

Evidence of $H \rightarrow \mu^+ \mu^-$ with the ATLAS experiment

Particle Physics Seminar - University of Warwick
Eleonora Rossi



UNIVERSITY OF
OXFORD

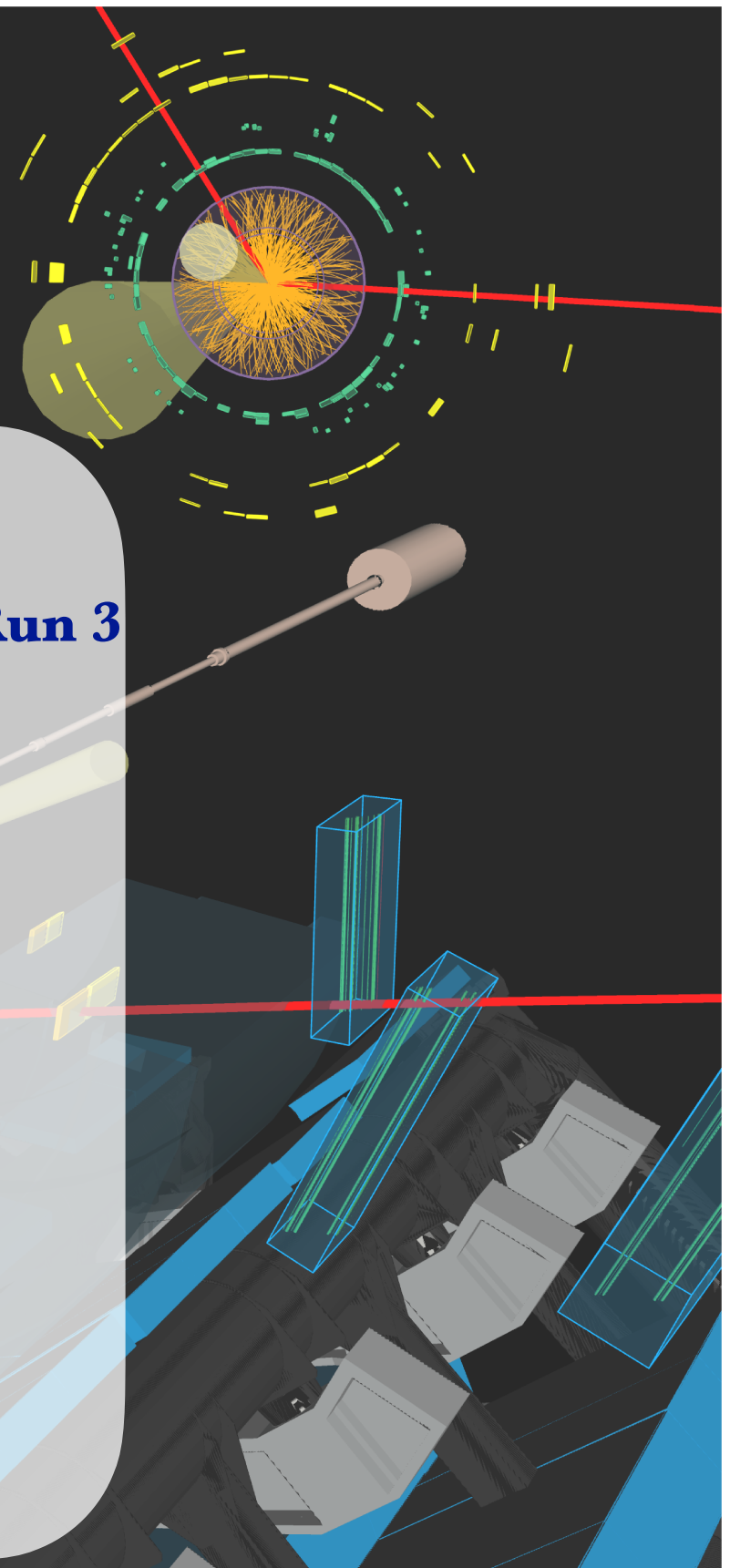
Introduction



Run: 484466

Event: 3913031636

2024-09-13 05:46:24 CEST



The Large Hadron Collider

The ATLAS detector - general purpose + upgrades for Run 3

Physics motivation

Run 2 ATLAS + CMS results

Run 3 Muon performances

Run 3 (+ Run 2) analysis

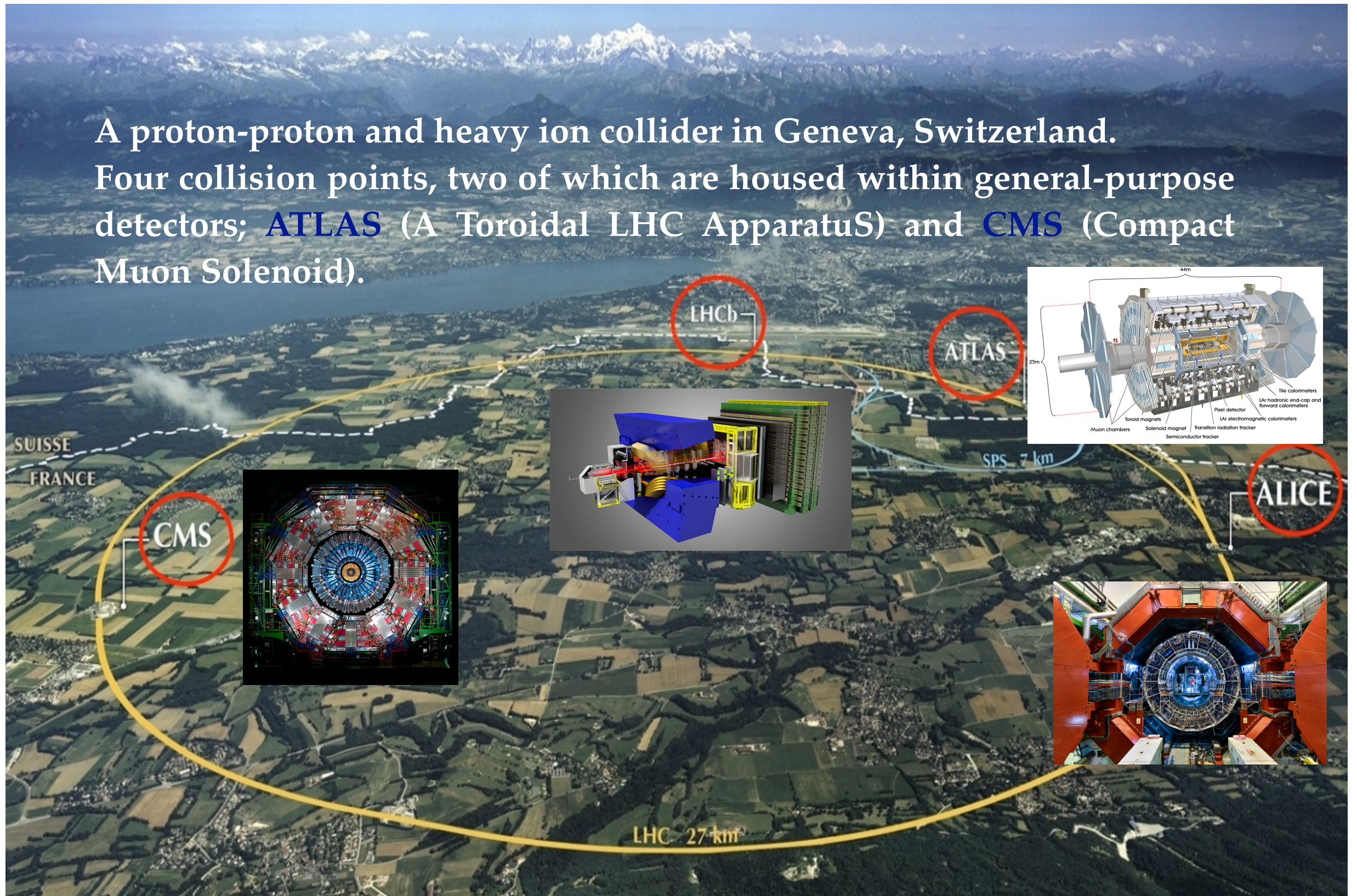
$H \rightarrow \mu^+ \mu^-$ as a tool to probe New Physics

$H \rightarrow \mu^+ \mu^-$ in the combined Higgs coupling picture

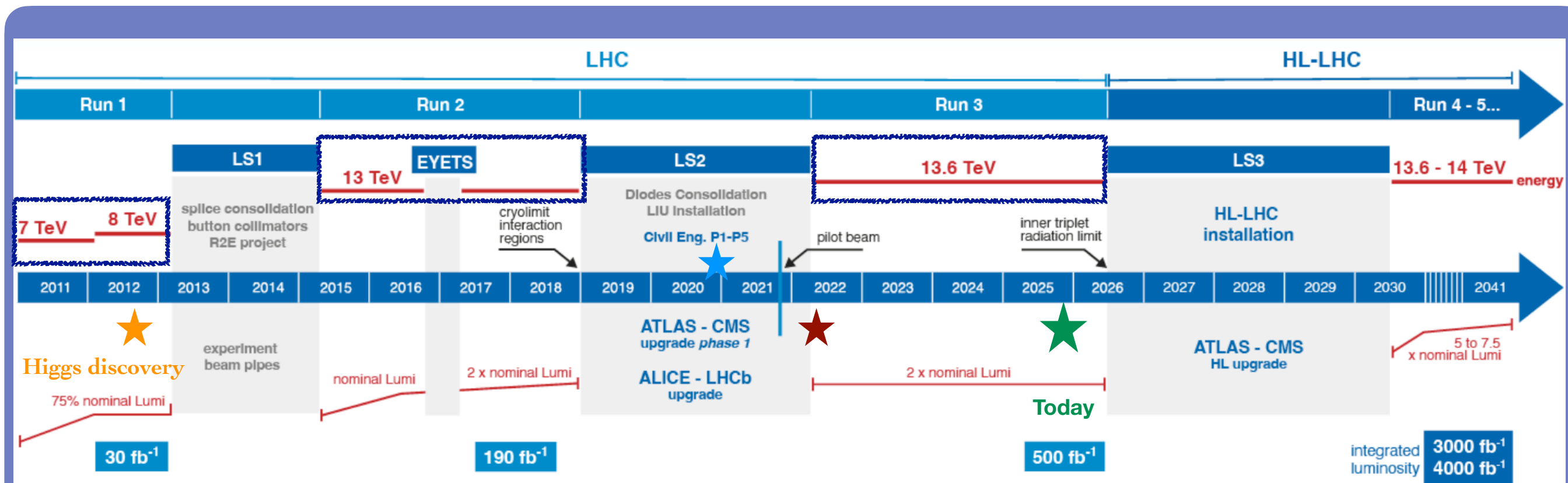
Projections for HL-LHC

The Large Hadron Collider (LHC)

A proton-proton and heavy ion collider in Geneva, Switzerland.
Four collision points, two of which are housed within general-purpose detectors; **ATLAS** (A Toroidal LHC ApparatuS) and **CMS** (Compact Muon Solenoid).



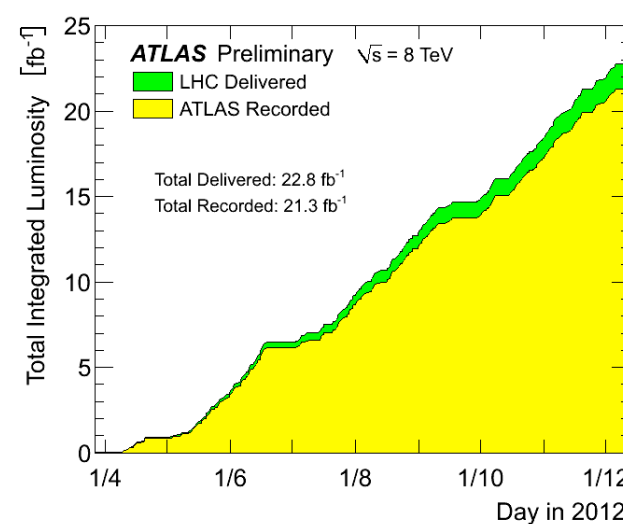
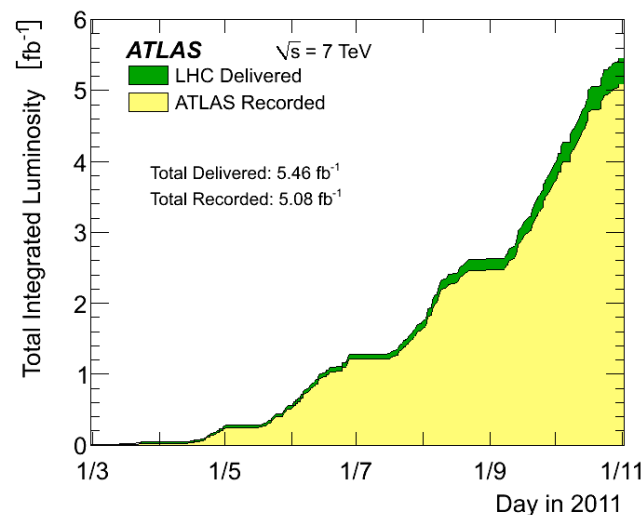
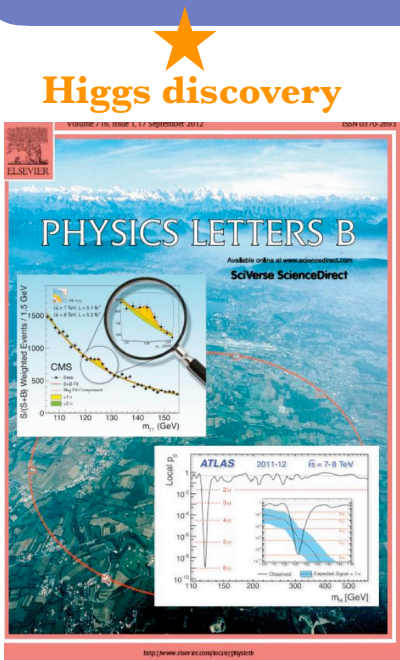
The Large Hadron Collider (LHC)



$$R_{event} = \frac{dN_{event}}{dt} = \mathcal{L} \sigma_{event} = \frac{N_b^2 n_b f_{rev} \gamma_r F}{4\pi \epsilon_n \beta^*} F$$

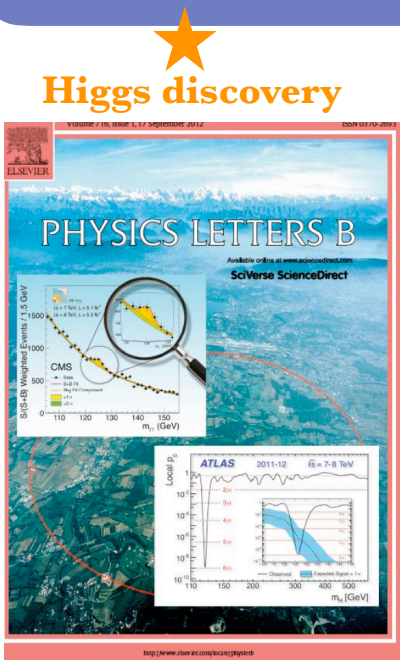
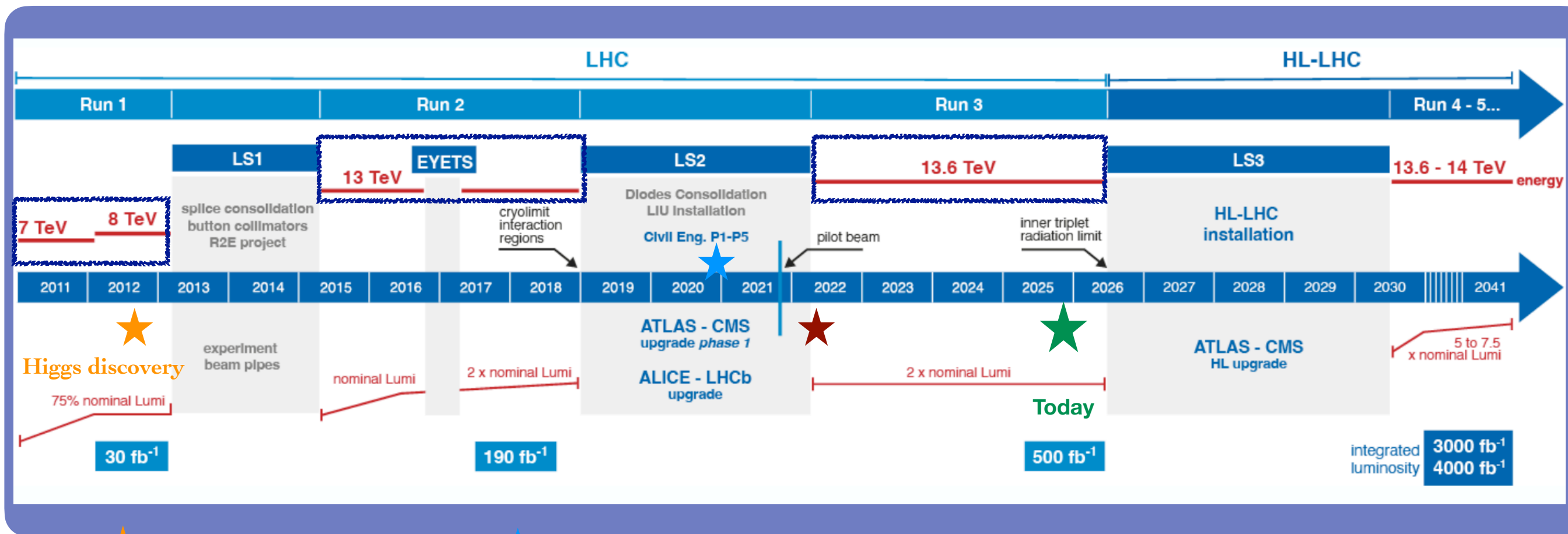
Integrated luminosity

$$L = \frac{\text{number of events of interest}}{\sigma_{event}} = \int_0^T \mathcal{L} dt$$

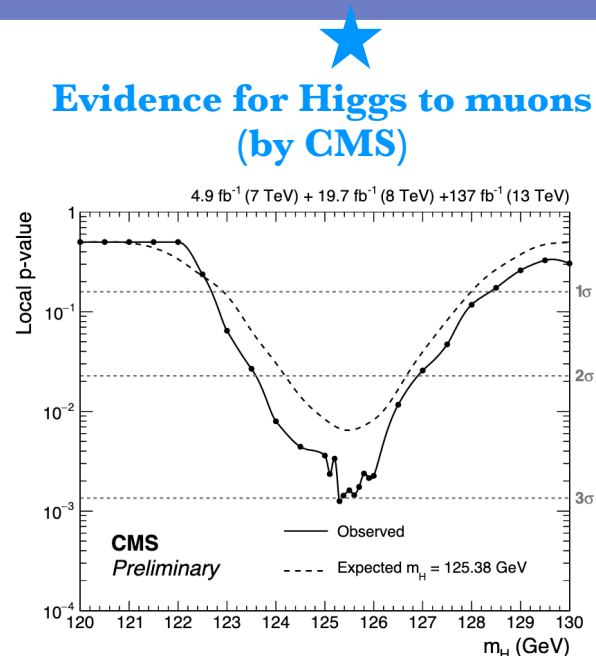


Phys.Lett. B716 (2012) 1-29

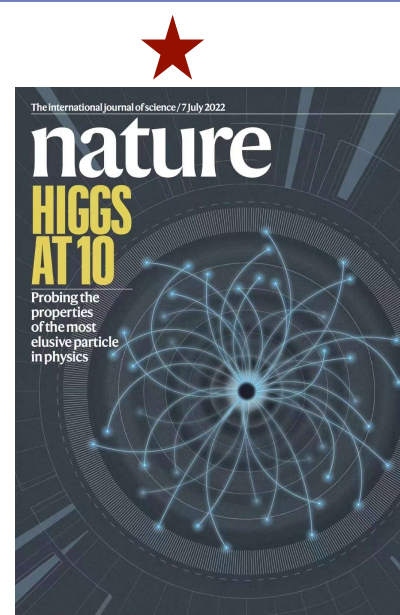
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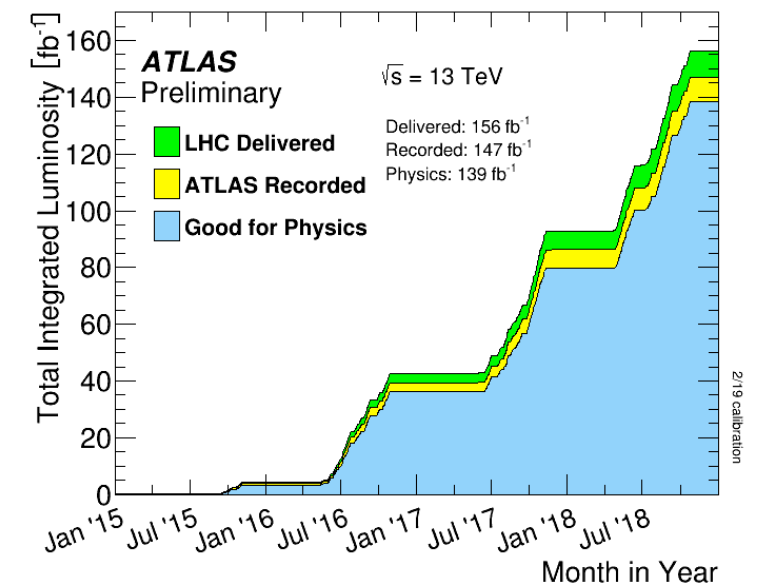
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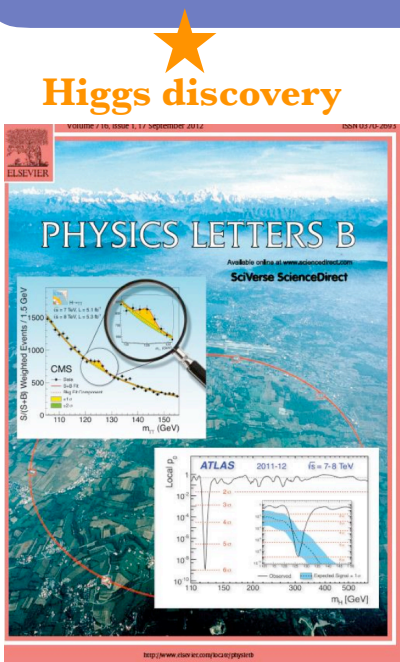
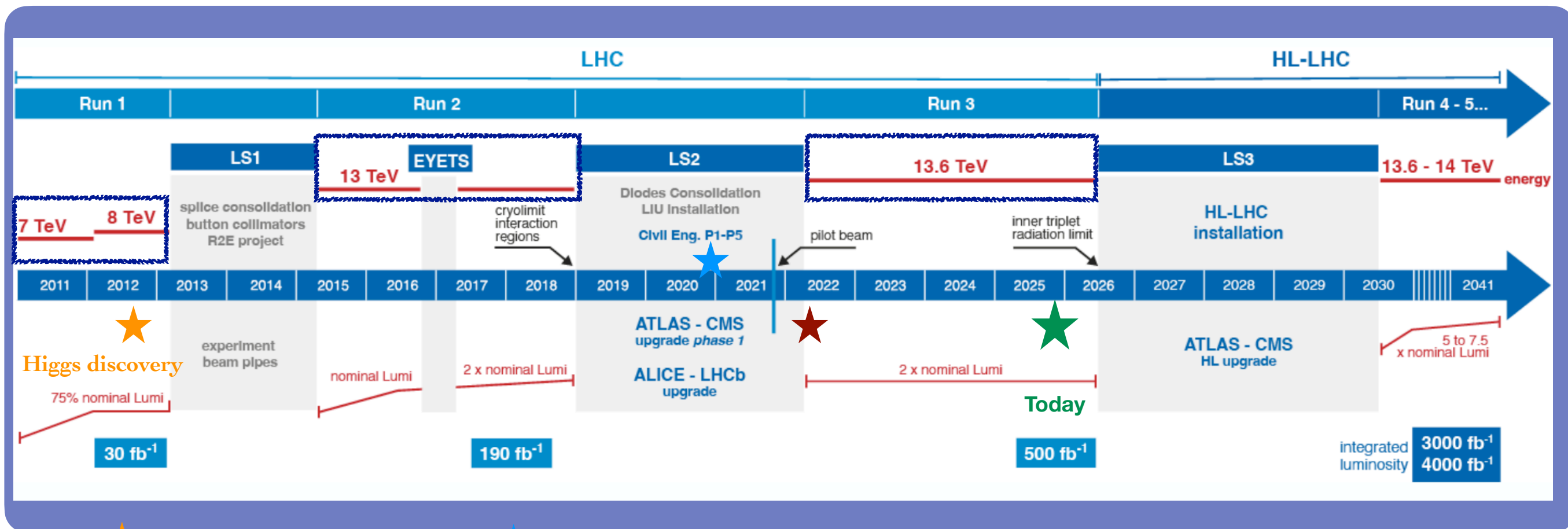
JHEP01(2021)148



Nature paper

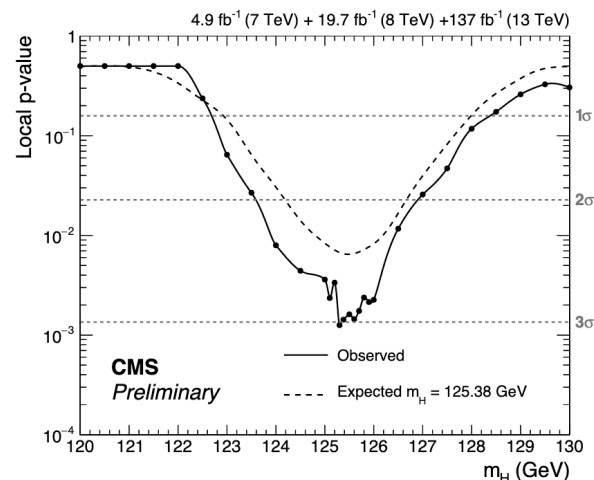


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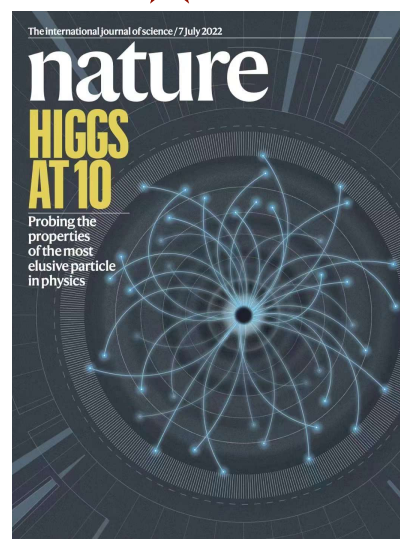


Phys.Lett. B716 (2012) 1-29

Evidence for Higgs to muons (by CMS)



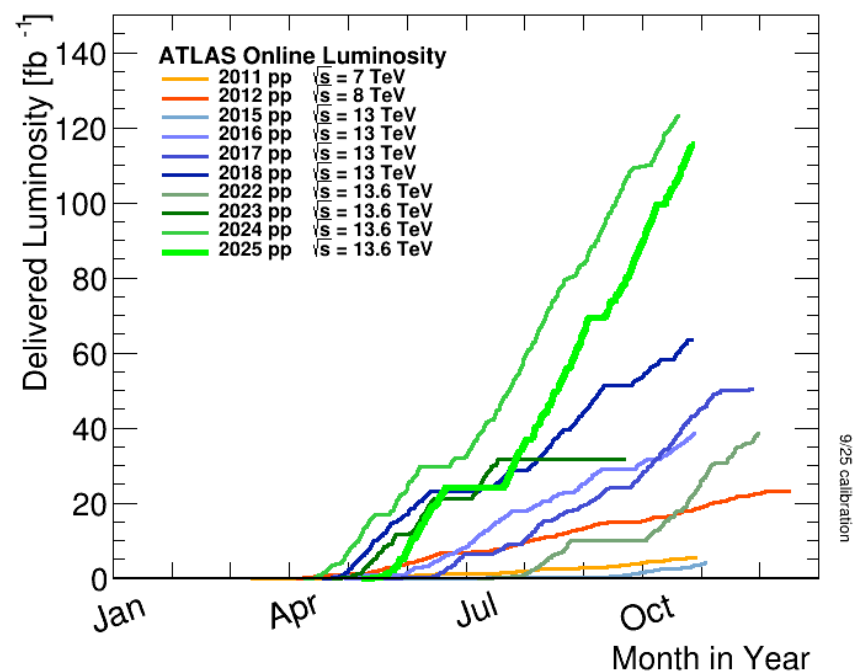
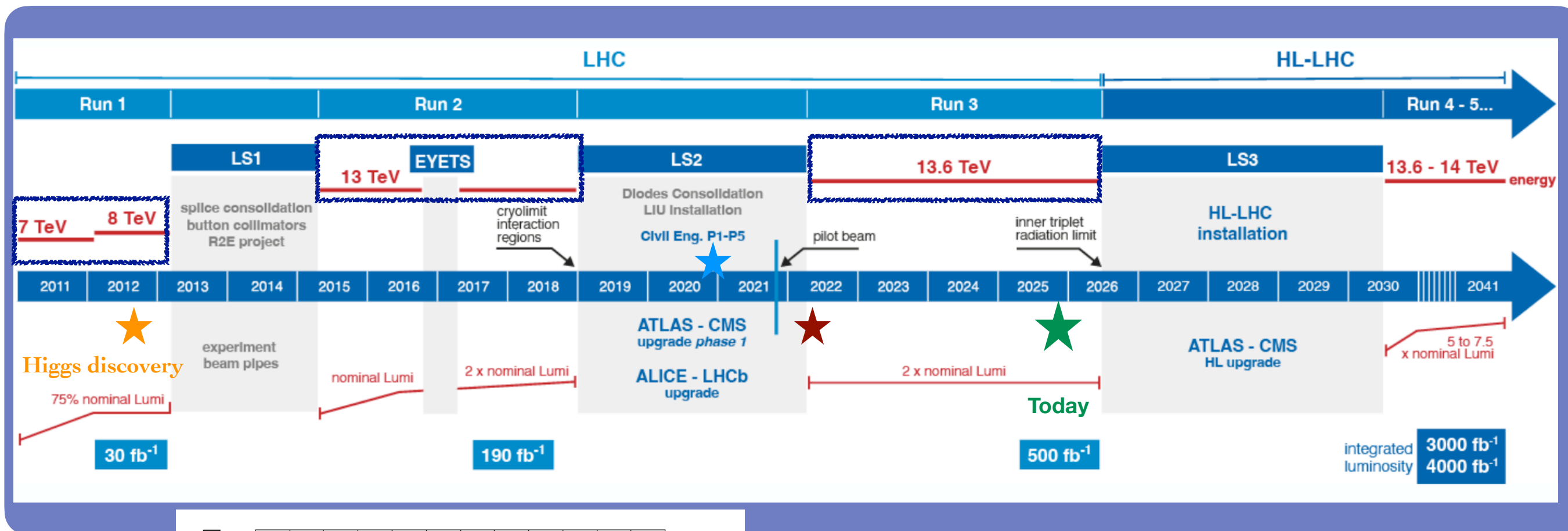
JHEP01(2021)148



Nature paper

★ ★ ★
Era of precision Higgs boson property measurements
Most of the production modes have been experimentally already confirmed (more than 5σ) as well as the dominant (cleanest) decay modes

The Large Hadron Collider (LHC)



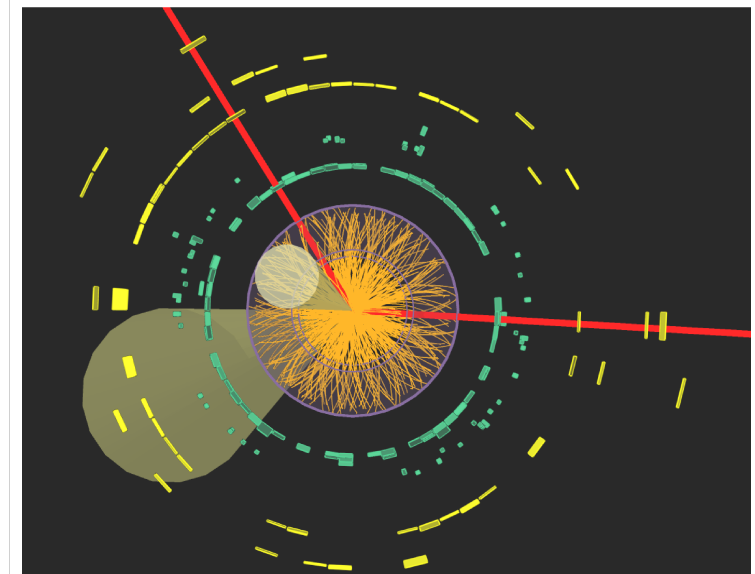
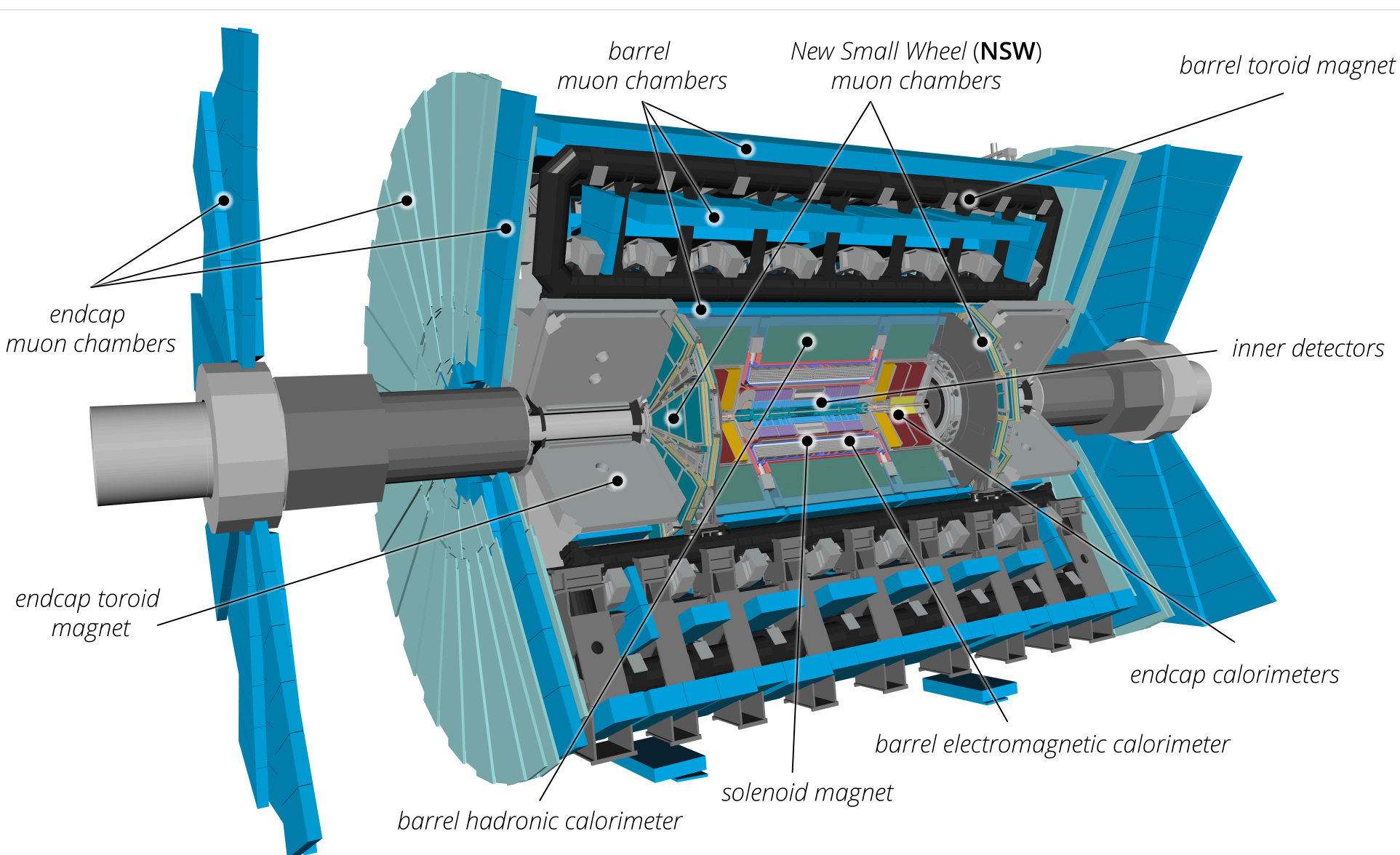
Today: Collecting pp collisions at ECM = 13.6 TeV (world record collider energy) at instantaneous luminosity $\sim 2 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$ with ~ 60 minimum bias interactions per bunch crossing (well above the design value of 20)



The ATLAS detector

ATLAS (**A** Toroidal **LHC** Apparatu**S**):

- **General-purpose detector** running at the LHC collider with excellent reconstruction, identification and energy-momentum measurement covering a wide energy range (sub-GeV à TeV);
- targeting **Higgs** and **beyond standard model** physics searches;
- forward-backward symmetric with respect to the interaction point, it covers almost the entire 4π solid angle.
- onion layer detector structure: Inner detector -> Calorimeter -> Muon spectrometer



The ATLAS detector: Run 3 upgrades

The ATLAS detector has been upgraded to recover Run 1 single-lepton trigger thresholds while operating comfortably under Run 3 sustained pileup conditions.

ATLAS DETECTOR LS2 UPGRADES

MUON NEW SMALL WHEELS (NSW)

Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.



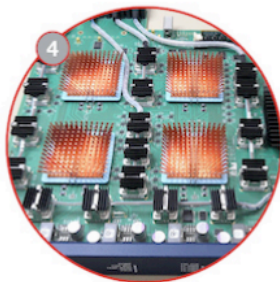
NEW READOUT SYSTEM FOR THE NSWs

The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (STGC) electronic readout channels.



LIQUID ARGON CALORIMETER

New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.

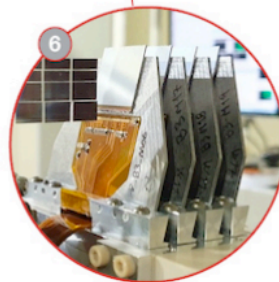
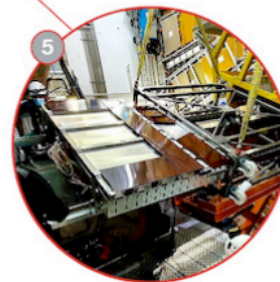


TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)

Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

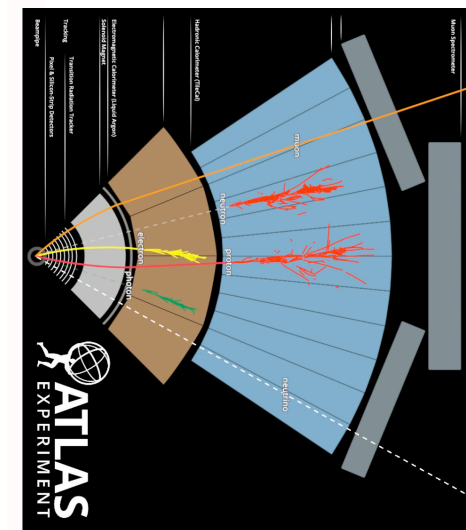
NEW MUON CHAMBERS IN THE CENTRE OF ATLAS

Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.



ATLAS FORWARD PROTON (AFP)

Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new "out-of-vacuum" solution.



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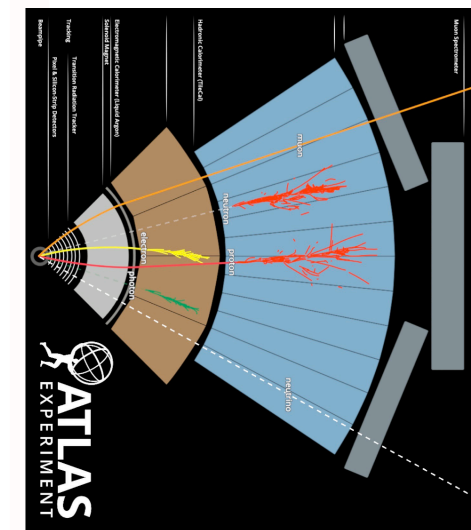
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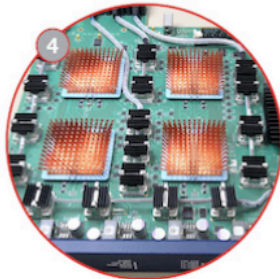


New sTGC (small-strip Thin Gap Chambers) and MicroMegas station, replacing the old Small Wheel with Cathode Strip Chambers and MDTs.

NSW η range: [1.3, 2.7]

Upgrade goal

NSW designed for high background rate of HL-LHC with similar spatial resolution (100 μm)

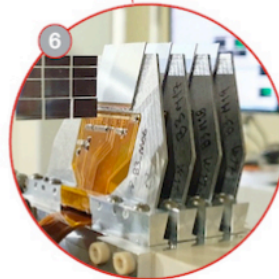


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Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

Physics motivation



- The **precision measurement** of the properties of the Higgs boson including mass, spin-parity, **couplings** and evidences of production processes, which are essential tests of the SM, is **one of the main focus of ATLAS and CMS physics analyses** after the Higgs boson discovery in 2012.

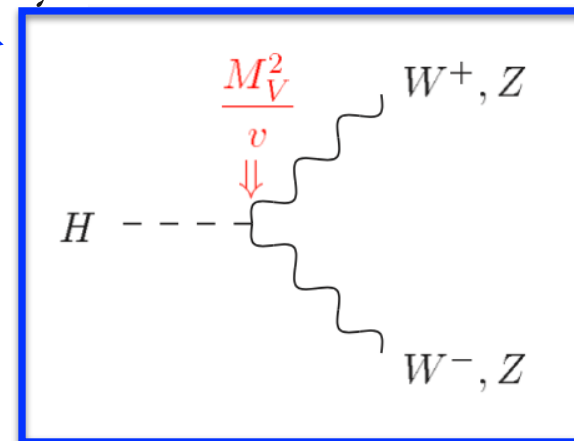
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi$$

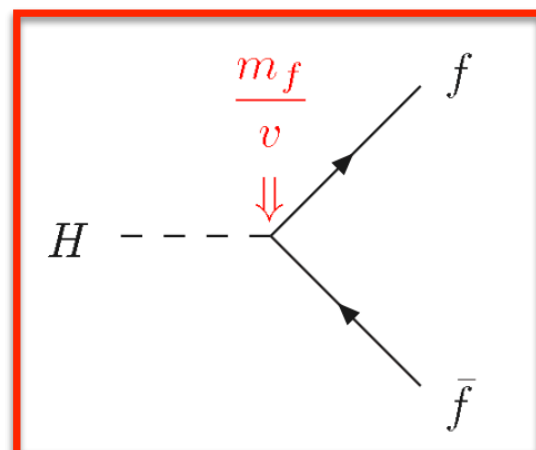
$$+ \underbrace{|\mathcal{D}_\mu \phi|^2}_{\text{Bosons}} - V(\phi)$$

$$+ \underbrace{\bar{\psi}_i y_{ij} \psi_j \phi + \text{h.c.}}_{\text{Fermions}}$$

- The Higgs boson provides mass to bosons and fermions through the electroweak spontaneous symmetry breaking.
- Two types of tree-level couplings to other SM particles are predicted, determining all Higgs-boson production and decay modes.
- Fermions, in particular, acquire mass through Yukawa interactions with the Higgs boson
 - EWSB does not provide any explanation of the flavour hierarchy!



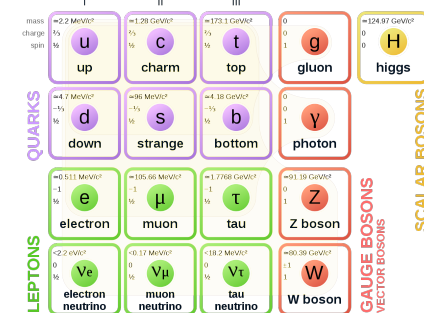
Bosons



Fermions

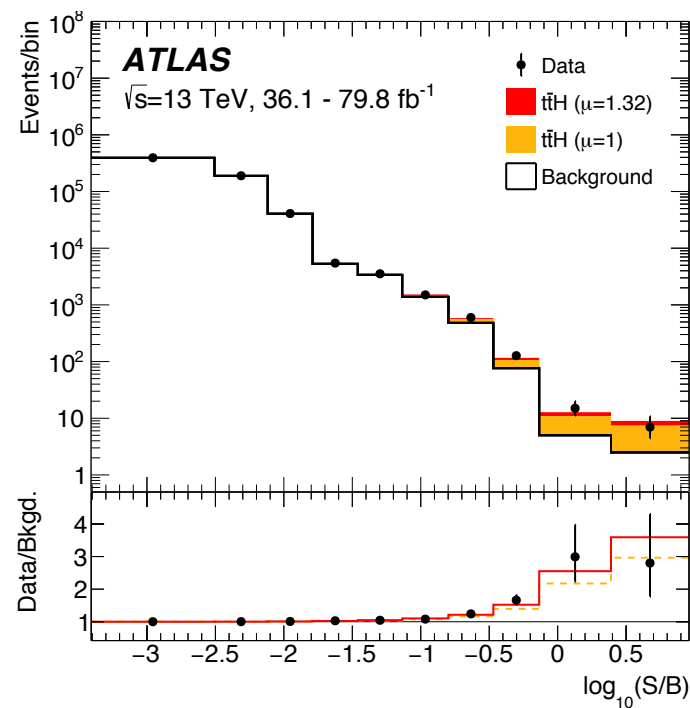


Physics motivation

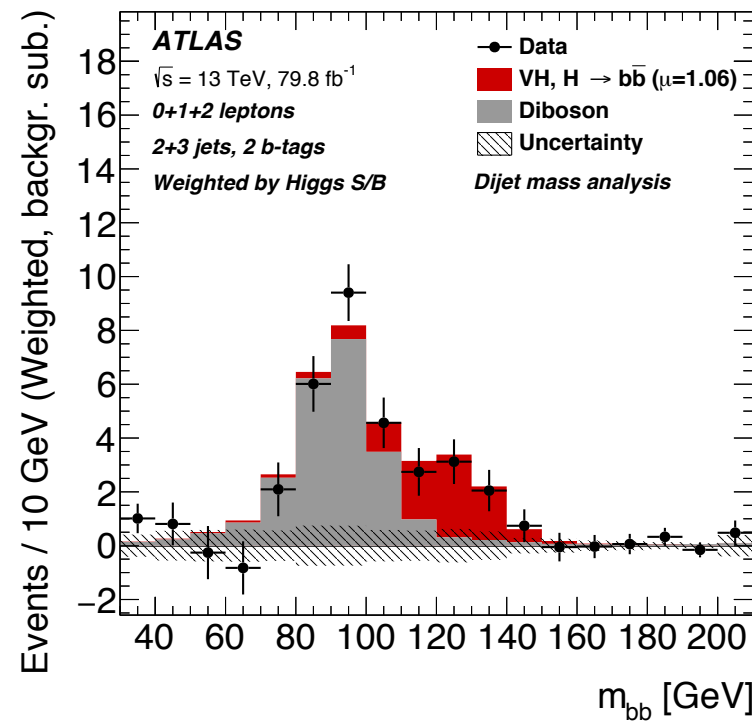


Thanks to LHC's Run 2 data, ATLAS and CMS directly probed Higgs boson couplings to *third generation* fermions

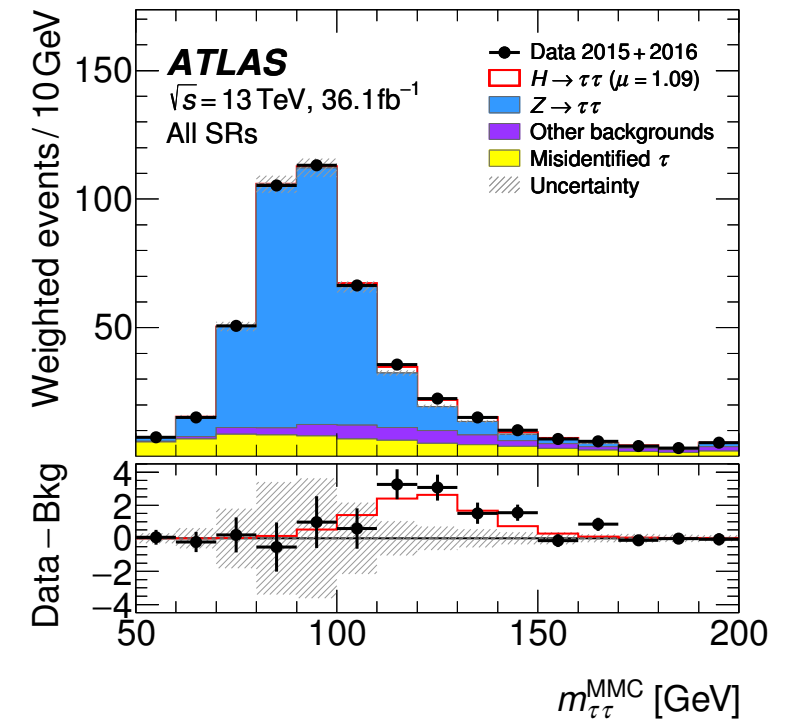
[Phys. Lett. B 784 \(2018\) 173](#)



[Phys. Lett. B 786 \(2018\) 59](#)

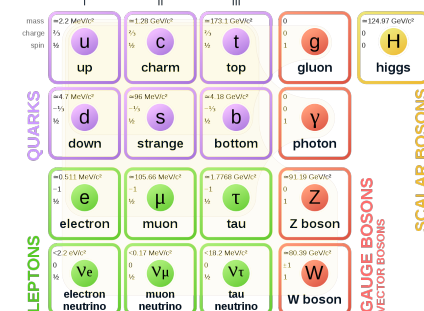


[Phys. Rev. D 99 \(2019\) 072001](#)



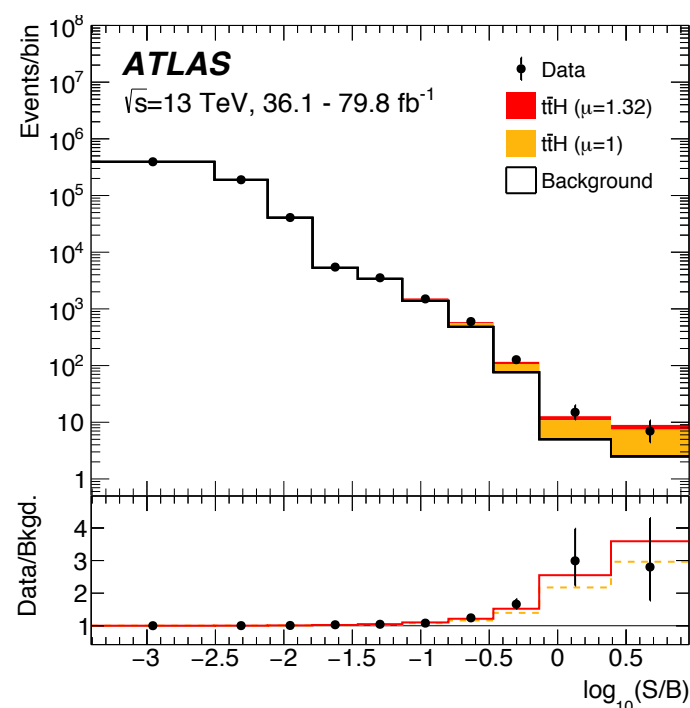


Physics motivation

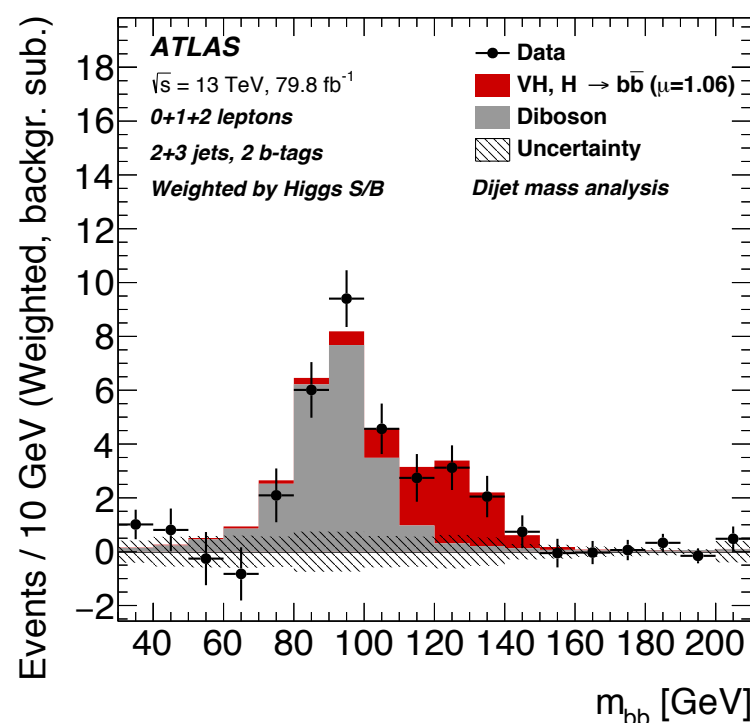


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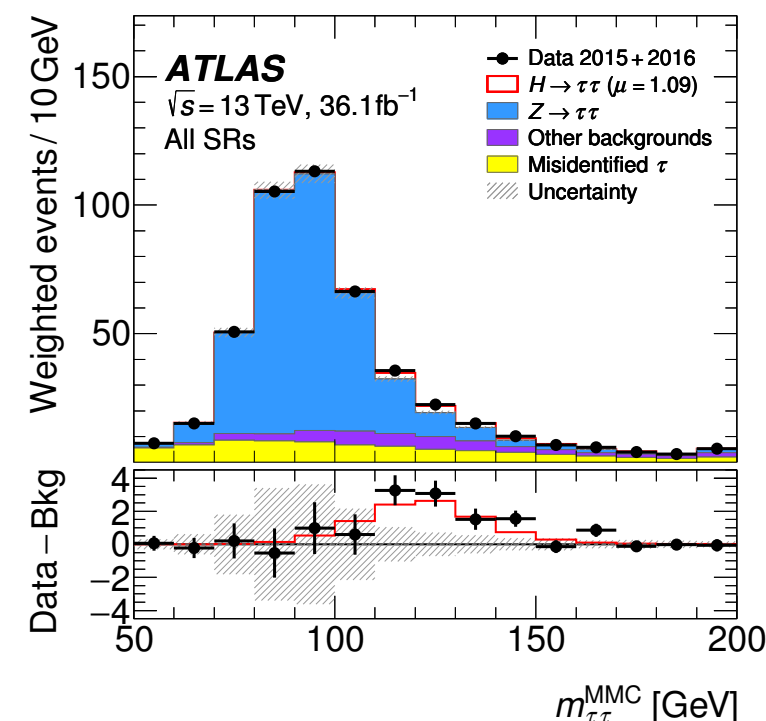
[Phys. Lett. B 784 \(2018\) 173](#)



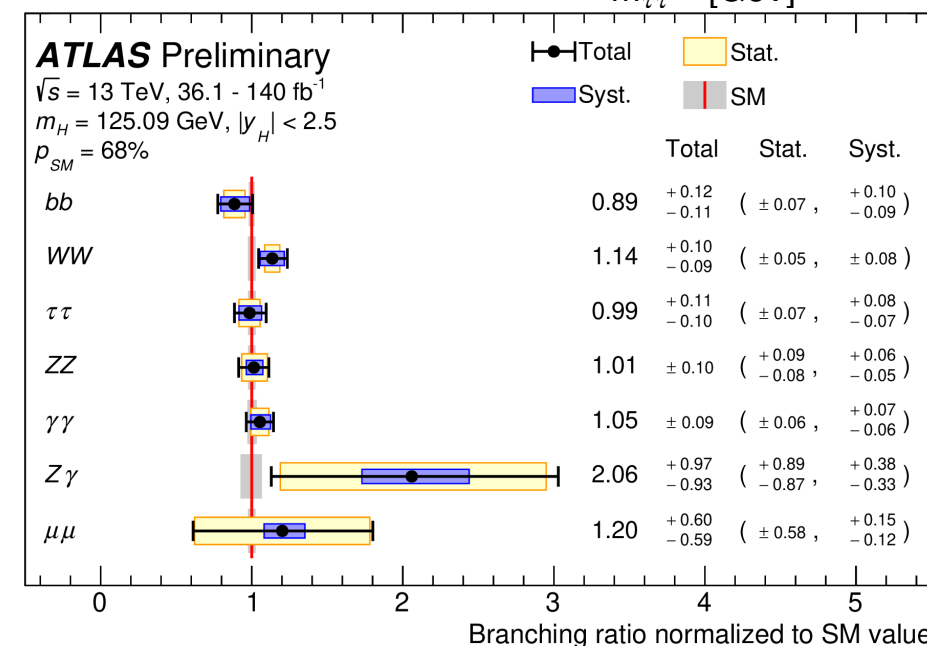
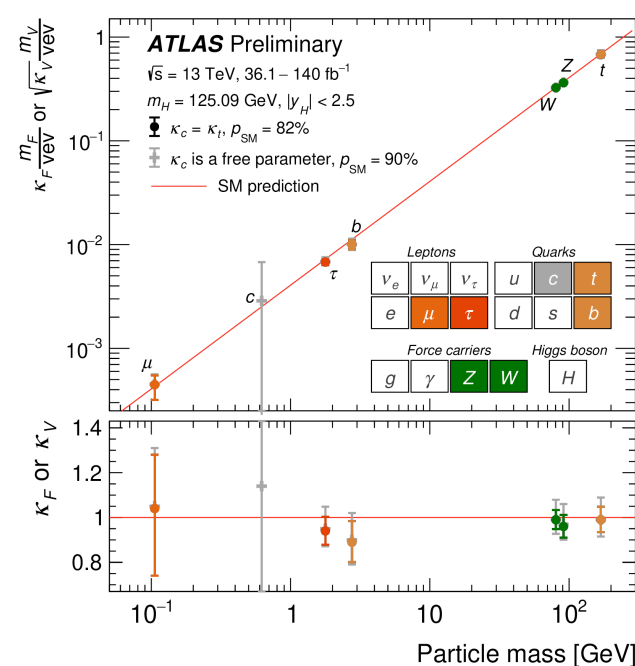
[Phys. Lett. B 786 \(2018\) 59](#)



[Phys. Rev. D 99 \(2019\) 072001](#)



- Reached measurement of Higgs decay branching ratios at **8-13% level precision** → in good agreement with SM



ATLAS-CONF-2025-006



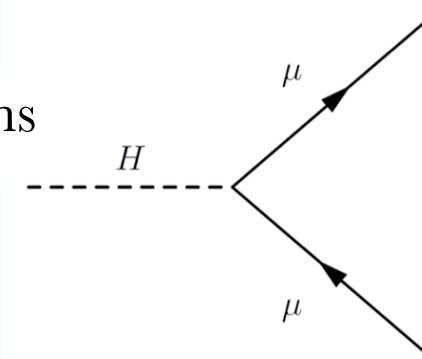
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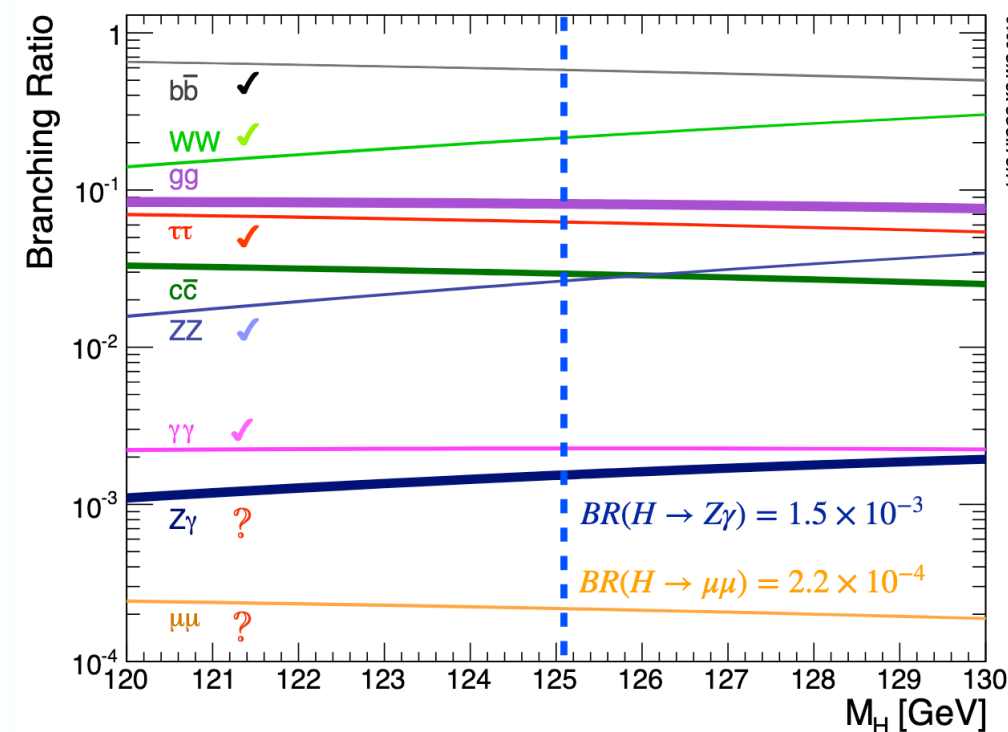
Reached measurement of Higgs decay branching ratios at **8-13% level precision** → in good agreement with SM

The **next frontier** is to probe the Higgs boson interaction with 2nd generation fermions

- ❖ $H \rightarrow f\bar{f}$ coupling proportional to m_f
- ❖ Small $\text{BR}(H \rightarrow f\bar{f})$ for 1st, 2nd gen. fermions
- ❖ Probing Higgs couplings to second-generation fermions is a key challenge at the LHC: $H \rightarrow \mu\mu$ is probably **the only accessible 2nd or 1st generation interaction**

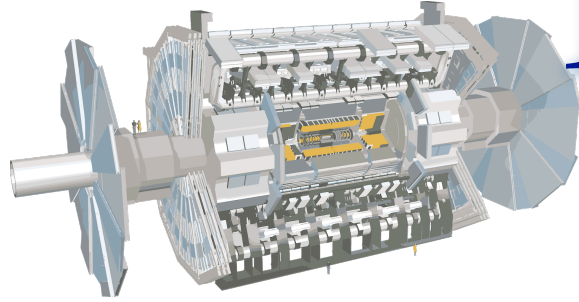


	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	$\frac{1}{2}$	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

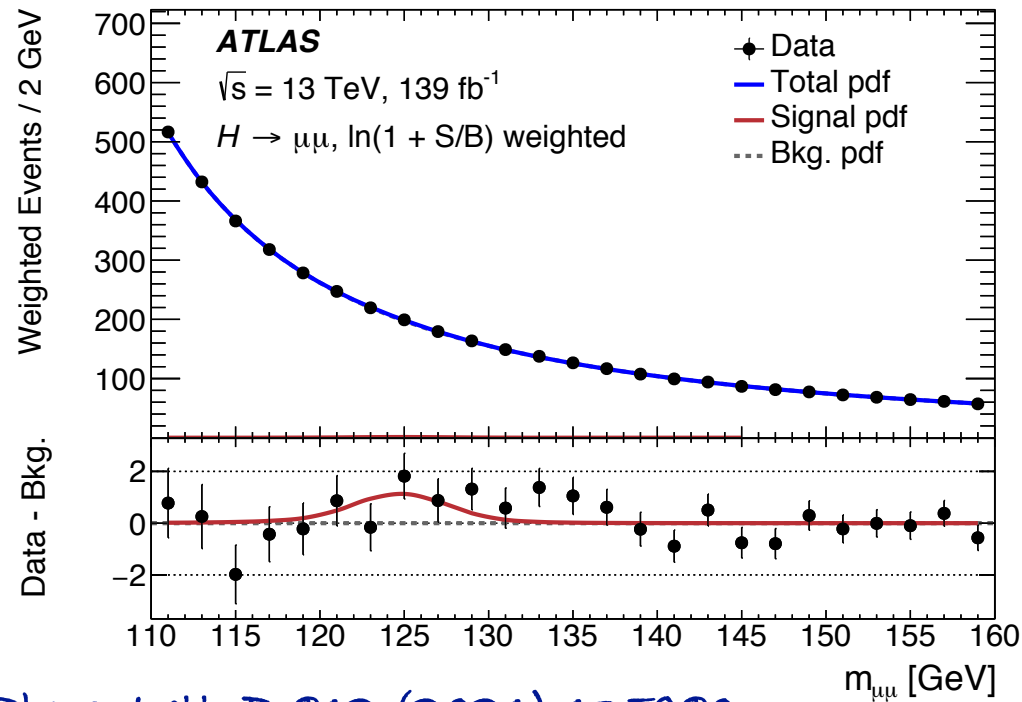
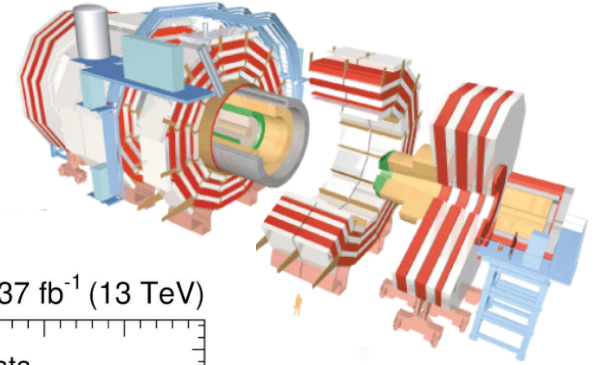


Run 2 results

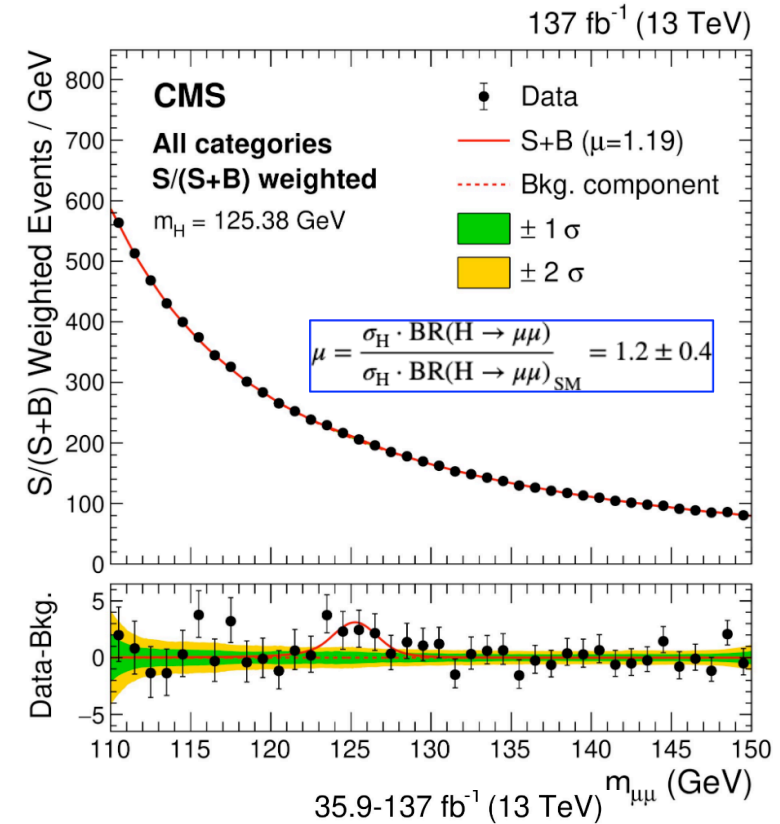
ATLAS



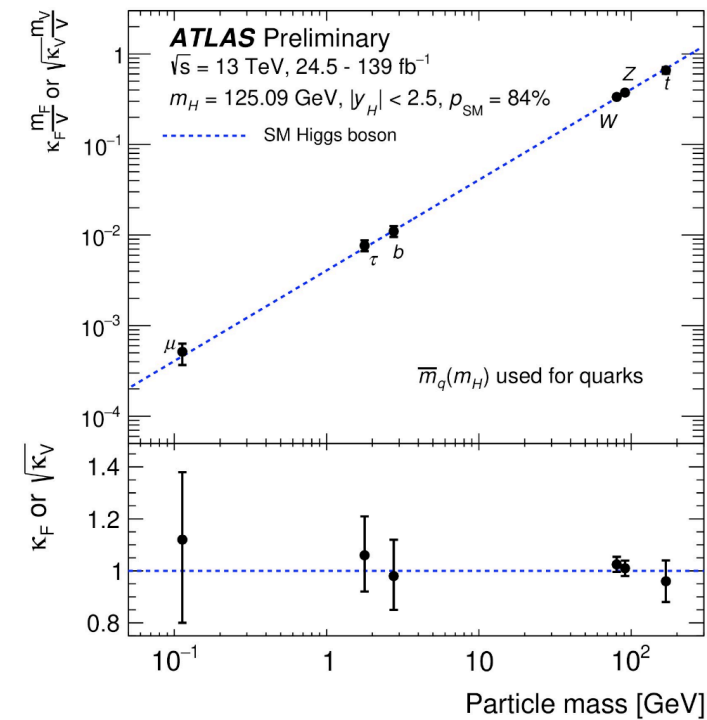
CMS



[Phys. Lett. B 812 \(2021\) 135980](#)



[JHEP01\(2021\)148](#)

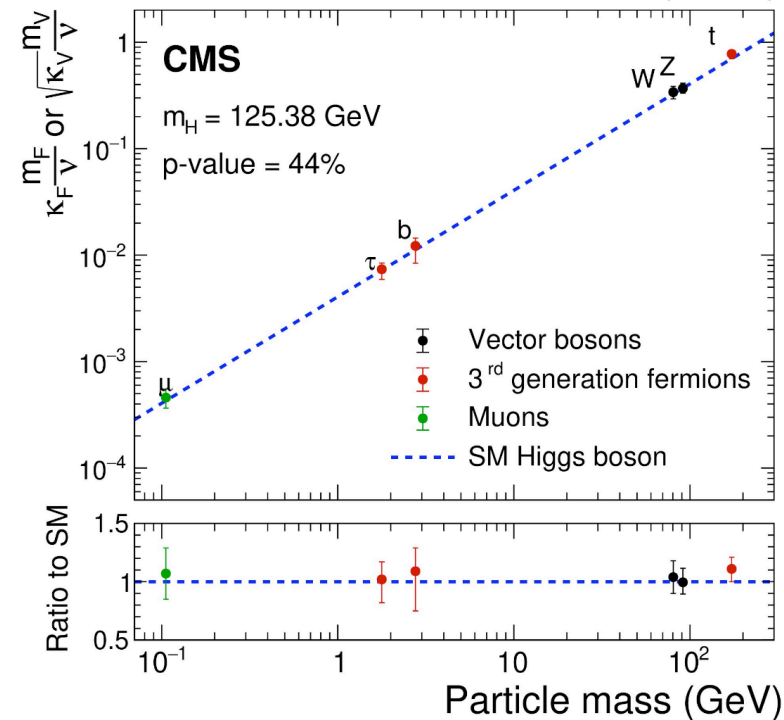


Significance (w.r.t. no
 $H \rightarrow \mu\mu$ signal
 hypothesis)

Observed (expected)
 significance:

2.0 (1.7) σ

Signal strength:
 1.2 ± 0.6



Significance (w.r.t. no
 $H \rightarrow \mu\mu$ signal
 hypothesis)

Observed (expected)
 significance:

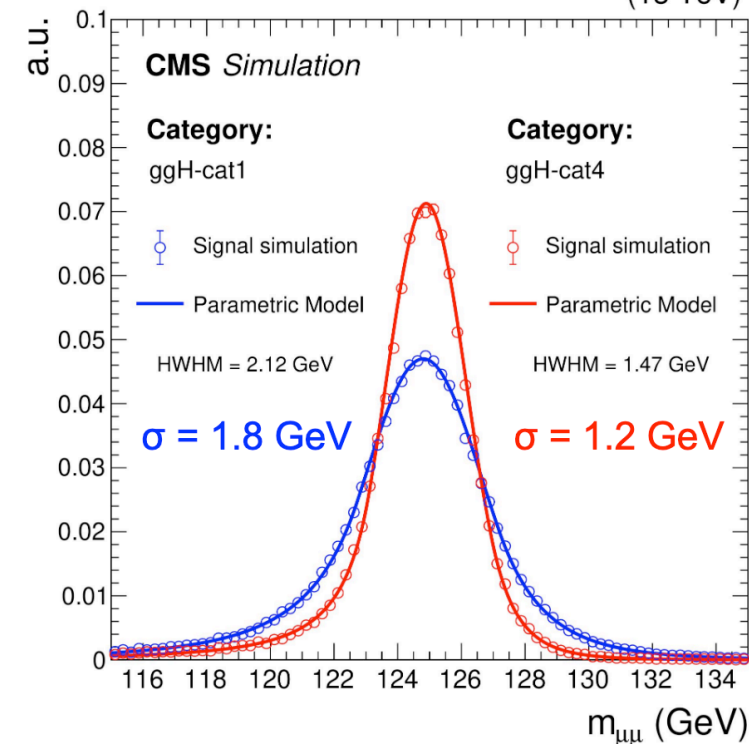
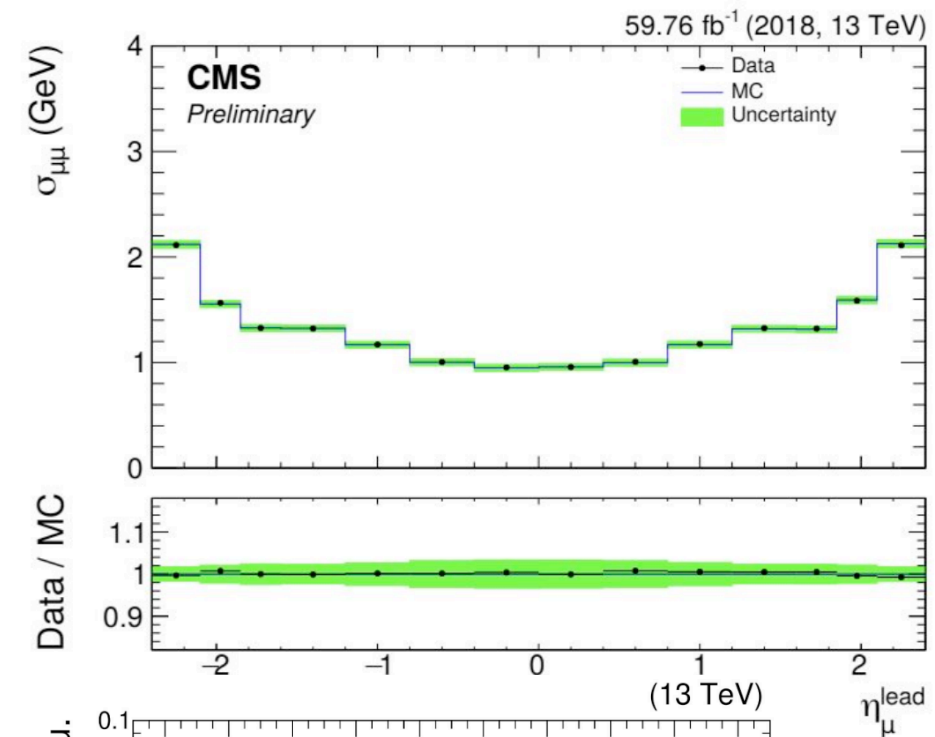
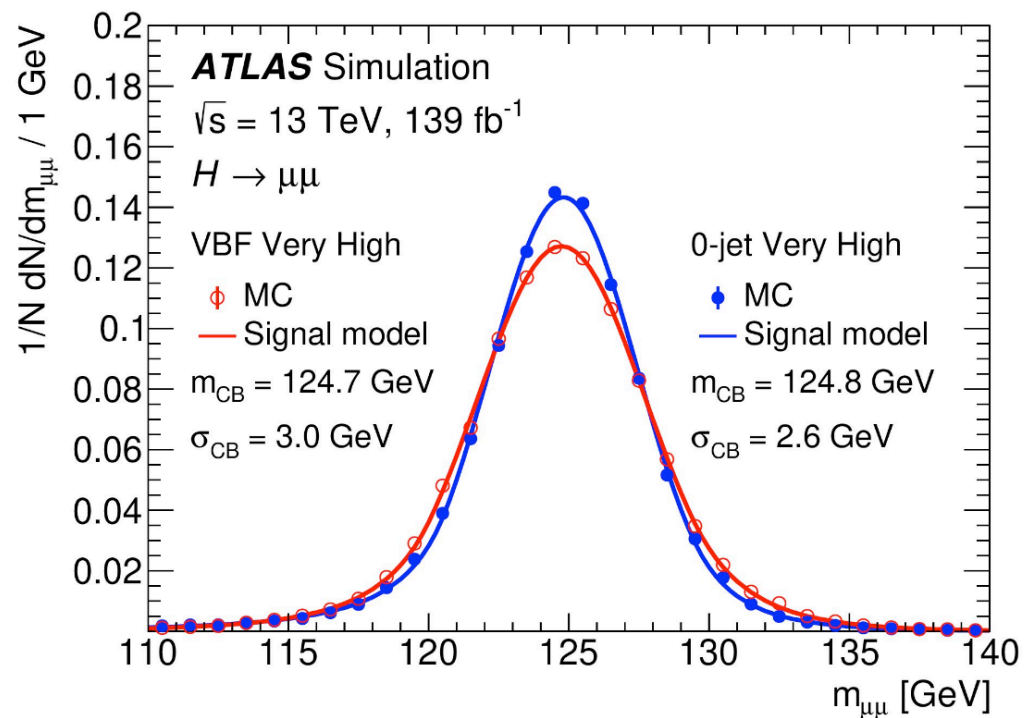
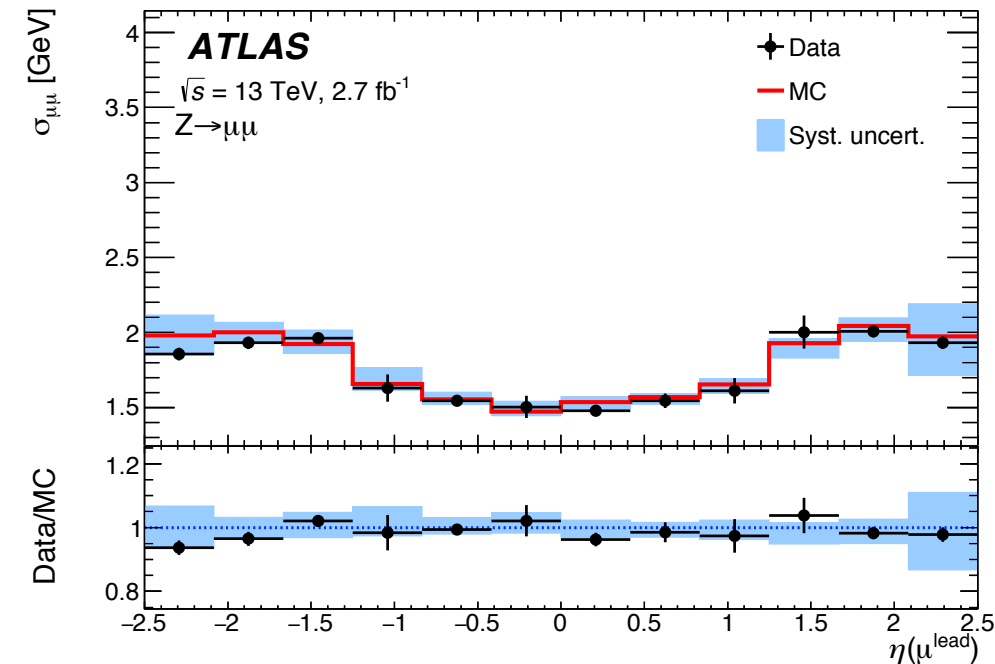
3.0 (2.5) σ

Signal strength:
 1.2 ± 0.4

First evidence!

ATLAS vs CMS - Run2

- CMS has a stronger magnetic field - better resolution
- ATLAS: 1.7 (2.3 %) momentum resolution in the central region for muons from $J/\psi \rightarrow \mu\mu$ ($Z \rightarrow \mu\mu$) decays.
- CMS: the relative p_T resolution of muons with $p_T > 20$ GeV passing through the barrel region of the detector ($|\eta| < 0.9$) ranges from 1.5 to 2%

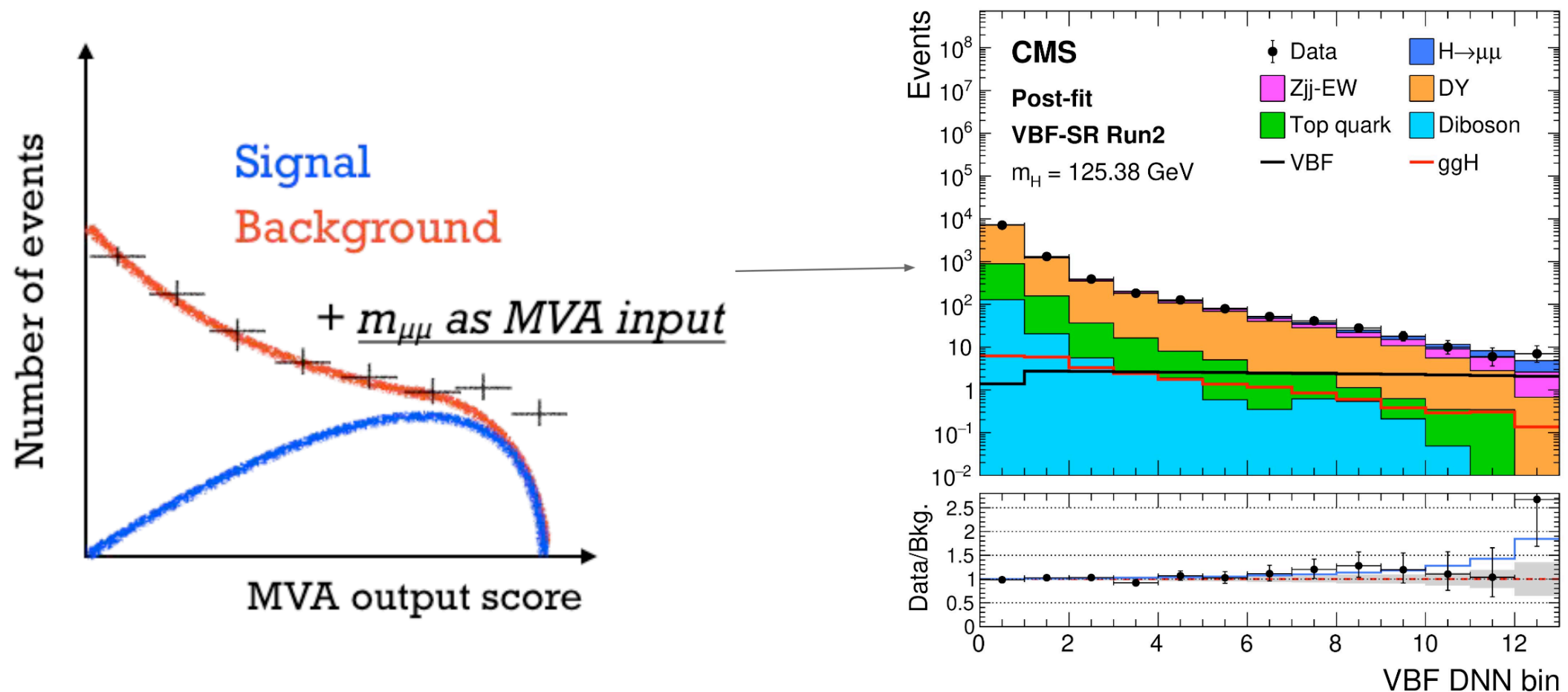


Events with high
 dimuon mass resolution ($\sim 1\%$)
 typical both muons in the barrel

ATLAS vs CMS - Run 2

- Common strategy used by ATLAS analysis and CMS non-VBF categories
 - Machine learning techniques extensively exploited by both experiments in order to reach optimal sensitivity
- Alternative approach used by CMS for VBF categories - about **20% improvement** in expected significance w.r.t. usual strategy
 - Include the $m_{\mu\mu}$ directly in the **MVA classifier**
 - Perform a binned fit of the **MVA classifier output**
 - Take **background estimate from simulation**
 - Use **data in the Higgs SB** [110-115], [135-150] GeV to validate, constrain bkg. prediction

Overall impact of the systematic uncertainties is small (less than 5%)



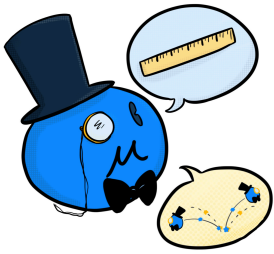
Run: 484466

Event: 3913031636

2024-09-13 05:46:24 CEST

ATLAS Run 3 (+Run 2)

analysis

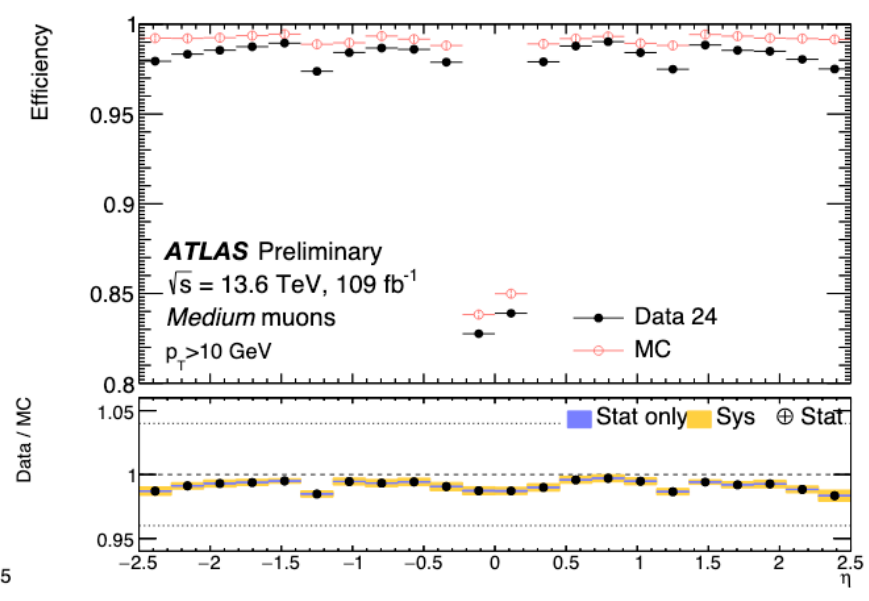
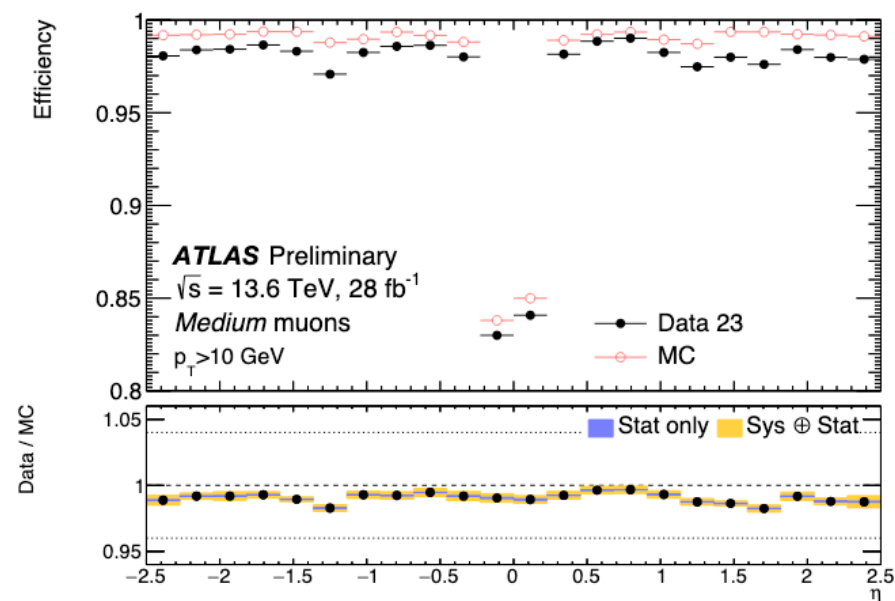
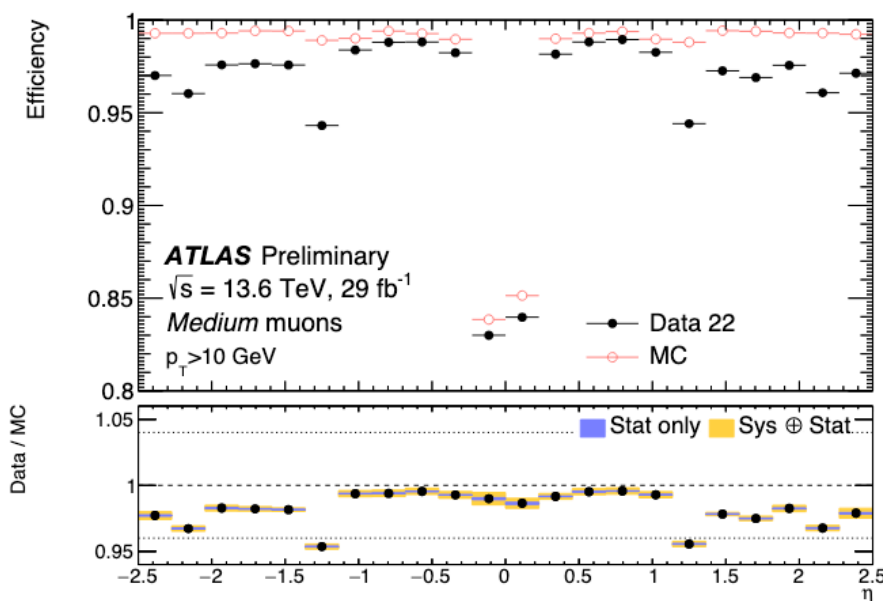


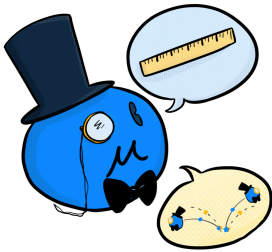
Muon reconstruction performance

ATL-COM-PHYS-2025-870

- **Physics object calibrations** have been updated using Run 3 dataset (2022-2024).
- Good muon reconstruction performance of the ATLAS experiment with Run 3 data.
- Muon Reconstruction and Identification measured using **Tag & Probe method**, applied to $Z \rightarrow \mu\mu$ or $J/\psi \rightarrow \mu\mu$ decays.
- In **Data 2022**, the NSW was still in a commissioning phase, resulting in lower data efficiency in the endcap regions.
- From **2023**, NSW operates as expected, bringing the Data / MC ratio closer to unity.

Identification and reconstruction efficiency **at the level of Run 2**, after the addition of NSW data to the working point definition.





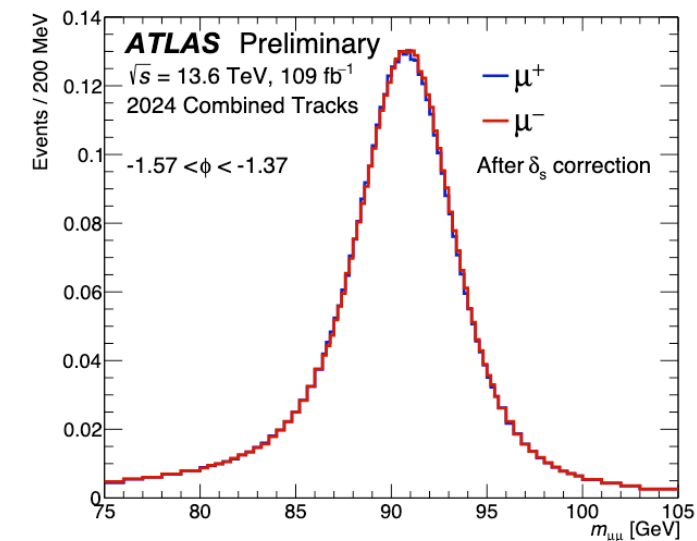
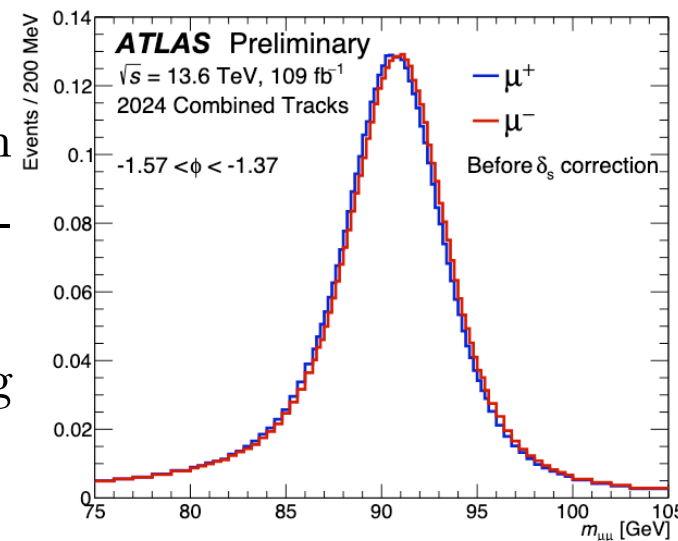
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ATL-COM-PHYS-2025-870

Muon momentum calibration performed applying to set of corrections:

Opposite charge bias (applied to data): Twist, Curls and Shift in the detector can create charge-dependent effects

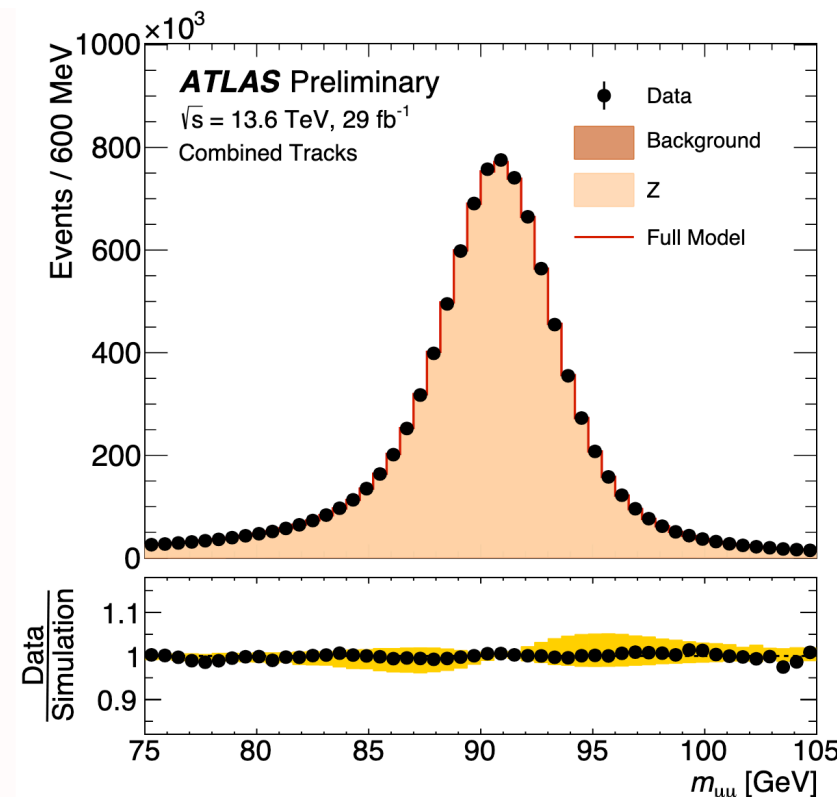
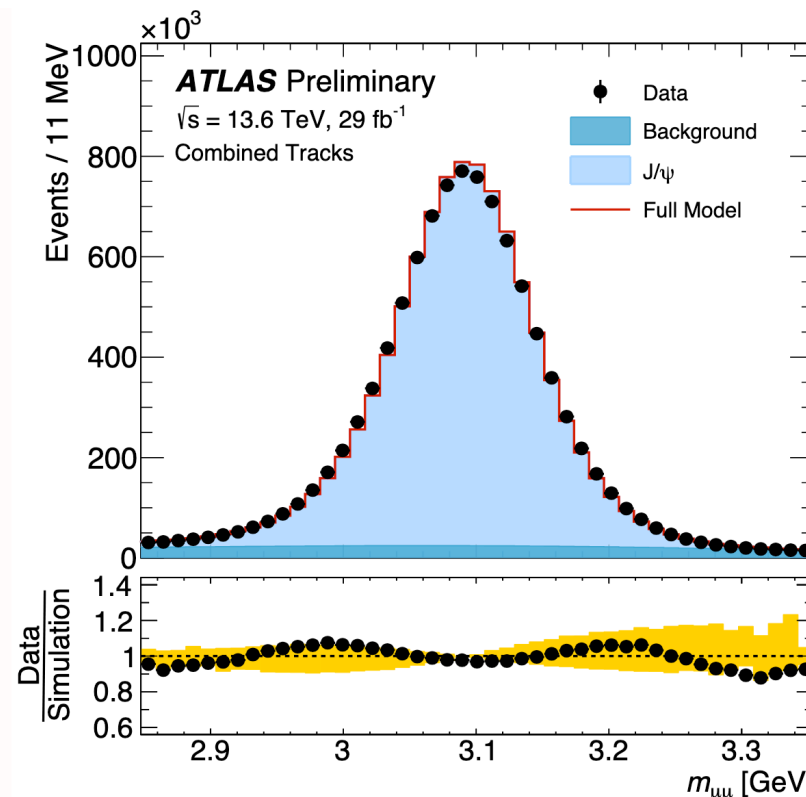
- In 2023 NSW data had a major role in the muon reconstruction, resulting in minor opposite charge-based effect in the endcap regions
- Improved alignment came available in 2024, resulting in smaller correction factors (on average)



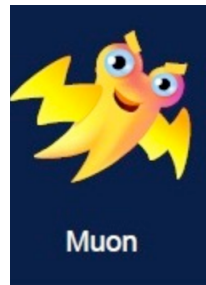
Scale and Smearing (applied to simulation): Corrections of mismodelling effects in simulation

- Data/Simulation agreement close to unity after scale and smearing calibration.
- Not perfect agreement, due to missing alignment in the endcap regions and lower statistics in 2022

Calibration work reached similar Run 2 performance, thanks to the updated calibration and increased statistics in 2024



ATL-COM-PHYS-2024-158



Updates w.r.t. Run2 paper

Major Updates w.r.t. Run-2 Paper

- **Improved object performance:**
 - GN2 b-tagging algorithm (60% to 85% WP)
 - Fitting decay vertex of the dimuon system
- **More robust bkg. modeling:**
 - Moved from fast-sim smearing to official full-sim for DY samples (5B events)
 - $c\bar{c}$ and $b\bar{b}$ contributions added to core function
- **More complete phase space for categorization:**
 - Addition of $Z(\rightarrow \nu\nu)$ $H(\rightarrow \mu\mu)$ channel
 - Fully hadronic channel added for ttH categorization
 - Retrained neural networks and BDTs - with newly added variables

Objects + event selection

Object Definition

- 2 opposite charged muons, loose ID with $p_T > 5$ GeV, $|\eta| < 2.5$, requirements on d_0/z_0 and isolation
- Fitting the decay vertex of dimuon system ($\sim 2\%$ improvement on resolution)
- FSR recovery (only near candidate included)

Cut	Leading muon	Subleading muon	Jet	b-jets
p_T	$> 27\text{GeV}$	$> 15\text{GeV}$	$> 25\text{GeV}$	$> 25\text{GeV}$
ID/ISO	Loose/ Loose	Medium/ Loose	Tight/ FCLoose	Loose (FixedEffPt)

$t\bar{t}H$ categories

at least one b -jet

VH 4-lepton category

exactly two additional e or μ with $p_T > 8\text{ GeV}$, $5\text{ GeV } (\mu) / 7\text{ GeV } (e)$, no b -jets

VH 3-lepton categories

exactly one additional e or μ with $p_T > 15\text{ GeV}$, no b -jets

VH 2-lepton categories

no additional e or μ , no b -jets, $E_T^{\text{miss}} > 120\text{ GeV}$

VBF and ggF categories

no additional lepton, no b -jets, $E_T^{\text{miss}} < 120\text{ GeV}$

23 exclusive categories in order of $t\bar{t}H \rightarrow VH \rightarrow \text{VBF} \rightarrow \text{ggF}$

- NN or BDTs to separate signal and background
- 2 $t\bar{t}H$ categories
- 3 ZH categories
- 2 WH categories
- 4 VBF categories and 12 ggF categories

Event selection

$t\bar{t}H$ categories

VH 4-lepton category

VH 3-lepton categories

VH 2-lepton categories

VBF and ggF categories

at least one b -jet

exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b -jets

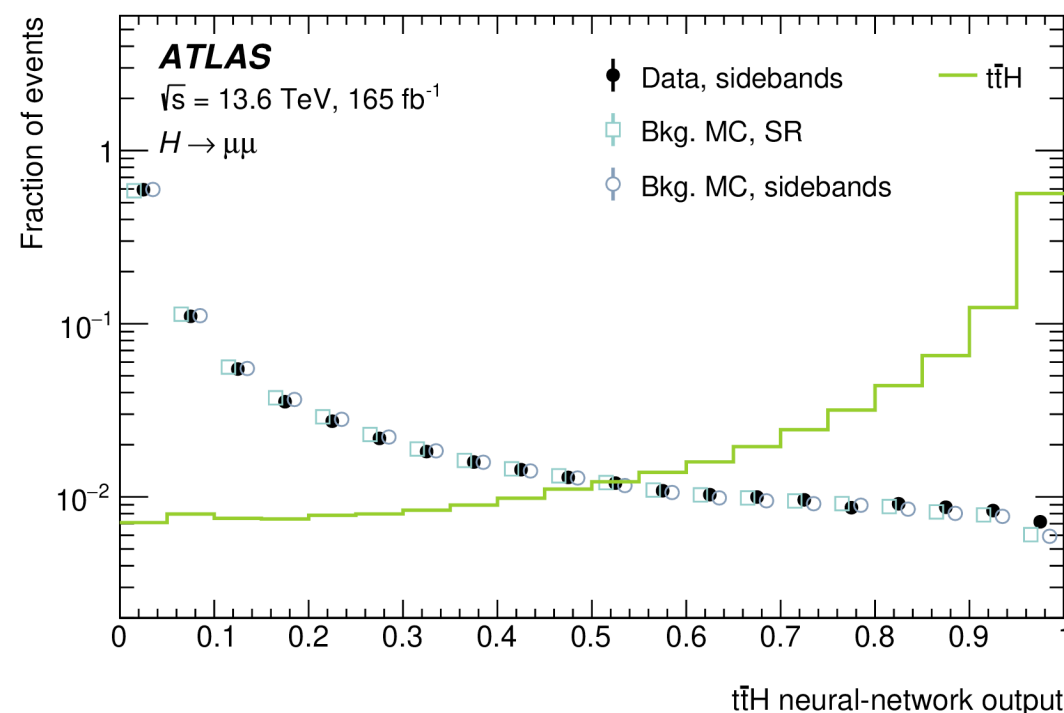
exactly one additional e or μ with $p_T > 15$ GeV, no b -jets

no additional e or μ , no b -jets, $E_T^{\text{miss}} > 120$ GeV

no additional lepton, no b -jets, $E_T^{\text{miss}} < 120$ GeV

$t\bar{t}H$ categories: both hadronic and leptonic decays

- NN trained on 30 variables, **2 categories** defined based on NN output



Event selection

$t\bar{t}H$ categories

VH 4-lepton category

VH 3-lepton categories

VH 2-lepton categories

VBF and ggF categories

at least one b -jet

exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b -jets

exactly one additional e or μ with $p_T > 15$ GeV, no b -jets

no additional e or μ , no b -jets, $E_T^{\text{miss}} > 120$ GeV

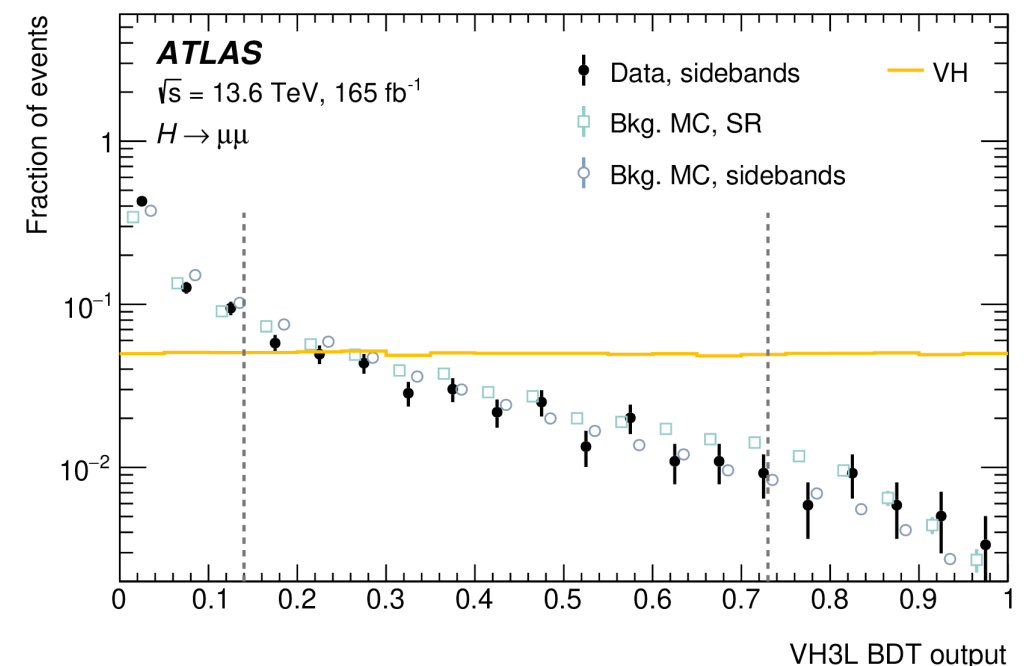
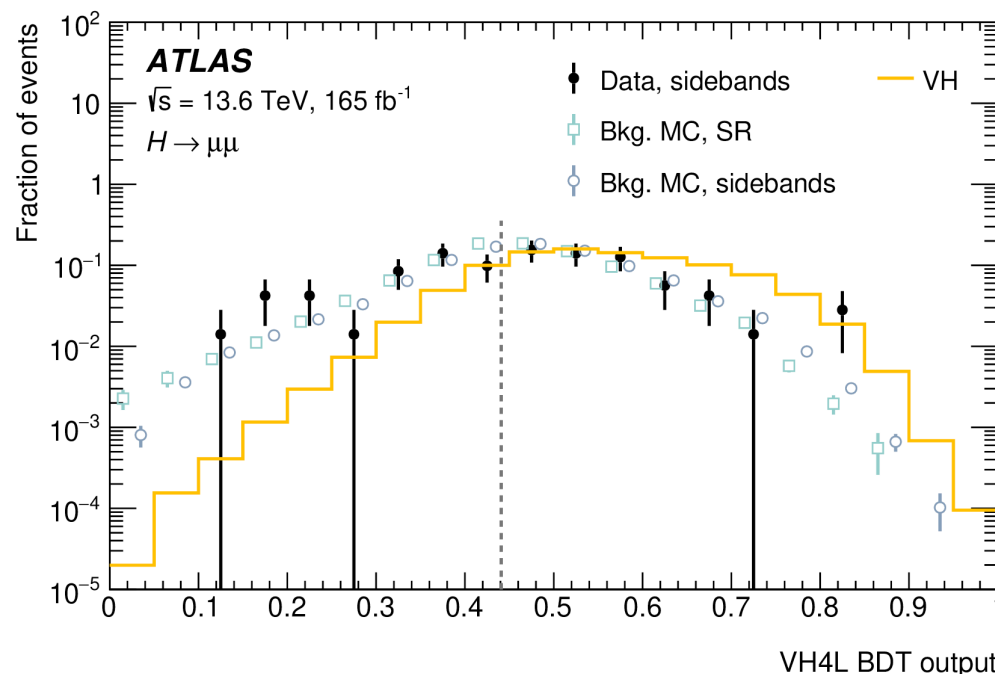
no additional lepton, no b -jets, $E_T^{\text{miss}} < 120$ GeV

ZH categories: 4-lep and 2-lep ($Z \rightarrow \nu\nu$) channels

- BDTs trained on 15 (9) variables for 4-lep (2-lep)
- **1 category** for 4-lep and **2 categories** for 2-lep

WH categories: events with 3-leptons

- χ^2 minimisation used for pairing 3μ events
- BDTs trained on 12 variables $\rightarrow$ **2 categories**



Event selection

$t\bar{t}H$ categories

VH 4-lepton category

VH 3-lepton categories

VH 2-lepton categories

VBF and ggF categories

at least one b -jet

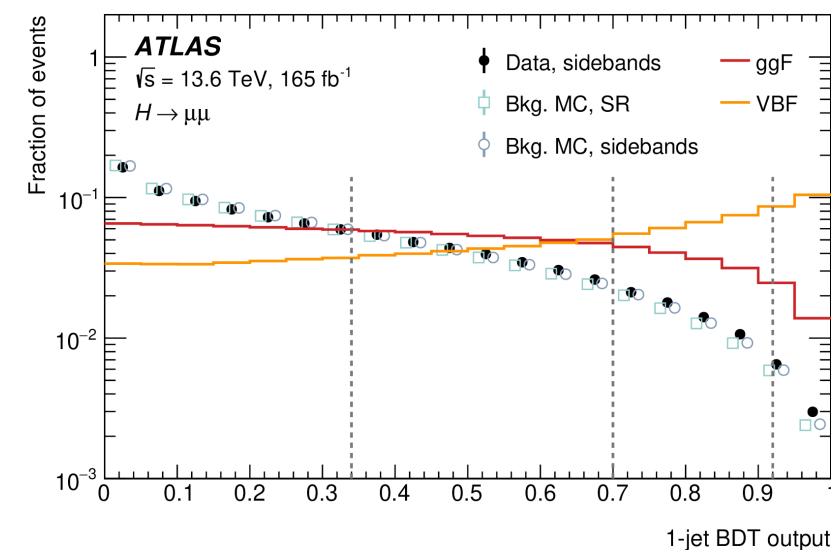
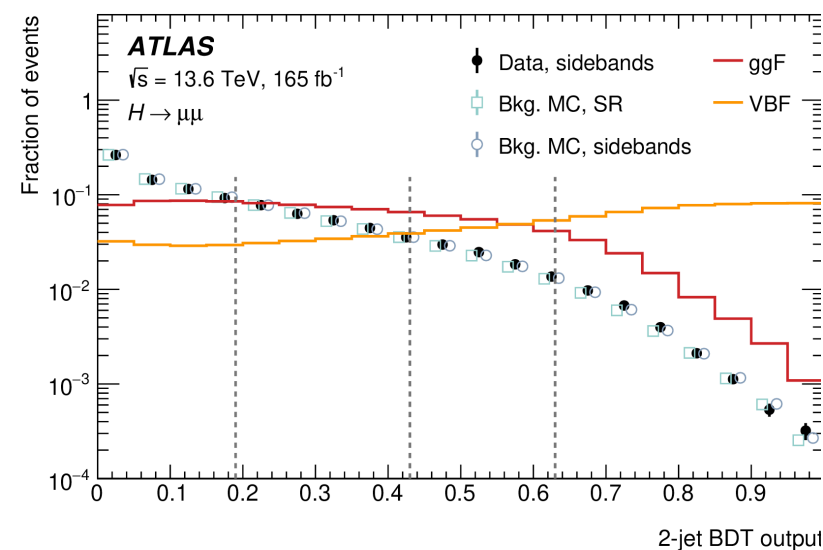
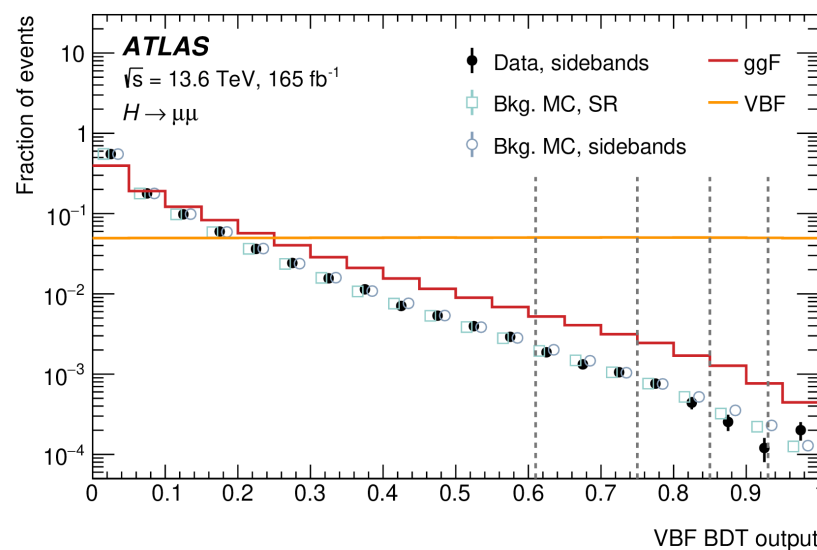
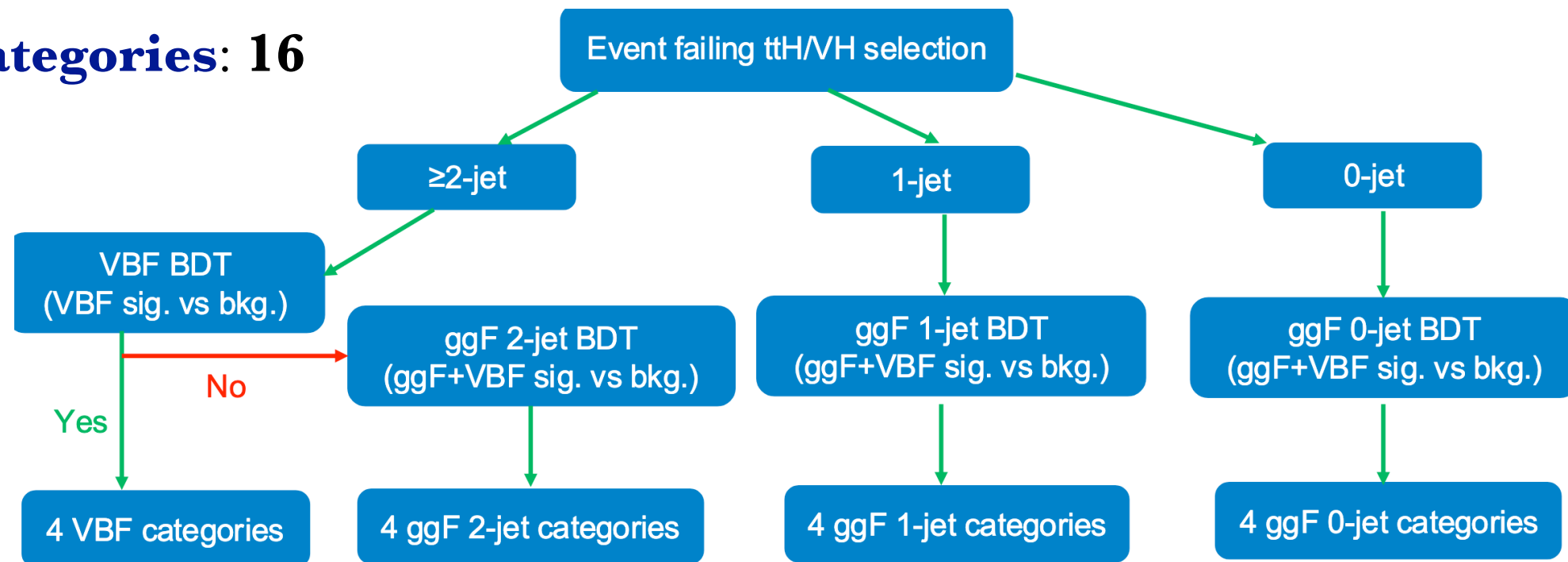
exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b -jets

exactly one additional e or μ with $p_T > 15$ GeV, no b -jets

no additional e or μ , no b -jets, $E_T^{\text{miss}} > 120$ GeV

no additional lepton, no b -jets, $E_T^{\text{miss}} < 120$ GeV

ggF/VBF categories: 16 categories

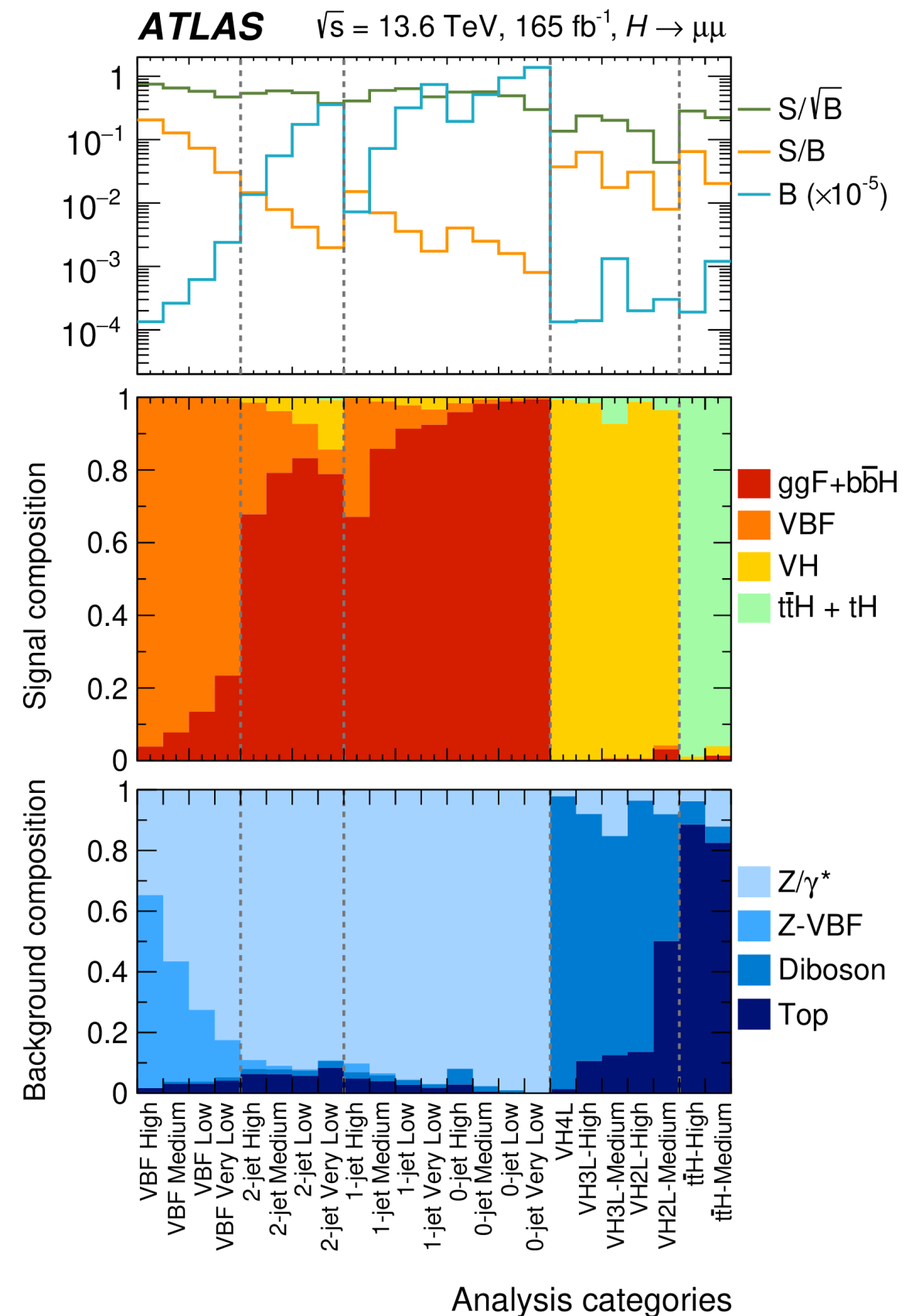


Categorisation performance

Most sensitive categories: VBF-High, VBF-Medium

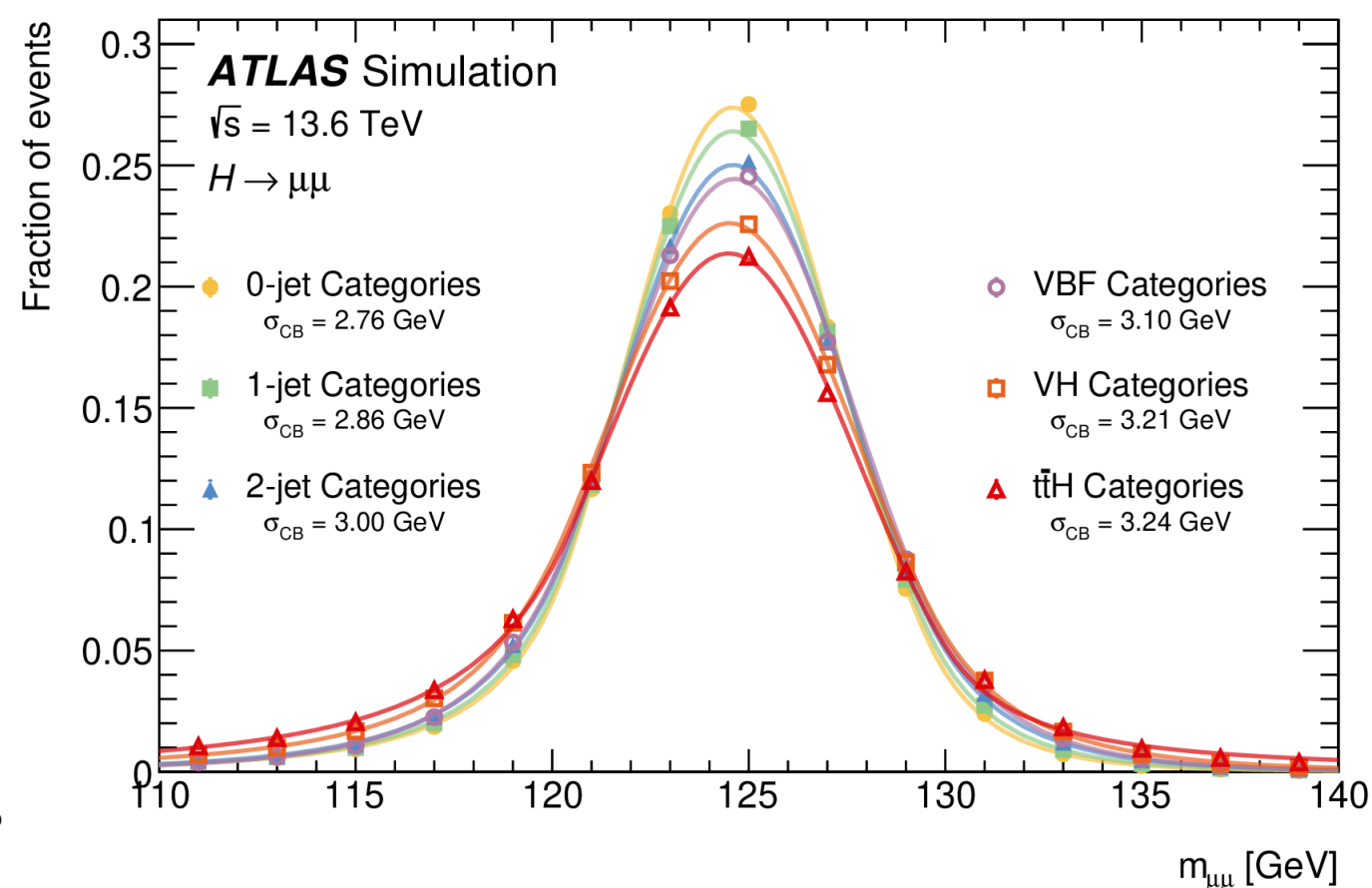
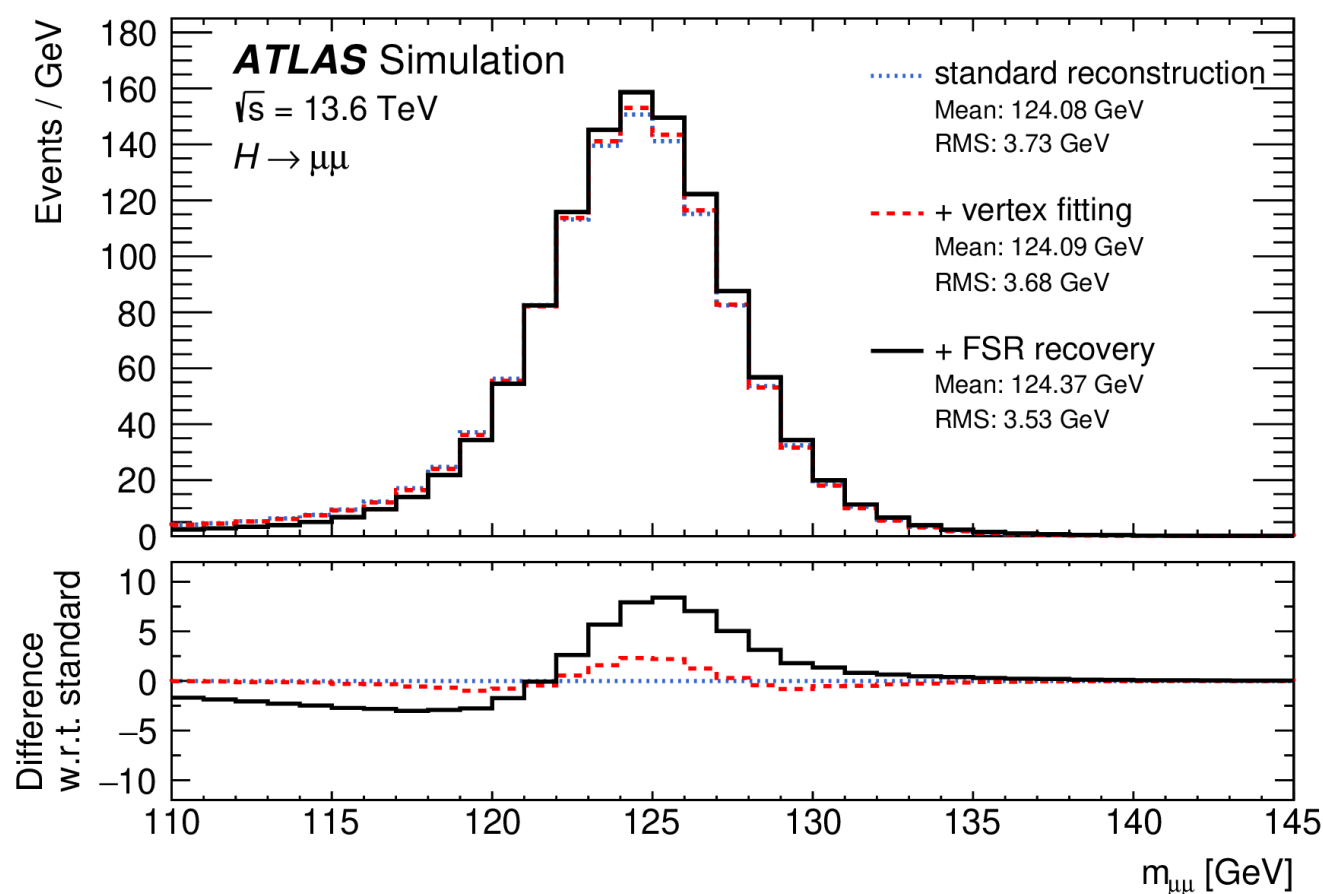
Signal and background composition in 23 analysis categories

Category	Data	S	B	$S/\sqrt{B}$	S/B [%]
$t\bar{t}H$ -High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$ -Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very Low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1 399	31 ± 12	$1 367 \pm 25$	0.84	2.3
2-jet Medium	5 657	69 ± 26	$5 560 \pm 50$	0.92	1.2
2-jet Low	17 684	110 ± 40	$17 300 \pm 70$	0.87	0.7
2-jet Very Low	35 147	110 ± 40	$35 160 \pm 140$	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7 166	80 ± 30	$7 140 \pm 70$	0.95	1.1
1-jet Low	31 761	180 ± 70	$31 510 \pm 120$	1.00	0.6
1-jet Very Low	73 578	200 ± 80	$73 330 \pm 200$	0.75	0.3
0-jet High	19 445	120 ± 50	$19 260 \pm 90$	0.89	0.6
0-jet Medium	50 742	200 ± 80	$50 830 \pm 190$	0.90	0.4
0-jet Low	94 032	240 ± 90	$93 770 \pm 210$	0.78	0.3
0-jet Very Low	136 762	170 ± 60	$136 510 \pm 290$	0.47	0.1



Signal modelling

- Signal shape dominated by **detector resolution**
- Modelling signal distribution with **double-sided Crystal Ball (CB)** as analytic parameterisation for the signal.
- Gaussian core (model signal peak) + power-law curves (model outer tails)
- Resolution ranging between 2.8 - 3.3 GeV
- **Fitting decay vertex of dimuon system $\rightarrow$ 2% improvement** on resolution
- **FSR recovery (5% of total events) $\rightarrow$ 4% improvement** on resolution



Background modelling

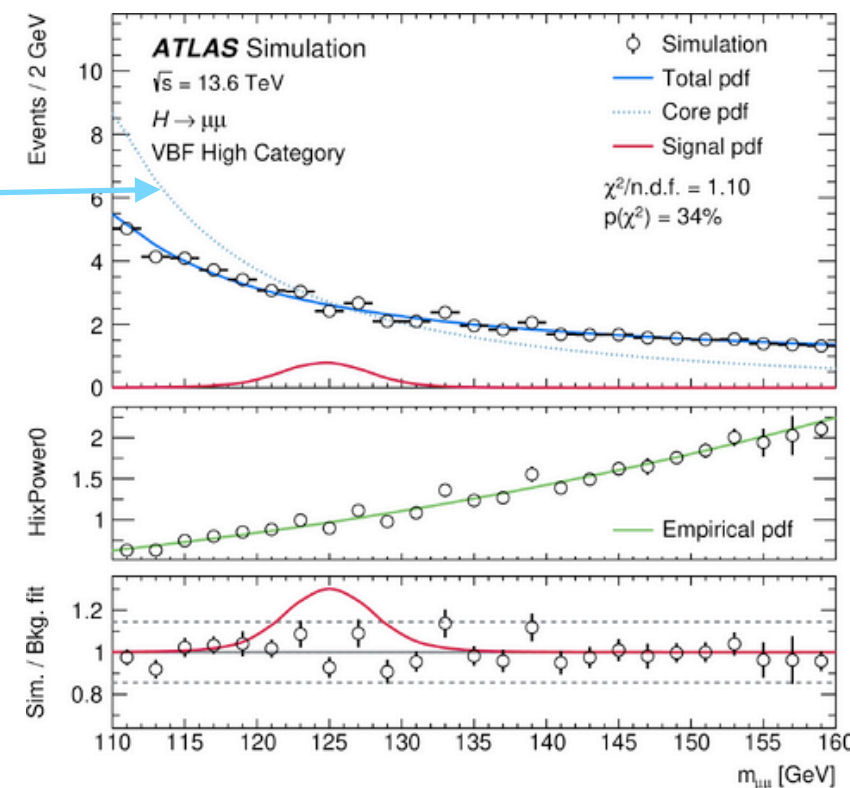
- Very small signal-to-background ratio ($\sim 0.2\%$ in the region $m_{\mu\mu} = 120\text{--}130\text{ GeV}$ in an inclusive selection): an accurate determination of the background is of **paramount importance**.
- Mass range used for the fit ($m_{\mu\mu} = 110\text{--}160\text{ GeV}$) optimised to obtain the best signal sensitivity taking into account the statistical and systematic uncertainties

Background modelling: Core function $\times$ empirical function

$$F(m_{\mu\mu}, a_1)^{cat} = \text{Core}(m_{\mu\mu}) \times \text{Empirical}(m_{\mu\mu}, a_i)^{cat}$$

- Core function:
 - same LO DY line-shape for all categories
 - fully rigid (no extra degrees of freedom)
 - Calculated with parton luminosity, new $c\bar{c}$ and $b\bar{b}$ contribution in Run-3
 - more accurate treatment for experimental dimuon mass-resolution effects
- (Smeared with a detector resolution from FullSim samples)

$$DY_{LS}(m_{\mu\mu}) = \sum_q \mathcal{L}_{q\bar{q}} \cdot \sigma_{q\bar{q}} \cdot m_{\mu\mu}, \quad q = u, s, d, c, b$$



Background modelling

Background modelling: Core function $\times$ empirical function

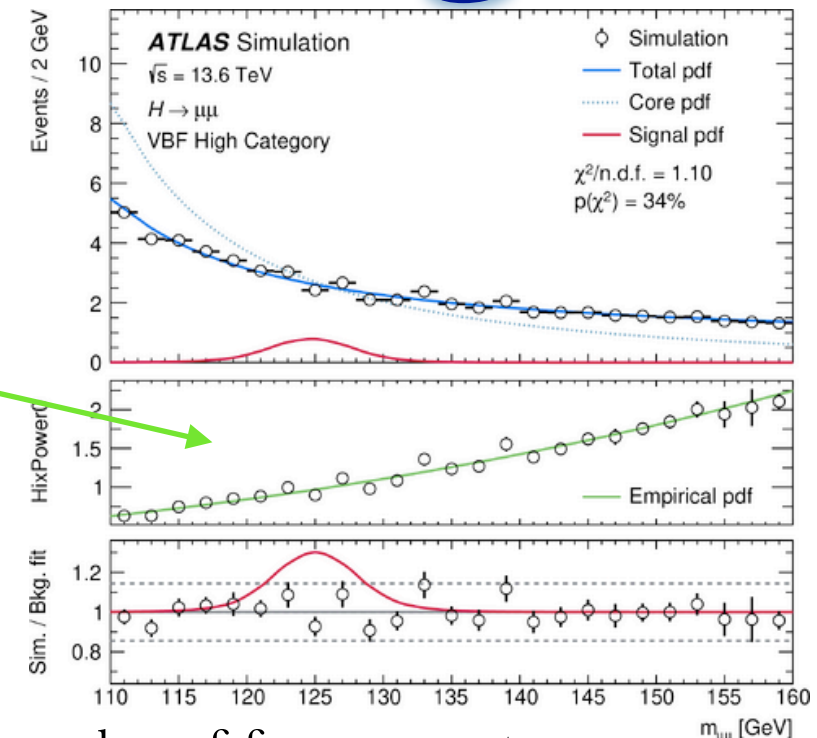
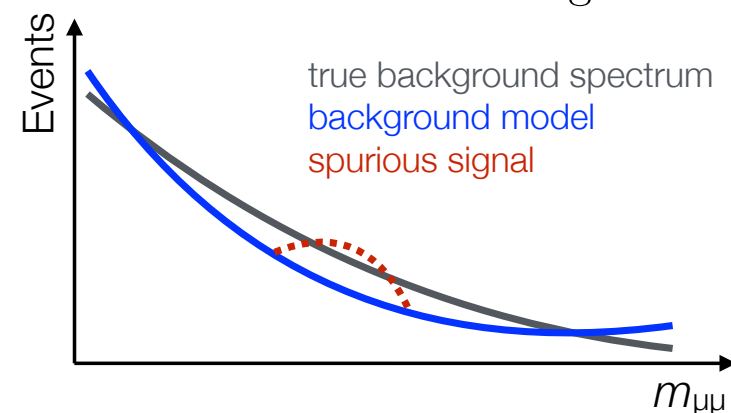
$$F(m_{\mu\mu}, a_1)^{cat} = \text{Core}(m_{\mu\mu}) \times \text{Empirical}(m_{\mu\mu}, a_i)^{cat}$$

- Empirical function: correct for distortions of the mass shape due to the event selection and categorisation, higher-order theory corrections and other smaller background contributions.
- Using two “families” of functions: *PowerN* (N+1 parameters) and *EpolyN* (N parameters)

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0+a_1m_{\mu\mu}+a_2m_{\mu\mu}^2+\dots+a_Nm_{\mu\mu}^N)}$
EpolyN	$\exp(a_1m_{\mu\mu} + a_2m_{\mu\mu}^2 + \dots + a_Nm_{\mu\mu}^N)$

Category	Empirical Function	max(SS/ δ S) [%]	max(SS/ S_{SM}) [%]
$t\bar{t}H$ -High	Power0	31.2	120
$t\bar{t}H$ -Medium	Epoly2	13.7	80
VH4L	Power0	-2.01	-30.7
VH3L-High	Epoly2	24.7	156
VH3L-Medium	Epoly4	-25.7	203
VH2L-High	Epoly2	26.8	255
VH2L-Medium	Power0	28	685
VBF High	Power0	16.2	28.8
VBF Medium	Power0	-15.3	-30.4
VBF Low	Epoly1	12.1	-23
VBF Very Low	Power0	21.6	51.4
2-jet High	Epoly2	-27.3	-65.8
2-jet Medium	Power1	-13.6	-24.4
2-jet Low	Power0	29.2	49.7
2-jet Very Low	Power1	38.4	120
1-jet High	Power0	29.8	97
1-jet Medium	Epoly3	-31.6	-72.6
1-jet Low	Power1	16.9	27.2
1-jet Very Low	Power1	32.5	95.4
0-jet High	Power0	43.5	86.2
0-jet Medium	Epoly3	-33.7	-86.1
0-jet Low	Power1	13.5	34.8
0-jet Very Low	Epoly3	-6.89	-37.8

- One function per category, with varying number of free parameters
- Keep only functions that can fit data sidebands, full-sim background with $P(\chi^2) > 1\%$
- Determined by spurious signal test
 - S+B fit on B-only template (from FullSim MC)
 - SS less than 20% of the statistical error on the signal
 - Retain only functions with the smallest number of degrees of freedom (+ smallest spurious signal)



Uncertainties

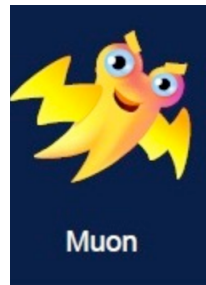
- **Theoretical uncertainties:**
 - BR, QCD scale and PDF unc. on all production modes
 - UE and PS unc. on ggF and VBF
 - HF unc.: 100% on ggF yield in ttH categories
 - **Correlated between Run-2 and Run-3** except for PDF
- **Experimental uncertainties:**
 - Muon momentum scale/resolution, efficiencies
 - Luminosity, PRW, Higgs mass, e/γ , E_{Tmiss}
 - JER, JES, JVT, flavour tagging, and non-closure unc. in fwd region (account for mismodelling of pileup jets)
 - **Uncorrelated between Run-2 and Run-3**

Run3

Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.55	+0.55
Systematic uncertainty	-0.18	+0.24
Spurious signal	-0.14	+0.15
Theory	-0.08	+0.13
Luminosity	-0.04	+0.08
Muon	-0.03	+0.07
Jets, flavor tagging	-0.02	+0.03
Other	-0.04	+0.07
Total	-0.57	+0.60

Run2 + Run3

Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.40	+0.41
Systematic uncertainty	-0.12	+0.15
Spurious signal	-0.09	+0.09
Theory	-0.07	+0.10
Luminosity	-0.02	+0.04
Muon	-0.02	+0.04
Jets, flavor tagging	-0.01	+0.01
Other	-0.02	+0.03
Total	-0.42	+0.43

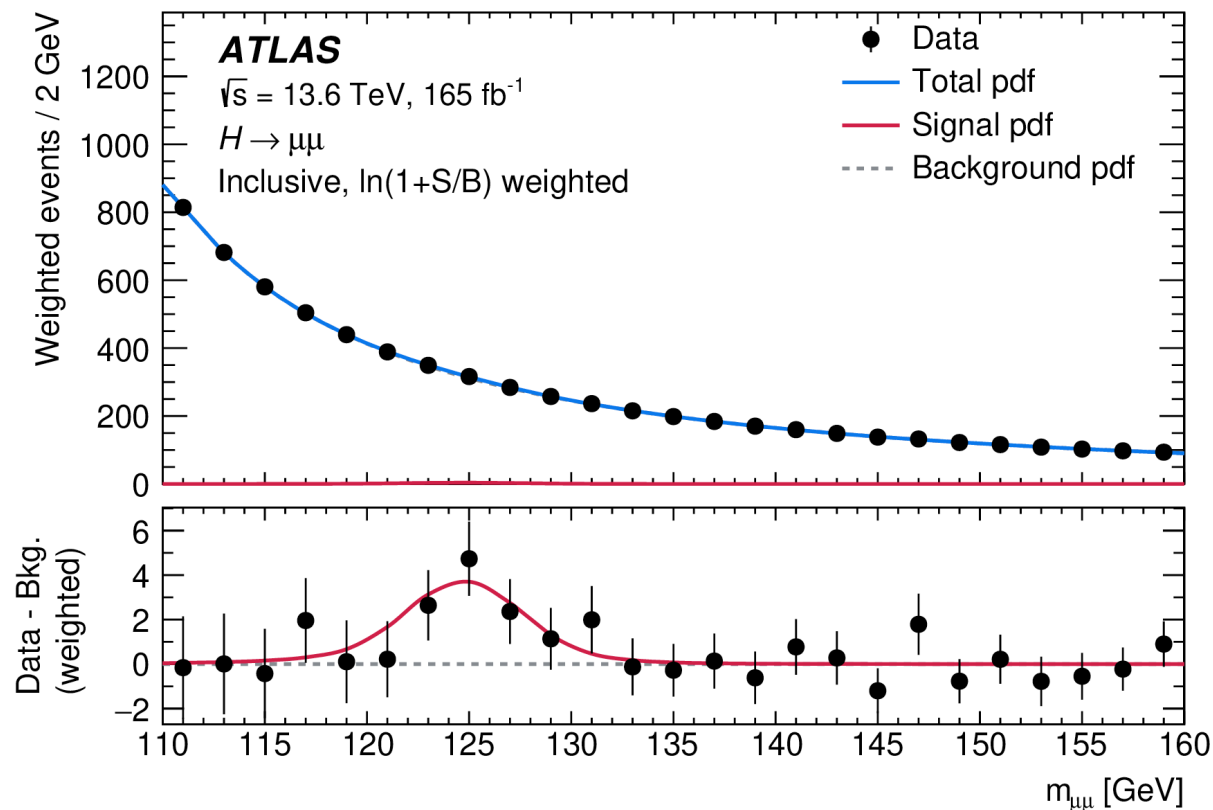


Results

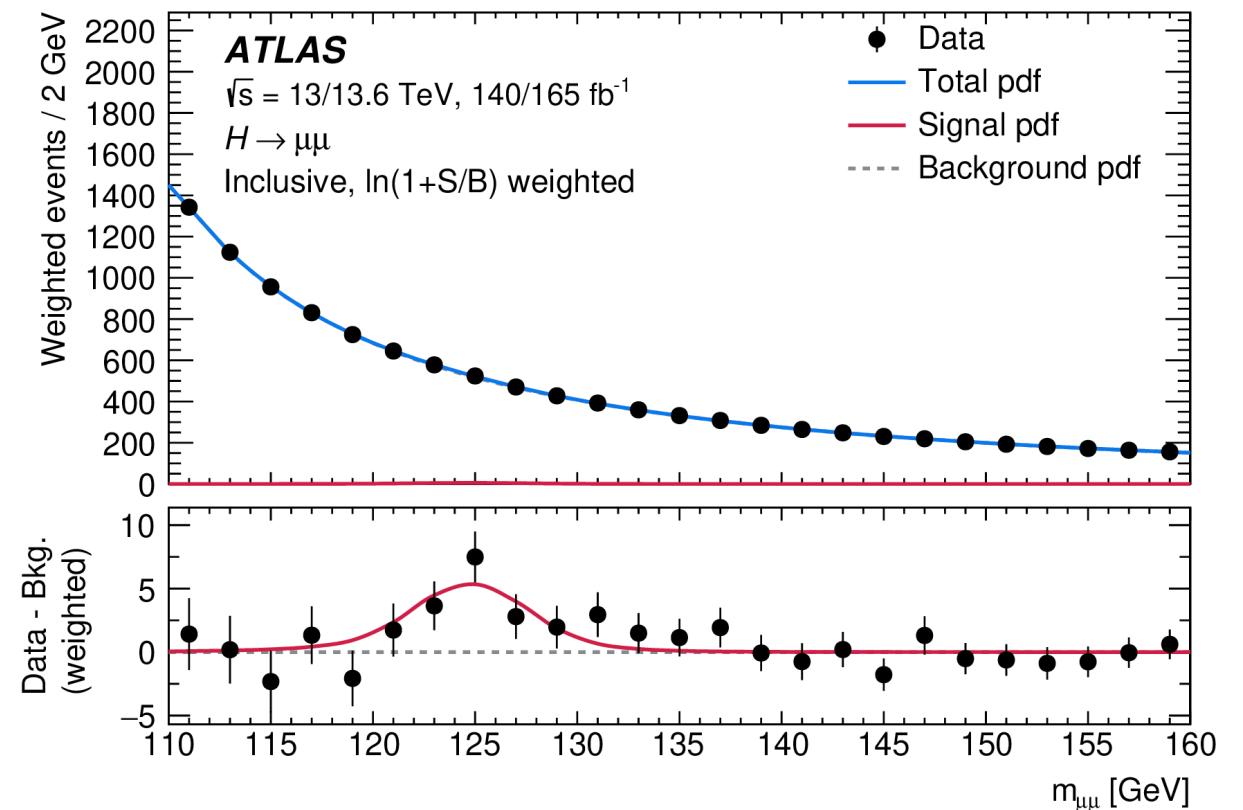
Results from binned Likelihood fit:

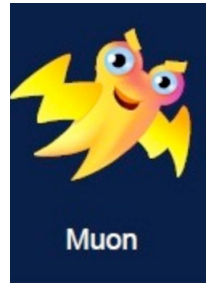
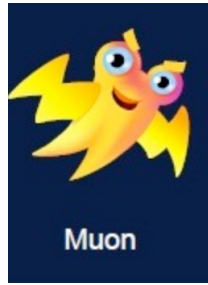
- **Run 3** observed (expected) significance w.r.t bkg.-only hypothesis: 2.8σ (1.8σ)
- **Run 2 + Run 3** observed (expected) significance: 3.4σ (2.5σ) $\rightarrow$ evidence!
- Assuming SM Higgs cross section, $\text{BR}(H \rightarrow \mu\mu) = (3.0 \pm 0.9) \times 10^{-4}$

Run3



Run2 + Run3

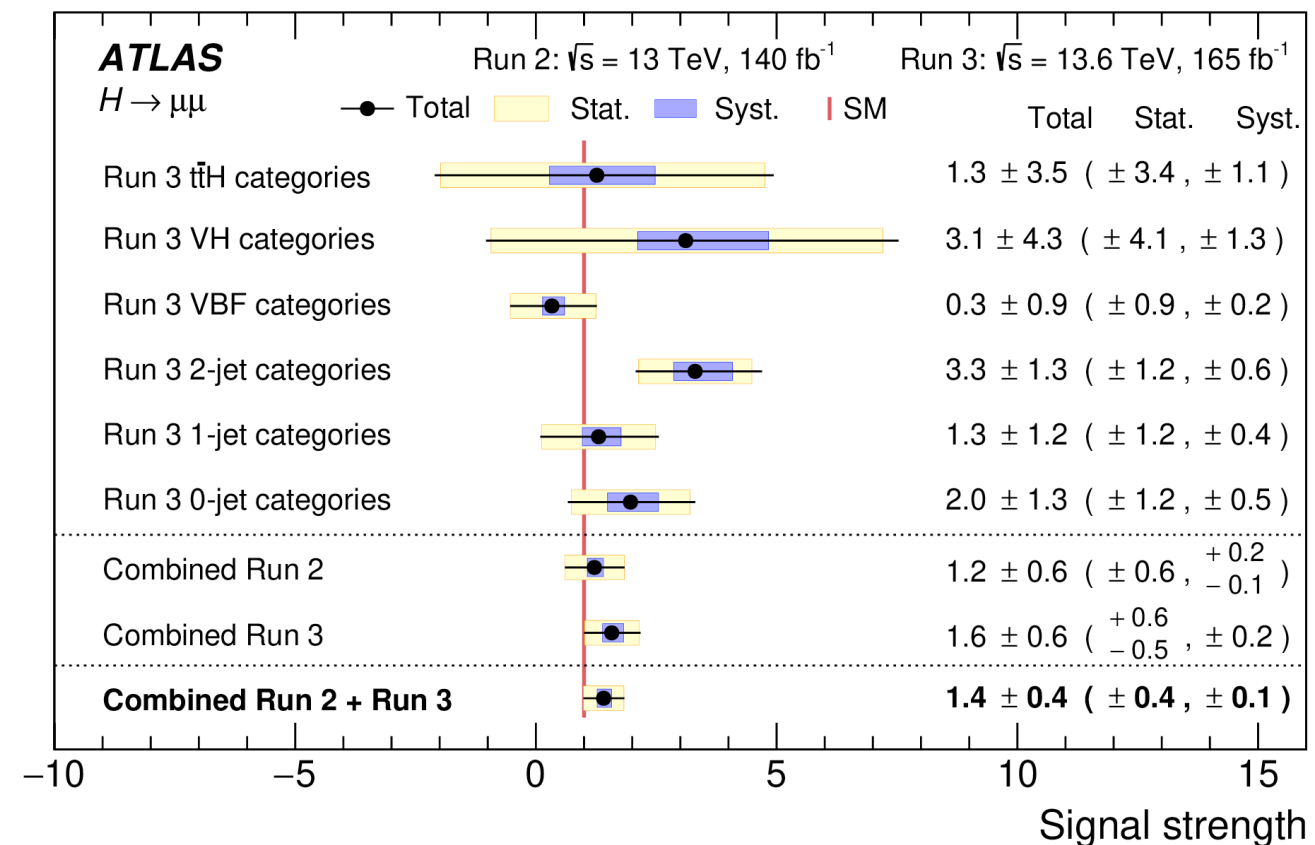
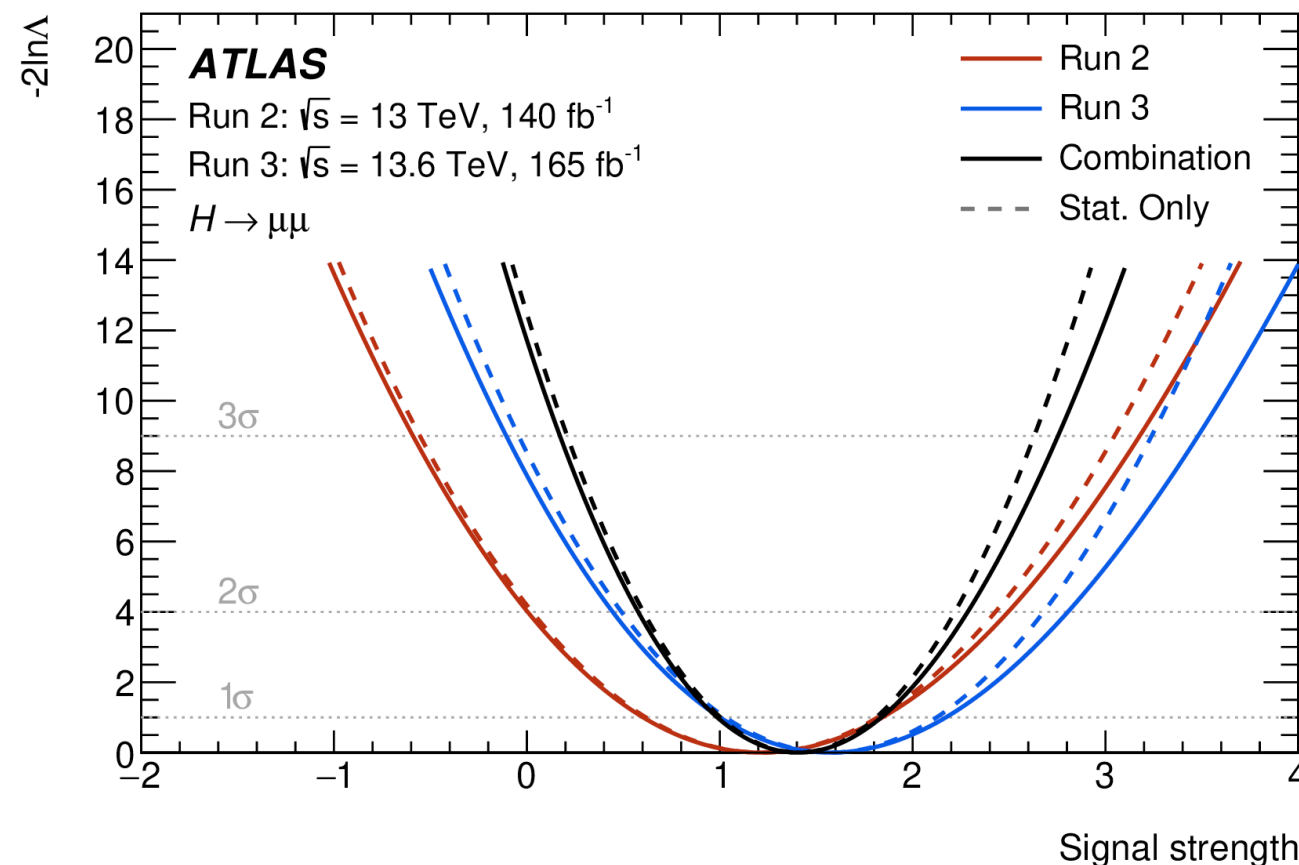




Results

- The measured signal strength is $\mu = 1.6 \pm 0.6$ for **Run 3**
- In the combined Run2+Run3 fit, the signal strength is $\mu = 1.4 \pm 0.4$, and the individual results for Run 2 and Run 3 are compatible within 68%
- Compatibility among 6 groups of categories is 54% in Run 3

Sensitivity improved by 50% relative to Run 2 analysis



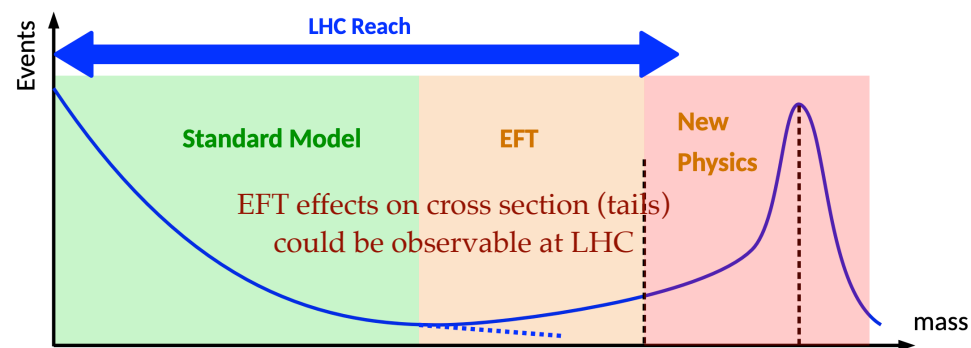


Going beyond - probe of New Physics

The Higgs results can be interpreted in the context of SMEFT:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots,$$

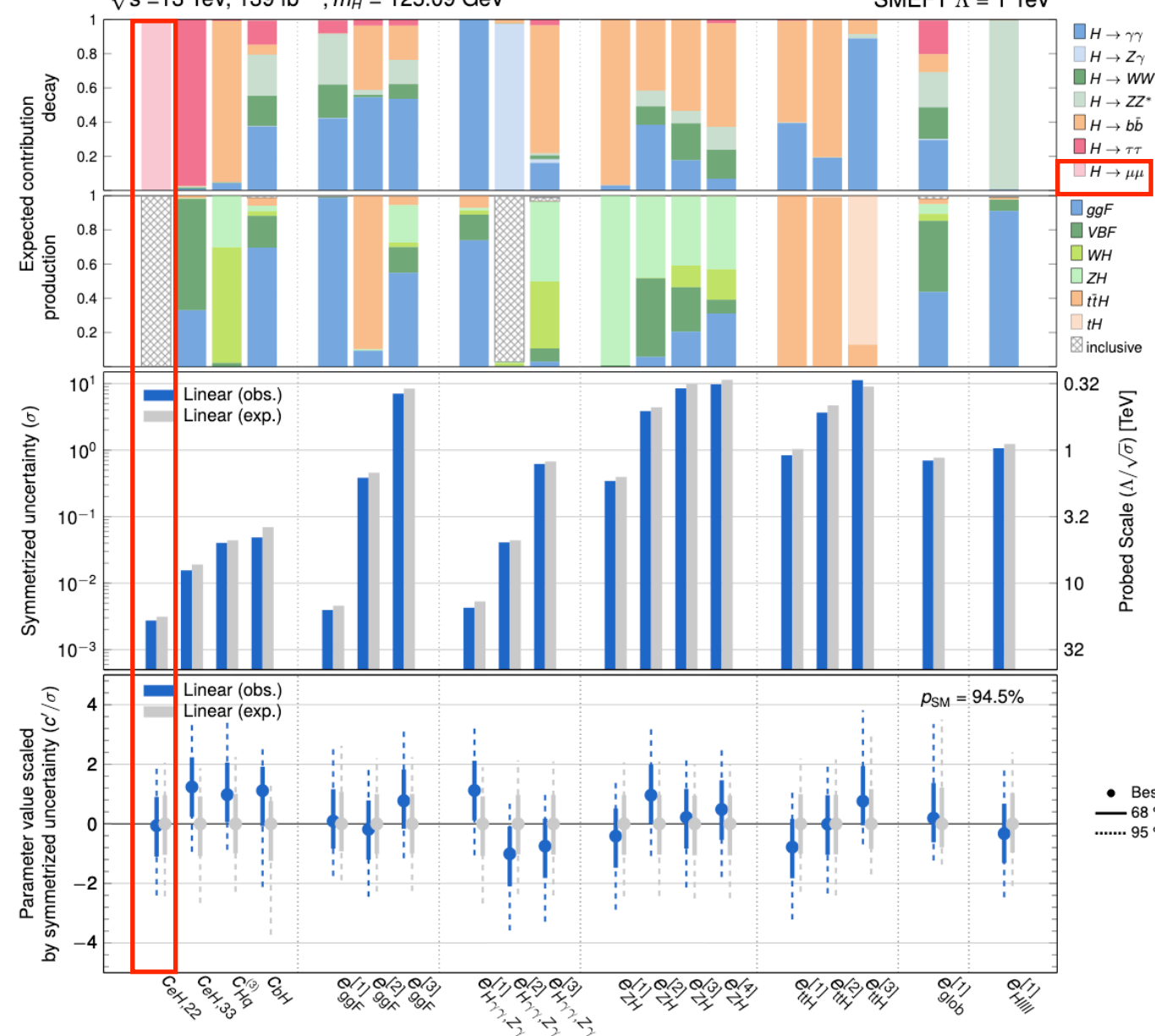
Wilson coefficients



ATLAS

$\sqrt{s}=13$ TeV, 139 fb^{-1} , $m_H = 125.09$ GeV

SMEFT $\Lambda = 1$ TeV

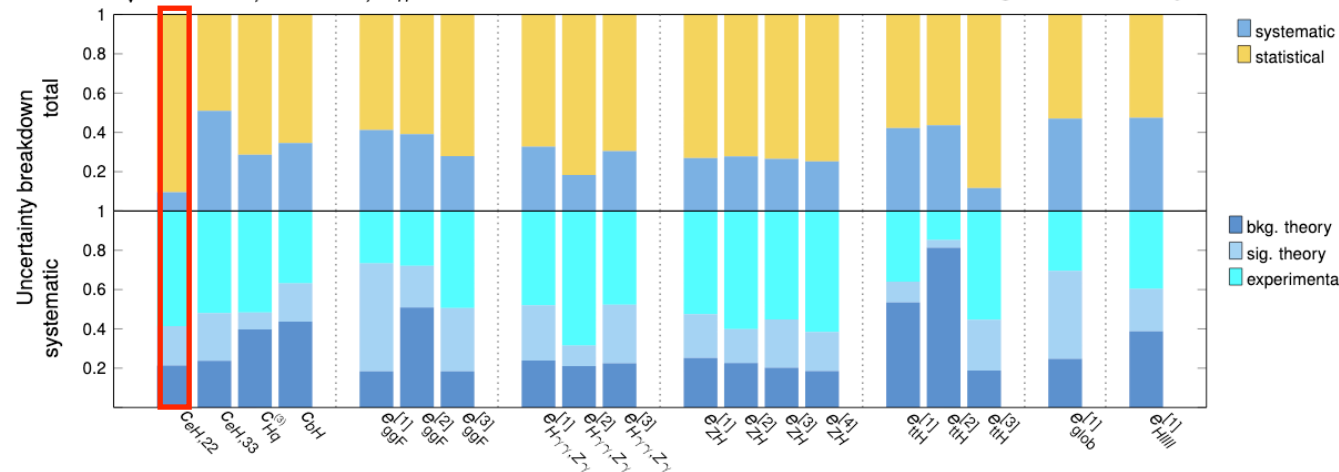


- SM $H \rightarrow \mu\mu$ amplitude is **strongly suppressed** by the Yukawa factor but is at tree level in SMEFT: it is the **most precisely** measured coefficient, despite being constrained only by the very low-yield $H \rightarrow \mu\mu$ channel.
- The uncertainties in the $c_{eH,22}$ coefficient, are almost completely dominated by the **statistical** component.

ATLAS

$\sqrt{s}=13$ TeV, 139 fb^{-1} , $m_H = 125.09$ GeV

SMEFT $\Lambda = 1$ TeV



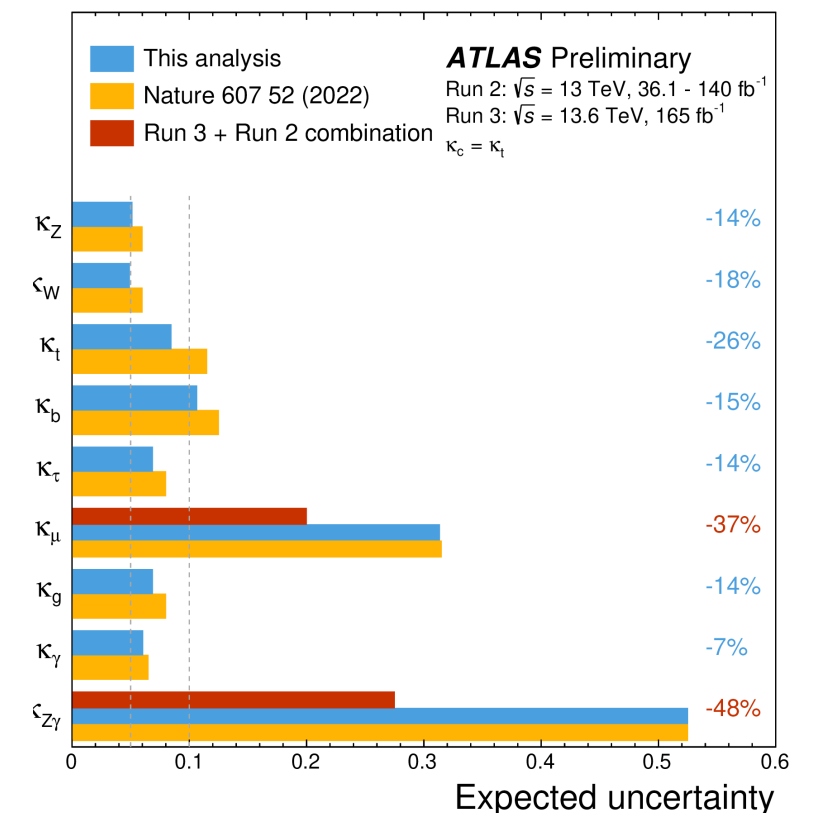
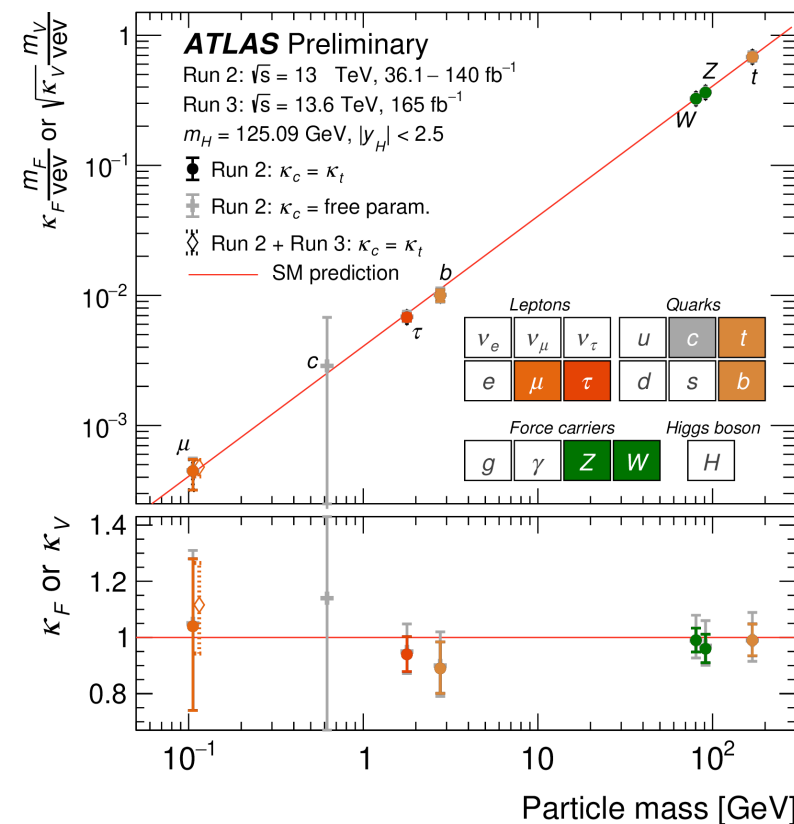
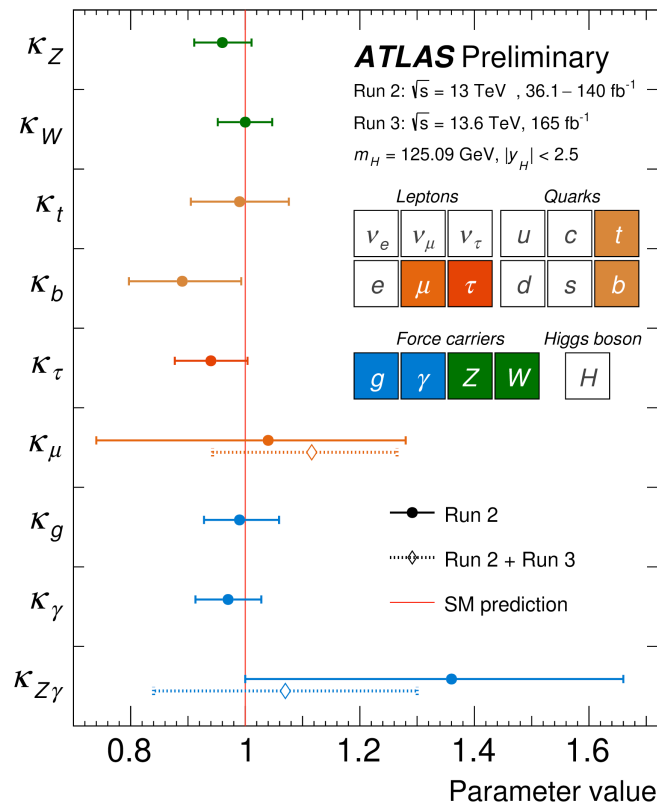


Evolution of Higgs couplings including Run3

ATLAS-CONF-2025-006

- **Run2 Legacy combination + new partial Run3** analyses are combined together
- Adding $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$ Run 3 results, coupling modifiers are improved by $\sim 37\%$ (**48%**) for $H \rightarrow \mu\mu$ ($H \rightarrow Z\gamma$)

Analysis	Prod. modes	$\mathcal{L}$ (fb $^{-1}$)	Improvements relative to Nature
$H \rightarrow ZZ^* \rightarrow 4\ell$	All	140	-
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	ggF,VBF	140	Reanalysis
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	VH	140	Full Run 2
$H \rightarrow \gamma\gamma$	All	140	-
$H \rightarrow Z\gamma$	All	140	-
$H \rightarrow \tau\tau$	All	140	Reanalysis
$H \rightarrow \tau\tau$	VH	140	New analysis
$H \rightarrow \mu\mu$	All	140	-
$H \rightarrow bb$	VBF	126	-
$H \rightarrow bb, cc$	VH	140	Reanalysis
$H \rightarrow \text{multileptons}$	ttH	36.1	-
$H \rightarrow bb$	ttH	140	Reanalysis



What's Next?

HL-LHC projections

ATL-PHYS-PUB-2025-014

Same analysis strategy employed in the full Run 2 measurements.

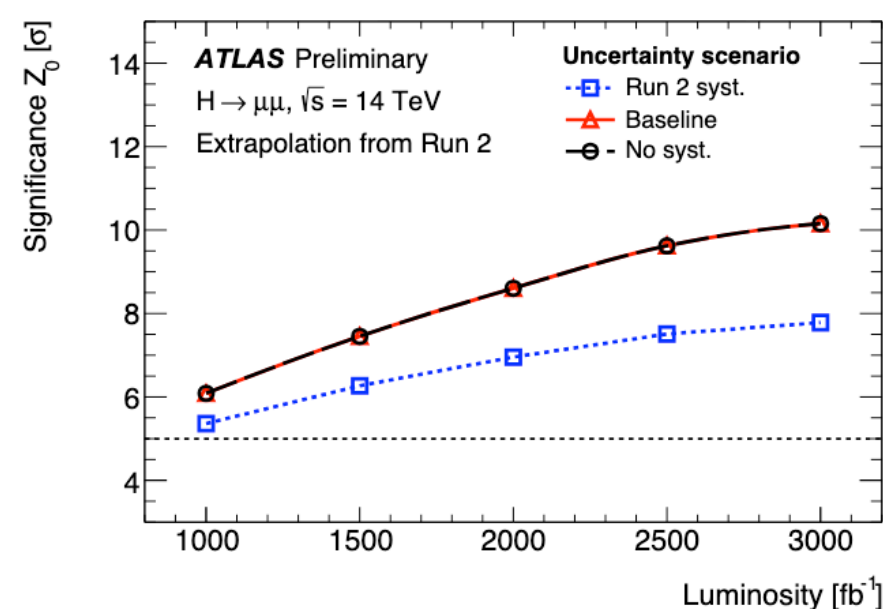
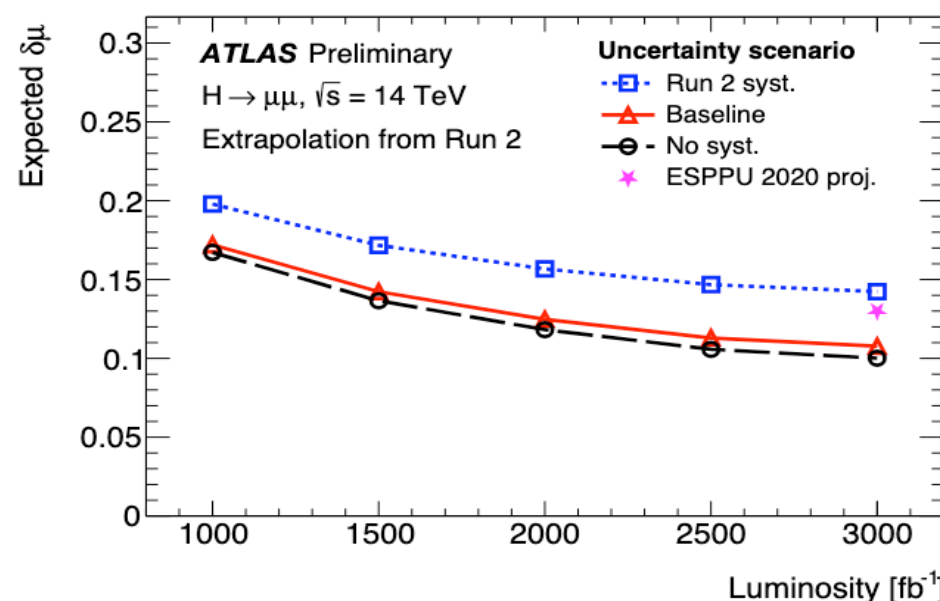
The resolution of the Higgs boson peak is reduced by 30% in VBF and 0-jet categories, and 15% in other categories to account for **expected improvements in the muon momentum resolution** brought by the ITk.

Three scenarios are considered:

- **Run 2 systematic:** conservative scenario, all systematic uncertainties are of the same size as in Run 2 analyses

- **Baseline:** reasonable reduction of systematic uncertainty (assumes no spurious signal and MC-stat uncertainty), theory uncertainties are halved.
- **No systematics:** optimistic scenario with extremely accurate theoretical calculation and detector calibration -> negligible systematics.

In all scenarios considered the signal would be observed with **significance greater than five standard deviation**



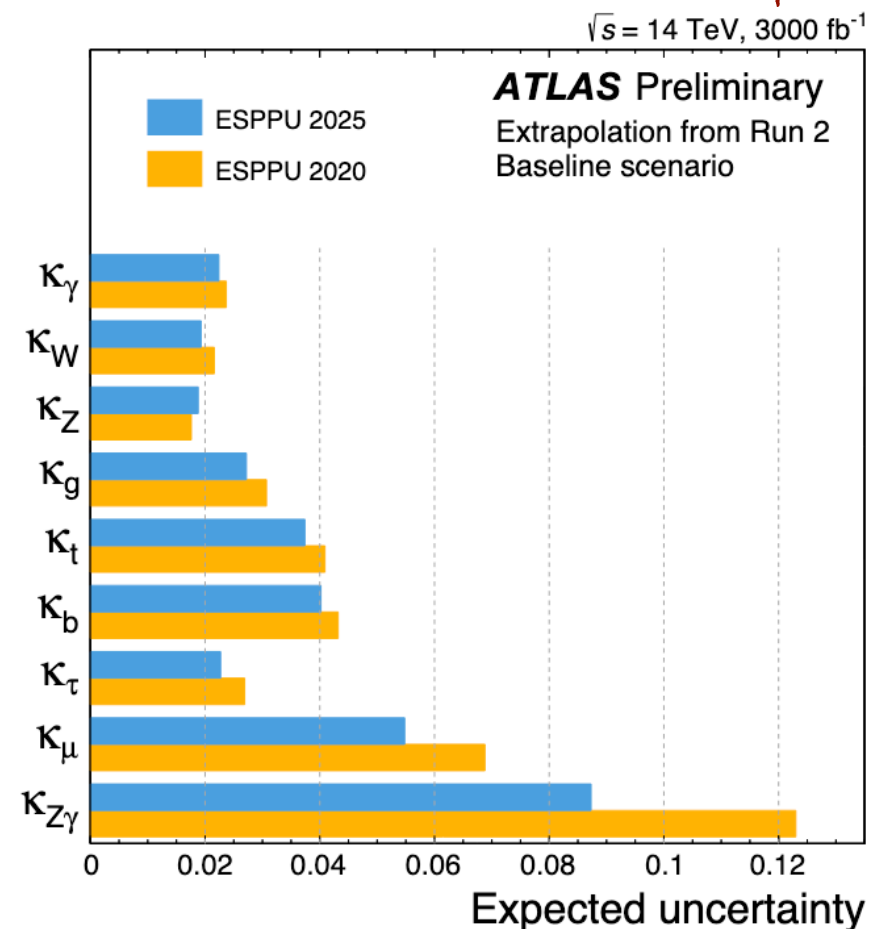
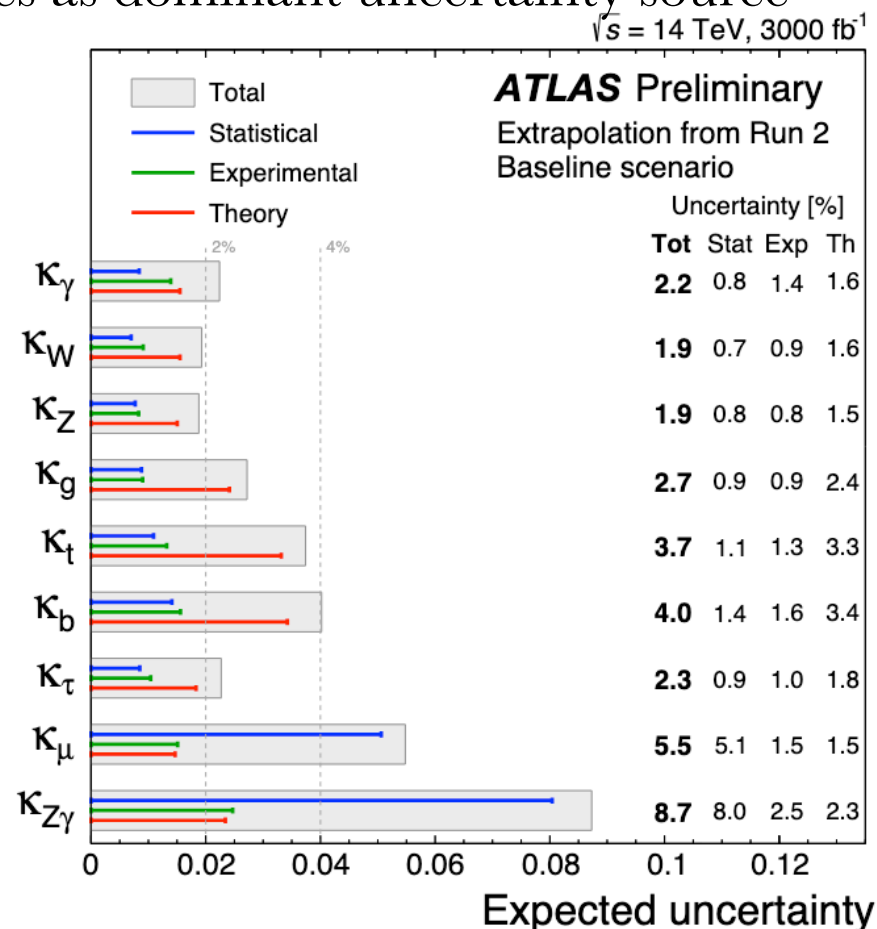
What's Next?

HL-LHC projections - combination

- Updated projections combined with previous projections to simultaneously extract Higgs boson coupling modifiers
- With respect to the previous extrapolations (ESPPU 2020), the projected uncertainties in the coupling strength scale factors are **reduced by 7%–29%** depending on the coupling, with the exception of κ_Z .
- **Precision of 2% ~ 4%** for most cases
- Theory uncertainties as dominant uncertainty source

Production	Decay	$\mathcal{L}$ of projected measurement [fb^{-1}]	
		this study	previous study [4]
ggF, VBF, WH , ZH , $t\bar{t}H$, tH	$H \rightarrow \gamma\gamma$	140	80
ggF, VBF	$H \rightarrow Z\gamma$	140	36
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow \mu\mu$	140	80
WH , ZH	$H \rightarrow b\bar{b}$	140	80
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow \tau\tau$	140	36
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow ZZ$	80	80
ggF, VBF	$H \rightarrow WW$	36	36
$t\bar{t}H + tH$	$H \rightarrow b\bar{b}$	36	36
$t\bar{t}H + tH$	$H \rightarrow WW, ZZ, \tau\tau$	36	36

ATL-PHYS-PUB-2025-014



Conclusion

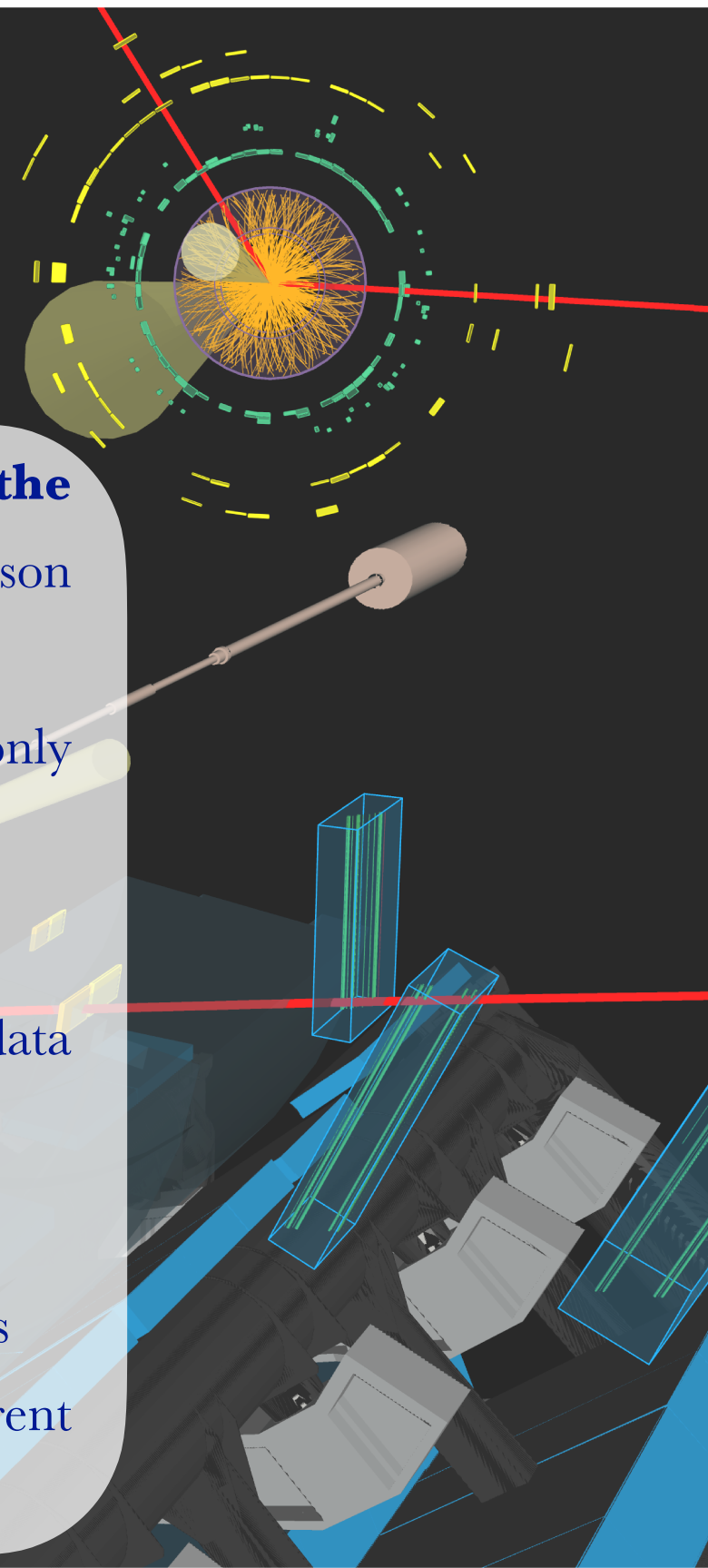


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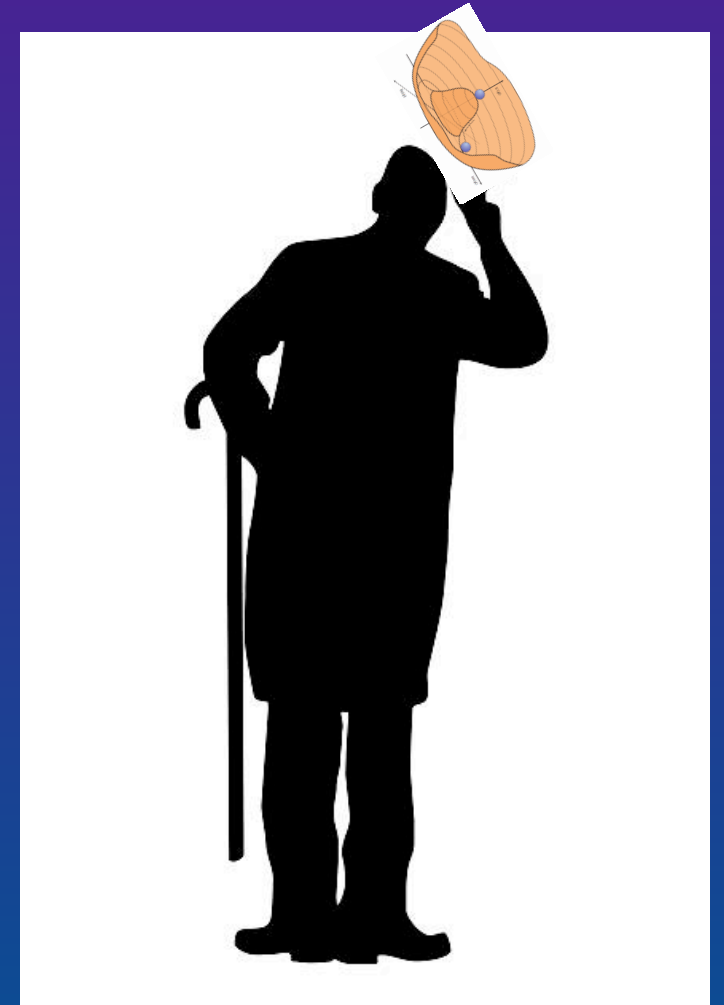
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- The ATLAS experiment sees **evidence for the rare decay of the Higgs boson into two muons**, and hence for the Higgs-boson Yukawa coupling to **second-generation fermions**.
- **Observed (expected) significance** over the background-only hypothesis of **3.4 (2.5) σ**
- Results obtained by analysing **165 fb⁻¹** of *pp* data collected at $\sqrt{s} = 13.6$ TeV and combining with the results from **140 fb⁻¹** of data collected at $\sqrt{s} = 13$ TeV.
- These results are **compatible with the SM** expectation.
- **Going beyond**, $H \rightarrow \mu\mu$ might also serve as a probe for New Physics
- **Observation** by ATLAS expected by HL-LHC with different systematic scenarios.



Thanks for your
attention



Muon reconstruction performance

- ◆ Set of **identification working points** are defined for different needs, **five Working Points** released for Run3:
 - **loose**, higher efficiency for multilepton analyses;
 - **medium**, best compromise efficiency/purity for most analyses, slightly lower efficiency at low p_T/η , lower fake rate;
 - **Tight**: highest fake rejection
 - **high-pT**: for the MS-dominated regime, ensures best momentum resolution even at very high p_T
 - **Low-pT**: precise identification down to 3.5 GeV

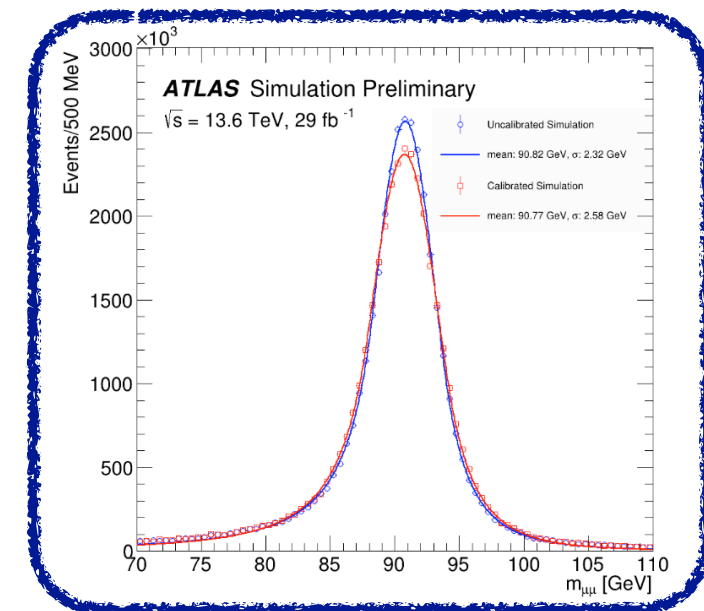
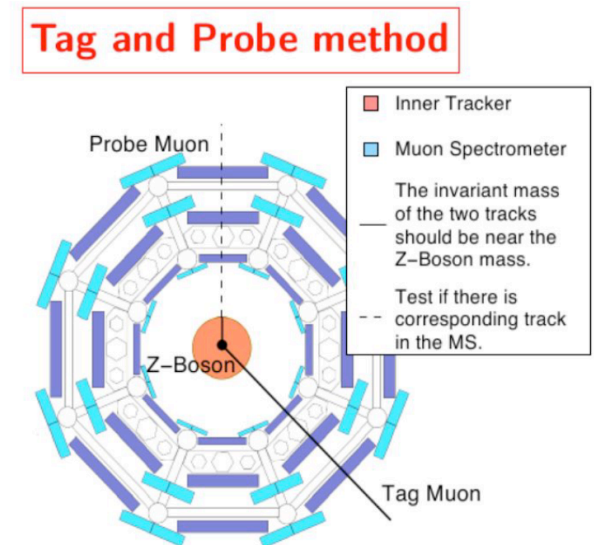
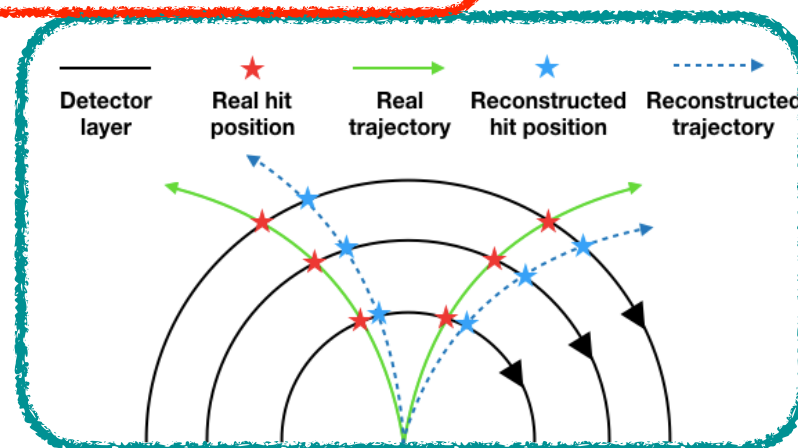
- ◆ Similarly to the identification working points, **Isolation WPs** are defined.

- ◆ **Efficiency calibration** using **Tag and Probe method** to measure the data and mc efficiencies and derive their ratio (Scale Factors SF) using the same algorithm used to derive muon trigger SFs.
 - Measurements in bins of (η, ϕ) depending on WPs
 - In order to measure the efficiencies, high-purity samples of $Z \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow \mu^+\mu^-$ events are selected

$$\epsilon(X) \approx (\epsilon(X|ID \wedge MS) \epsilon(MS|CT) + \epsilon(X \wedge \neg MS|CT)) \epsilon(ID|MS)$$

- ◆ **Momentum calibration:**

- **sagitta bias corrections**
- **scale and resolution corrections** for MC.



Objects + event selection

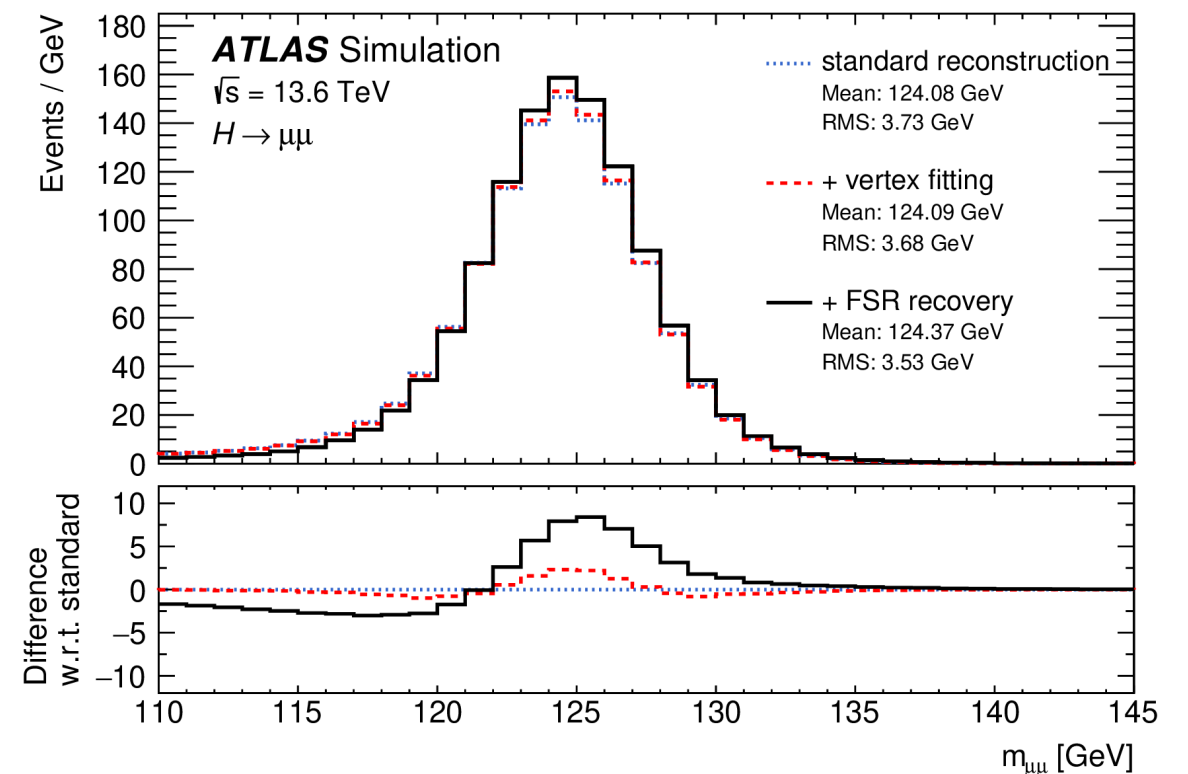
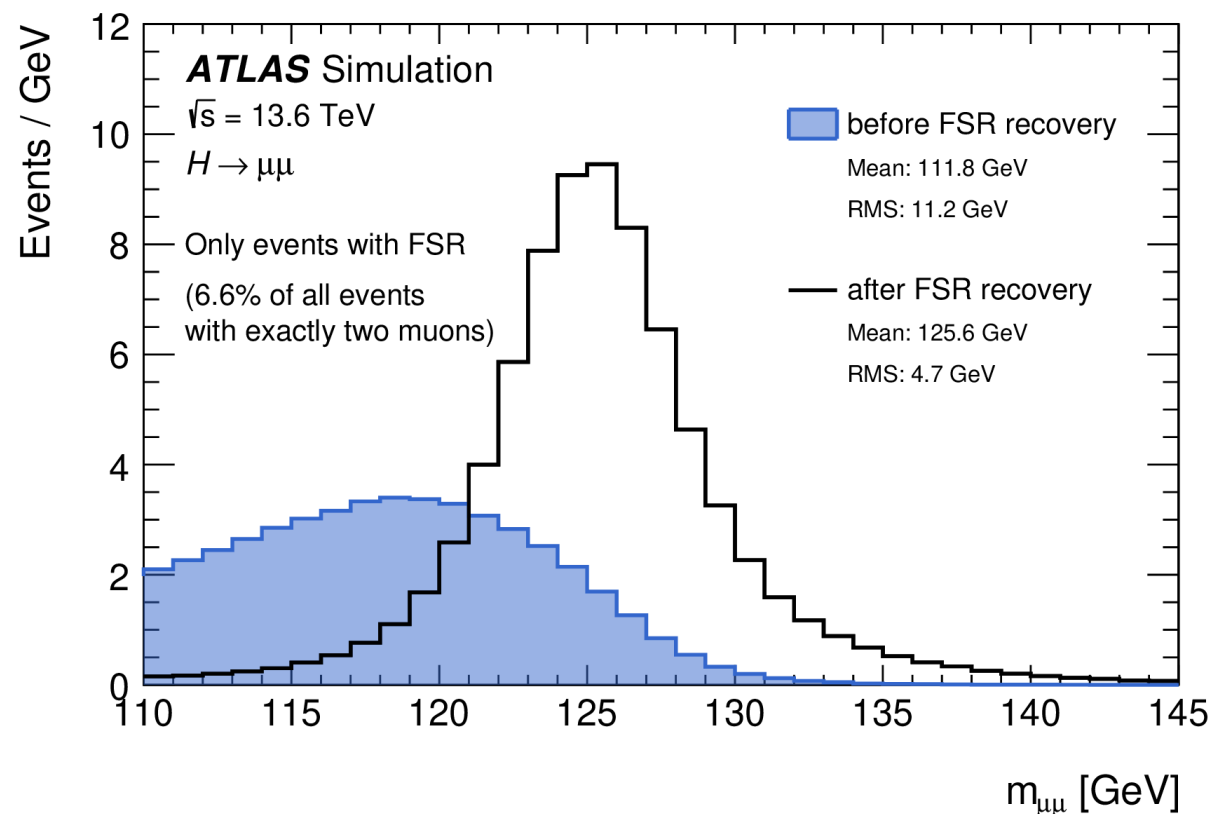
Selection	
Common preselection	Primary vertex
	Two opposite-charge muons Muons: $ \eta < 2.5$, $p_T^{\text{lead}} > 27 \text{ GeV}$, $p_T^{\text{sublead}} > 15 \text{ GeV}$
Fit region	$m_{\mu\mu} = 110 - 160 \text{ GeV}$
Jets	$p_T > 25 \text{ GeV}$ and $ \eta < 2.4$ or with $p_T > 30 \text{ GeV}$ and $2.4 < \eta < 4.5$
b -tagged jets	$p_T > 25 \text{ GeV}$ and $ \eta < 2.4$ or with $p_T > 30 \text{ GeV}$ and $2.4 < \eta < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b -jet
VH 4-lepton category	Exactly two additional e or μ with $p_T > 8 \text{ GeV}$, 5 GeV (μ) / 7 GeV (e), no b -jets
VH 3-lepton categories	Exactly one additional e or μ with $p_T > 15 \text{ GeV}$, no b -jets
VH 2-lepton categories	No additional lepton, no b -jets, $E_T^{\text{miss}} > 120 \text{ GeV}$
VBF and ggF categories	No additional lepton, no b -jets, $E_T^{\text{miss}} < 120 \text{ GeV}$

23 exclusive categories in order of $t\bar{t}H \rightarrow VH \rightarrow \text{VBF} \rightarrow \text{ggF}$

- NN or BDTs to separate signal and background
- 2 $t\bar{t}H$ categories
- 3 ZH categories
- 2 WH categories
- 4 VBF categories and 12 ggF categories

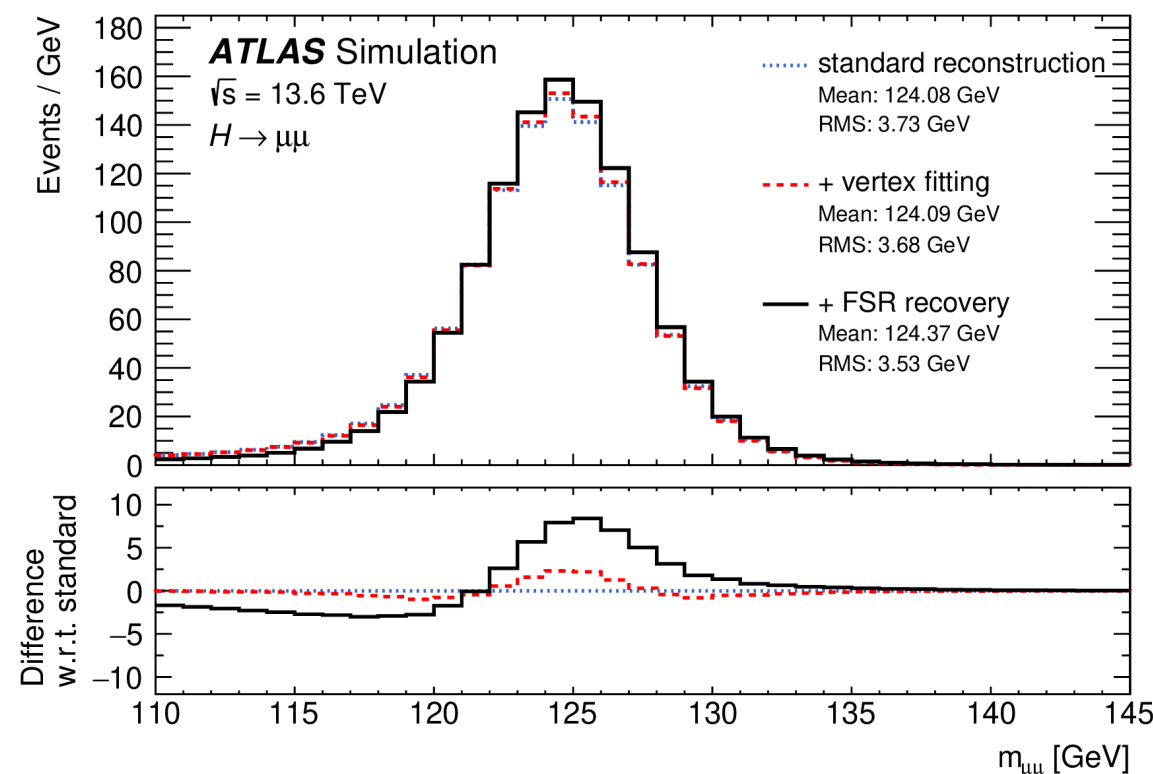
FSR recovery

- Muons from the $H \rightarrow \mu\mu$ decay can lose a fraction of their energy by **QED final-state radiation** (FSR), impacting the $m_{\mu\mu}$ shape and peak position
- Photon candidates are included in the $m_{\mu\mu}$ calculation if they are found in categories requiring **exactly two muons** and meet a minimum-energy requirement dependent on their closeness to the muon.
- Only near FSR selection applied to avoid contamination from $HZ\gamma$
- ggF RMS of mass peak: improve from 3.7 GeV to 3.5 GeV in ggF signal($\sim 5\%$)



Vertex fitting

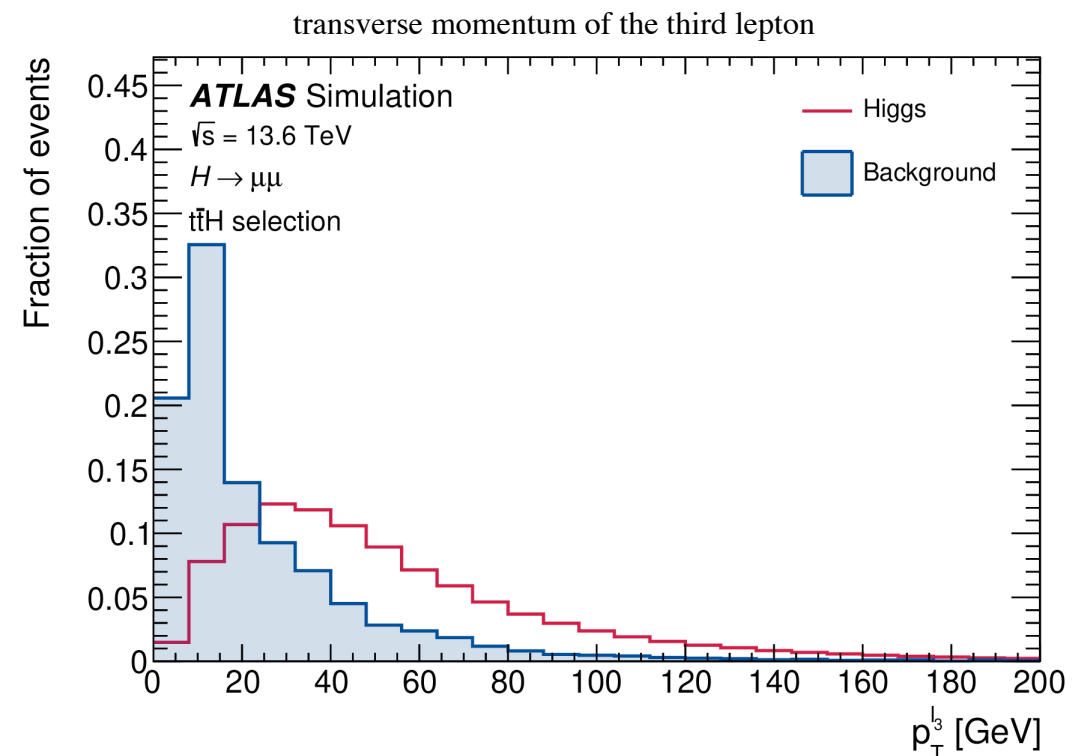
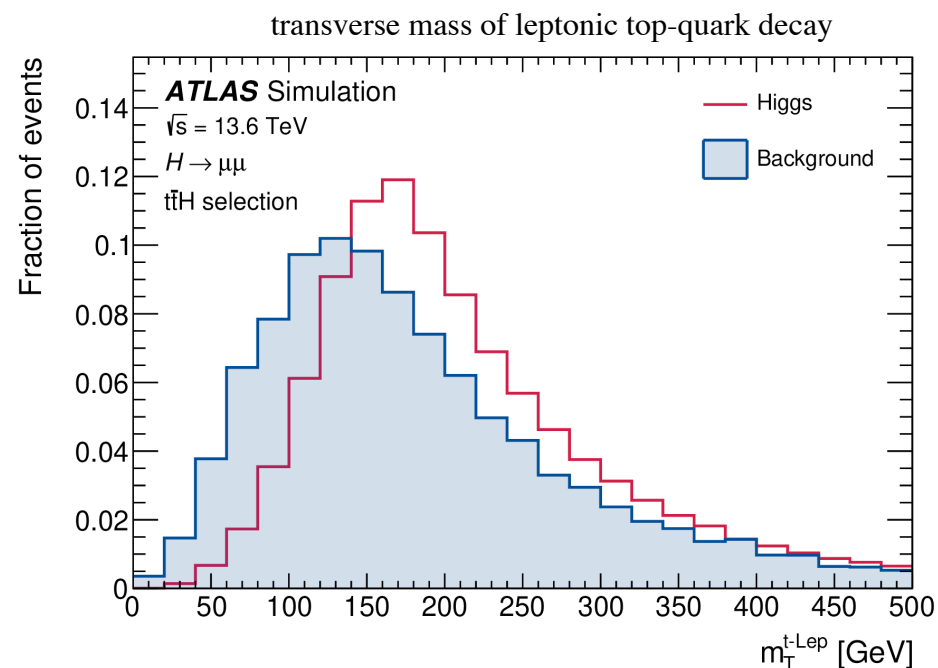
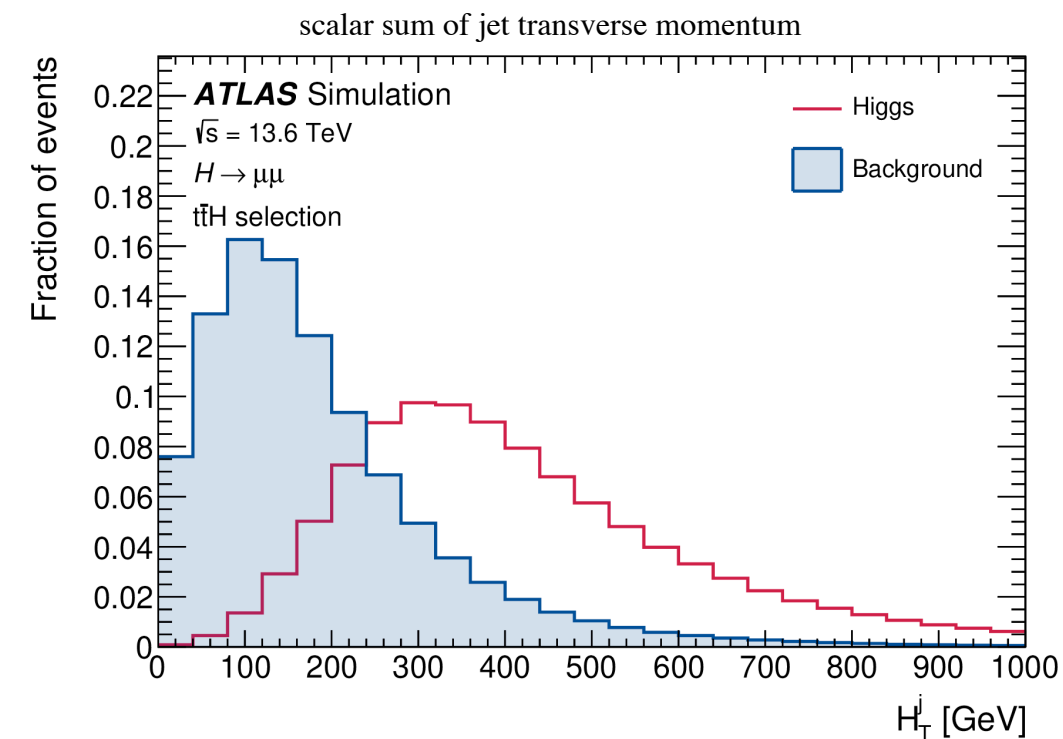
- Fitting the Higgs-boson decay vertex, **a more precise value for $d0$** can be determined, yielding a better estimate of $m_{\mu\mu}$.
- This decay vertex is fitted with a **least-squares method, that minimizes a set of estimators related to the muon tracks (track θ and ϕ , and the charge-to-momentum ratio, q/p) and vertex parameters (x, y, z position)** with respect to the measured values, taking into account their covariances and a constraint to keep the fitted decay vertex within the beamspot envelope.
- This procedure is applied to categories requiring **exactly two muons**, resulting in an improvement of the $m_{\mu\mu}$ resolution of nearly 2%.



ttH categories

Target: both hadronic and leptonic decays

- Selection: At least 1 b-jet at 85% WP
- Higgs candidate: 2 highest- p_T muons with opposite charge
- NN trained with 30 variables to separate sig.vs bkg.
- 2 categories defined based on NN output
- NN-Based Classification New in Run3



Variables used (ttH categories)

Variable	Description
$p_T^{\mu_1}$	Transverse momentum of the leading muon
$p_T^{\mu_2}$	Transverse momentum of the sub-leading muon
η^{μ_1}	Pseudorapidity of the leading muon
η^{μ_2}	Pseudorapidity of the sub-leading muon
ϕ^{μ_1}	Azimuthal angle of the leading muon
ϕ^{μ_2}	Azimuthal angle of the sub-leading muon
N_μ	Number of muons
$\cos \theta^*$	μ^- decay angle in the Collins–Soper frame
$p_T^{j_1}$	Transverse momentum of the leading jet
$p_T^{j_2}$	Transverse momentum of the sub-leading jet
η^{j_1}	Pseudorapidity of the leading jet
η^{j_2}	Pseudorapidity of the sub-leading jet
$N_{\text{Track}}^{j_1}$	Number of tracks in the leading jet with $p_T > 0.5$ GeV
$N_{\text{Track}}^{j_2}$	Number of tracks in the sub-leading jet with $p_T > 0.5$ GeV
m^{jj}	Invariant mass of the dijet system
H_T^j	Scalar sum of jet transverse momentum
$N_{j\text{-central}}$	Number of central ($ \eta < 2.5$) jets
$N_{b\text{-jet}}$	Number of b -jets with 85% working point
E_T^{miss}	Missing transverse energy
N_e	Number of electrons
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$p_T^{\ell_4}$	Transverse momentum of the fourth lepton
m^{sub}	Mass of leading non-Higgs-boson-candidate muon and opposite-sign Higgs-boson-candidate muon
$m^{\ell_3\ell_4}$	Mass of third and fourth leptons
$\Delta\phi(\ell_3, \ell_4)$	Azimuthal angle between the third and fourth leptons
$\Delta\eta(\ell\ell, \ell_3)$	Pseudorapidity separation between the dimuon system and third lepton
$m_T^{\text{t-Lep}}$	Transverse mass of leptonic top-quark decay
$m^{\text{t-Had}}$	Mass of hadronic top-quark decay
$m_T^{W\text{-Lep}}$	Transverse mass of leptonic W -boson decay
$m^{W\text{-Had}}$	Mass of hadronic W -boson decay

VH categories

4-lep and 2-lep ($Z \rightarrow \nu\nu$) channels considered

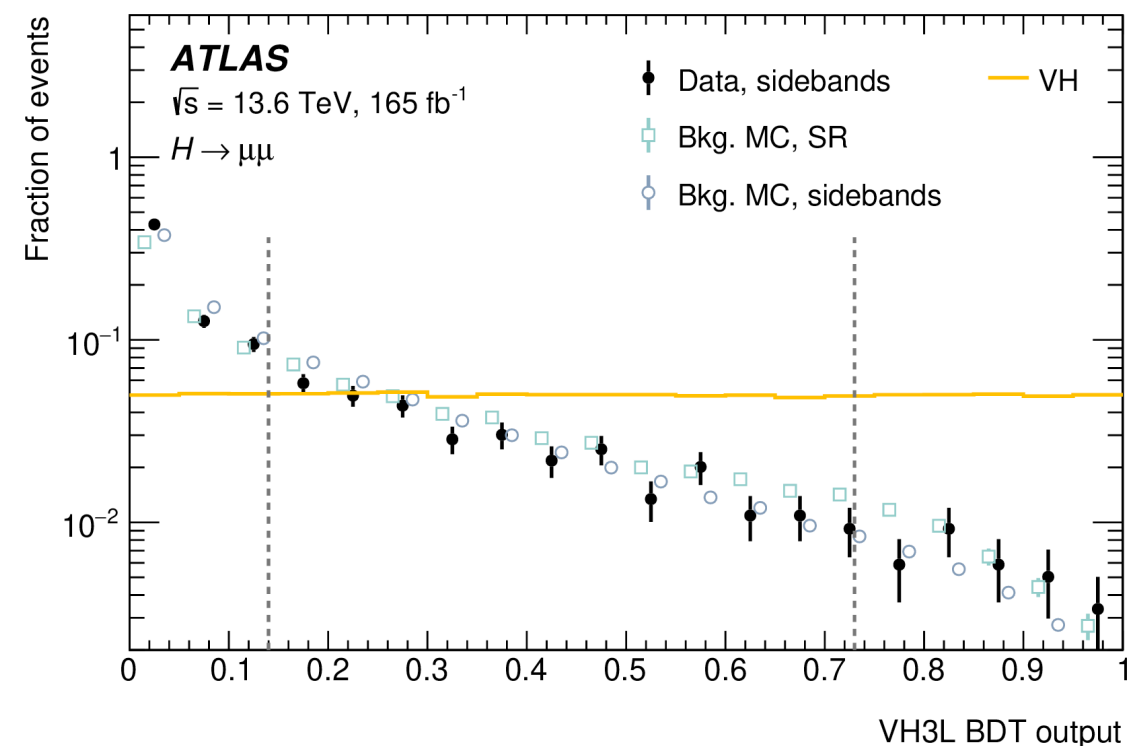
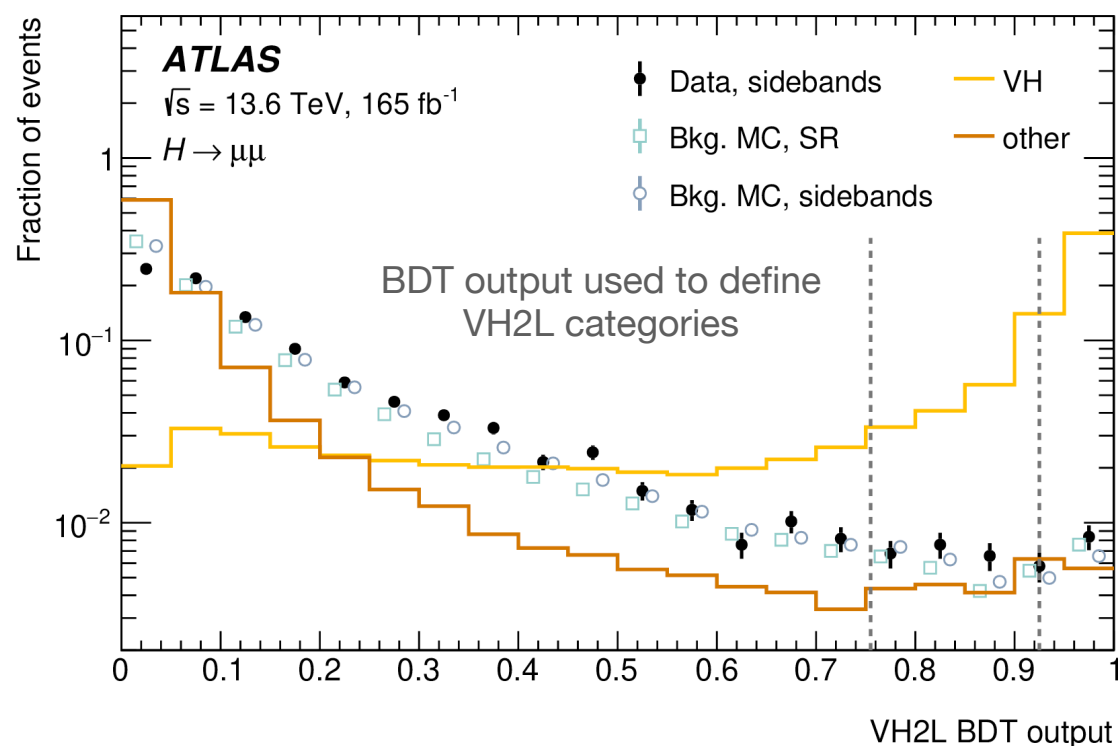
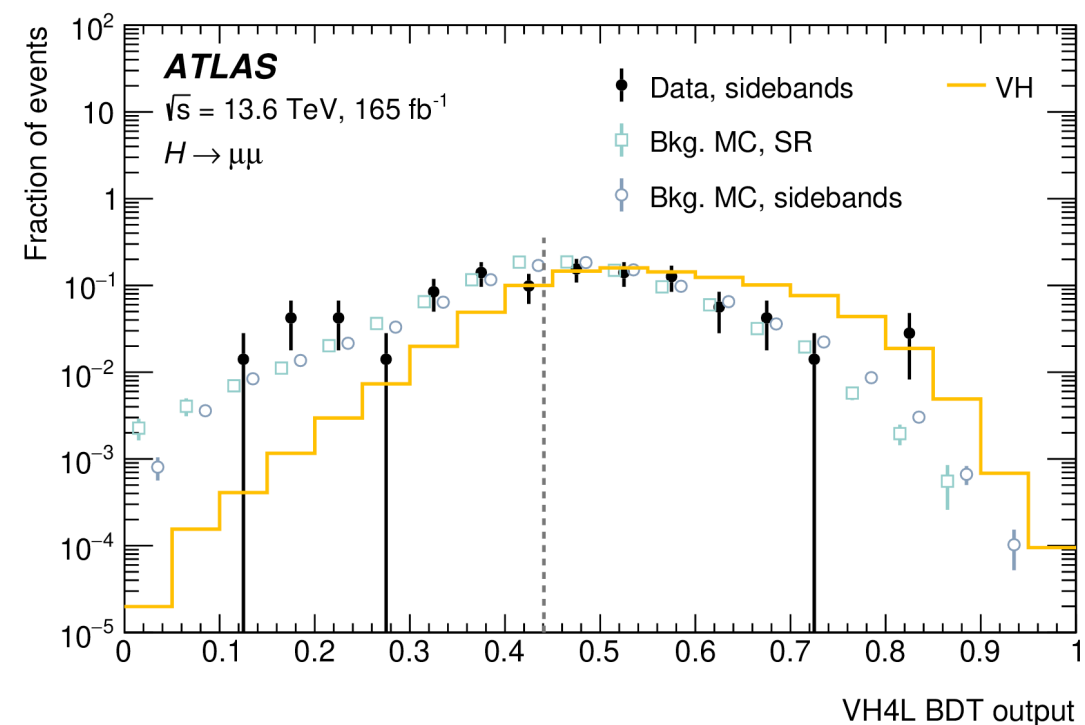
- 4 μ : pair with $m_{\mu\mu}$ closest to m_Z selected as Z candidate, the other pair is Higgs candidate
- BDTs trained with 15 variables (4-lep) and 9 variables (2-lep) to extract signals
- 1 category for 4-lep and 2 categories for 2-lep
- 2-lep: New categories in Run3

3-lep Selection: events with 3 leptons, new Tight isolation cut for W lepton in Run3

- Pairing for 3 μ events: χ^2 minimization

$$\chi^2 = \left(\frac{m_{\mu_1\mu_2} - M_H}{\sigma_H} \right)^2 + \left(\frac{m_T - m_T^W}{\sigma_W} \right)^2$$

- BDT trained with 12 variables



Variables used (VH categories)

Variable	Description
$p_T^{\mu_1}$	Transverse momentum of leading muon
$p_T^{\mu_2}$	Transverse momentum of sub-leading muon
E_T^{miss}	Missing transverse energy
N_j	Number of jets
$\Delta R(\mu, \mu)$	ΔR between the Higgs-boson candidate muons
$\Delta\phi(\ell\ell, E_T^{\text{miss}})$	Azimuthal angle between the muon pair and the missing transverse momentum
V_T/H_T	Ratio of vectorial V_T and scalar H_T sum of reconstructed objects in event
$\cos\theta^*$	μ^- decay angle in the Collins–Soper frame
$\sigma(E_T^{\text{miss}})$	Missing transverse energy significance

VH2LEP

Variable	Description
$p_T^{\ell_W}$	Transverse momentum of the W -boson lepton
E_T^{miss}	Missing transverse energy
m_T^W	Transverse mass of the W boson
N_j	Number of jets
N_μ	Number of muons
$\Delta R(\mu, \mu)$	ΔR between the Higgs-boson candidate muons
$\cos\theta^*$	μ^- decay angle in the Collins–Soper frame
$m^{3\ell}$	Invariant mass of the three leptons
$p_T^{j_1}$	Transverse momenta of the leading jet
$\Delta\phi(\ell\ell, \ell_W)$	Azimuthal angle between the muon pair and the W -boson lepton
$\Delta\eta(\ell\ell, \ell_W)$	Pseudorapidity separation between muon pair and W -boson lepton
$\Delta\phi(\ell\ell, E_T^{\text{miss}})$	Azimuthal angle between the muon pair and the missing transverse momentum

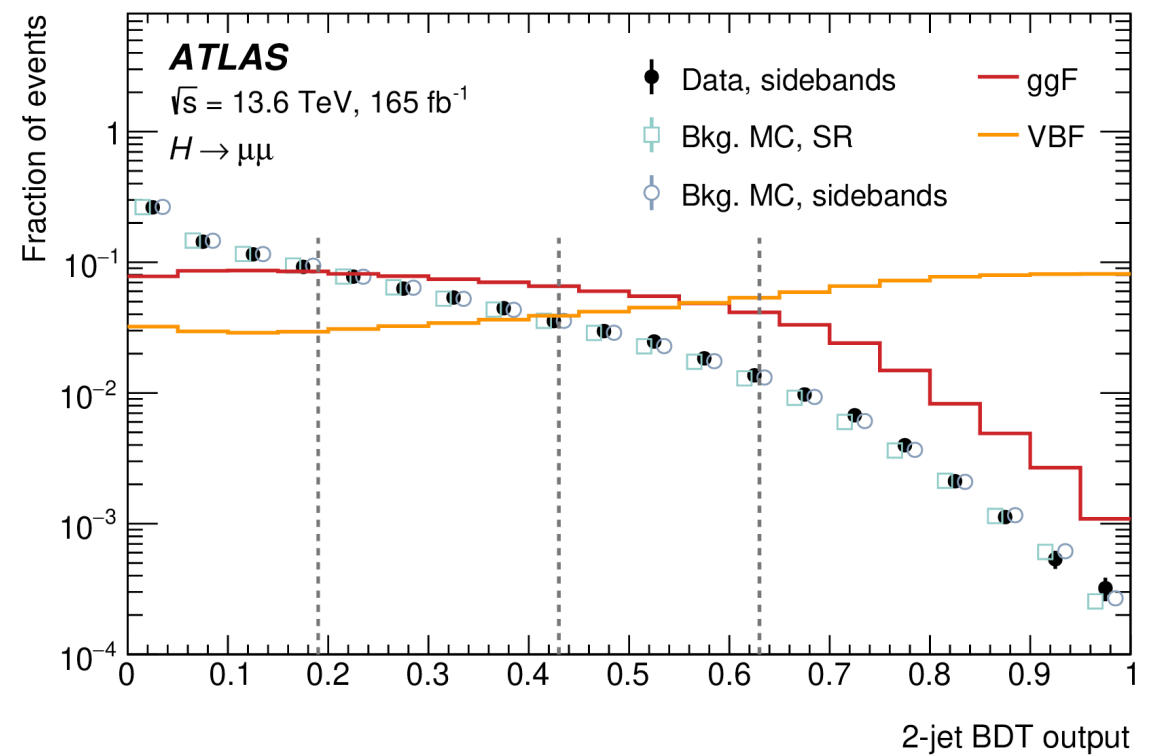
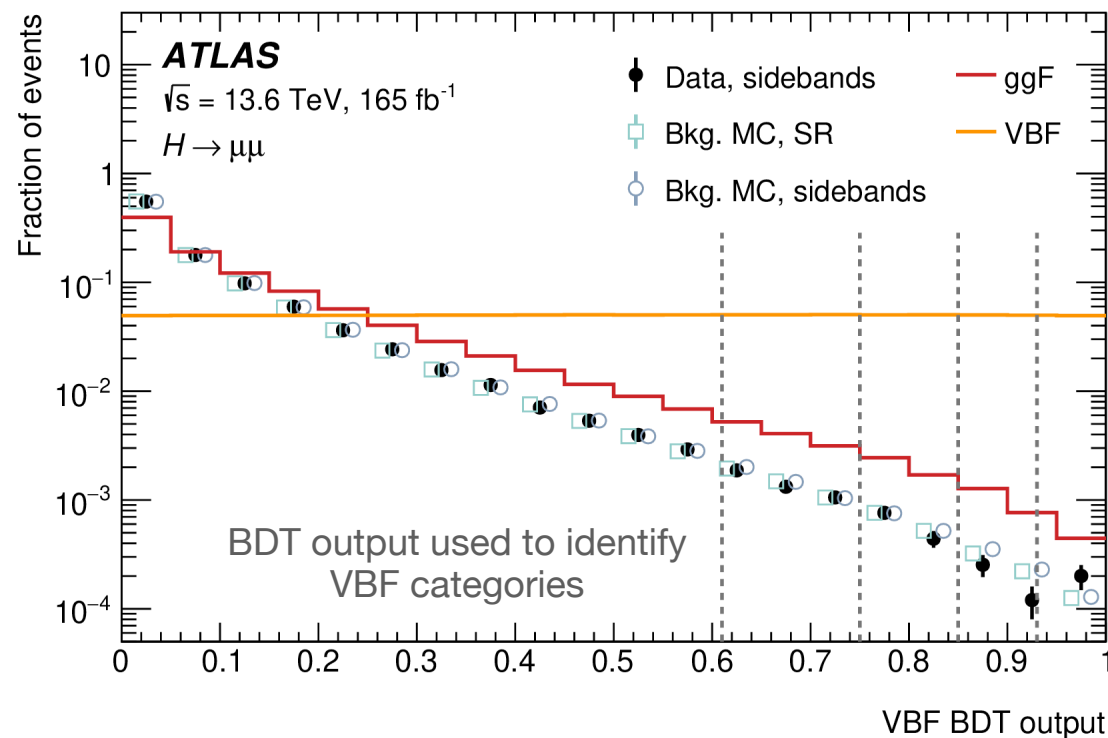
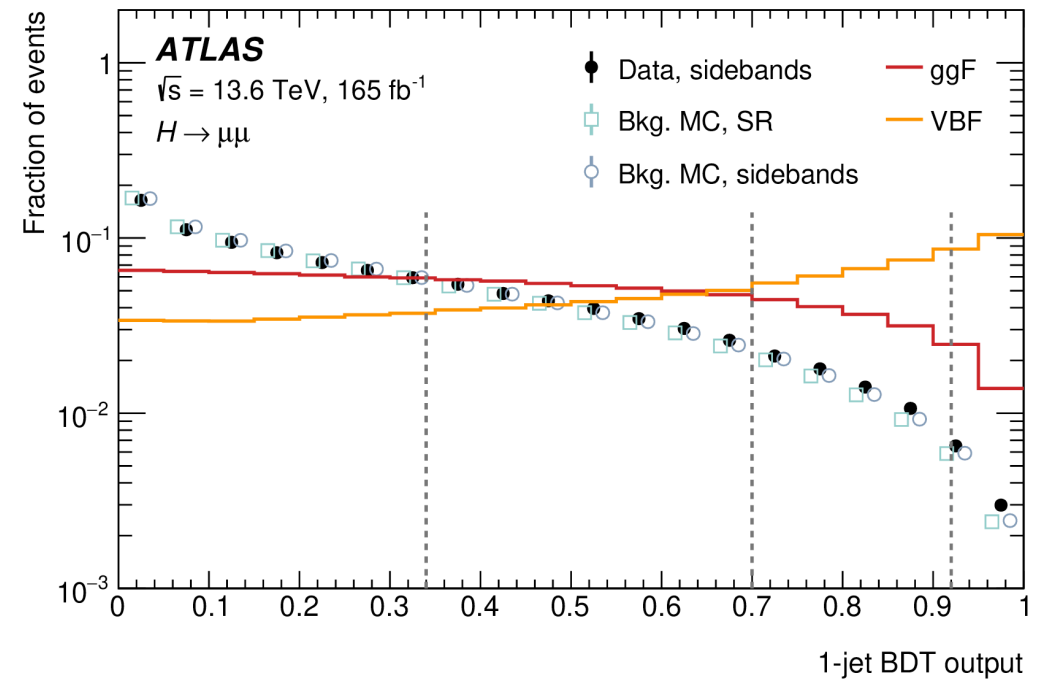
VH3LEP

Variable	Description
$p_T^{\text{pair}_1}$	Transverse momentum of the first pair of leptons
$p_T^{\text{pair}_2}$	Transverse momentum of the second pair of leptons
$p_T^{\text{pair}_1 \ell_1}$	Transverse momenta of the leading lepton of the first pair
$\Delta R(\text{pair}_1, \text{pair}_2)$	ΔR between the first and second pair
$\Delta R(\ell_1, \ell_2)$	ΔR between the leading leptons of each pair
$\alpha(\text{pair}_1, \text{pair}_2)$	Opening angle between the lepton pairs
$\log_{10}(-u), \log_{10}(-t)$	Mandelstam u – and t -variables
H_T^ℓ	Scalar sum of transverse momentum of the four leptons
$p_T^{\ell_i} (i = 2, 3, 4)$	p_T of the second, third and fourth lepton
$ \eta_{\text{forward}} $	Pseudorapidity of most forward lepton pair
$\alpha_{CMF}(\ell_1^{\text{pair}_1}, \ell_2^{\text{pair}_1})$	Opening angle between leptons of Z -like pair (or pair_1) in center-of-mass frame
$\theta_{CMF}(\text{pair}_2)$	Polar angle of H -boson candidate pair (or pair_2) in center-of-mass frame

VH4LEP

VBF+ggF categories

- Selection for ggF/VBF:
 - $110 \text{ GeV} < m_{\mu\mu} < 160 \text{ GeV}$
 - Exactly 2 muons (no extra leptons)
 - B-jet veto at 85% WP
 - $E_{T,miss} < 120 \text{ GeV}$ (orthogonal to ZH2L)
- BDT-based classifiers (XGBoost):
- Signal: VBF (VBF Classifier), ggF + VBF (Higgs Classifier)
- Background: DY + VBFZ + top + DiBoson
- Kinematic distribution of BDT inputs
- 16 categories defined in total for ggF/VBF



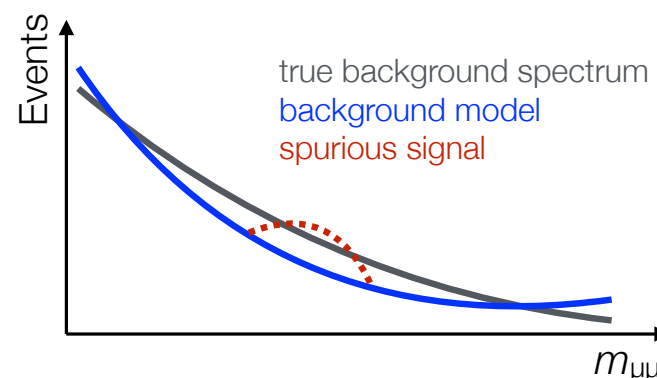
Variables used (VBF + N-jet categories)

Variable	Description	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ and VBF
$p_T^{\mu\mu}$	Transverse momentum of muon pair	X	X	X
$Y^{\mu\mu}$	Rapidity of muon pair	X	X	X
$\cos \theta^*$	μ^- decay angle in the Collins–Soper frame	X	X	X
$p_T^{j_1}$	Transverse momentum of leading jet		X	X
η^{j_1}	Pseudorapidity of leading jet		X	X
$\Delta\phi(\mu\mu, j_1)$	Azimuthal angle between the muon pair and the leading jet		X	X
$N_{\text{Track}}^{j_1}$	Number of tracks in leading jet with $p_T > 0.5$ GeV		X	X
$p_T^{j_2}$	Transverse momentum of sub-leading jet			X
η^{j_2}	Pseudorapidity of sub-leading jet			X
$\Delta\phi(\mu\mu, j_2)$	Azimuthal angle between the muon pair and the sub-leading jet			X
$N_{\text{Track}}^{j_2}$	Number of tracks in sub-leading jet with $p_T > 0.5$ GeV			X
p_T^{jj}	Transverse momentum of dijet system			X
Y^{jj}	Rapidity of dijet system			X
$\Delta\phi(\mu\mu, jj)$	Azimuthal angle between the muon pair and the dijet system			X
m^{jj}	Invariant mass of dijet system			X
E_T^{miss}	Missing transverse energy			X
H_T^j	Scalar sum of jet transverse momentum			X

Background modelling - spurious signal

$$F(m_{\mu\mu}, a_1)^{cat} = \text{Core}(m_{\mu\mu}) \times \text{Empirical}(m_{\mu\mu}, a_i)^{cat}$$

- Measured signal yield from a ***S+B fit*** performed on background-only templates
 - built from high-statistics background samples
 - Taking maximum absolute value of spurious signal in the 120-130 GeV mass range - ($S \pm 1\sigma / \delta S < 20\%$)
- Dominant experimental systematic
 - accounting for imperfect choice of analytic model for the background and potential local biases in the $m_{\mu\mu}$ spectrum (induced by selections, for example)
- All spurious signal uncertainties considered uncorrelated
 - Expected significance only impacted by $\sim 2\%$ if switching to full correlation



SMEFT parameterisation

e.g. σ^{STXS}

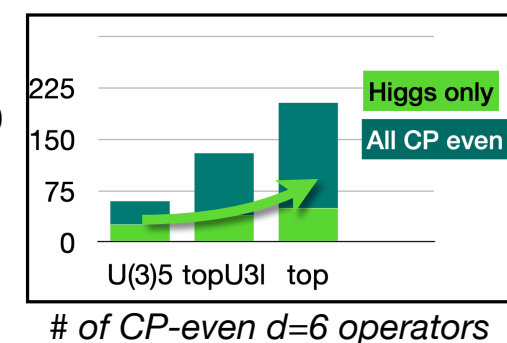
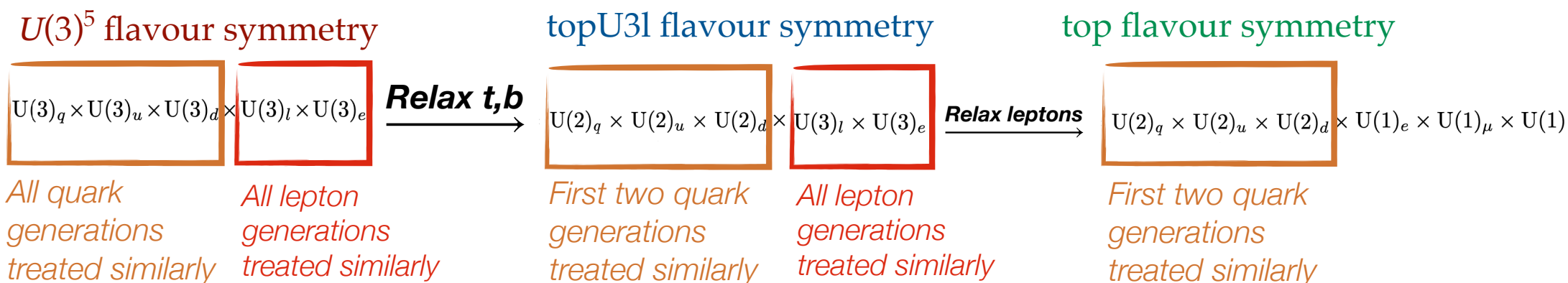
$$\sigma_{\text{SMEFT}} \sim \left| \text{SM} \right|^2 + 2 \frac{c}{\Lambda^2} \text{Re} \left(\text{SM} \times \text{dim-6 interference} \right) + \frac{c^2}{\Lambda^4} \left| \text{dim-6 squared} \right|^2$$

SM / dim-6 interference
"linear": $(v/\Lambda)^2, (E/\Lambda)^2$

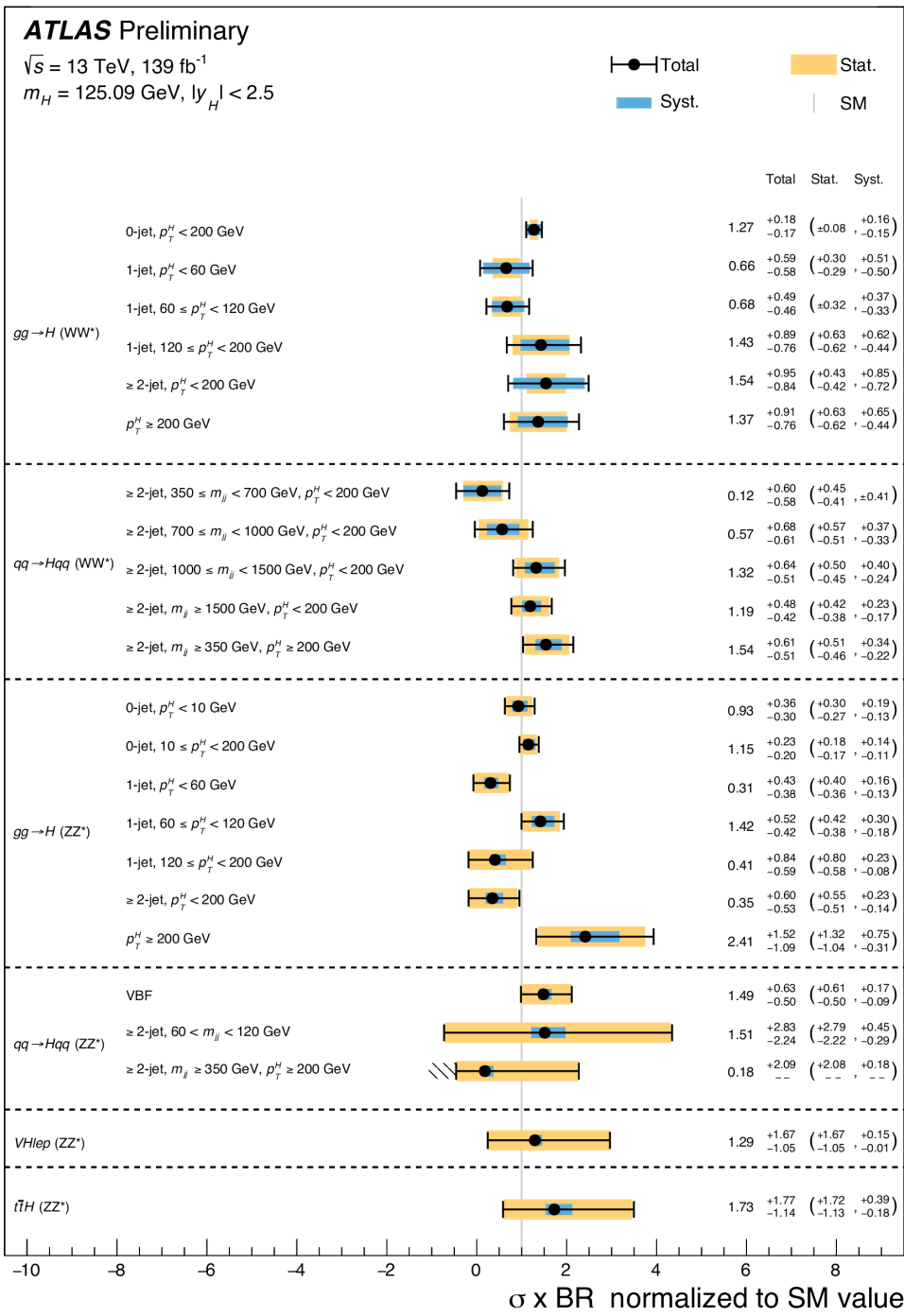
dim-6 squared
"quad.": $(v/\Lambda)^4, (E/\Lambda)^4$

- Warsaw basis, assuming $\Lambda = 1$ TeV.
- SMEFTsim + SMEFT@NLO
- Results are usually provided for **linear** model (+ **linear-quadratic** models).
- SMEFTsim: different flavour symmetries used to reduce the number of Wilson coefficients.

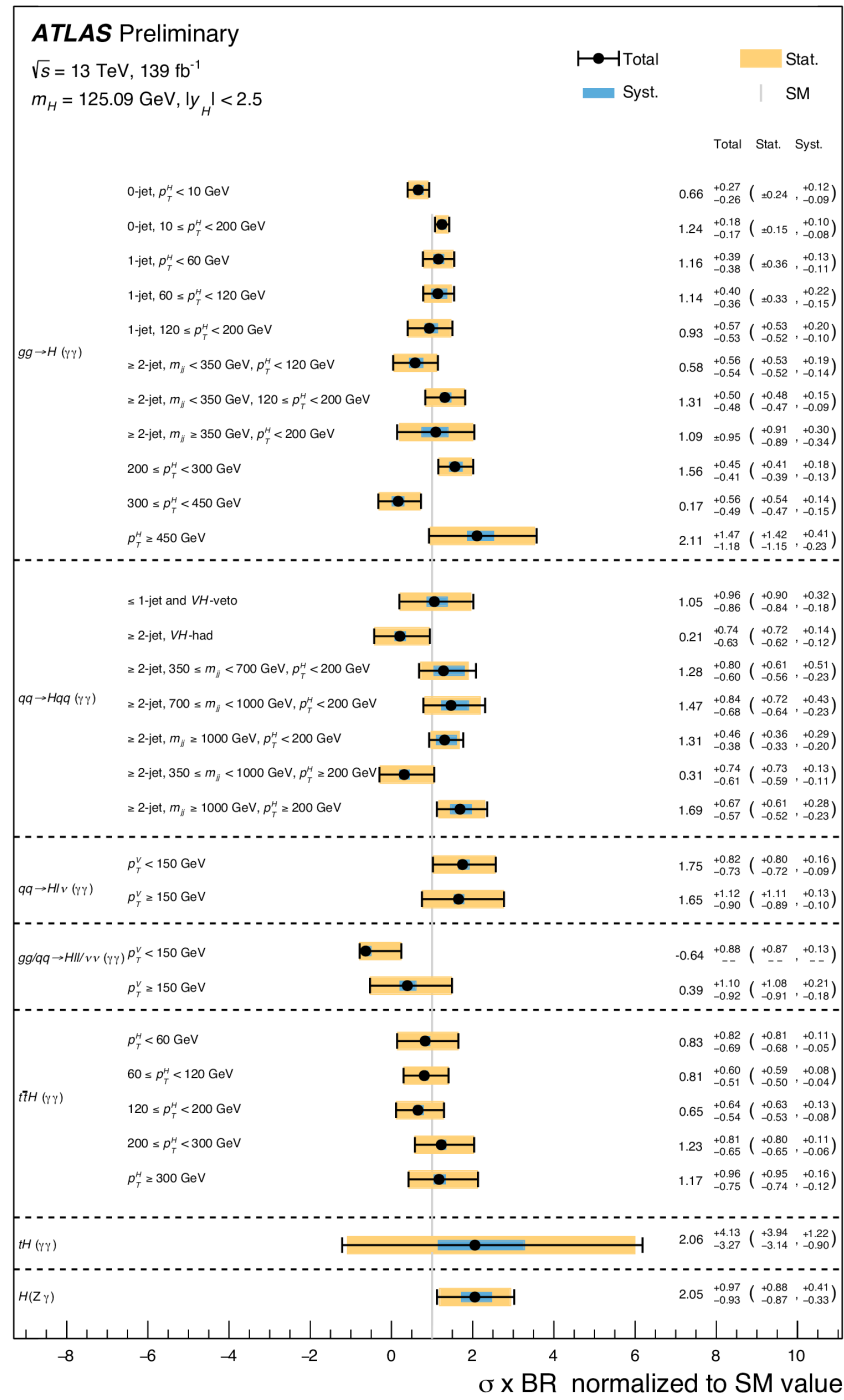
("U(3)⁵ flavour symmetry", "topU3I", "top")



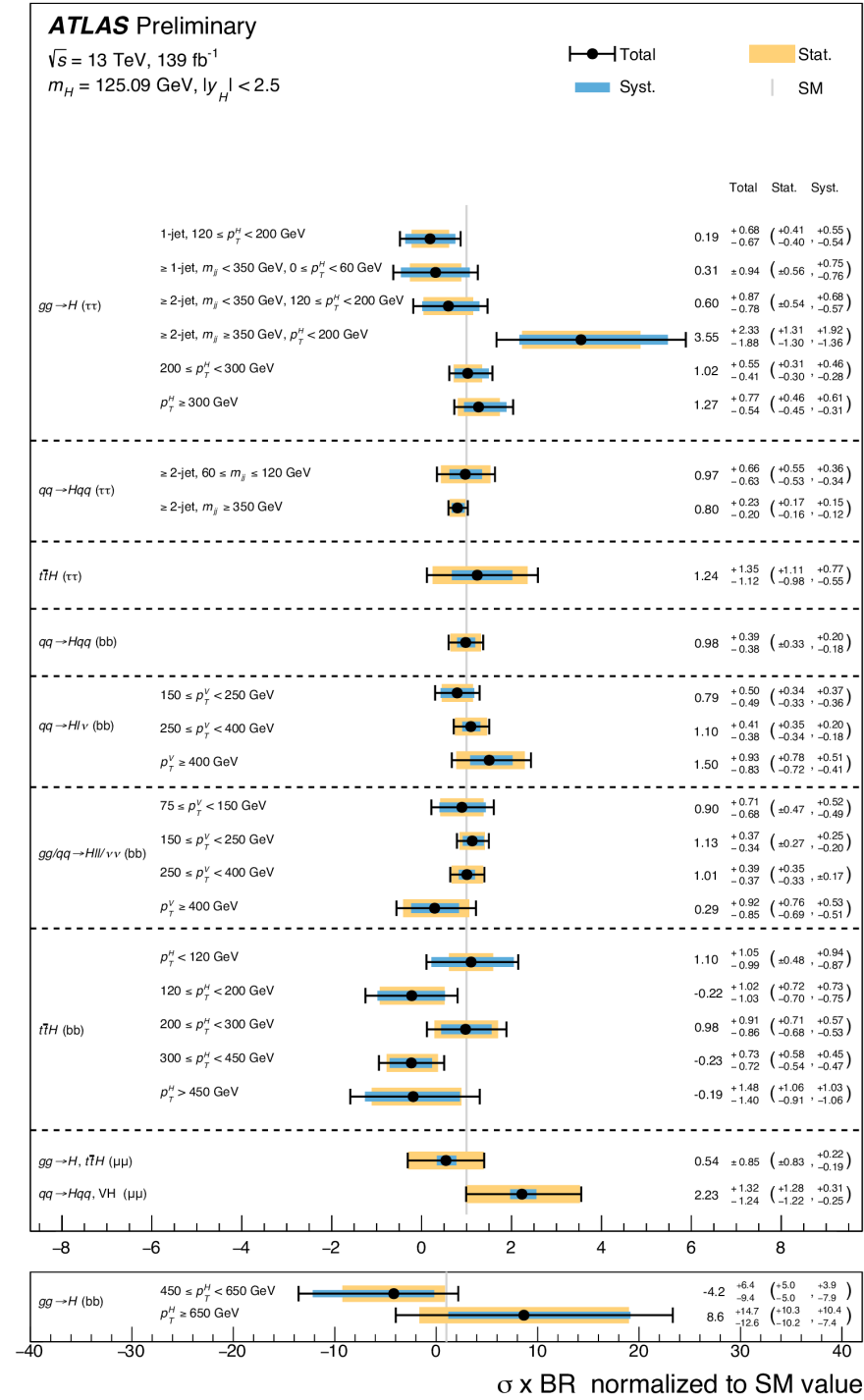
SMEFT fits: STXS inputs



WW, ZZ



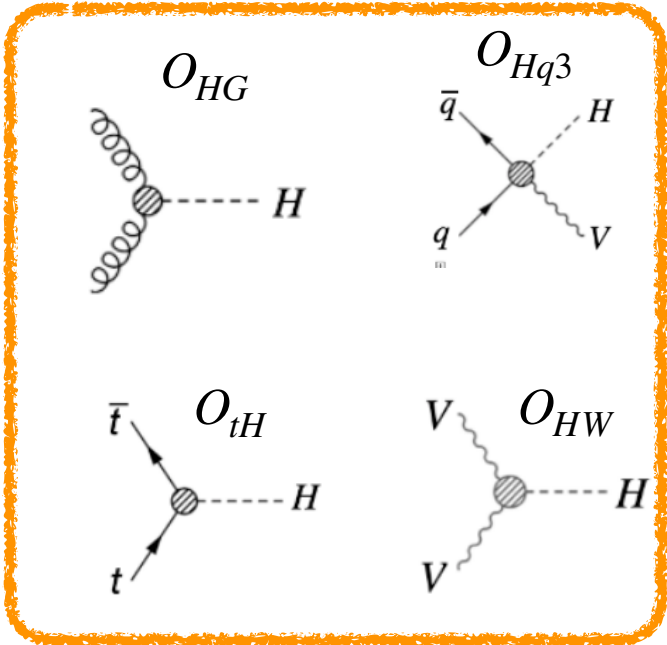
$\gamma\gamma, Z\gamma$



$\tau\tau, \mu\mu, b\bar{b}$

SMEFT impact on STXS bins and decay

- Impact of Wilson coefficients can be visualised-> Value of c_i scaled appropriately for plotting.
- 33 WCs plotted, remaining are subleading.
- Impact of quadratic terms significant for WH, ZH and tH.

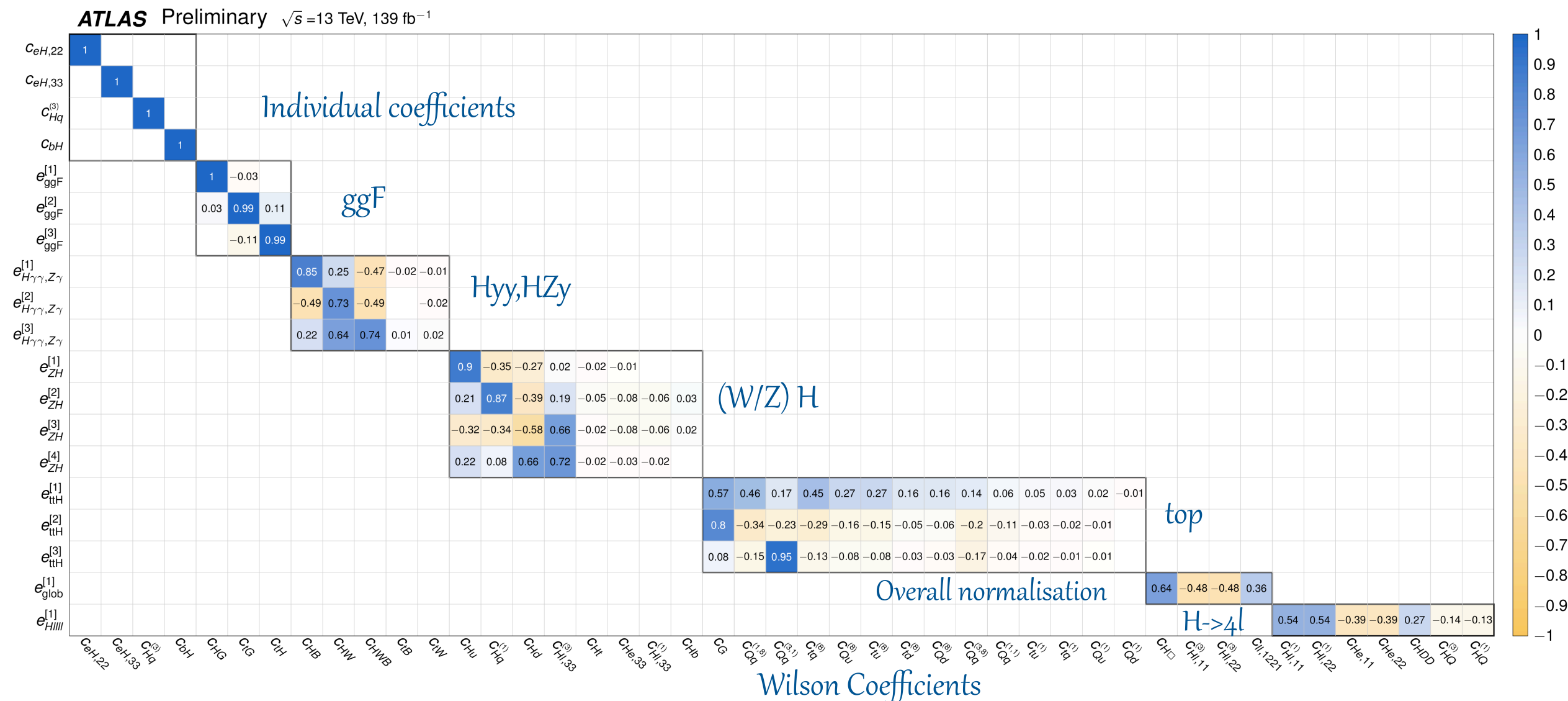


STXS sensitivity study

- 50 Wilson coefficients have a non-negligible impact on STXS bins.
- Not all the parameters can be constrained directly in the Warsaw basis, need to identify sensitive directions that can be reasonably constrained.
- Principal component analysis on information matrix:

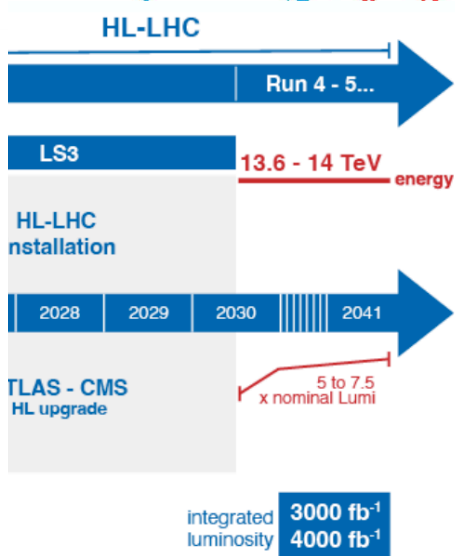
$$H_{SMEFT} = P^T H_\mu P$$

- Full eigenvector basis-> Negligible correlation, hard to interpret.
- Fit basis-> Higher correlation, easy to interpret -> 19 directions



What's Next?

HL-LHC projections [Link](#)



Same analysis strategy employed in the full Run 2 measurements.

The resolution of the Higgs boson peak is reduced by 30% in VBF and 0-jet categories, and 15% in other categories to account for **expected improvements in the muon momentum resolution** brought by the ITk.

Three scenarios are considered:

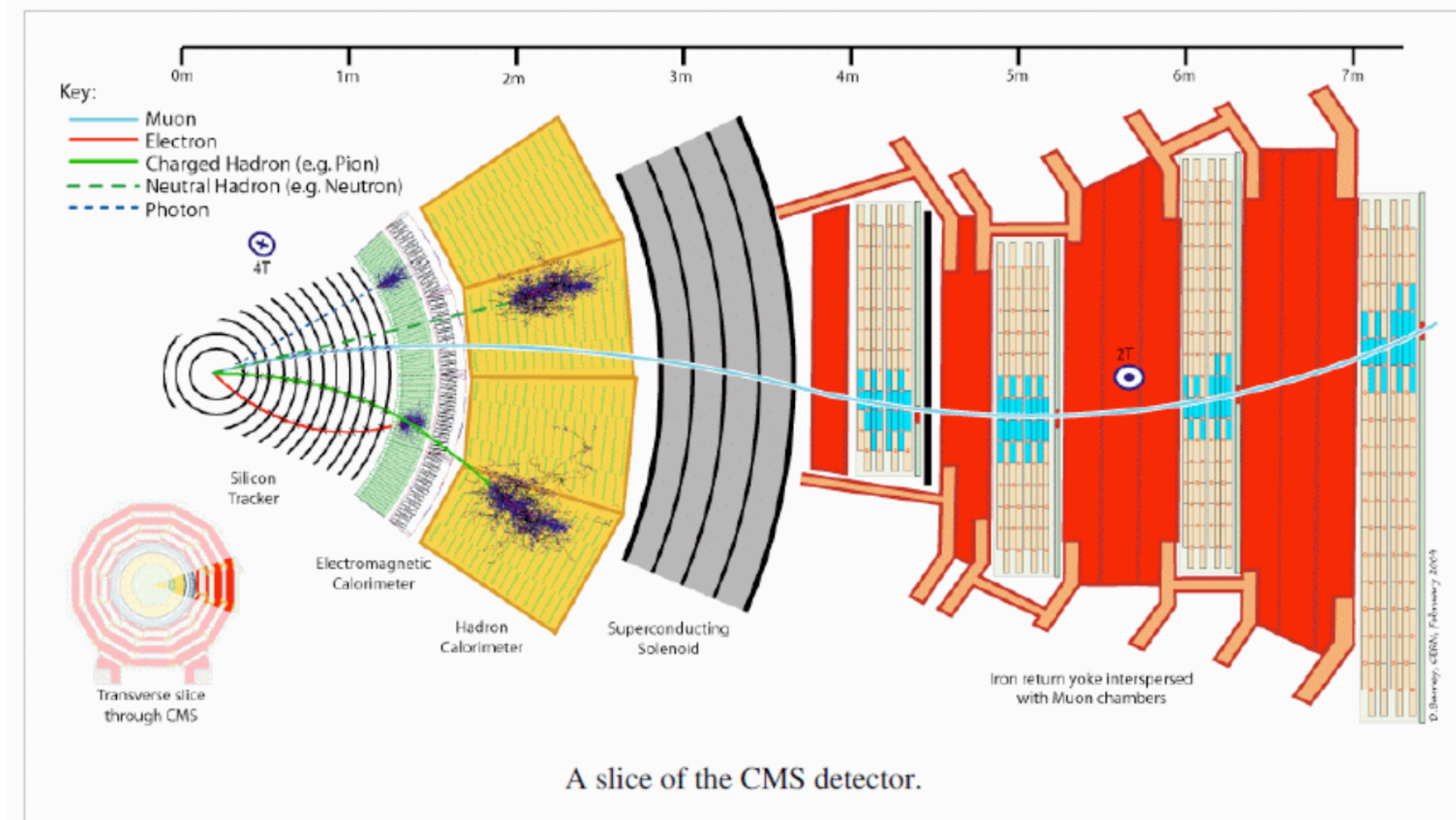
- **Run 2 systematic:** conservative scenario, all systematic uncertainty are of the same size as in Run 2 analyses
- **Baseline:** reasonable reduction of systematic uncertainty (assumes no spurious signal and MC-stat uncertainty), theory uncertainties are halved.
- **No systematics:** optimistic scenario with extremely accurate theoretical calculation and detector calibration -> negligible systematics.

In all scenarios considered the signal would be observed with significance greater than five standard deviation

Uncertainty source	Uncertainty scale factor		
	Run 2 systematic uncertainties	Baseline	No systematic uncertainties
Background modelling uncertainties	1.0	0.0	0.0
MC statistical uncertainties	1.0	0.0	0.0
Photon identification and isolation	1.0	0.8	0.0
Flavour tagging of b , c jets	1.0	0.5	0.0
Other experimental systematic uncertainties	1.0	1.0	0.0
Theoretical uncertainties	1.0	0.5	0.0

Magnetic field, CMS approach

[LINK](#)



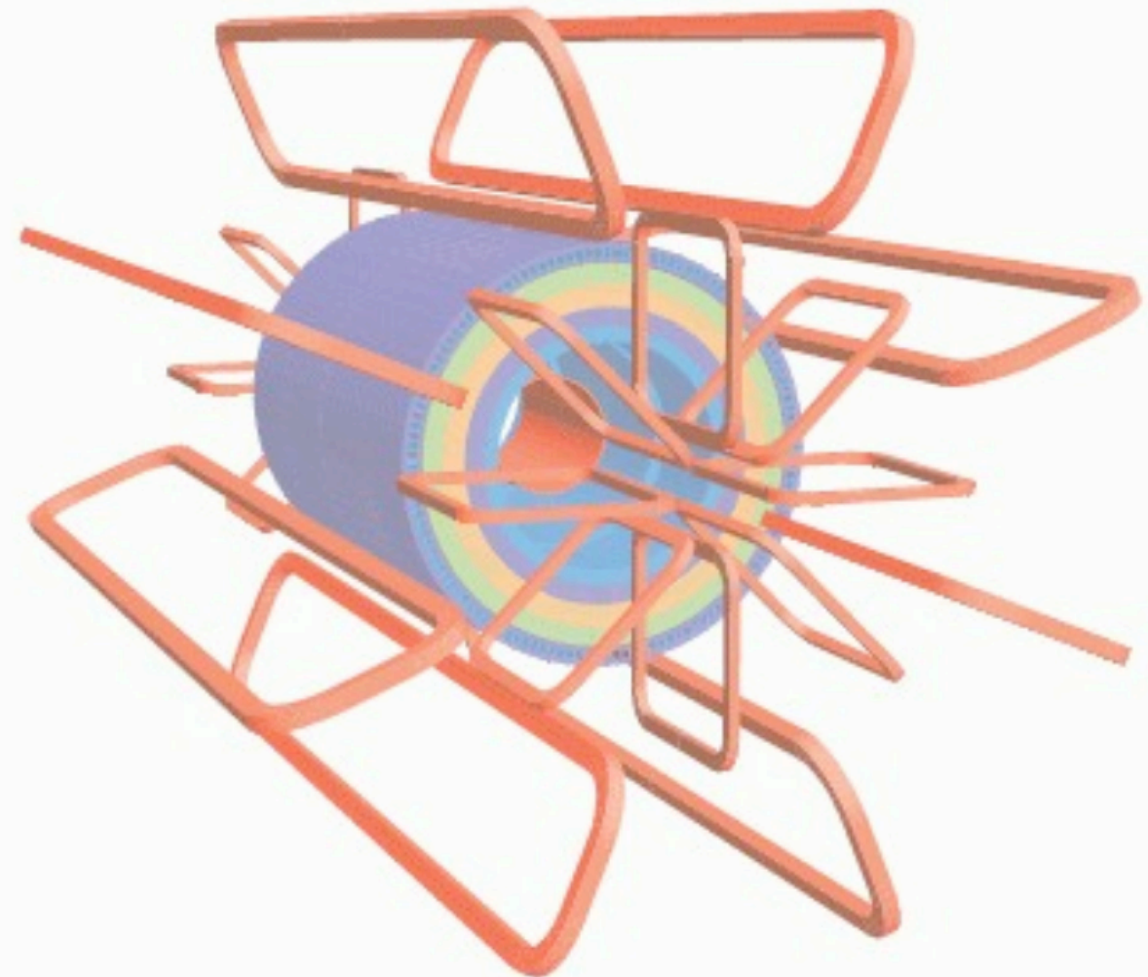
Very high solenoidal field in
(relatively) small volume !

- $L=3\text{m}$ in 4T bending field, $BL^2=36\text{ Tm}^2$
- Another bending from return flux (another 5 Tm^2)
- Tracks of charged particles have characteristic S-shape

Magnetic field, ATLAS approach

[LINK](#)

- ▶ Central solenoid: $L=1\text{m}$ in 2T bending field, $BL^2=2\text{ Tm}^2$
- ▶ Outside of the solenoid are large air-core toroids with bending field of 1T over a distance of m , $BL^2=36\text{ Tm}^2$
- ▶ Additional endcap toroids in forward and backward direction
- ▶ Similar bending power then in CMS, but in much larger volume





Results

- The measured signal strength is $\mu = 1.6 \pm 0.6$ for **Run3**
- In the combined Run2+Run3 fit, the signal strength is $\mu = 1.4 \pm 0.4$, and the individual results for Run 2 and Run 3 are compatible within 68%
- Compatibility among 6 groups of categories is 54% in Run 3

