Differential Higgs cross section as a function of p_T^H

HIGGS 2020

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ATLAS EXPERIMENT

On behalf of the
ATLAS and CMS Collaborations

CMS

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

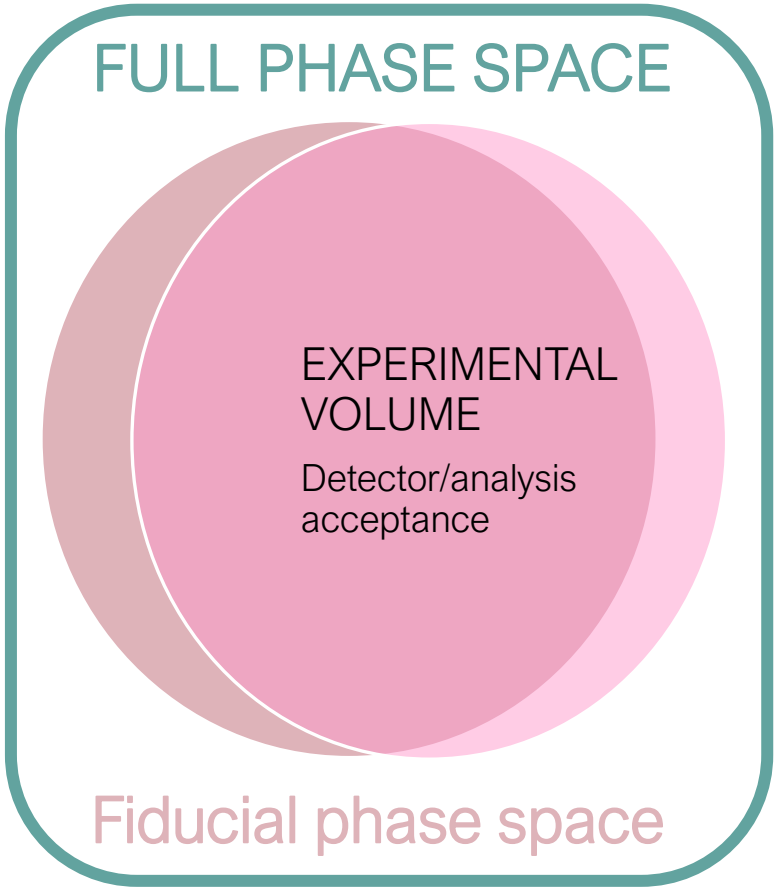
Exploring H production differentially

Definition of fiducial phase spaces to measure H cross section

- Largely model independent measurements
- Factorization of theoretical and experimental uncertainties
- Results easily reproducible for future comparisons

Differential H xsec

- **Test SM predictions** for the full spectra of observables of interest
- Probe for the perturbative QCD modelling of the H production
- **Sensitive probes for BSM** effects and for new heavy particles contributing to the ggF loop



Exploring H production differentially

Definition of fiducial phase spaces to measure H cross section

Different models are provided by theorists to describe the shape distortions due to BSM physics

Differential H xsec

- **Test SM predictions** for the full spectra of observables of interest
- Probe for the perturbative QCD modelling of the H production
- **Sensitive probes for BSM** effects and for new heavy particles contributing to the ggF loop

p_T^H spectrum

- **Shape distortion** due to couplings modification
- Handle to set **limits on coupling modifiers**

Low p_T^H High p_T^H

Exploring H production differentially

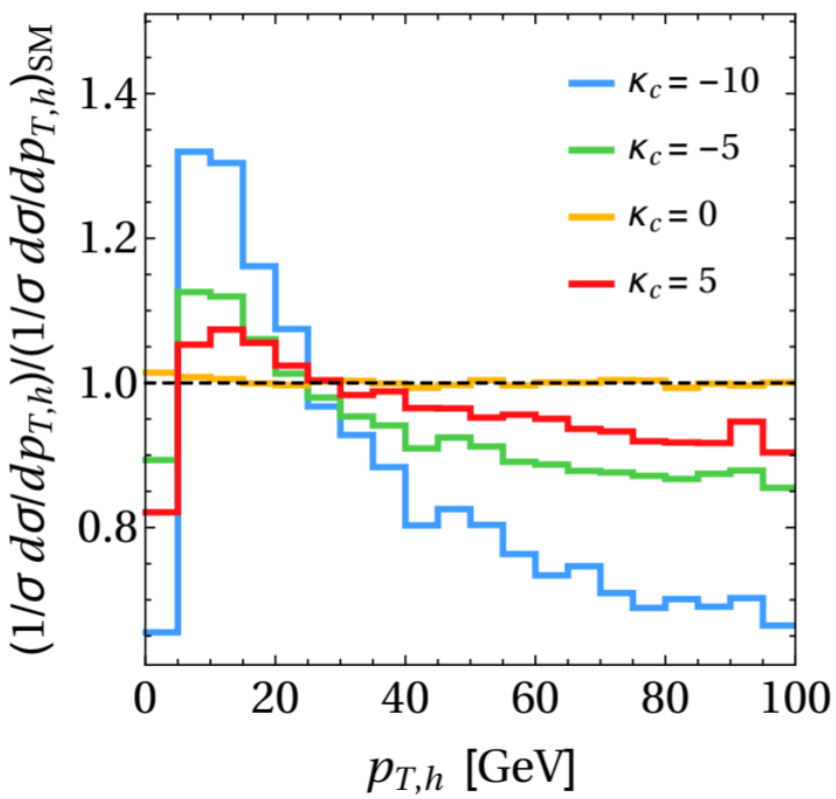
arXiv:1606.09253
arXiv:1612.00283

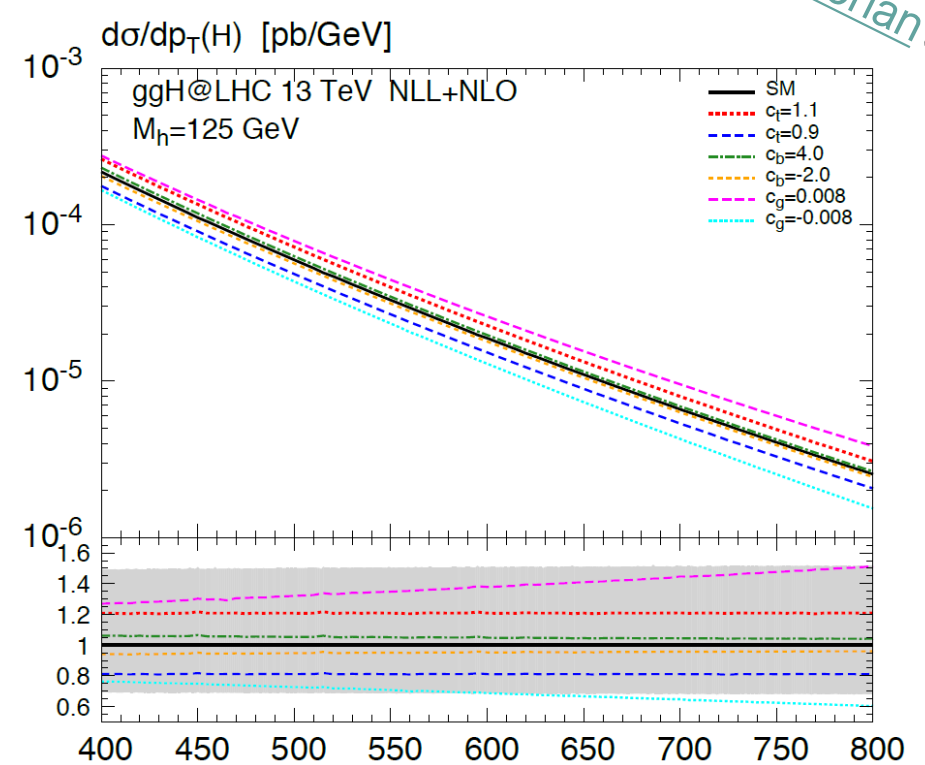
Definition of fiducial phase spaces to measure H cross section

Different models are provided by theorists to describe the shape distortions due to BSM physics

Low p_T^H ⟷ High p_T^H

See D. de Florian's talk





sensitive to light quark Yukawa couplings (κ_b and κ_c)

sensitive to effective coupling to gluon with dim-6 operator

Full Run 2: Higgs precision measurements era!

Measurements: fiducial versus STXS

Two complementary differential measurements to explore H properties

FIDUCIAL DIFFERENTIAL CROSS SECTION

Fiducial phase space:
to match as closely as possible the analysis selection

Measurement largely model independent
of different decay modes (w.r.t. inclusive approach)

Extrapolation to the full phase space
needed to combine measurements

Less sensitive to BSM couplings

Difficult to include multivariate techniques

SIMPLIFIED TEMPLATE CROSS SECTION

Granular description of the phase space:
Predefined bins to target H production ($|y_H| < 2.5$)

Reduction of theory dependence
maximizing experimental sensitivity

Common to different decay modes:
easy combination and comparison

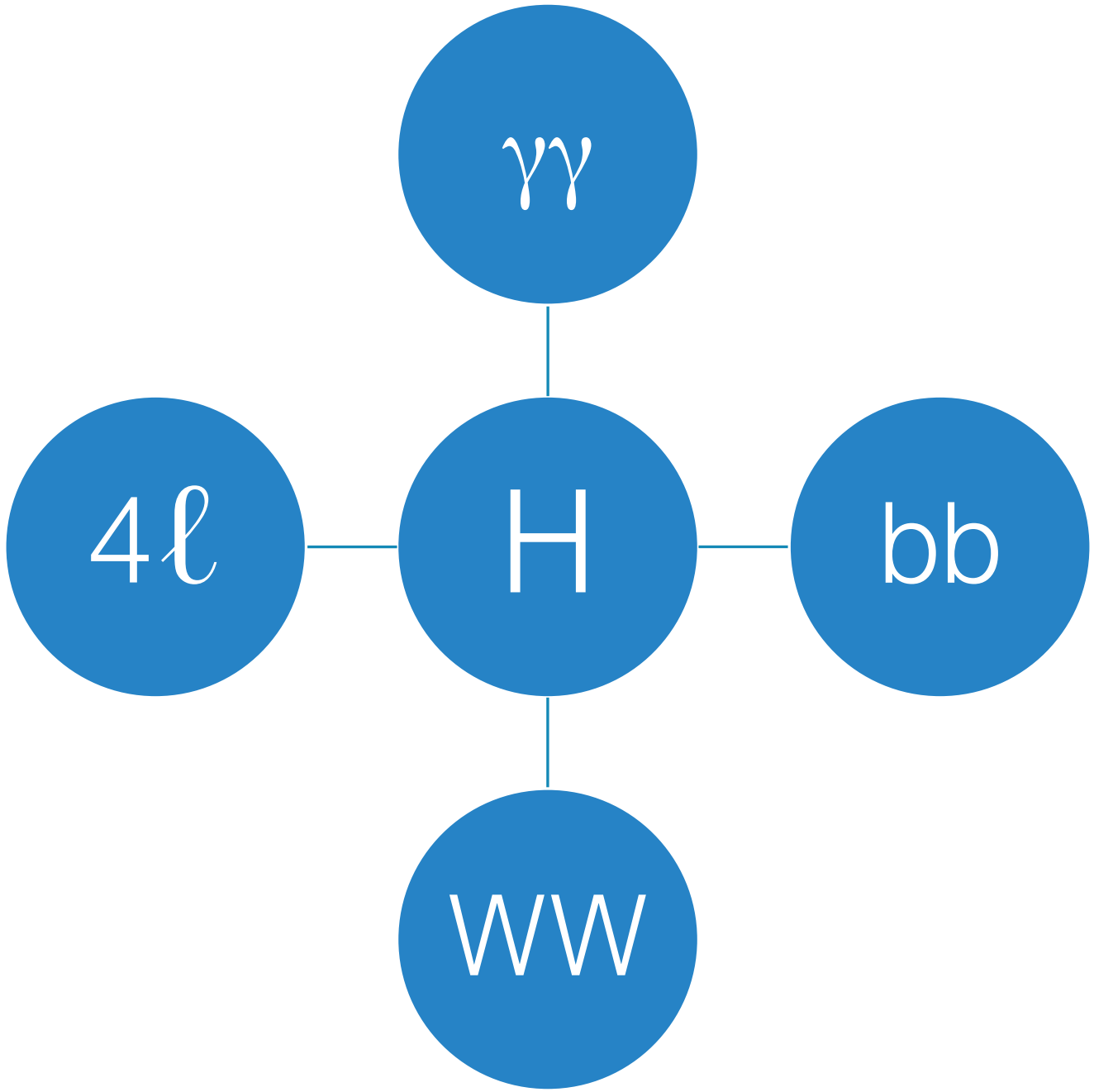
Enhancement of BSM sensitivity

Large use of multivariate techniques

…many other observables!
(Dimitris' and V. Dao's talks)

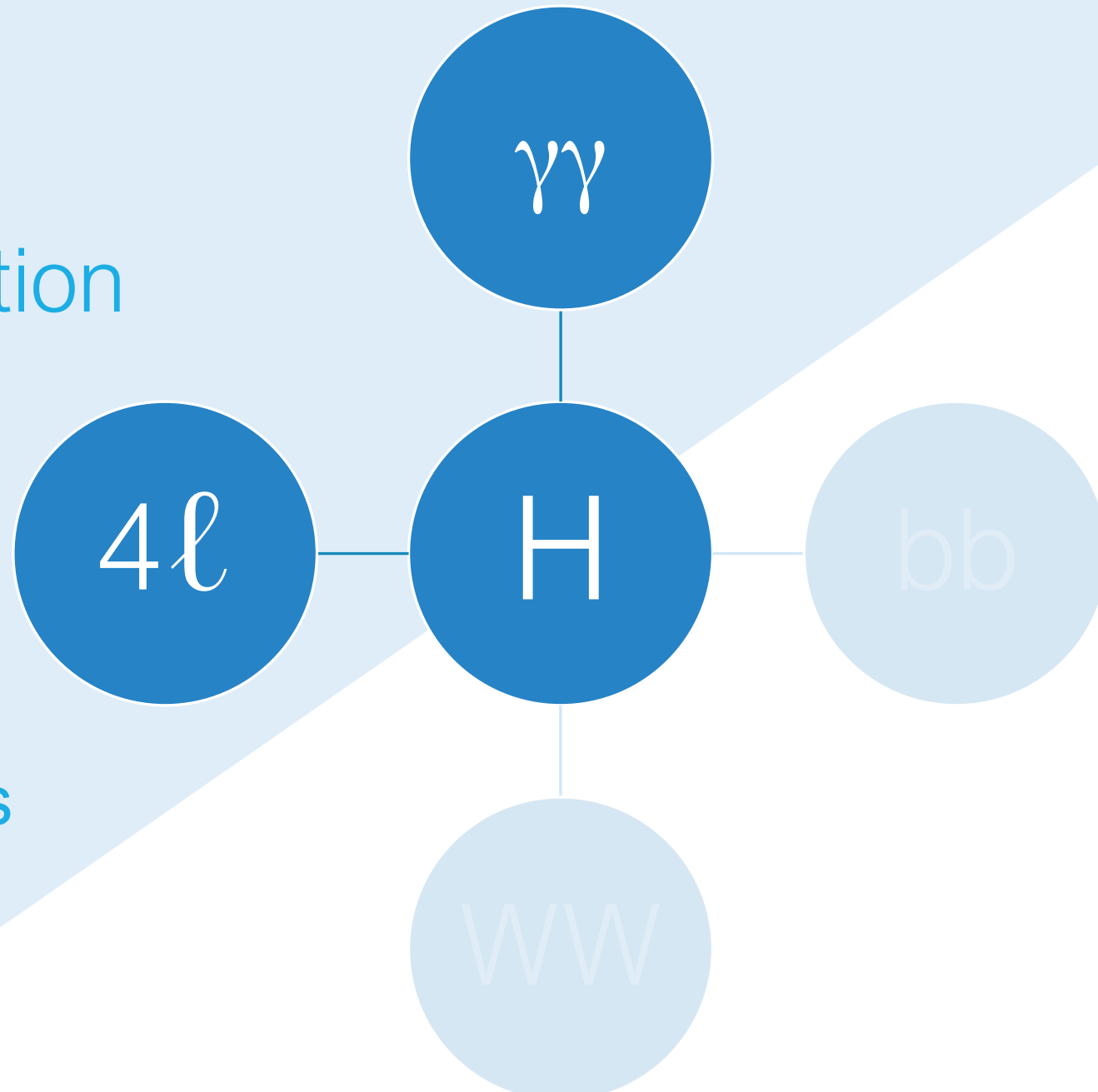
Related presentations:
Davide's talks tomorrow

Overview of the analyses



ATLAS

- ✓ $H \rightarrow 4\ell$
- ✓ $H \rightarrow \gamma\gamma$
- ✓ Combination



Full Run 2 results
139 fb^{-1}

ATLAS

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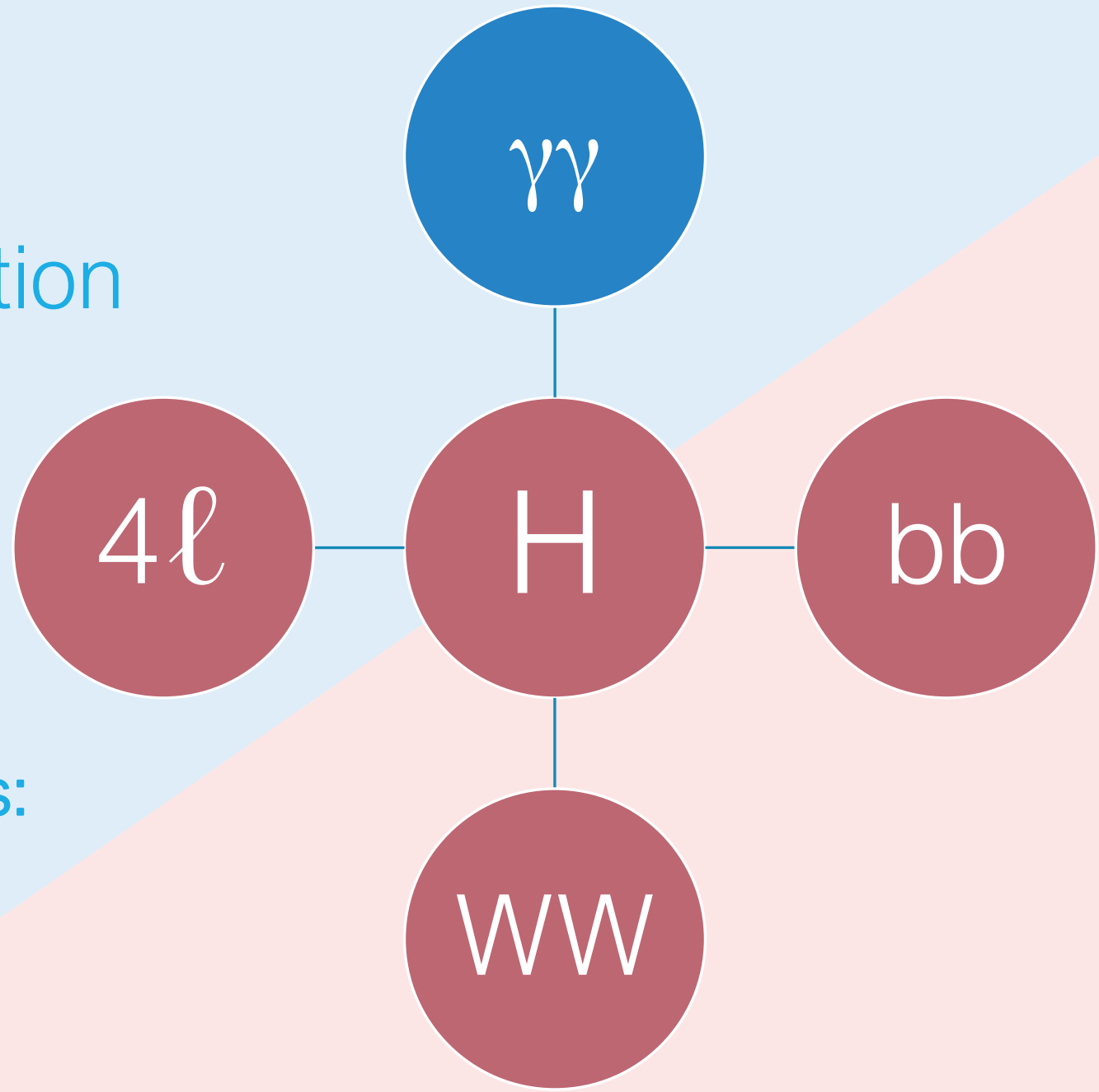
Full Run 2 results:
139 fb^{-1}



CMS

- ✓ $H \rightarrow 4\ell$
- ✓ $H \rightarrow WW$
- ✓ $H \rightarrow bb$

Full Run 2 results:
137 fb^{-1}

$H \rightarrow ZZ \rightarrow 4\ell$

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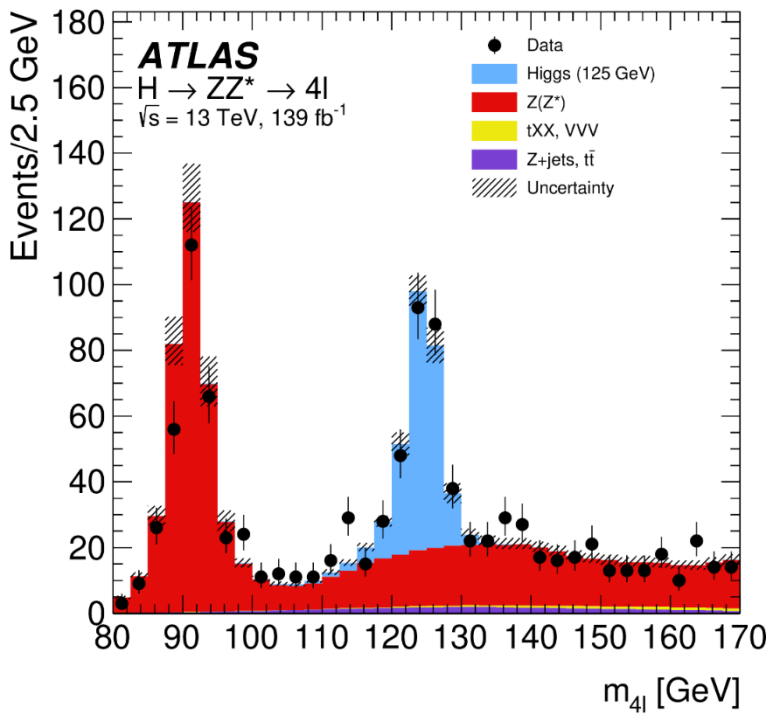
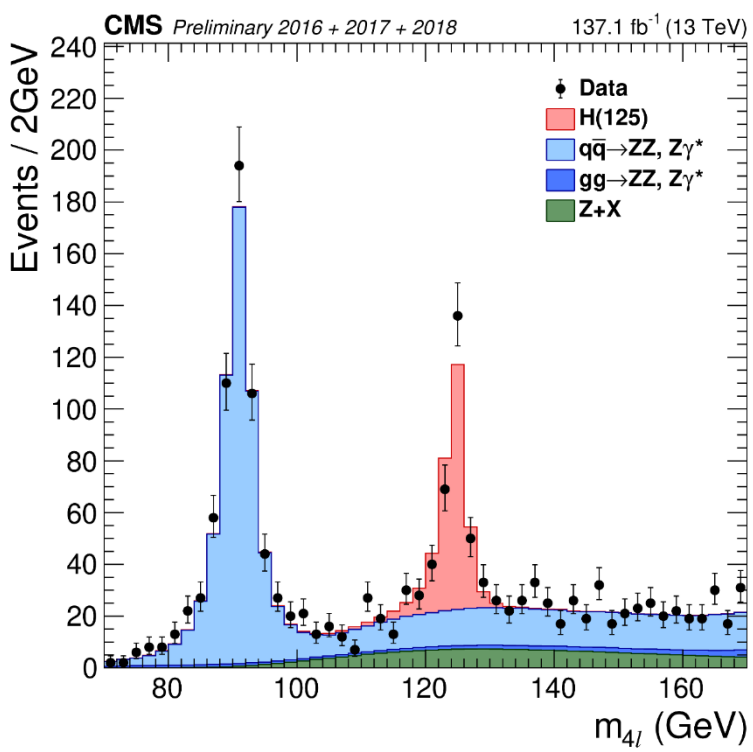
CMS-PAS-HIG-19-001





Channel description

- Small $\mathcal{B}$ (~0.0124%)
- Clean final state: S/B~2
- Same flavor and opposite charge lepton pairs
- Main backgrounds:
  - Irreducible background: ZZ production from qq/gg
  - Reducible background: Z+X (misidentified leptons)

Fiducial differential measurement

- 1D maximum likelihood fit of the observed $m_{4\ell}$
- Fit done for each bin of the differential observable
- Unfolding: matrix inversion

H → ZZ → 4ℓ: differential cross section

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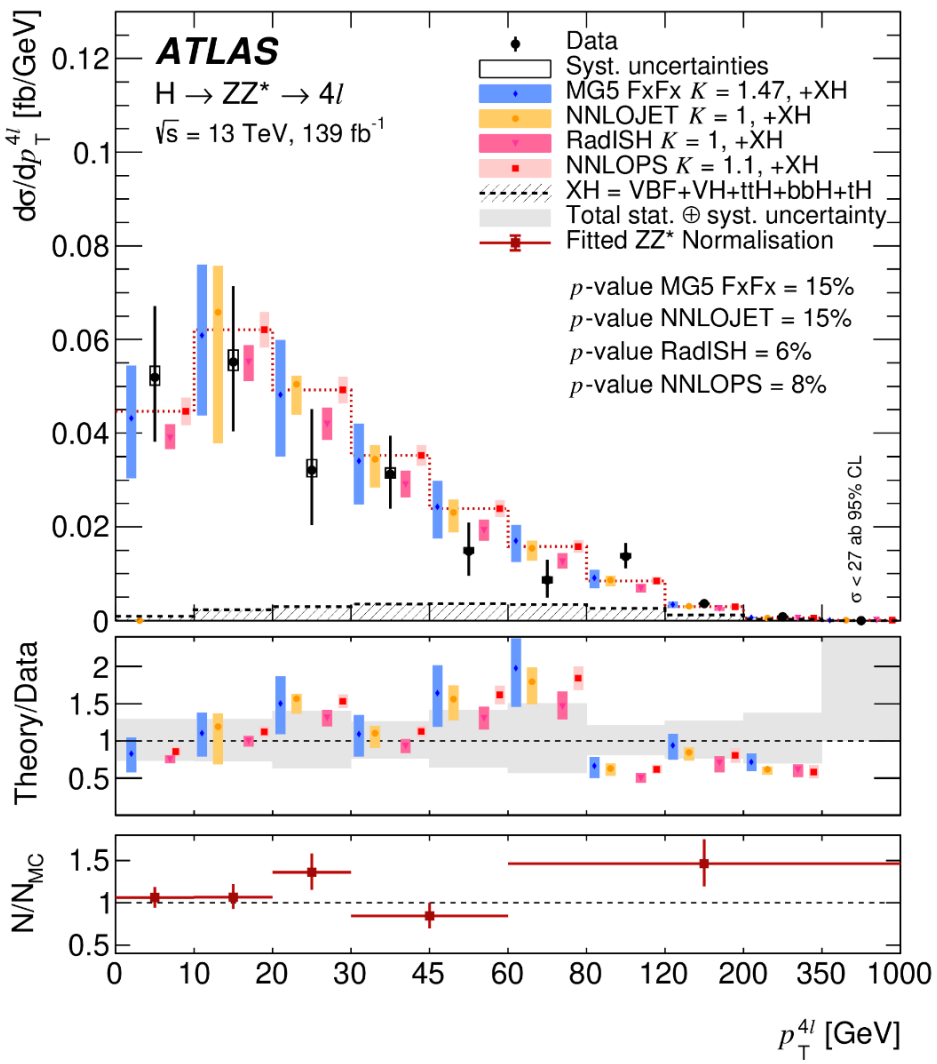

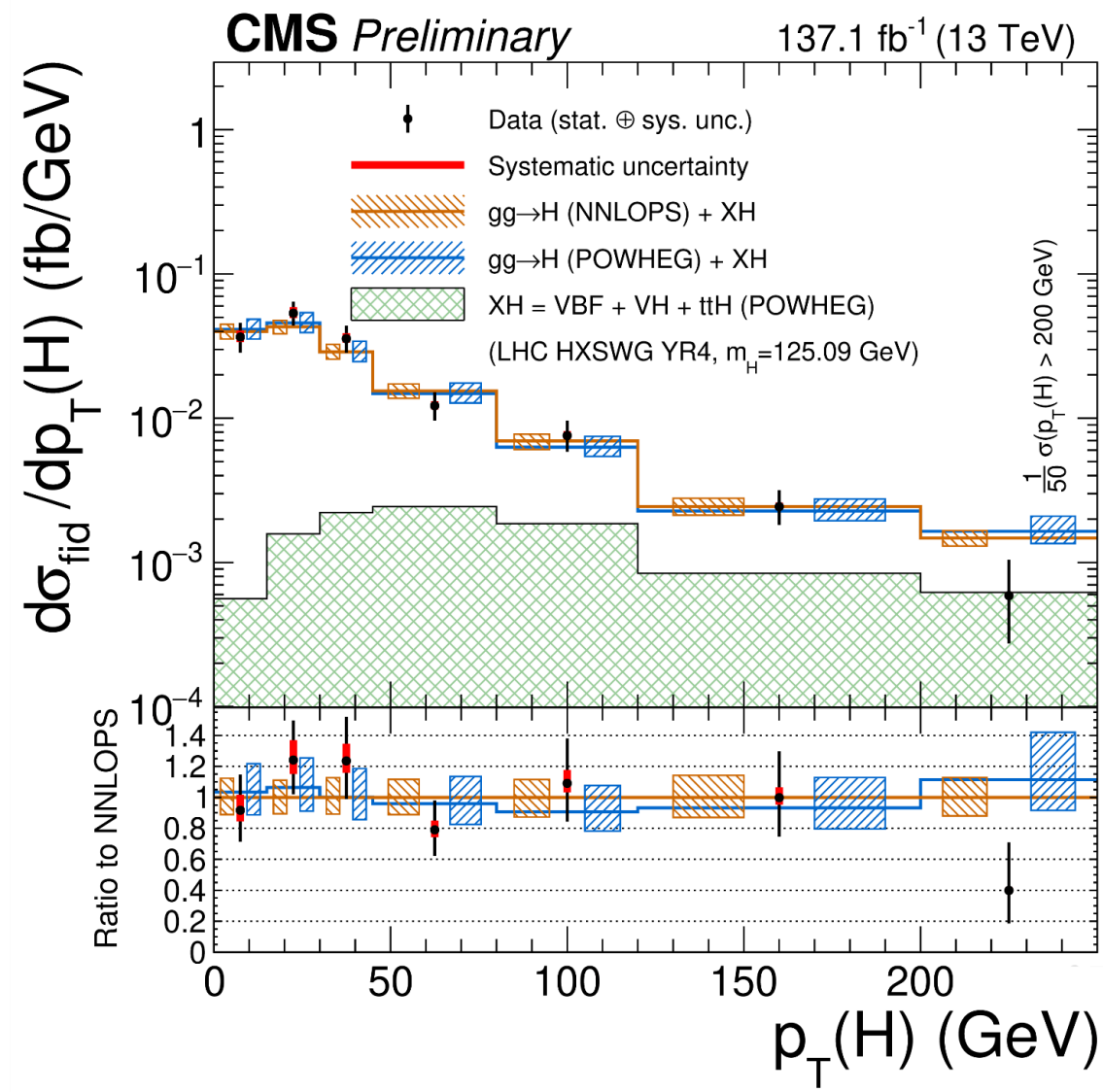

Comparison with four theoretical predictions

Good compatibility between the measurement and the SM prediction

Good agreement with POWHEG and NNLOPS theoretical predictions

Precision around 20-30% for all p_T^H bins

$H \to ZZ \to 4\ell$: interpretation

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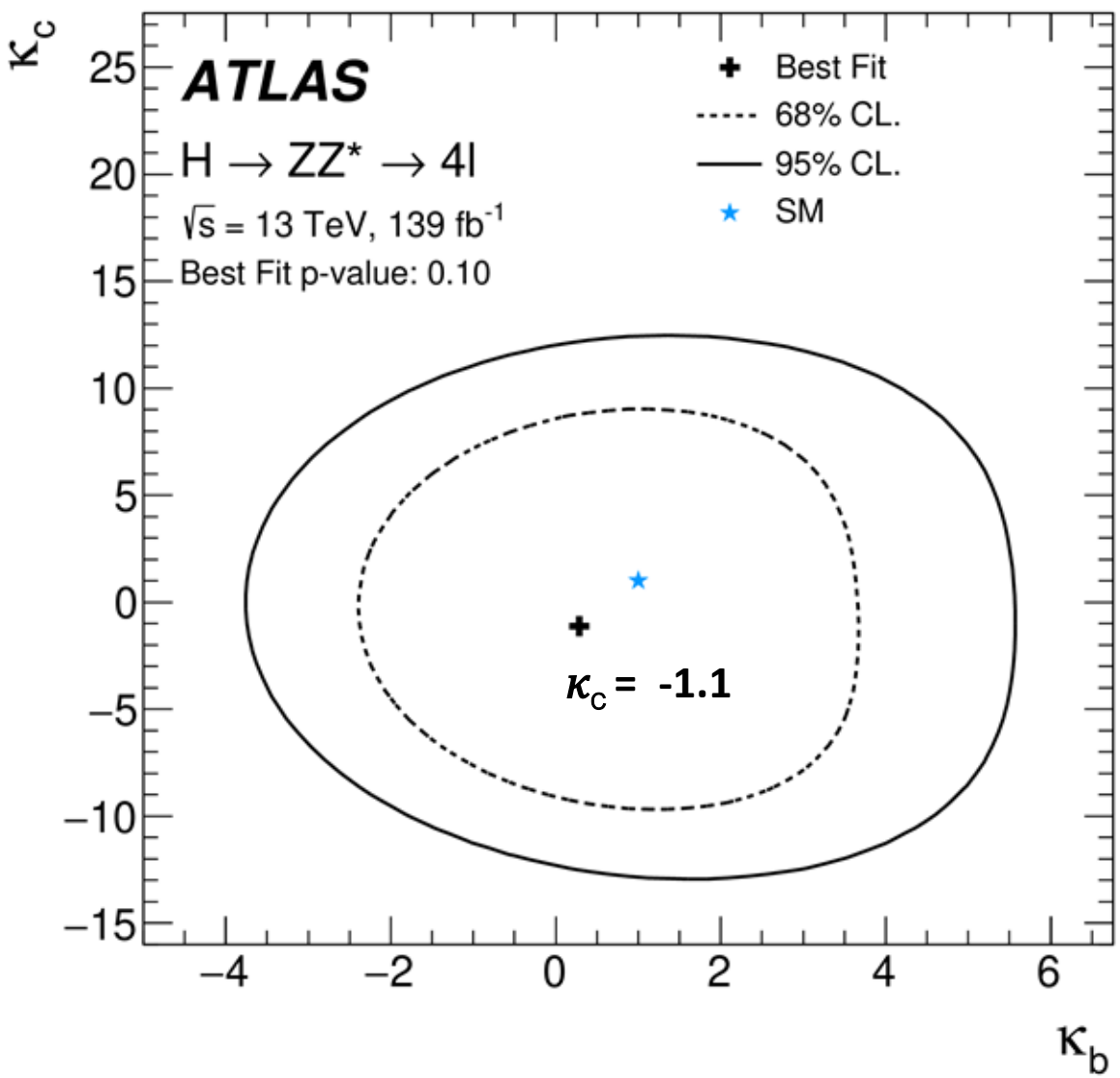
Limits on the H coupling to the charm quark
exploiting the information of the $p_T^{4\ell}$ region



Three different approaches adopted to constrain κ_b and κ_c:

- $p_T^{4\ell}$ shape only;
- $p_T^{4\ell}$ differential xsec;
- both the predicted $p_T^{4\ell}$ cross section and modifications to the B due to κ_b and κ_c.

Increasing model dependence

κ_C = [-11.7, 10.5] @ 95% CL
(κ_b floating)

H → γγ

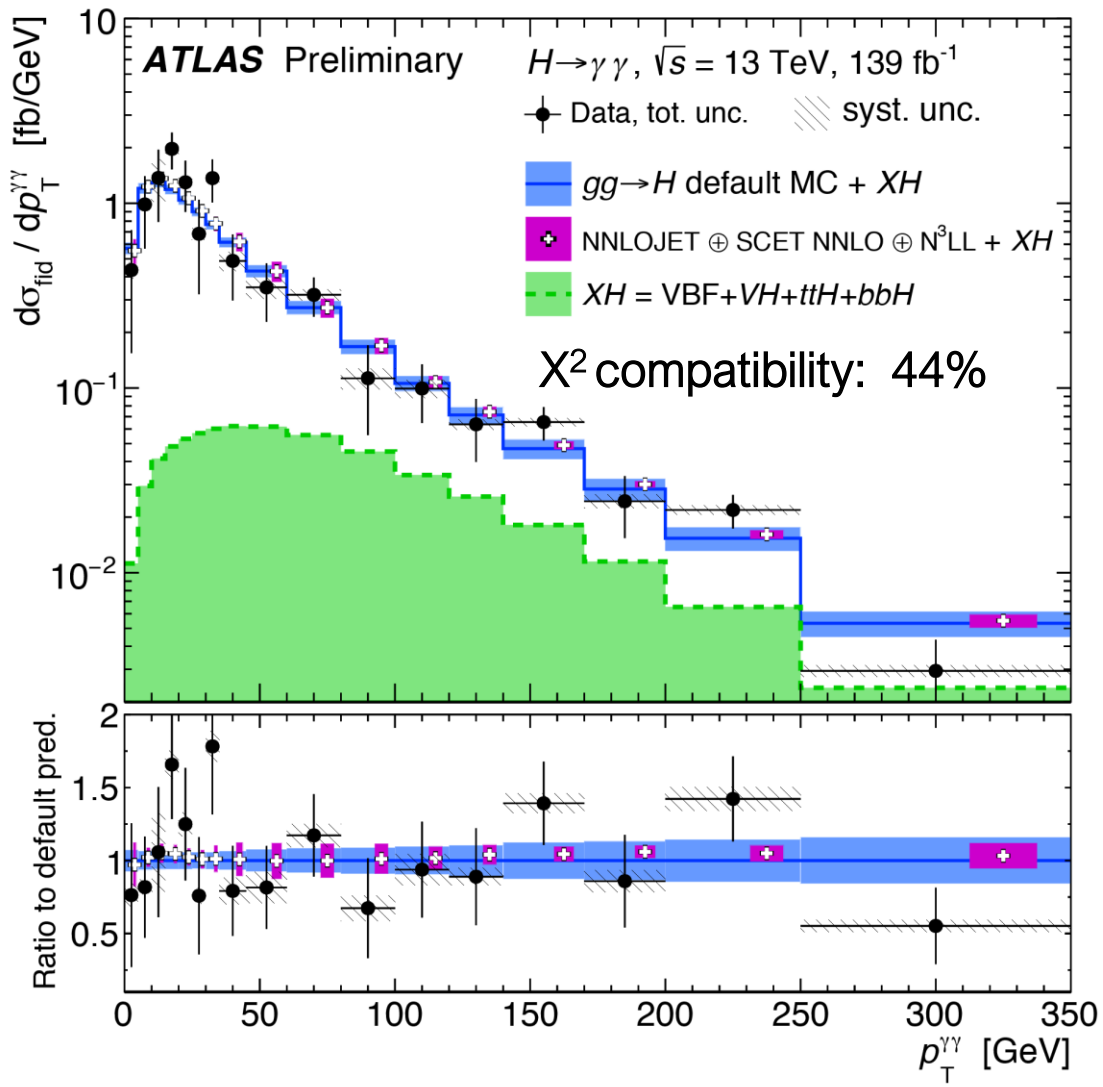
Clean final state topology and precise reconstruction of the diphoton invariant mass: powerful channel for precision measurements of a large variety of observables

Channel description

- Small $\mathcal{B}$ (~0.2%)
- Lower S/B w.r.t. 4ℓ (< 0.1)
- Diphoton pairs: excellent mass resolution (1-2% m_H)
- Main backgrounds: γγ continuum (estimate from data sideband), γ+jets, dijet

Fiducial differential measurement

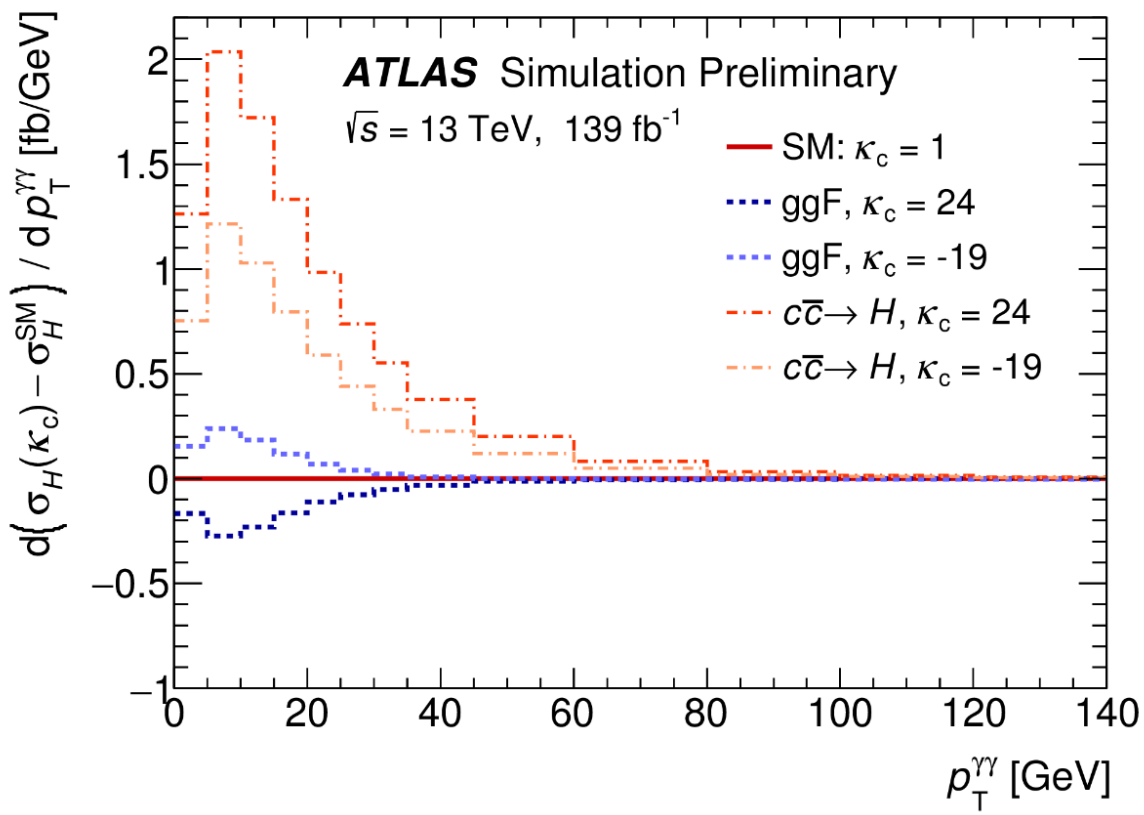
- Fit to diphoton invariant mass
- Unfolding: bin-per-bin correction factor
- Dominated by statistical uncertainty

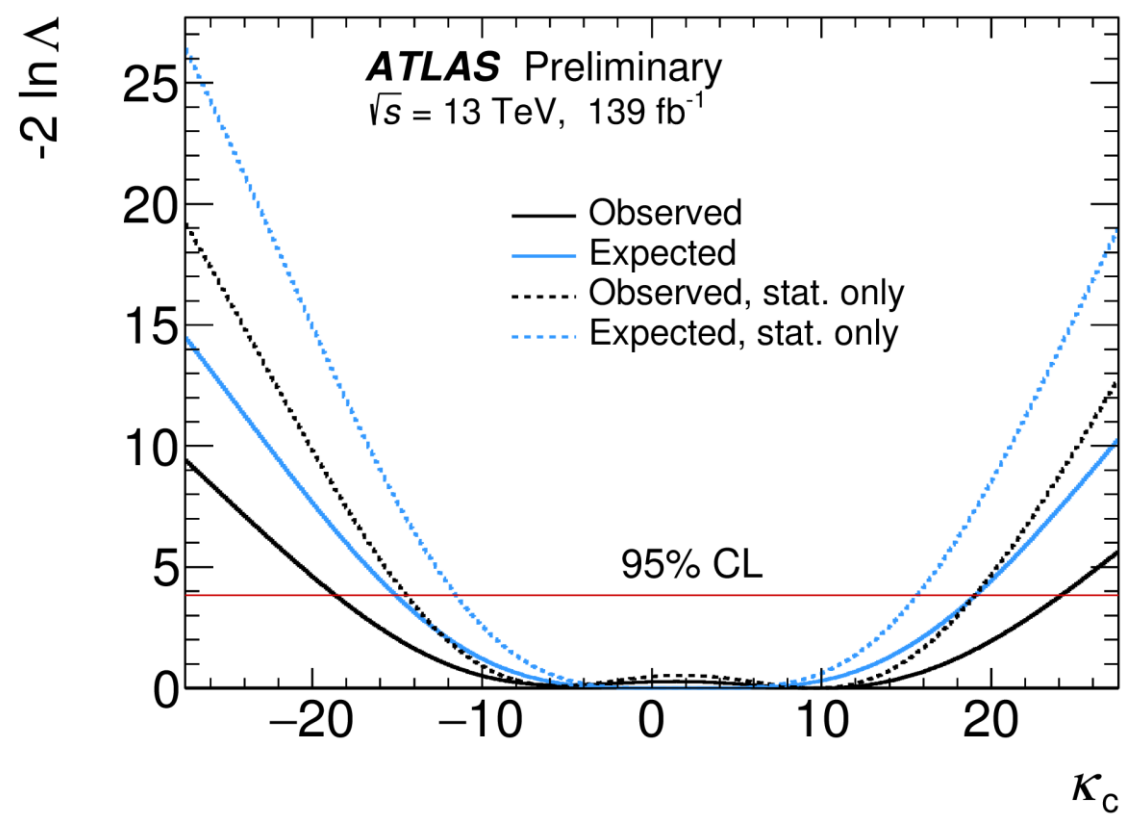


Good agreement between SM expectation and experimental results

H → γγ: interpretation

Light Yukawa couplings interpretation





Finer binning at lower $p_T^{\gamma\gamma}$ to:

- more statistics;
- **probe the charm Yukawa coupling;**
- probe the region where resummation effects are important.

κ_C = [-19, 24] @ 95% CL
(shape only)

H → WW: analysis strategy

First differential measurement in HWW with full Run 2 data

Motivation

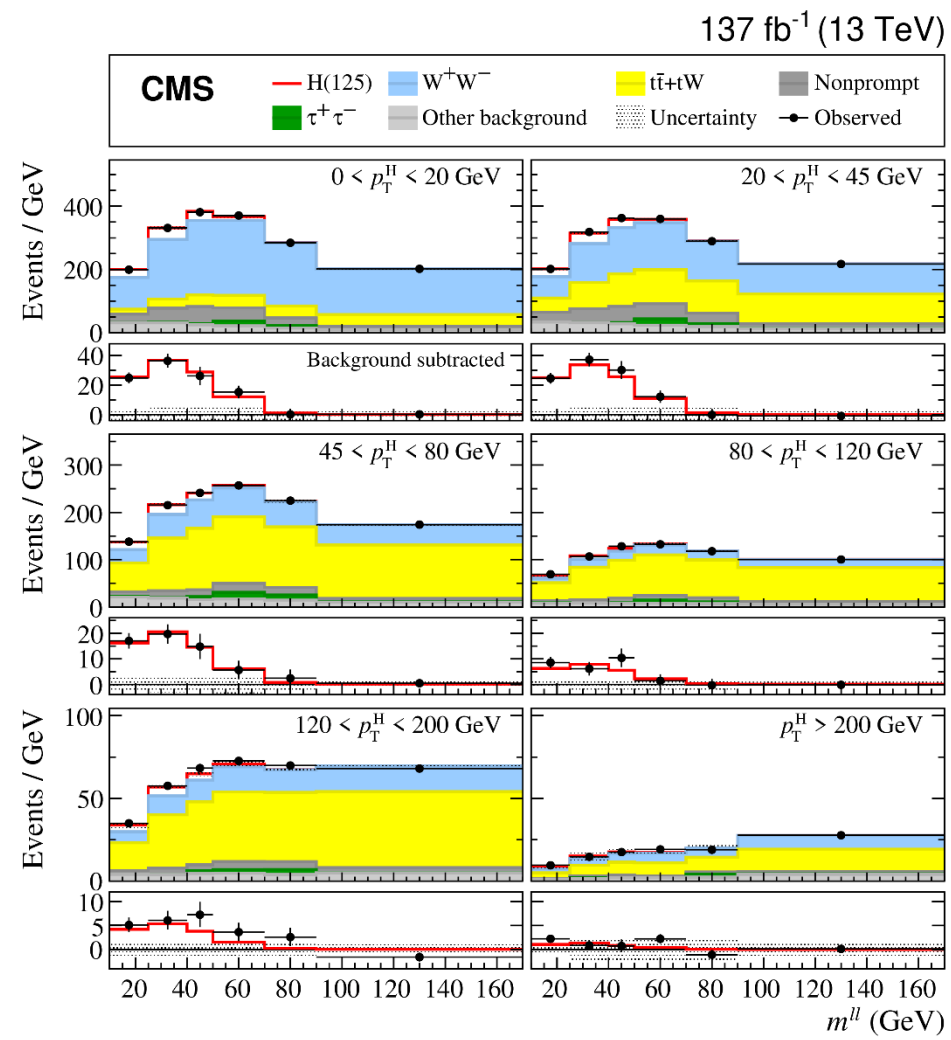
- Large $\mathcal{B}$ (H → WW, 21.4%): final state sensitivity competitive with $\gamma\gamma$ and ZZ
- The full p_T^H spectrum can be studied

Channel description

- Fully leptonic final state ($\mathcal{B}$ ~0.5%): $e^{\pm}\mu^{\mp}\nu\nu$
- Good signal sensitivity
- Large backgrounds: WW, top quark (tt, tW), nonprompt leptons from single W
- Poor resolution due to ν pair

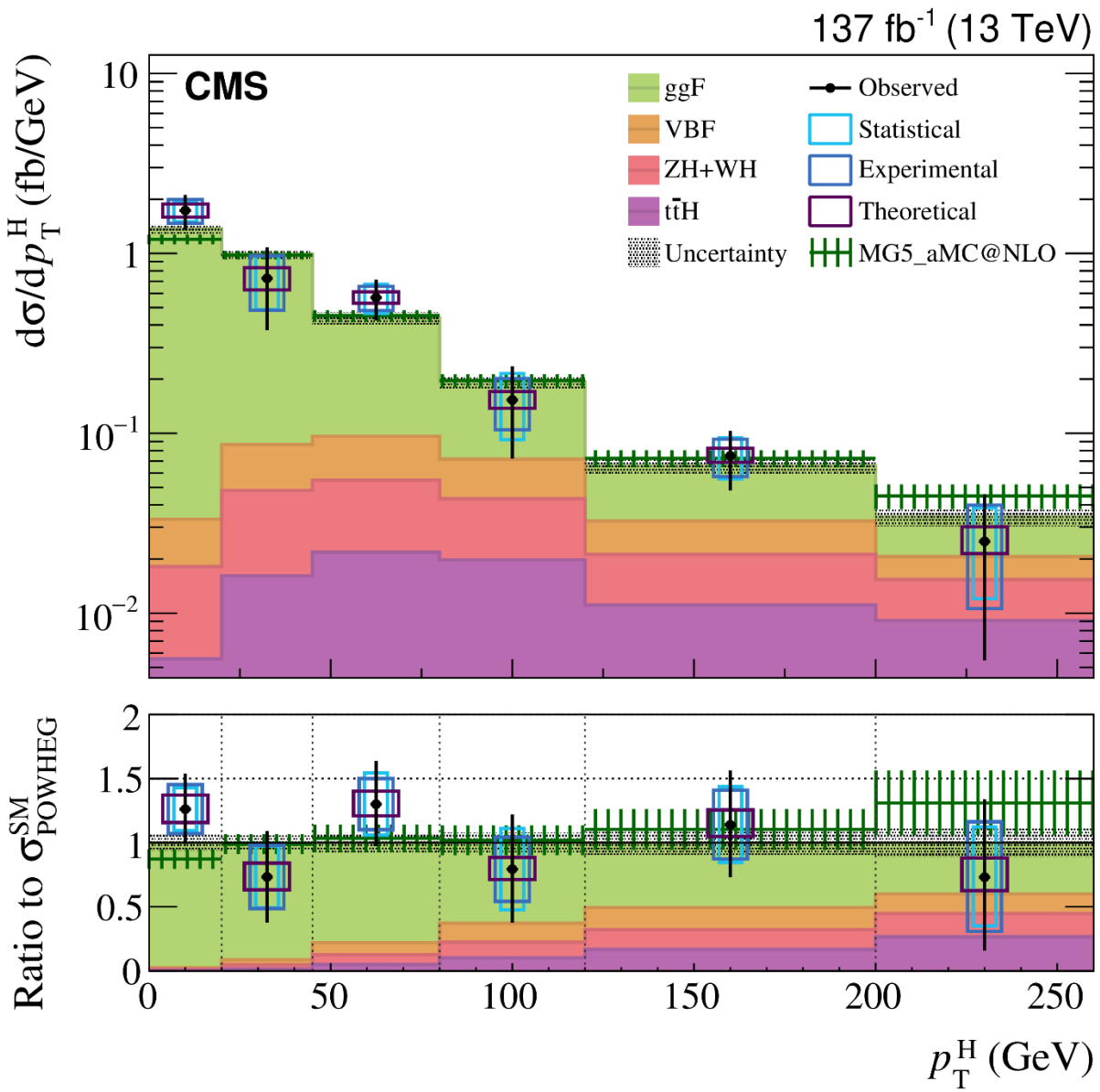
Statistical analysis

- Two observables: $m^{\ell\ell}$ and m_T^H
- Different template binnings
- Signal extraction and unfolding simultaneously performed



H → WW: differential cross section

Bin widths at lower p_T^H values dictated by the resolution of p_T^{miss} that affects the resolution of p_T^H



- Two theoretical predictions: POWHEG and Madgraph
- Regularization procedure: unfolding highly sensitive to the statistical fluctuations in the observed distributions, especially for the p_T^H measurement
- Uncertainties around 20% at low p_T^H
- Good agreement with the theoretical predictions in all bins

H → bb

arXiv:2006.13251

Differential exploration of the high p_T^H region at 13 TeV relying on boosted Higgs

Motivation

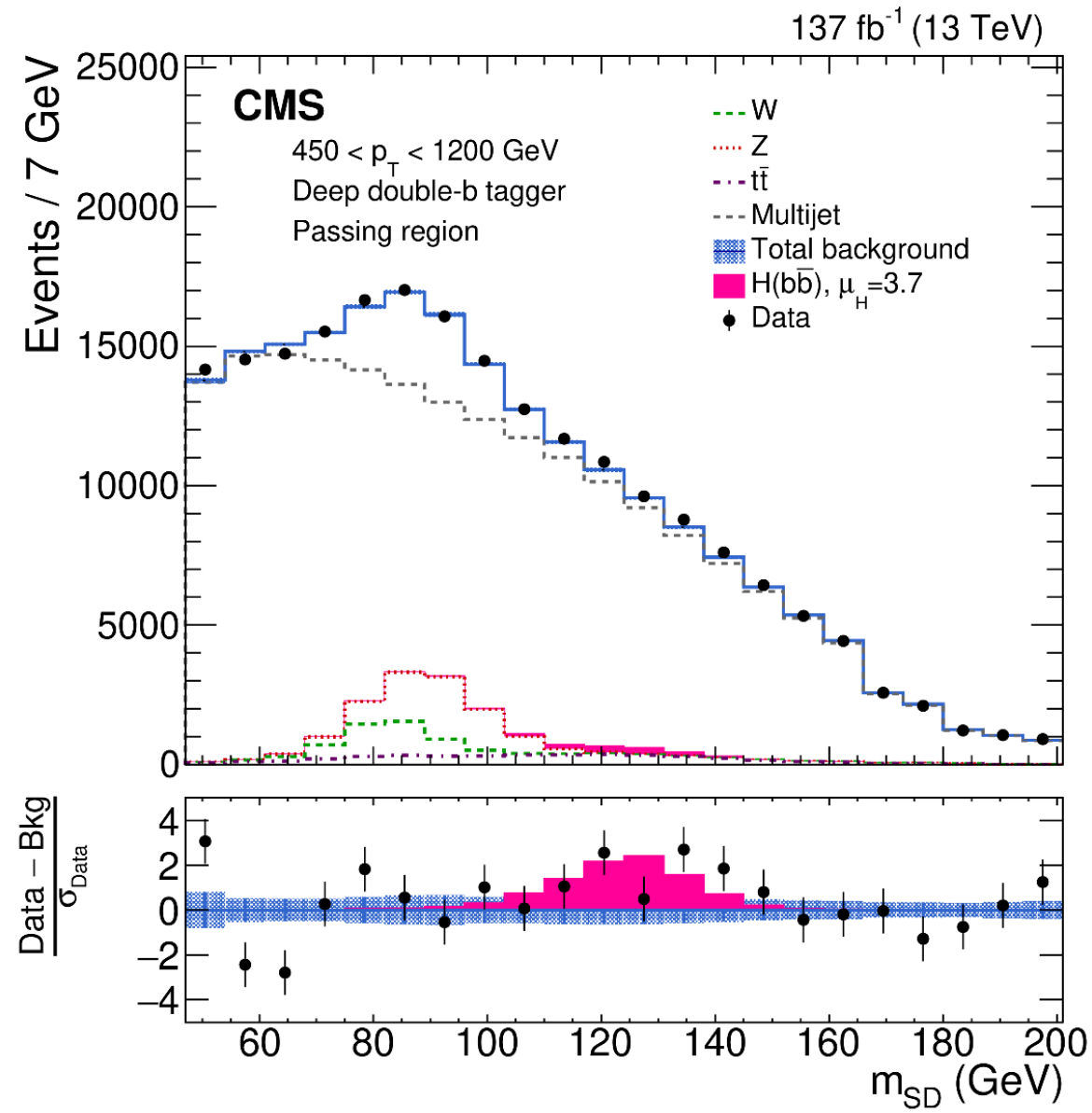
- Largest $\mathcal{B}$ (58.1%)
- Alternative way to study the H-t coupling
- Sensitivity to BSM couplings at high p_T^H (due to the increased statistics available)

Channel description

- Dominant production mode: ggH (larger VH contribution increasing p_T^H)
- Poor kinematic resolution
- Large background rates

Analysis strategy

- Boosted AK8 jets (two prong substructure)
- Soft-drop (SD) mass algorithm
- Search for peak in jet mass spectrum

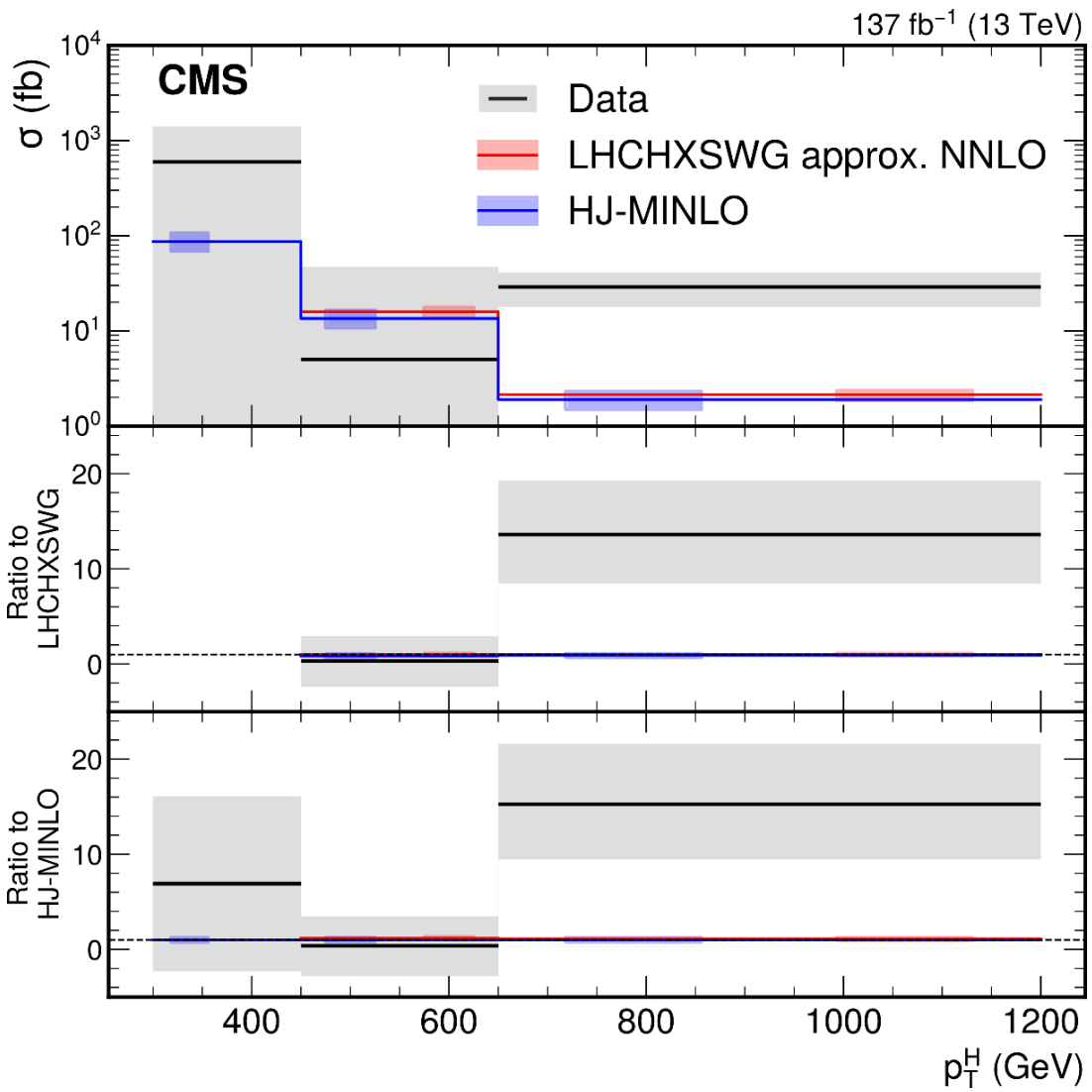


Large effort by theory community to provide precise predictions for boosted H production

arXiv:2005.07762

H → bb: differential cross section

Differential cross section for a high p_T Higgs produced through gluon fusion: maximum likelihood unfolding technique

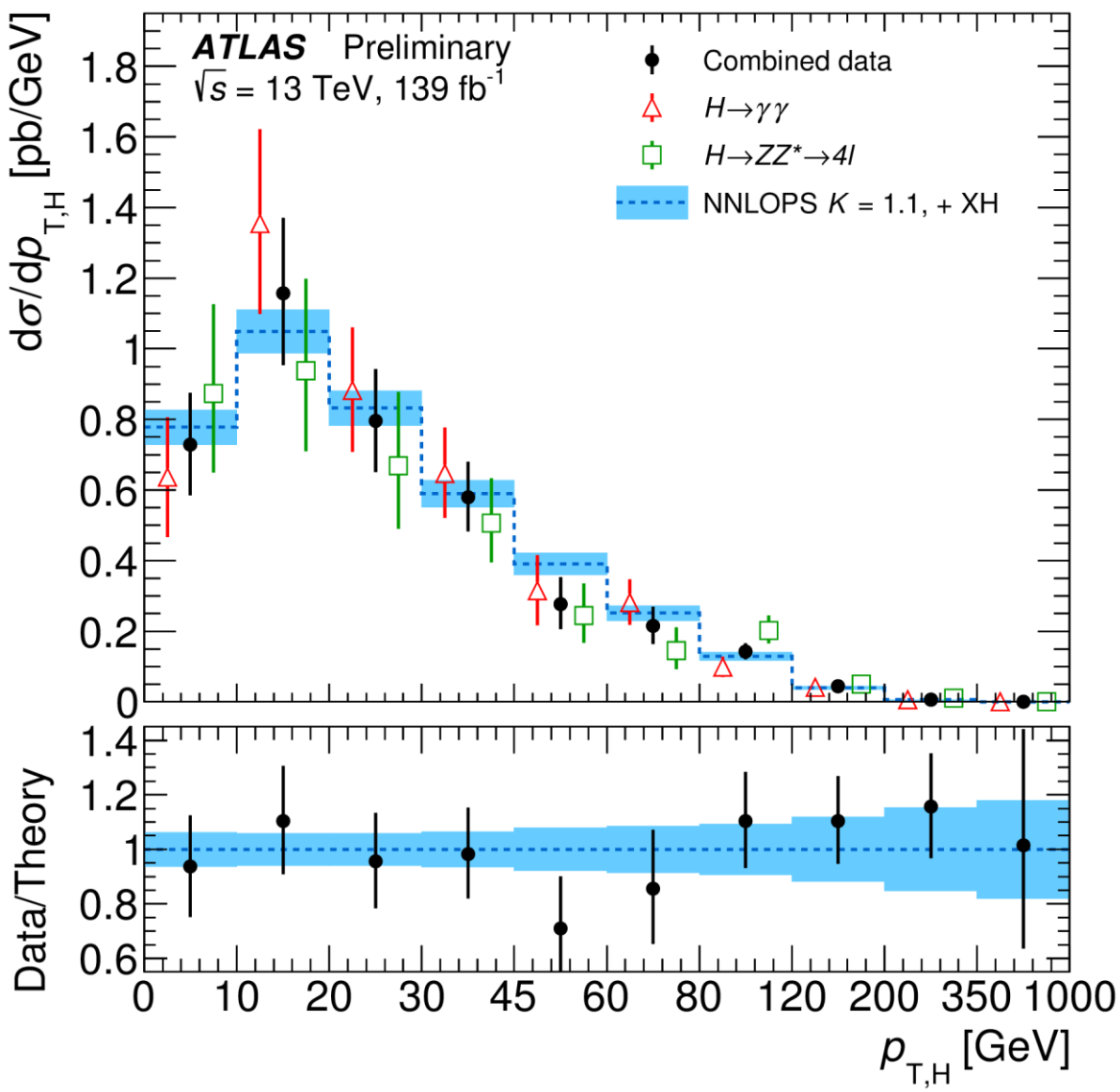


- ggH splitting in three particle level p_T^H bins following STXS recommendations: 300 - 450, 450 - 650 and > 650 GeV (designed to target BSM effects)
- SM rates assumed for other production modes

Local significance of 2.6 σ over expected SM production rate for $p_T^H \geq 650$ GeV

First Run 2 combination

Combination of HZZ4ℓ and Hγγ differential cross section as a function of p_T^H



- Results combined in the full phase space
- Uncertainty dominated by the statistical component: ≤ 20% in all bins
- Results compatible with each other (*p*-value = 11%)
- Combination in good agreement with the SM predictions: *p*-value = 78%

Summary

Differential cross section measurements
as a key **to further explore the H** physics
and **search for BSM** effects:
large interest on p_T^H

Rich set of differential measurements based on full Run 2 statistics
by ATLAS and CMS:
all measurements have been found to be consistent **with the SM expectation**

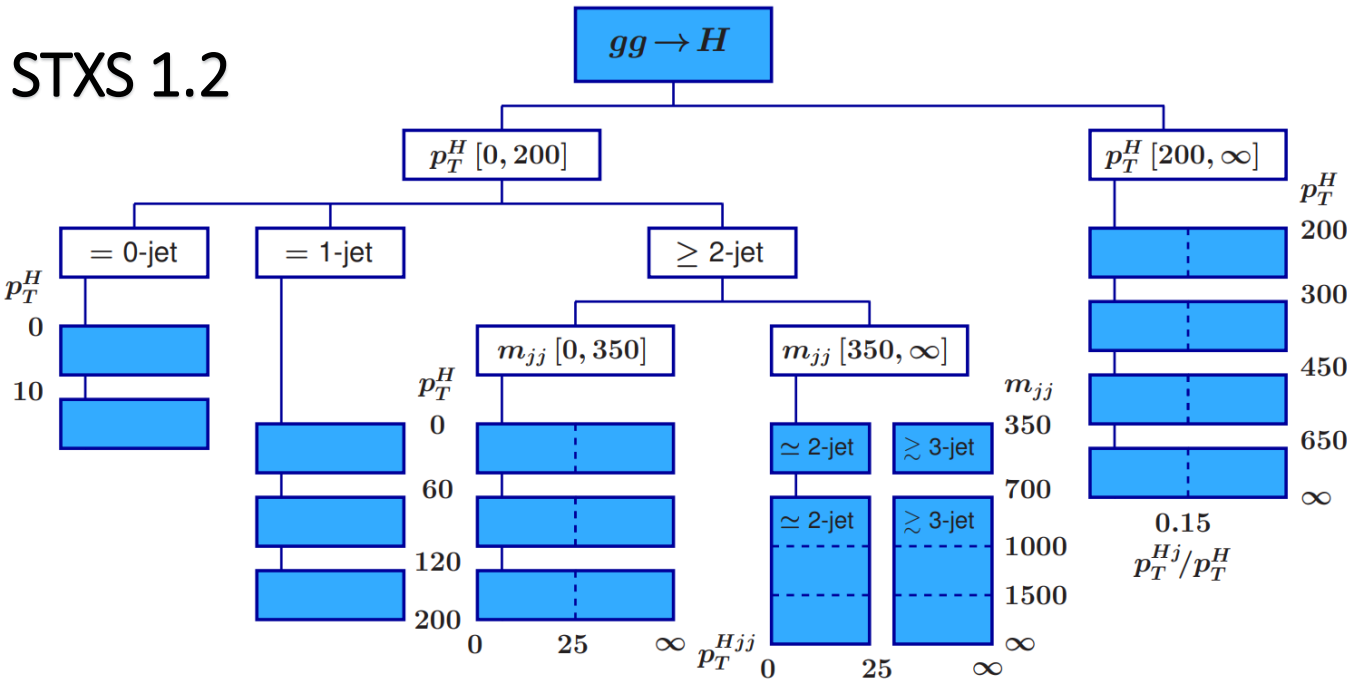
Work ongoing on other analyses and improved set of results expected from
full Run 2 combinations

Thank you!

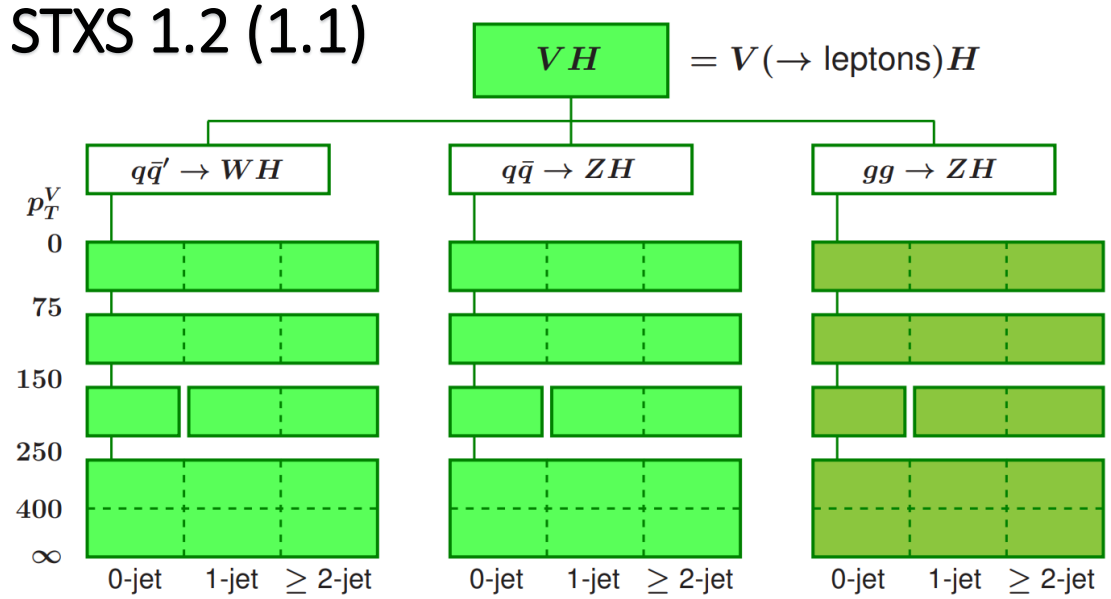
Additional slides

Simplified Template Cross Sections (1.2)

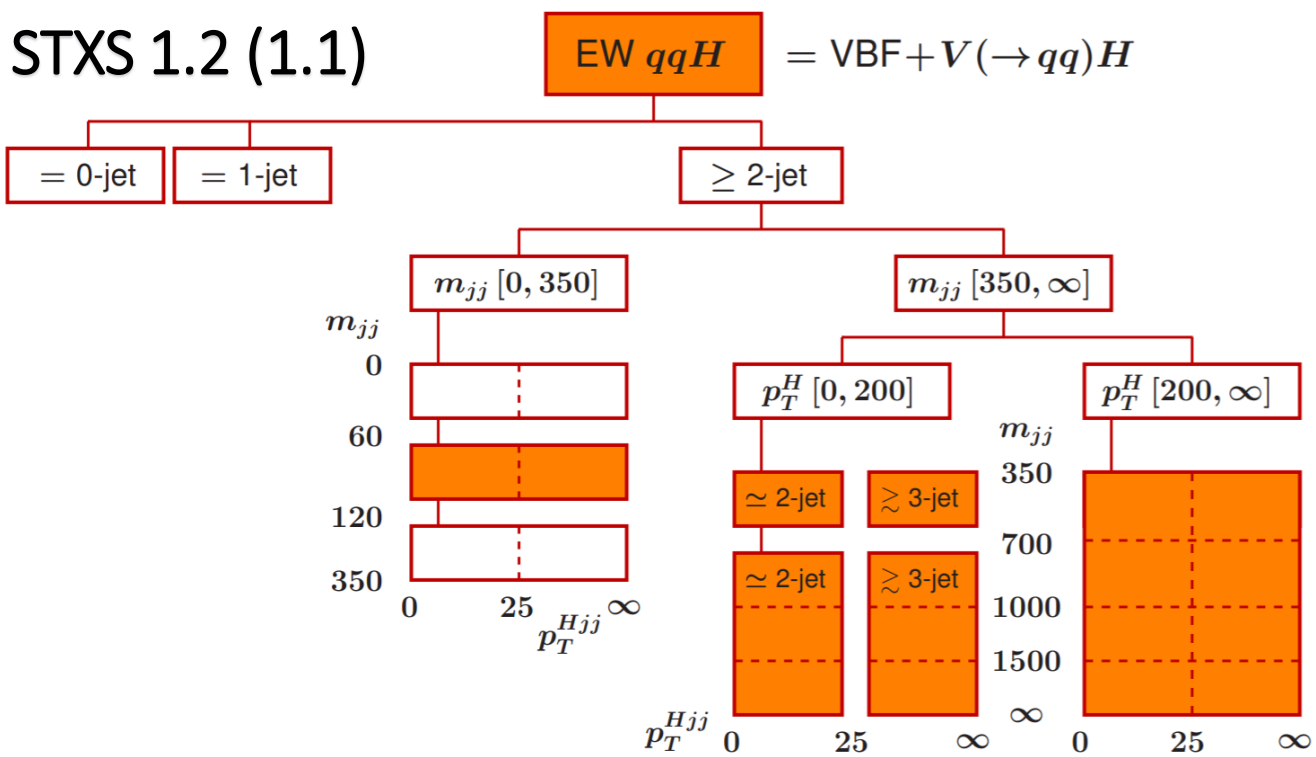
STXS 1.2



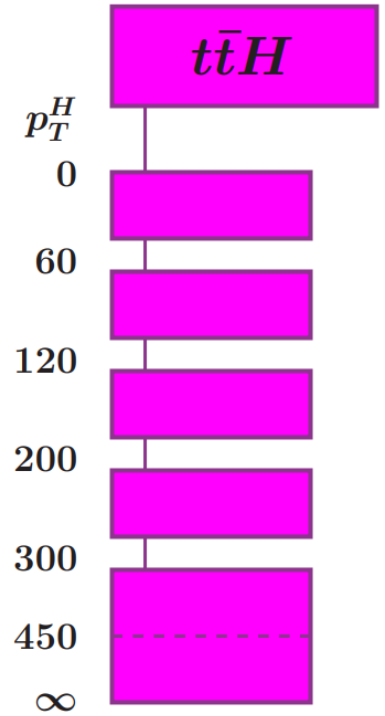
STXS 1.2 (1.1)



STXS 1.2 (1.1)



STXS 1.2



Differential H cross section as a function of p_T^H: STXS

κ-framework

Parametrization based on the coupling strength modifiers
used for the interpretation of most of the LHC results

- Extensively used characterization of Higgs coupling properties in terms of individual coupling modifiers, corresponding to tree-level Higgs boson couplings to each particle (κ_W, κ_Z, κ_t, κ_b, κ_c, κ_τ, κ_μ), and three additional effective coupling modifiers (κ_g, κ_γ, $\kappa_{Z\gamma}$):

$$\mu_i^f \equiv \frac{\sigma_i \cdot B_f}{\sigma_i^{SM} \cdot B_f^{SM}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \quad \text{where} \quad \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \quad \text{or} \quad \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

- Simple way to parametrize potential deviations in the couplings of the Higgs to bosons and fermions according to the SM predictions

- The κ-framework can be generalized to incorporate a BSM width (invisible and untagged decays):

$$\Gamma_H = \frac{\kappa_H^2 . \Gamma_H^{SM}}{1 - B_{BSM}} \quad \text{where} \quad \kappa_H^2 = \sum_j B_{SM}^j \kappa_j^2$$

$H \rightarrow ZZ \rightarrow 4\ell$

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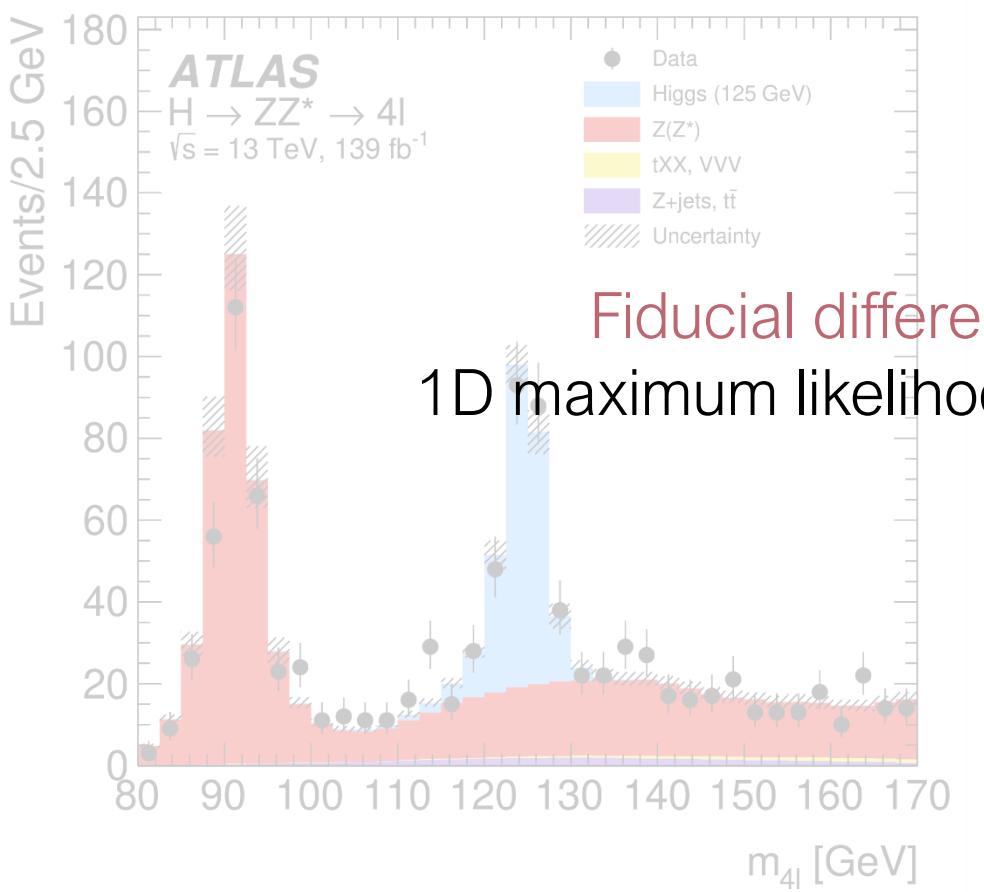
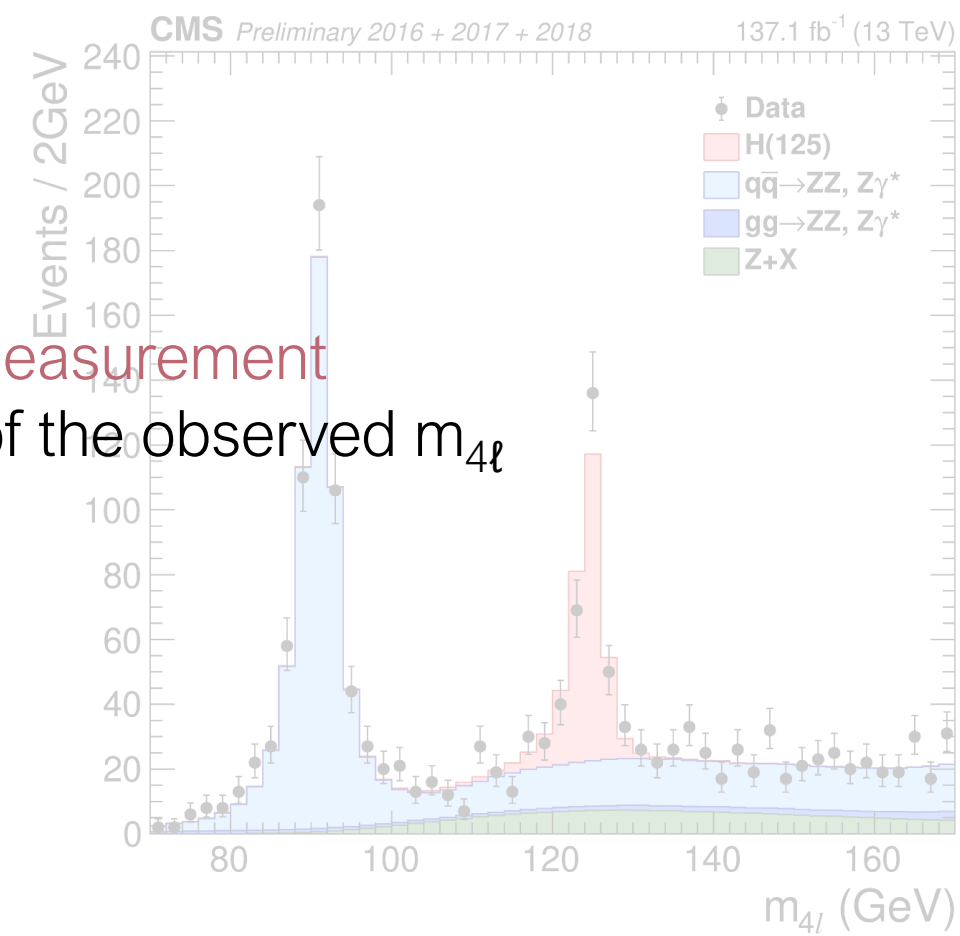
- Dressed leptons: $p_T^{\ell} > 5$ GeV, $|\eta^{\ell}| < 2.7$, $p_T^{\ell_{1,2,3}} > 20, 15, 10$ GeV, $\Delta R(\ell_i, \ell_j) > 0.01$
- Jets: $p_T > 30$ GeV, $\Delta R(\ell_i, \text{jet}) > 0.01$, $|y| < 4.4$
- Mass range: $m_{4\ell} = [105, 160]$ GeV



- Dressed leptons: $p_T^{e(\mu)} > 7\ (5)$ GeV, $|\eta^{e(\mu)}| < 2.4\ (2.5)$, $p_T^{\ell_{1,2}} > 20\ (10)$ GeV, $\mathcal{I}_{rel} < 0.35$, $\Delta R(\ell_i, \ell_j) > 0.02$
- No event categorization and kinematic discriminants
- Mass range: $m_{4\ell} = [105, 140]$ GeV



Fiducial differential measurement

1D maximum likelihood fit of the observed $m_{4\ell}$

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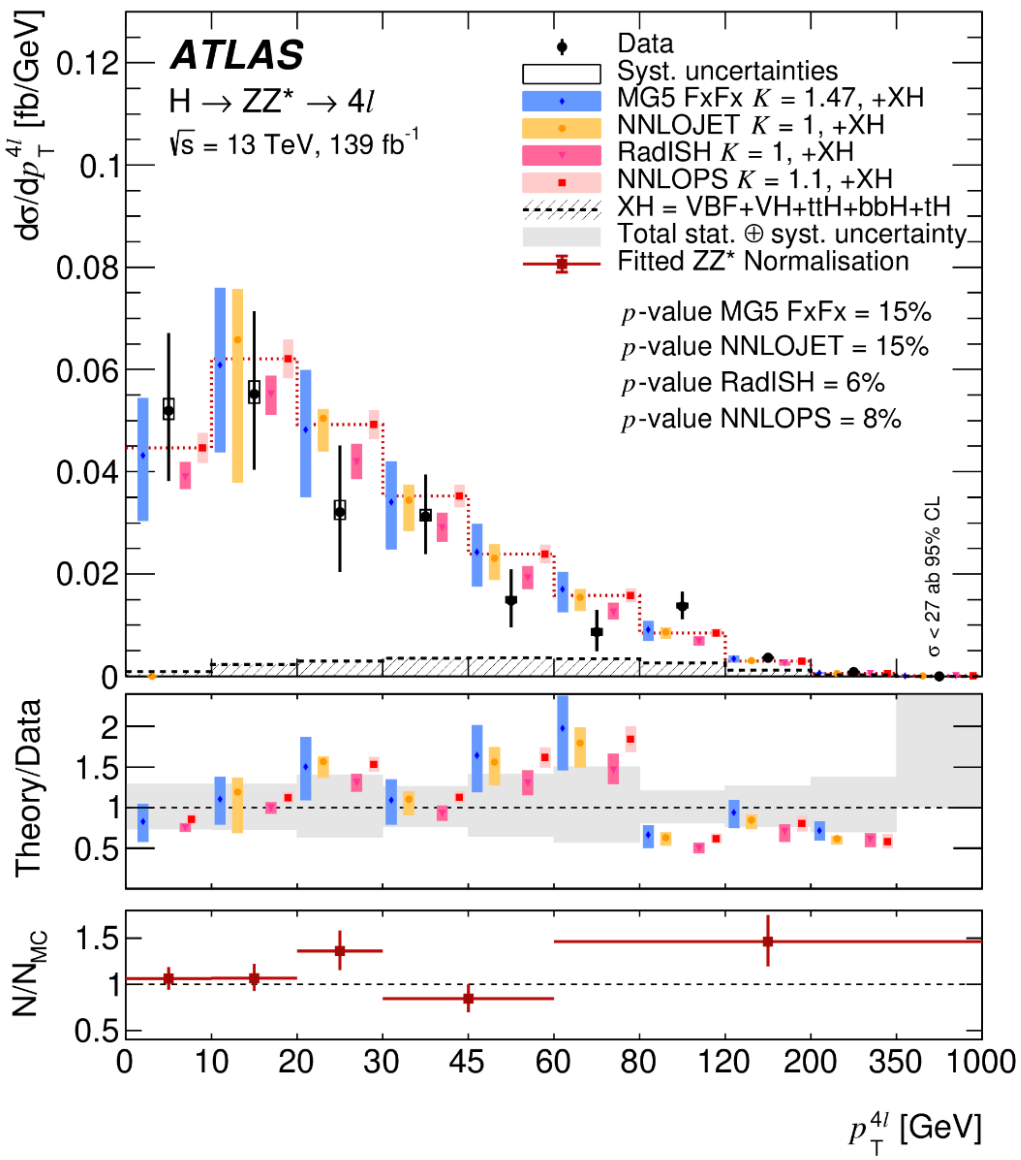
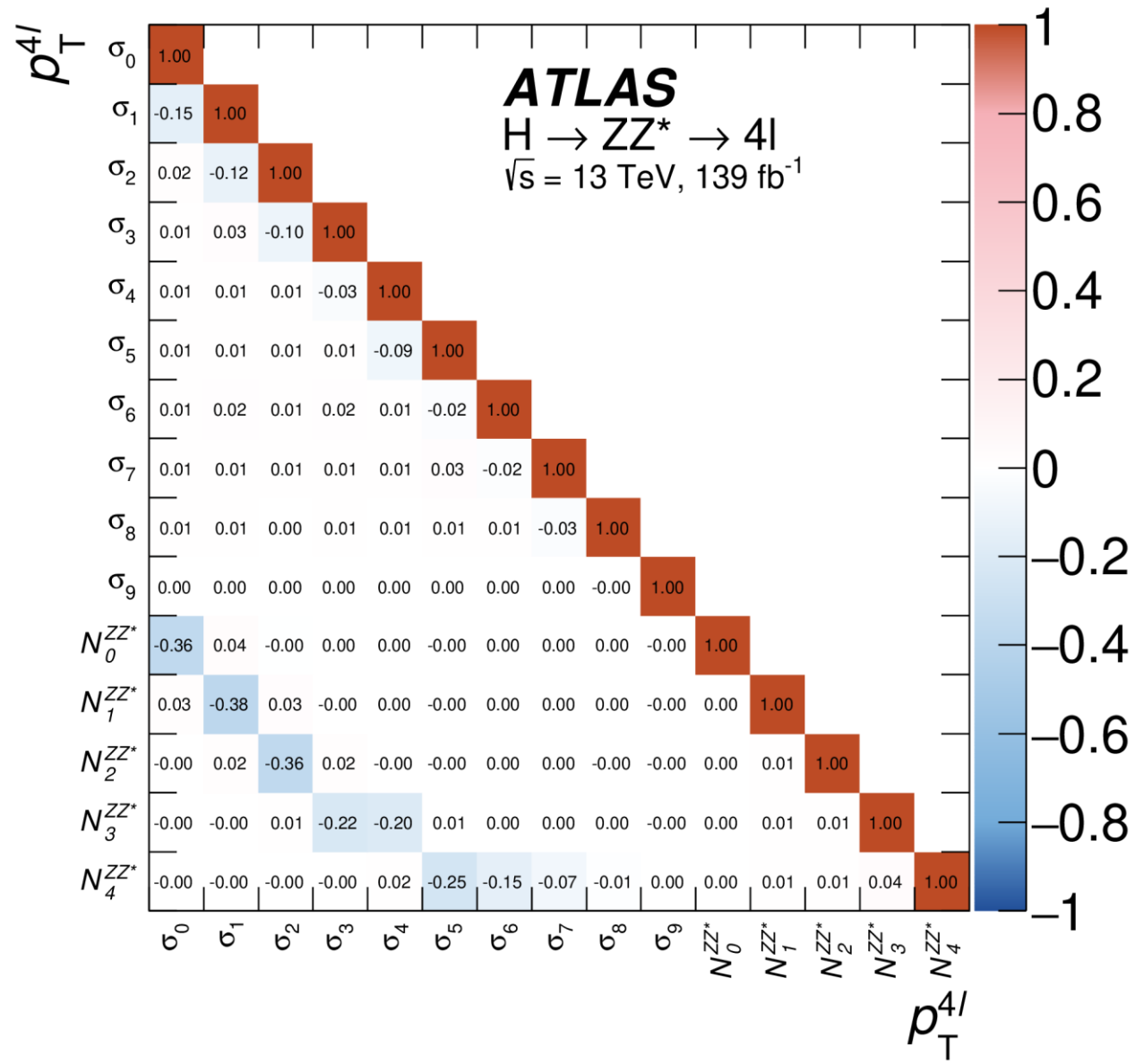
H → ZZ → 4ℓ: differential cross section





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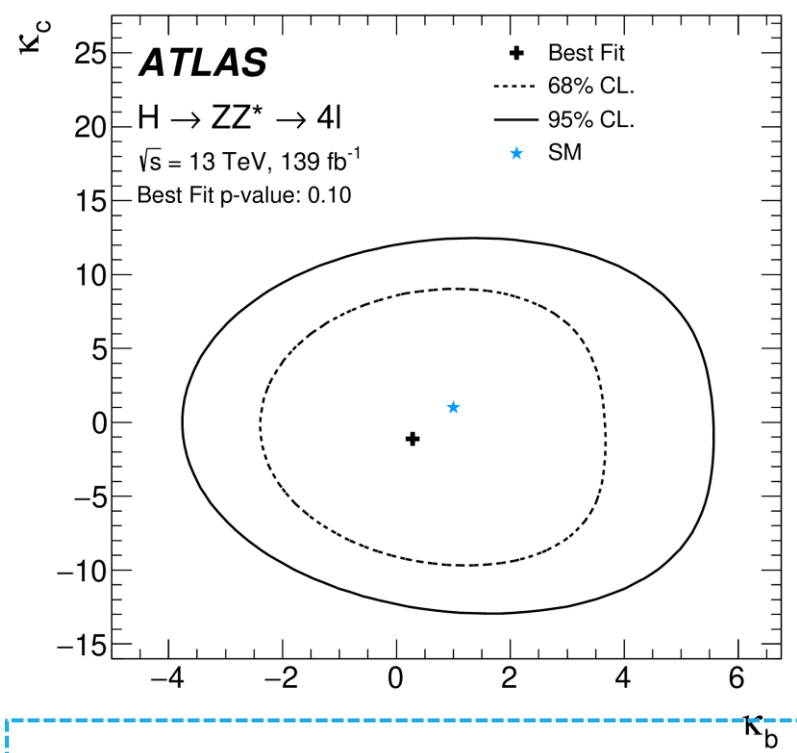
$H \to ZZ \to 4\ell$: ATLAS interpretation

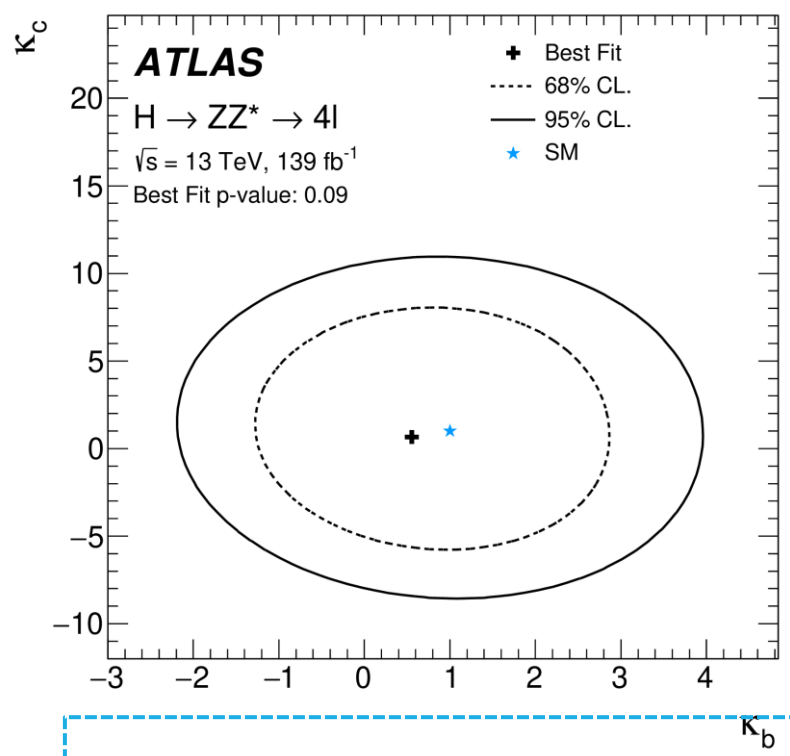
Limits on the H coupling to the charm quark exploiting the information of the $p_T^{4\ell}$ region

Three different approaches adopted to constrain κ_b and κ_c:

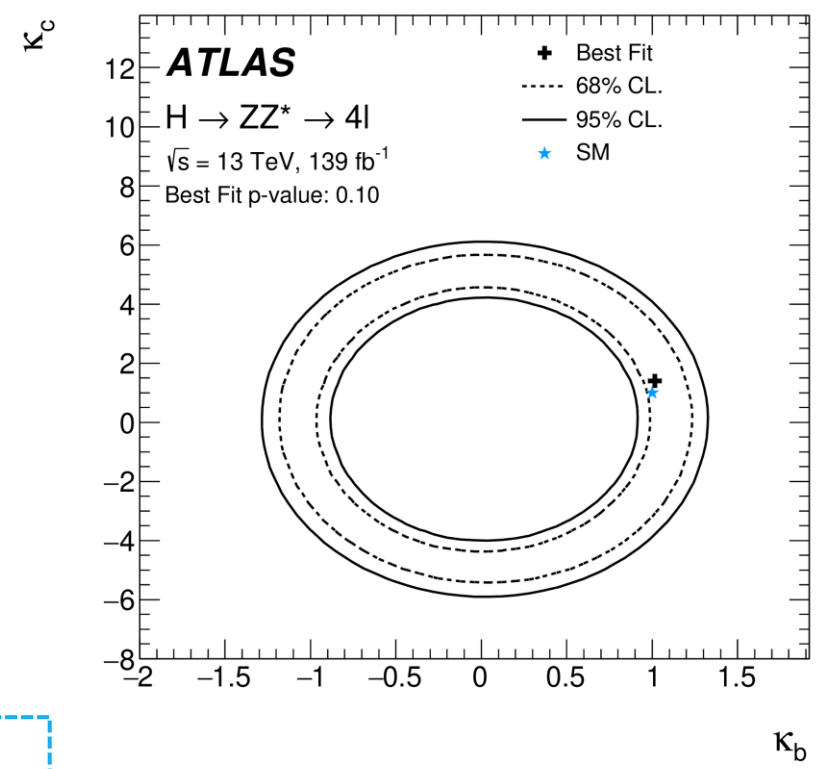
- $p_T^{4\ell}$ shape only;
- $p_T^{4\ell}$ differential xsec;
- both the predicted $p_T^{4\ell}$ cross section and modifications to the B due to κb and κc.



κ_c = [-11.7, 10.5] @ 95% CL
κ_b = [-3.21, 4.50] @ 95% CL

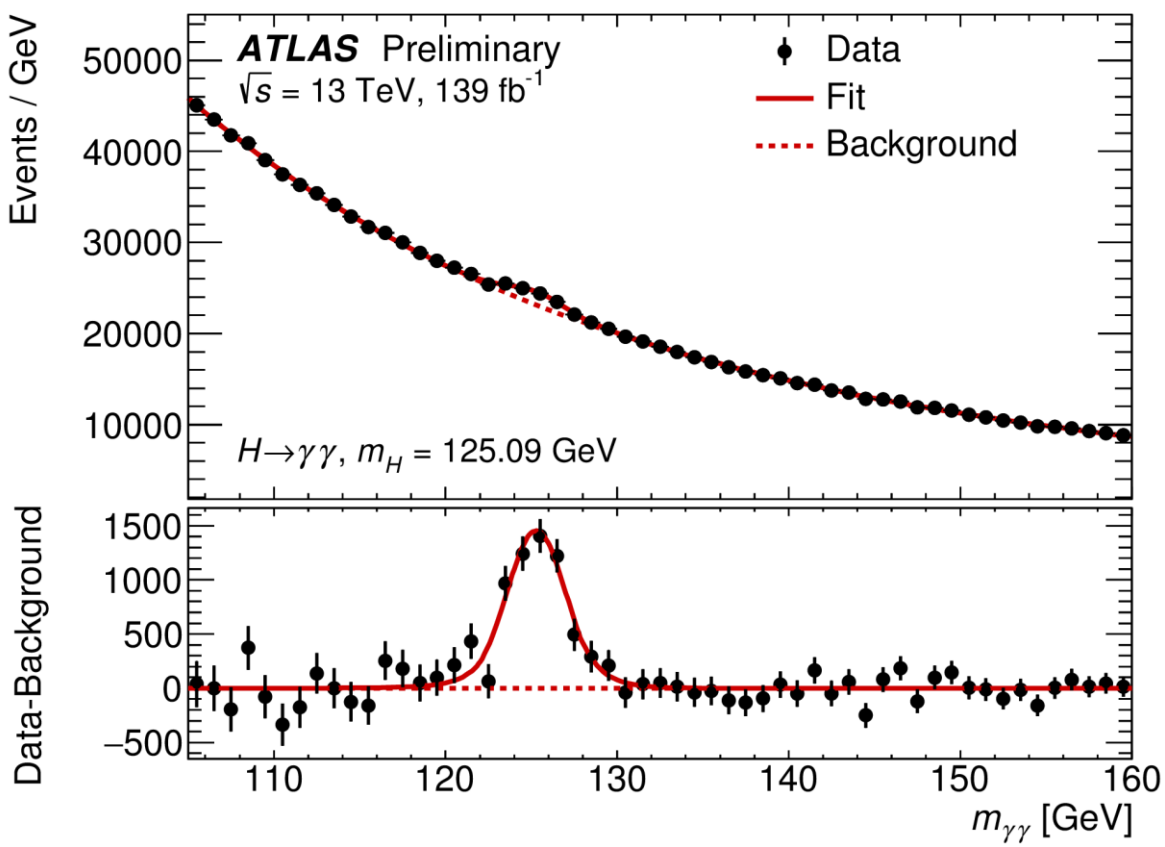


κ_c = [-7.46, 9.27] @ 95% CL
κ_b = [-1.82, 3.34] @ 95% CL



$H \rightarrow \gamma\gamma$

Clean final state topology and precise reconstruction of the diphoton invariant mass: powerful channel for precision measurements



Fiducial selection

- Photons: $|\eta| < 2.37$ and $\Sigma\, p_T^i / p_T^\gamma < 0.05$ (excluding $1.37 < |\eta| < 1.52$)
- Jets: anti-κ_T, R = 0.4, $p_T > 30$ GeV, $|\eta| < 4.4$
- Diphoton: $N_\gamma > 2$, $p_T^{\gamma 1} / m_{\gamma\gamma} > 0.35$, $p_T^{\gamma 2} / m_{\gamma\gamma} > 0.25$, $m_{\gamma\gamma} = [105, 160]$ GeV

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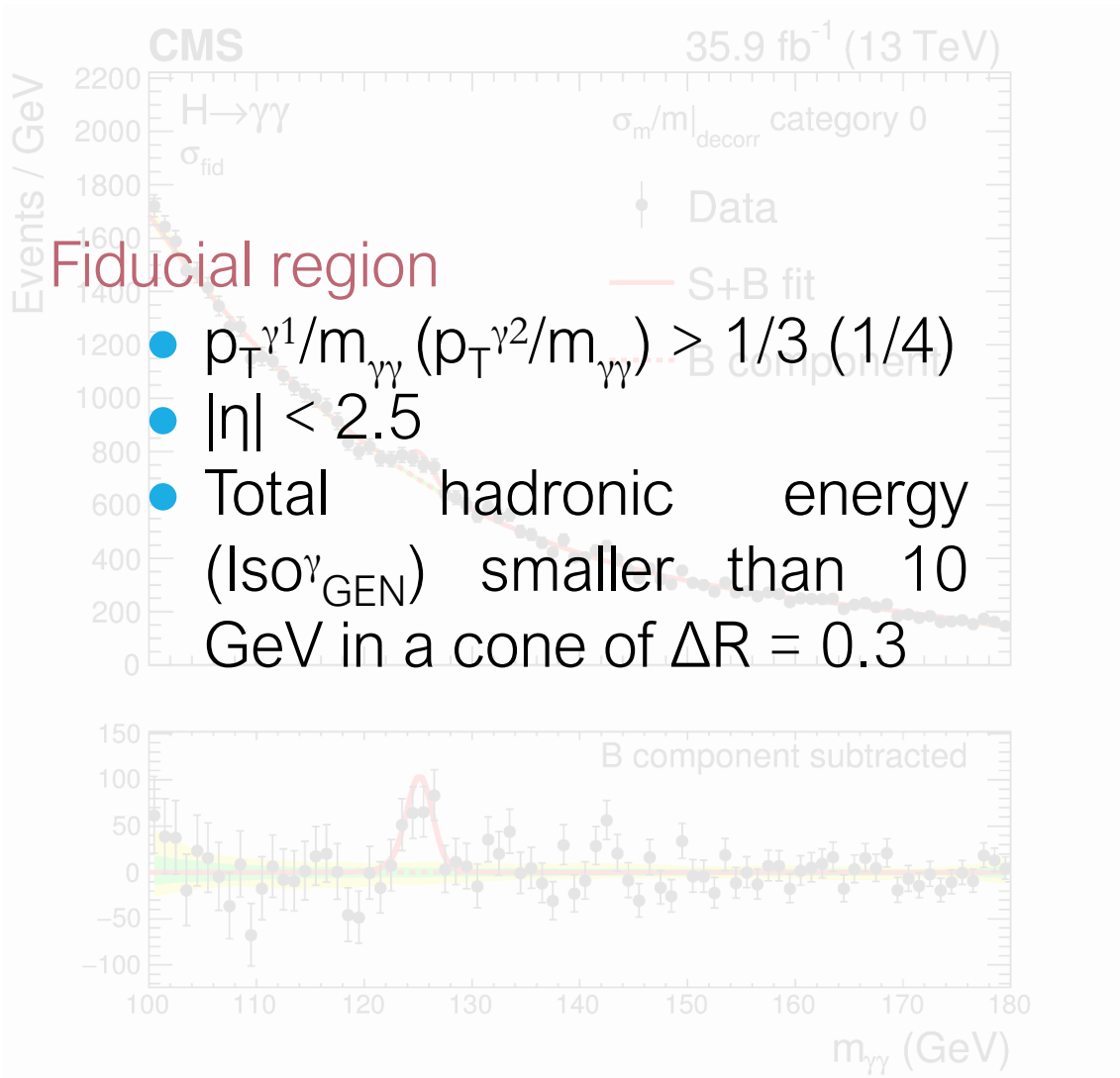
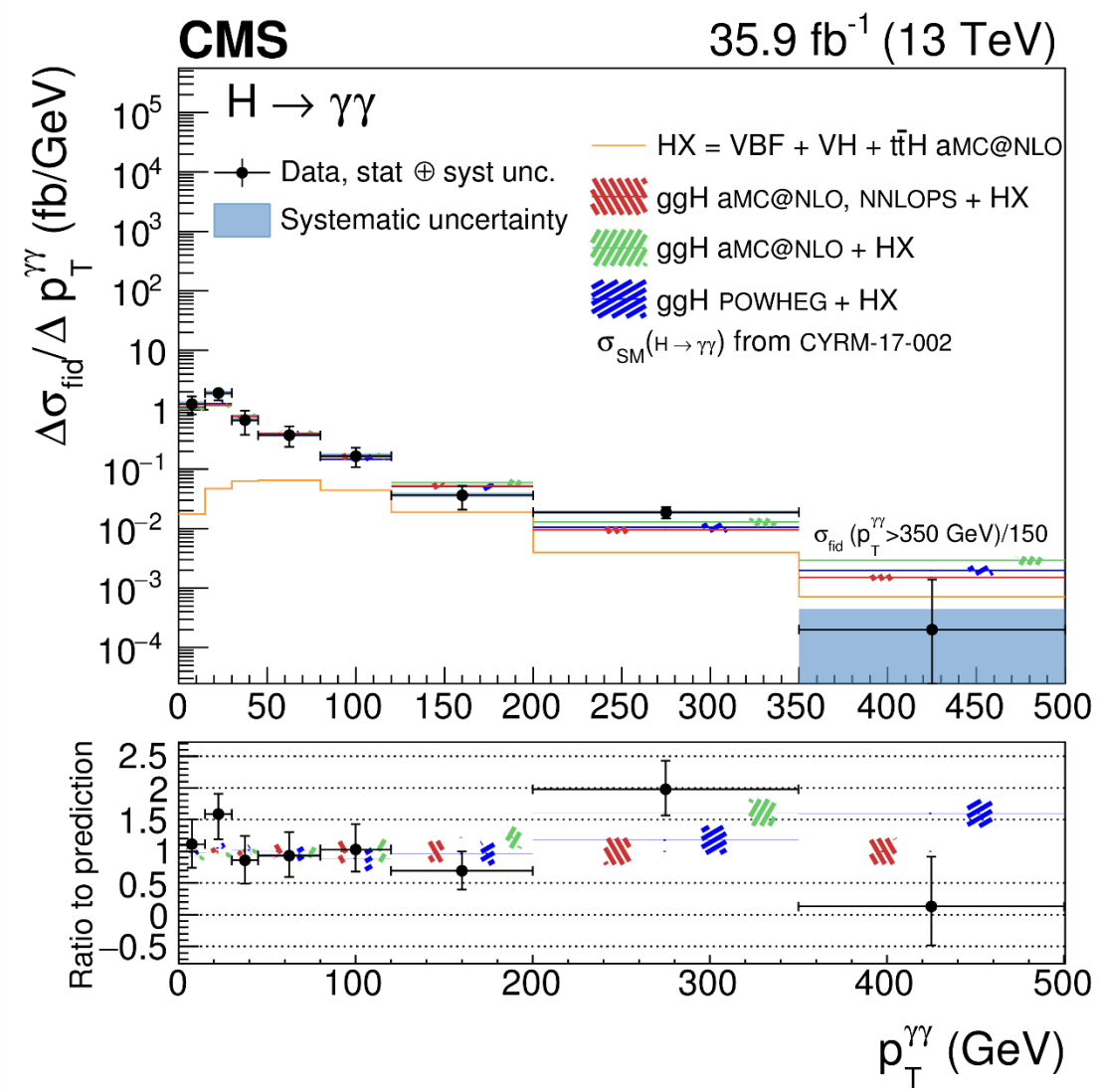
H → γγ: CMS 2016 differential cross section



Fiducial region

- $p_T^{\gamma 1}/m_{\gamma\gamma}$ ($p_T^{\gamma 2}/m_{\gamma\gamma}$) > 1/3 (1/4)
- $|\eta| < 2.5$
- Total hadronic energy (Iso^{γ}_{GEN}) smaller than 10 GeV in a cone of $\Delta R = 0.3$



$p_T^{\gamma\gamma}$: most precise measurement (~40% average uncertainty)
Largest number of bins

Good agreement with three different theoretical predictions

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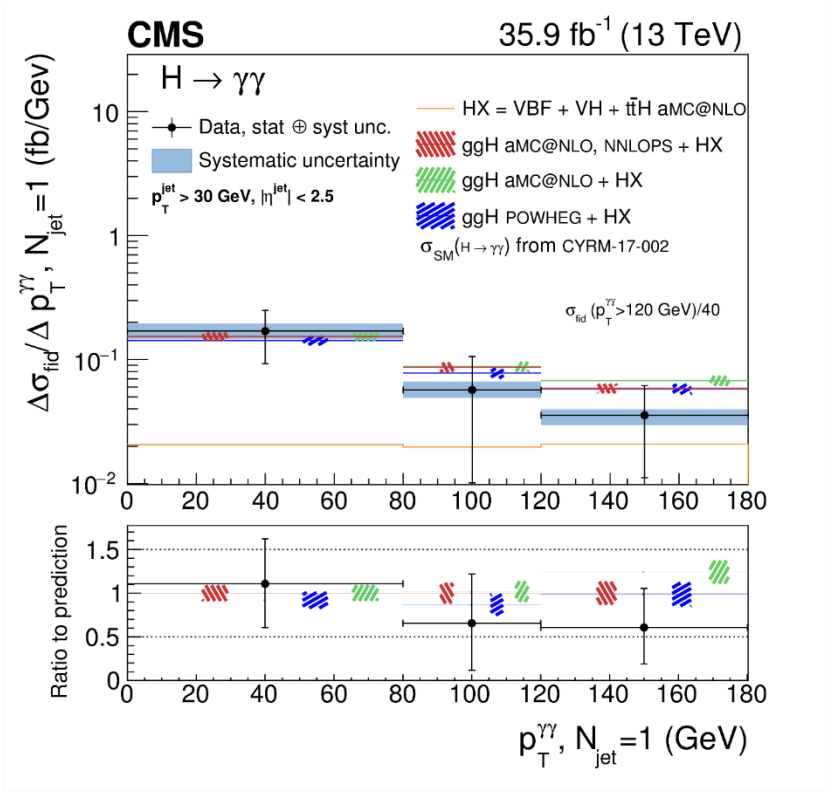
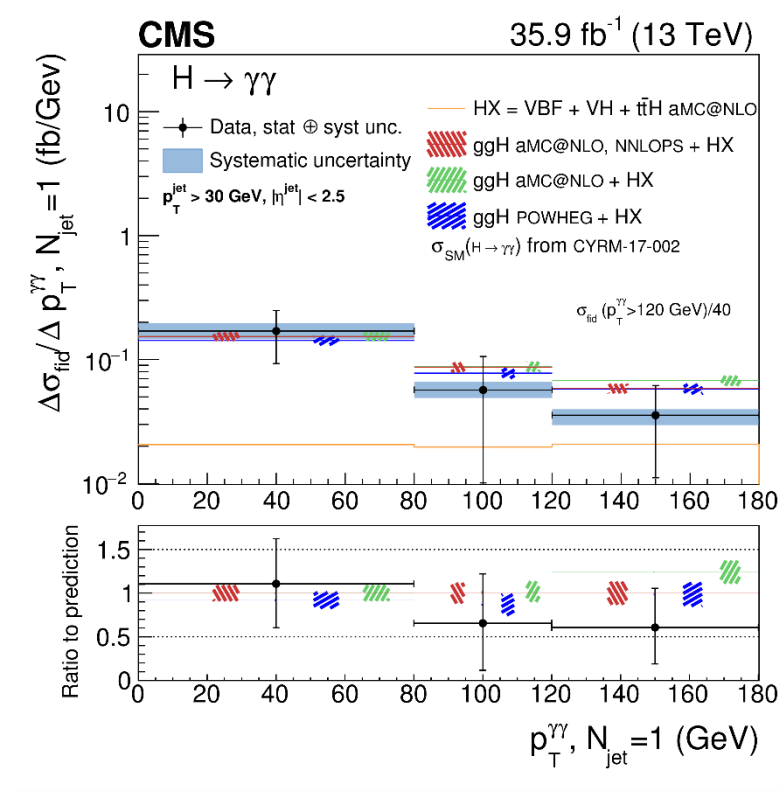
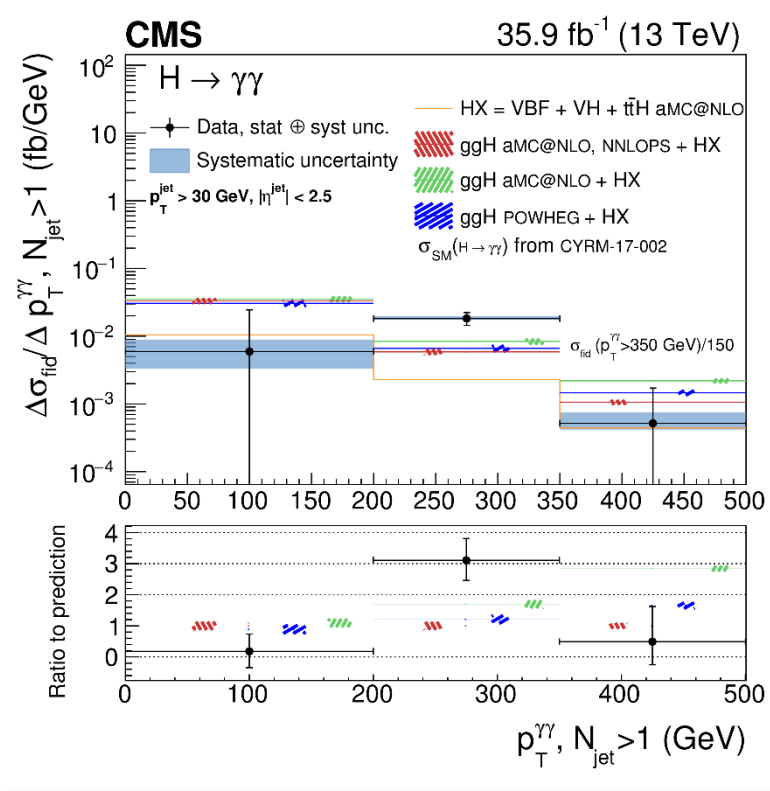
H → γγ: double differential distributions ($p_T^{\gamma\gamma}$ - Njet)

Cross section measured in 9 bins
with uncertainties ranging from ~35% to ~60%

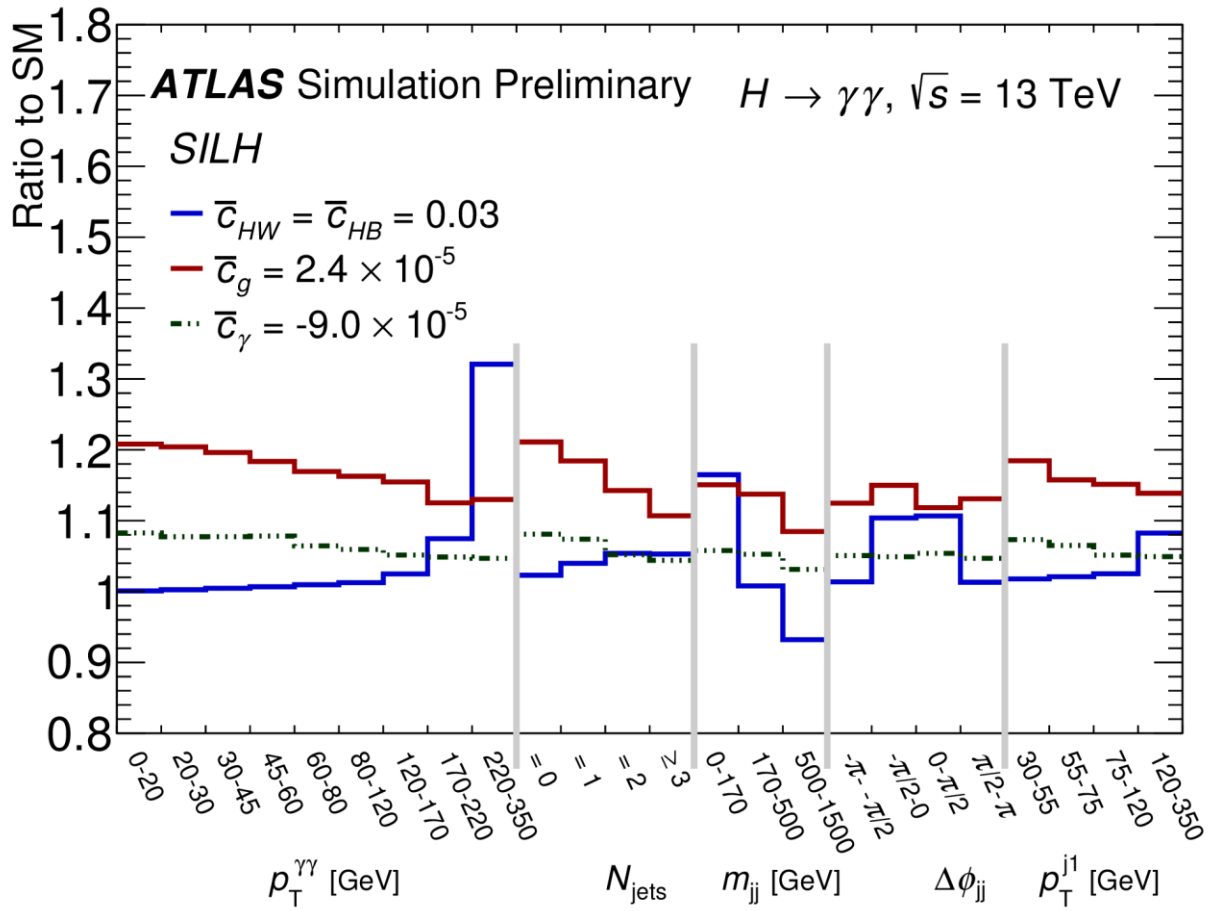


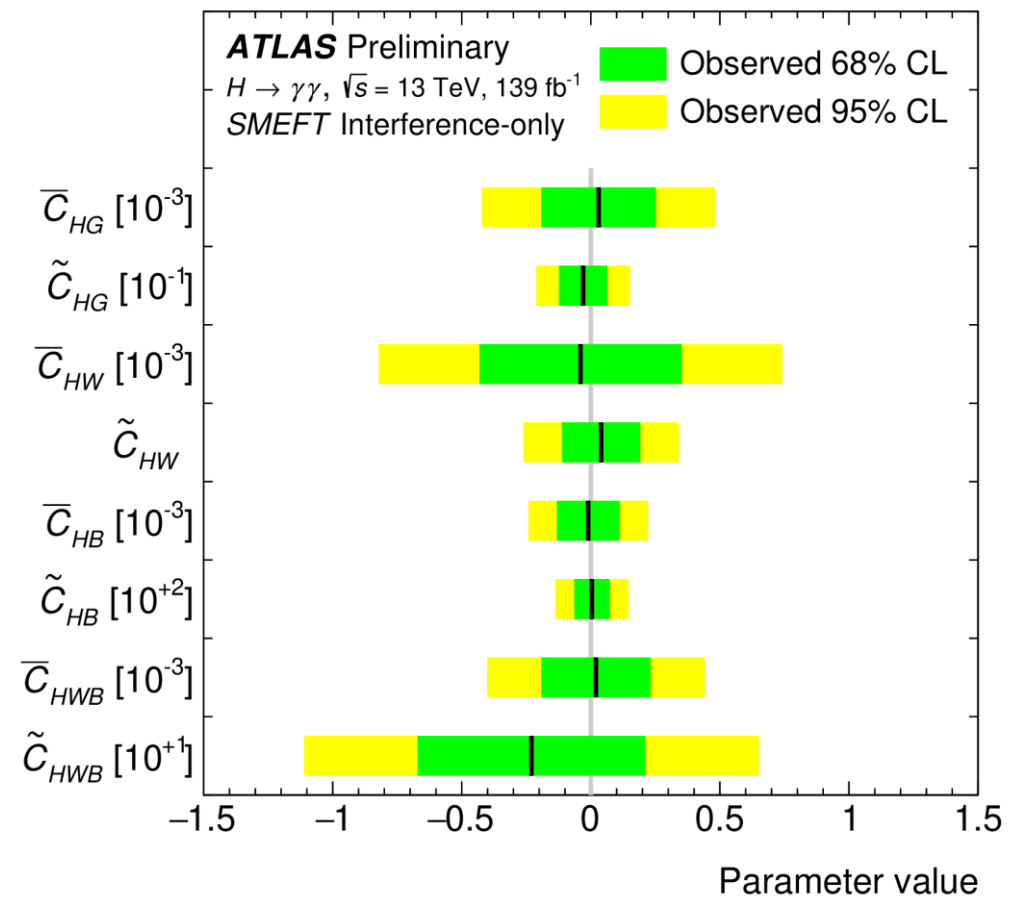




ATLAS-CONF-2019-029

H → γγ: ATLAS EFT interpretation





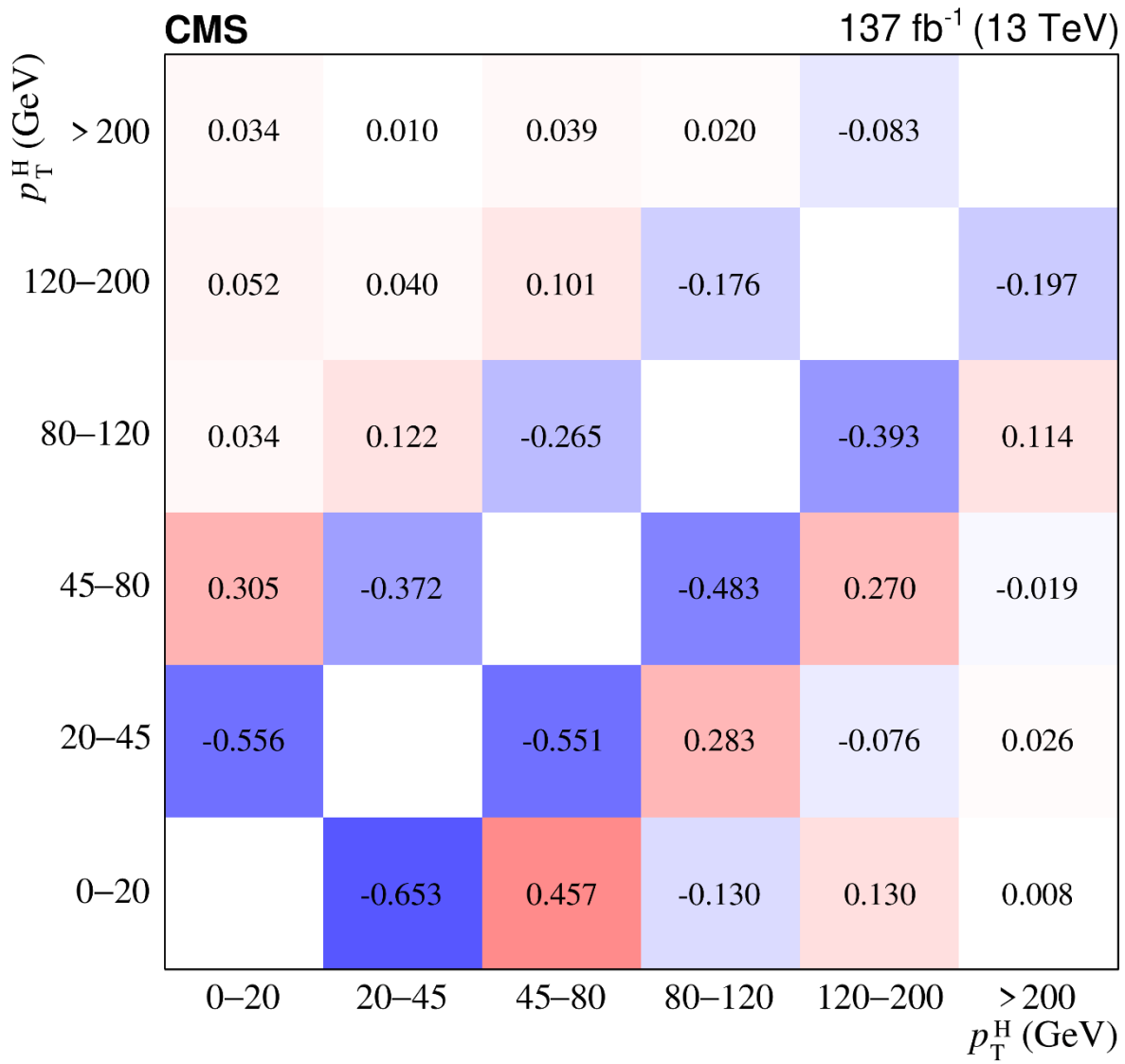
Differential measurements of various observables can be used to constrain dimensionless Wilson coefficients of dimension-six anomalous interactions of EFT Lagrangian:

No BSM contributions observed

arXiv:2007.0198419-029

H → WW: differential cross section

Correlation matrices among p_T^H signal strength measurements



Regularization term tends to smooth out unphysical anticorrelations and minimizes the global correlation coefficient.

H →WW: differential cross section

Binning of the differential-basis observables and signal categorizations used in each bin

p_T^H Binning (GeV):	0–20	20–45	45–80	80–120	120–200	>200
Categorization:	$4\mathcal{W}$	$4\mathcal{W}$	$4\mathcal{W}$	$3\mathcal{W}$	$2\mathcal{W}$	$2\mathcal{W}$

N_{jet} Binning:	0	1	2	3	≥ 4
Categorization:	$4\mathcal{W}$	$4\mathcal{W}$	$2\mathcal{W}$	$1\mathcal{W}$	$1\mathcal{W}$

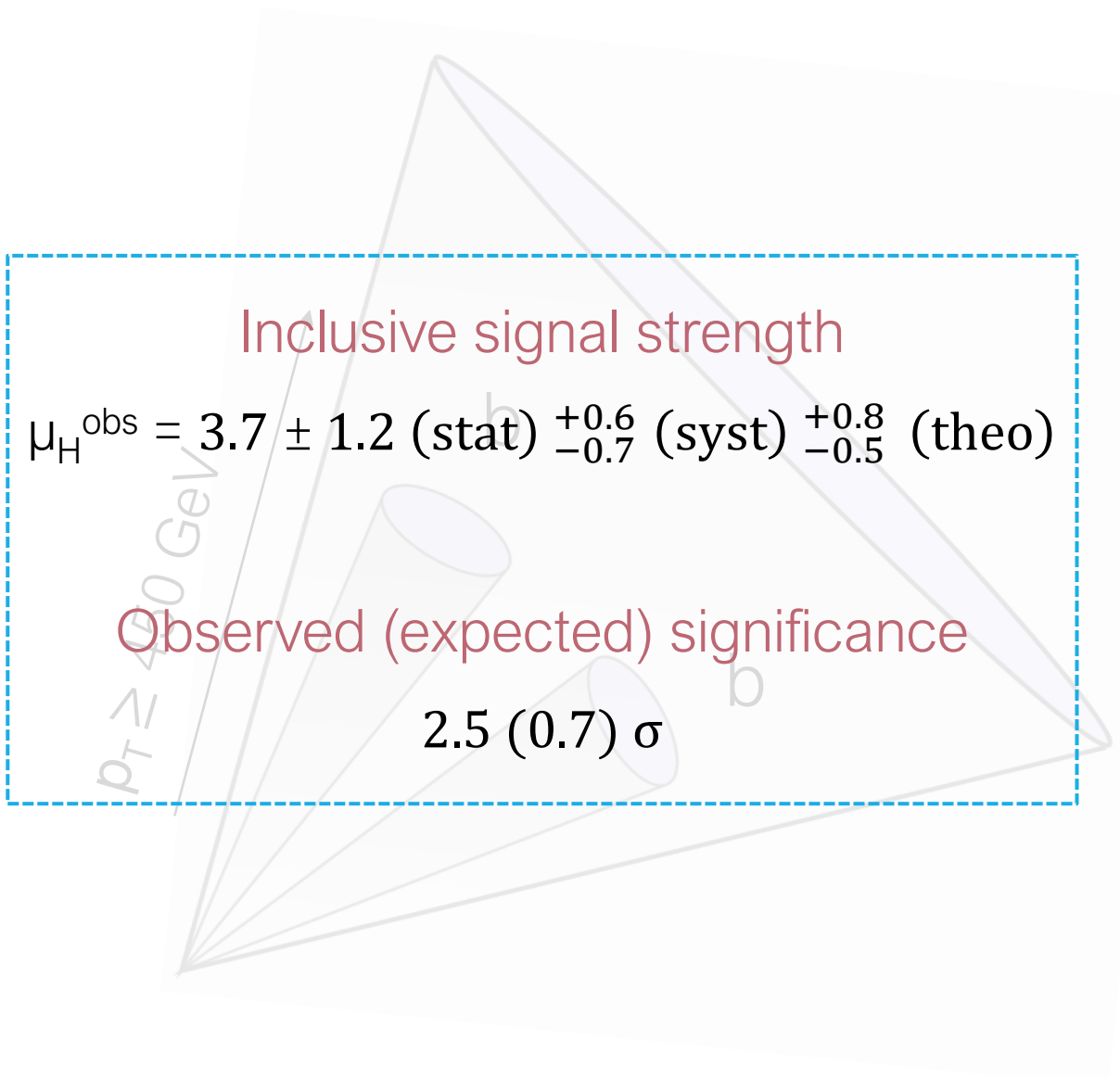
Observed cross sections in fiducial p_T^H bins

p_T^H (GeV)	σ^{SM} (fb)	μ	Regularized μ Value	stat	exp	signal	bkg	lumi	Bias	σ^{obs} (fb)
0–20	27.45	1.37 ± 0.30	1.26 ± 0.27	± 0.17	± 0.19	± 0.01	± 0.10	± 0.03	$+0.00$	34.6 ± 7.5
20–45	24.76	0.52 ± 0.42	0.73 ± 0.36	± 0.24	± 0.25	± 0.01	± 0.10	± 0.03	-0.12	18.2 ± 8.9
45–80	15.28	1.55 ± 0.41	1.30 ± 0.33	± 0.24	± 0.20	± 0.03	± 0.09	± 0.03	-0.03	19.9 ± 5.2
80–120	7.72	0.49 ± 0.52	0.79 ± 0.42	± 0.32	± 0.25	± 0.02	± 0.08	± 0.03	-0.16	6.1 ± 3.3
120–200	5.26	$1.34^{+0.51}_{-0.48}$	1.14 ± 0.41	± 0.29	± 0.27	± 0.04	± 0.08	± 0.03	$+0.11$	6.0 ± 2.2
>200	2.05	$0.64^{+0.63}_{-0.60}$	$0.73^{+0.61}_{-0.57}$	± 0.38	± 0.42	$^{+0.09}_{-0.03}$	± 0.10	± 0.03	$+0.19$	1.5 ± 1.2

H → bb

arXiv:2006.13251

Differential exploration of the high p_T^H region at 13 TeV relying on boosted Higgs

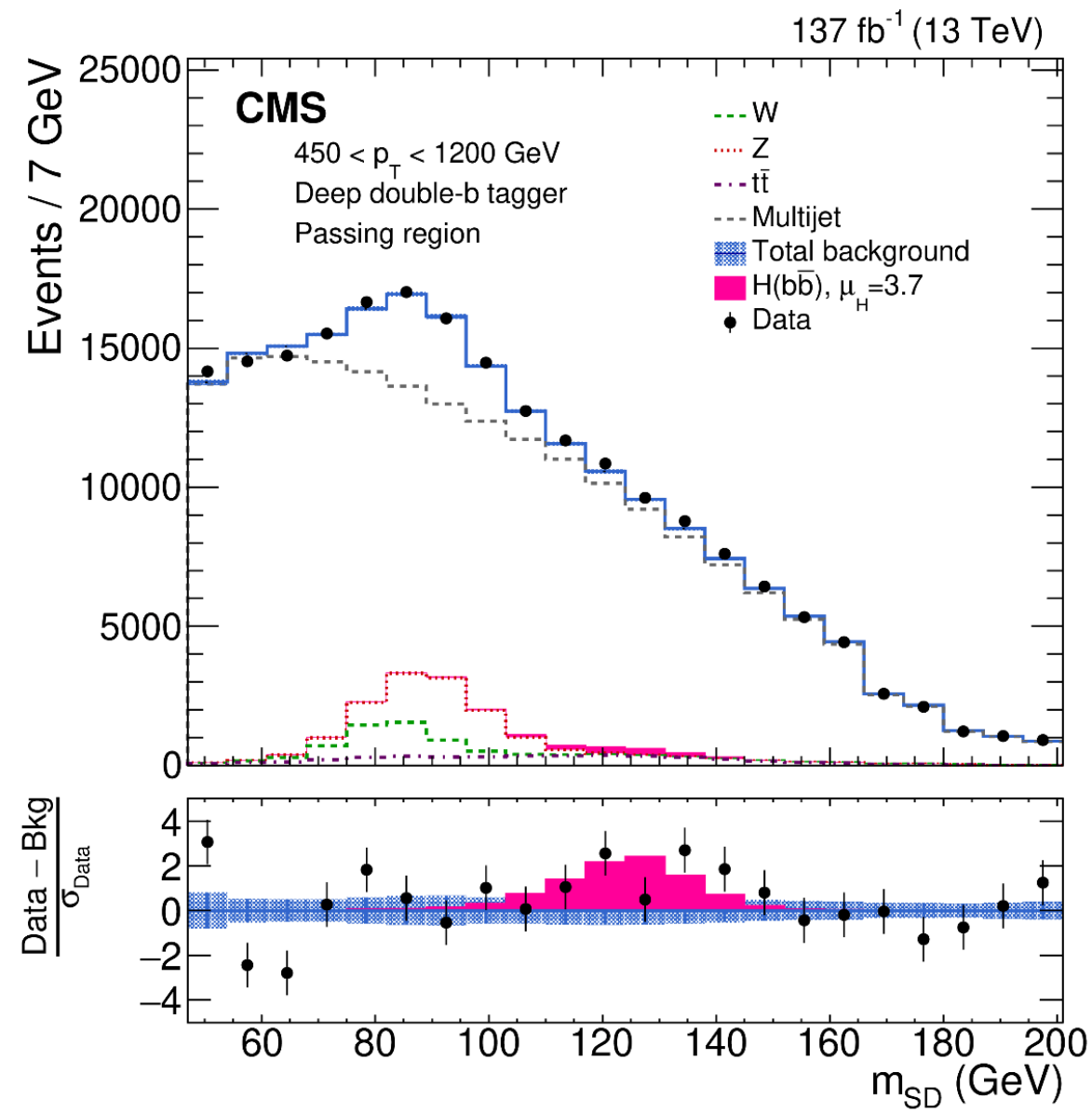


Inclusive signal strength

$\mu_H^{obs} = 3.7 \pm 1.2\ (\text{stat})\ ^{+0.6}_{-0.7}\ (\text{syst})\ ^{+0.8}_{-0.5}\ (\text{theo})$

Observed (expected) significance

$2.5\ (0.7)\ \sigma$



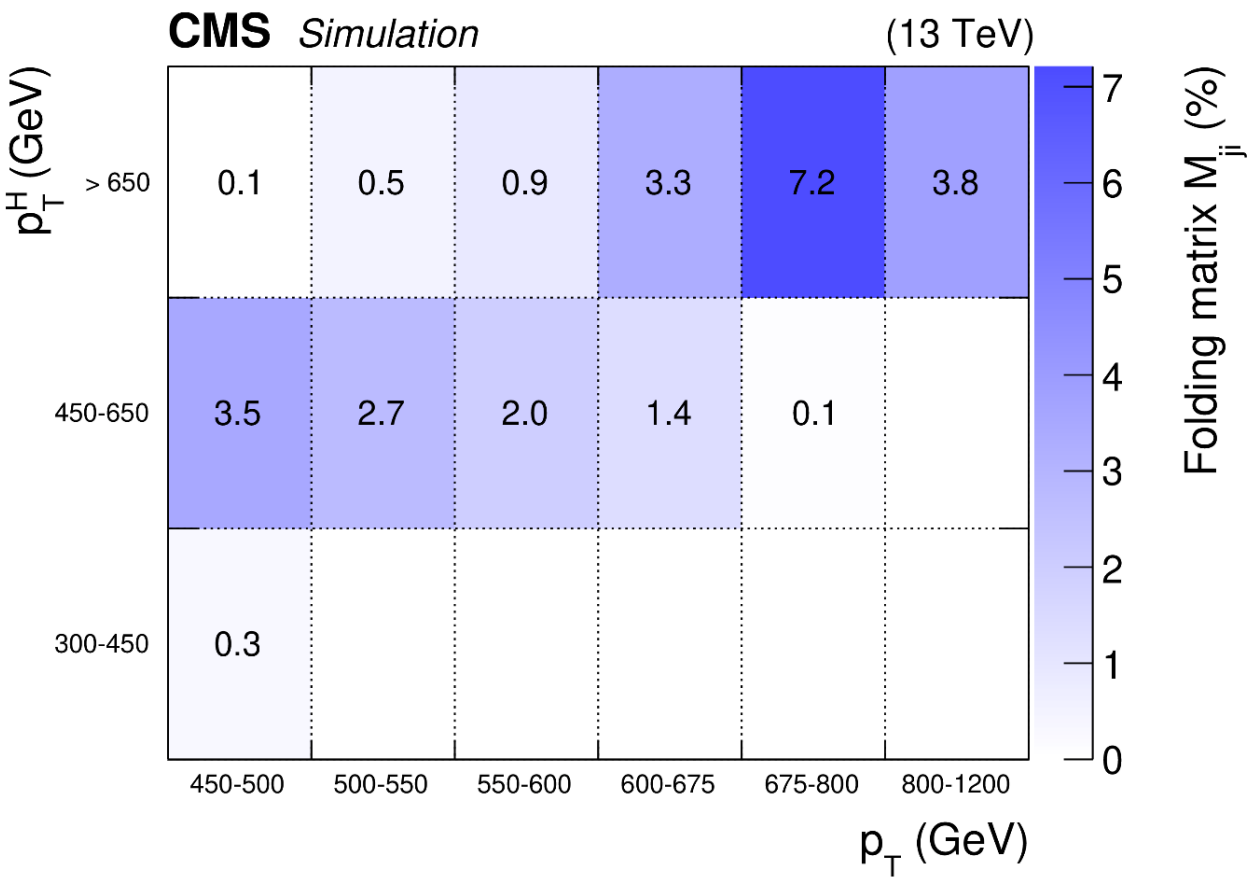
Large effort by theory community to provide precise predictions for boosted H production

arXiv:2005.07762

arXiv:2006.13251

H → bb: differential cross section

Differential cross section for a high p_T Higgs produced through gluon fusion: maximum likelihood unfolding technique

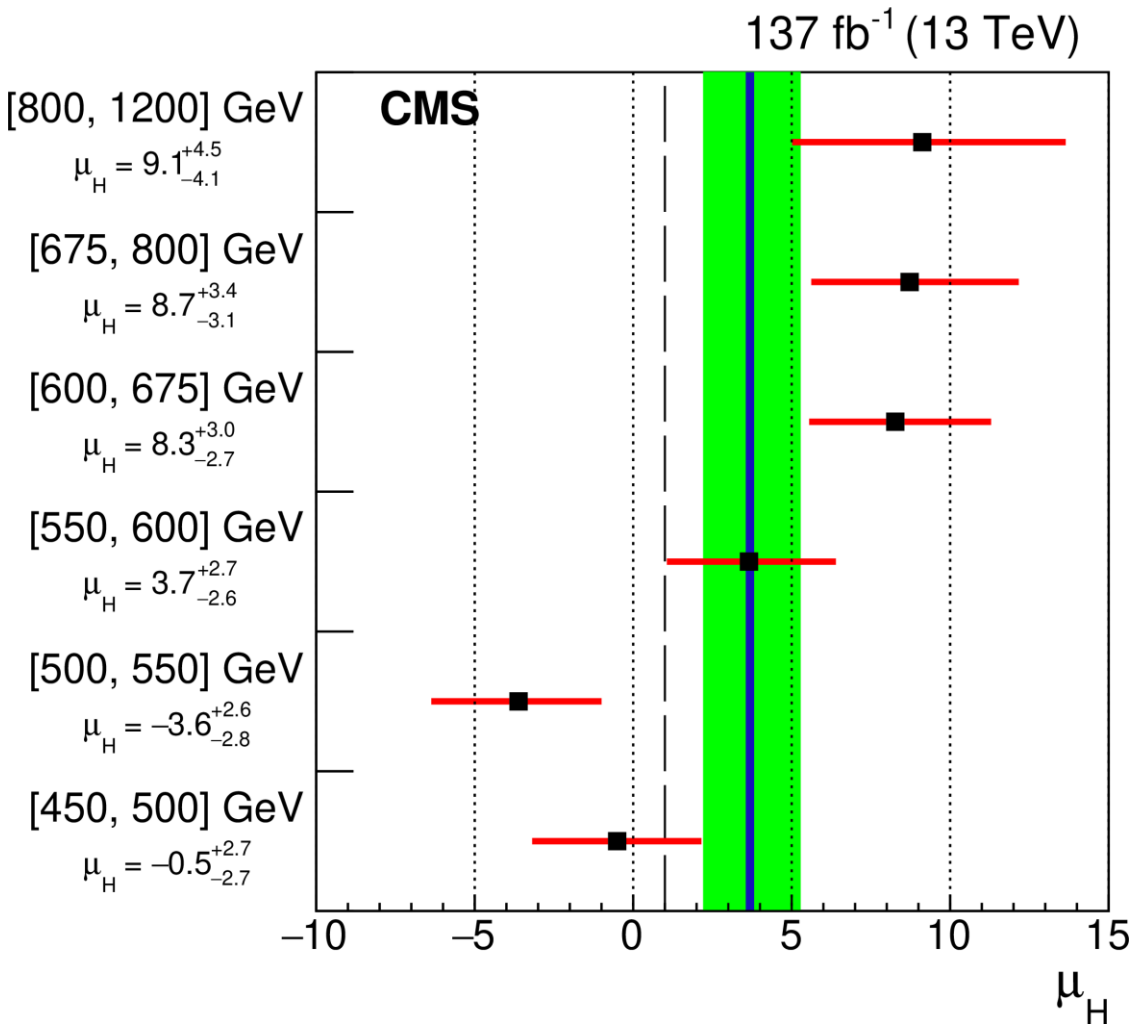


- ggH splitting in three particle level p_T^H bins following STXS recommedations: 300 - 450, 450 - 650 and > 650 GeV
- Each p_T^H bin is considered as a separate process with a freely floating signal strength in the likelihood function;
- other production modes are fixed to SM expectation.
- No regularization performed in the unfolding procedure

p_T^H (GeV)	300–450		450–650		>650	
Measured	580	±790	5	±43	29	±11
		±720 (stat) ± 350 (syst)		±37 (stat) ± 22 (syst)		±9 (stat) ± 7 (syst)
LHCHXSWG		—	16.0	$^{+1.7}_{-2.0}$	2.1	$^{+0.2}_{-0.3}$
HJ-MINLO	89	$^{+20}_{-18}$	13.5	$^{+3.0}_{-2.7}$	1.9	±0.4
Ref.	152	±46	34	±10	7.6	±3.0

H → bb

Alternative fit: independent signal strength per p_T^H category



An independent μ_H is assigned to each of the six reconstructed jet p_T bins:

- μ unconstrained in the fit and varied simultaneously;
- all other parameters are profiled.

Excess with respect to the SM expectation for categories with jet p_T above 550 GeV.

Combination

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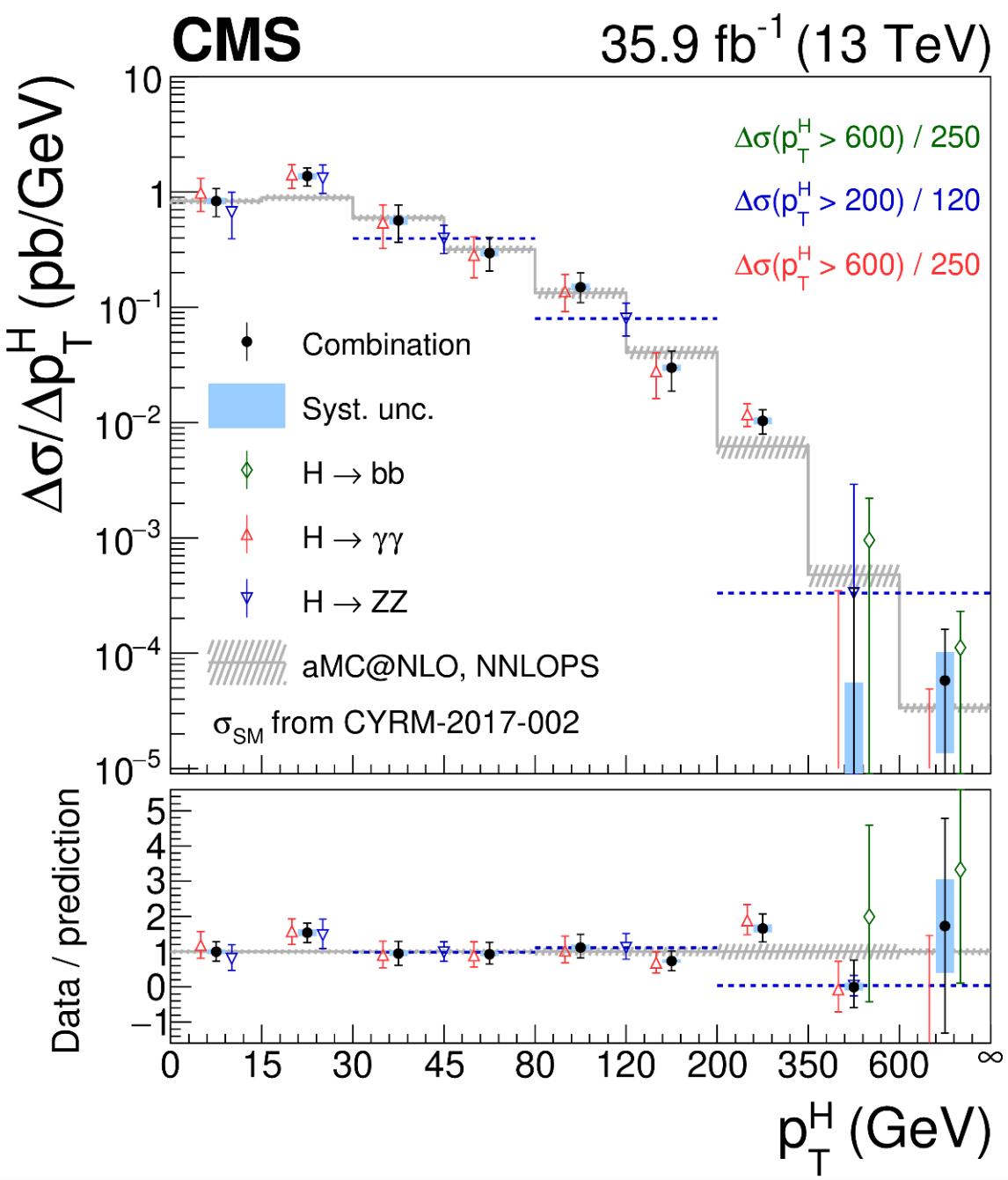

- Most precisely measured with 4ℓ + $\gamma\gamma$
- Sensitivity at high p_T improved by boosted H → bb

- Probe p_T^H modeling of ggH up to 1 TeV
- Uncertainties in the high p_T^H region at the level of **20 - 30% with full Run2** dataset

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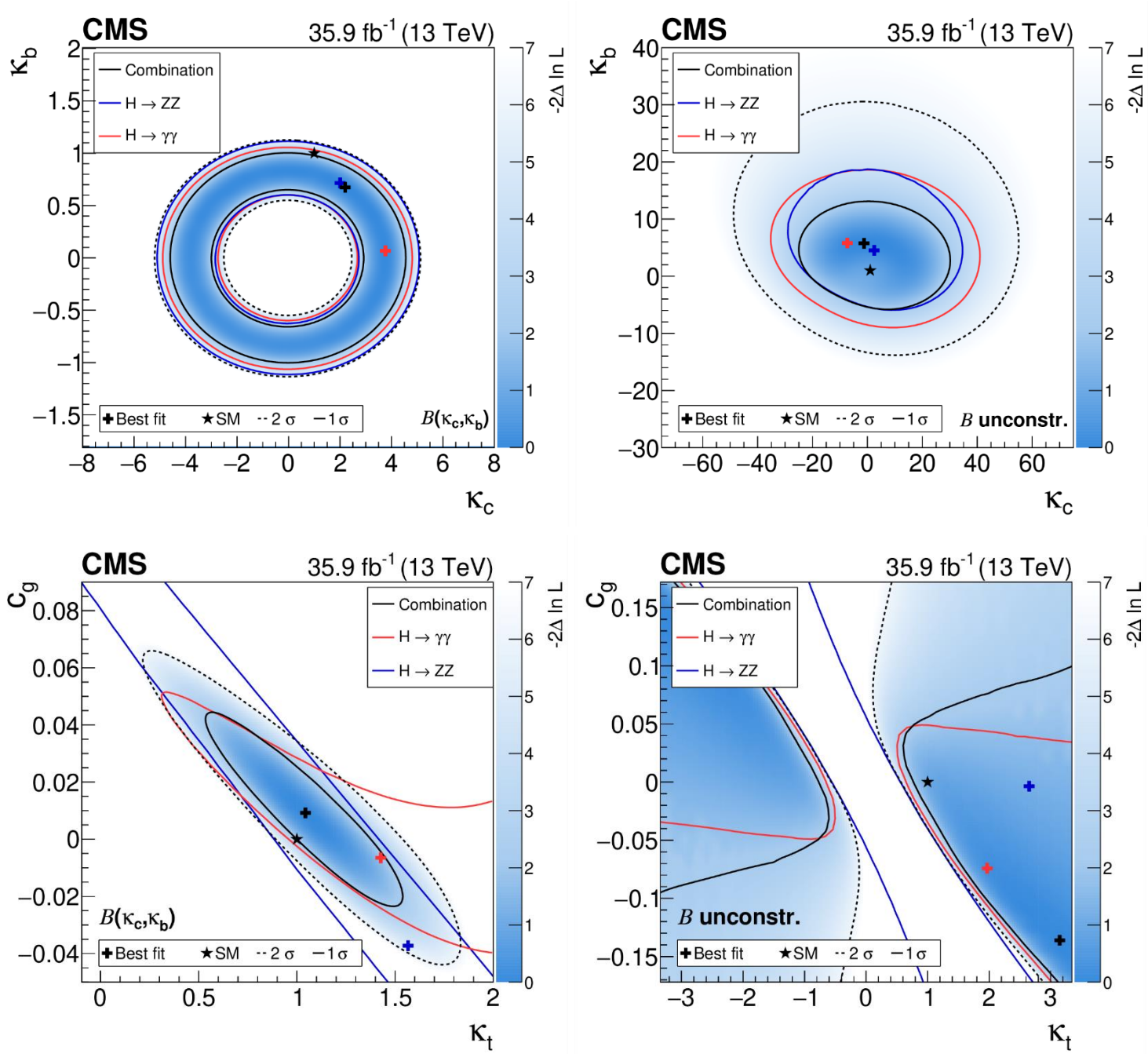
Combination

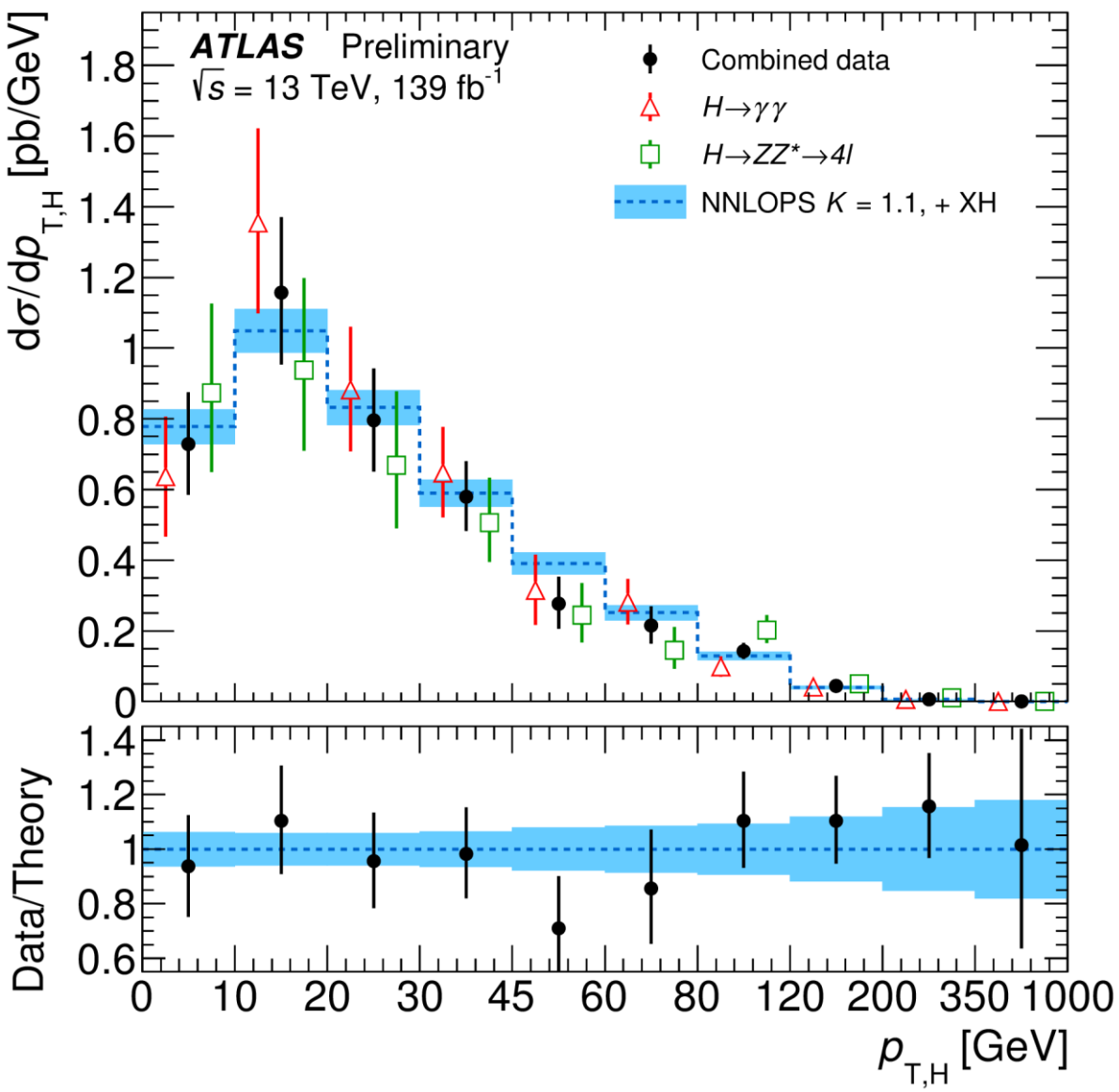
Possibility to constrain coupling modifiers fitting theoretical predictions for p_T^H to data: results are dependent on the assumptions on B under coupling variation



Assuming B freely floating: nuisance parameters with no prior constraint

Combination

Combination of HZZ4ℓ and Hγγ differential cross section as a function of p_T^H



$p_{T,H}$ Bin	$d\sigma/dp_{T,H}$ (pb/GeV)
0-10 GeV	0.73 ± 0.15
10-20 GeV	1.16 ± 0.21
20-30 GeV	0.80 ± 0.15
30-45 GeV	0.58 ± 0.10
45-60 GeV	0.278 ± 0.075
60-80 GeV	0.215 ± 0.054
80-120 GeV	0.142 ± 0.023
120-200 GeV	0.044 ± 0.007
200-350 GeV	0.007 ± 0.001
350-1000 GeV	$0.0002 \pm 8 \times 10^{-5}$

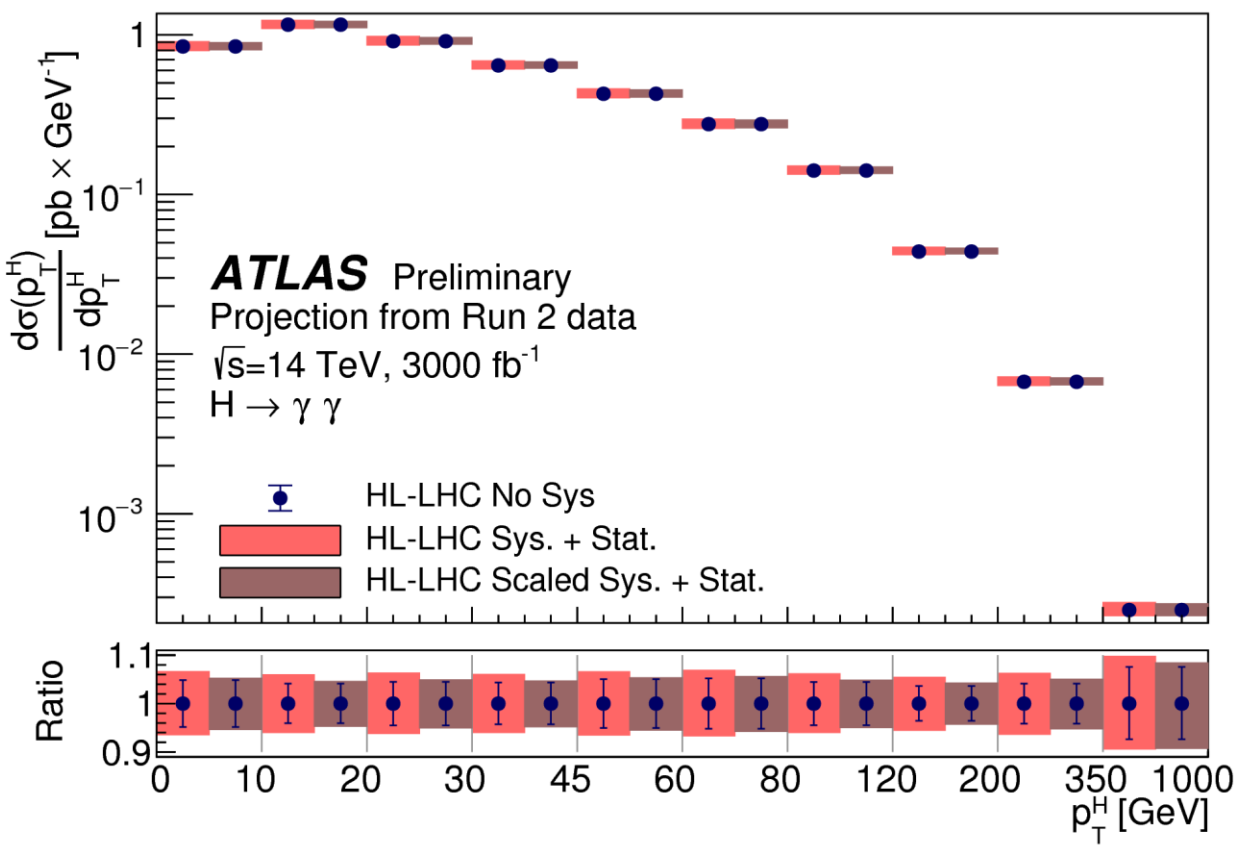
Prospects at HL-LHC

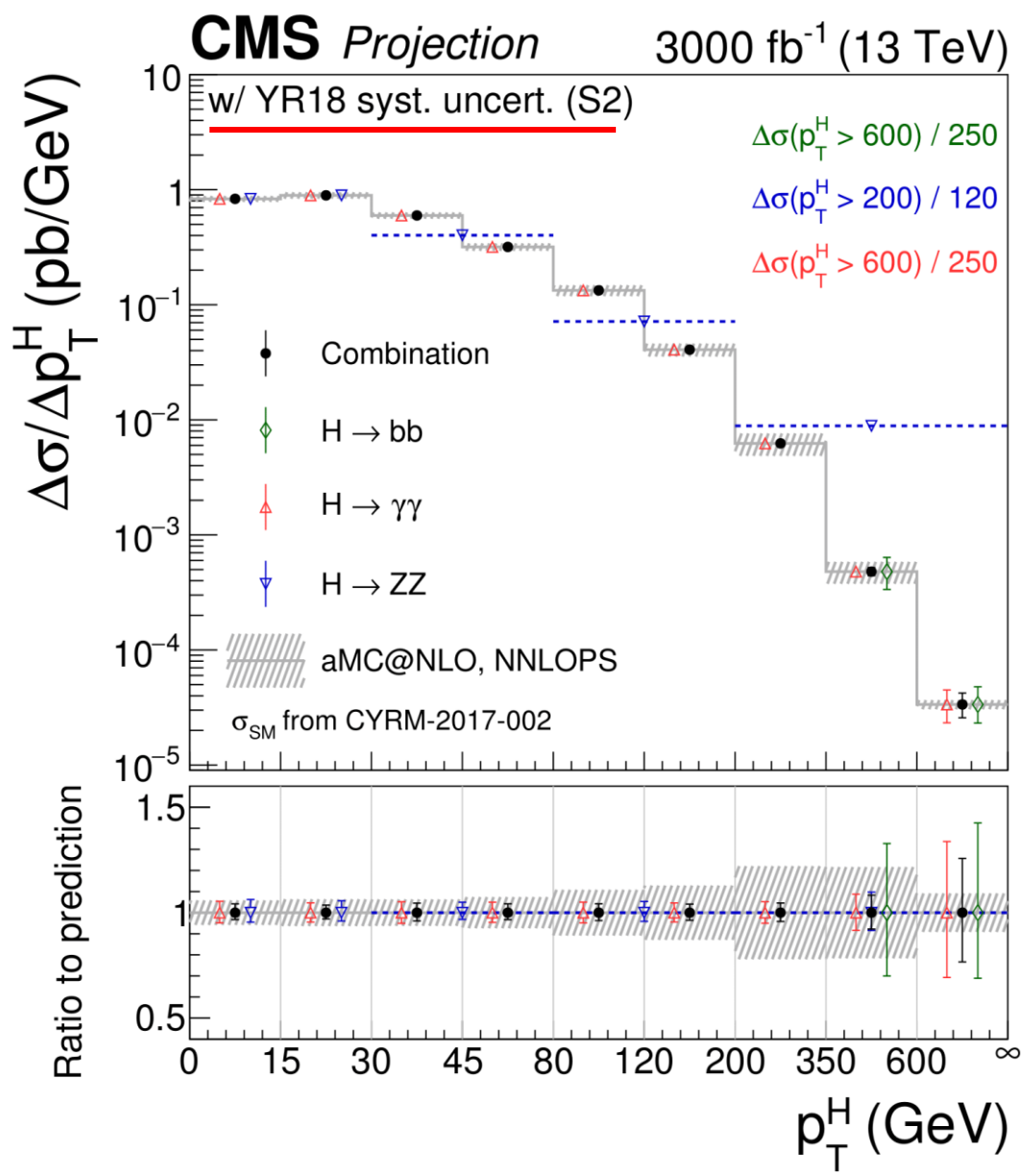
ATL-PHYS-PUB-2018-040
CMS-PAS-FTR-18-011

Performance of the future detector assumed to be comparable to Run 2
(based on the combination of 2016 results)

Two different scenarios for systematics uncertainties:

- S1: same systematic uncertainties as Run 2
- S2: expected improvements in systematic uncertainties are taken into account with scaling





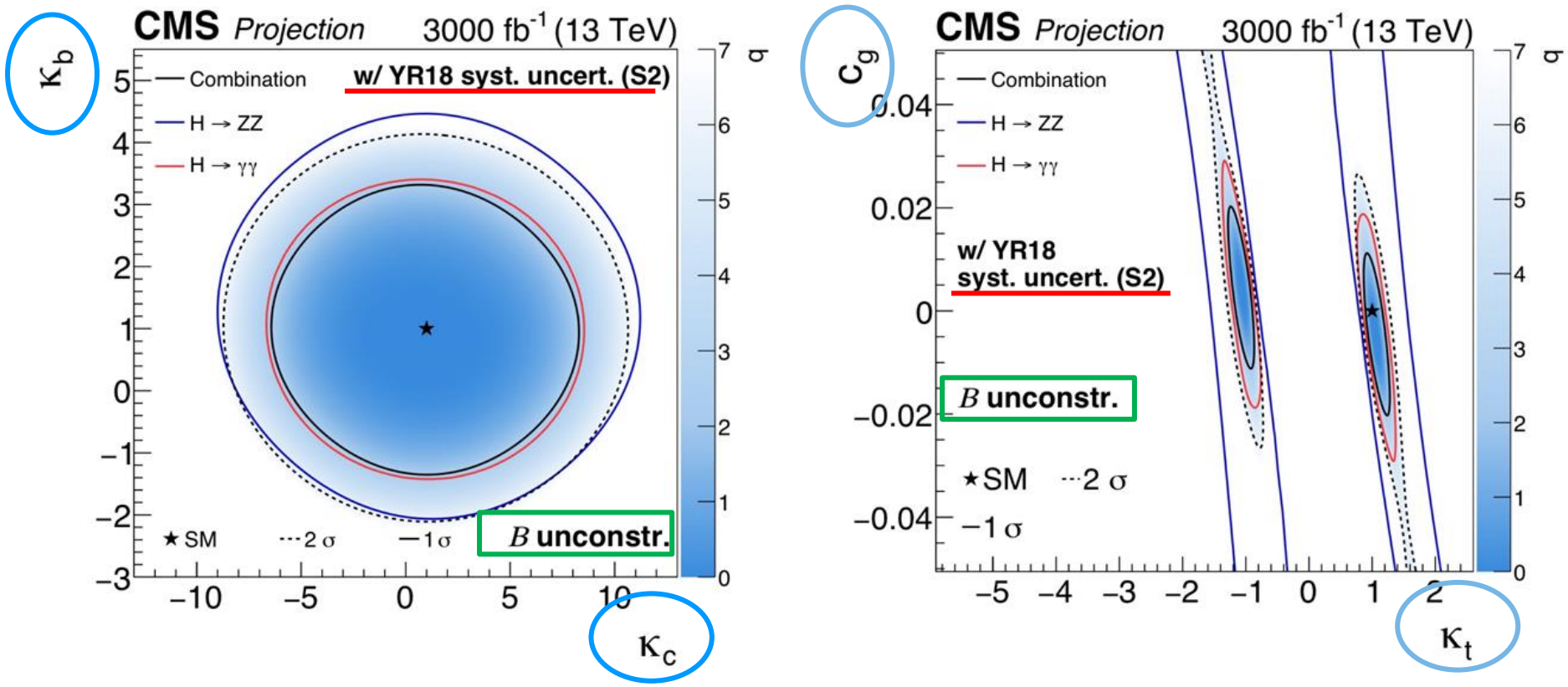
Differential H cross section as a function of p_T^H: HL-LHC

Prospects at HL-LHC

ATL-PHYS-PUB-2018-040
CMS-PAS-FTR-18-011

- Possibility to constrain coupling modifiers fitting theoretical predictions for p_T^H to data
- Results are dependent on the assumptions on *B* under coupling variation

Assuming *B* freely floating: nuisance parameters with no prior constraint



No sensitivity to the κ_t sign

Sensitivity to κ_b/κ_c at low p_T and κ_t/c_g BSM at high p_T

- κ-framework: Yukawa coupling to b, c
- Run 2 resulting 95% CL intervals:
  $-33 < \kappa_c < 38$ & $-8.5 < \kappa_b < 18$

- EFT-based parametrization: effective coupling to g
- Heavy top mass limit ($\kappa_t = 0$, $c_g \approx 1/12$) distinguished from the point-like coupling to the gluon field

Differential H cross section as a function of p_T^H : HL-LHC