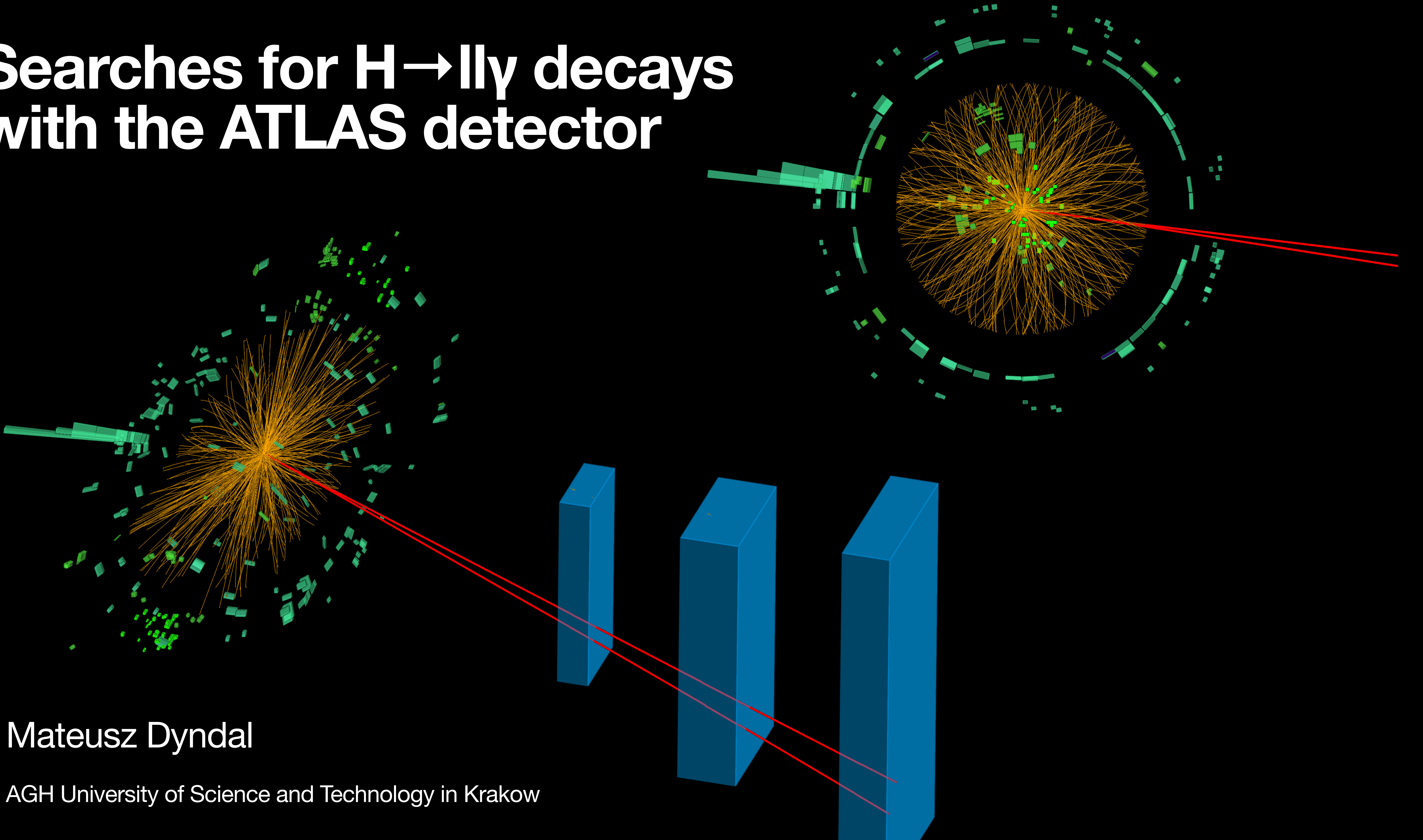
Searches for H→llγ decays with the ATLAS detector

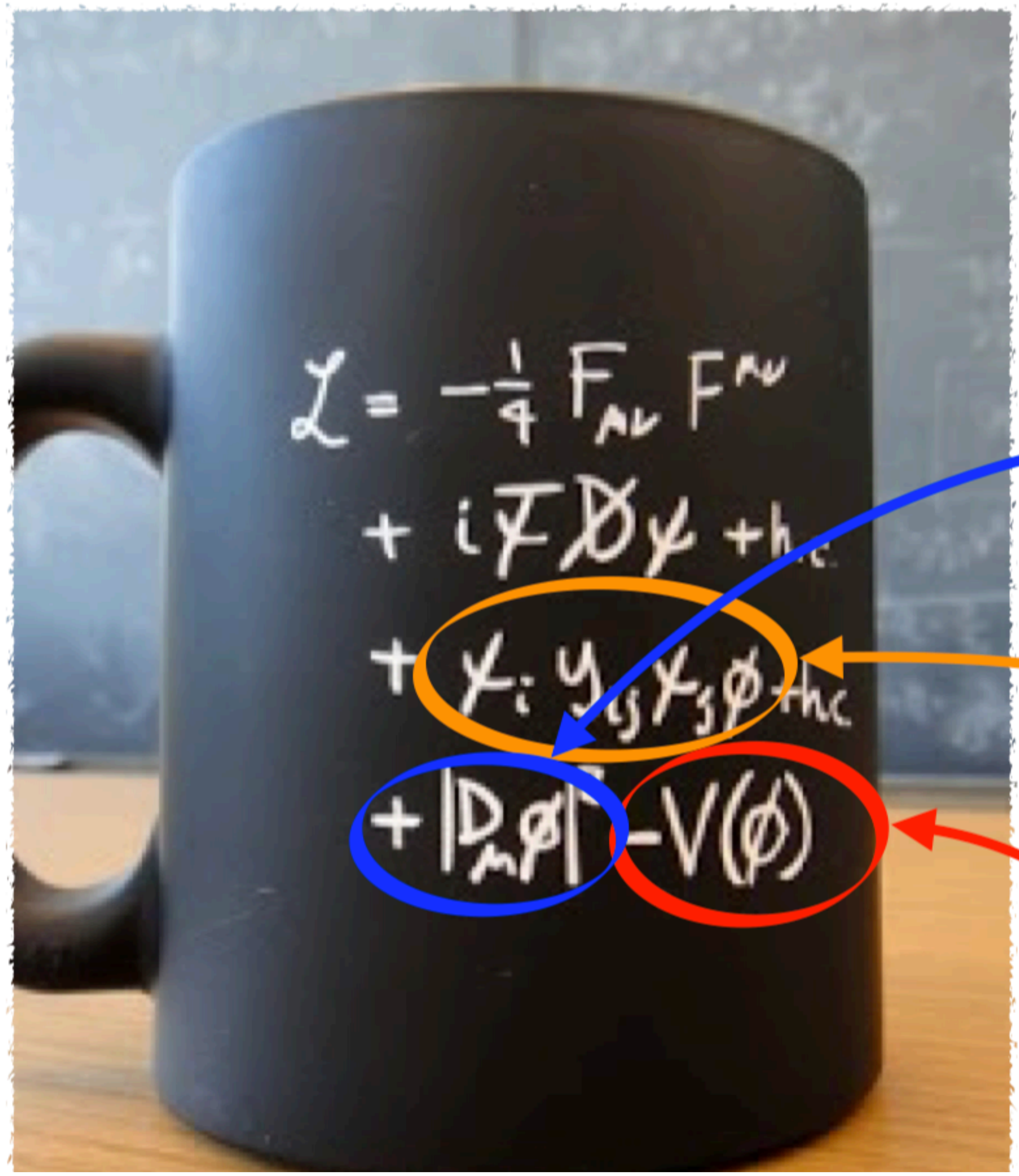


Mateusz Dyndal

AGH University of Science and Technology in Krakow

The Higgs boson

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



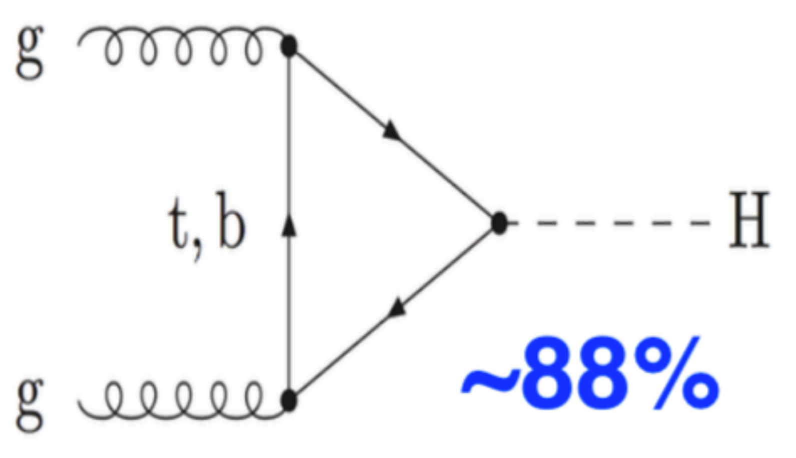
Discovery allows to access a new sector in the Lagrangian:

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

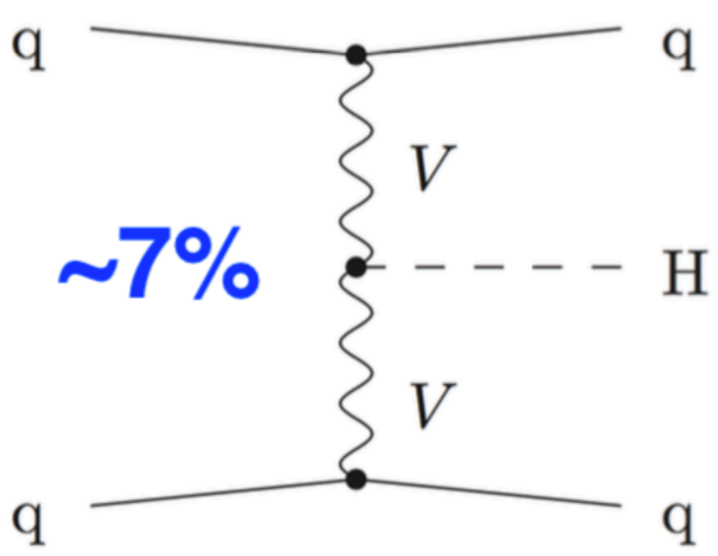
from G. Zanderighi Higgs Hunting'19 talk

Higgs boson production and decay at the LHC

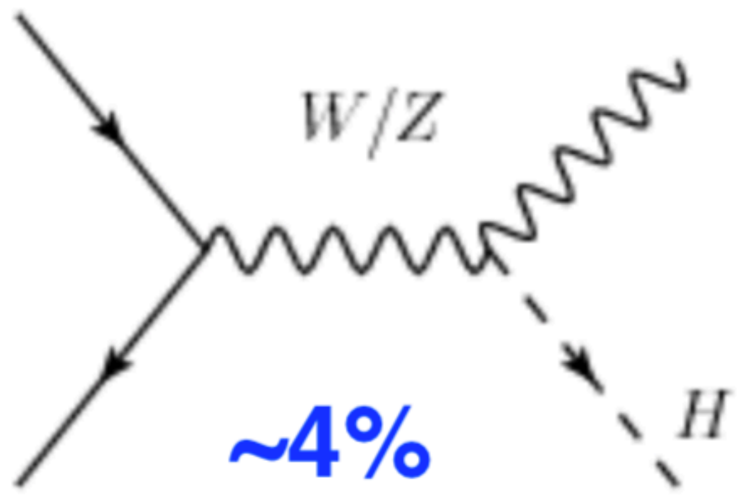
gluon-gluon fusion(ggF)



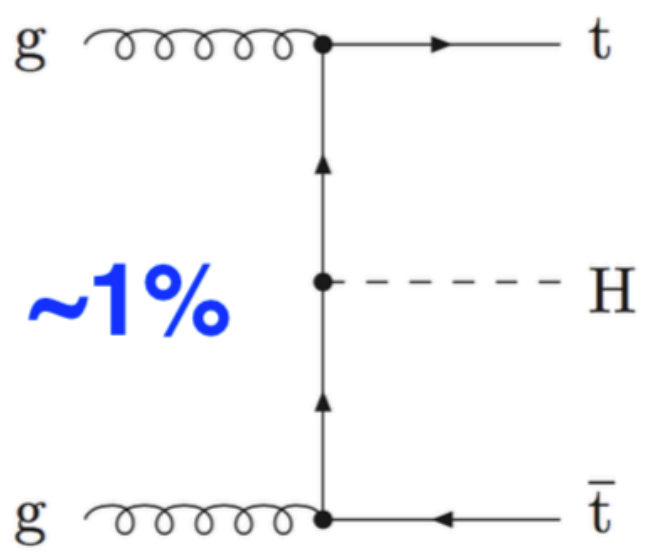
Vector boson fusion(VBF)

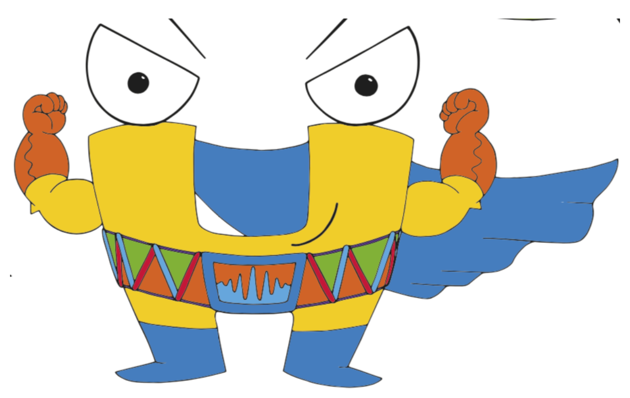


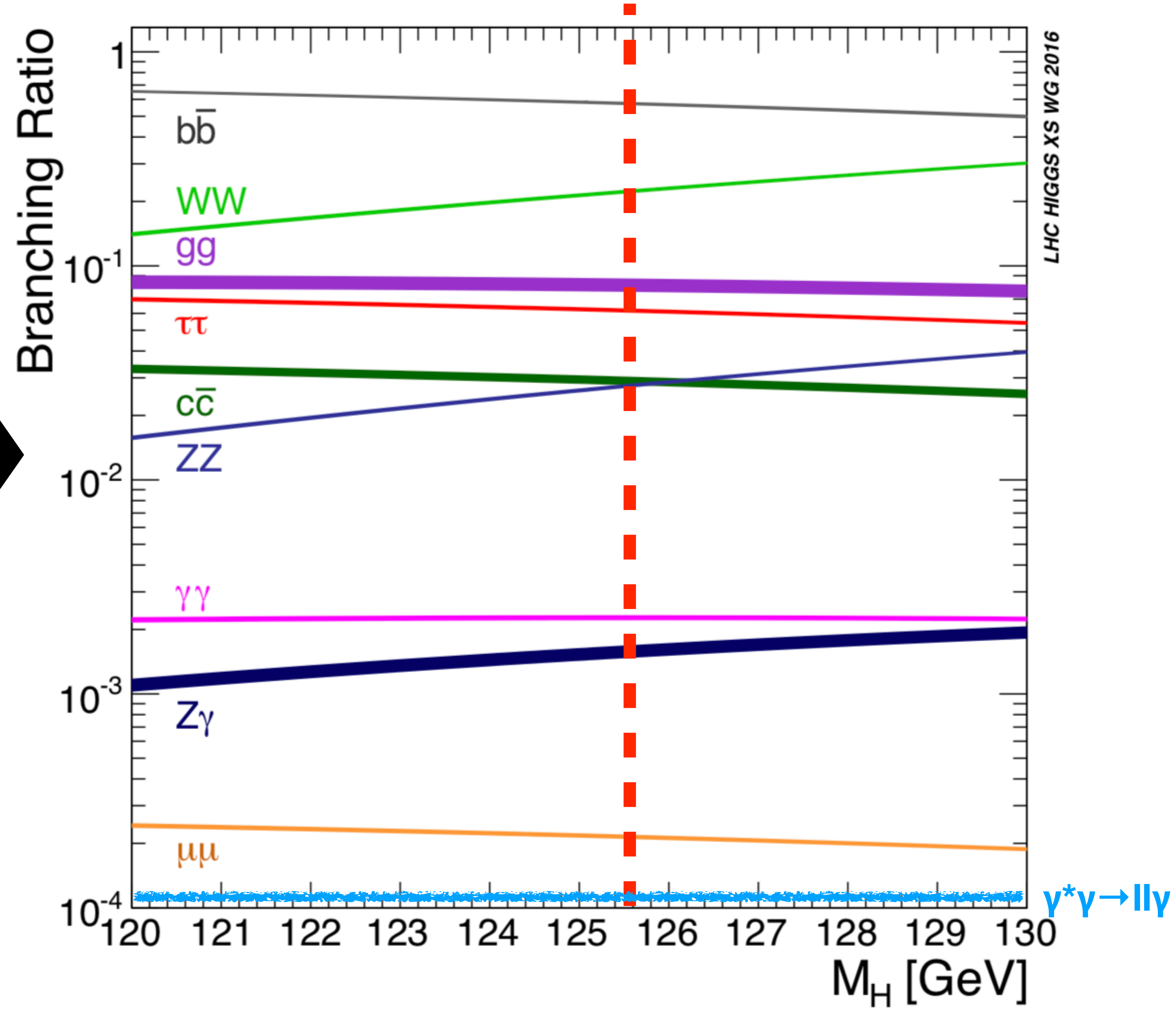
Higgs associated production with vector bosons (VH)



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

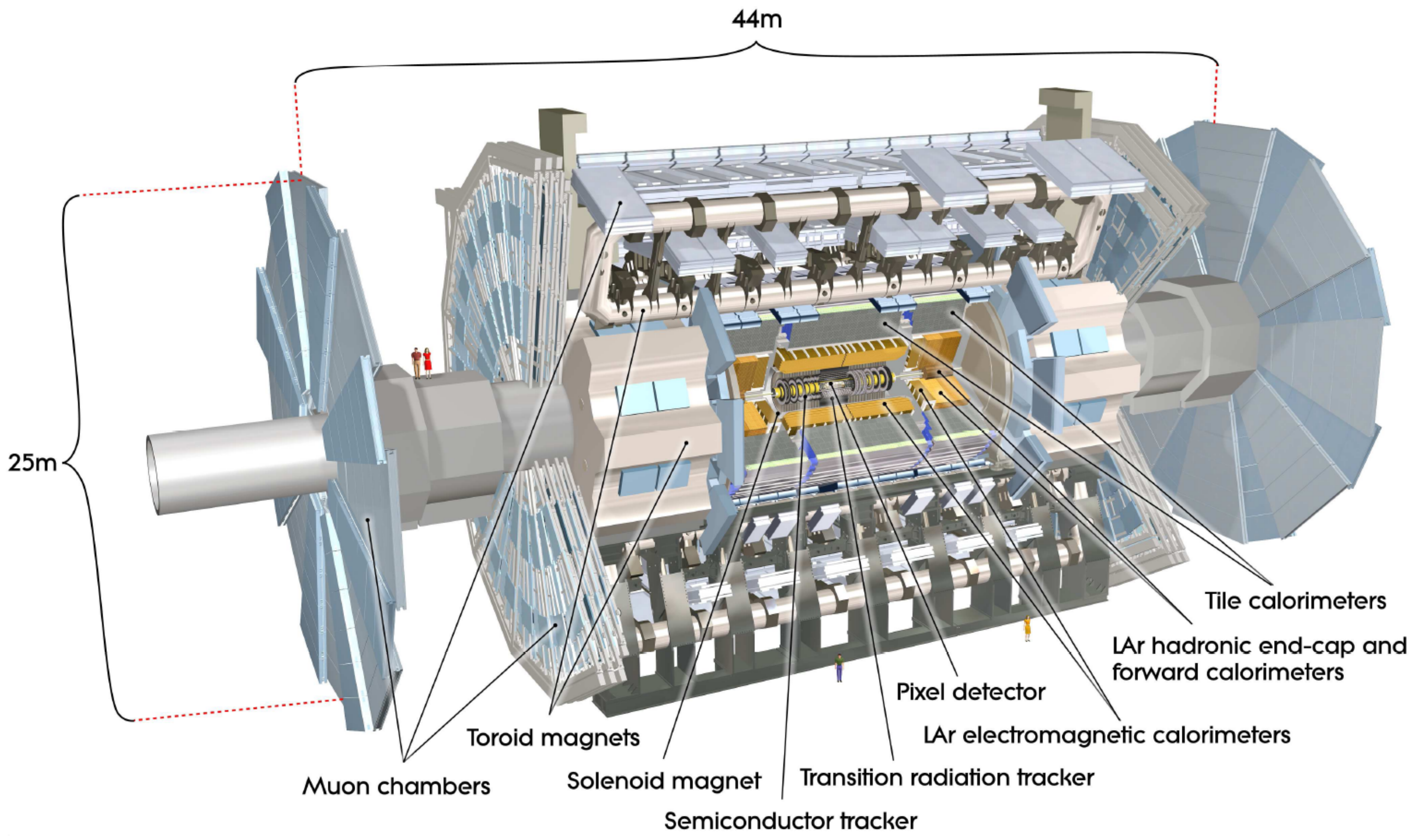


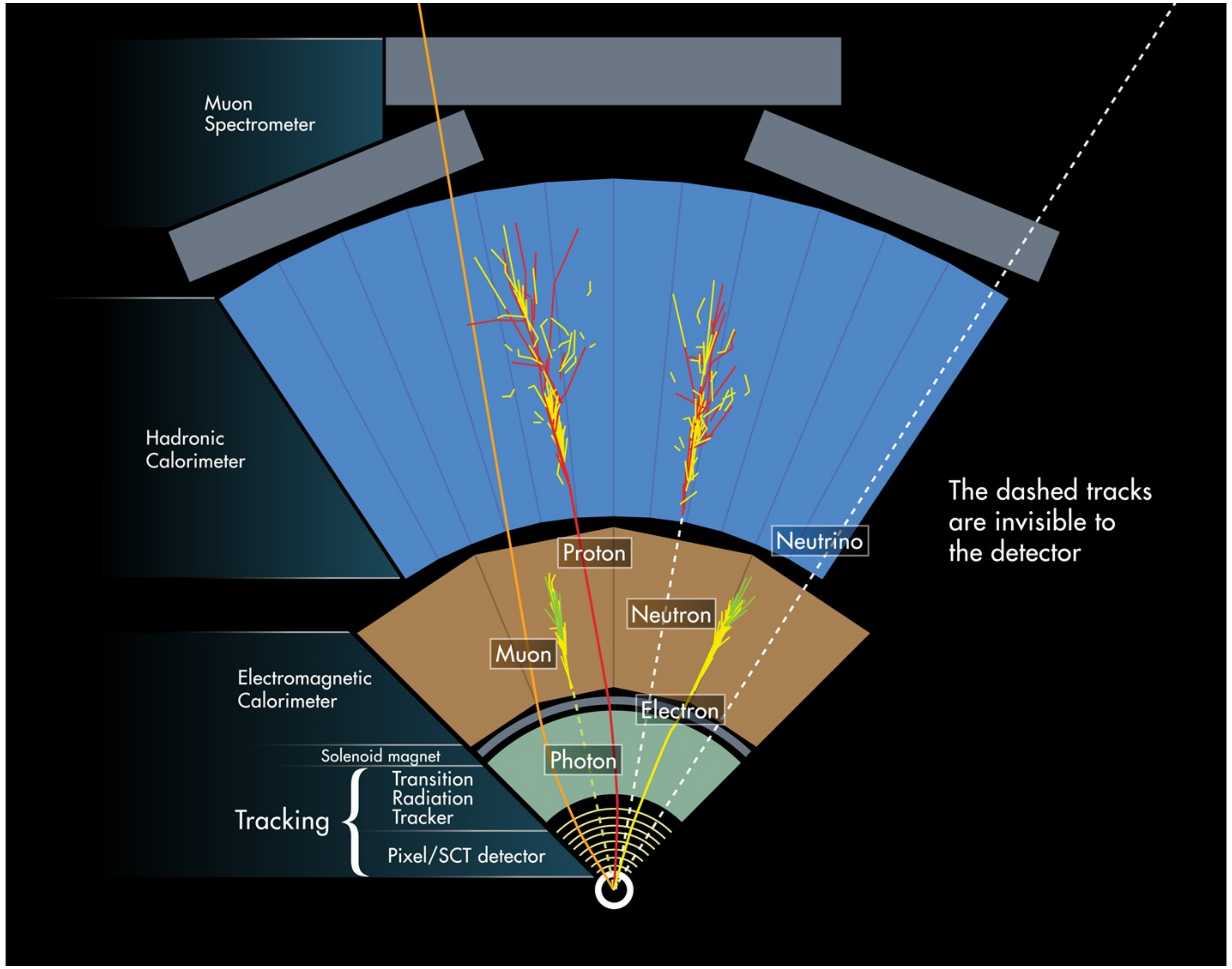




The ATLAS detector at the LHC

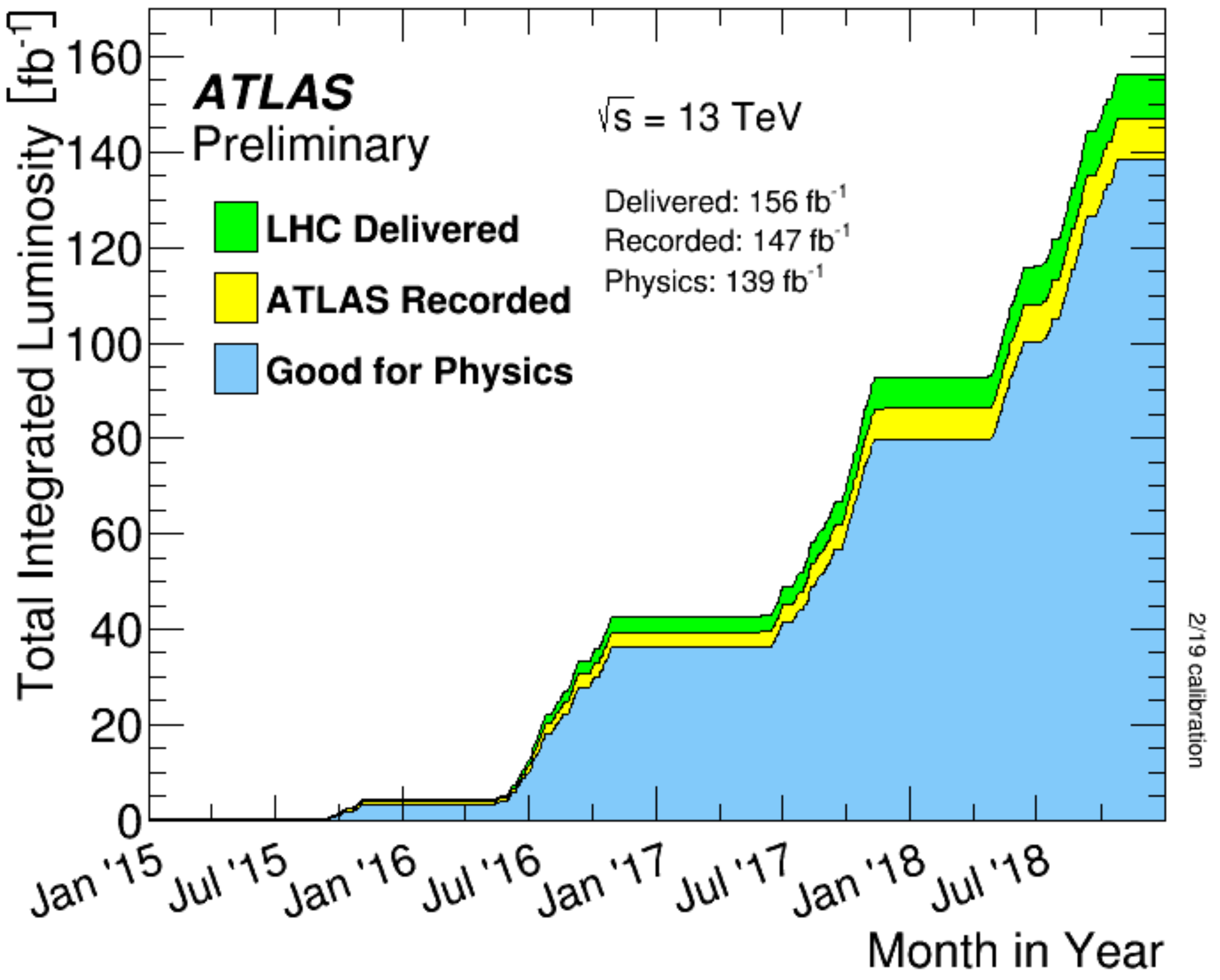
- General-purpose particle physics experiment
  - Designed to exploit the full discovery potential and vast range of physics opportunities that LHC provides

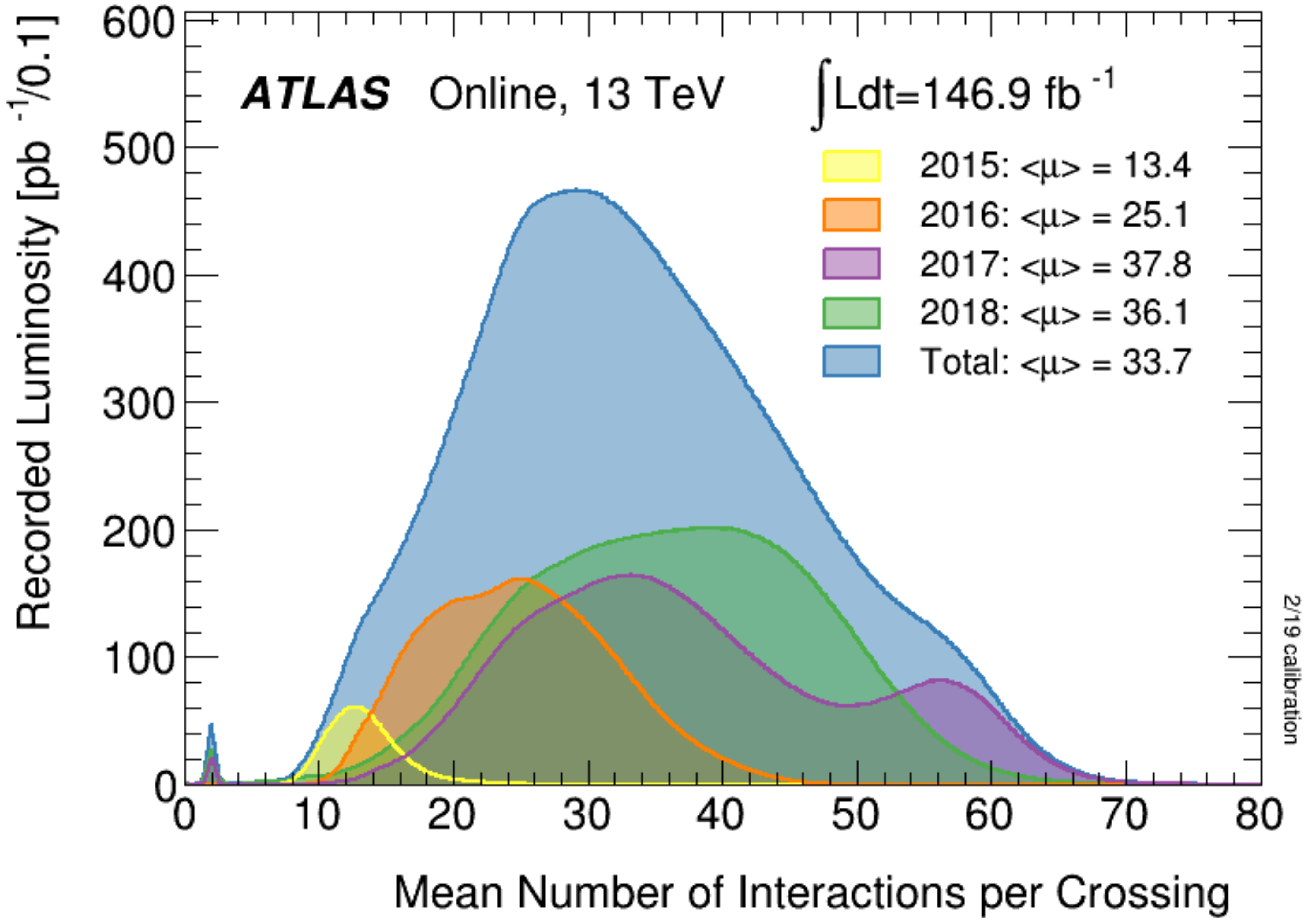




LHC Run 2 period (2015-2018)

- ATLAS experiment has successfully collected **~140 fb^{-1}** luminosity at **pp 13 TeV** centre-of-mass energy in the full LHC Run 2 period
  - Big thanks to the CERN accelerator team for the excellent LHC performance!

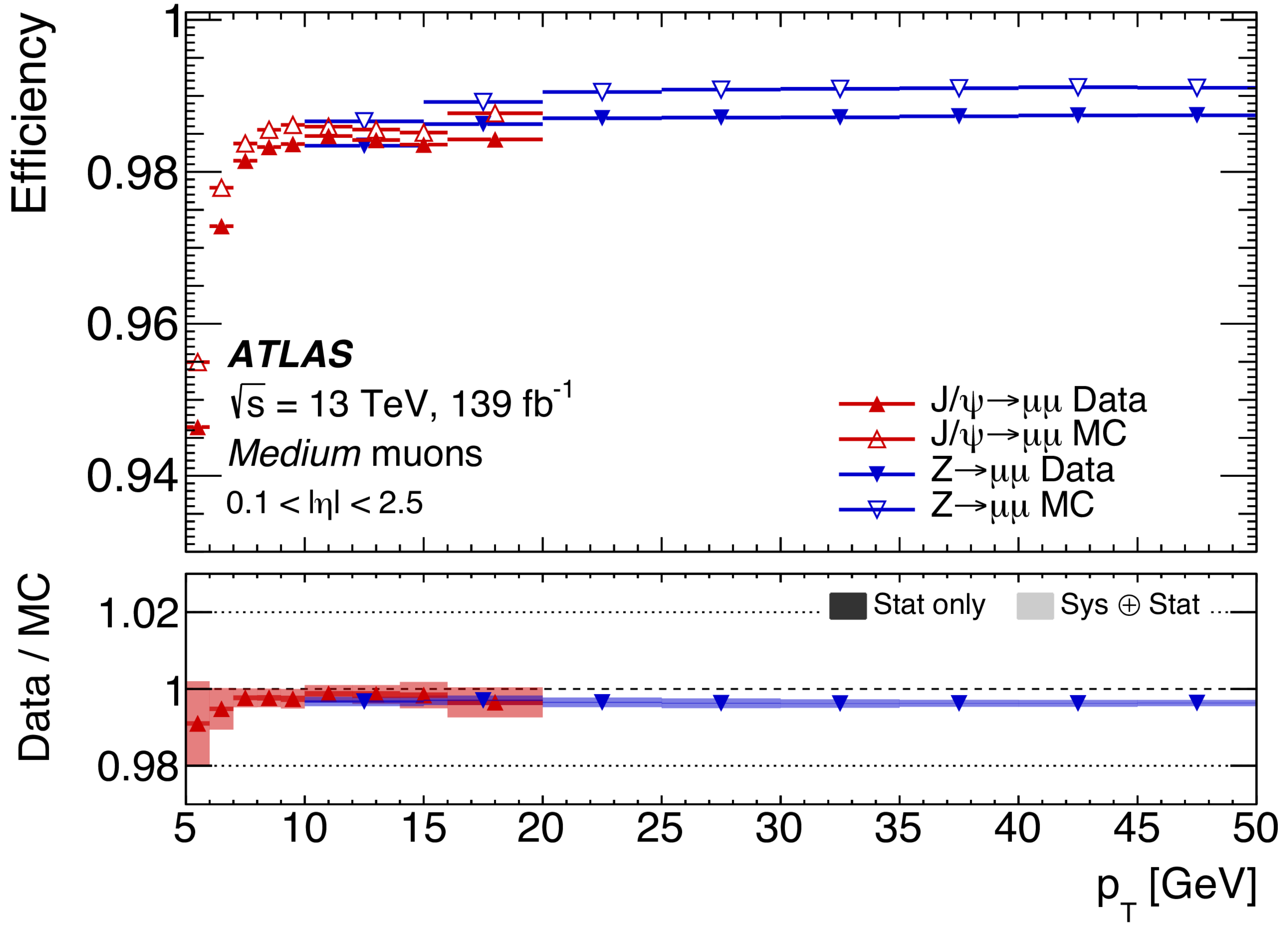




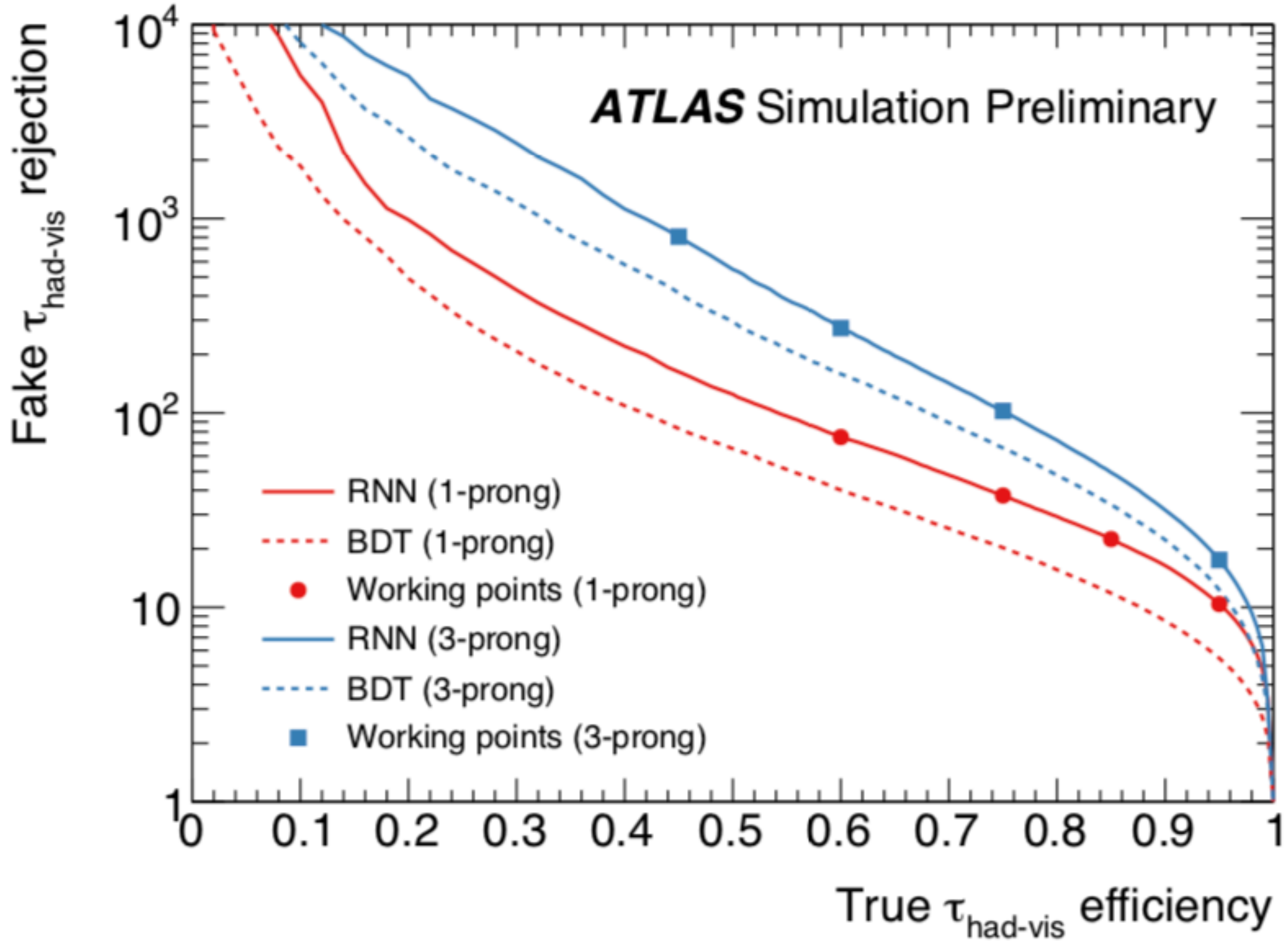
ATLAS detector performance

- 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

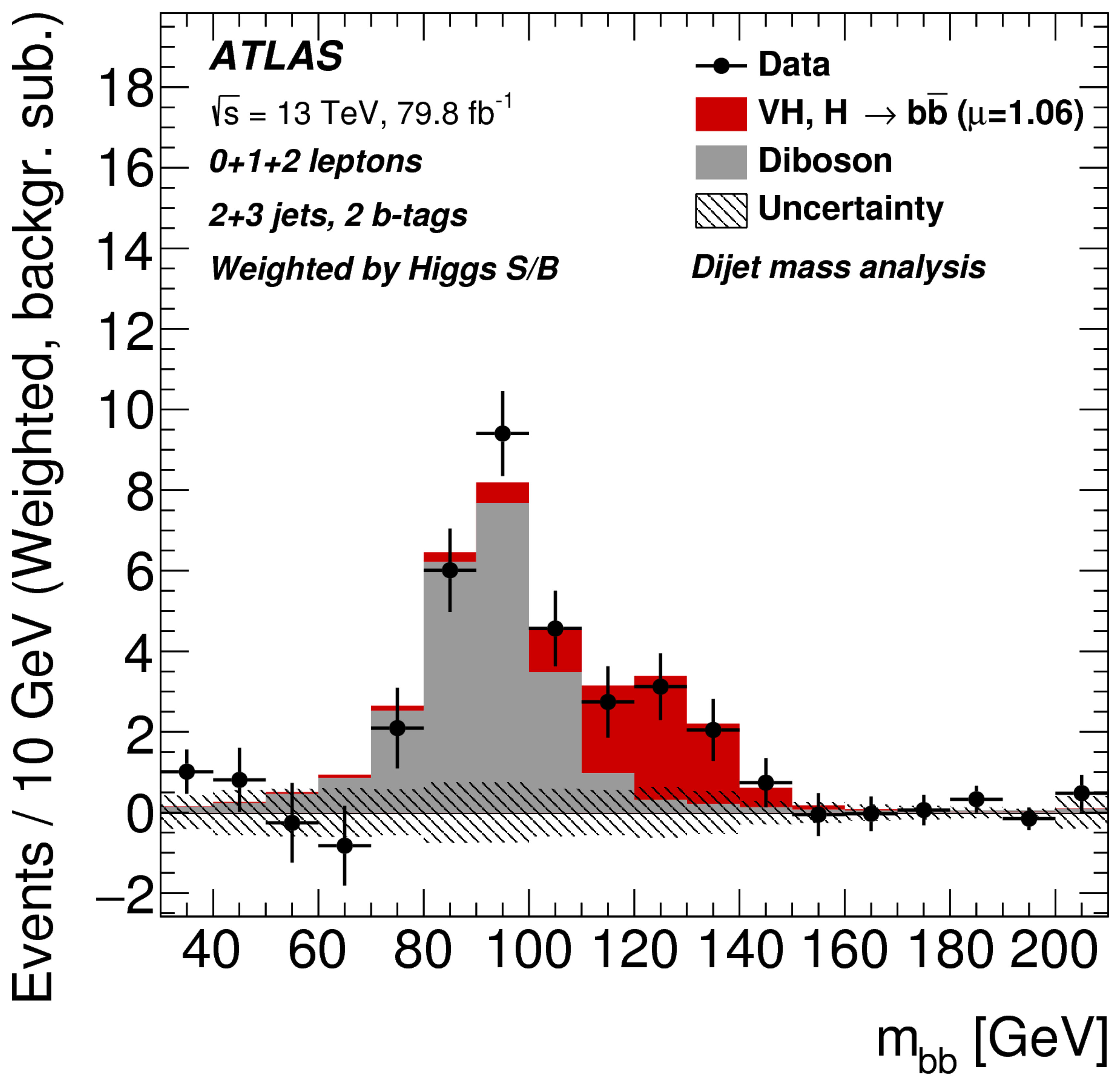


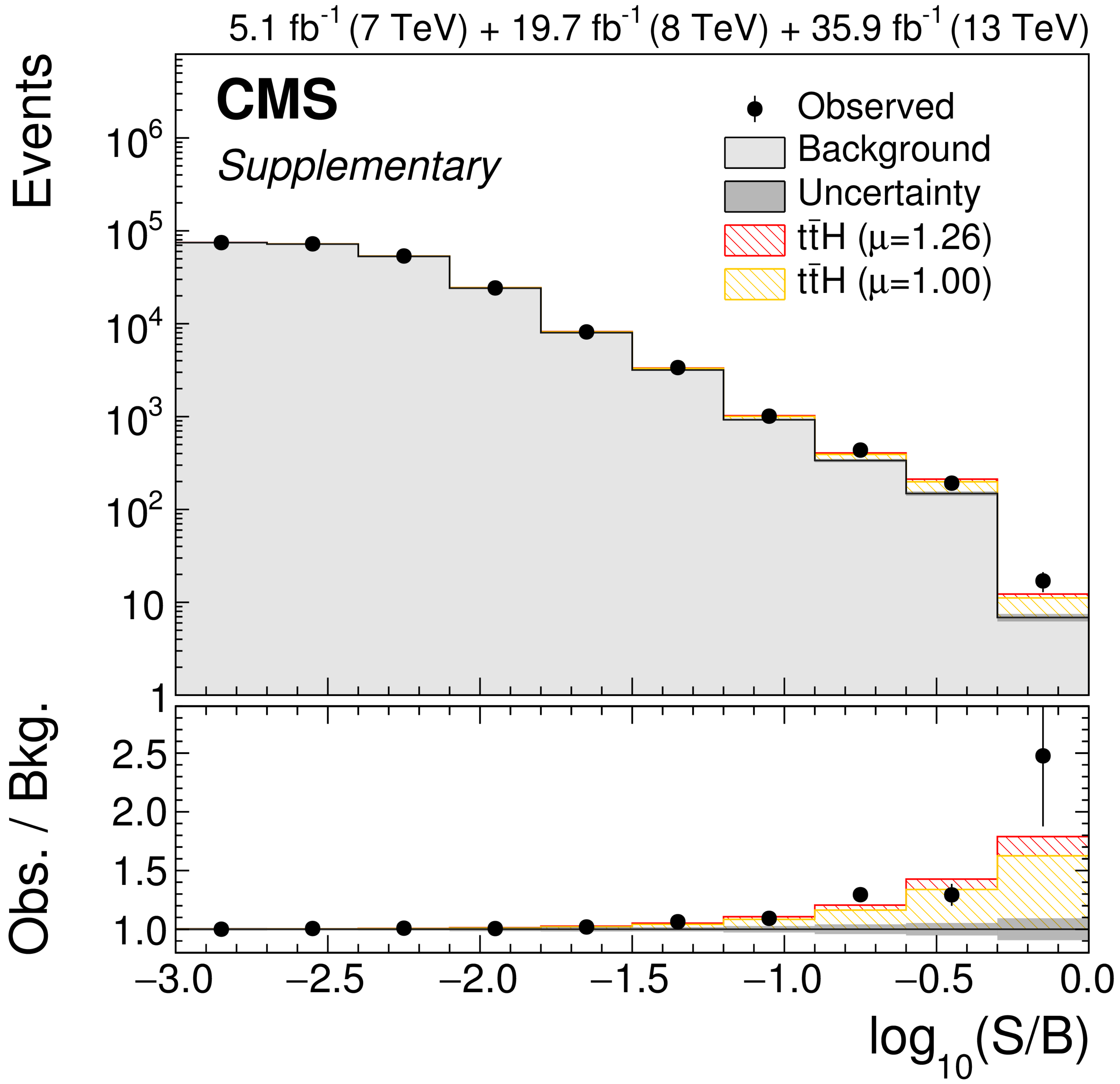
ATL-PHYS-PUB-2019-033



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

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

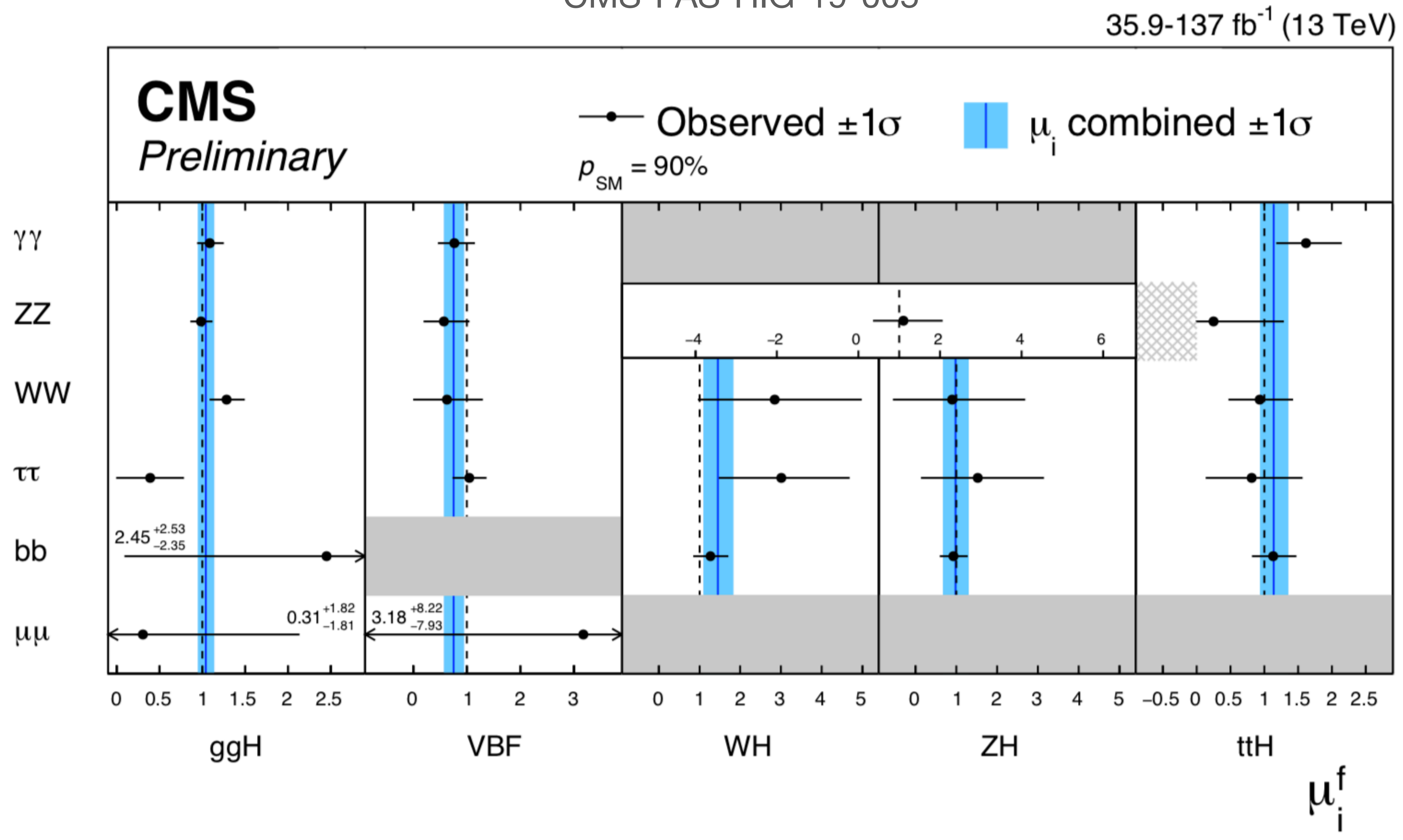




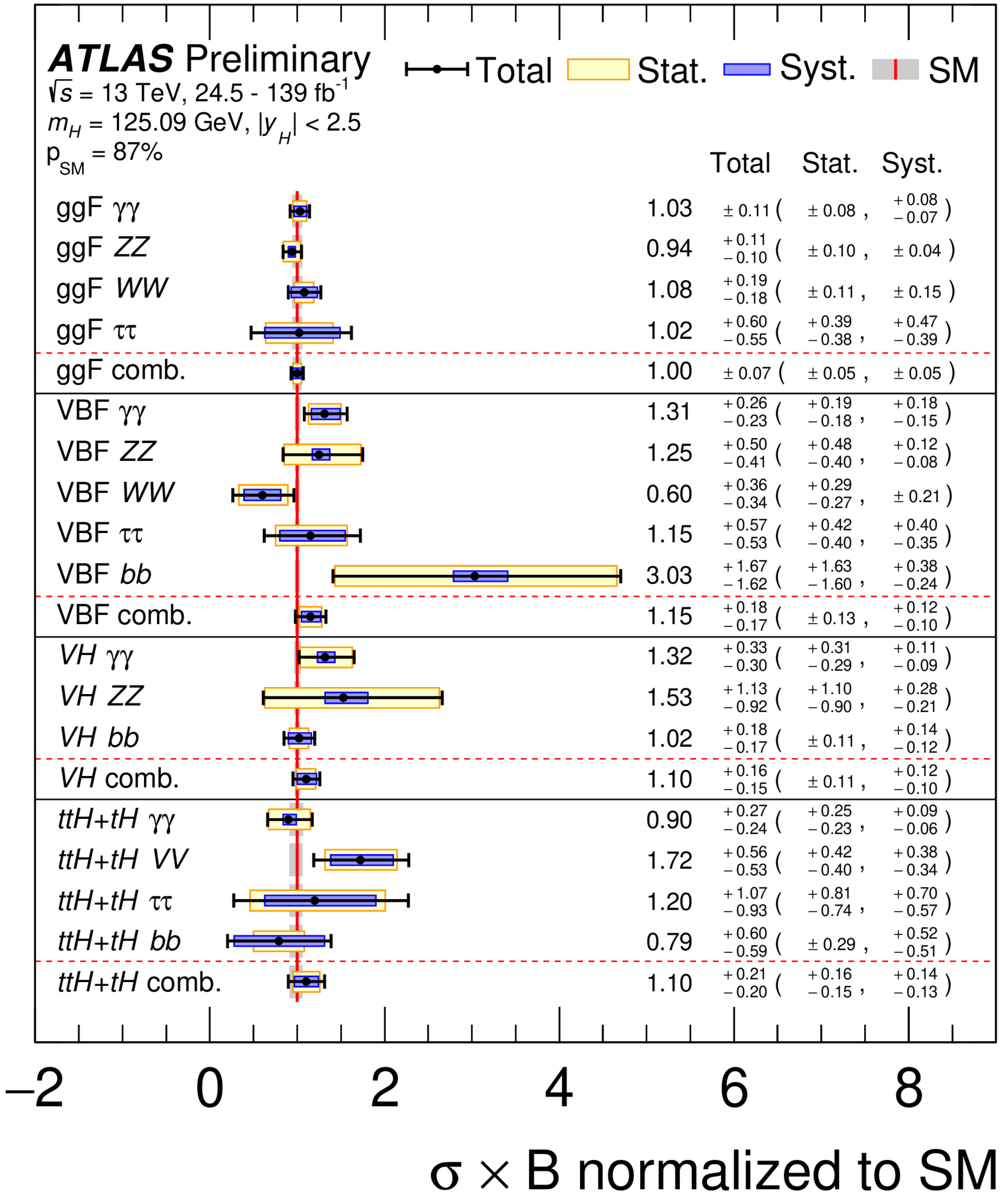
What do we know about the Higgs boson after LHC Run 2?

- 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)
  - in good agreement with the SM prediction

CMS-PAS-HIG-19-005



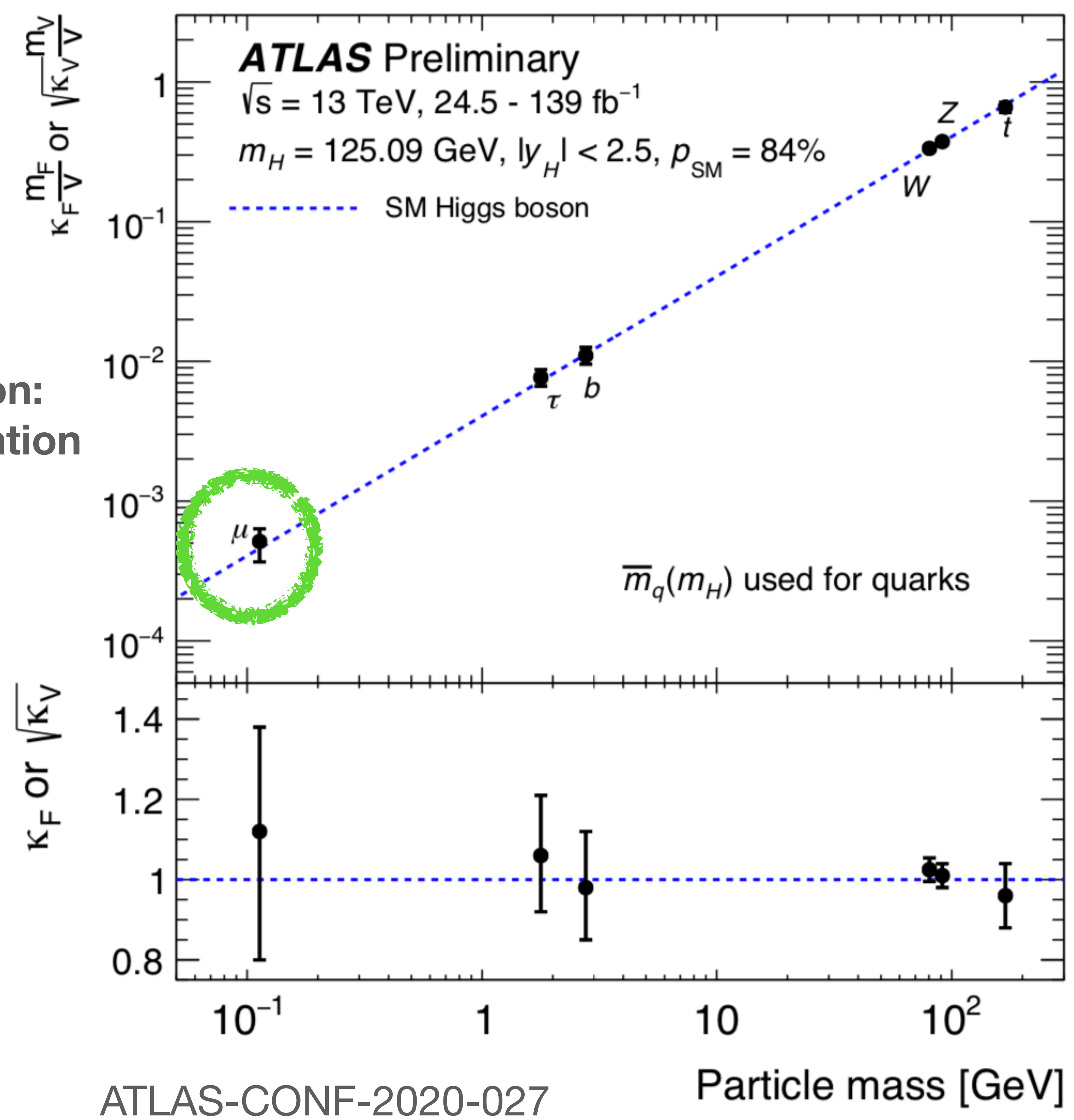
ATLAS-CONF-2020-027



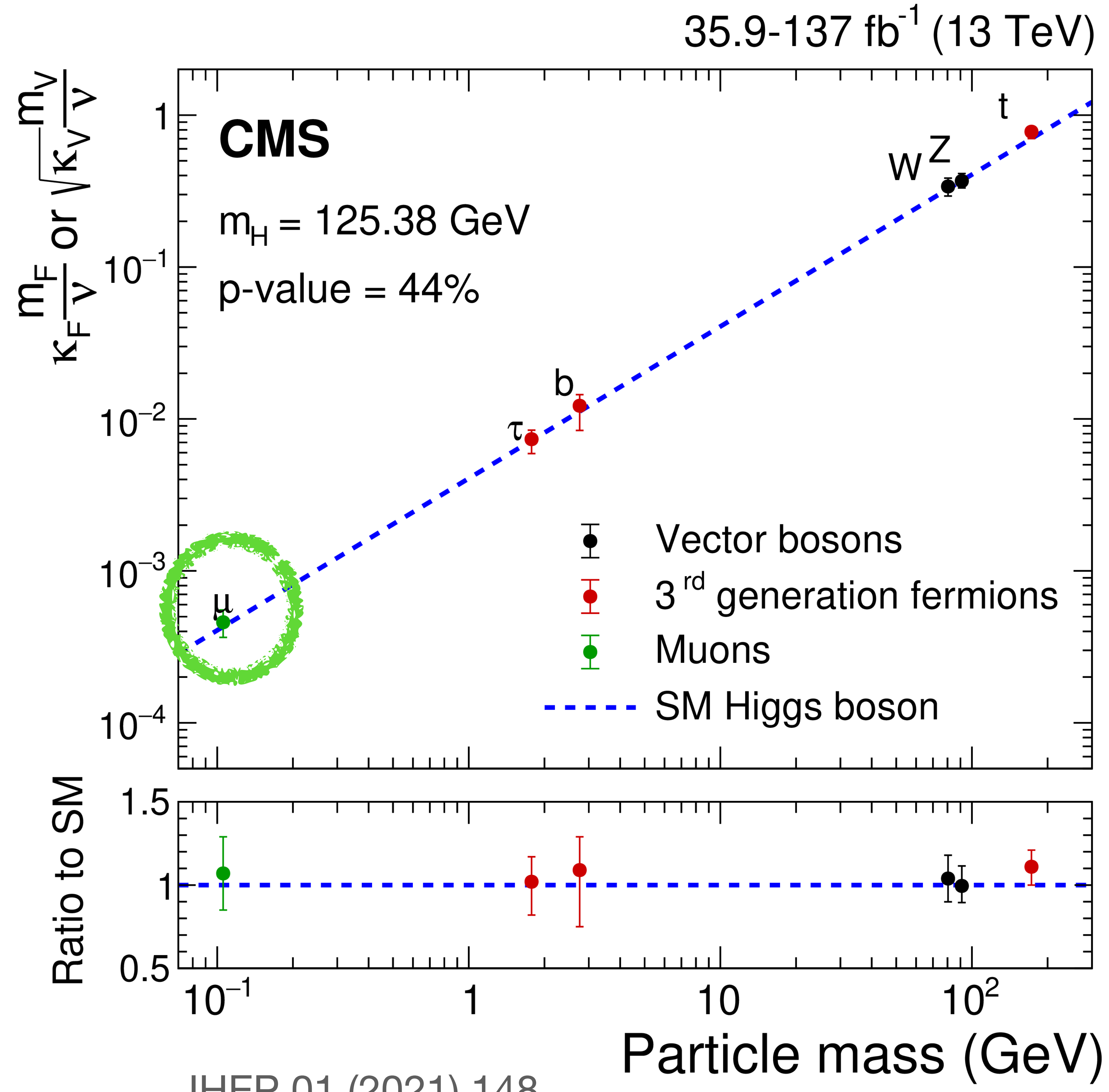
What do we know about the Higgs boson after LHC Run 2?

- 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



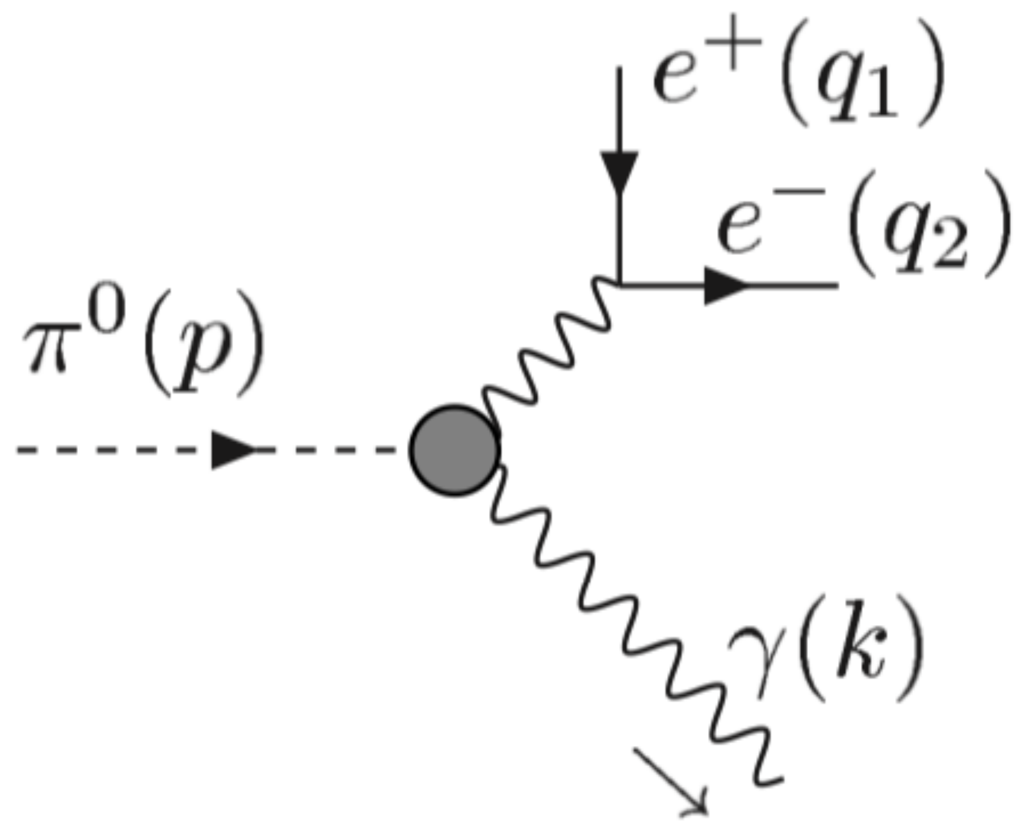
ATLAS-CONF-2020-027



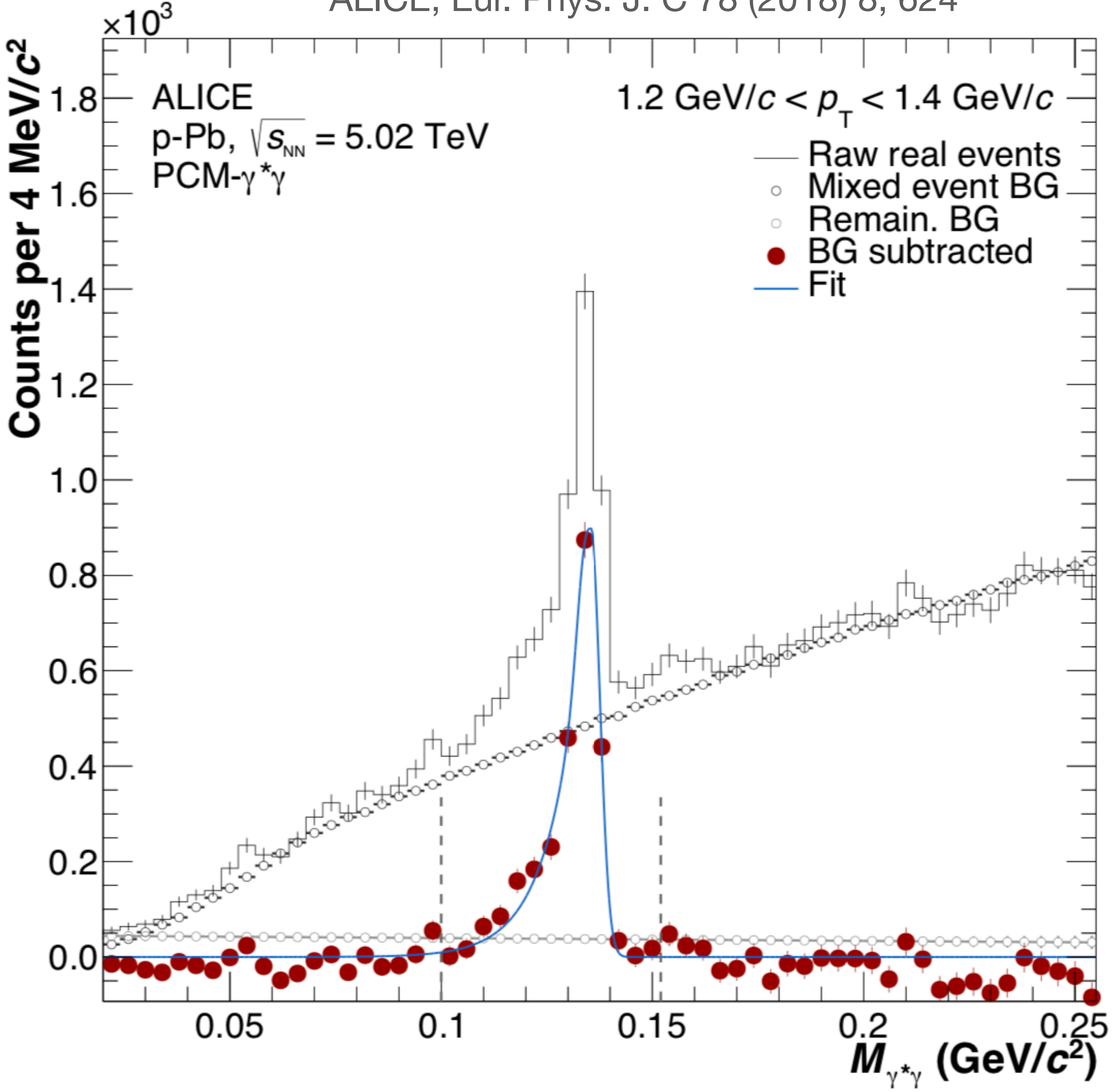
JHEP 01 (2021) 148

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**

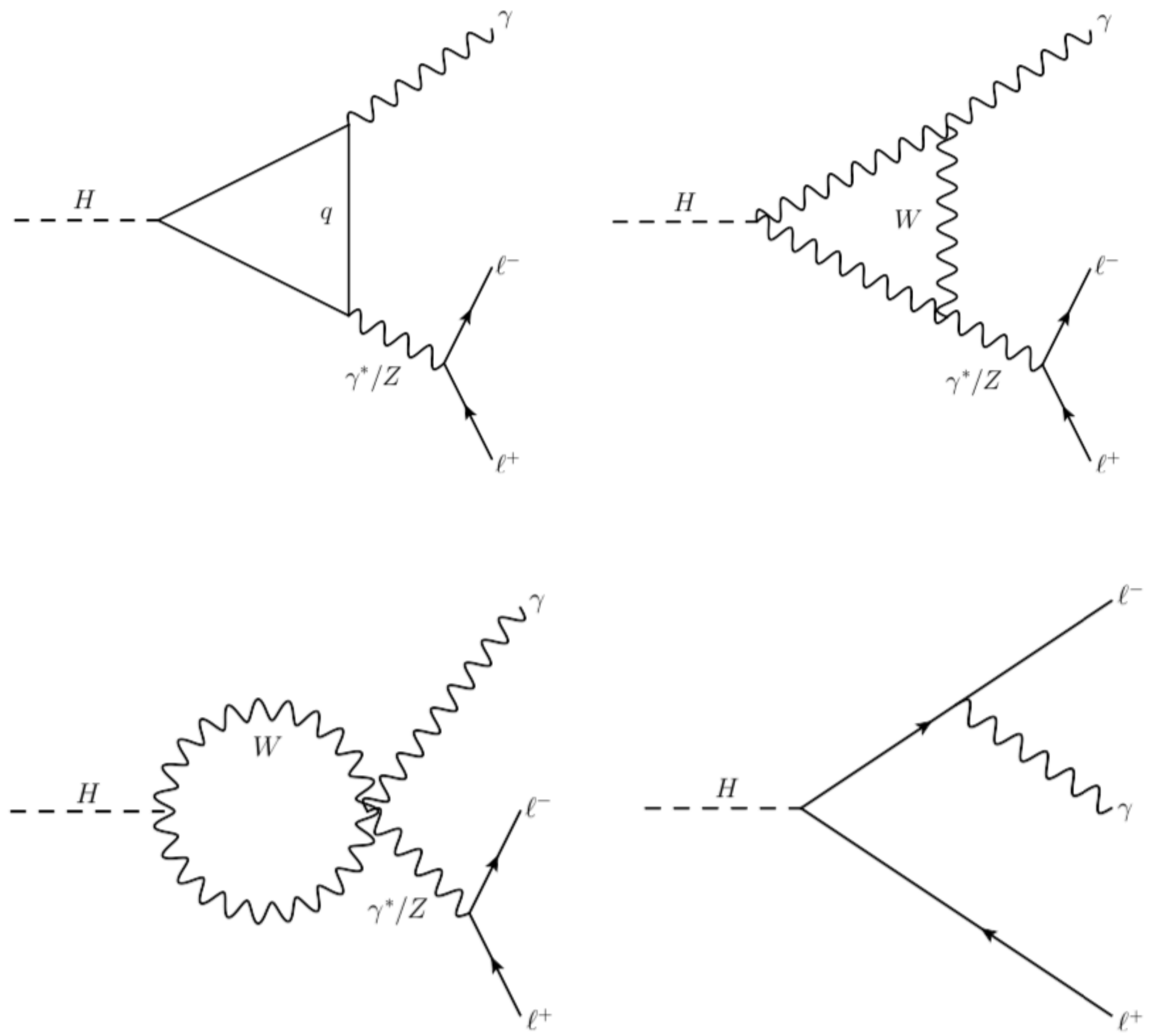


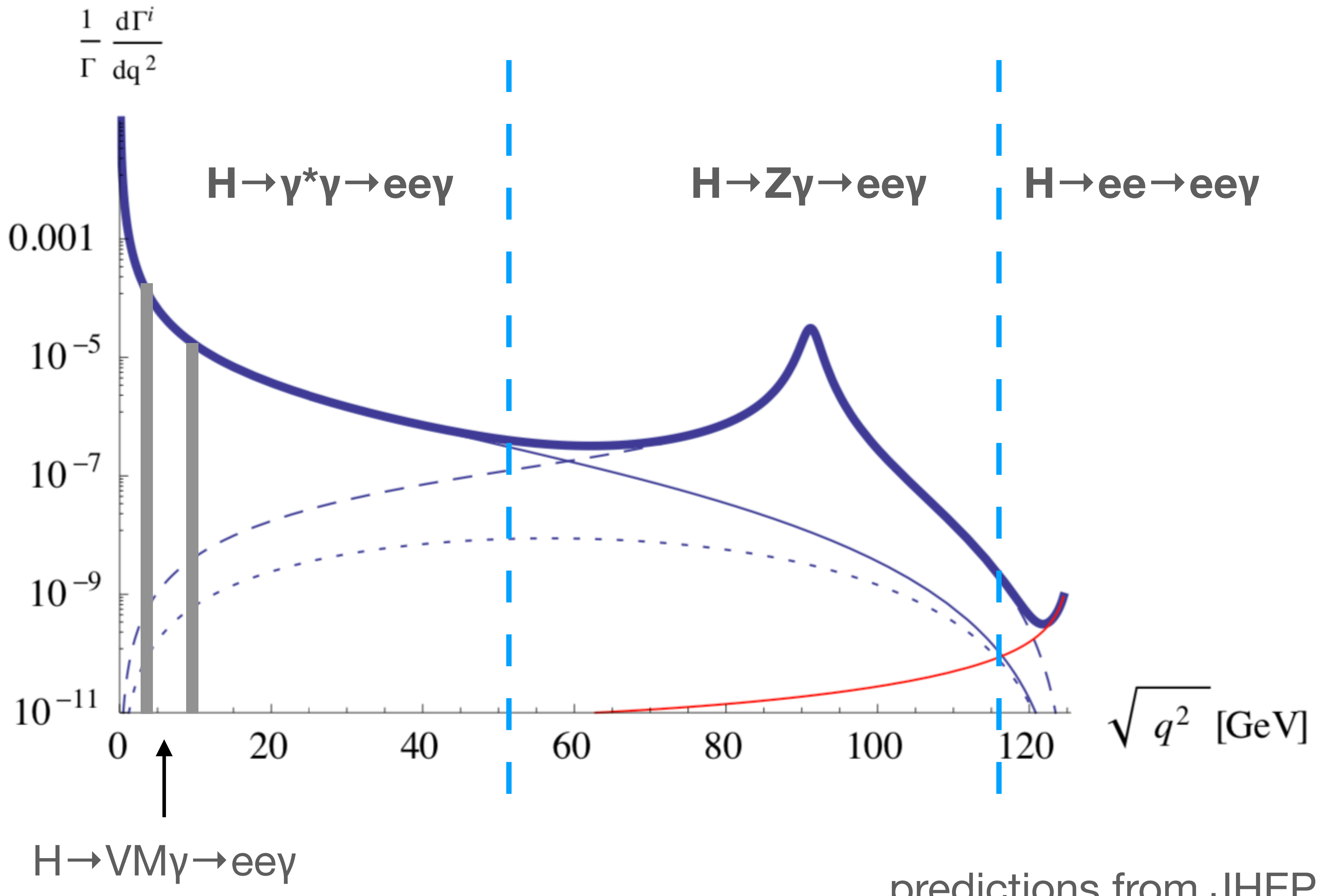
ALICE, Eur. Phys. J. C 78 (2018) 8, 624

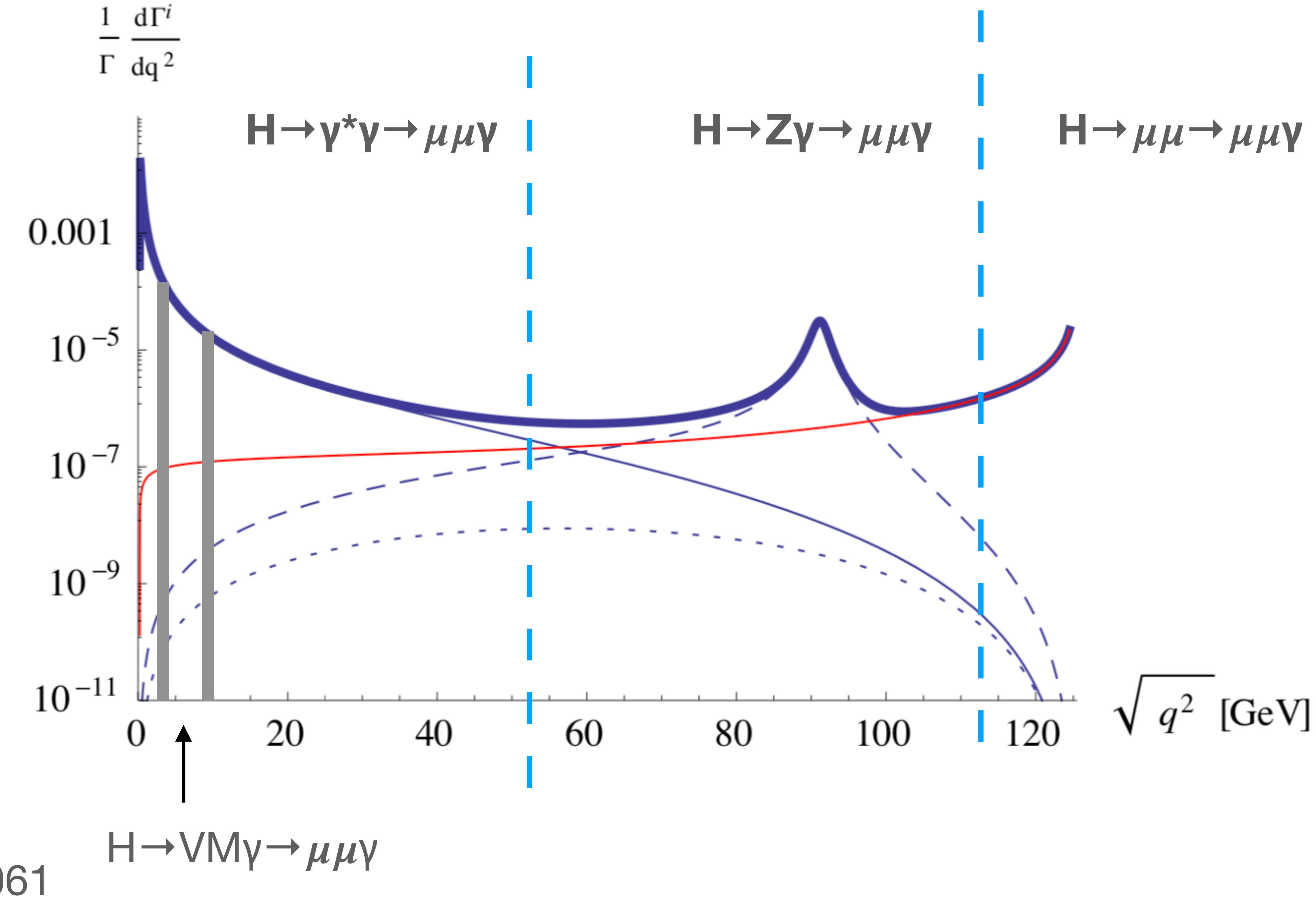


Higgs Dalitz decay (H→llγ)

- Very rare decays (**B < 2×10^{-4}**)
- Several processes contribute to the final state
  - BSM sensitivity through loops
- Diverse final state kinematics
  - **Dedicated measurements are performed for each region of phase-space**



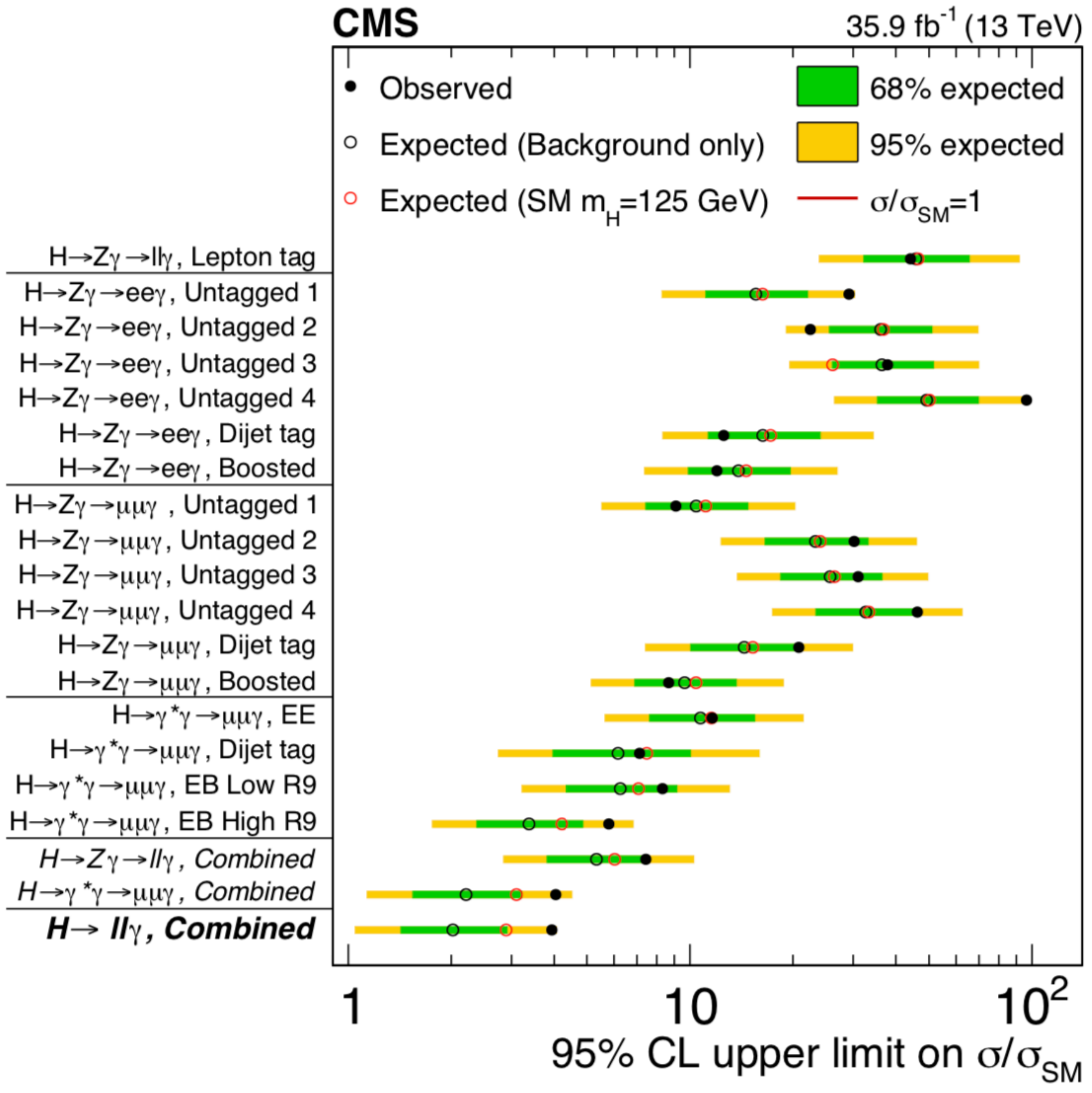




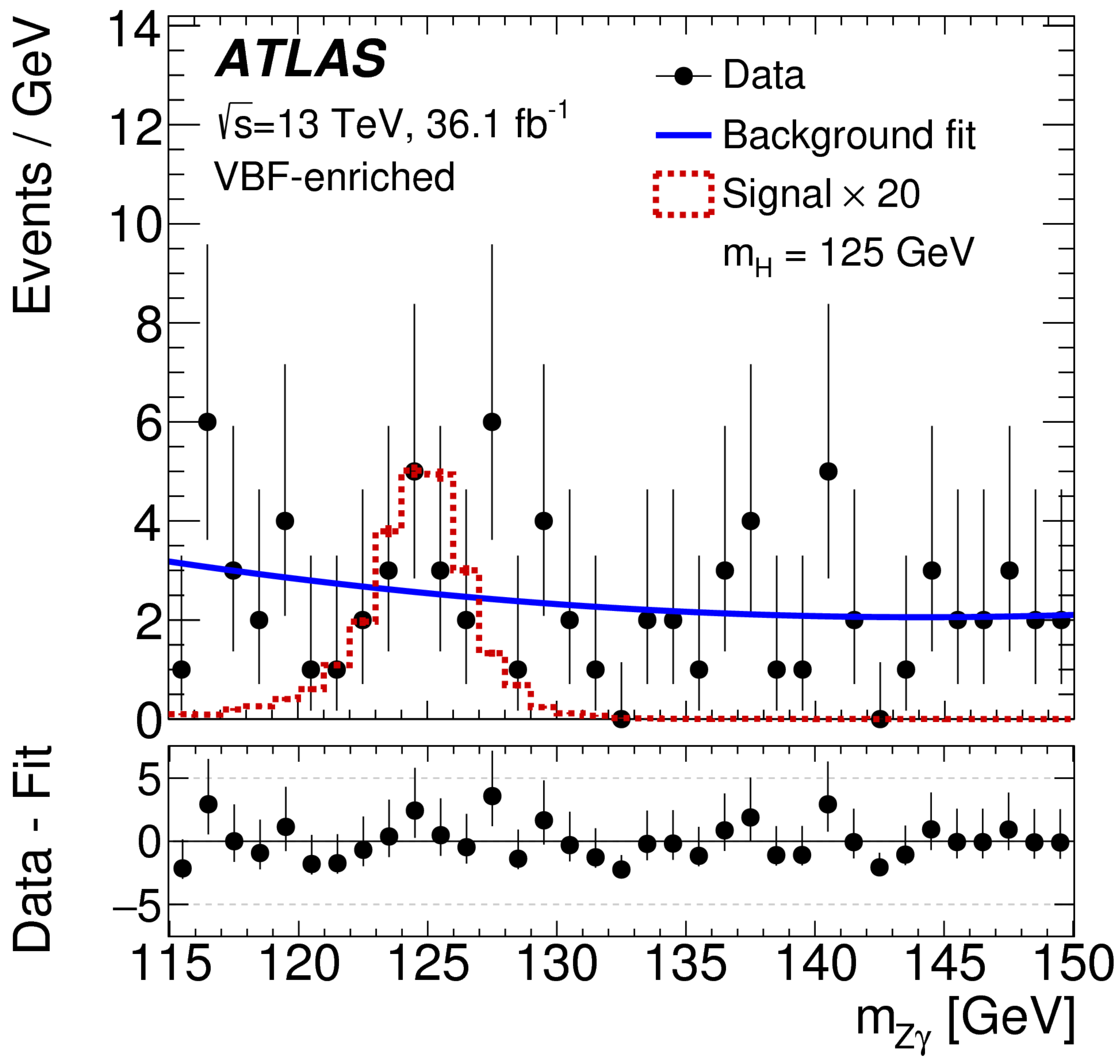
predictions from JHEP 05 (2013) 061

Previous measurements of H→llγ

- Run 1 and early Run 2 searches for H→llγ are all statistically limited and consistent with background-only hypothesis

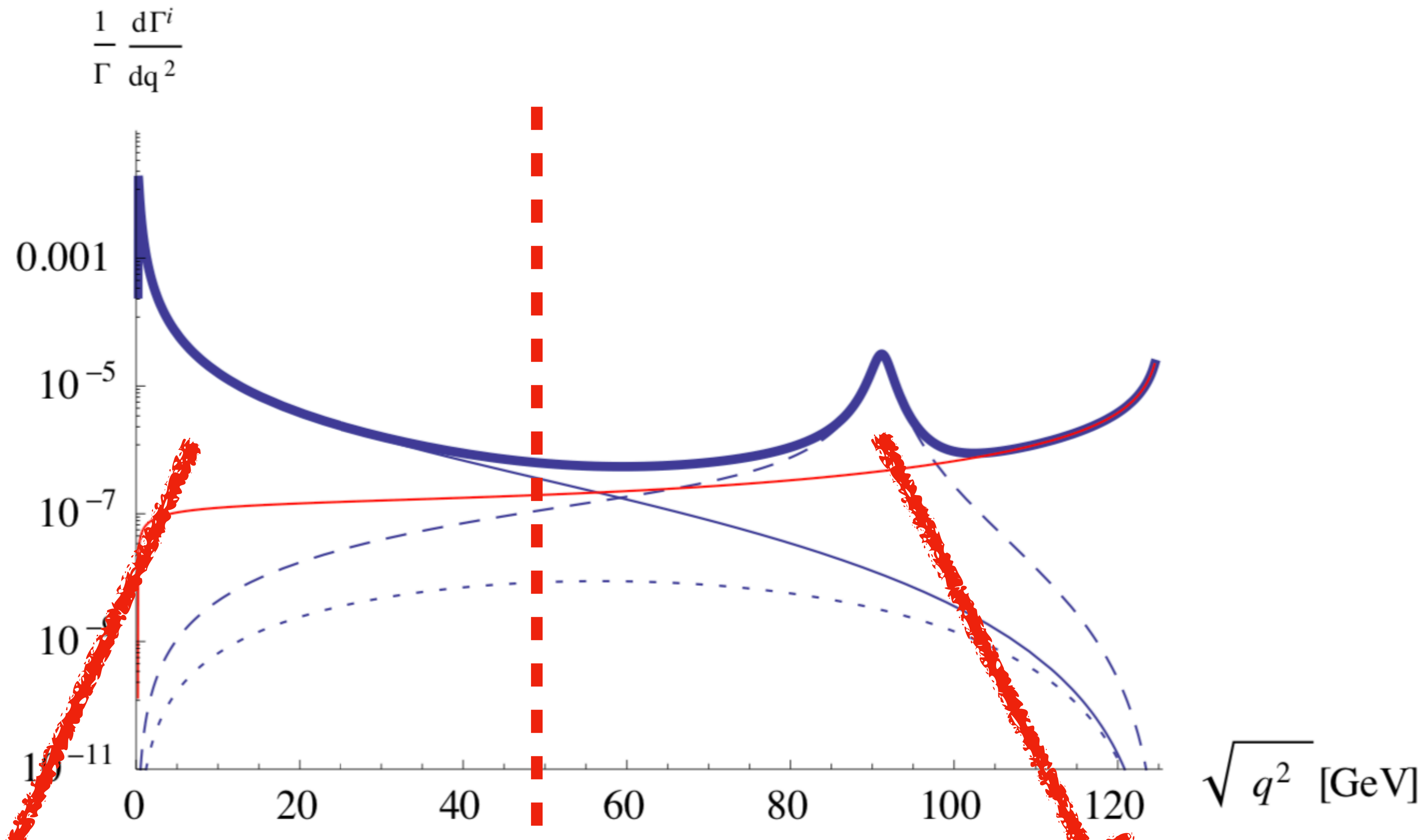


JHEP 11 (2018) 152



JHEP 10 (2017) 112

New searches for H→llγ decays with ATLAS



arXiv:2103.10322

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B

CERN-EP-2021-035
19th March 2021

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

The ATLAS Collaboration

Phys. Lett. B 809 (2020) 135754

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Lett. B 809 (2020) 135754
DOI: 10.1016/j.physletb.2020.135754

CERN-EP-2020-052
6th October 2020

A search for the $Z\gamma$ decay mode of the Higgs boson in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

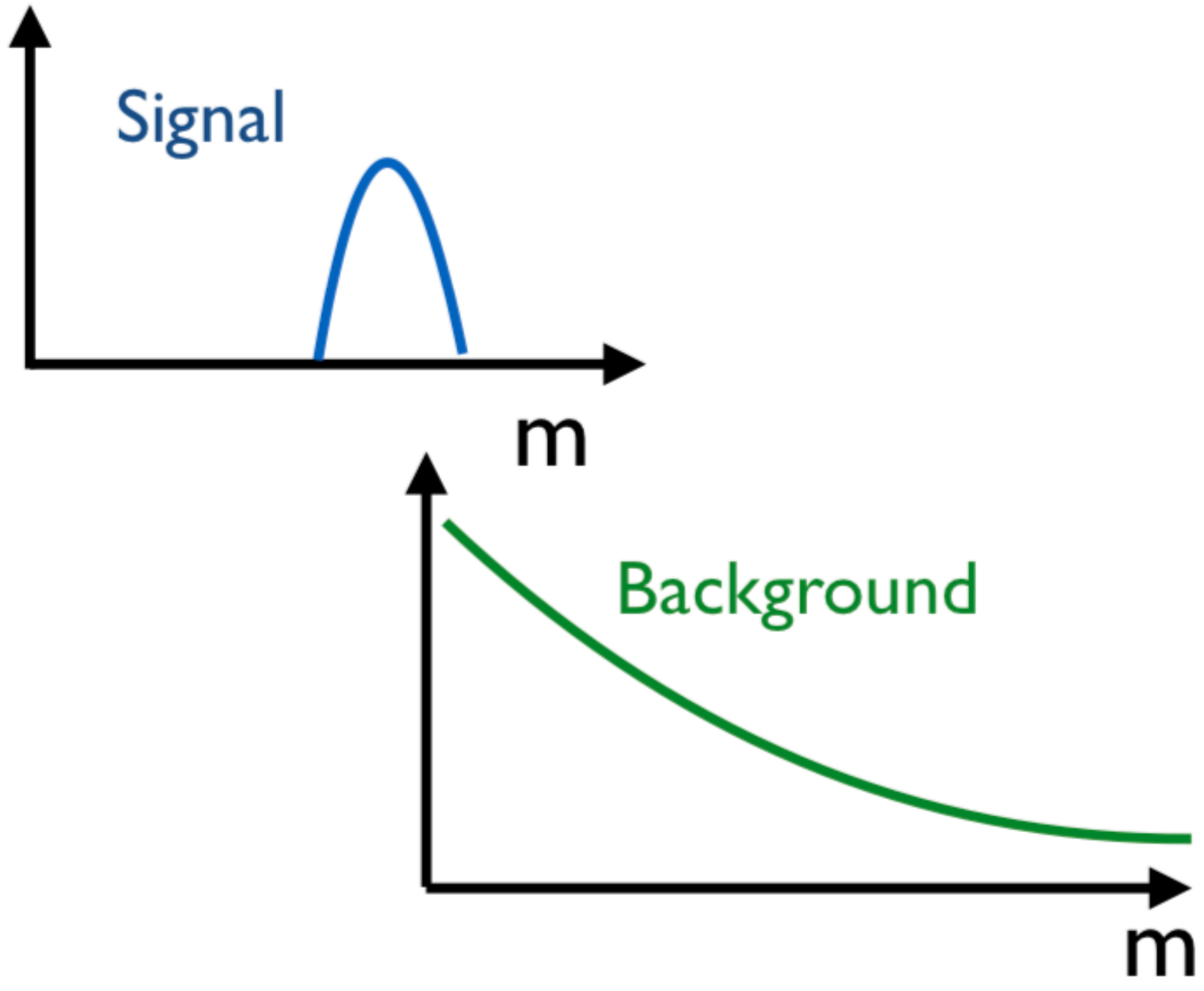
The ATLAS Collaboration

Search for H→llγ decays with ATLAS

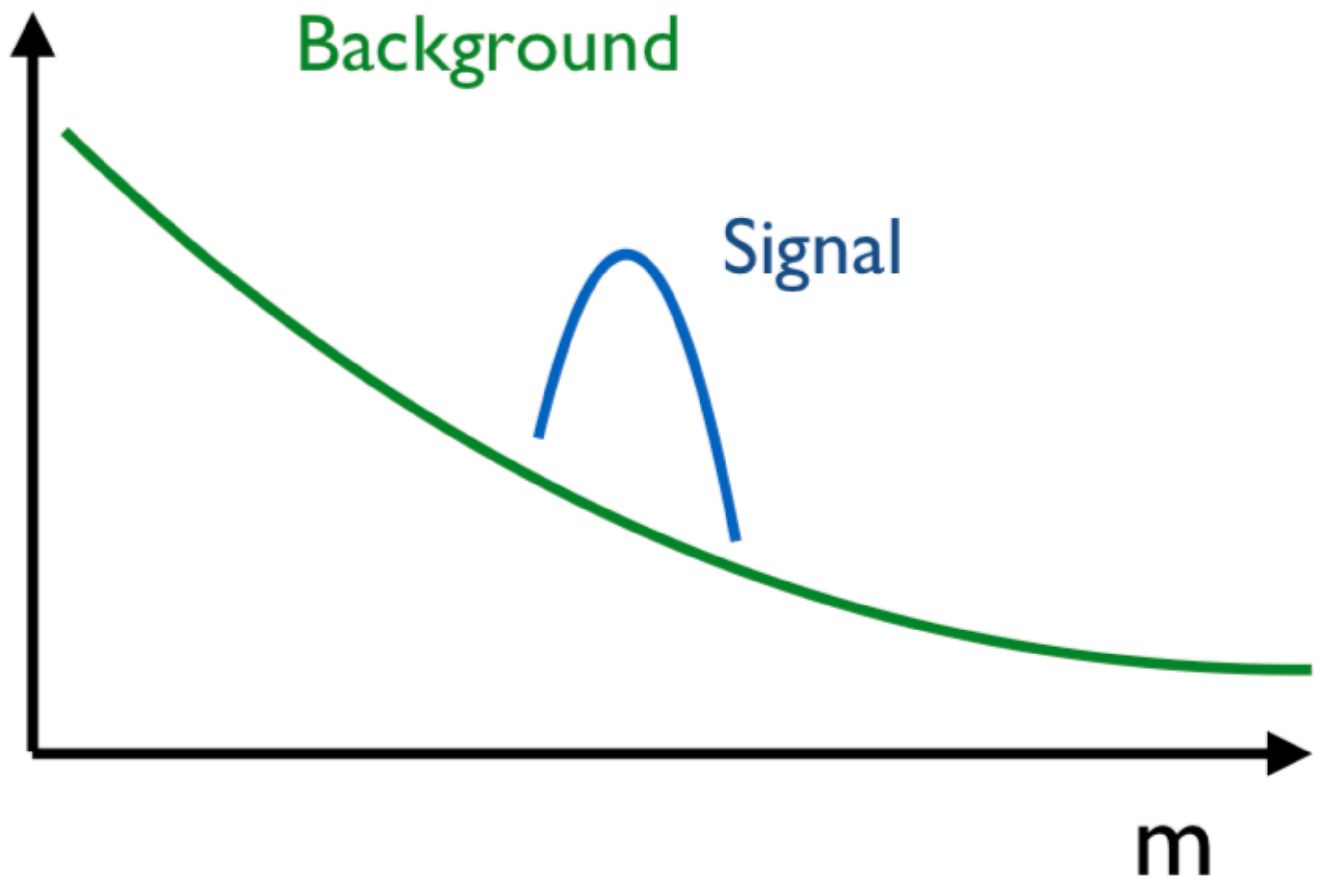
- Rough sketch of analysis procedure:
  - Object and event selection + categorisation (**Step 1**)
  - Signal and background parameterisations (**Step 2**)
  - Simultaneous fit to all categories (**Step 3**)

Step 1

Step 2



Step 3

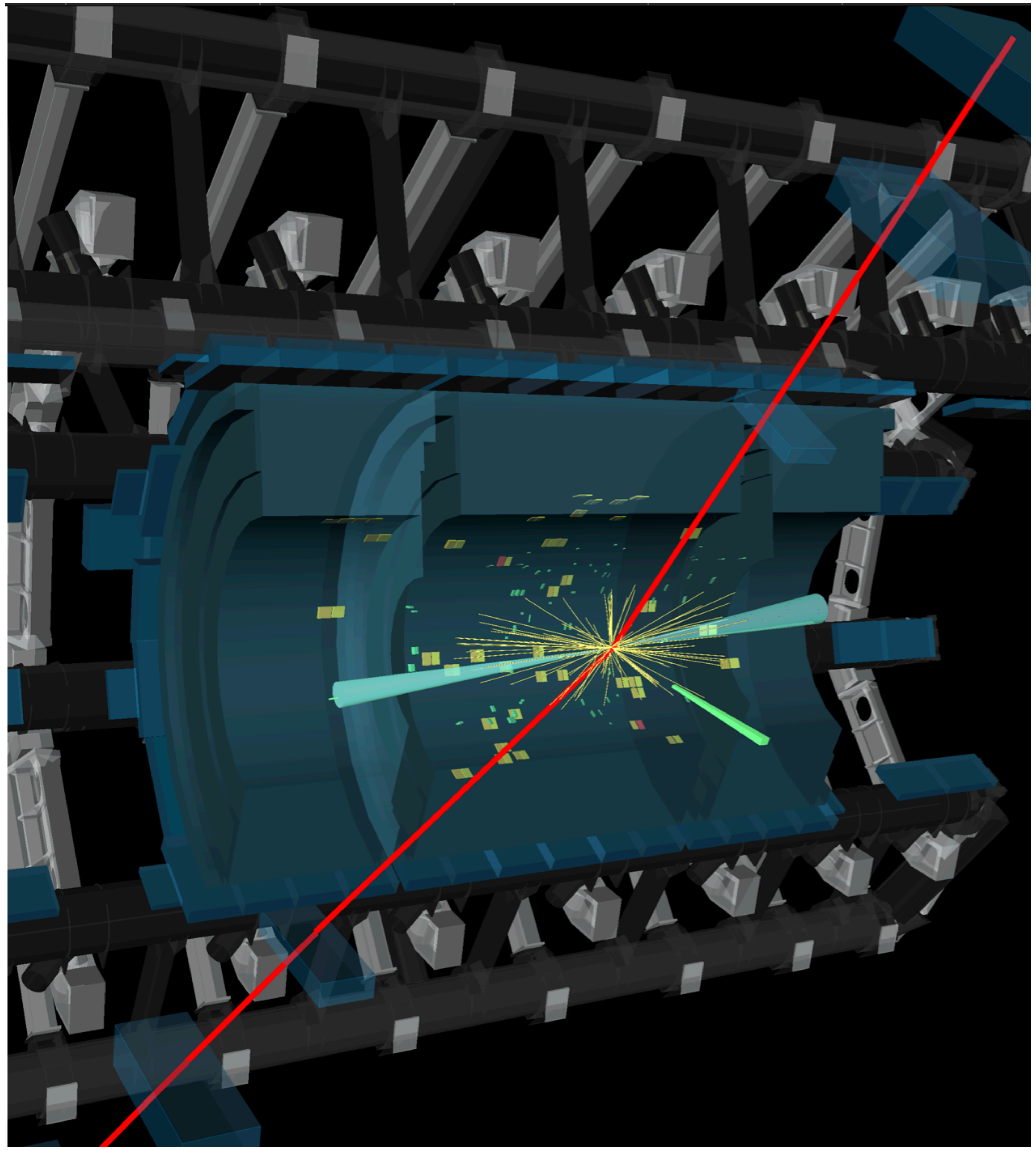


Event preselection

Phys. Lett. B 809 (2020) 135754

- **Search for H→Zγ→llγ decay**

- Single & di-leptonic triggered events
- Object selection:
  - Muons: Isolated with $p_T > 10$ GeV
  - Electrons: Isolated with $p_T > 10$ GeV
  - Jets: $p_T > 25$ GeV
- Select an opposite-sign same flavor lepton pair (ee or μμ) + γ
  - **$50 < m_{ll} < 101$ GeV**
  - $p_{T\gamma}/m_{ll\gamma} > 0.12$



VBF H→Zγ Candidate Event

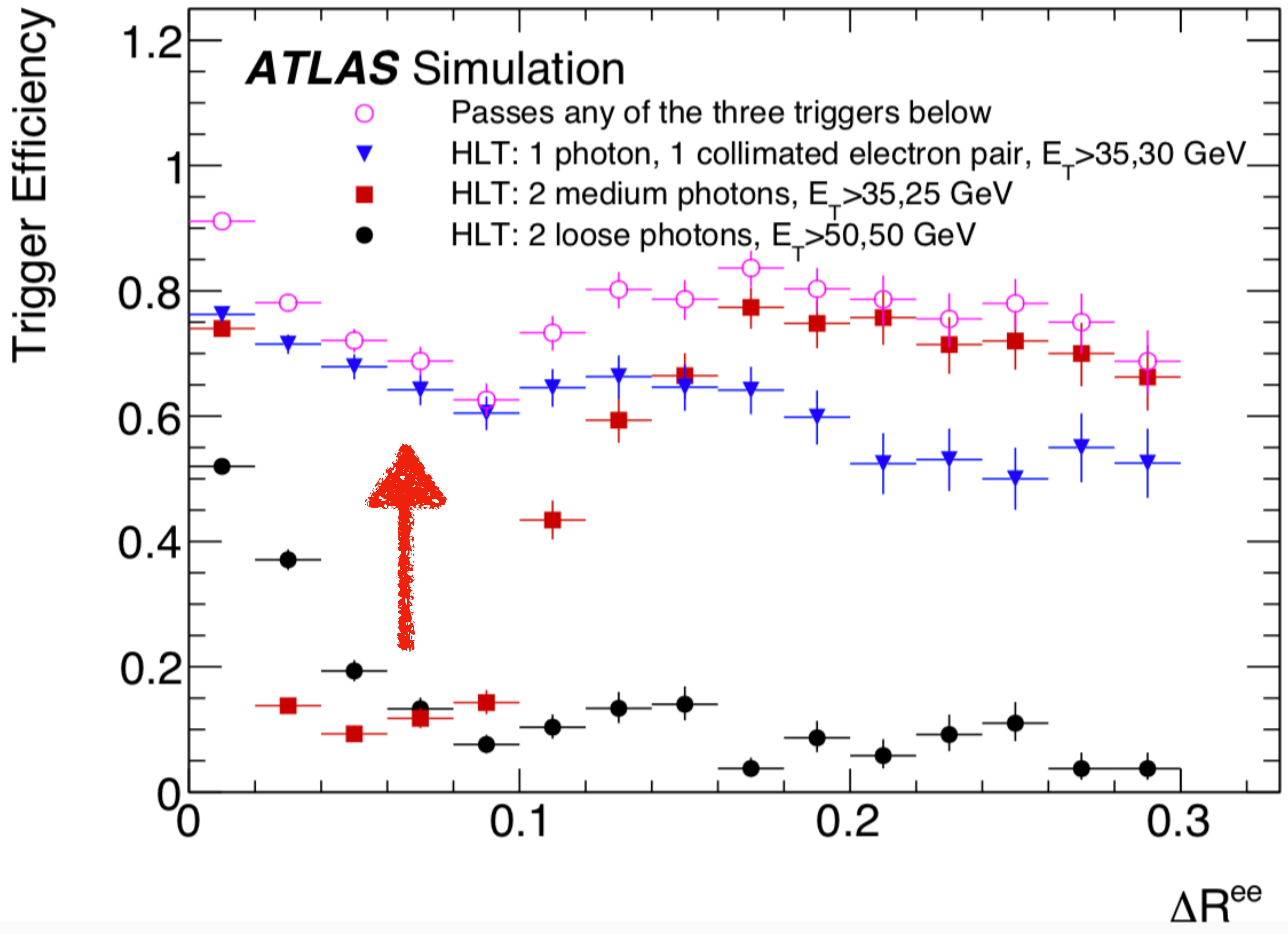
Event preselection

arXiv:2103.10322

- **Search for H→llγ decay at low-m_{ll}**

- Can't rely on regular single-lepton triggers alone
  - Combination of single-l, 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%



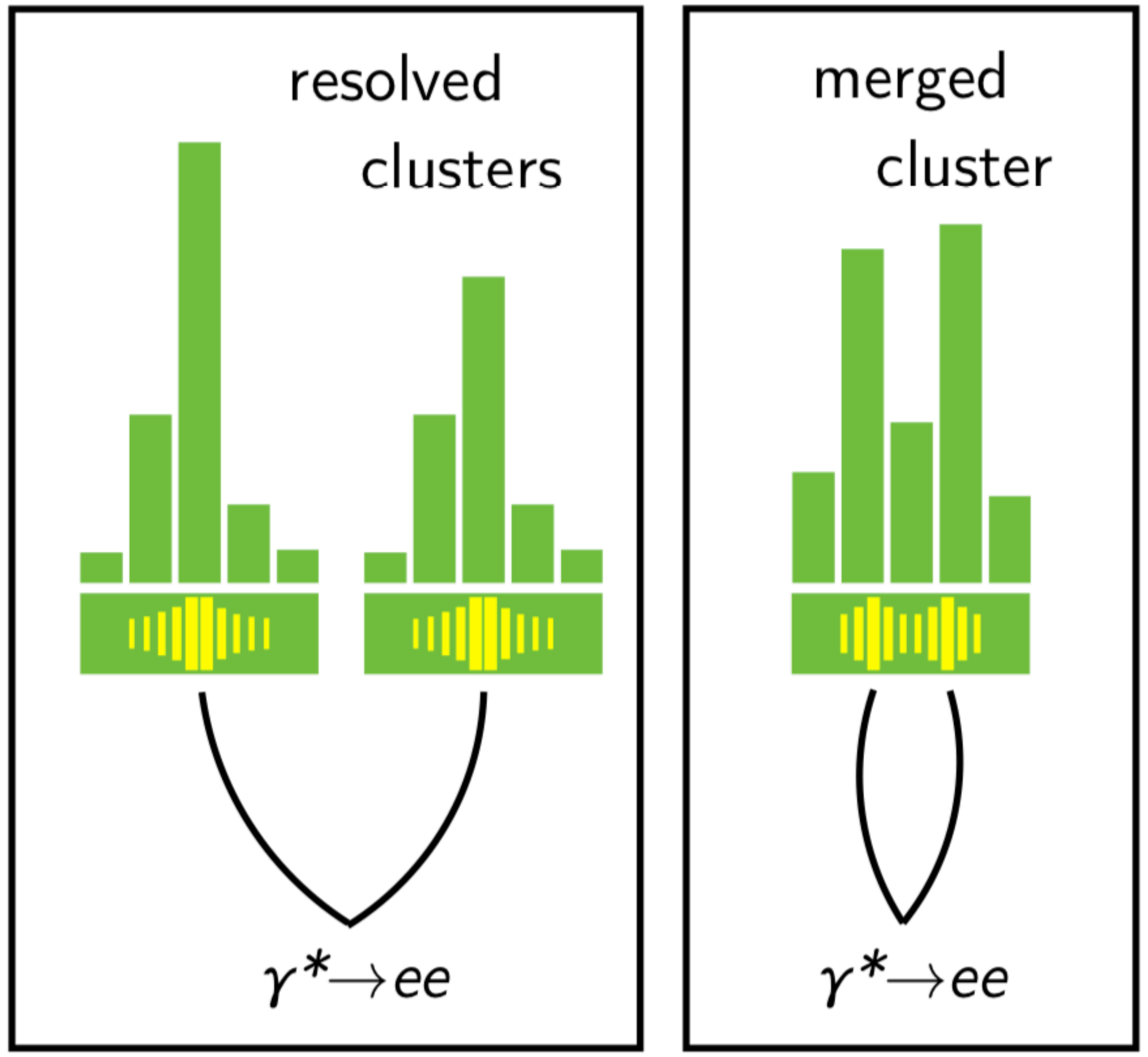
Eur. Phys. J. C 80 (2020) 47

Event preselection

arXiv:2103.10322

- **Search for H→llγ decay at low-m_{ll}**

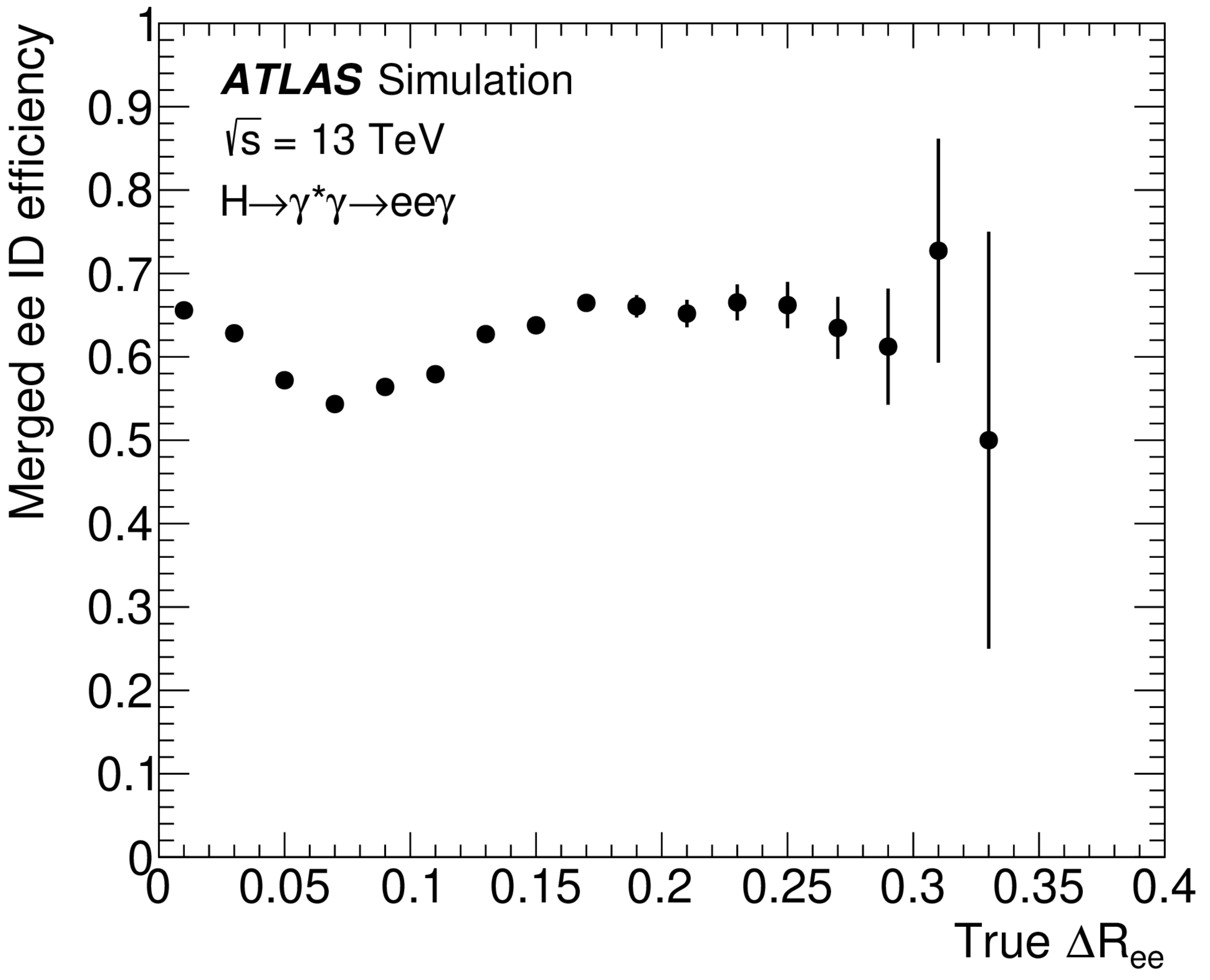
- Object selection:
  - Photons: Isolated with $p_T > 20$ GeV
  - Muons: Isolated (leading) with $p_T > 3$ (11) GeV
  - Electrons: Isolated (leading) with $p_T > 4.5$ (13) GeV
  - **Merged-ee**: isolated with $p_T > 20$ GeV
  - Jets: $p_T > 25$ GeV
- Select an opposite-sign same flavor lepton pair (μμ 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 algorithm

arXiv:2103.10322

- **Search for H→llγ decay at low-m_{ll}**
  - Due to the low mass of the **dielectron pair** they are often collimated
  - Requires dedicated identification (PID) to ensure reasonable efficiency is maintained vs angular separation
- Cut-based PID 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
- MVA cut optimisation is performed



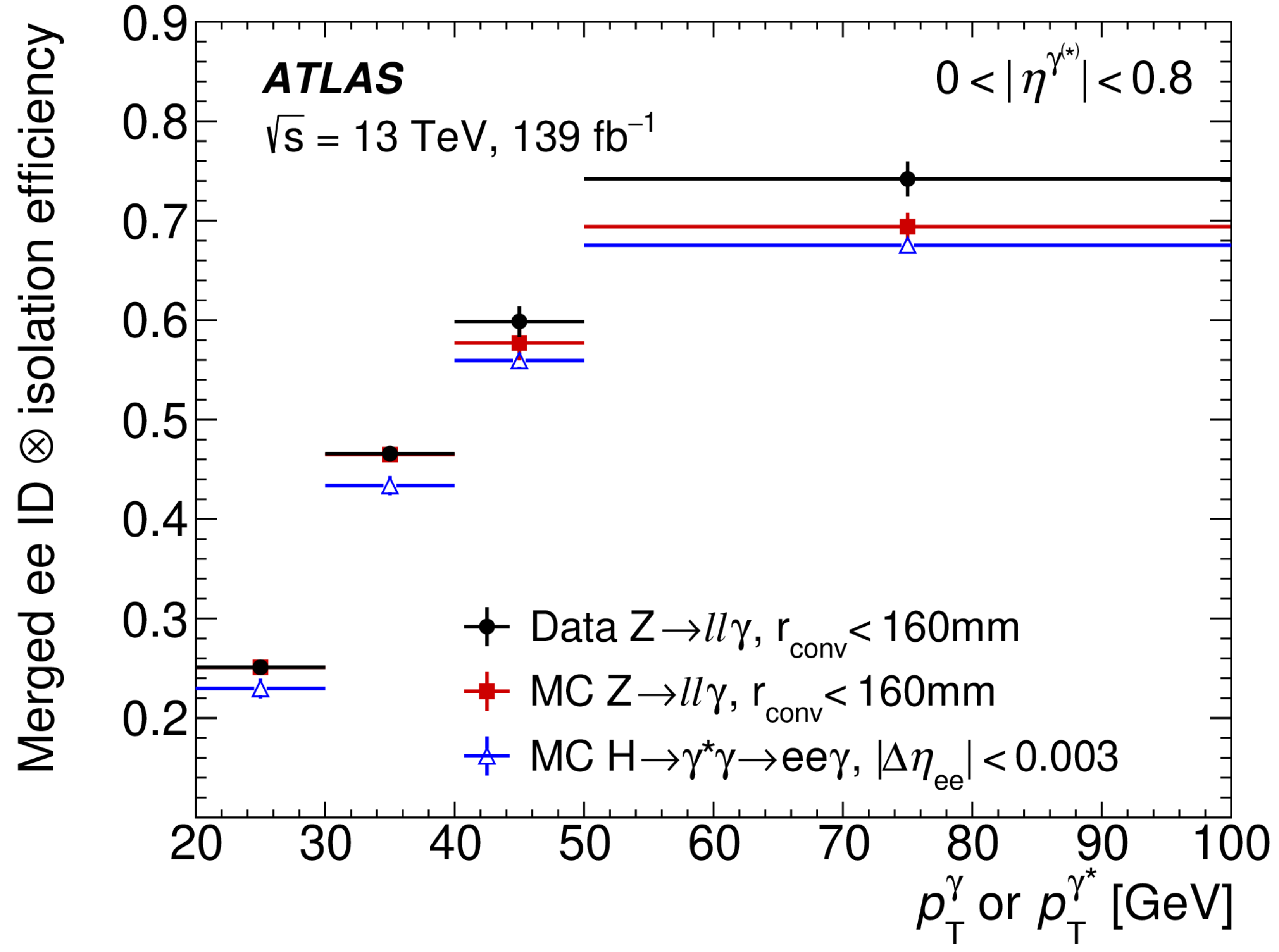
Merged-ee identification and calibration

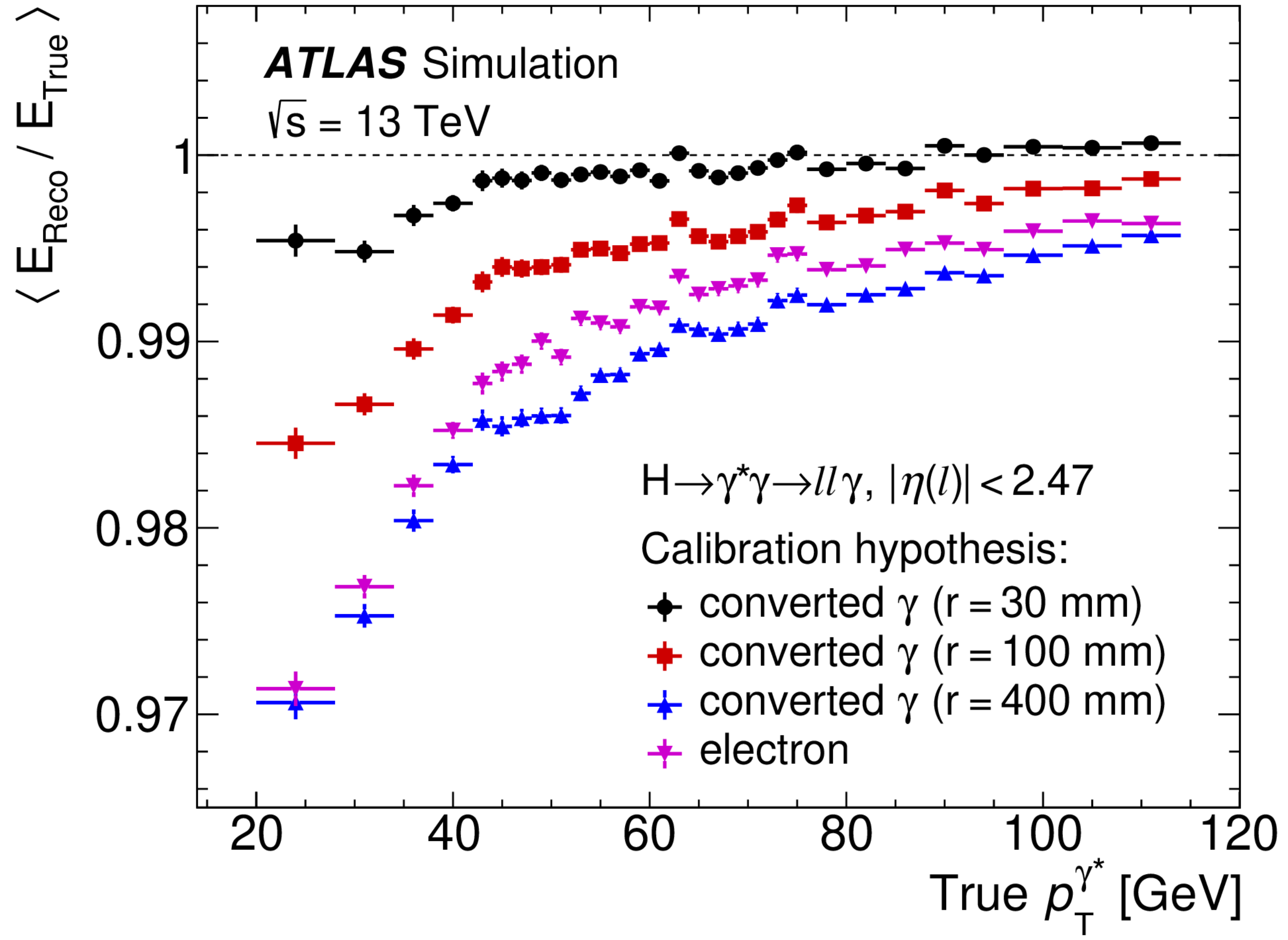
arXiv:2103.10322

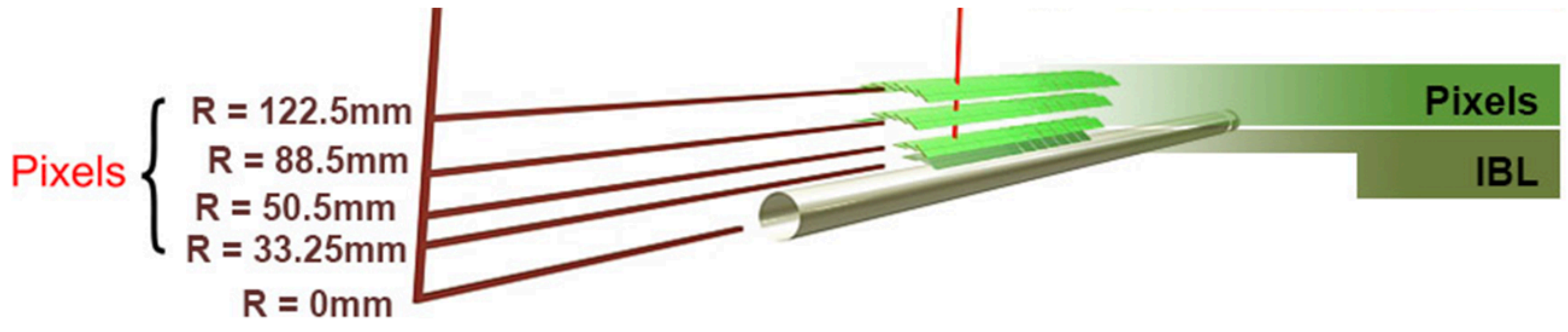
- **Search for H→llγ decay at low-m_{ll}**

- 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

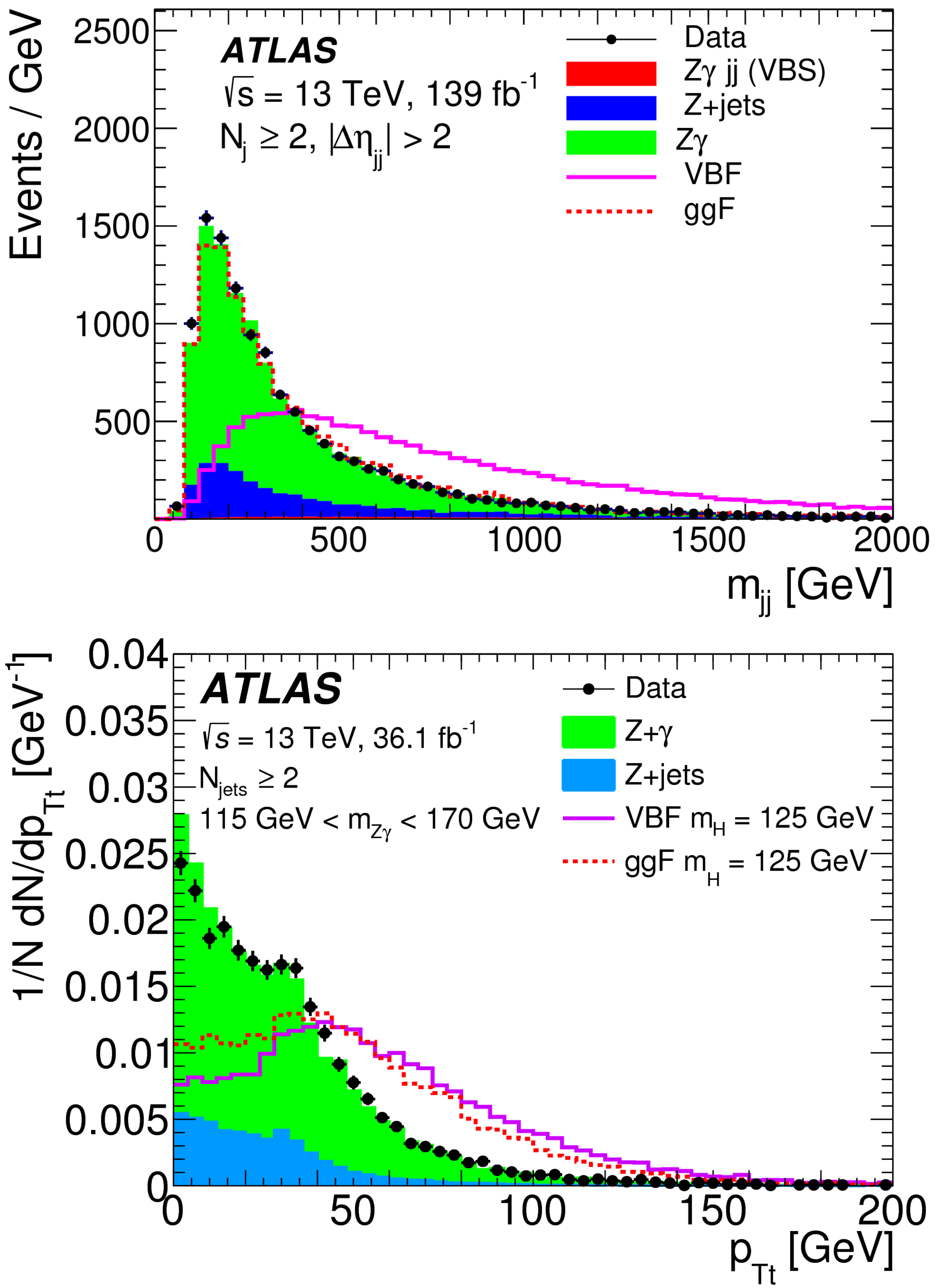






Event kinematics

- 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 p_T**, p_{Tt} has lower experimental uncertainties & lower correlation with the Higgs boson mass
  - Larger values for signal than the non-resonant backgrounds

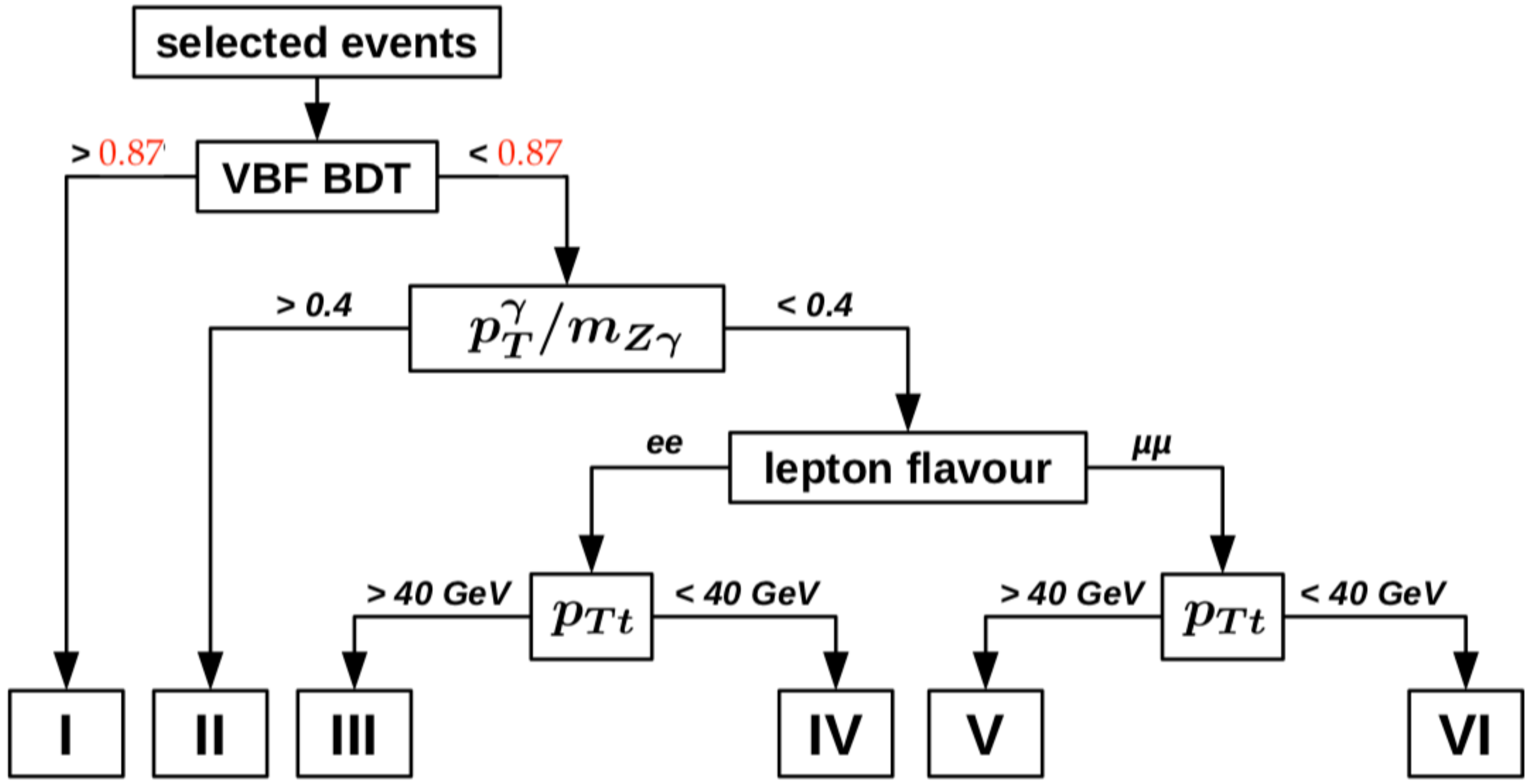


Event categorisation

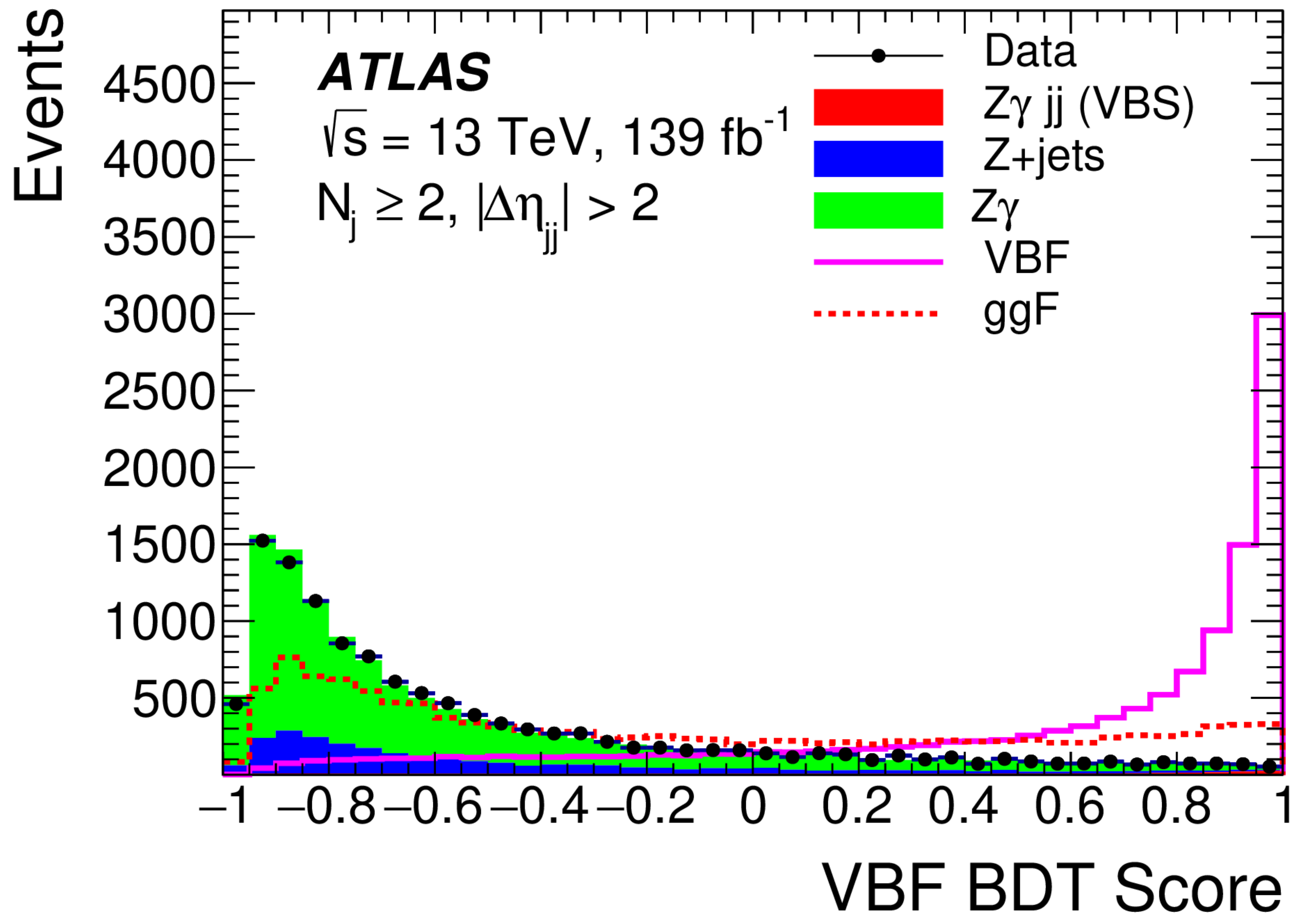
Phys. Lett. B 809 (2020) 135754

- **Search for H→Zγ→llγ decay**

- Sort events into mutually exclusive categories
  - 6 categories of events starting with **VBF-enriched** (**I**) and the **pTt categories** are more ggF-like (**III-VI**)



- VBF-enriched classification is BDT-based and uses several kinematic variables:
  - Leading Jet p_T
  - $\Delta\phi(Z,\gamma)$
  - $\Delta\eta_{jj}$
  - m_{jj}
  - …



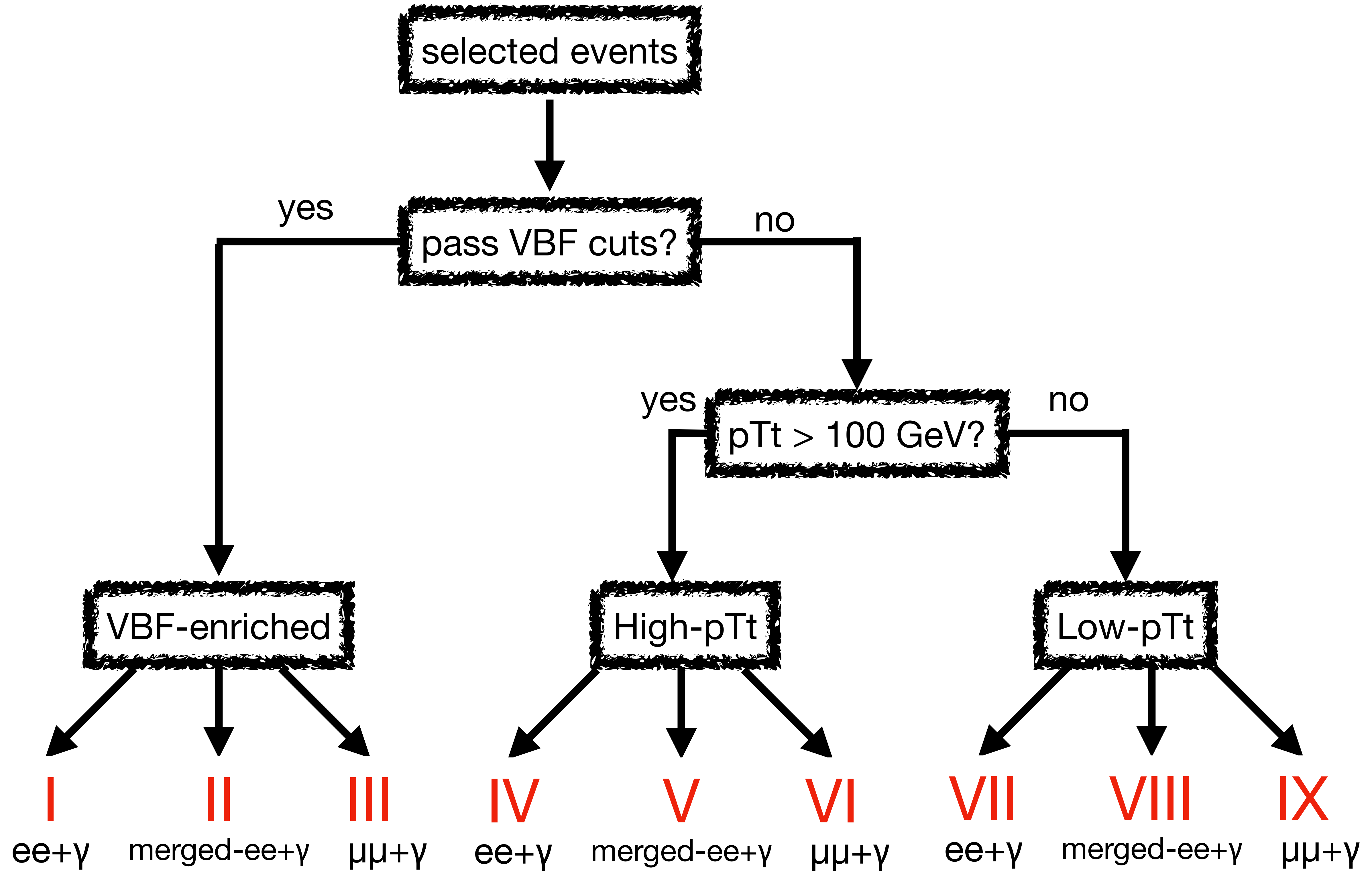
Event categorisation

arXiv:2103.10322

- **Search for H→llγ decay at low-m_{ll}**

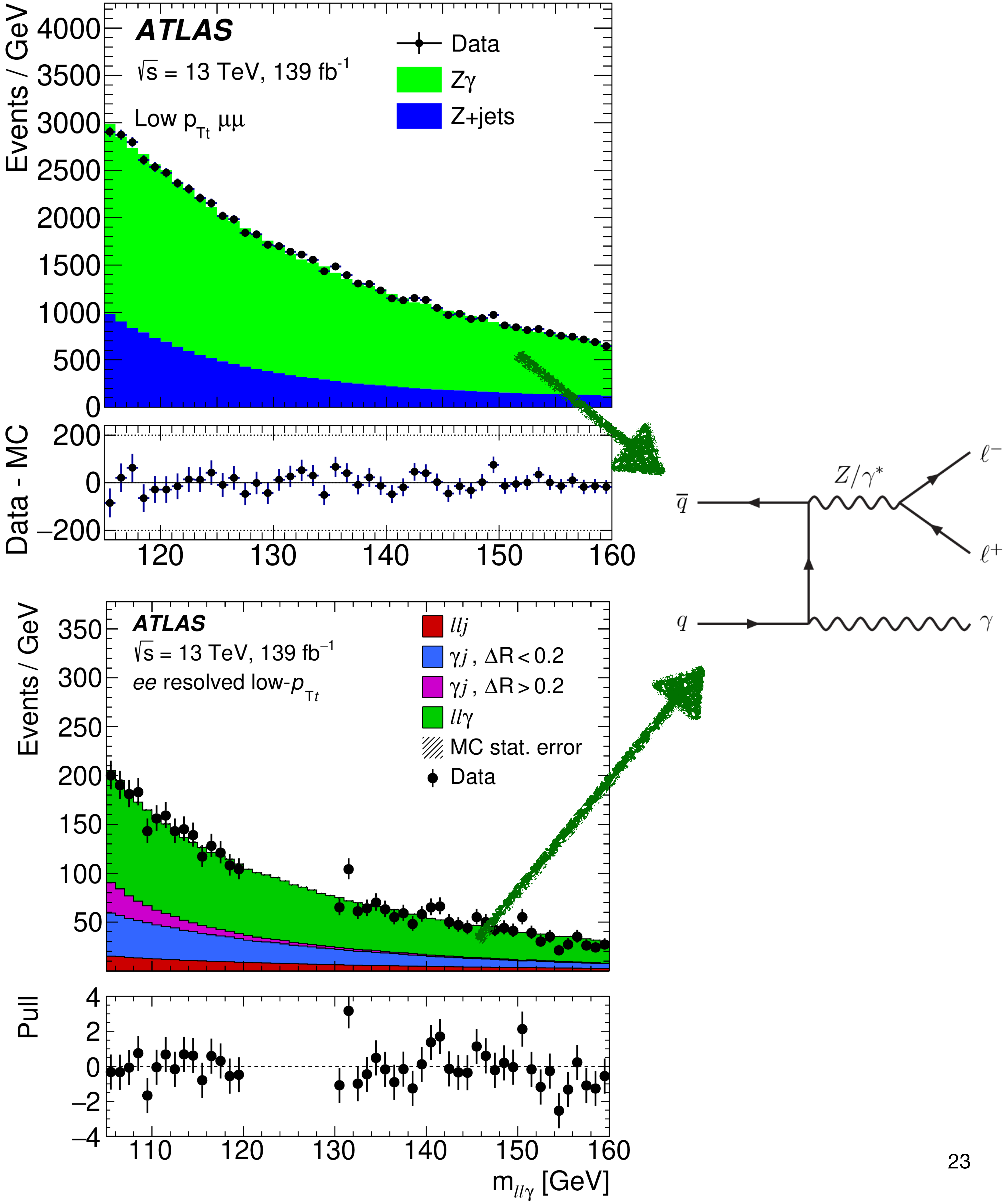
- For each signature 3 kinematic categories are created (9 categories in total)

- **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



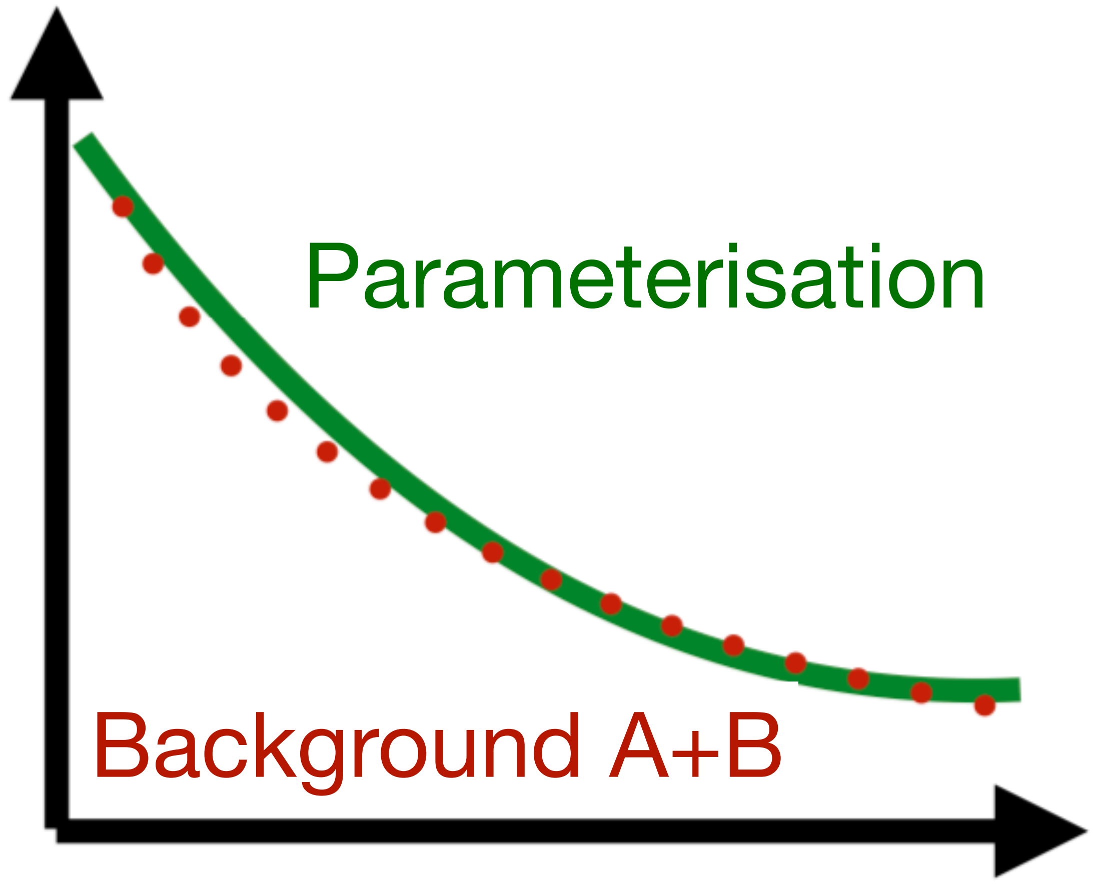
Background studies

- **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 bkg. shape is performed using parametric functions
  - Choices of functions: exponential, Bernstein, and power functions
- Background function choice
  - Sig+Bkg 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



Search for H→llγ decay at low-m_{ll}

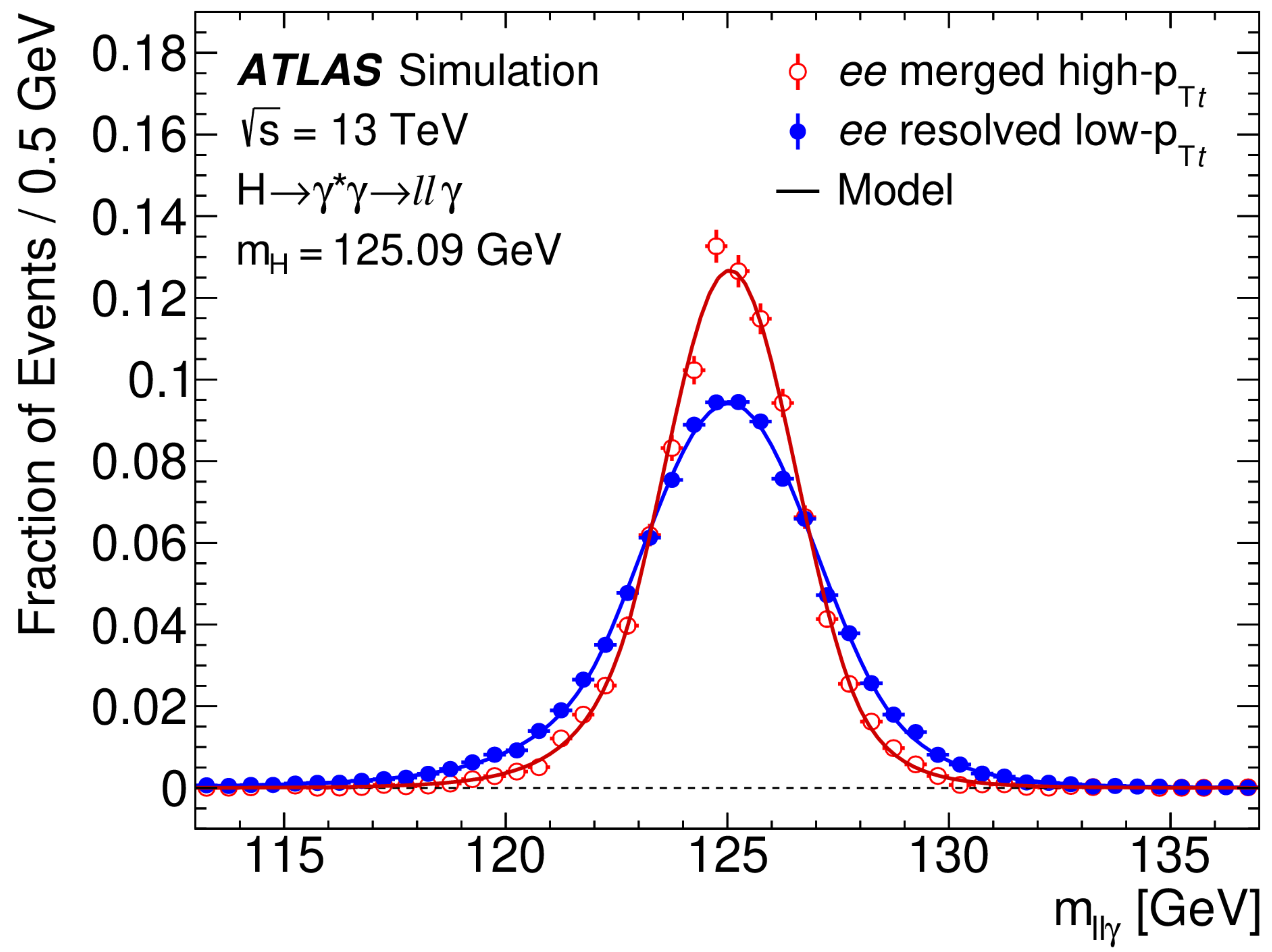
Channel	Function
μμ VBF-enriched	m^{α}
μμ High-$p_{T\text{-Thrust}}$	m^{α}
μμ Low-$p_{T\text{-Thrust}}$	$e^{\alpha m+\beta m\times m}$
Merged e VBF-enriched	m^{α}
Merged e High-$p_{T\text{-Thrust}}$	m^{α}
Merged e Low-$p_{T\text{-Thrust}}$	$e^{\alpha m+\beta m\times m}$
Resolved e VBF-enriched	$e^{\alpha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

Search for H→Zγ→llγ decay

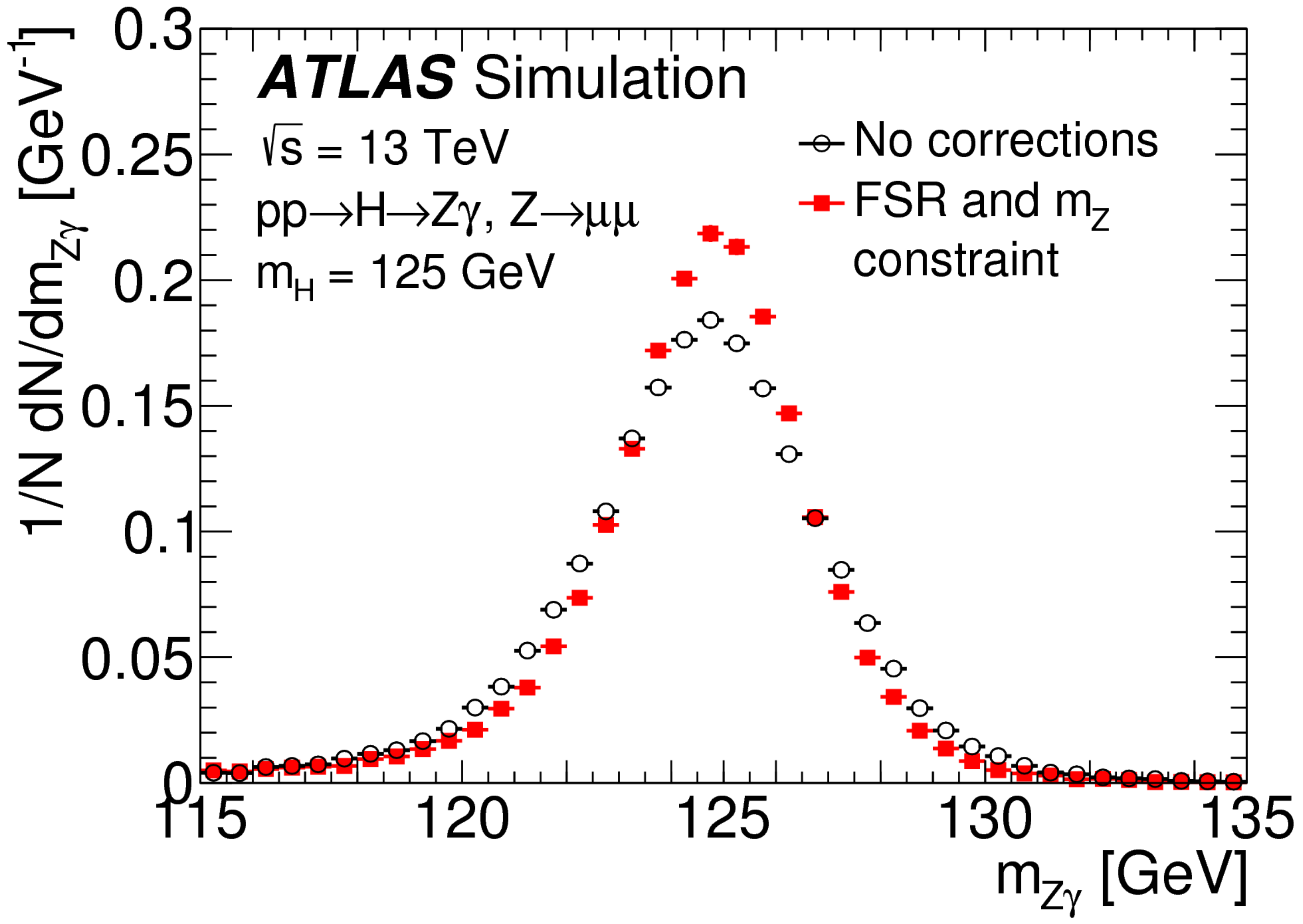
Category	Function Type	Fit range [GeV]
VBF-enriched	Second-order power function	110–155
High relative p_T	Second-order exponential polynomial	105–155
ee high p_{Tt}	Second-order Bernstein polynomial	115–145
ee low p_{Tt}	Second-order exponential polynomial	115–160
$\mu\mu$ high p_{Tt}	Third-order Bernstein polynomial	115–160
$\mu\mu$ low p_{Tt}	Third-order Bernstein polynomial	115–160

Signal modeling

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



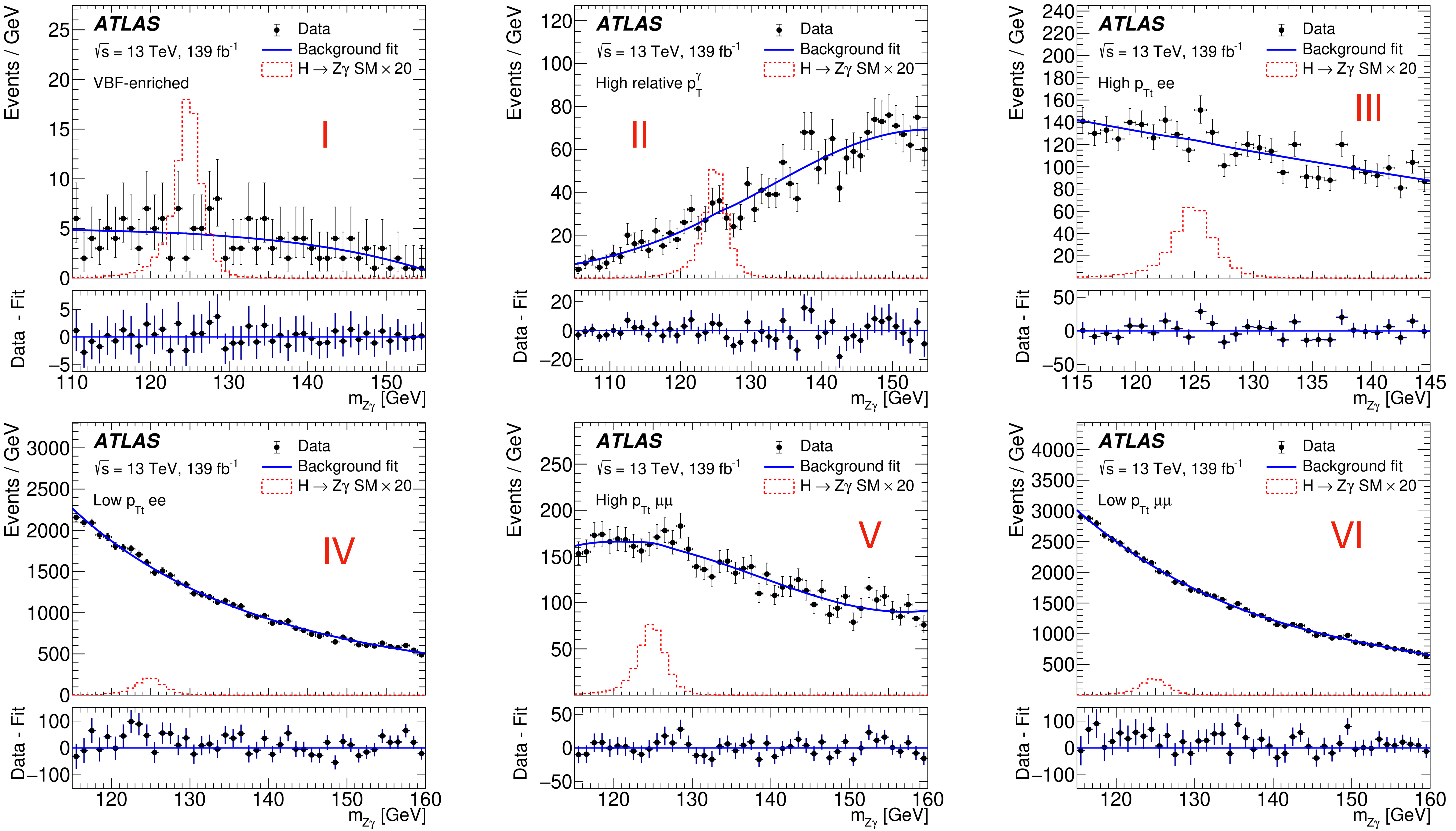
- For H→Zγ→llγ analysis muons are corrected for final state radiation by adding EM calorimeter contributions with p_T>1.5 GeV within ΔR<0.15 of the muon
  - Results in ~3% improvement in mass resolution



Signal regions

- **Search for H→Zγ→llγ decay**

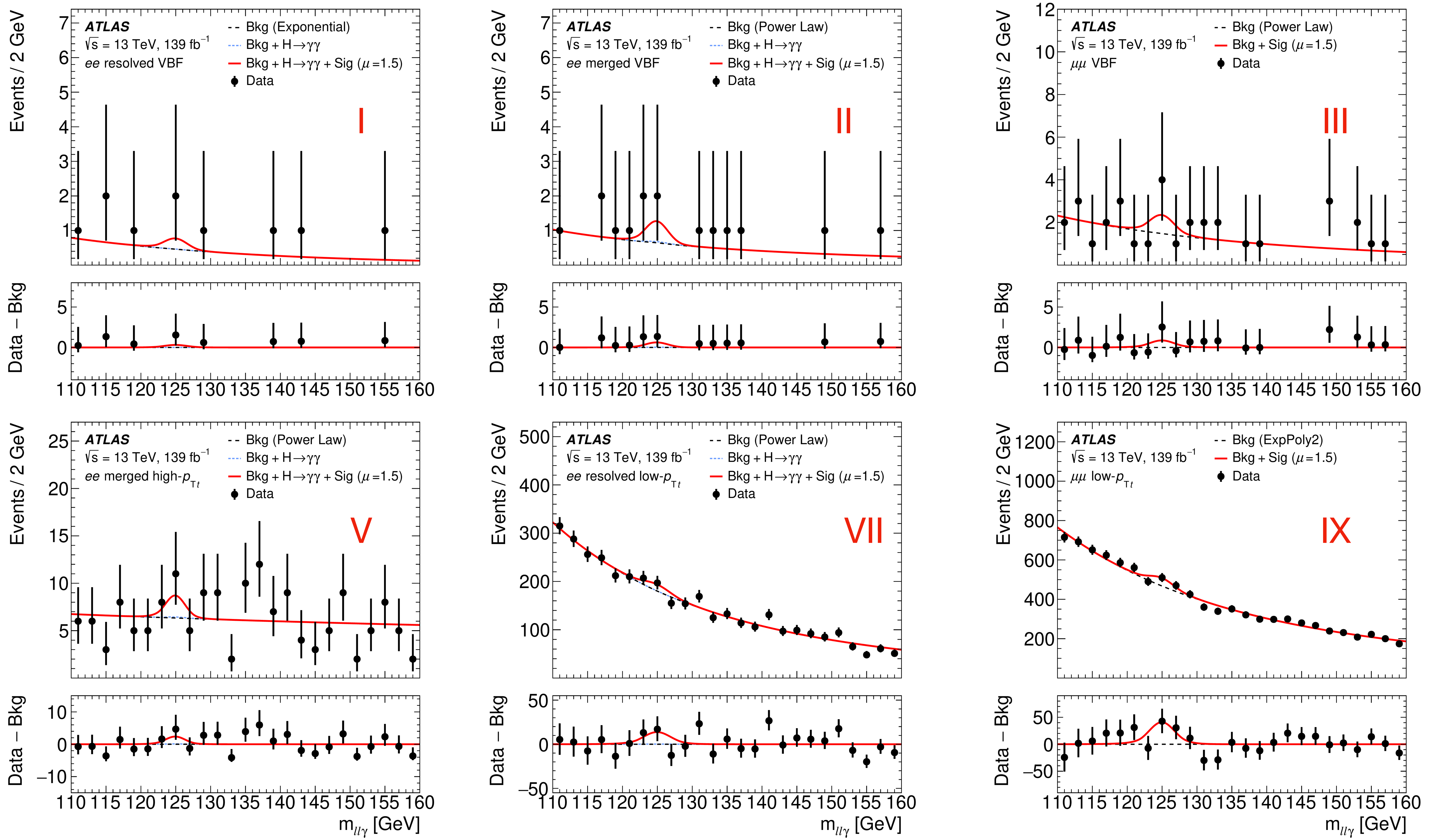
Phys. Lett. B 809 (2020) 135754



Signal regions

- **Search for H→llγ decay at low-m_{ll}**

arXiv:2103.10322

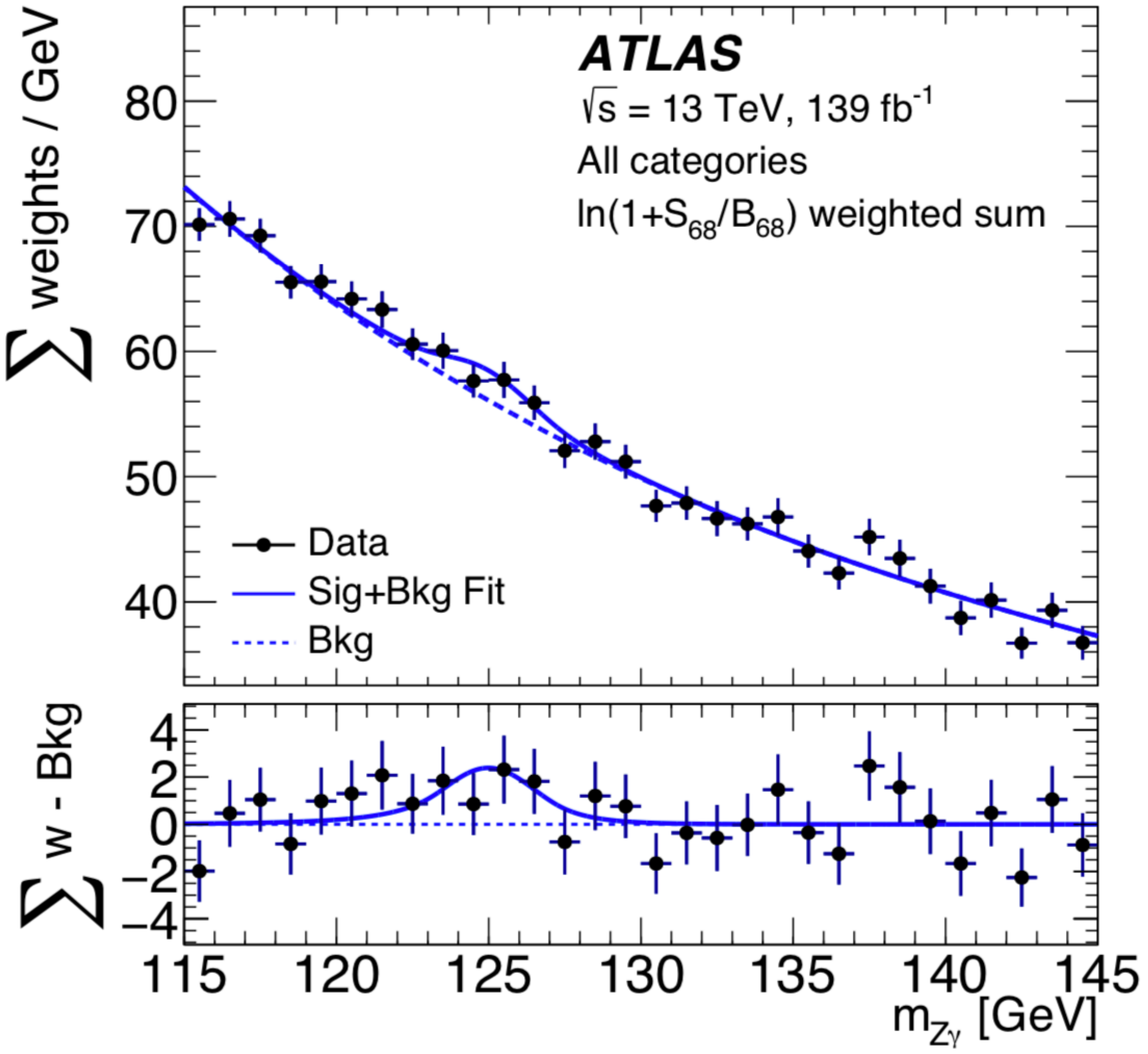


Results

Phys. Lett. B 809 (2020) 135754

- **Search for H→Zγ→llγ decay**

- Background-only hypothesis: observed local significance at 125.09 GeV has a p-value of **2.2σ**
- Best-fit signal strength (**$\mu_{Z\gamma}$**):
    - Observed **$\mu_{Z\gamma}$ = 2.0 ±1.0**
    - Analysis is statistically-dominated
    - Leading systematic uncertainty: background modeling
- Observed upper limit on σ(pp→H)×B(H→Zγ) is **305 fb** (3.6 times the SM prediction) at 95% C.L.

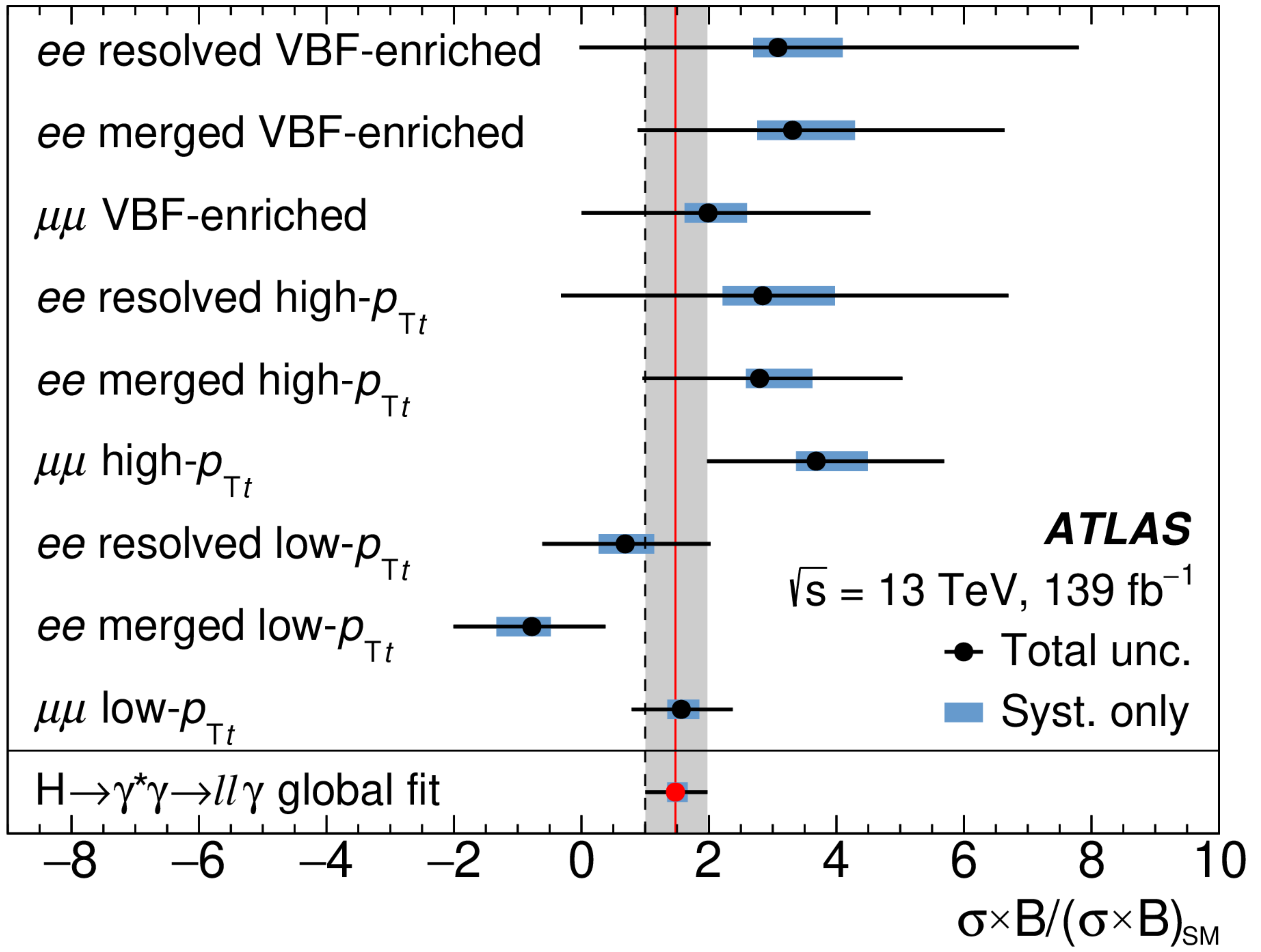


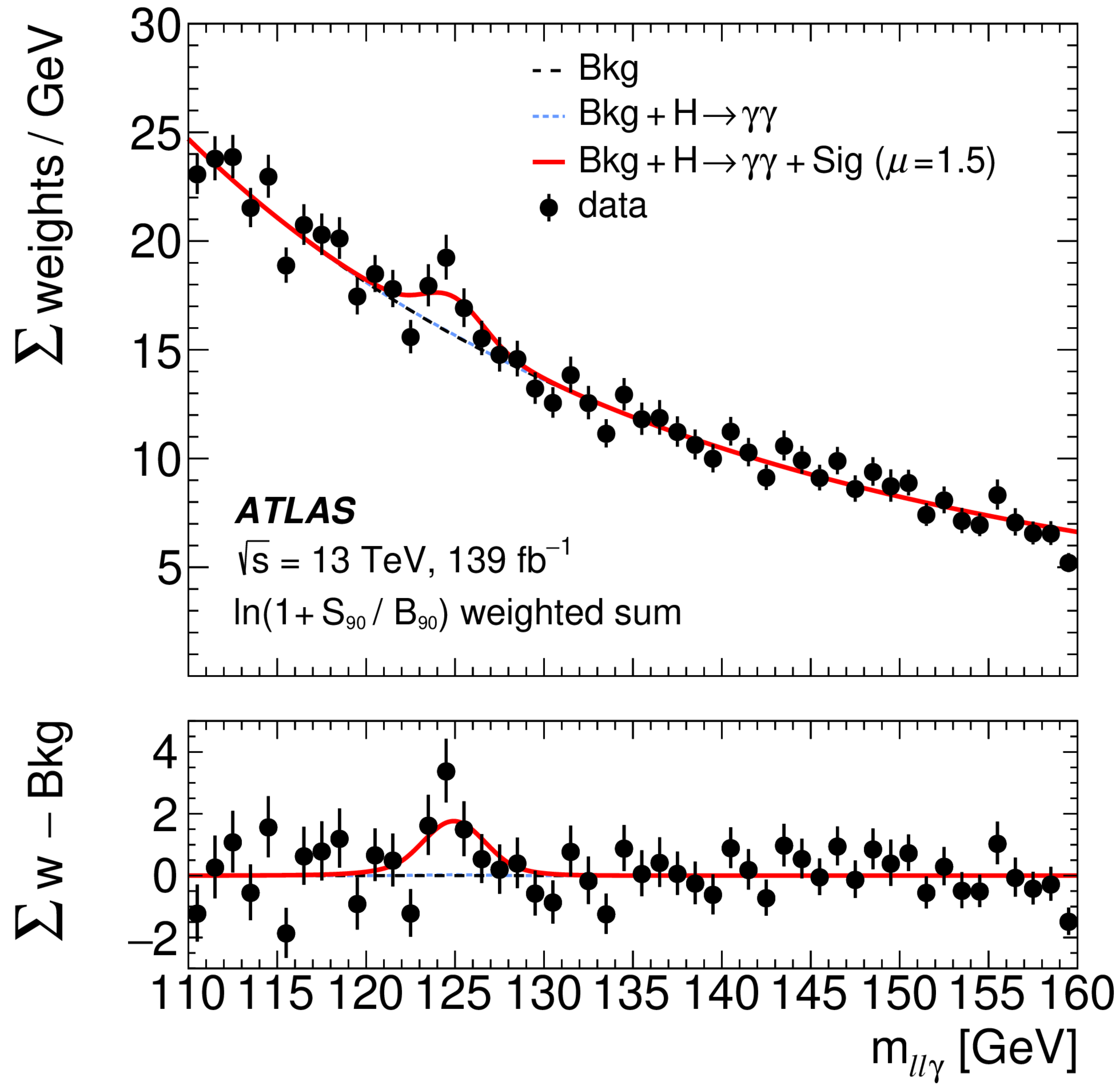
Results

Search for H→llγ decay at low-m_{ll}

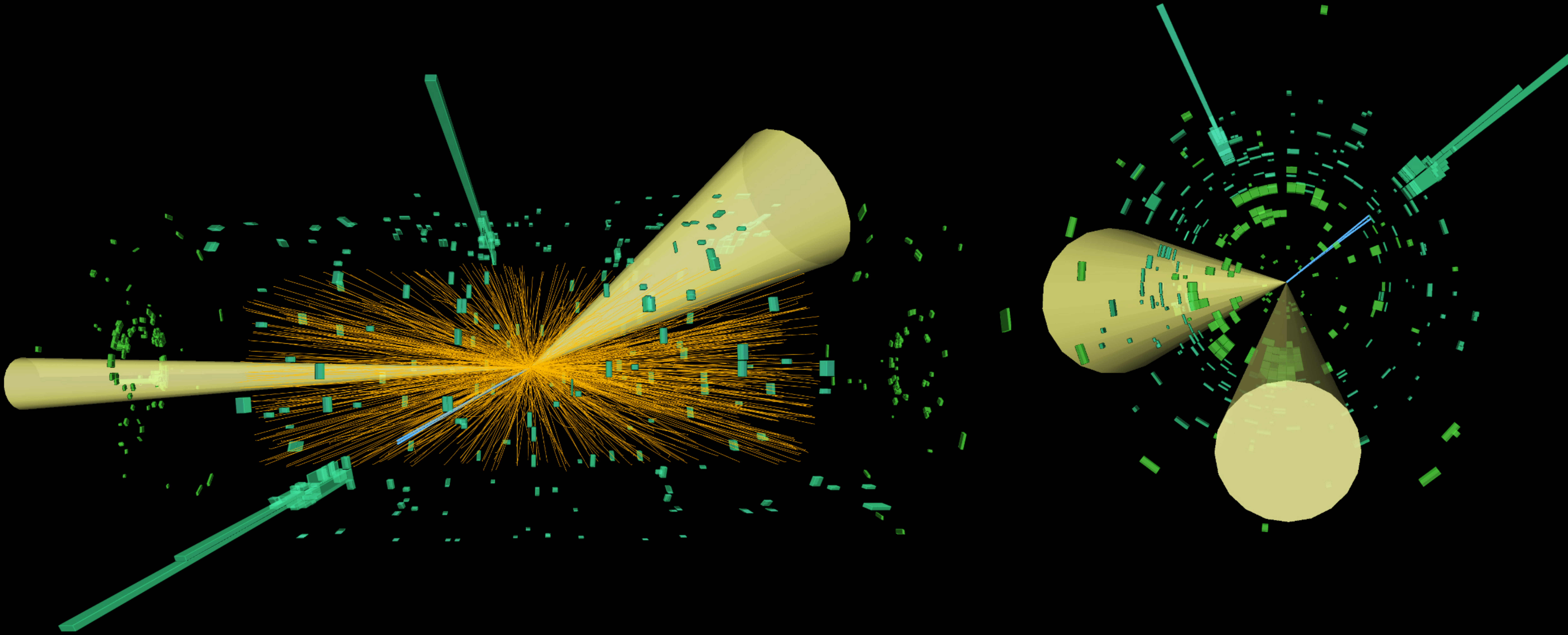
arXiv:2103.10322

- 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}



VBF H→eeγ event candidate with merged-ee

ATLAS-CONF-2021-002

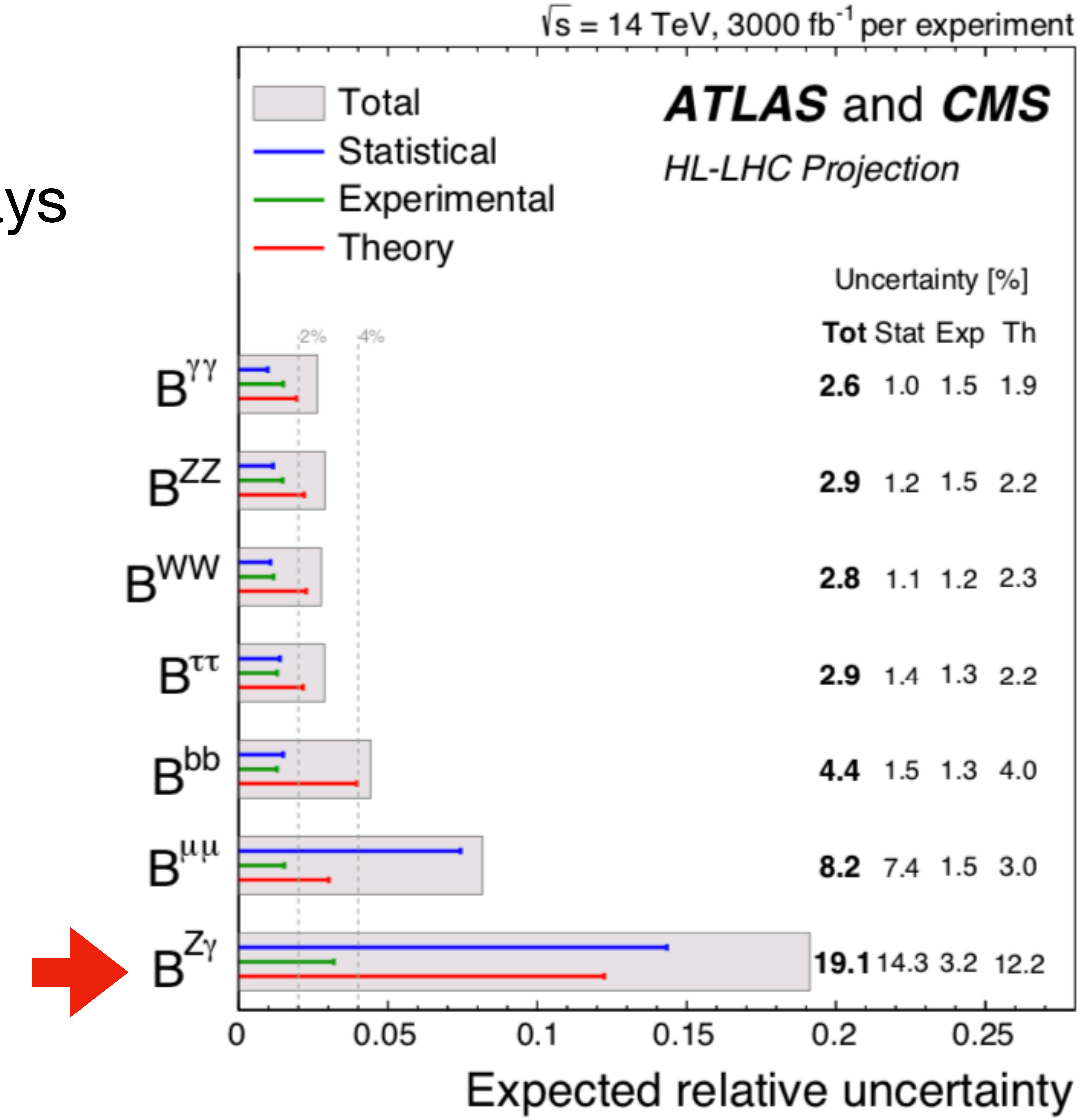
The High-Luminosity LHC

- 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

	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			2×10^{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})

- 3-8% precision of Higgs Br to W/Z, 3rd gen. fermions and muons
- Discovery of **H→Zγ** (and **H→γ*γ**) decays



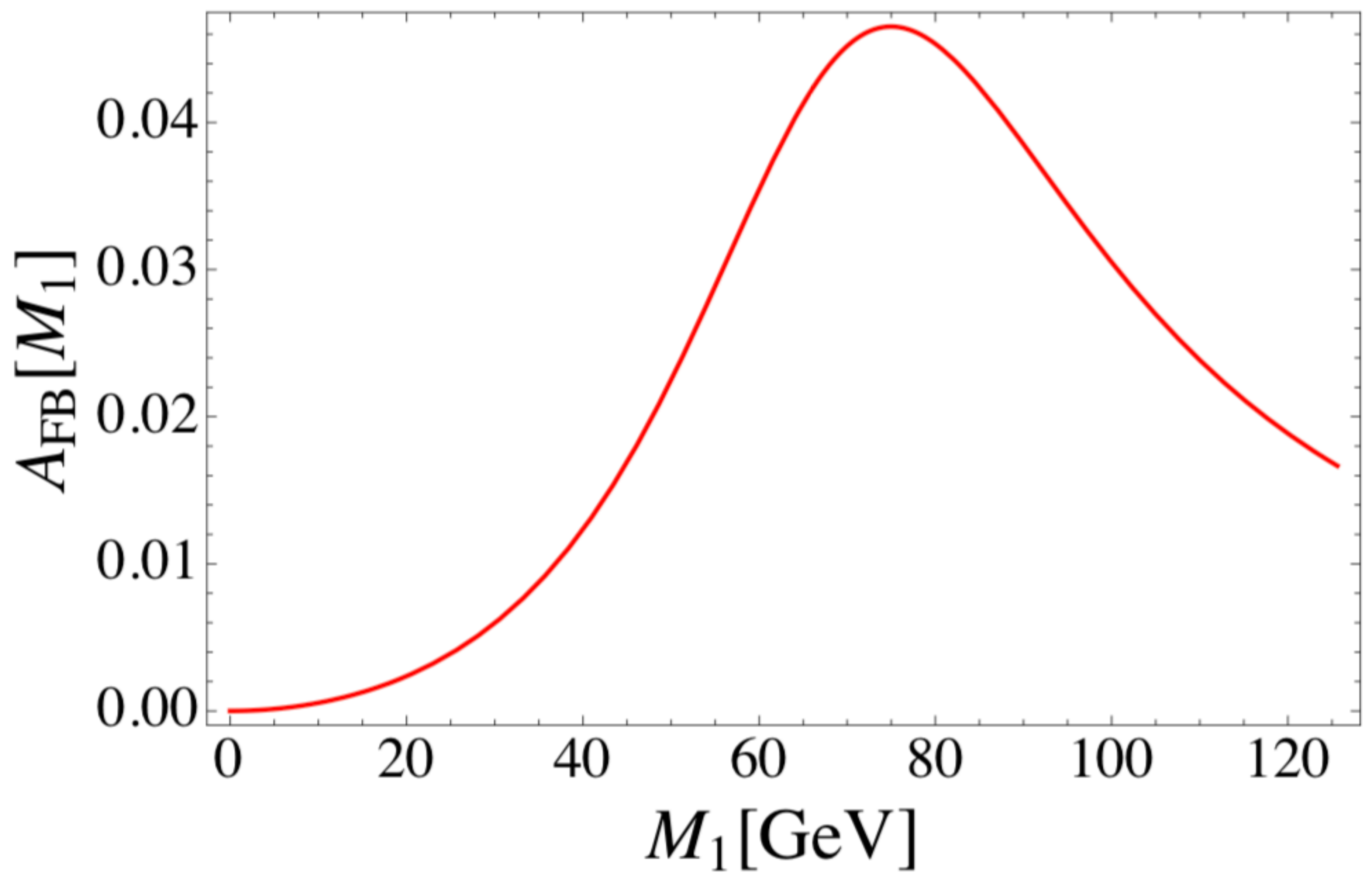
arXiv:1902.00134

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

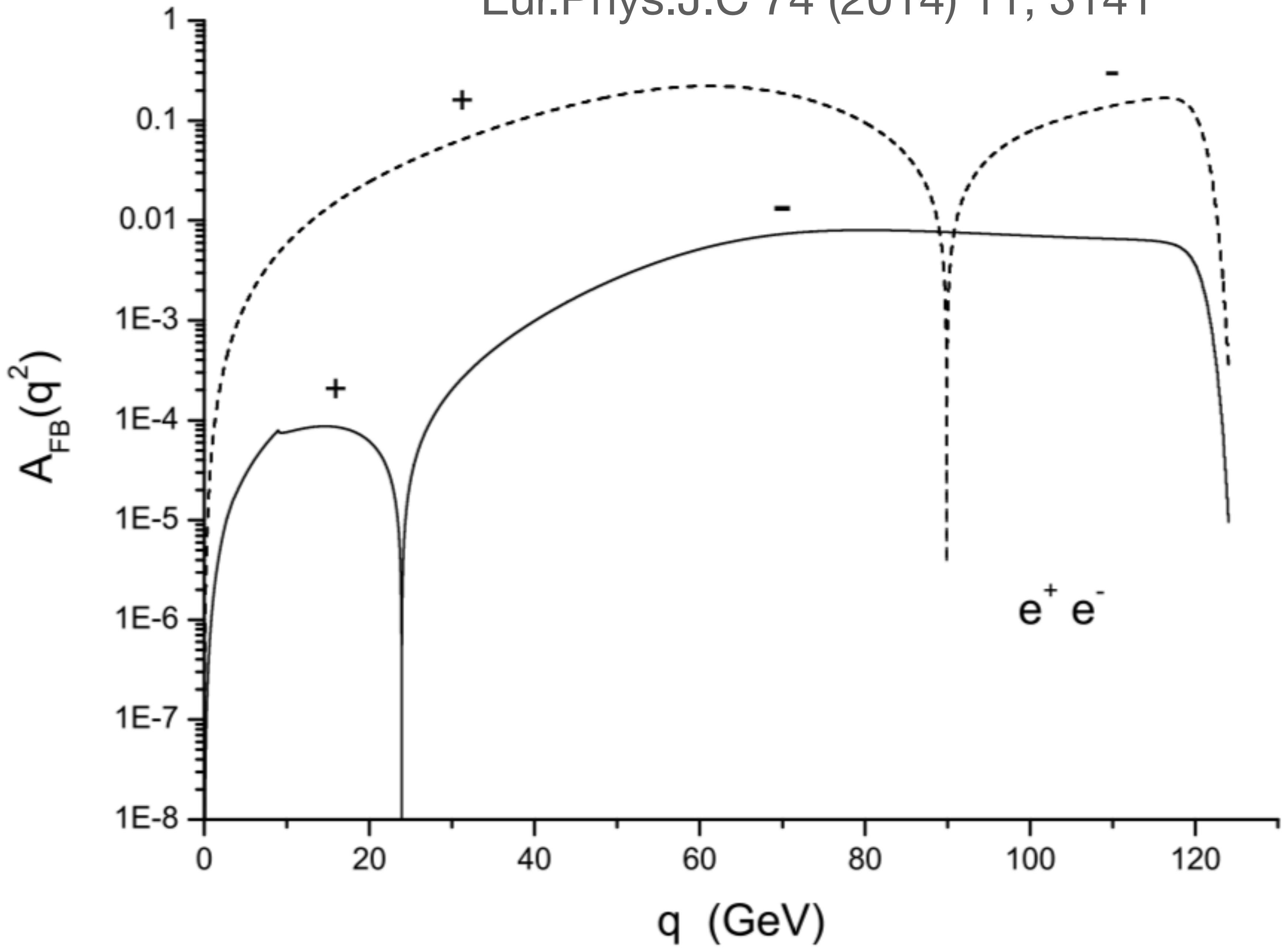
- With three-body $H \to ll\gamma$ decay, it is possible to probe CP-violating Higgs couplings
  - Lepton forward-backward asymmetry measurements (note $A_{FB}(q^2) = 0$ for SM Higgs boson)
  - More detailed access to loops, BSM couplings, …

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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



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



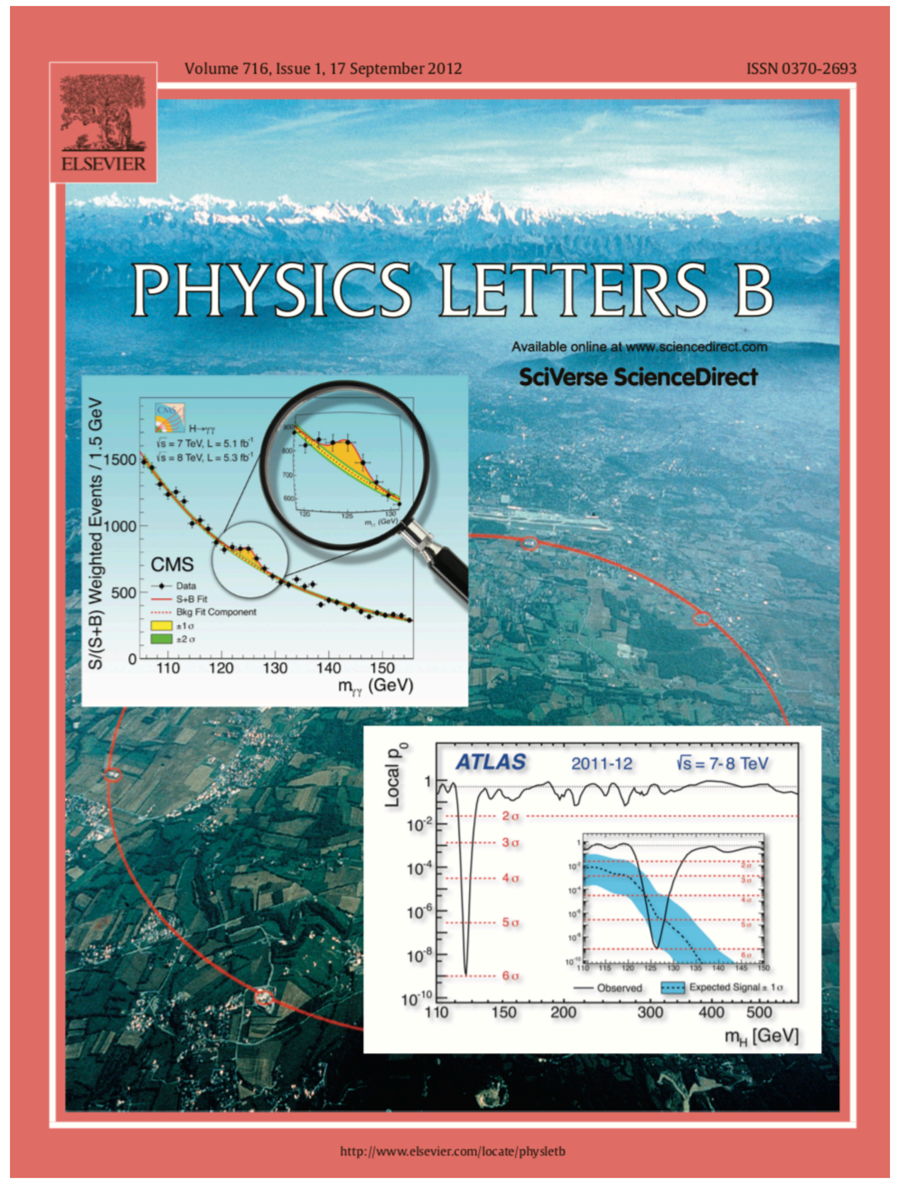
Summary

- 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
- Stay tuned for new measurements!

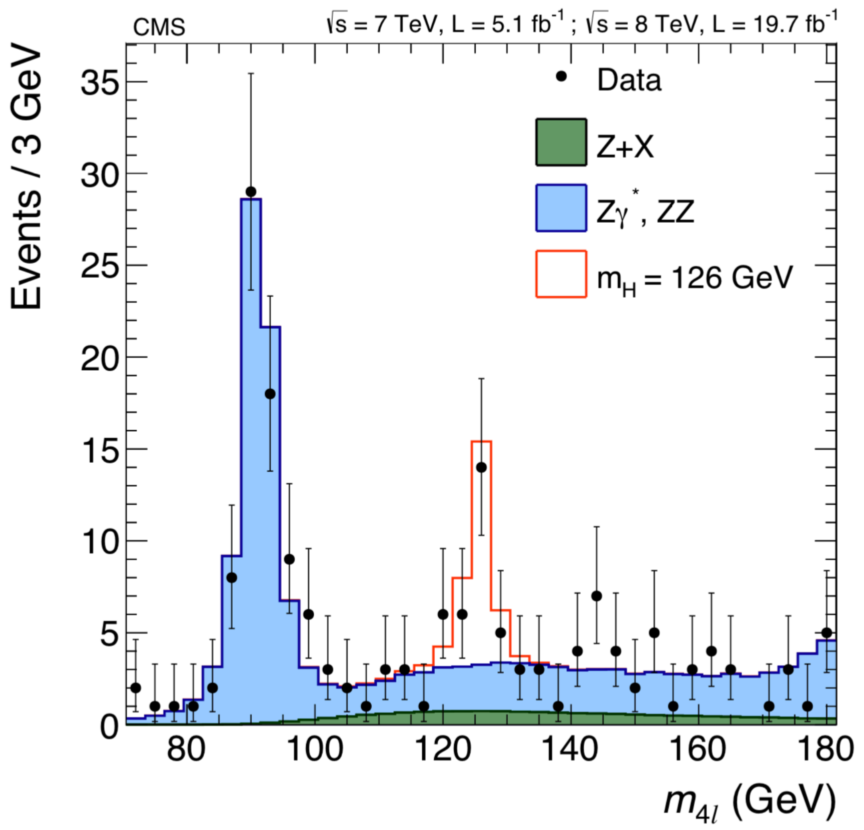
Backup

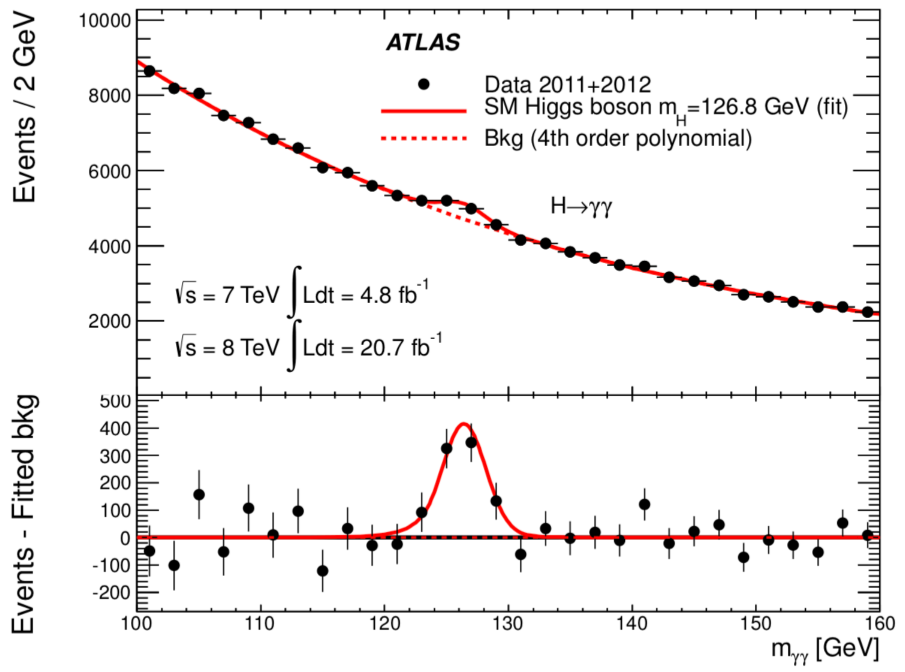
Higgs boson observation timeline at the LHC

SM-like Higgs discovery
(ggF → γγ + ZZ + WW)

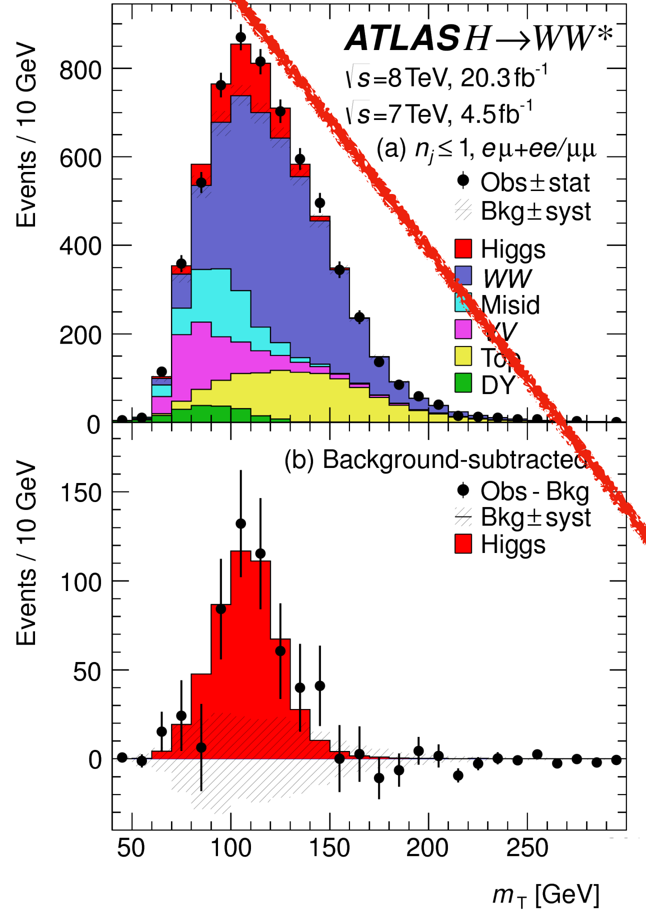


H→γγ , H→ZZ observation,
spin-0 and parity+

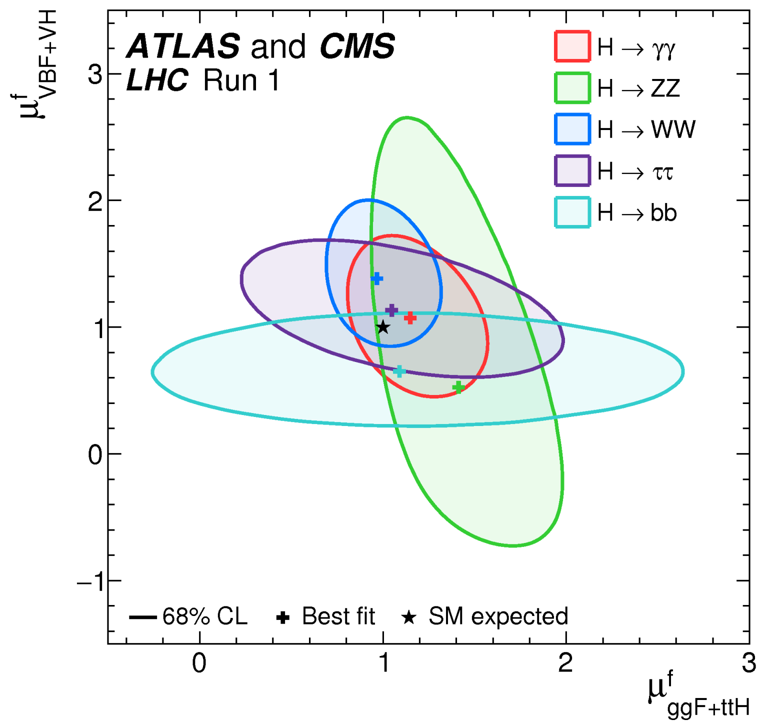




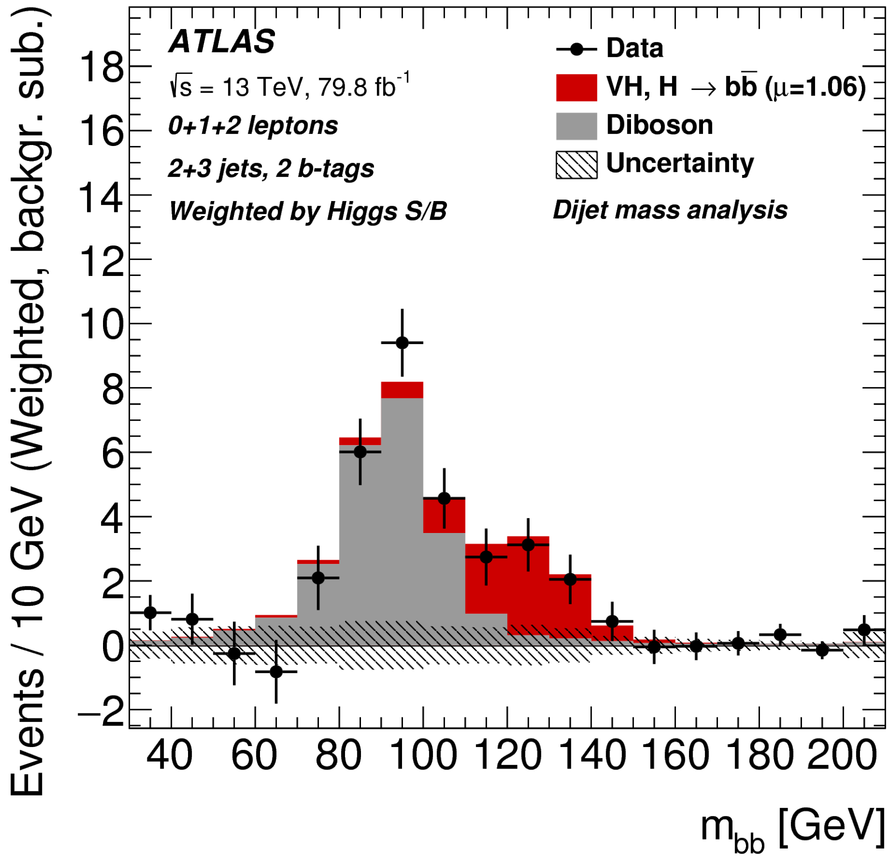
H→WW observation



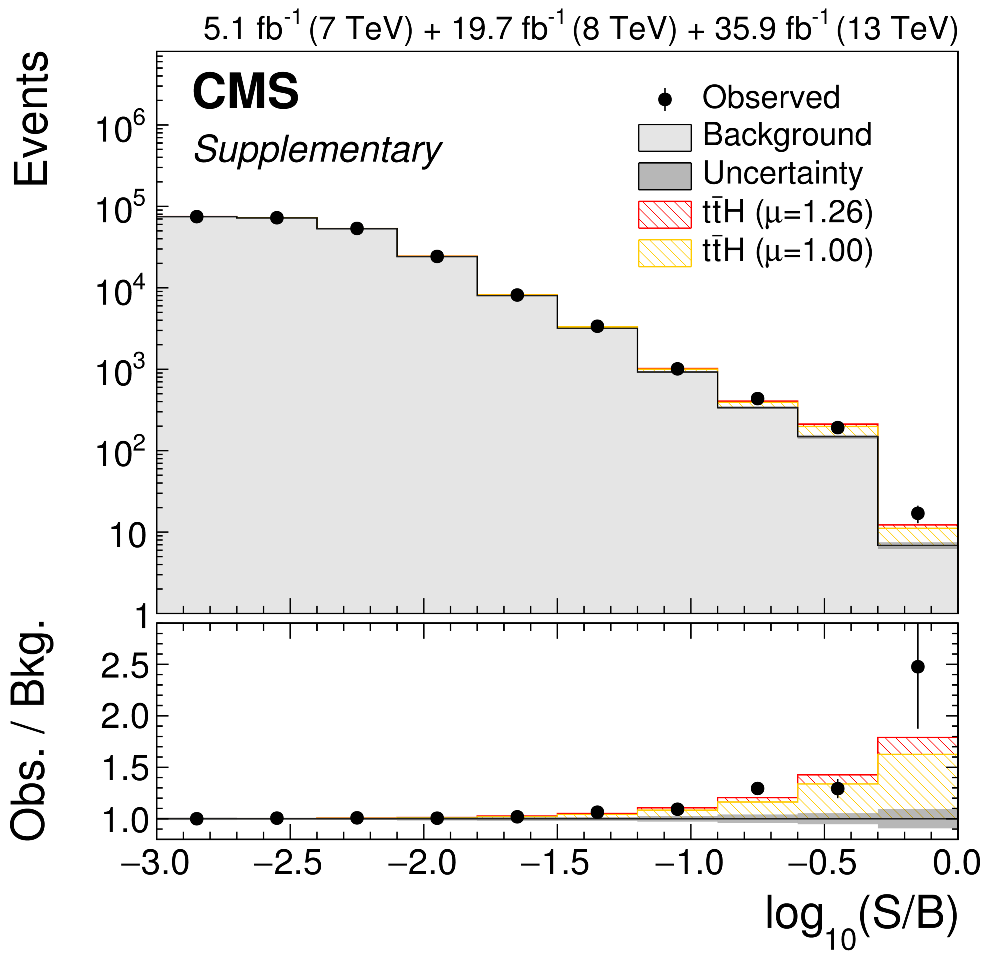
VBF observation,
H→ττ observation



VH, H→bb observation

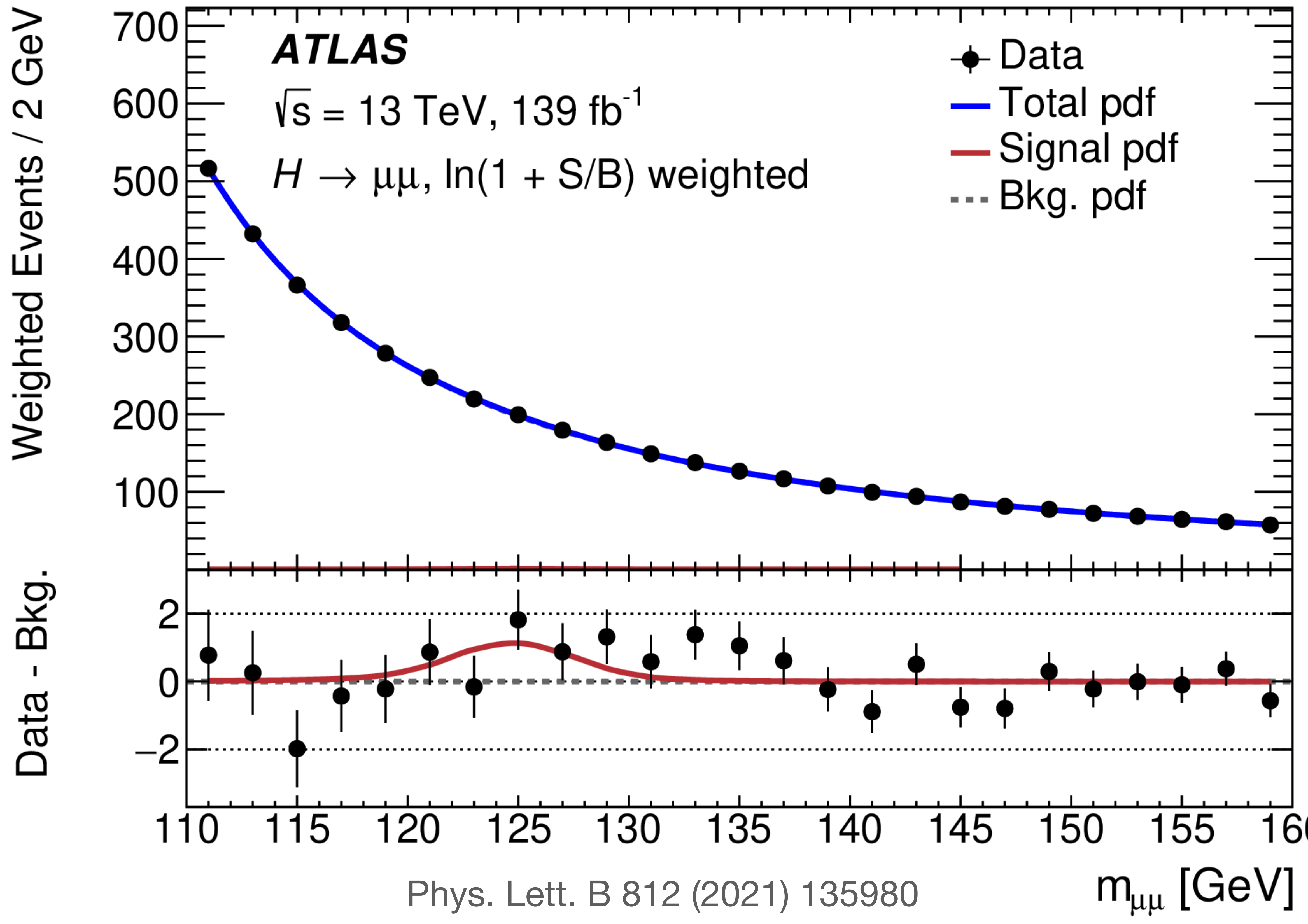


ttH observation

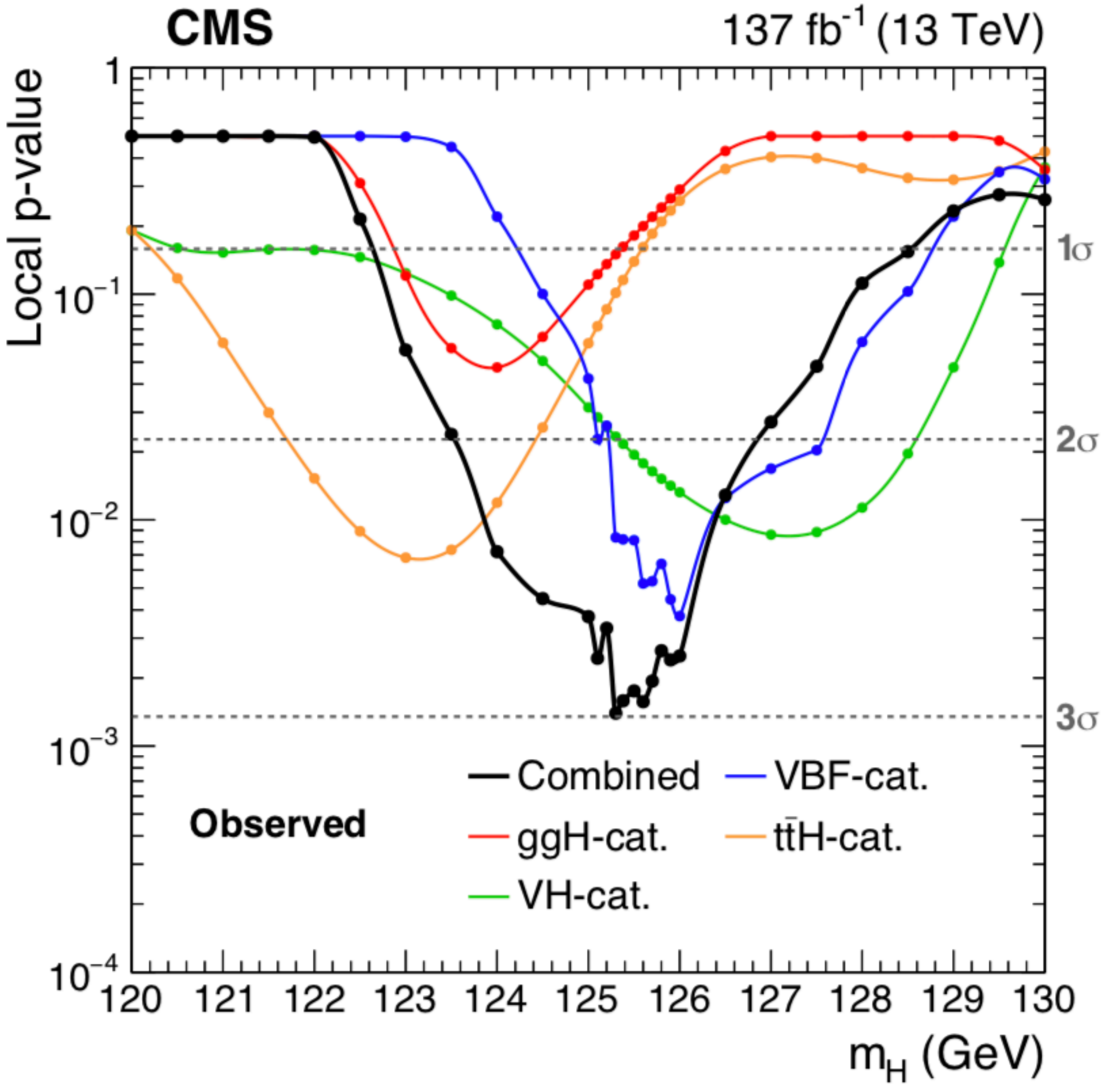


What do we know about the Higgs boson after LHC Run 2?

- 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**



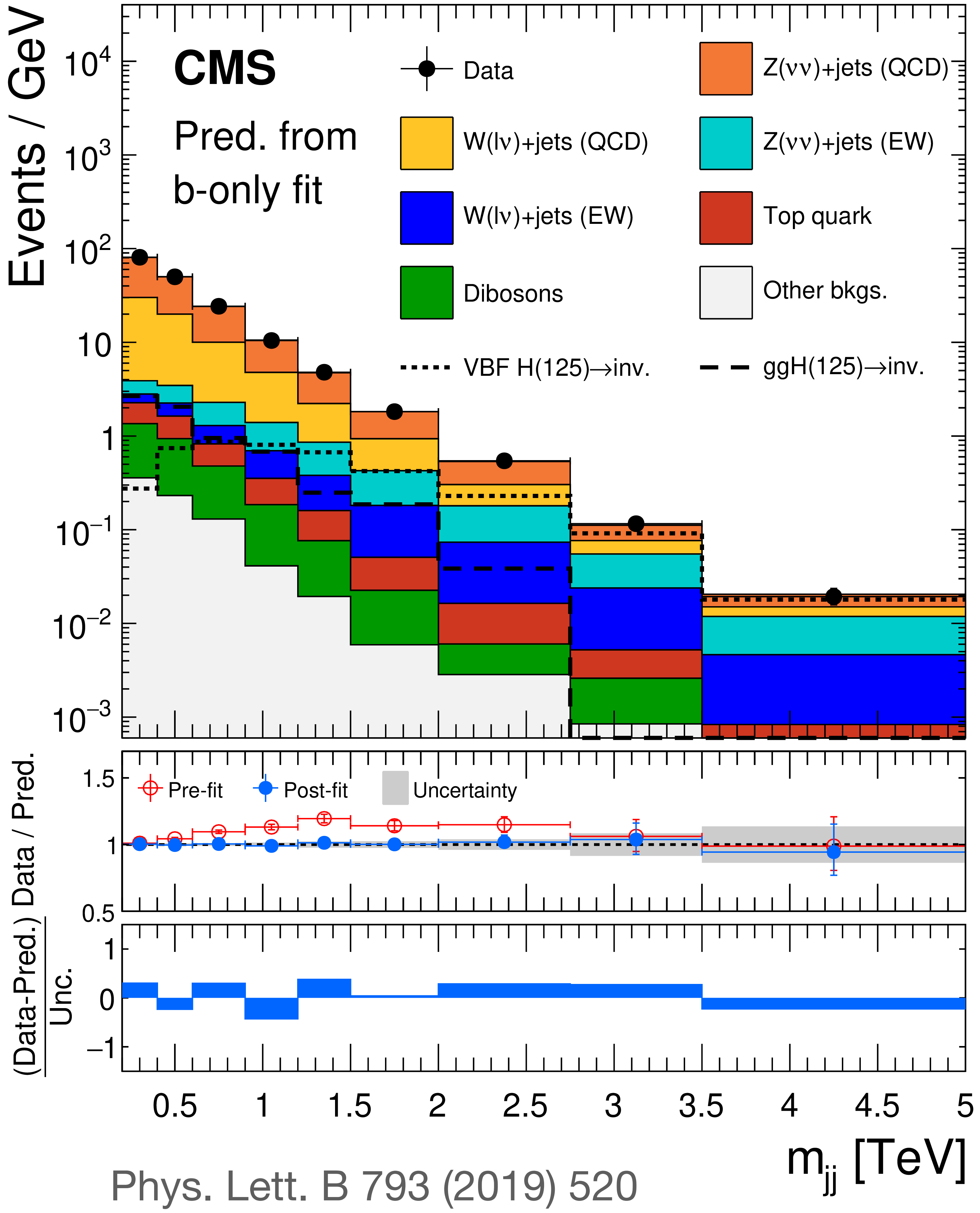
Phys. Lett. B 812 (2021) 135980



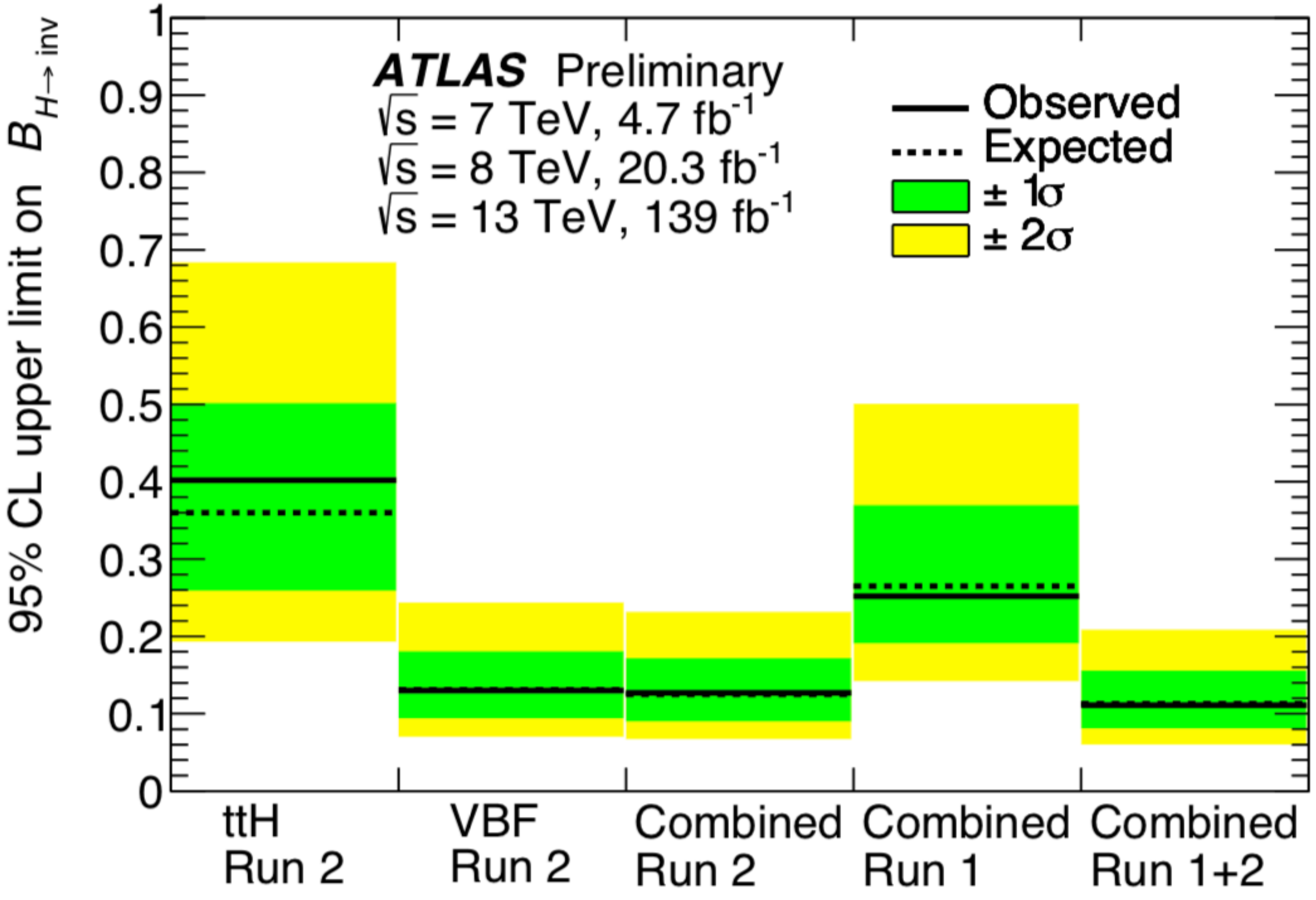
JHEP 01 (2021) 148

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

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

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:
  - 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**

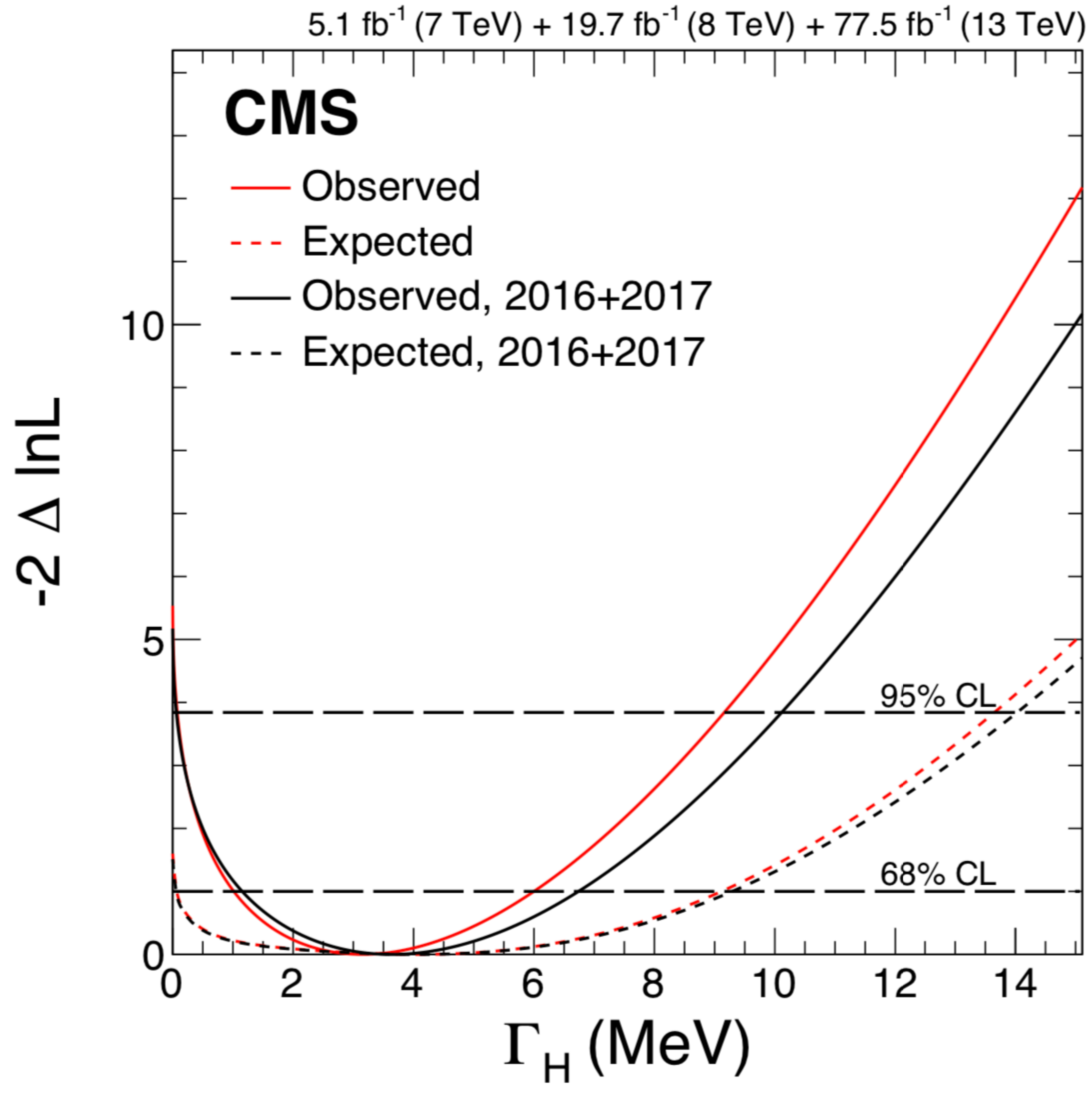
$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}} \quad \text{and} \quad \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}}\,\Gamma_{\text{H}}.$$

HL-LHC projections:

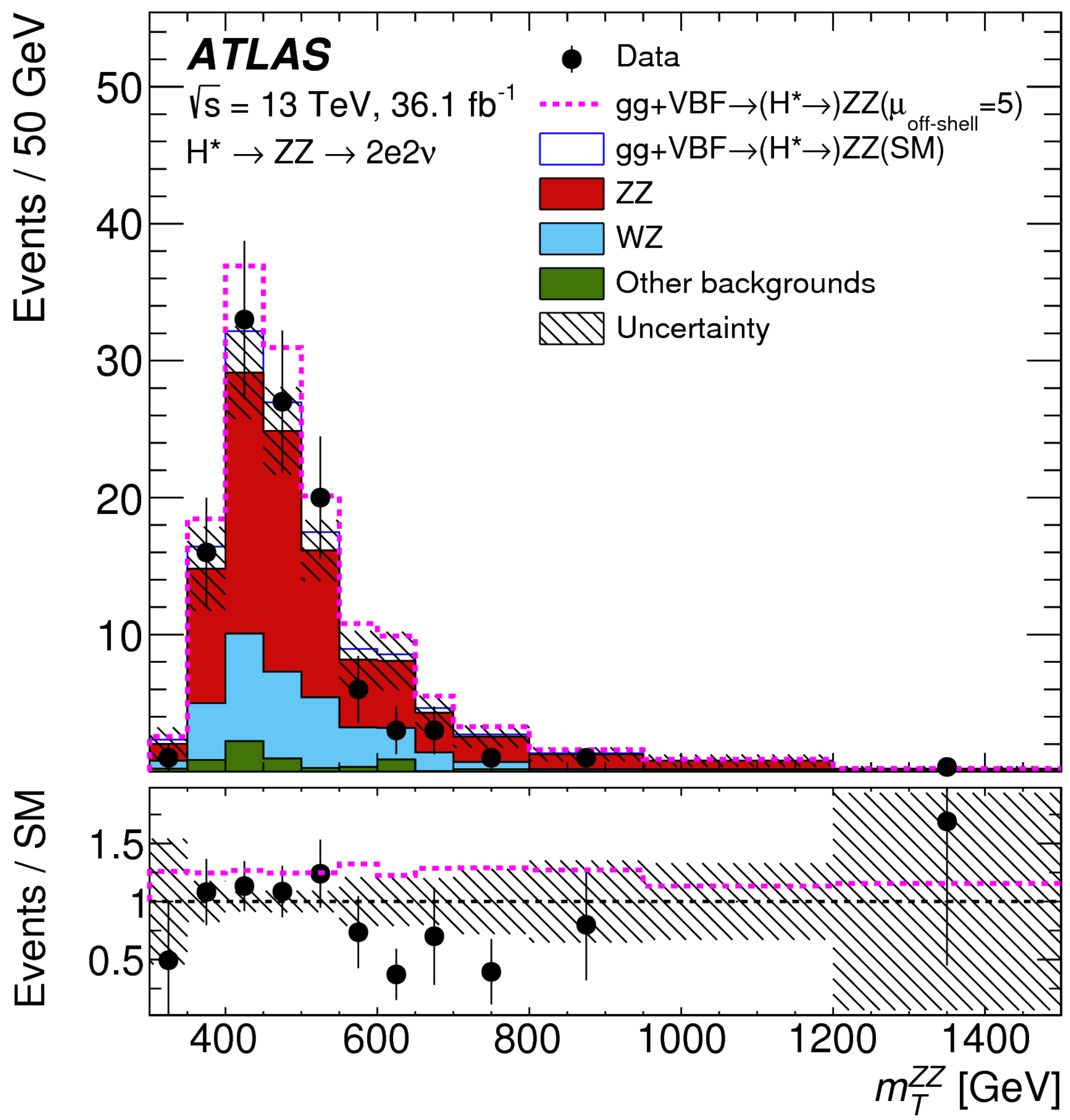
CMS: $4.1^{+1.0}_{-1.1}$ MeV

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

arXiv:1902.00134



PRD 99 (2019) 112003



PLB 786 (2018) 223