Higgs 2020 Program Committee

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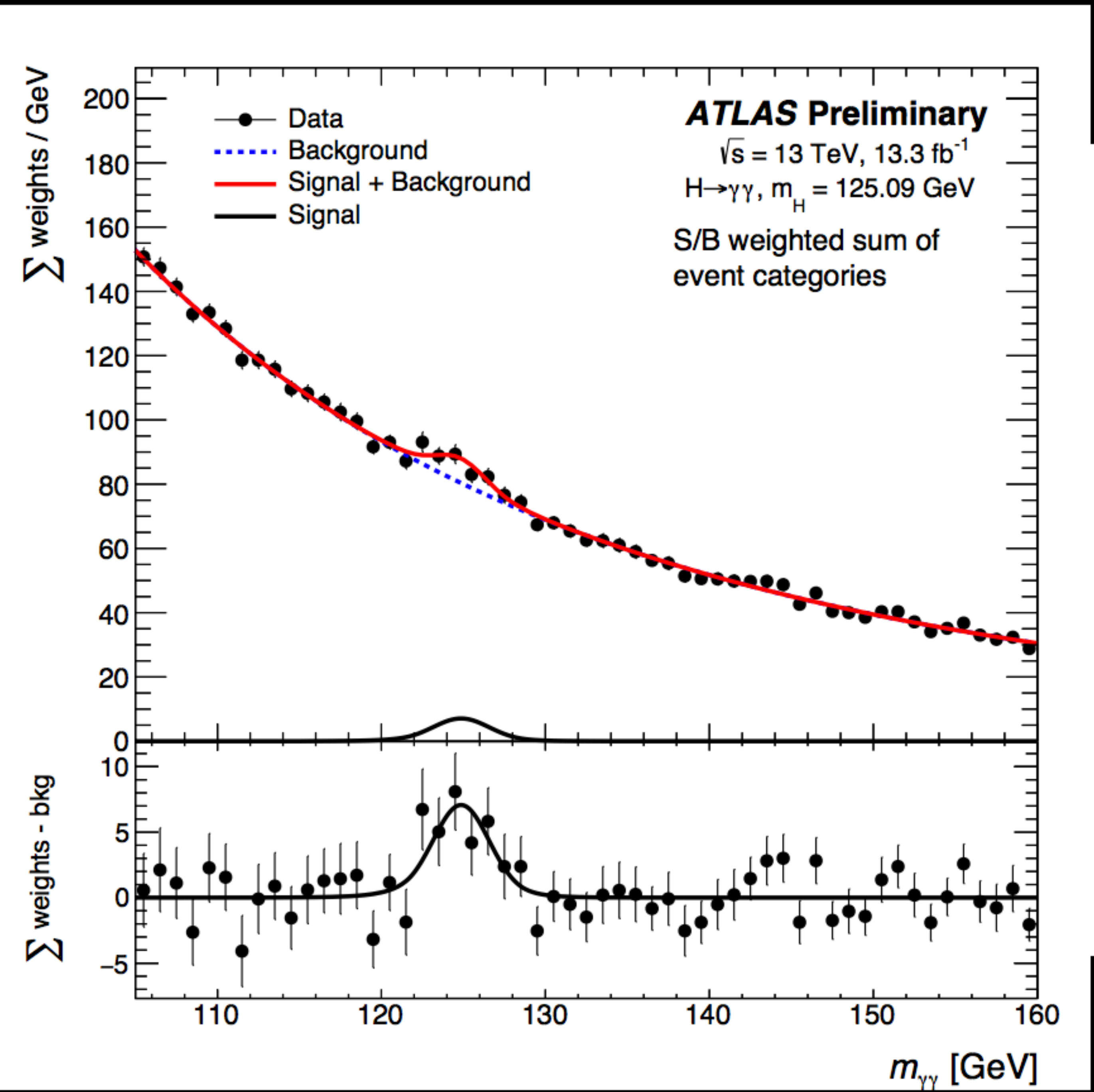
Highlights from HIGGS2020 conference

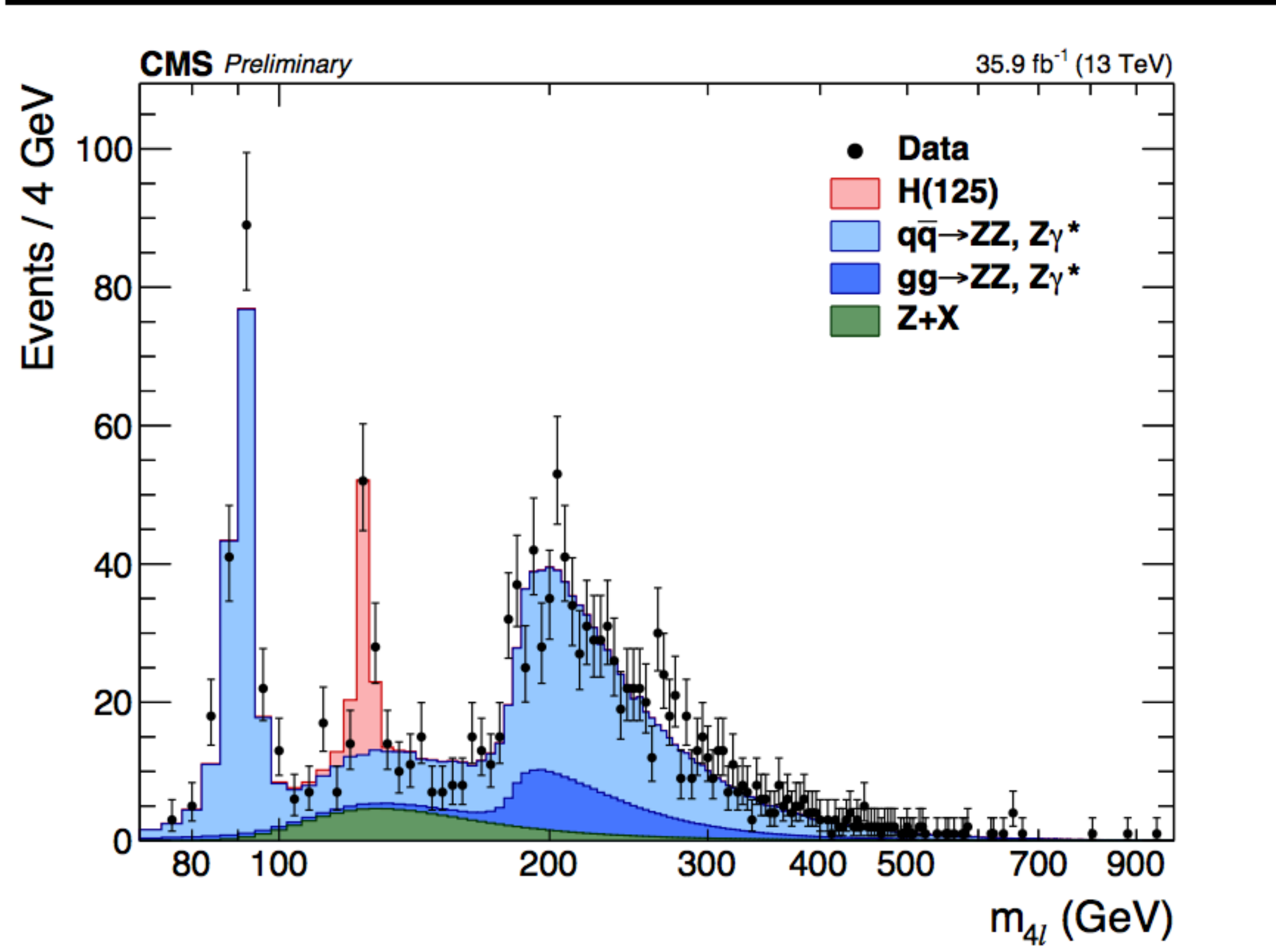
Valerio Dao *(CERN)*

ATLAS weekly - 10-11-2020

H. Murayama

Higgs exists!





Why do we still care?

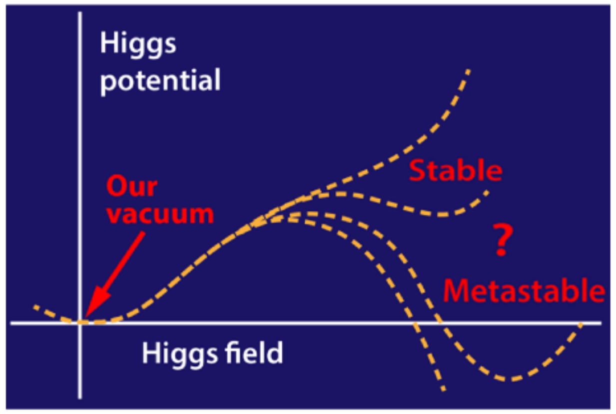
experimental side:

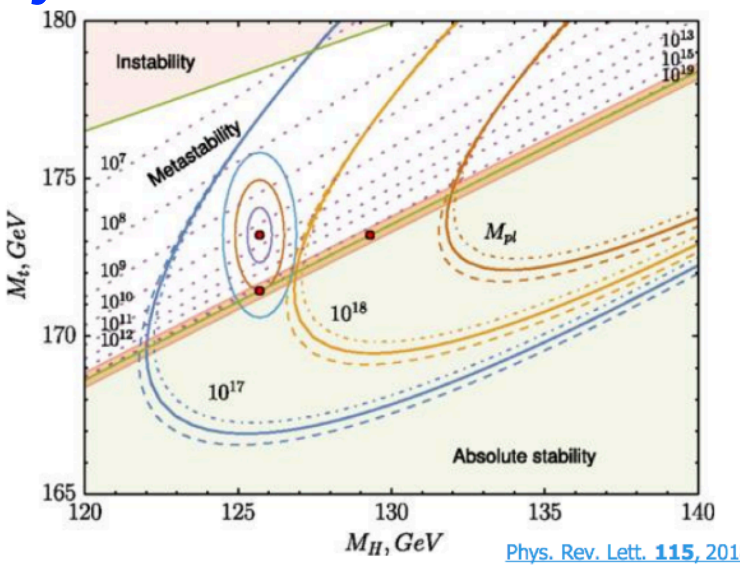
Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu, \tau e, e\mu$
- $H \to J/\Psi\gamma, Y\gamma$, …

… and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- …

theory side:





Phys. Rev. Lett. 115, 201

C. Grojean

The **Higgs** boson is the **simplest Q-bit**/particle:
as far as we know, it has no spin, no charge, no structure.
This vacancy can make its richness:
e.g., unlike other SM particle, it can easily couple to a Hidden Sector.
The **intricacy** of the Higgs boson lies in its **simplicity**
(aka **naturalness**)

J. Shelton

NMSSM | composite H | EWBG | H portal DM

- Why expect new physics near the weak scale?
  - co-responsible for generating it
  - stabilize it
  - thermal dark matter
  - ...why not?
- Light, neutral particles: exotic Higgs decays

Overview

Yukawa: bb/cc/mm/tau/ttH

- ***A very dense program: https://indico.cern.ch/event/900384/timetable/***
  - 664 registered participants, ~200 (70-150) simultaneous connection for plenary (parallel talks)

	Mon	Tue	Wed	Thur	Fri
12.30	**opening**				**future prospects**
	precision			**Di-Higgs**	**future prospects**
	precision	**YSF**	**BSM**	**YSF**	
18.30	**opening**	**precision**	**public lecture**	**EFT**	

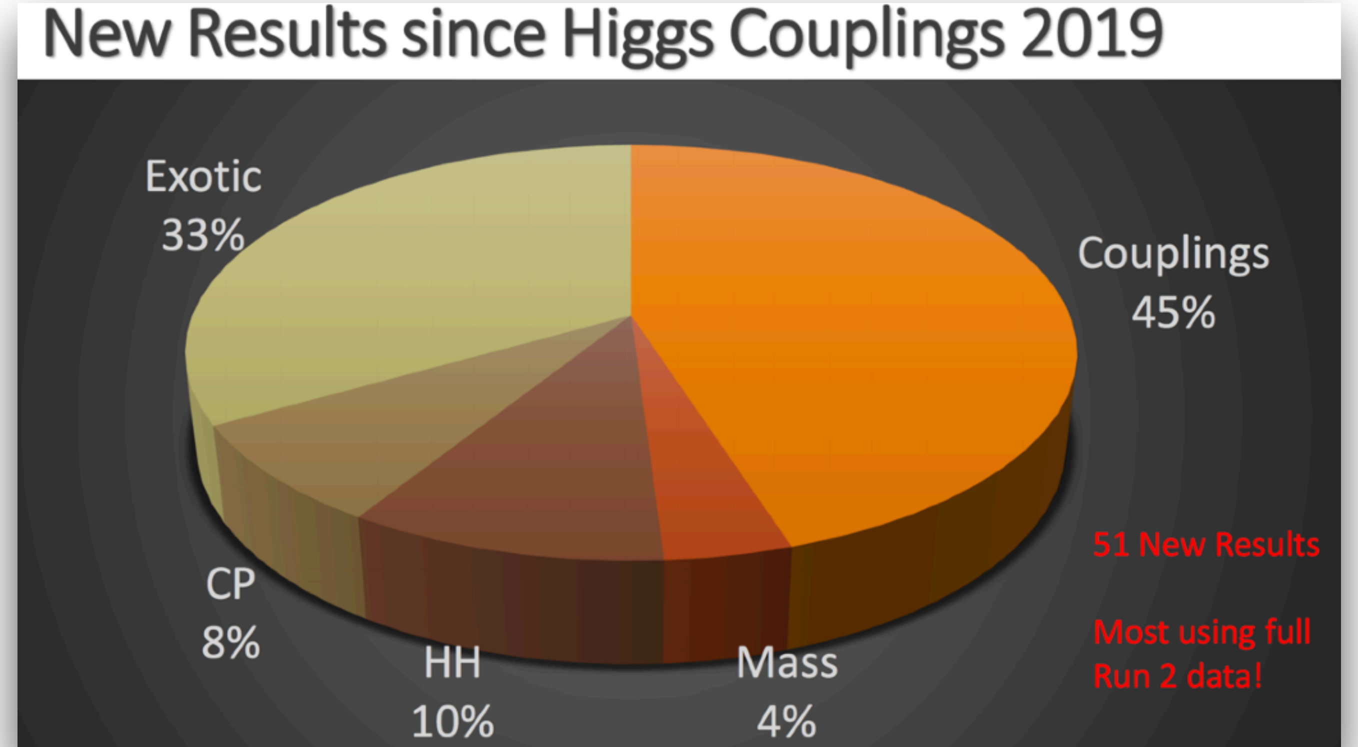
- 10 Plenary sessions, 2 Plenary Young scientist sessions (8 talk), 15 parallel sessions (always three at the time) —> **98 talks!!!**

- interesting mixing of theory and exp. in each session, most experimental talks were ATLAS+CMS

is zoom webinar the best format for a CONF?

Impossible to summarise in 15 min (apology if I omit your favourite topic!!)

What is new at HIGGS2020?



- ***The experimental community is very active in analysing Run2 data:***
  - a large amount of updated and new results came out for ICHEP (H->μμ, VBF H->WW, full combination)

New Results this Week!

J. Olsen's exp. overview

- CMS: new di-Higgs in bbγγ full Run 2
  - Talk tomorrow by Soumya Mukherjee
- ATLAS:
  - VBF inclusive H → bb and incl.+photon combination: Zhijun Liang on Tuesday
  - Dark Matter search with H → yy + MET: Samuel Ross Mehan on Thursday in th "Beyond the Standard Model III" parallel session
  - VBF & ggF+2-jet H → WW 36/fb properties: Shown by Merjin Van De Klundert
  - ttH, H → bb with >= 1 lepton: Shown by Valeria Botta on Tuesday
  - Combination MSSM/EFT interpretation: Shown by Saskia Falke on Thursday
  - H → invisible combination: Shown by Benedikt Maier on Wednesday

also: H^{++} , V+jets inputs to PDF,

Jim Olsen (Princeton University) EXPERIMENTAL OVERVIEW - HIGGS 2020

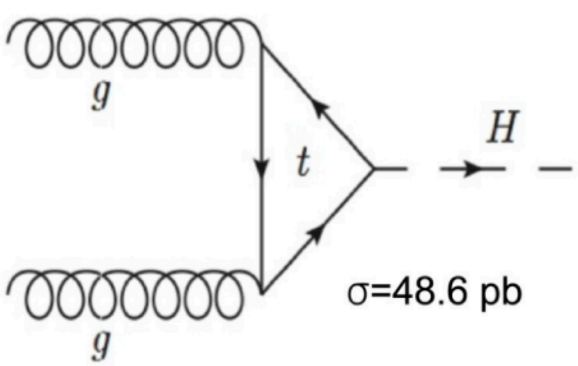
- ***…. ATLAS kept the bar quite high by providing several new results:***
  - full Run2 updates, more combinations, more interpretations

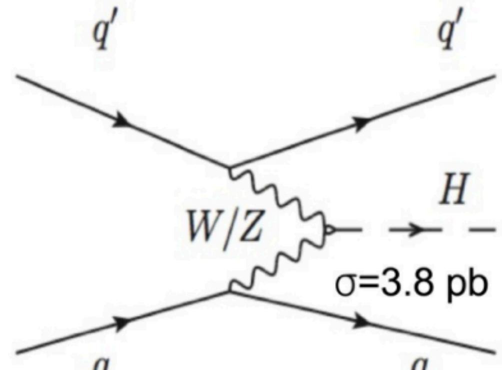
- WARNING: this is not a review of ATLAS Higgs results

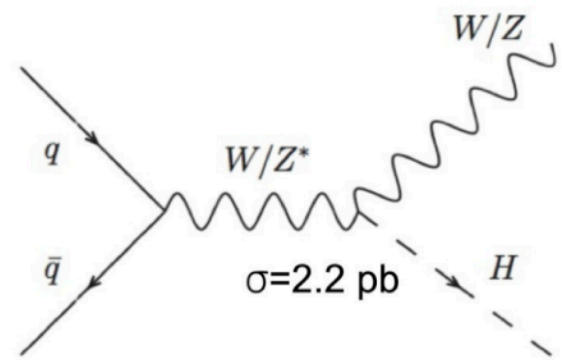
The revenge of H->bb

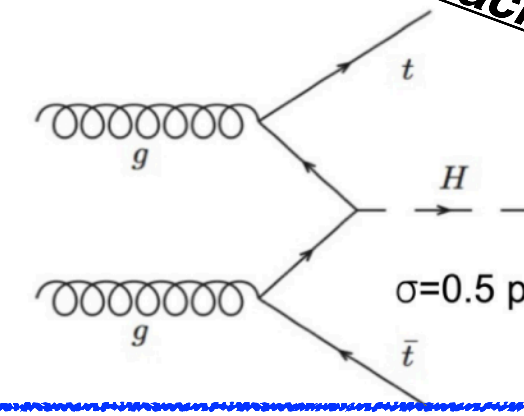
R. Camacho

ggF boosted	VBF	VH	ttH



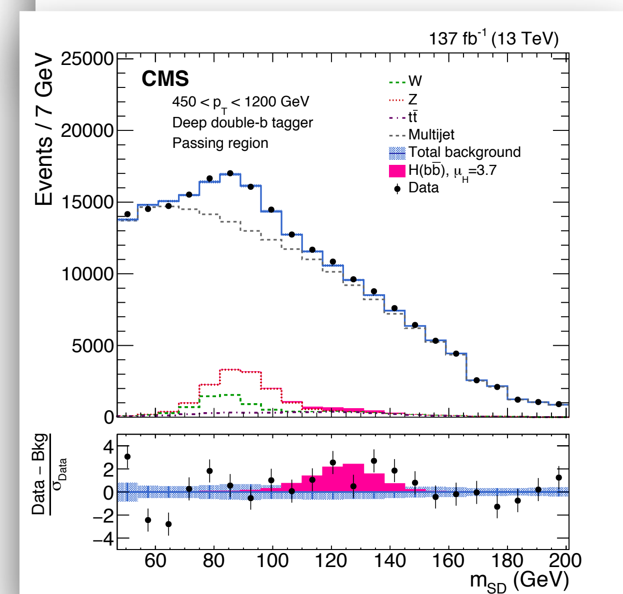






ggF boosted

- ATLAS: ATLAS-CONF-2018-052
- **CMS: HIG-19-003**

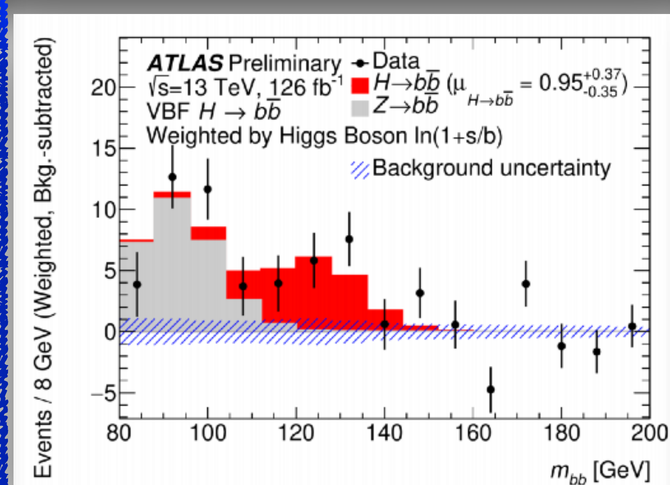


- **full Run2: 2.5σ** (0.7σ exp)
- excess concentrated at high p_T
- full Run2 ATLAS analysis ongoing

VBF

- Two ATLAS analyses:
- **Hadronic/inclusive: CERN-EP-2020-195**
- **VBF+γ: CERN-EP-2020-179**

(papers to be submitted)

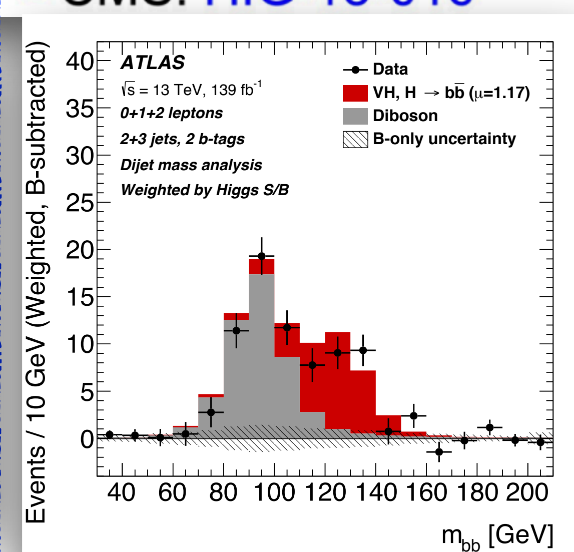


- **full Run2: ~3σ**
- was 0.5σ (36 fb^{-1})
- no Run2 results from CMS

NEW for HIGGS2020

VH

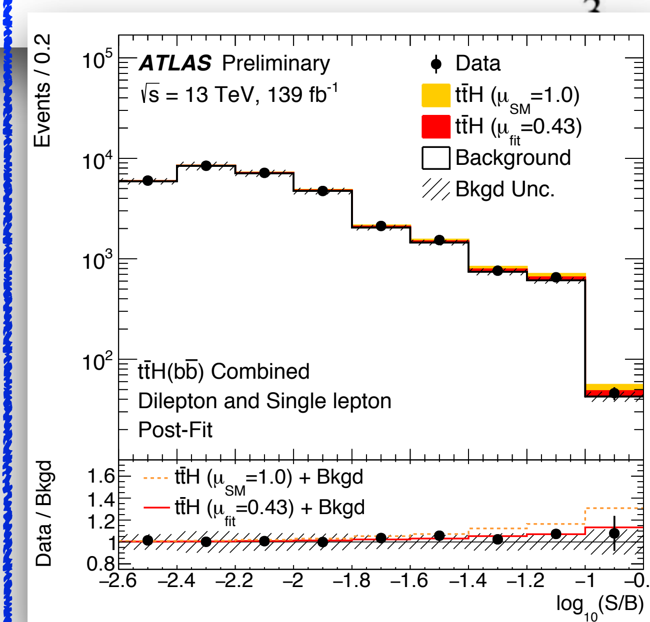
- **ATLAS: arXiv:2007.02873 arXiv:2008.02508**
- CMS: HIG-18-016



- **full Run2: 6.7σ**
- STXS + WH/ZH + boosted
- no full Run2 CMS result

ttH

- ATLAS: **ATLAS-CONF-2020-058**
- CMS: HIG-18-030



- **full Run2: 1.3σ** (3.0σ exp)
- first STXS measurement
- CMS (70fb^{-1}): **3.9σ** (3.5σ exp)

NEW for HIGGS2020

Next Target: $H \to c\bar{c}$

- Do the first and second generation fermions also get their masses from the same doublet?

F. Bishara — a multi-prong approach

… ideas for a hadron collic

- Exclusive Higgs decays $h \to MV$
- Vh and associated hQ production
- Higgs differential distributions
- Charge assymmetry in $W^{\pm}h$

$$\mathrm{BR}_{h\to J/\psi\gamma} = 2.95\cdot 10^{-6}\,(1.07 - 0.07\kappa_c)$$

$$\mathcal{BR}(h\to J/\psi\gamma) < 3.5\times 10^{-4} \text{ at } 95\%\text{ CL}$$

ATLAS $36fb^{-1}$

- **Direct VH H->cc search:**
  - CMS ($36fb^{-1}$) : μ < 70 (37) obs. (exp.)
  - ATLAS ($36fb^{-1}$): μ < 100 (150) obs. (exp.)
  - note 1: contribution from cs -> VH diagrams
  - note 2: theorist asked if we are set to consider common Hbb + Hcc analysis. CMS admitted that most of their sensitivity is coming from H->bb regions (upcoming ATLAS analysis is set for this)

even stronger constraints if considering modifications to the branching fractions (but more model dependency)

ATLAS analysis (140ifb)	k_c 95% CL obs.
H->γγ , ptH shape (*)	[-19,24]
H->ZZ , ptH shape (*)	[-12,11]
H->ZZ , shape+norm (*)	[-7.5, 9.3]

Combinations

✦ New level of precision in Higgs measurements from full Run2 dataset:

- inclusive Higgs production measured at <10% accuracy
- all 5 main production modes observed
- assessing kinematics of production: multiple bins measured simultaneously with precision ranging from 20% to 100% accuracy
- expanded list of differential distributions, first double-differential distributions

Analyses overview: channels included and luminosity

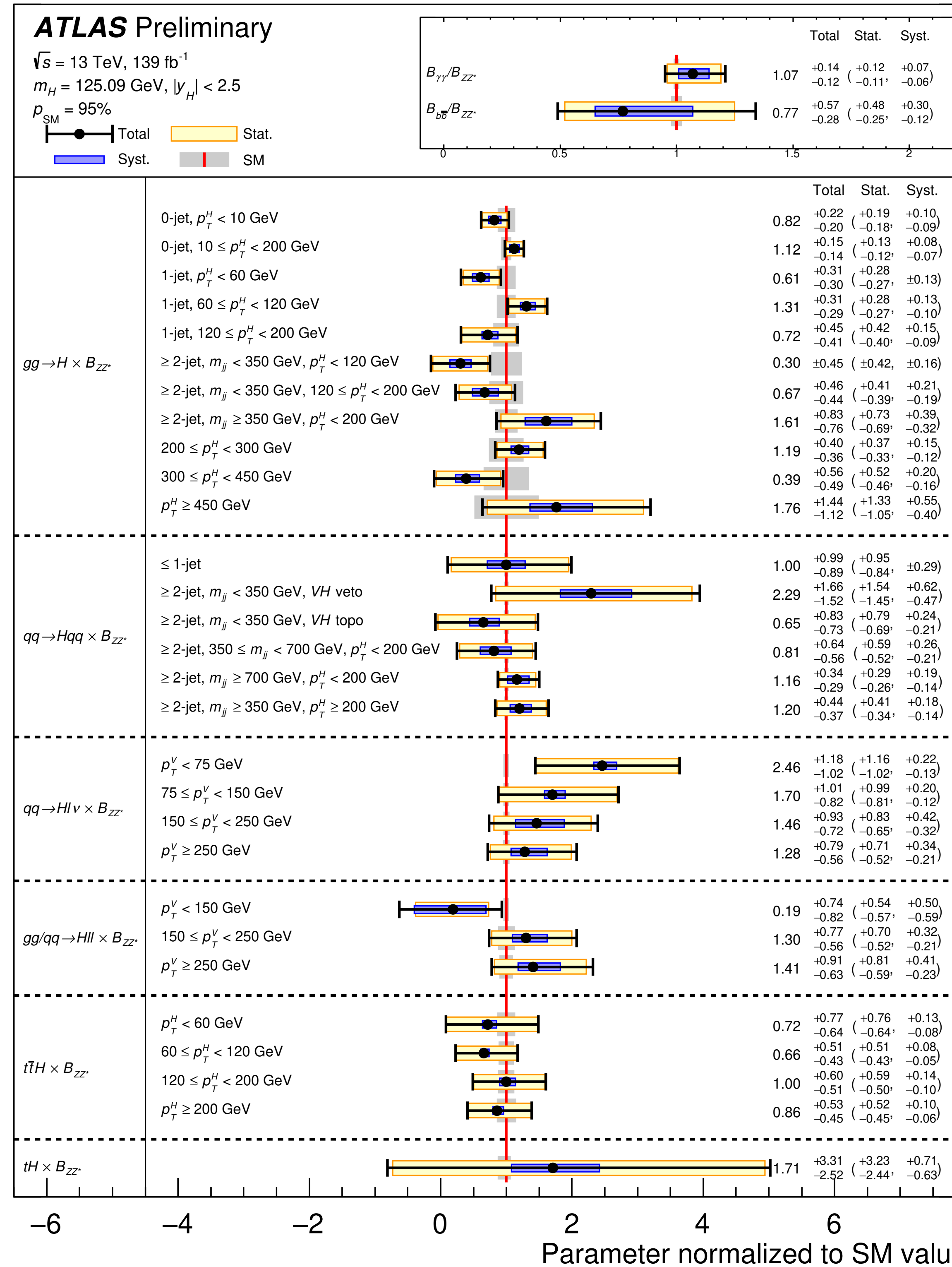
Exp	PMode	STXS 1.2: $H \to \gamma\gamma$	STXS 1.2: $H \to ZZ^*$	($\sigma \times$ BR): $H \to b\bar{b}$	($\sigma \times$ BR): $H \to WW^*$	($\sigma \times$ BR): $H \to \tau\tau$	κ and MSSM: $H \to \mu\mu$	κ and MSSM: $H \to inv$
ATLAS	ggF	Full Run2	Full Run2	- (*)	2015-16	2015-16	Full Run2	-
ATLAS	VBF	Full Run2	Full Run2	2015-16 (*)	2015-16(*)	2015-16	Full Run2	Full Run2
ATLAS	WH	Full Run2	Full Run2	Full Run2	-	-	Full Run2	-
ATLAS	ZH	Full Run2	Full Run2	Full Run2	-	-		-
ATLAS	$t\bar{t}H$	Full Run2	Full Run2	2015-16 (*)	2015-16(*)	2015-16	Full Run2	-
ATLAS	tH	Full Run2	-	-	-	-	-	-
CMS	ggF	2015-17(*)	Full Run2	2015-16(*)	2015-16(*)	2015-17(*)	2015-16(*)	-
CMS	VBF	2015-17(*)	Full Run2	-	2015-16	2015-17(*)	2015-16(*)	-
CMS	WH	- (*)	Full Run2	2015-17	2015-16	2015-17(*)	- (*)	-
CMS	ZH	- (*)		2015-17	2015-16		- (*)	-
CMS	$t\bar{t}H$	2015-17 (*)	Full Run2	2015-17	-	2015-16	- (*)	-
CMS	tH	-	-	-	-	-	-	-

μ and κ

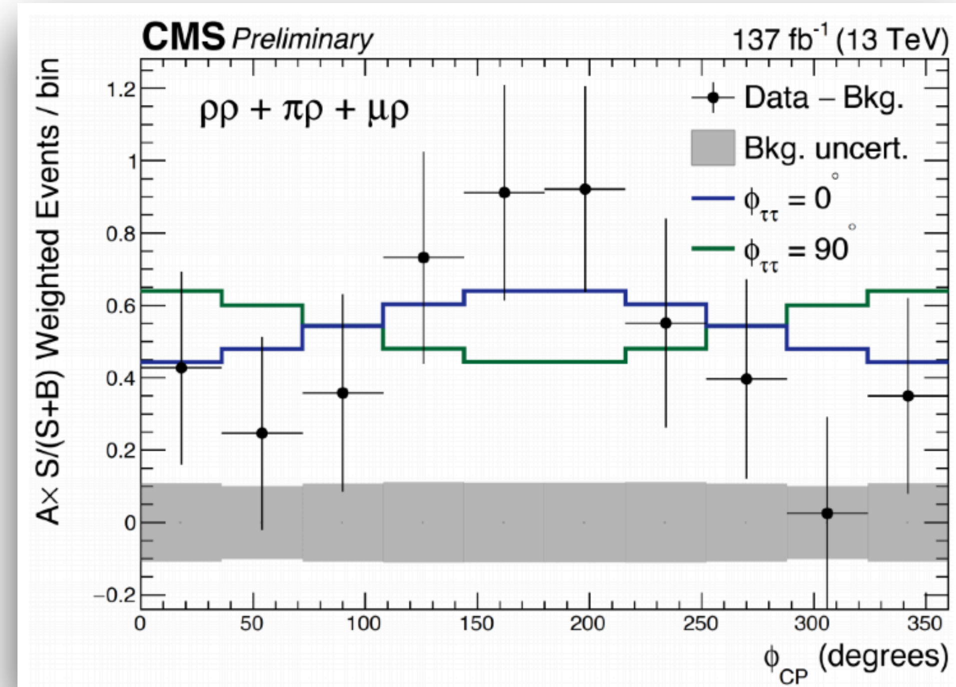
D. Mungo

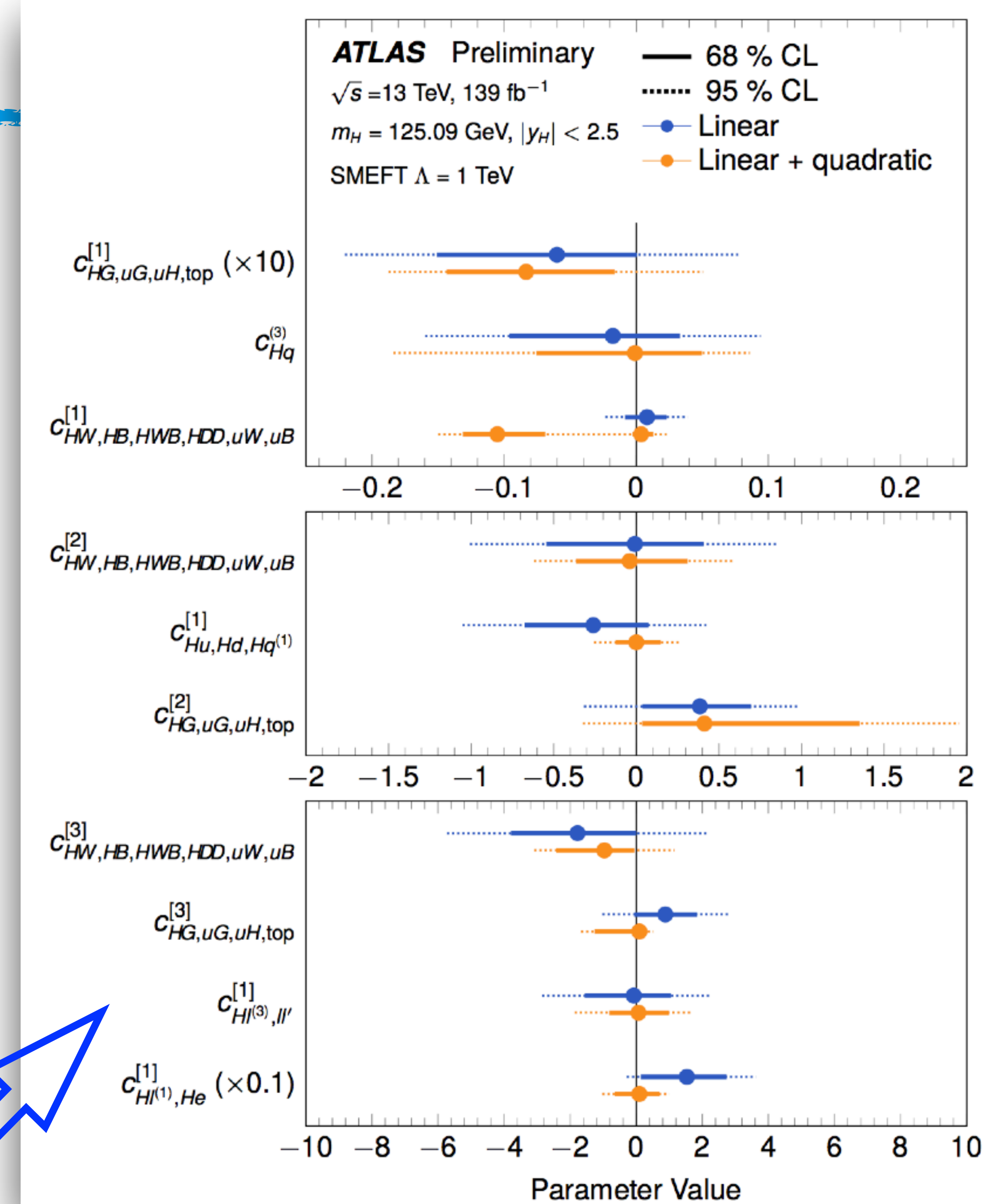
(*) Note: more updated analyses available and not included in the combinations

> *good agreement with SM predictions*
> *let's use them for setting limits on NP*



EFT: experimental snapshot



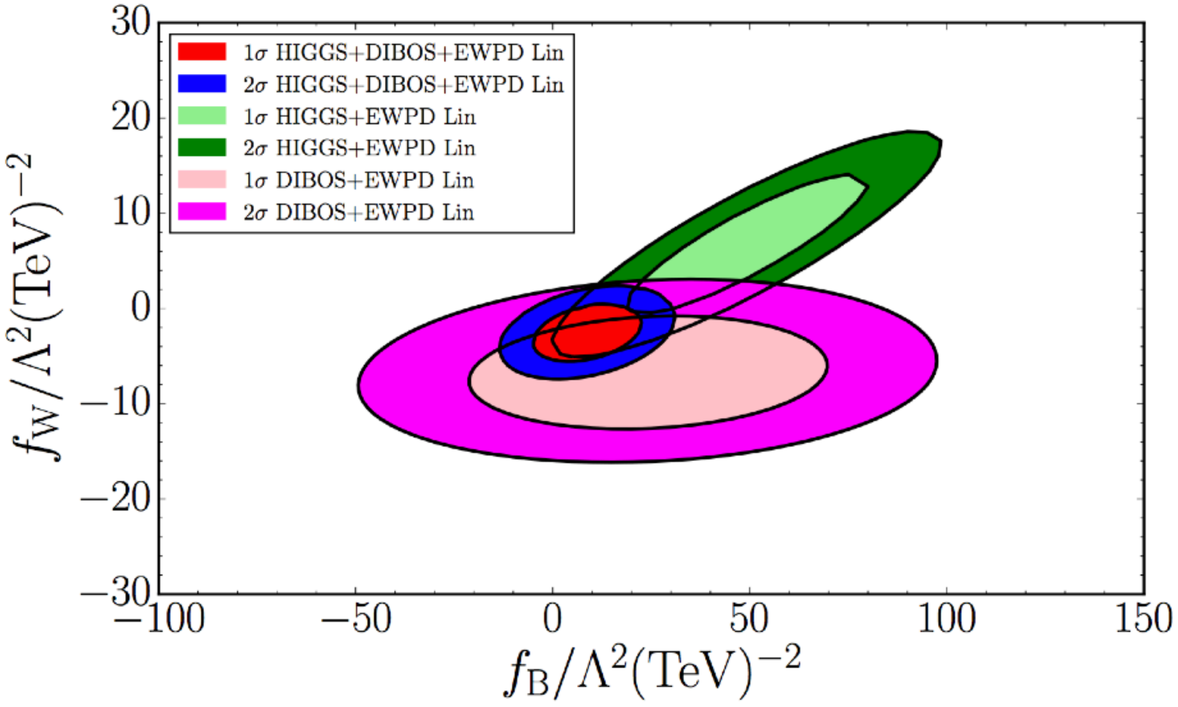


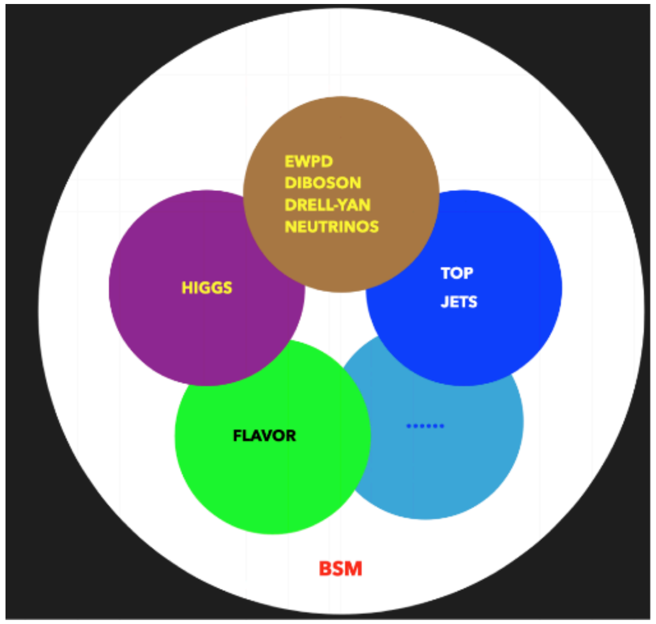
- ***Dedicated analyses targeting specific effects:***
  - CP-odd operators in H->$\tau\tau$ and ttH
- ***Measuring* bins of kinematic distributions allows to be sensitive to a larger variety of new physics effects** *(in a less optimal way due to practical choices)*
- ***We are able to probe multiple EFT operators simultaneously:***
  - still non negligible correlation/degeneracy (leading effort from ATLAS in dealing with them)
- ***Interesting proposal on how to get the best of the two worlds: K. Cranmer, F. Kling***
  - ML-based method to estimate Likelihood dependency on NP set using full event kinematics

EFT theory view

O. Eboli

- Large number of Wilson coefficients and correlations between processes call for a global analysis





- This demands a large effort form the experimental and theoretical communities

- profile sensitivity of different processes (Higgs, Diboson, EWPO, top …) to various operators: what is interesting to measure?
- implement the effect of operators in higher order generators, inclusion of loop effects
- understanding validity range of EFT approach (beyond lowest order effects, Dim6 VS Dim8 operators effects)
- how to make our results available to the outside word? (**see HEPdata talk**)

Direct searches for new physics: a snapshot

briefing

D. Curtin *et al.*, 1312.4992, PRD 90 (2014)

PROMPT DECAYS

- Many, MANY searches proposed in exotic Higgs decay paper. How do we do now, 7 years later?
- h to ss to 4 fermions: pretty good coverage of 4b, 2b+2lepton, 4 lepton (taus & muons)
  e.g., ATLAS 1806.07355; CMS 1812.06359; CMS 2005.08694
- h to ss to 4 gauge bosons: some searches for 2 photon + 2 gluon, 4 photons
  e.g., ATLAS 1509.05051; ATLAS 1803.11145
- h to two dark photons, Z + A': extensive searches with leptonic decays of dark photon
  e.g., ATLAS 1802.03388, CMS 1812.00380, ATLAS 2004.01678
- Flavour-violating decays: $h \to \bar{\ell}\ell'$
  e.g., ATLAS 1909.10235, CMS 1911.10267

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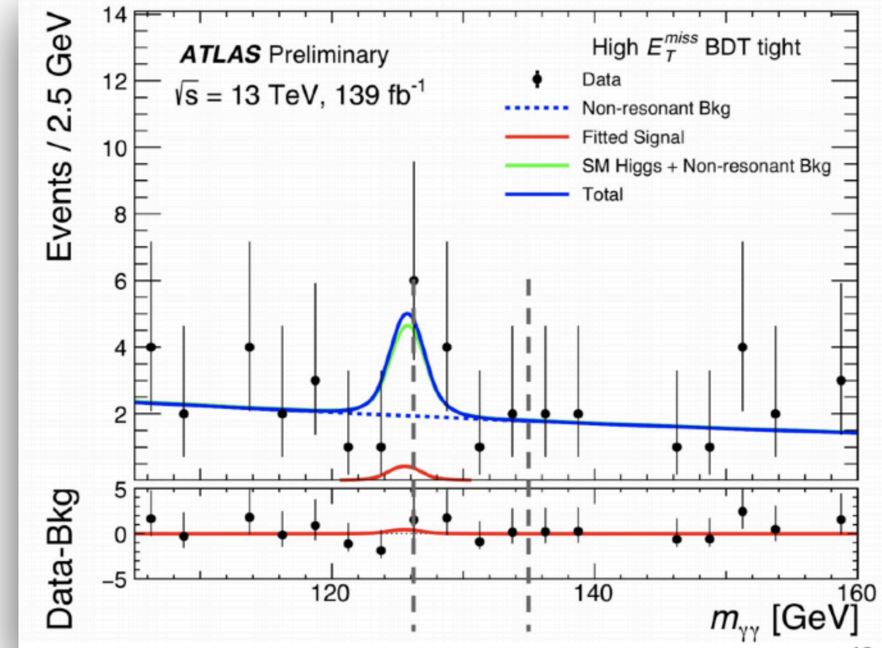
J. Alimena *et al.*, 1903.04497, J.Phys.G 47 (2020)

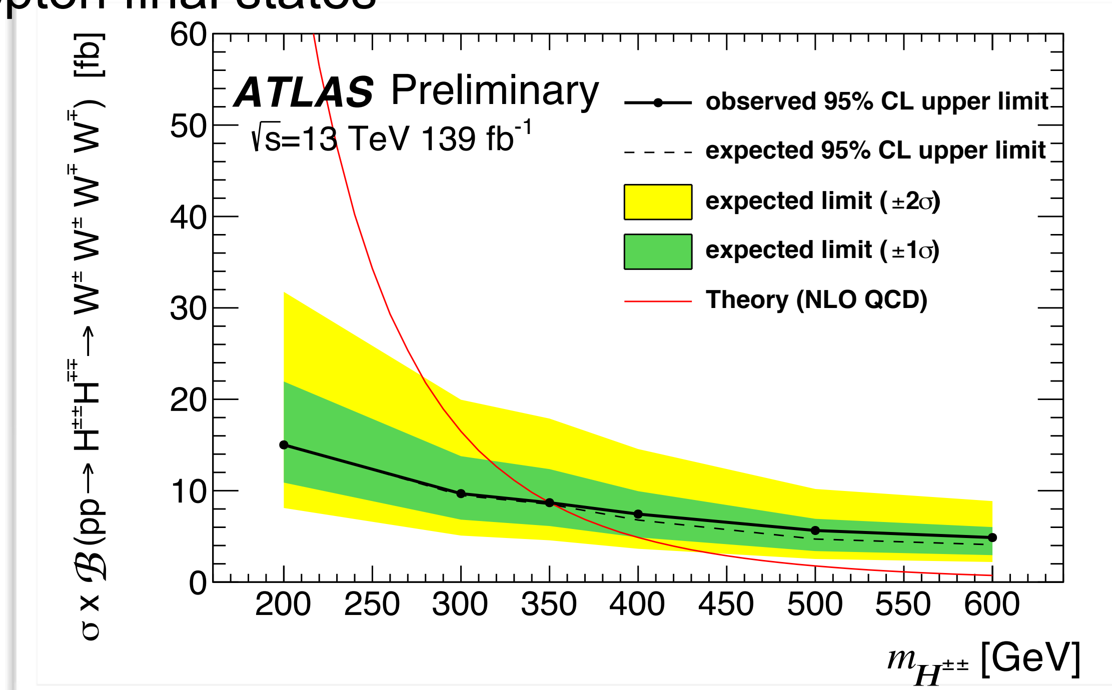
HIGGS + LONG-LIVED

- Recently published LLP white paper takes a comprehensive look at (gaps in) coverage of LLP signatures, including from Higgs decays
- Where coverage is currently pretty solid:
  - LLP produced in Higgs decays & decaying to muons (some coverage of other flavour combinations too)
    ATLAS, 1808.03057, PRD 99 (2019); CMS, 1409.4789, PRL 114 (2015) ATLAS, 1504.05162, PRD 92 (2015)
  - Multiple lepton jets (collimated sprays of leptons + pions)
    ATLAS, 1909.01246, EPJC 80 (2020)
  - 1 or 2 LLPs produced in Higgs decays & decaying hadronically, **provided** they live long enough to reach HCAL and/or MS
    ATLAS, 1911.12575, PRD 101 (2020)

- ***SM Higgs boson signature as a tool in the questo for NP:***
  - full Run2 H->yy+MET search



- ***Investigations ongoing also in extended Higgs sectors:*** $H^{\pm\pm}$ pair and single production in multi lepton final states

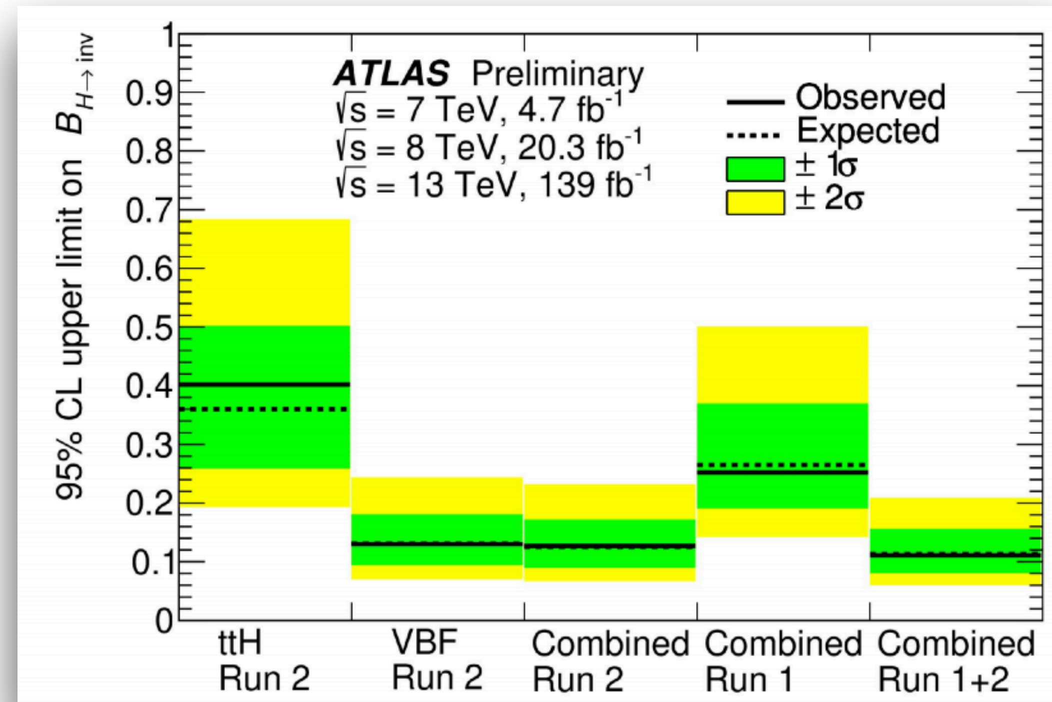


.... and many more ...

searches H->invisible

✦ ***ATLAS has an updated combination:***

- Full Run2 (VBF+ttH) + Run1 (VBF+ZH+VHhad)
- first re-interpretation of SUSY tt+MET searches for H->inv signal



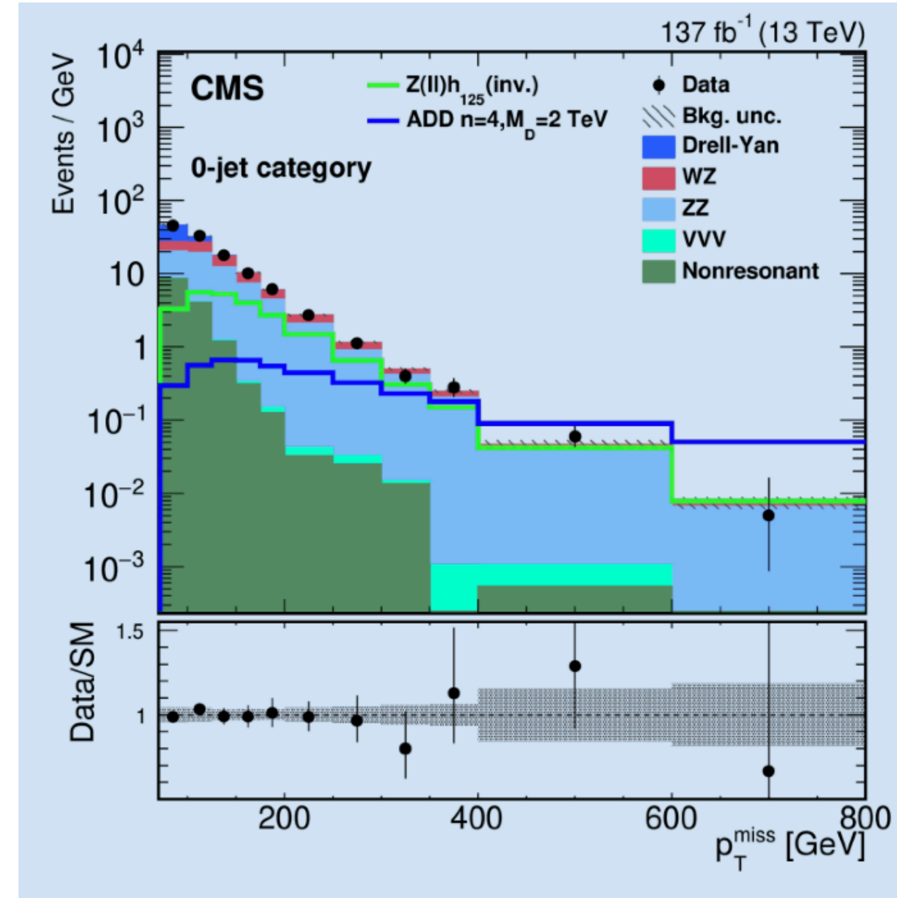
✦ *H->inv Br 95% U.L.:* ***11% (11%) obs. (exp)***

- [dominated by VBF Run2 (13%)]
- asked few times why we didn't include previous ZH or status of the full Run2 one

✦ *ongoing ATLAS **ll+MET analysis has ~20% UL** exp. … and more to come*

- VBF improvement, VBF+y, VHhad, more ttH channels

✦ ***CMS: only ZH-> ll+MET updated to full Run2***



- not so stat. limited

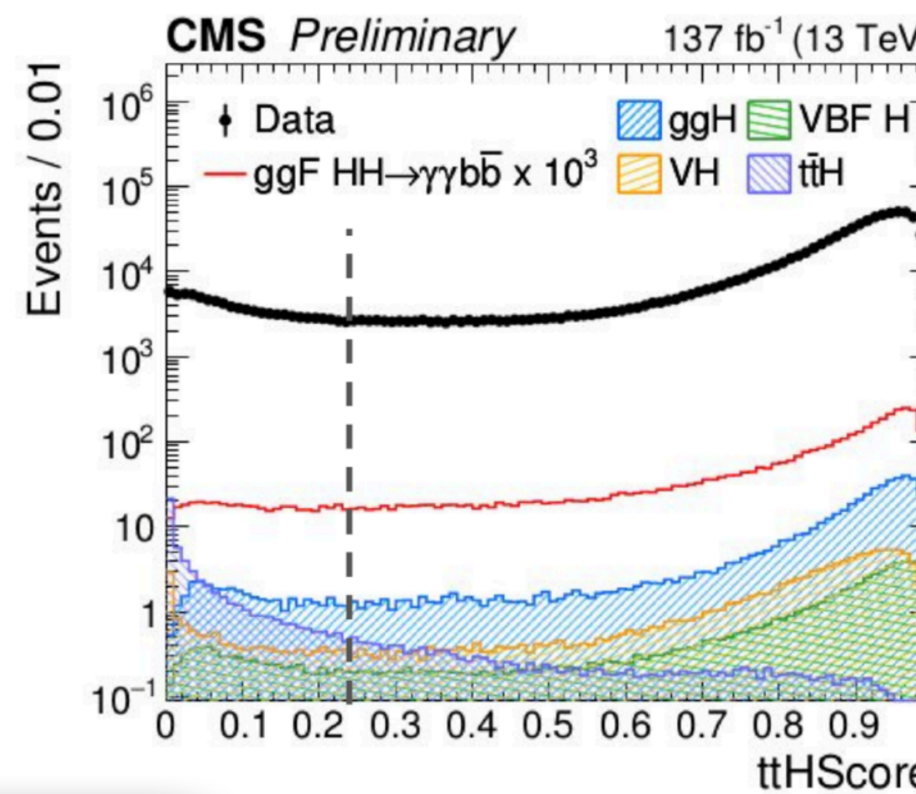
Total systematic uncertainty	0.11
Statistical uncertainty	0.089
Total uncertainty	0.14

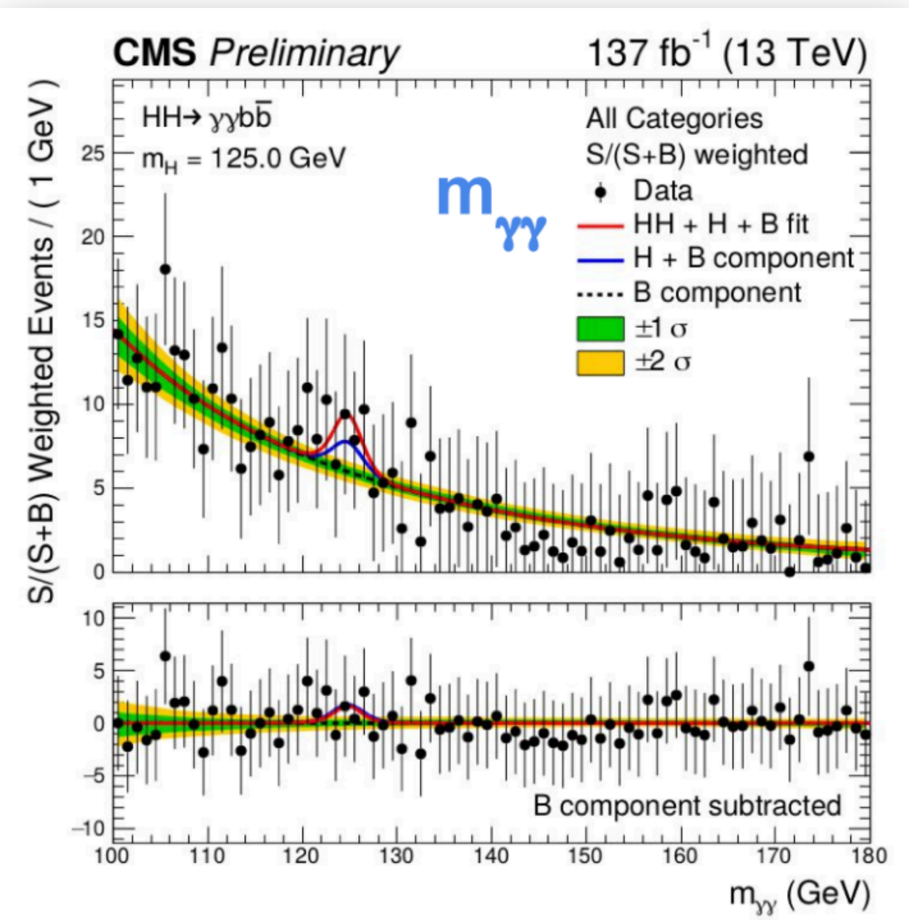
✦ *H->inv Br 95% U.L.:*

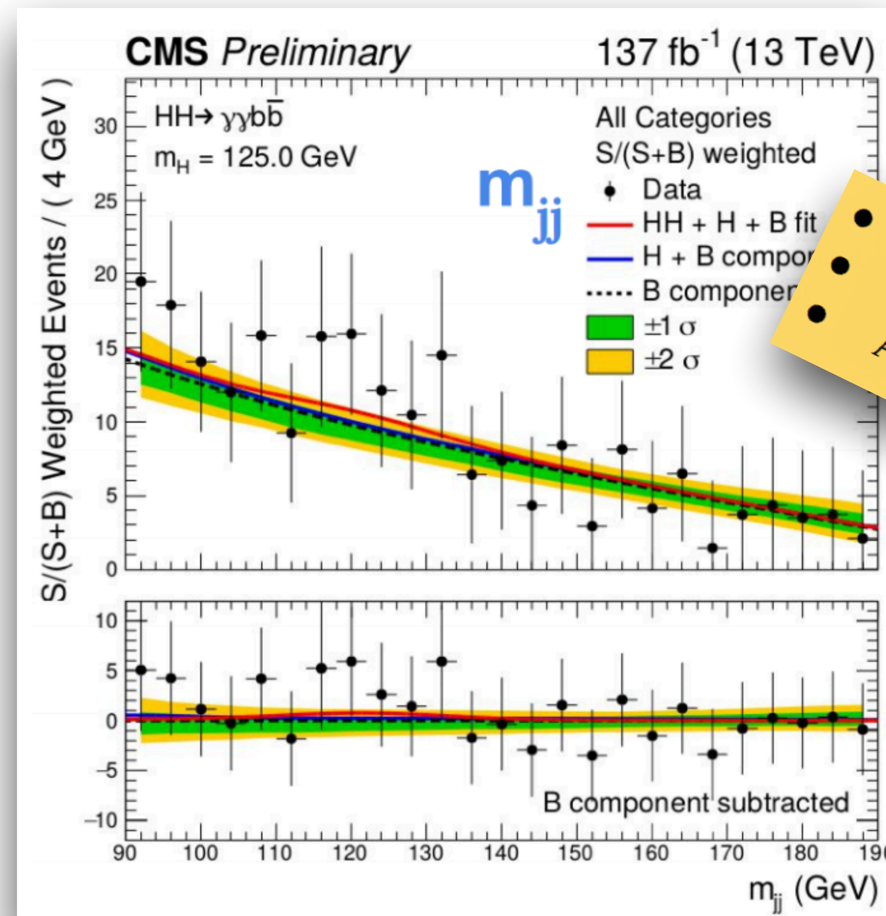
- ZH (full Run2): **29% (25%) obs. (exp)** [was ~40% in 36fb^{-1}]
- previous Run1+Run2(36fb^{-1}) combo: **19% (15%) obs. (exp)**

HH->bbyy: CMS

- ***2y + 2 b-jets + (2 jets for VBF):***
  - b-jets: pt>25 GeV, highest b-tag score, m_{bb} in [70,190]
  - VBF jets: p_T>40/30 GeV, highest m_{jj}
- ***several MVAs used*** (variables in backUp)***:***
  - isolate different production modes (also in bins of MX)
  - reject main ttH background
  - SM signal and BSM benchmarks used in the training together



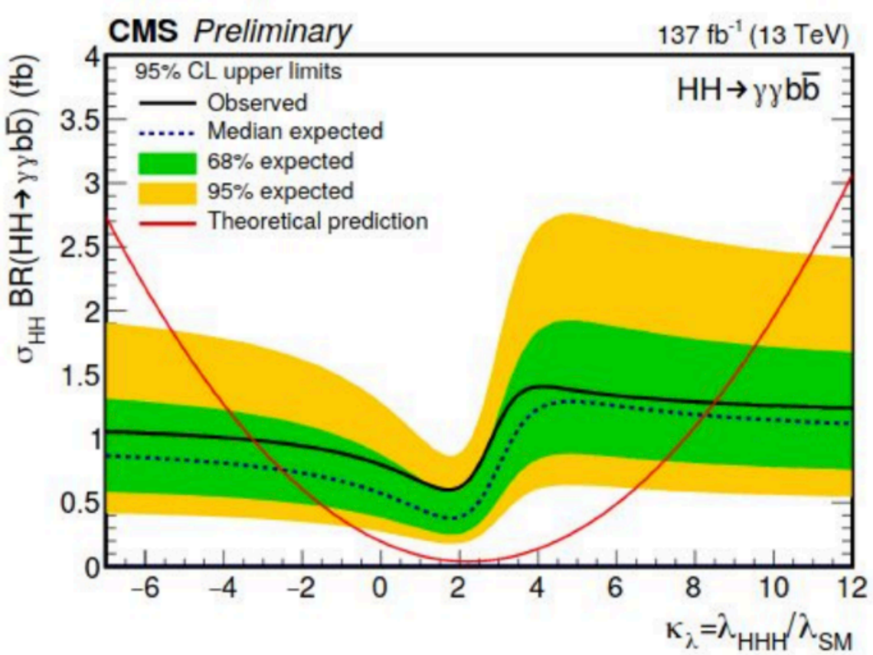


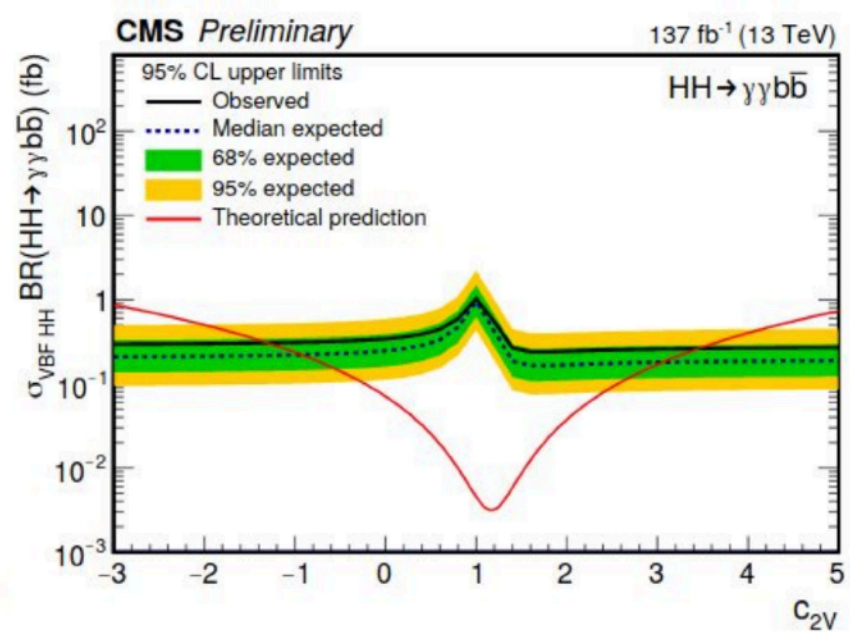


- Total 14 categories based on MX & MVA
- Simultaneous 2D fit to $m_{\gamma\gamma}$ x m_{jj} distributions
- Assuming no $m_{\gamma\gamma}$ - m_{jj} correlation

HH->bbγγ: CMS (result)

S. Mukherjee





Allowed range @ 95% CL

Observed: $-3.3 < \kappa_\lambda < 8.5$
Expected: $-2.5 < \kappa_\lambda < 8.2$

Observed: $-1.3 < C_{2V} < 3.5$
Expected: $-0.9 < C_{2V} < 3.0$

Best-to-date !

Fi

95% CL Upper Limit on (inclusive cross section*BR) :

Inclusive HH (* SM)	
Observed	7.7
Expected	5.2

ATLAS VBF HH->4b result:

$-0.6 < K_{2V} < 2.9$

$-0.9 < K_{2V} < 3.1$

36 fb^{-1} results ~ 20

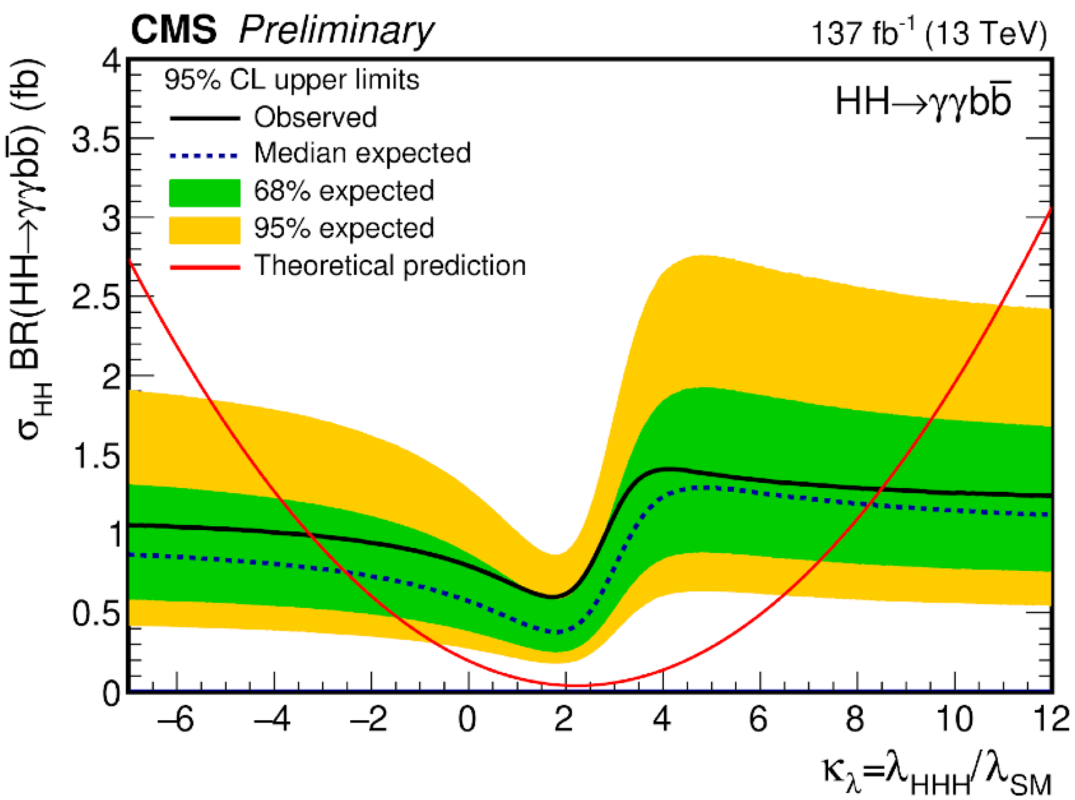
-- Statistically dominated analysis
-- Total impact of systematics on signal strengths is around 2%

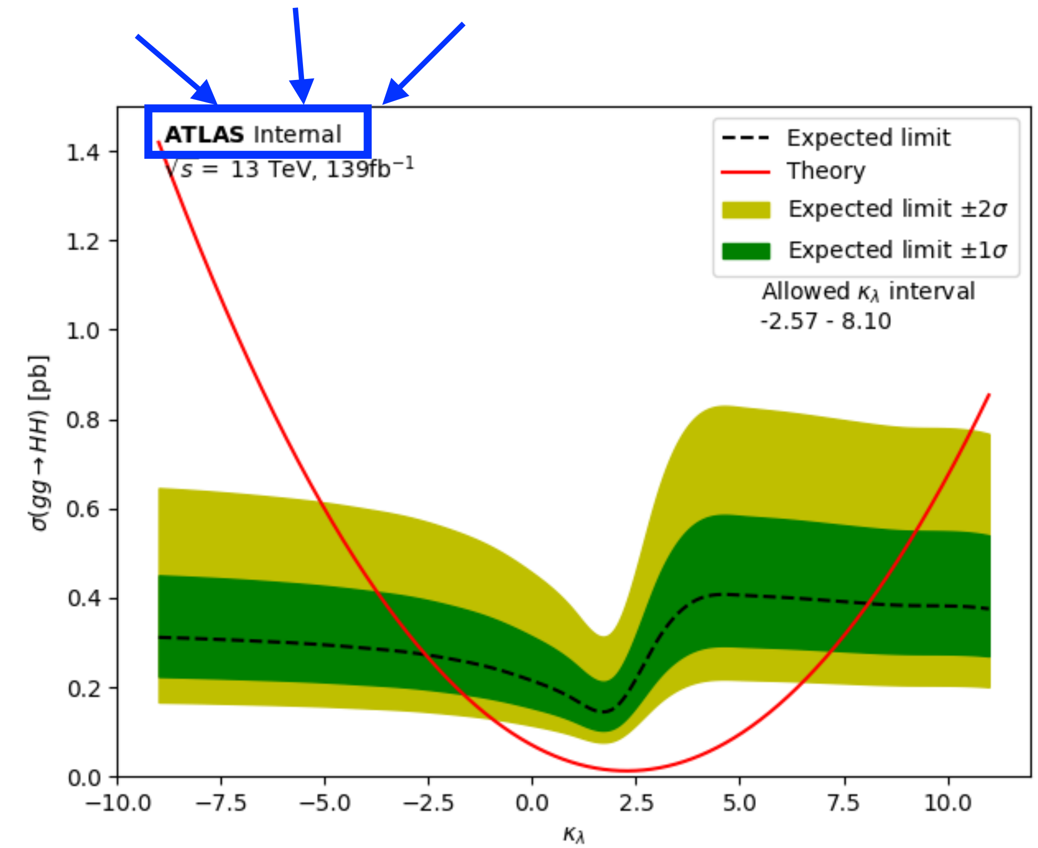
✦ *x4 reduction of upper limit with x4 more data*

(intermezzo) HH->bbγγ: ATLAS status

Courtesy of HH->bbγγ group

- ***ATLAS full Run2 result expected in early 2021:***
  - analysis selection / categorisation has been frozen
  - systematics are being evaluated (impact expected to be small) [few %]





CMS:

- exp. constrain of ***k_λ is [-2.5, 8.2]***
- exp. limit on SM HH: **5.2 times** prediction

ATLAS:

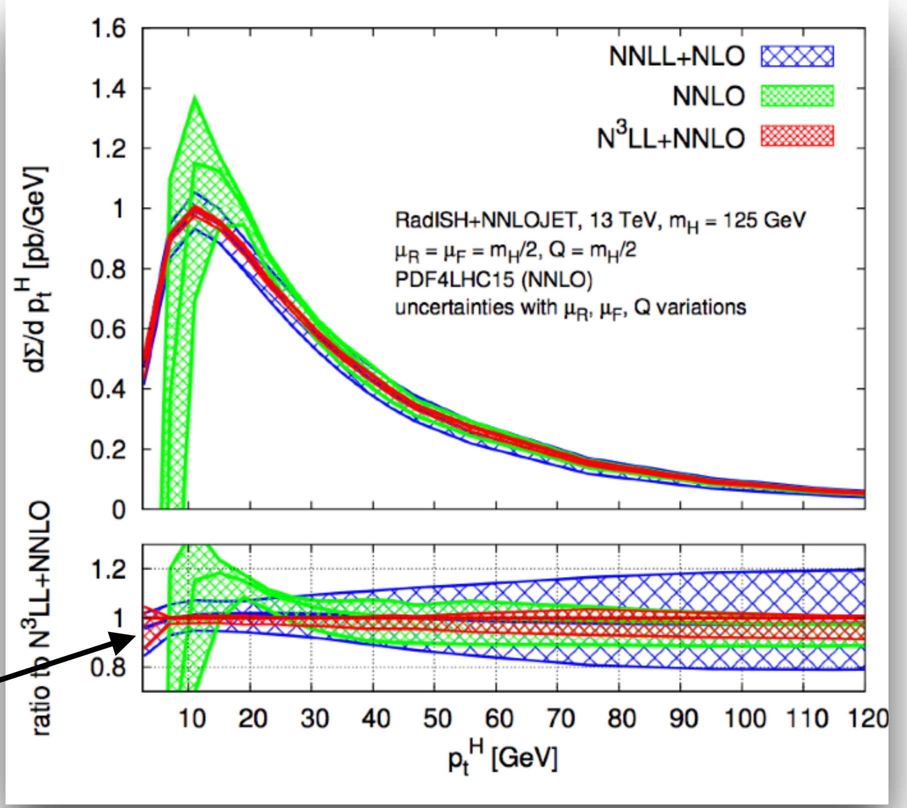
- exp. constrain of ***k_λ is [-2.6, 8.1]***
- exp. limit on SM HH: **5.5 times** prediction

ATLAS results competitive with CMS one!

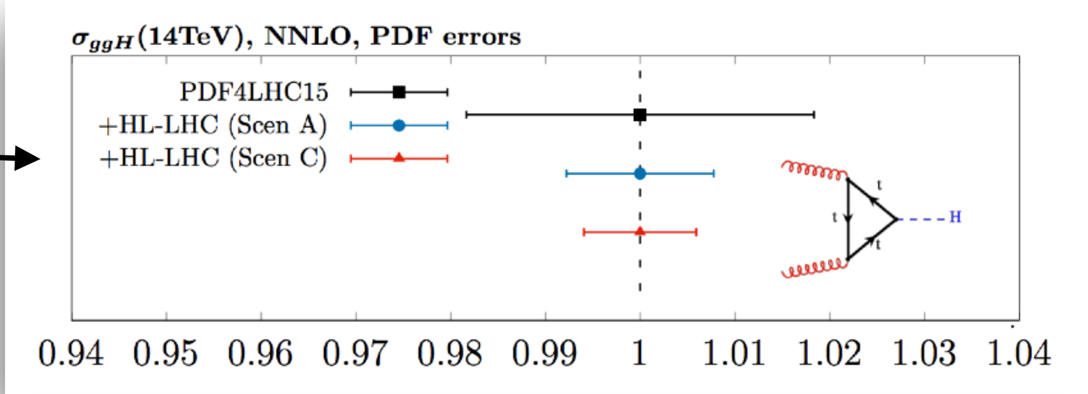
Theory efforts

- ***Theory predictions are crucial and theory uncertainties will play a larger role when more data and more experimental precision is achieved (HL-LHC)***

- ***Developments ongoing on all fronts:***
  - refinement of N3LO predictions: full NLO QCD-EW corrections, H+jets @ NNLO including fiducial cuts
  - full high pt prediction at NLO and approximated top mass effects @ NLO (caveat: large uncertainties from top mass schema unc: 25% @ 1 TeV)
  - N^3LL improves precision at low p_T Higgs
  - benchmarking different generators
  - beyond NextLeadingLog in parton showers
  - reduction of negative weights in NLO generators
  - PDF for HL-LHC: including latest experimental inputs from Hera / LHC



- Good agreement between different MC generators when using similar setups / assumptions



LHC HIGGS WG workshop this week

A bridge between past and future

The Higgs boson and more

Luciano Maiani
Sapienza Università di Roma

public lecture

- we should keep ***all options*** open...for the time being.
- LHC , HL-LHC or a Higgs factory (see later) could search for precursor signals of high energy new physics in deviations from ST of Higgs decays;
- or find SUSY particles and /or other Higgs bosons and/or Techicolor bound state

A few lessons learned

- Do not save on tunnel: a long and large tunnel has a longer lifetime than the first machine you put in;
- A global project, but centralised construction and responsibility: CERN management had the responsibility to stay within cost and, when extracosts were detected, CERN reacted coherently and responsibly;
- Starting from a big lab, already financed, no green grass, helps!
- A full globalised management (e.g. ITER) is more vulnerable to cost increase
- Cost-to-Completion crisis in 2001. CERN has profited from it to enforce real changes: a leaner programme, a well-focused Laboratory.
- LHC final costs to CERN:

	Personnel	Material	Total
Machine and Experimental Areas	1 150	3 685	4 835
Injectors	86	67	153
Detectors: construction, R&D	879	312	1 191
Detectors: test and pre-operation	–	181	181
LHC Computing	86	93	179
Grand Total	2 202	4 337	6 539

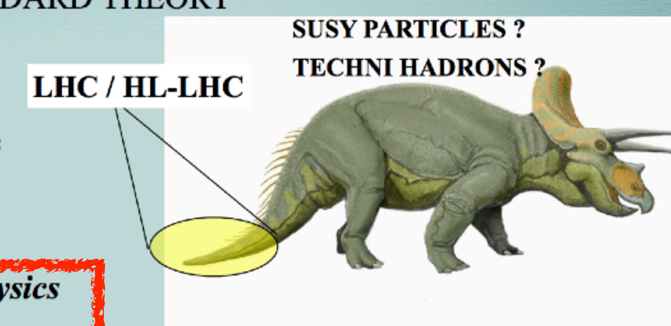
Table 1: Cost to CERN of LHC and associated detectors, in Millions CHF. Source: CERN/2840, May 27, 2009.

- Global collaboration for detectors worked out very well

The result of more that 25 years of work (1984-2012) is an increadibly robust, upgradable complex, e.g. HL-LHC, that will produce physics for at least two other decades

7. What's next at High Energy?

- With the LHC / HL-HLC energy limitation, it is not likely that we can see all particles implied by SUSY or by Technicolor and find out which is the next step BEYOND the STANDARD THEORY
- but we may be able to see the tail of the dinosaur….do not leave any possibilty untested



- ***Can we really guess what New Physics at High Energy is?***
- In the 80s we thought that the unnaturalness of ST could give the key to a complete theory of what is Beyond the Standard Theory (SUSY, GUT, then Gravity…)
- we may have guessed some real point…. compositeness, supersymmetry …but there are so many things we do not fully understand (which kind of SUSY, dark matter, hierarchy, strong interactions) that the physics we will find there will be, most likely, ***entirely new, strange and unexpected.***
- Only direct experiments will tell.

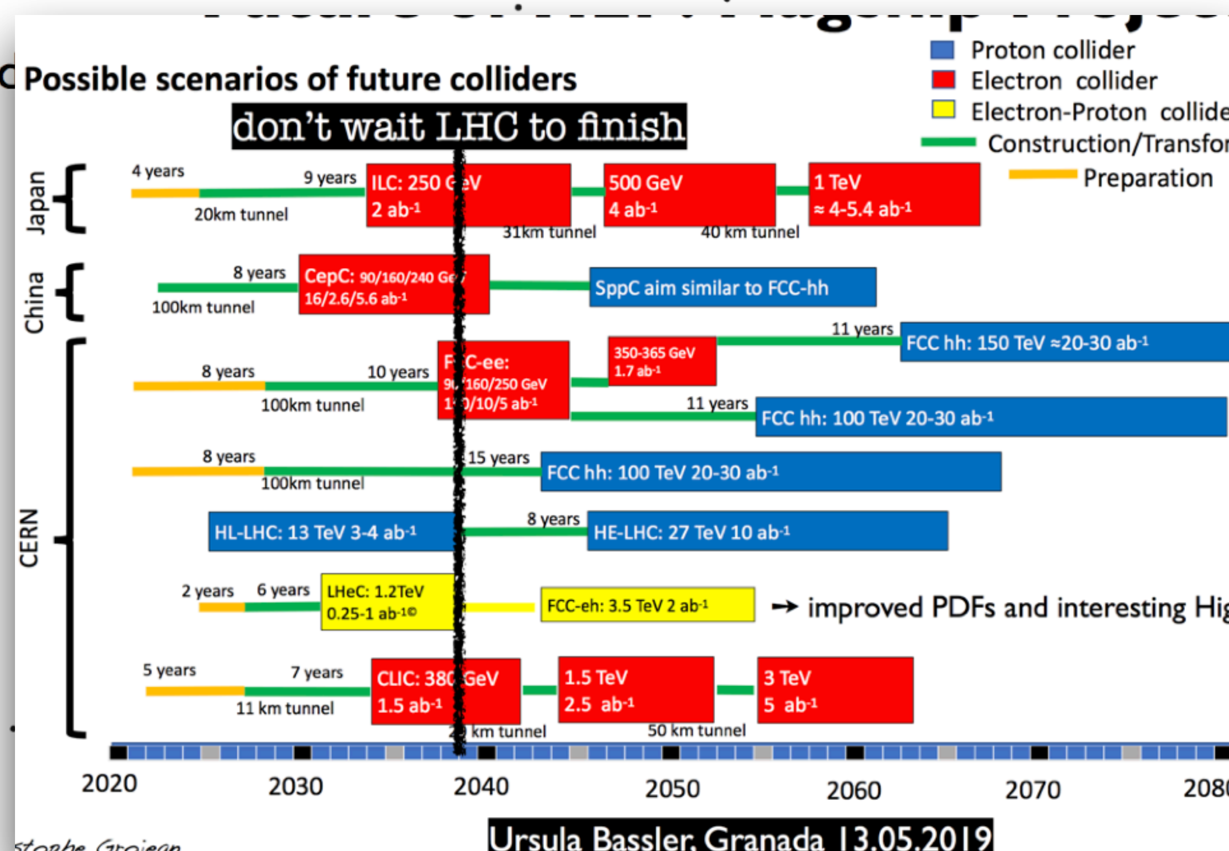
Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- ▹ S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- ▹ only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks anc

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ings



Circular

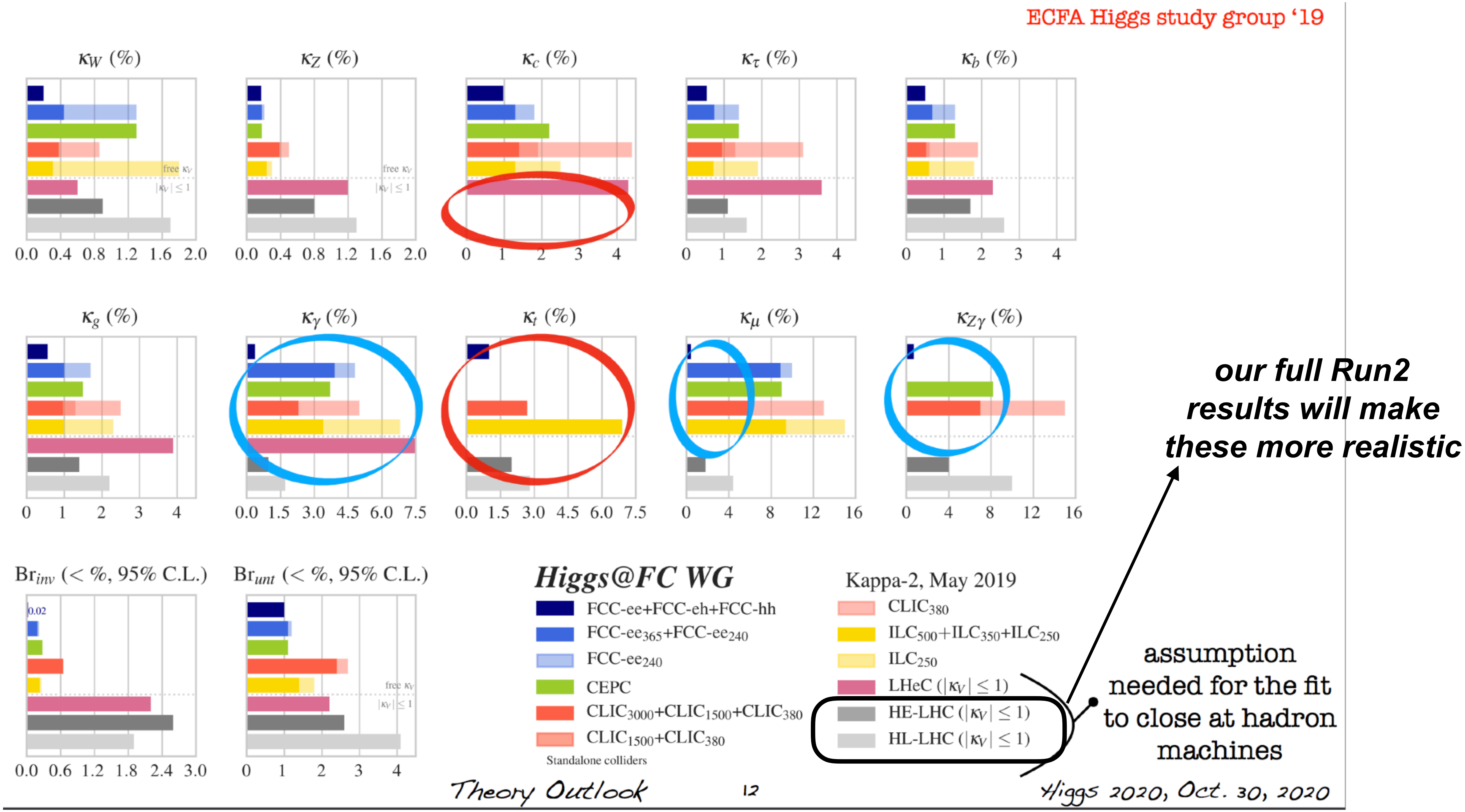
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- ▹ $\sqrt{s}$ limited by synchroton radiation

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- ▹ large beamsthralung
- ▹ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear collide

Which machine?



huge effort to understand performance of various machines

complementarity among leptonic and hadronic colliders is the key

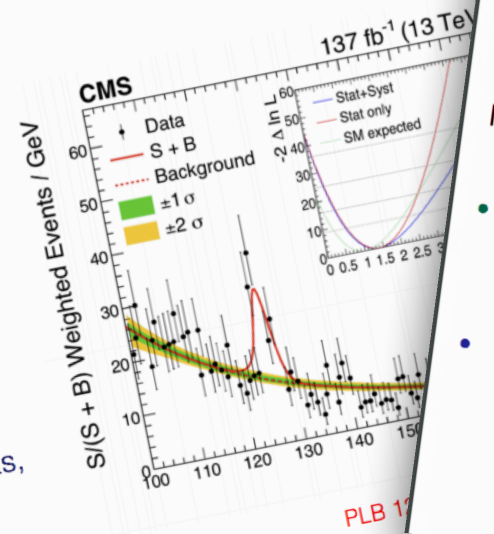
(biased) selection of closing messages

P. Savard

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 γγ by both ATLAS and CMS
  - HH: prospects keep improving through new ideas, better performance
  - Width → use of off-shell/on-shell couplings, mass spectrum

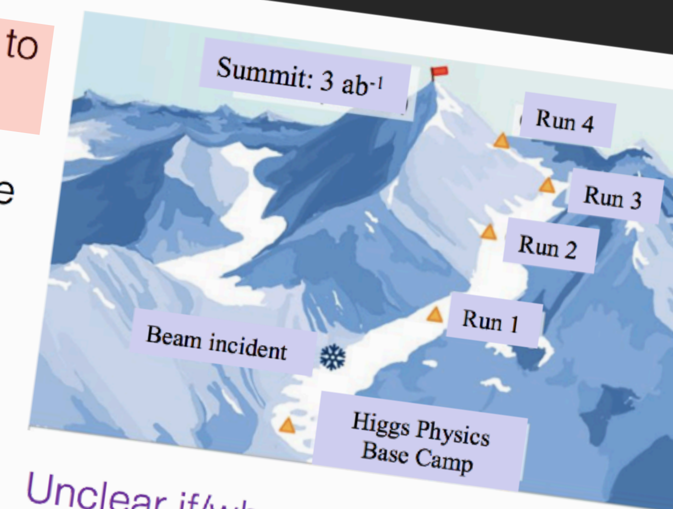


Some concluding thoughts (II)

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!

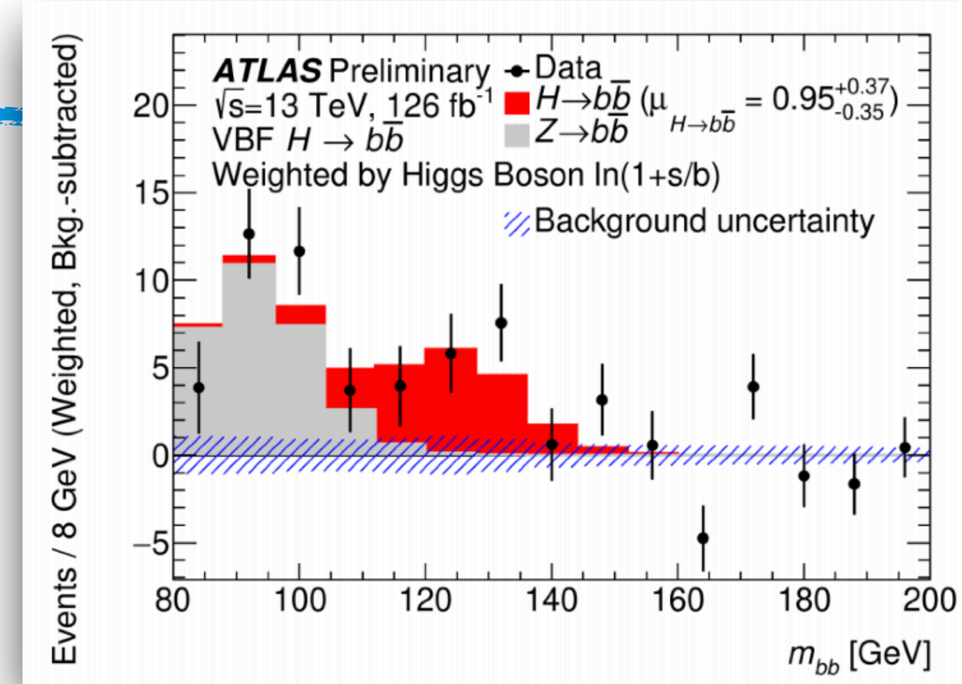
J. Olsen

- Data makes experimentalists smarter
  - New/improved experimental methods often lead to better than $1/\sqrt{L}$ scaling
  - Sometimes new methods open up channels that were thought to be "hopeless" (e.g. $pp \to H \to b\bar{b}$)
- Data makes theorists more creative
  - Reality of experimental possibilities motivates deeper thinking about possible ways to maximize the data

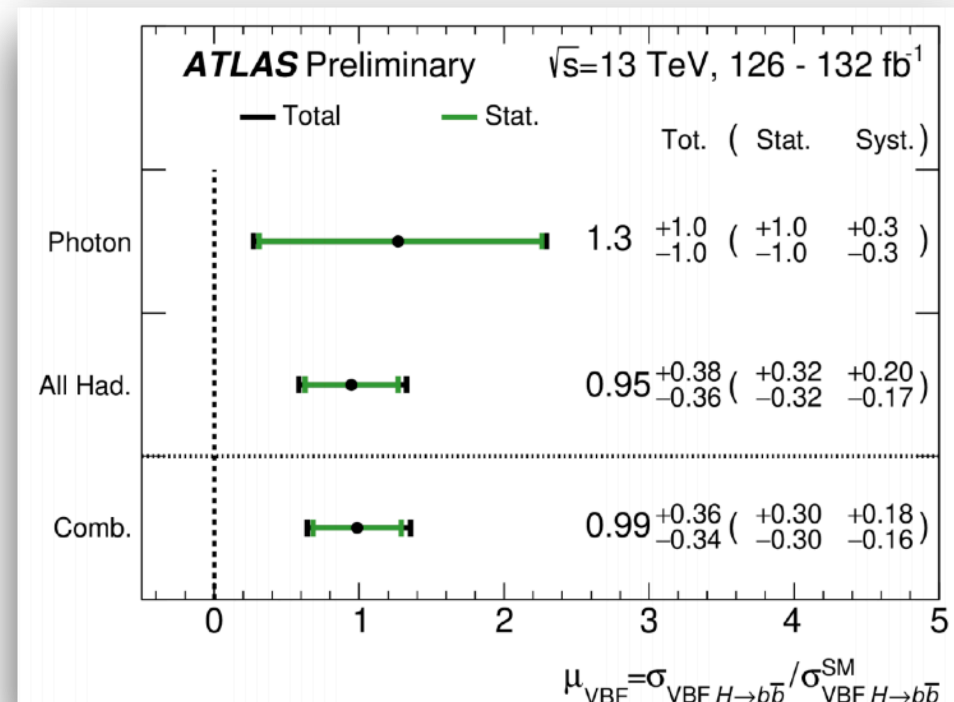
BackUp

VBF H->bb

- ***Impressive developments of VBF H->bb analysis:***
  - adversarial training of NN
  - "embedding" techniques for Z->bb predictions
  - still a very intuitive analysis with convincing signal



- ***Huge jump in sensitivity:***
  - from 0.5σ (36fb^{-1}) to ~3σ (130fb^{-1})
  - Xsection measurement for H p_T>200 GeV
  - combination with VBF+y analysis (out at ICHEP)
  - [intermezzo: phone studies on EFT in ***VBF H+y*** production]
  - can help constraining Br_bb / Br_ZZ



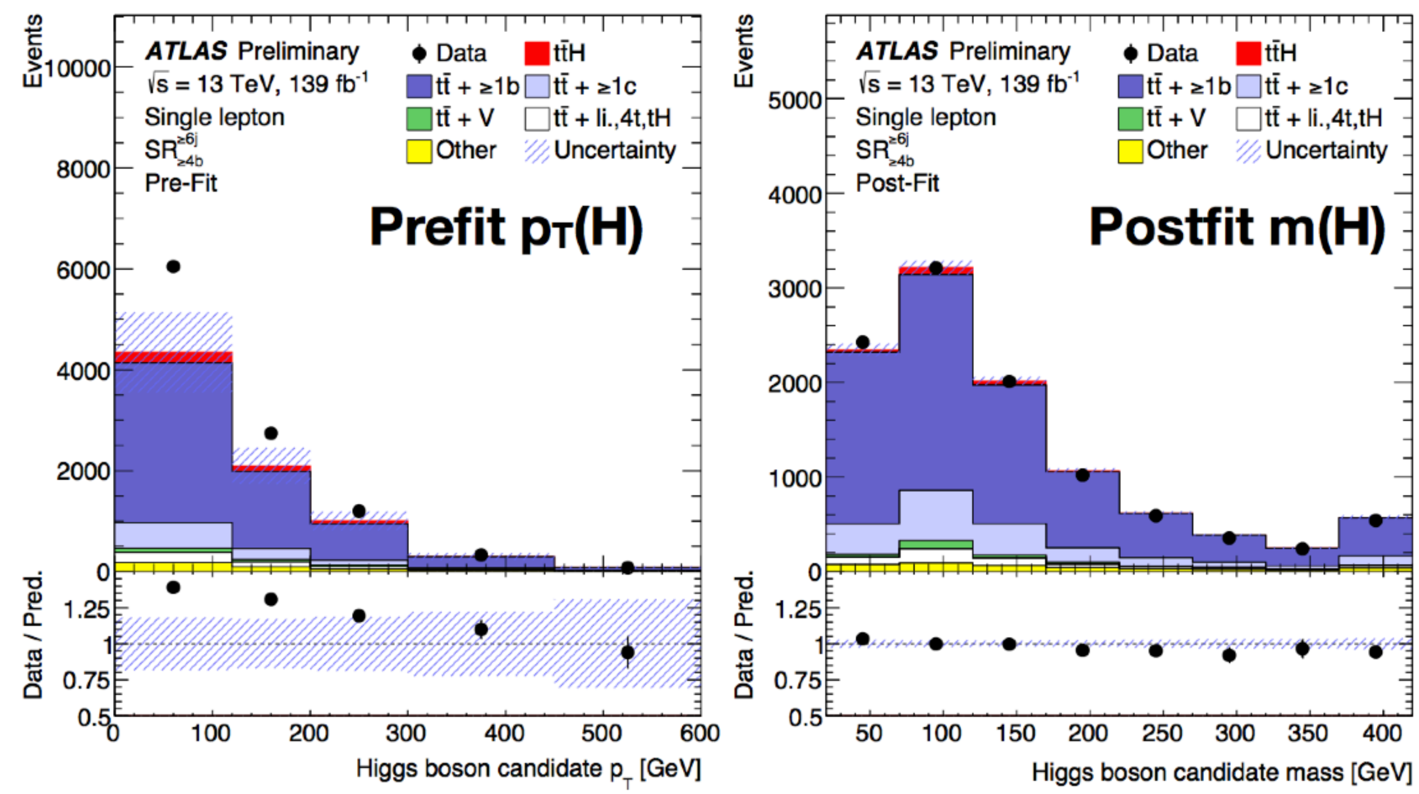
VBF H(→bb)

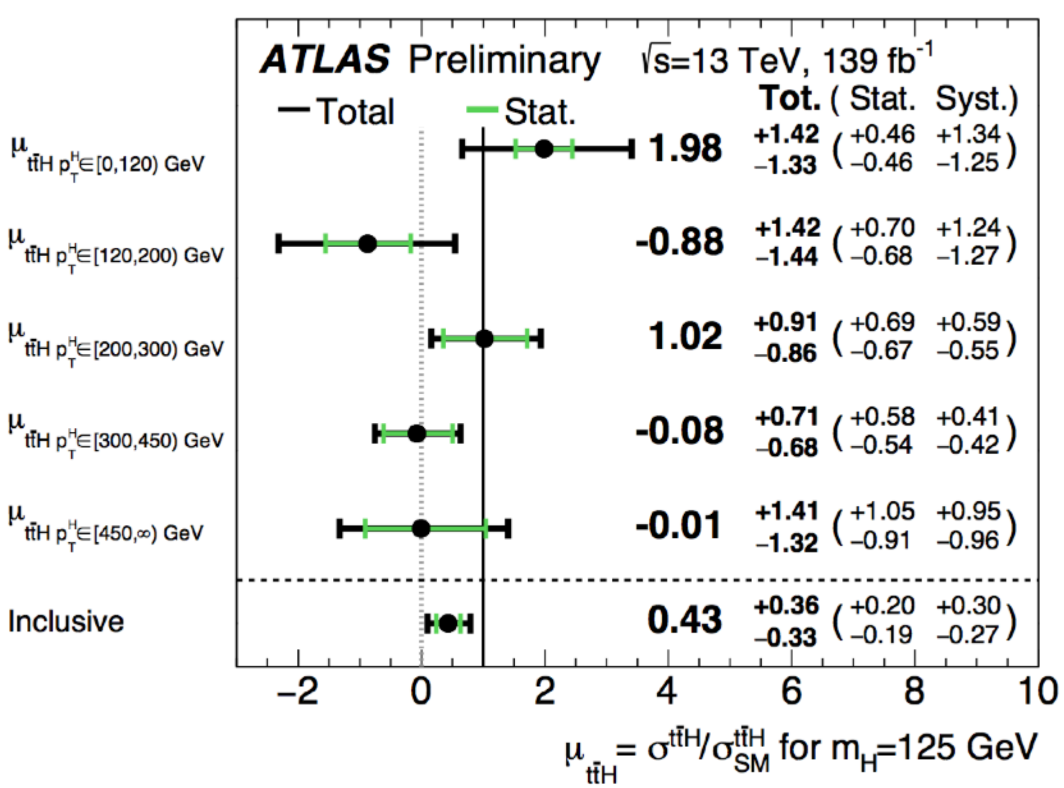
VBF H→bb	Dataset	obs. (exp.) Significance	Paper Reference
ATLAS	Full Run 2	2.9σ(2.9σ)	CERN-EP-2020-195, CERN-EP-2020-179
CMS	Run 1	2.2σ(0.8σ)	Phys. Rev. D 92 (2015) 032008

- ***No Run2 results yet from CMS***

✦ *Full run2 ttHbb:*

- analysis simplefication: fewer non ttbb regions
- a huge effort on MC: both stat. and available samples
- resolved + 'boosted' reconstruction: with priority to boosted
- first time targeting STXS interpretation





- Expected significance : **3.0σ**
- Observed significance : **1.3σ**

✦ Significance increase (1.6 —> 3.0) as sqrt(L) …. for a sys limited analysis!!!

✦ still tt+b(b) uncertainties are the leading limitation (mainly at low p_T)

✦ highest p_T H measurement in ttH:

- H->bb has the strength (or stat.) to put strong upper limit even when a precision measurement cannot be made

ttH summary

I. Connelly

Channel		ATLAS		CMS	
ttH	$\gamma\gamma$	5.2σ (4.4σ)	139	6.6σ (4.7σ)	137
ttH	bb	1.3σ (3.0σ)	139	3.9σ (3.5σ)	77.4
tH	$\gamma\gamma$	8 x SM*		12 x SM	upper limit
tH	bb	-		25 x SM	

- Consistent limits also being placed on Top Yukawa CP properties (at 95% CL)
  - ATLAS - tH+ttH($\gamma\gamma$) : $|\alpha| > 43°$ excluded
  - CMS - ttH($\gamma\gamma$) : $f_{CP} > 0.67$ excluded
    - ATLAS→CMS : $f_{CP} \gtrsim 0.53$ excluded

C. Alvarez

ttHML

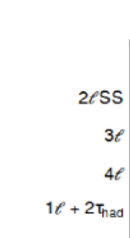
CMS:
- Lumi: 137 fb^{-1}
- Above **5σ sensitivity** for $t\bar{t}H$
- **4.7σ observed** significance for $t\bar{t}H$
- Observed tH significance: **1.4σ**

$\mu_{ttH} = 0.92^{+0.26}_{-0.23}$

$\mu_{tH} = 5.67^{+4.1}_{-4.0}$

ATLAS EXPERIMENT:
- Lumi: 79.9 fb^{-1}
- **3.1σ expected** significance
- **1.8σ observed** significance

$\mu_{ttH} = 0.58^{+0.36}_{-0.33}$

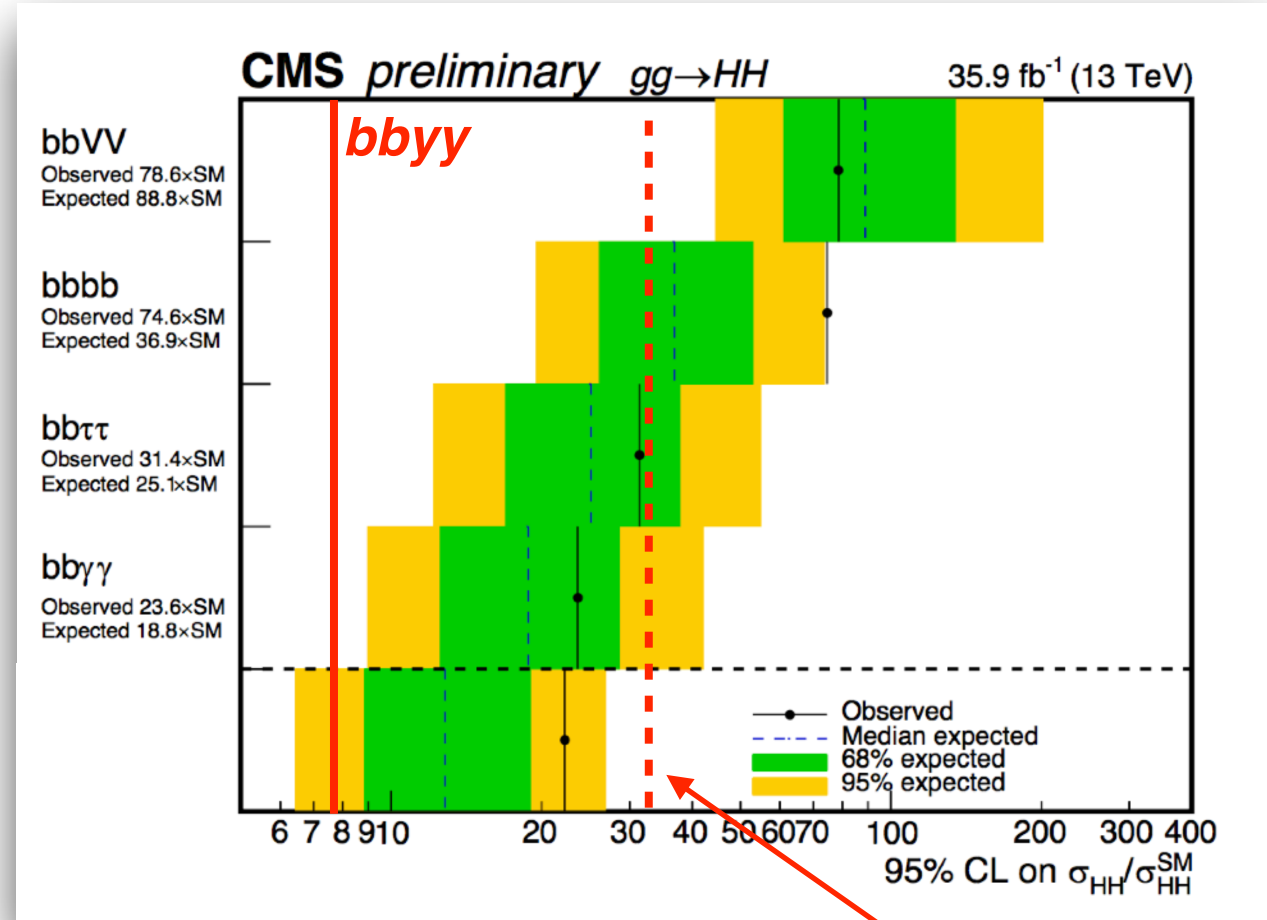


✦ *Non exhaustive ATLAS-CMS comparison:*

- similar status for ttH H->yy: similar performance, presentations of results/interpretations (STXS bins, CP)
- in bb and ML CMS uses more aggressive ML techniques and seems to be "less sensitive" (or less caring) about modelling of key backgrounds (ttW and ttbb)
- ATLAS has first STXS results in bb final state (up to 400 GeV)
- CMS targets tH in all the main final states (yy, bb, ML): strong constraints on t also from ggH and H->yy decay

DiHiggs: intro

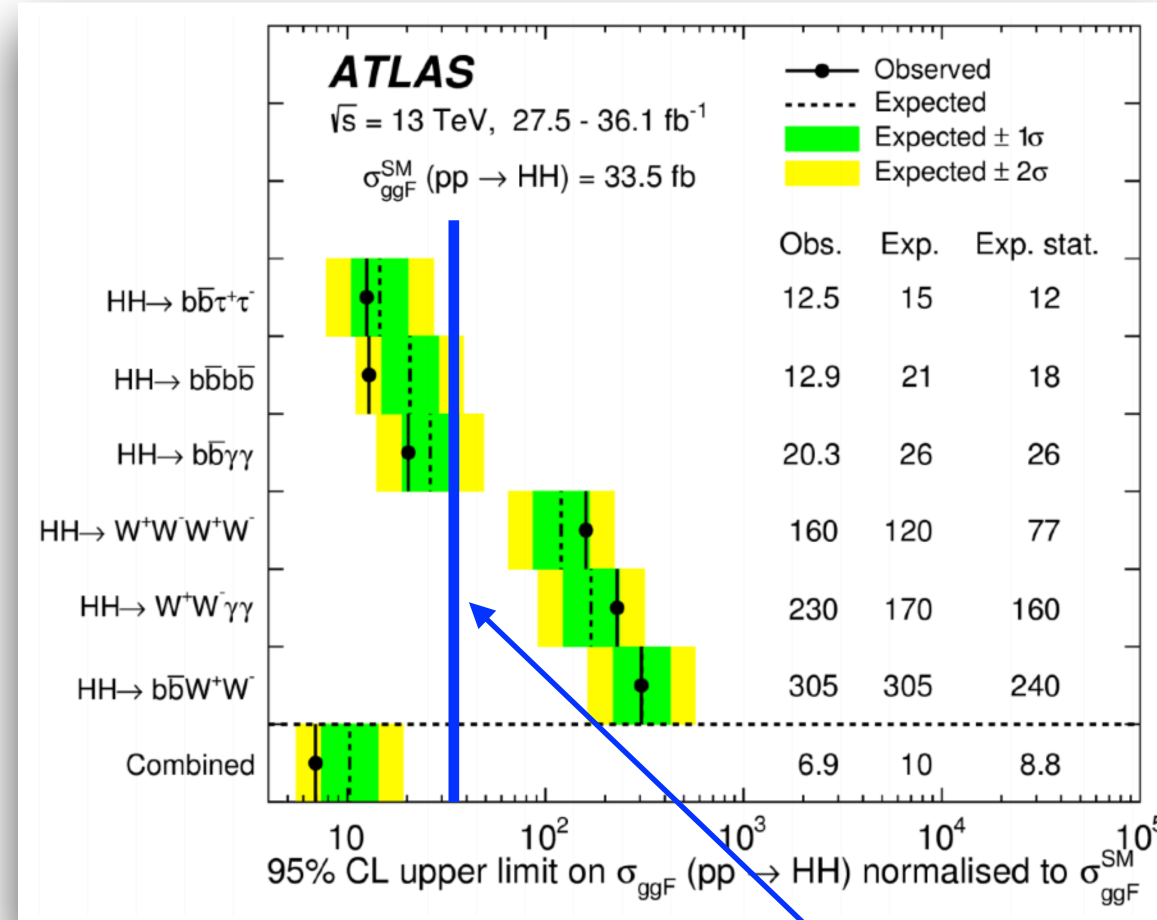
A. Bethani



Full Run2 results from CMS:

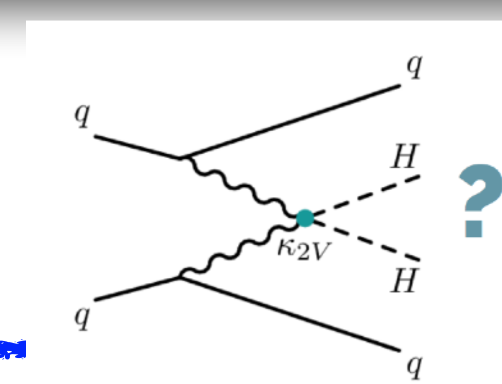
- ✦ ***HH->bbZZ->bb+4l***: looking for bump in a single Higgs+2b analysis *[presented at ICHEP]*
- ✦ **HH->bbyy**: *new for the conference*

E. Brost



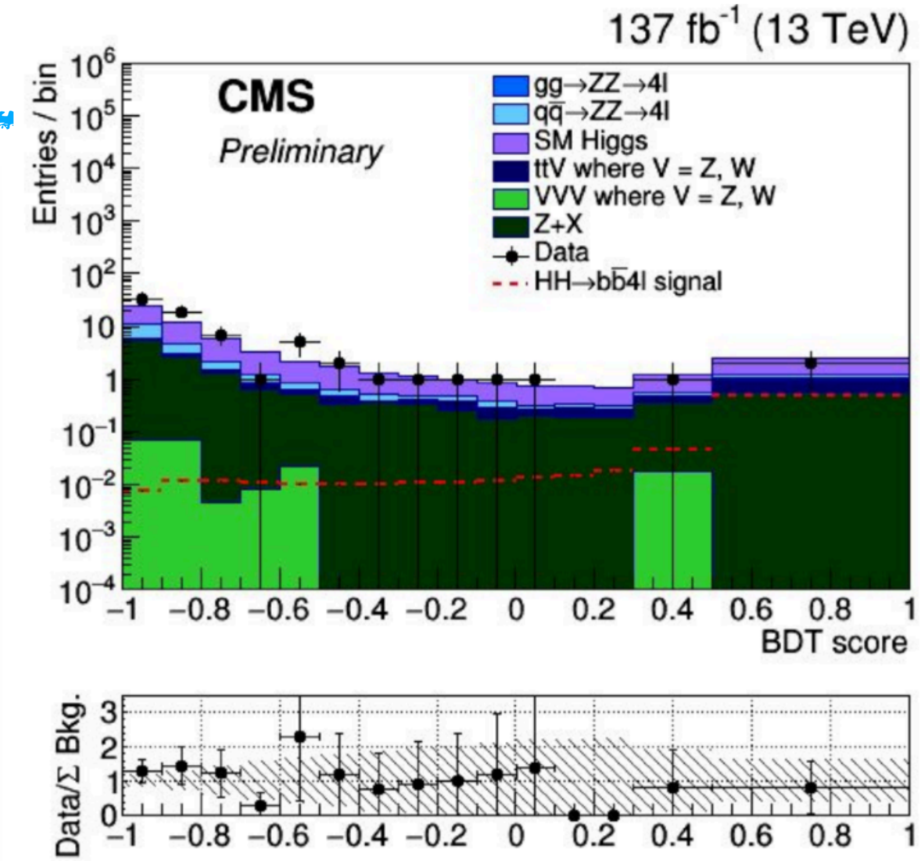
New since the 36 fb-1 combination:

- updated analysis techniques (HH→bbWW 2ℓ)
- new production modes (VBF HH→bbbb)

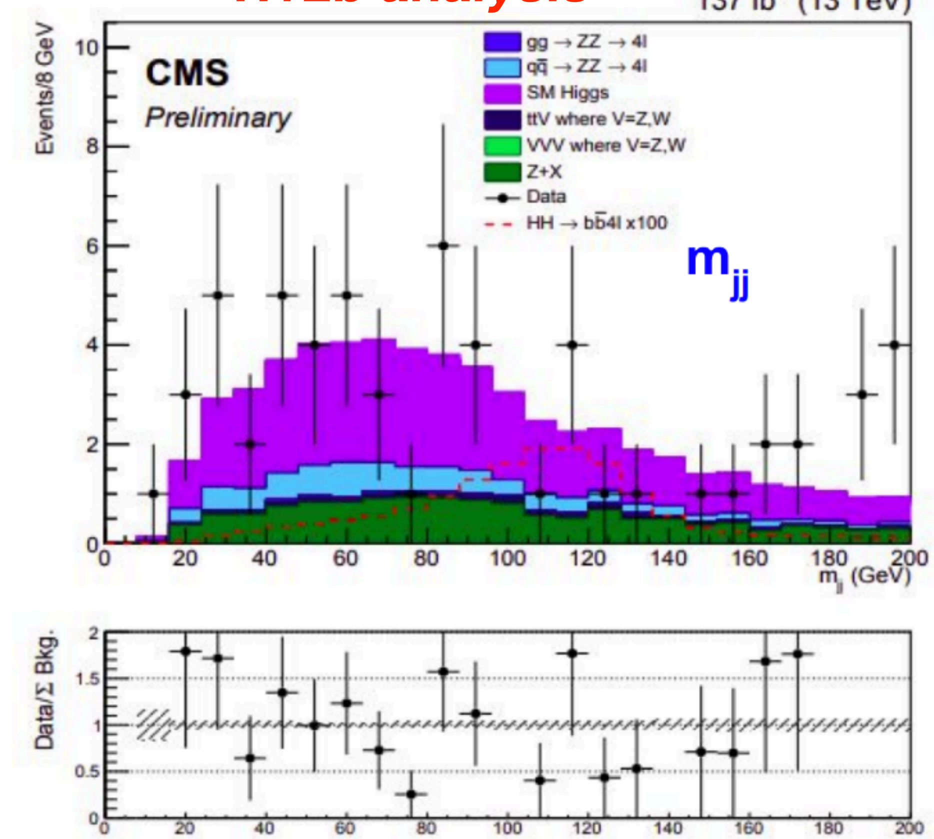


bbZZ(4l) : analysis strategy

- Backgrounds:
  (i) Irreducible: determined from Monte Carlo
  (a) single Higgs production: ggH, VBFH, HW, HZ, ttH, bbH
  (b) QCD induced nonresonant production: $qq \to ZZ^*$, $gg \to ZZ^*$
  (c) ttW, ttZ
  (ii) Reducible: Z + X : where one or two leptons are fakes, mainly from heavy flavour decays, mis-reconstructed jets and converted γ
  → determined from data by measuring probability of *fake* **e**, μ in control regions
- Total 9 BDT trainings: 3 separate years (2016, 17, 18) & 3 channels (4e, 4μ and 2e2μ)
- Signal extracted using shape analysis: maximum likelihood fit to merged BDT output distribution of all years and all channels with proper weightage.



H+2b analysis



- 95% U.L. on σ/σ_{SM}: **30 (37) obs. (exp)**
  - stat. dominated

bbγγ:List of input variables used for training

Common variables with ggHH analysis

1. Leading & subleading DeepJet score
2. $\cos(\theta^*_{CS})$, $\cos(\theta_{\gamma\gamma})$ and $\cos(\theta_{bb})$ - Helicity angles
3. $p_T^{\gamma\gamma}/M_{HH}$, p_T^{bb}/M_{HH}
4. Leading & subleading photon ID MVA
5. $p_T^{\gamma}/m_{\gamma\gamma}$ → lead and sublead photon
6. p_T^{b}/m_{bb} → lead and sublead b-jet
7. min $\Delta R_{\gamma b}$ and other $\Delta R_{\gamma b}$
8. p_T^{HH}
9. MX
10. Leading and subleading photon resolution, σ_E/E
11. Diphoton mass resolution, $\sigma_m/m_{\gamma\gamma}$
12. Leading ans subleading b-jet resolution σ_E/E
13. Di-bjet mass resolution, σ_m/m_{bb}
14. Median energy density in an event (ρ)

VBF jet related variables

1. Leading and subleading VBF jet p_T/M_{jj}^{VBF}
2. Leading and subleading VBF jet η
3. Product of VBF jet η
4. Difference of VBF jet η
5. Quark Gluon Likelihood(QGL) of two VBF jets
6. Minimum angular distance between one VBF jet and one photon & one VBF jet and one b-jet
   → min $\Delta R_{j\gamma}$ and min ΔR_{jb}
7. Centrality variables between diphoton and di-bjet system with respect two the two VBF jets, $C_{\gamma\gamma}$, C_{bb}

$$C_{xx} = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_{xx}-\frac{\eta_1+\eta_2}{2}\right)^2\right]$$

where x= γ or b

QGL: CMS DP -2016/070

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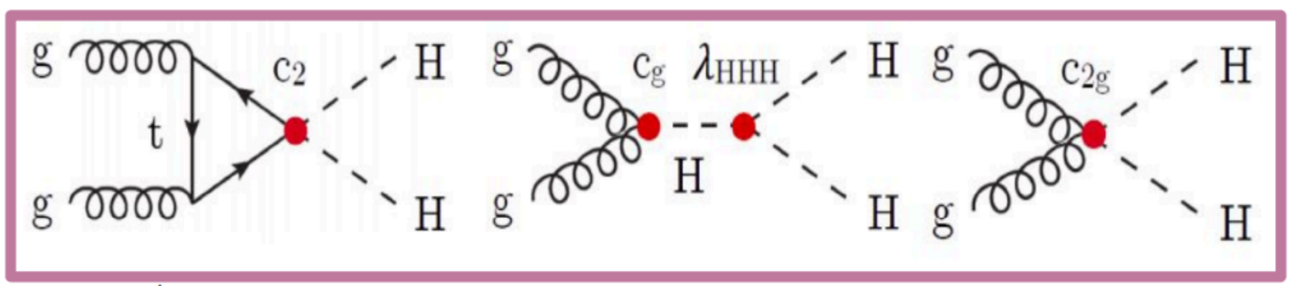
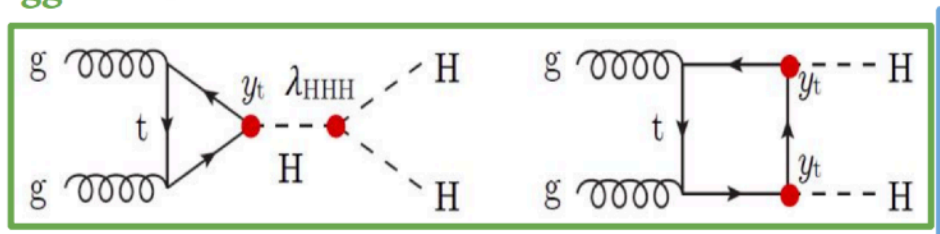
HH: EFT BSM Benchmark [7]

- The different values of coupling parameters leads different kinematics and cross-sections
- In CMS HH analysis 12 benchmark points have been explored to get the EFT sensitivity
- Each benchmark points have been defined by a set of 5 coupling parameters
- The generator level m_{HH} distributions is hugely different in each benchmark scheme

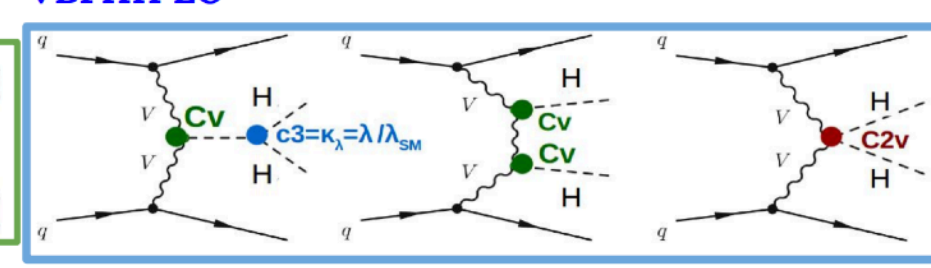
Benchmark points:	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0



ggHH LO

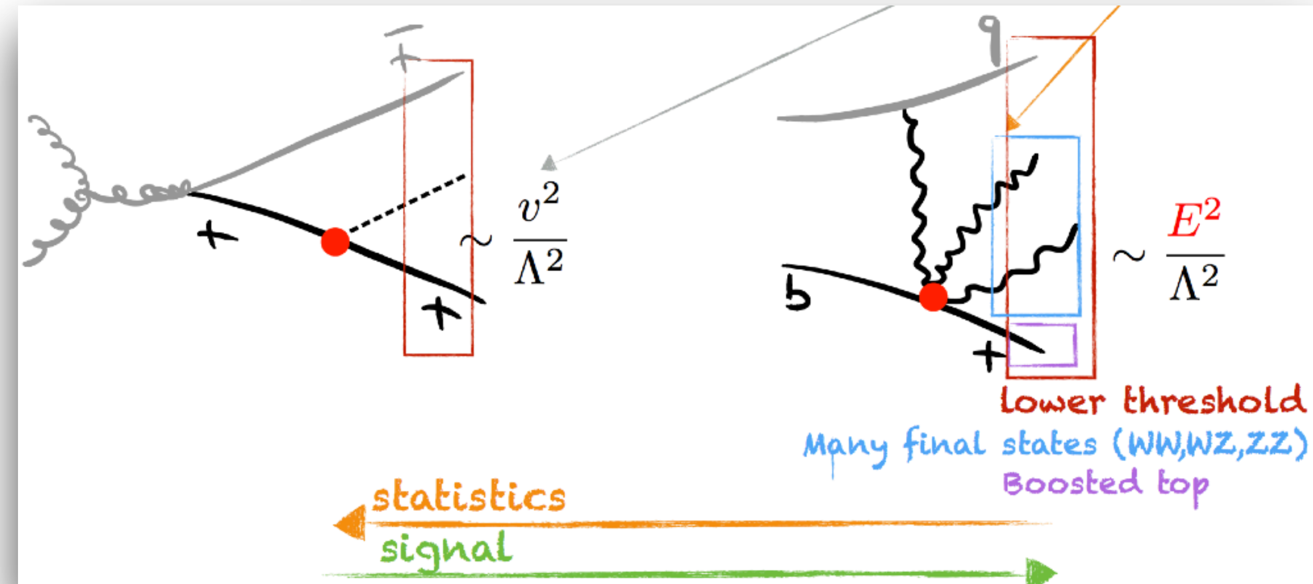


VBFHH LO



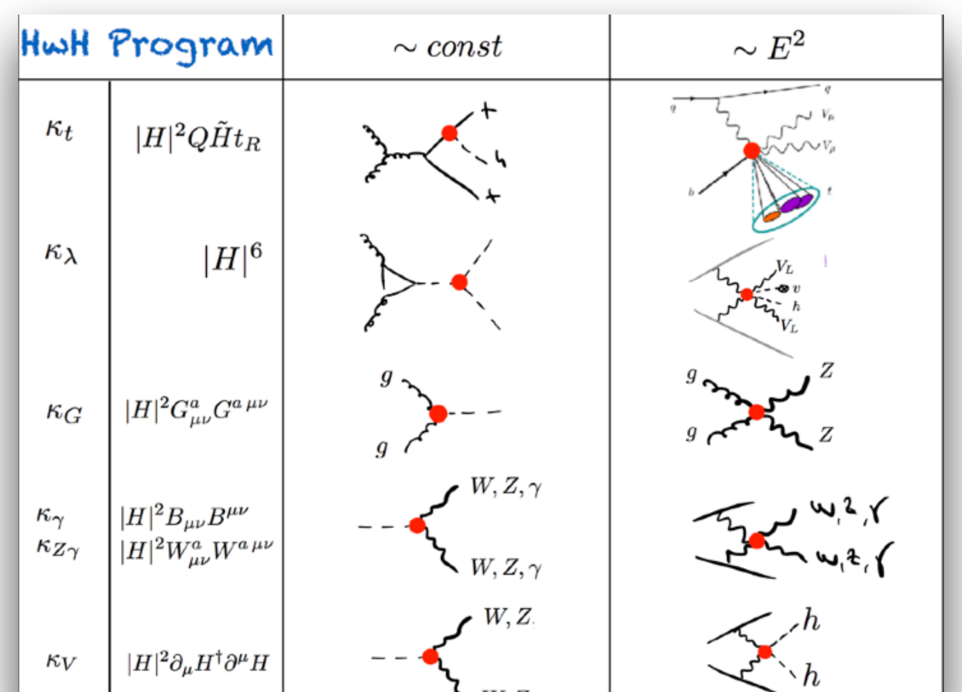
C_i / κ_i: modifier of SM coupling

Any modifications of Higgs couplings induces E^2 growth in some process with longitudinal W,Z bosons!



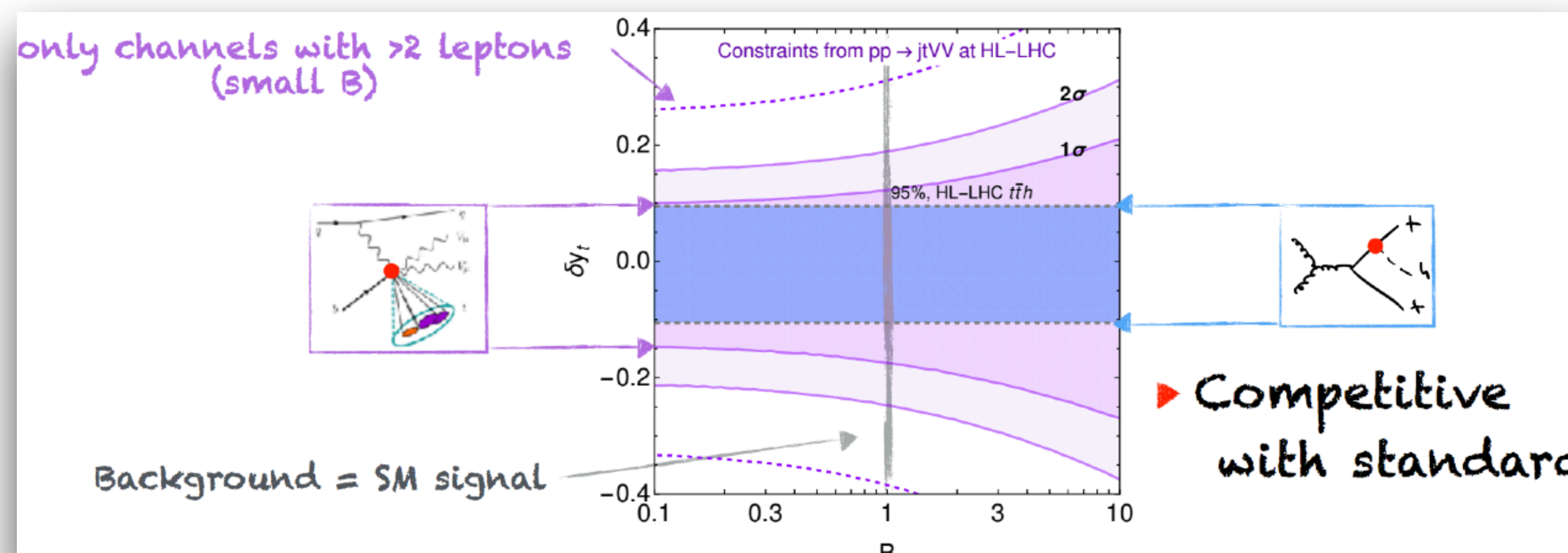
larger effect when replacing Higgs with longitudinal V bosons

In STXS we are exploiting to kinematic dependence of anomalous couplings to increase the sensitivity



pp -> VVtj will represent a very striking signature in the detector

(targetting low B final states)



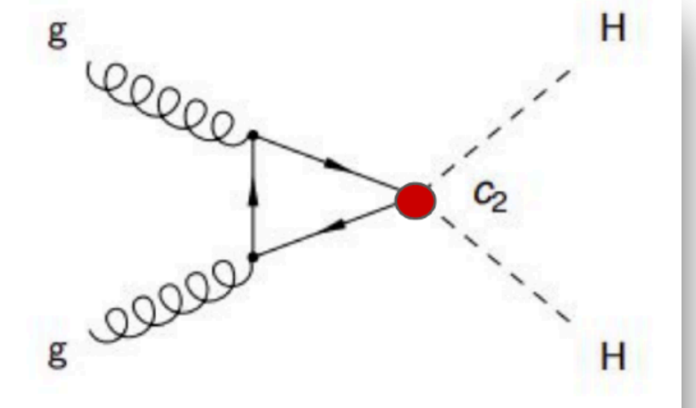
Analyses overview: channels included and luminosity

Exp	PMode	$H \to \gamma\gamma$ (STXS 1.2)	$H \to ZZ^*$ (STXS 1.2)	$H \to b\bar{b}$ ($\sigma \times$ BR)	$H \to WW^*$ ($\sigma \times$ BR)	$H \to \tau\tau$ ($\sigma \times$ BR)	$H \to \mu\mu$ (κ and MSSM)	$H \to inv$ (κ and MSSM)
ATLAS	ggF	Full Run2	Full Run2	-	2015-16	2015-16	Full Run2	-
	VBF	Full Run2	Full Run2	2015-16	2015-16	2015-16	Full Run2	Full Run2
	WH	Full Run2	Full Run2	Full Run2	-	-	Full Run2	-
	ZH	Full Run2	Full Run2	Full Run2	-	-		-
	$t\bar{t}H$	Full Run2	Full Run2	2015-16	2015-16	2015-16	Full Run2	-
	tH	Full Run2	-	-	-	-	-	-
CMS	ggF	2015-17	Full Run2	2015-16	2015-16	2015-17	2015-16	-
	VBF	2015-17	Full Run2	-	2015-16	2015-17	2015-16	-
	WH	-	Full Run2	2015-17	2015-16	2015-17	-	-
	ZH	-		2015-17	2015-16	-	-	-
	$t\bar{t}H$	2015-17	Full Run2	2015-17	-	2015-16	-	-
	tH	-	-	-	-	-	-	-

μ and κ

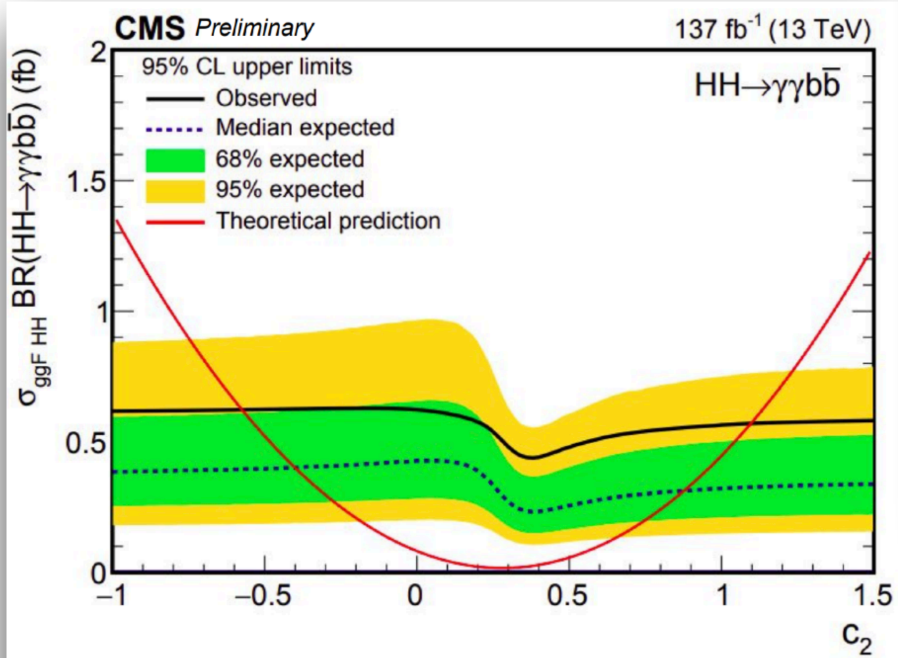
- ATLAS does not use all the analysis in each results
  - Only $H \to \gamma\gamma$, $H \to ZZ^*$ and $VH(b\bar{b})$ have STXS Stage 1.2 capabilities
  - $H \to \mu\mu$ does not have STXS implemented $\Rightarrow$ not used for ($\sigma \times$ BR)
  - $H \to inv$ used only when BSM constraints are needed $\Rightarrow$ μ and κ
- CMS uses all the available analyses in its signal strengths and κ result

HH->bbγγ: CMS (interpretation)



C_2 : ttHH coupling modifier

$C_2 = 0$ in SM



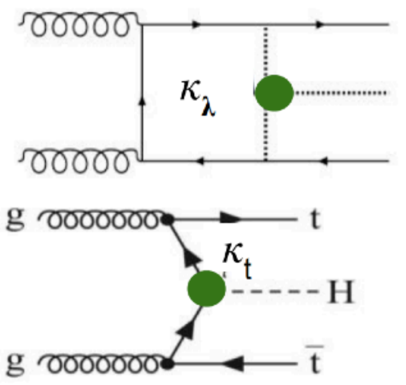
Allowed range @ 95% CL

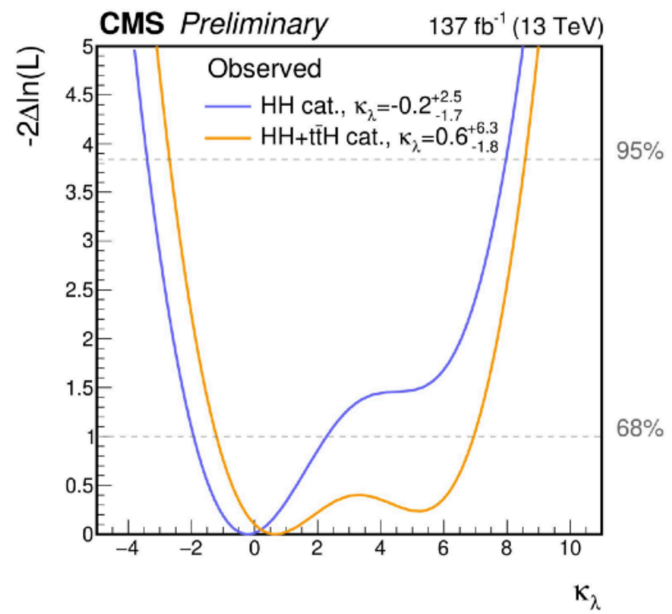
Observed: $-0.6 < C_2 < 1.0$
Expected: $-0.4 < C_2 < 0.9$

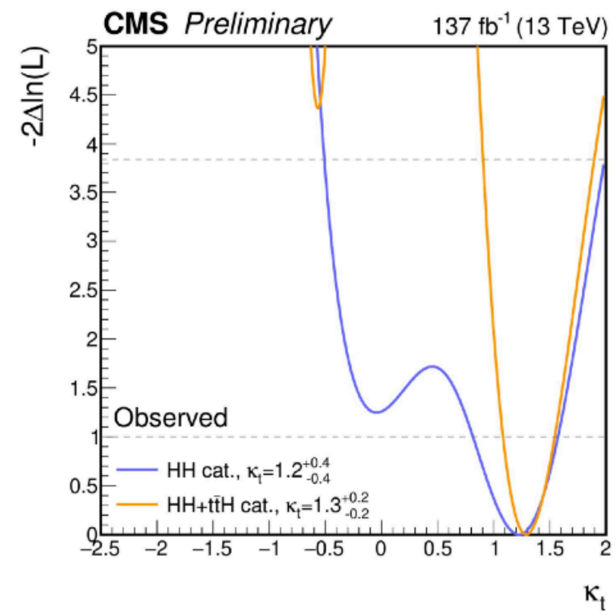
bbγγ: 1D Likelihood scans

NEW

→ ttH process considered for better constraint on κ_λ and κ_t
→ ttH categories are mutually exclusive to the all HH categories [4]







→ Inclusion of ttH makes positive κ_λ preferable
rules out negative κ_t at 95% CL

10/1

Exotics Higgs decays : wishlist

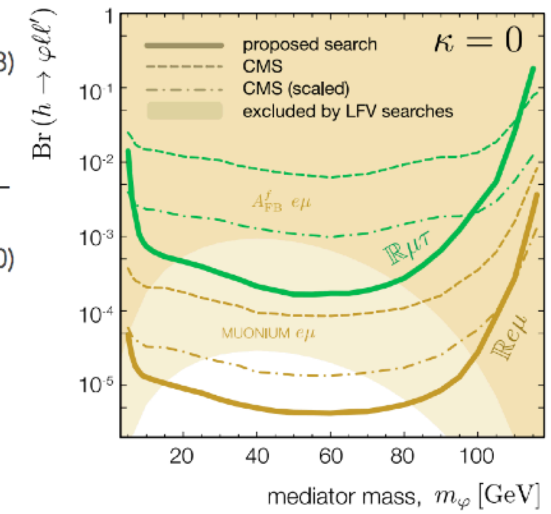
J. Alimena *et al.*, 1903.04497, J.Phys.G 47 (2020)

HIGGS + LONG-LIVED

- Where there exist major gaps/opportunities:
  - Leptonically decaying LLPs with low pT, different flavour combinations
  - Hadronically decaying LLPs with proper lifetimes < 0.1 m
  - (Hadronically decaying) taus from LLPs
  - High multiplicities (6-8 final-state particles!), including Majorana neutrinos (3-body, semi-leptonic decays)
  - Compressed scenarios (*e.g.*, inelastic dark matter)
  - Delayed photons (little to no MET), photon jets
  - Emerging jets & dark showers

PROMPT DECAYS

- Where are there gaps?
  - Partially visible signatures, like $h \to b\bar{b} + \not{E}_T$
    D. Curtin *et al.*, 1312.4992, PRD 90 (2014)
  - High multiplicity decays like $h \to ss \to A'A'A'A'$, $h \to NN \to 6f$
    e.g., E. Izaguirre, D. Stolarski, 1805.12136, PRL 121 (2018)
  - Interesting/more exotic flavour violation like $h \to e^+e^+\mu^-\mu^-$
    J. Evans, P. Tanedo, M. Zakeri, 1910.07533, JHEP 01 (2020)



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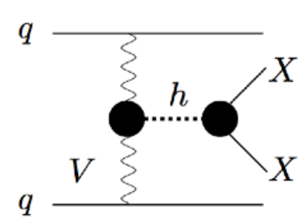
HIGGS + LONG-LIVED

- Higgs also presents trigger opportunities!



- Higgs produced in association with VBF jets or W/Z: can be used to trigger on otherwise difficult signals!

- So far, this approach only seems to have been used in one published analysis looking for $h \to ZA'$
  ATLAS, 1811.02542, PRL 122 (2019)

- Can low-mass tau triggers for Higgs studies be useful for low-mass, narrow displaced hadronically decaying LLPs?

Combinations

- *Very difficult to compare combinations apple-to-apples:*
  - performed at different stages with available analyses

lumi in the combination ← **80**/140 → lumi in greatest public analysis

CMS combination performed early this year(*)

lumi	ZZ	yy	bb	WW	tautau	μμ
ggF	140	80/140	40/140	40/140	80/140	140
VBF	140	80/140		40	80/140	140
VH	140	80/140	80	40	80/140	140
ttH	80	80/140	40/80	80/140		140

ATLAS combination performed for ICHEP

lumi	ZZ	yy	bb	WW	tautau	μμ
ggF	140	140	/ 80	40	40	140
VBF	140	140	40/140	40/140	40	140
VH	140	140	140	/ 40	40	140
ttH	140	140	40/140	40 / 80		140

- **ATLAS combination is more complete having come out later.**
- As more individual analyses are becoming available, it will be difficult to argue that the combination is our best knowledge (for some specific quantities):
  - aka "how often should we update combinations?"

(*) updated to include H->mumu in its own paper