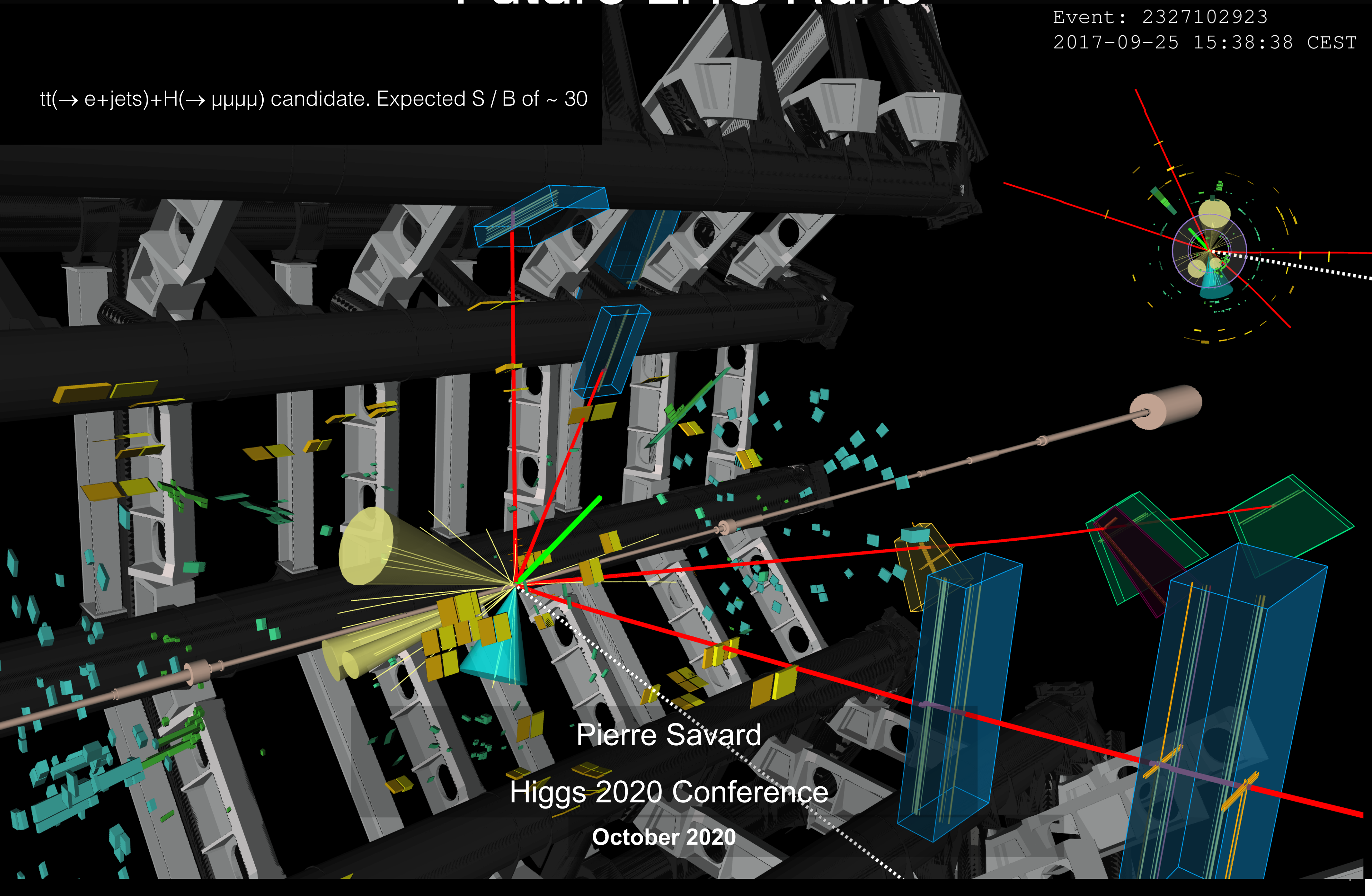
Experimental Prospects for Higgs Physics in Future LHC Runs

tt(→ e+jets)+H(→ μμμμ) candidate. Expected S / B of ~ 30



Pierre Savard

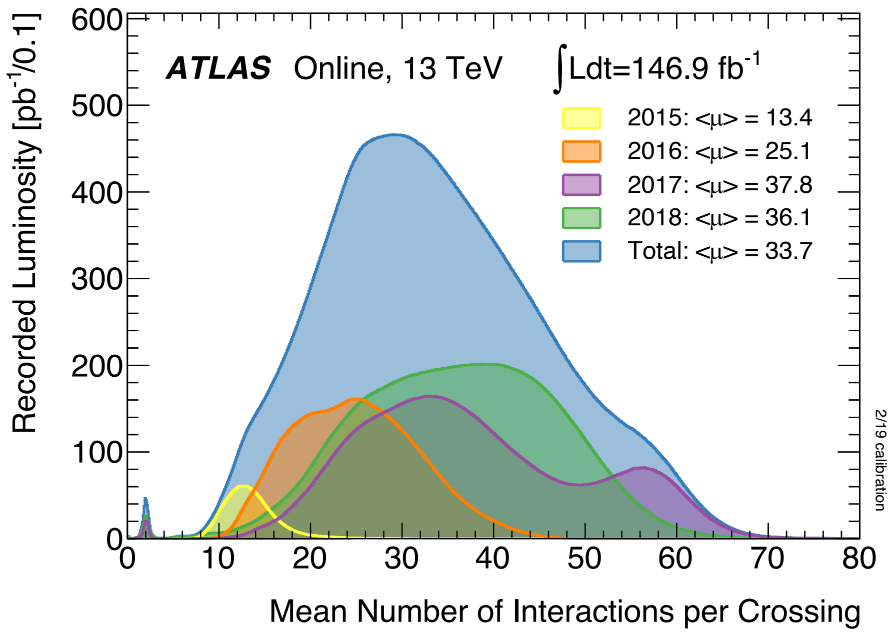
Higgs 2020 Conference

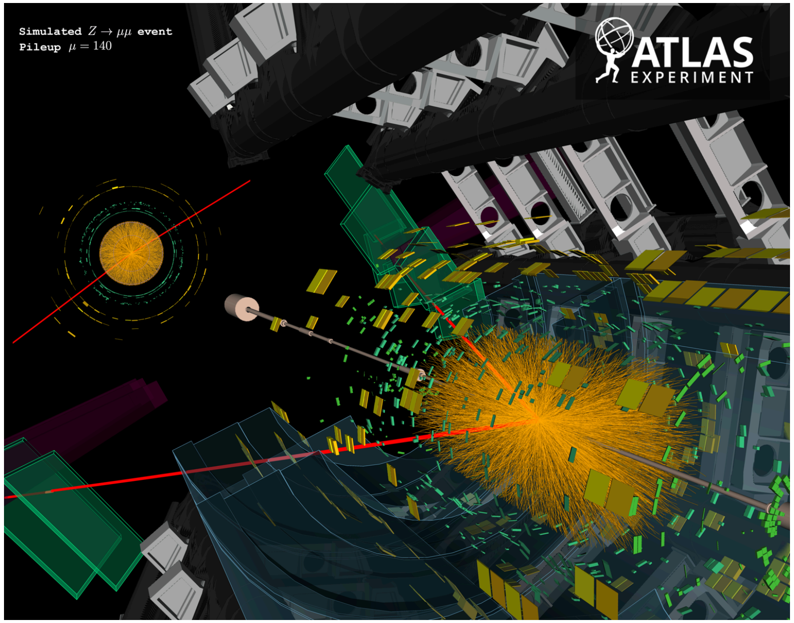
October 2020

LHC Datasets

Proton-proton datasets:

- Run 2 ~140 fb^{-1} used for physics analyses by ATLAS and CMS
  - Large, high quality dataset yielding very impressive results
- Run 3 expected to yield ~170-190 fb^{-1} with CM energy to be determined
  - Next 8 years: Run 2 dataset will be combined with Run 3 data for most measurements
- HL-LHC expected to yield 3000 fb^{-1} at 14 TeV: a ~20-fold increase over current dataset
  - A Higgs factory that will produce close to 200M Higgs bosons
  - Challenging collision environment: up to 200 interactions per bunch crossing



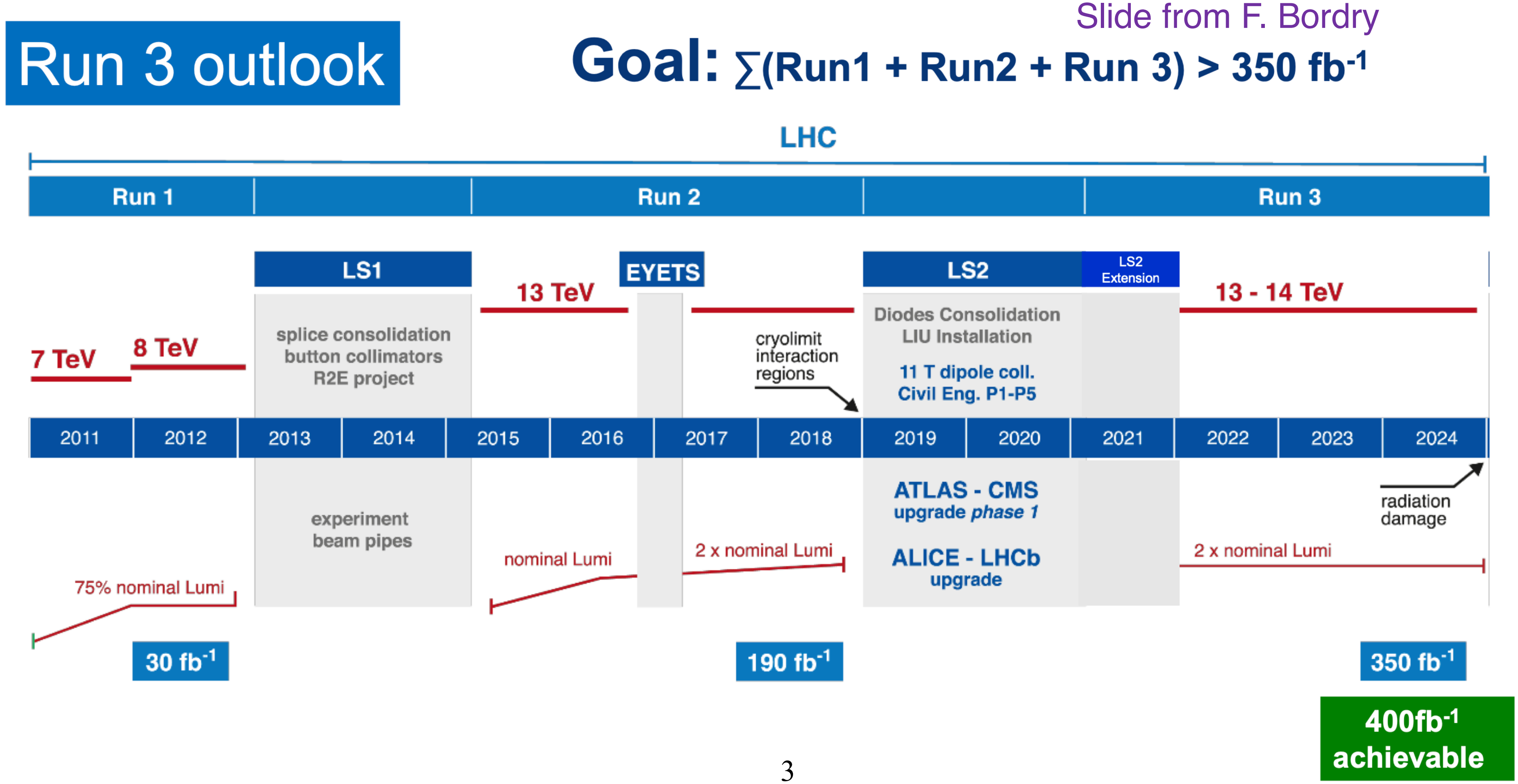


Run 3 Schedule

Start of Run 3 has been delayed due to the pandemic

- A 3-year Run
- Plan to run at 2 times nominal luminosity

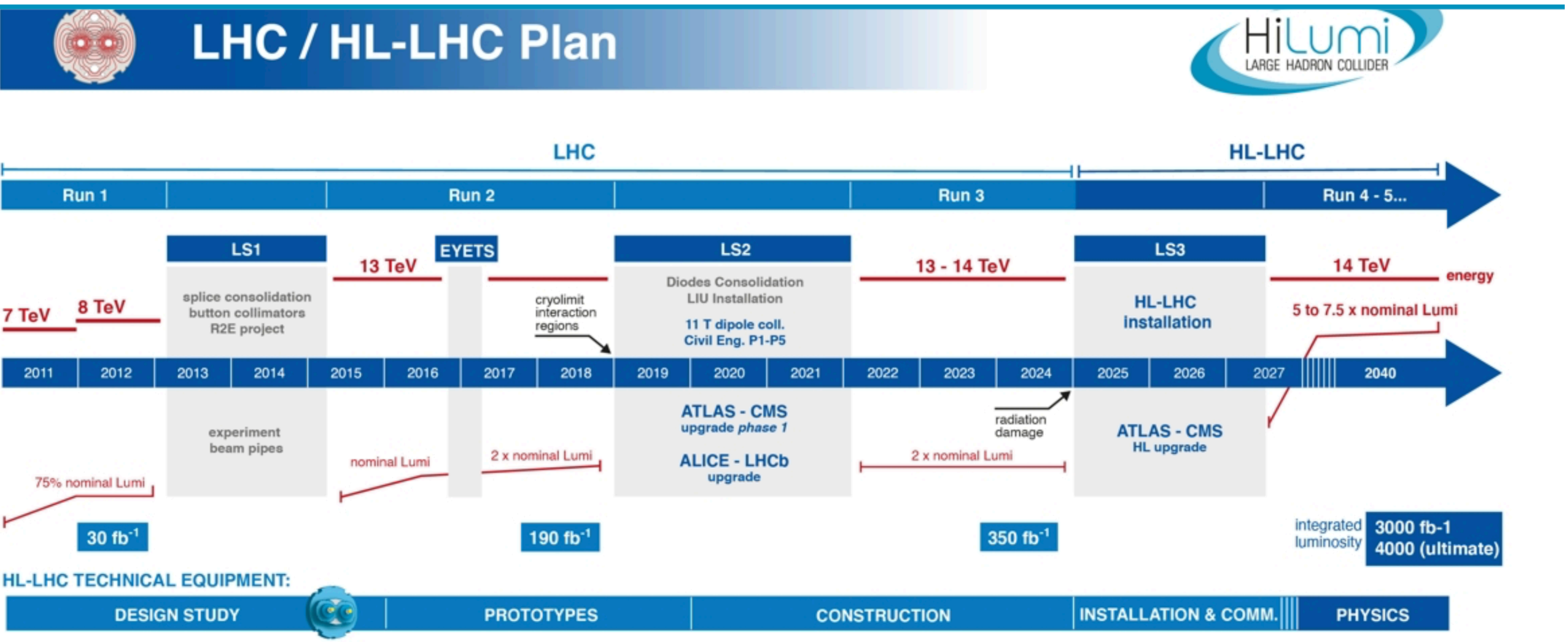
Slide from F. Bordry



HL-LHC Schedule

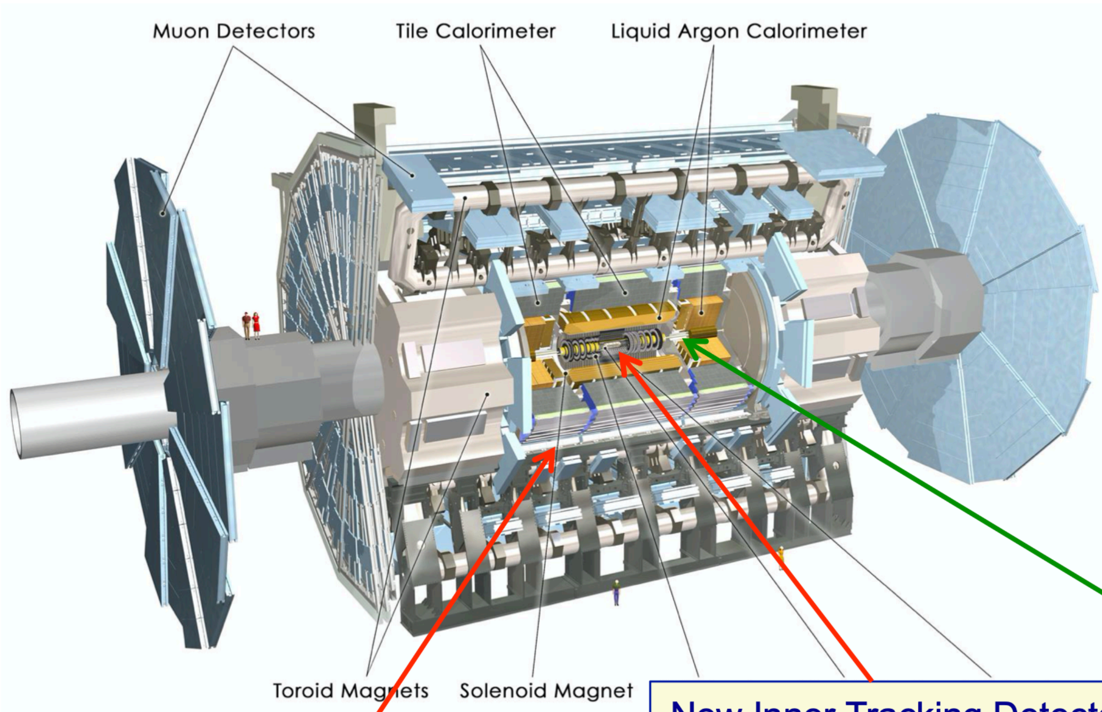
Start of HL-LHC planned for 2027, physics ~2028

- Run at nominal energy of 14 TeV
- Plan to run at 5-7.5 times nominal luminosity



ATLAS Phase-II Upgrade

From K. Jakobs



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector (all silicon tracker, up to $|\eta|$ =4)

New muon chambers in the inner barrel region

High granularity timing detector (forward region)

Approved by CERN Research Board (16th Sept.)

CMS Phase-II Upgrades

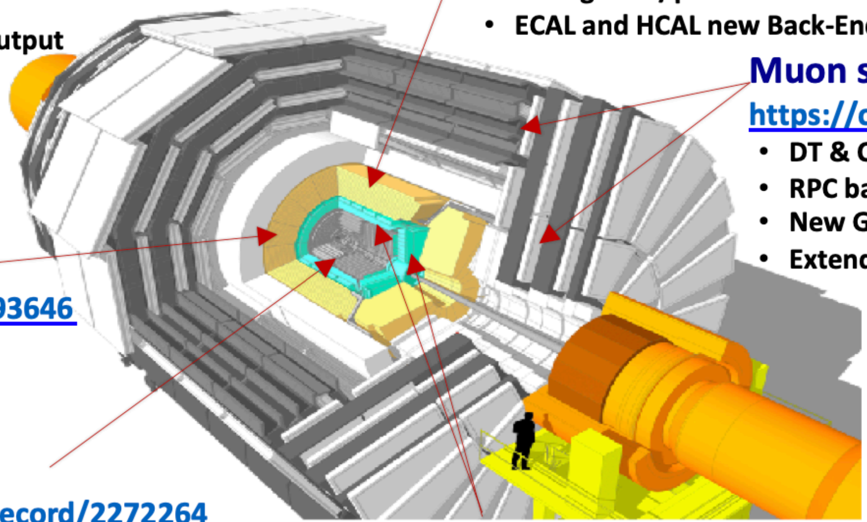
From R. Carlin
ICHEP 2020

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/002706512

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612

Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Higgs Boson Physics: where we are now

- Large sample of ~8M Higgs bosons (per experiment) produced in Run 2 allows for precision tests of the Higgs sector of the SM:

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

Major progress in last few years:

- Observation of H→bb decay
- Observation of ttH production
- Evidence of H→$\mu\mu$ decay

At the end of Run 2:

- Mass measurement precision ~0.1%
- All major production and decay modes have been observed. Other targets for future runs:
  - Zγ decay mode
  - tH production mode (if SM, very difficult…)

Where we are now, before start of Run 3

The 125 GeV Higgs boson has been shown to be very compatible with the Standard Model:

- Recent ATLAS and CMS combined signal strengths:

  ATLAS-CONF-2019-037 $\mu = 1.06 \pm 0.07$

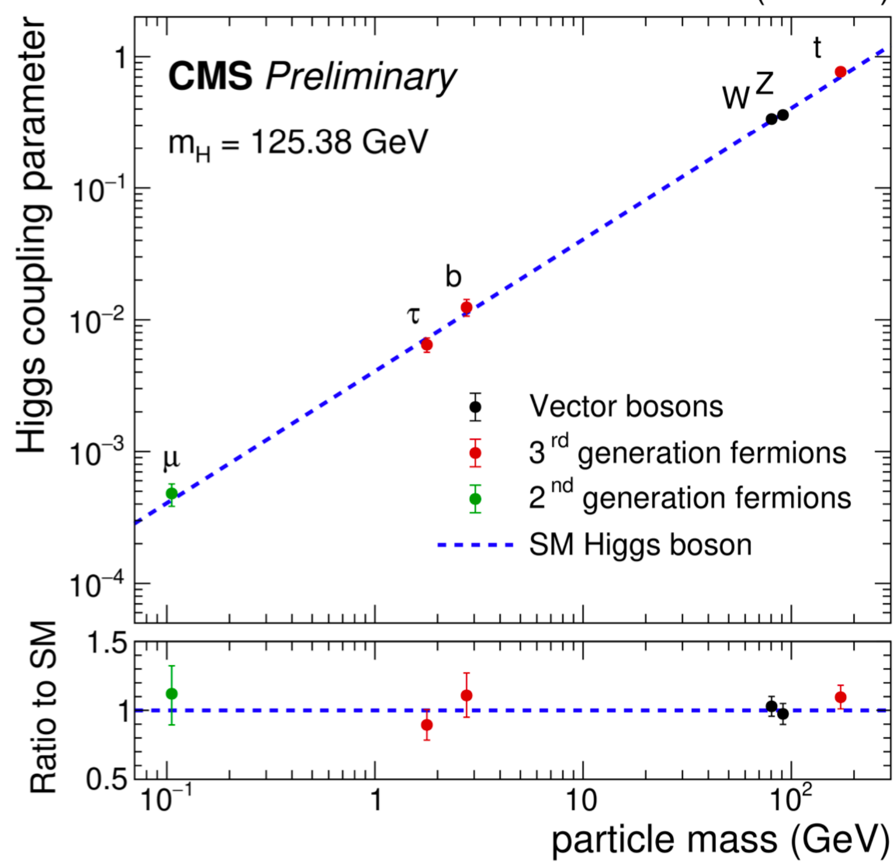
  CMS-PAS-HIG-19-005 $\mu = 1.02^{+0.07}_{-0.06}$

- Coupling to weak bosons (κ_V) consistent to within ~5% of the SM

- Yukawa couplings observed for top, bottom, and tau fermions with non-universal pattern predicted by the SM

- Spin 0 confirmed during Run 1 with pure CP-odd state easily excluded in H→ZZ
  - No hints yet of CP-odd coupling component to SM particles

CMS-PAS-HIG-19-006



- No evidence of non-SM decays

- Best fit to invisible BR compatible with SM: 0.00 +/- 0.06, with BR < 0.11 excluded at 95% CL ATLAS-CONF-2020-052

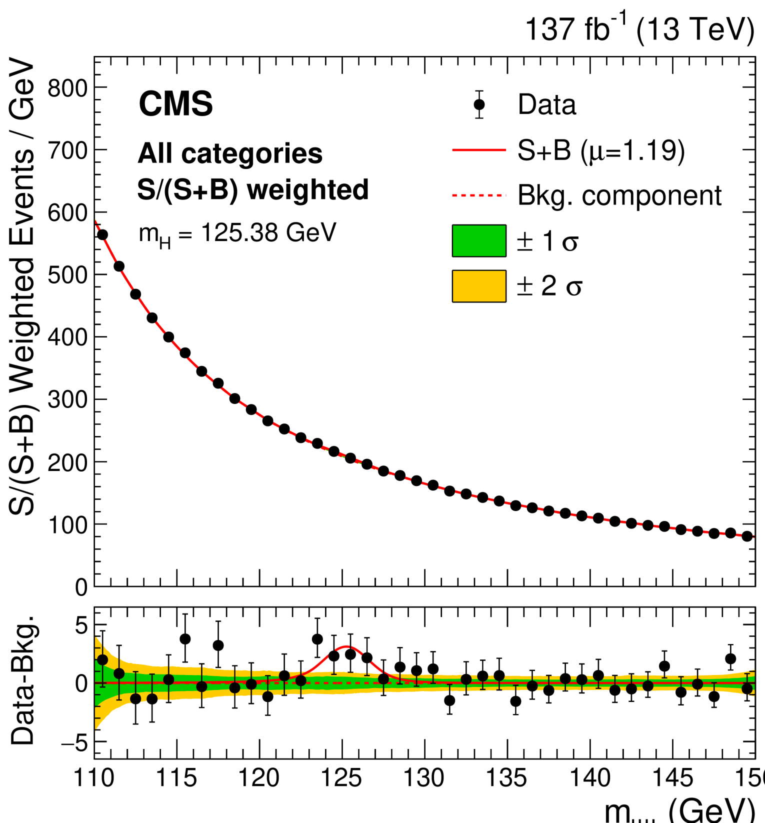
Where we are now: recent developments

A new frontier: the 2nd generation

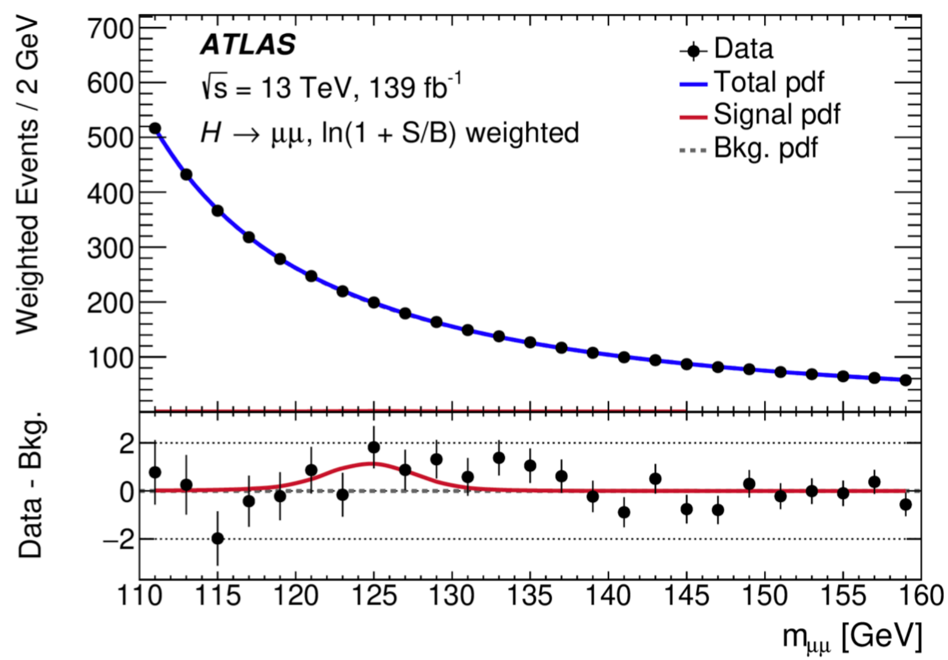
- Challenging! small couplings in the SM and large backgrounds

- Full Run 2 dataset search for Higgs → μμ
- Results: CMS 3.0σ (obs), 2.5σ (exp), ATLAS: 2.0σ (obs), 1.7σ (exp)

Results consistent with SM prediction



CERN-EP-2020-164 Sub. to JHEP



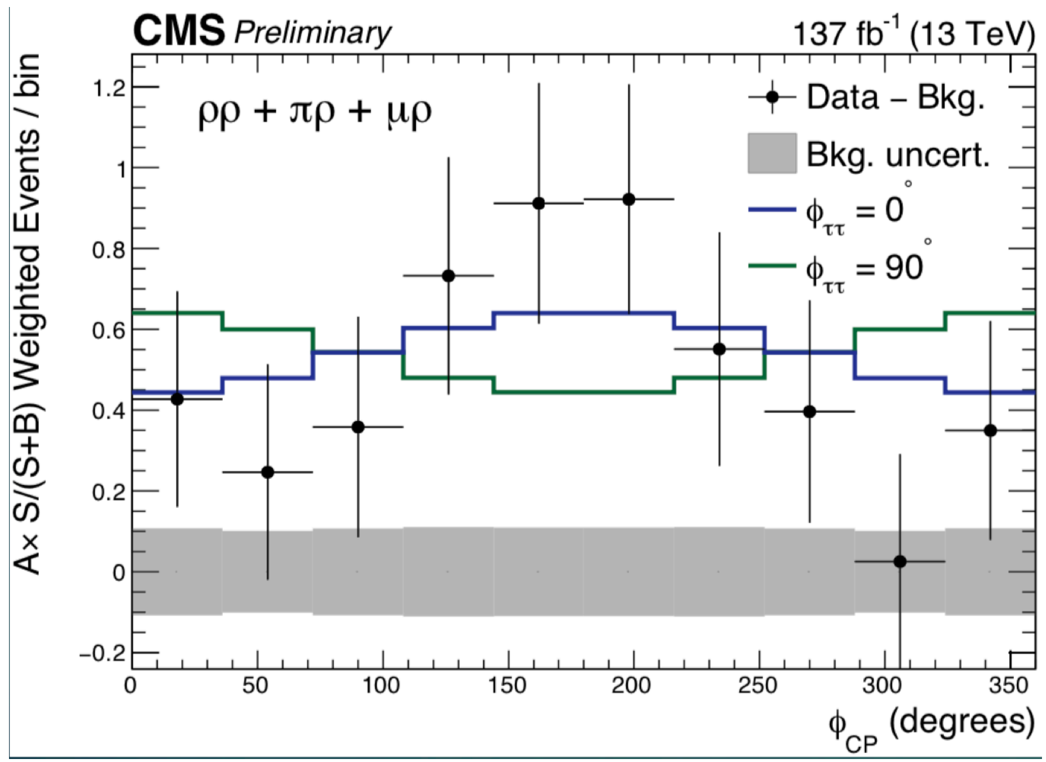
CERN-EP-2020-117 Sub. to PLB

Where we are now: recent developments

CP properties: CP-odd component to couplings with fermions?

- Recent result from CMS using tau polarization information
  - challenging!
- Analysis excludes pure CP-odd coupling at more than 3σ C.L.

$$\tan\phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau} = \frac{CP\ odd}{CP\ even\ (SM)}$$



CMS-PAS-HIG-20-006

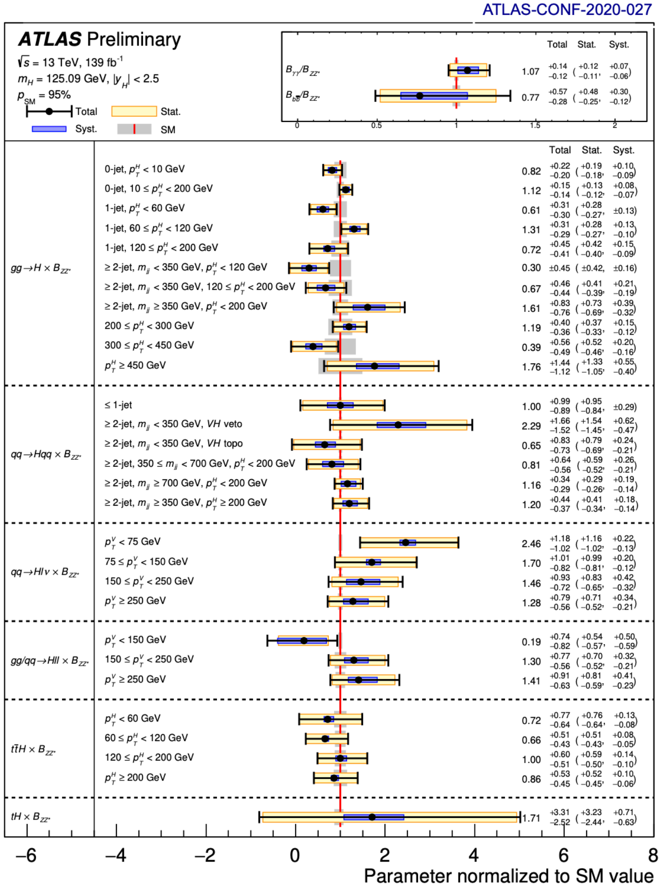
Note: analyses using ttH production by ATLAS and CMS exclude pure CP-odd top coupling at more than 3σ C.L.

Where we are now: comprehensive kinematic studies

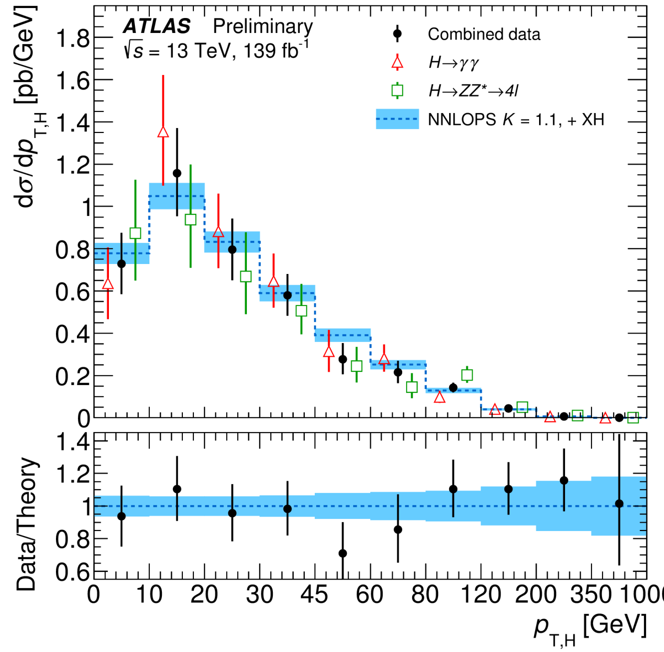
After observation, vast programme of kinematic measurements was launched

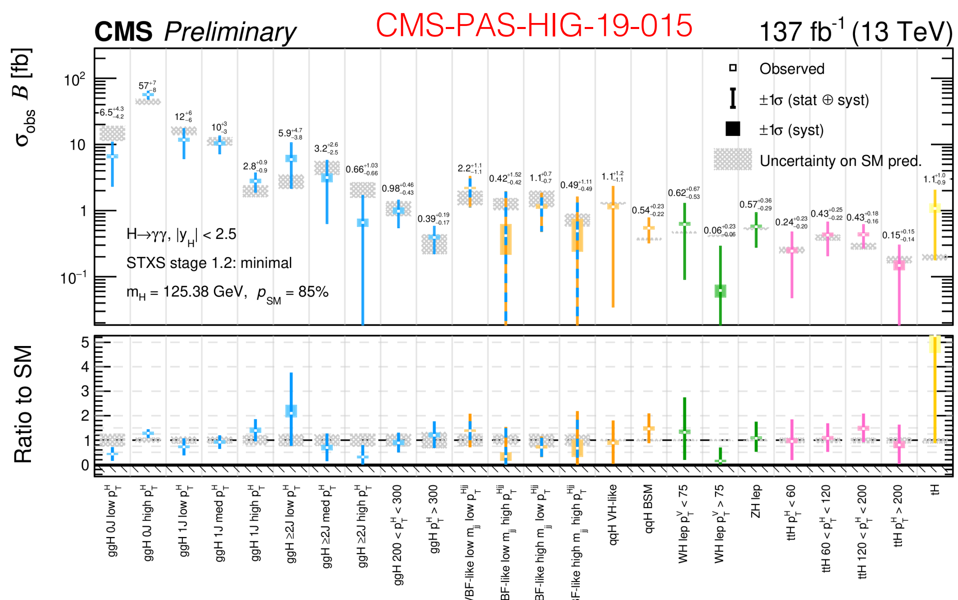
- Differential cross sections
- Measurements by production mode in various kinematic regions (STXS)

ATLAS-CONF-2020-027



ATLAS-CONF-2020-026

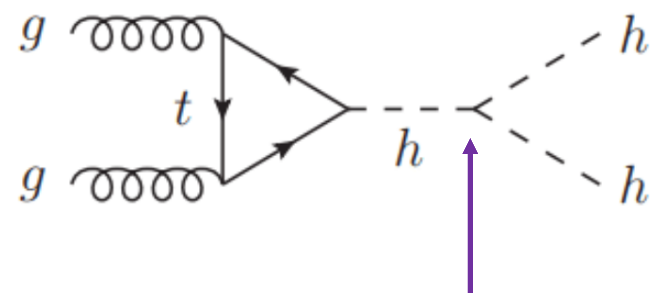




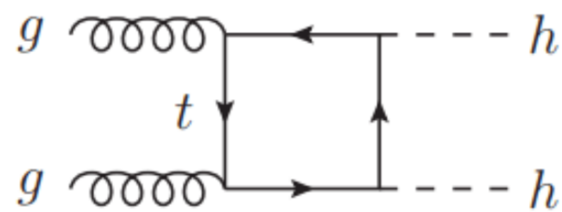
Where we are now: towards the self-coupling

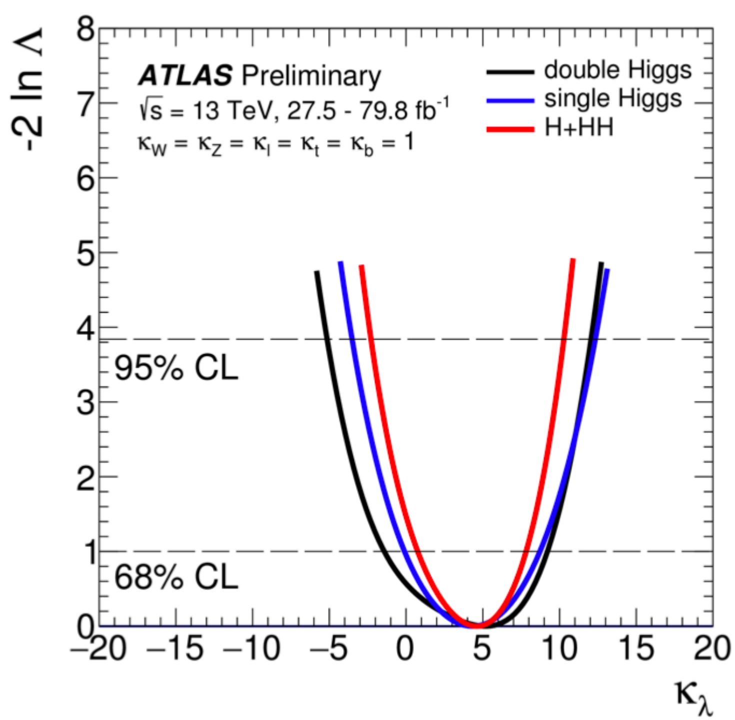
Making progress towards testing the shape of the Higgs potential through the Higgs self-coupling (λ_3)

Sensitivity to SM coupling will require HL-LHC but much progress can be made in coming years (more later…)



$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$





Model	$\kappa_{\lambda}{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
	$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

ATLAS-CONF-2019-049

Run 3: some considerations

- Last 8 years: enormous progress
  - Large increases in integrated luminosity vs time
  - LHC collision energy increase
  - Major improvements in performance and analysis techniques
- Next 8 years: analysis of Run 2 and Run 3 data
  - ~2-2.5 increase in integrated luminosity
  - Modest increase in energy
    - From a strict SM Higgs measurement perspective, staying at 13 TeV for Run 3 would make things simpler (but there are other considerations)
  - Most results will need to include Run 2 data: need to setup combinations in advance to facilitate merging of results in the best way possible
  - Significant progress possible on many fronts

Run 3: challenges and opportunities

- Systematic uncertainties are becoming a more dominant for many results
  - CMS H tautau (μ) $0.85^{+0.12}_{-0.11}$ th. $^{+0.08}_{-0.07}$ stat. $^{+0.06}_{-0.06}$ syst. $^{+0.07}_{-0.06}$ bbb $^{+0.04}_{-0.03}$
  - ATLAS H bb (μ) $1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$
  - ATLAS VBF (σ) $0.85 \pm 0.10\ (\text{stat.})\ ^{+0.08}_{-0.07}\ (\text{exp syst.})\ ^{+0.13}_{-0.10}\ (\text{sig. theo.})\ ^{+0.07}_{-0.06}\ (\text{bkg. theo.})$ pb
  - CMS global μ fit: $1.02 \pm 0.04(\text{th}) \pm 0.04(\text{exp}) \pm 0.04(\text{stat})$
- Need to reduce systematics (Theory, Modelling, PDFs), and improve our treatment of systematics
  - e.g. two-point systematics: in the distant past, analyses often used two PDF sets as a systematic and we evolved to the current prescription
    - need to do the same with other systematic uncertainties e.g. parton showers (this is happening already)
  - Can analyses find ways to reduce their sensitivity to some systematics?
  - Can we trade some statistical uncertainty to lower some systematic uncertainties?

Run 3: Opportunities

- We have clear targets that will benefit from the increased statistics
  - $H \rightarrow \mu\mu$. We are within reach of observation by the end of Run 3, combining ATLAS and CMS
  - Use increased statistics (and energy?) to study
    - Higgs impact at high energy, VBF/VBS scattering, off-shell Higgs
    - Gain stats in all high kinematic pt bins
- Work on integrating Higgs measurements in global LHC combinations e.g. global SMEFT fits to EWK, Top, Higgs measurements (New LHC EFT WG just created)
- The Undetected Branching Ratio:
  - Vast phase space that remains to be explored (BSM decays, LLPs, etc.)
- Higgs + X
  - The Higgs boson is a narrow resonance that can be tagged.
  - Has been used as a decay product in BSM searches. Can we think about more generic, less model-dependent Higgs+X searches?

HL-LHC Higgs Physics

Physics potential of the HL-LHC recently re-appraised and documented in a series of Yellow Reports

Yellow reports were submitted to the European Strategy Group at the end of 2018

Higgs Yellow Report:

CERN-LPCC-2018-04

- A huge effort: 400 authors, 340 pages

Can't do justice to the work in this document: I encourage you to take a look and see the full extent and promise of HL-LHC Higgs physics

FERMILAB-PUB-19-074-PPD-T

CERN-LPCC-2018-04
February 4, 2019

arXiv:1902.00134v1 [hep-ph] 31 Jan 2019

Higgs Physics at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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This document was prepared by [HL-LHC and HE-LHC Collaborations] using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

HL-LHC Higgs Physics

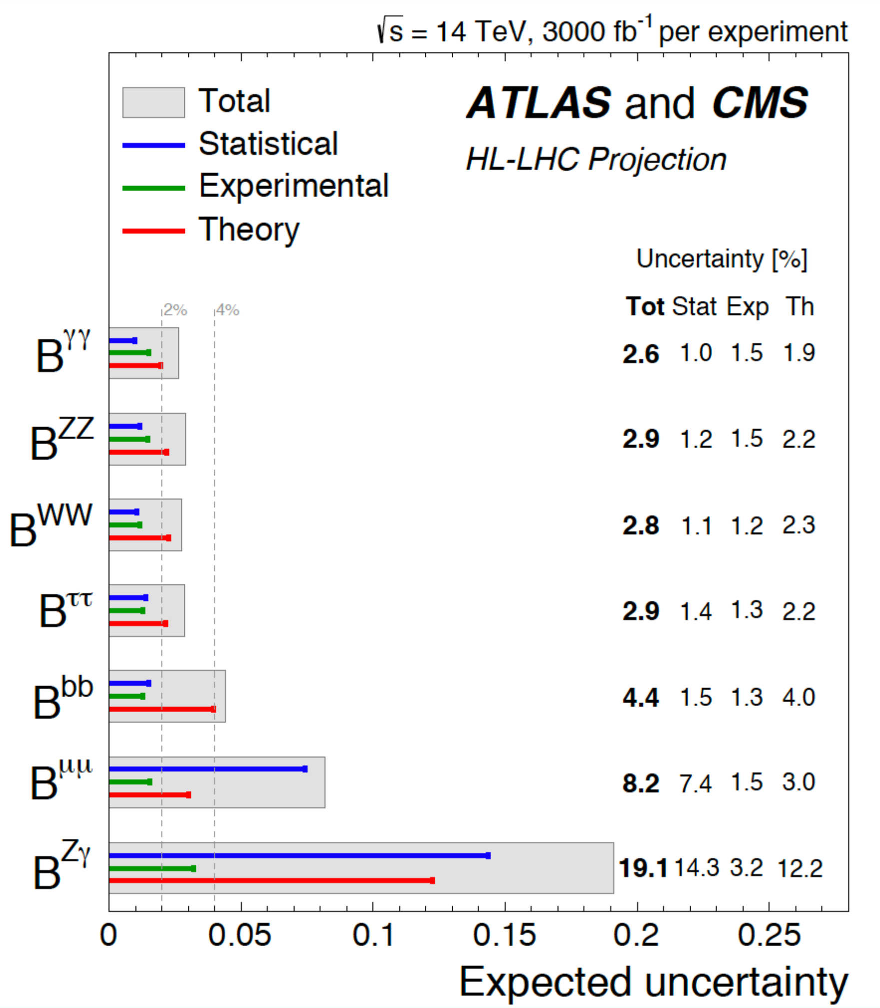
Two uncertainty scenarios were considered for the projections:

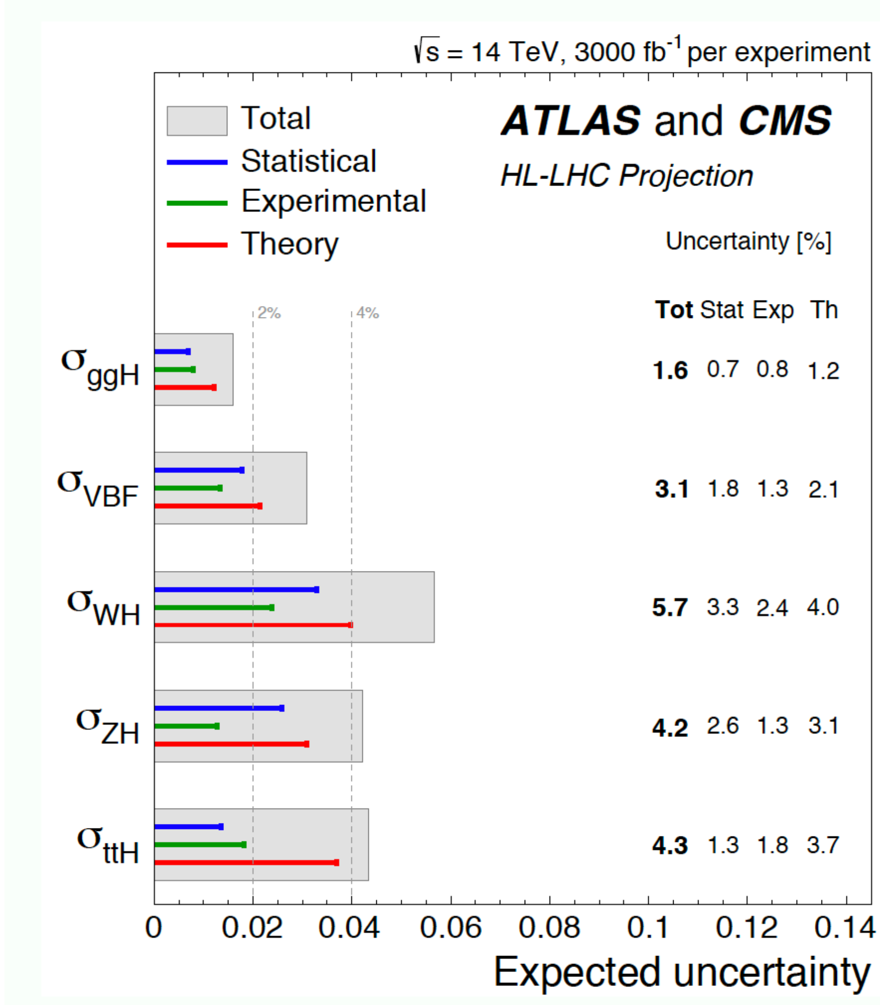
- S1 - Conservative, based on the current Run2 systematic uncertainties (including theory)

- S2 - Ultimate, based on estimates of ultimate performance for experimental uncertainties, and applying a factor of 1/2 for theoretical uncertainties

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

HL-LHC: Branching Ratios and Cross Sections

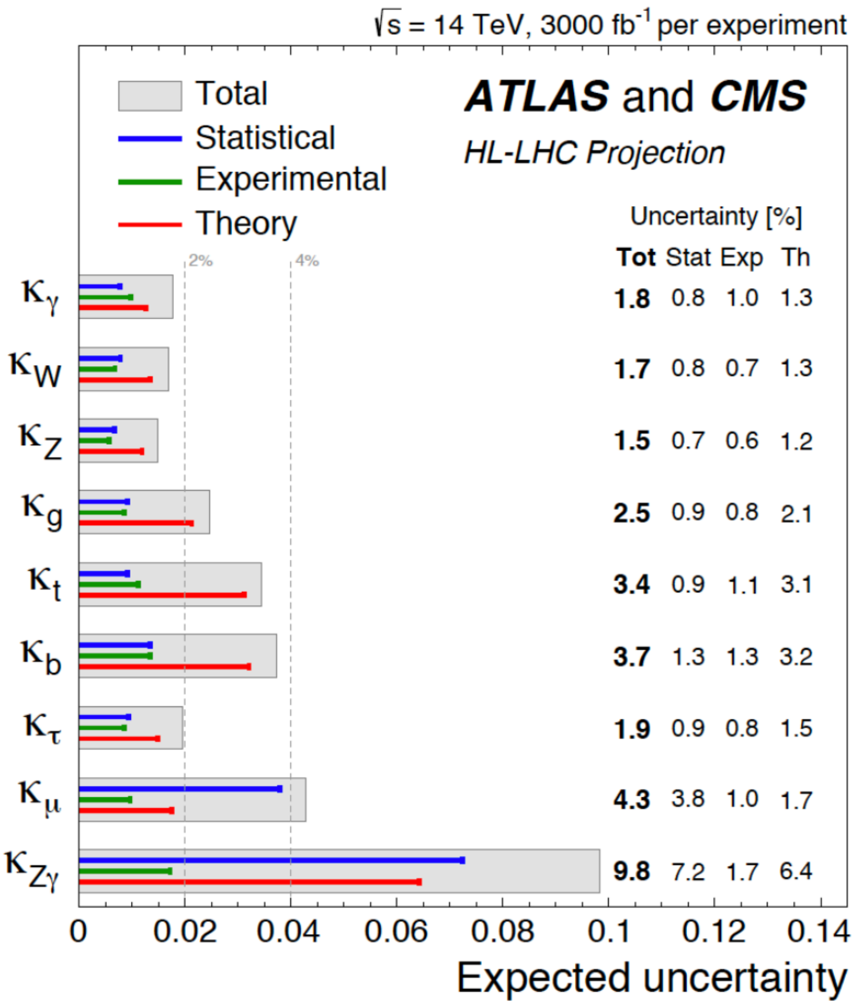


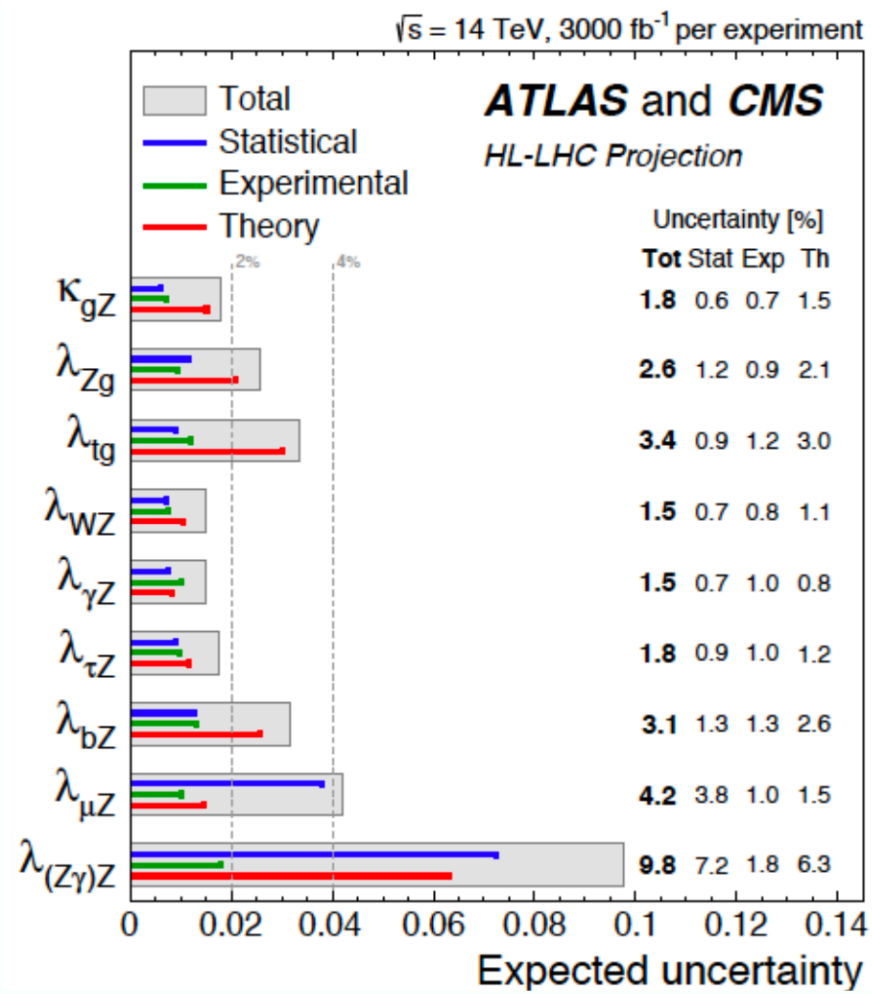


Combination of ATLAS and CMS for systematic uncertainty scenario 2

- Theory uncertainty remains the largest component for most measurements

HL-LHC: Couplings and Coupling Ratios

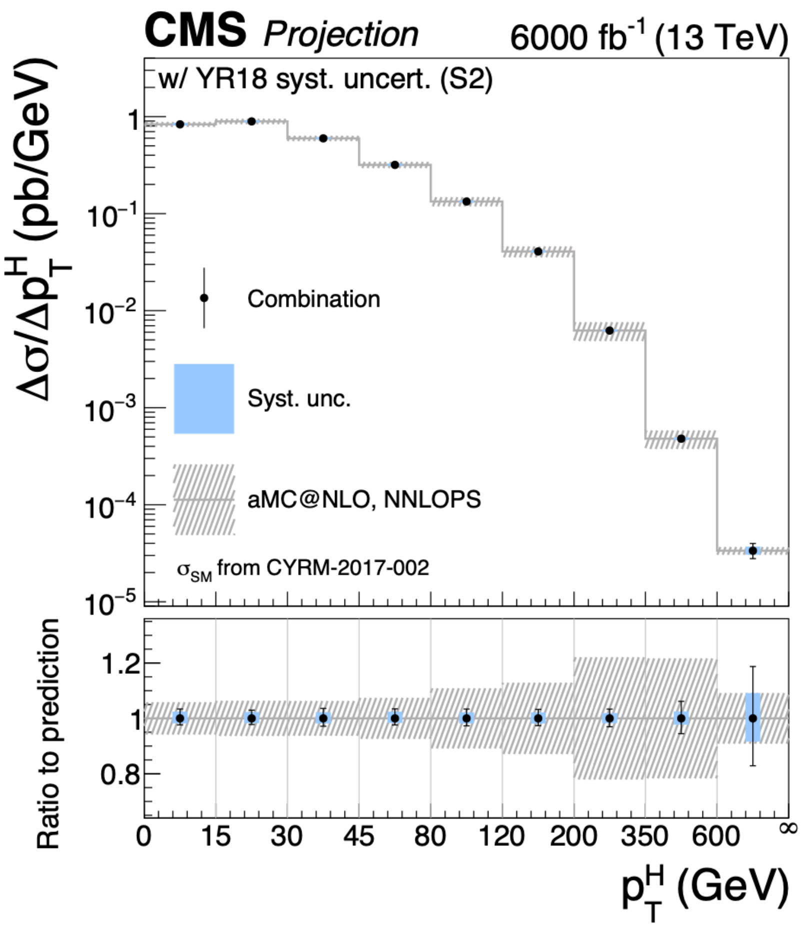


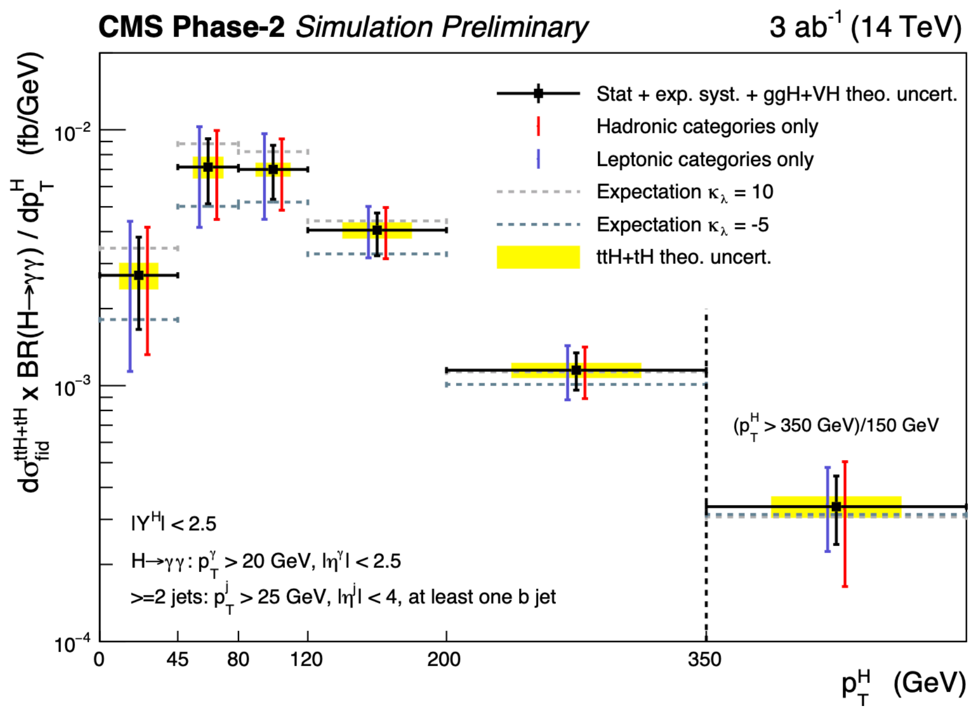


Combined results for ATLAS and CMS for systematic uncertainty scenario 2

- Coupling ratios on the right allow for reduced uncertainties in general

HL-LHC: Differential Cross Sections





CMS-PAS-FTR-18-020

Left plot: results for CMS for systematic uncertainty scenario 2

- Theory uncertainty dominates in all bins except p_T > 600 GeV

Right plot: p_T^H distribution for ttH production using the H→γγ decay

HL-LHC: Width, Invisible BR, etc.

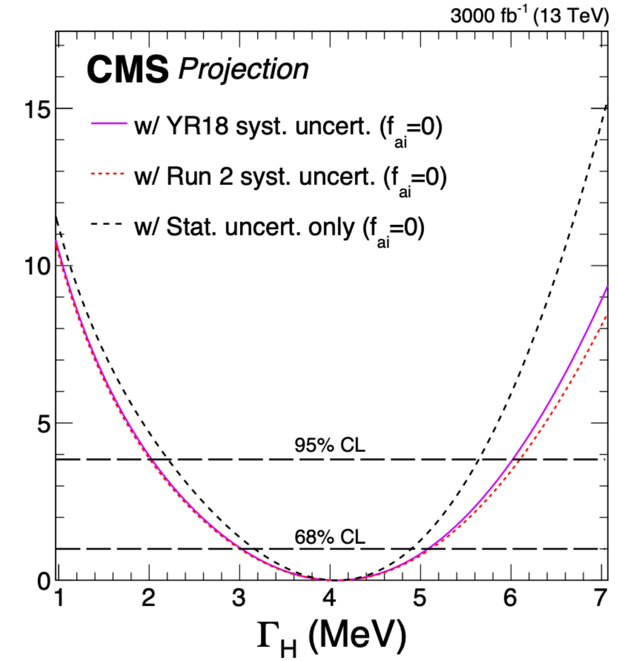
Width

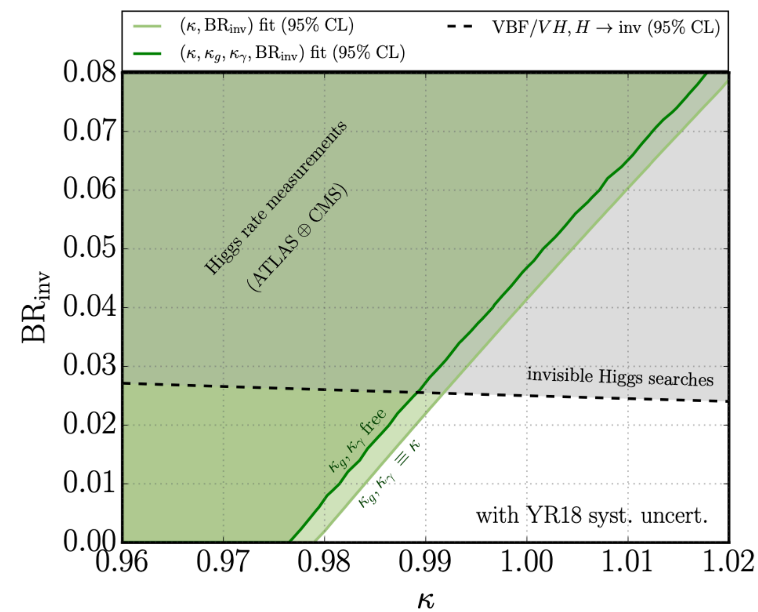
- Little sensitivity from direct measurements, or H→γγ mass shape
- Using offshell couplings, obtain 20% precision
- Using coupling fits with k_V <= 1, obtain 5% at 95% CL

Invisible width or BR

- From VBF +VH measurements: 2.5%
- Invisible width can also be constrained from coupling fits (right)

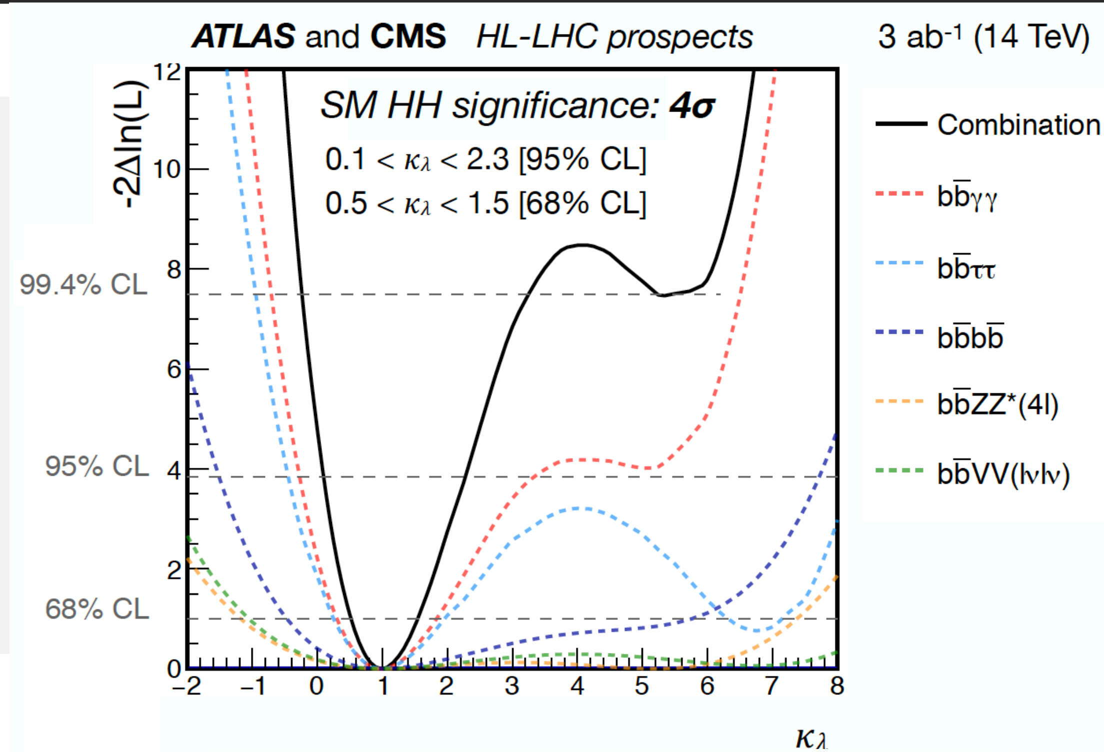
Not covered here: BSM decays will be big part of the programme. Studies of CP-properties (discussed by C. Grojean)



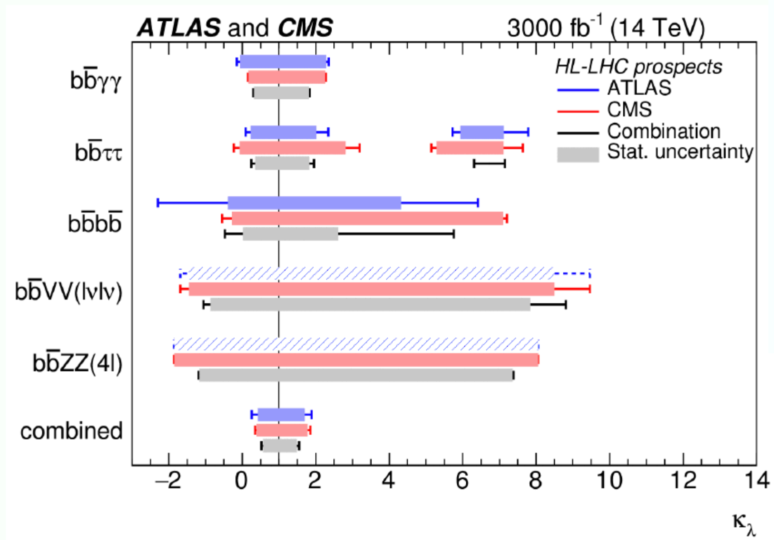


HL-LHC: Higgs Self-Coupling

- Significance of HH signal at the 4σ level (both exp.)
- Uncertainty on κ_λ of 50%
  - 2nd minimum excluded at > 99% CL
- Note that HH observation analysis and κ_λ analysis require different optimizations



	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

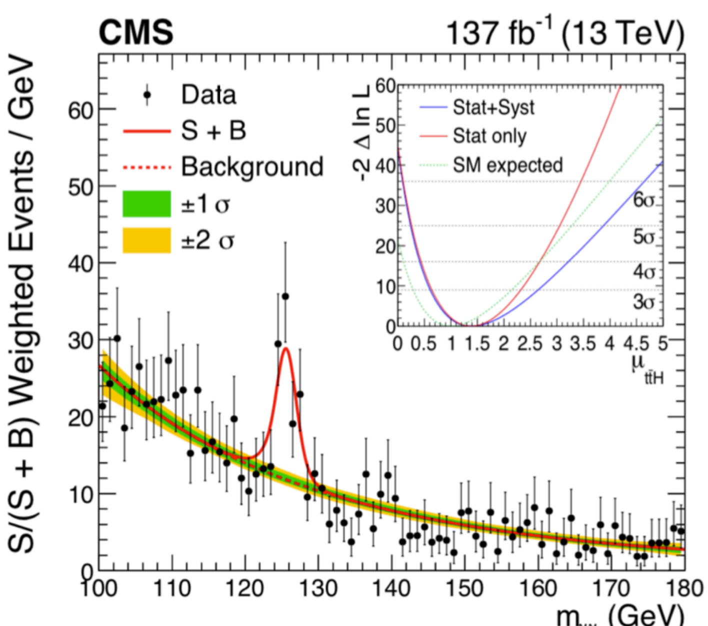


Run 3 and HL-LHC: Expect New Ideas

New ideas from experimental and theory will come

- 20 years ago, we did not imagine or foresee the quality and scope of the Higgs physics results we now have. Some examples:

- Performance, for example enormous advances in pileup mitigation
- Analysis and reconstruction/id techniques: extensive use of MVAs, DNNs
- WW: became a discovery channel, a channel for precision Higgs physics
- ttH: was unclear if it could be observed at all, now observed even in $\gamma\gamma$ by both ATLAS and CMS
- HH: prospects keep improving through new ideas, better performance
- Width → use of off-shell/on-shell couplings, mass spectrum



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Run 3 and HL-LHC: Expect New Ideas

- We have not run out of ideas! There will be breakthroughs and game-changers
  - With slower dataset doubling time and the fact that systematic uncertainties are often already larger than statistical uncertainties, major progress will be possible through new ideas and **hard work** on:
    - Improving performance
    - Reducing systematic uncertainties (experimental and theoretical)
    - Improving analysis techniques
    - Improving MCs → will require more involvement from experiments
    - Coming up with new and original ways to measure Higgs properties

Some concluding thoughts (I)

We have a fantastic Run 2 dataset to work with thanks to our LHC machine colleagues and our ATLAS and CMS collaborators who kept the detectors running and solved problems along the way

That Run 2 dataset will now serve as the foundation for combinations with the larger Run 3 dataset

HL-LHC Yellow Reports provides an extensive set of studies that highlight the really beautiful physics that can studied at the HL-LHC

Some concluding thoughts (II)

After Run 2, we still have a long way to go before we reach the summit

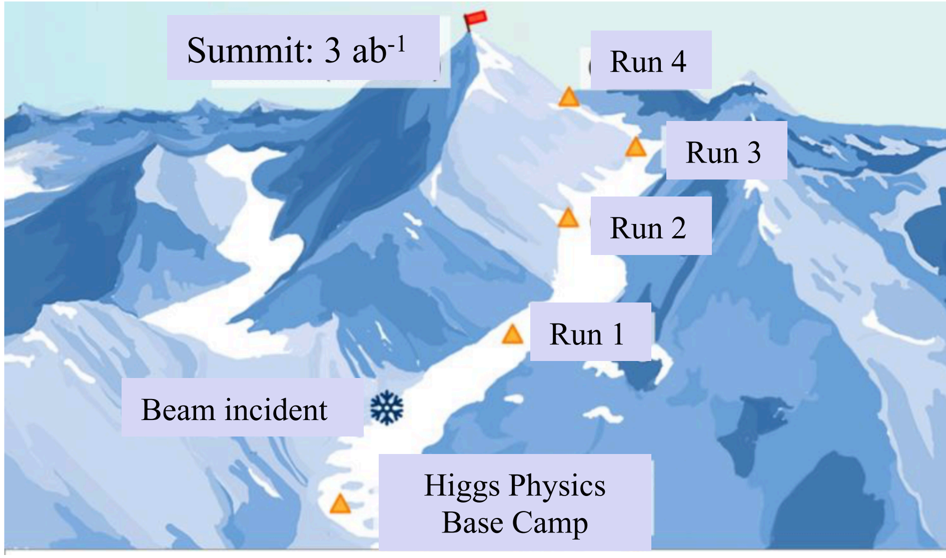
Some concluding thoughts (II)

After Run 2, there is still a long way to go before we reach the summit

Slower dataset doubling time and the fact that systematics are already larger than statistical uncertainties in many analyses means that we will need to work hard and innovate:

- True for both experimental and theory communities

- Studies in Higgs HL-LHC Yellow Report imply that we will need major advances in theory to reach the "summit" i.e. exploit the full potential of HL-LHC



Unclear if/when new machines will provide results competitive with most LHC results:

- This challenging work we do in coming years could have a very, very long shelf life – worth the effort!

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