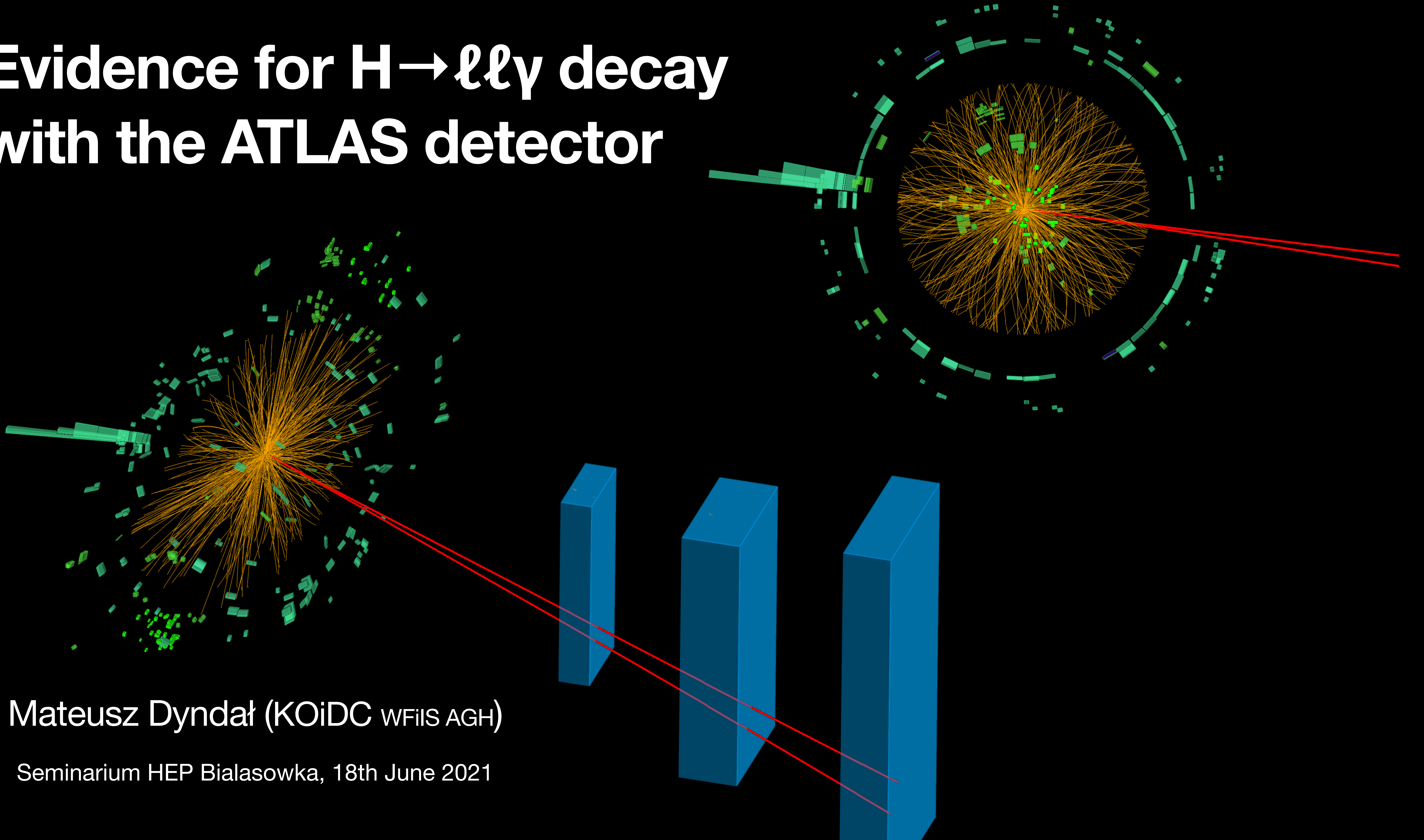
Evidence for H→ℓℓγ decay with the ATLAS detector

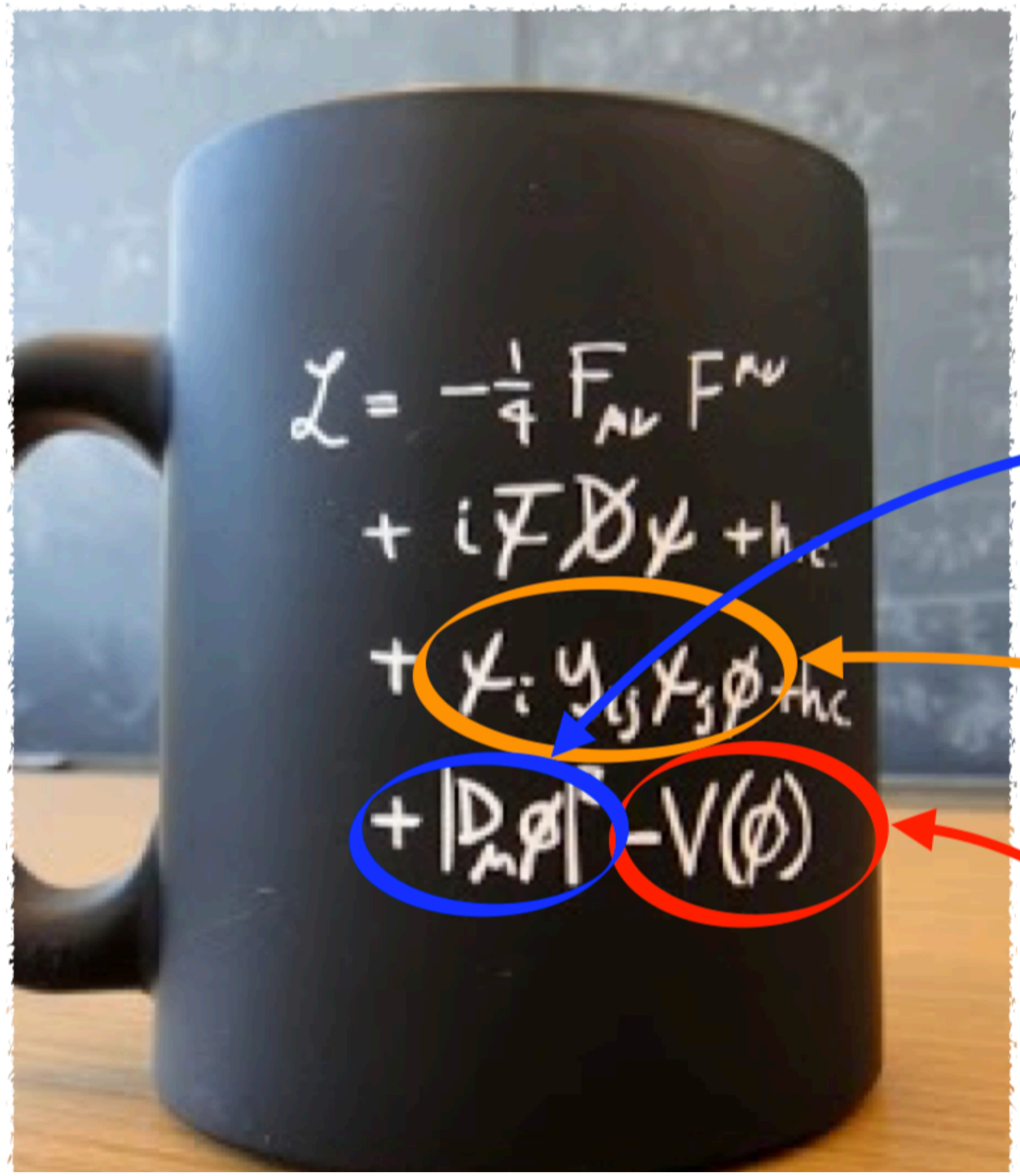


Mateusz Dyndał (KOiDC WFiIS AGH)

Seminarium HEP Bialasowka, 18th June 2021

The 125 GeV Higgs boson

It is the only fundamental scalar with spin 0 we have seen so far



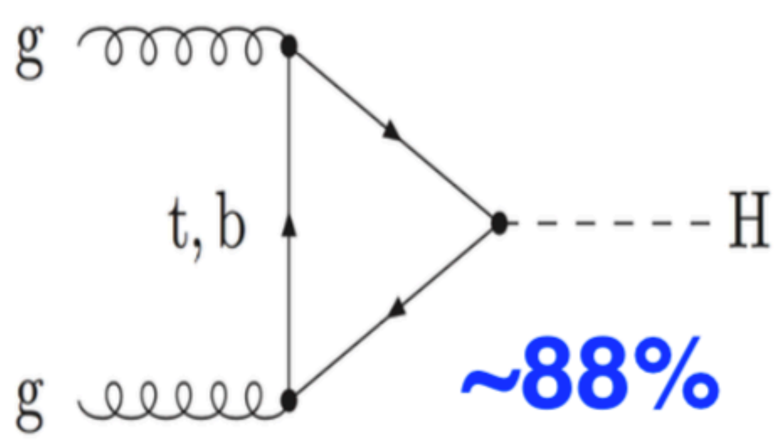
Discovery allows to access a new sector in the Lagrangian:

- Scalar-Gauge boson interactions
- Yukawa couplings (new type of interaction)
- Higgs potential: cornerstone of BEH mechanism, not yet probed experimentally

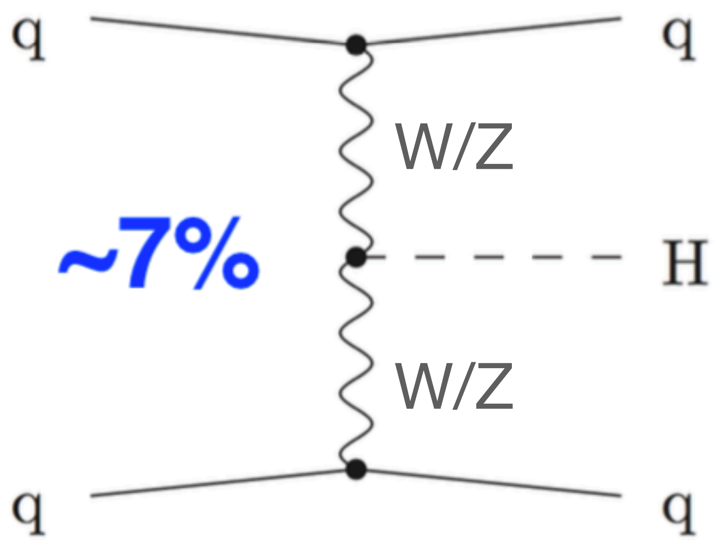
from G. Zanderighi Higgs Hunting'19 talk

Higgs boson production and decay at the LHC

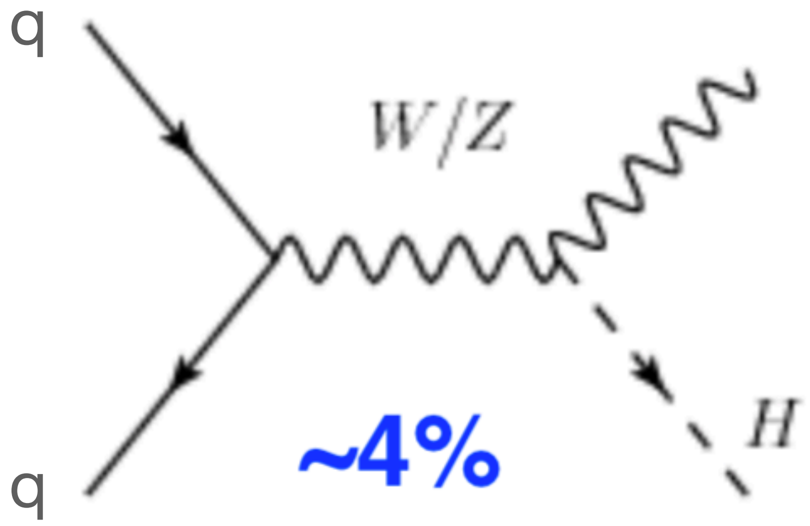
gluon-gluon fusion(ggF)



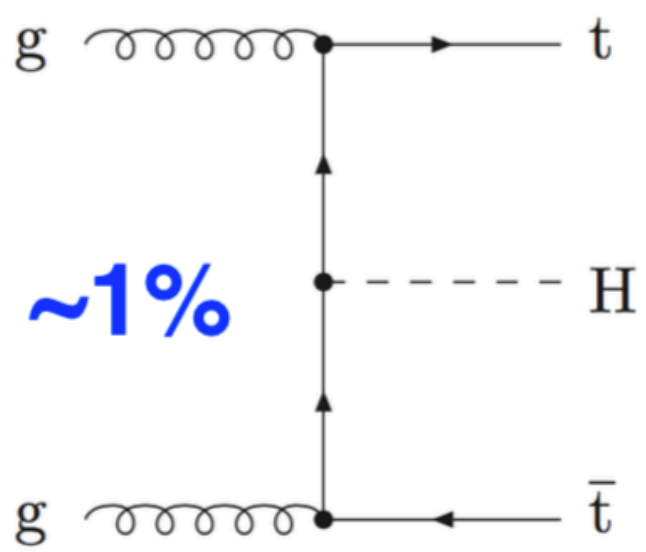
Vector boson fusion(VBF)

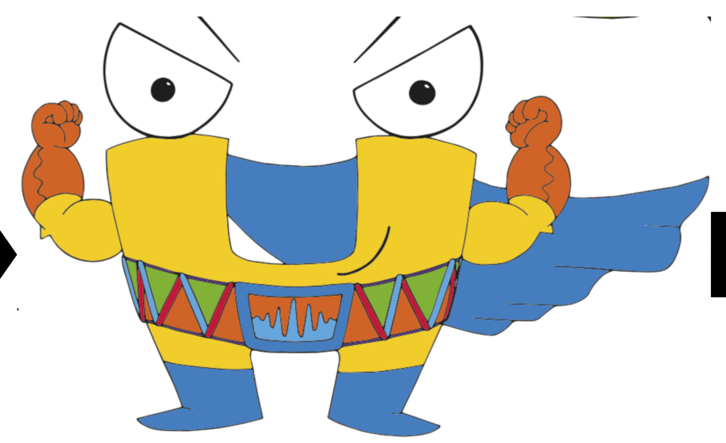


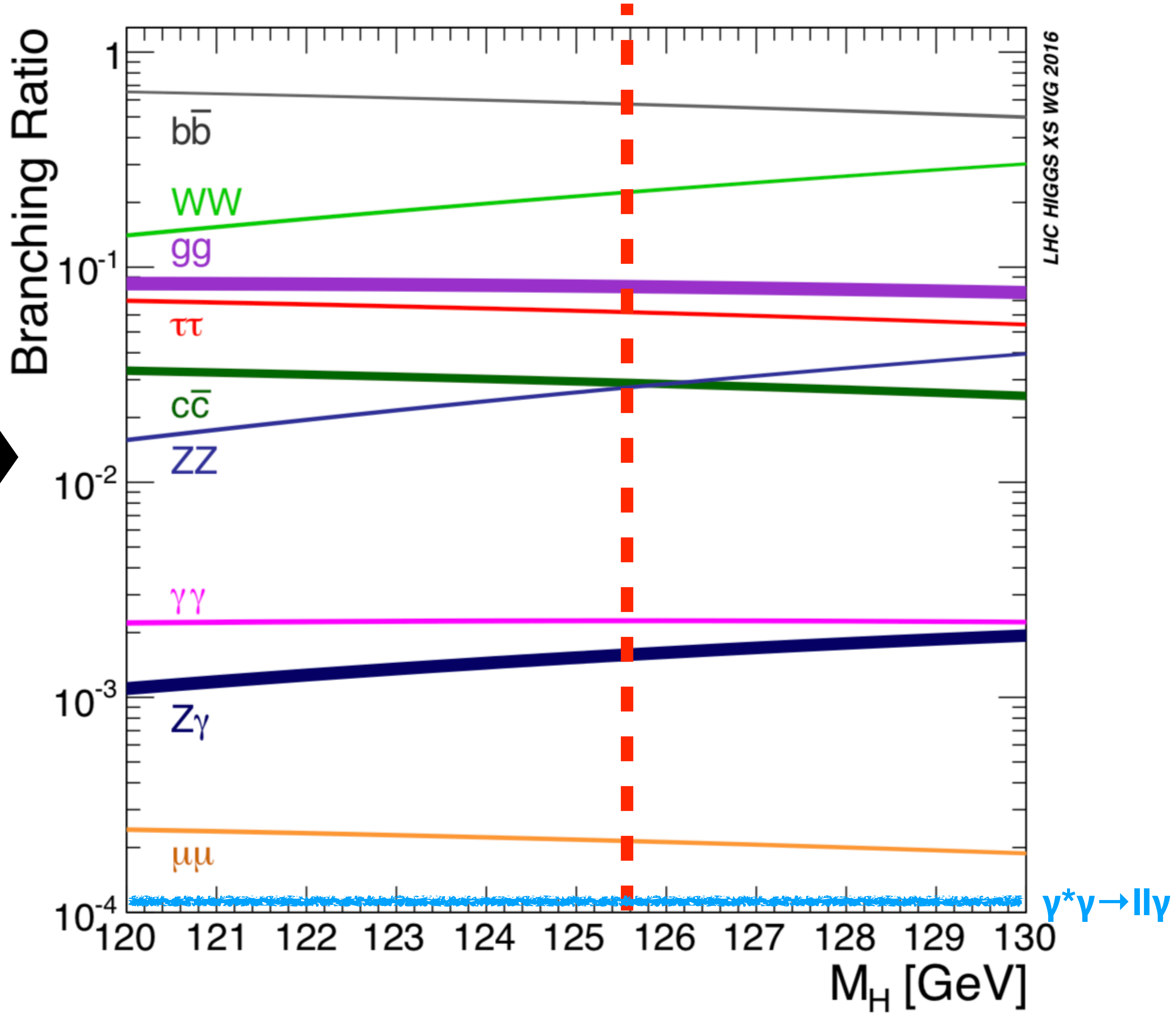
Higgs associated production with vector bosons (VH)



Higgs associated production with a top-quark pair (ttH)

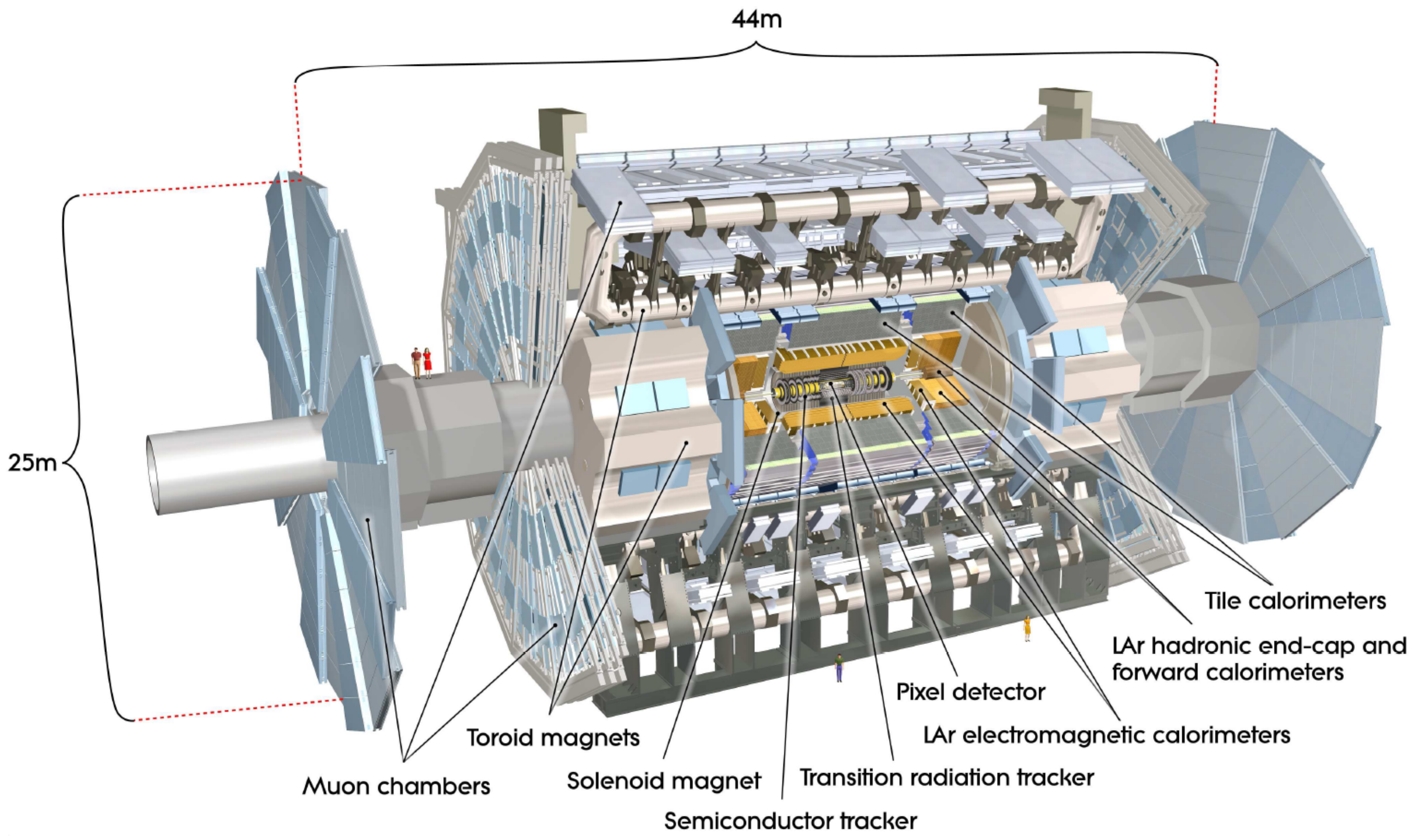


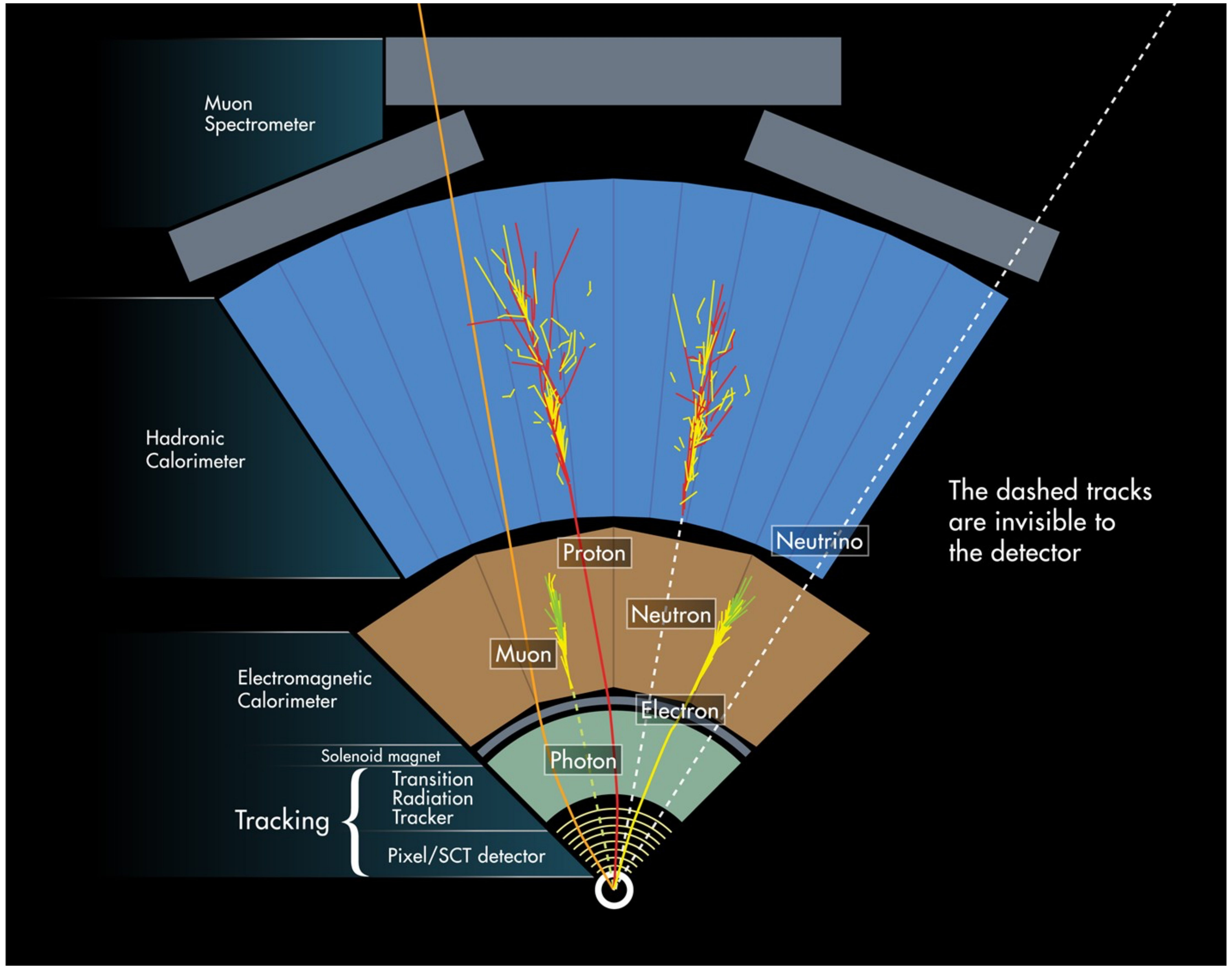




The ATLAS detector at the LHC

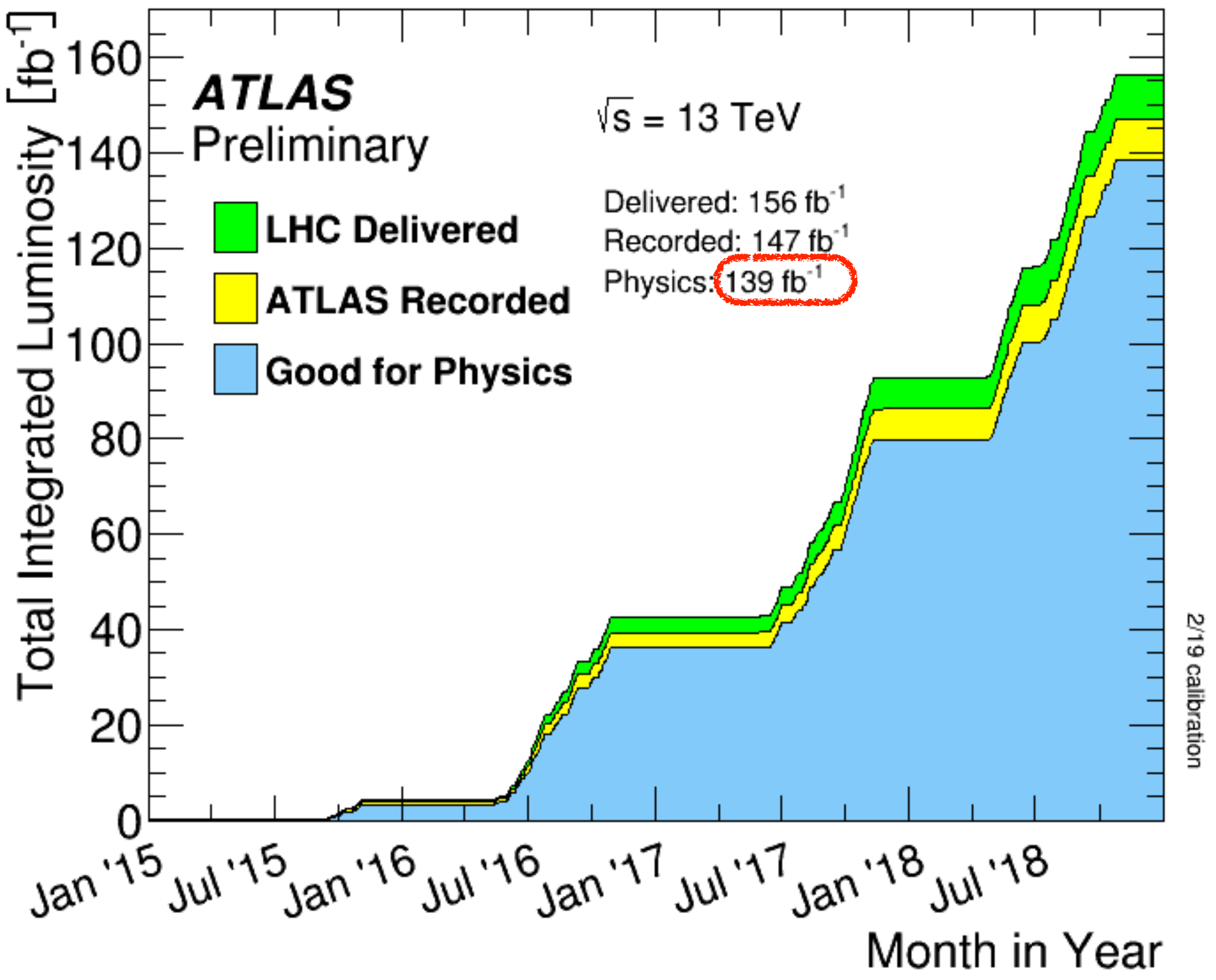
- General-purpose particle physics experiment
  - Designed to exploit the full discovery potential and vast range of physics opportunities that LHC provides





LHC Run 2 period (2015-2018)

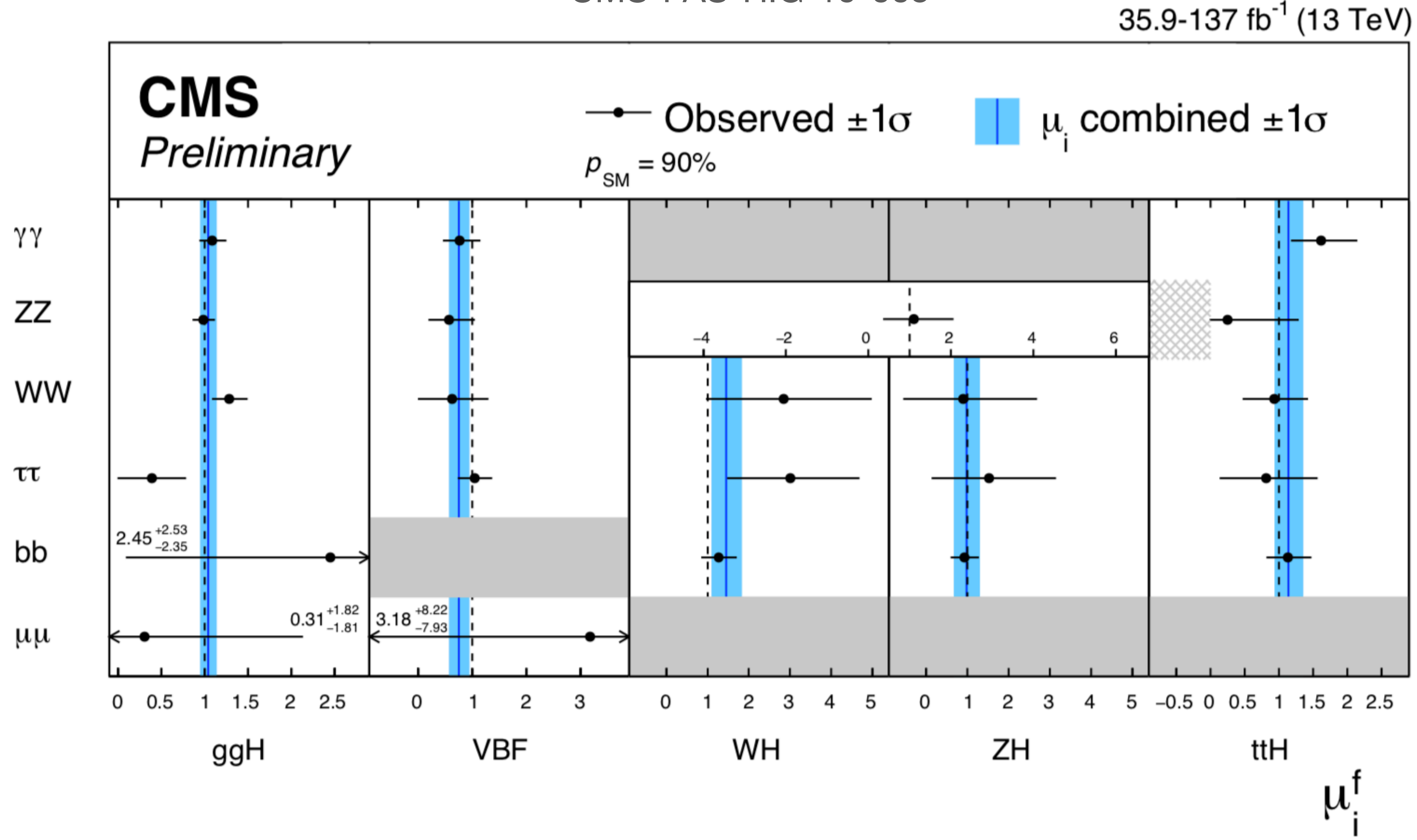
- ATLAS experiment has successfully collected **~140 $\mathbf{fb^{-1}}$** luminosity at **pp 13 TeV** centre-of-mass energy in the full LHC Run 2 period



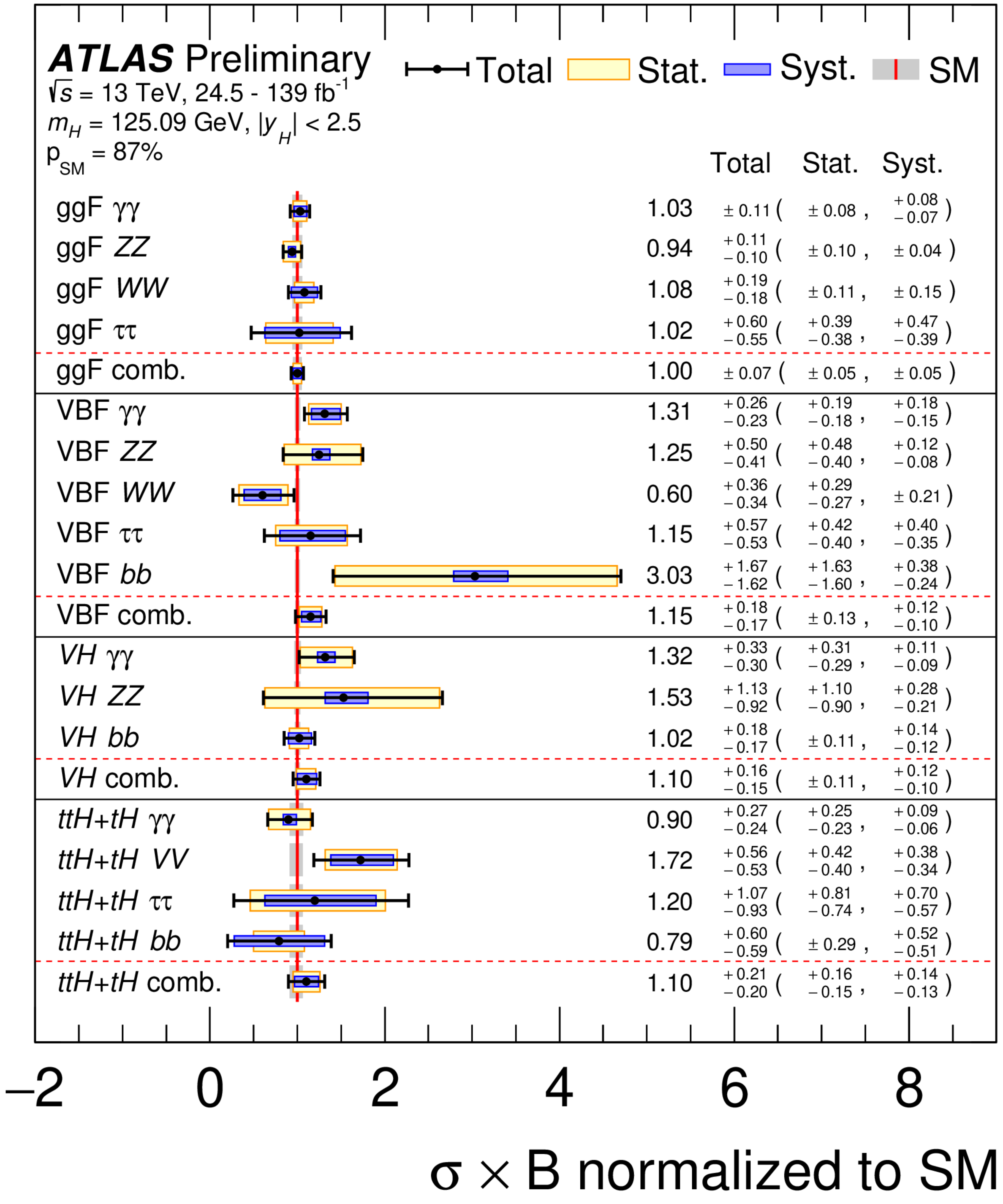
What do we know about the Higgs boson after LHC Run 2?

- Inclusive Higgs **signal strength** combination:
  - **μ = 1.02 ± 0.07** [±0.04(th) ±0.04(exp) ±0.04(stat)] (CMS)
  - **μ = 1.06 ± 0.07** (ATLAS)

CMS-PAS-HIG-19-005



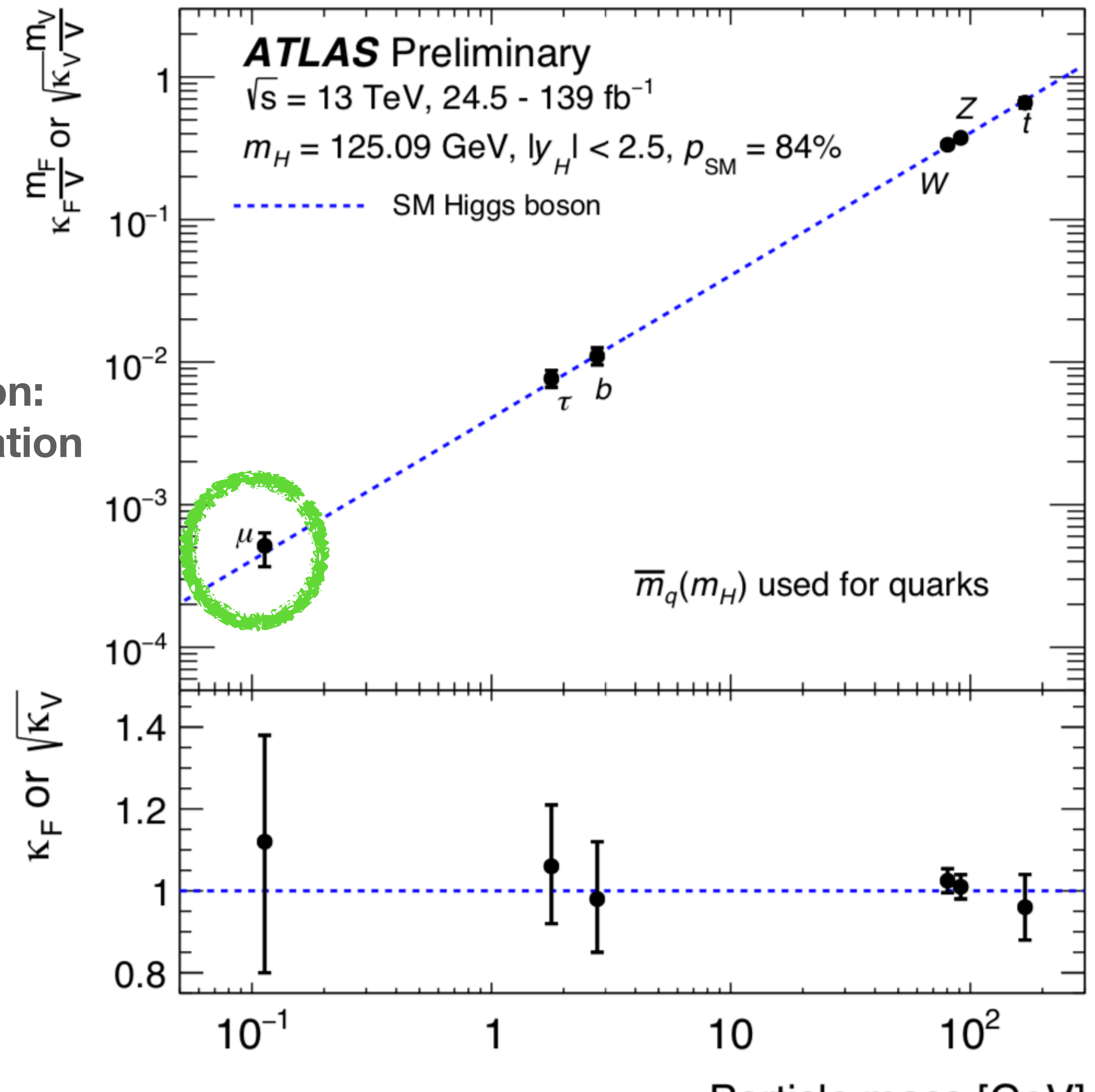
ATLAS-CONF-2020-027



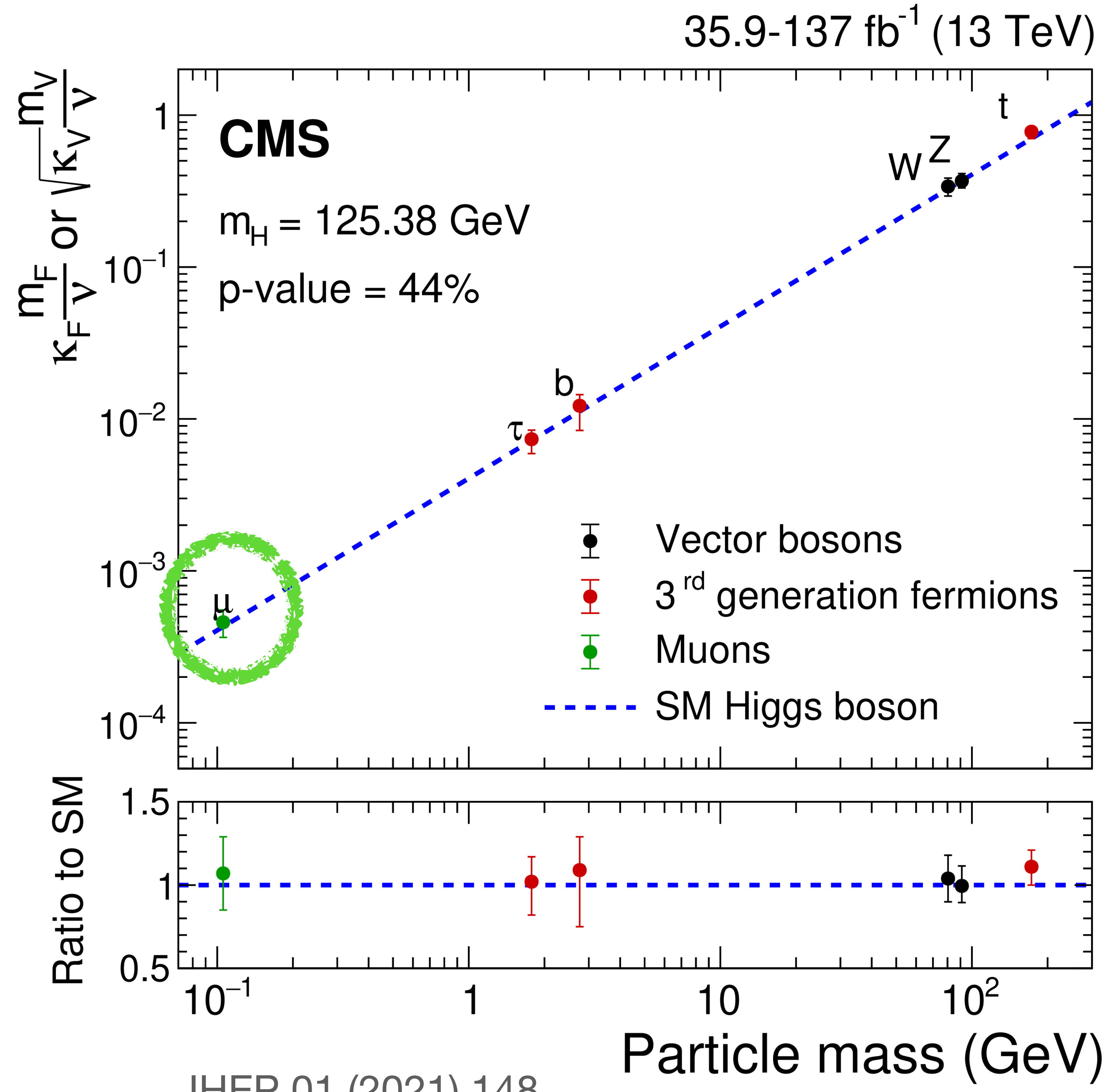
What do we know about the Higgs boson after LHC Run 2?

- ATLAS and CMS have performed global fit of coupling modifiers
  - ~6% uncertainty on Higgs to vector boson couplings
  - ~10-15% uncertainty on Higgs to the 3rd generation fermion couplings
  - This includes recent evidence for H→μμ decay

Footprint of SM Higgs boson: mass versus coupling correlation



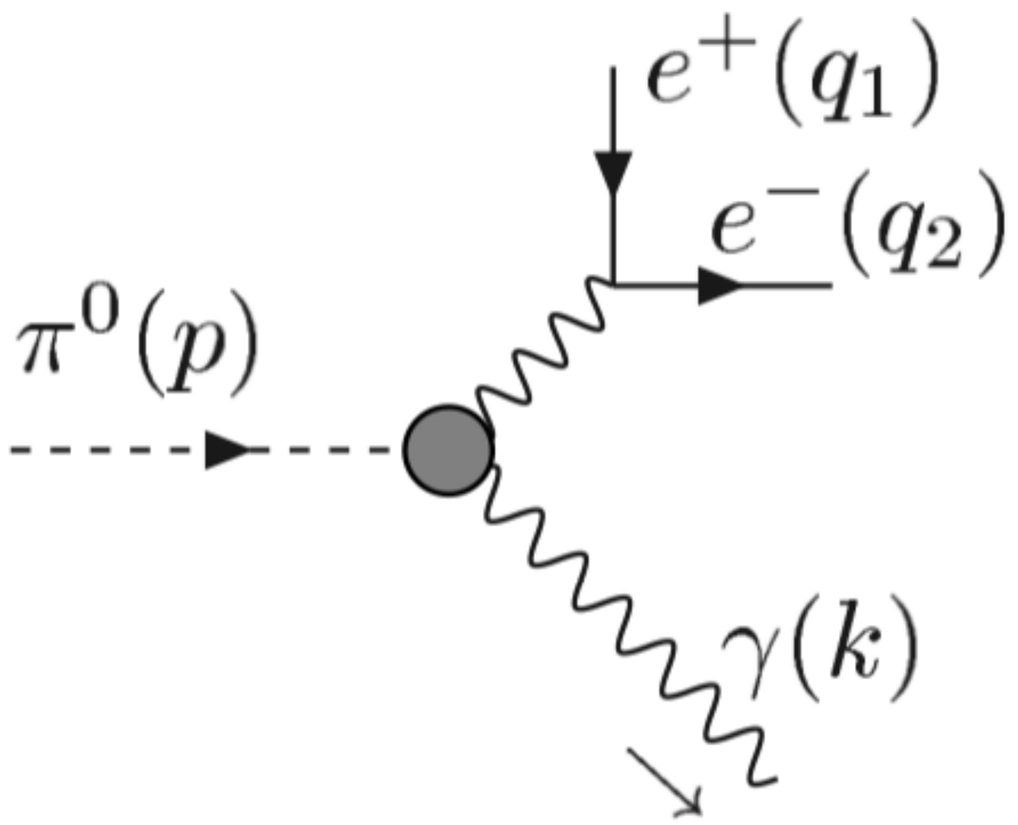
ATLAS-CONF-2020-027



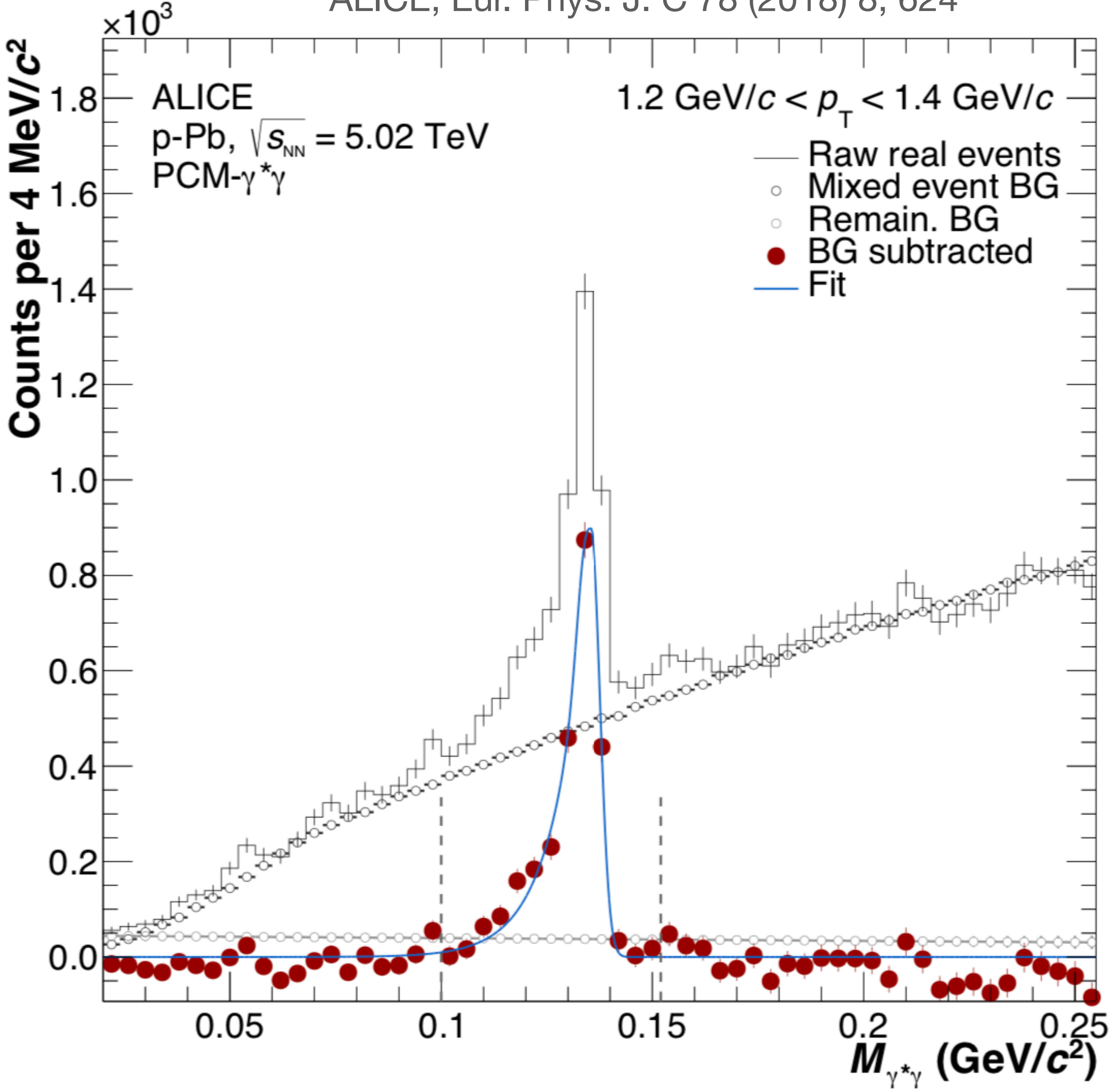
JHEP 01 (2021) 148

Dalitz decay

- Traditionally attributed to mesons decaying to **two leptons** plus a **photon**
  - Mediated via virtual photon exchange
- Famous example: **neutral pion decay**
  - **B(π0→γγ) = 0.988**
  - **B(π0→eeγ) = 0.012**

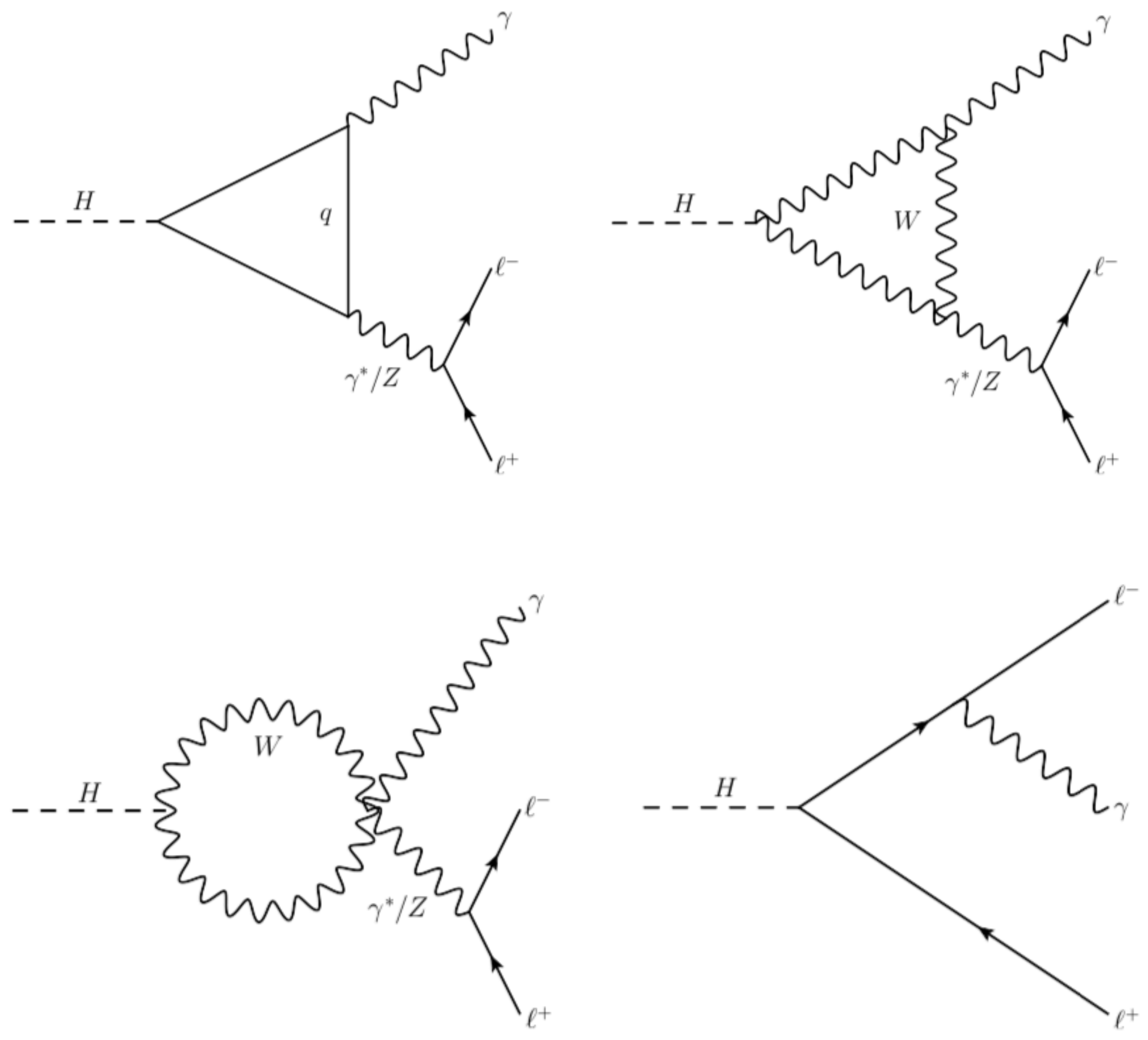


ALICE, Eur. Phys. J. C 78 (2018) 8, 624

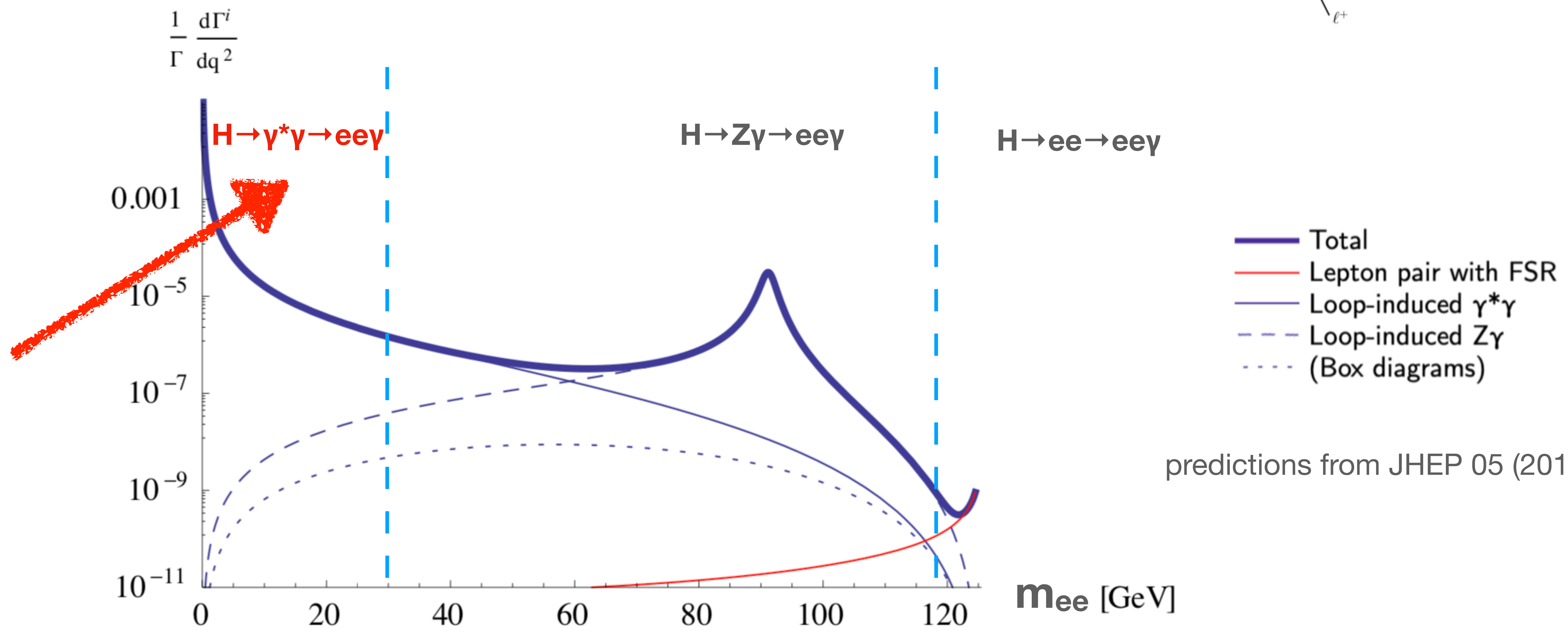


Higgs Dalitz decay (H→llγ)

- Very rare decays (**B < 2×10^{-4}**)
- Several processes contribute to the final state
  - Test of exotic couplings through loops
- Diverse final state kinematics



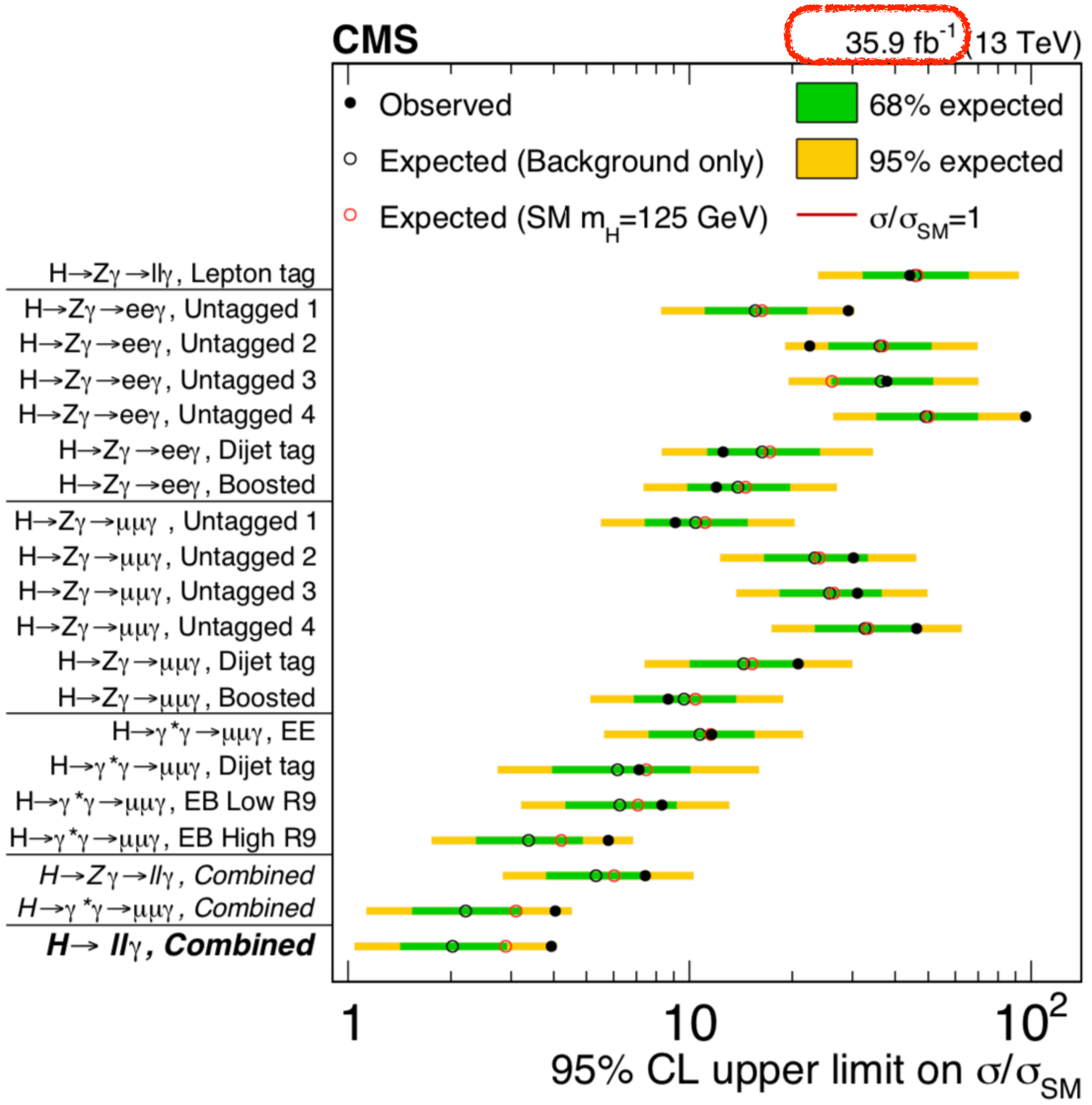
Phase-space of
our new analysis



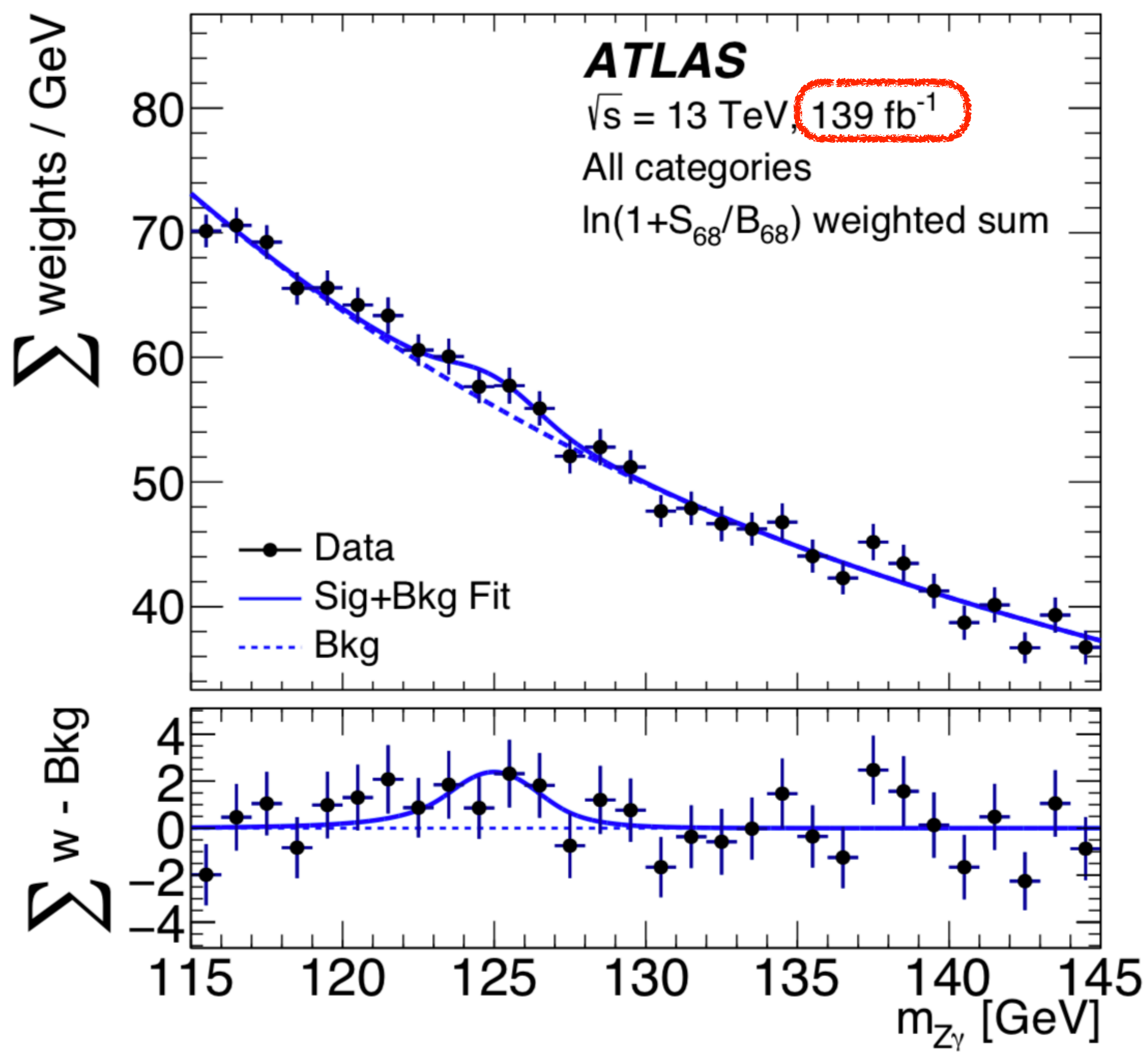
predictions from JHEP 05 (2013) 061

Previous measurements of H→llγ

H→llγ [CMS, JHEP 11 (2018) 152]
Upper limit Zγ: 7.5 * SM (expected w/ Higgs: 6 * SM)
Upper limit γ*γ (μμ): 4 * SM (expected w/Higgs: 3 * SM)



H→Zγ [ATLAS, Phys. Lett. B 809 (2020) 135754]
mll: Z boson mass +/-10 GeV
significance: 2.2 σ (expected w/ Higgs: 1.2 σ)
upper limit: 3.6 * SM (expected w/ Higgs: 2.6 * SM)



New search for H→llγ decays with ATLAS

Phys. Lett. B 819 (2021) 136412

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Evidence for Higgs boson decays to a low-mass dilepton system and a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Check for updates

The ATLAS Collaboration *

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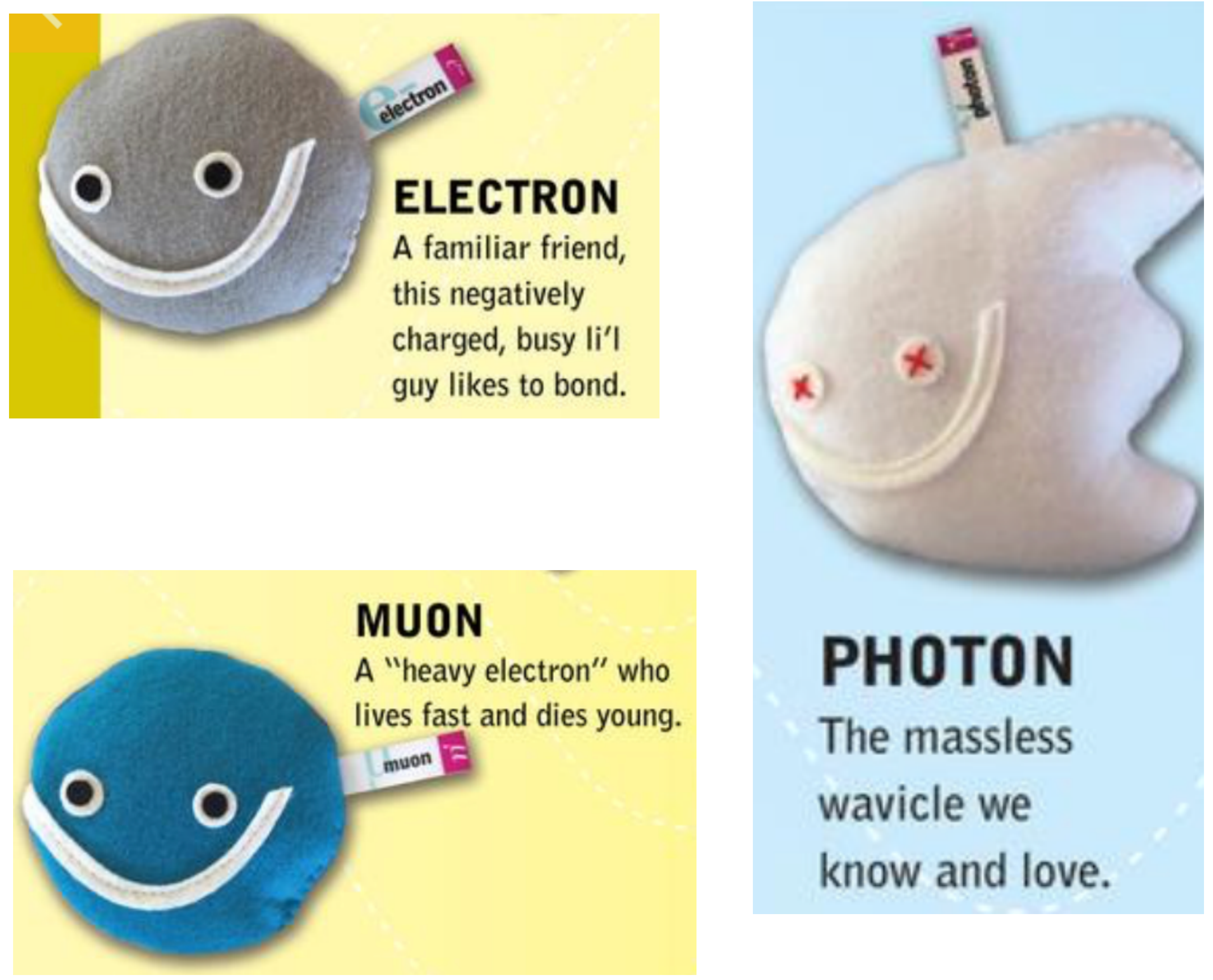
ABSTRACT

A search for the Higgs boson decaying into a photon and a pair of electrons or muons with an invariant mass $m_{\ell\ell} < 30$ GeV is presented. The analysis is performed using 139 fb^{-1} of proton–proton collision data, produced by the LHC at a centre-of-mass energy of 13 TeV and collected by the ATLAS experiment. Evidence for the $H \to \ell\ell\gamma$ process is found with a significance of 3.2 over the background-only hypothesis, compared to an expected significance of 2.1 for the Standard Model prediction. The best-fit value of the signal-strength parameter, defined as the ratio of the observed signal yield to the one expected in the Standard Model, is $\mu = 1.5 \pm 0.5$. The Higgs boson production cross-section times the $H \to \ell\ell\gamma$ branching ratio for $m_{\ell\ell} < 30$ GeV is determined to be $8.7^{+2.8}_{-2.7}$ fb.

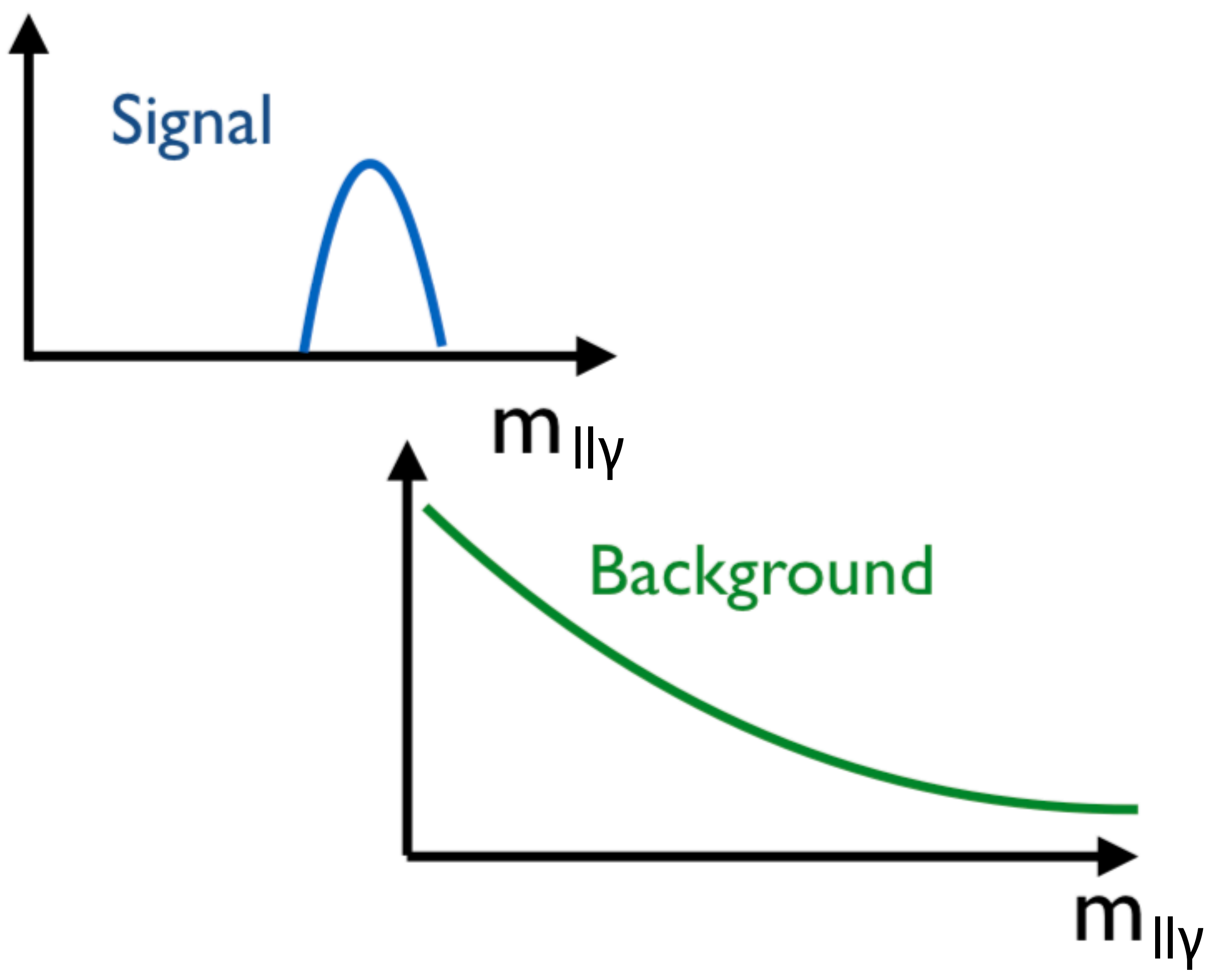
Search for H→llγ decays at low-m_{ll} with ATLAS

- Rough sketch of analysis procedure:
  - Object and event selection + categorisation (**Step 1**)
  - Signal and background parameterisations (**Step 2**)
  - Simultaneous fit to all categories (**Step 3**)

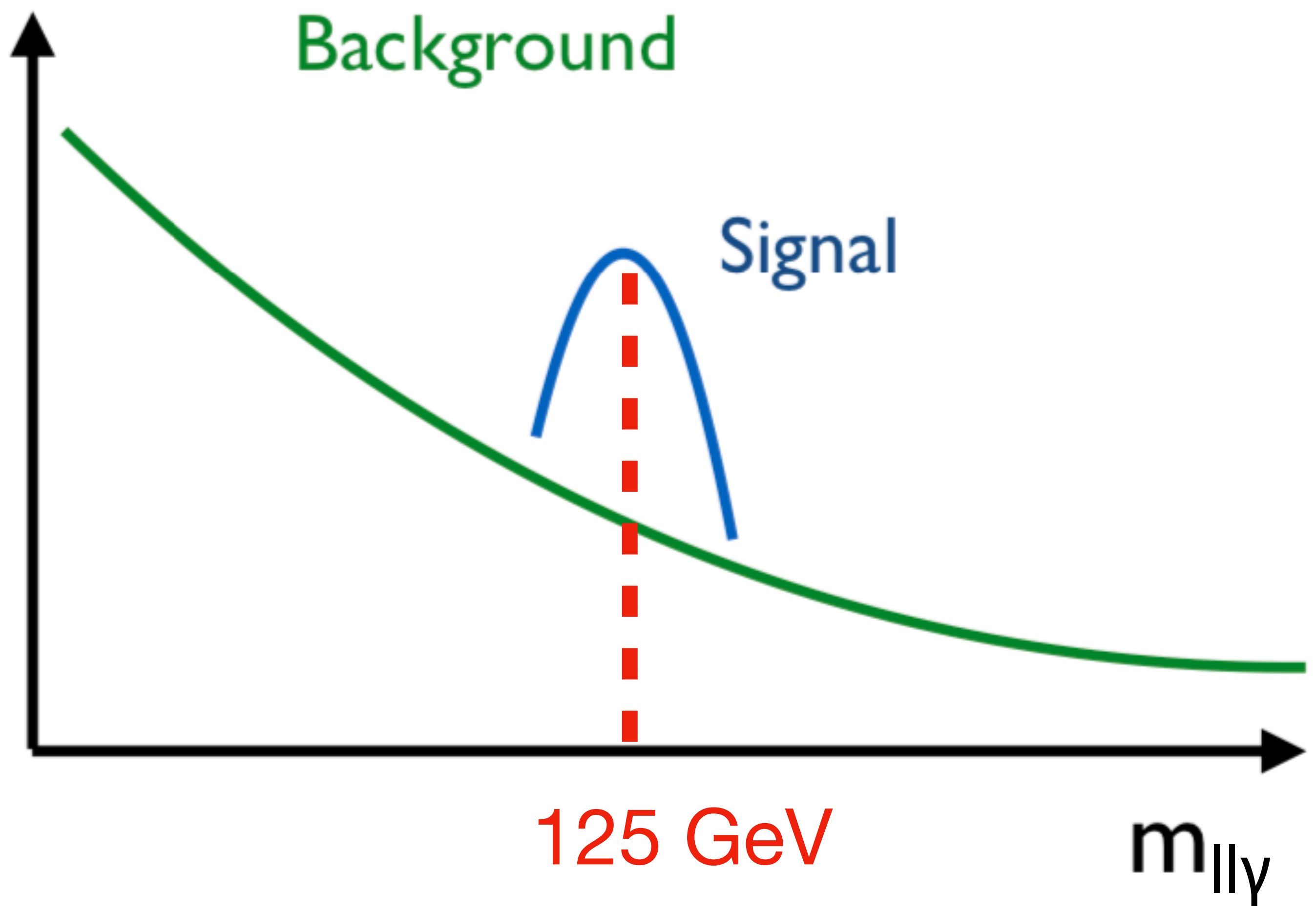
Step 1



Step 2



Step 3

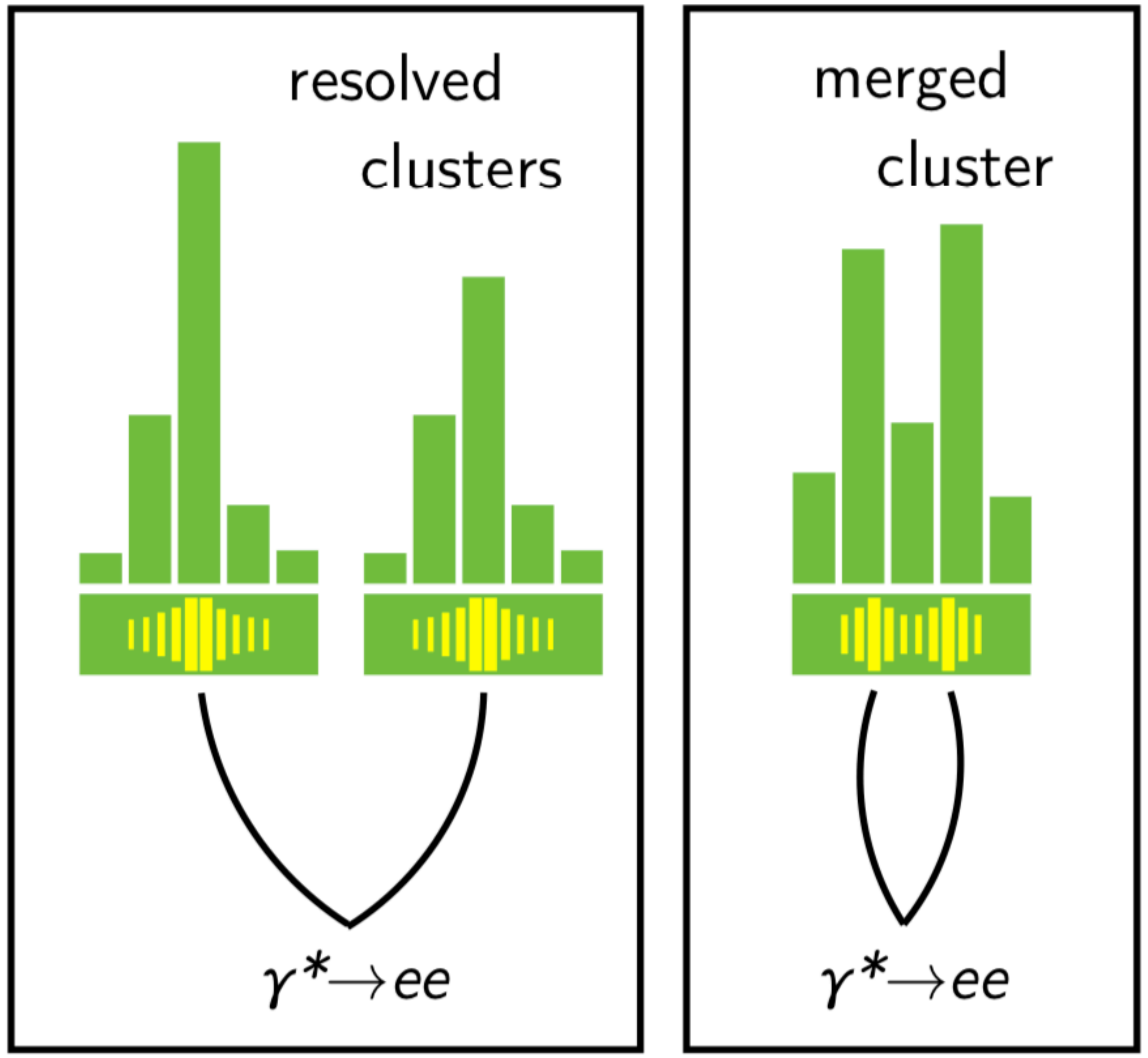


Event selection

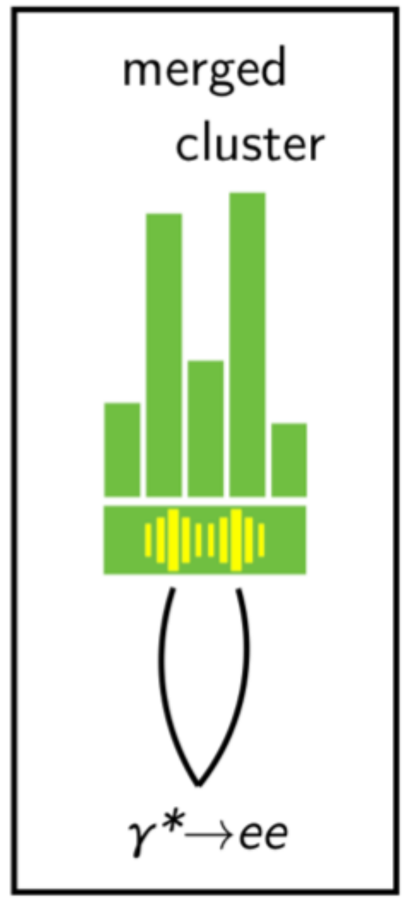
- Trigger:
  - Combination of **single-lepton**, **2l**, **γ+l, γγ**, **γ+2l** triggers is used
  - Dedicated **merged-ee + γ** trigger is also employed

- Object selection:
  - Photons: Isolated with $p_T > 20$ GeV
  - Muons: Isolated (leading) with $p_T > 3$ (11) GeV
  - Electrons: Isolated (leading) with $p_T > 4.5$ (13) GeV
  - **Merged-ee**: isolated with $p_T > 20$ GeV
  - Jets: $p_T > 25$ GeV

- Select an opposite-sign same flavor lepton pair (μμ or ee or merged-ee) + γ
  - **$m_{ll} < 30$ GeV** and veto J/Psi and Upsilon mass range
  - Relative p_T cuts: $p_{T,ll} / m_{ll\gamma} > 0.3$, $p_T(\gamma)/m_{ll\gamma} > 0.3$



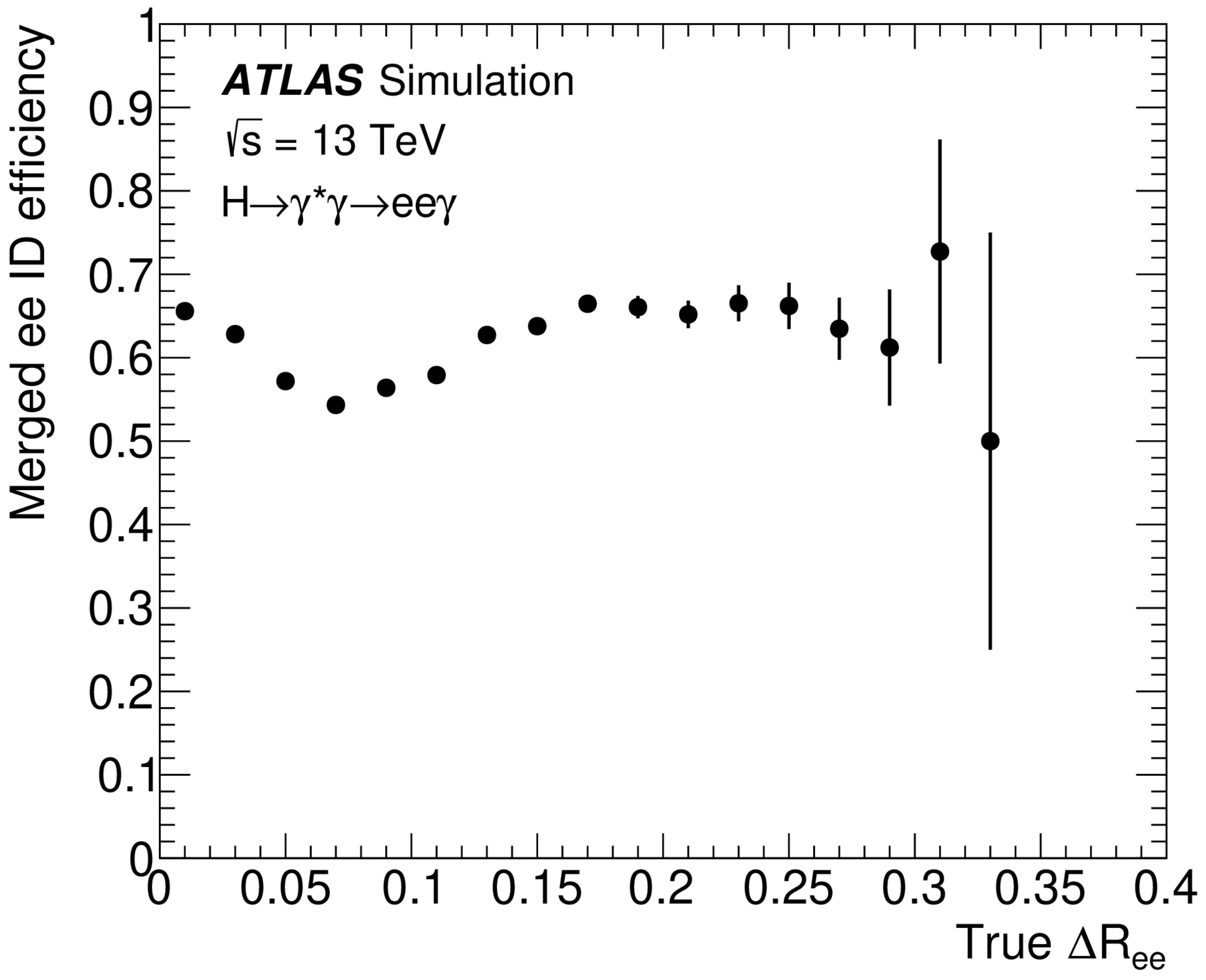
Merged-ee identification



- The algorithm
  - Due to the low mass of the **dielectron pair** they are often collimated
  - Requires dedicated identification (**ID**) to ensure reasonable efficiency is maintained vs angular separation

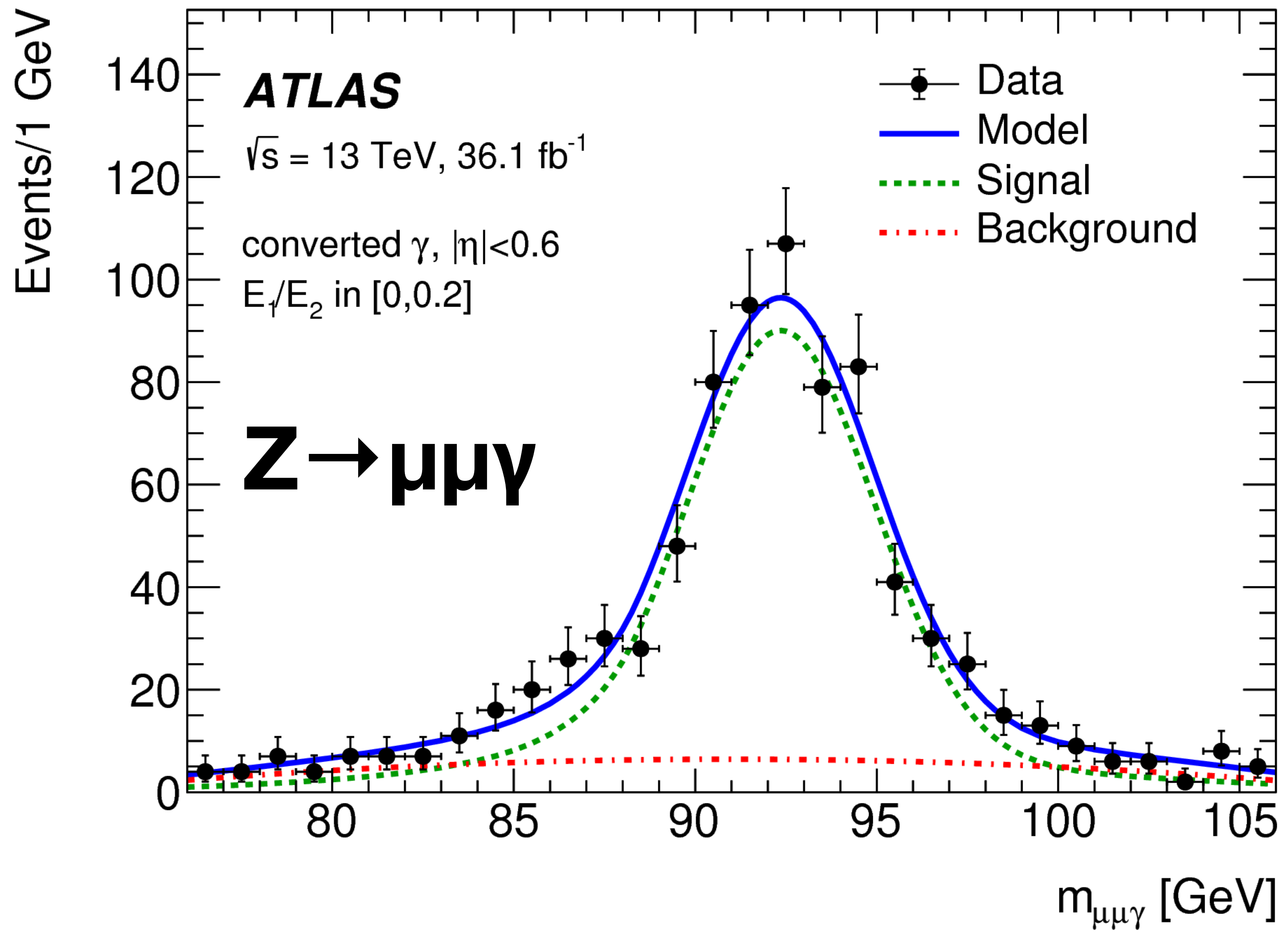
- Cut-based **ID** inputs:
  - EM shower shapes
  - Vertex contracted from the 2 selected tracks
  - Vertex-cluster and track-cluster matching requirements
  - Additional cuts to reduce background from single electrons

- Optimisation is performed using **multivariate analysis techniques**

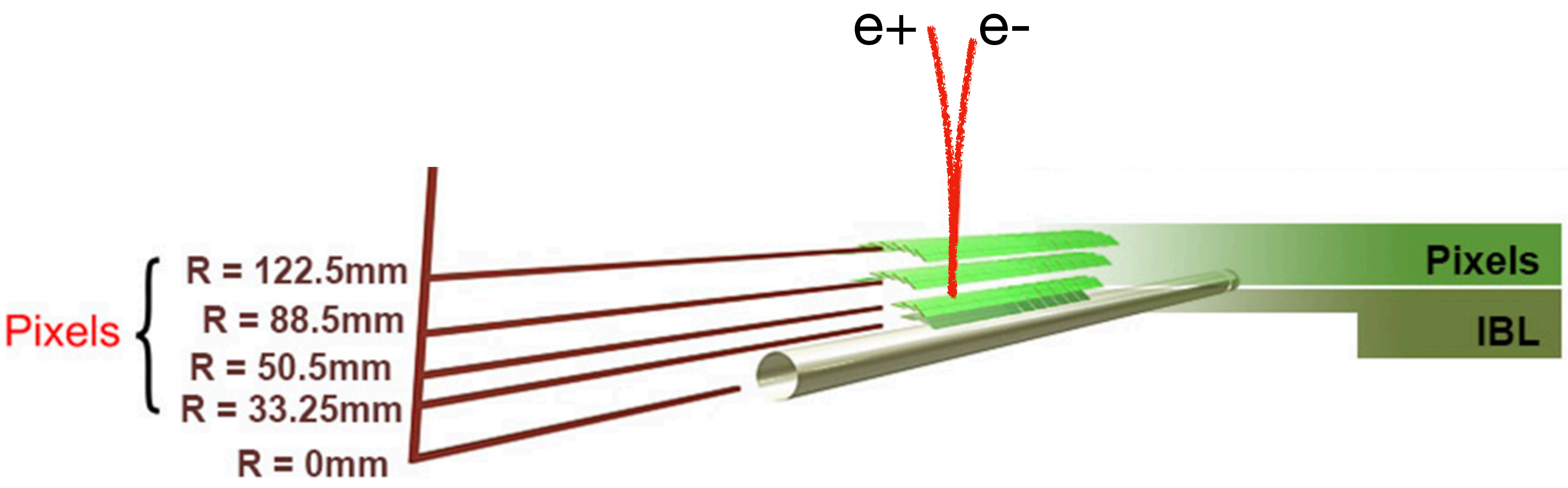


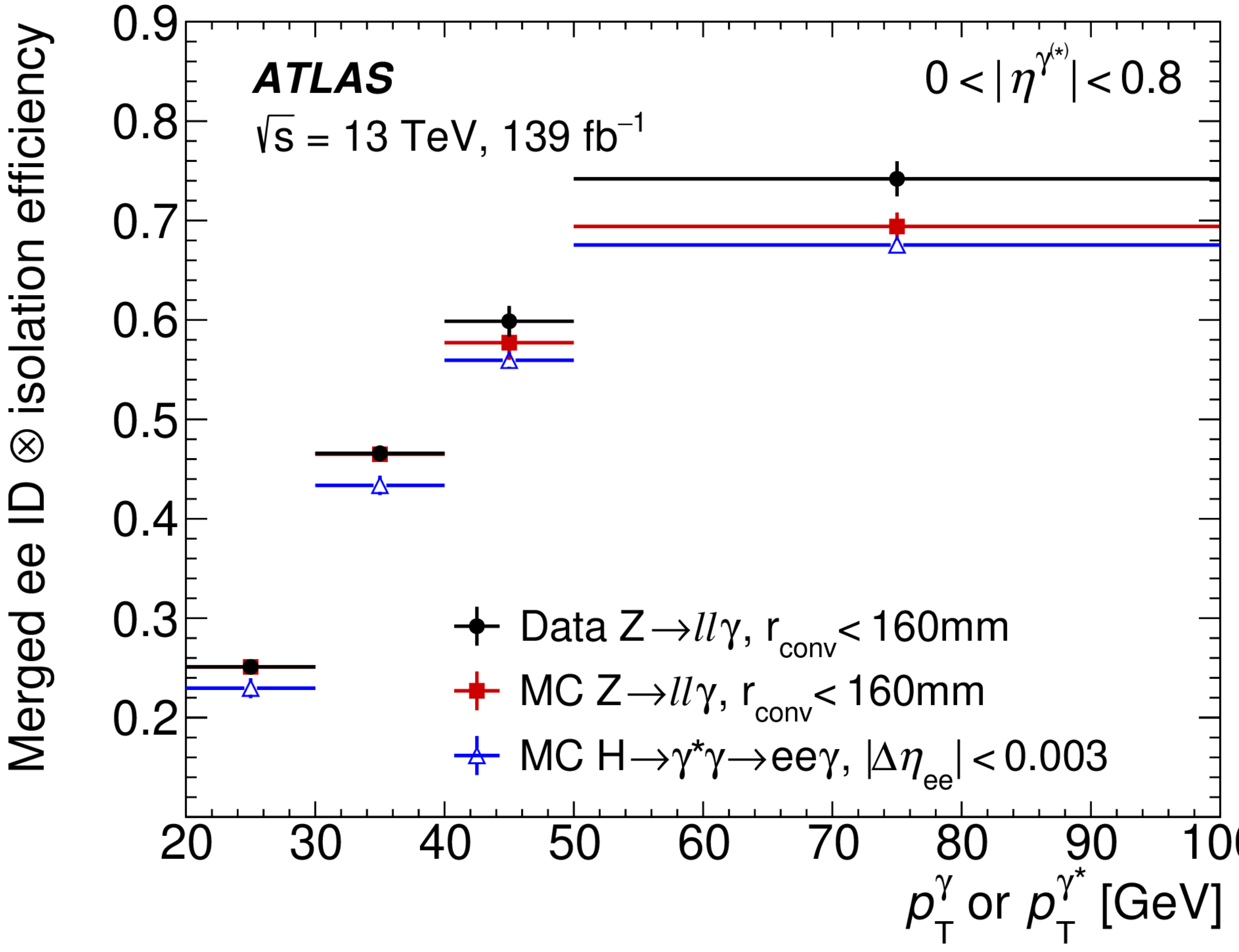
Merged-ee identification and calibration

- Use **Z→llγ** events to perform efficiency measurements
  - Consider only **converted photons**, with conversion radius <160 mm to have an object similar to γ*
  - Extract efficiency of combined merged-ee PID + isolation requirements



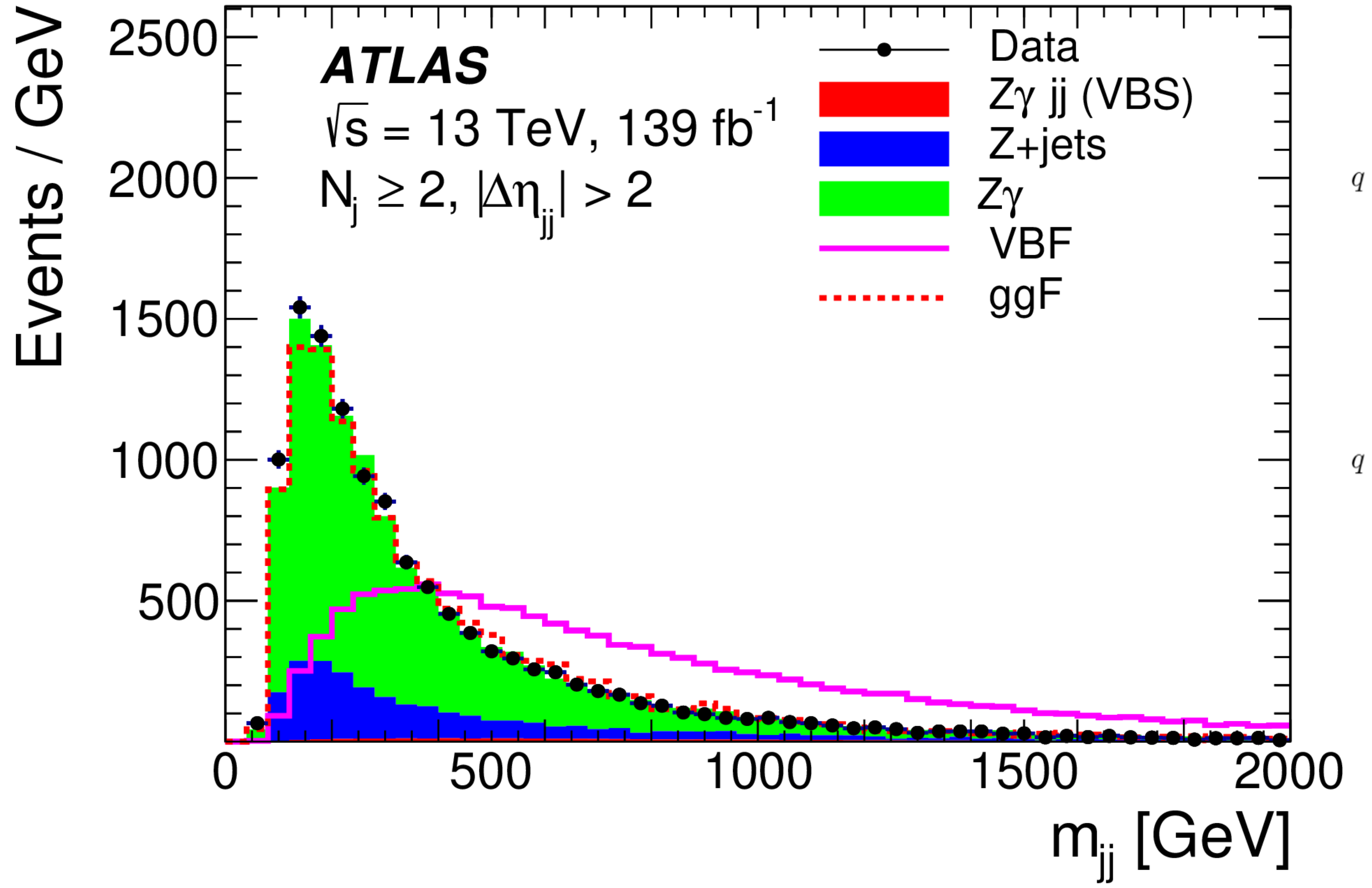
- Energy calibration
  - Merged-ee objects are similar to converted photons
  - Calibrate γ* as an early converted photon with radius 30 mm

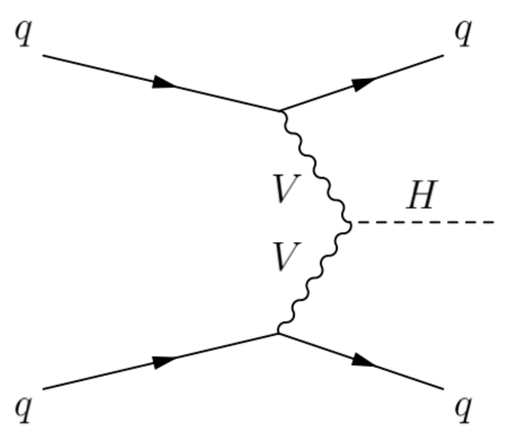


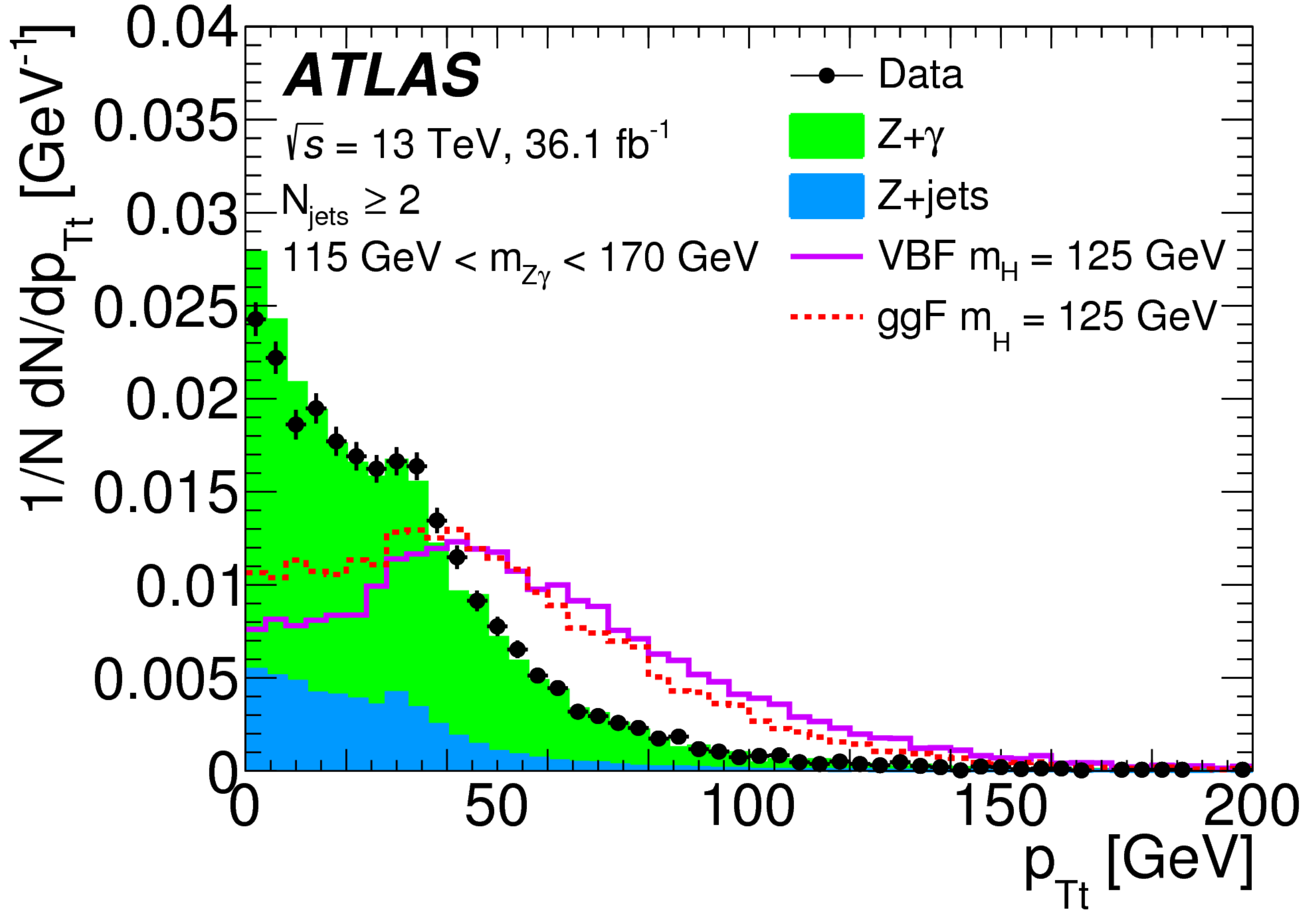


Event kinematics

- In **VBF process**, valence quarks scatter resulting in a large dijet invariant mass
    - Jets in non-resonant llγ are mostly from gluon radiation and have lower invariant masses
- $\mathbf{p_{Tt}} = 2|p_{T,ll}||p_{T,\gamma}| \sin \Delta\phi_{ll,\gamma} / p_{T,ll\gamma}$
    - While **correlated with Higgs $\mathbf{p_T}$**, p_{Tt} has lower experimental uncertainties & lower correlation with the Higgs boson mass
    - Larger values for signal than the non-resonant backgrounds



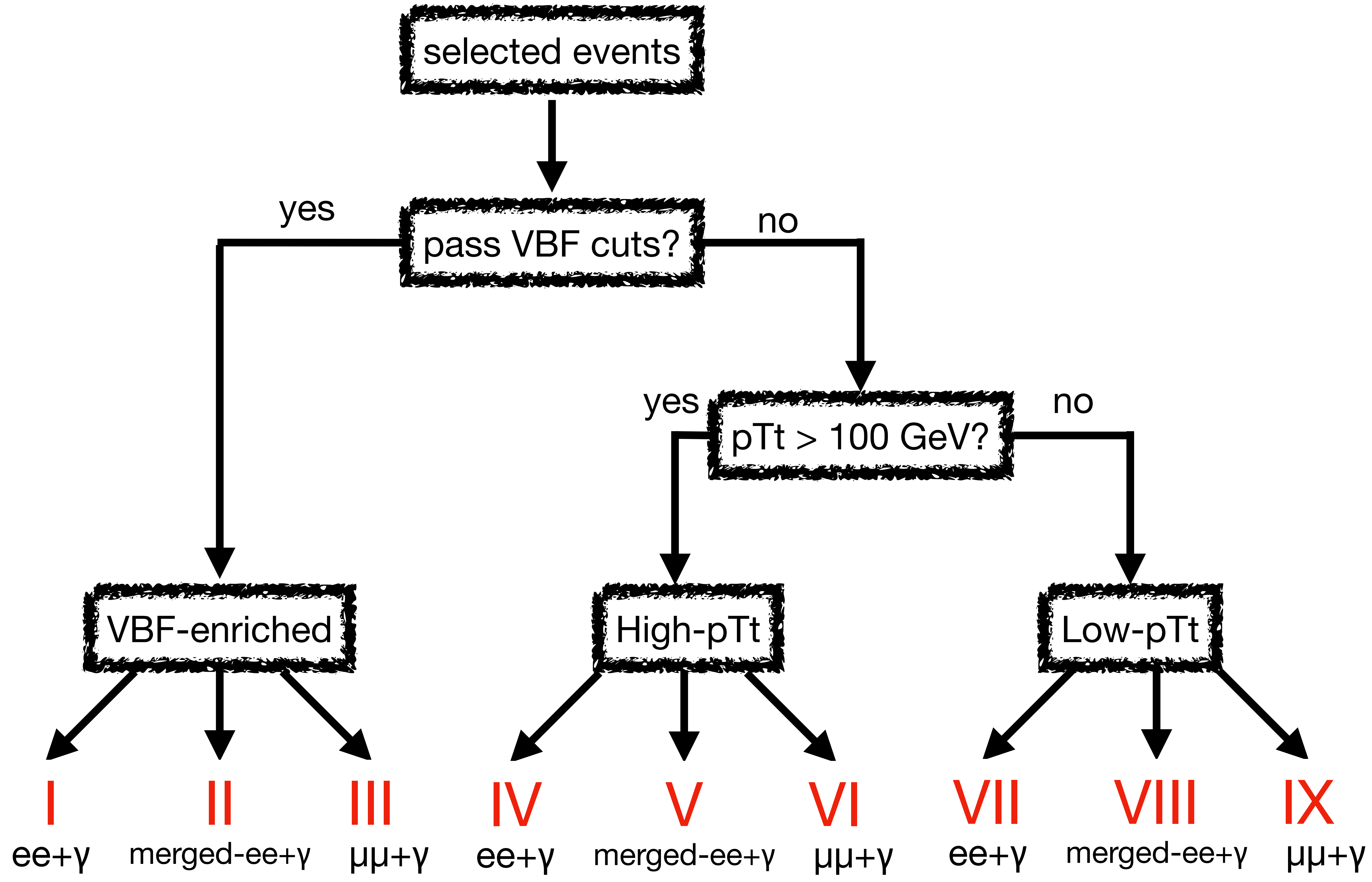




Event categorisation

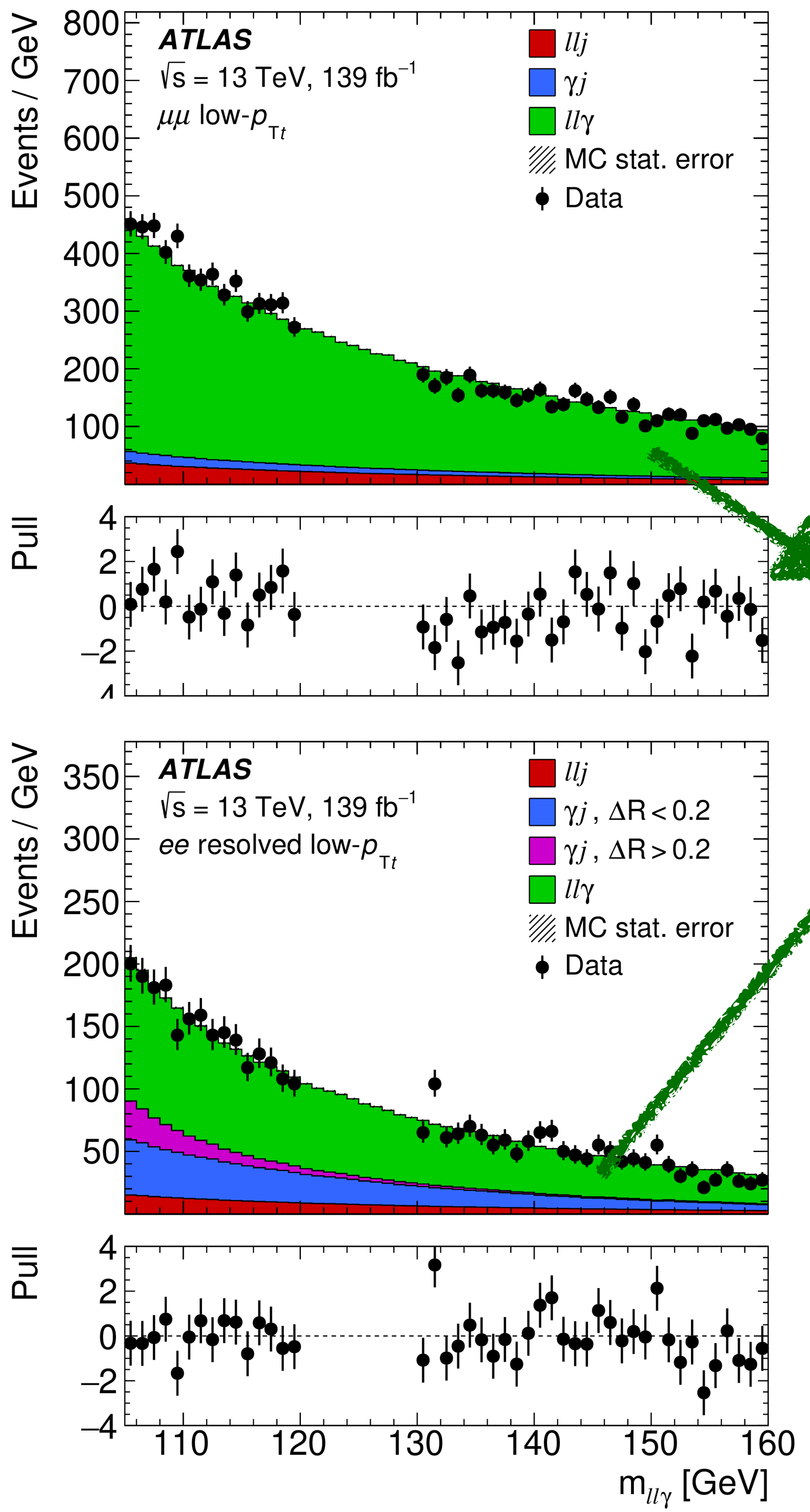
- For each event signature (μμ, ee, merged-ee),
  3 kinematic categories are created (**9 categories** in total)

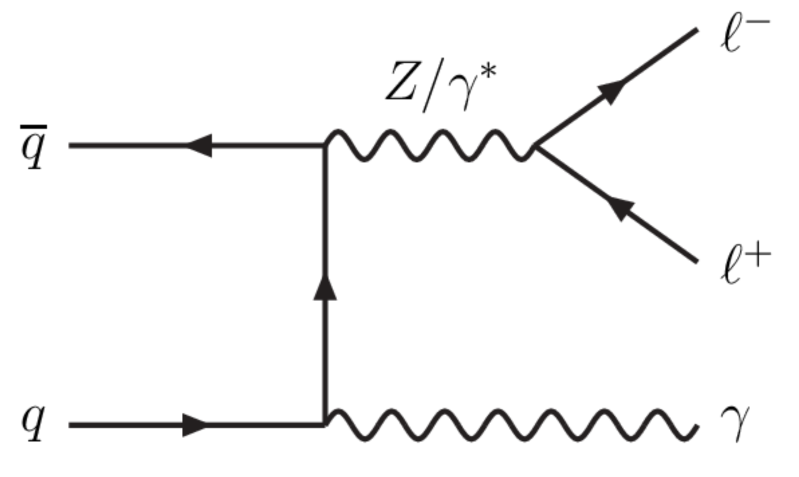
- **VBF-enriched**
  - >= 2 jets
  - $m_{jj} > 500$ GeV
  - $\Delta\eta_{jj} > 2.7$
  - $\Delta\phi(ll\gamma,jj) > 2.8$
  - …
- **High-p_{Tt}**
  - !VBF-enriched & $p_{Tt} > 100$ GeV
- **Low-p_{Tt}**
  - Remaining events



Background studies

- **Estimated backgrounds** are used for:
  - Optimization
  - Background fit choice
  - Note the final background estimation is from data
- Non-resonant llγ (prompt photons)
  - Obtained from MC simulation
- Fake background (jets faking photons or jets faking leptons)
  - Obtained from data control regions
  - Relative fraction is also estimated from data

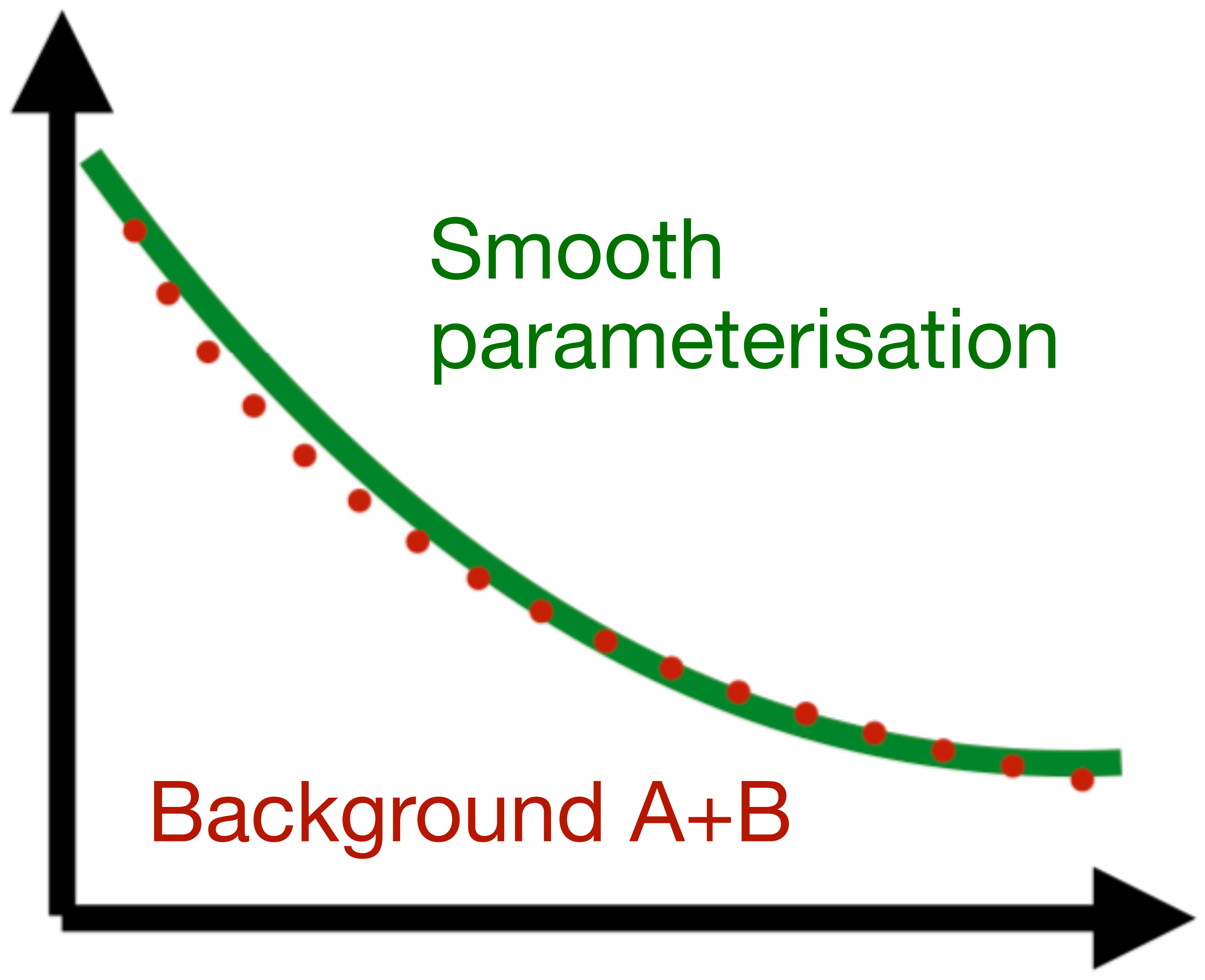




Background modeling

- Parameterisation of the background shape is performed using parametric functions
  - Choices of functions: exponential, Bernstein, and power functions

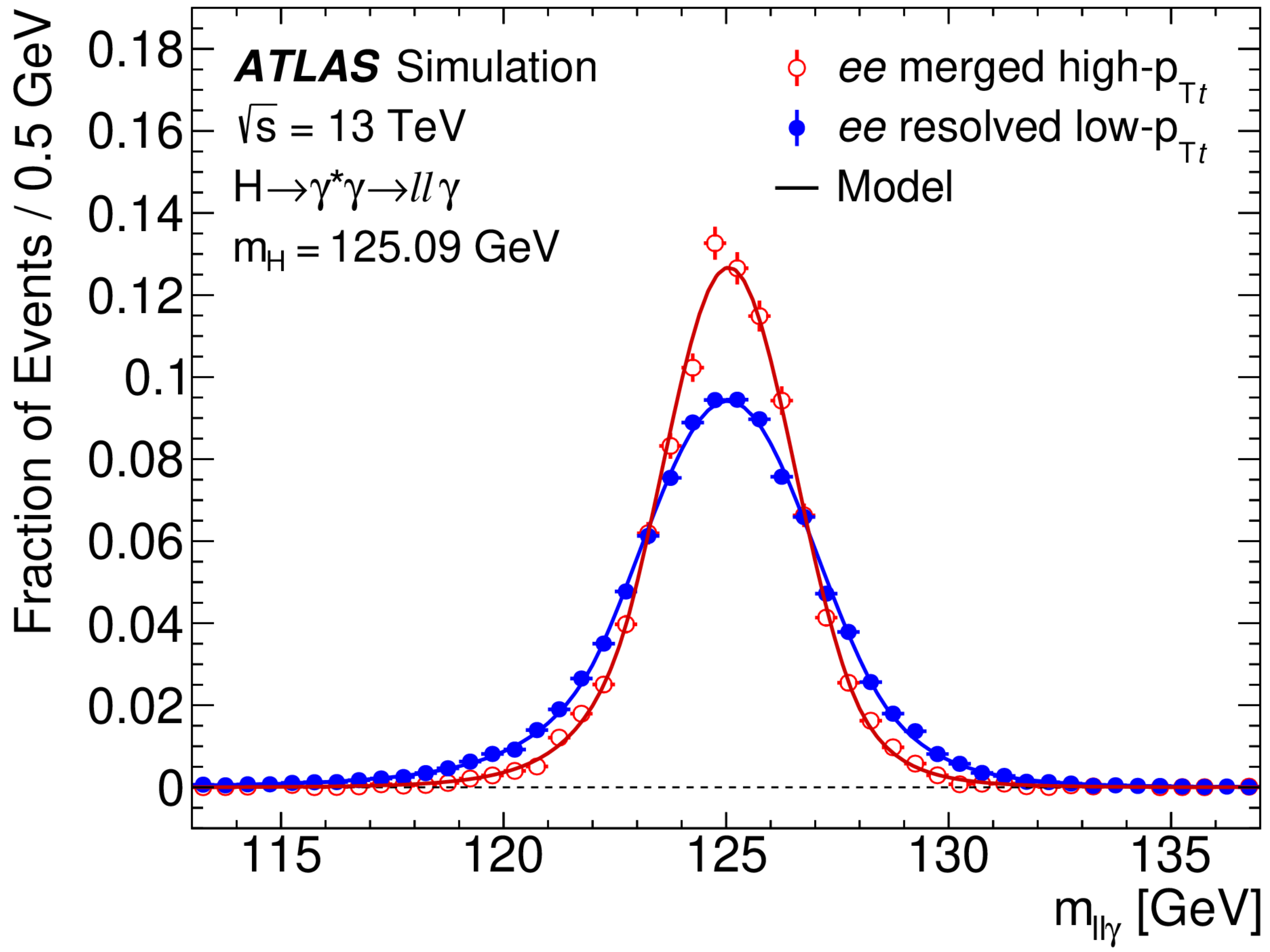
- Background function choice
  - Signal+Background fit to **expected background templates**
  - Functions with **low bias** and with **low degrees of freedom** are preferred
  - Any bias in the signal strength is taken as a systematic uncertainty



Channel	Function
μμ VBF-enriched	m^{α}
μμ High-$p_{T\text{-Thrust}}$	m^{α}
μμ Low-$p_{T\text{-Thrust}}$	$e^{\alpha m+\beta m\times m}$
Merged e VBF-enriched	m^{α}
Merged e High-$p_{T\text{-Thrust}}$	m^{α}
Merged e Low-$p_{T\text{-Thrust}}$	$e^{\alpha m+\beta m\times m}$
Resolved e VBF-enriched	$e^{\alpha m}$
Resolved e High-$p_{T\text{-Thrust}}$	m^{α}
Resolved e Low-$p_{T\text{-Thrust}}$	m^{α}

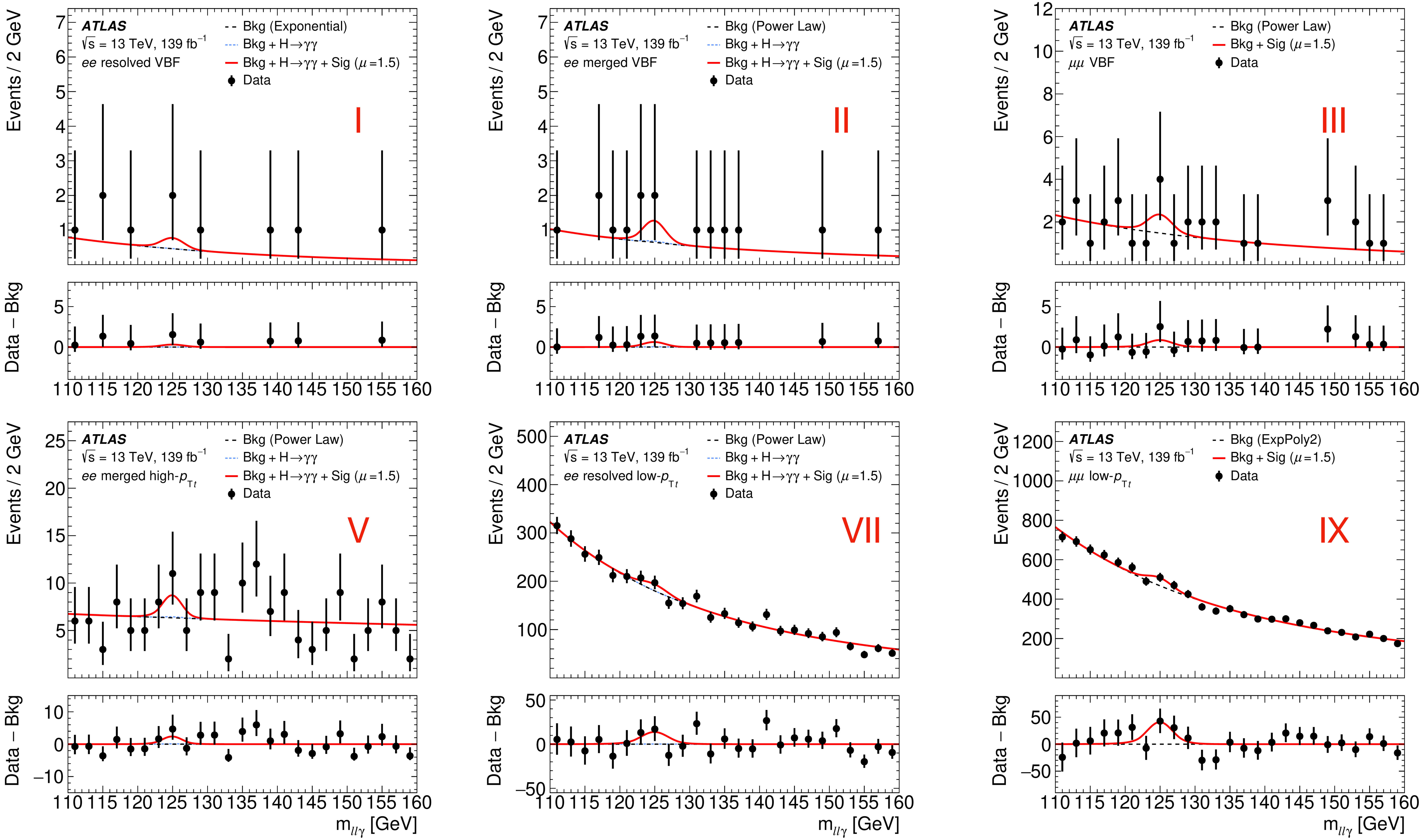
Signal modeling

- Double-sided Crystal Ball function (DSCB) is used to model the signal in each event category
  - Gaussian core + (asymmetric) power-law tails



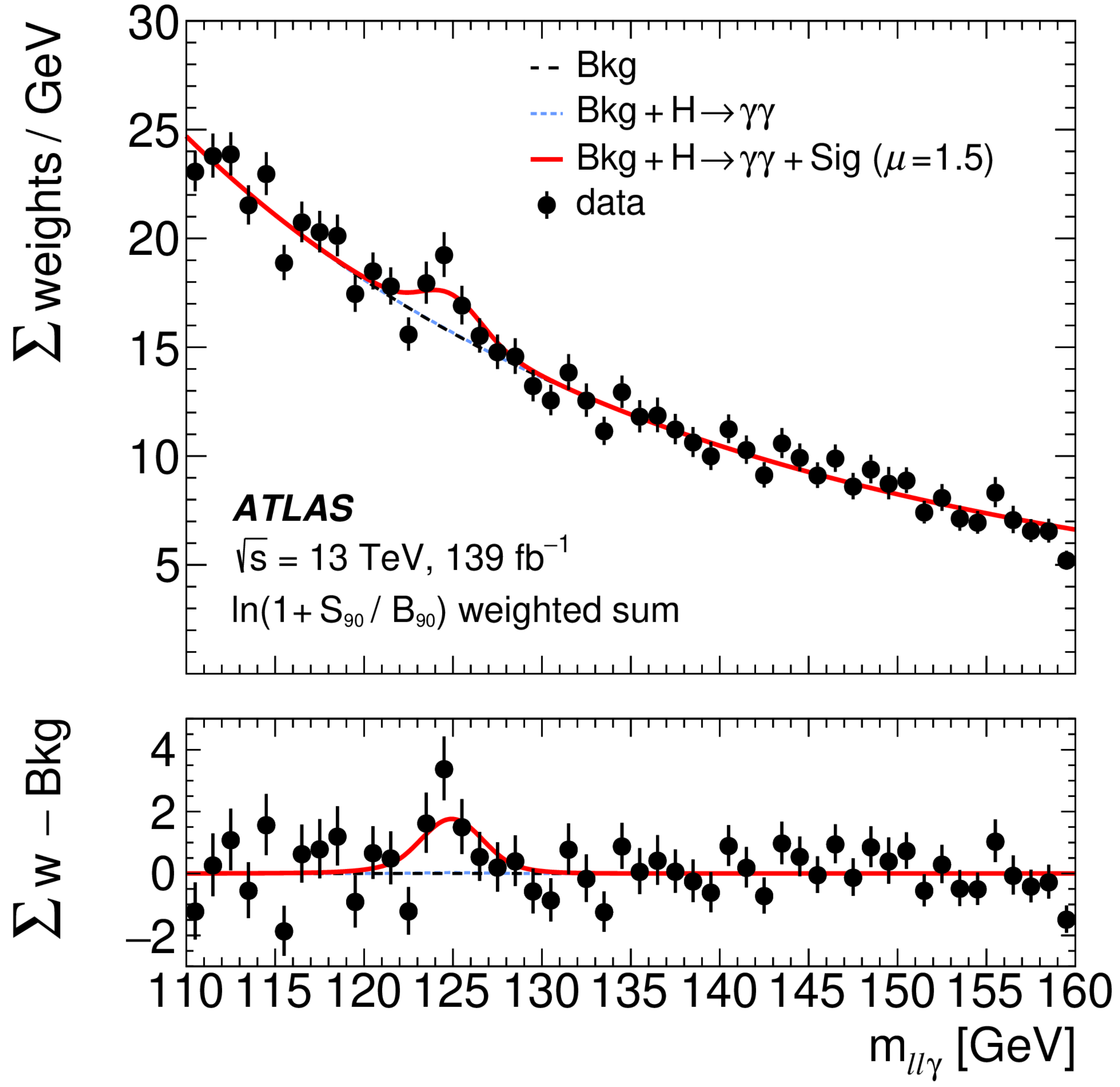
Signal regions

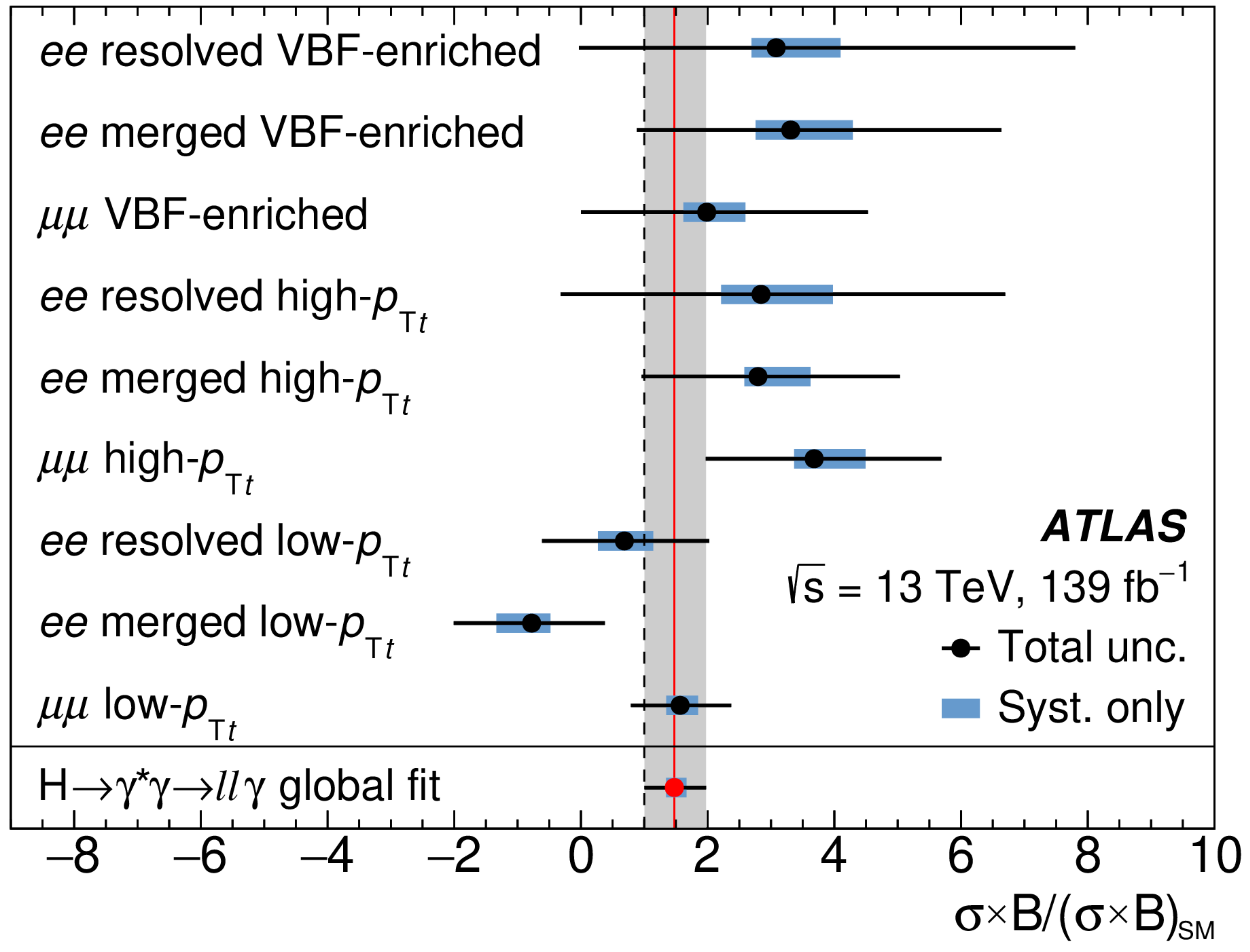
Six (out of nine) signal regions are shown below



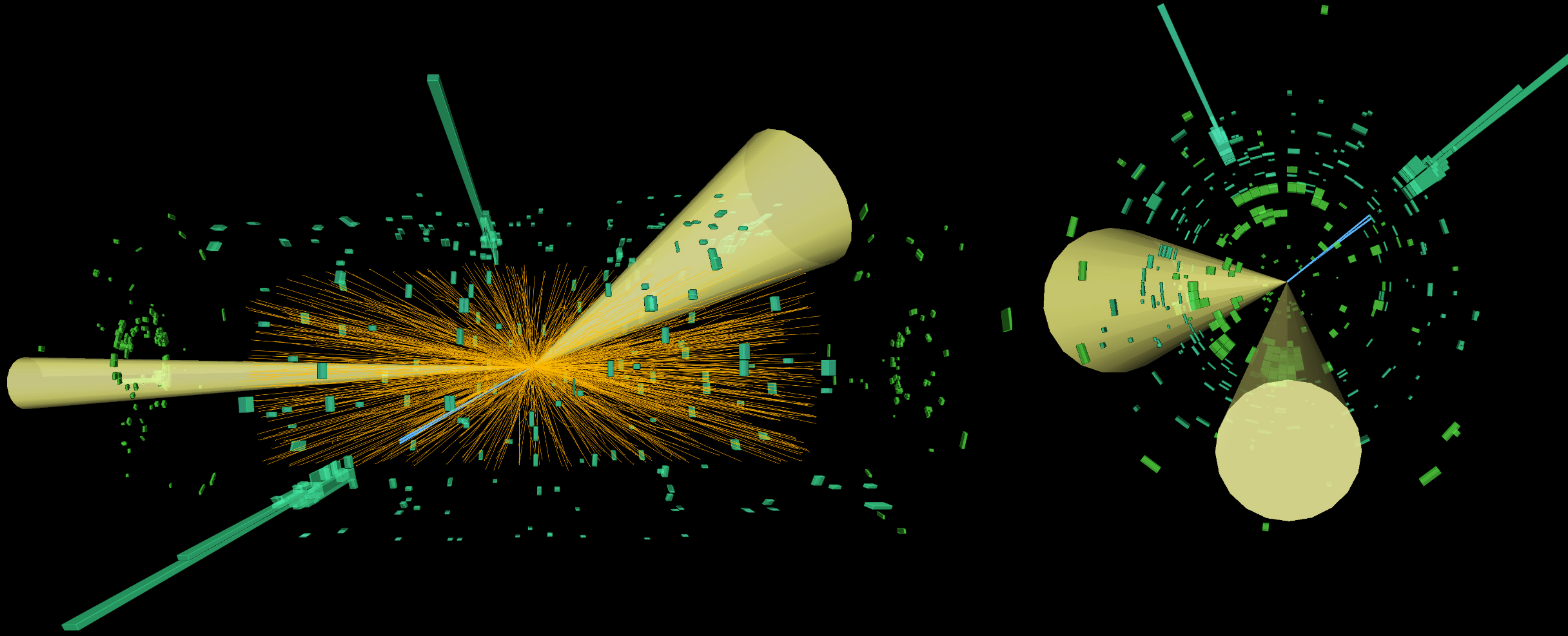
Results

- Measured fiducial σ(pp→H)×B(H→llγ) (m_{ll} < 30 GeV): **8.7 ± 2.8 fb**
  - Corresponds to the signal strength **μ = 1.5 ±0.5**
  - Analysis is statistically-dominated, leading systematic uncertainty: background modeling
- Significance above background-only hypothesis: **3.2σ**
  - **First evidence for H→llγ decay!**





Search for H→llγ decays at low-m_{ll}



Vector Boson Fusion H→eeγ event candidate with merged-ee

The High-Luminosity LHC

- 20 times more integrated luminosity than LHC Run 2
  - Up to 200 pp interactions per bunch crossing!
- Better detectors, larger acceptance, better triggers
- Improved theory and analysis methods

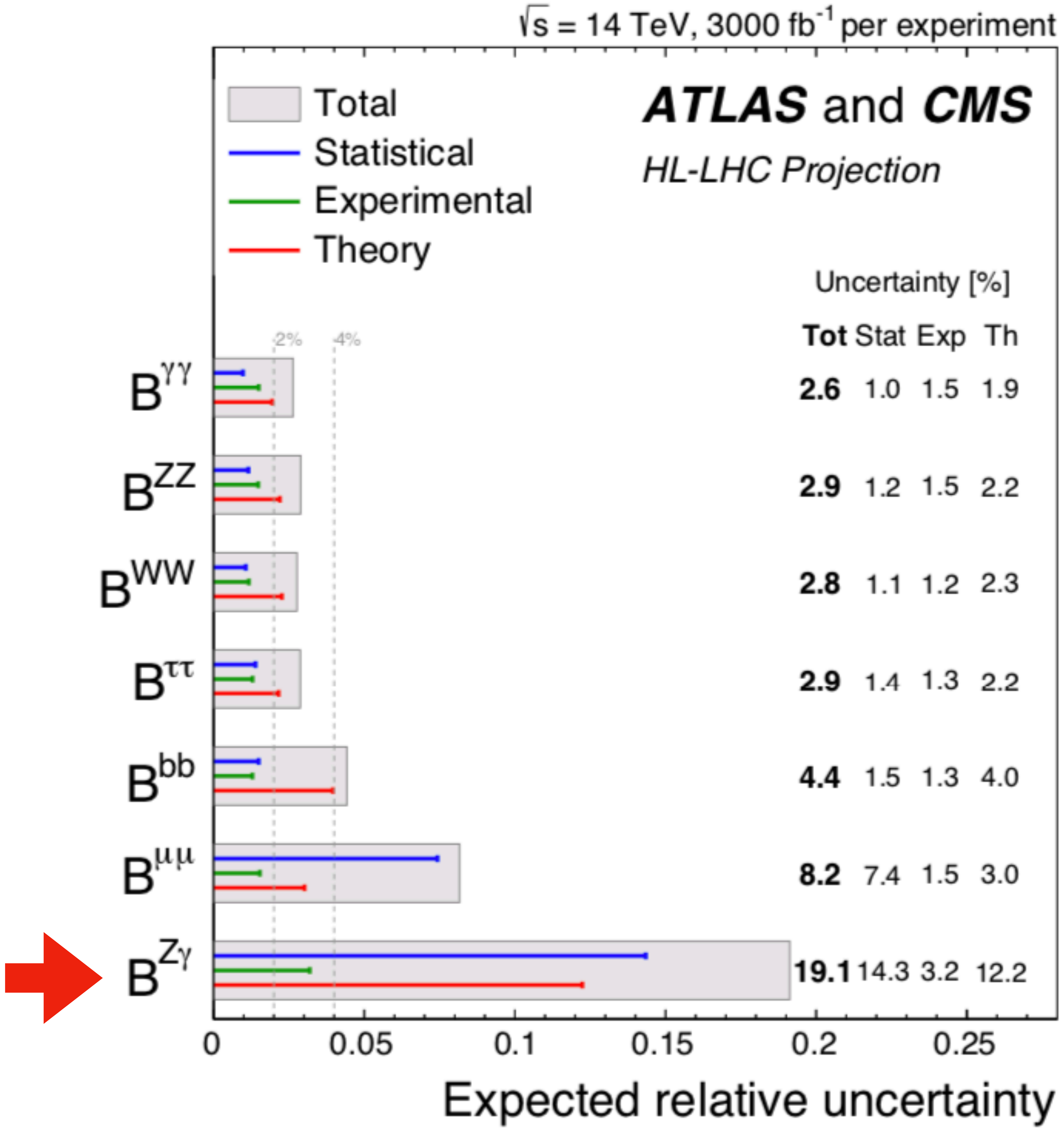
we are here

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034

	LHC		High-Luminosity LHC			
	LS2	Run 3	LS3	Run 4	LS4	Run 5
ATLAS and CMS		2 x 10^{34} 300 fb^{-1}	Detector Upgrade	5-7 x 10^{34} ~1000 fb^{-1}		5-7 x 10^{34} 3000 fb^{-1}

Prospects at High-Luminosity LHC (3000 fb^{-1})

- Good potential for discovery of **H→Zγ** (and **H→γ*γ**) decays



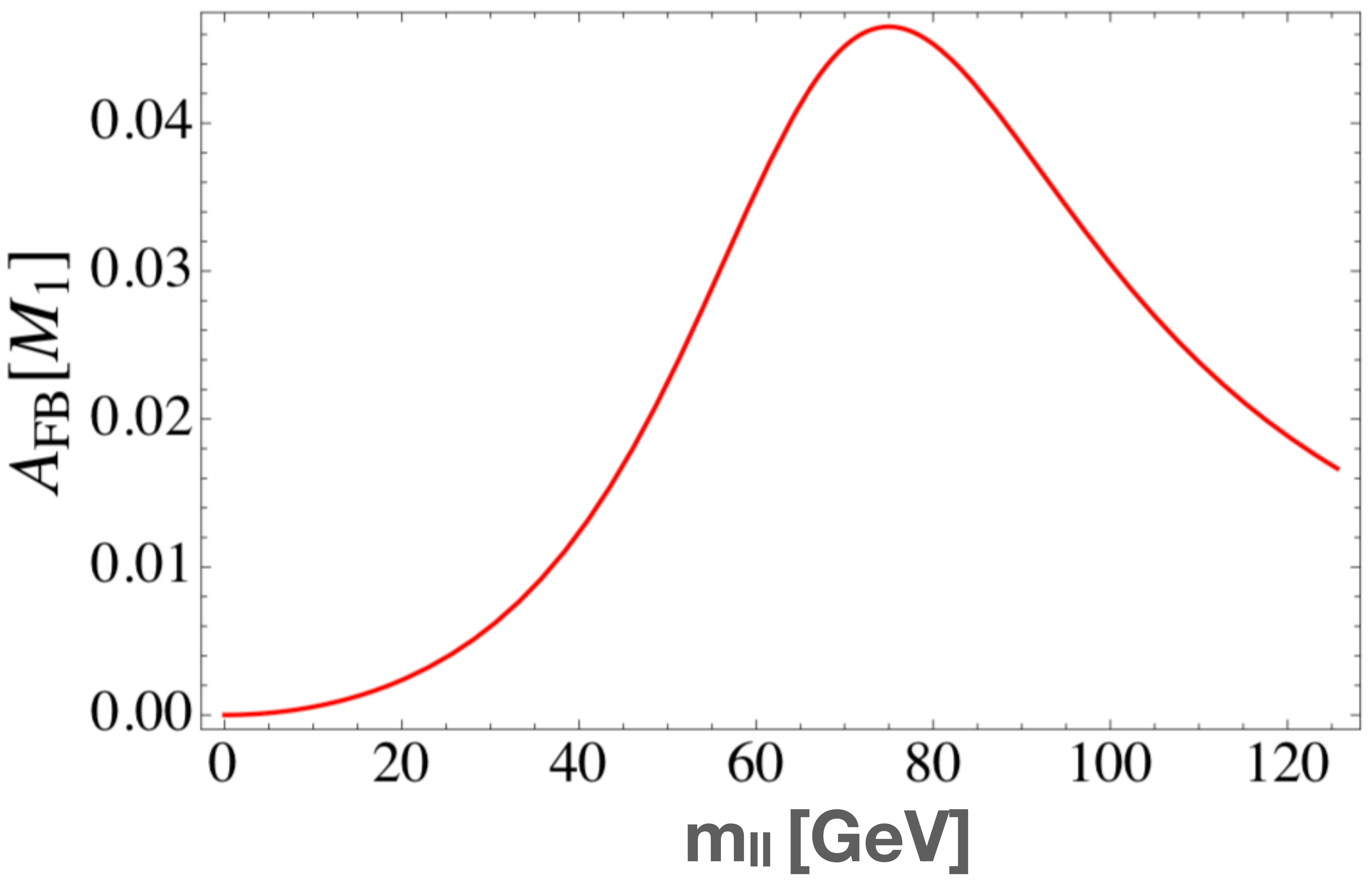
arXiv:1902.00134

Prospects at High-Luminosity LHC (3000 fb^{-1})

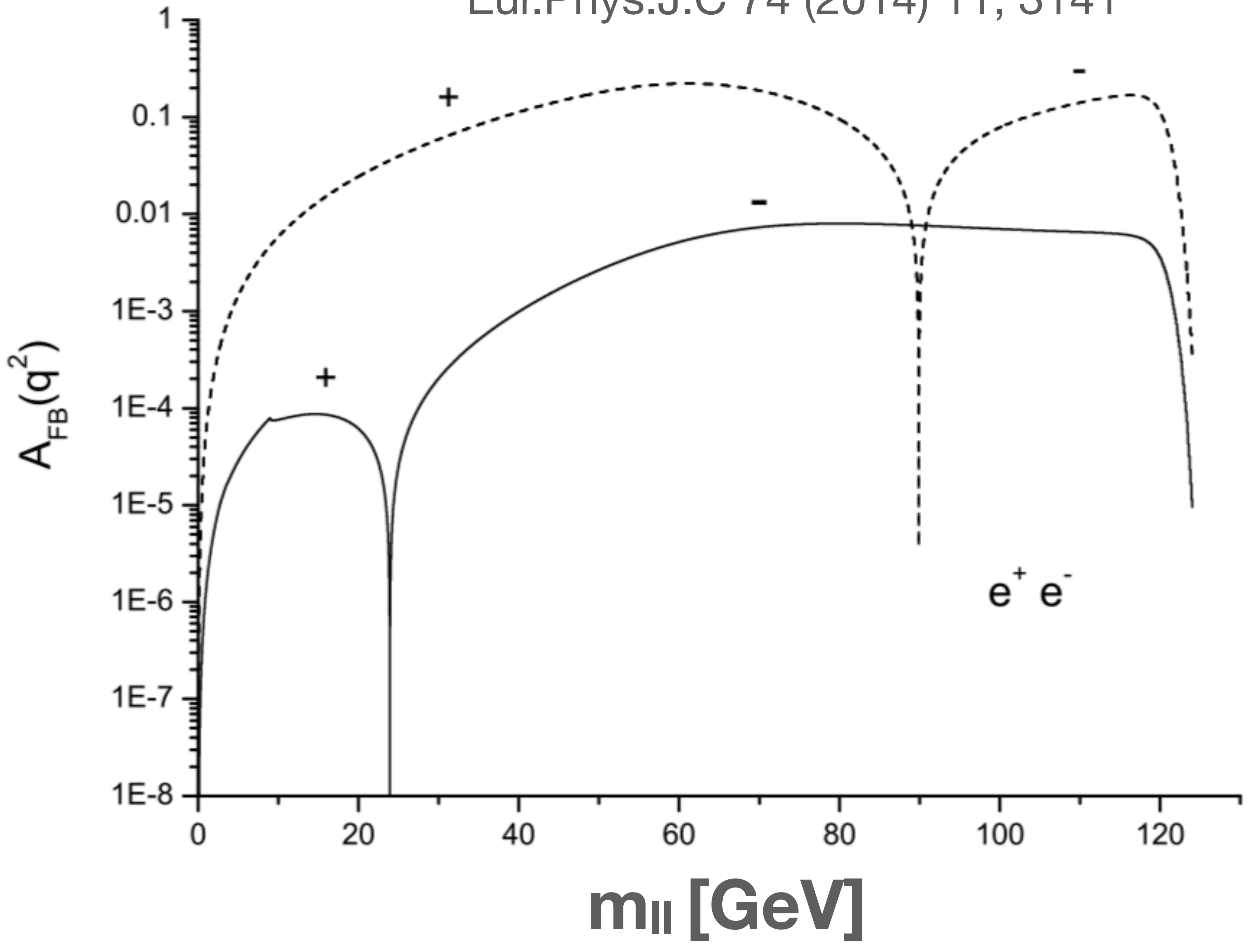
- With three-body $H \to ll\gamma$ decay, it is possible to probe CP-violating Higgs couplings
  - Lepton forward-backward asymmetry measurements (**note $A_{FB}(q^2)$ = 0 for SM Higgs boson**)
  - More detailed access to loops, exotic couplings, …

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

Phys.Rev.D 90 (2014) 11, 113006



Eur.Phys.J.C 74 (2014) 11, 3141



Summary

- ATLAS experiment continues to probe the nature of the Higgs boson using full LHC Run 2 pp data at 13 TeV (~140 fb^{-1})

- Evidence for $H \rightarrow ll\gamma$ decay at low-m_{ll}
  - **3.2σ**, μ=1.5 ±0.5
  - One of the rarest Higgs boson decays with **$B=10^{-4}$**

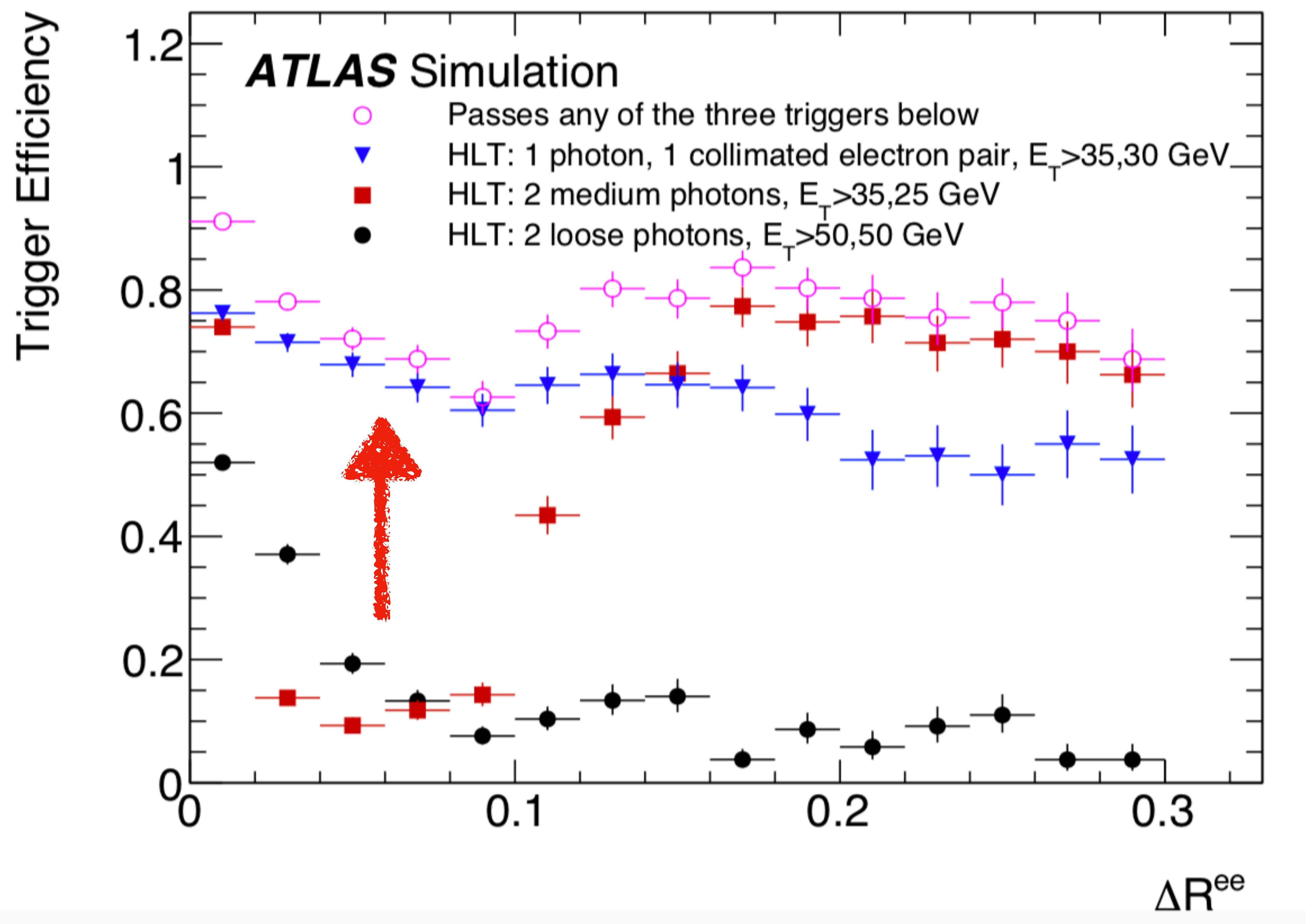
- ~5% of the LHC integrated luminosity has been achieved so far
  - HL-LHC will be able to probe more precisely rare Higgs boson decays

Backup

Trigger

- Can't rely on regular single-lepton triggers alone
  - Combination of **single-lepton**, **2l**, **γ+l, γγ**, **γ+2l** triggers is used
  - Dedicated **merged-ee + γ** trigger is also employed
- Trigger efficiency wrt final selection:
  - Muon channels: 96.2%
  - Resolved electron categories: 96.5%
  - Merged electron categories: 99.8%

Eur. Phys. J. C 80 (2020) 47



Systematic uncertainties

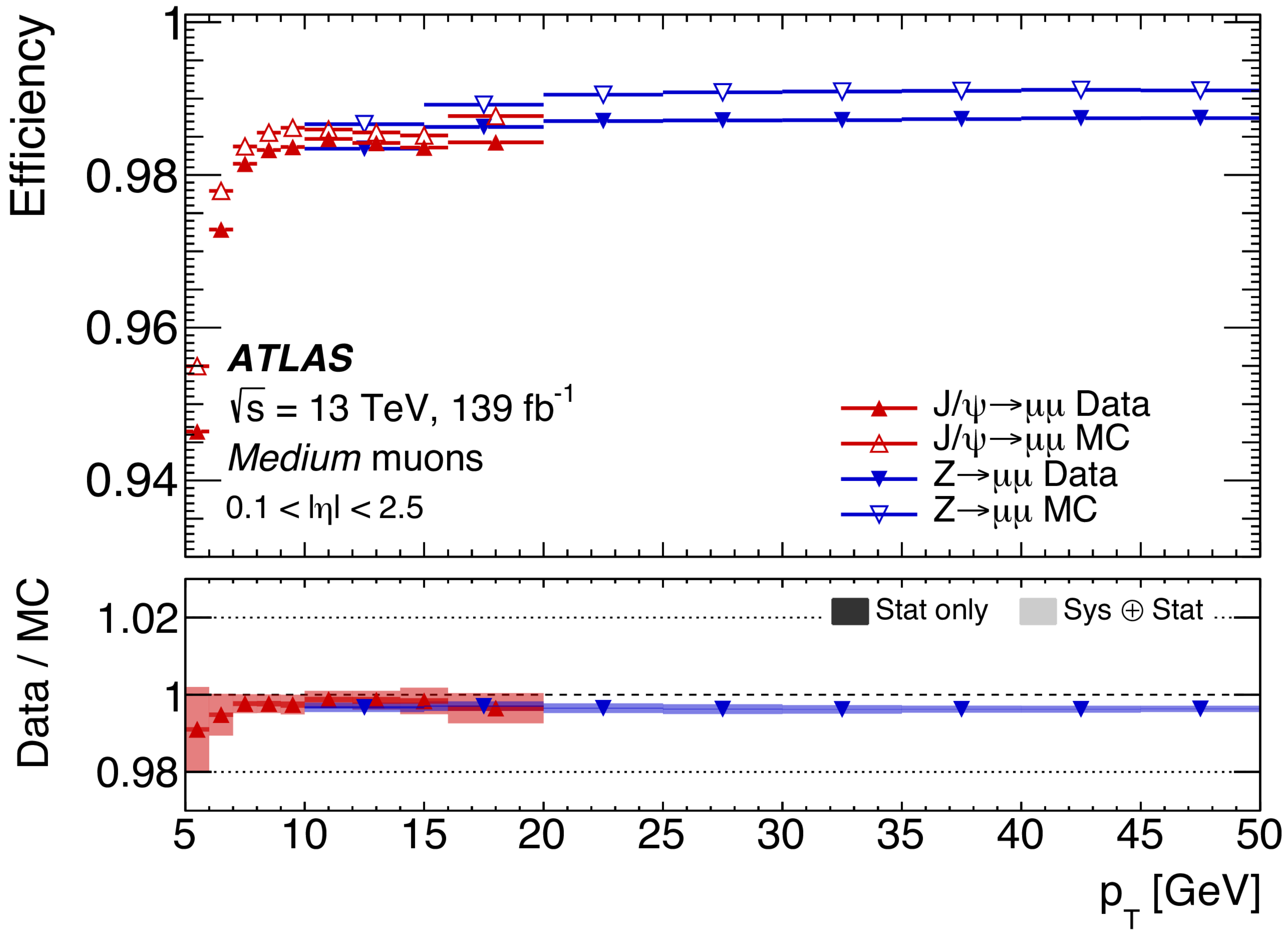
Relative systematic uncertainties (in per cent) in the measured signal strength and the measured cross-section times branching ratio

<table>
<tr><th>Uncertainty source</th><th>μ</th><th>$\sigma \times \mathcal{B}$</th></tr>
<tr><td>Spurious Signal</td><td colspan="2">6.1</td></tr>
<tr><td>$\mathcal{B}(H \to \ell\ell\gamma)$</td><td>5.8</td><td>–</td></tr>
<tr><td>QCD scale</td><td>4.7</td><td>1.1</td></tr>
<tr><td>ℓ, γ, jets</td><td colspan="2">4.0</td></tr>
<tr><td>PDF</td><td>2.3</td><td>0.9</td></tr>
<tr><td>Luminosity</td><td colspan="2">1.7</td></tr>
<tr><td>Pile-up</td><td colspan="2">1.7</td></tr>
<tr><td>Minor prod. modes</td><td colspan="2">0.8</td></tr>
<tr><td>$H \to \gamma\gamma$ background</td><td colspan="2">0.7</td></tr>
<tr><td>Parton Shower</td><td colspan="2">0.3</td></tr>
<tr><td>Total systematic</td><td>11</td><td>7.9</td></tr>
<tr><td>Statistical</td><td colspan="2">31</td></tr>
<tr><td>Total</td><td>33</td><td>32</td></tr>
</table>

ATLAS detector performance

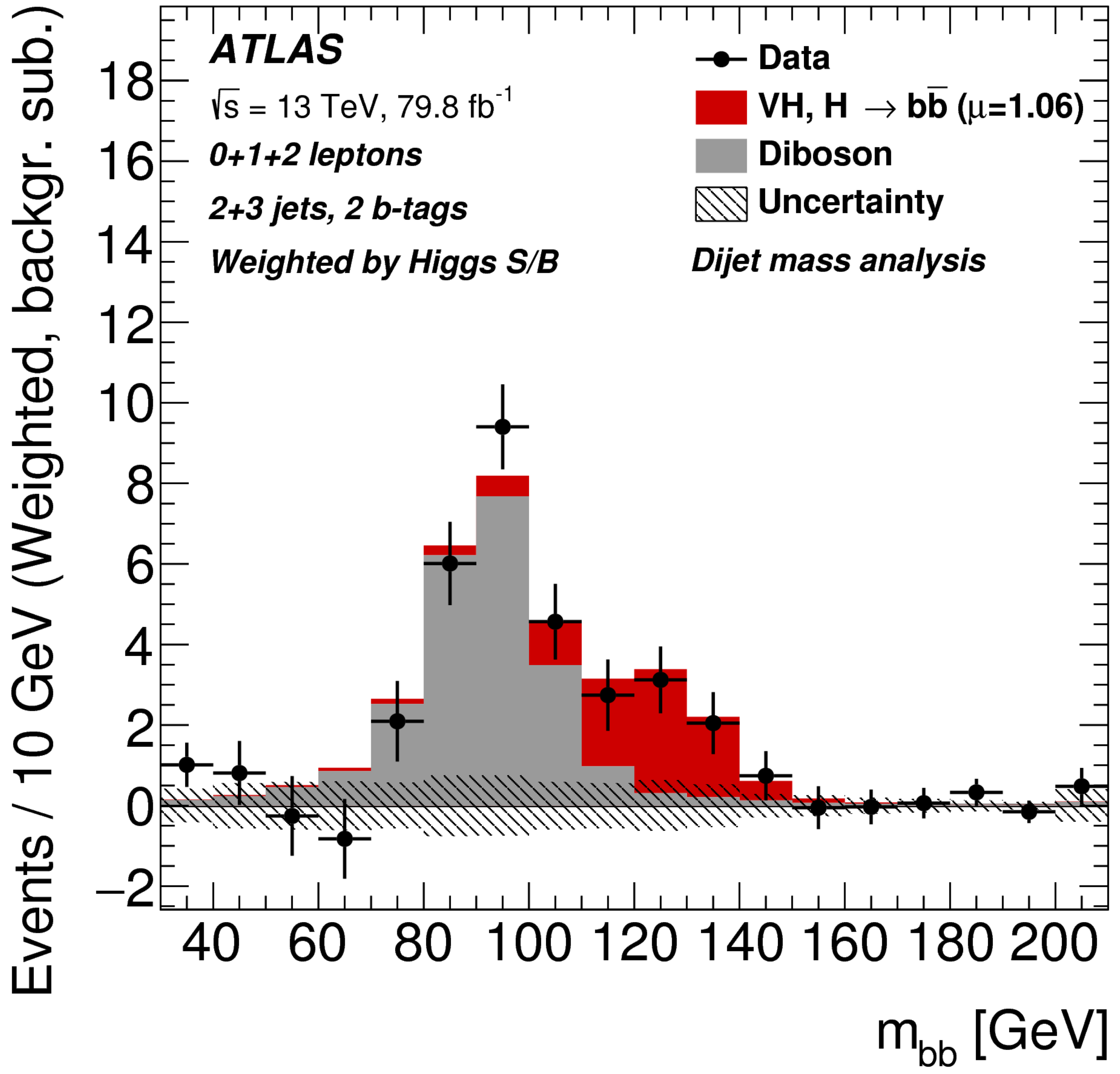
- Good understanding of the detector is critical
- Reconstruction of physics objects (e, γ, μ, τ, jets, …) precisely known from careful data-driven calibrations
- Several improvements during the last years using machine learning techniques

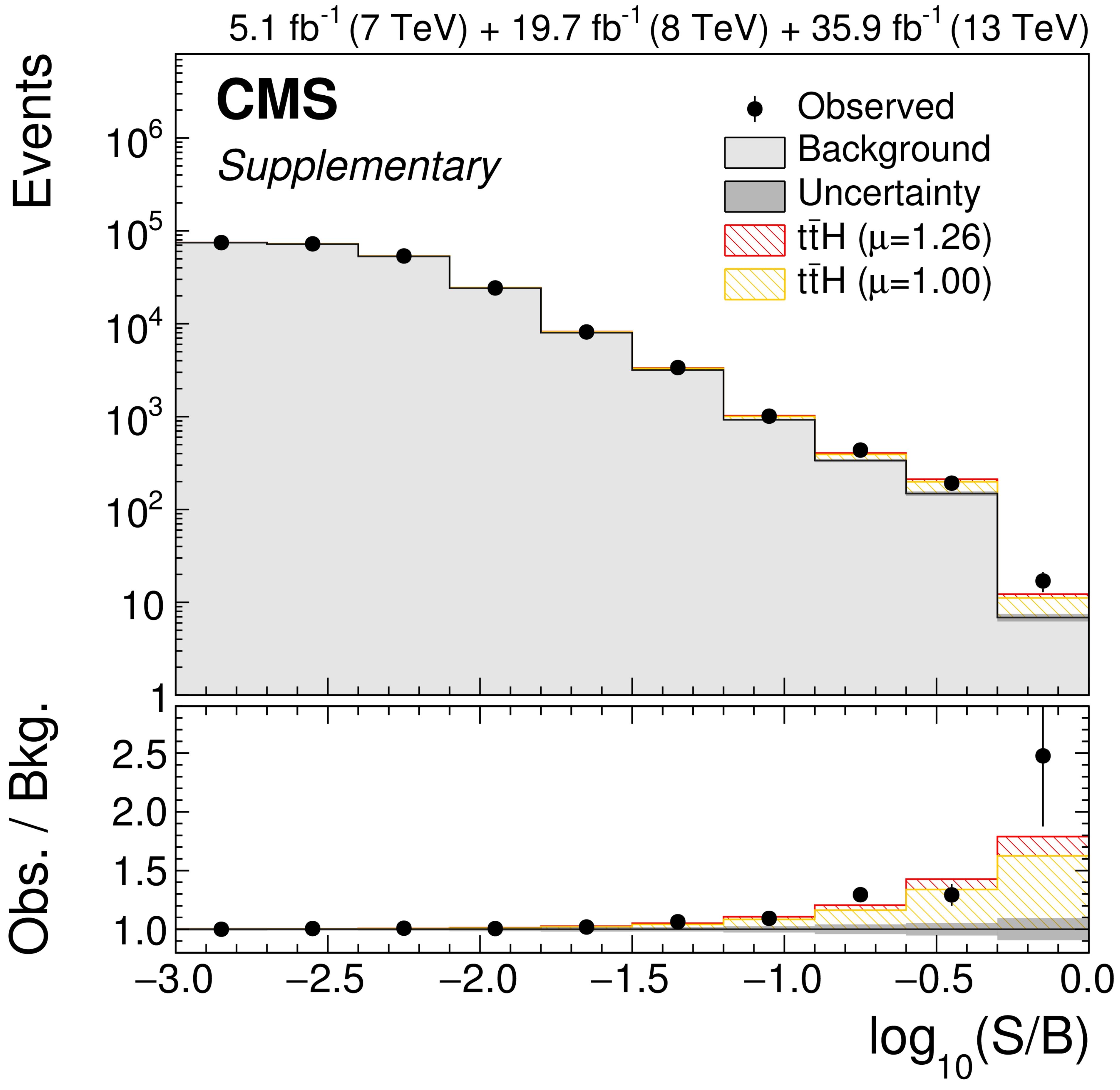
arXiv:2012.00578



What do we know about the Higgs boson after LHC Run 2?

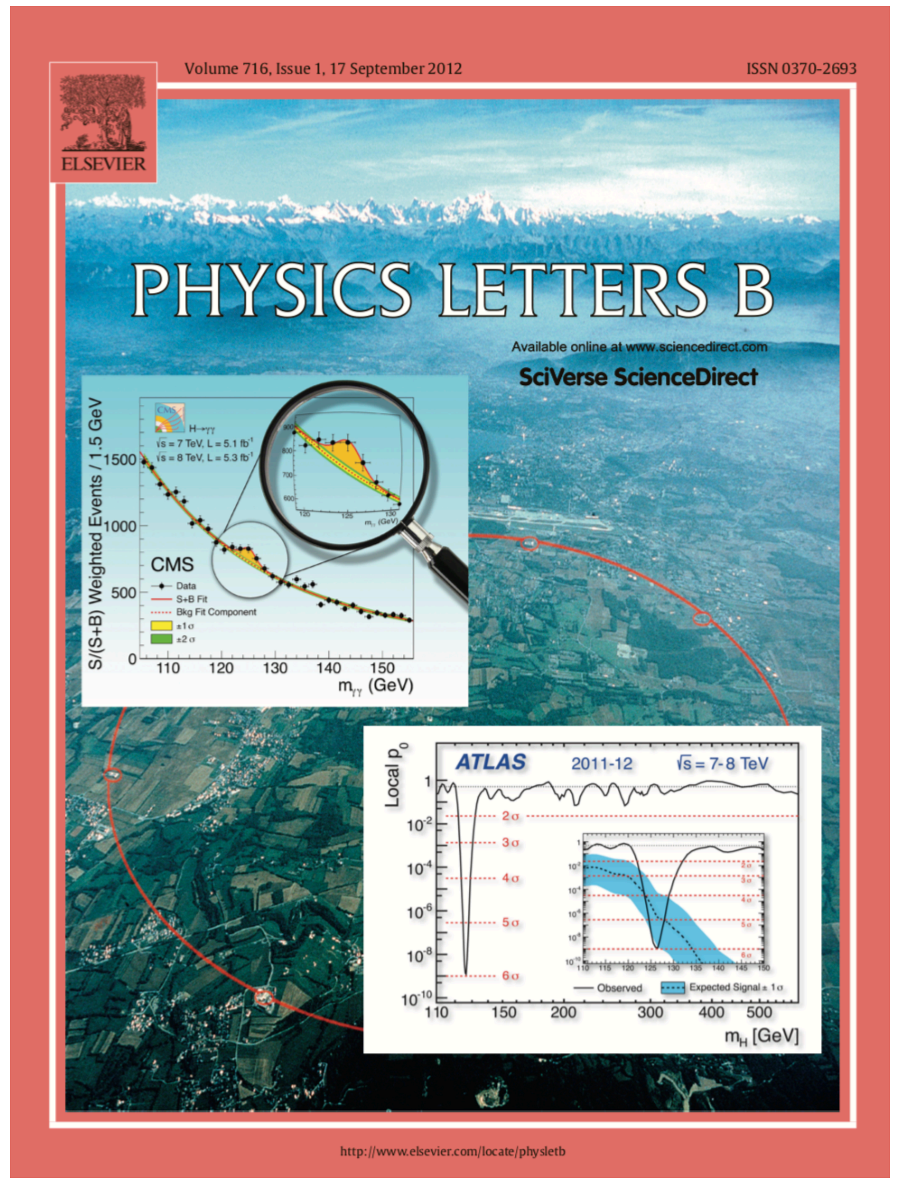
- Fermionic couplings confirmed: observation of **H→bb** decay and **ttH** process



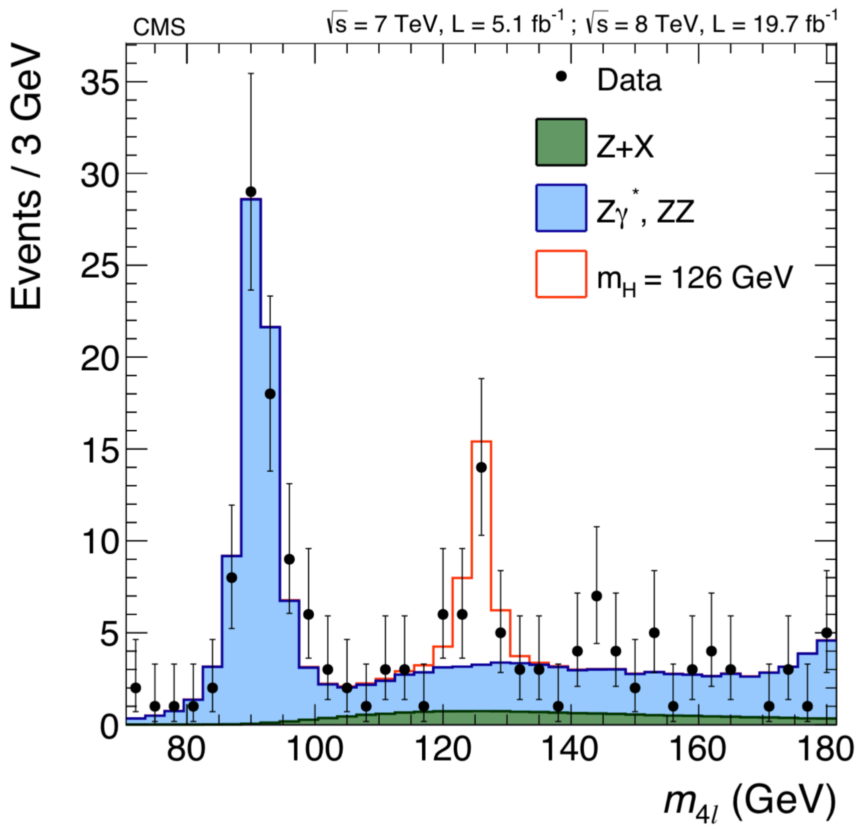


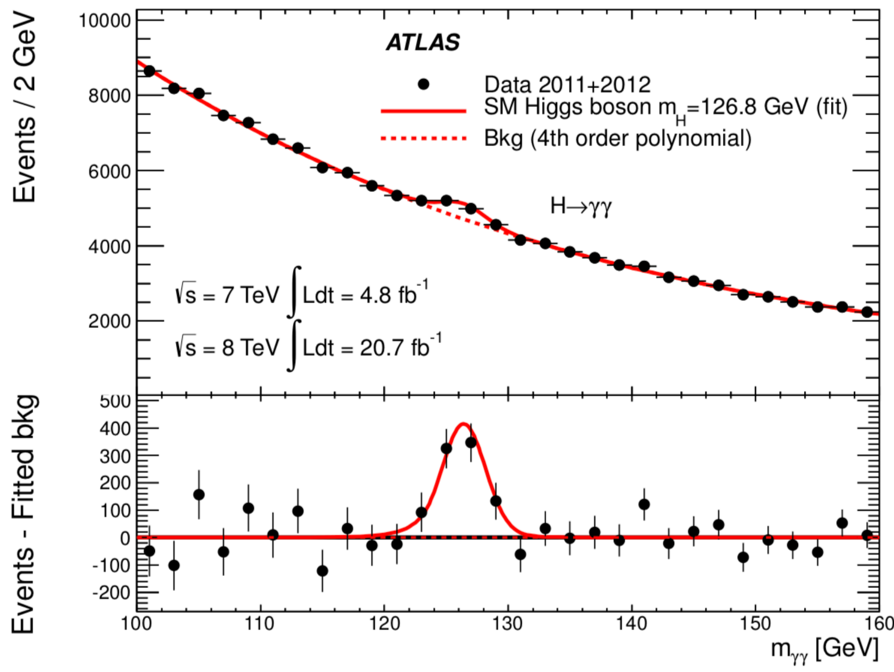
Higgs boson observation timeline at the LHC

SM-like Higgs discovery
(ggF → $\gamma\gamma$ + ZZ + WW)

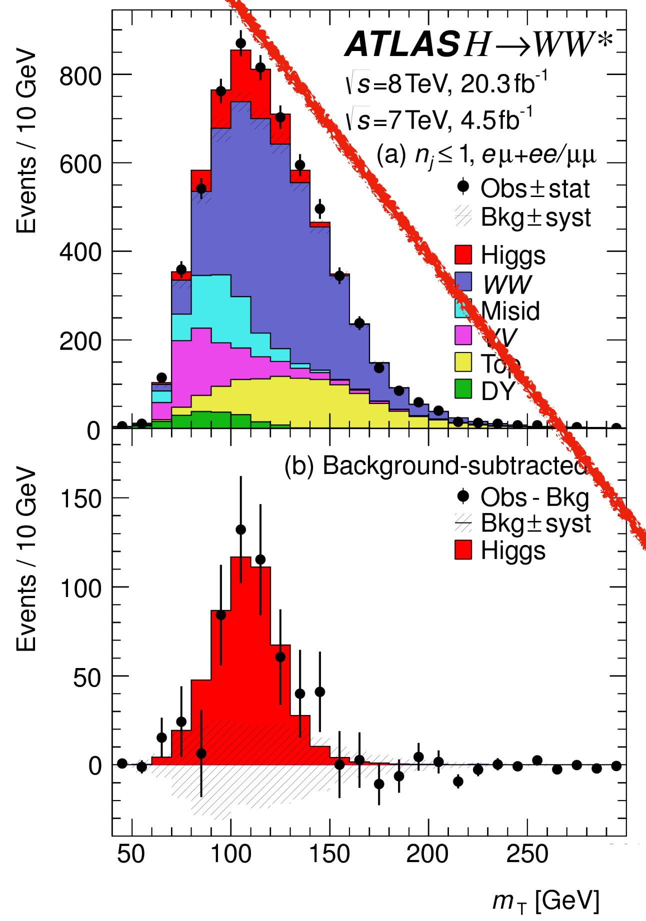


H→$\gamma\gamma$, H→ZZ observation,
spin-0 and parity+

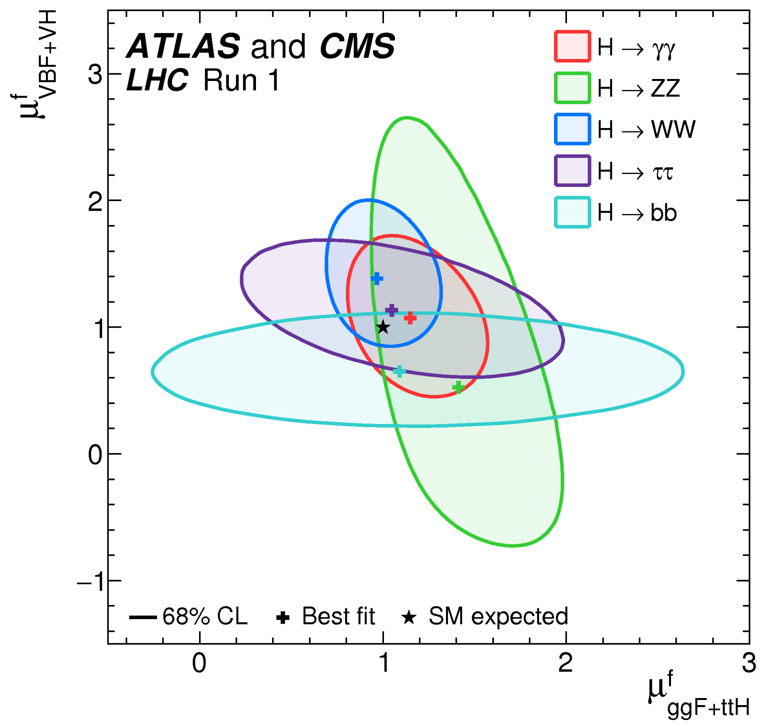




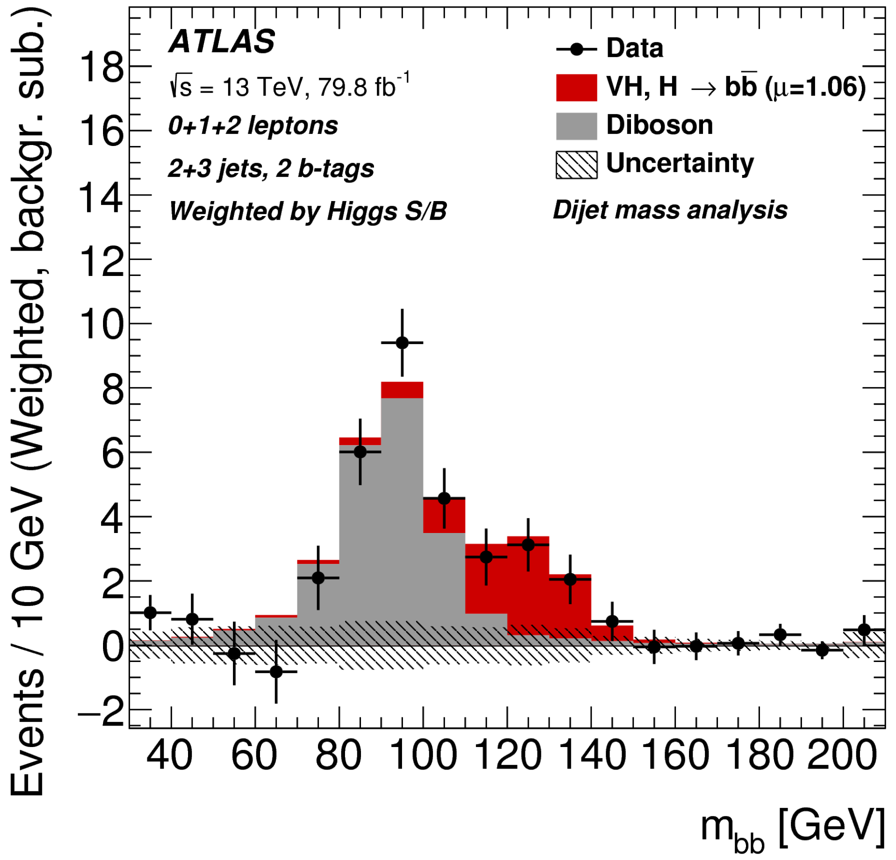
H→WW observation



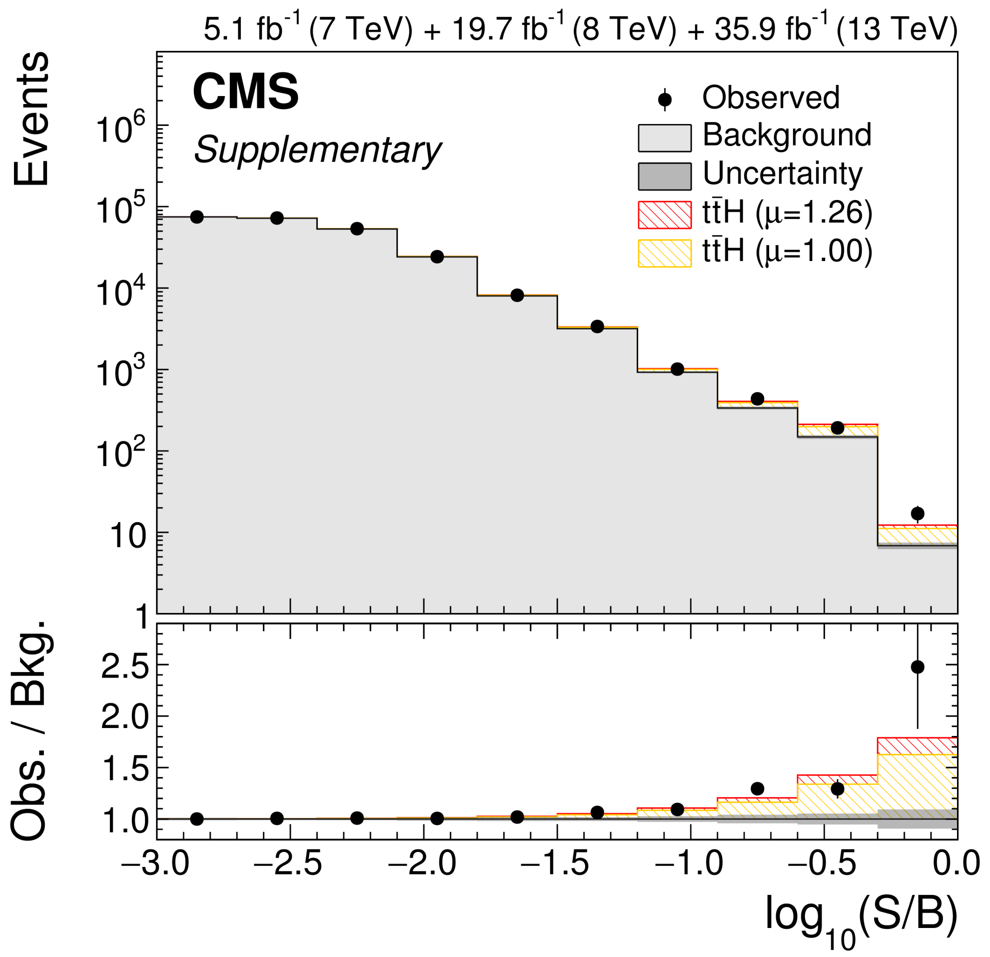
VBF observation,
H→ττ observation



VH, H→bb observation

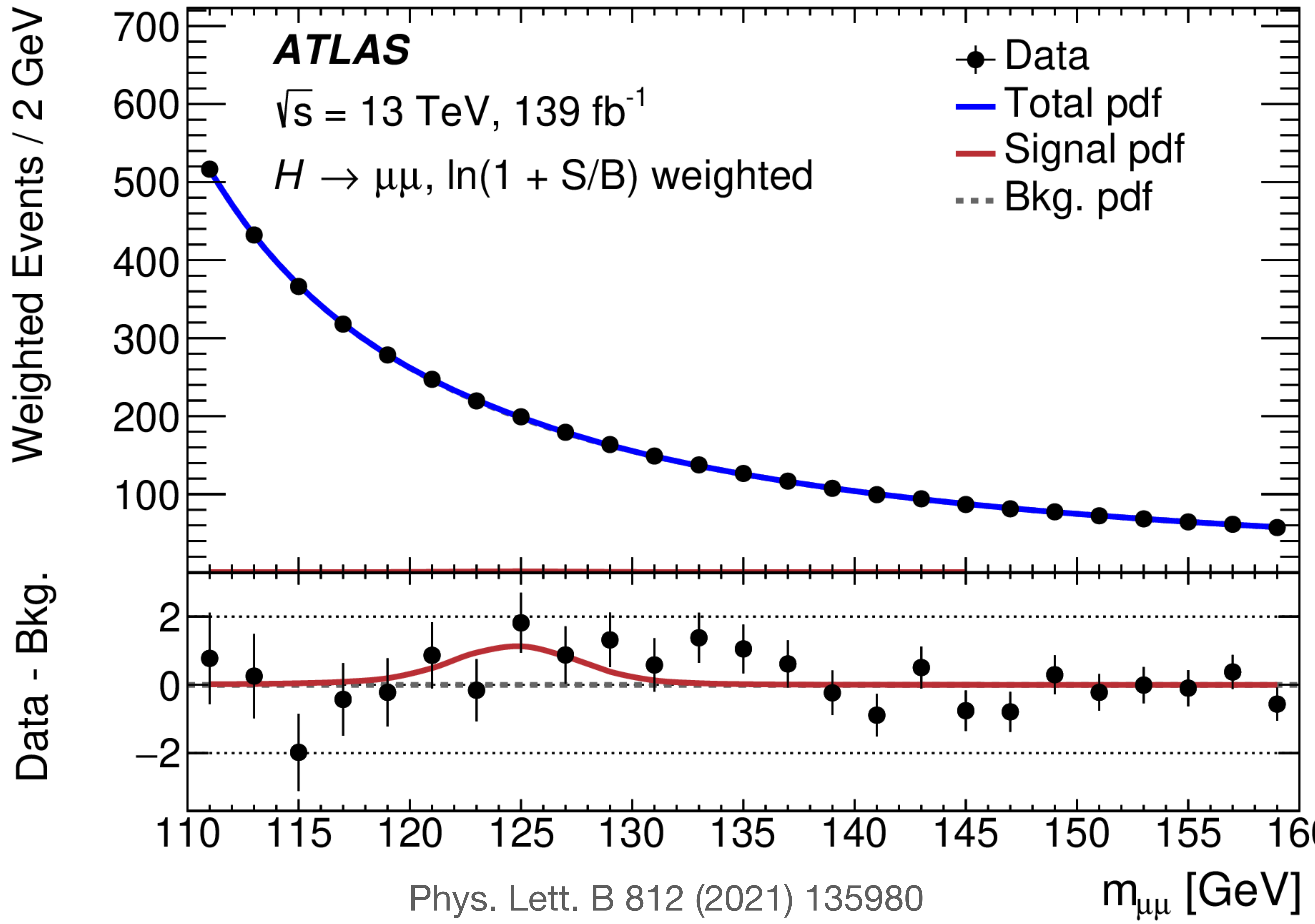


ttH observation

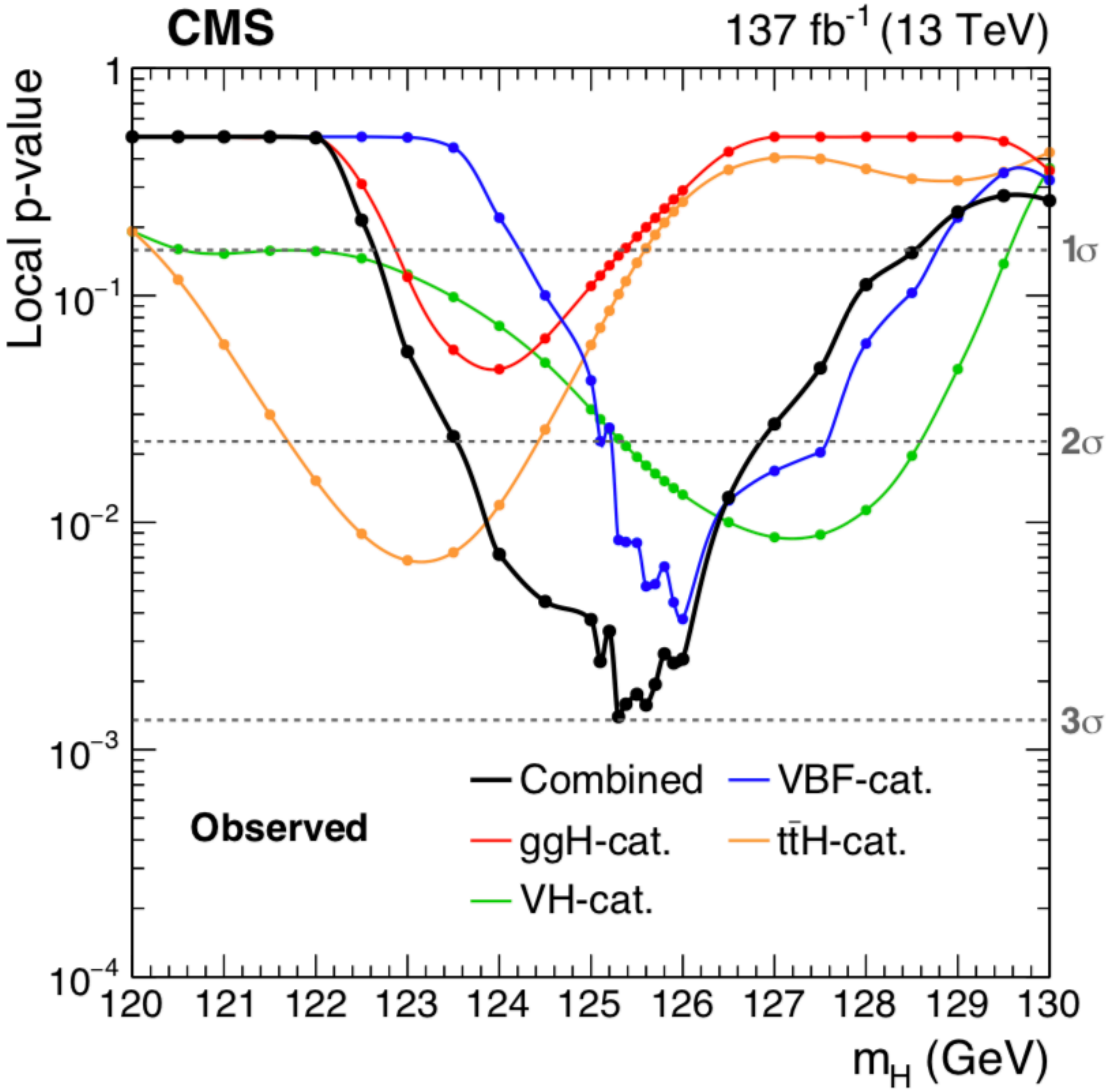


What do we know about the Higgs boson after LHC Run 2?

- LHC data gives access to very rare Higgs decays: **B(H→μμ) = 2.2 ×10^{-4}**
- Evidence for H→μμ decay
  - ATLAS: **2.0σ** (1.7σ) obs. (exp.) significance, **μ = 1.2 ± 0.6**
  - CMS: **3.0σ** (2.5σ) obs. (exp.), **μ = 1.2 ± 0.4**



Phys. Lett. B 812 (2021) 135980



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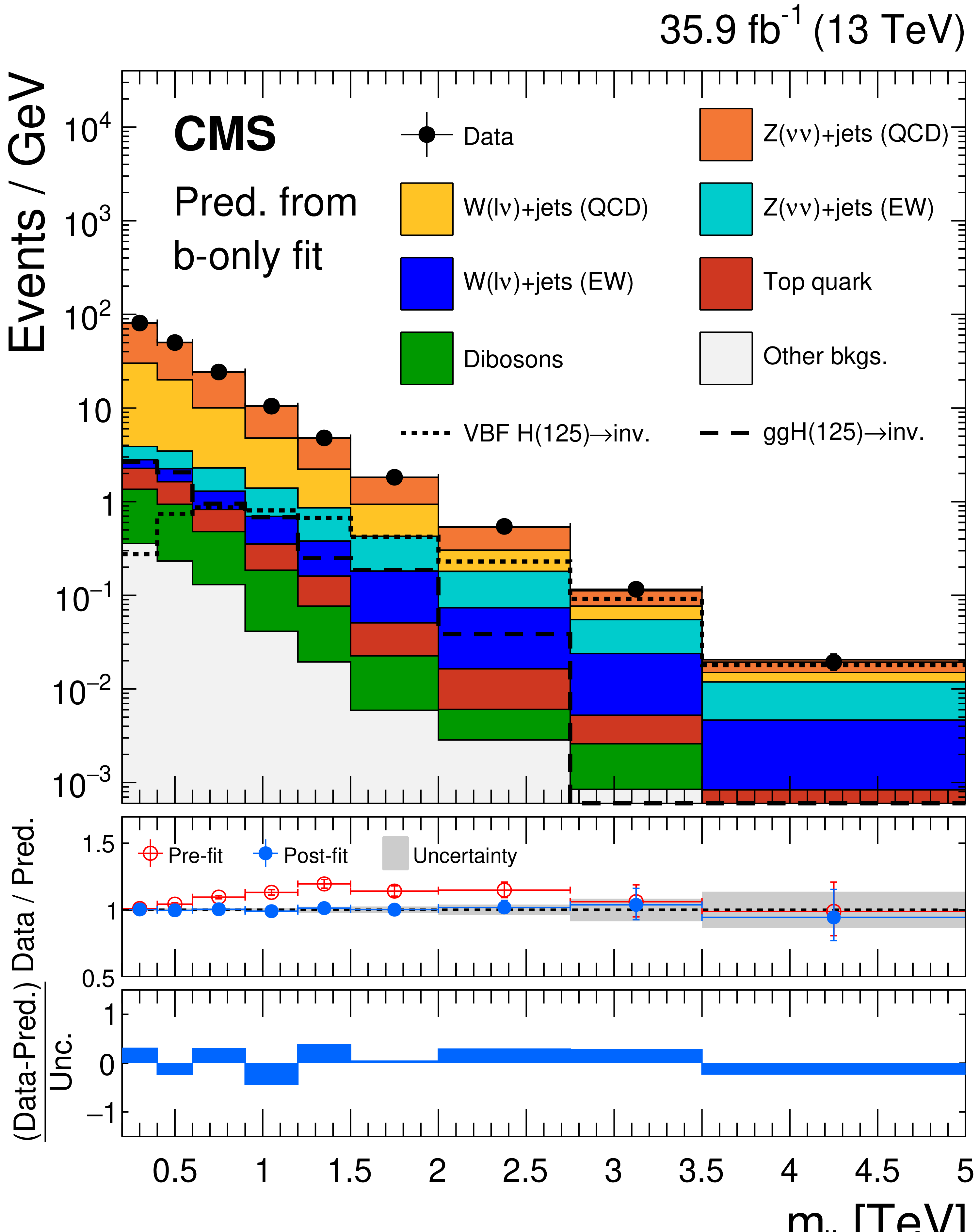
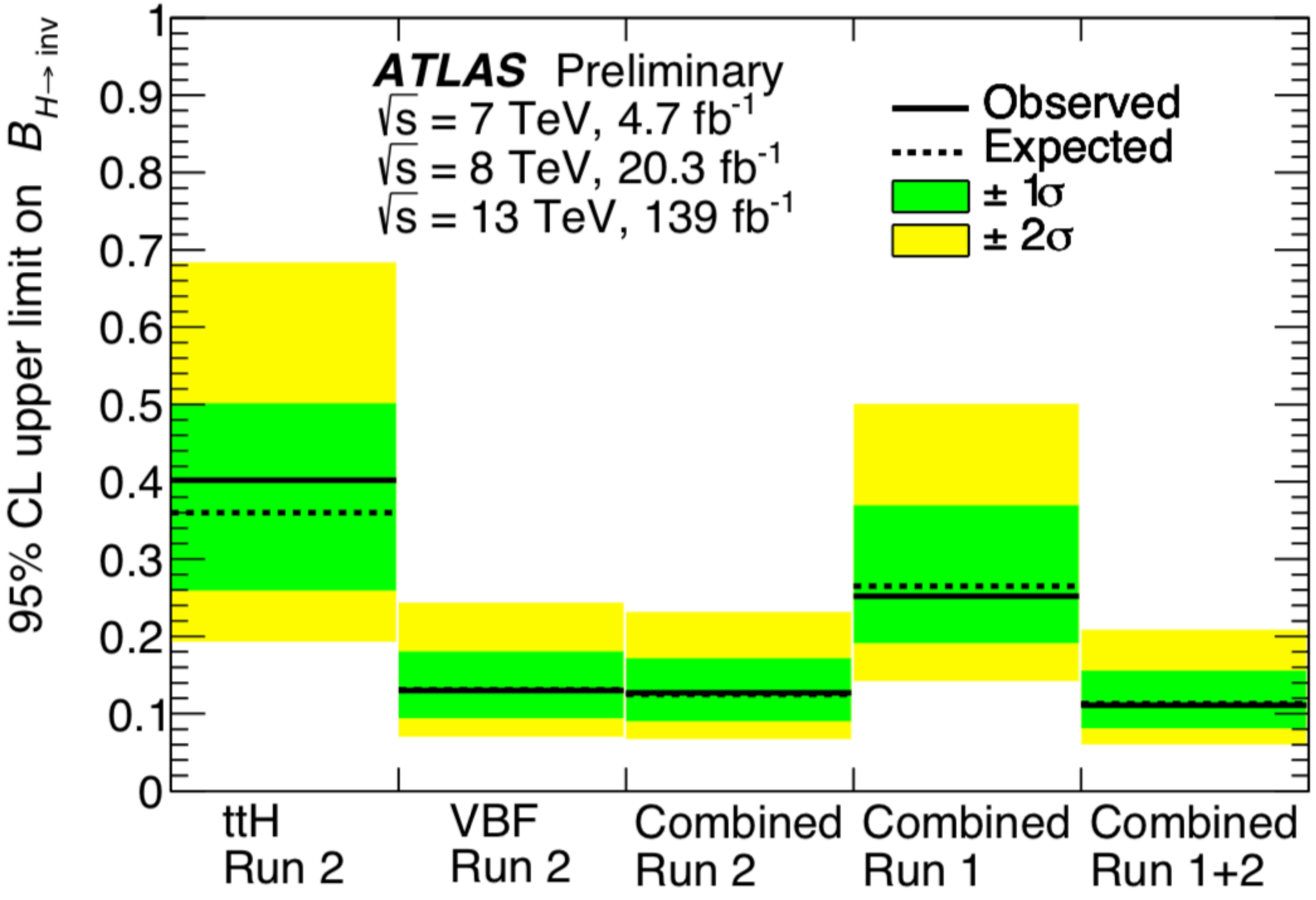
What do we know about the Higgs boson after LHC Run 2?

- Searches for **Higgs to invisible** have been performed in VBF, ttH and VH channels in both ATLAS and CMS
    - Observed upper limit **B(H → inv.) = 0.11** (95% CL) from recent ATLAS combination



Phys. Lett. B 793 (2019) 520



ATLAS-CONF-2020-052

Higgs coupling measurements - the kappa framework

- Parameterisations of Higgs boson production cross-sections and decay widths as a function of coupling strength modifiers using kappa framework
- Considering leading order contributions only
  - Other assumptions are typically made

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}$$

Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Constraints on Higgs boson width

- Indirect measurement from off-shell production in H→ZZ channel
- Obs. limit on Higgs width:

$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to 4\ell} \propto \mu_{\text{vvH}} \quad \text{and} \quad \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to 4\ell} \propto \mu_{\text{vvH}}\, \Gamma_{\text{H}}.$$

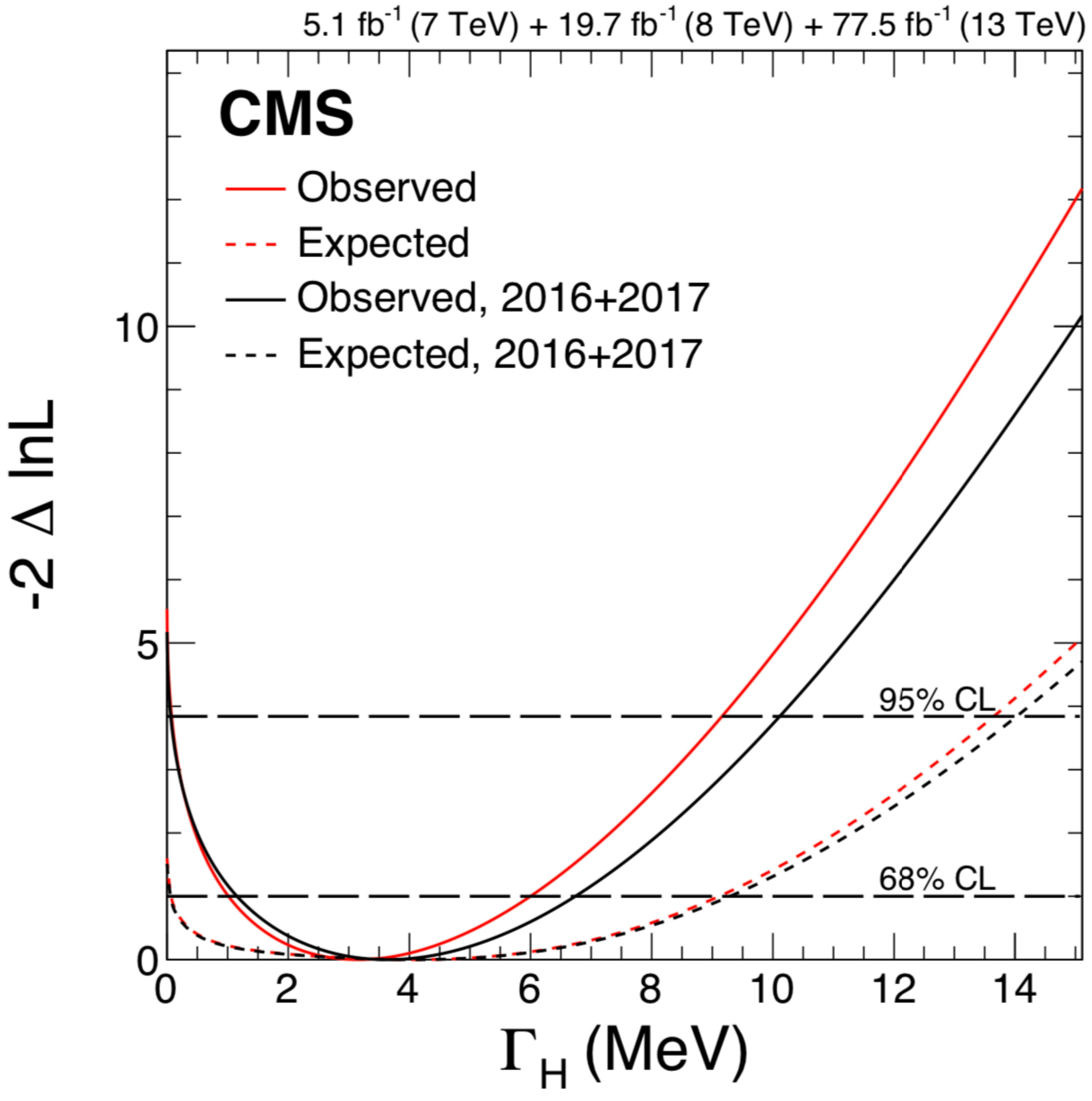
  - ATLAS Run 2 (36.1fb^{-1}): **< 14.4 MeV**
  - CMS Run 1+2 (77 fb^{-1}): **[0.08, 9.16] MeV**
  - SM prediction: **4.1 MeV**

HL-LHC projections:

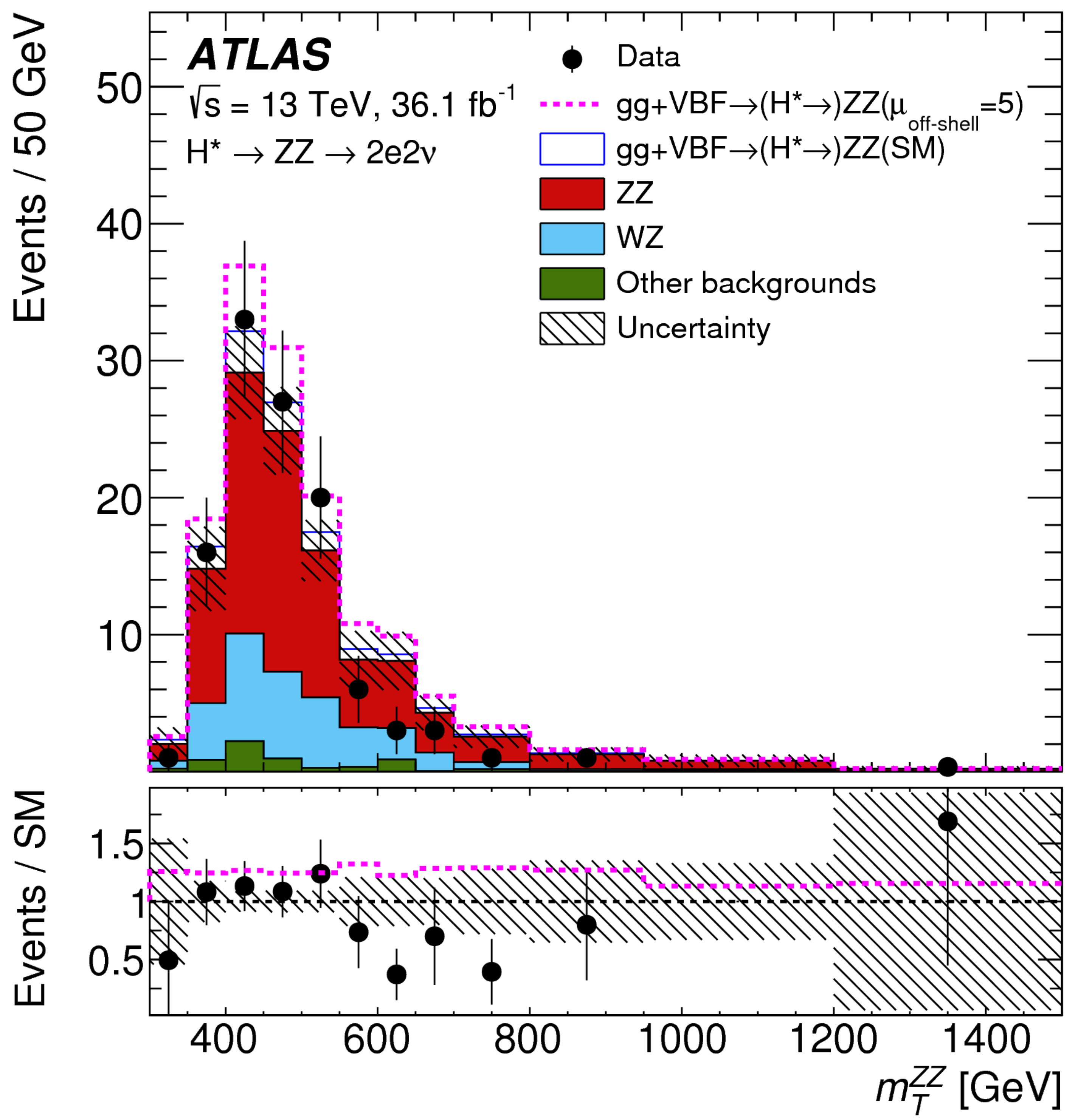
CMS: $4.1^{+1.0}_{-1.1}$ MeV

ATLAS: $4.2^{+1.5}_{-2.1}$ MeV

arXiv:1902.00134



PRD 99 (2019) 112003



PLB 786 (2018) 223