Experimental concluding talk

Higgs Hunting 2024

September 25, 2024

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(DESY and Universität Hamburg)

DESY.

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

A few comments to start....

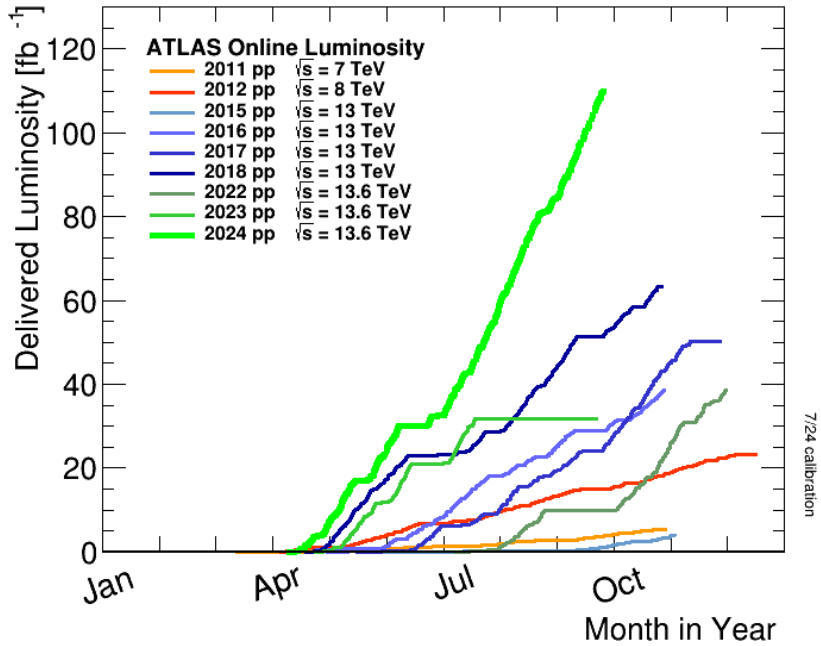
- Thank you to organizers, speakers, session chairs, ... for a very nice conference!
- Cannot do justice to everything shown in the past days – just a biased selection
- Please excuse if your favorite topic/your talk is not represented here!
- Picking results from one or the other collaboration – in many cases, the other collaboration has similar results as well, see https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults and https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults and https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

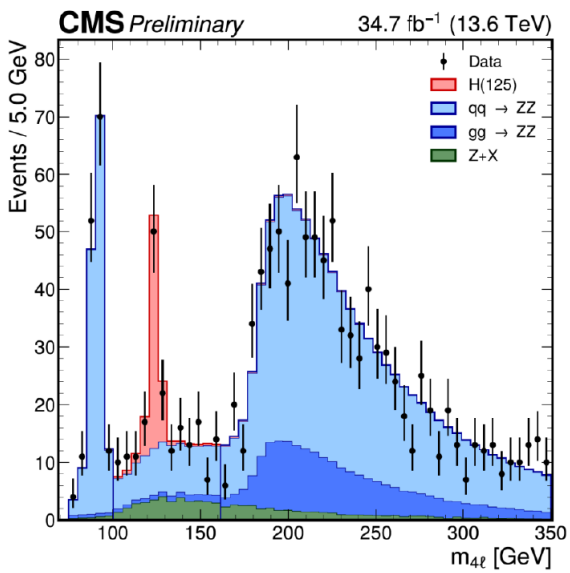
- Note: I am giving the references to the talks where the material was discussed, further references can be found there.

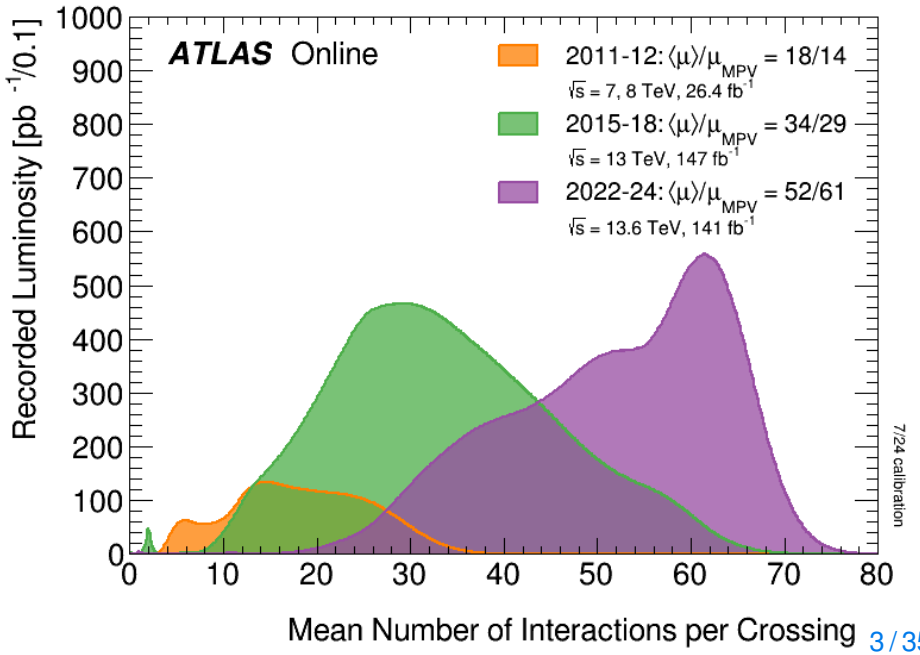
[ATLAS wiki, Nico Härringer]

Where are we standing?

- Most precise measurements and most stringent limits from full Run2 dataset, and we are still seeing new results from Run2 data
- Run3 recorded luminosity now more than Run2 recorded luminosity – much to look forward to for the next Higgs Hunting(s)





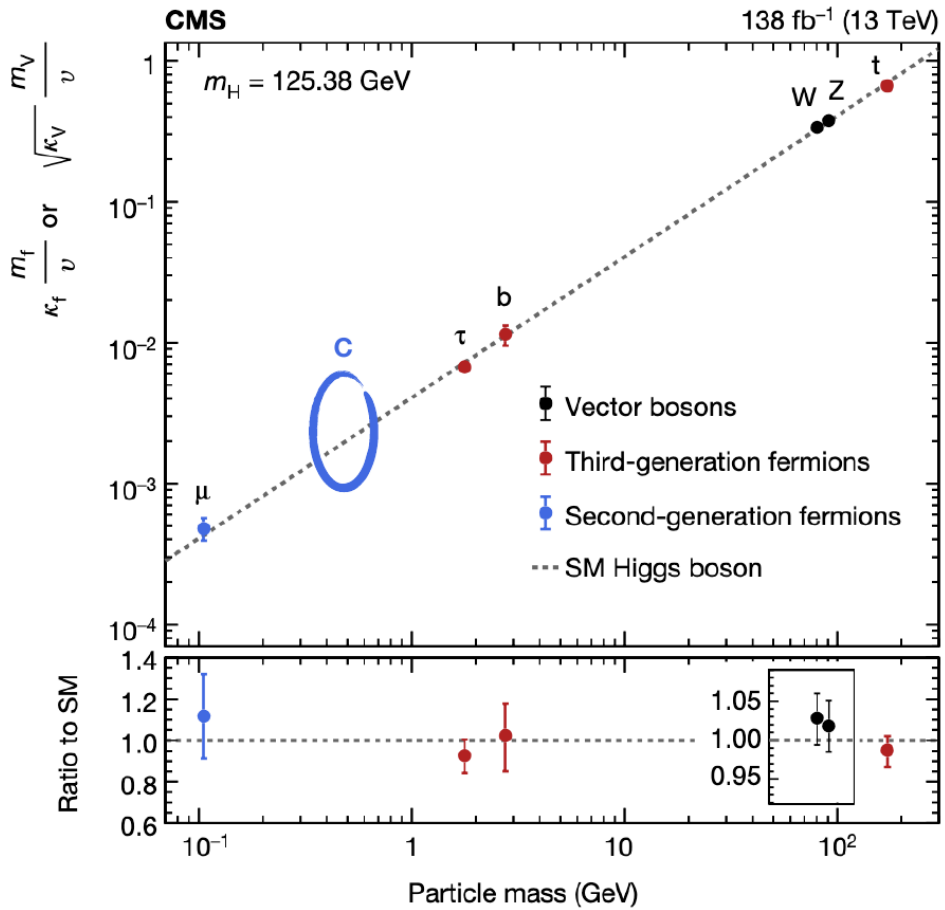


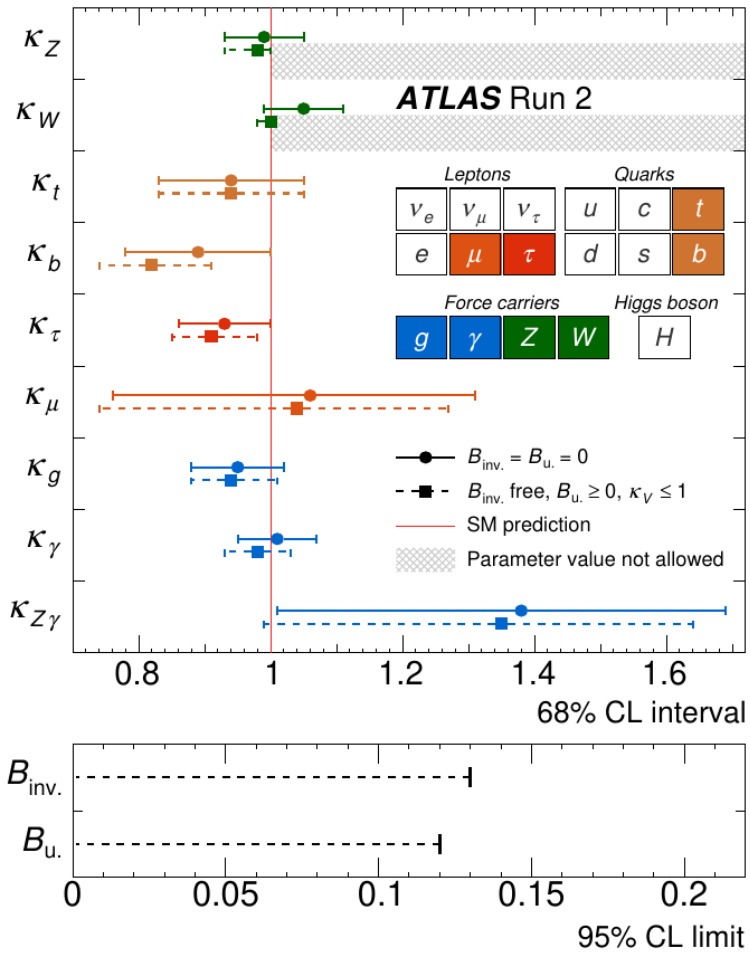
Higgs boson couplings (to other particles)

Combinations and updated/new analyses beyond the combinations

Combined couplings measurements.

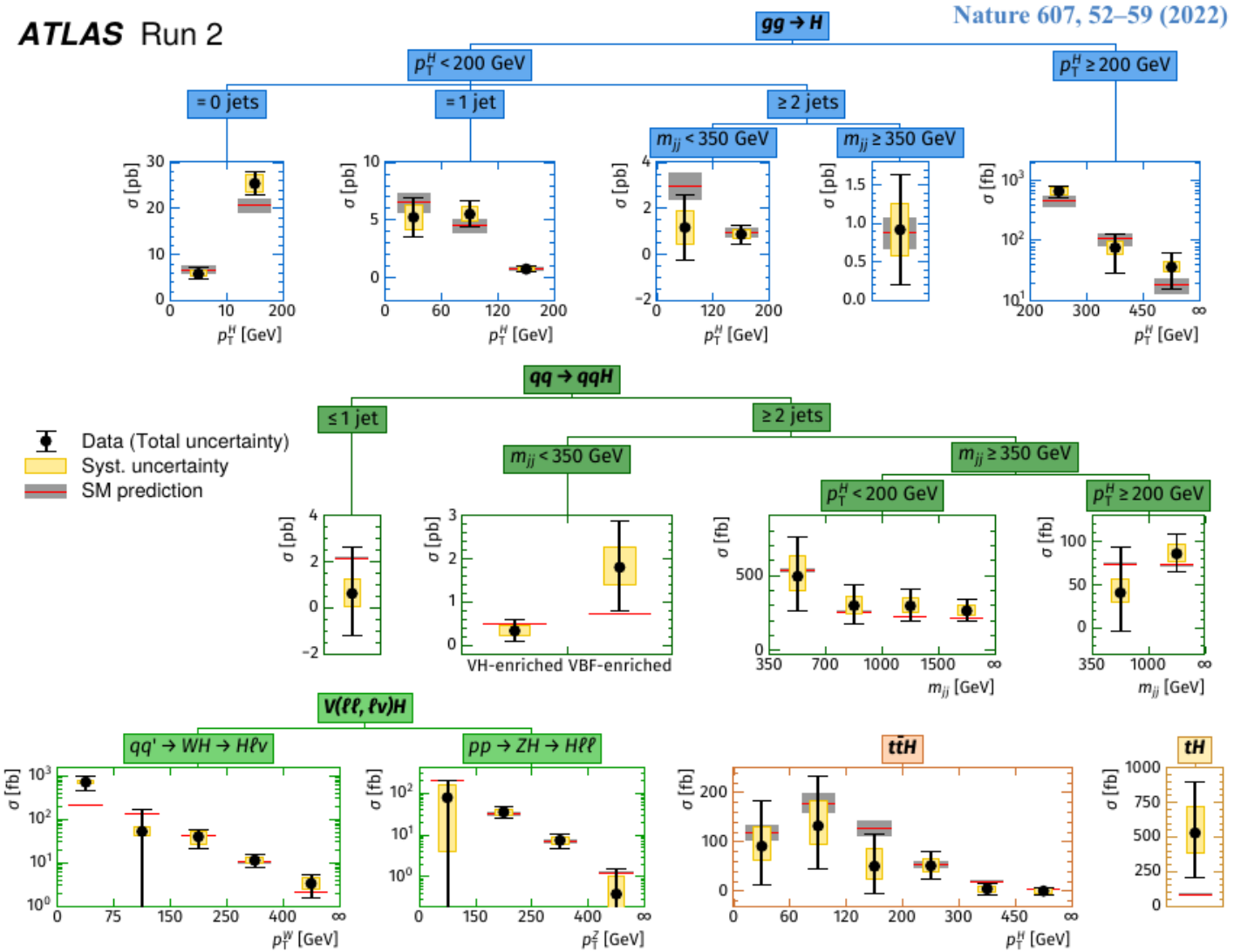
- Most precise measurements of (most) Higgs couplings to-date from combinations of Run2 data: from 6% (to weak bosons) to 7-12% (for third generation fermions)





Simplified Template Cross Sections (STXS).

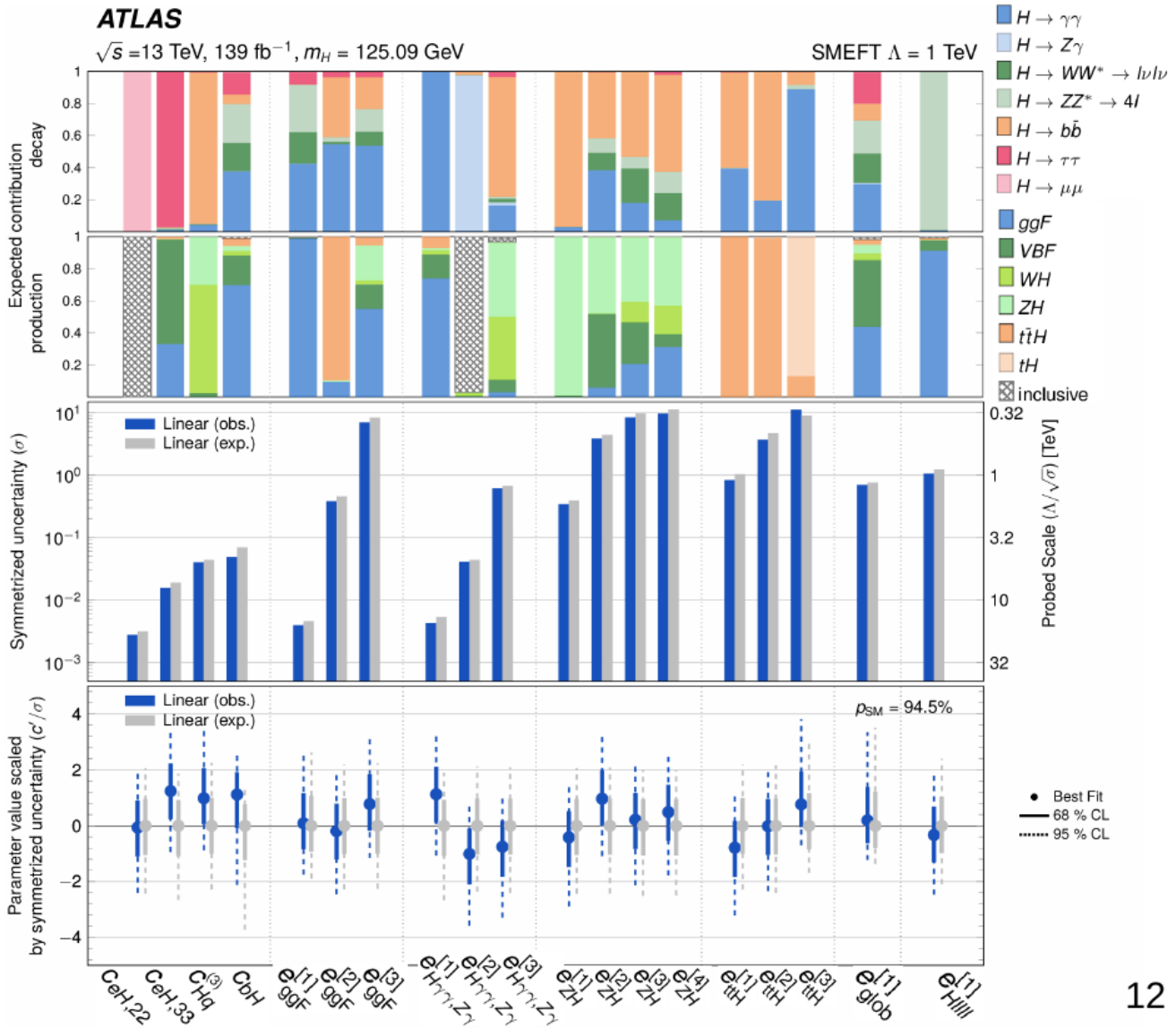
- Cross sections in various kinematic regions, split by production process chosen to reduce theory uncertainties and to optimize BSM sensitivity



[Yicong Huang]

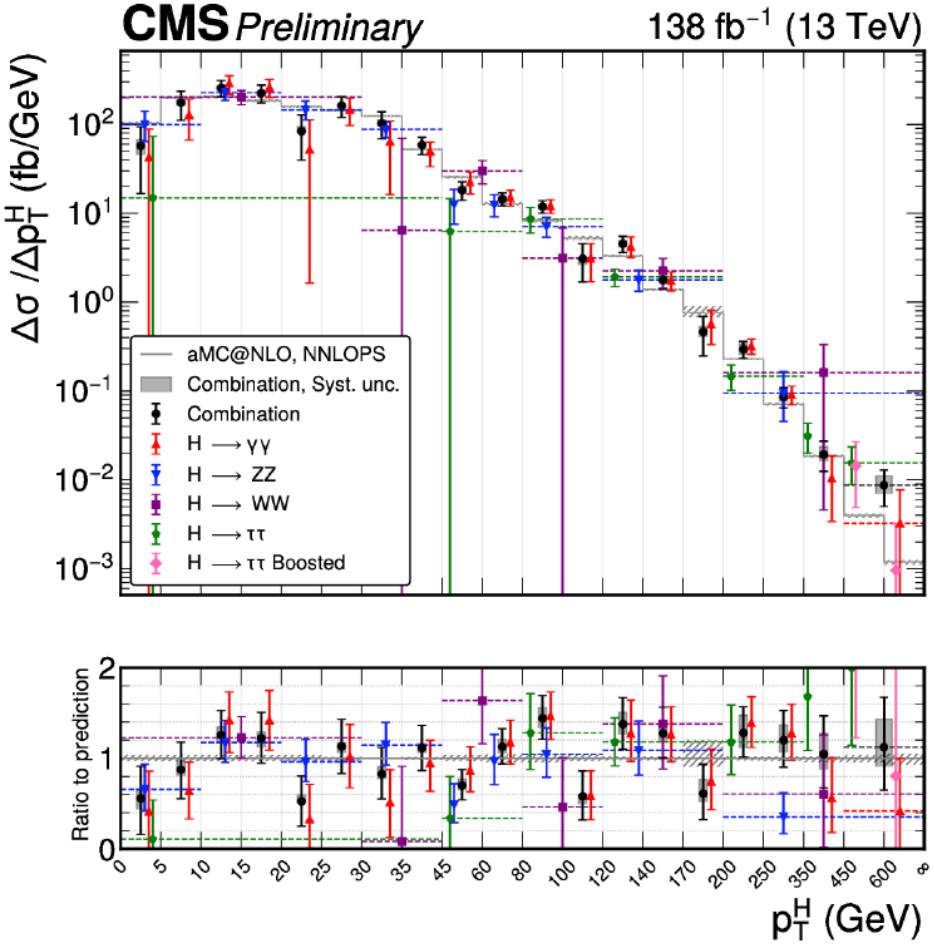
EFT interpretation.

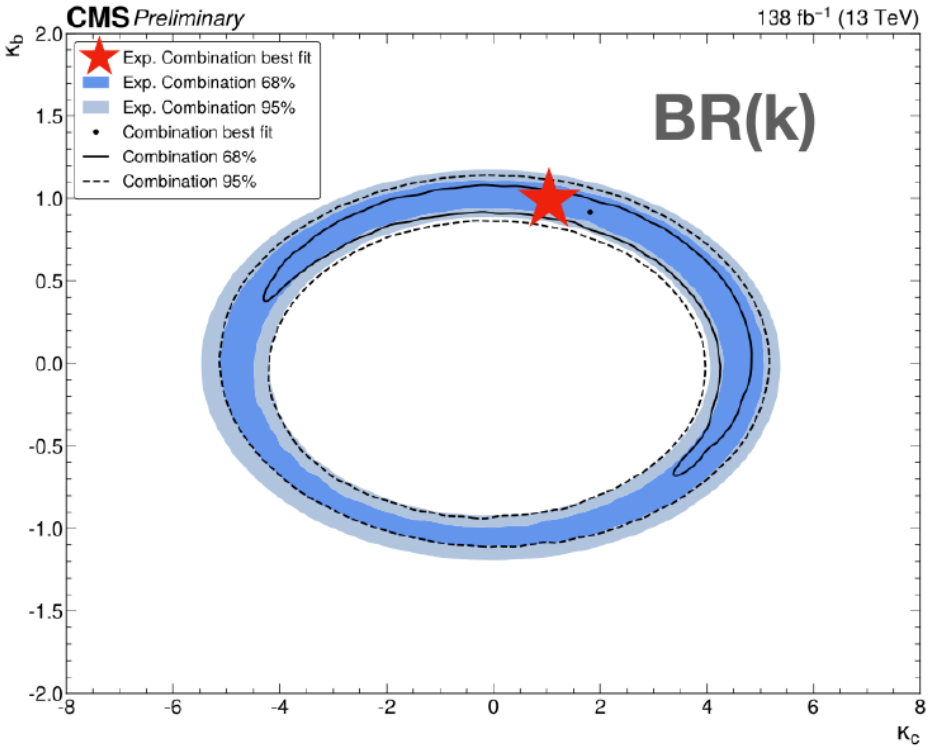
- SMEFT interpretation of STXS
- Linear: no Λ^4 terms
- Fit basis of linear combinations of Wilson coefficients



Couplings from Higgs p_T.

- Dedicated differential measurements can be obtained in finer bins, and with less model-dependence
- Interpreted in terms of b- and c-quark couplings considering only the p_T shape (weaker) or also the branching ratios (stronger)

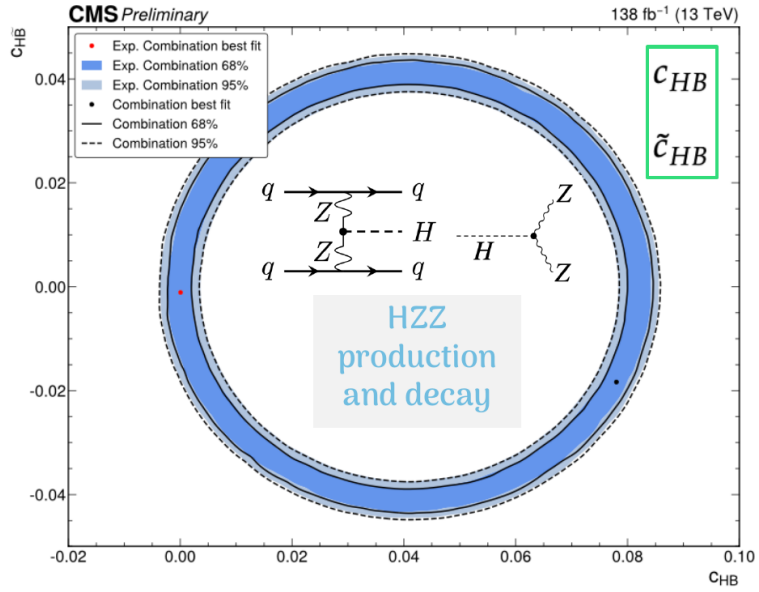




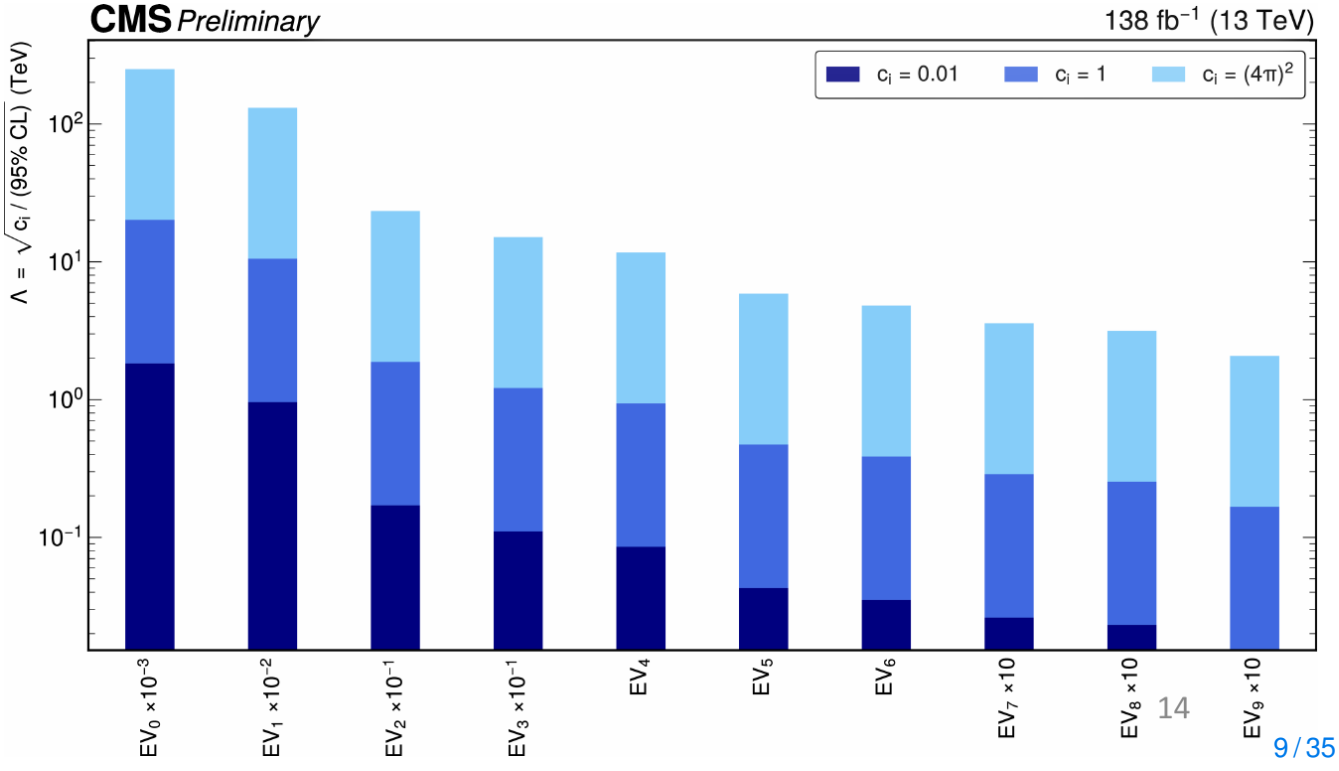
[Lourdes Urda]

EFT interpretation.

- EFT interpretation of p_T
- 2d constraints for pairs of CP-even and CP-odd operators



- Fit for 10 linear combinations of Wilson coefficients
- Limits on the BSM energy scale for different values of Wilson coefficients



EFT: Sandra's comparison.

→ comparing eigenvectors that have the strongest relation to a given Warsaw-basis Wilson coefficient.

CMS $EV1 : (\boxed{0.94c_{HG},}\ 0.26c_{HB},\ -0.15c_{HWB},\ 0.08c_{HW},\ 0.14c_{bH},\ -0.03c_{tG},\ 0.01c_{tB}\ )$

ATLAS $E^{[1]}_{ggF} : (\boxed{1.00c_{HG},}\ -0.03c_{tG}\ )$

ATLAS Higgs STXS-1.2, arXiv:2402.05742:
$(ggH, VBF, WH, ZH, ttH, tH)\ x\ (p_T^H, N_{jets}, m_{jj})$
combining $\gamma\gamma, Z\gamma, WW, ZZ, bb, \tau\tau$ & $\mu\mu$ decays
** lin-only & lin+quad parametrization*

CMS differential p_T^H, CMS-PAS-HIG-23-013:
inclusive Higgs production,
combining $\gamma\gamma, WW, ZZ, \&\ \tau\tau$ decay channels
** lin+quad parametrization*

EV dominated by a **single WC**

EV with a **strong contribution** from a given WC

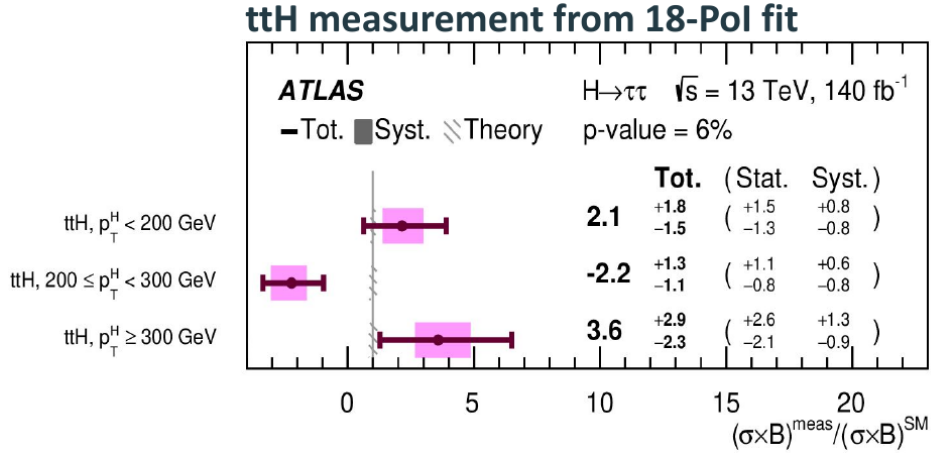
EV with **moderate/small contribution** from a given WC

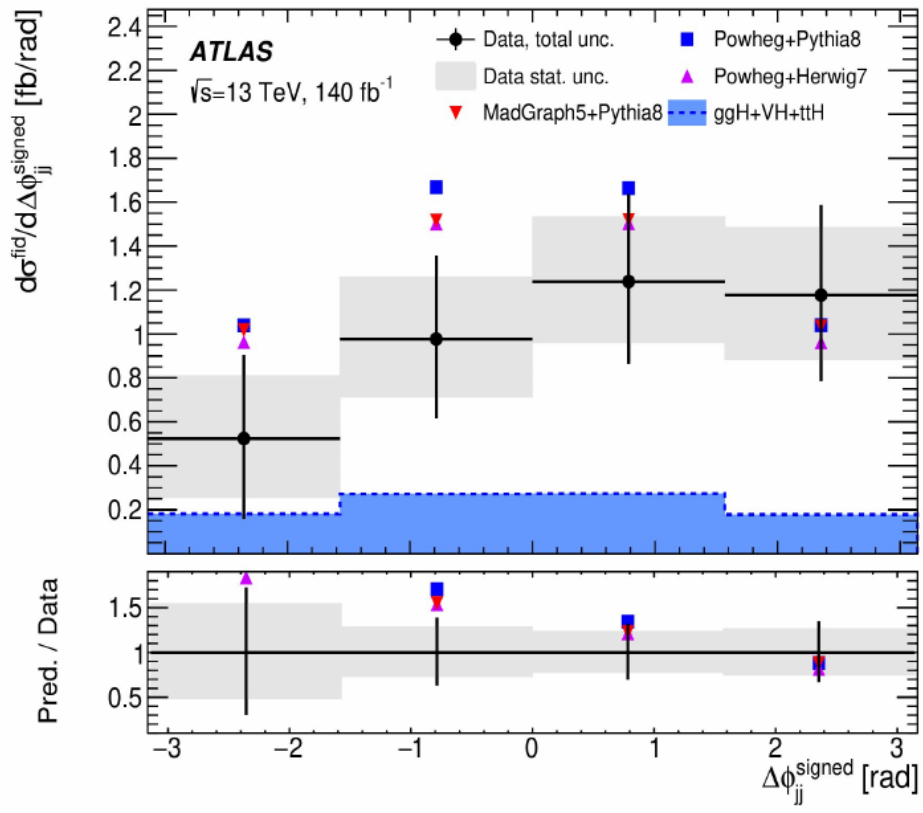
	$\mathcal{O}$(Uncertainty on c_i/Λ^2)			
Warsaw-basis Wilson coeff.	ATLAS STXS	CMS differential p_T^H	Vertex	Most sensitive observables
c_{HW}, c_{HB}, c_{HWB}	0.001 - 0.1	0.001 - 1	HVV	STXS (yy, Zy) & diff
c_{HG}	0.001	0.001	Hgg	STXS (ggH) & diff
c_{tG}	0.1	0.1	Hgtt	STXS (ggH) & diff
c_{tH}	10	-	Hqq	STXS (ttH)
c_{bH}	0.01	0.1		STXS (Higgs width)
$c_{eH,22}$	0.001	1	Hll	STXS (mumu)
$c_{eH,33}$	0.01			STXS (tautau)
c_{Hq3}	0.01	0.1	HVqq	STXS (VHbb)
c_{Hu}	0.1	10		STXS (ZHbb)
c_{Hq1}	1	1		STXS (VHbb)
c_{Hd}	10	10		STXS (VHbb)

- STXS-based eigenvectors more strongly related to a single WC.
- Comparable sensitivity from STXS & differential measurements, but STXS adds some more sensitivity to Hqq, Hll and HVqq vertices.
- Significant dependence on quadratic terms for $c_{HB}, c_{tG}, c_{tH}, c_{Hq}^{(1)}$ (4 - 10 times stronger limits).

Updated measurement of $H \to \tau\tau$: more differential.

- $t\bar{t}H$ measurement improved with multiclass classifiers to separate signal and backgrounds, and neural network reconstruction of Higgs p_T
  - ⋆ Differential analysis of Higgs p_T in $t\bar{t}H$ in this channel, still with large uncertainties
- Differential analysis of Higgs p_T and m_{jj} in VBF, with good precision at high p_T and/or m_{jj} thanks to low backgrounds
- Fiducial differential cross section measurement in $H \to \tau\tau$ in VBF enhanced phase space

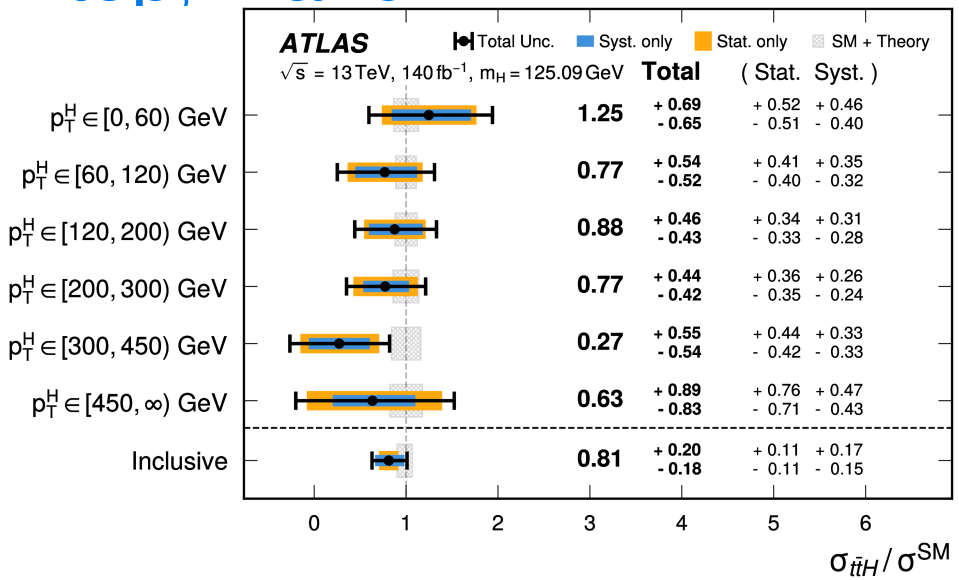


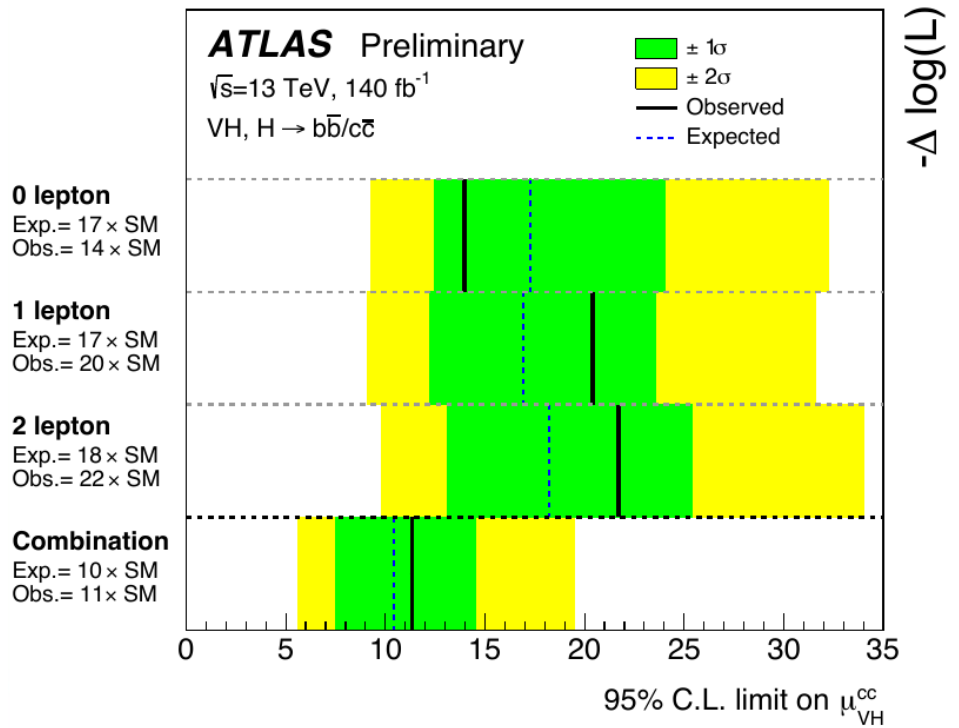


Updated measurements with top, b and c.

- Updated measurement of $t\bar{t}H(\rightarrow b\bar{b})$ with e.g. improved modeling of backgrounds ($t\bar{t}b(\bar{b}), ...$) and uncertainties
- Most precise single-channel analysis of $t\bar{t}H$

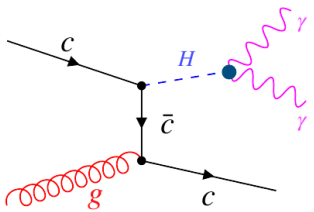
- Updated measurement of $VH(\rightarrow b\bar{b}|c\bar{c})$ with e.g. better heavy flavor tagging, improved boosted analysis, ...
- 15% improvement on $\mu^{b\bar{b}}_{VH}$ and x3 for $\mu^{c\bar{c}}_{VH}$
- $|\kappa_c| < 4.2$ at 95% CL (exp. 4.1)

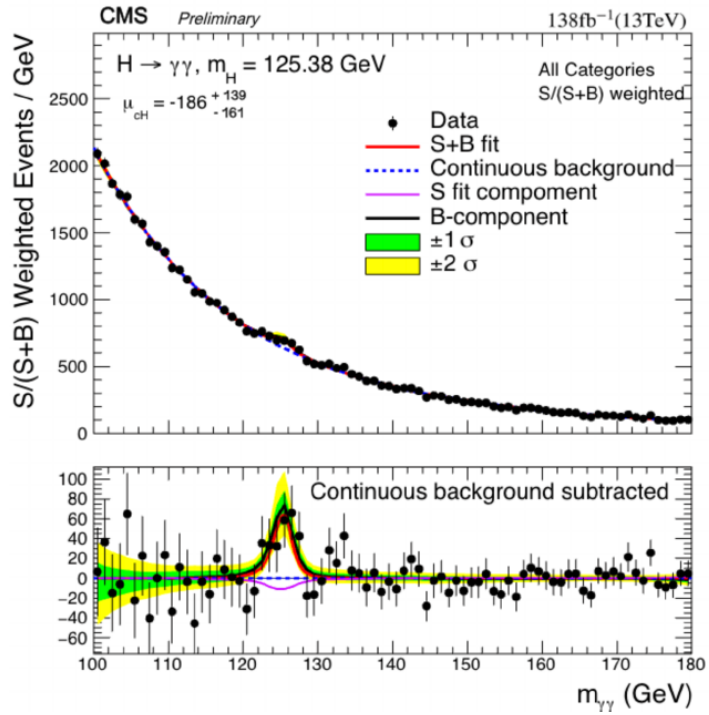




Looking for very rare production processes.

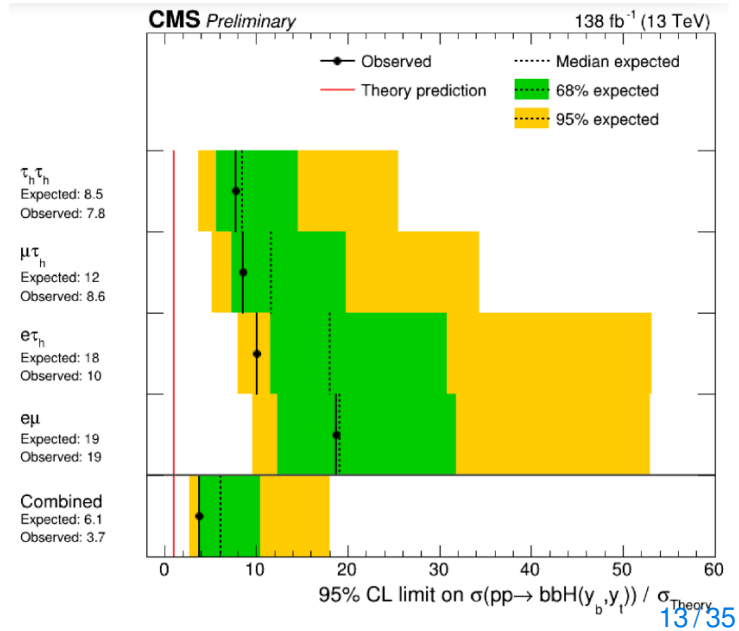
- Search for $H(\rightarrow \gamma\gamma) + c$





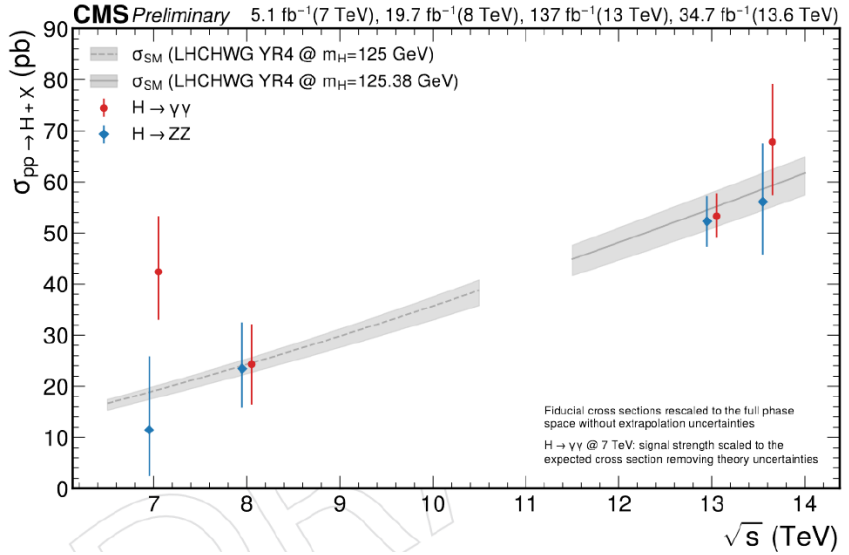
- Higgs background from ggH production
- μ <243 at 95% CL (exp. 355)

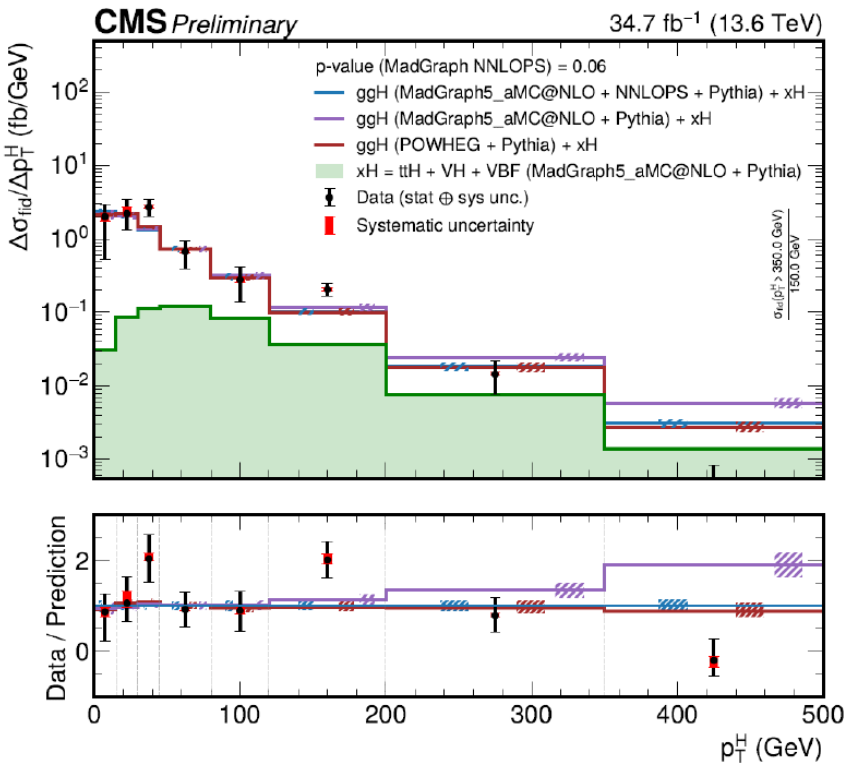
- Search for $b\bar{b}H$ with $H \rightarrow \tau\tau|WW$
- μ <3.7 at 95% CL (exp. 6.1)



Cross section measurements at 13.6 TeV.

- 34.7 fb^{-1} of Run3 (2022) data at 13.6 TeV
- Using new lightweight data format – important development towards HL-LHC
- Use of normalizing flows to correct data/MC differences in shower shapes, isolation and energy resolution, based on $Z \rightarrow ee$

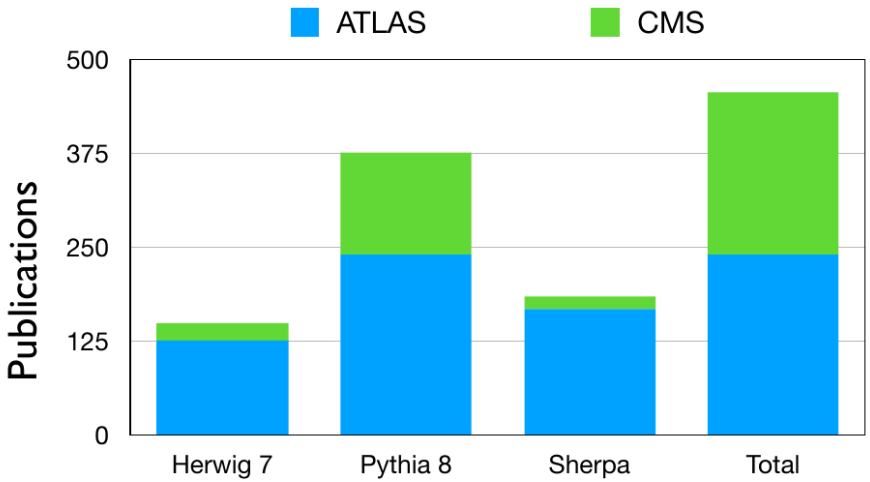




[Brian Webber]

Uncertainties on parton shower modeling.

Citations: LHC Higgs



- ATLAS cites Pythia + 1 or 2 others
- CMS cites mainly Pythia or none (i.e. MG5_aMC and/or POWHEG BOX)

Estimating PSEG Uncertainties

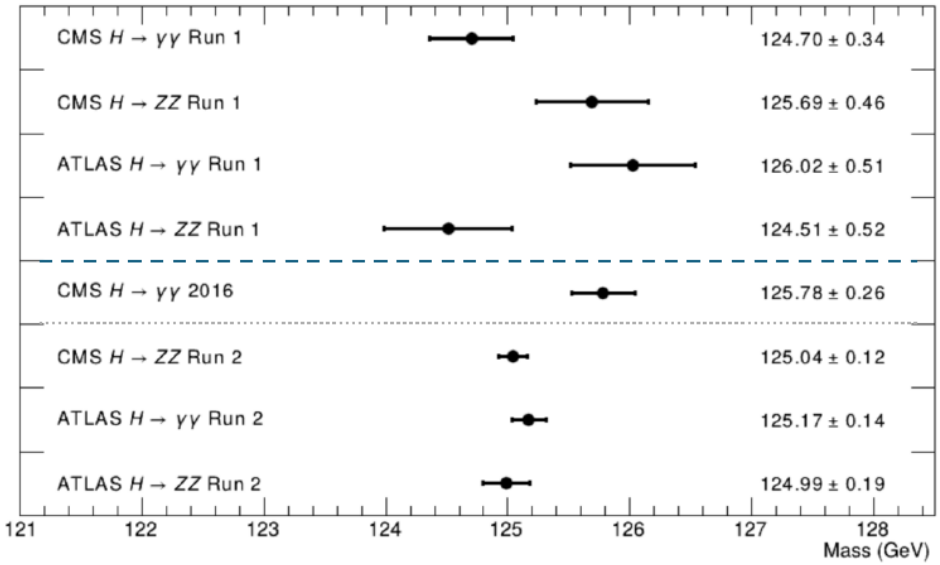
- ATLAS: compare Pythia with Herwig
- CMS: vary parameters within Pythia
- Both have their dangers!

- These uncertainties can be very sizable or even the leading systematic uncertainties
- Profile likelihood relies on good uncertainty estimates!
- We would really benefit from theory/experiment collaboration on this!

Other Higgs boson properties

Higgs mass.

- Measurements with full Run2 dataset individually with uncertainties better than 200 MeV
- For ATLAS, better precision from $H \to \gamma\gamma$ after reduction of the systematic uncertainties on the photon energy calibration
  - ⋆ Precision of 0.09% from Run1+2, $H \to \gamma\gamma$+$H \to 4\ell$

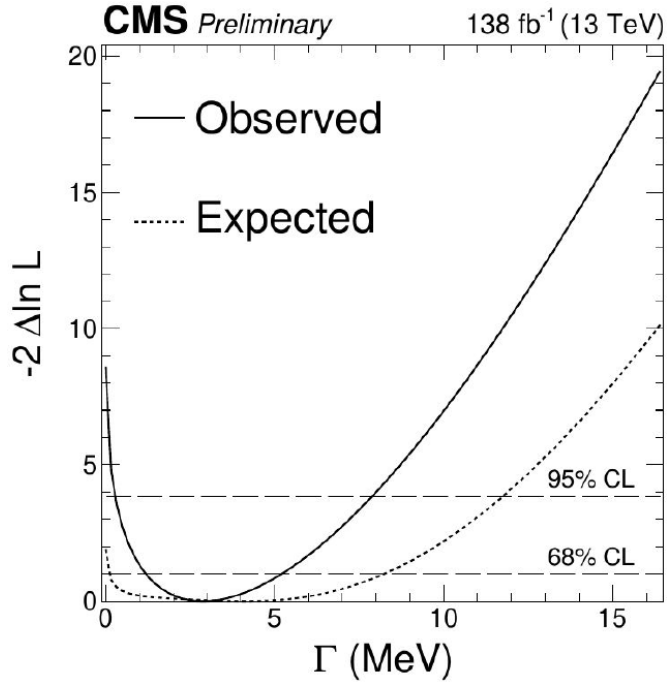


- New CMS measurement with full Run2 $H \to 4\ell$ with precision of 0.1%
- Ongoing effort to reduce the dominant systematic uncertainty on non-uniformity of light collection in CMS $H \to \gamma\gamma$ measurement

$H \to 4\ell$ still dominated by statistical uncertainties, $H \to \gamma\gamma$ competitive thanks to large effort put to reduce uncertainties on photon energy calibration

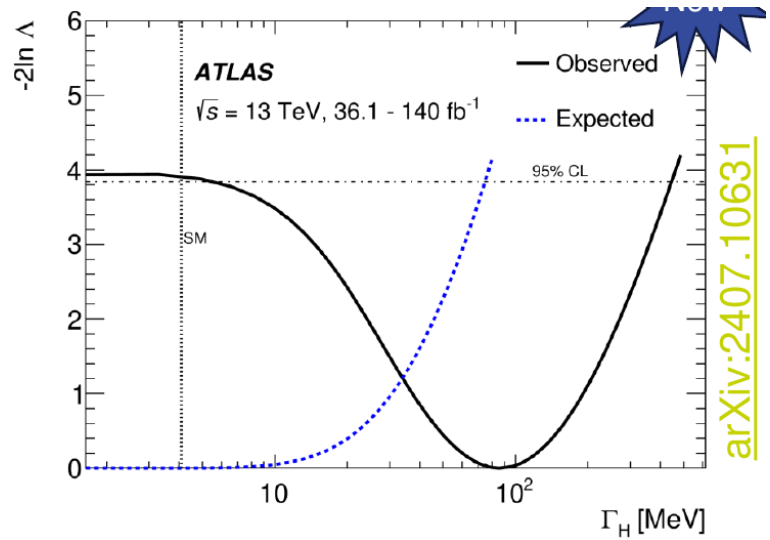
Higgs width.

- Higgs width from $H \to 4\ell$
  - ⋆ Relies on on- and off-shell couplings being the same, and no contributions to ggH loop



$$\Gamma_H = 2.9^{+2.3}_{-1.7} \text{ MeV}$$

- First attempt to constrain Higgs width from $t\bar{t}t\bar{t}$ production cross section and Higgs on-shell measurements
  - ⋆ Assume on- and off-shell couplings to top are the same



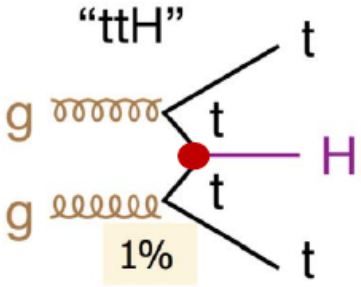
$$\Gamma_H = 86^{+110}_{-49} \text{ MeV}$$

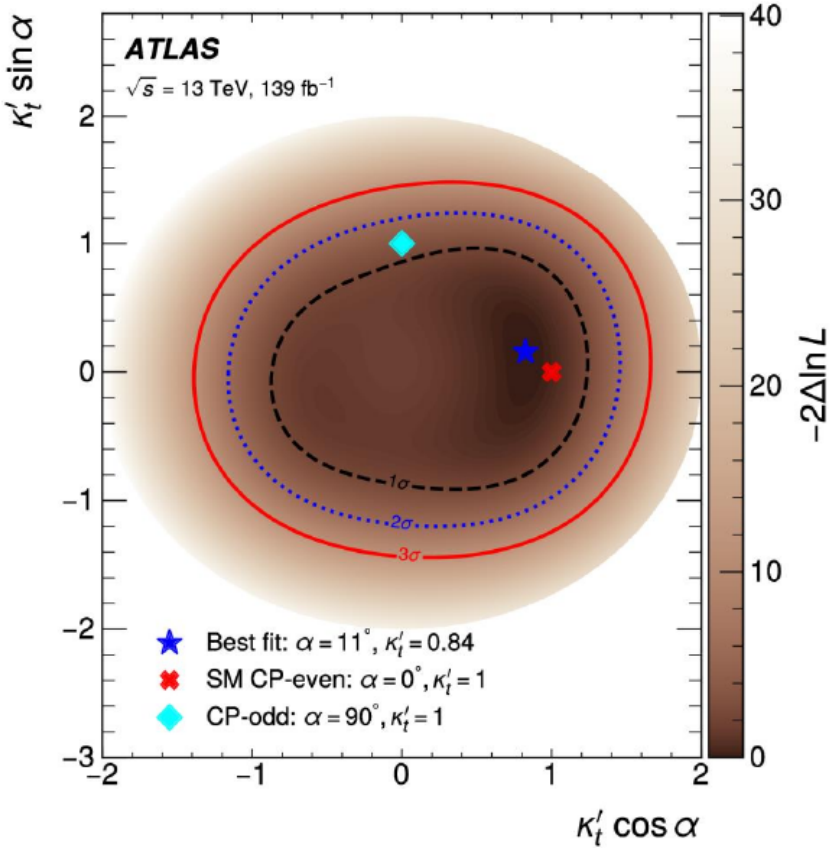
- Some discussion here – theory uncertainties play important role

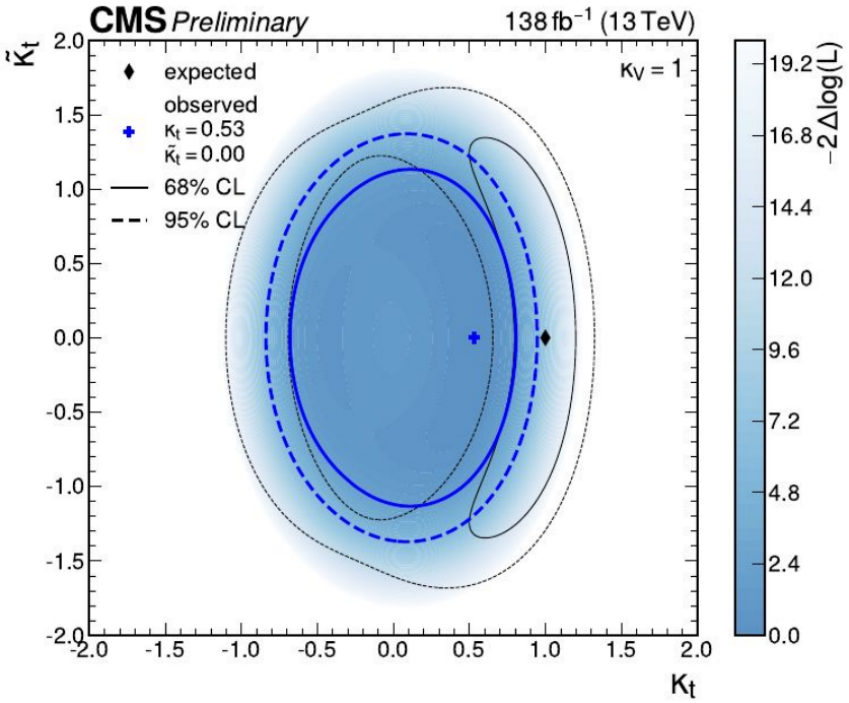
Tests of CP in fermion interactions.

[Valerie Lang, Fabio Iemmi, Giovanni Petrucciani]

Accessible in $t\bar{t}H$ production for interactions with top



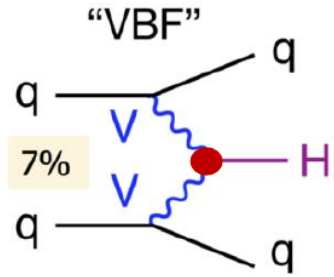




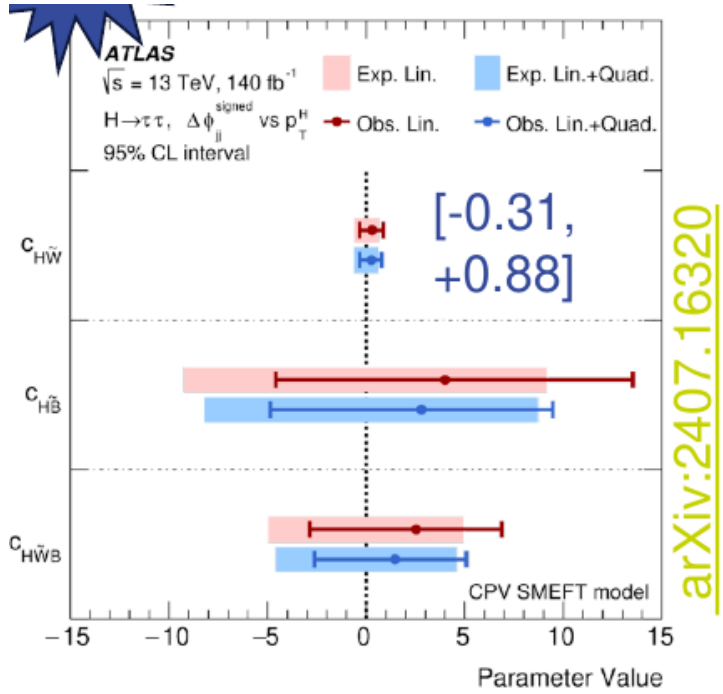
- Recent results from ATLAS and CMS use $H \to b\bar{b}$, compatible with the SM

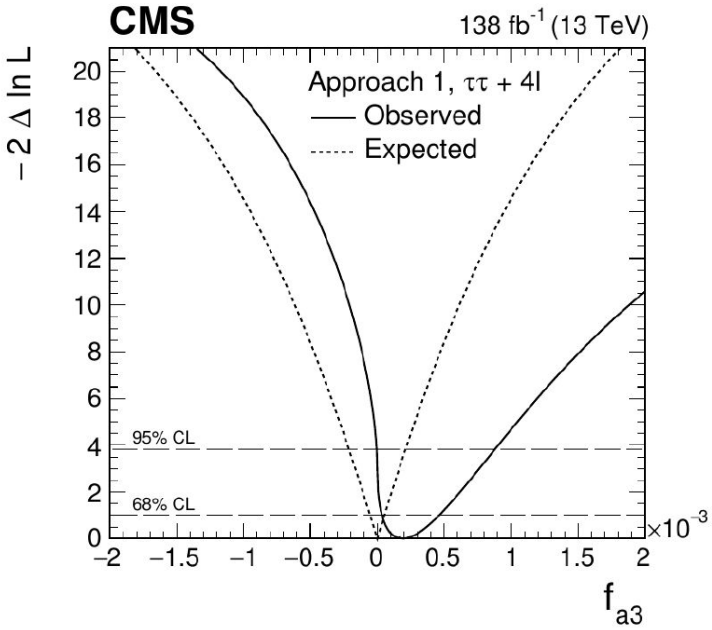
[Valerie Lang, Fabio Iemmi, Giovanni Petrucciani]

Tests of CP in interactions with vector bosons.



- Accessible in VBF, but also decays to vector bosons
- Various parametrizations, now mostly SMEFT operators or anomalous couplings (AC)
  - ⋆ Results from different analyses not always easy to compare
- New VBF $H \to \tau\tau$ (ATLAS) yields strongest constraints to-date on $c_{H\tilde{W}}$
- Constraints on AC in many channels from CMS
- All results compatible with the SM





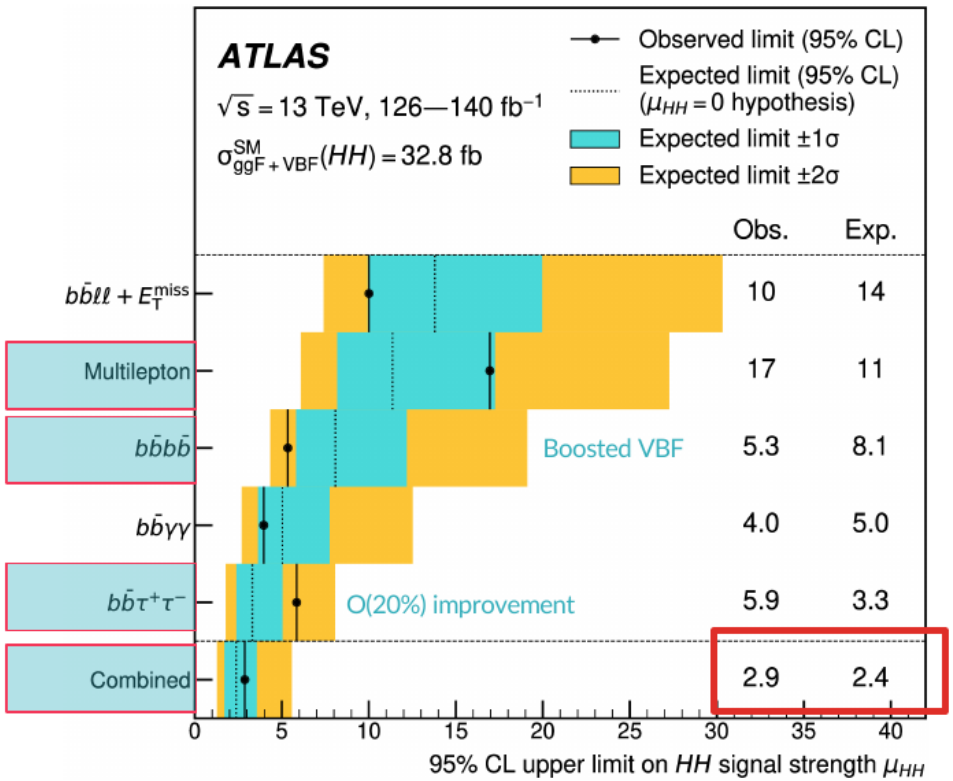
Higgs boson self-coupling

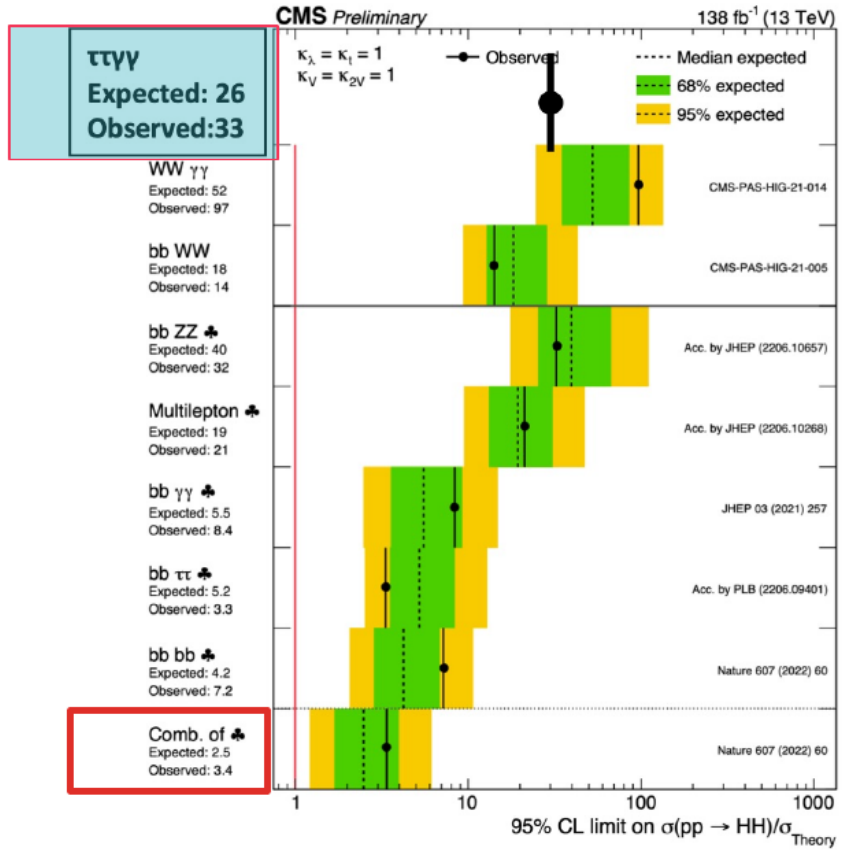
Valentina's summary:

HH CROSS SECTION

Z. Liang's talk, A. Bethani's talk

Legend:
New from HH2023





Phys. Rev. Lett. 133 (2024) 101801

CMSPublic/SummaryResultsHIG

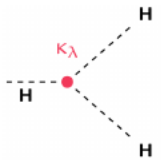
V.M.M.CAIRO

Valentina's summary

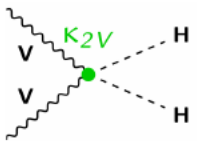
Legend:
New from HH2023

COUPLINGS

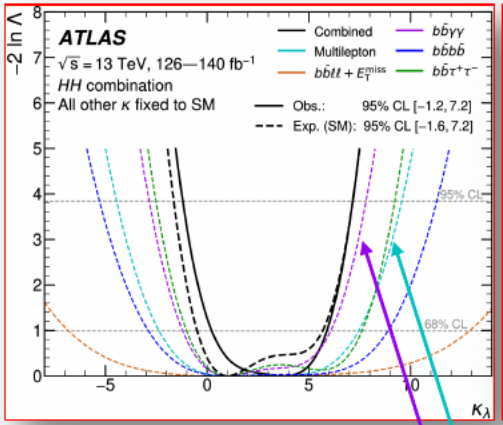
Z. Liang's talk, A. Bethani's talk

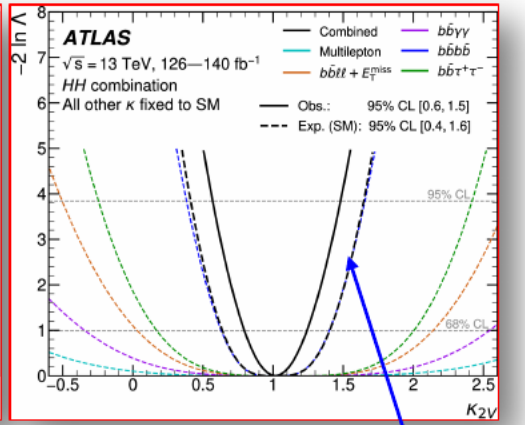


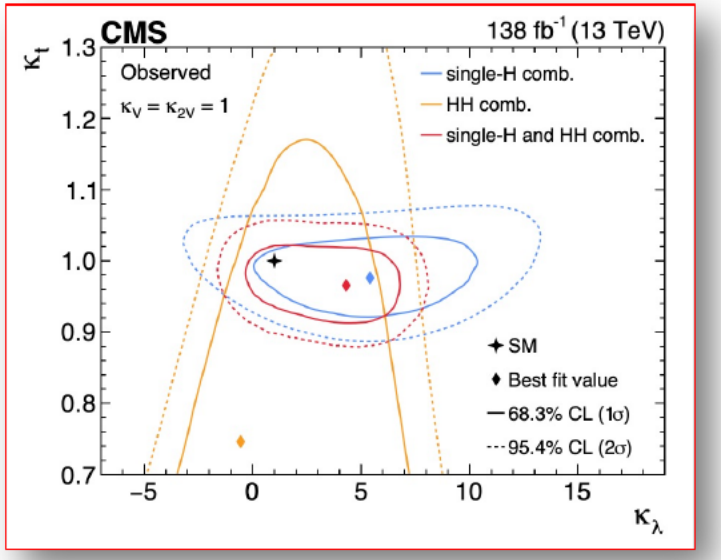
ATLAS
HH
Phys. Rev. Lett. 133 (2024) 101801



CMS
H+HH
https://arxiv.org/pdf/2407.13554







Photon and lepton triggers powerful at low m_{HH}

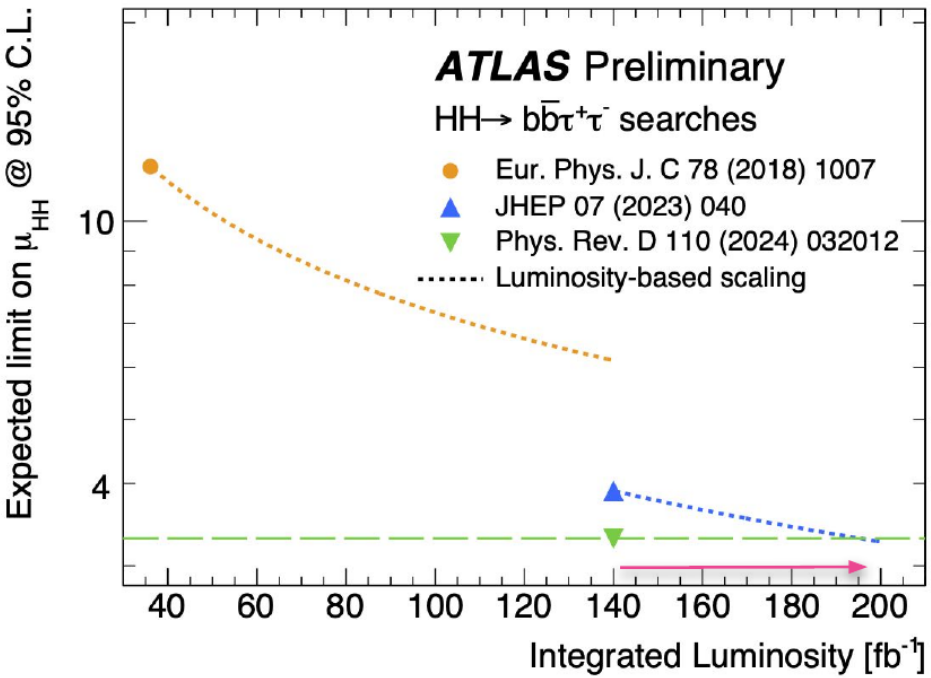
Boosted hadronic signatures powerful at high m_{HH}

Latest observed (expected) constraints on k_λ at 95% CL: **ATLAS [-1.2;7.2] (-1.6;7.2), CMS [-1.2;7.5] (-2.0;7.7)**

V.M.M.CAIRO

Analysis improvements

Significant improvements in analyses beyond more data, $H \to b\bar{b}\tau\tau$ as example:



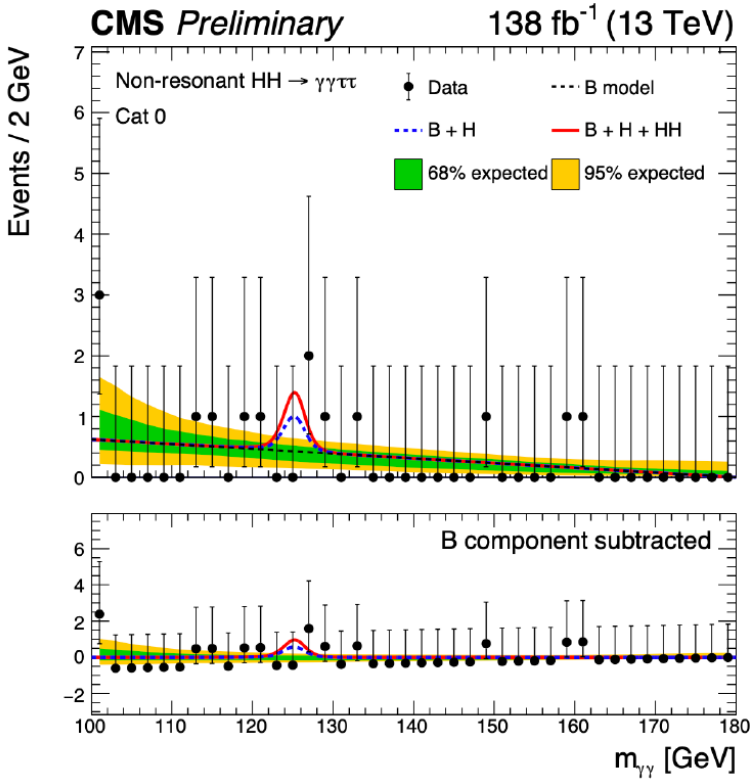
- Improved MC modeling
- Improved MVA discriminants
- Improved event categorization optimized for κ_λ and κ_V constraints

- In general also improvements in object performance and calibrations
- All this is promising for Run3 and HL-LHC

[Agni Bethani, Zhijun Liang]

New channels in HH searches.

$HH \to \tau\tau\gamma\gamma$



Clean, but small BR

Using ML-based event categorization

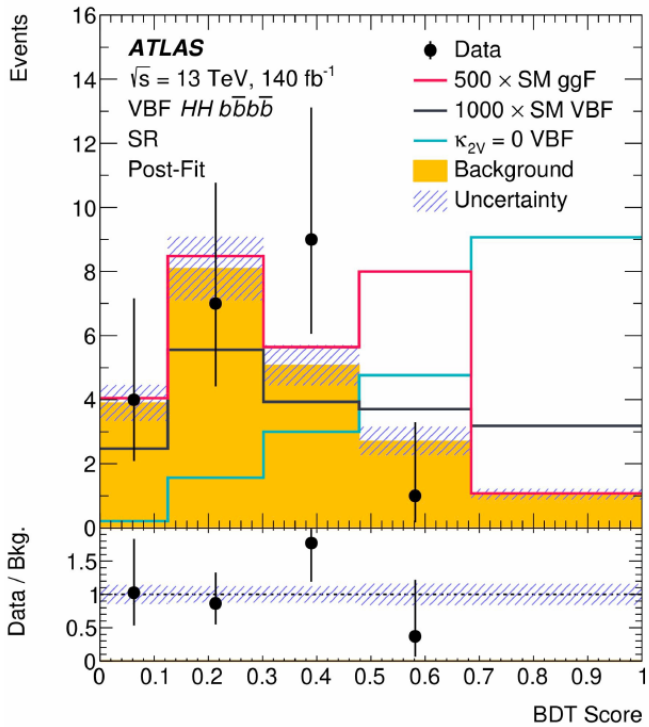
Limits on cross secrion:

33 x σ_{SM} (expected 26 x σ_{SM})

Constraints on κλ:

κλ [−13, 18] (expected [−11, 16])

VBF $HH \to b\bar{b}b\bar{b}$



Using ML-tagger for boosted $b\bar{b}$ in large-R jets

Observed: $\kappa_{2V} \in [-0.55, 1.49]$

Expected: $\kappa_{2V} \in [-0.37, 1.67]$

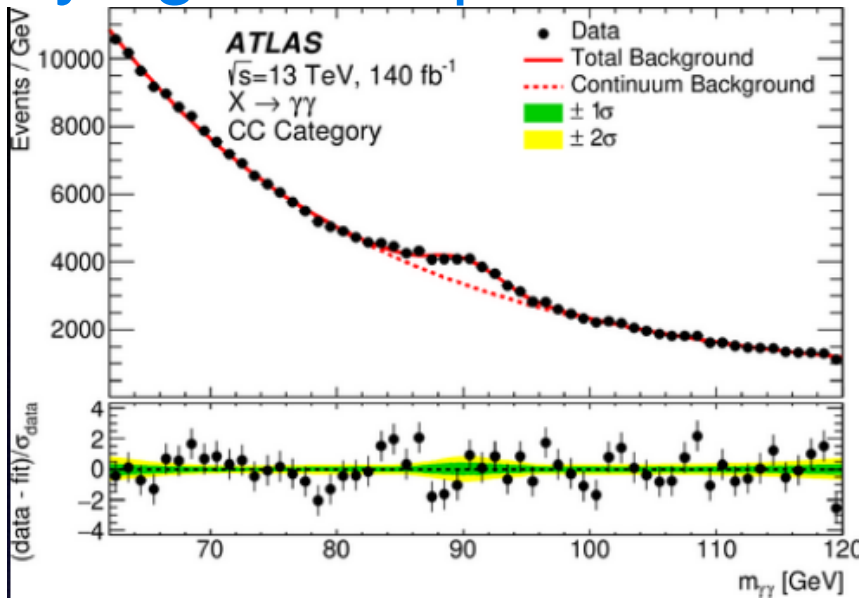
The rare and the not (yet?) seen

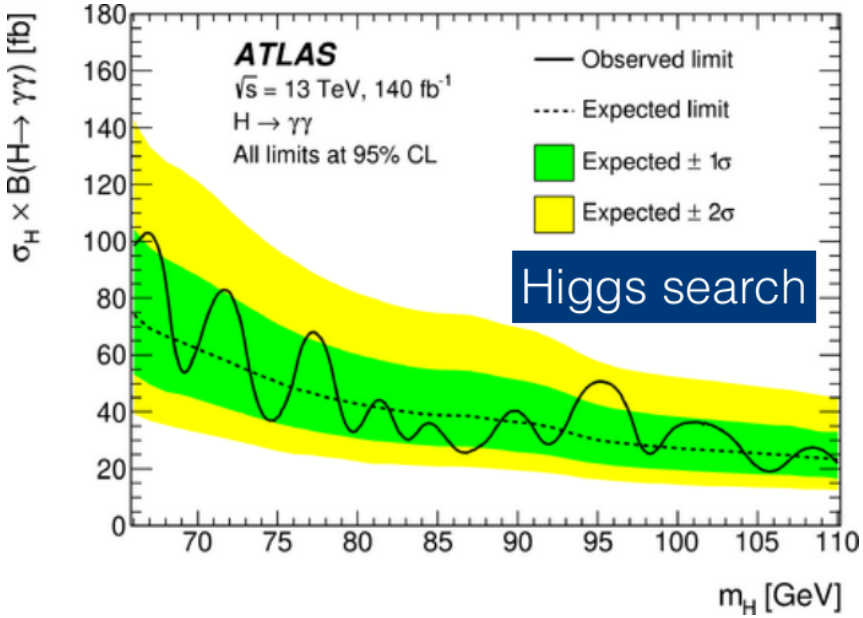
Searches for many different signatures, I can only cover a very small subset!
I picked some of the results that brought some discussion

[Erich Varnes]

Search for light resonance decaying to two photons.

- Search for resonance decaying to $\gamma\gamma$ in $62 < m_{\gamma\gamma} < 120$ GeV
- Experimental challenge: suppressing and understanding background from $Z \to ee$ with e misreconstructed as (converted) photon
- No significant excess (largest excess: $1.7\,\sigma$ (local) at 95.4 GeV)
  - ⋆ CMS: $2.9\,\sigma$ (local) at the same mass
- Let's see what the Run3 data has to say...

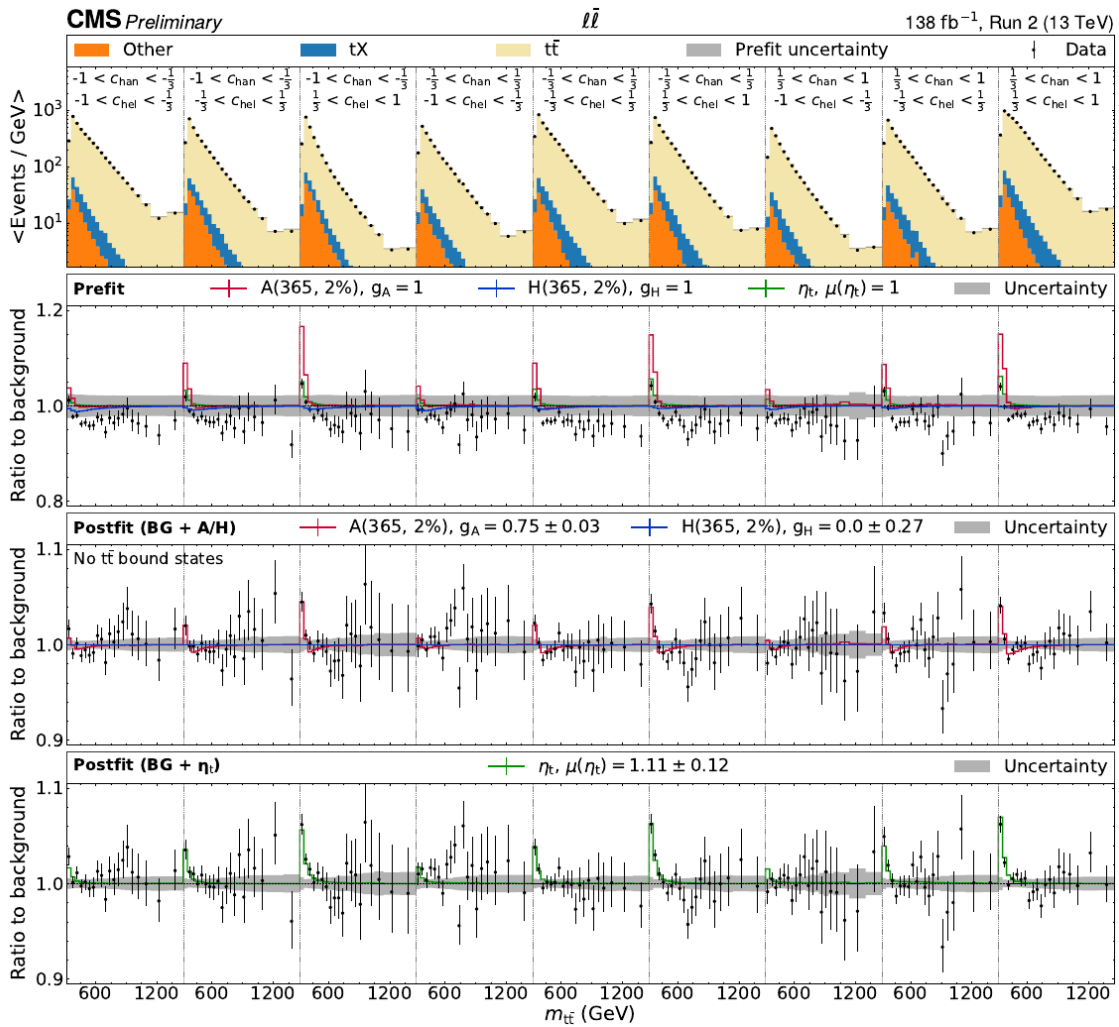




Search for $A/H \to t\bar{t}$.

[Samuel Baxter, Efe Yazgan, see also Erich Varnes]

- Search for $t\bar{t}$ resonances
  - ⋆ Dominant A/H decay for low tanβ
  - ⋆ Complicated peak-dip interference structure
- Excess of $>5\,\sigma$ (local) close to threshold, fitted equally well by A and by color-singlet $t\bar{t}$ bound state
- Some things to be understood...

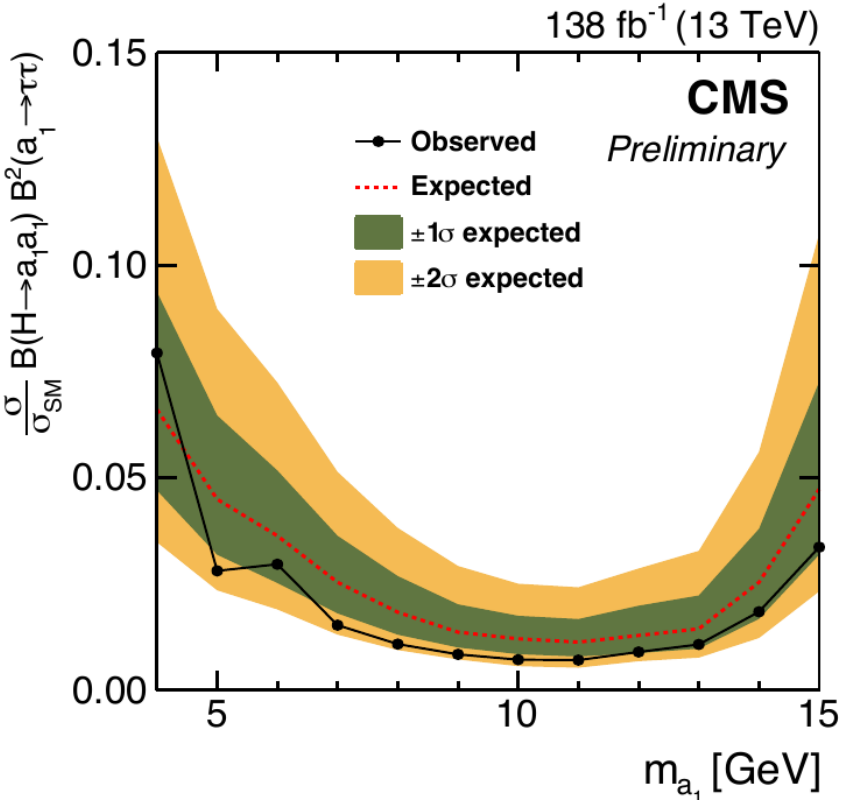


[Lakshmi Priya Nair, Huacheng Cai]

Searches for $H \to aa$.

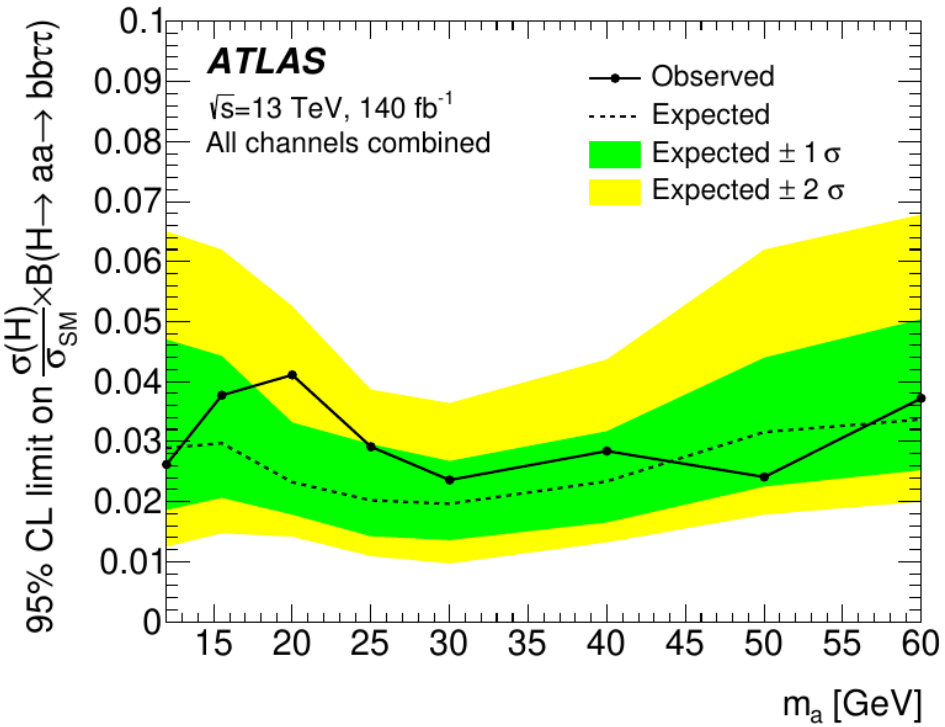
- Motivated in models with additional light pseudo scalar

$H \to aa \to 4\tau$



Boosted a bosons
$\to$ non-isolated leptons

$H \to aa \to b\bar{b}\tau\tau$

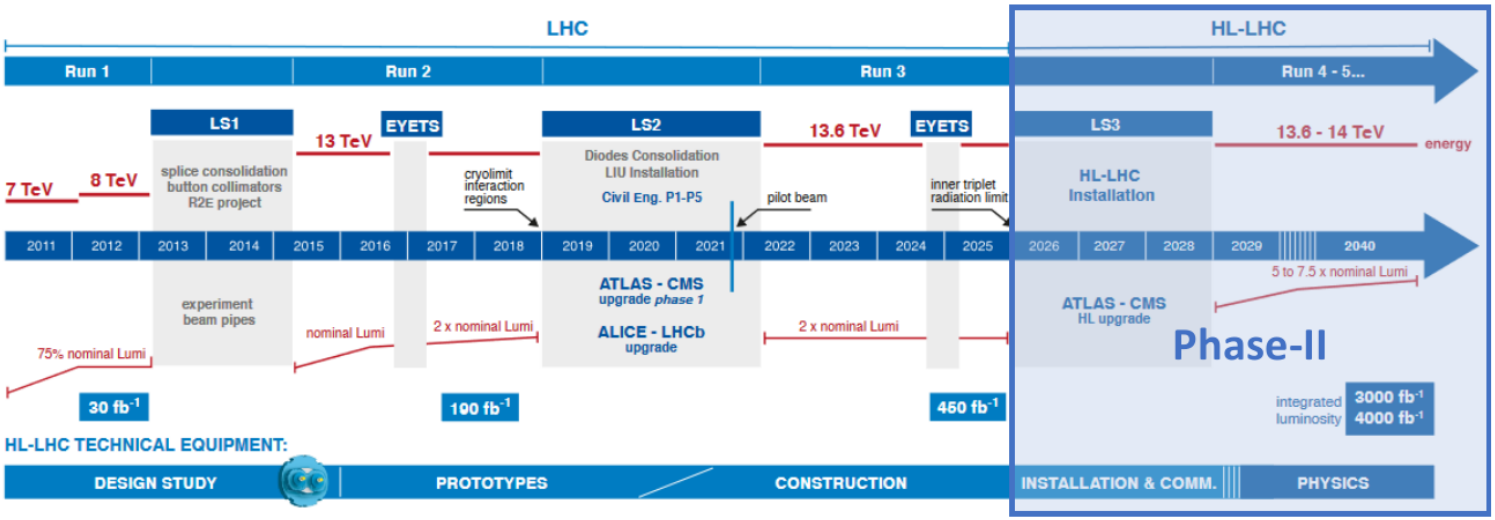


First search for this signature in ATLAS

HL-LHC and beyond

[Khuram Tariq, Federico De Guio]

Towards HL-LHC: phase 2 upgrades.



Challenges:
pile up,
radiation dose,
trigger rates, ...

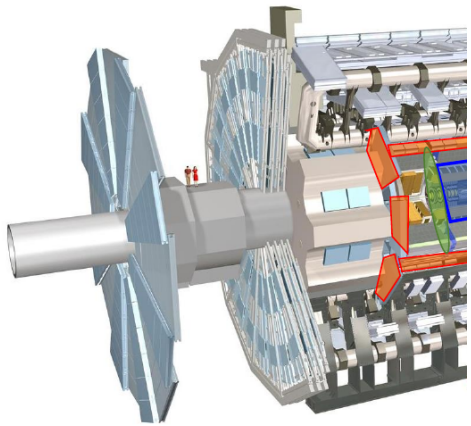
Upgrades to many of the detector components:

New Inner Tracking Detector (ITk)
- All silicon with 9 layers up to $|\eta| = 4$
- Less material, finer segmentation
- Improve vertexing, tracking, b-tagging

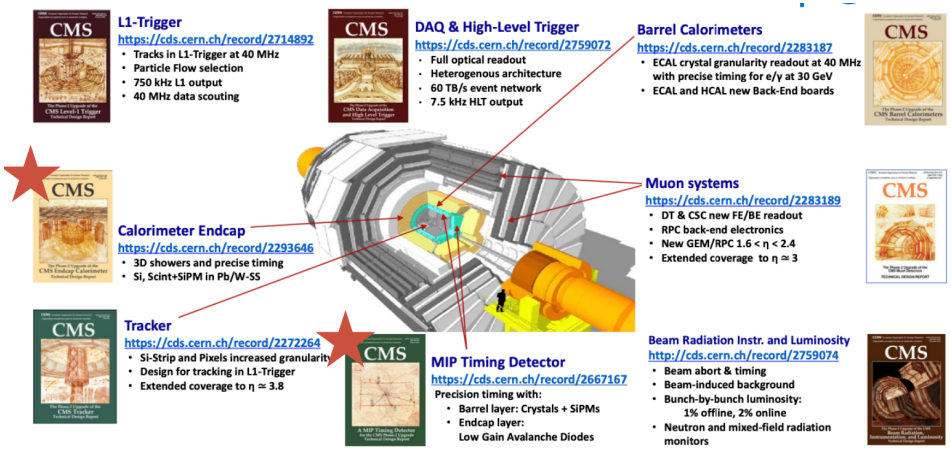
New High Granularity Timing Detector (HGTD)
- Precision track timing (30 ps) with LGAD in the forward region
- Improved pile-up separation and bunch-by-bunch luminosity

Calorimeter Electronics
- On-detector/off-detector electronics upgrades of LAr and Tile Calorimeter
- Provide 40 MHz readout for triggering

New Muon Chambers and electronics
- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

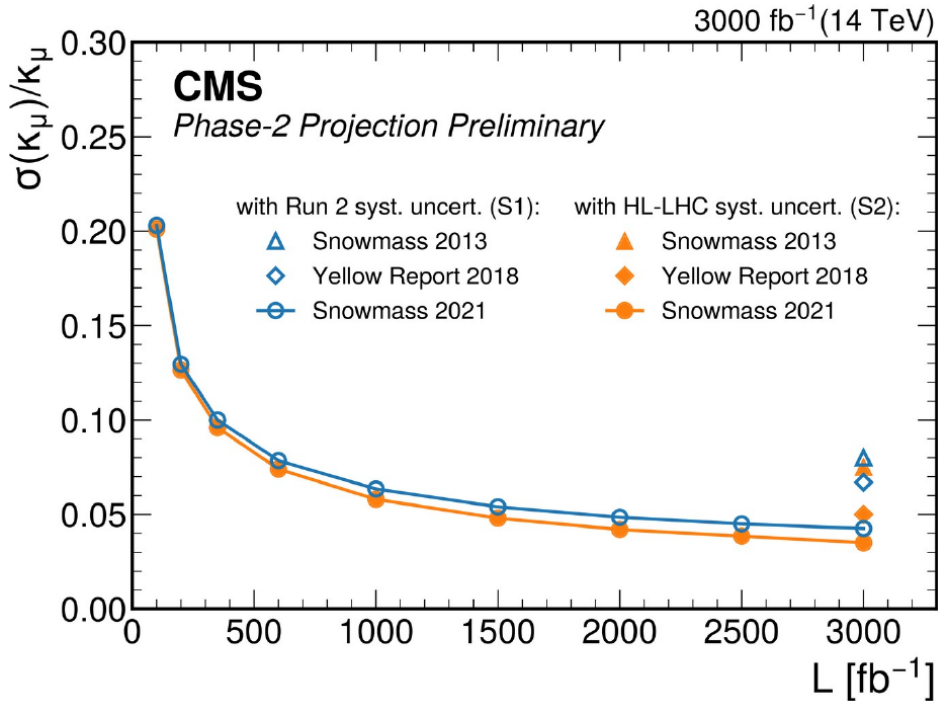


Upgraded Trigger and Data Acquisition System
- Single Level Trigger with 1 MHz output (x 10 current)
- Improved DAQ system with faster FPGAs

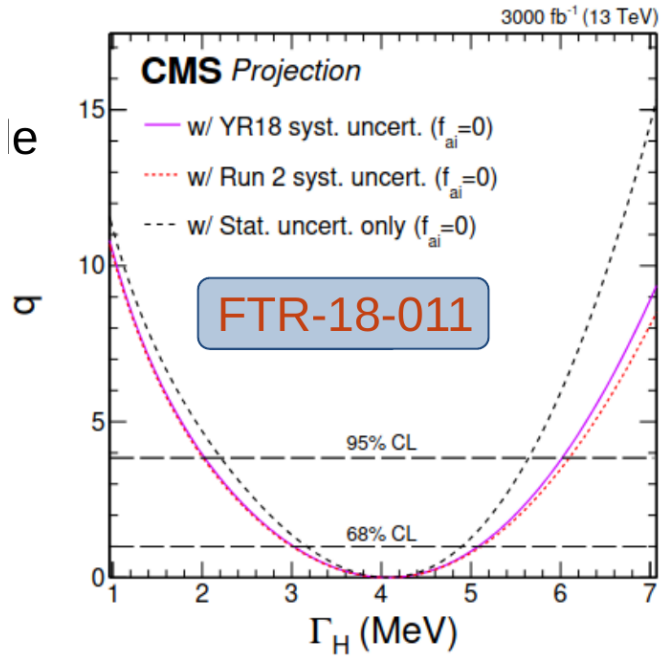


$H \to \mu\mu$ and Higgs width with HL-LHC.

- Improvements in tracker and muon spectrometer (extended acceptance, reduced material budget for tracker)



Expect $\sim$ 5% precision with HL-LHC

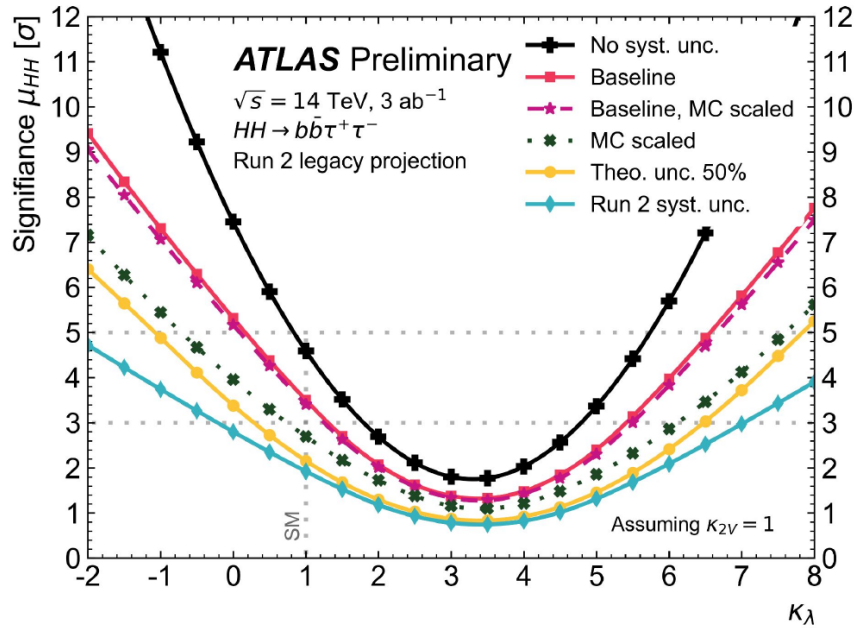


Expect 30% constraint with HL-LHC (with the usual assumptions)

[Florian Haslbeck, Sam Van Stroud]

$HH \to b\bar{b}\tau\tau$ at HL-LHC.

- Extrapolate new $HH \to b\bar{b}\tau\tau$ search to 3000 fb^{-1} under various assumptions on systematic uncertainties
- New: projections for non-SM κ_λ
- Improvements in b-tagging, τ identification, triggers, ... can bring further improvements

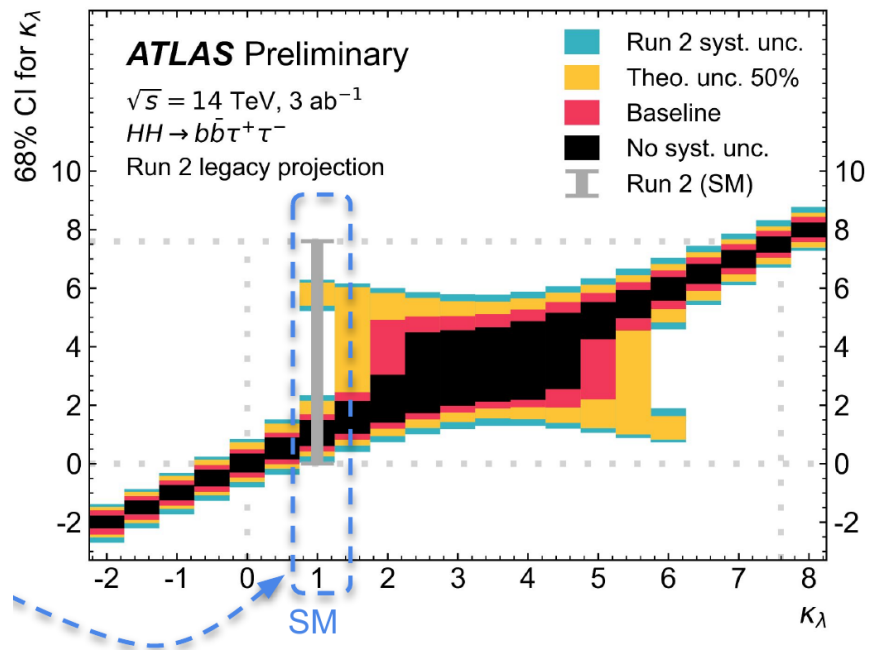


MVAs have never been more accessible! Analyses will be able train advanced models

But let's be cautious!

➢ Explainability / interpretability tradeoffs

➢ Harmonise tooling & models to minimise expensive trainings



- Discussion: need improvements in theory predictions and uncertainties for HL-LHC (top mass renormalization scheme, EW corrections, ...)

Conclusions.

- New and improved results on Run2 data with improvements in object performance, analysis strategies, ...
- We have a sizeable Run3 dataset to explore
- In some places we are/will be impacted by theory uncertainties – close collaboration between theory and experiment is crucial
- Much effort in upgrades for phase 2
- There is much to look forward to for future Higgs Huntings

Thank you for a very nice conference!