HIGGS & FLAVORS
SEARCHES FOR H-C COUPLING, LFV, AND LIGHTER FERMIONS

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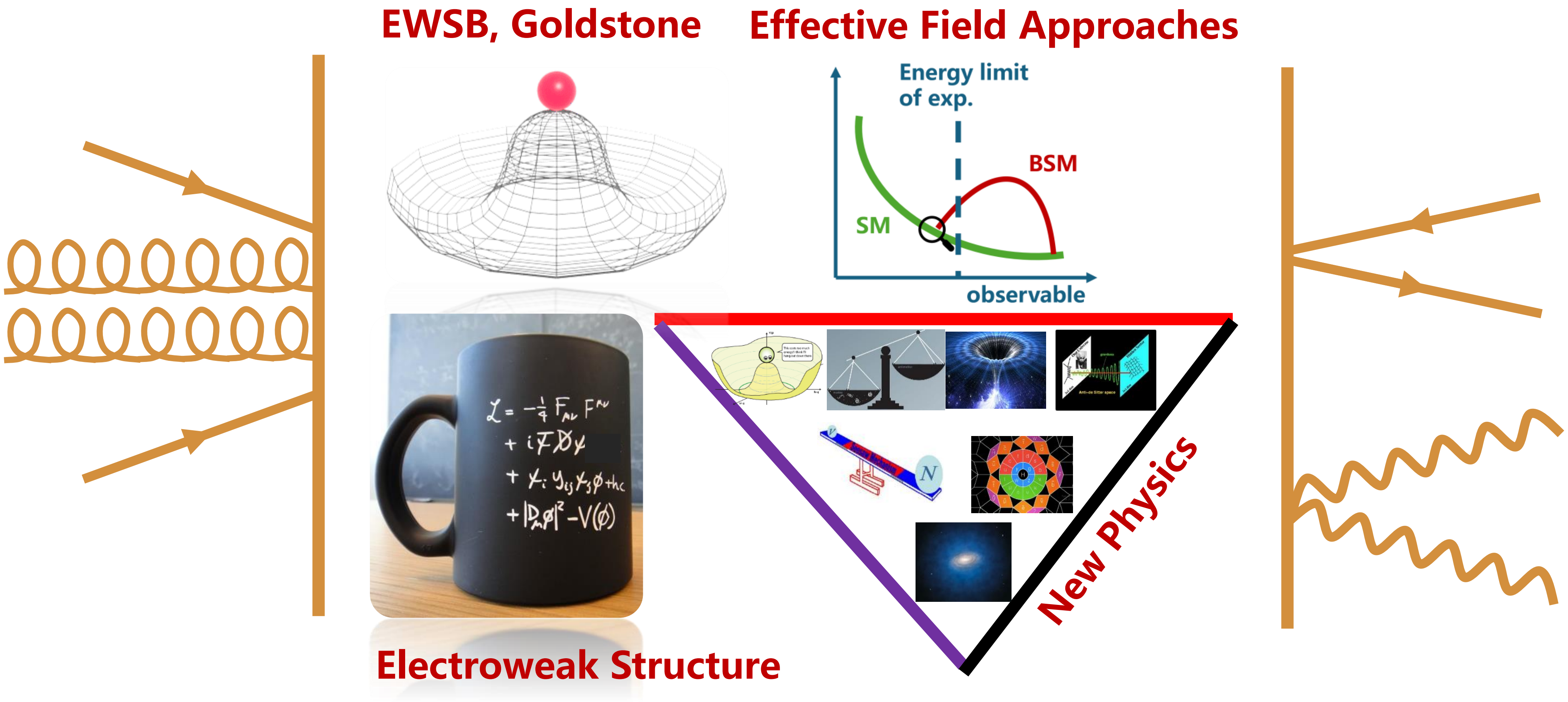
For ATLAS and CMS collaborations

Extended Scalar Sectors From All Angles Workshop

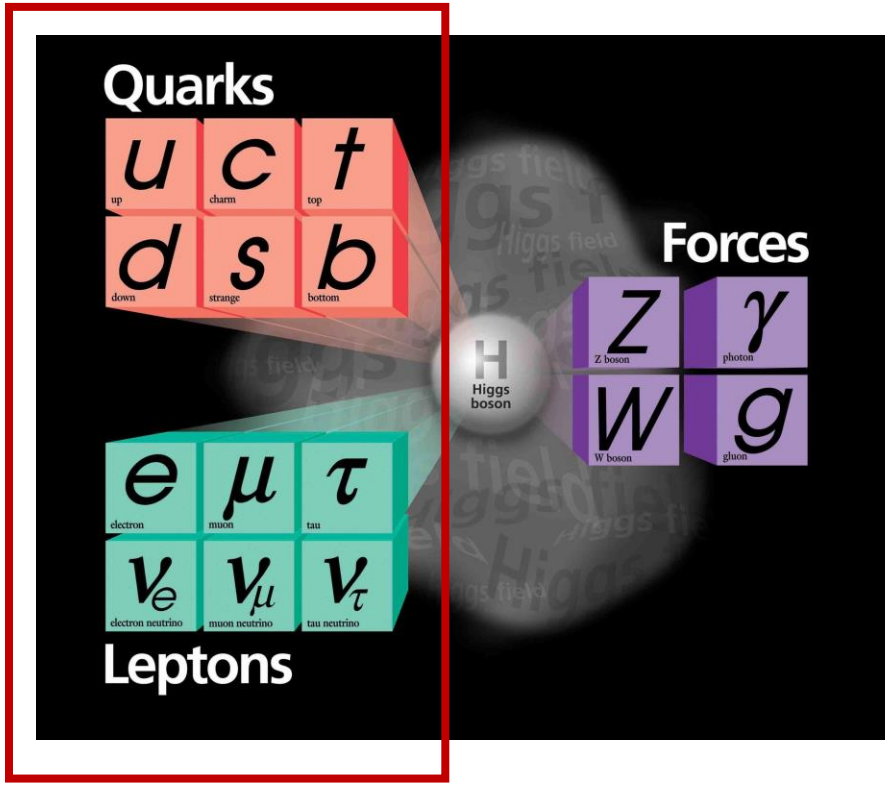
CERN, Oct. 21-25, 2024

Physics @ Electroweak Scale



A central piece of LHC Physics Program:
Higgs measurements and searches

Higgs & Flavor



❖ **Higgs Yukawa interactions**
at the heart of flavor-related questions
the source of fermion masses and CKM matrix

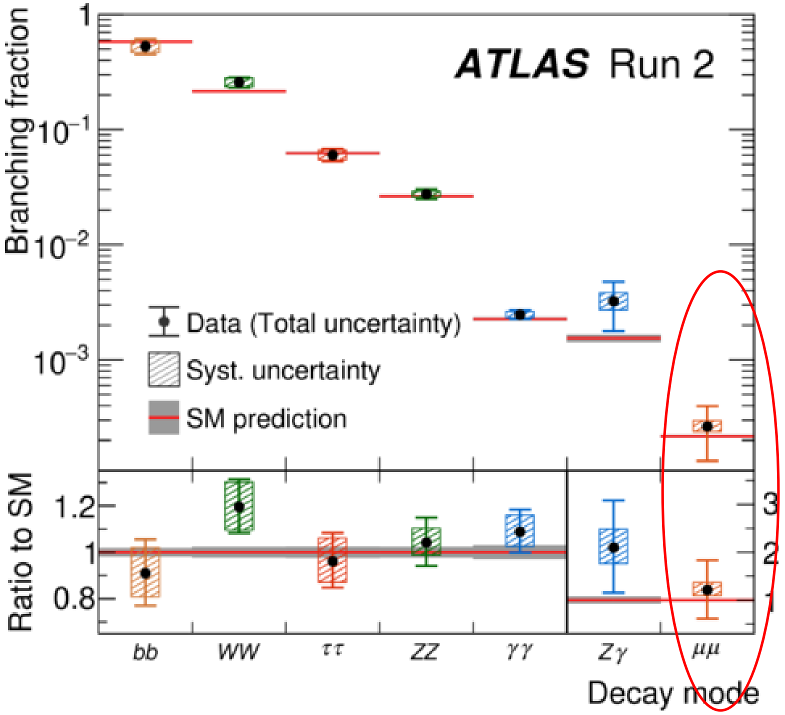
$$
\mathcal{L}_Y = \sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} u'_{kR} \right] + \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.},
$$

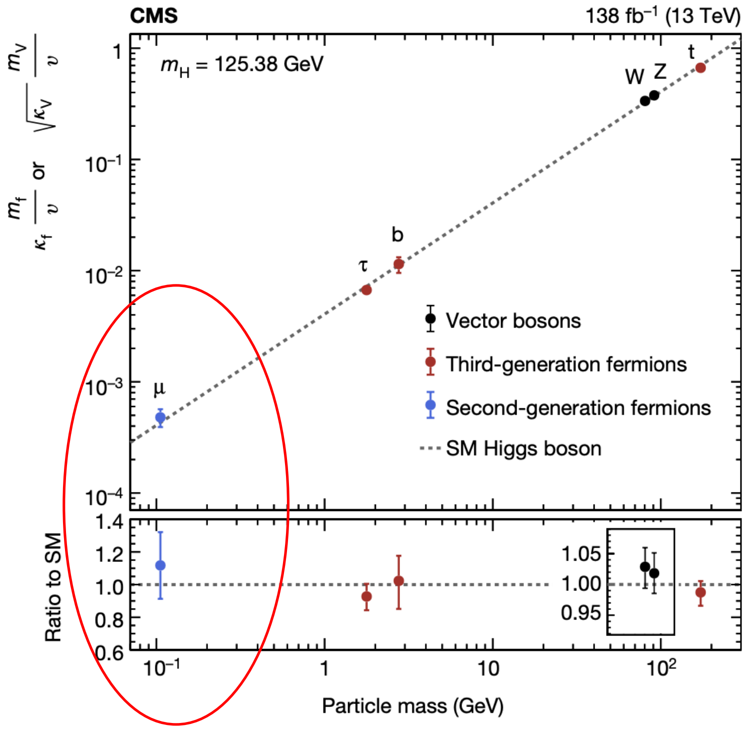
❖ **Study of Yukawa couplings is an essential part of Higgs physics program**

- ✓ span over many orders, from accessible to ~inaccessible (active fronts for HL-LHC and for future collider)
- ✓ deviation expected from BSM models (2HDM, ...)

Experimental Status

Nature 607, 52 (2022) *Nature 607, 60 (2022)*





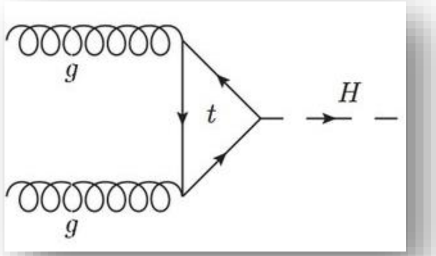
SM consistency observed so far

- ❖ Heavy flavor Yukawa coupling (τ, b, t) observed and enter **O(10%) precision** regime with **property measurements started**
- ❖ Second generation coupling pursued (**3σ H→μμ, ~3 SM accuracy for H→cc**)
- ❖ Search for anomalies with **lighter fermions**, and **FCNC/LFV** processes

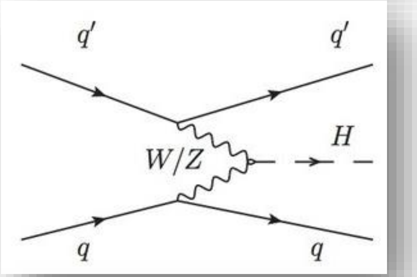
Focus of this talk

Experimental Charateristics

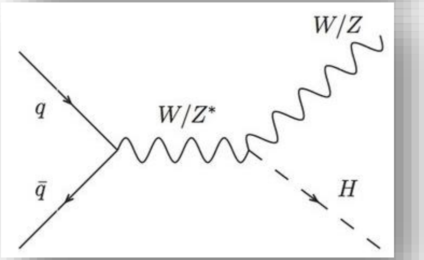
ggF



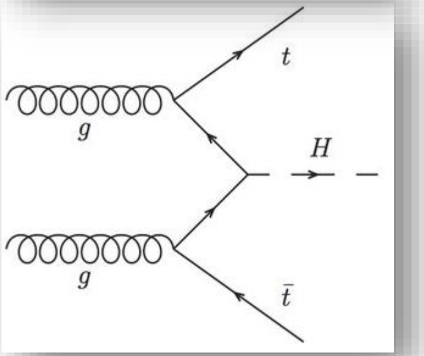
VBF

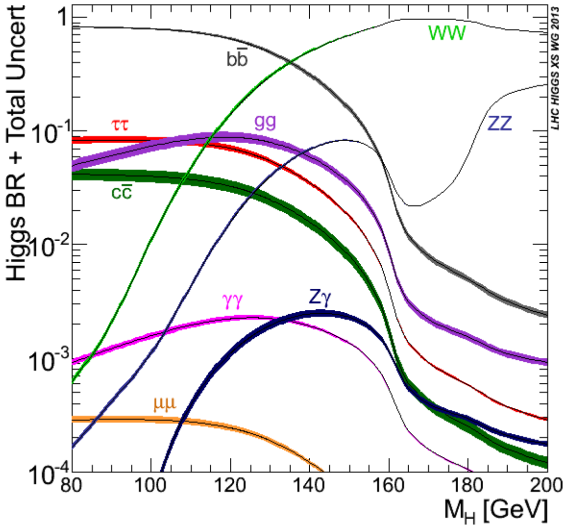


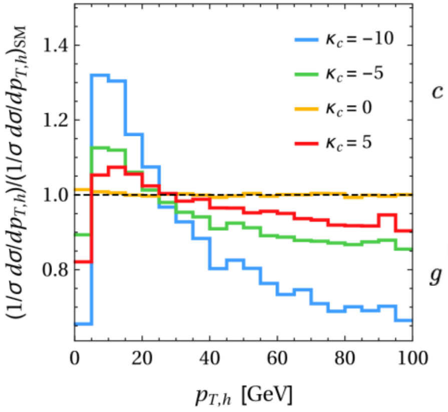
VH

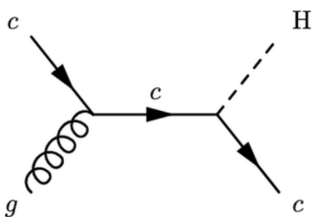


ttH









PRL 118 (2017) 121801

Primary sensitivity from Higgs decay channels

➔ Rely on successful reconstruction of decay final states (b, c, τ, μ, ...)

➔ Contribution from different production modes varies w.r.t. S/B

Complementary sensitivity with Yukawa interactions in production

➔ Indirect constraint from pT(H): sensitivity for inaccessible channels

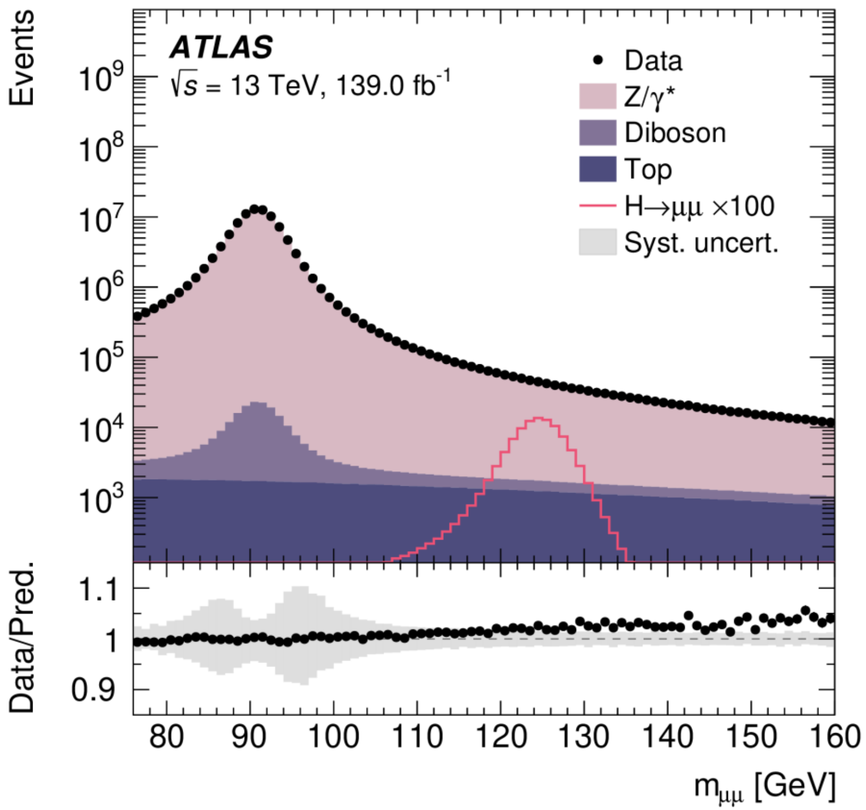
➔ (Di-) Quark + H production

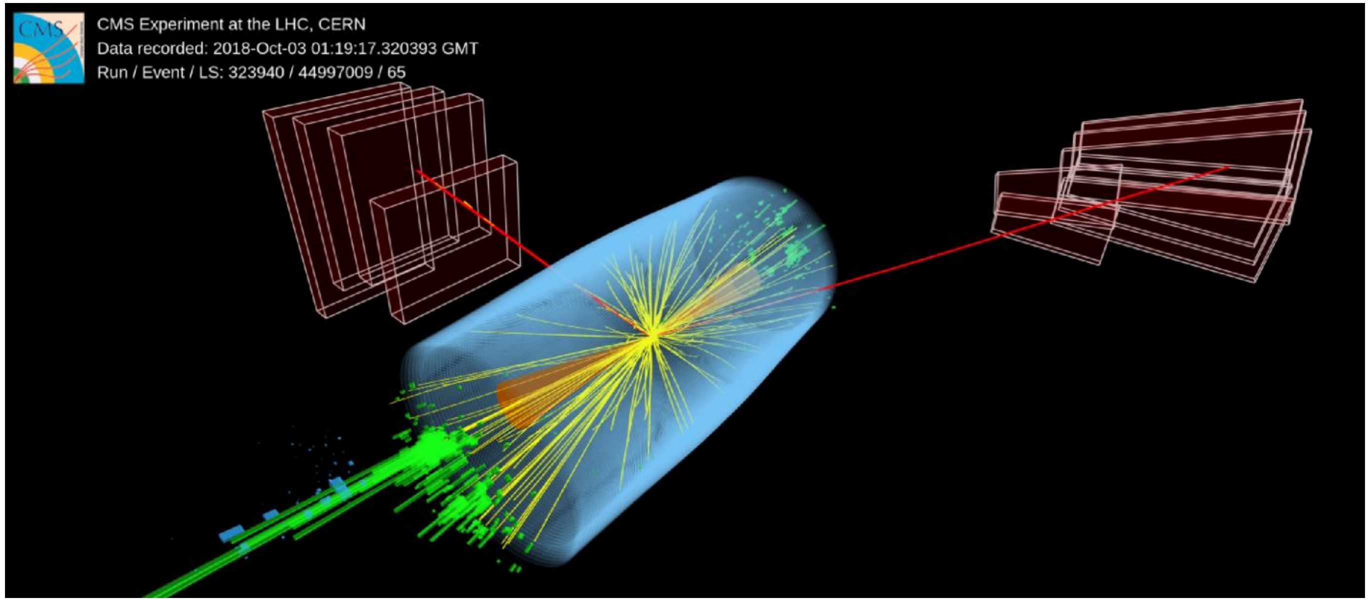
Flavor tagging, background modelling and control are essential

Higgs and Muon

ATLAS: *PLB 812 (2021) 135980*
CMS: *JHEP 01 (2021) 148*

A Sketch of H→μμ Study





Easily accessible final state of μμ

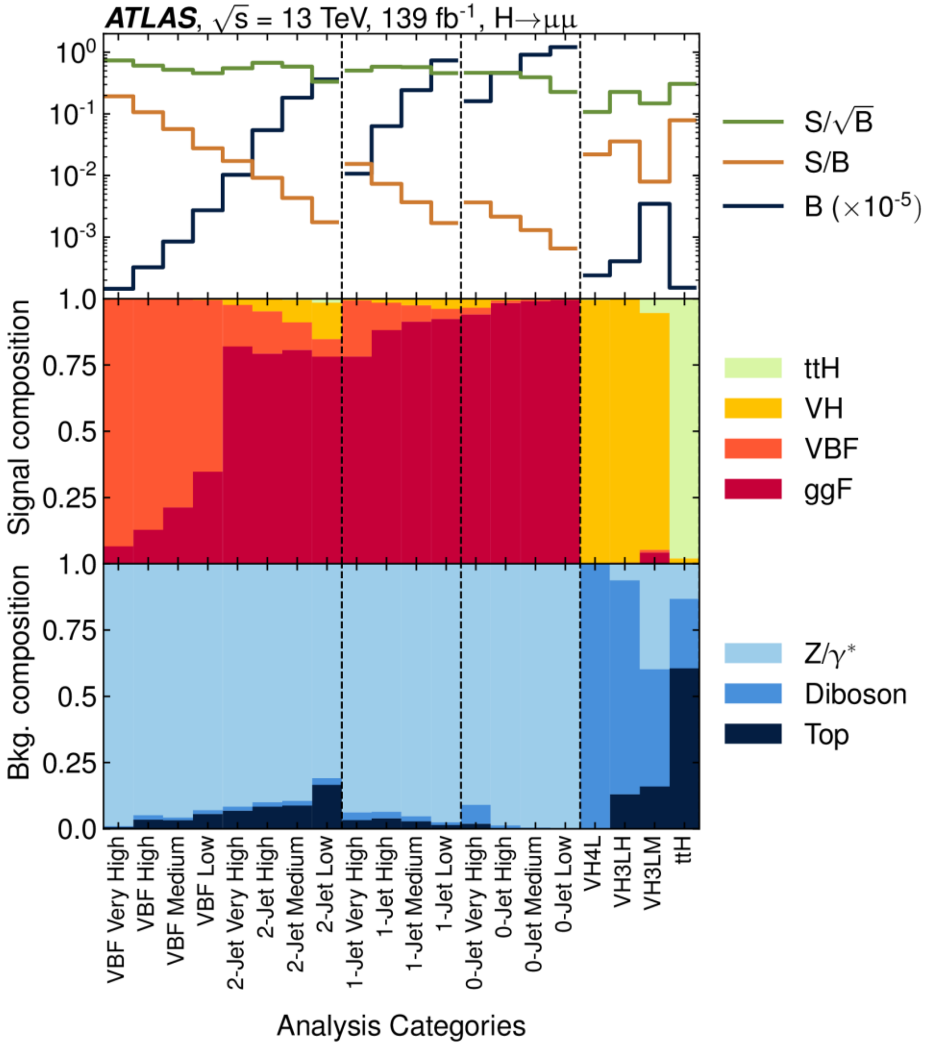
Orders of magnitude larger background from Drell-Yan processes

Master Recipes:

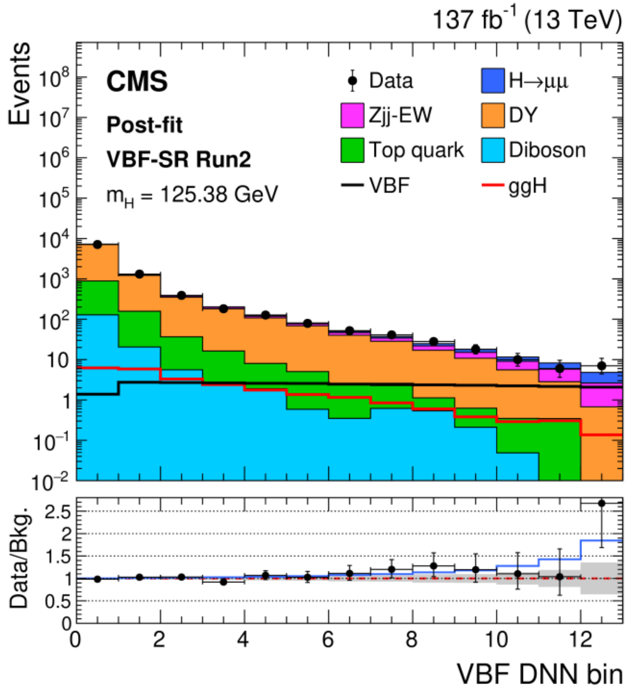
Fit m(μμ) distribution with parametrized functions → utilize the full power of data

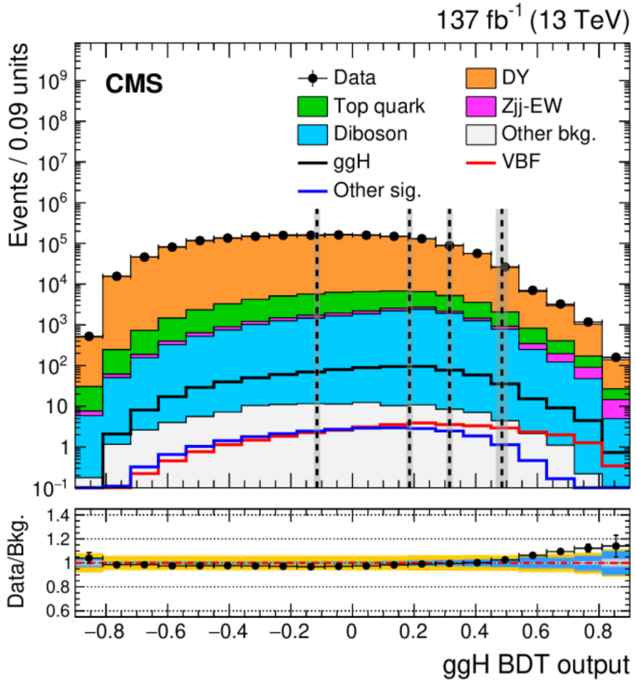
May turn to simulation-based study if side-band statistics poor

Improve Precision: Categorization, MVA



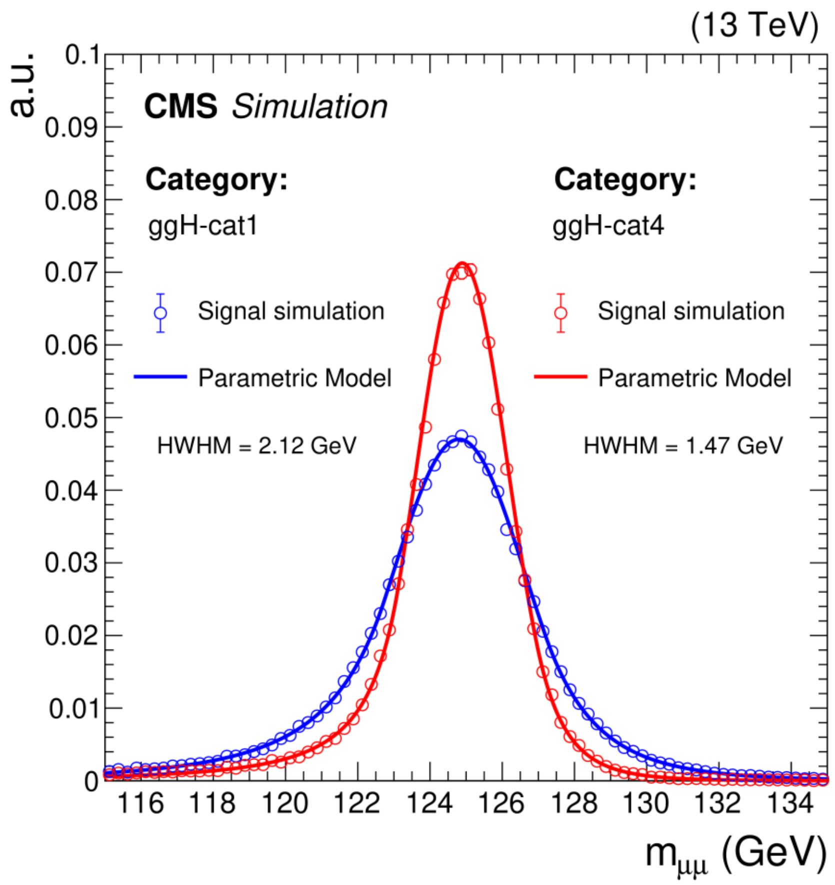
Statistical power gained via exploring different S-B configuration at different production modes



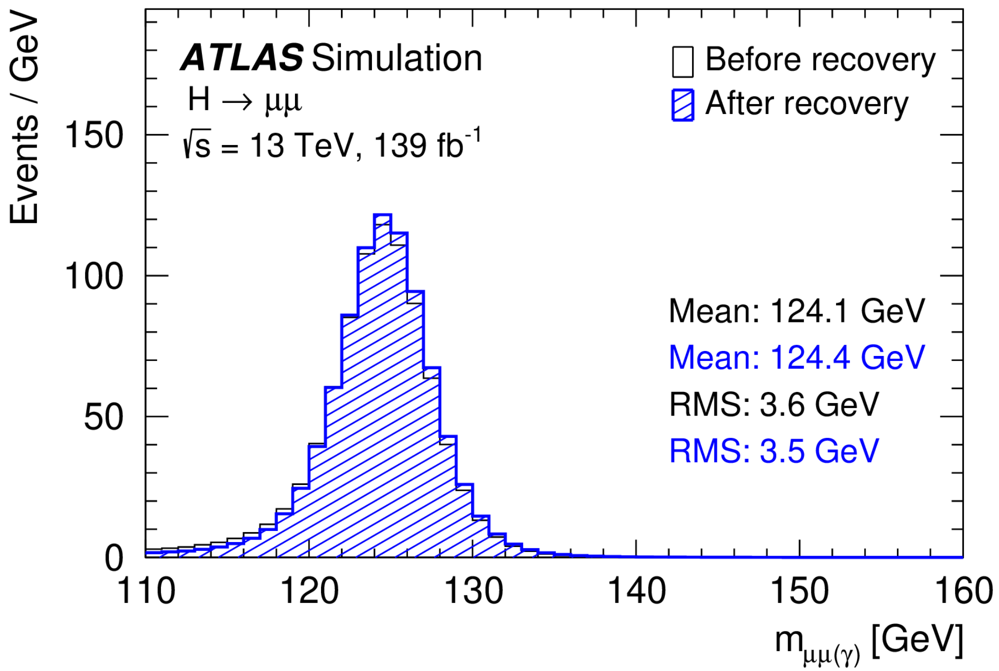


MVA (based on characteristic kinematic variables) to guide categorization or act as fitting variable

Improve Precision: Resolution of μ



Precision parametrization



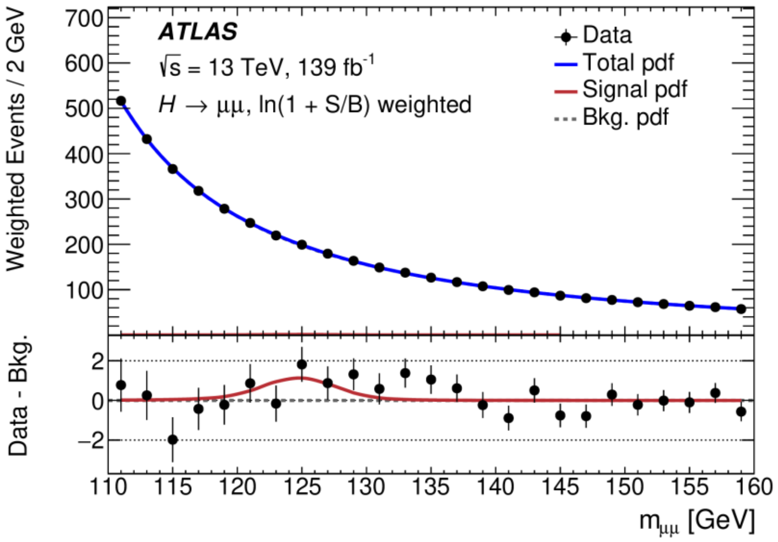
FSR recovery for part of events

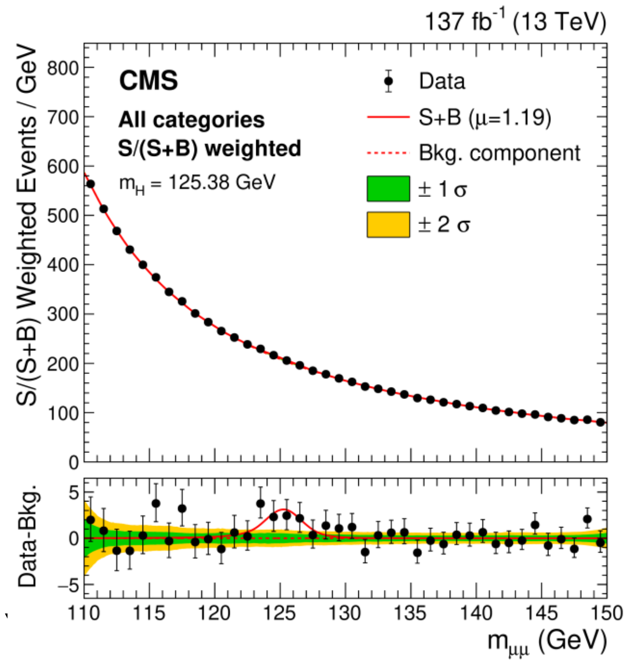
Careful work in detector and reconstruction calibration
➔ 1-2% per muon momentum resolution

Endeavors to gain further precision
➔ Refit muons to common vertex
➔ FSR recovery
➔ Consider event-by-event resolution

HEP 01 (2021) 148

Improve Precision: Background Modelling





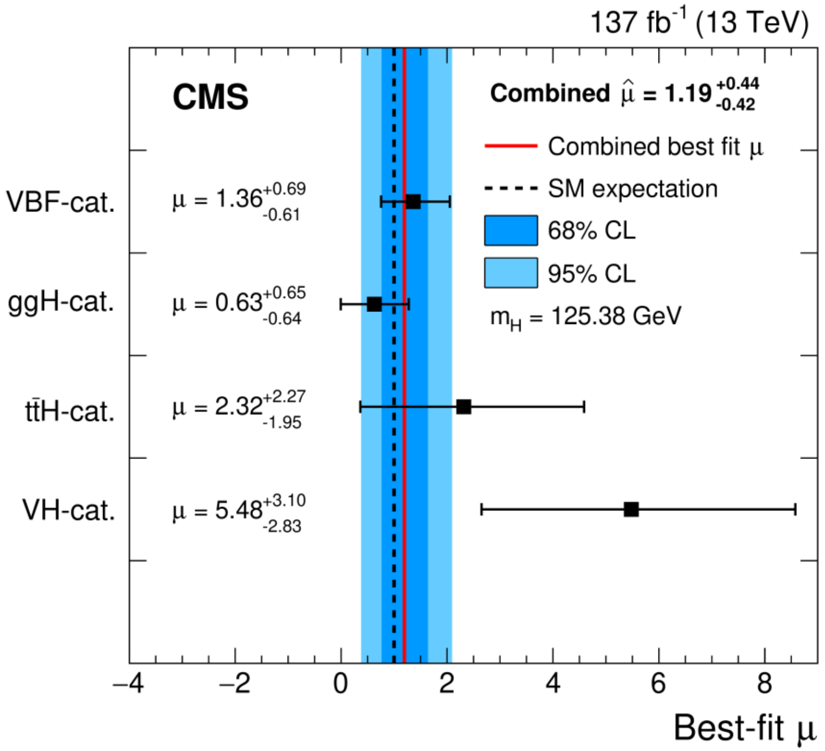
Key: a less-free background function that models full spectrum

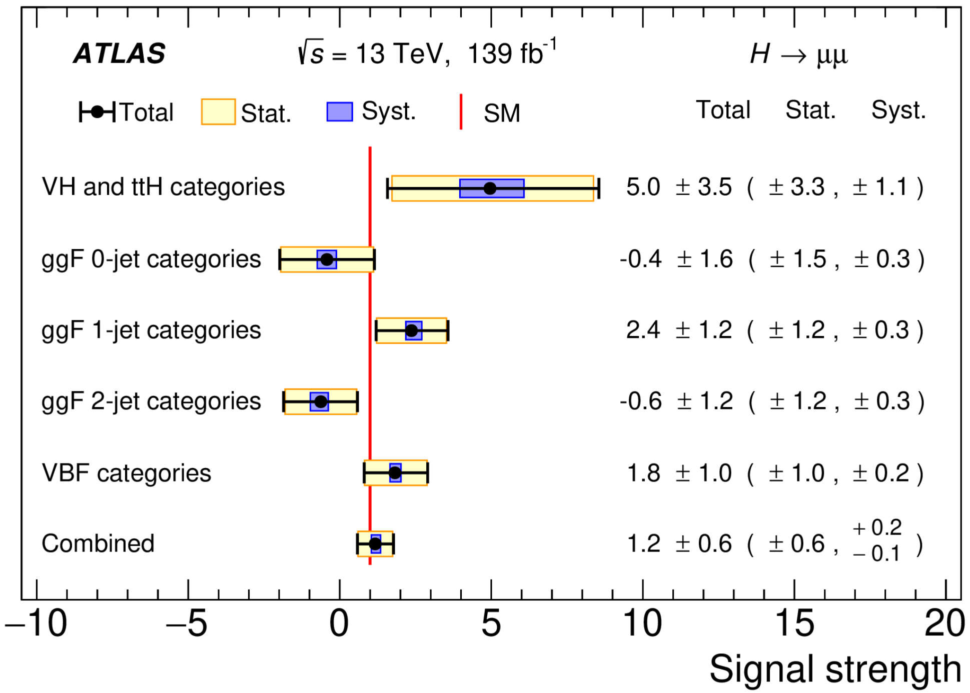
- Breit-Wigner line-shape (Drell-Yan) plus empirical functions
- Cutting-edge techniques to assure no biases to signal from background modelling

Category	Empirical Function	max(SS/ δS)[%]	max(SS/S_{SM})[%]
VBF Very High	Epoly1	-20.3	-34.8
VBF High	Power0	11.7	20.0
VBF Medium	Power0	8.5	16.4
VBF Low	Power0	11.2	2.4
2-jet Very High	Power1	-13.3	-34.5
2-jet High	Epoly2	-19.8	-41.2
2-jet Medium	Power1	19.8	40.9
2-jet Low	Epoly3	2.1	8.0
1-jet Very High	Epoly2	21.9	-53.4
1-jet High	Epoly2	-7.8	-18.5
1-jet Medium	Power1	4.2	7.9
1-jet Low	Power1	17.3	51.5
0-jet Very High	Power1	19.2	50.9
0-jet High	Power1	-19.4	43.5
0-jet Medium	Power1	25.8	69.4
0-jet Low	Epoly3	-20.8	-100.4
VH4L	Power1	20.7	230
VH3LH	Epoly2	36.9	210
VH3LM	Epoly3	33.6	276
$t\bar{t}H$	Power0	32.2	117

Example from ATLAS: spurious signal should be small enough

State of Art Results





	Measured σ/σ_{SM}	Observed Significance	Expected Significance
ATLAS	1.2 ± 0.6	2.0 σ	1.7 σ
CMS	1.19 ± 0.43	2.95 σ 2.98 σ (+ Run 1)	2.46 σ 2.48 σ (+ Run 1)

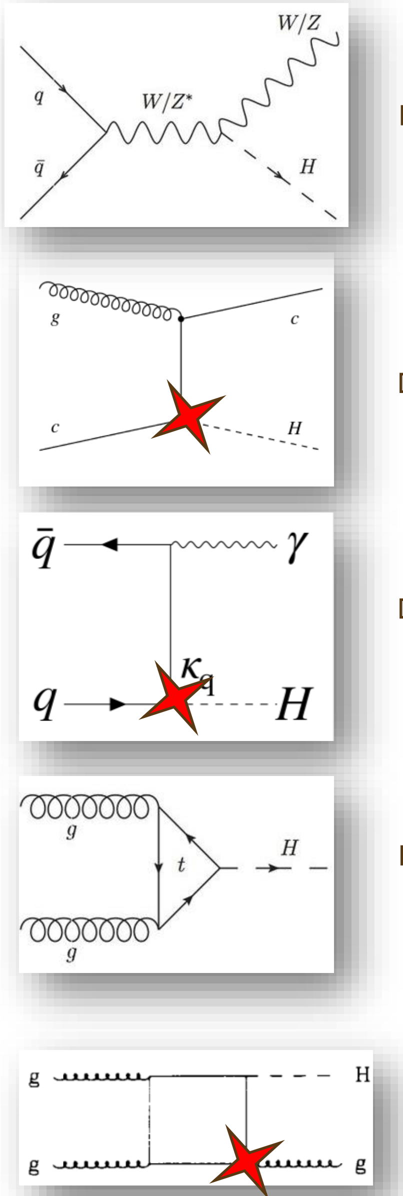
- Strong evidence for H→μμ
- Statistically limited results
- Sensitivity varies due to intrinsic muon resolution
- Room for improvements with larger stats. in Run-3

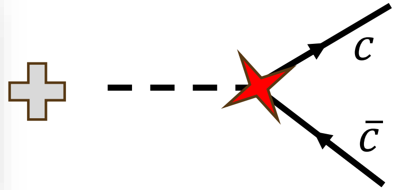
Higgs and Charm

A Charming Field for Exploration

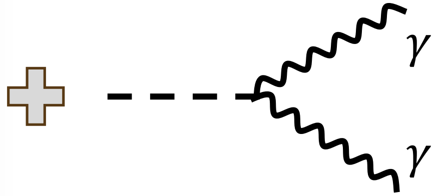
Charm quark:
more complex backgrounds,
difficulty of charm tagging

Larger c-H coupling:
affordable to look at rarer,
clean process or at production

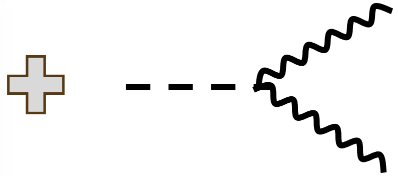




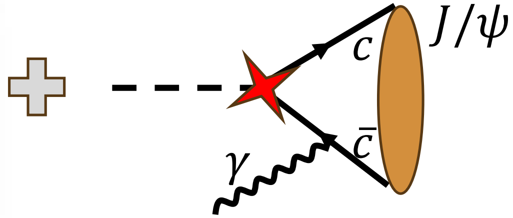
VH(cc):
main sensitivity, c-jet tagging



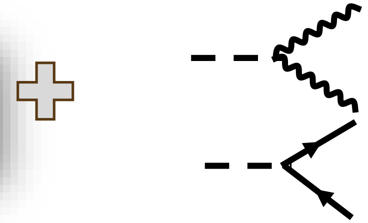
c + H($\gamma\gamma$):
complementary, c-jet tagging



γ+ H(ZZ):
indirect, mix with lighter coupling
other processes (triboson, Vbb, ...)



$\gamma + J/\psi$ or $Z + J/\psi$
complementary, bump hunting



jet + H:
Indirect through interference, can
perform inclusive pT measurement

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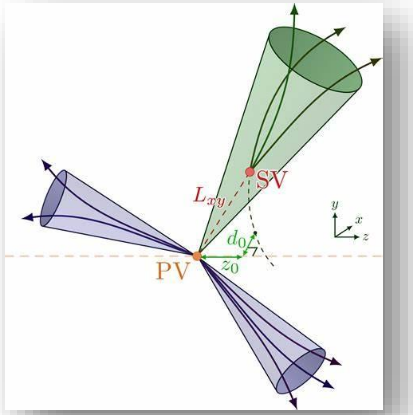
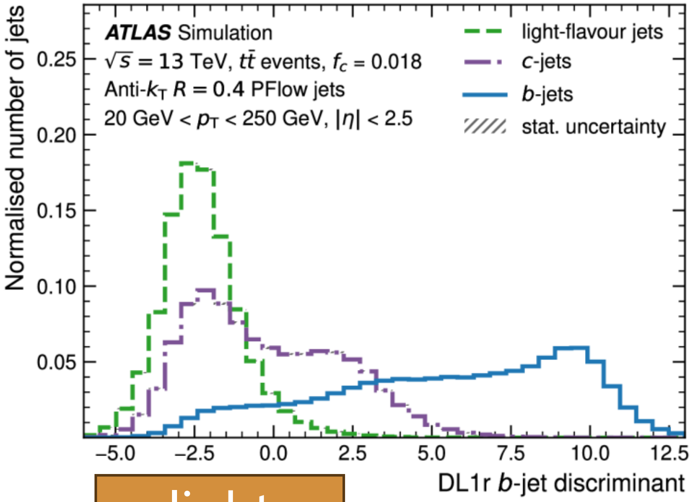
Direct Probe Needs C-tagging

Not easy task ...



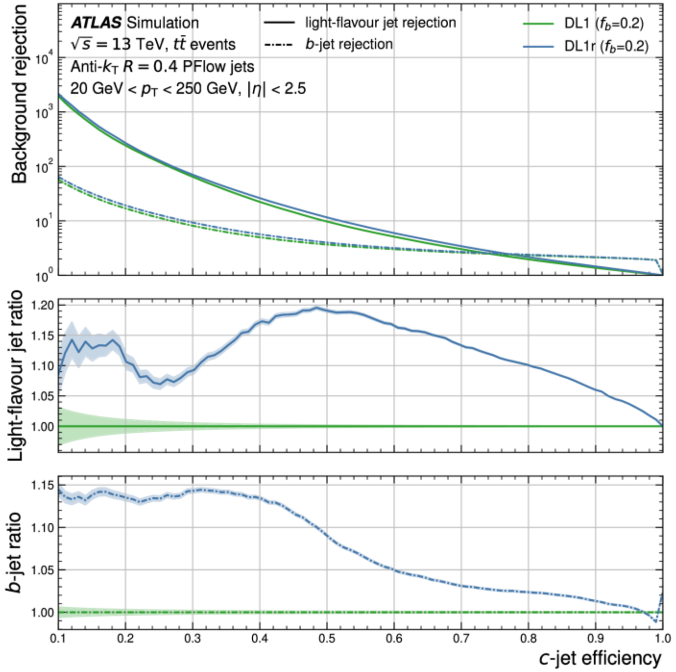


light

charm

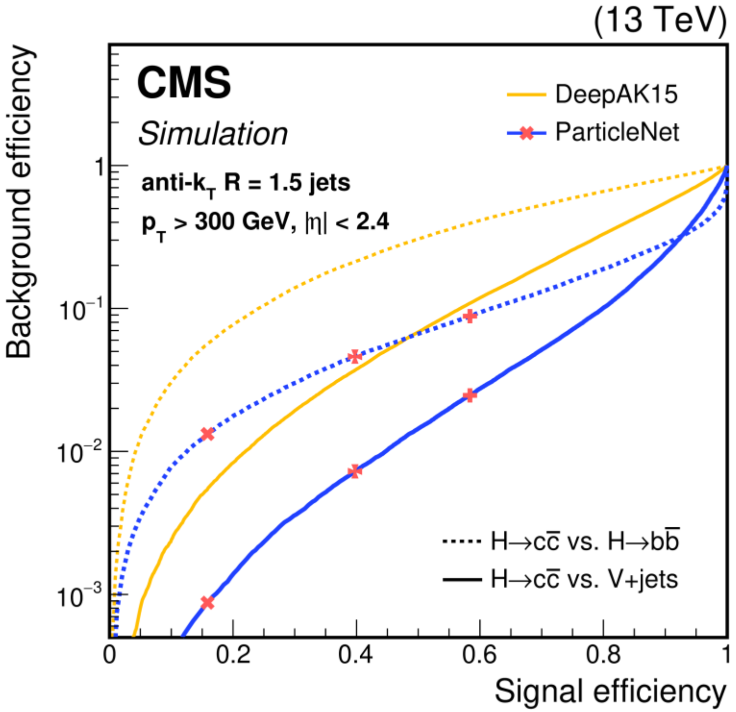
bottom

EPJC 83 (2023) 681



ATLAS small-R c-jet ROC

PRL 131 (2023) 061801



CMS large-R c-jet ROC

- **Neutral networks** maximize performance combining all known knowledge (SV, Impact Parameter, Kinematic Topology)
- Use taggers to **categorize events** into different c-like regions
- **Careful calibration** with top, g→cc before full analysis

A Sketch of VH(cc) Study

Final state: 0/1/2 charged leptons + two c-jets

Overwhelming SM backgrounds: from **instrumental** to **QCD** to **EWK**

Advanced techniques (**c-tagging**, **MVA**, **background control**) to push the limit

Boosted tagging utilized if explore high-pT

Master formula:

$$\textbf{Event categories} \times \textbf{c-purity categories} \times \textbf{fit discriminants}$$

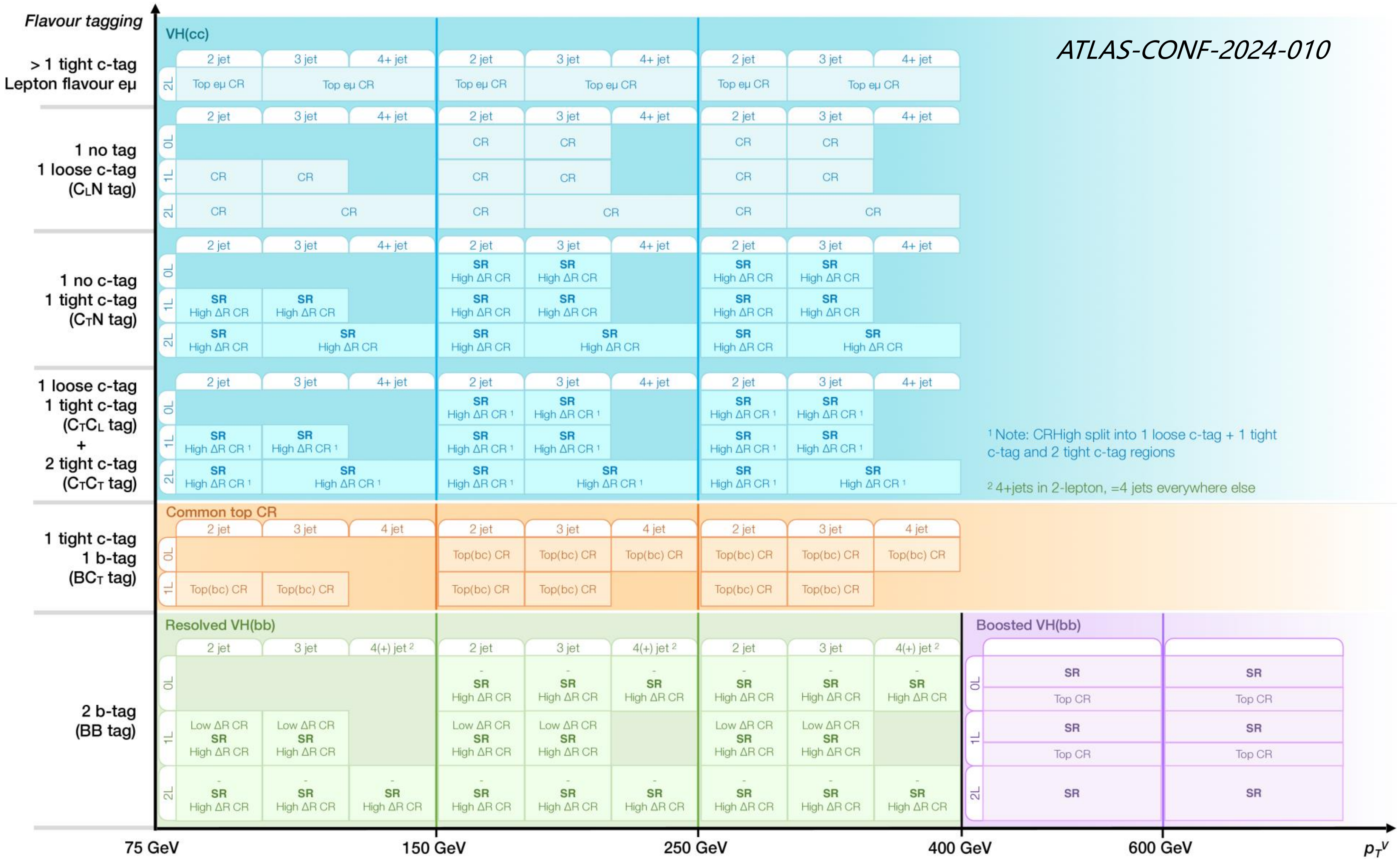
Data **control regions** to correct modelling of backgrounds

categorization either MVA or cut-based; discriminant MVA or m(cc)

Simultaneous fit of O(100) regions

Statistical results on VH, with proof of principle **validation with VV**

VH(cc): Final States and Categories



Example of
BIG data science

Careful design to optimize sensitivity and care of backgrounds

- ATLAS as example, CMS uses simpler categories but explore boosted region

VH(cc): Selected MVA discriminants

ATLAS-CONF-2024-010
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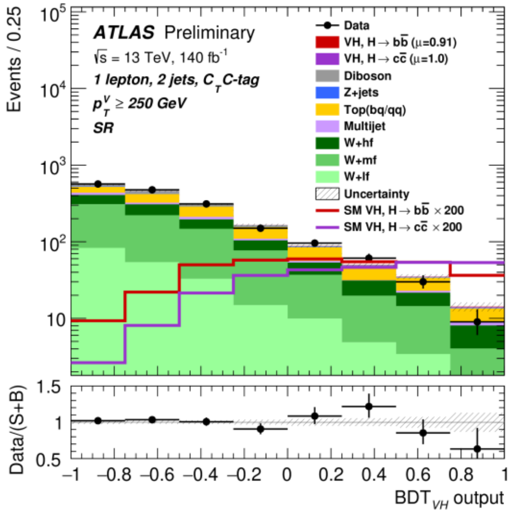
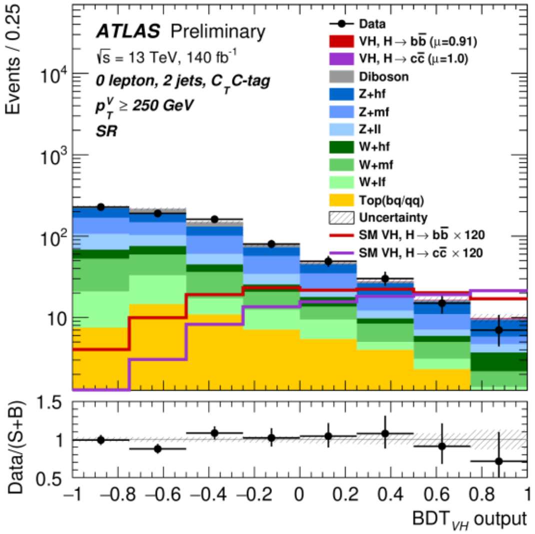
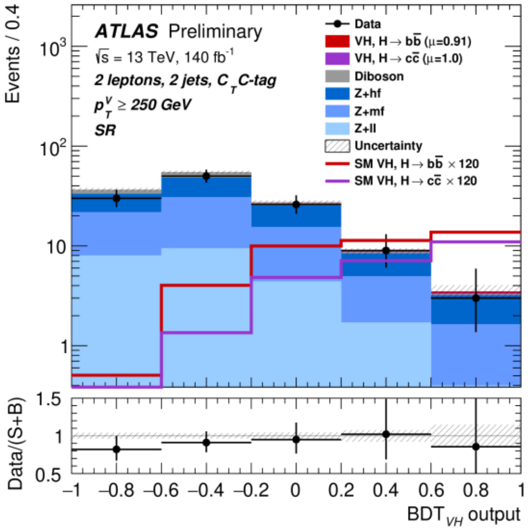


1-lepton
pT(H)>250 GeV

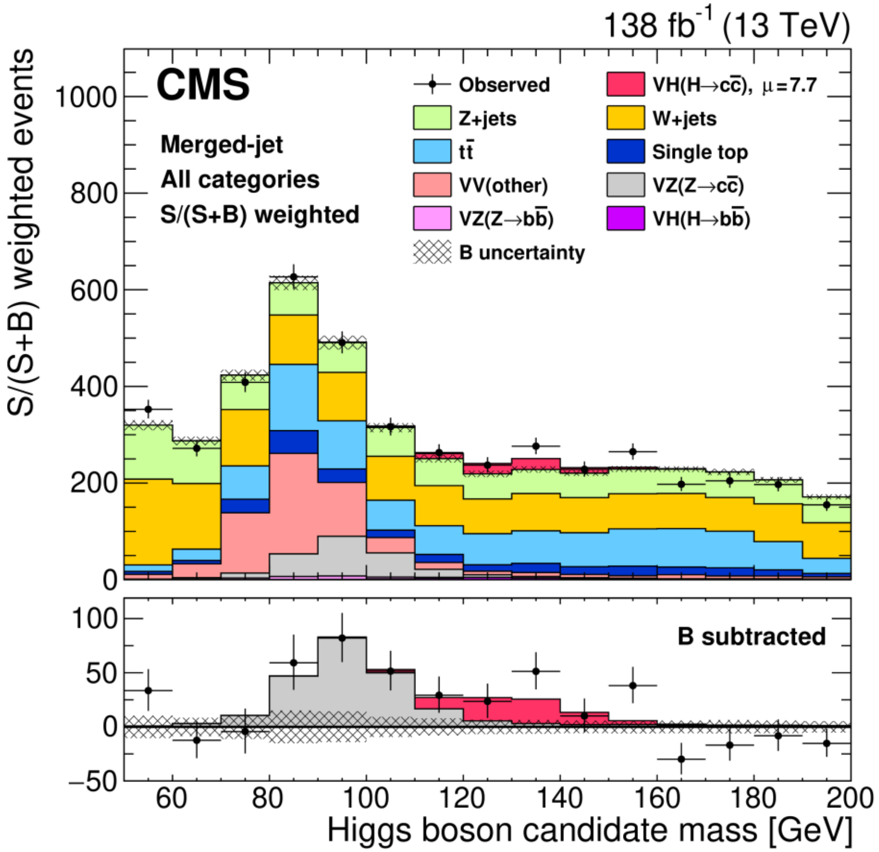
0-lepton
pT(H)>250 GeV





2-lepton
pT(H)>250 GeV

Combined for large-R jet
SR defined with MVA



Impossible to pursue H(cc) without the comprehensive techniques

VH(cc): Statistical Results

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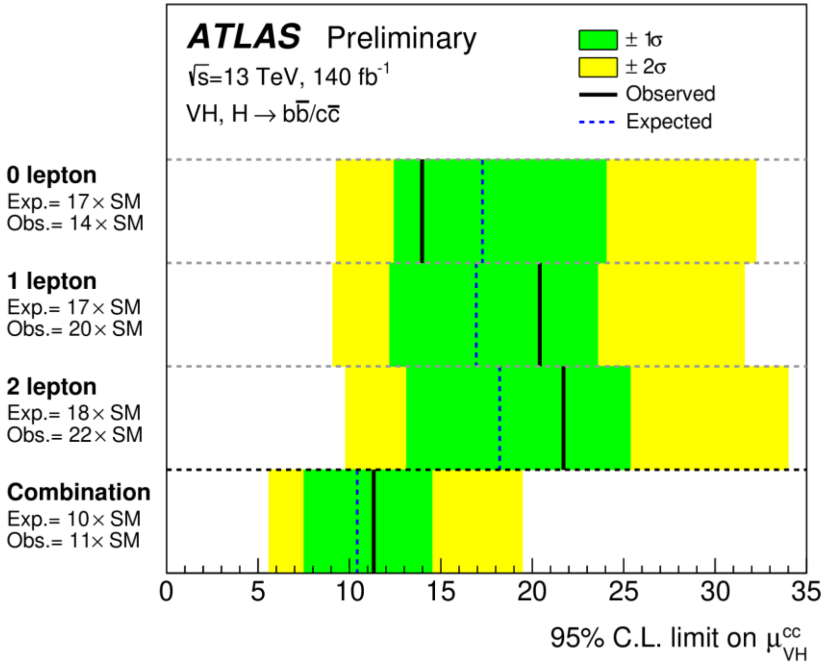
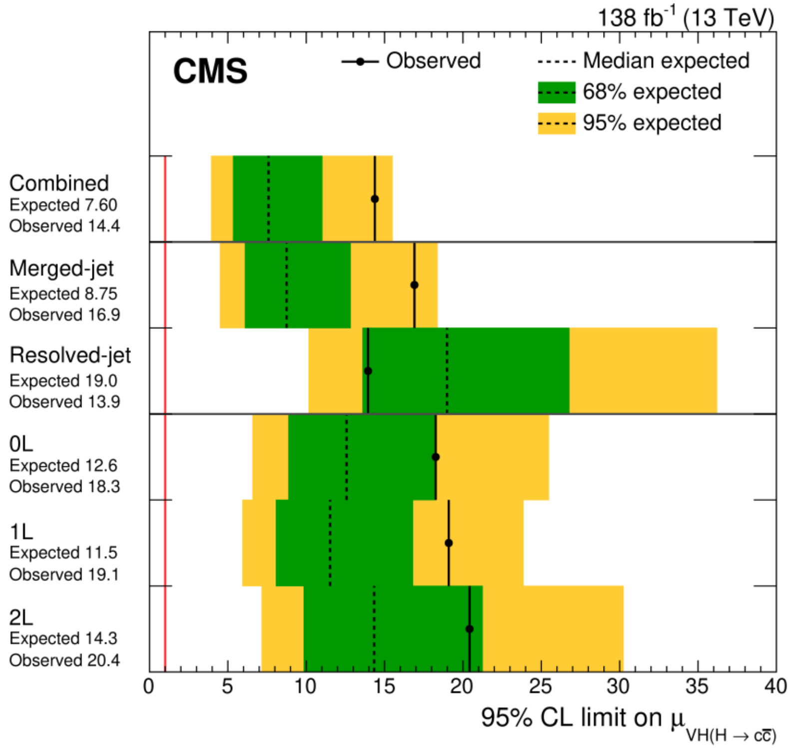




- **Compatible results** (precision of 3.5-5 on signal strength !!!)

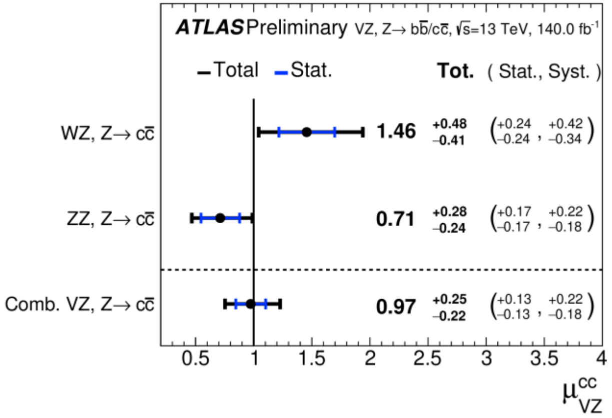
κ_c 95% interval

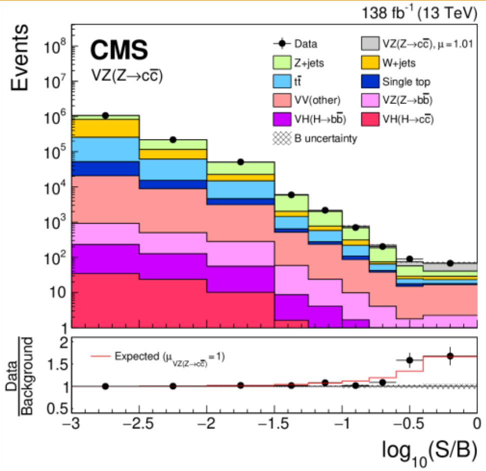
ATLAS: $|\kappa_c| < 4.2$

CMS: $1.1 < |\kappa_c| < 5.5$

- **Everything Counts** in such a comprehensive physics study
- May hint on future directions: categorization, pT v.s. jet radius, c-tagging

VZ(cc) well observed





VH(cc): Uncertainty

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Uncertainty source	$\Delta\mu / (\Delta\mu)_{\text{tot}}$
Statistical	85%
Background normalizations	37%
Experimental	48%
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	22%
Backgrounds	17%
Signal	15%

Uncertainty breakdown

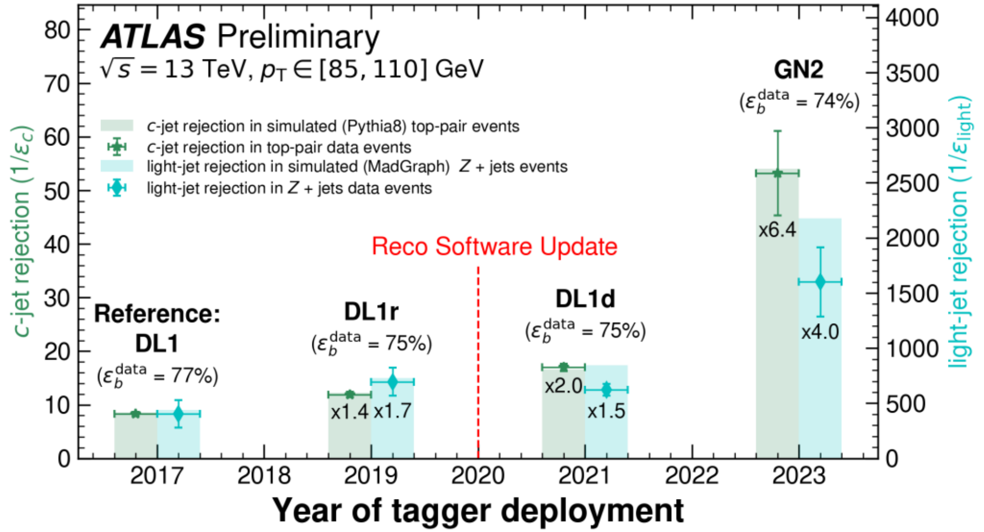
→ Valuable info. for designing future studies

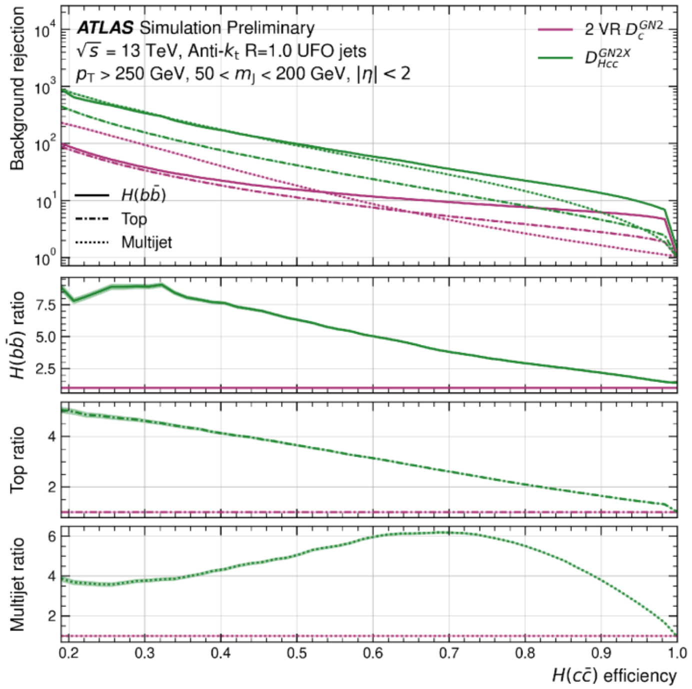
CMS table as example

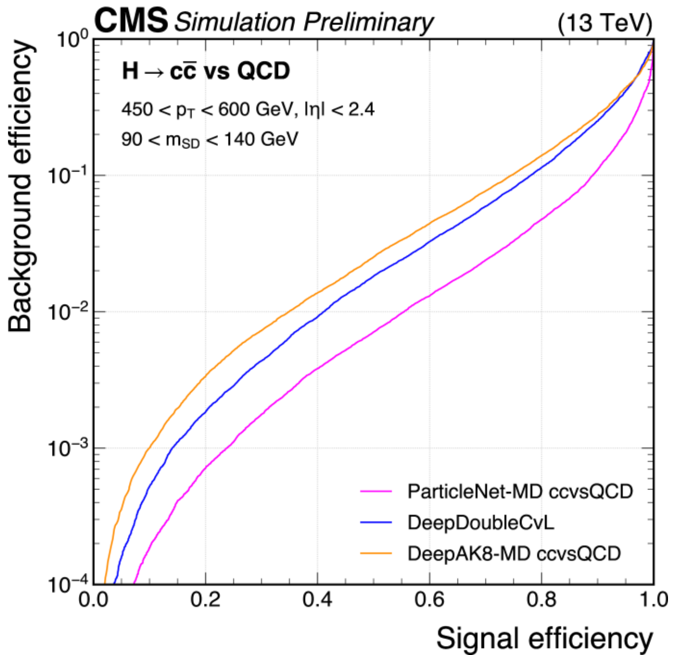
→ *ATLAS breakdown tells similar story, except that systematics weight more*

VH(cc): Peek into future from tagging perspectives

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2023-07/
ATL-PHYS-PUB-2023-021
CMS-PAS-BTV-22-001





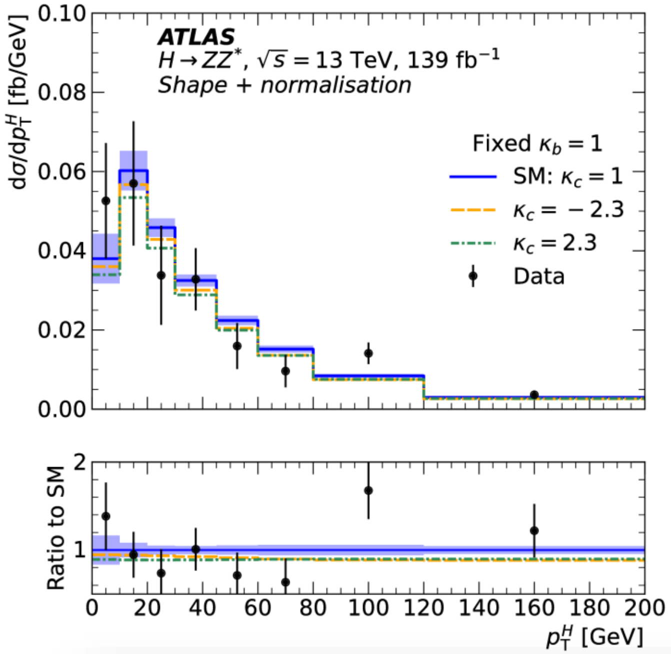


Updated ML techniques lead to improved tagging performance

→ Exciting results expected!

Indirect but Sensitive Probes

JHEP 05 (2023) 028

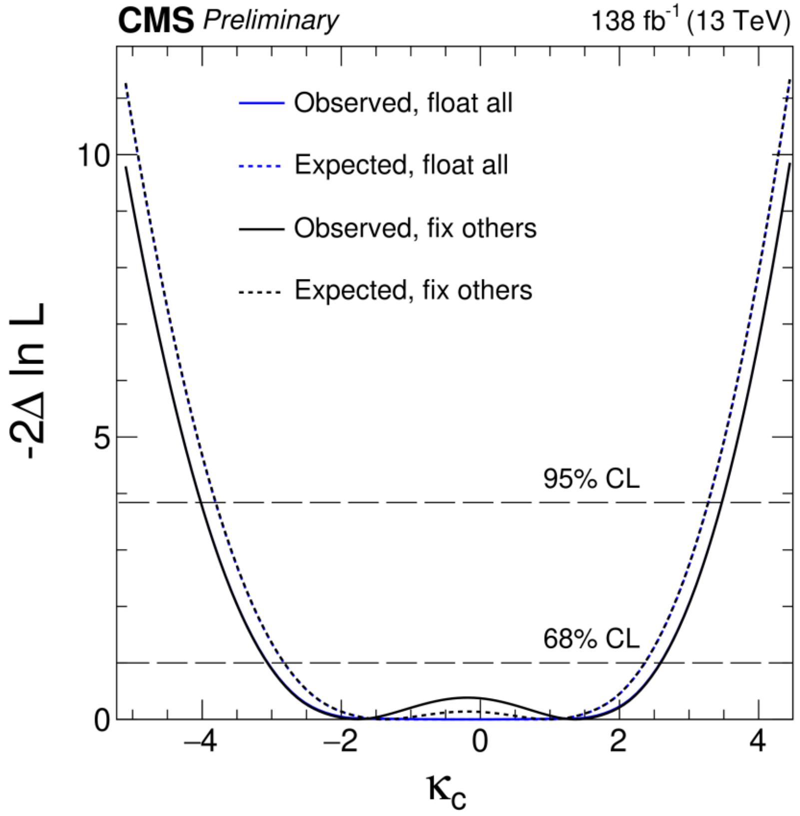


pT(H) from H→ZZ and γγ combined with VH(bb) and VH(cc) (previous version of ATLAS VH(cc) results)

Lead to **tight κ_c precision**

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM}=0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

CMS-PAS-HIG-23-011

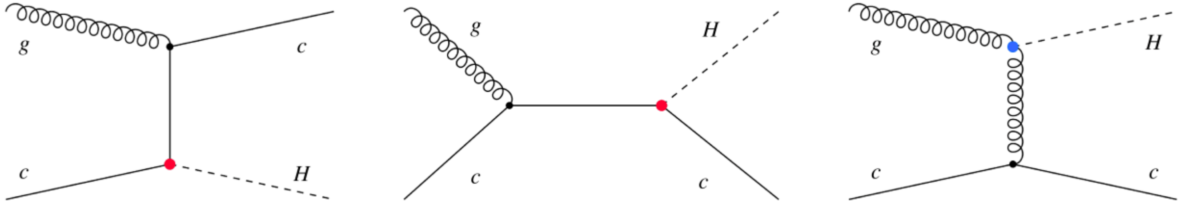


γ+ H(ZZ→4l) cross-section leads to **κ_c 95% interval of [-4.0, 3.4]**

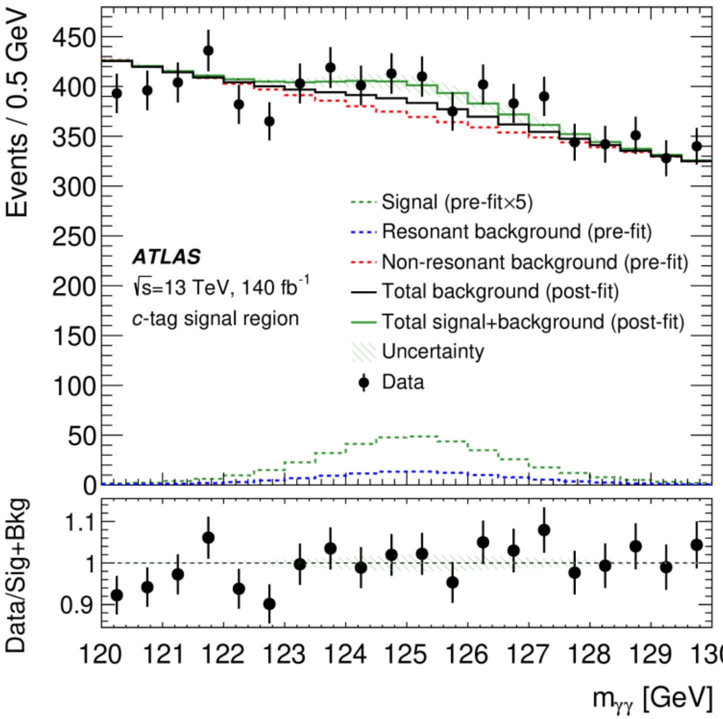
Various assumptions in the indirect constraints, complementary to direct probes

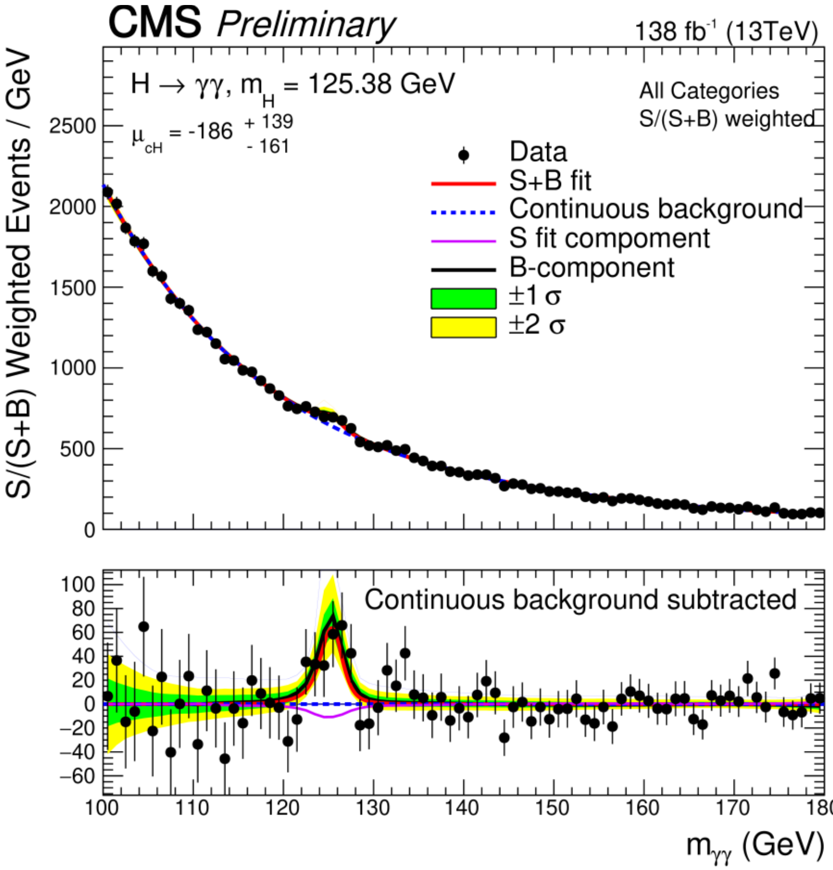
c + H Probes

arXiv:2407.15550
CMS-PAS-HIG-23-010



First studies deal with **c-jet + H(→γγ)**: benefit from good S/B and fitting strategy for background control





ATLAS measures **a first inclusive c + H cross-section**:

5.2 ± 3.0 pb

CMS **attempts to constrain κ_c** by fixing non-Yukawa terms

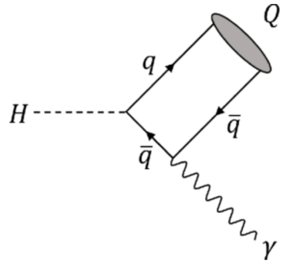
$$|\kappa_c| < 38.1$$

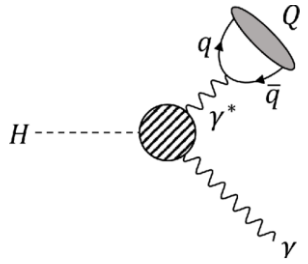
Good start, long way to go

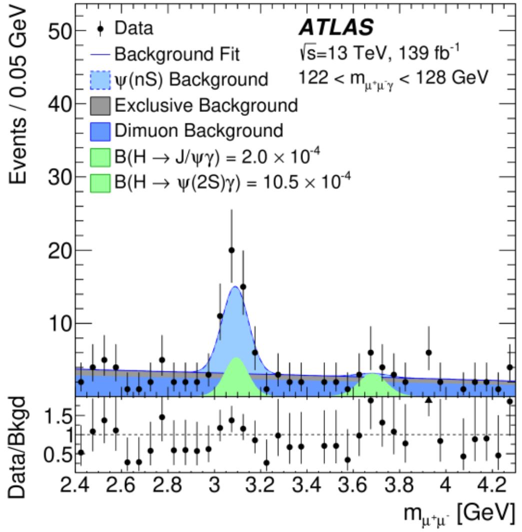
Probes from Flavor Sector

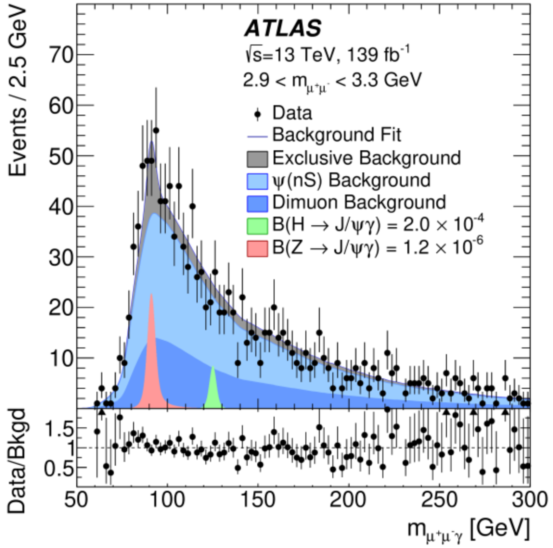
EPJC 83 (2023) 781

PLB 842 (2023) 137534



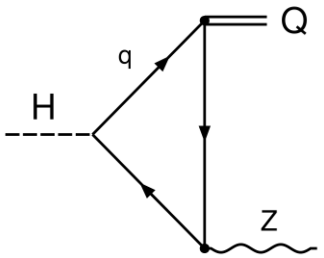


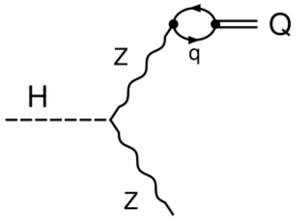


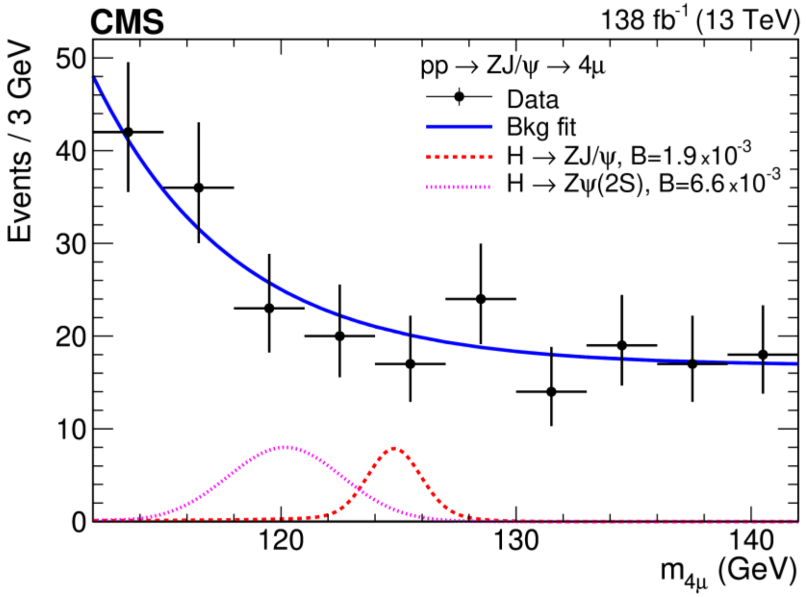


$\gamma + J/\psi(\rightarrow \mu\mu)$

Simultaneous fit on 2-body and 3-body masses (with parametrization)







$Z + J/\psi(\rightarrow \mu\mu)$

Similar to H→ZZ→4l

$B(H \rightarrow \gamma + J/\psi)$ < 2 x 10^{-4}
SM expectation ~ 3 x 10^{-6}

95% CL interval [-133, 175] for κ_c/κ_γ

$B(H \rightarrow Z + J/\psi)$ < 1.9 x 10^{-3}
SM expectation ~ 2.3 x 10^{-6}

Room for future improvements
SM precision for the rare decay at HL-LHC

Higgs and Light, FCNC, LFV

Higgs FCNC with top and light

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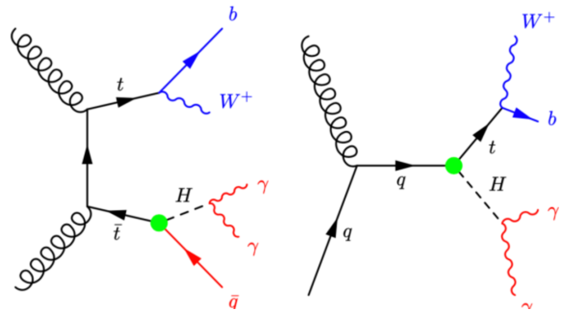
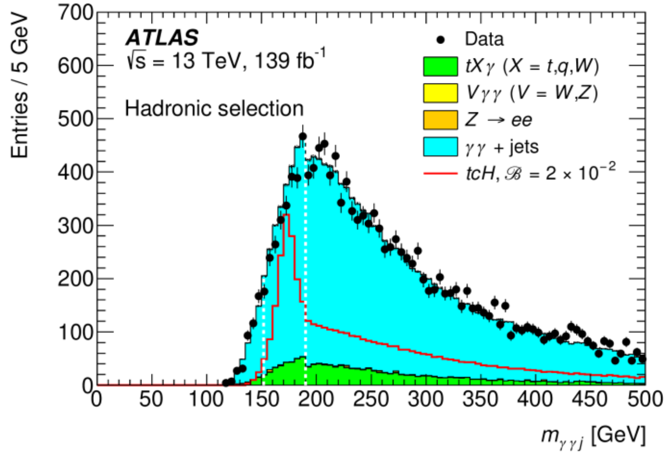
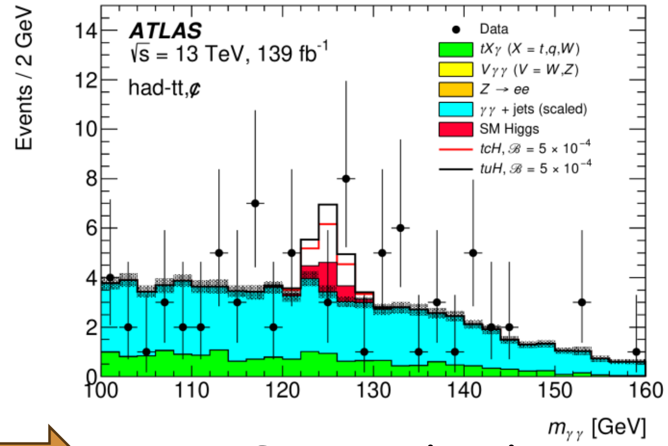
Explore two different production modes, and both hadronic and leptonic final states + **H(→γγ)**



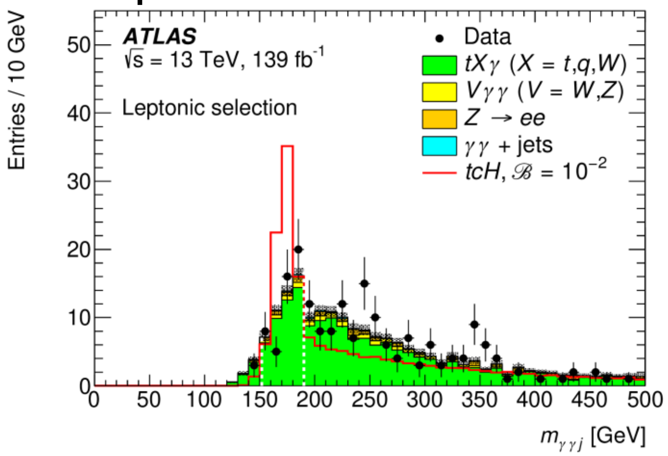
Hadronic final states

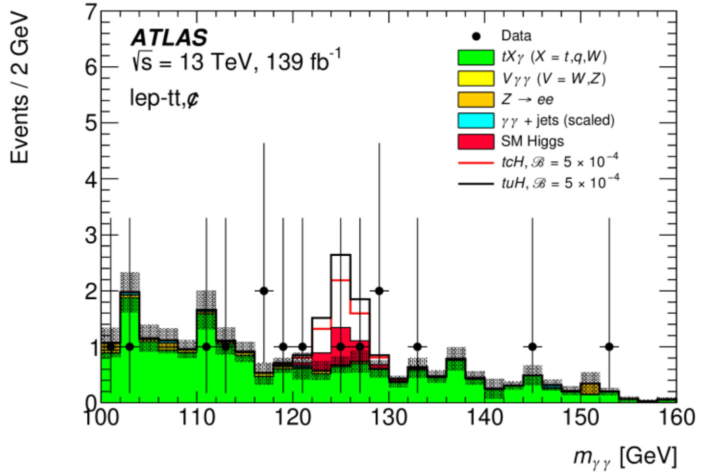


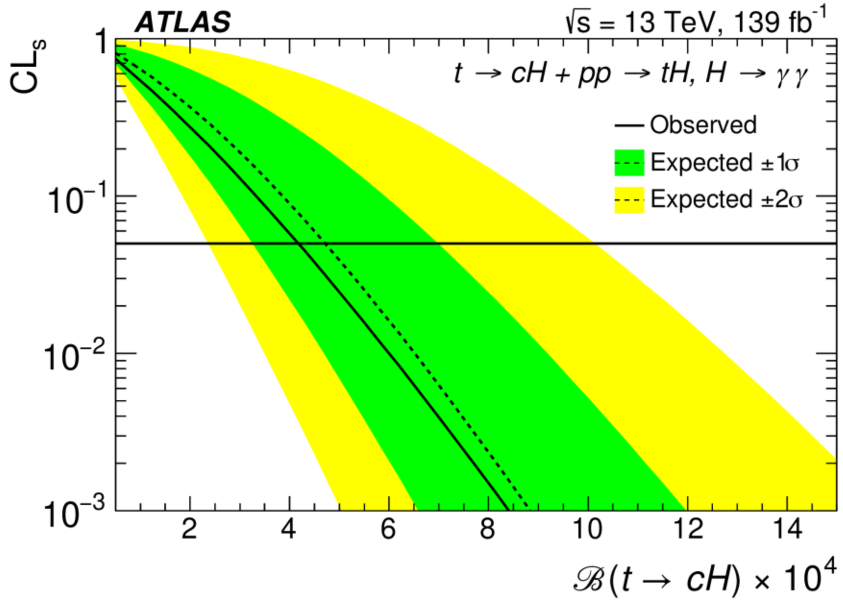


Leptonic final states

MVA, Categorization







m(γγ) fit offer 95% CL constraints:

B(t→cH) < 4.3 x 10^{-4} **Most stringent**

B(t→uH) < 3.8 x 10^{-4}

Higgs with Strange and Light

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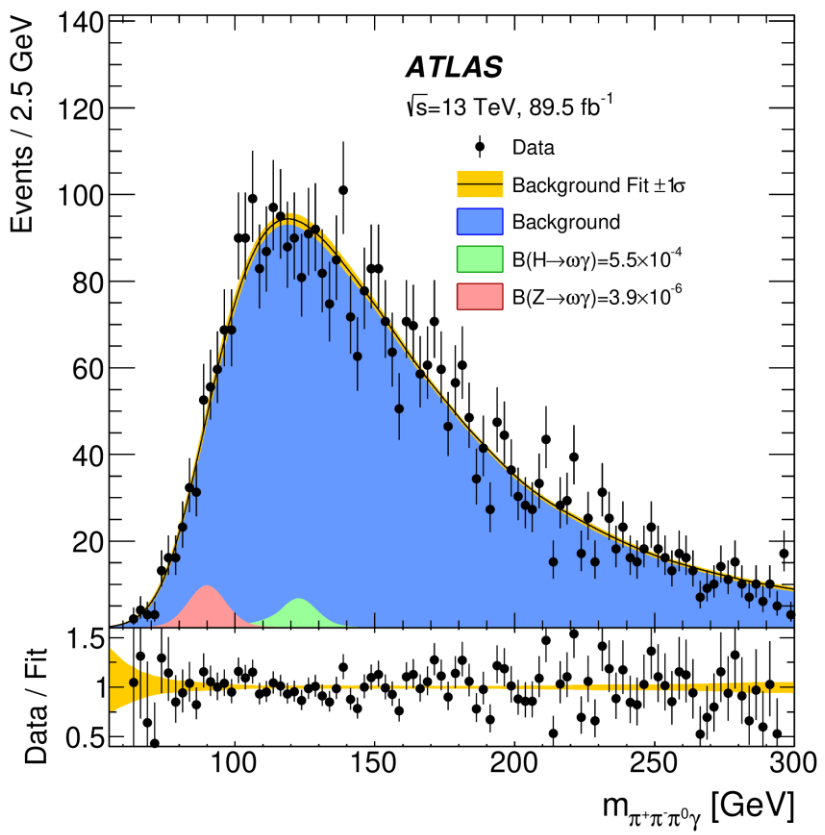
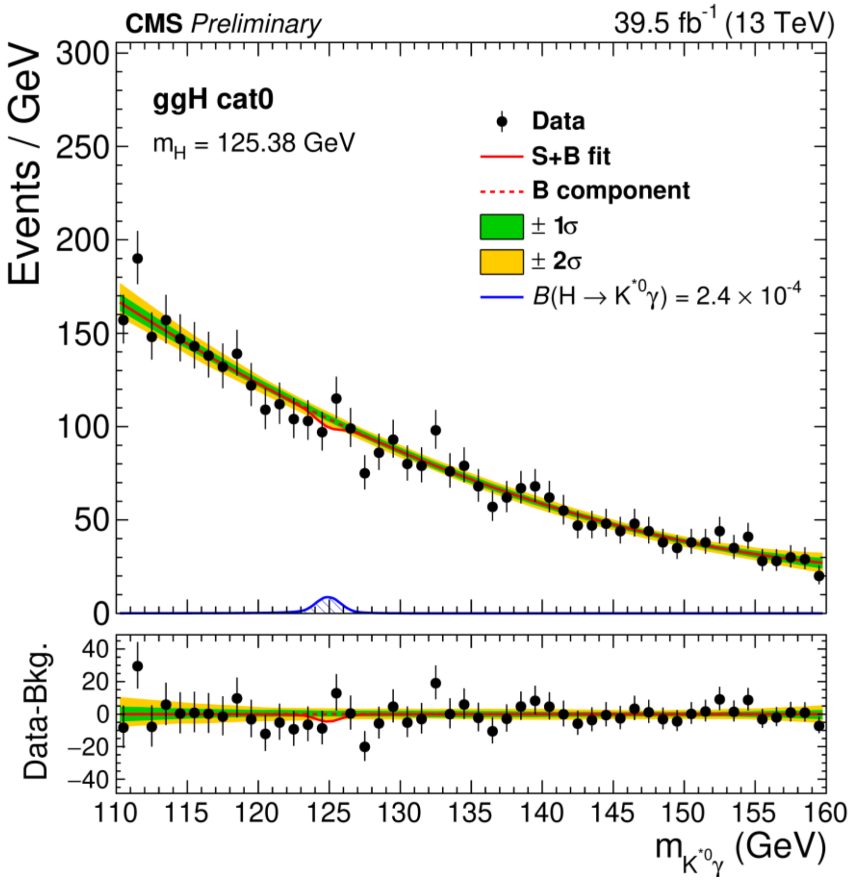
CMS-PAS-HIG-23-005

CMS: H→$\gamma+\rho_0(770)$ or $\varphi(1010)$ or $K^*(892)$
ATLAS: H→$\gamma+\omega_0(782)$ or $K^*(892)$

Multiple tracks + kinematic/mass constraints
→ mass fitting leads to 95% constraints on B





ATLAS:
B(H→$\gamma+\omega_0$) < 5.5 x 10^{-4}
B(H→$\gamma+K^*$) < 2.2 x 10^{-4}

CMS:
B(H→$\gamma+\rho_0$) < 3.7 x 10^{-4}
B(H→$\gamma+\varphi$) < 3.0 x 10^{-4}
B(H→$\gamma+K^*$) < 1.7 x 10^{-4}

Previous discussion of using γ+ **H(ZZ→4l)** can also probe light Yukawa:

$|\kappa_s| < 50$

$|\kappa_{u,d}| < O(1000)$

CMS-PAS-HIG-23-011

The way to light flavor started …

Higgs with LFV

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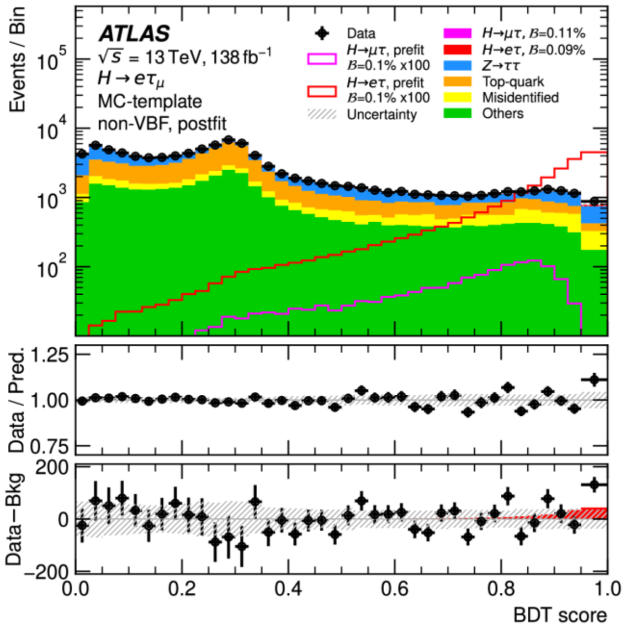
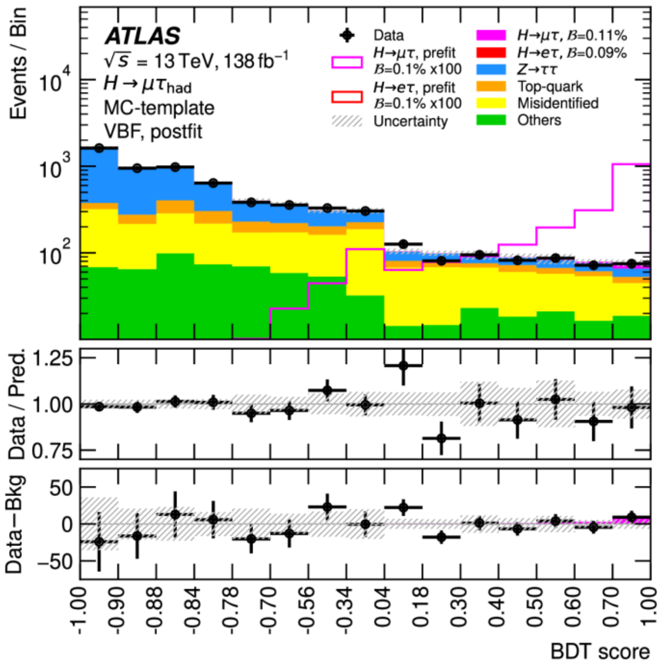
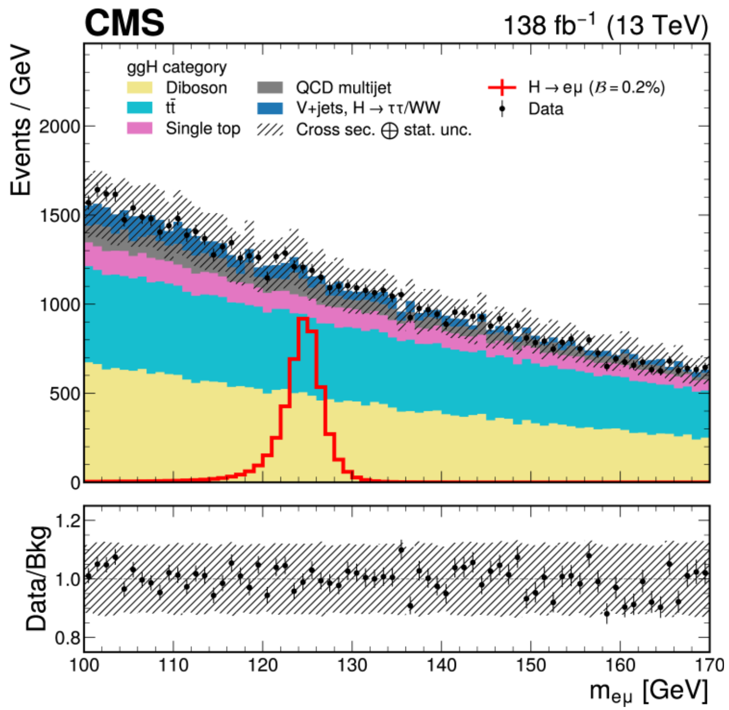
H→μτ, eτ, eμ probes LFV at Higgs sector
➔ new input to the global LFV efforts

τ reconstruction + MVA





H→eμ similar strategy as H→μμ

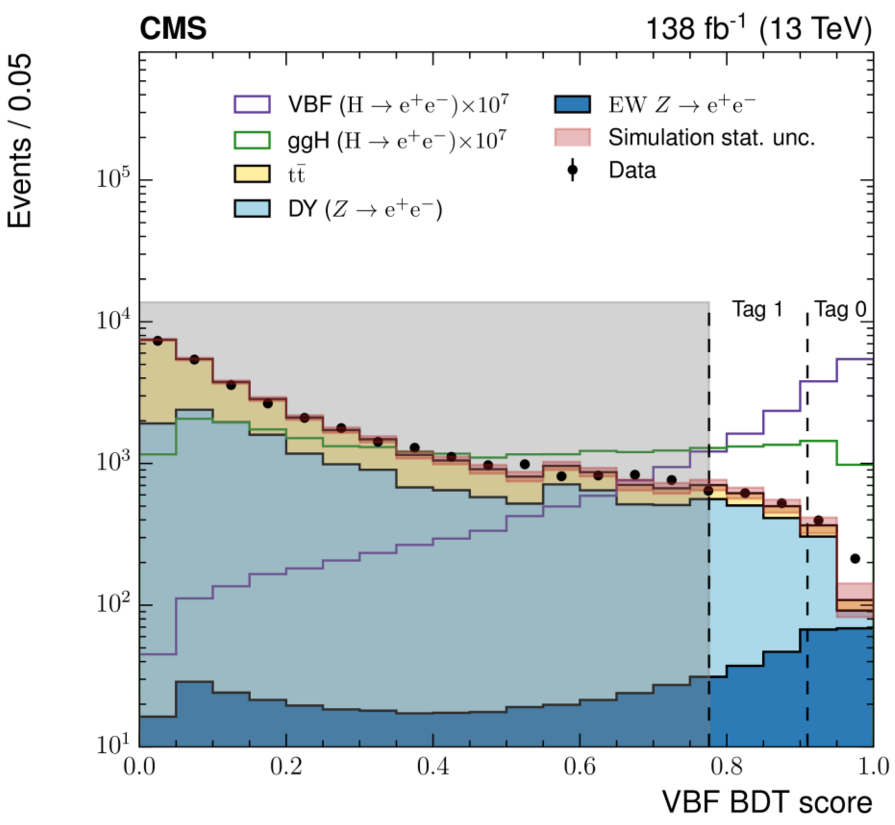


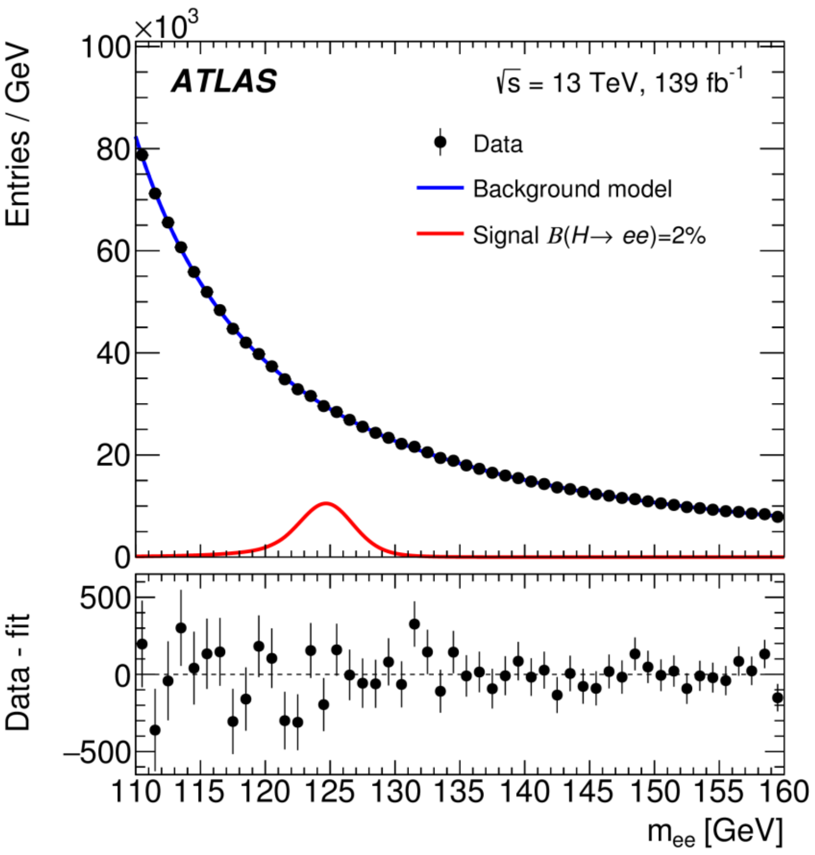
Latest stringent upper limit at 95% CL:
B(H→ μτ) < 1.8 x 10^{-3}, B(H→ eτ) < 2.0 x 10^{-3}, B(H→ eμ) < 4.4 x 10^{-5}

Higgs with electrons

PLB 846 (2023) 137783
PLB 801 (2020) 135148

The lightest to imagine at the LHC





Upper limit at 95% CL:

B(H→ ee) < 3.6 x 10^{-4} (ATLAS)

B(H→ ee) < 3.0 x 10^{-4} (CMS)

Pursue better precision?

- Important to separate 1st and 2nd lepton generation
- Careful study needed to deal with loop contributions (like Dalitz decays to ee+γ)

Conclusion

- Higgs Yukawa interactions play key roles in the SM, and the phenomena with **second generation and lighter, rarer processes are actively pursued**

- Throughout years, many novel methods implemented for studying **H-μ and H-c → precision is now at unprecedented level**

- Lighter fermions, FCNC, LFV-related phenomena are extremely difficult to observe, the march is on the way …

- Expect more novel methods along with enlarged Run3 + HL-LHC data

Will be surprised by
the ultimate precision then w.r.t. today
as we are now w.r.t. beginning of LHC!

A LONG, CHARMING WAY TO GO
THANKS!