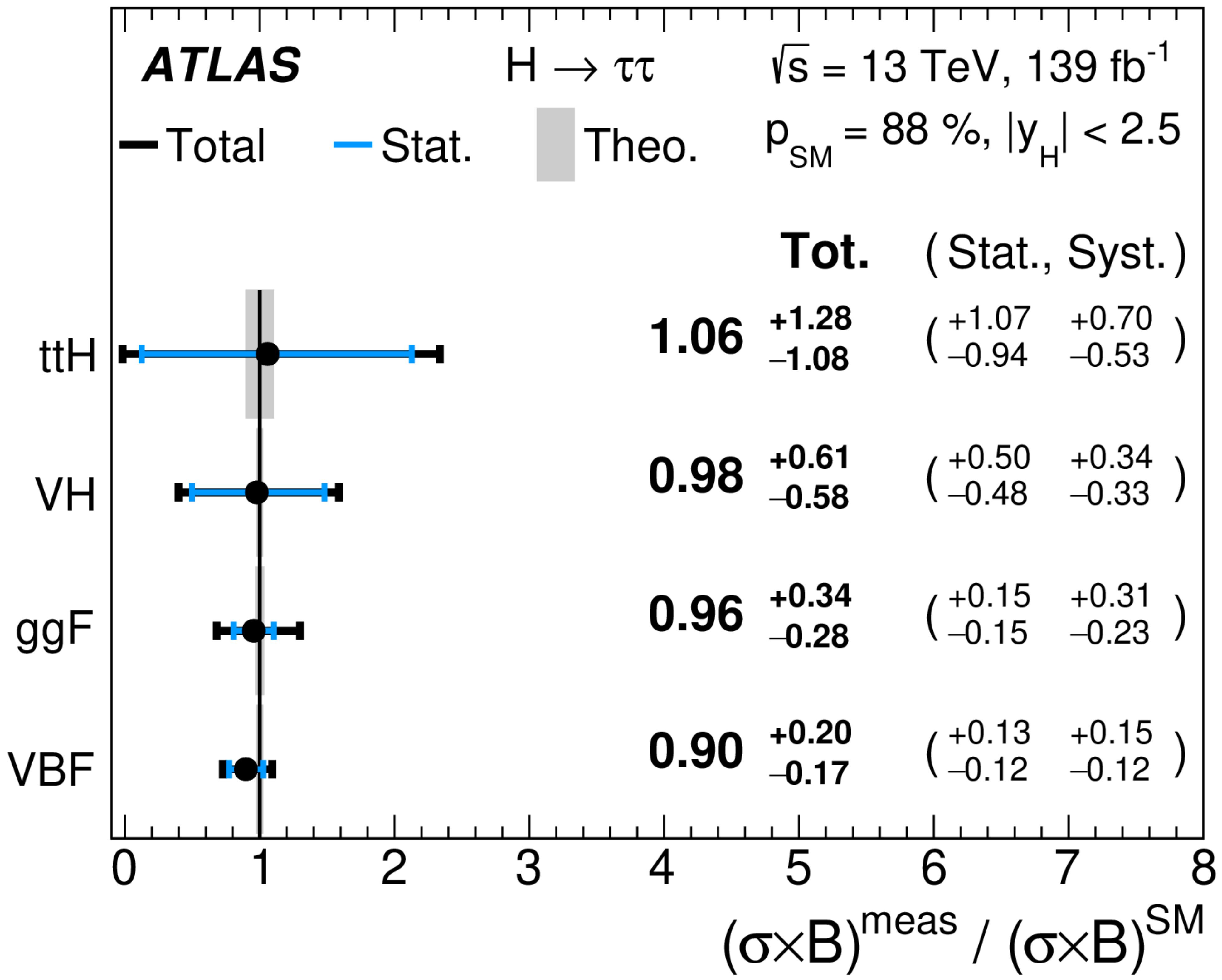
JHEP 08 (2022) 175

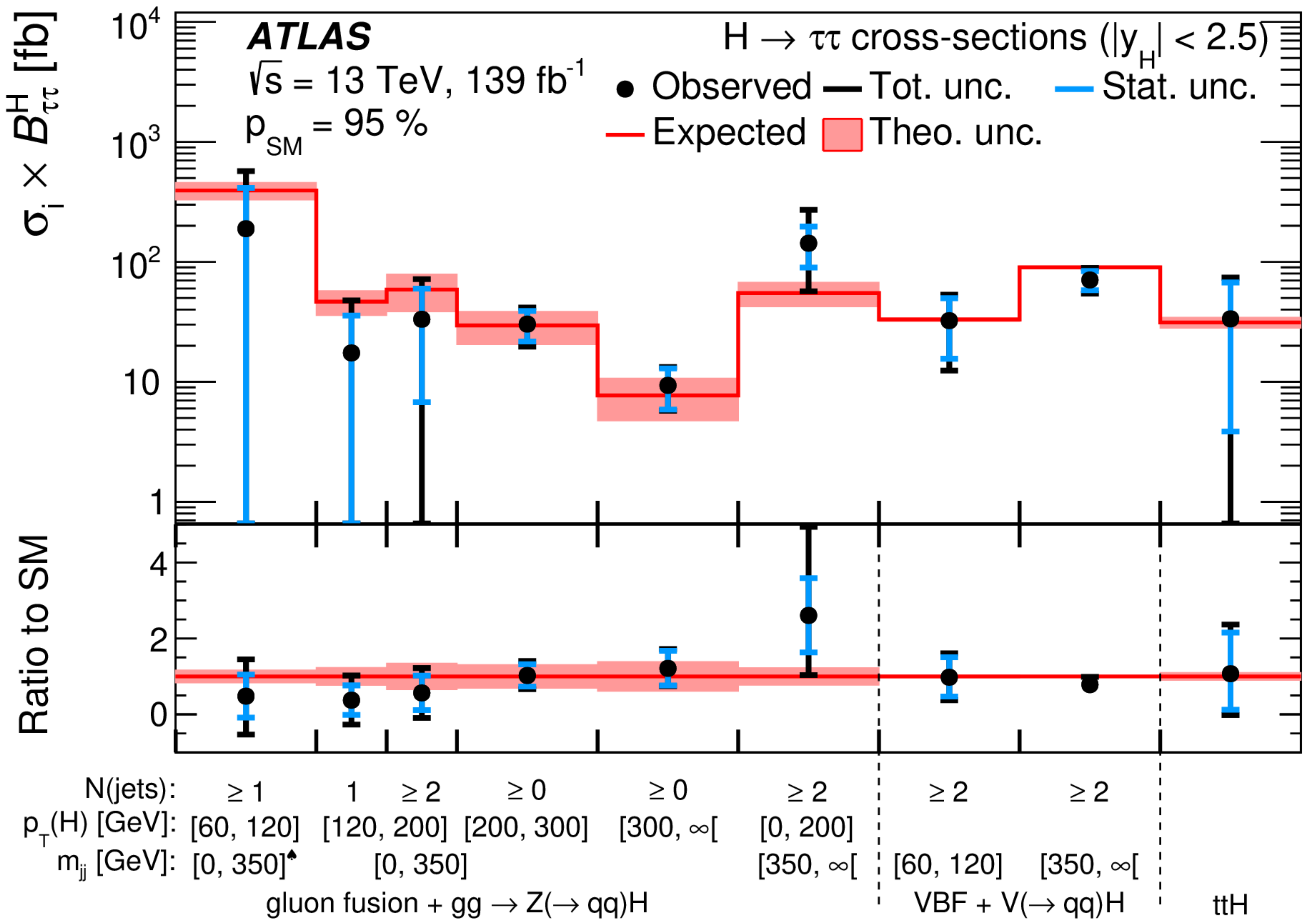


$m_{\tau^+\tau^-}^{\text{MMC}}$ distributions for the sum of boosted (left) and individual purified VBF (centre) and VH (right) categories

# $H \to \tau\tau$ production measurement

JHEP 08 (2022) 175

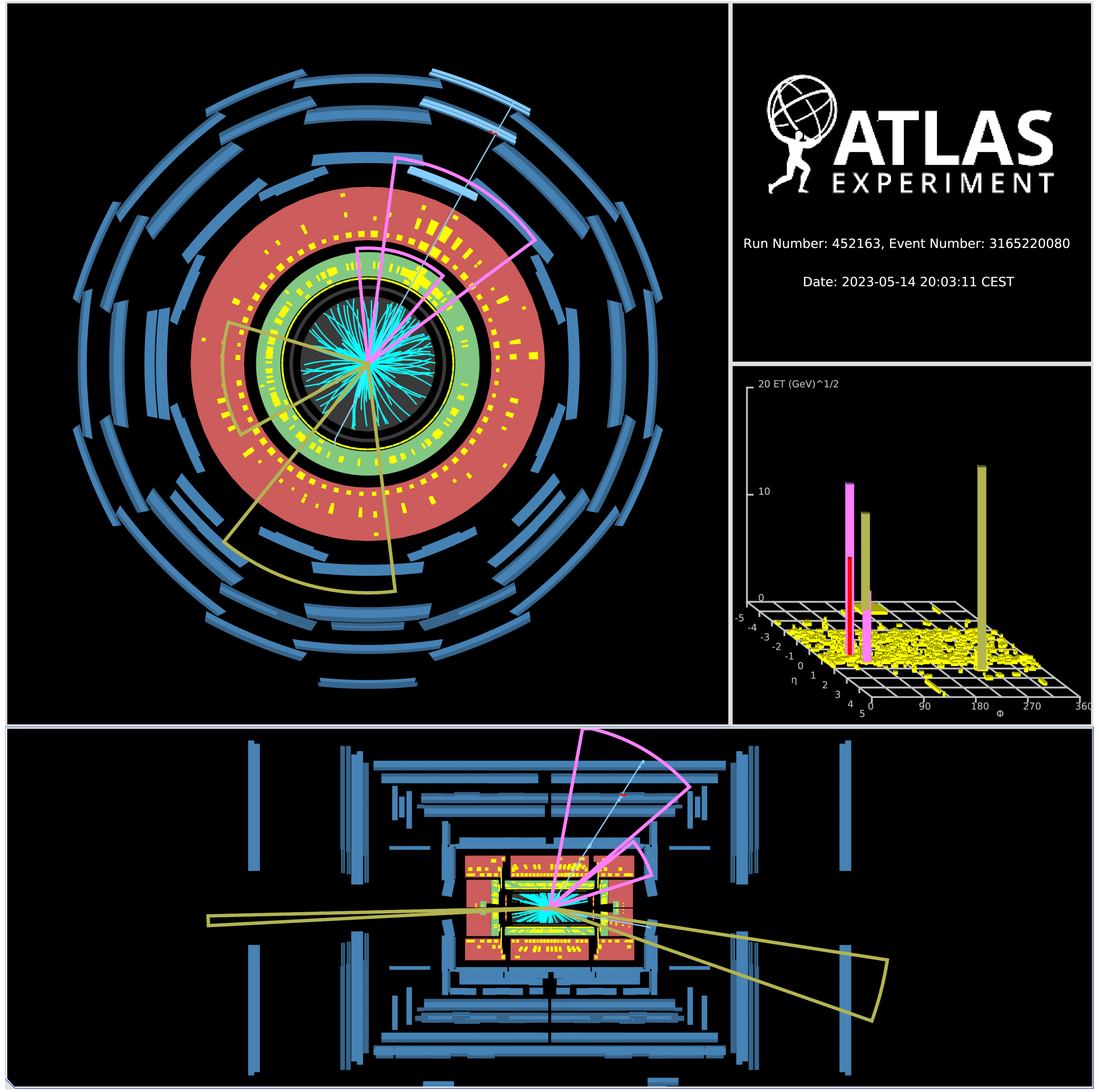




STXS measurements

# Higgs —> bb

# $H \to b\bar{b}$ decay



- Tree level decay, directly sensitive to Hbb Yukawa coupling Highest branching fraction for mH = 125 GeV at B(H → bb) ≈ 58%

- Huge background from multi-jet production at the LHC,

- impossible to observe with an inclusive di-jet analysis

  - **Solution 1:** Consider production channels with additional hard objects, such as (W/Z)H and VBF production, to reduce multi-jet background

  - **Solution 2:** Use b-tagging techniques to identify products of b-quark fragmentation

- A sample event from the Run-3 (13.6 TeV) H →$b\bar{b}$ channel.

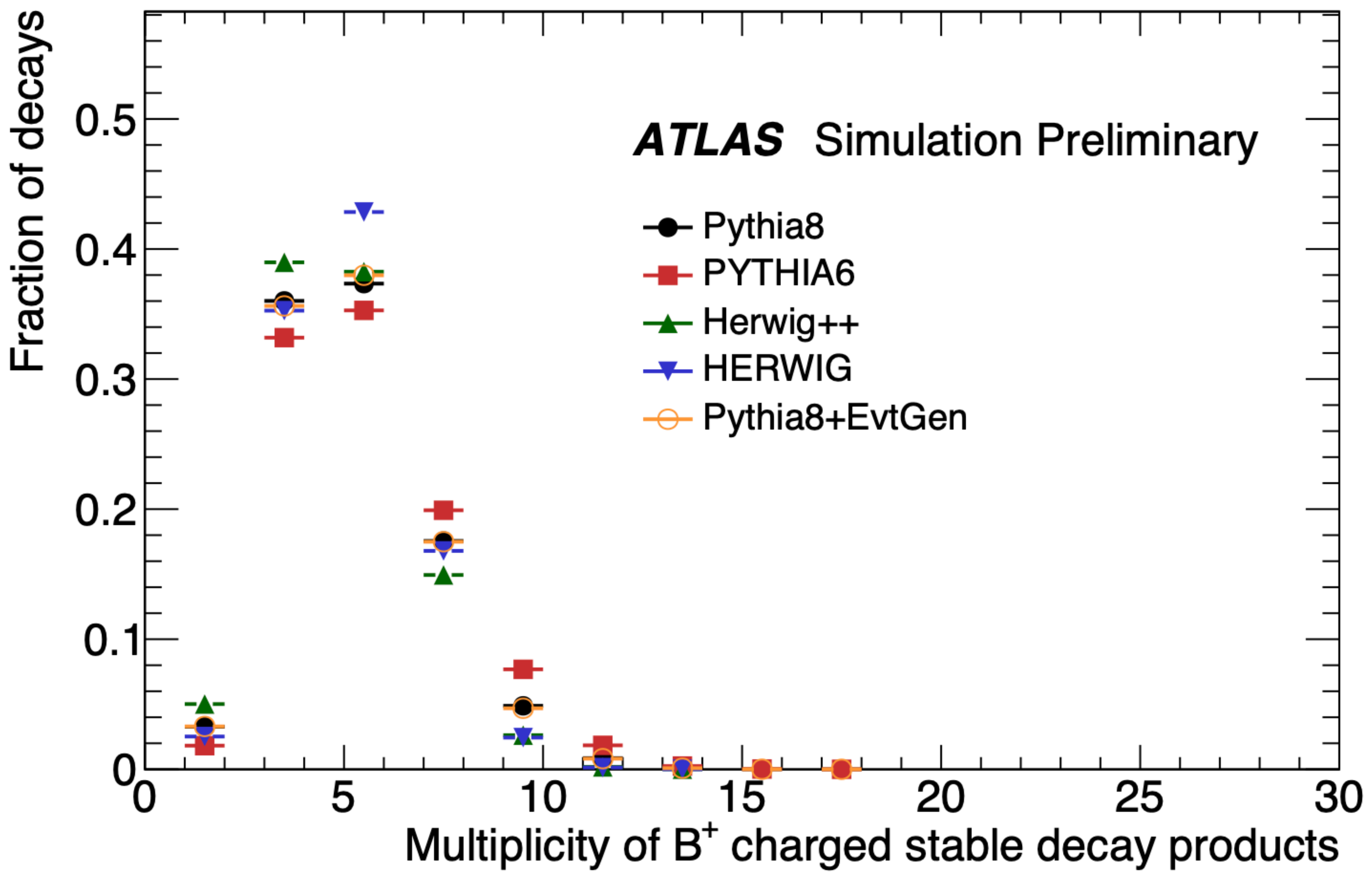
- The two b-tagged Higgs boson candidate jets, b1 and b2, are show in purple.

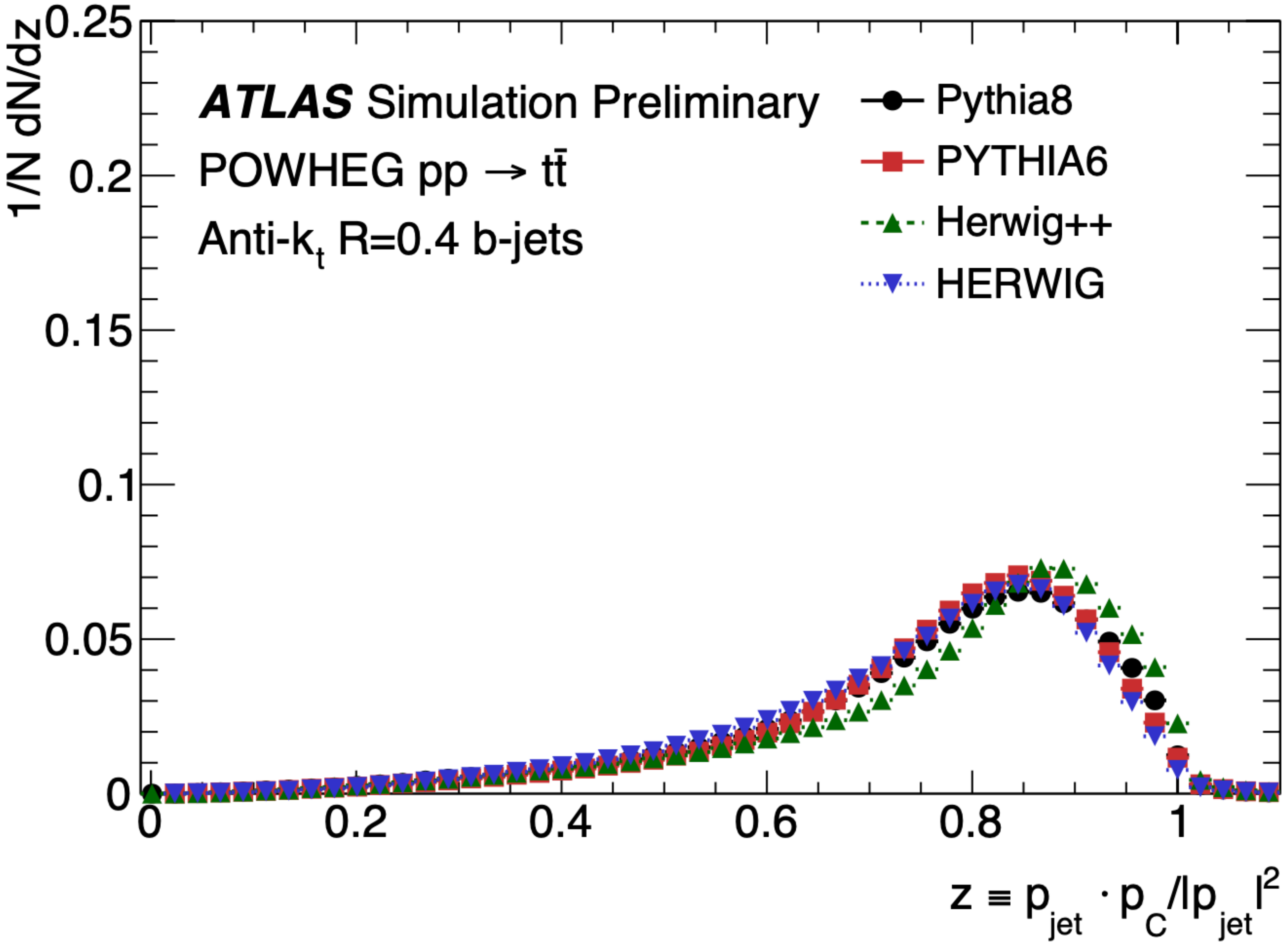
- The two VBF candidate jets, j1 and j2, are shown in yellow.

- The value of $m_{jj}$ for this event is 4.1 TeV and the value of mbb is 125.8 GeV.

# A bit about flavour tagging: properties of b-hadrons

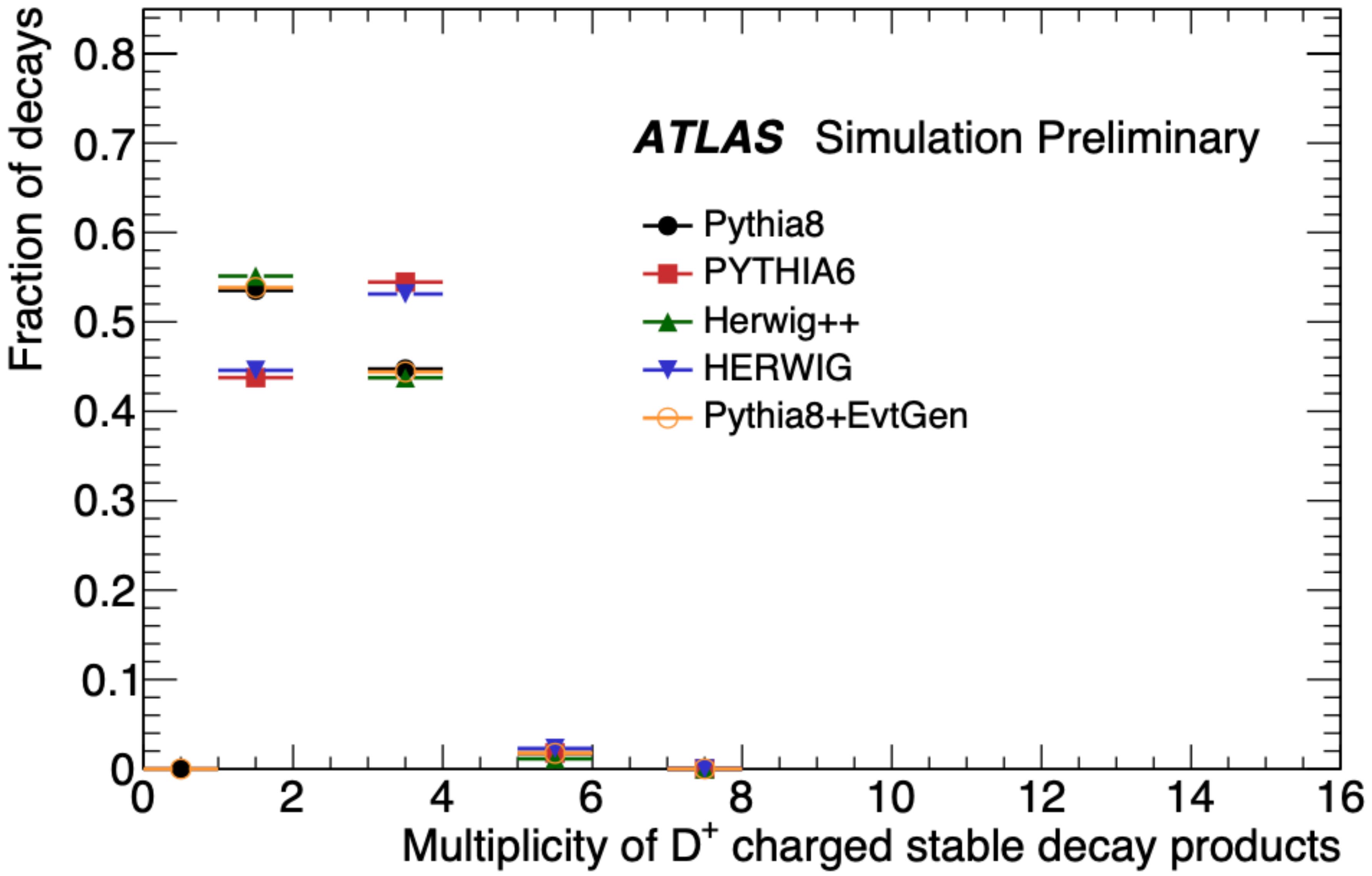
- Lifetime: Long enough to lead to a measurable decay length (around 5mm for a 50 GeV boost)
- Mass: Weakly decaying b-hadrons have masses around 5 GeV, leading to high decay product multiplicities (average of 5 charged particles per decay)
- Fragmentation: Much harder than jets initiated by other species (b-hadrons carry around 75% of jet energy, on average)

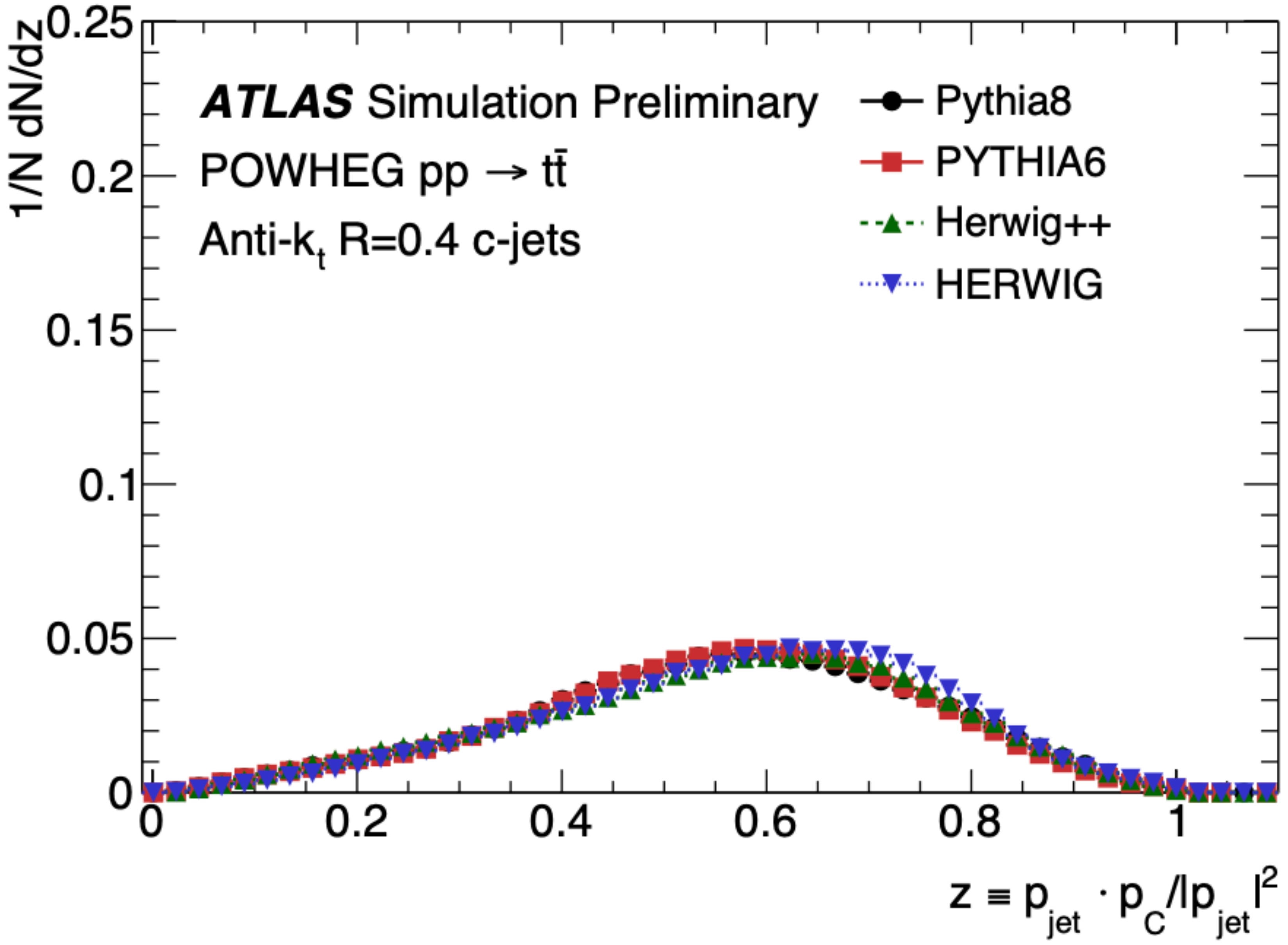




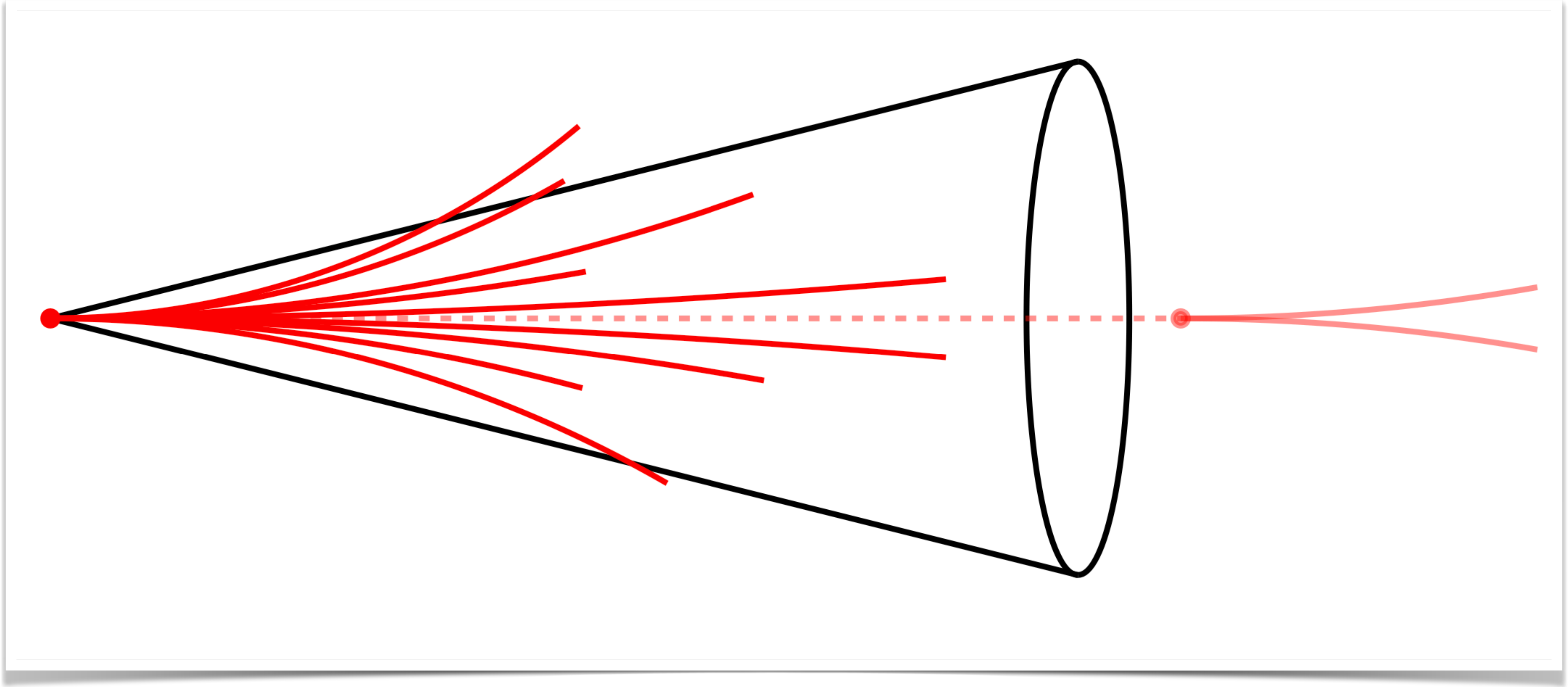
# A bit about flavour tagging: properties of c-hadrons

- Lifetime: Shorter than the b-hadrons by around a factor of 2-3, still enough for measurable decay length (around 1-3mm for a 50 GeV boost)
- Mass: Weakly decaying c-hadrons have masses around 2 GeV, around 2–3× lower than b-hadrons (mean of ≈ 2 charged particles per decay)
- Fragmentation: Softer than b-jets, but still harder than jets initiated by light species (c-hadrons carry around 55% of jet energy, on average)





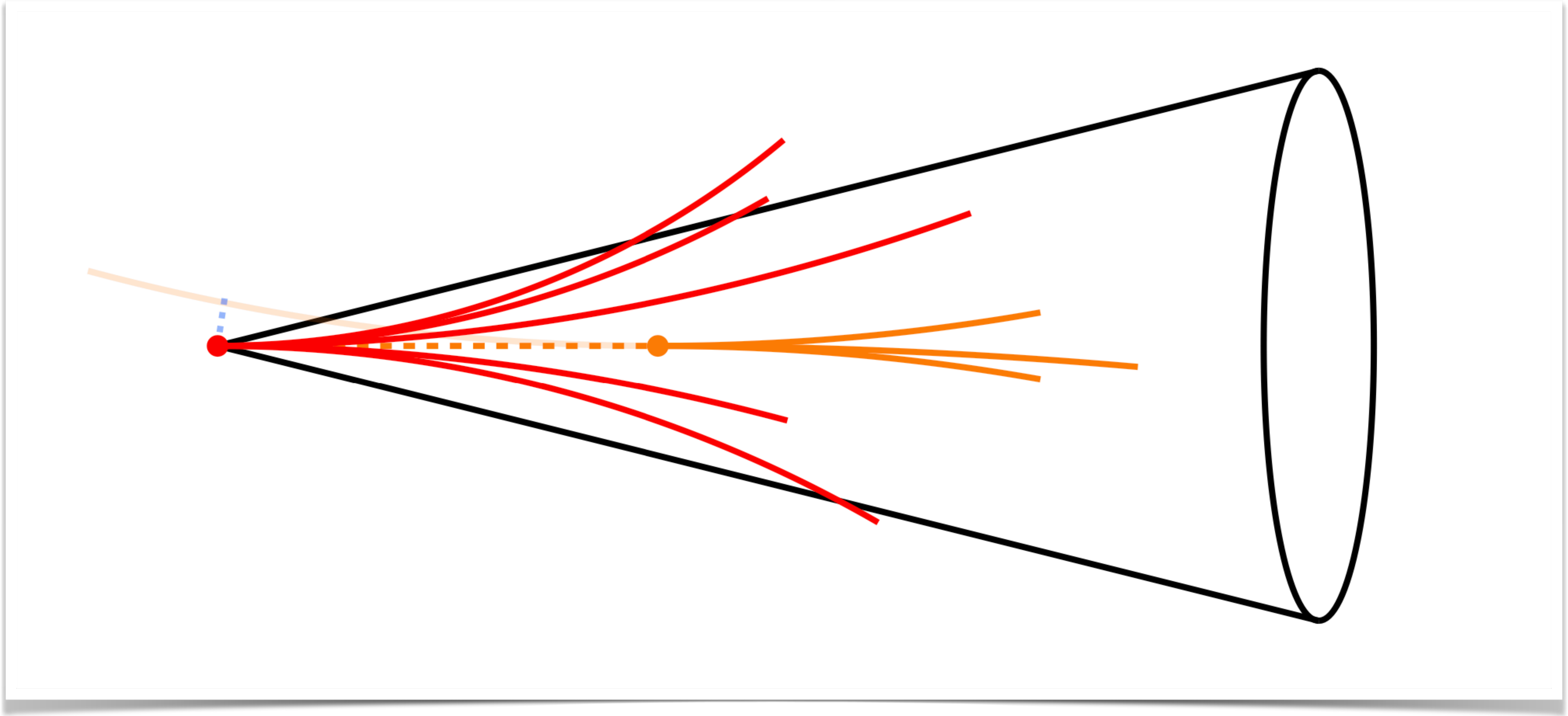
# Anatomy of a light flavour (u, d, s) jet



**Typical Experimental Signature**

- Light-quarks hadronise into many light hadrons which share the jet energy
- Tracks from this vertex often have impact parameters consistent with zero
- Long-lived light hadrons (e.g. KS0, Λ0) can be produced, though they are more likely to decay very far (many cm) from the primary pp vertex

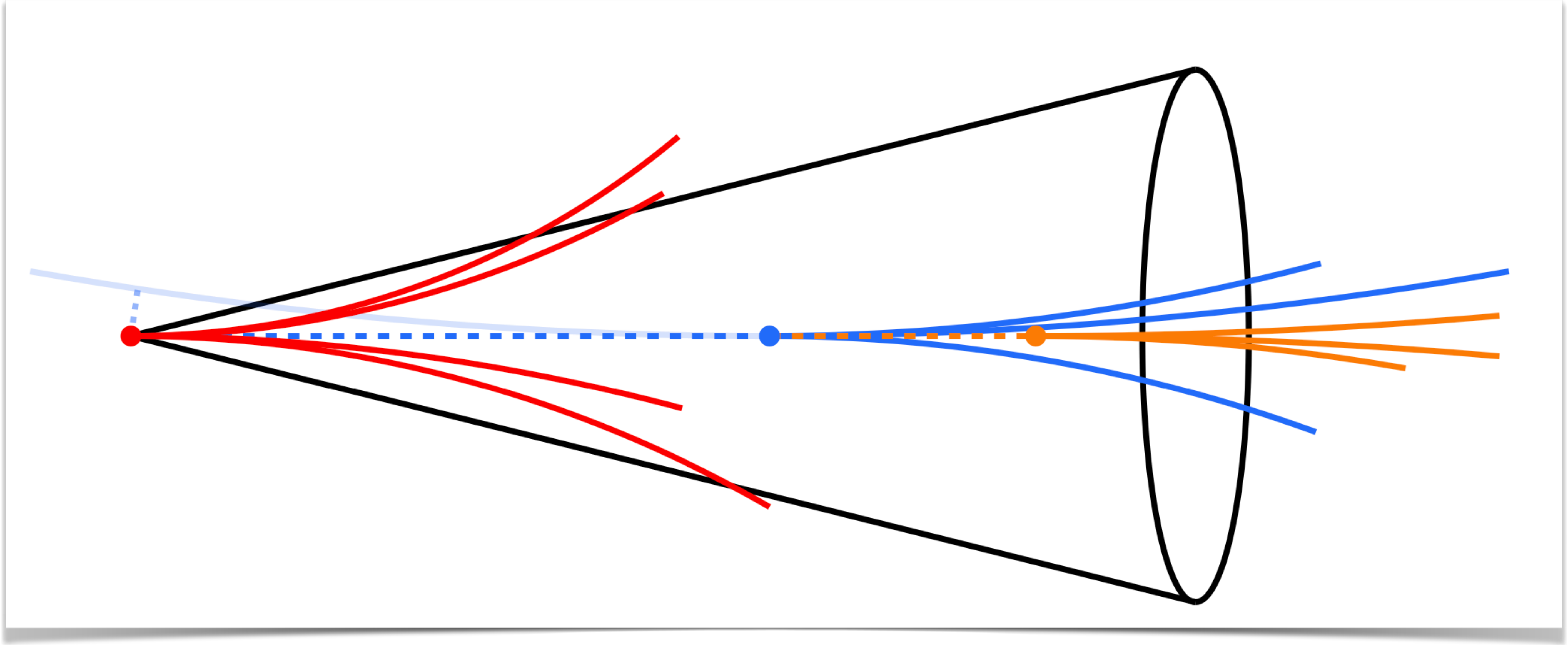
# Anatomy of a c-jet



**Typical Experimental Signature**

- c-quark fragments into a c-hadron which carries around half of the jet energy
- c-hadron decay vertex often displaced from the primary pp vertex by a few mm
- Tracks from this vertex can often have large impact parameters

# Anatomy of a b-jet



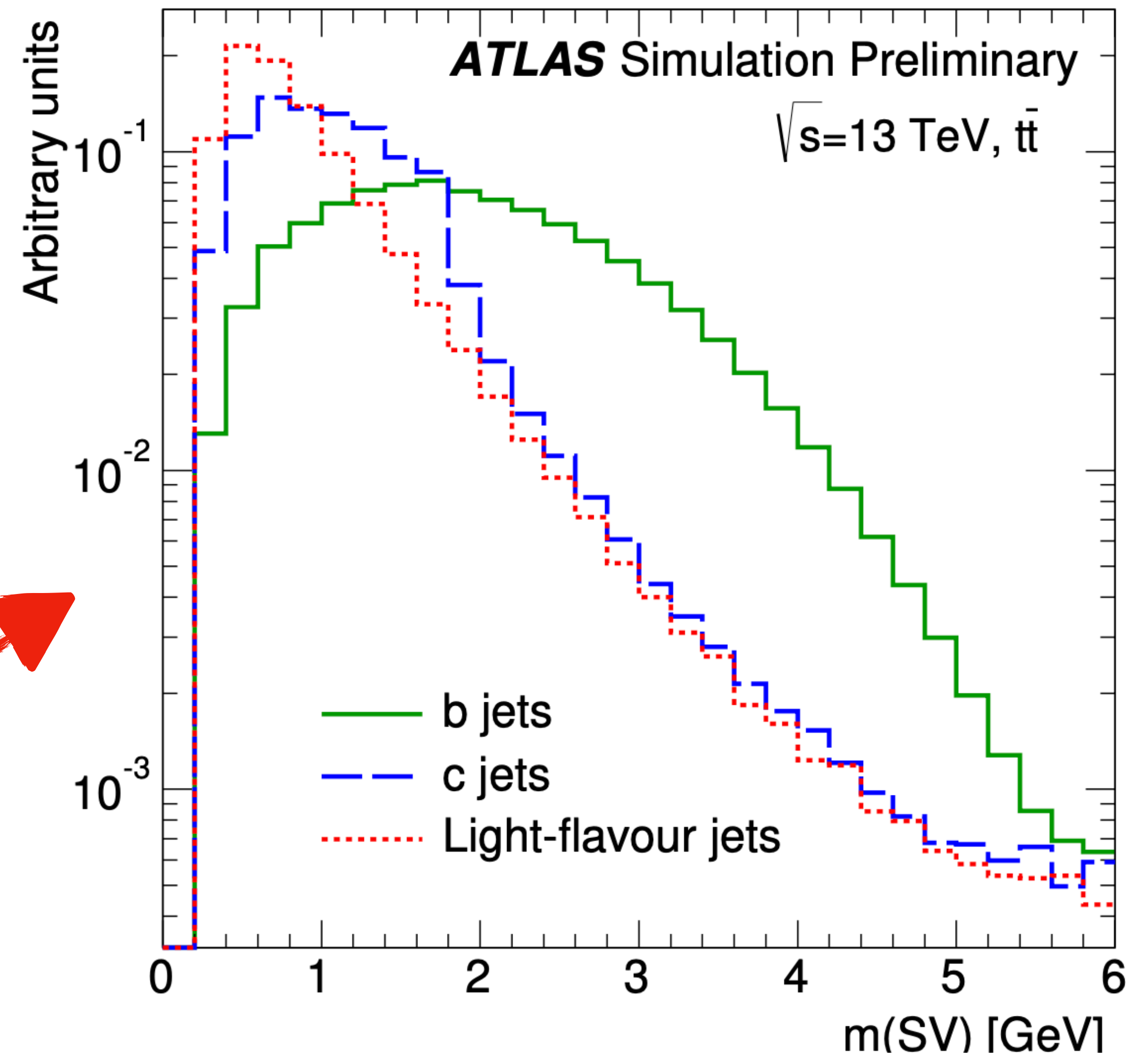
## Typical Experimental Signature

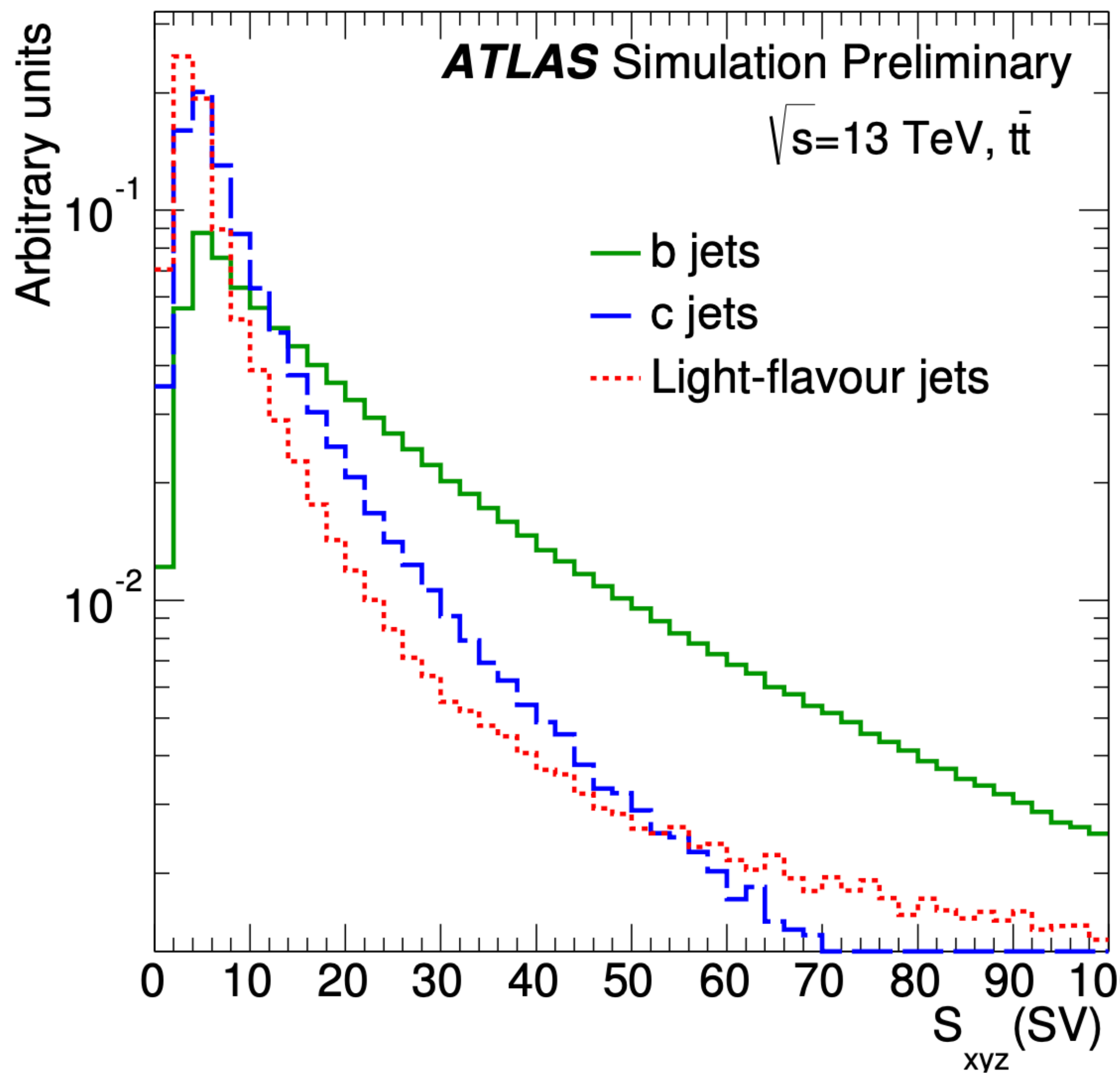
- b-quark fragments into a b-hadron which carries most of the jet energy
- Most b-hadrons (≈ 90%) decay into c-hadrons
  b-hadron decay vertex often displaced from the primary pp vertex by a few
- Subsequent c-hadron decay vertex often displaced by a further few mm Tracks from both of these vertices often have large impact parameters

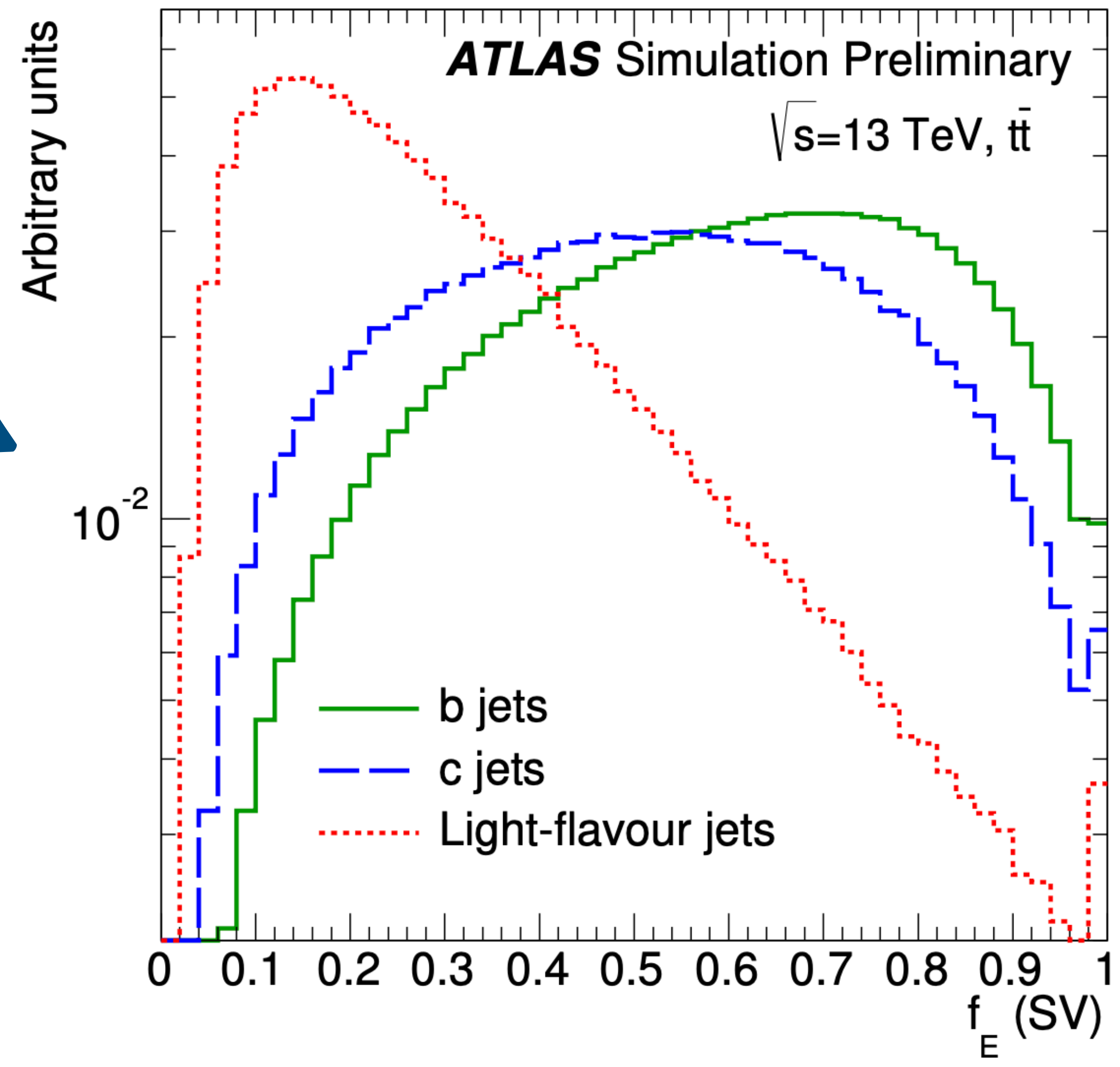
# Exploiting b-hadron properties: Secondary Vertices (SV)

Exploit expectation of a secondary vertex from either b or c-hadron decays:

- Attempt to reconstruct a secondary vertex from high IP tracks associated with jet
- Use invariant mass of tracks at SV to discriminate b or c-hadron decay vertices from V 0 decays or material interactions
- Further exploit hard b-jet fragmentation, SV should carry a large fraction of jet energy
- ✓ SV found in up to ≈ 80% of b-jets but only a few % of light flavour jets
- ✗ Degraded light jet rejection as jet pT increases, careful considerations to mitigate “tagging” of material interactions required



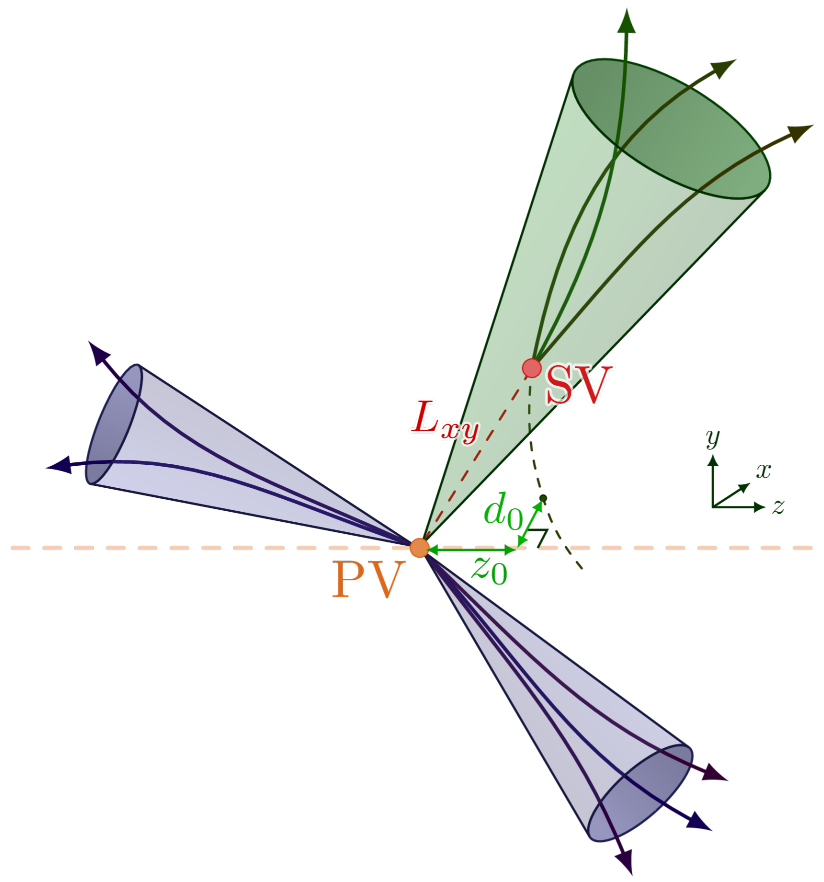


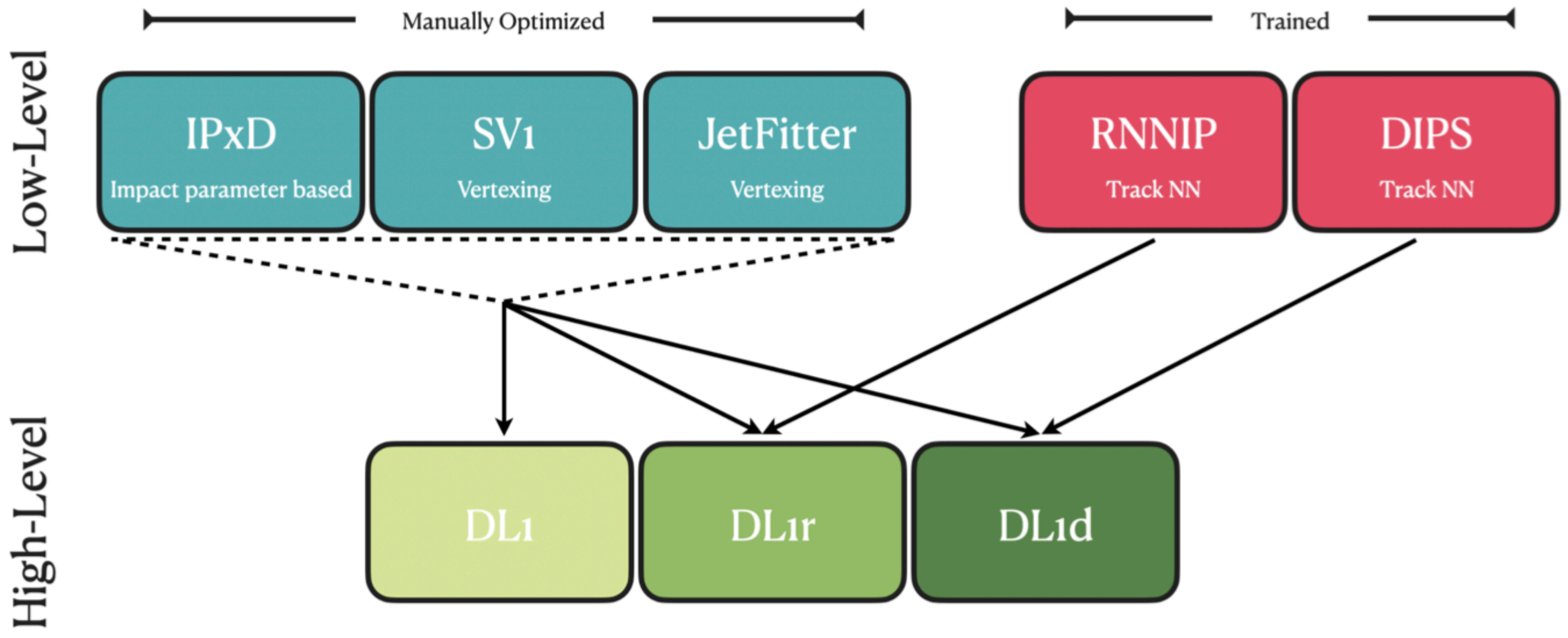


# Exploiting b-hadron properties: Leptons (muons)

Exploit the large branching fractions for the semi-leptonic c/b hadron decays and the clean “muon-in-jet” experimental signature:

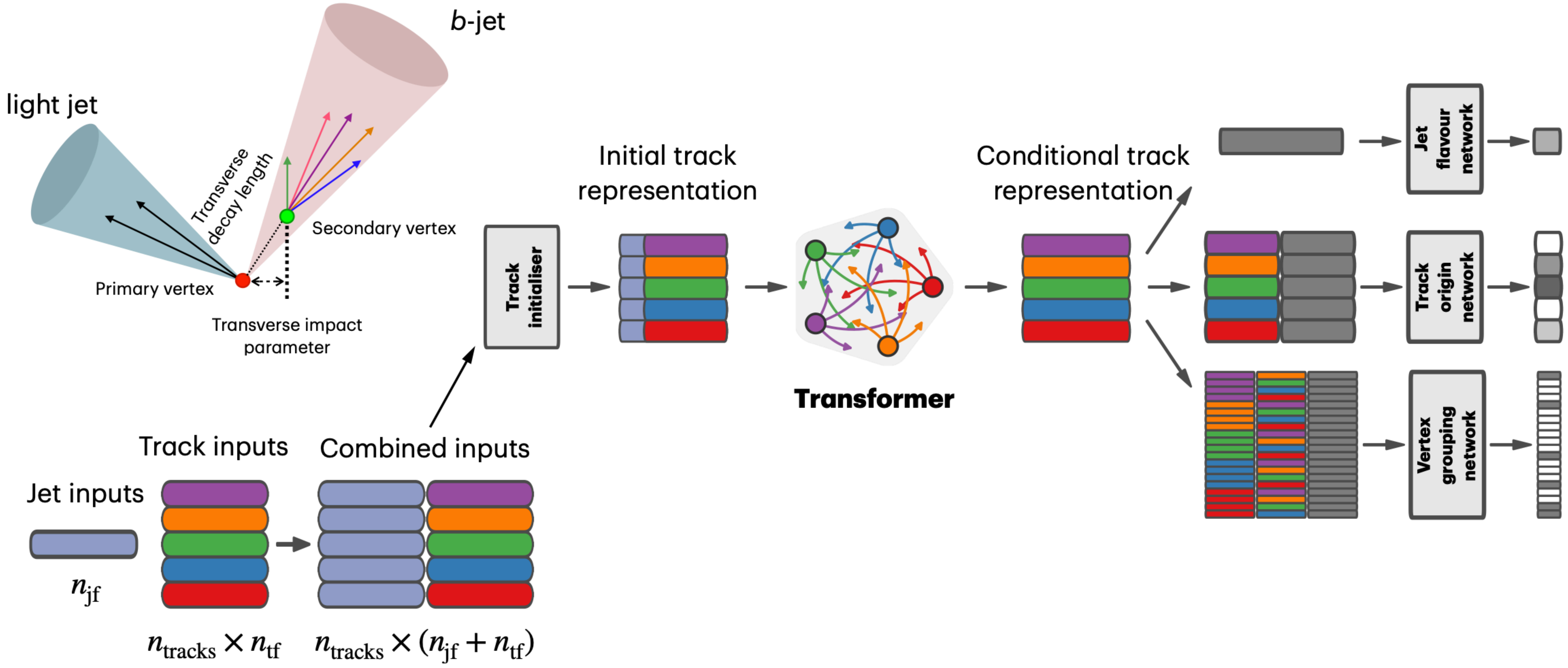
- Expect much higher rate of muons within b/c-jets, relative to light flavour jets, due to the decays $B \to \mu\nu X$ and $B \to DX \to \mu\nu X'$ (B of around 10% each)
- ✓ Complementary to SV and IP based taggers, different c/b hadron properties exploited and ATLAS detector components employed
- ✗ Light flavour jet backgrounds from muons produced in π/K decays in flight difficult to model in simulation





# Next generation of b-tagging

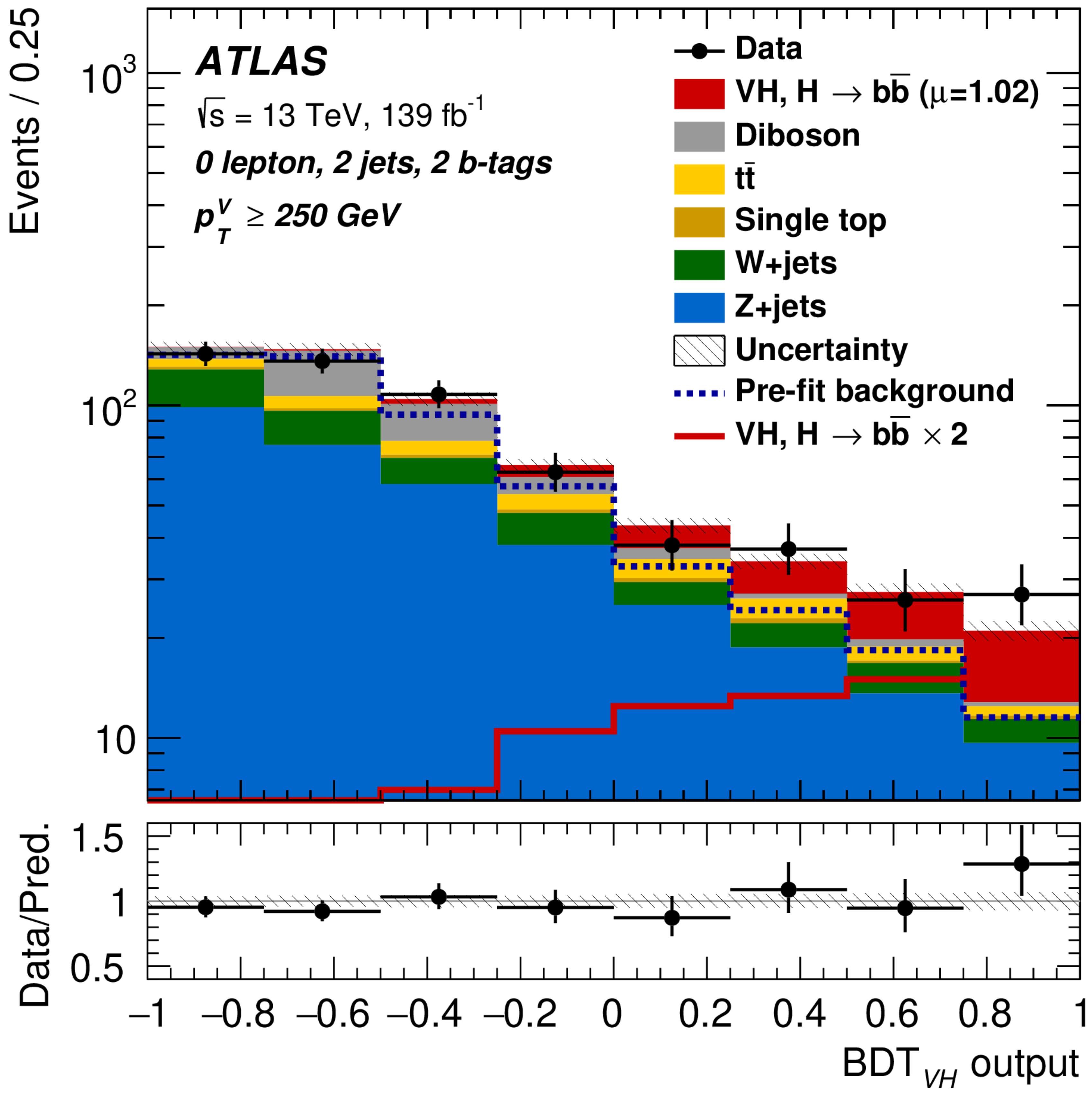
arXiv:2505.19689



- General Network (GN) series: directly process track and jet information
- Trained using target labels extracted from Monte Carlo (MC) simulation
- Uses jet flavour prediction as its primary training target and introduces auxiliary training objectives to reconstruct the internal structure of a jet by grouping tracks originating from a common vertex and by predicting the underlying physics process from which each track originated

# $H \to b\bar{b}$ with VH associate production

Eur. Phys. J. C 81 (2021) 178



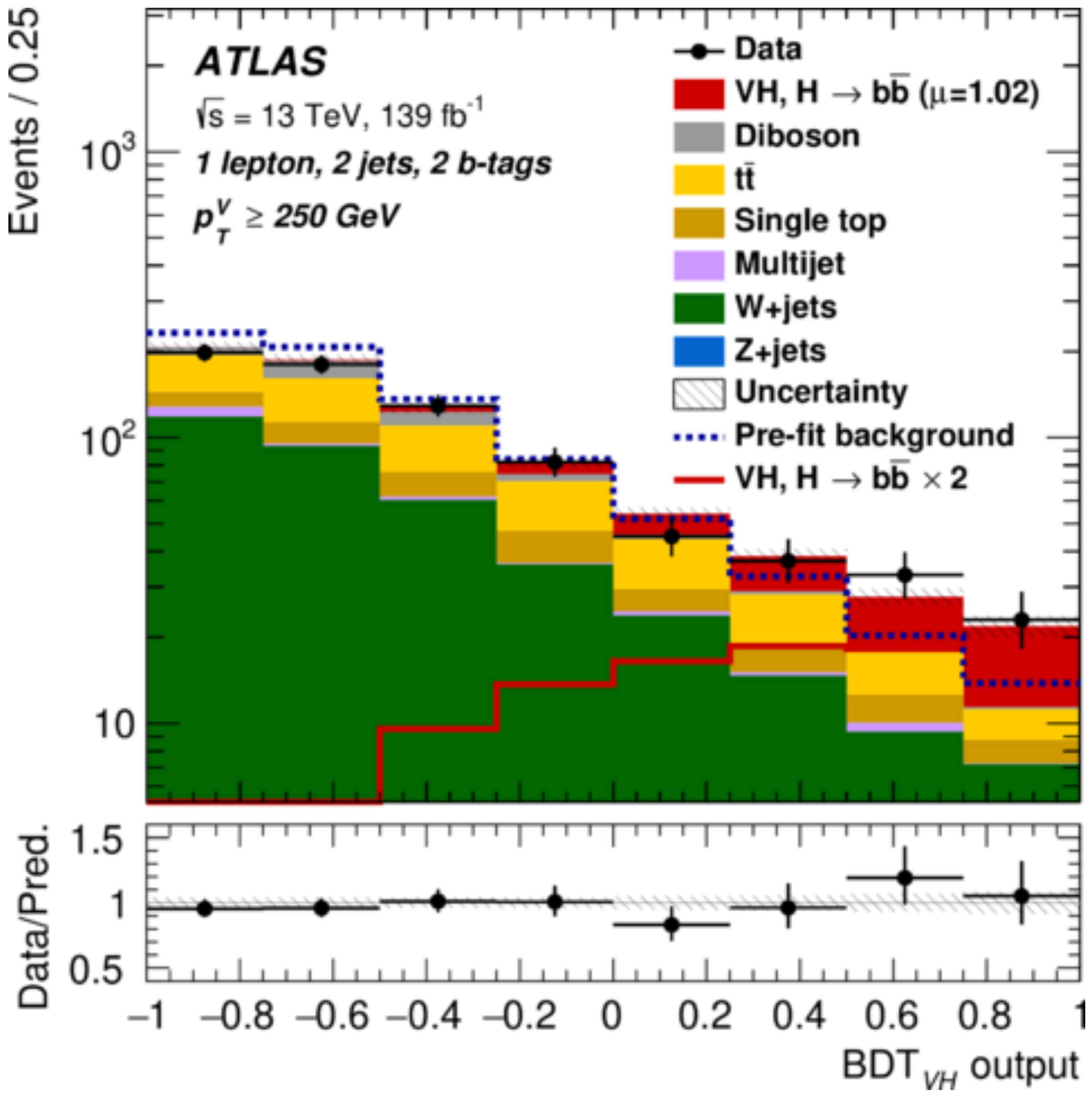
0 leptons, 2 jets

VH channel traditionally expected to be brightest hope of finding $H \to b\bar{b}$ at LHC

- Search for events with **0**, 1 or 2 leptons ($Z \to \nu\nu, W \to \ell\nu$ and $Z \to \ell\ell$)
- ≥ 2b-tagged jets, focus on high $p_T^V$ events to suppress V + jets and $t\bar{t}$ background
- $139$ fb$^{-1}$ of 13 TeV data from LHC Run 2 (2015 - 2018)
- BDT used as nominal S/B discriminant: trained with kinematic variables (e.g.$m_{b\bar{b}}$, $p_T^V$, $E_T^{miss}$, $\Delta R_{bb}$, $p_T^b$ etc.) in each channel
- Eight signal regions used: (3 lepton multiplicity) × (2 jet multiplicity) + 1 additional jet multiplicity and 1 additional $p_T^V$ region for 2 lepton channel

# $H \to b\bar{b}$ with VH associate production

Eur. Phys. J. C 81 (2021) 178



1 leptons, 2 jets

VH channel traditionally expected to be brightest hope of finding $H \to b\bar{b}$ at LHC

- Search for events with 0, **1** or 2 leptons ($Z \to \nu\nu, W \to \ell\nu$ and $Z \to \ell\ell$)
- ≥ 2b-tagged jets, focus on high $p_T^V$ events to suppress V + jets and $t\bar{t}$ background
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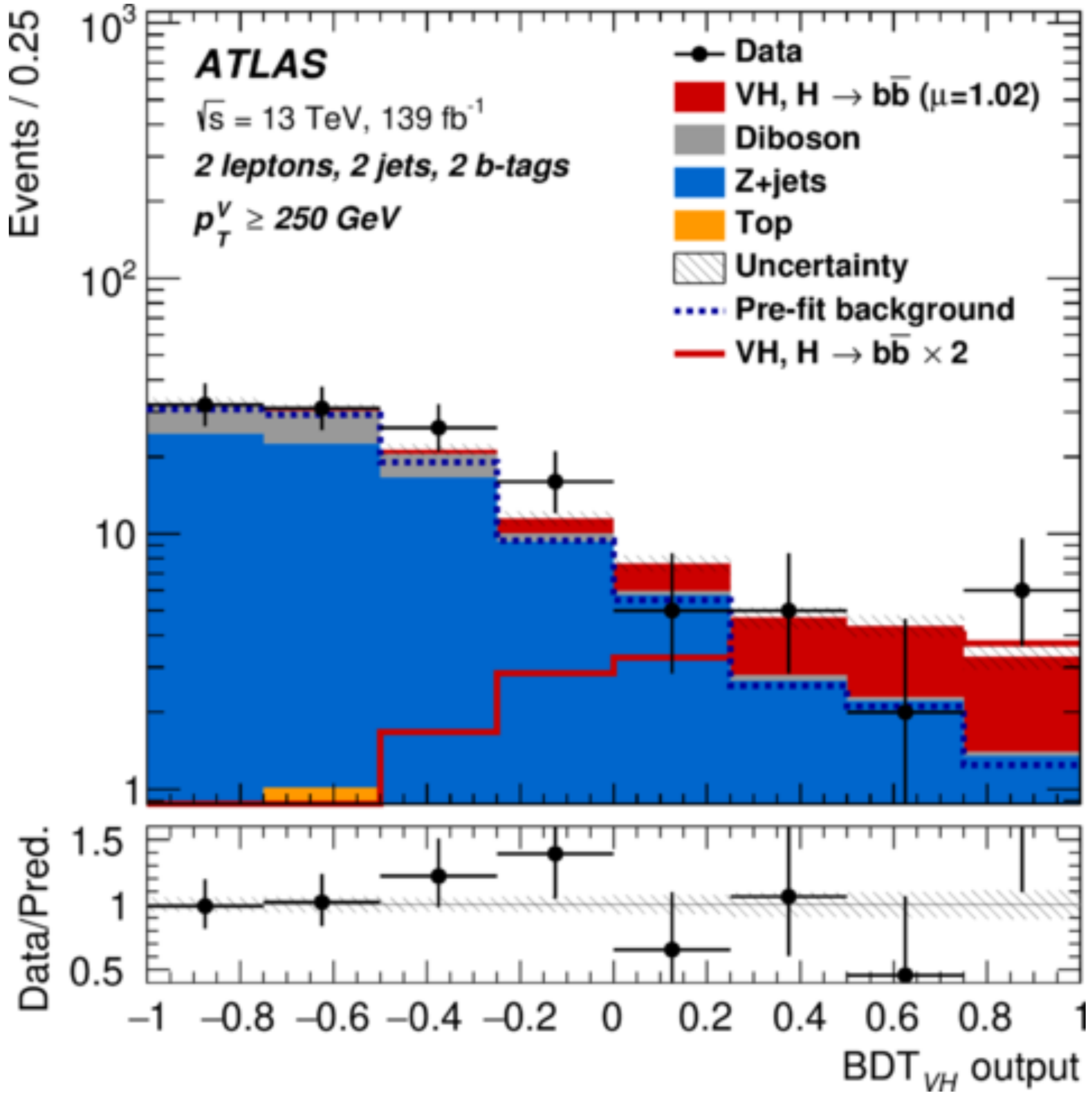
- BDT used as nominal S/B discriminant: trained with kinematic variables (e.g.$m_{b\bar{b}}$, $p_T^V$, $E_T^{miss}$, $\Delta R_{bb}$, $p_T^b$ etc.) in each channel
- Eight signal regions used: (3 lepton multiplicity) × (2 jet multiplicity) + 1 additional jet multiplicity and 1 additional $p_T^V$ region for 2 lepton channel

# $H \to b\bar{b}$ with VH associate production

Eur. Phys. J. C 81 (2021) 178



2 leptons, 2 jets

VH channel traditionally expected to be brightest hope of finding $H \to b\bar{b}$ at LHC

- Search for events with 0, 1 or **2** leptons ($Z \to \nu\nu$, $W \to \ell\nu$ and $Z \to \ell\ell$)
- ≥ 2b-tagged jets, focus on high $p_T^V$ events to suppress V + jets and $t\bar{t}$ background
- $139$ fb$^{-1}$ of 13 TeV data from LHC Run 2 (2015 - 2018)
- BDT used as nominal S/B discriminant: trained with kinematic variables (e.g. $m_{b\bar{b}}$, $p_T^V$, $E_T^{miss}$, $\Delta R_{bb}$, $p_T^b$ etc.) in each channel
- Eight signal regions used: (3 lepton multiplicity) × (2 jet multiplicity) + 1 additional jet multiplicity and 1 additional $p_T^V$ region for 2 lepton channel

# $H \to b\bar{b}$ with VH associate production

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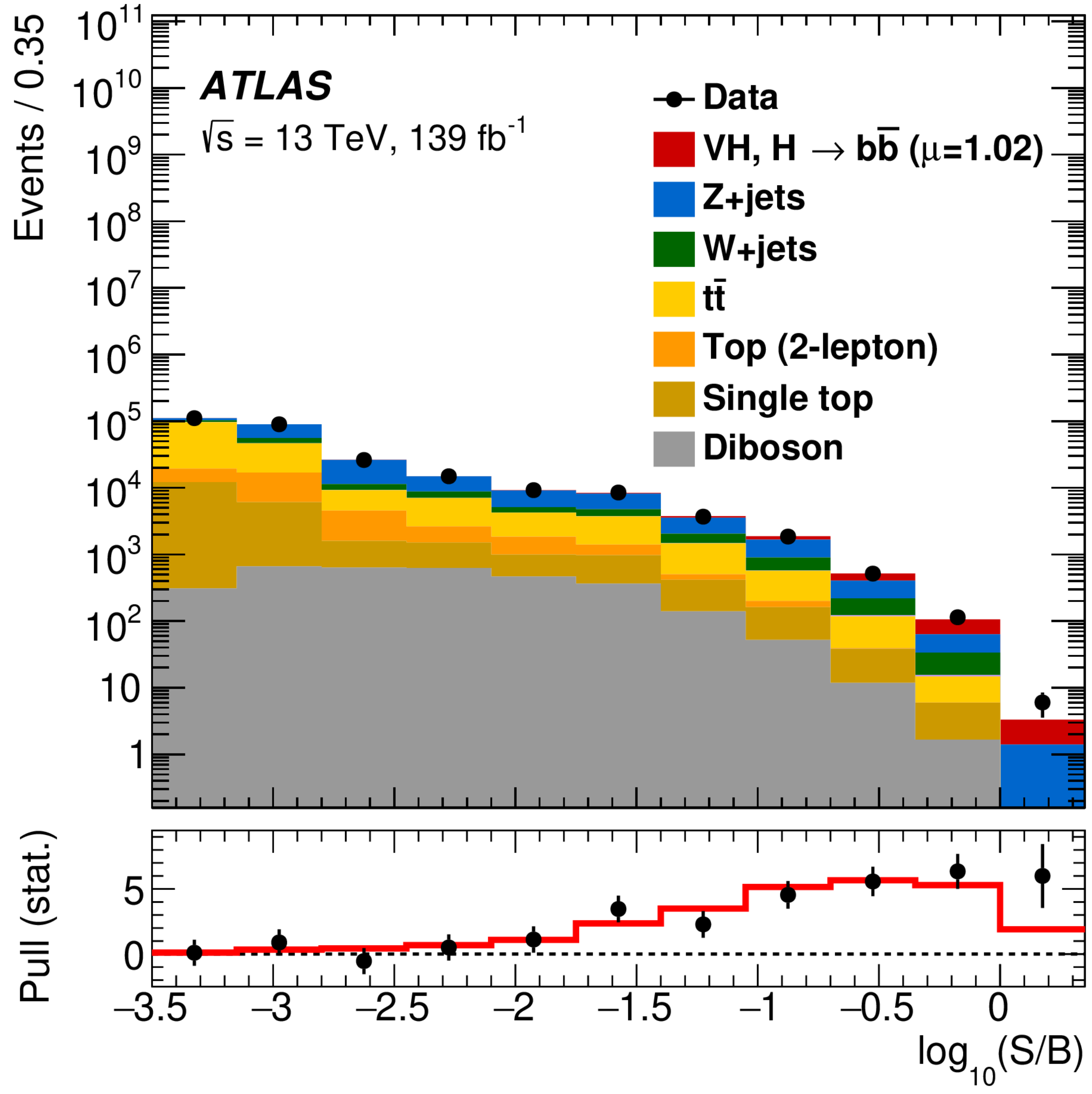
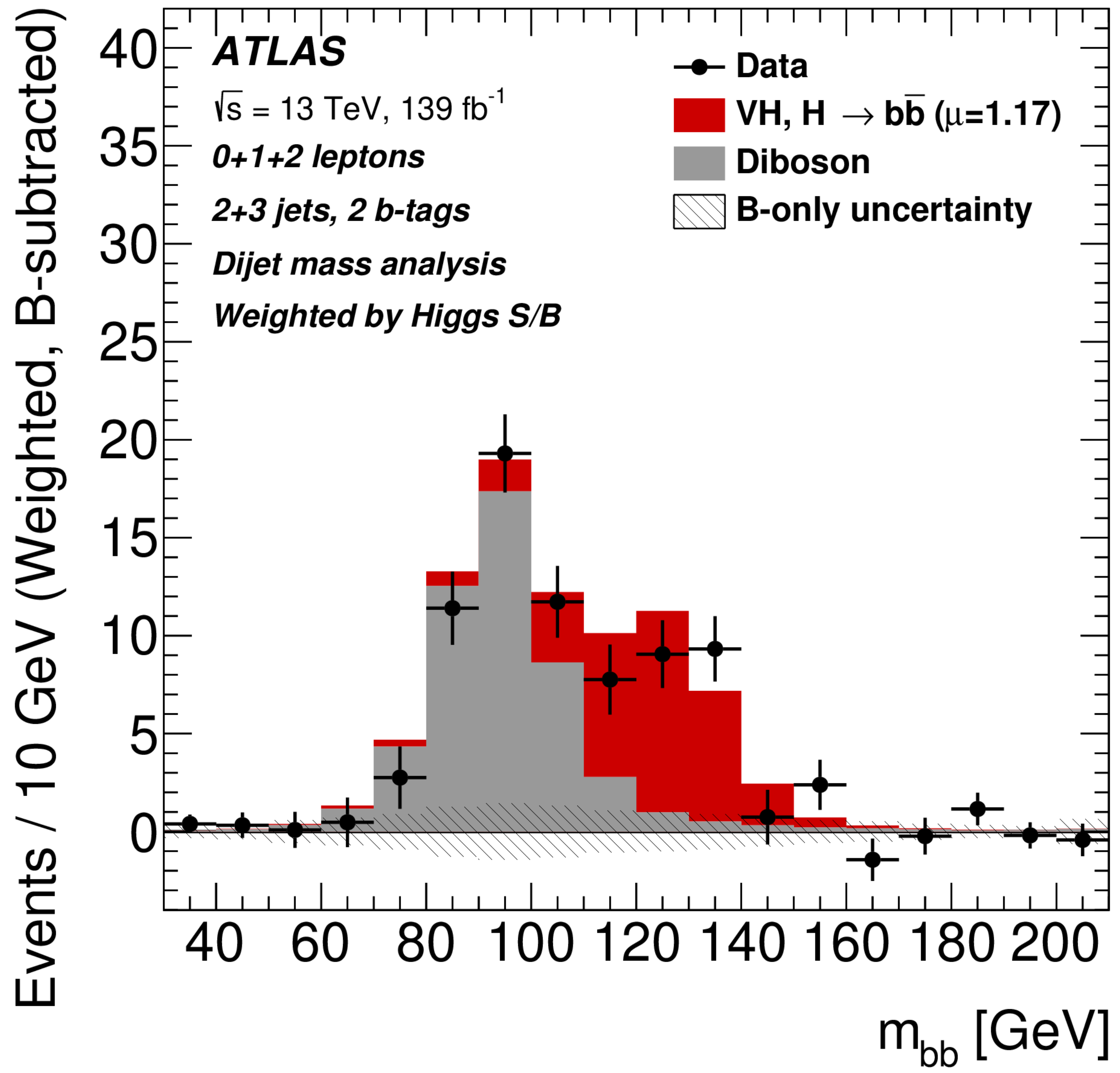
**VH, $H \to b\bar{b}$ signal now very clearly visible by eye!** For 13 TeV (Run 2) alone, observed (expected) significance is 6.7(6.7)σ, signal strength $\mu_{VH(b\bar{b})} = 1.02^{+0.18}_{-0.17}$



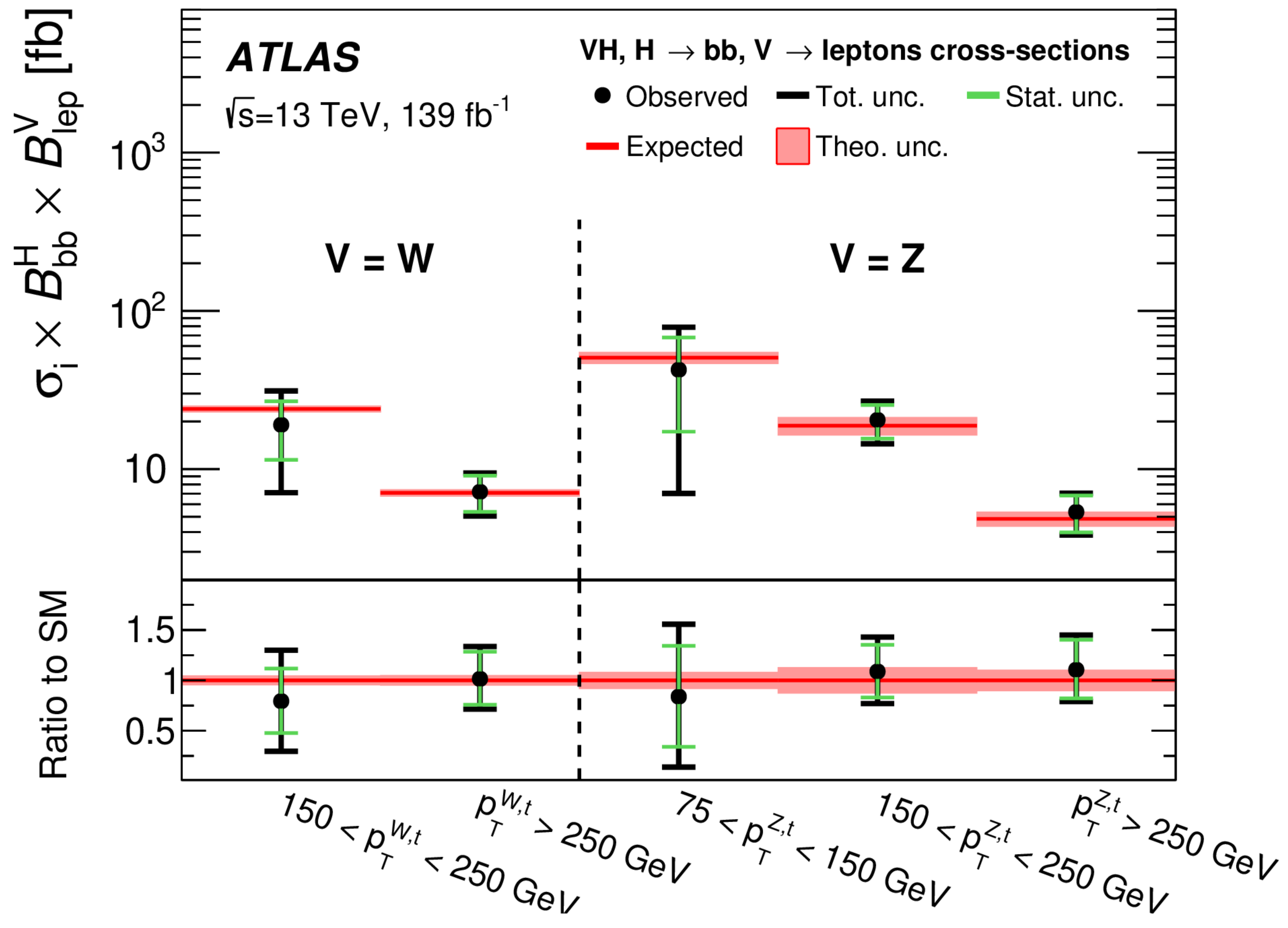
Bkgd. subtracted $m_{b\bar{b}}$ distribution for CBA



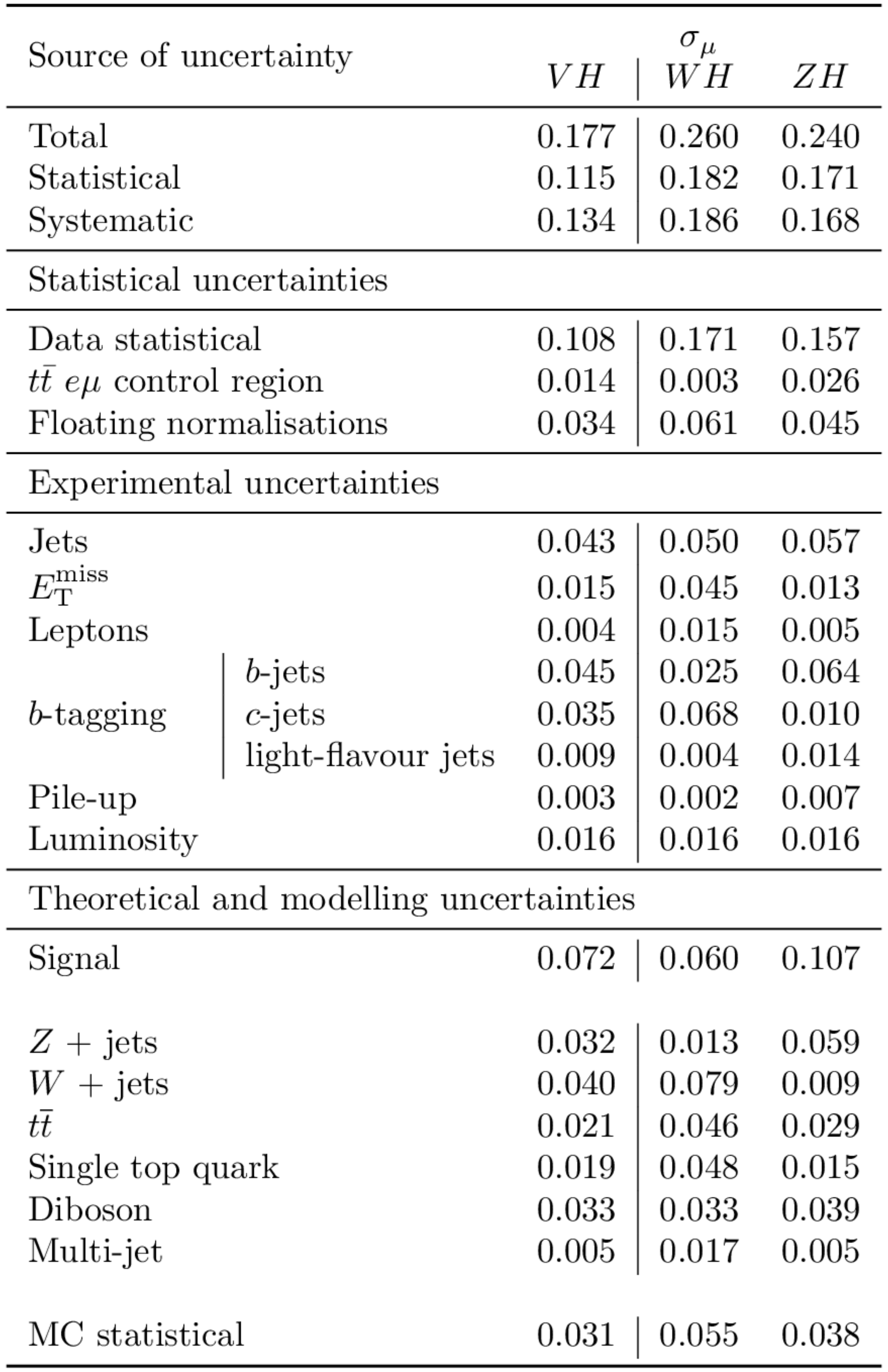
Cut-based analysis (CBA) also performed as a cross-check, selection performed using many of the same variables used in BDT

# $H \rightarrow b\bar{b}$ with VH associate production

Eur. Phys. J. C 81 (2021) 178



- "Theory" systematics largest for signal strength measurement, particularly signal and V + jets background modelling
- Experimental systematics dominated by b-tagging uncertainties
- STXS measurements still limited by statistics

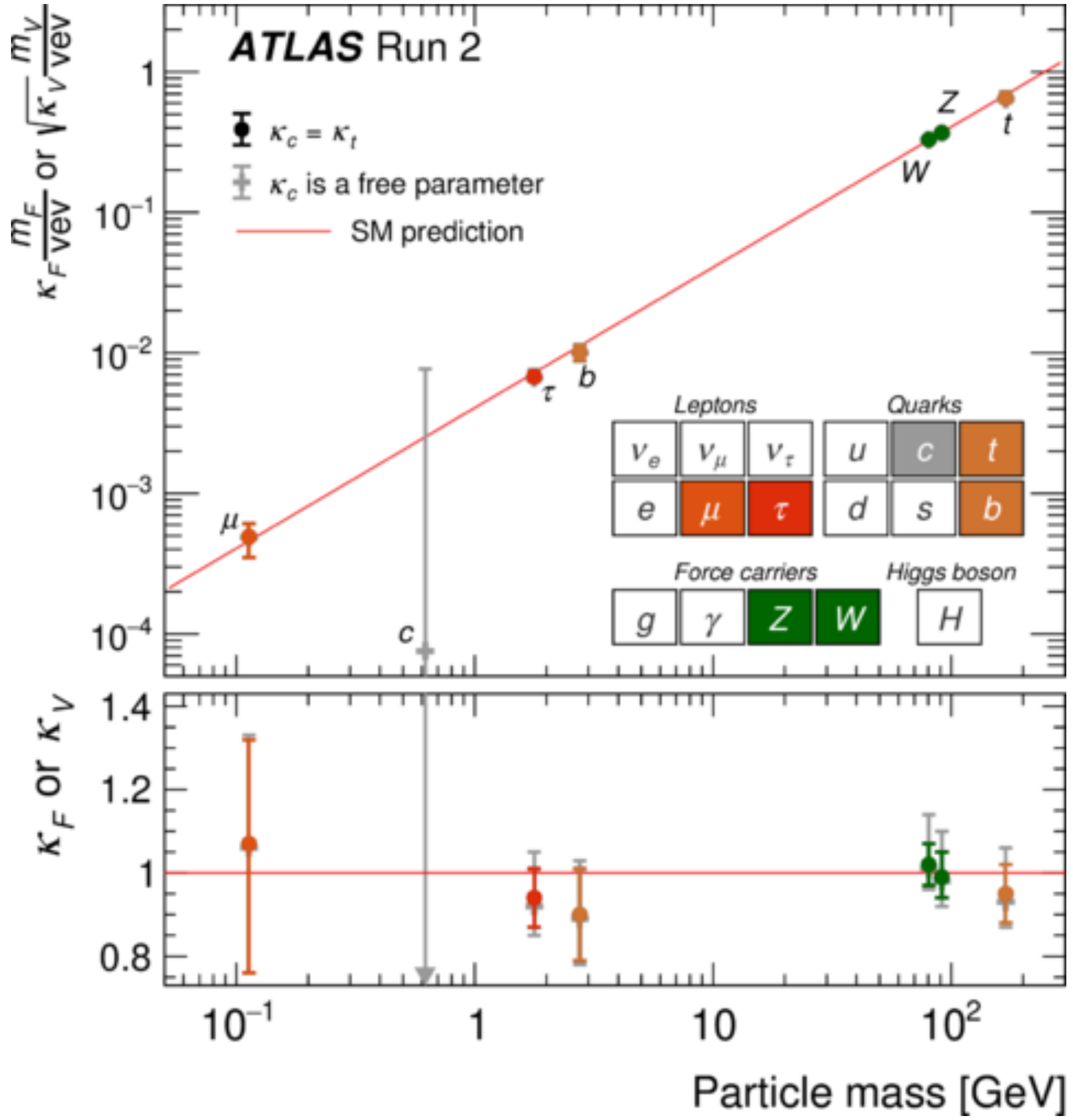


| Source of uncertainty | | $\sigma_\mu$ | | |
|---|---|---|---|---|
| | | $VH$ | $WH$ | $ZH$ |
| Total | | 0.177 | 0.260 | 0.240 |
| Statistical | | 0.115 | 0.182 | 0.171 |
| Systematic | | 0.134 | 0.186 | 0.168 |
| Statistical uncertainties | | | | |
| Data statistical | | 0.108 | 0.171 | 0.157 |
| $t\bar{t}$ $e\mu$ control region | | 0.014 | 0.003 | 0.026 |
| Floating normalisations | | 0.034 | 0.061 | 0.045 |
| Experimental uncertainties | | | | |
| Jets | | 0.043 | 0.050 | 0.057 |
| $E_T^{miss}$ | | 0.015 | 0.045 | 0.013 |
| Leptons | | 0.004 | 0.015 | 0.005 |
| $b$-tagging | $b$-jets | 0.045 | 0.025 | 0.064 |
| | $c$-jets | 0.035 | 0.068 | 0.010 |
| | light-flavour jets | 0.009 | 0.004 | 0.014 |
| Pile-up | | 0.003 | 0.002 | 0.007 |
| Luminosity | | 0.016 | 0.016 | 0.016 |
| Theoretical and modelling uncertainties | | | | |
| Signal | | 0.072 | 0.060 | 0.107 |
| $Z$ + jets | | 0.032 | 0.013 | 0.059 |
| $W$ + jets | | 0.040 | 0.079 | 0.009 |
| $t\bar{t}$ | | 0.021 | 0.046 | 0.029 |
| Single top quark | | 0.019 | 0.048 | 0.015 |
| Diboson | | 0.033 | 0.033 | 0.039 |
| Multi-jet | | 0.005 | 0.017 | 0.005 |
| MC statistical | | 0.031 | 0.055 | 0.038 |

# Higgs combinations

# Higgs couplings to fermions measurements

## Latest ATLAS 125 GeV Higgs combination with 13 TeV data



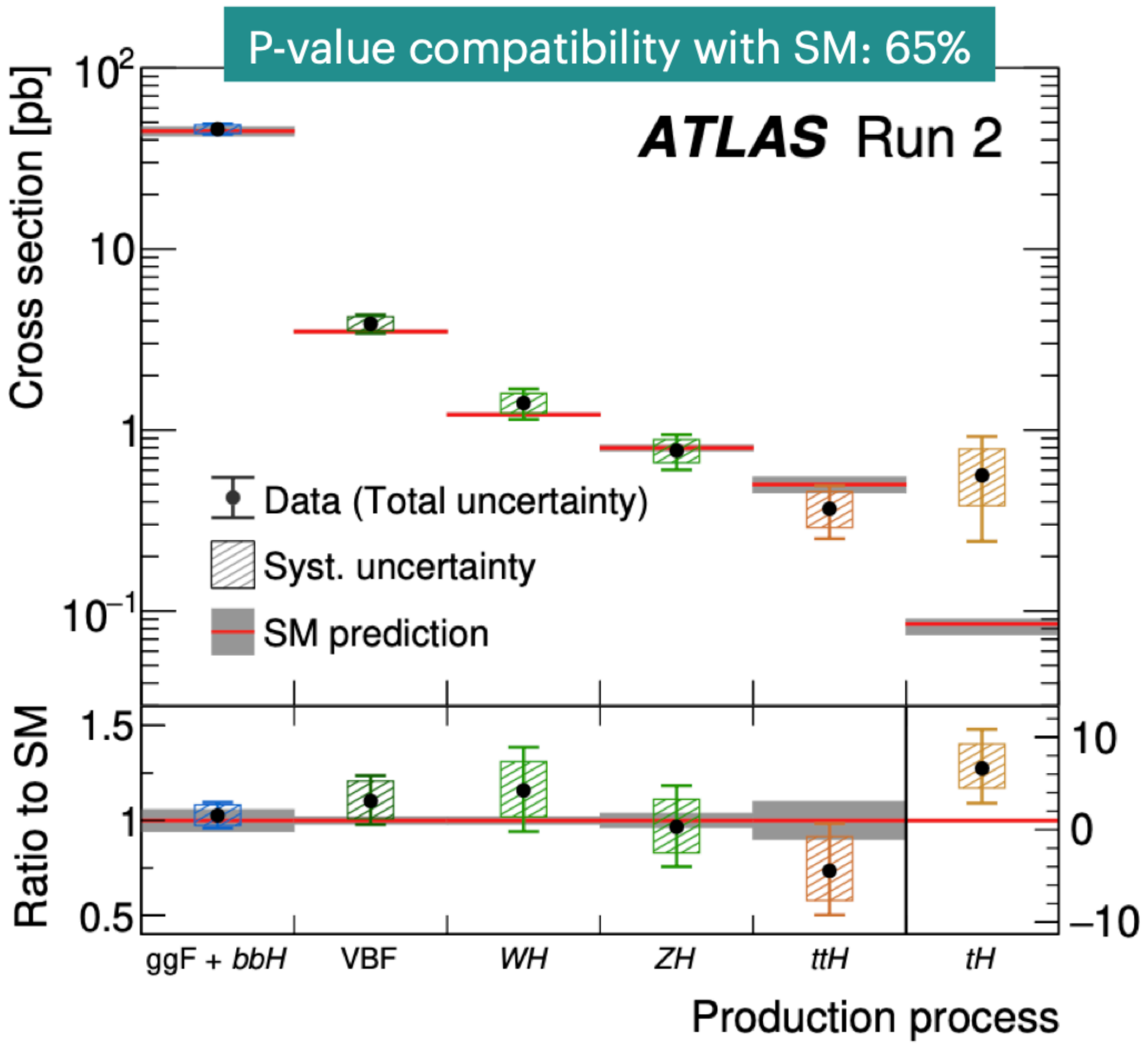
Reduced coupling strength modifiers as a function of fermion/boson mass, assuming no BSM contributions to ΓH and the SM structure of loop processes

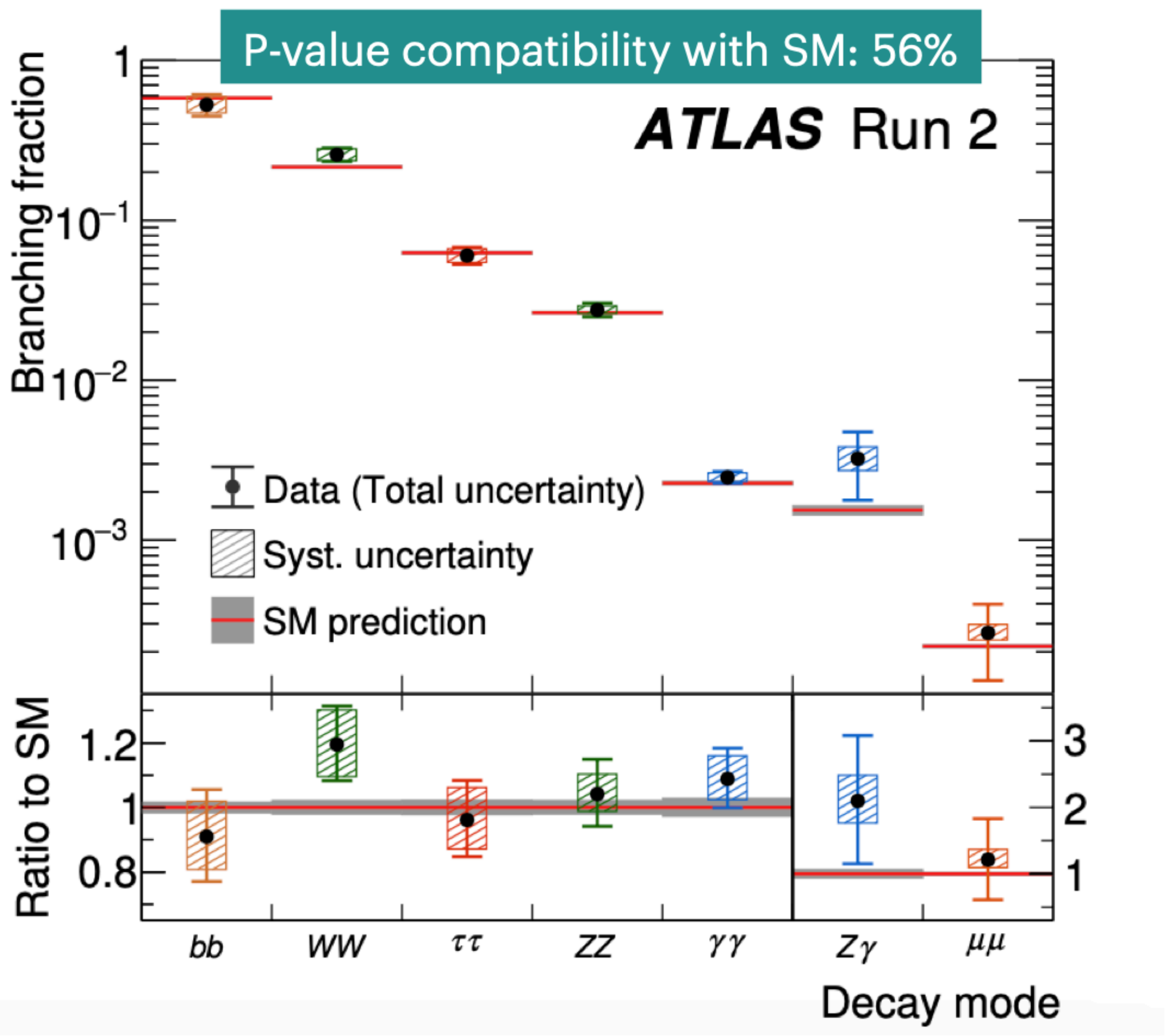
# Combination of single Higgs measurents:

- Production cross sections (free parameter in the fit, BR fixed to SM values):

- ggF and VBF observed in Run1, precision in Run2 7% and 12% respectively

- Observed in Run2: WH ( 5.8 σ), ZH (5.0σ ) and (6.4σ)


P-value compatibility with SM: 65%


P-value compatibility with SM: 56%

# Summary

**The experimental characterisation of the 125 GeV Higgs boson is advancing rapidly, many ATLAS/CMS results with full Run 2 dataset and new to come with Run-3**

- Around 90% of total width (by SM expectation) is now accounted for experimentally
- All main production mechanisms have also been unambiguously observed
- To date, all measurements seem to indicate properties in very good agreement with the SM!
- However, surprises may be lurking in the very poorly studied couplings to the first and second generation fermions
- Remember, the Yukawa picture is really just an “effective” description, new physics is required to understand the fermion mass hierarchy!

# Additional material

# A quick recap on differences between jets

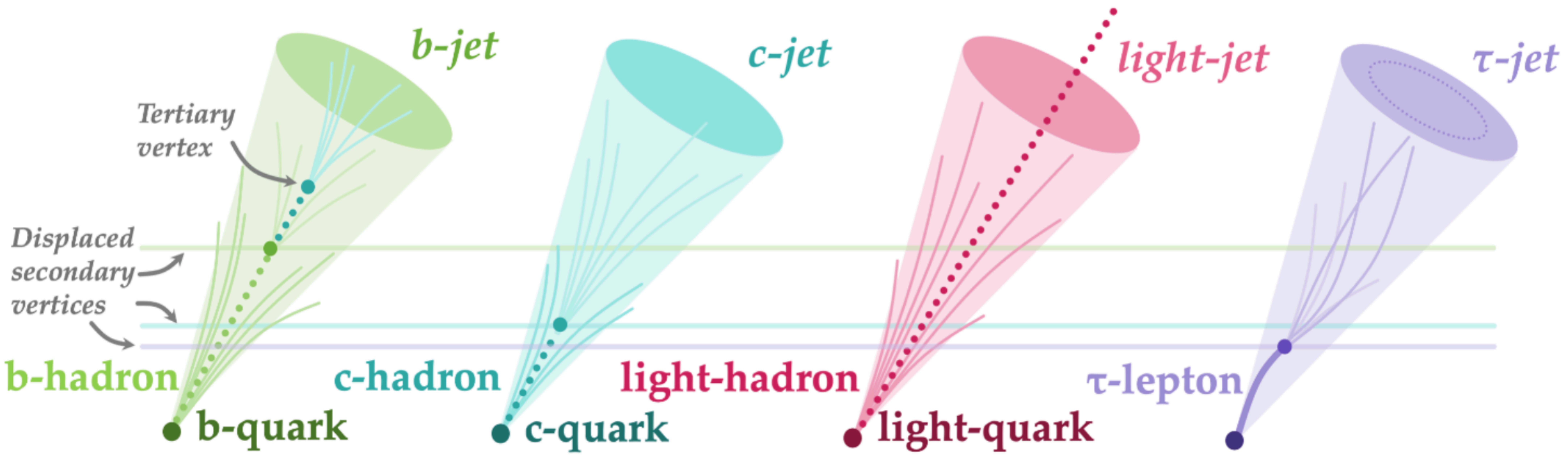
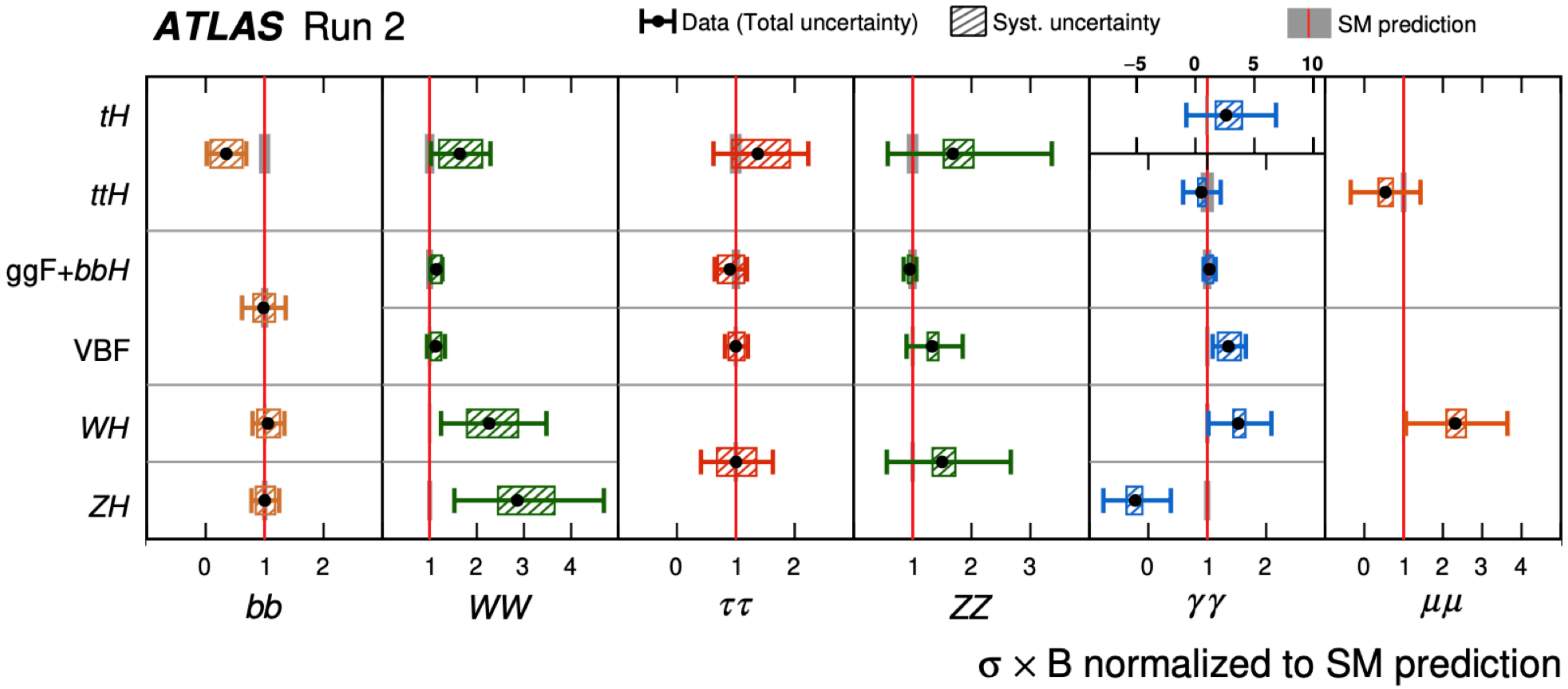


Figure from CERN-THESIS-2022-158

P-value compatibility with SM: 72%



# Signal strength and the κ-framework

## Signal strength

- The first characterisation of the Higgs couplings properties happens via the measurement of the signal strength
  - Can fit a global μ or fit $\mu_i$ assuming SM for the decay, or fit $\mu_f$ assuming SM for the production cross section
  - Global μ fit results:
    - ATLAS **μ = 1.05 ± 0.06 = 1.05 ± 0.03(stat) ± 0.03(exp) ± 0.02(bkg th) ± 0.04(sig th)**
    - CMS **μ = 1.002 ± 0.057 = 1.002 ± 0.029(stat) ± 0.033(syst) ± 0.036(sig th)**

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}}$$

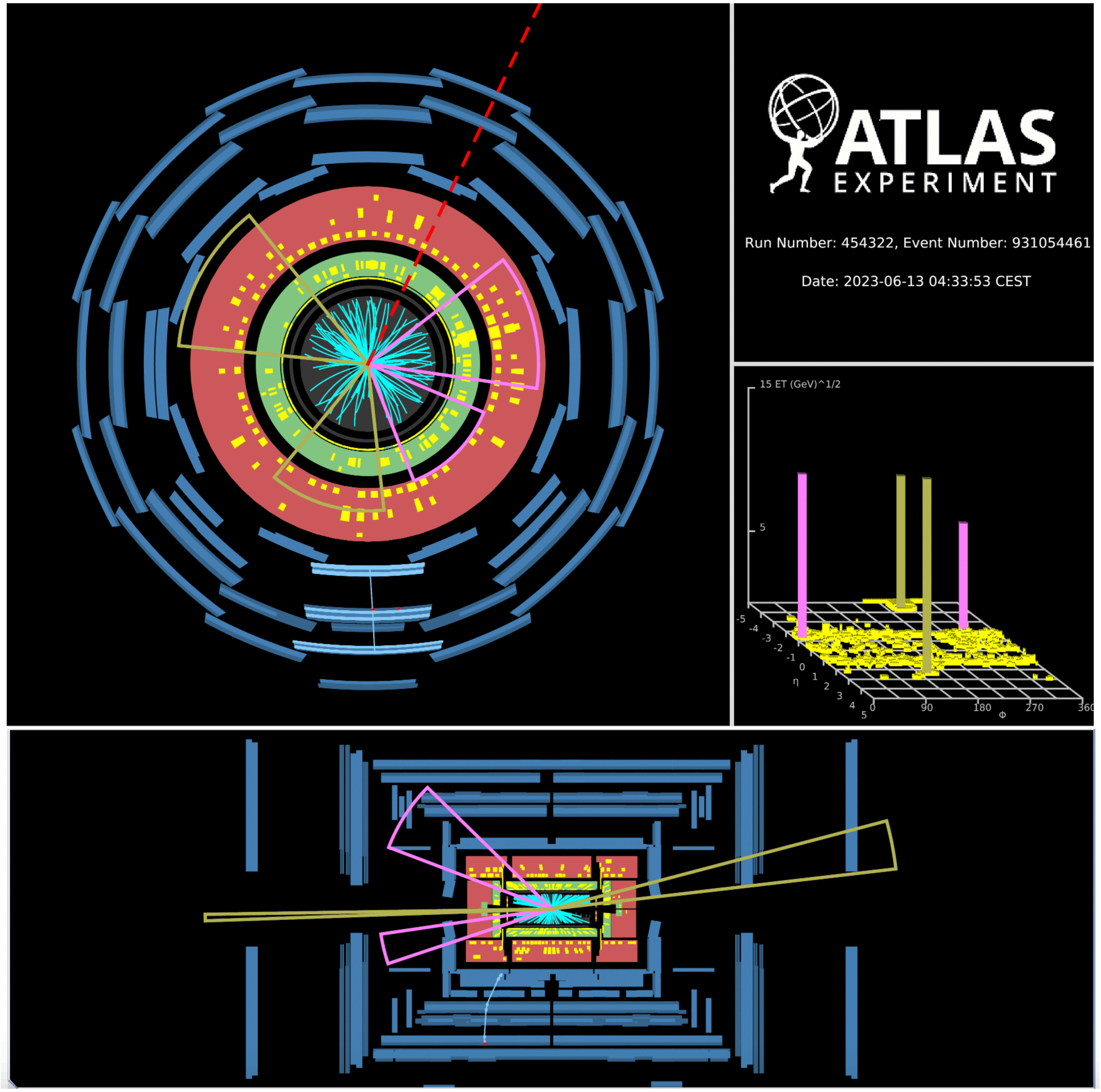
## κ-framework

- In this framework a set of coupling modifiers κ alter the signal strength, without affecting the kinematic distributions
- Each σ x BR can be parametrized in terms of these couplings strength modifiers
- Can also accomodate any non-SM invisible or undetected component

$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

- Slide from Stefano Rosati

# Higgs -> cc



- A sample event from the Run-3 $H \rightarrow c\bar{c}$ channel.
- The two c-tagged Higgs boson candidate signal jets, $c_1$ and $c_2$, are show in purple.
- The two VBF candidate jets, $j_1$ and $j_2$ are shown in yellow.
- The value of $m_{jj}$ for this event is 4.0 TeV and the value of mcc is 124.9 GeV.

# Higgs ->μμ