Higgs Physics at HL-LHC

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on behalf of the ATLAS and CMS Collaboration

DIS2023 (27-31 March 2023)

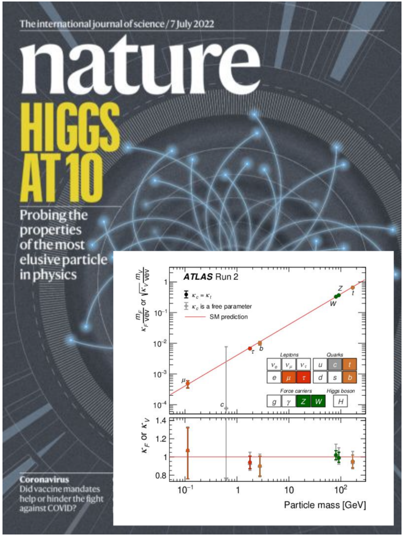
Introduction

The Higgs boson at the heart of SM, linked to many **fundamental questions** about our universe

- We **have to** study it in all possible aspects
- And the LHC will remain our only tool for a while

We have achieved **a lot** in the past 10 years !

- Covering **all of our programme**
  - Spanning all possible production modes and decay channels
  - Both SM and BSM
- Very impressive results
  - Precision on the mass: 0.1%
  - Couplings known at 5% (bosons) and 10% (heaviest fermions)
  - Huge progress on searches for couplings to second generation fermions, for di-Higgs production
  - + many others shown at this conference

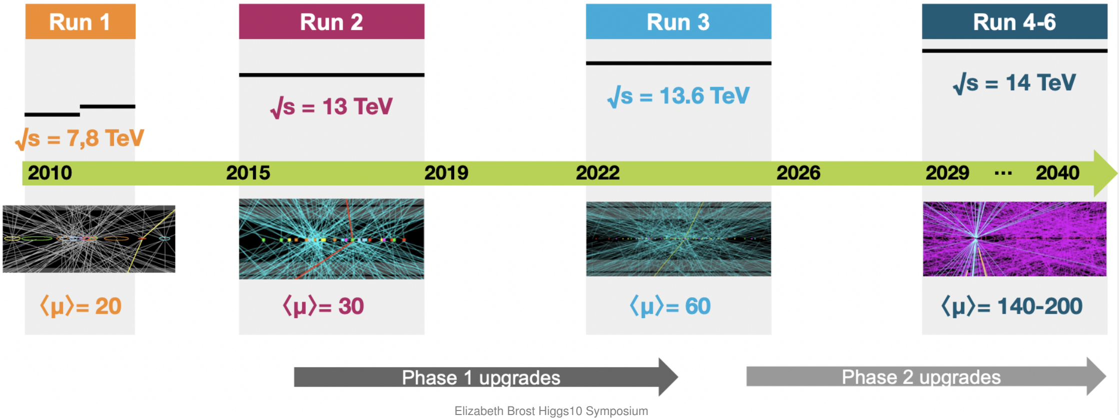


Nature 607 (2022)

LHC proton-proton dataset

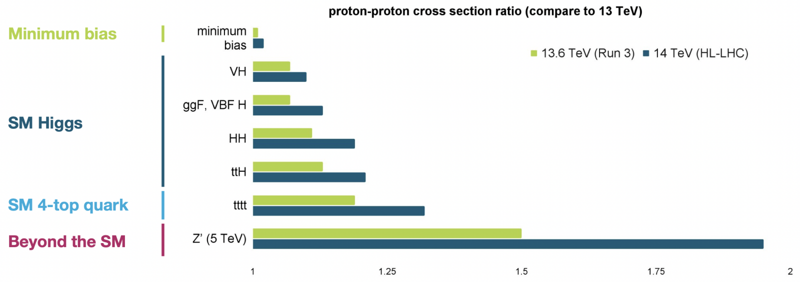
- Expect 3000 fb^{-1} per experiment

The LHC schedule, from the ATLAS and CMS perspective

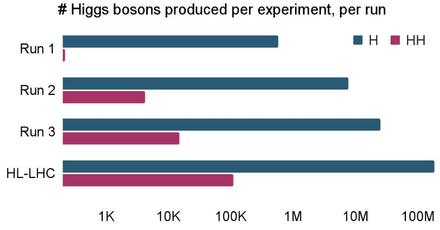


- Center of mass energy will raise to 14 TeV
- Average number of interactions per bunch-crossing (pile-up) up to 140-200 is very challenging, detector upgrades needed

Larger center-of-mass energy → larger Higgs boson cross sections



- 180M Higgs bosons produced per experiment!
- **Recent efforts for HL-LHC projections**
  - European Strategy Update (2018-2020)
  - CERN Yellow report (CERN-2019-007)
  - Snowmass White Paper Contribution, 2022



Elizabeth Brost Higgs10 Symposium

How are HL-LHC projections made

- **Start from:**
  - published LHC Run 2 results, or
  - simulations (usually using a simplified detector simulation such as DELPHES)
- **Adapt to HL-LHC conditions:**
  - center-of-mass energy: 13 TeV $\rightarrow$ 14 TeV
  - larger dataset: 140 fb^{-1} $\rightarrow$ 3000 fb^{-1}
  - simulated detector and reconstruction performance
  - theory and experimental uncertainties: usually present a few scenarios
- **Detector and trigger performance comparable to Run 2**
  - New detectors and reconstruction algorithms expected to **counteract pile-up effects**

Systematic Uncertainties

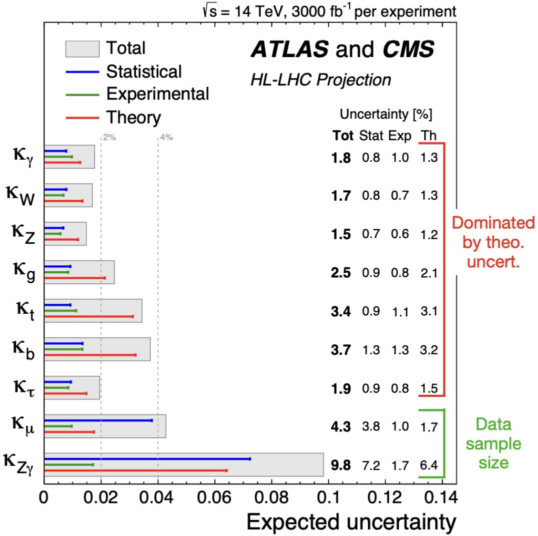
- Projections are based on **educated estimates**, especially regarding **systematic uncertainties**
  - **Experimental uncertainties expected to decrease**
    - Clever use of larger datasets and new detectors
    - 1% goal for luminosity uncertainty
  - **Theoretical uncertainties halved** with respect to current values
    - Improvements expected in perturbative corrections, PDFs, α_S
  - **Larger available dataset**
    - Will help to define more control regions or allow to optimise differently the analysis strategy in general
  - Many **analysis uncertainties** will shrink
    - Use of profiling / better control regions
  - **MC statistical uncertainties** expected to be **negligible**
    - Requires huge improvements for generators
    - Requires improvements to our simulation and reconstruction software, in order to fit within our CPU and disk storage limits

Higgs couplings to SM particles

Higgs couplings to SM particles

Yellow report projections

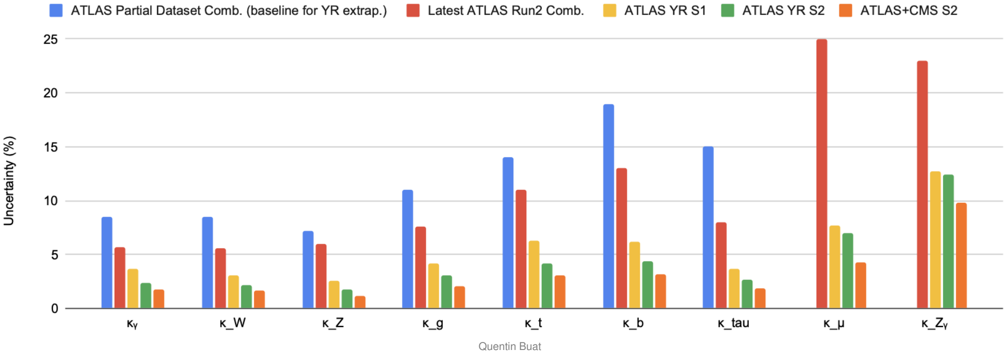
- Study performed in 2017 for the European strategy
- $H \to \mu\mu$ and $H \to Z\gamma$ measurements still limited by size of the collected dataset
- Other couplings dominated by theoretical uncertainties (despite assumed /2 improvement)
  - Impressive projected precisions
    - 1.5% for boson couplings
    - 2-4% for fermion couplings



Yellow report

Higgs couplings to SM particles - evolution of the measurements

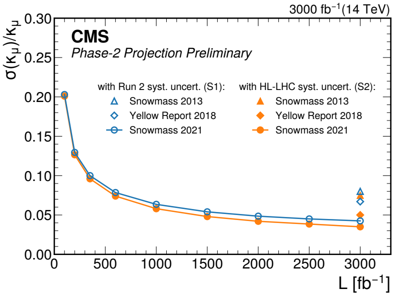
- ATLAS partial Run 2 dataset analyses (36.1fb^{-1})
- ATLAS full Run 2 measurements have improved beyond expectations (139 fb^{-1})
  - i.e. $H \to \tau\tau$ or $H \to bb$ improved as $\sim \sqrt{\mathcal{L}}$ despite being dominated by systematic uncertainties
- **YR projections (3000 fb^{-1})** based on ATLAS partial Run 2 dataset analyses (36.1fb^{-1})
  - Two different **scenarios for systematic uncertainties** - **S1** and **S2**
  - **ATLAS+CMS, S2 scenario**

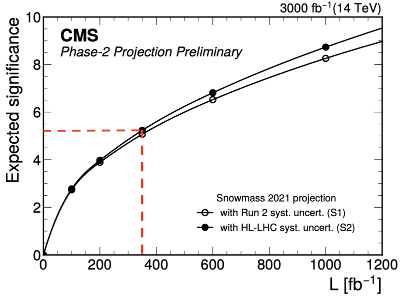


Higgs couplings to SM particles

Evolution of the projections

- YR projections performed from partial Run 2 dataset analyses
- Full Run 2 measurements have improved beyond expectations
- $H \to \mu\mu$ projection based on the CMS Run 2 3σ evidence analysis (DELPHES)
    - 30-35% improvement compared to Yellow report 2018 (♦)
    - 3-4% uncertainty on κ_μ at HL-LHC
    - Observation plausible with 350 fb^{-1} of data (caveat: assumes CMS Phase 2 upgrade tracker)



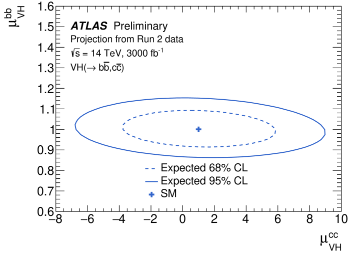


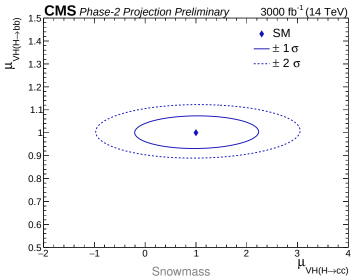
CMS-PAS-FTR-21-006

Higgs couplings to the second generation fermions

$H \to c\bar{c}$

- VH, $H \to c\bar{c}$ channel, combined with VH, $H \to b\bar{b}$
- Projection based on recent updates from ATLAS and CMS using Run 2 dataset
- CMS projection makes use of the powerful boosted analysis strategy
  - Based on merged-jet topology of the Run 2 analysis
  - $b\bar{b}$ and $c\bar{c}$ tagging efficiencies are directly constrained in the analysis by the $VZ(Z \to b\bar{b})$ and $VZ(Z \to c\bar{c})$ events
- CMS: $\mu_{VH(H\to cc)} = 1.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$
- ATLAS: $\mu_{VH(H\to cc)} = 1.0 \pm 3.2$
  - Dominated by background uncertainties
- Very interesting results from $H \to c\bar{c}$ to be expected





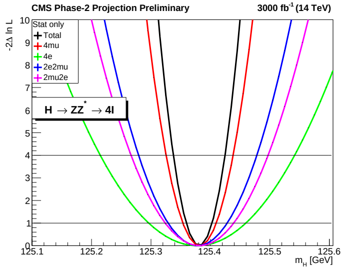
Higgs mass and width

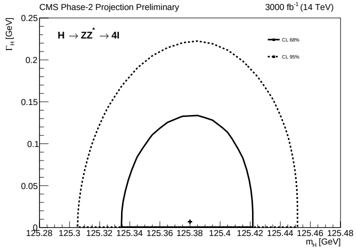
Mass measurement

- Updated CMS projection: $\Delta m_H \sim 30$ MeV
  - $H \rightarrow ZZ \rightarrow 4\ell$: 125.38 ± 0.03 [0.022(stat) ± 0.020(syst)] GeV
  - $H \rightarrow \gamma\gamma$: 125.38 ± 0.02(stat) ± 0.07(syst) GeV
- Detector upgrades (impact estimated with DELPHES)
  - 25% improvement in resolution for the 4μ final state
  - 17% yield increase for $4e$ and 4μ (tracker and muon stations acceptance)

Width measurement

- Direct measurement possible in precision channels
  - $\Gamma_H < 177$ MeV at 95% C.L.
  - Limited by the mass lineshape resolution

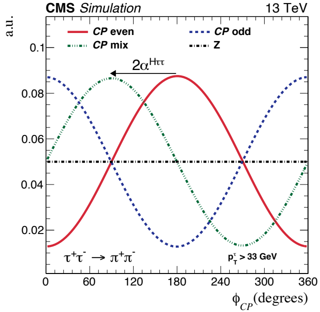


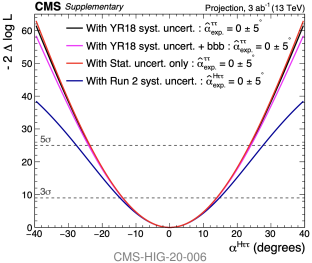


CMS-PAS-FTR-21-007

Higgs CP properties

- **All indications that Higgs is a 0+ particle**
- Pure pseudo-scalar hypothesis essentially ruled out but still a lot of room for mixed states
  - Study done with vector boson and fermion couplings in production (VBFH, ttH) and decays ($H \to \tau\tau$, $H \to VV$)
- $H \to \tau\tau$
  - The angle between the planes spanned by the pion pairs, is used to determine the CP-mixing angle
  - Update from CMS for Snowmass
    - Could constrain the mixing angle between pseudoscalar and the scalar Higgs Boson $\alpha^{H\tau\tau}$ at the level of 5°



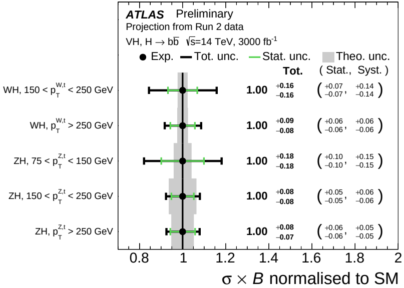


CMS-HIG-20-006

Differential measurements

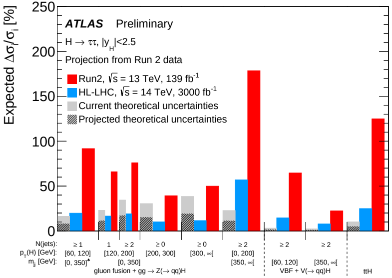
VH, $H \to bb$ prospects (ATL-PHYS-PUB-2021-039)

- $<10\%$ uncertainty at high p_T
- Smaller gain wrt Run 2 at low p_T
  - Requires progress in bkg modelling / theory unc



$H \to \tau\tau$ prospects (ATL-PHYS-PUB-2022-003)

- $\sim 10\%$ for p_T^H around 200-300 GeV
- $<5\%$ for high m_{jj} VBF



→**Both measurements limited by systematic uncertainties** (except at very high p_T^H)

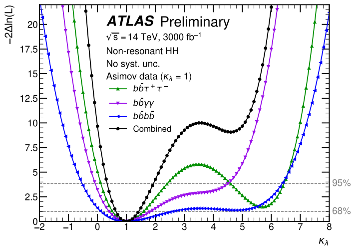
→ Projections results are still exploiting the STXS 1.2 stage but with the larger HL-LHC dataset, a **more granular binning will be considered**

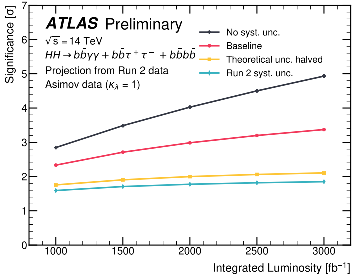
The road to di-Higgs observation?

Improving the main search channels

Significant progress on main channels since the European strategy

- Main HH channels require one $H \to bb$, as BR($H \to bb$)=58%:
  - $bbbb$, $bb\gamma\gamma$, $bb\tau\tau$
- ATLAS $bb\gamma\gamma$ and $bb\tau\tau$ and CMS $bb\gamma\gamma$ updated for Snowmass
  - Make use of latest Run 2 analysis improvements
- Recent ATLAS $bbbb$ update (combined with $bb\gamma\gamma$ and $bb\tau\tau$)
  - Based on the latest Run 2 analysis
  - Di-Higgs significance for 1 experiment
    - Reach 4.9σ stat-only
    - **3.4σ** with systematics (wrt 3.0σ at ESPP)
  - Constraints on self-coupling
    - $\kappa_\lambda \in$ **[0.5, 1.6]** wrt [0.25, 1.9] at 68% CL



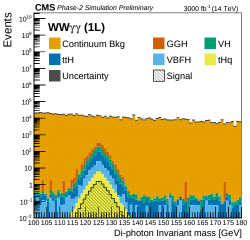


ATL-PHYS-PUB-2022-053

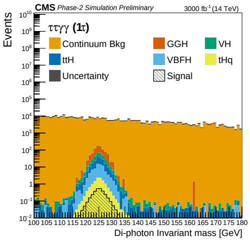
Exploring new channels

- Adding other channels to increase a bit overall *HH* sensitivity
- CMS $HH \rightarrow WW\gamma\gamma$ and $HH \rightarrow \tau\tau\gamma\gamma$
  - Exactly two photons with $100 < m_{\gamma\gamma} < 180$ GeV
  - 4 mutually exclusive final states
    - 1 or 2 lepton ($e^{\pm}$ or $\mu^{\pm}$)
    - 1 or 2 hadronic taus (no $e^{\pm}$ or $\mu^{\pm}$)
- Selections using DNN or cut-based analysis, then fit $m_{\gamma\gamma}$ spectrum

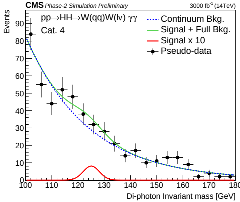
Final State	Significance (stat+exp+theory)
$WW\gamma\gamma$	0.21
$\tau\tau\gamma\gamma$	0.08
Combination	0.22

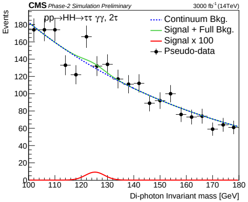


(a) One lepton final state



(b) One tau final state





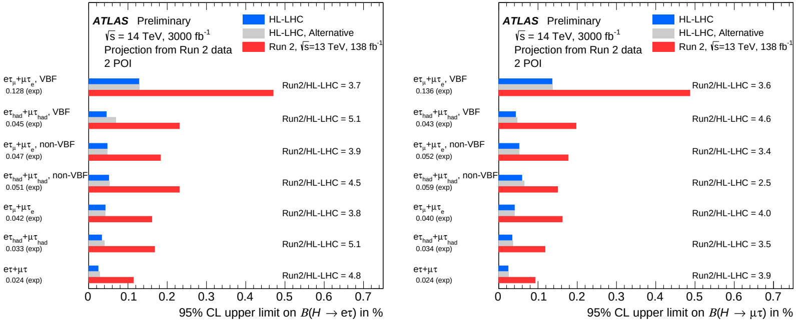
CMS-PAS-FTR-21-003

Higgs in search for BSM

Looking for rare or forbidden decays

Lepton-flavour violating decays with ATLAS

- $H \to e\tau$ and $H \to \mu\tau$, based on arXiv:2302.05225
  - Two bkg estimation methods
    - MC templates: dominated by systematics
    - Data-driven Symmetry method in $\tau_\ell \ell$ channels: dominated by data statistics
  - Limits improved by factors 4-5 wrt Run 2



ATL-PHYS-PUB-2022-054

Conclusions

- **HL-LHC will offer the opportunity for a wealth of measurements and searches with the Higgs boson**
  - Most couplings determined at the %-level
  - Differential measurements at the 5-10% level
  - Constrain the mixing angle between pseudoscalar and the scalar Higgs Boson at the level of 5°
  - $\sigma(m_H) \sim 30$ MeV, $\Gamma_H < 177$ MeV at 95% C.L.
- **Projections rely on our understanding of the detectors** using already collected data
  - Simulations indicate that the upgraded detectors will perform at least as good as the current detector but in harsher conditions and provide larger acceptance at high $|\eta|$
- **Improving theoretical uncertainties may bring the biggest gain on the measurement program**

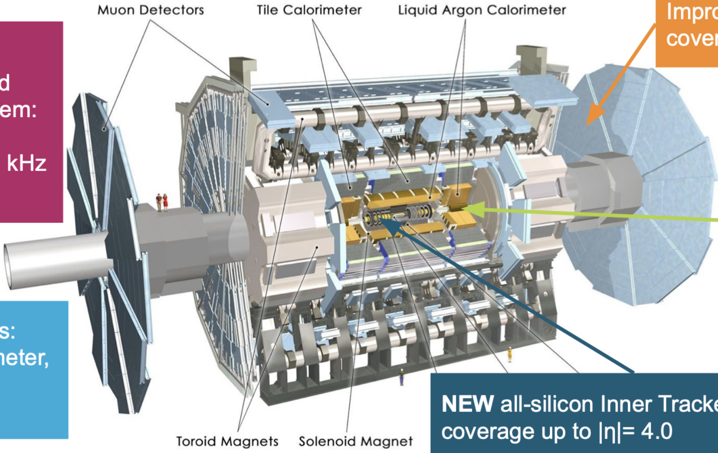
BONUS SLIDES

ATLAS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics: Liquid Argon Calorimeter, Tile Calorimeter, Muon system



Improved muon coverage and trigger

NEW endcap high - granularity timing detector

NEW all-silicon Inner Tracker, coverage up to $|\eta|= 4.0$

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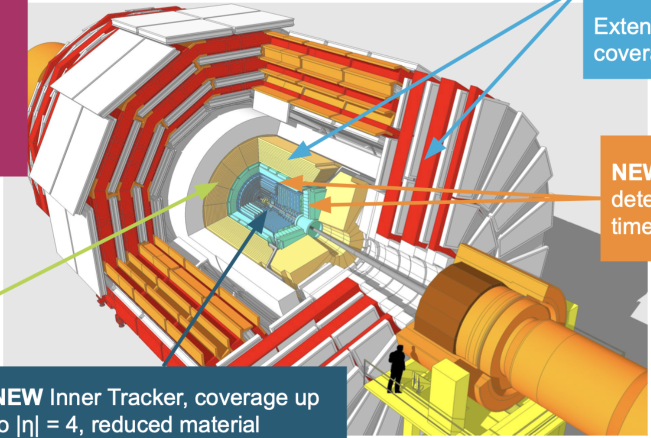
CMS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz



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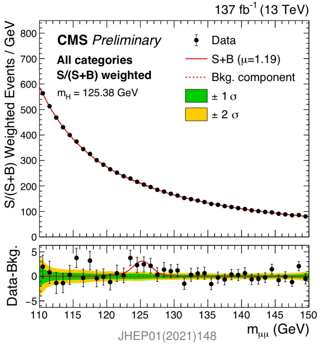
Evidence of $H \to \mu\mu$ in Run 2

Very challenging channel

- $\sim$2000 signal events, very low S/B
  - Invariant mass resolution is the key
  - Use of DNN/BDT and split production modes
  - Exquisite control of backgrounds (Fit with functional form)
- CMS Result
  - 3.0σ Evidence (2.5σ expected)
  - $\mu = 1.19 \pm 0.43$
- ATLAS Result
  - 2.0σ Observed (1.7σ expected)
  - $\mu = 1.2 \pm 0.6$
- Performance **much better than early Run 2 expectations**



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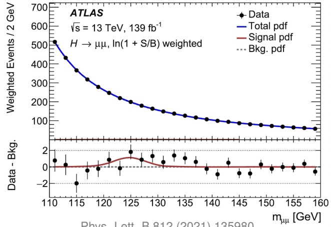
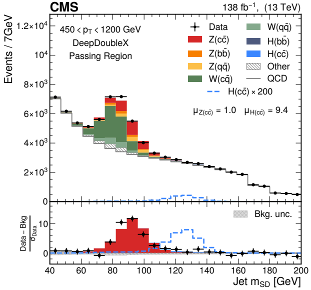


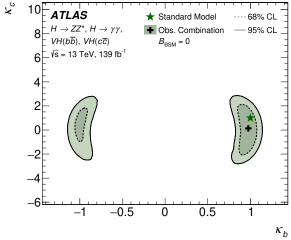
Phys. Lett. B 812 (2021) 135980

Charm quark coupling in Run 2

One of the most striking progress in Run 2

- Main channel: VH, $H \to cc$ (CMS-HIG-21-012)
    - Huge improvement from dedicated $H \to cc$ taggers, esp. in boosted regime
    - Observed limits: $|\kappa_c|$< 8.5 (ATLAS), 5.5 (CMS)
- Inclusive $H \to cc$ search in boosted regime (CMS-HIG-21-008)
    - Limit on signal strength: $\mu < 45$
- Constraints from differential measurements at low p_T^H in $H \to 4\ell$, $H \to \gamma\gamma$ (ATL-HIGG-2022-04)
- Complementary constraint: large gain in combination





Looking for rare or forbidden decays

Rare meson decays with CMS

- $H \to ZJ/\Psi$ and $H \to \Upsilon\Upsilon$
  - 4μ final state
  - Signal is searched for as a resonant peak in the distribution of the invariant mass of the 4μ
  - Limits on BR $\sim 10^{-4} - 10^{-5}$

Channel	3000 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)

CMS-PAS-FTR-21-009