Higgs physics at HL-LHC

Bill Murray,
Higgs Hunting, 29rd July 2019
On behalf of the ATLAS collaboration

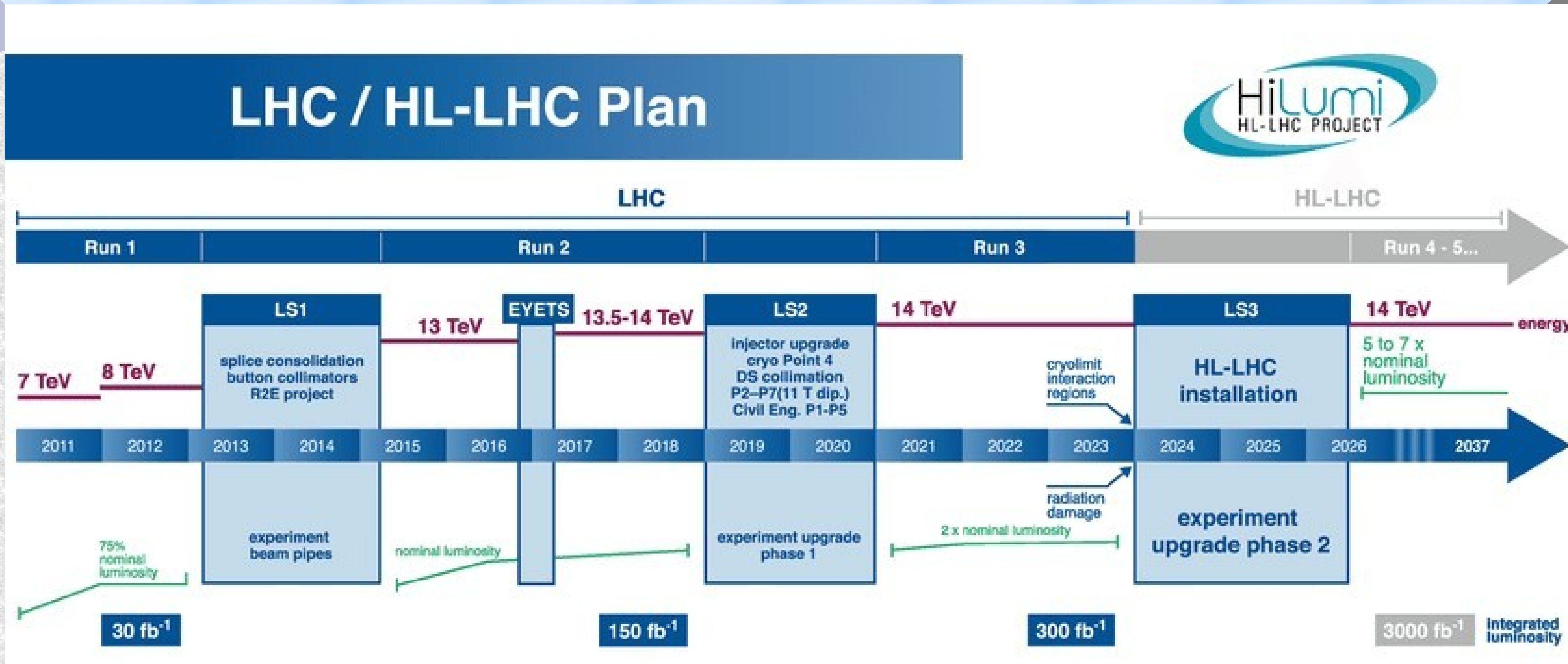
"Vague but exciting"

ATL-PHYS-PUB-2018-053 HH & self coupling
ATL-PHYS-PUB-2018-054 H properties
ATL-PHYS-PUB-2019-008 $H\rightarrow\tau\tau$ CP

The SM

- “A hunched black beast made of razor edges and barbs and ribbons of sharp metal; a chair that could kill a man”
  - George R R Martin
- Is HL-LHC going to be able to melt it?

Timeline



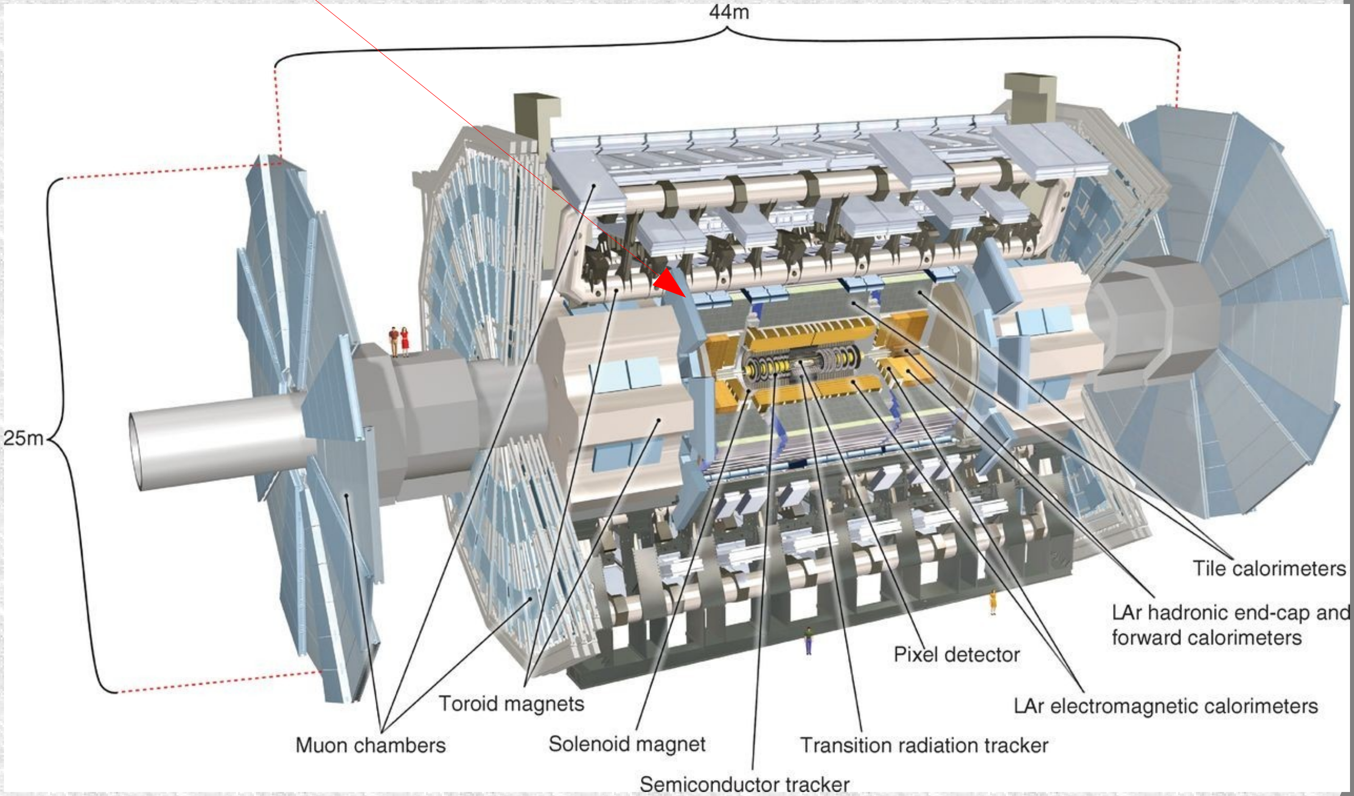
- LS3 in 2024 has major accelerator & ATLAS work
- From mid 2026 move into 200 pile-up events/BX
  - Luminosity limited by detectors constraints
  - Maintain maximum digestible rate for hours

The REAL Higgs factory

- All very difficult…..
  - "Men were real men, women were real women, small green furry creatures from alpha centauri were real small green furry creatures from alpha centauri"
- Seriously, it is a dirty,dangerous (for detectors) and harsh environment
  - But it will work...if we can work out how to handle it
- Most results so far are from 36fb^{-1}
  - Extrapolations and HL-LHC studies are for 3-4ab^{-1}
    - It's a big jump and not all will be done perfectly.
    - It is unlikely the final analyses will be done the same way

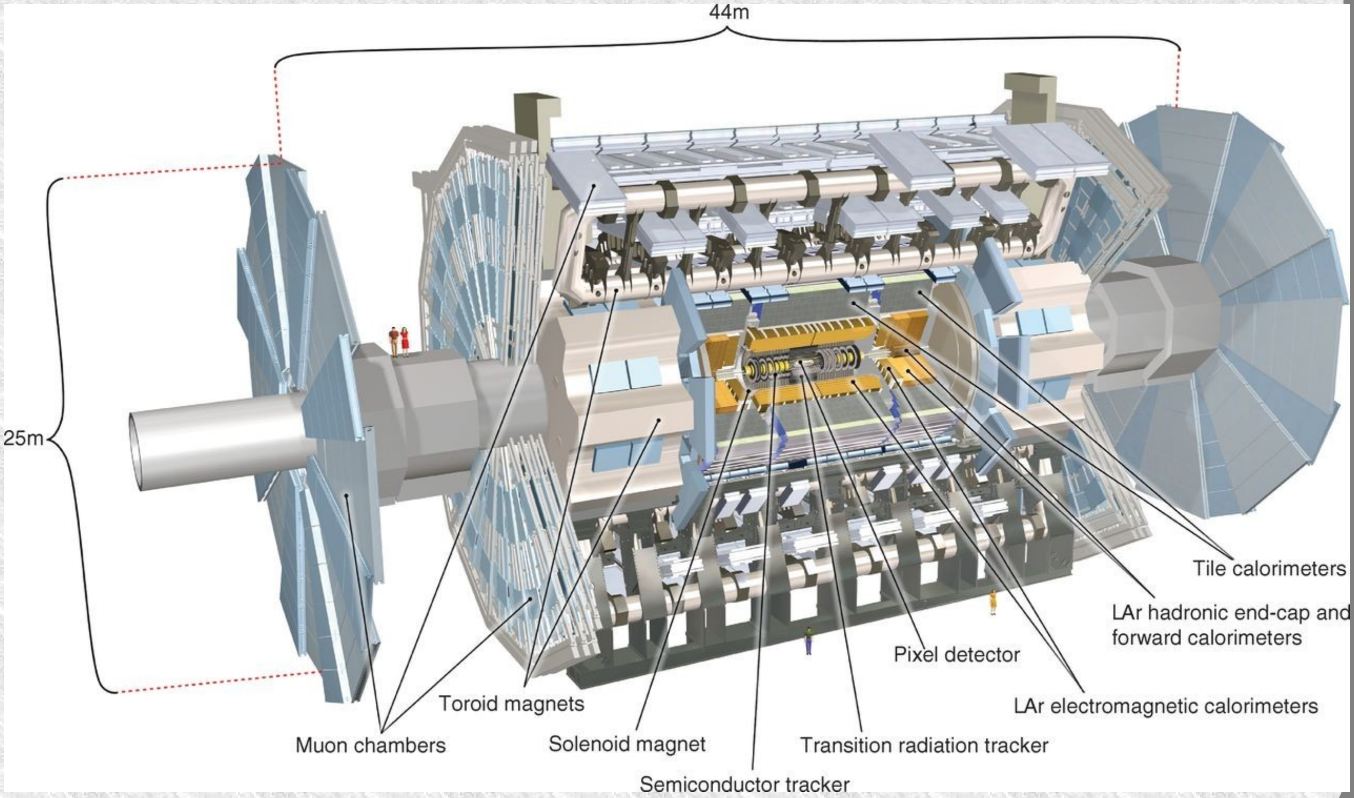
ATLAS upgrades

- Muons:
  - Innermost layers upgraded,
  - New Small Wheels
- Tracker:
  - New: All-silicon Itk
- Timing:
  - High Granularity Timing Detector in endcaps



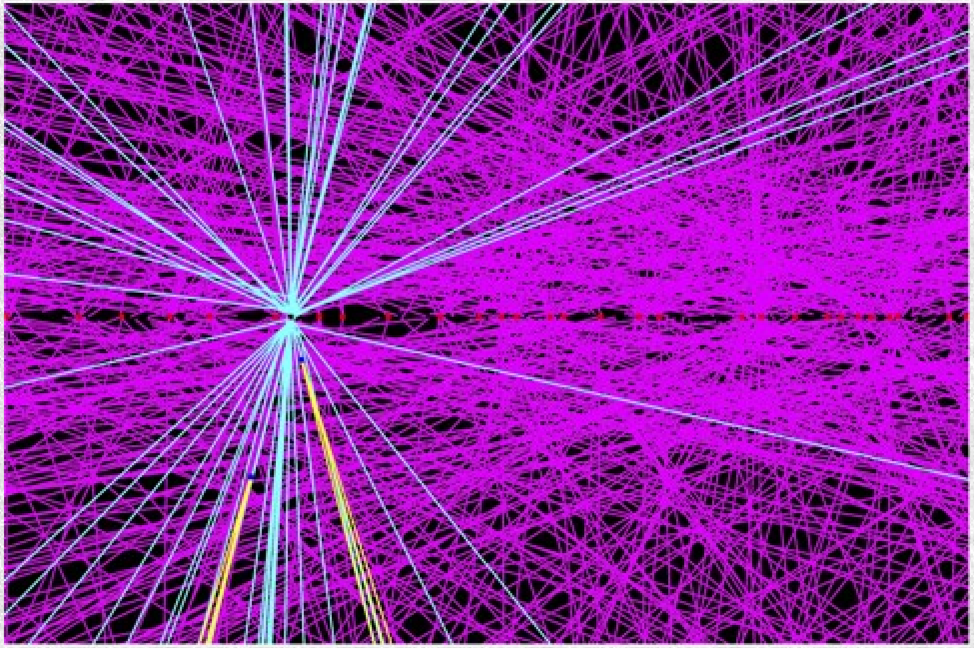
ATLAS upgrades

- Calorimeter: front end electronics replaced
  - Higher granularity
- Trigger total rebuild for 10x rate
  - Aim for similar thresholds
  - Non-trivial as pileup makes events more complex



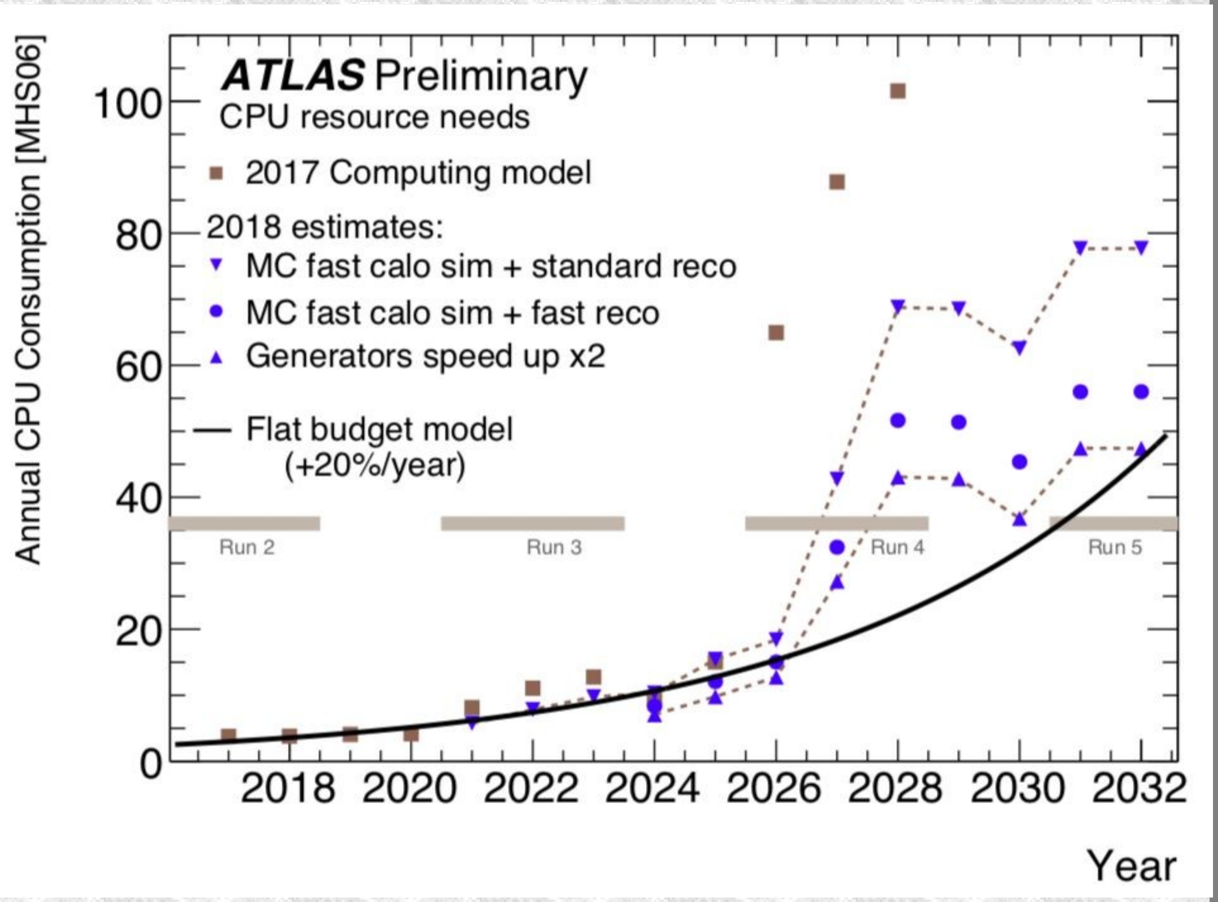
HL-LHC events

- Harsh environment
- Pileup goes from O(40) mean to O(200)
- Tracking scales factorially with hit density
  - Currently we do not have affordable solutions
  - This needs intellectual input now.



Computing model

- Assume a flat budget gives 20% improvement per year
  - Not guaranteed
- Revised 2018 computing model reduces demand
- Then with fast sim / reco / generators we ~ cope
  - Run 4 will be tough



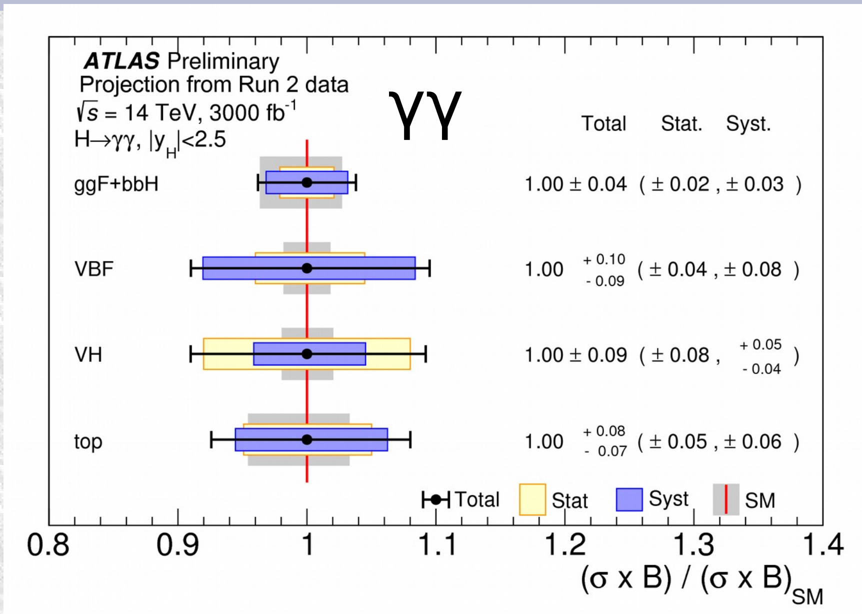
Systematic assumptions

- MC stats assumed negligible
- S1: Assume current uncertainties (safe)
- S2: Theory ½, lumi 1%
  - Detectors as detailed below

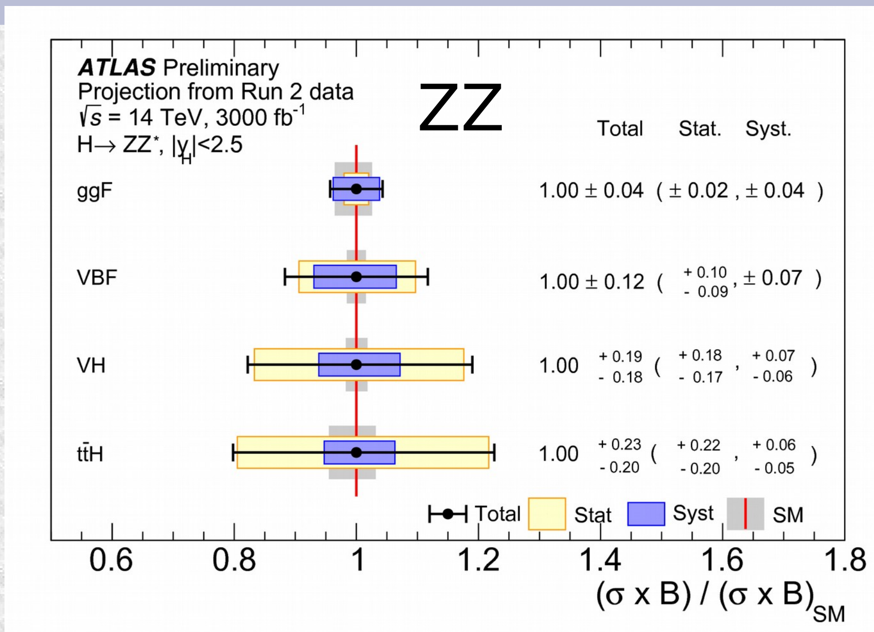
Used here

Source	Component	Run 2 unc.	Projection minimum unc.
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic τ ID		6%	Same as Run 2
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
$\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ 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%

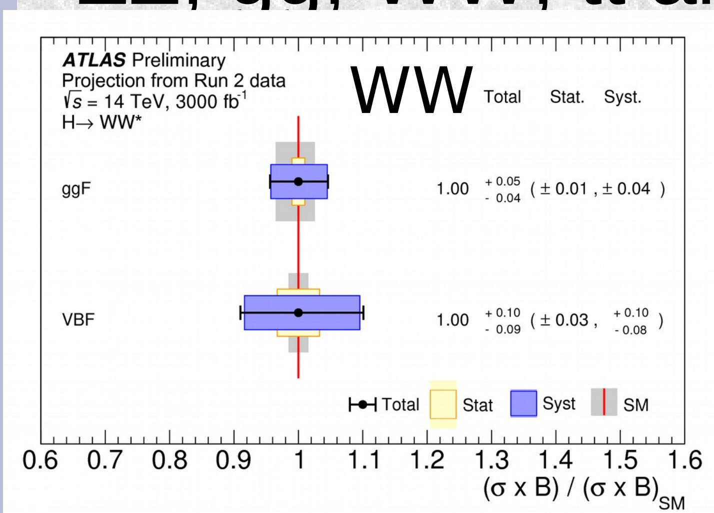
Higgs Production x decay

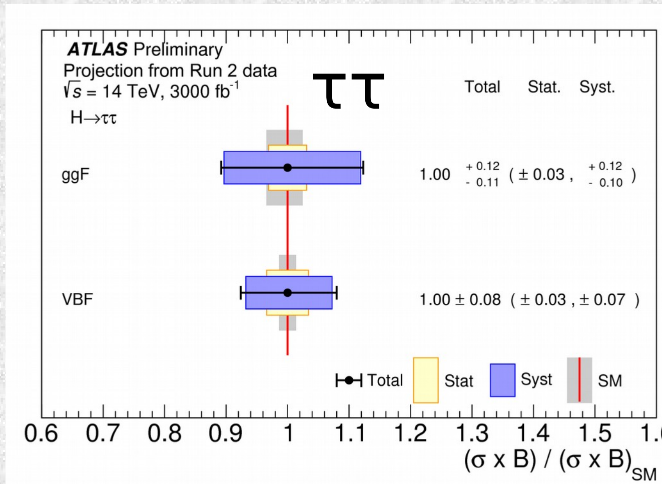


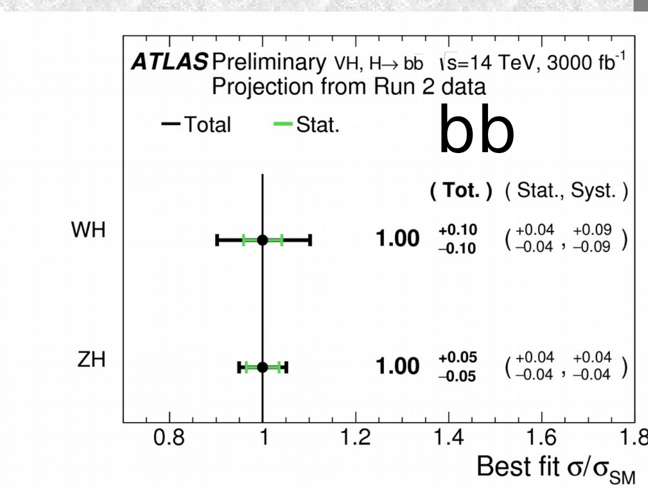
S2
sys



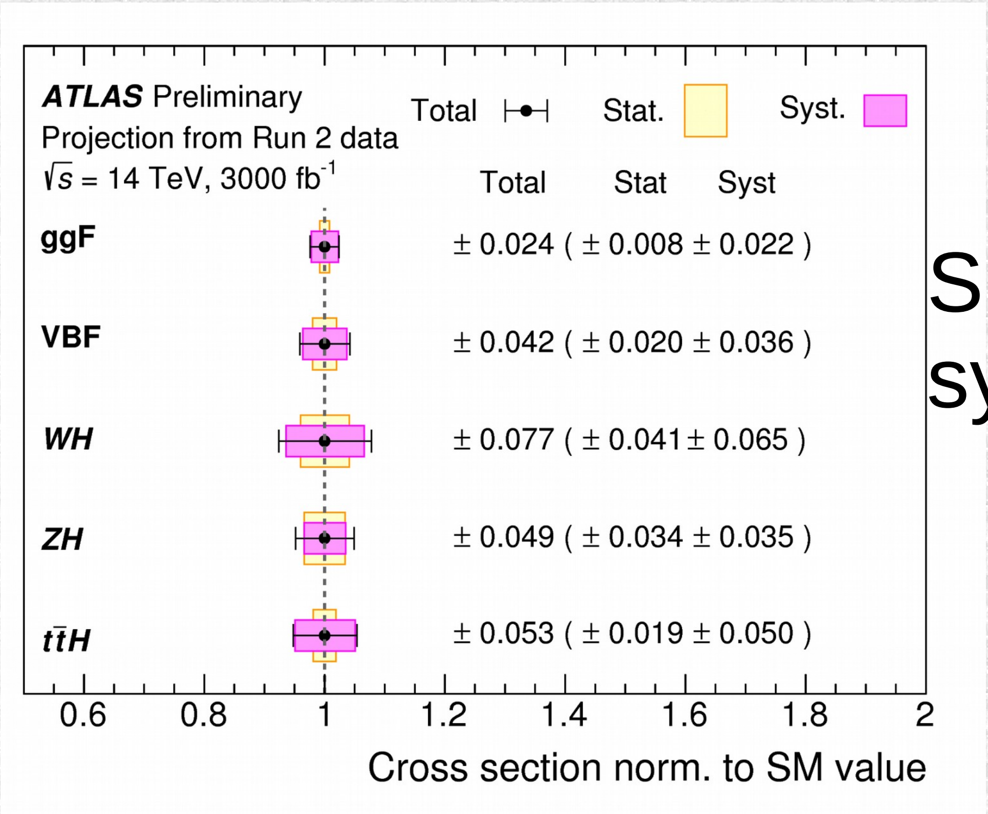
- ZZ, gg, WW, tt and bb modes



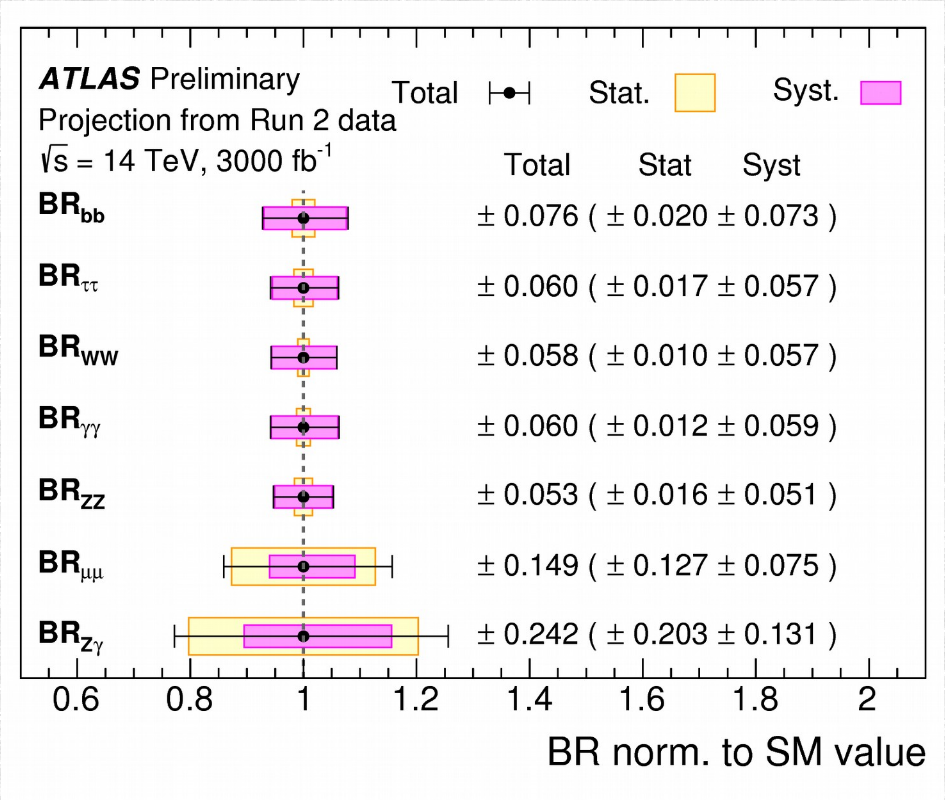




Production and decay modes

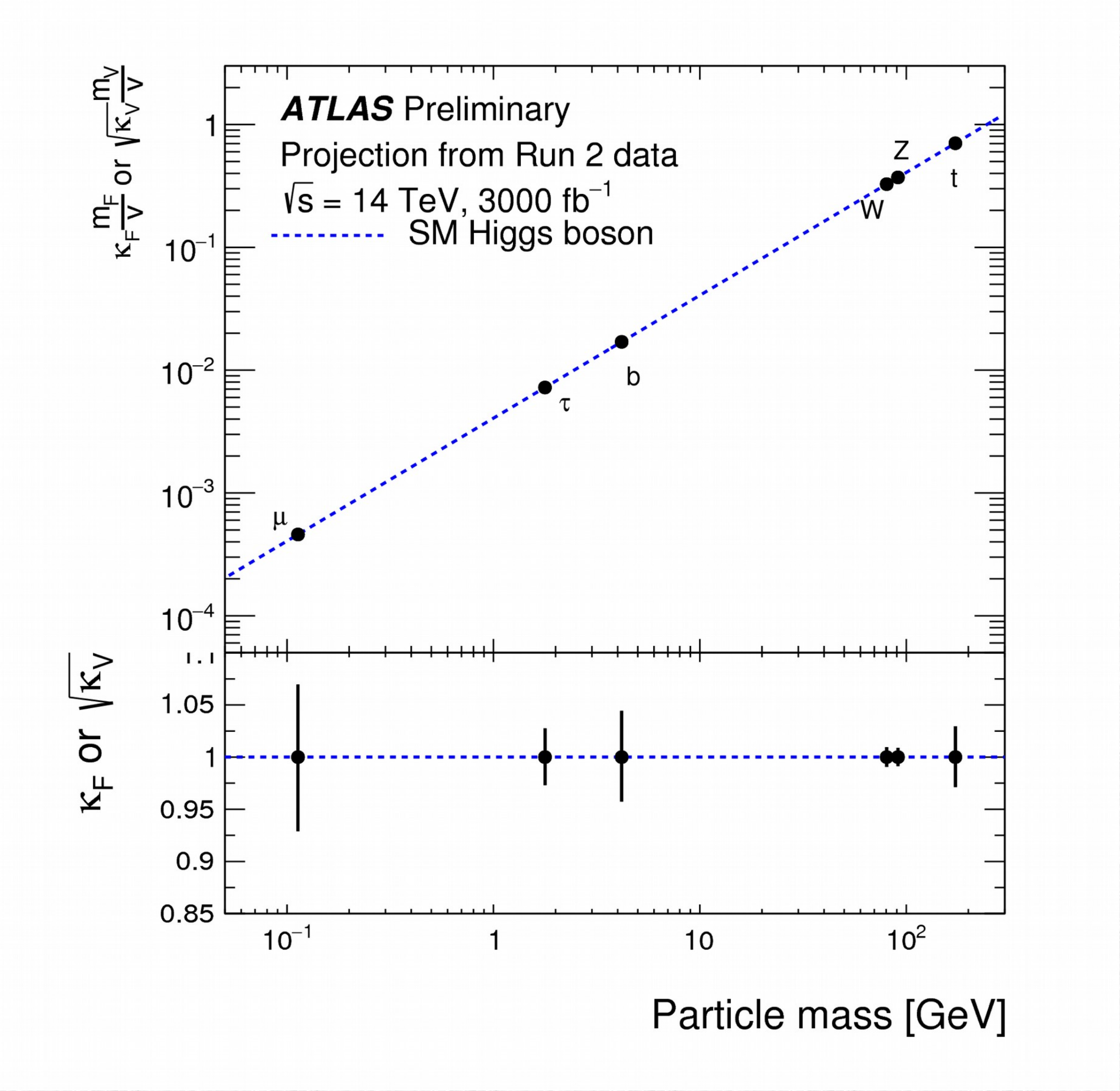


S2 sys



- Assume decay, measure production & vice versa
- All systematics limited, except μμ & Zγ
  - Expect μμ clearly seen, 4.9σ for Zγ

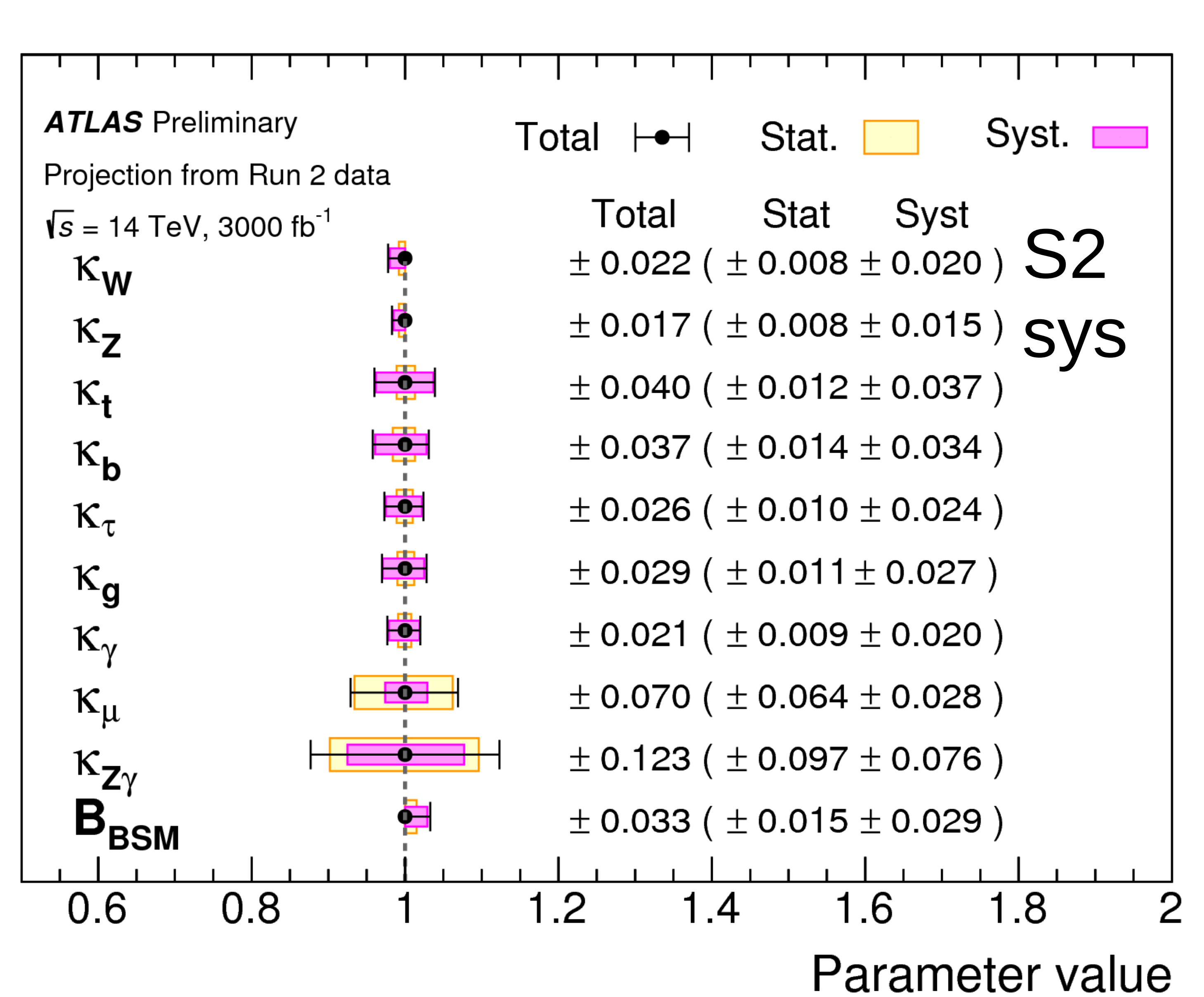
Extracted couplings v mass



S2
sys

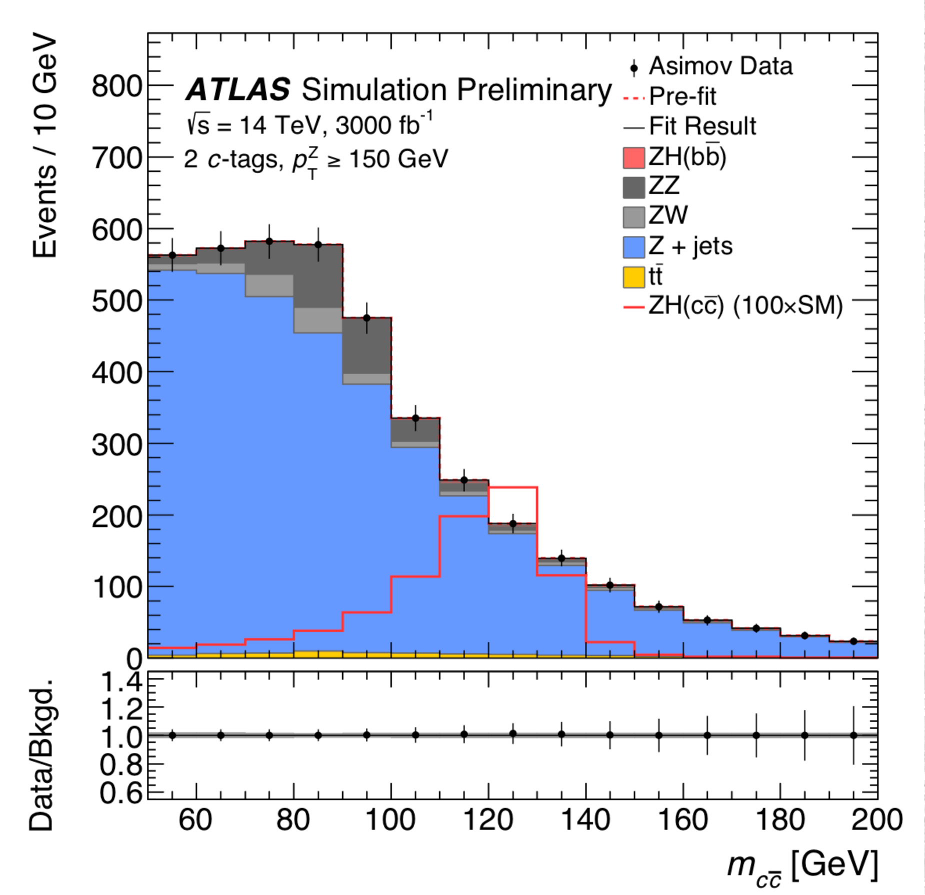
Extracted couplings

- 10 parameter general fit
  - Imposing UL on W,Z
- Gives 2-4% precision
  - Except μ & Zγ
- 3.3% limit on non-SM decays, e.g. DM



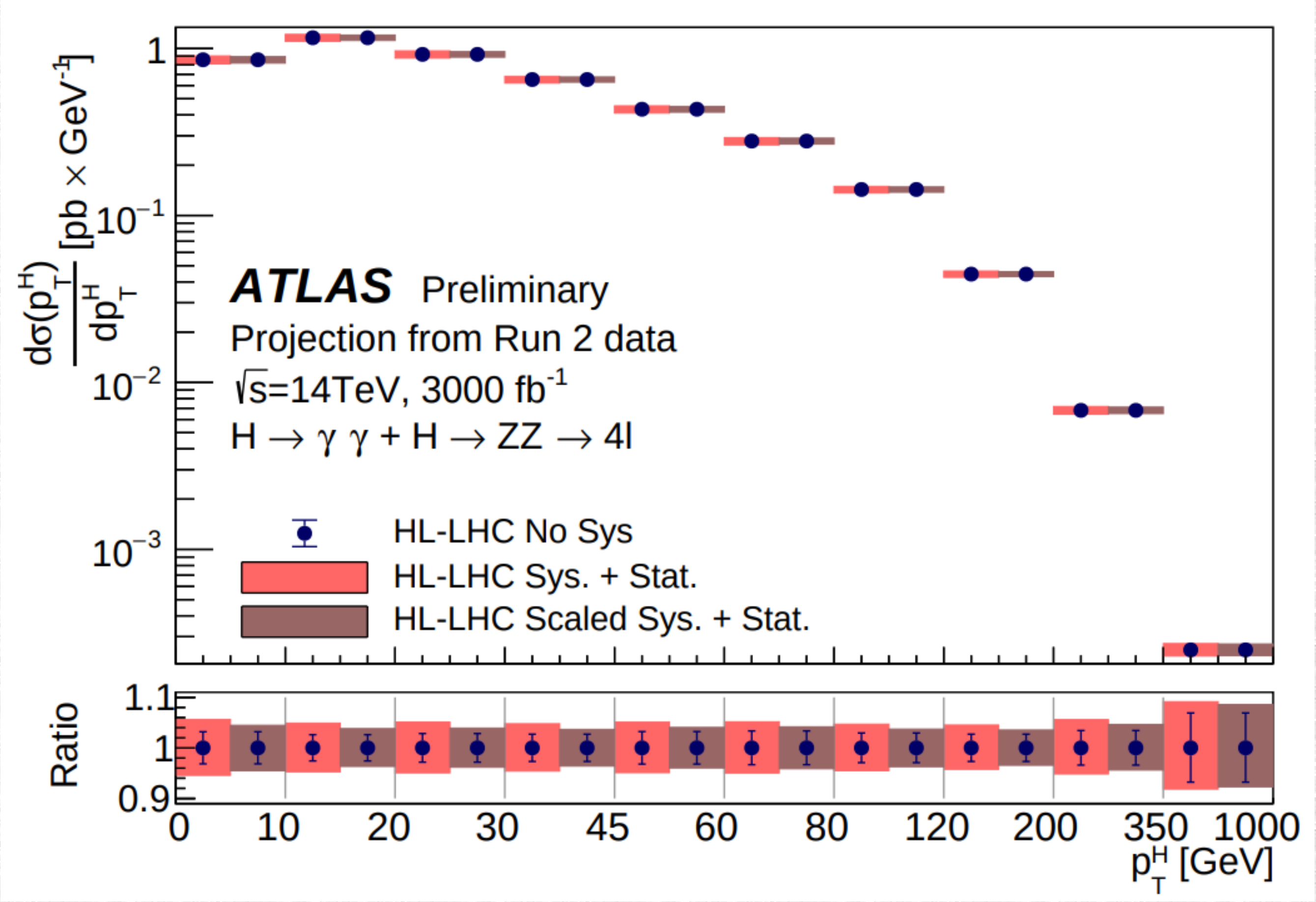
Hcc coupling

- Several approaches target Hcc ($H \to J/\psi\gamma$ or H pT)
  - Most straightforward is VH, $H \to cc$
- Four regions considered
  - 1 or 2 c tags
  - High or low p_T $Z \to ll$
  - Best is shown right
    - Signal multiplied by 100!
- Observation not expected
  - But expected limit 6.3xSM cross-section (stat only)
  - $Z \to$ neutrinos will add some sensitivity
  - As will analysis optimisation



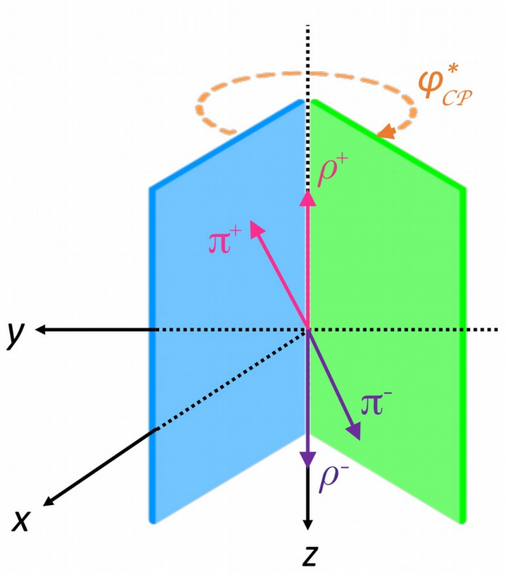
Differential distributions: ZZ+γγ

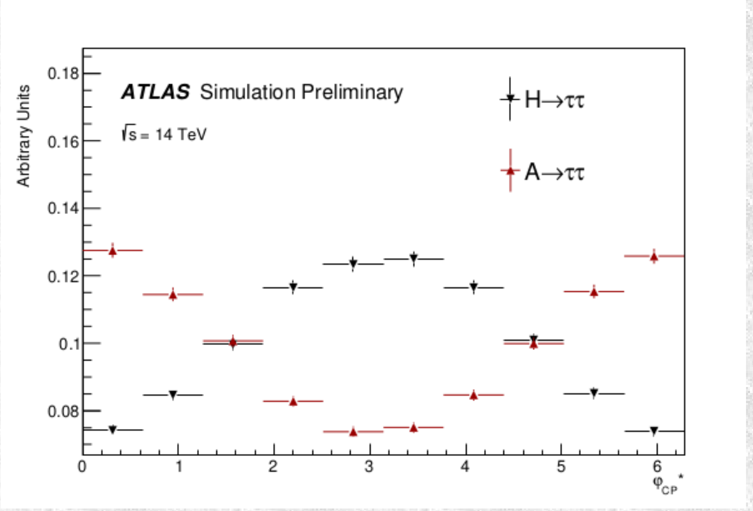
- Higgs p_T up to 1 TeV 10% precision or better
  - Statistics important here
- High-pT bin can be divided
- May be possible to add H→bb at high pT.



H→ττ CP properties

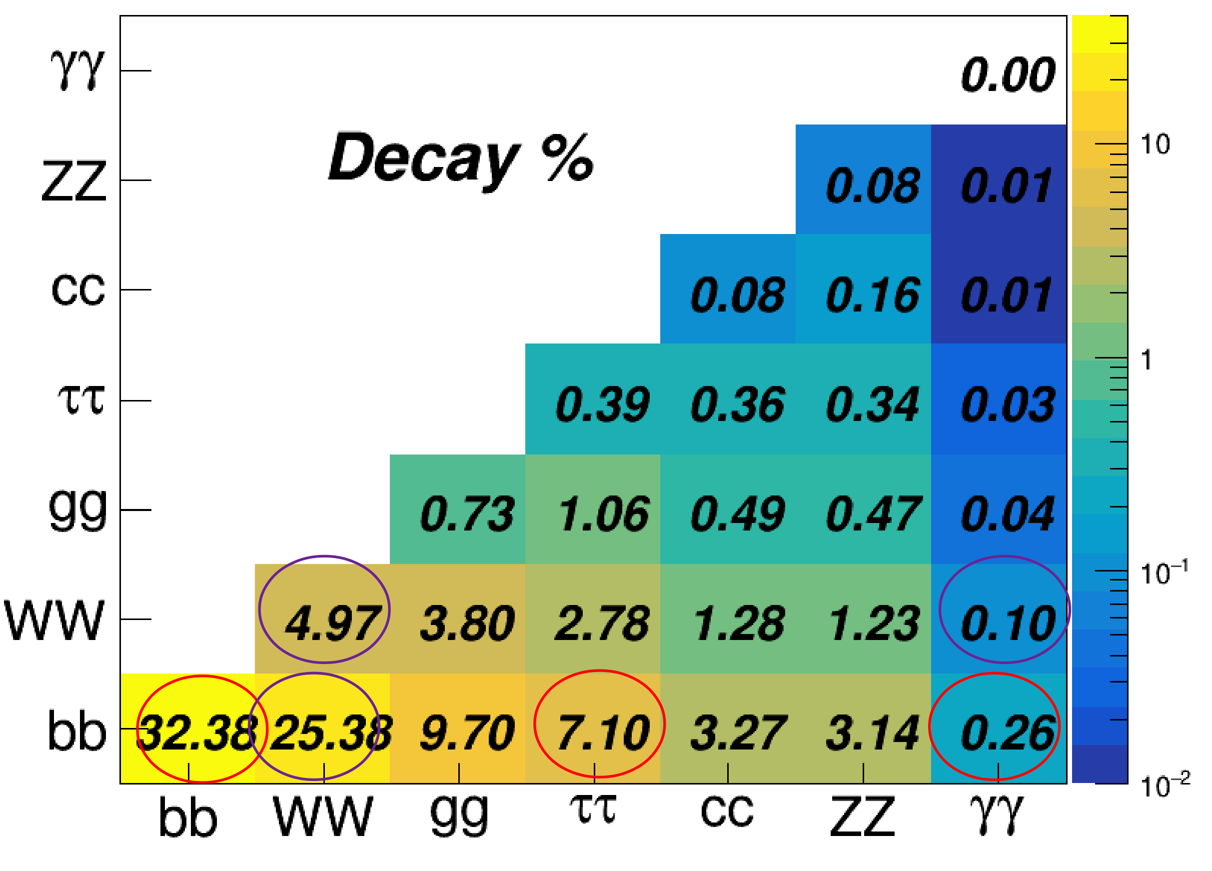
- Analysing tau decays probes coupling to fermions
  - CPX in MSSM hidden in bosons
- Use ττ→ ρνρν decays
- Analyse ρ→π$^+$π^0 energy sharing
  - As a probe of angle
- Use VBF and ggF production
  - In low/high pT modes
- Results depend upon π^0 resolution
  - 18^o↔33^o mixing angle resol.
  - for 1↔2x nominal π^0 resolution





Di Higgs production

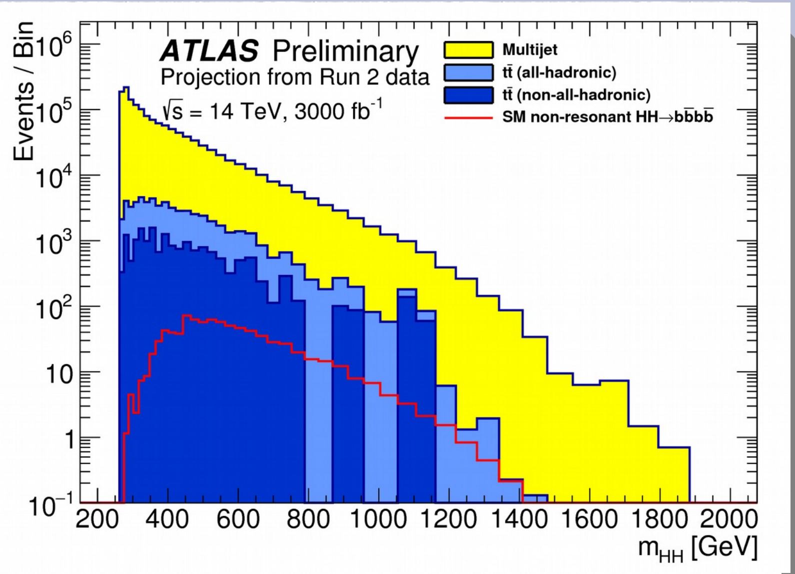
- Right:Branching ratios of various decay modes
- Red circled channels have ATLAS projections
- Purple have results at 13 TeV

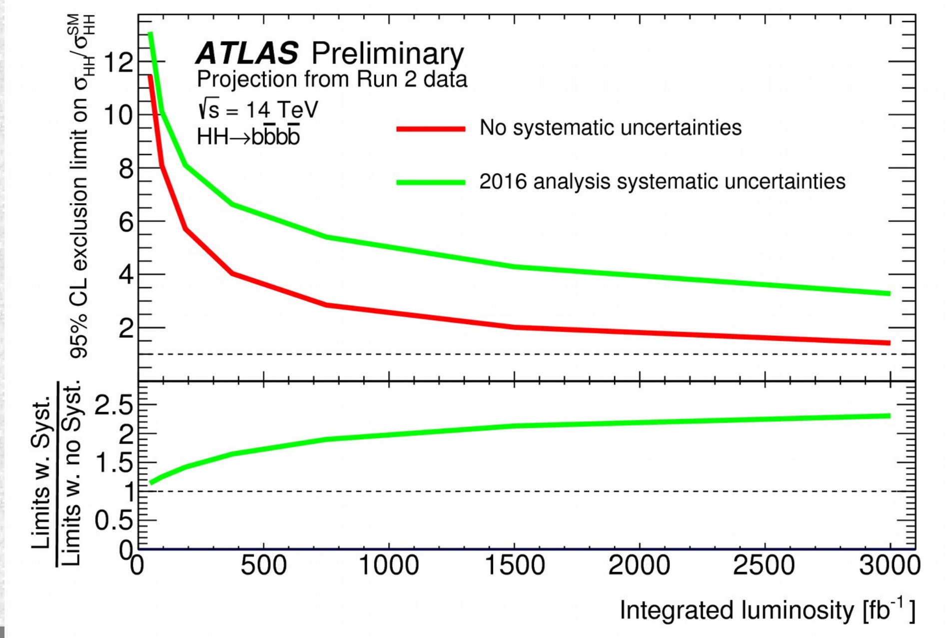


- Many weak channels are not exploited – some gain possible

HH → bbbb

- Extrapolating 36fb^{-1} analysis
  - Assumed 8% improvement in btag
  - From Itk improved performance
- Cocktail of multi-b triggers
  - 1 hard b, 225 Gev pT
  - 2 soft b, 35 or 55 GeV
  - Finally 90% efficient for SM
- The multijet background error is hard to predict
- UL from 1.5 to 3.3 x SM
  - Depending on this error



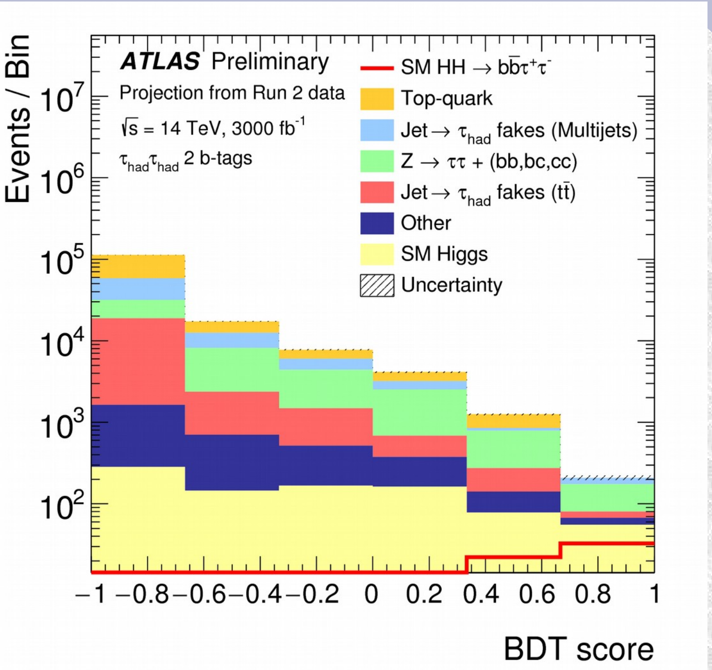


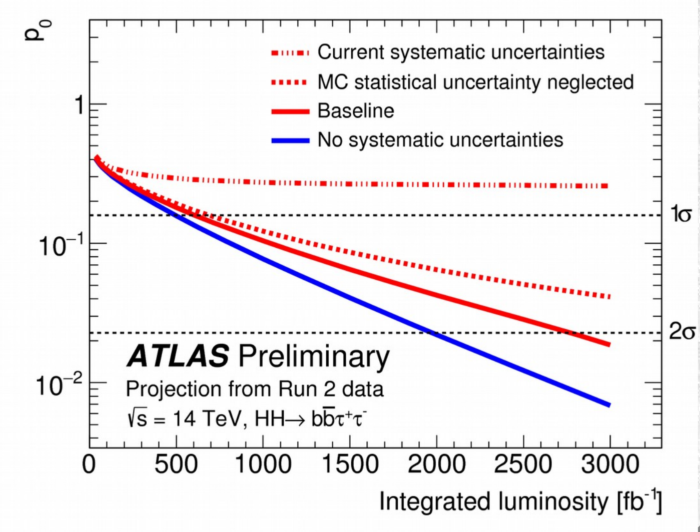
HH → bbττ

- The 36fb-1 analysis is extrapolated
- lh and hh channels analyses
  - hh, shown right, most powerful

Last bin	$\tau_{lep}\tau_{had}$ channel (SLT)	$\tau_{lep}\tau_{had}$ channel (LTT)	$\tau_{had}\tau_{had}$ channel
$t\bar{t}$ fake-$\tau_{had\text{-}vis}$	-	-	12.9 ± 2.0
$t\bar{t}$	235 ± 6	360 ± 30	0
Single top	283 ± 15	54 ± 3	0
Multijet fake-$\tau_{had\text{-}vis}$	-	-	33.7 ± 7.2
Fake-$\tau_{had\text{-}vis}$	300 ± 10	97 ± 9	-
$Z \to \tau\tau + (bb, bc, cc)$	340 ± 20	470 ± 40	95 ± 16
Other	105 ± 5	61 ± 7	12.2 ± 2.1
SM Higgs boson	78 ± 4	31 ± 2	55 ± 3
Total background	1343 ± 25	1069 ± 55	209 ± 17
SM *HH*	32.8 ± 1.6	9.8 ± 0.5	32 ± 3

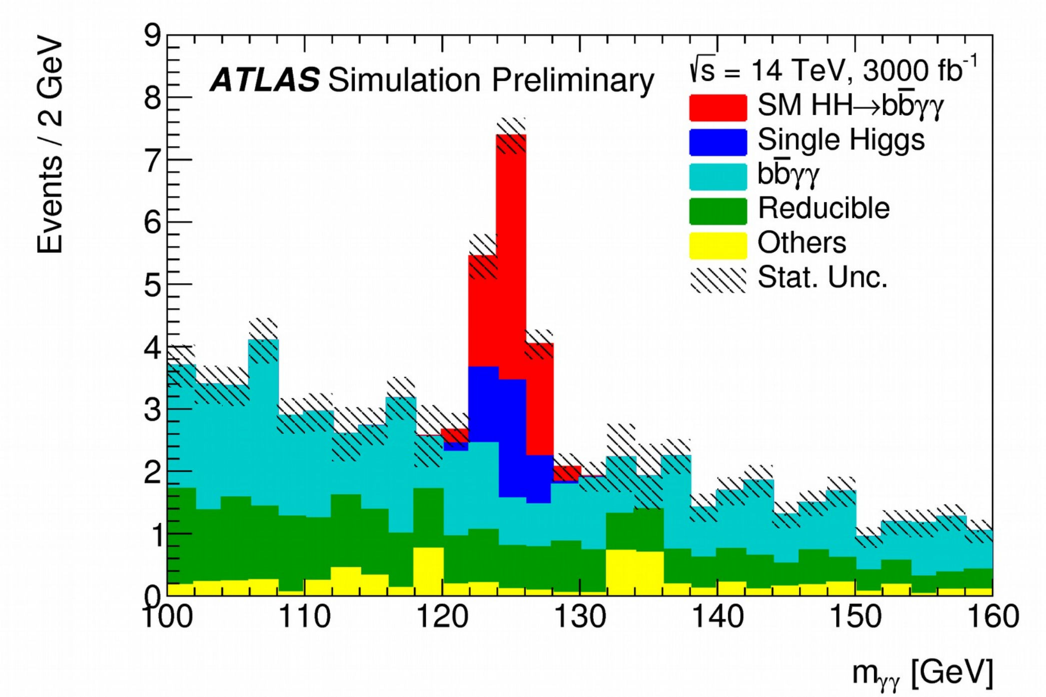
- Expected UL 1xSMσ





HH → bbγγ

- H → γγ has good resolution & triggering; H → bb is high rate,
- Use BDT to separate from background
- Two comparable backgrounds:
  - Continuum (sidebands)
    - 3.7 in 123-127
  - Single Higgs peaking
    - 3.2 in 123-127 (50% ttH)
- Signal 6.5 expected
- Expected UL 1.2xSMσ



Dominant systematics	Signal	H Background
Photon energy resolution	14%	14%
Jet Energy Resolution	2.9%	7.8%
QCD scale	2.5%	~11%

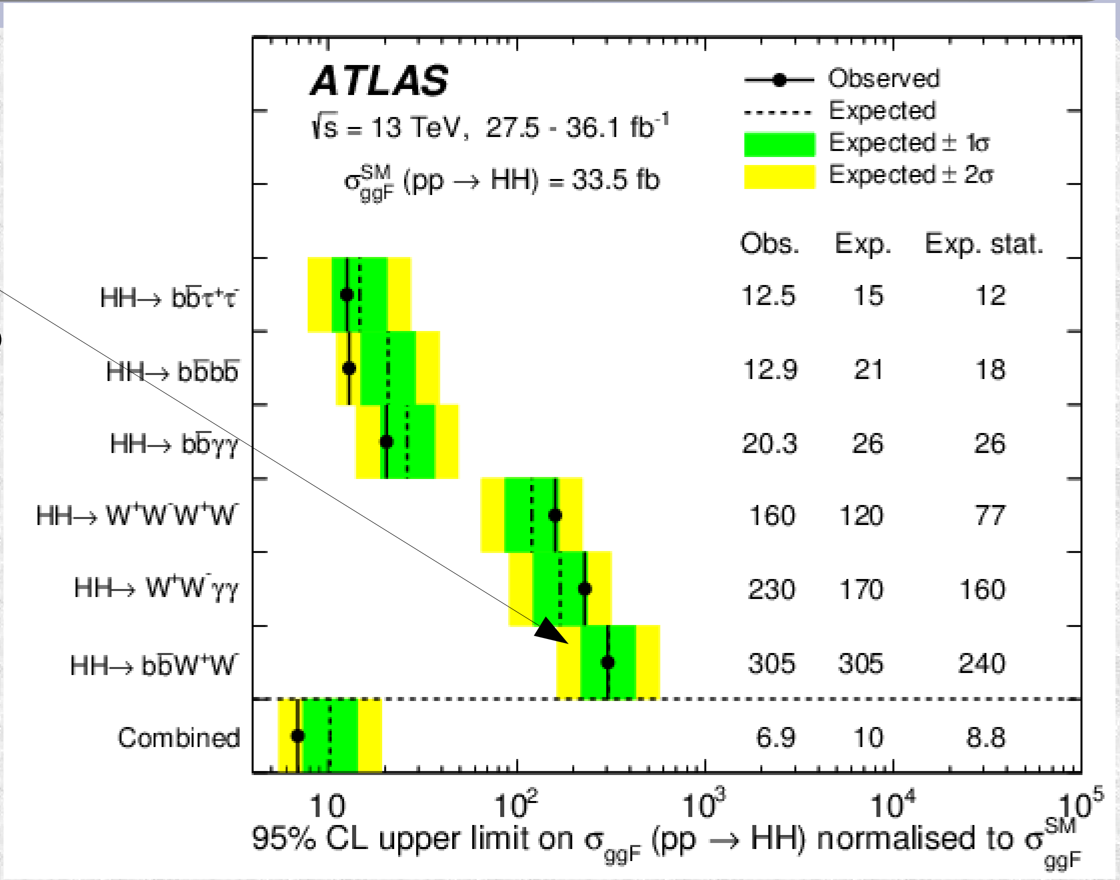
Combined sensitivity to HH

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

- The fitted HH signal μ can be extracted with about a 40% error

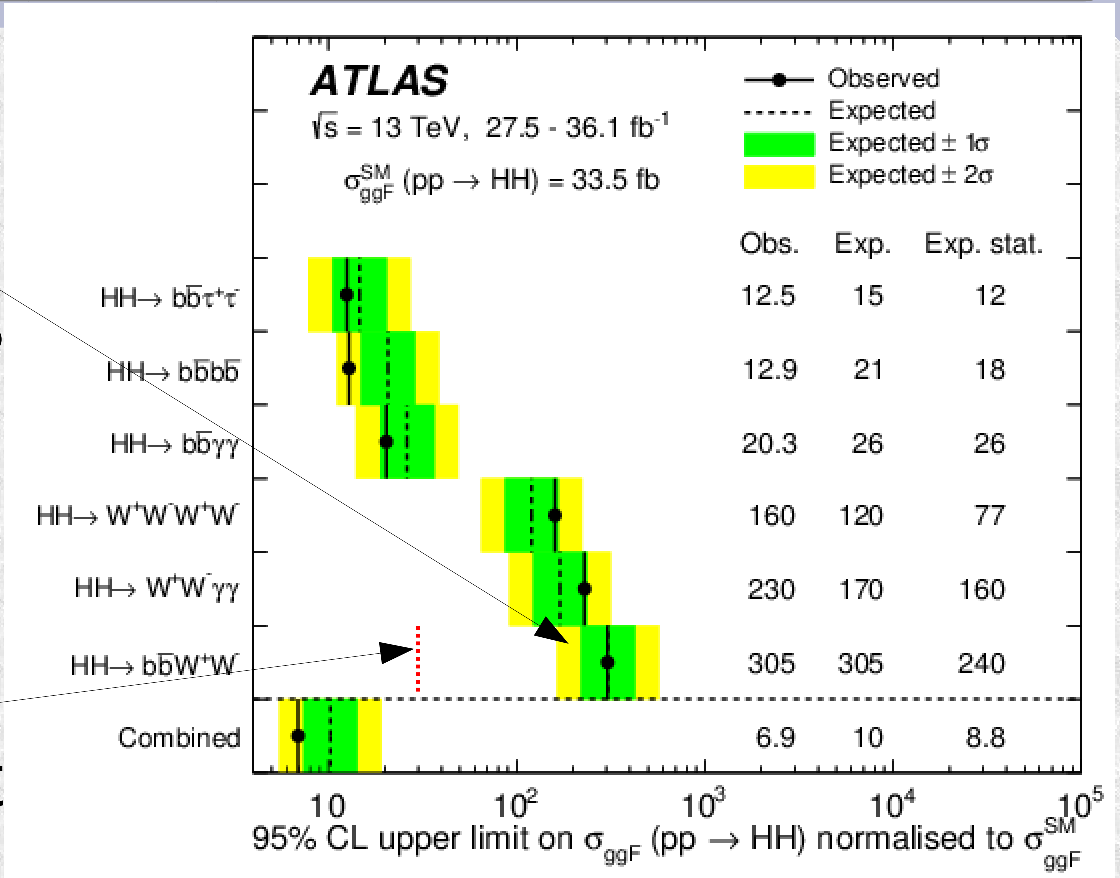
Caution on predictions

- ATLAS 36fb[-1] HH summary
  - bbWW at 305 x SM!
  - Looks pretty hopeless?

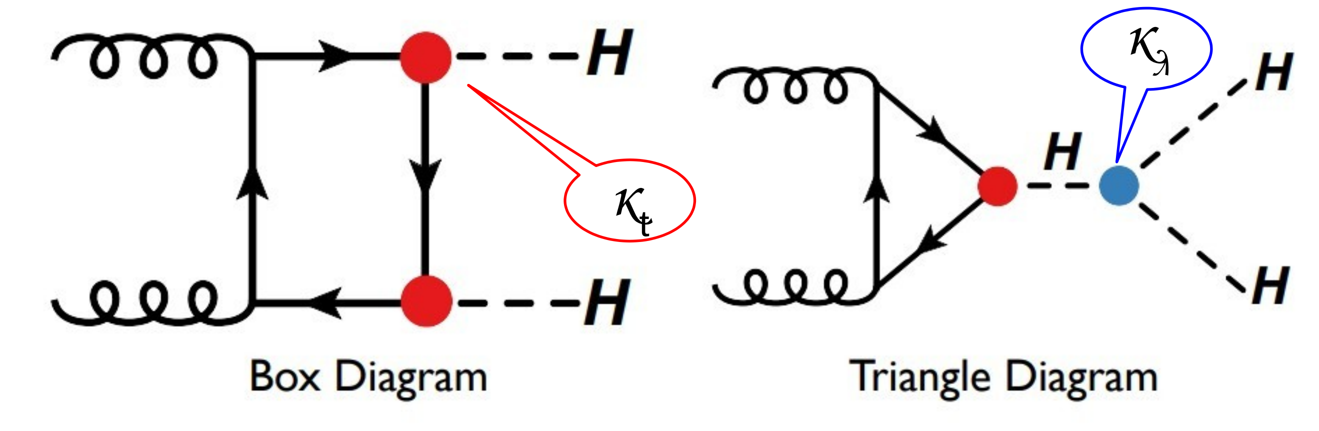


Caution on predictions

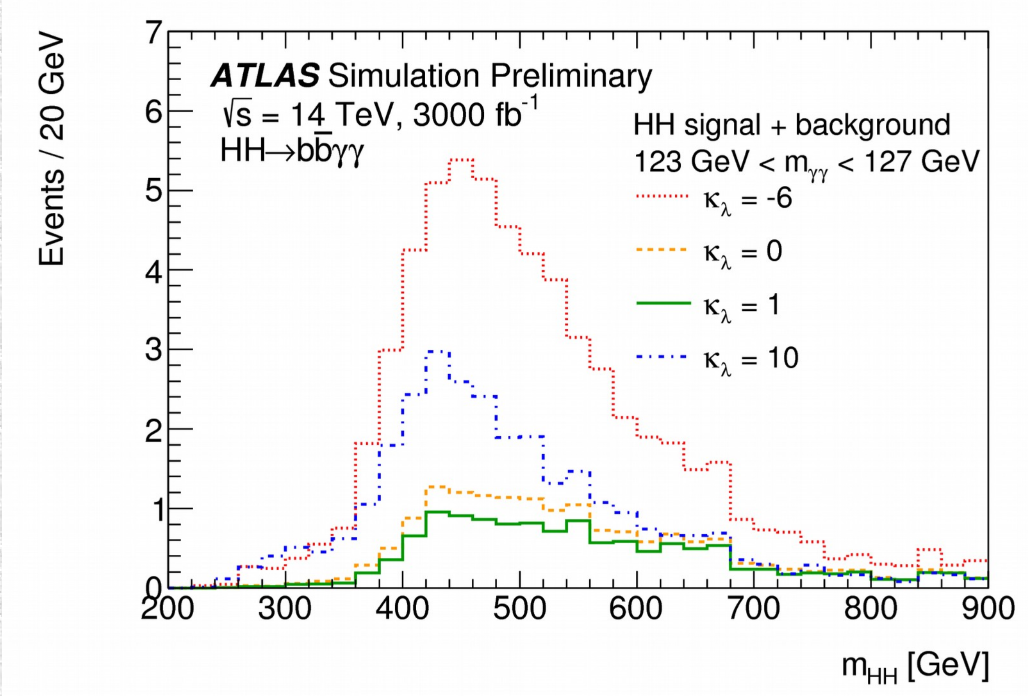
- ATLAS 36fb^{-1} HH summary
  - bbWW at 305 x SM!
  - Looks pretty hopeless?
- But 139fb^{-1} bbWW
  - Dileptonic; previous was single-lepton
  - Expected limit 29xSM
  - Factor 10 improvement
- Good ideas and hard work can still improve all the results



Di Higgs interpretation

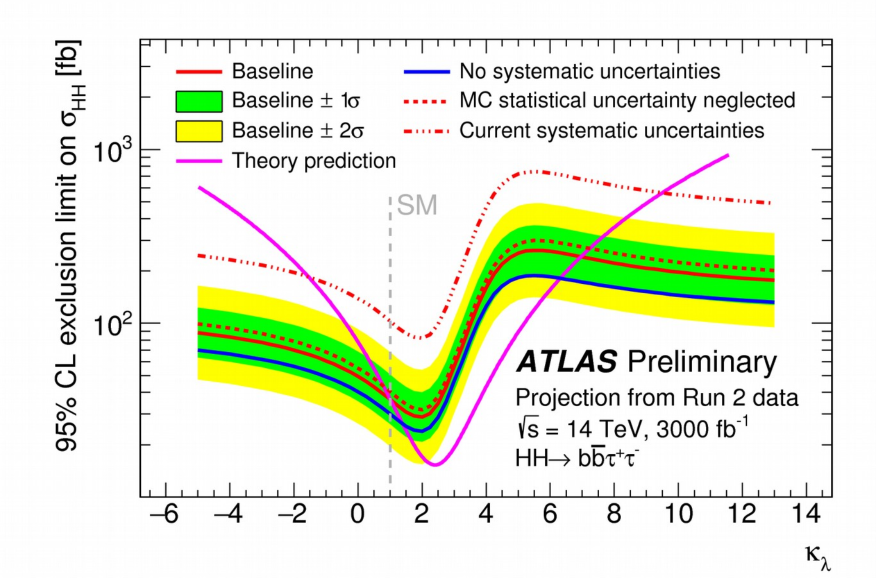


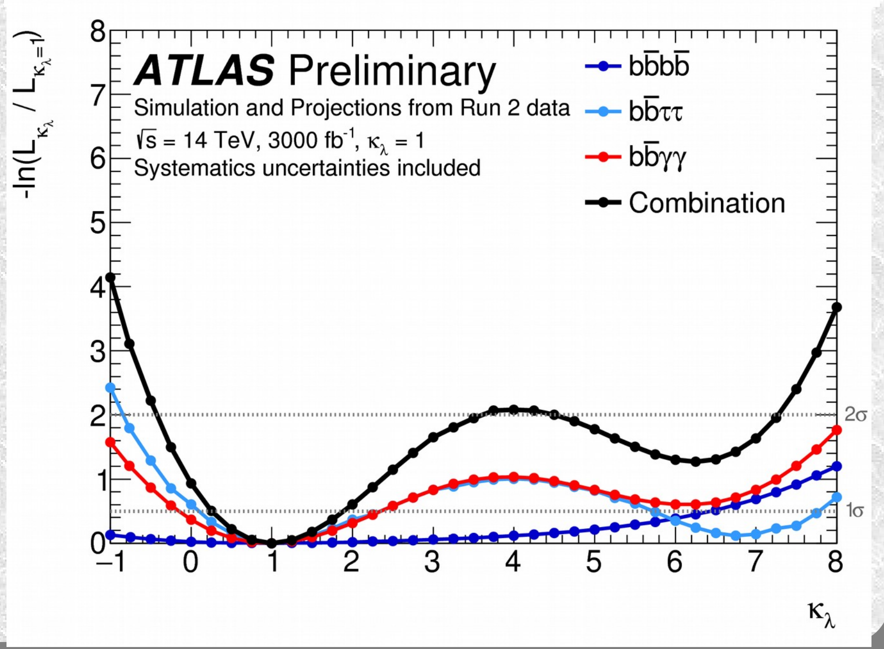
- Destructive interference between box and triangle
- Varying κ_λ injects signal
  - Mostly at low m_{HH}
- Example for bbγγ right
- Low mass is harder to trigger for bb and ττ modes
  - Limits degrade



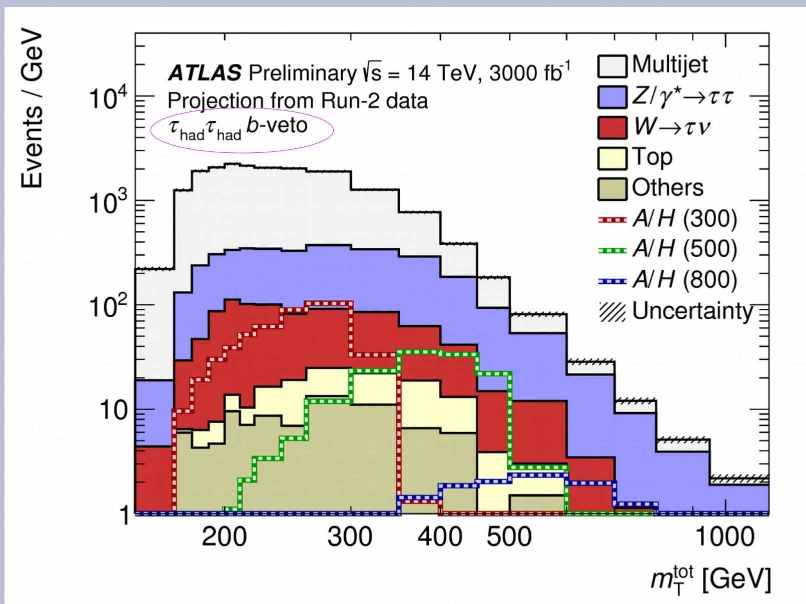
Limits v κ_λ

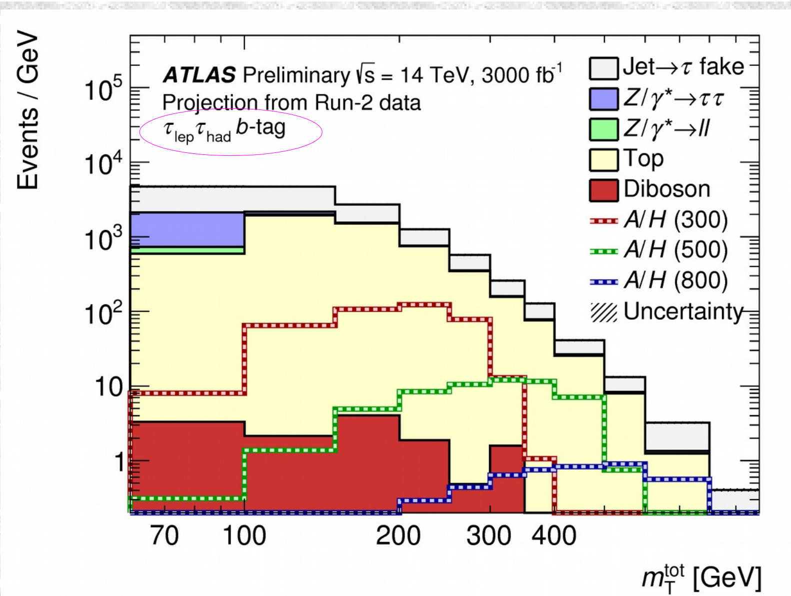
- Cross-section at SM κ_λ=1 and κ_λ=4 similar
  - Therefore approx degeneracy
  - But kinematics is different
- Result is second minimum in LR v κ_λ gg
  - Could be reduced by more detailed m_{HH} study
- Expected exclusion: κ_λ<0.4 or > 7.4



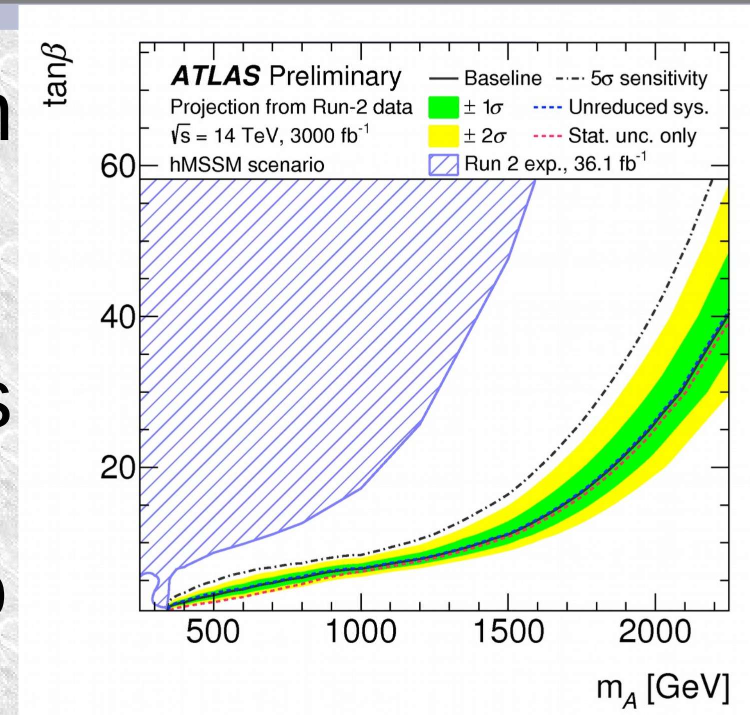


Searches continue: h/A to ττ





- Tau pair in l-h and h-h channels
- with b-tag or b-veto



- Expect to be sensitive to tan β>12 for m_A<1TeV in hMSSM
- Still sensitive at m_A=2TeV

More searches

- The list is long and incomplete
- Many potential new physics scenarios are possible
  - Many of them weakly coupled / aligned
- Examples:
  - h125 $\rightarrow$ Za
    - A light `a' decaying to photons or even stable
  - $H_3 \rightarrow H_2 H_1$ with any of these 125 GeV
  - $H^+ \rightarrow$ Wh $\tau\nu$ or tb
  - bH,H $\rightarrow \mu\mu$
  - H $\rightarrow$ aa $\rightarrow$ {bb, $\tau\tau$, $\mu\mu$, jj, $\gamma\gamma$, invisible}^{2}
  - $H^{++} \rightarrow W^+W^+$
- One small Higgs can ruin all your plans

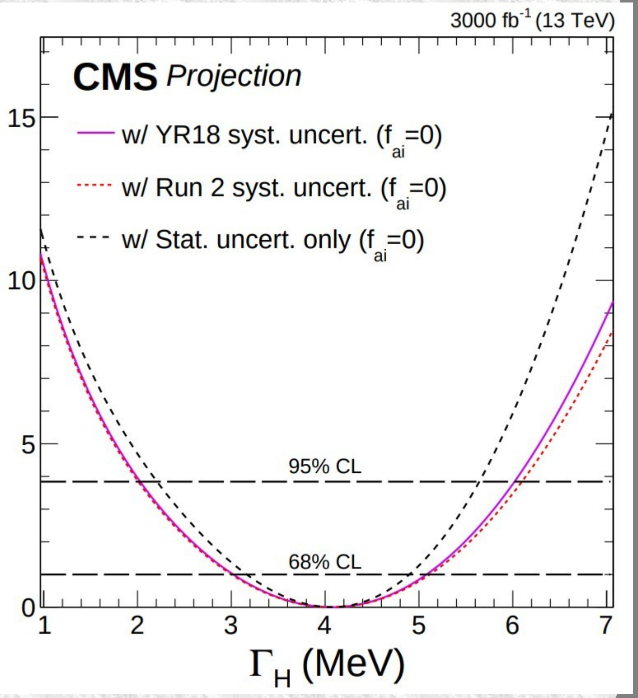
Conclusions

- The HL-LHC programme holds many exciting Higgs Hunting opportunities
  - The H125 couplings potential is excellent
    - The rare, and invisible decays will be strongly probed
  - The diHiggs studies are a must
    - 3 sigma evidence for HH seems possible
    - All studies of the BEH field are critical right now
  - And the search programme extended
- But to make it real we have to invest effort in hardware and software upgrades
  - These are comparable to building ATLAS (&CMS)
  - And will not happen without dedicated effort

How to punch a hole?

Higgs mass and width

- Higgs mass will improve from current 240 MeV (ATLAS)
  - 52 MeV if no improvements made
  - 47 MeV if Itk yields 30% resolution improvement
  - 33-38 MeV If also scale uncertainty reduced 50-80%
- Width
  - CMS project range 2-6 MeV @95%CL
    - S1/S2 similar here



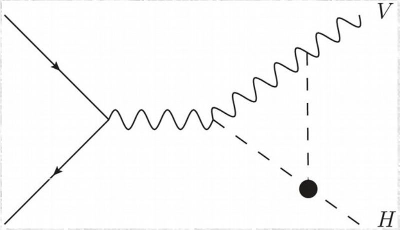
Self coupling from single H

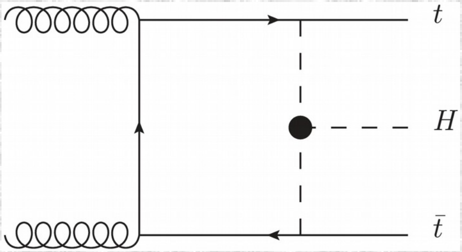
- Higgs self coupling is major target
- Loop diagrams mean single Higgs rates are sensitive
  - Especially using distributions
  - ttH structure different
- Extract limits on coupling:

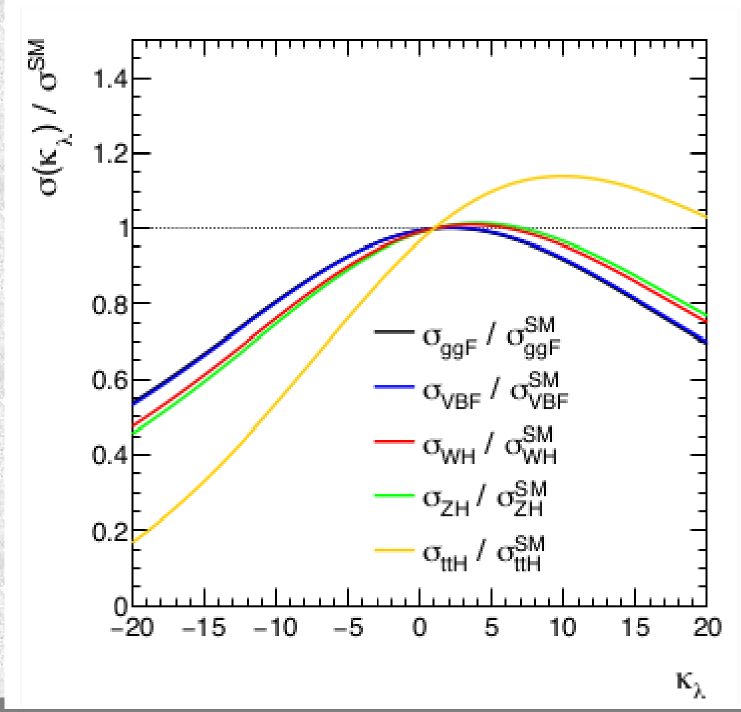
$$\kappa_\lambda = 4.0^{+3.7}_{-3.6}(\text{stat.})^{+1.6}_{-1.5}(\text{exp.})^{+1.3}_{-0.9}(\text{sig.th})^{+0.8}_{-0.9}(\text{bkg.th})$$

$$-3.2 < \kappa_\lambda < 11.9 \quad @ \text{ 95\% CL}$$

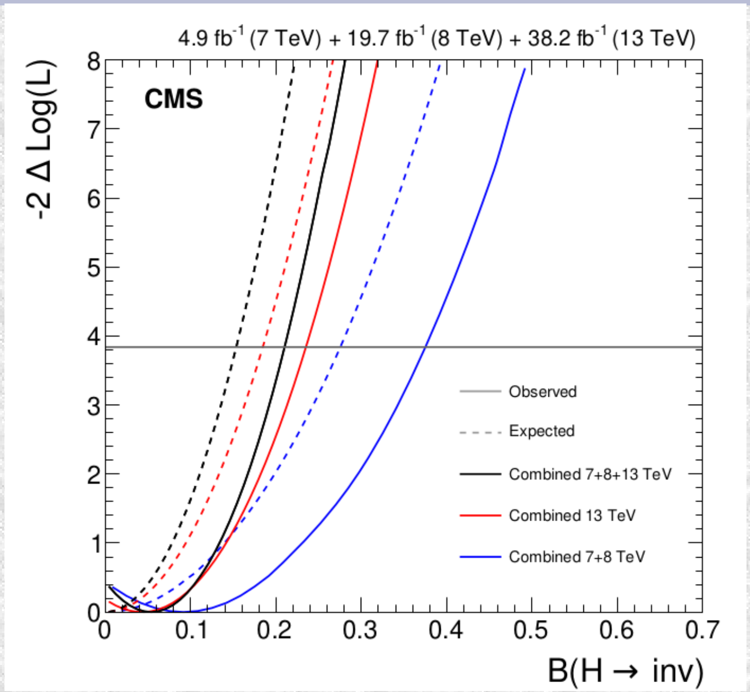
- Tighter than direct HH: $-5 < \kappa_\lambda < 12.1$
  - But using more data

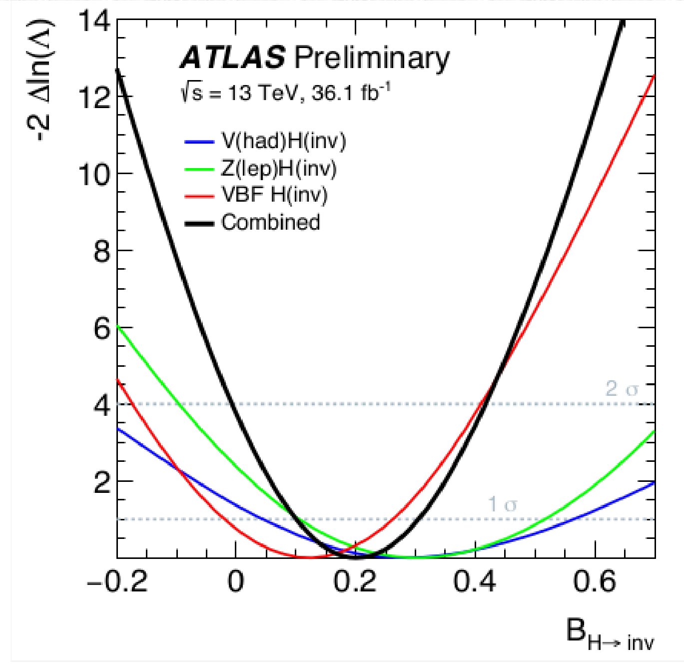






Invisible Higgs





- CMS released a new combination of datasets
  - Most powerful invisible Higgs limit
  - 15% expected, 19% observed
- ATLAS 13 TeV result:
  - 17% expected, 26% observed
  - Both have small preference for positive decay fraction?