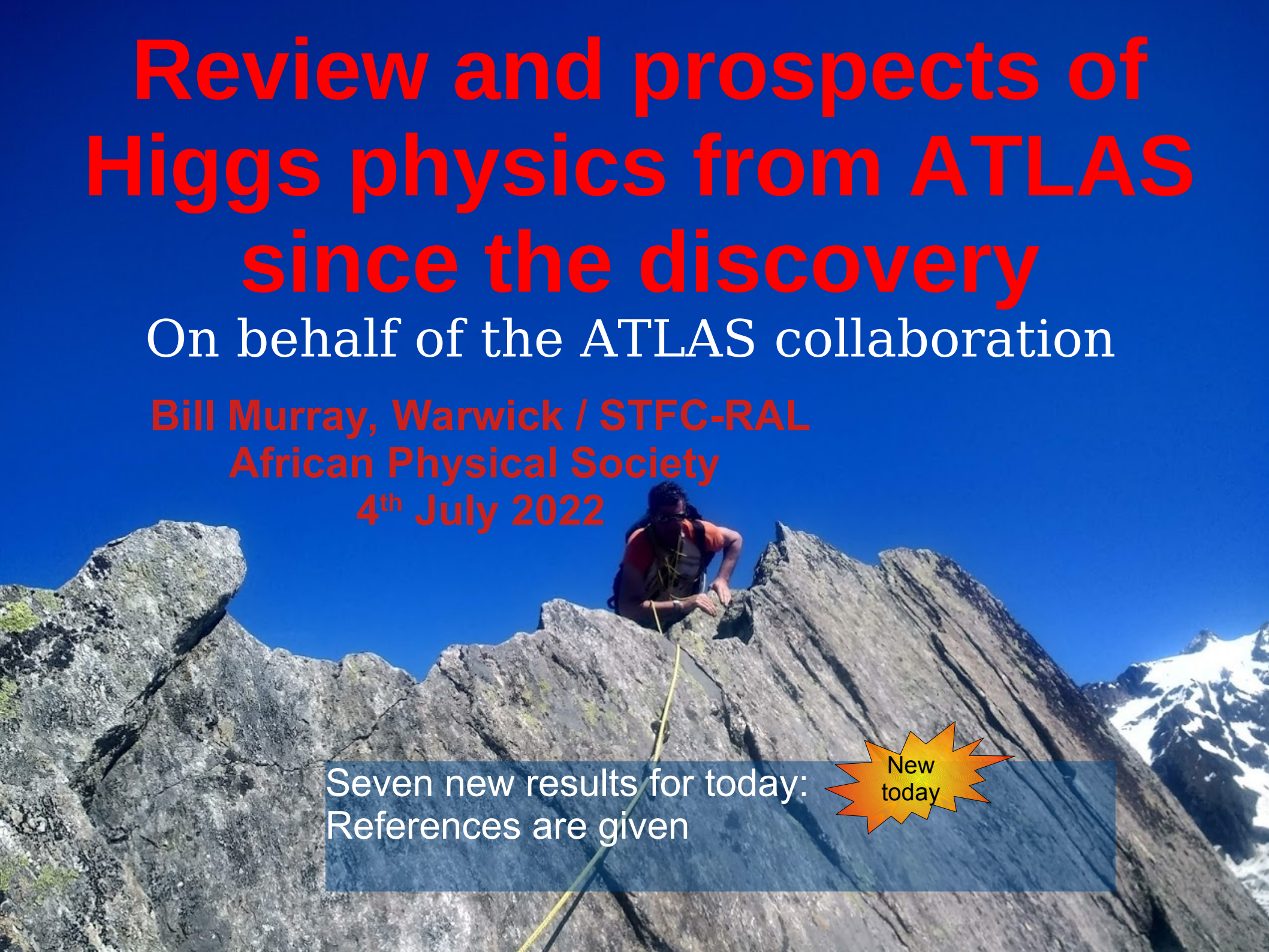
Review and prospects of Higgs physics from ATLAS since the discovery

On behalf of the ATLAS collaboration

Bill Murray, Warwick / STFC-RAL

African Physical Society

4th July 2022



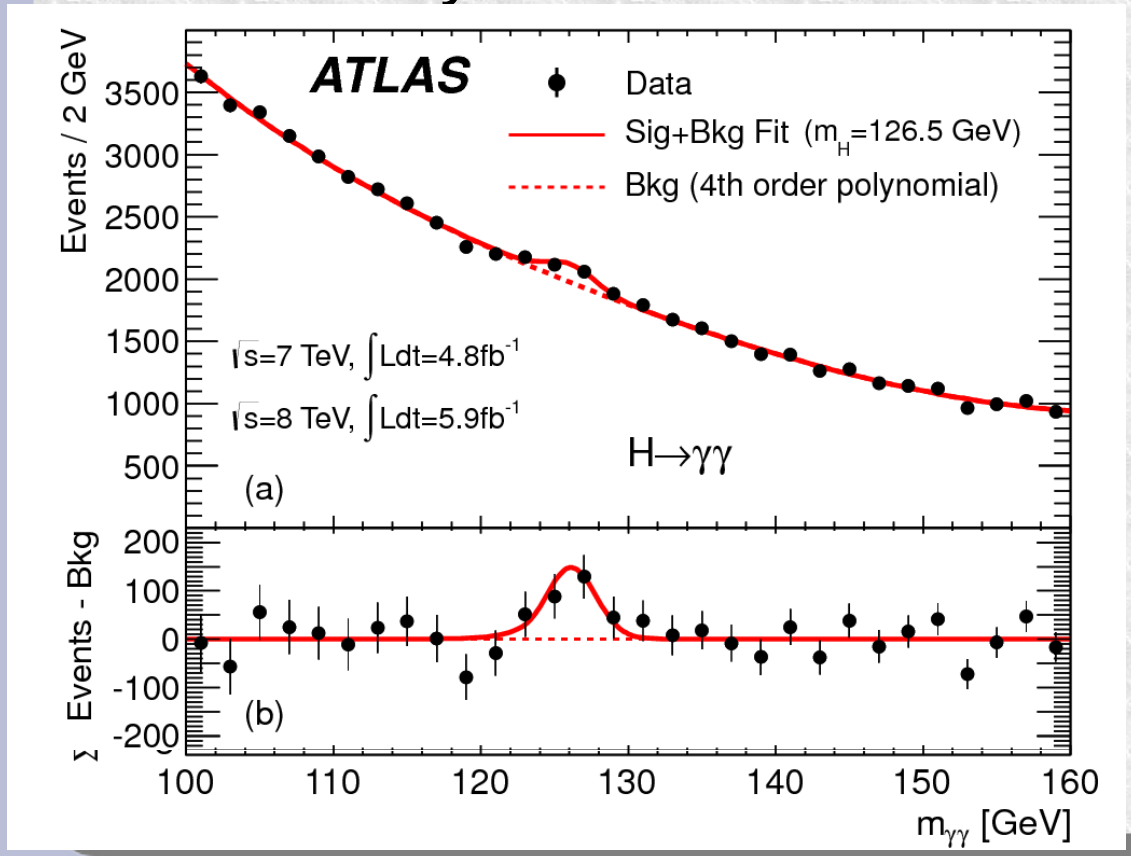
Seven new results for today:
References are given

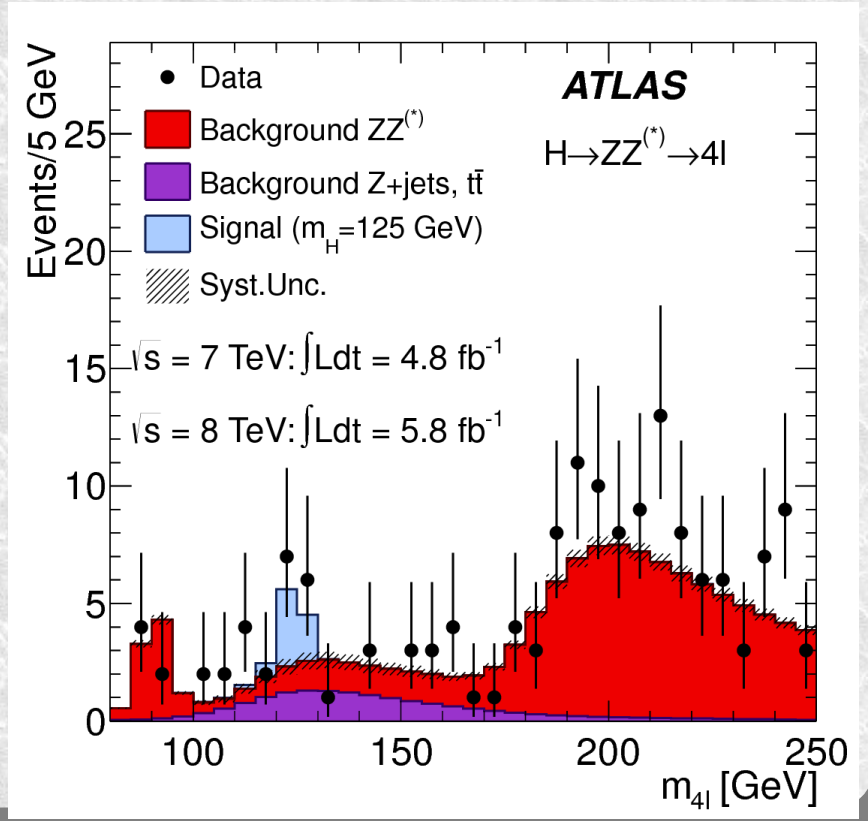
New today

Higgs boson: ATLAS overview

- 2012
  - Observation of a new particle in the search for the SM Higgs boson
    - Cited 19121 times

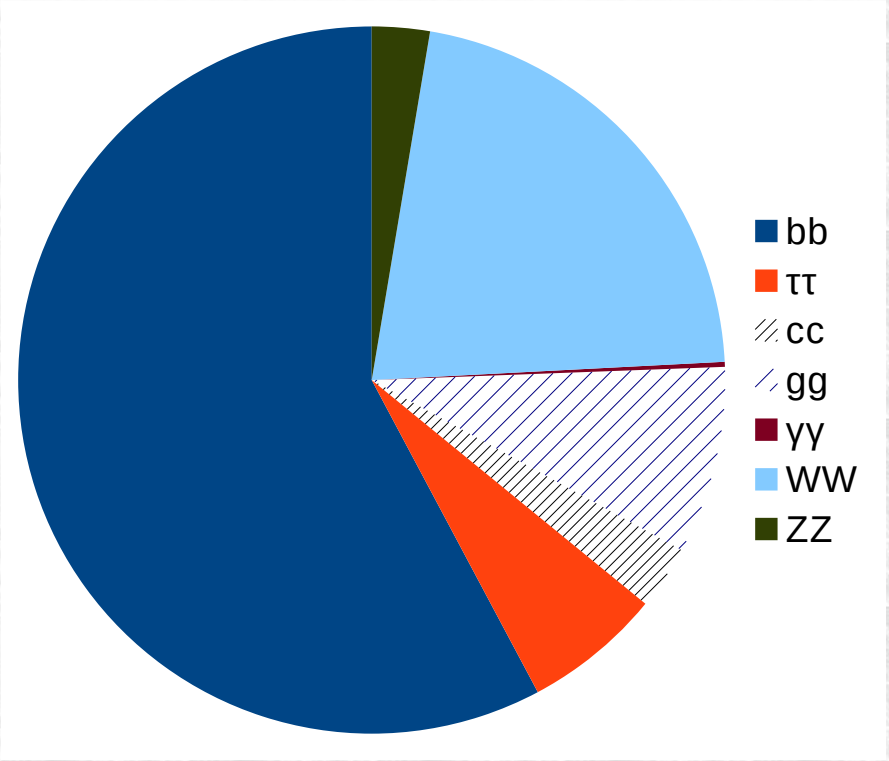
Mass is only unknown: A+C measured to 0.2%. done?





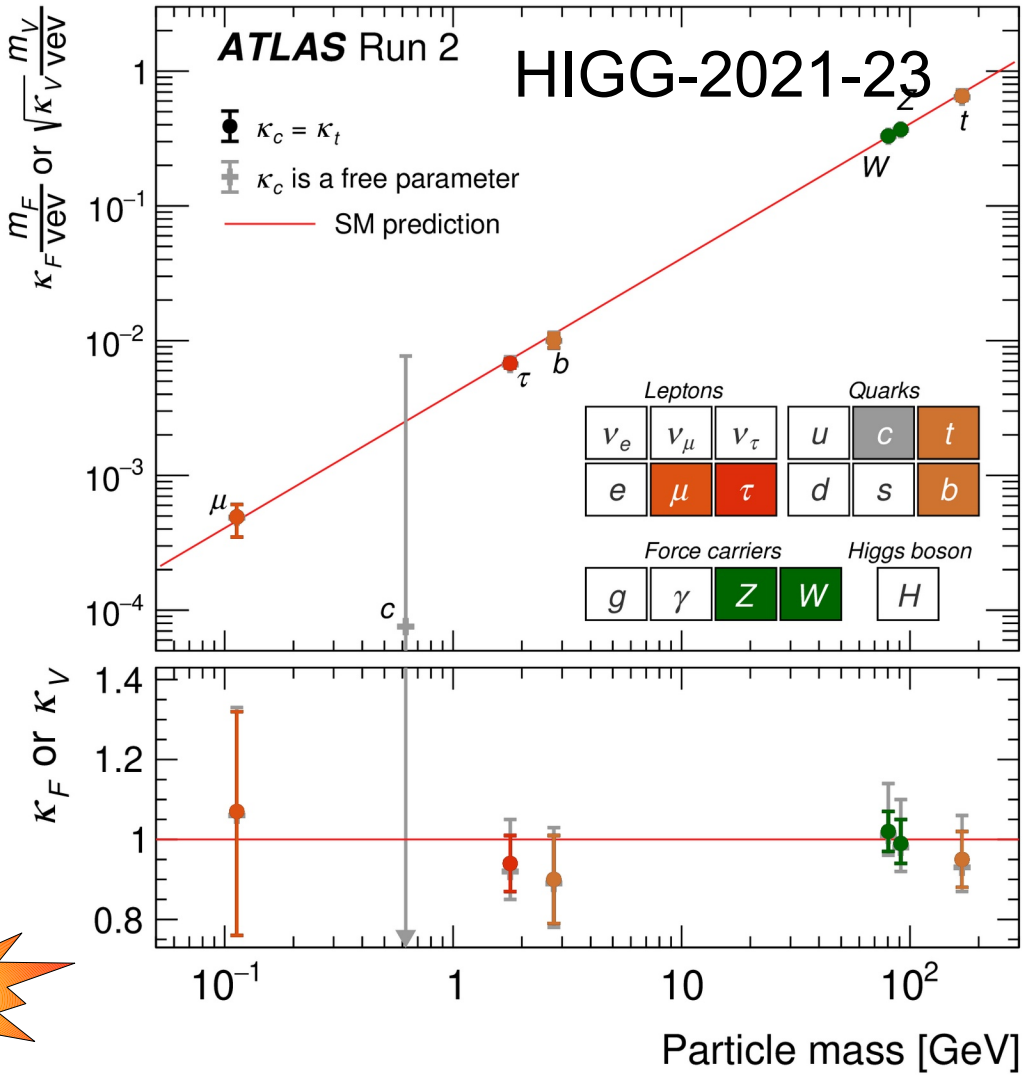
Higgs boson: ATLAS overview

- Summary: The defining discovery of the LHC
  - It completed a picture imagined in 1964
- But to know it is the Higgs boson need to measure
  - Decay to ZZ, γγ, WW, ττ, bb: all observed at 5σ
  - Same for ggH, VBF, VH and ttH production
- Is it the CP-even scalar expected? Seems to be
- We have to test properties in detail
  - This fundamental(?) scalar is unnatural!



Interactions with all particles?

- Interaction should be proportional to mass
- Confirmed for vector bosons and most 3rd generation fermions
  - None known when model written down!
- 2nd generation fermions now being constrained too



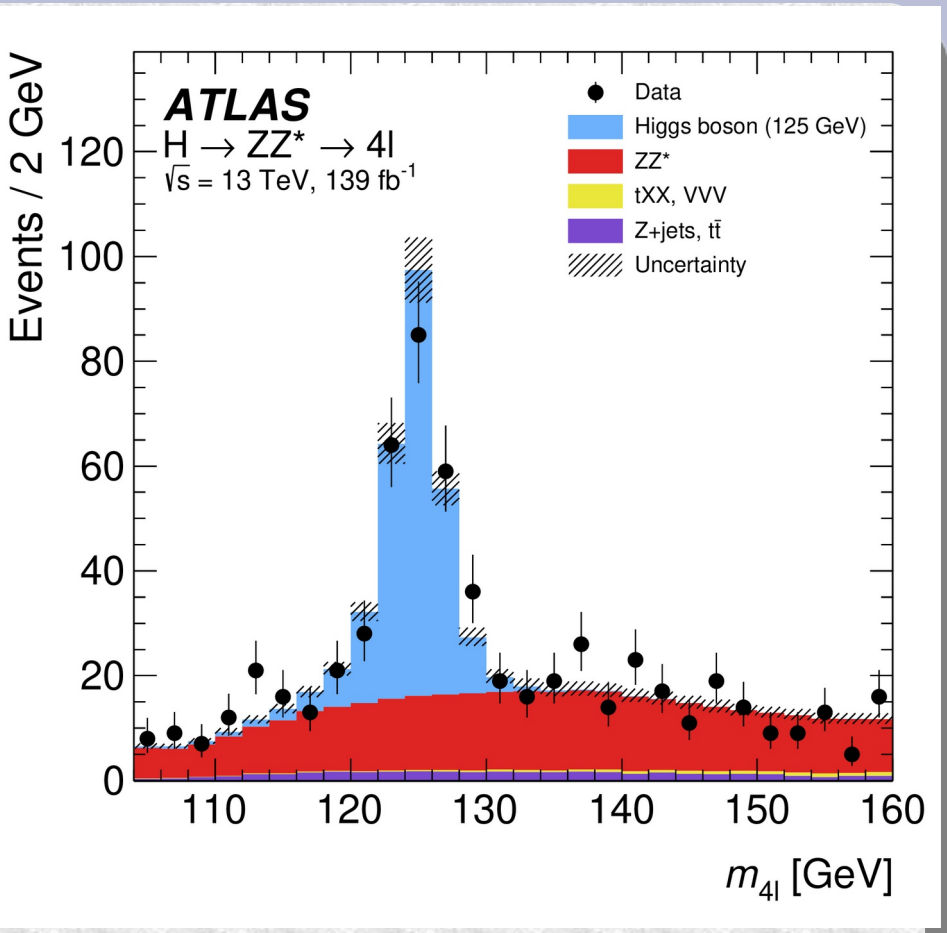
New today

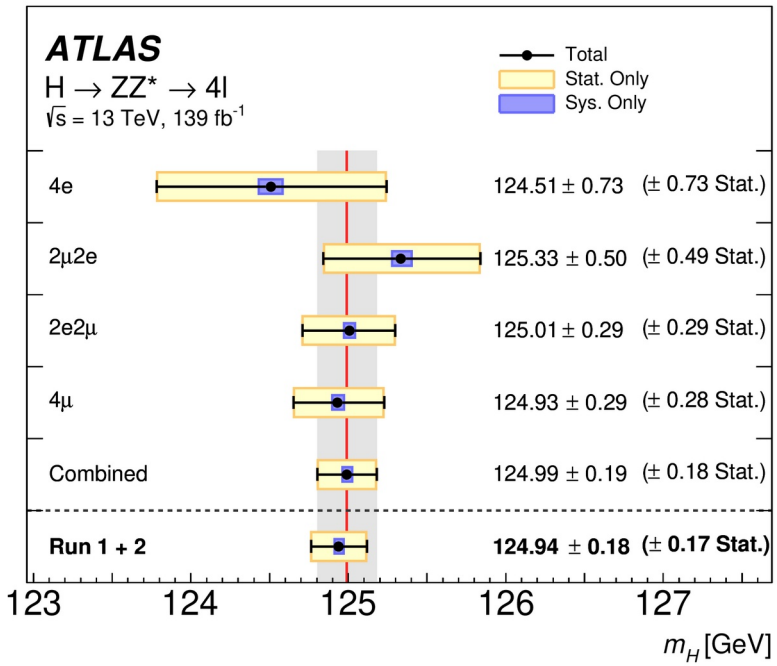
New today

H to ZZ & mass

HIGG-2020-07

- Clean mode used for much
  - Fig is from mass paper
- M_H=124.94±0.19GeV
  - Stat dominated
  - 28 MeV unc from μ p_T scale



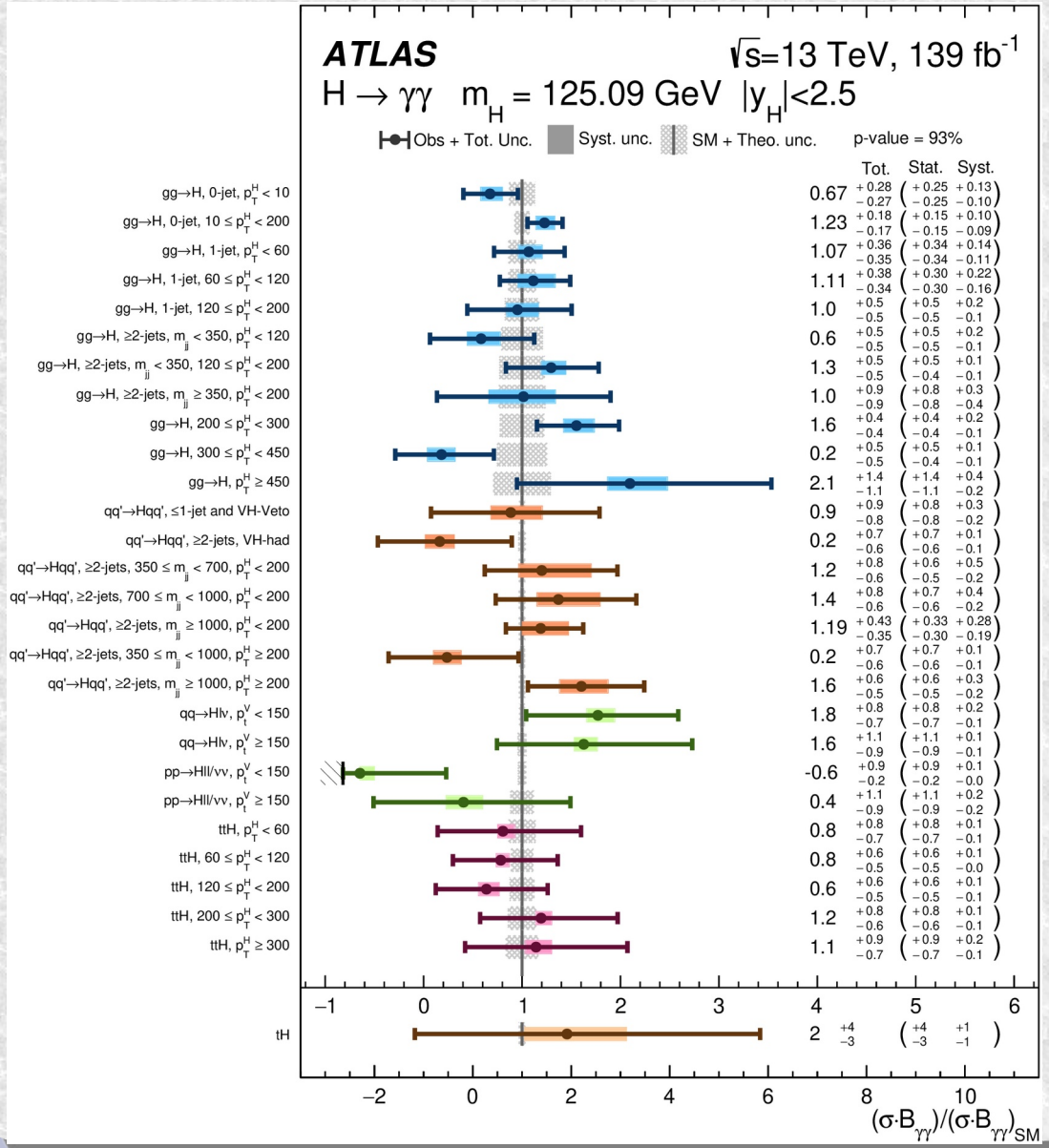


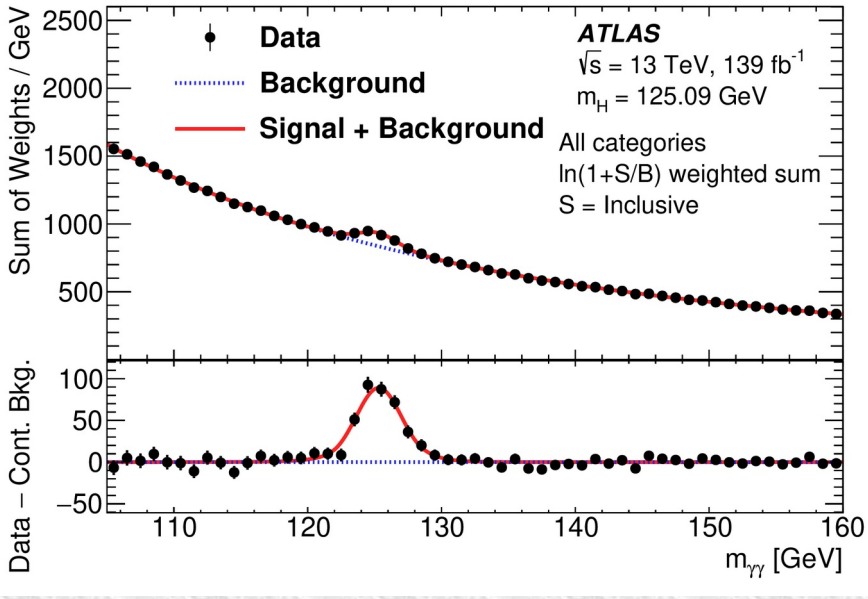
- 0.15% from single channel
  - More to come (γγ)

New today

H to γγ

HIGG-2020-16





- Thousands of events
  - Sensitive to all production modes
  - Overall $\mu = 1.04^{+0.10}_{-0.09}$
- Constrains κ_t positive
- Also VBF CP result

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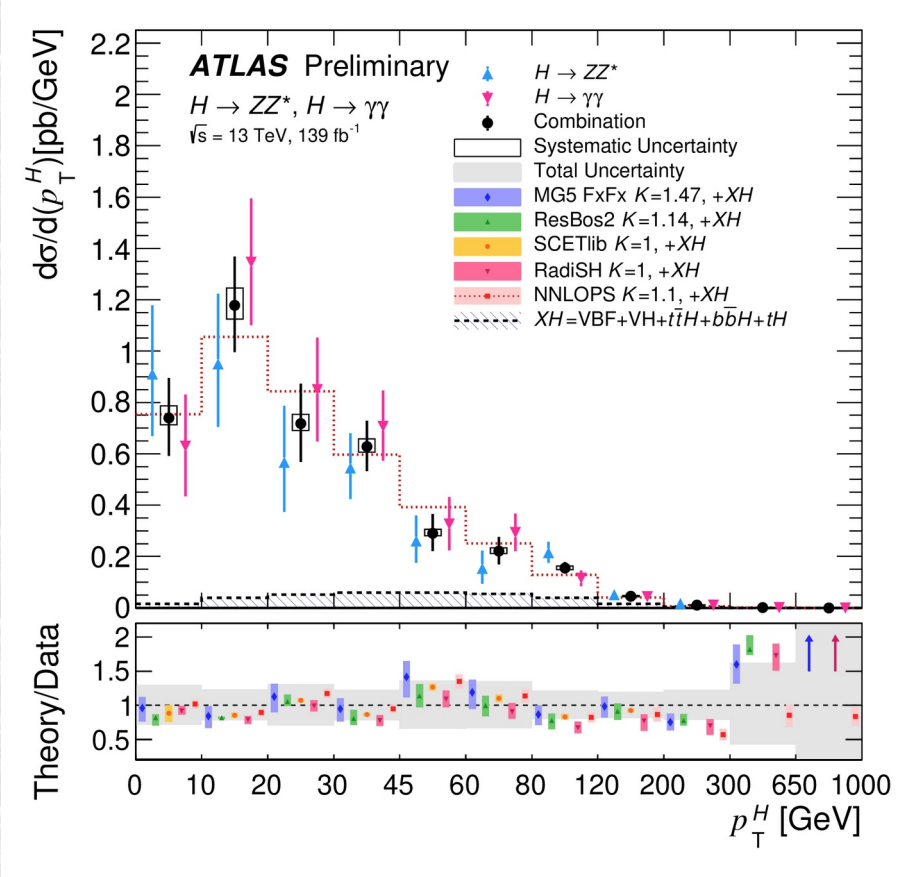
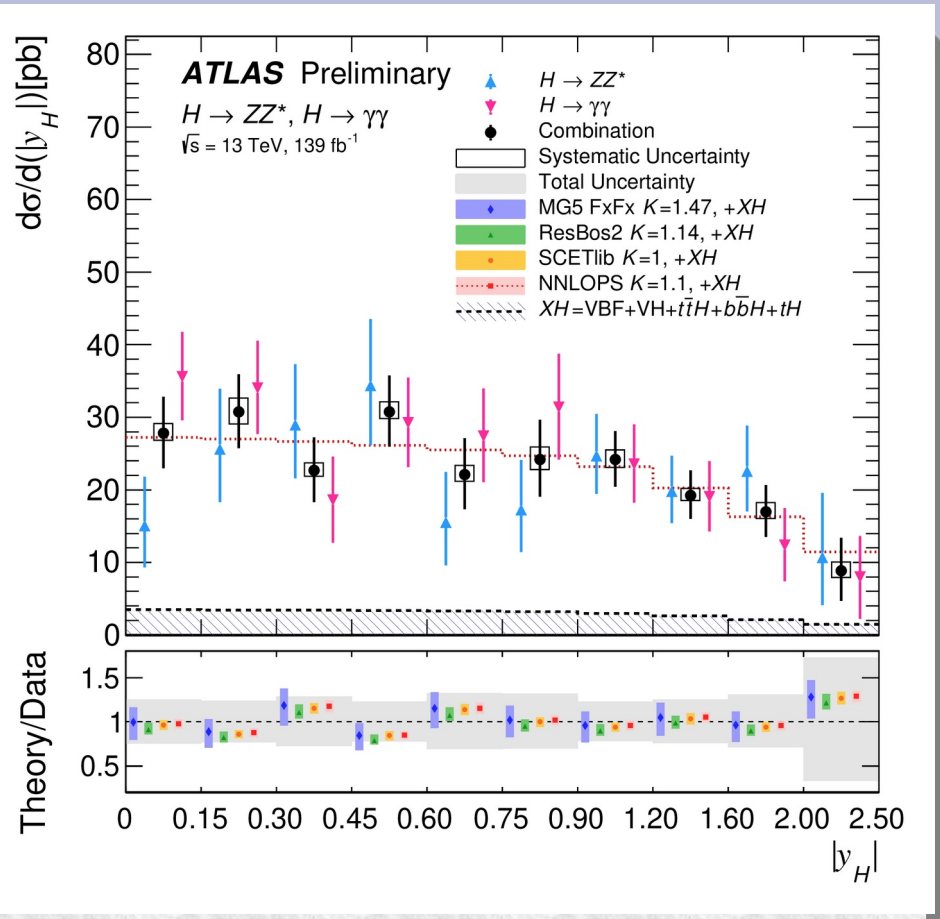
Differential distributions



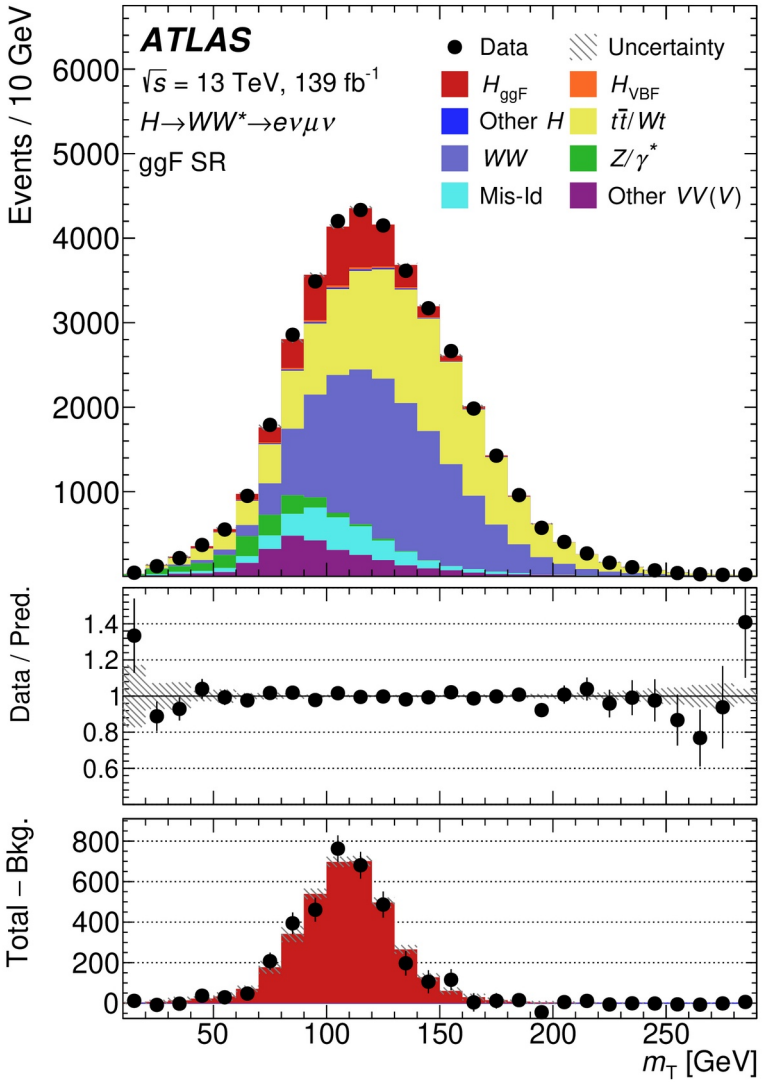


- Clean γγ and ZZ modes can access H p_T, η
- Distribution sensitive to b, c components of ggF loop: $-10.1 < \kappa_c < 18.3$

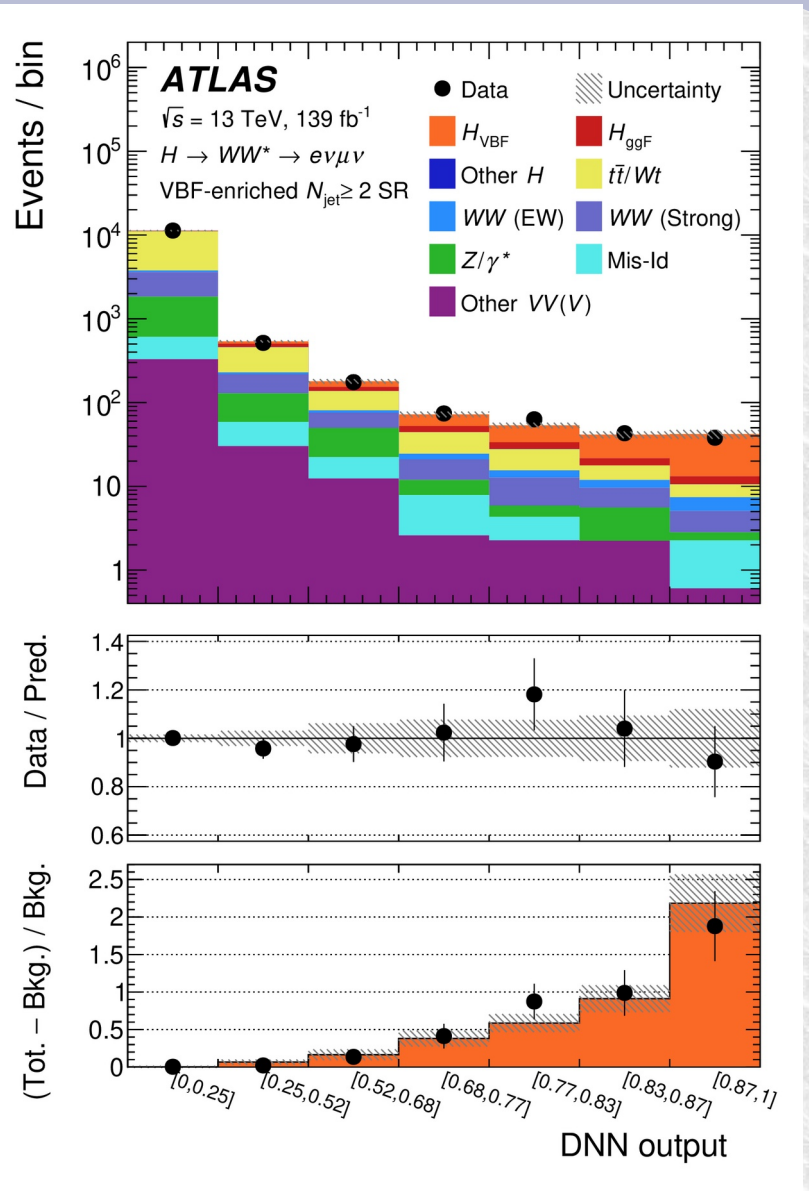
New today

ggF & VBF H to WW

HIGG-2021-20



- ggF (left) and VBF (right)
- High rate, but WW & tt bkds.

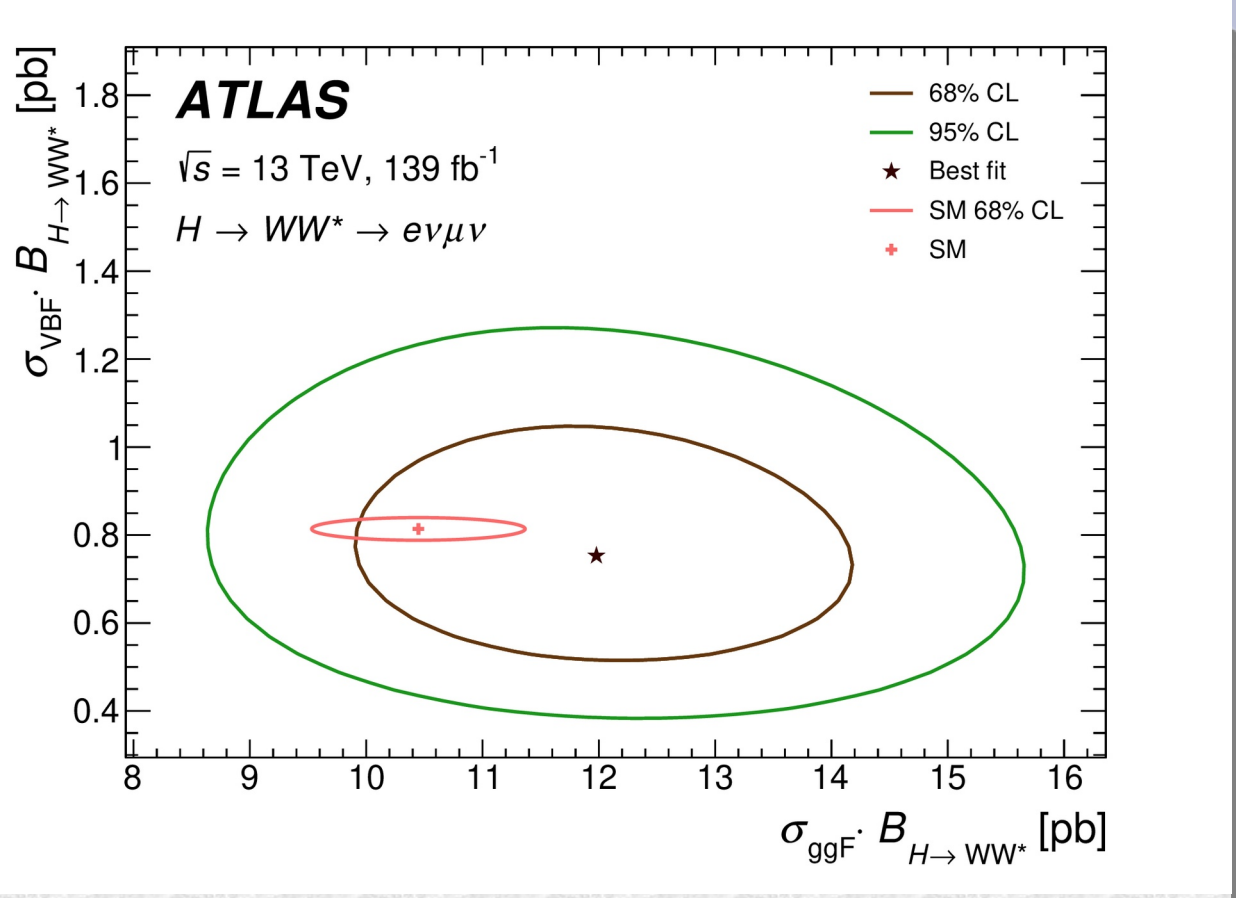


New today

H to WW

HIGG-2021-20

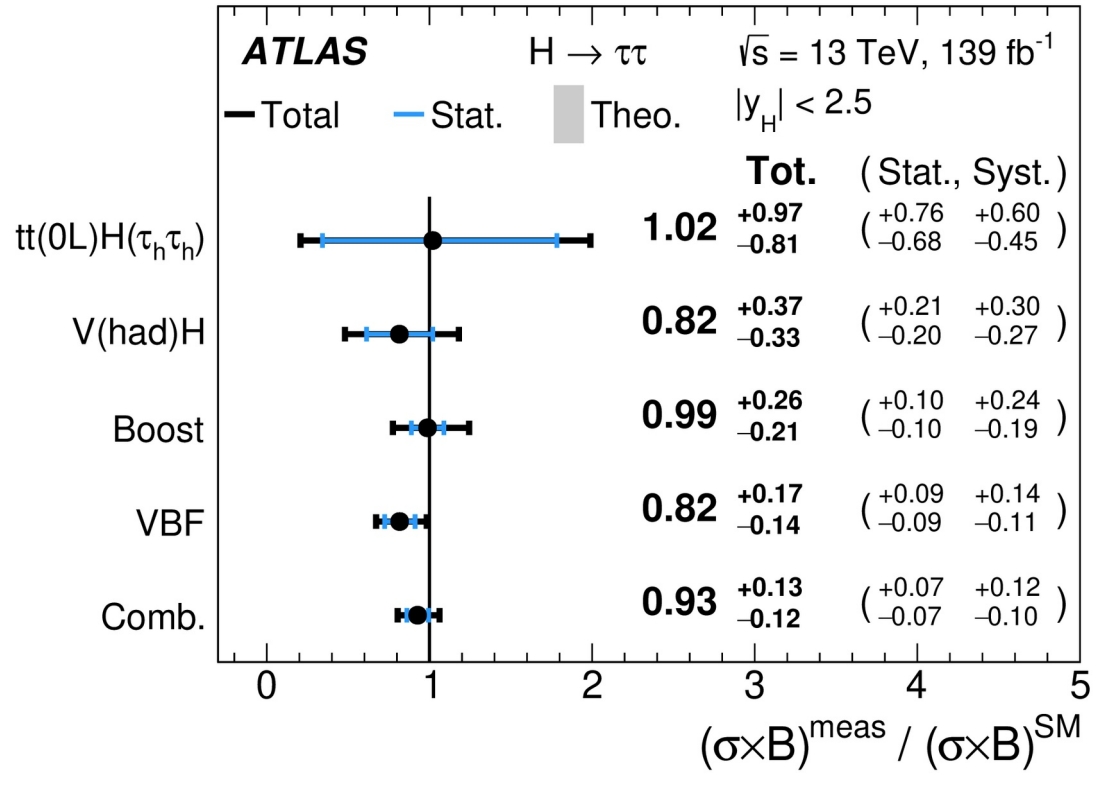
- 4200 signal events
- Precision measurements:
  - ggF: $\mu=1.15^{+0.14}_{-0.13}$
  - VBF: $\mu=0.93^{+0.23}_{-0.20}$
- Results also put out in STXS bins

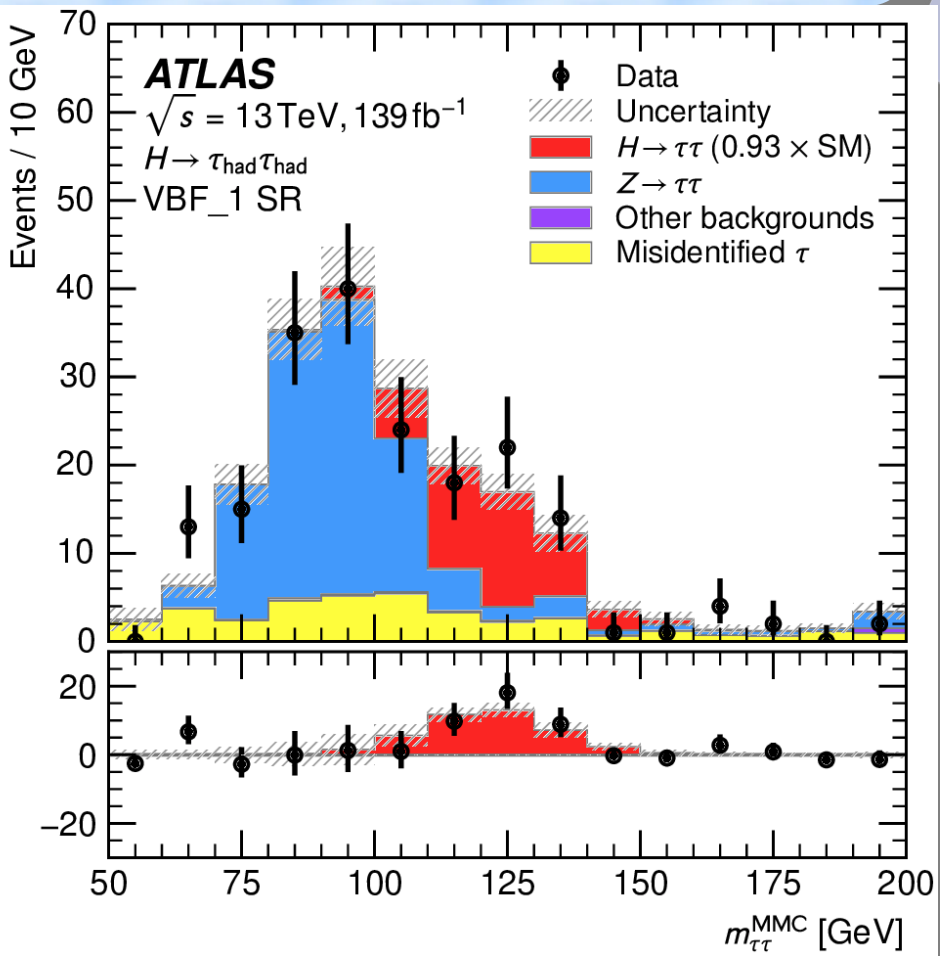


HIGG-2019-09

H to ττ

- h-h, l-h and e-μ channels; 4200 signal events
- 4 main production modes
  - VBF best measured





- All agree with SM

H to ττ decay

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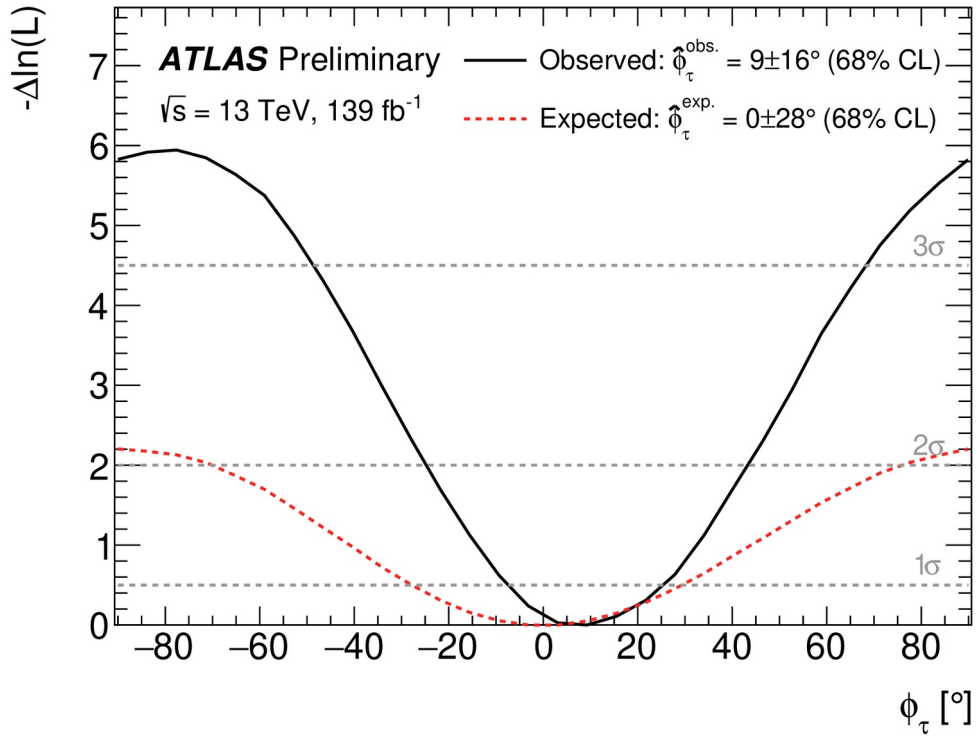
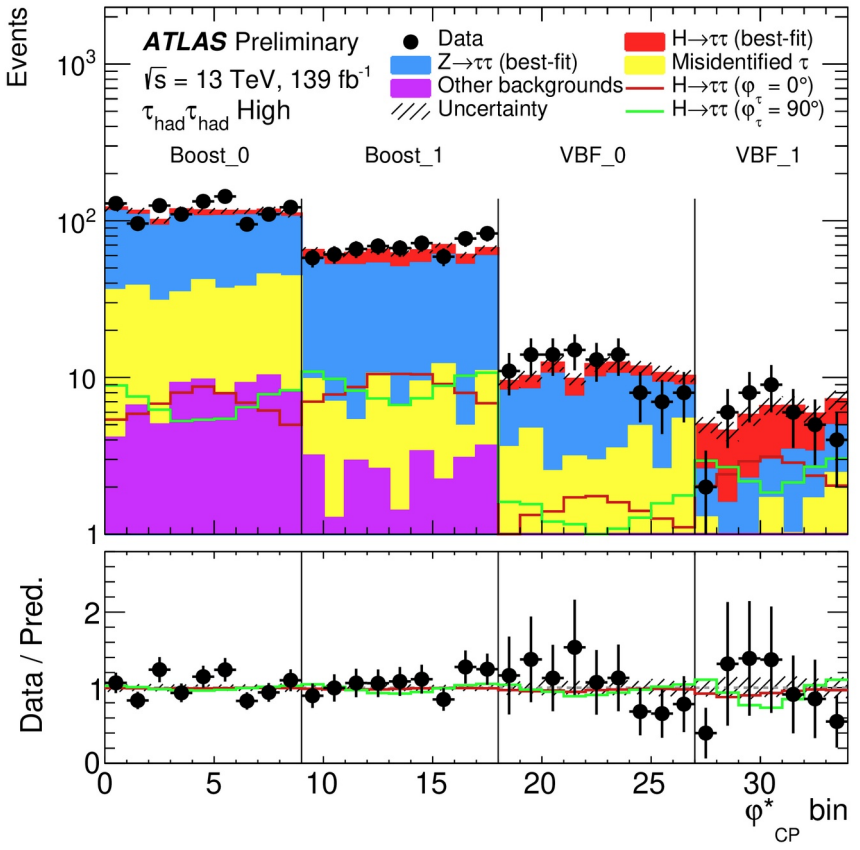
- Decay angles sensitive to CP coupling to fermions
  - Constrains mixing phase as 9±16°



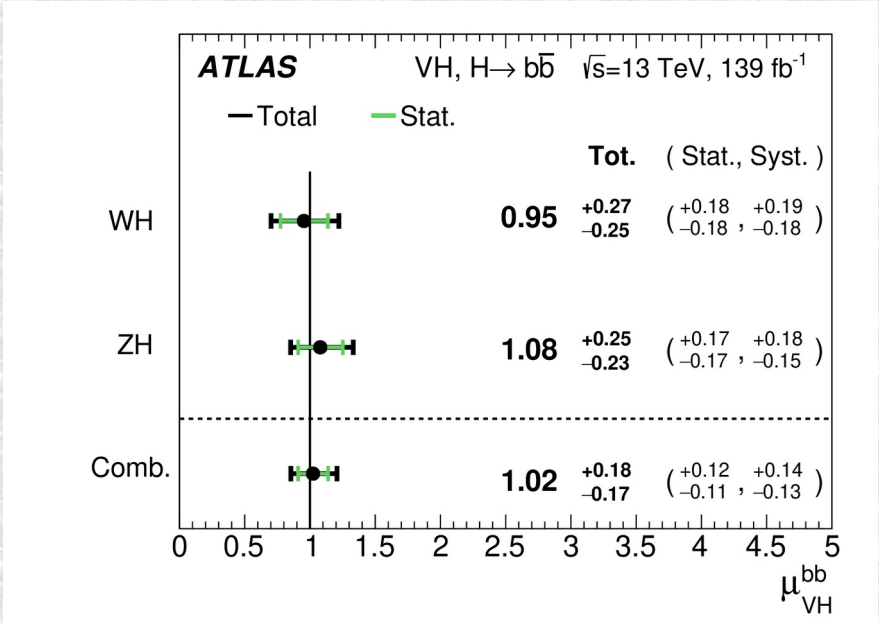


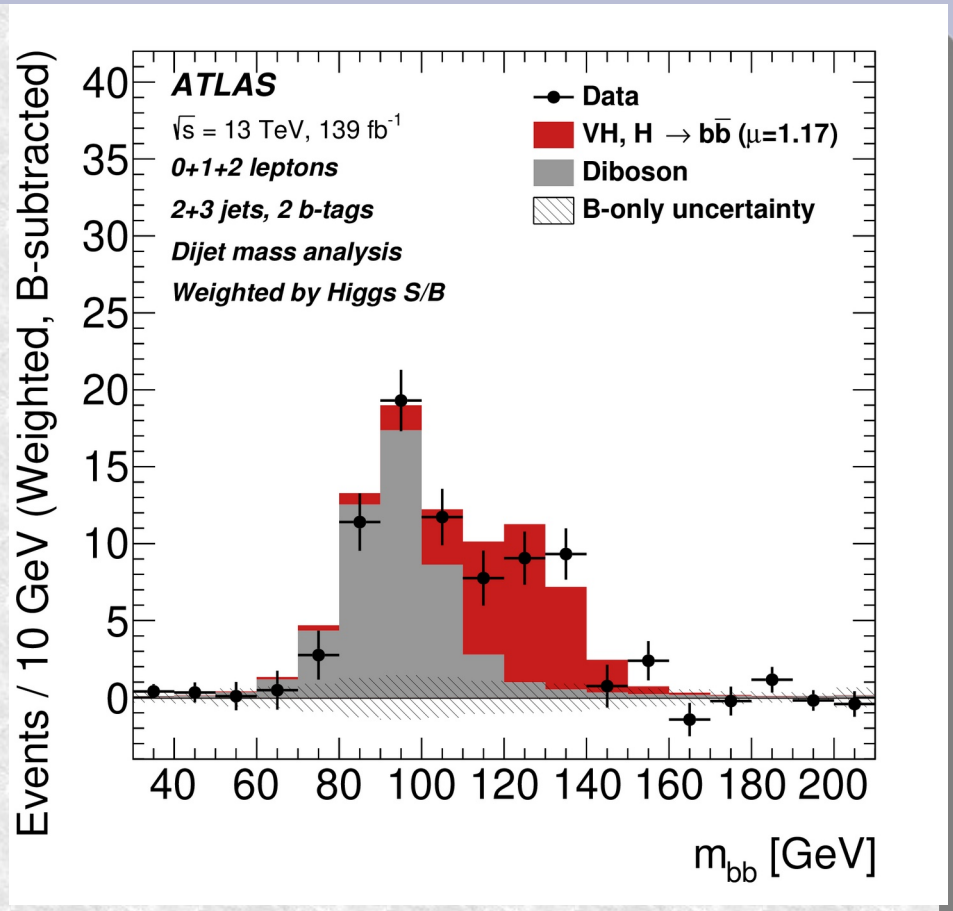
- Data gave unusually good error
- Other CP results older

H to bb

Eur. Phys. J. C 81 (2021) 178

- Best sensitivy in VH mode
  - Tag W or Z as trigger
- Analysis uses BDT
  - But cut-n-count easier to visualise.
- 0/1/2 leptons → Z/W/Z



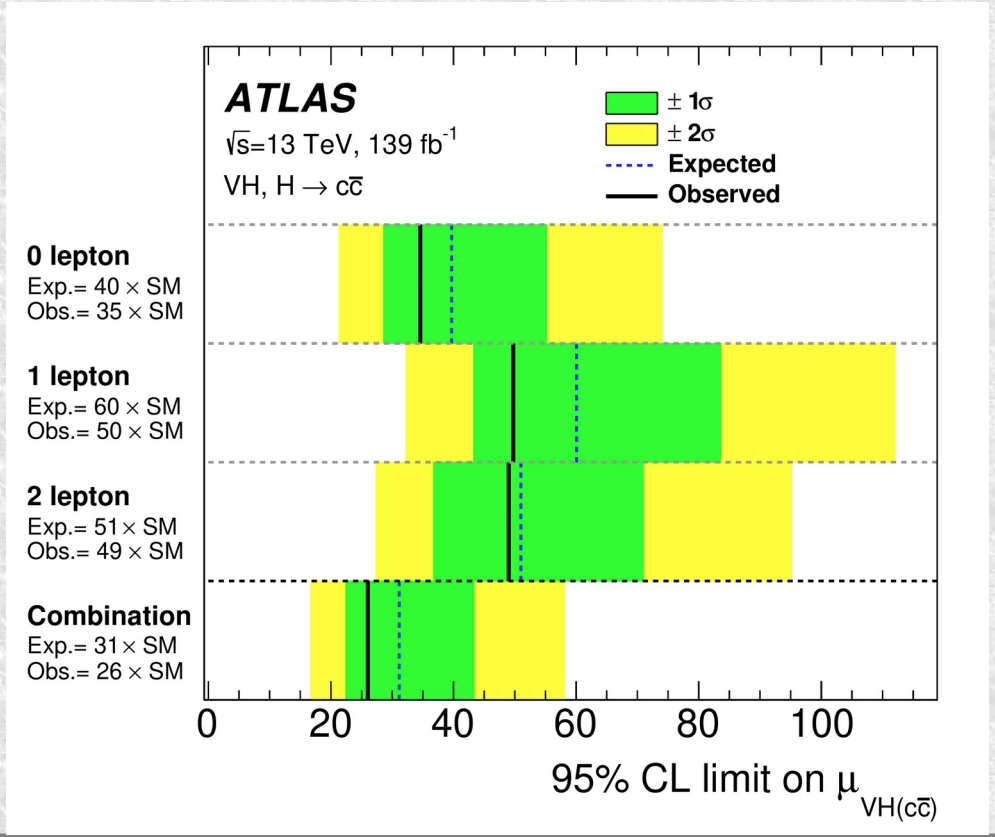


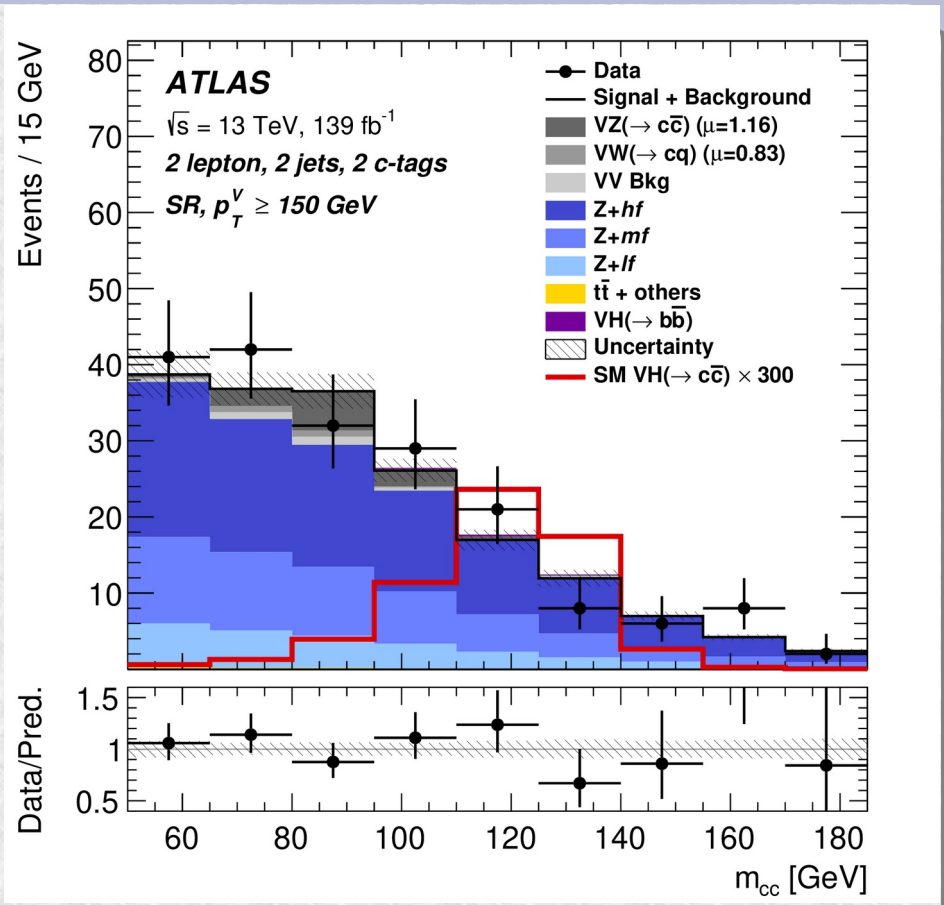
$$\mu_{VH}^{bb} = 1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$$

H to cc

arXiv:2201.11428

- Decay rate 3%, 1/20th bb
- Tagging charm quarks hard
  - Intermediate between light and b in mass and lifetime



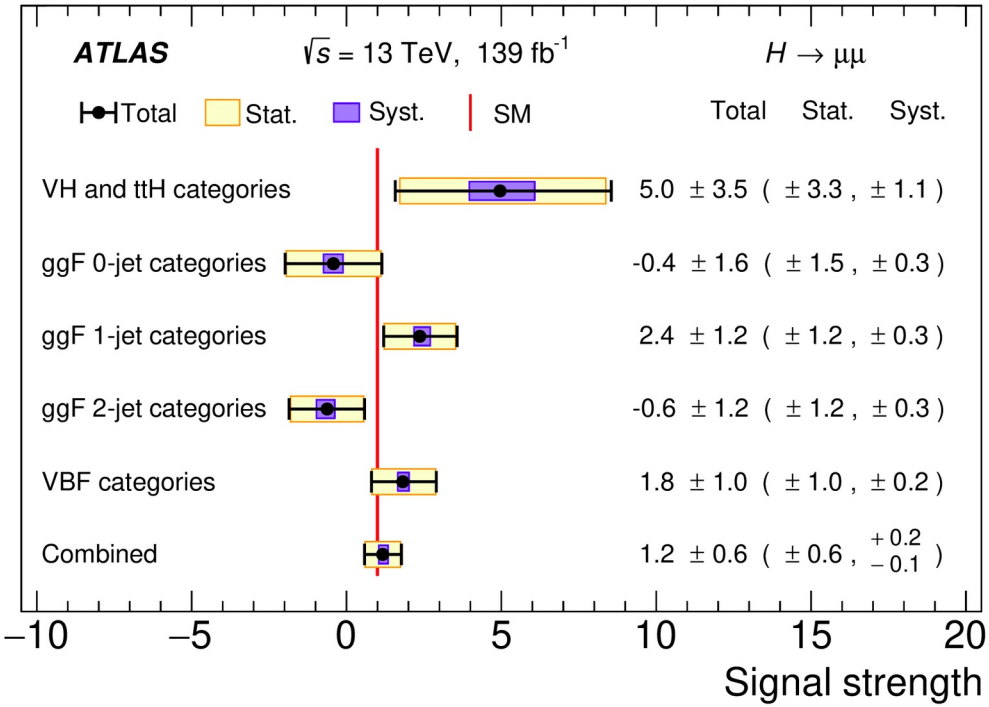


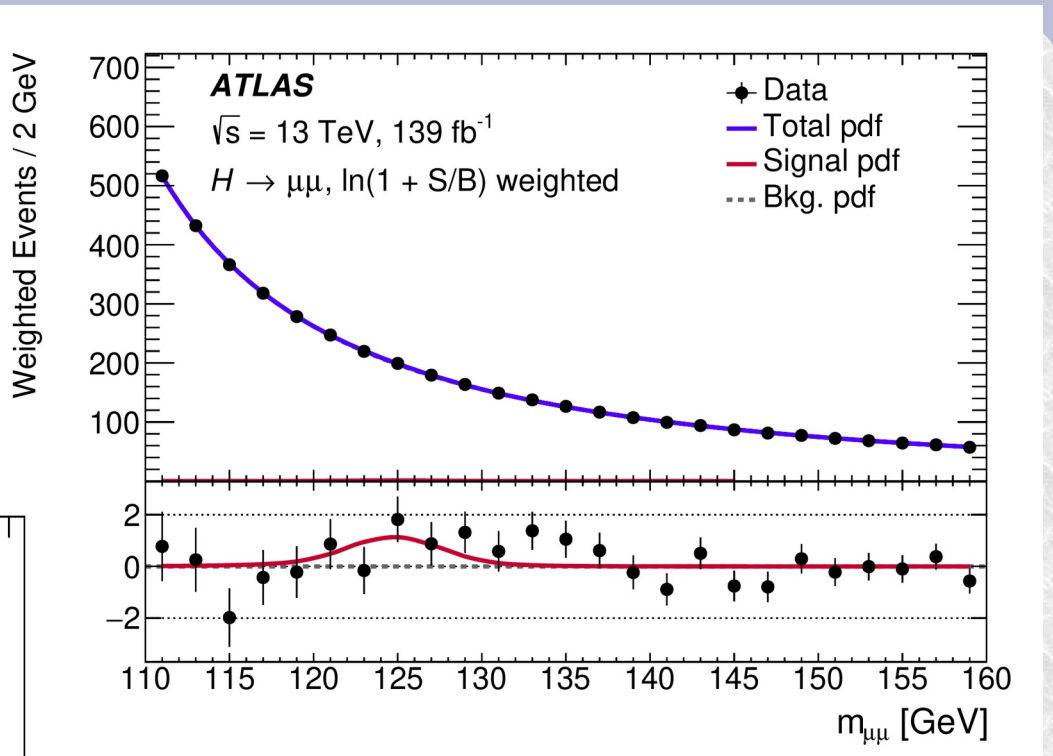
- Sensitive to O(30)x SM
  - Congrats. to CMS on their recent result!

H to μμ

Phys. Lett. B 812 (2021) 135980

- 'Simple' bump hunt
  - Similar to H → γγ
- 20 categories of pT, eta, VBF. VH, ttH
- Yield very like γγ



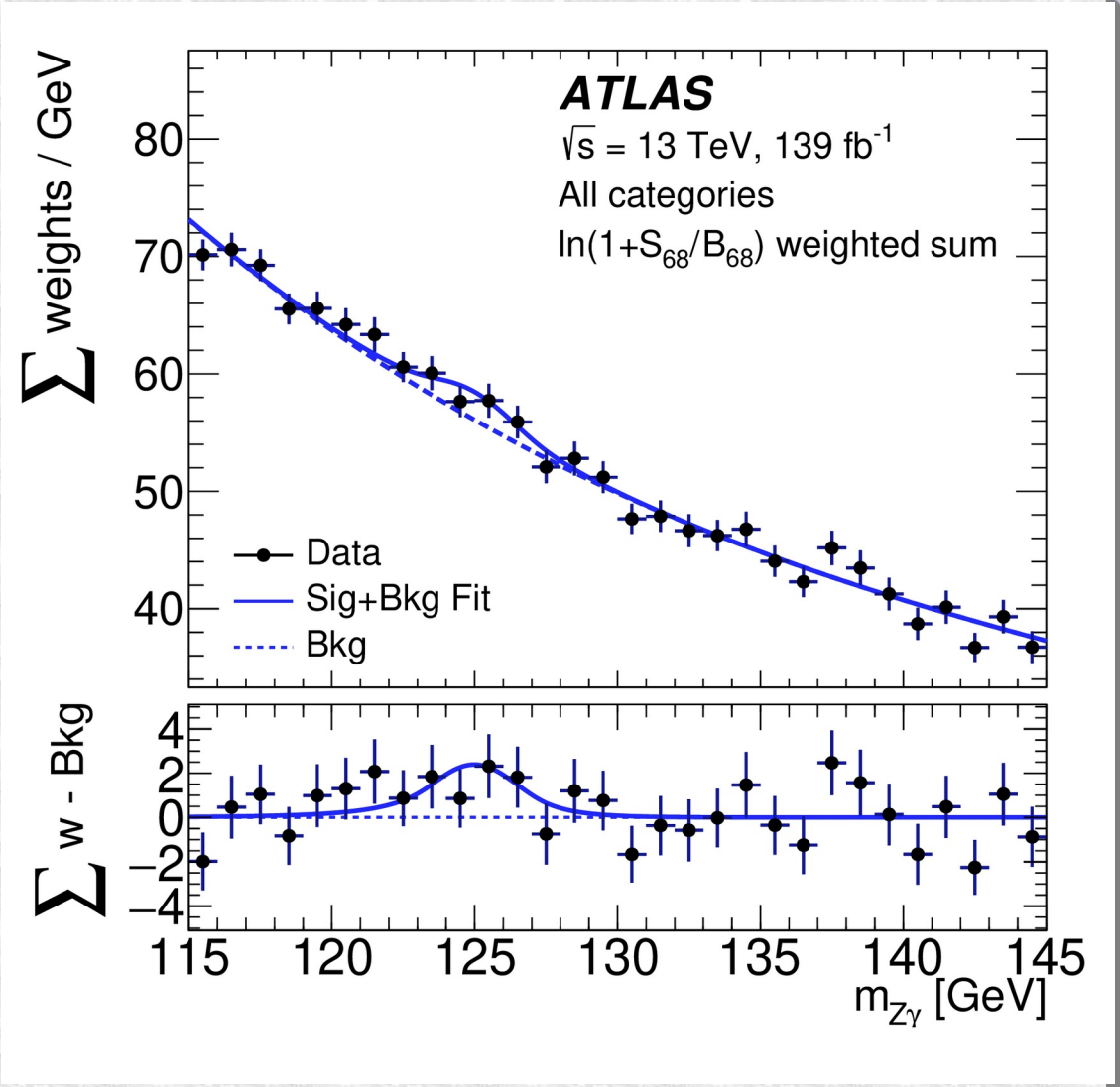


- But large Drell-Yan background
- Significance: 2σ obs (1.7σ exp. SM)
  - 2nd generation in sight!

H to Zγ

Phys. Lett. B 809 (2020) 135754

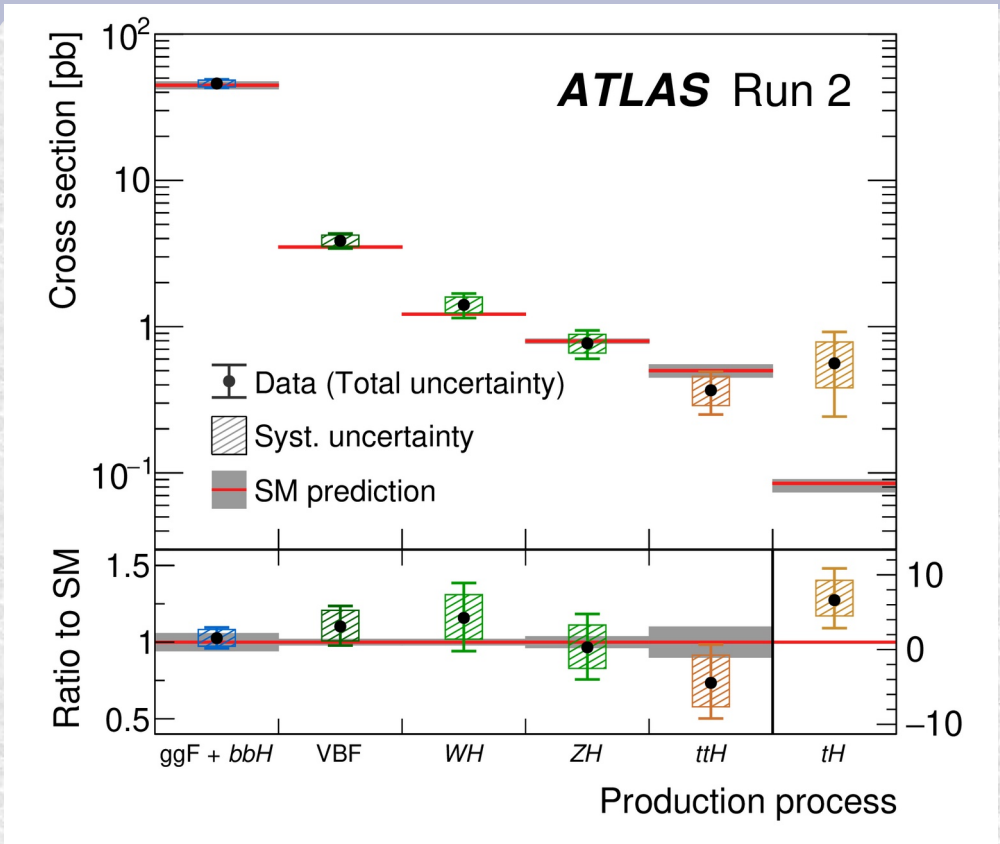
- Simple bump hunt
  - Similar to H→γγ
- 6 categories of flavour, kinematics and s/b BDT
- Yield very like γγ
- 110 signal expected in central 68% of distn
  - s/b 1/8 or worse
- Significance: 2.2σ obs (1.2σ exp. SM)
  - Getting there!

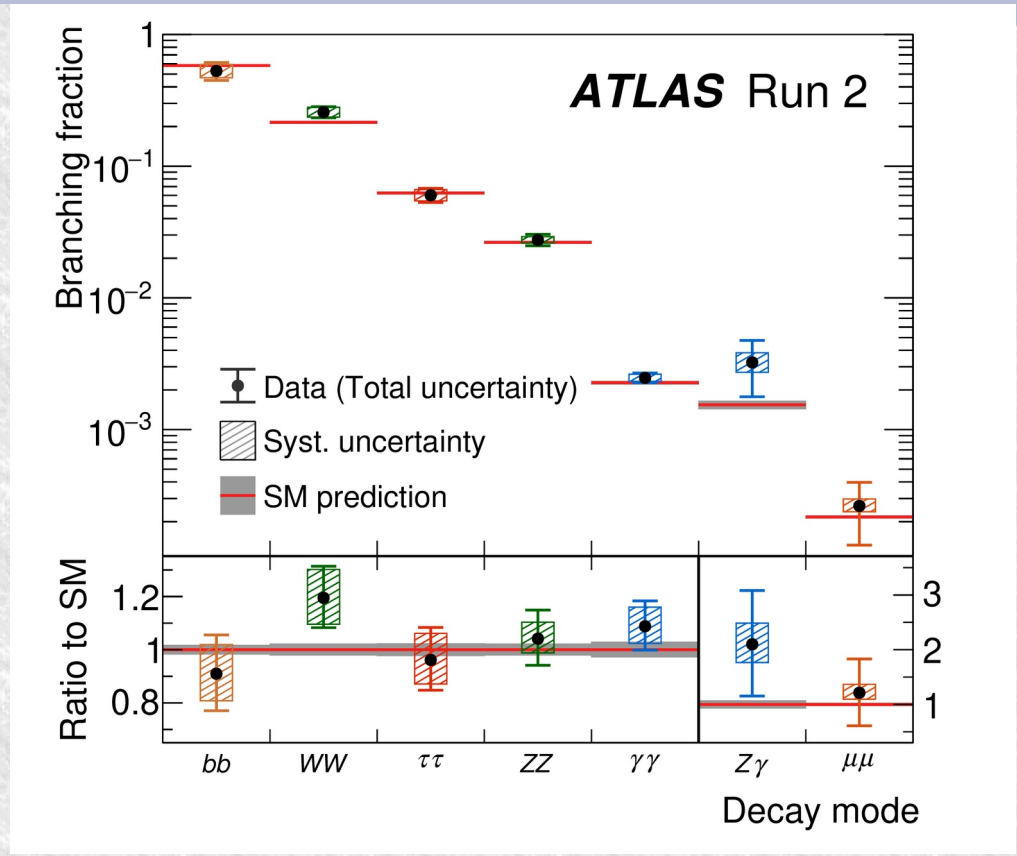


New today

Combined results

HIGG-2021-23





- Production and decay in agreement with SM
  - Order 10% precision on ‘big five’ decay modes

New today

Overall: $\kappa_V - \kappa_f$

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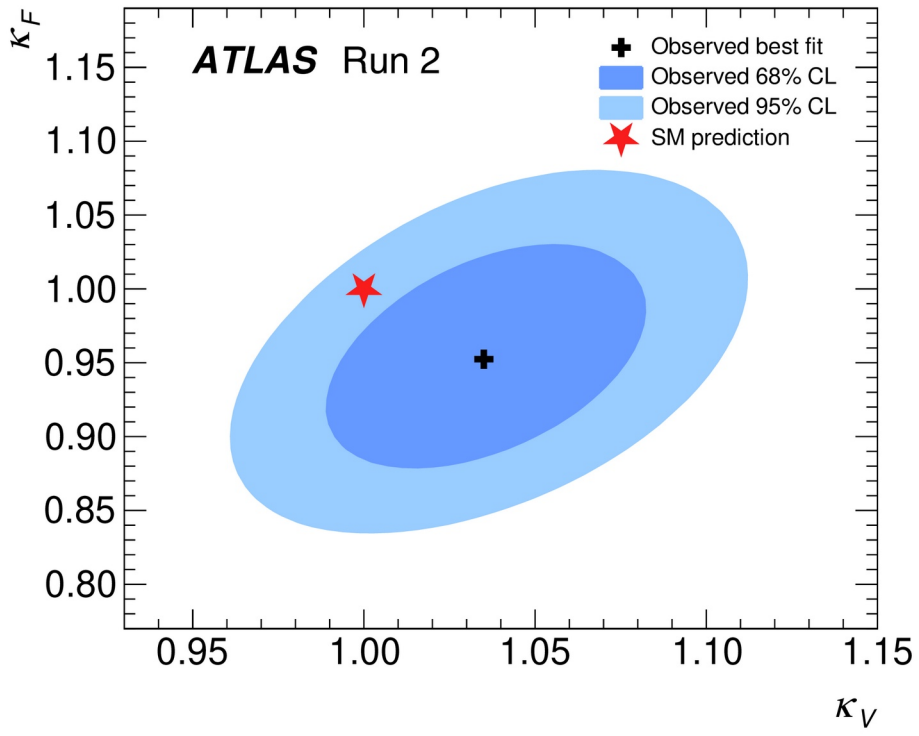
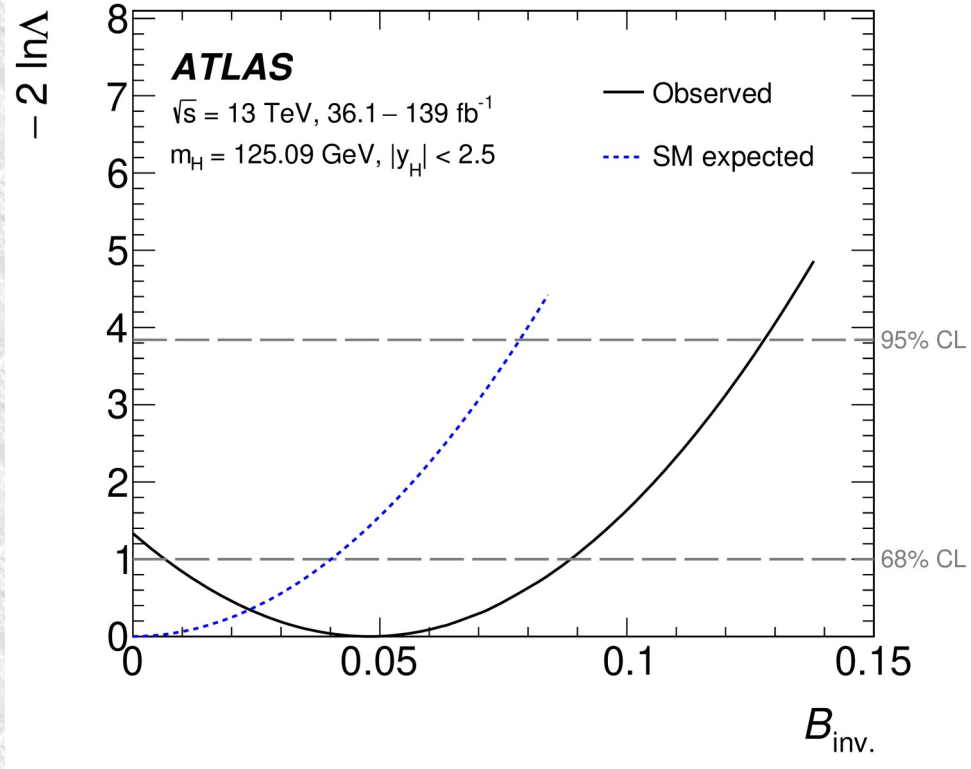
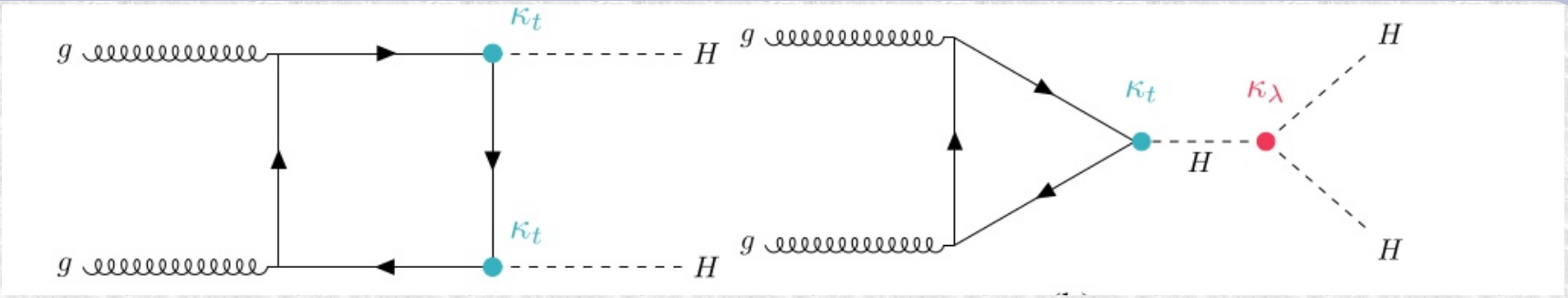




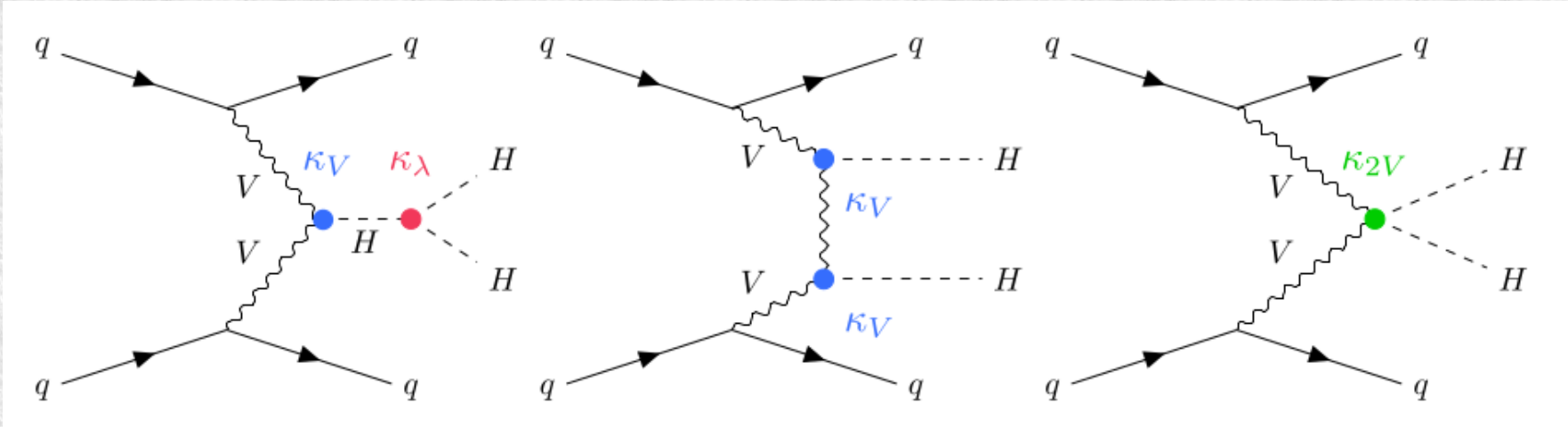
- Assuming a scaling for each of vector and fermion couplings, errors 5% in fermion, 3% boson
- $B_{inv} < 13\%$ (8% expected) [κ_V constrained ≤ 1]
  - c/f 14% (10%) from VBF paper

Di-Higgs production

- ggF



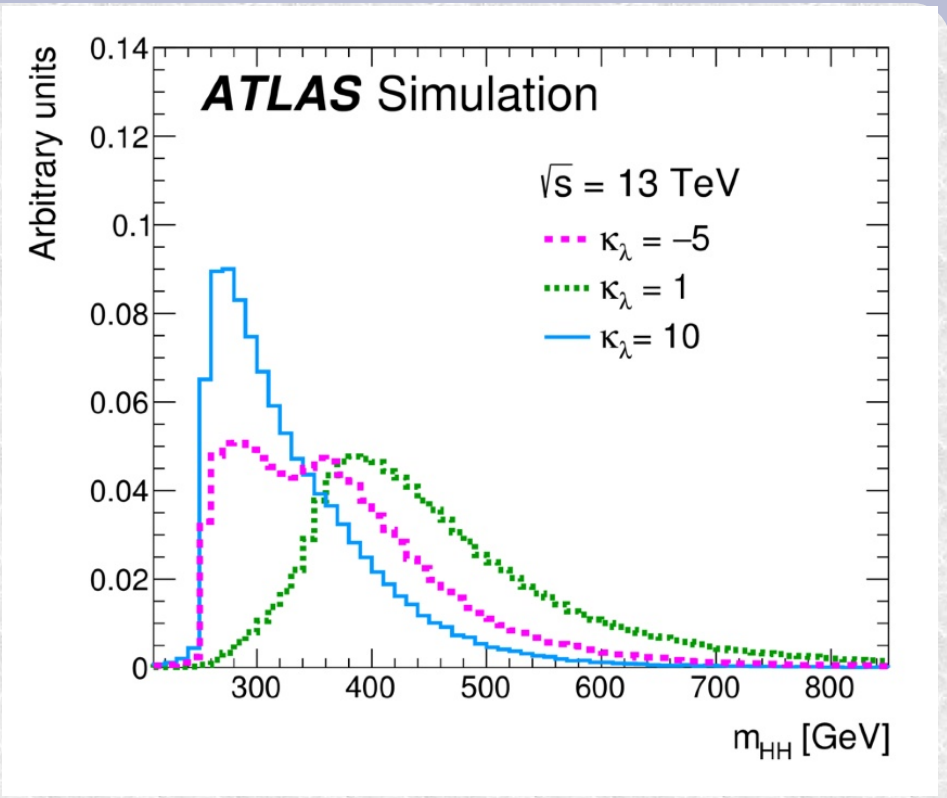
- VBF



- Interference between paths destructive for both
- κ_λ affects both modes,
  - Interplay with κ_t in ggF, κ_V and κ_{2V} in VBF
  - m(HH) spectrum shifts to higher masses for large $|\kappa_\lambda|$

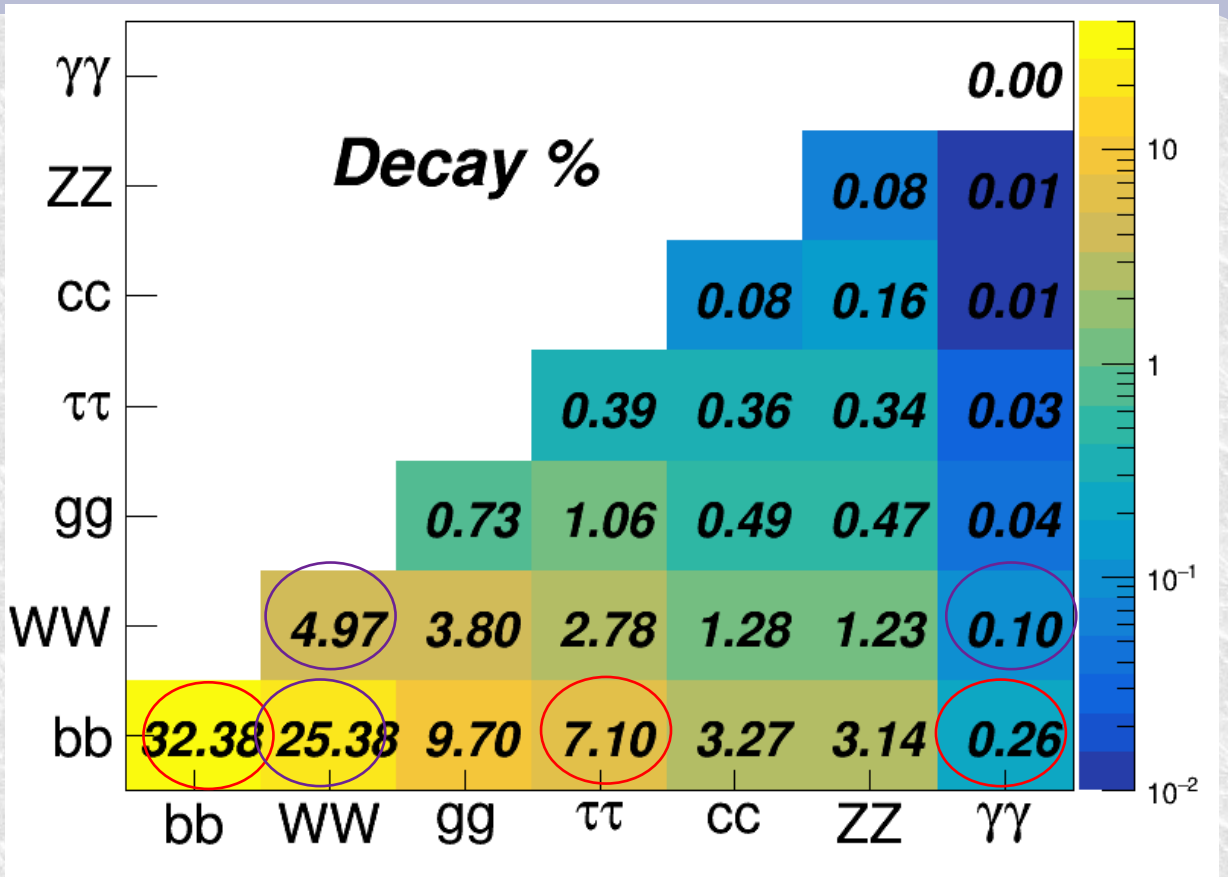
Kinematic effects of κ_λ variation

- Cross-section of HH is 32.7fb
- Low value enforced by interference between modes
  - If you set κ_λ to zero, rate increases
- The spectrum also changes
  - SM gives particularly high mass Higgs pairs.
  - Triggering easier than it might be



Di Higgs channels

- Right:Branching ratios of various decay modes
- Purple have results at 13 TeV
- Red circled channels have full run 2 data

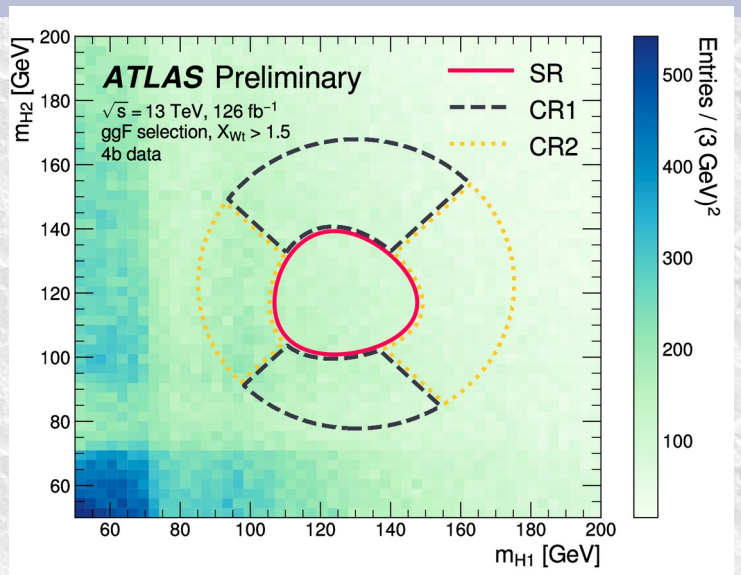


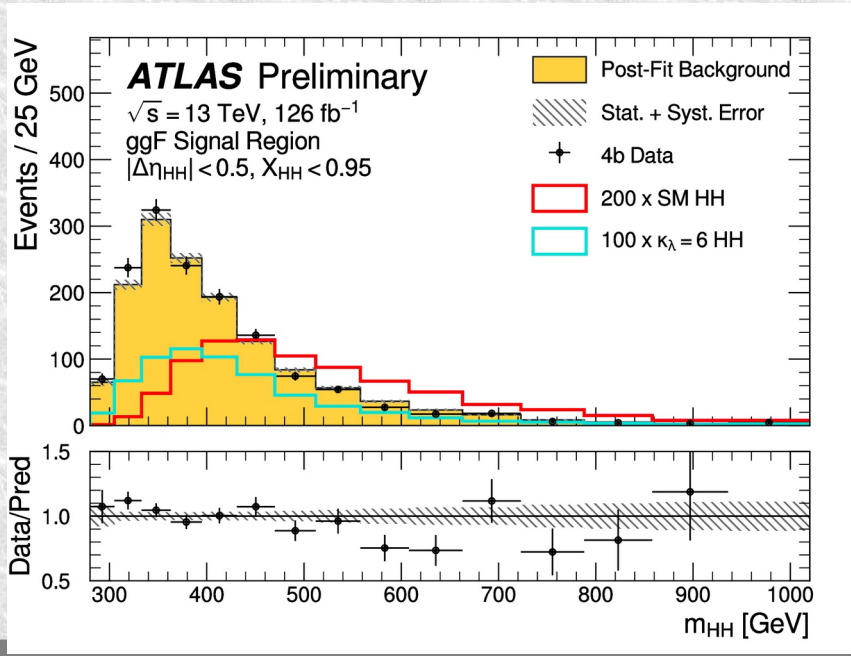
- Many weak channels are not exploited – some gain possible

HH → bbbb

ATLAS-CONF-2022-035

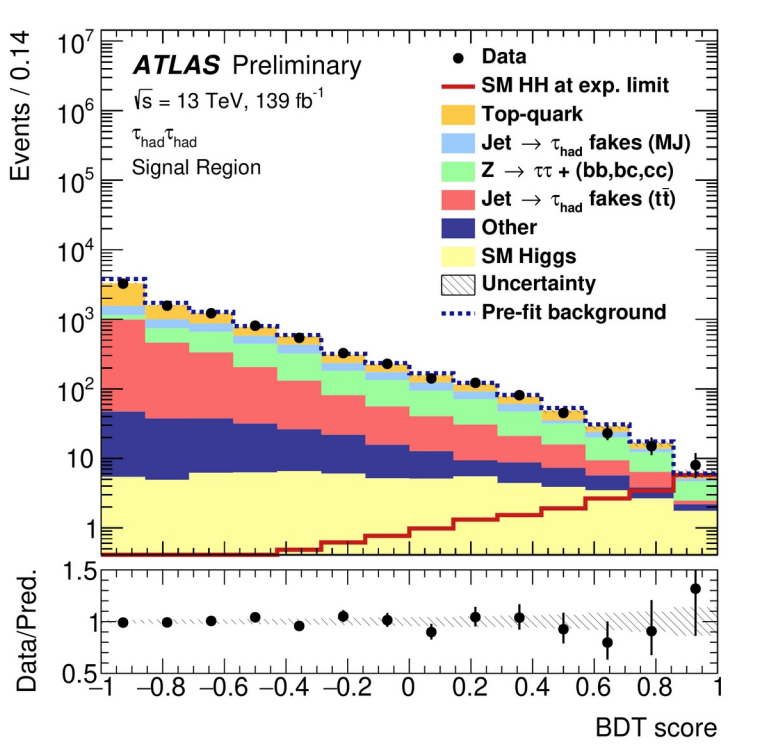
- Highest branching ratio
- ggF and VBF modes used
- Resolved channels
- Trigger tricky: combine:
  - 2b2j, pt>35 GeV all
  - 2b1j, non b jet pt>100-150
  - Tightened offline
- Backgrounds (multijet) from mass sidebands
- Best ggF signal region shown
- Obs (expected) limits:
  - 5.4(8.1) x SM rates





$HH \to bb\tau\tau$ ATLAS-CONF-2021-030

- Full data result just out
- lh and hh channels analyses
  - hh, shown right, most powerful
  - Z+HF most important background
    - Controlled with ll+HF CR
- Trigger: 1 or 2 tau, with thresholds/jets year dependen
- Most sensitive ATLAS channel

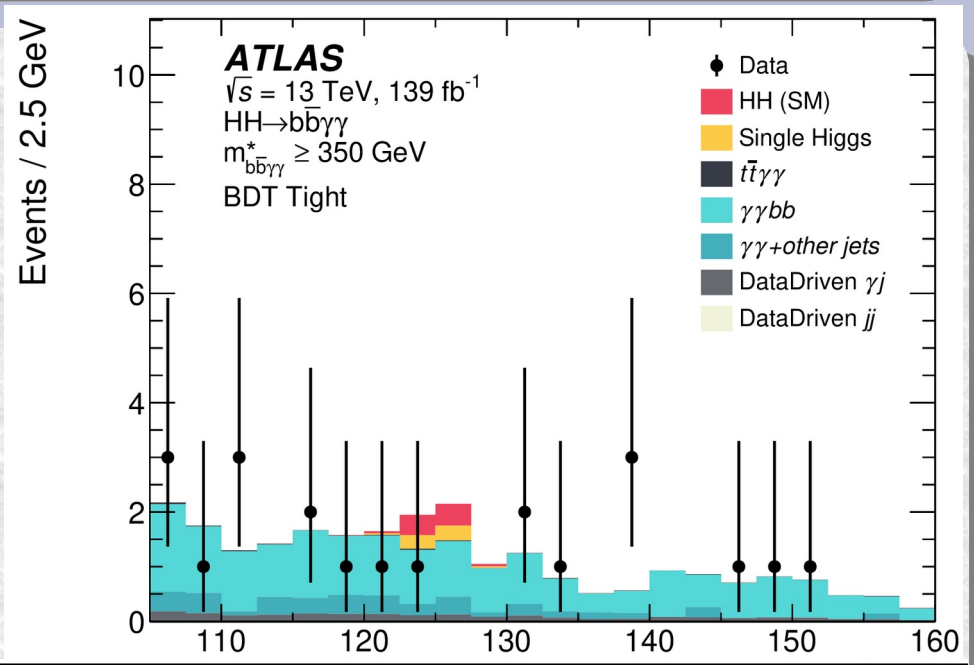


		Observed	$-2\,\sigma$	$-1\,\sigma$	Expected	$+1\,\sigma$	$+2\,\sigma$
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	265	124	167	231	322	432
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{\text{ggF+VBF}}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.65	2.08	2.79	3.87	5.39	7.22

HH → bbγγ

arXiv:2112.11876

- H → γγ has good resolution & triggering; H → bb is high rate,
- Four slices: BDT score & HH mass
- Fit using exponential for bkd
- Single Higgs comparable to HH
- 1.4 Signal expected
- Expected UL 5.7xSMσ
- Observed UL 4.2xSMσ



		Relative impact of the syst
Source	Type	Nonresonant analysis HH
Experimental		
Photon energy resolution	Norm. + Shape	0.4
Jet energy scale and resolution	Normalization	< 0.2
Flavor tagging	Normalization	< 0.2
Theoretical		
Factorization and renormalization scale	Normalization	0.3
Parton showering model	Norm. + Shape	0.6
Heavy-flavor content	Normalization	0.3
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2
Spurious signal	Normalization	3.0

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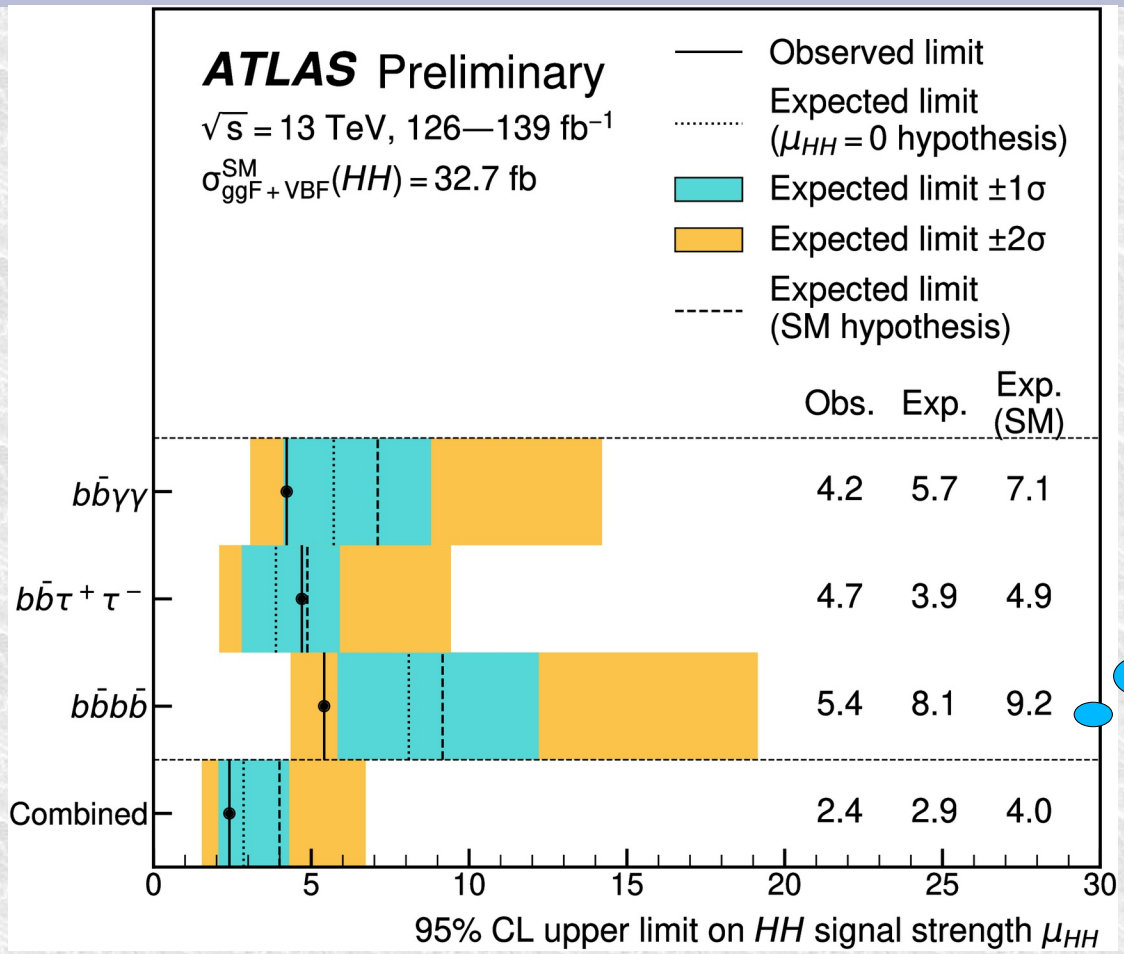
Combined sensitivity to HH

New today



bbbb seems least sensi-tive..but wait

- Limit HH production at 2.4 x SM strength
  - c/f 2.9 expected (no HH) or 4.0 (SM)

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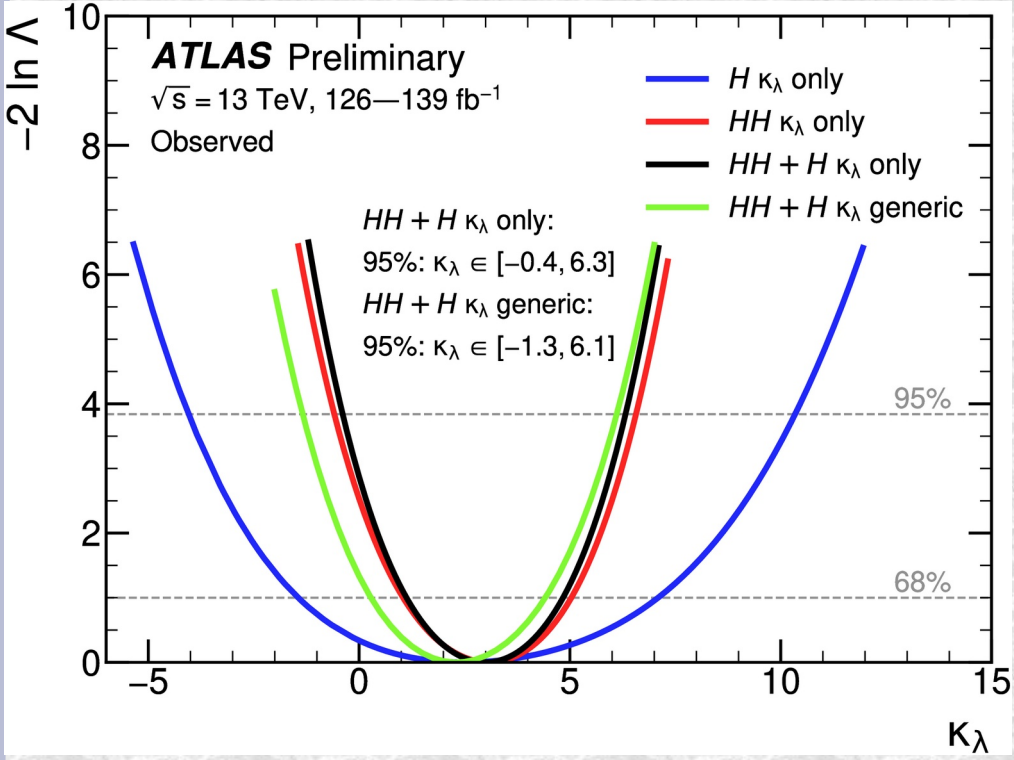
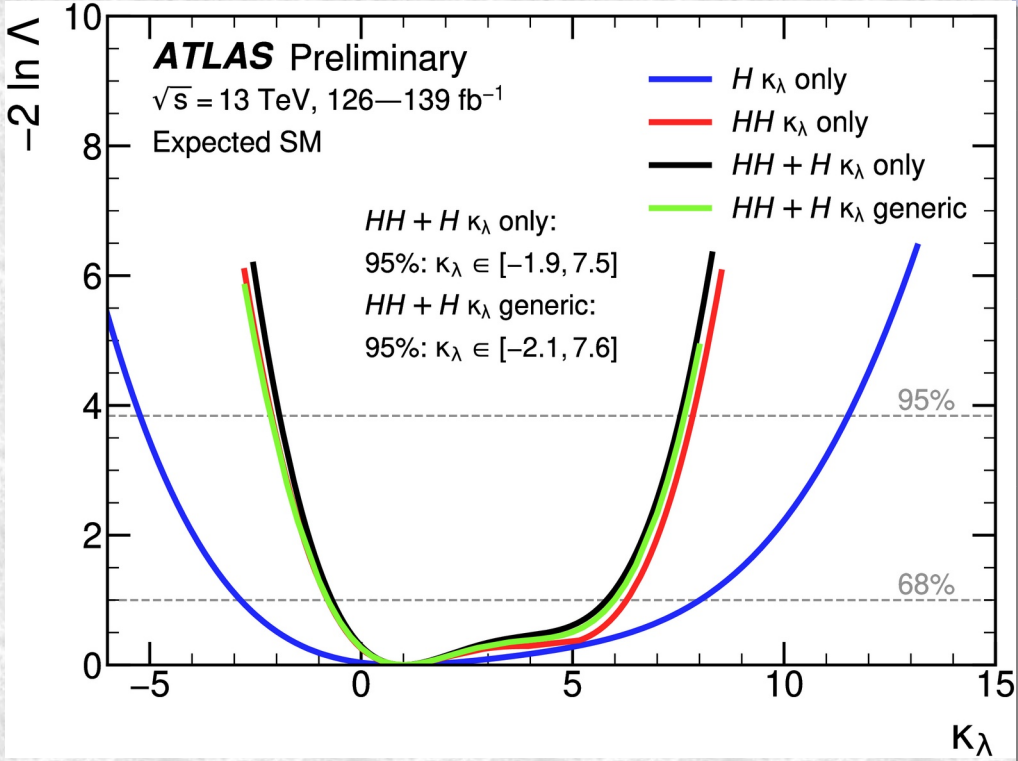
Restriction on self-coupling





- κ_λ restricted to -1.3 – 6.1 (-2.1 – 7.6 expected)
  - Tightest constraint on κ_λ so far (just!)
  - When only κ_λ is free
- Range expands *slightly*, if κ_V, κ_t, κ_b, κ_τ all released

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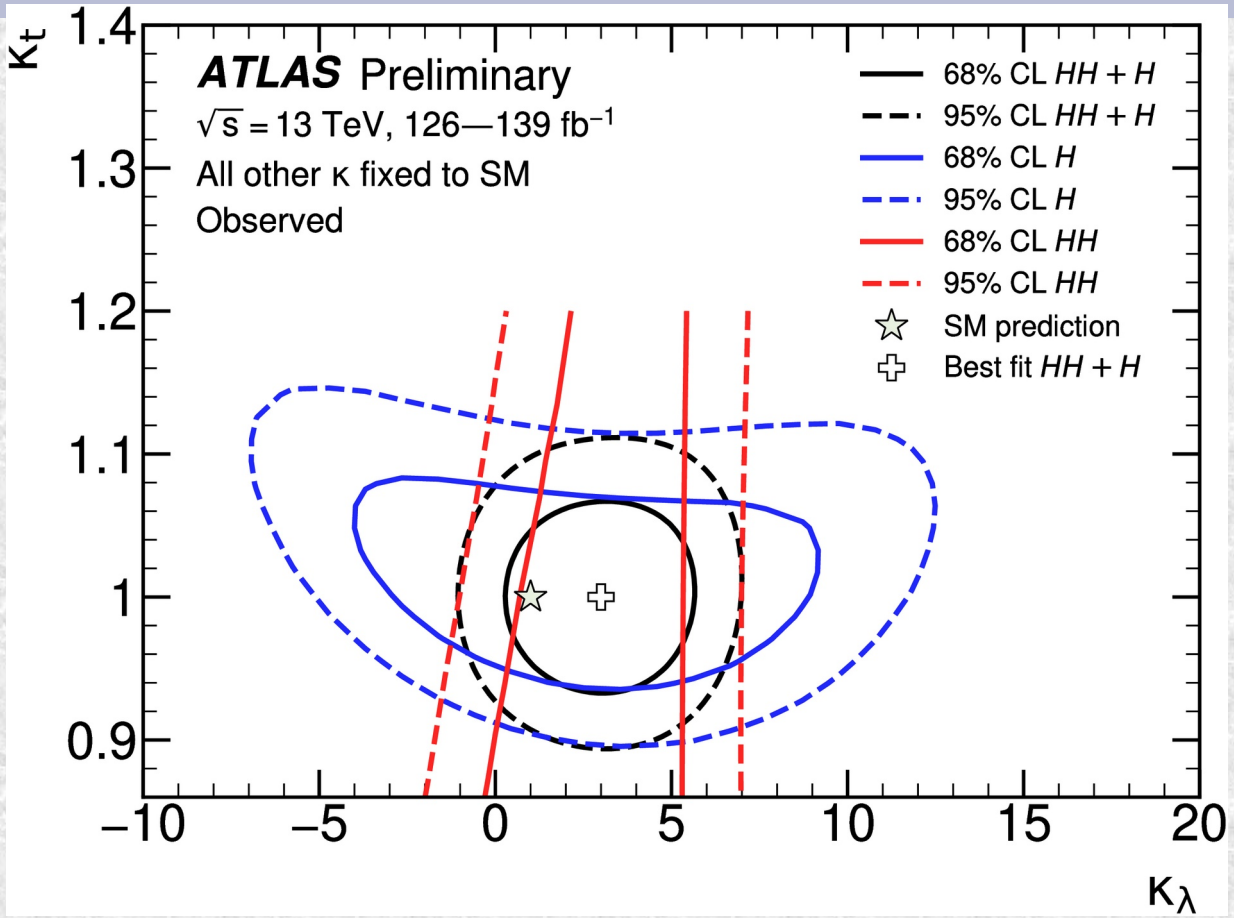
Fit with κ_λ and κ_t free

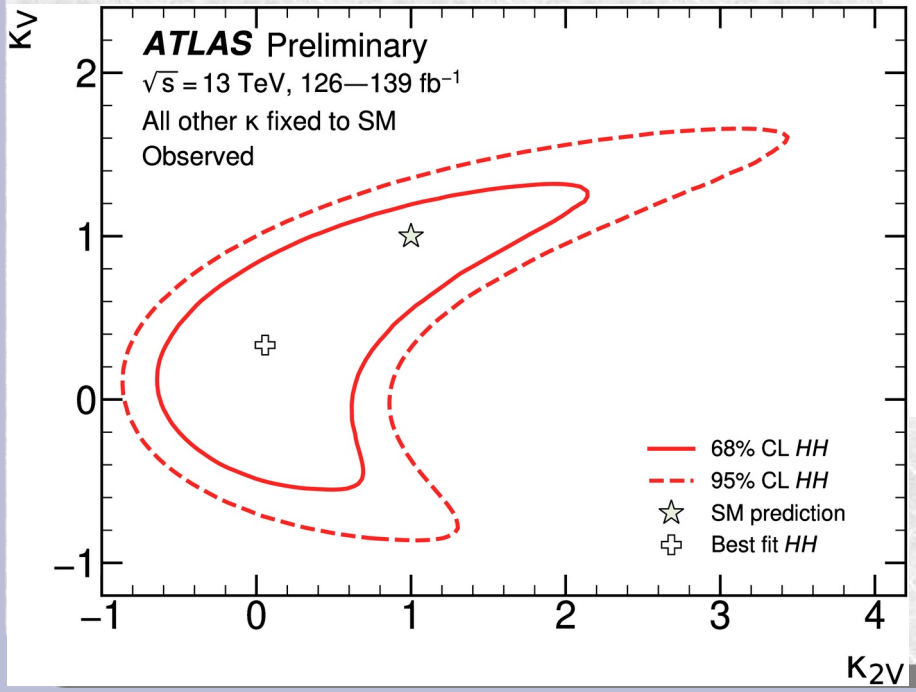


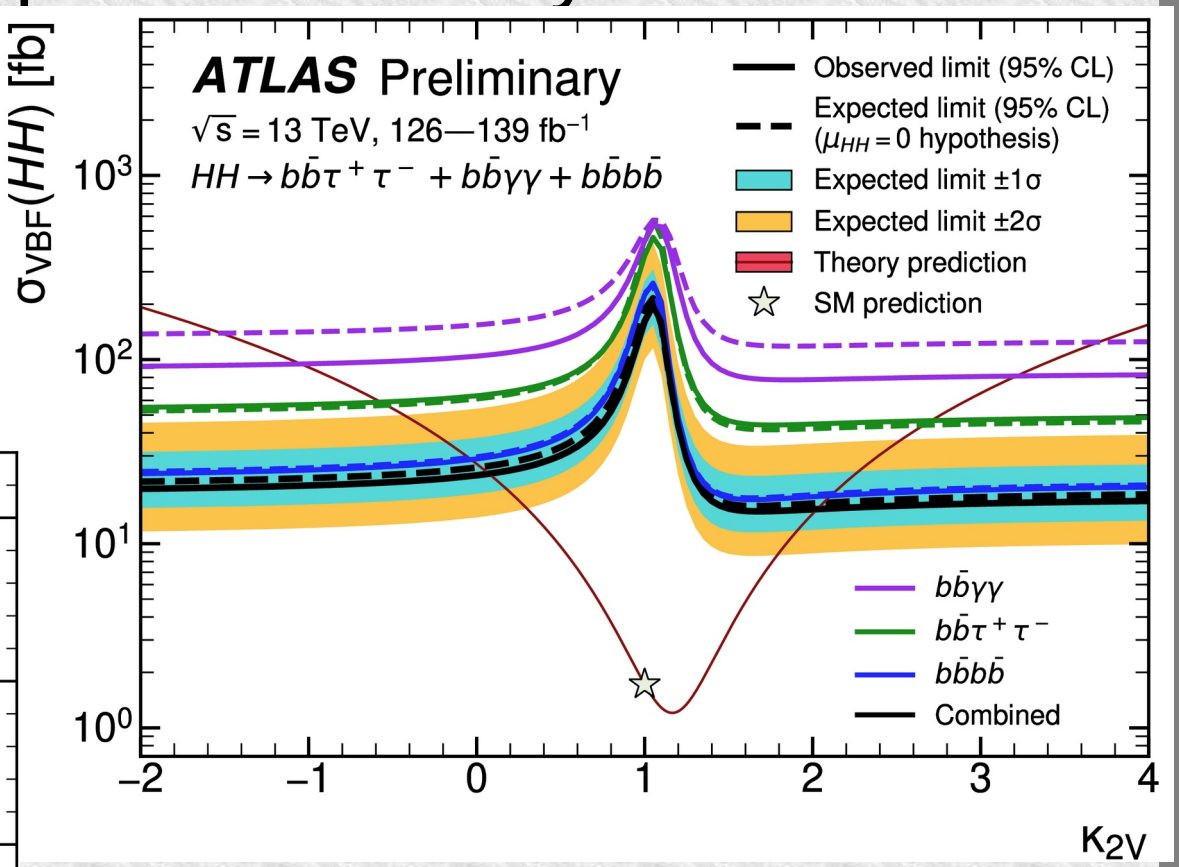
- With diHiggs alone, κ_λ bound expands for low κ_t
  - Combination with bounds from single Higgs
- DiHiggs and single higgs complementary.

ATLAS-CONF-2022-050

Limits on κ_{2V} – VVHH coupling

- Results from VBF HH production only
  - No boosted channels
- $\kappa_{2V}=0$ excluded
  - 4 boson interactions!
  - If κ_V fixed to SM
    - Single H fit wanted

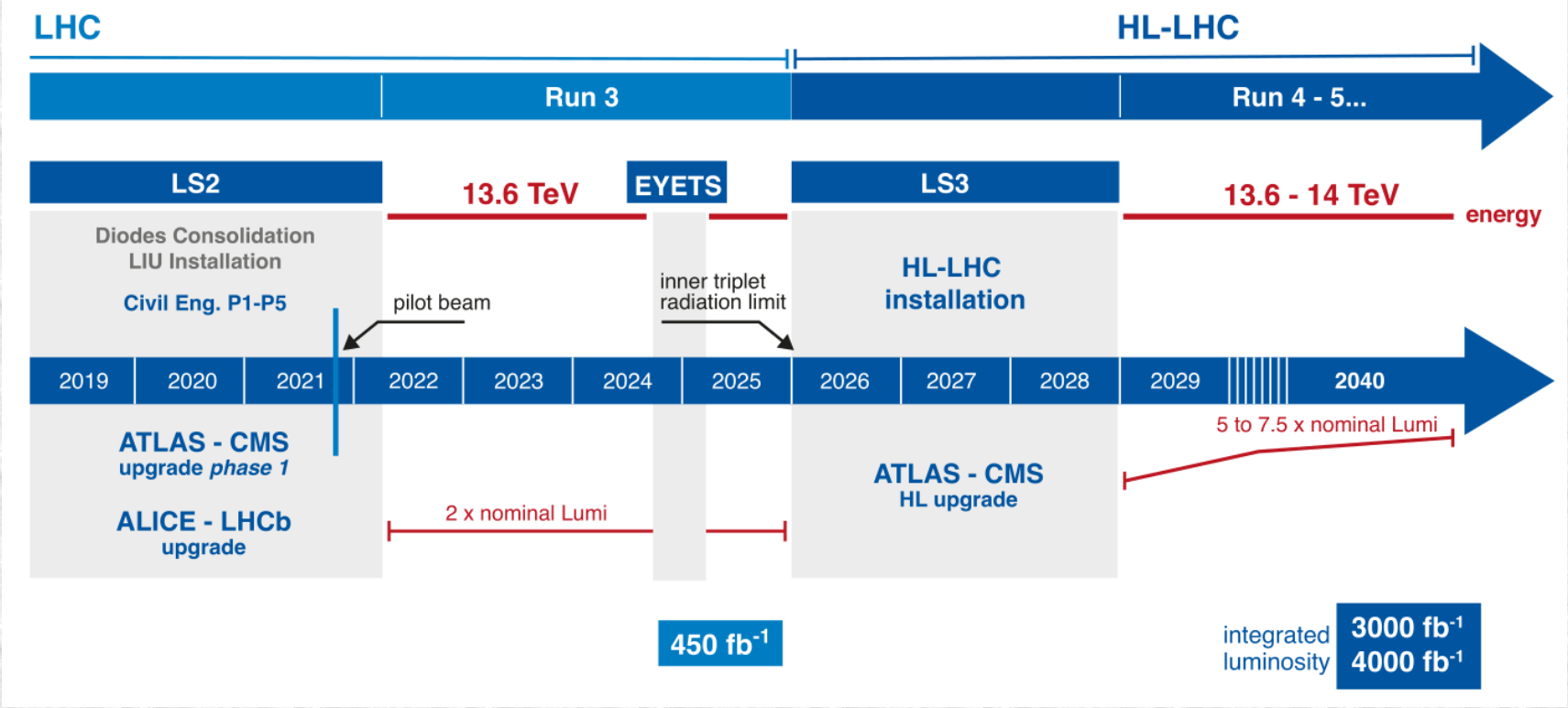




- Nb. Here bbbb is the most sensitive

The future

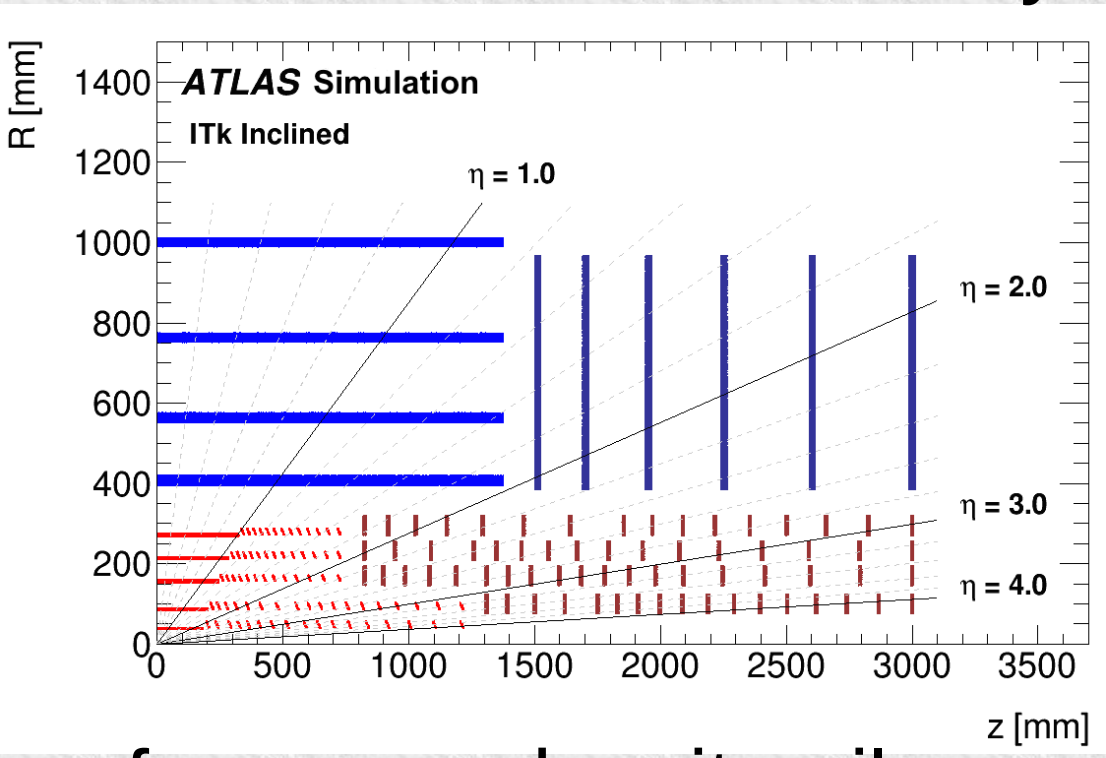
- ATLAS is using 139fb^{-1} @ 13TeV for most results
- Run 3 may bring 300fb^{-1} @ 13.6 TeV
- HL-LHC will bring an even larger increases



- As well as increasing experimental challenges

Upgrade Example: Inner tracker

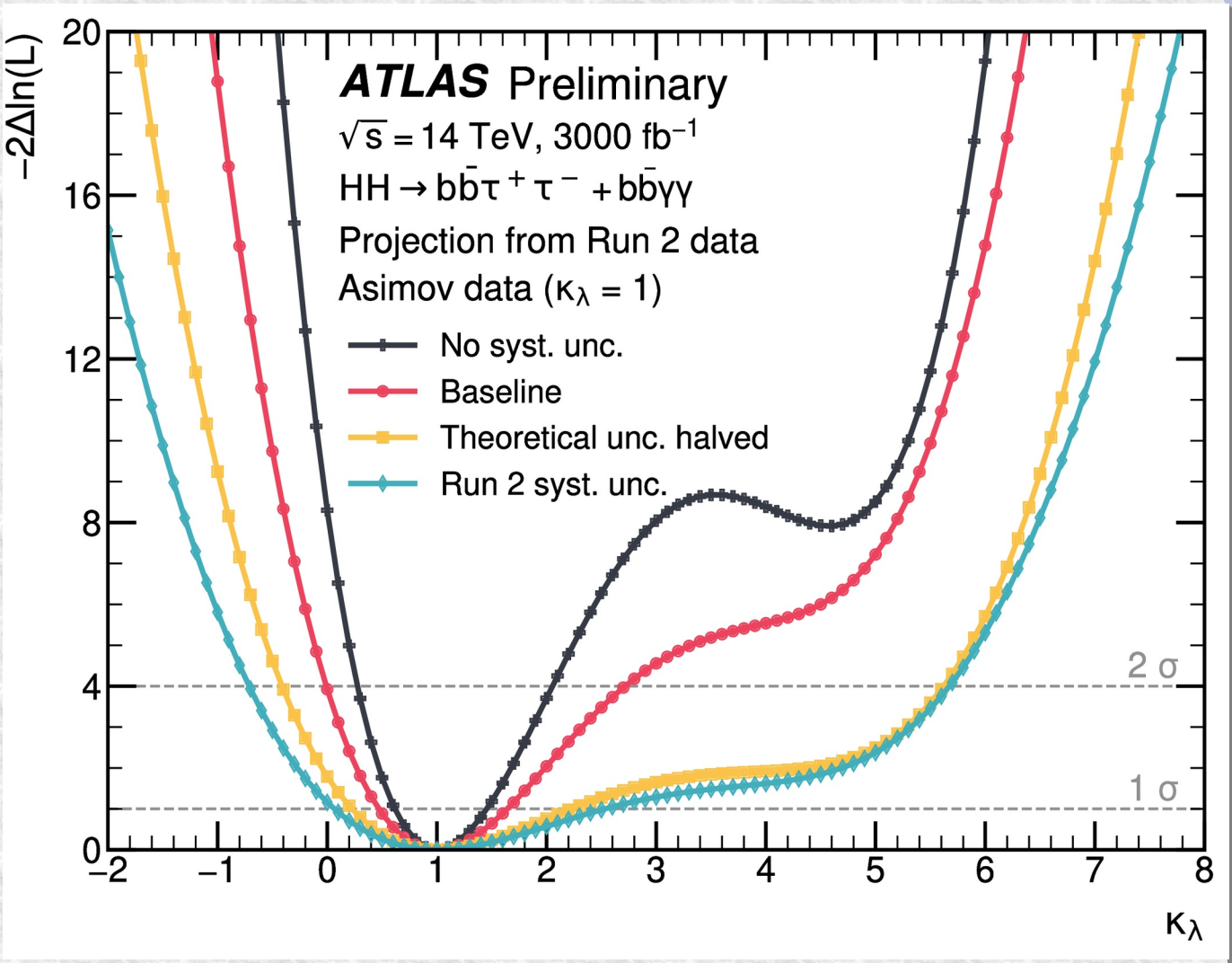
- Tracker rebuild to handle radiation & tracks density
- ITk features
  - All silicon (fast) layout
    - 5 pixel, 4 strip
  - Higher granularity
    - Reduced occupancy
  - Improved radiation handling
  - Extended coverage
    - |η| limit 2.5 → 4



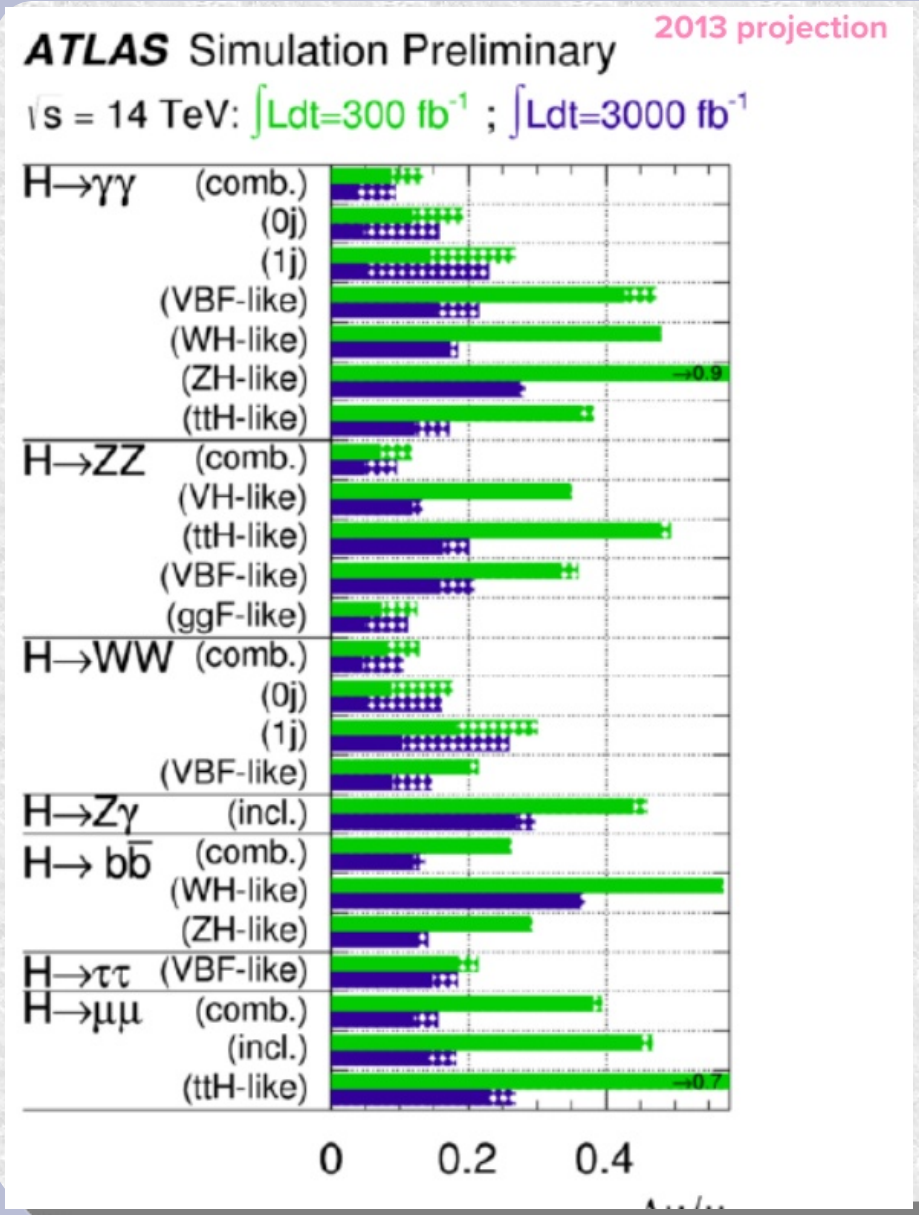
- Maintains or improves performance despite pileup
- The silicon build schedule is doable
  - But help would be very welcome

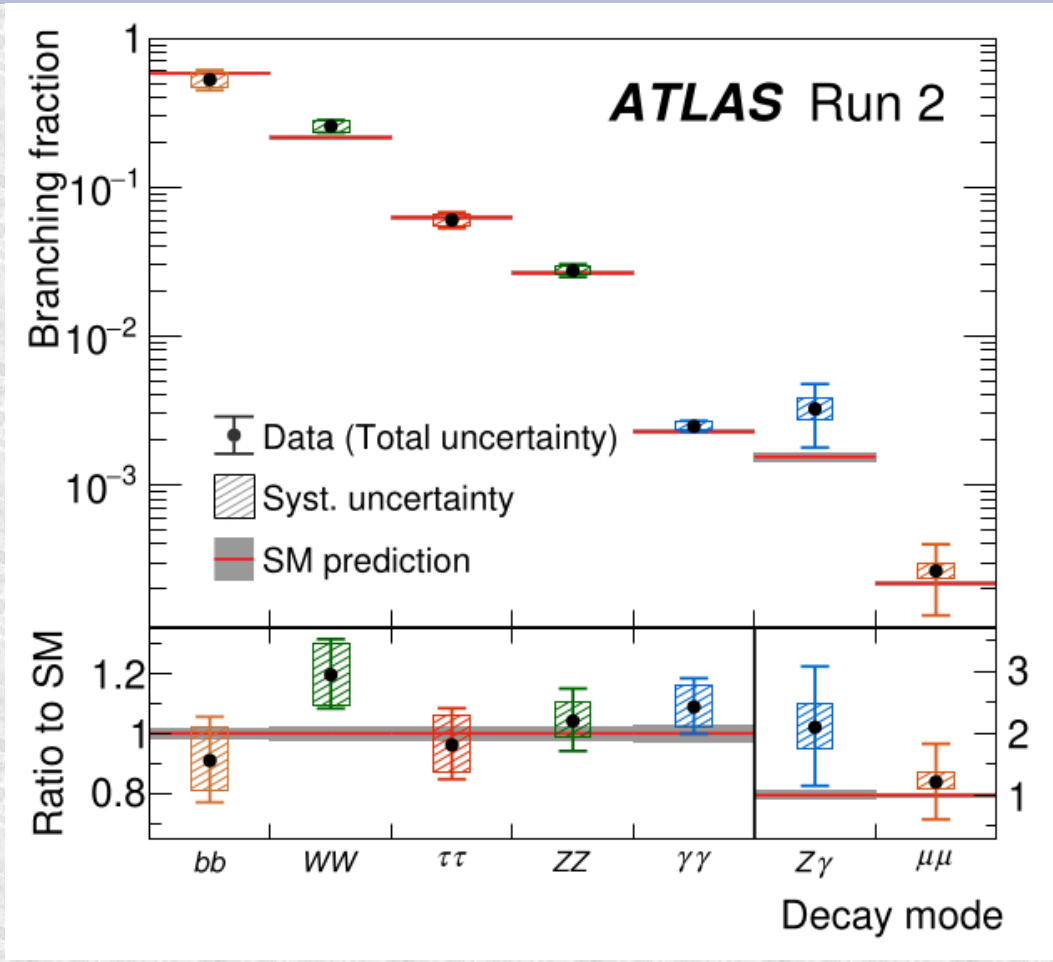
Example of HL-LHC sensitivity

- Baseline projection red
  - 1% lumi
  - Theory errors halved
  - Expt $1/\sqrt{L}$
- $0<\kappa_\lambda<2.7$
  - Combining bbττ and bbγγ only
- Experiments can combine too



Expectations: confounded

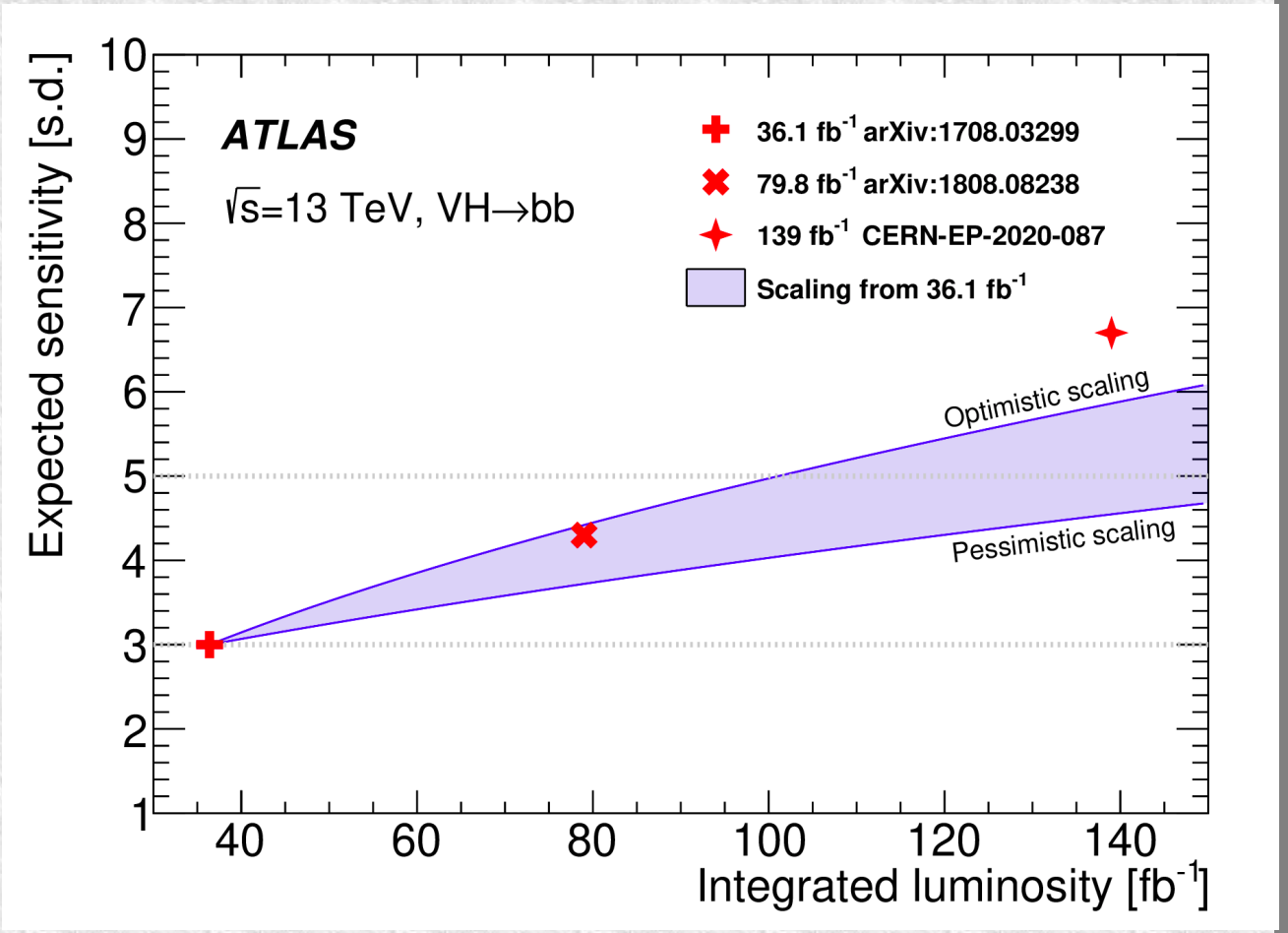




- Run 2 results are comparable to 2013 HL-LHC expectations

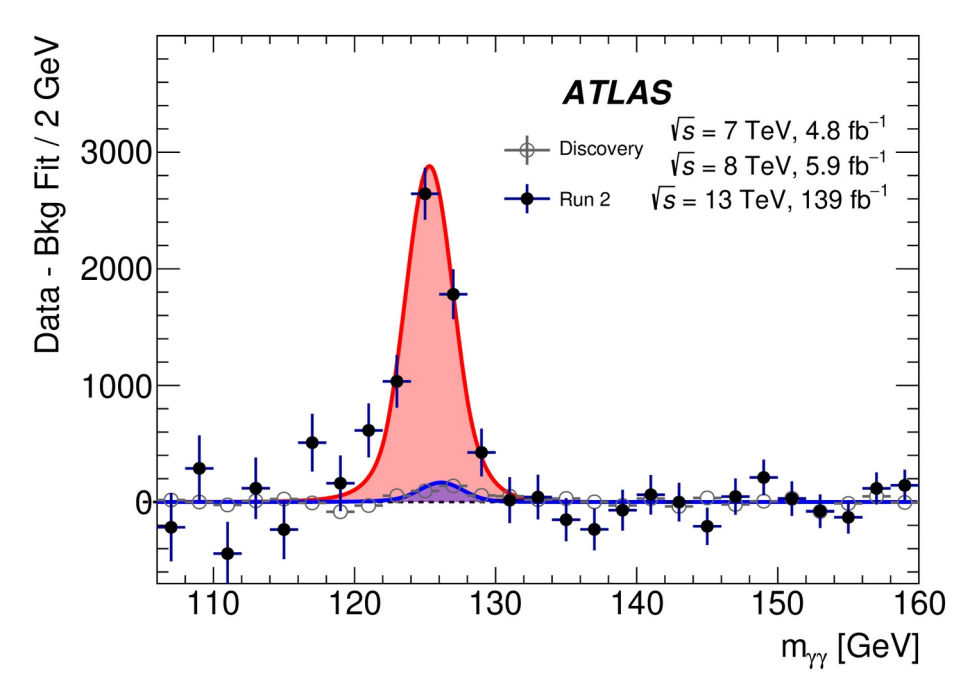
Detail for H → bb

- ATLAS sensitivity versus time
- Expected limits shown as points
- The effect of scaling luminosity with lines
- Actual sensitivity exceeds optimistic projections
- *Could* be true for HL-LHC too
  - If we work at it



Conclusions

- Higgs physics has advanced enormously in 10 years
- But we have another factor 30 increase to go
- Hard work and good ideas will yield results:
  - better than expected
  - Not expected at all?



- We have a very exciting programme ahead
  - Run 3 may start to show us DiHiggs
- HL-LHC will test this new sector in great detail