Measurement of Higgs boson properties with the ATLAS and CMS experiment

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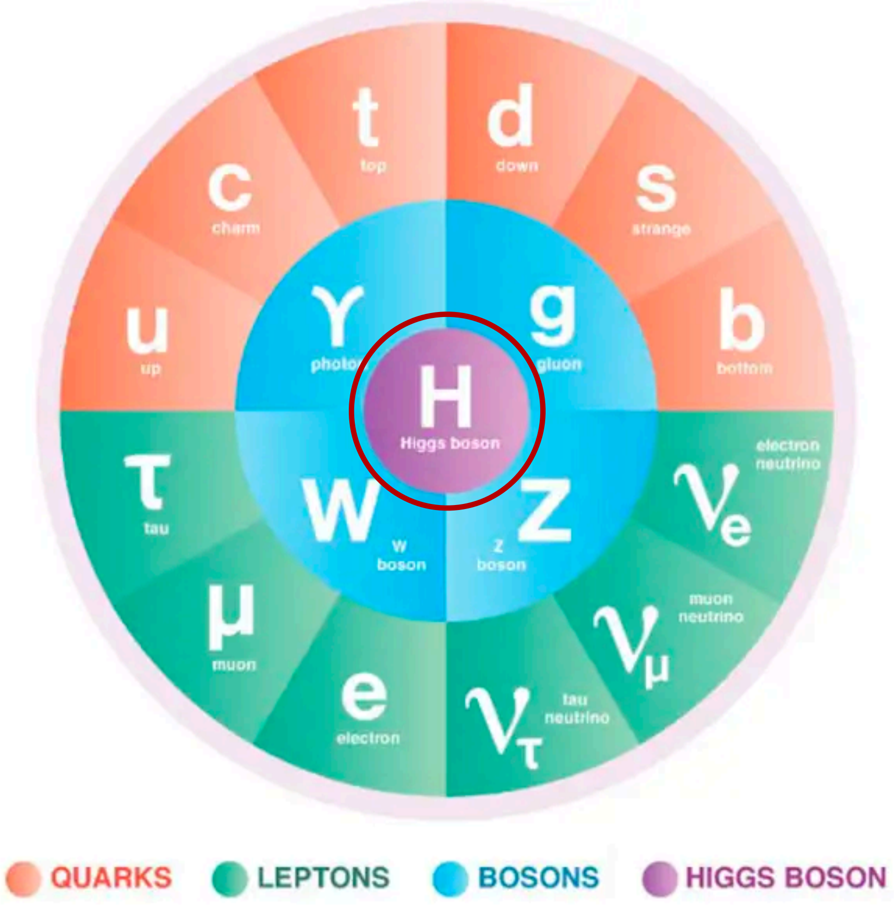
Viviana Cavaliere (BNL)

The Standard Model Higgs boson

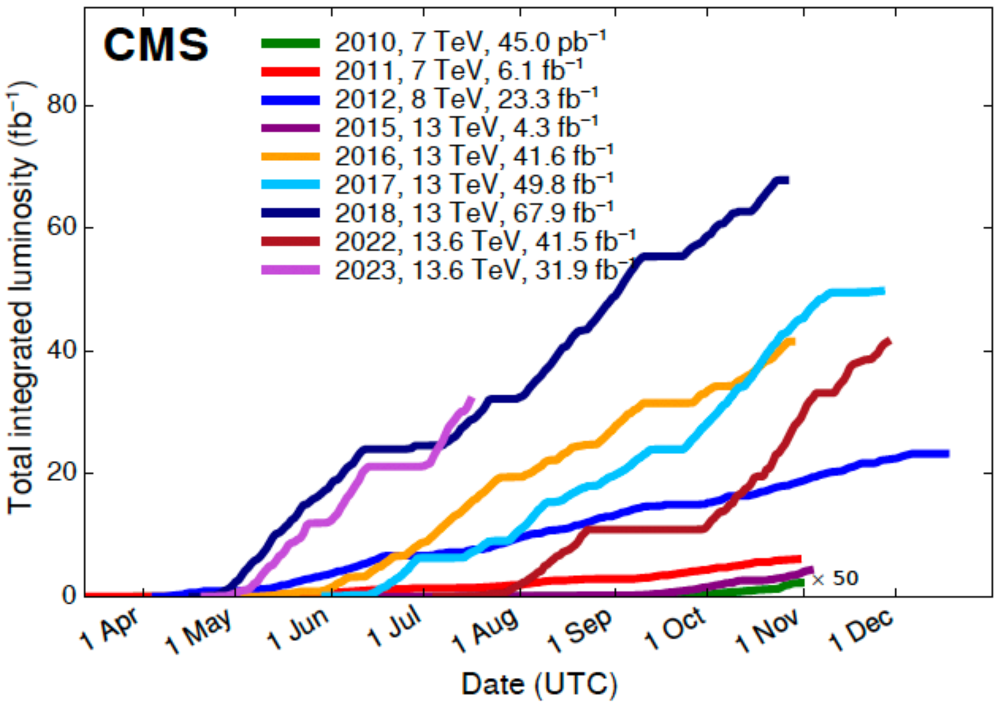


12 years from the discovery of the **Higgs boson!:**

- Origin of the mass of elementary particle
  - Fermions: Yukawa couplings
  - Bosons: Brout-Englert-Higgs (BEH) mechanism
- Potential portal to new physics e.g. Higgs coupling with dark matter

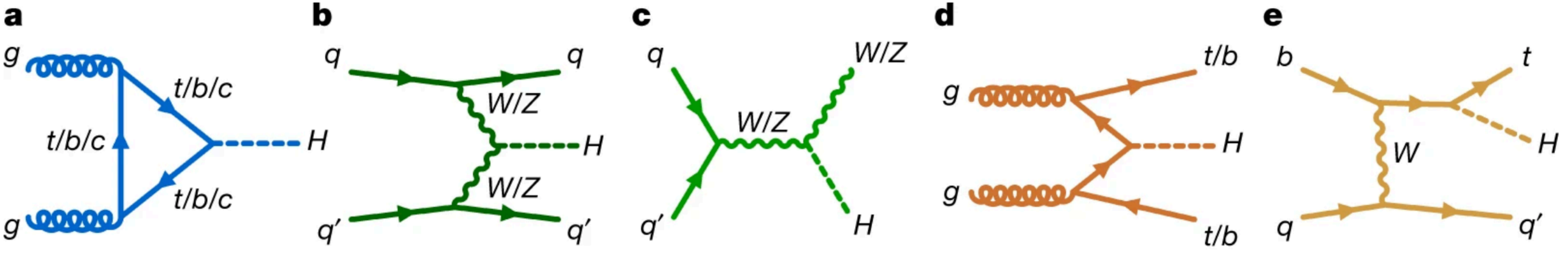
Precision era:

- Higgs boson is fundamental. We need best knowledge on its properties
- Precision could be portal to new physics
- **Thanks to the amazing work of LHC and ATLAS and CMS experiments ~8 million Higgs events produced with the Run 2 Data at sqrt(s) = 13 TeV with O(0.1%) selected for physics analysis**



Higgs production

bbH and tH are not vet discovered.



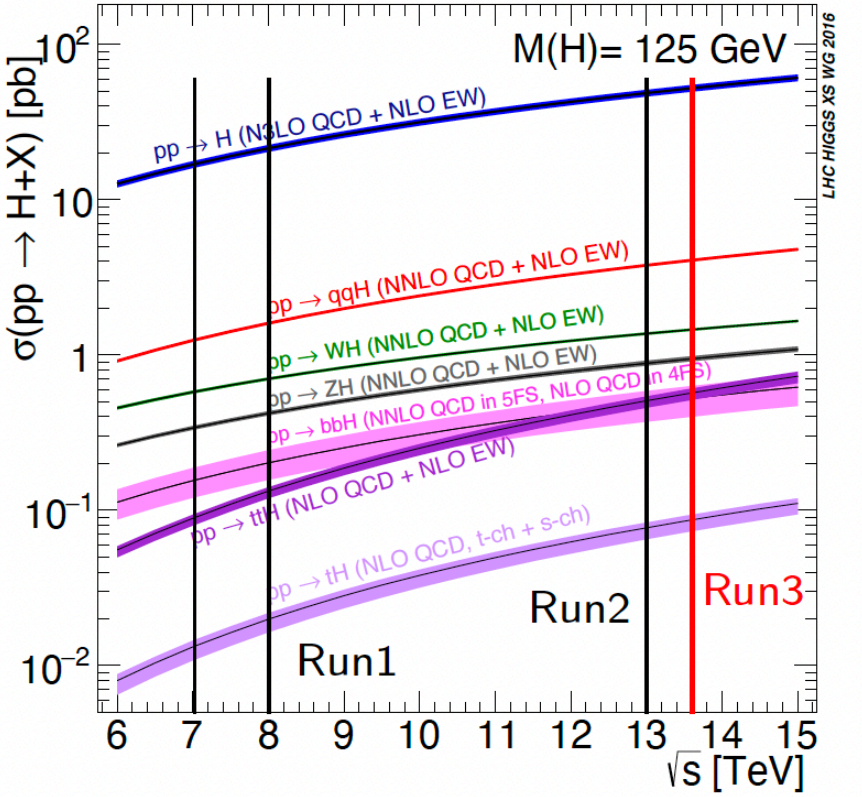
$\sigma_{H,ggF}$ ~ 49 pb

σ_{VBF}~ 3.8 pb

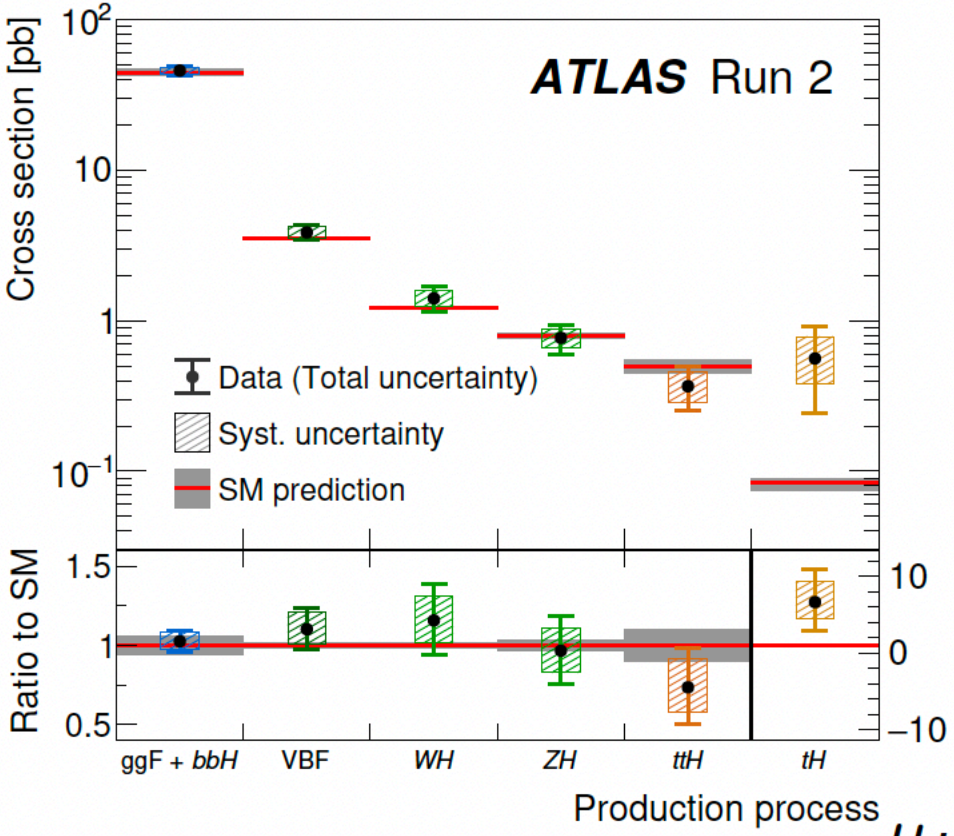
$\sigma_{W/Z+H}$ ~ 1.4/0.9 pb

σ_{ttH} ~ 0.5 pb

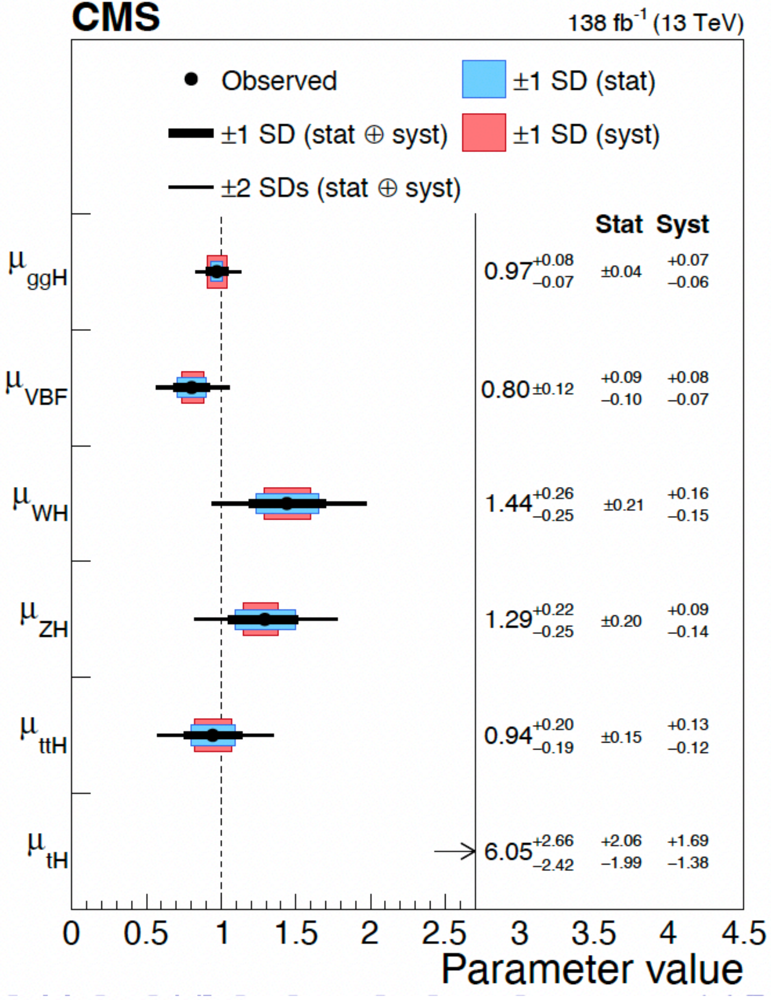
CERN Yellow Report 4



[Nature 607, 52 (2022)]



[Nature 607 (2022) 60-68]



$$\mu_i = \frac{\sigma_{obs}}{\sigma_{\text{SM}}}$$

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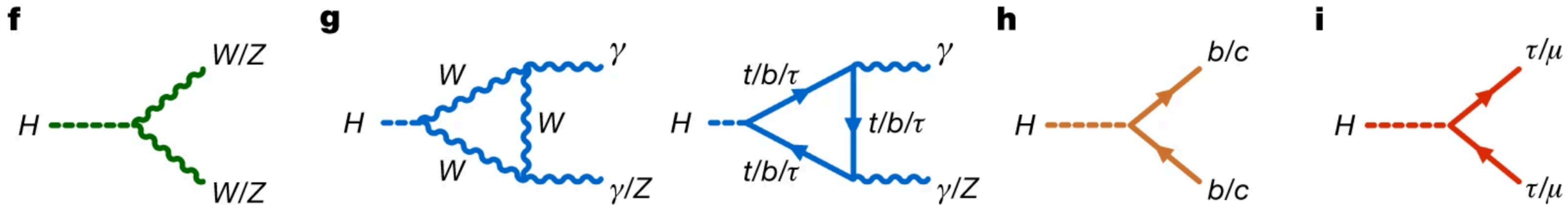
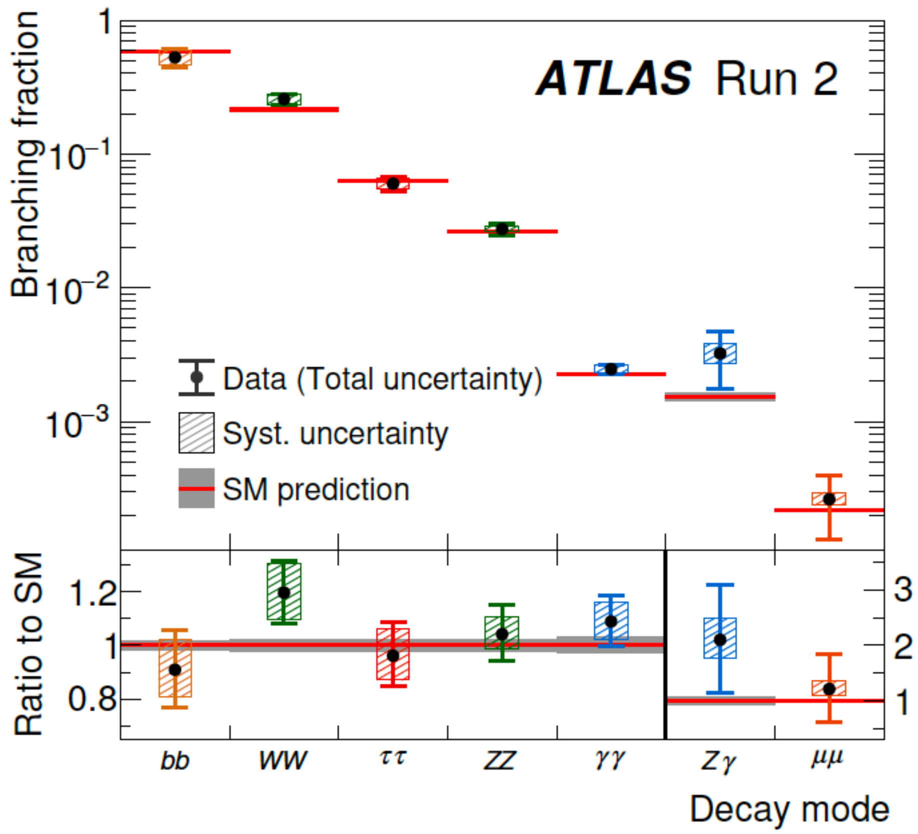
Higgs decay

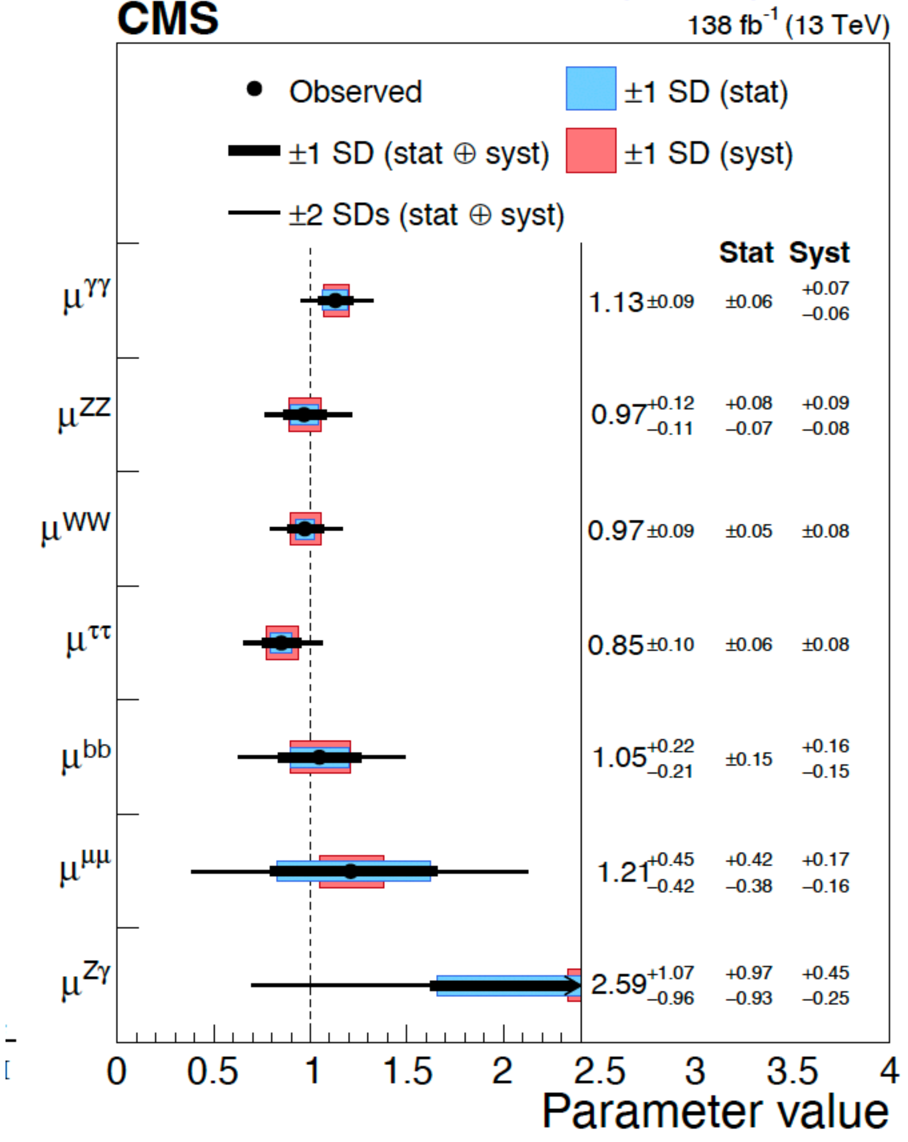


- cc and μμ are still being searched for.
- Zγ is above 3σ in the combination of ATLAS and CMS.

Nature 607, 52 (2022)



Nature 607 (2022) 60-68



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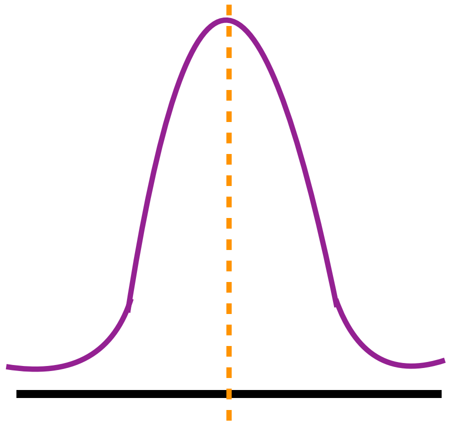
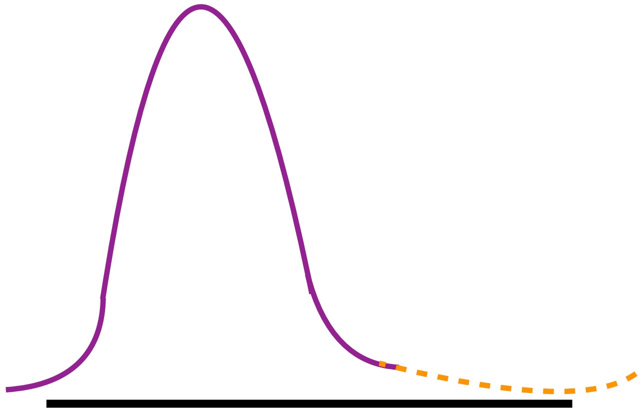
Important parameters for the Higgs boson



Mass

- Fixes phenomenology : production cross-sections and decay branching ratios
- Consistency tests of the SM at quantum level

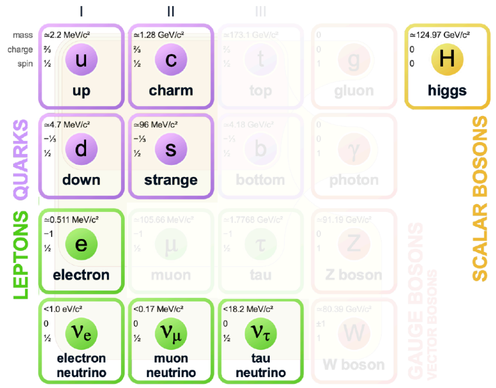


Total width

- tiny width predicted in SM : $\Gamma_{SM} = 4.1$ MeV
- *BSM contributions could bring a huge enhancement* (e.
  Higgs portal to DM)

Coupling to light quarks?

Coupling to electrons?



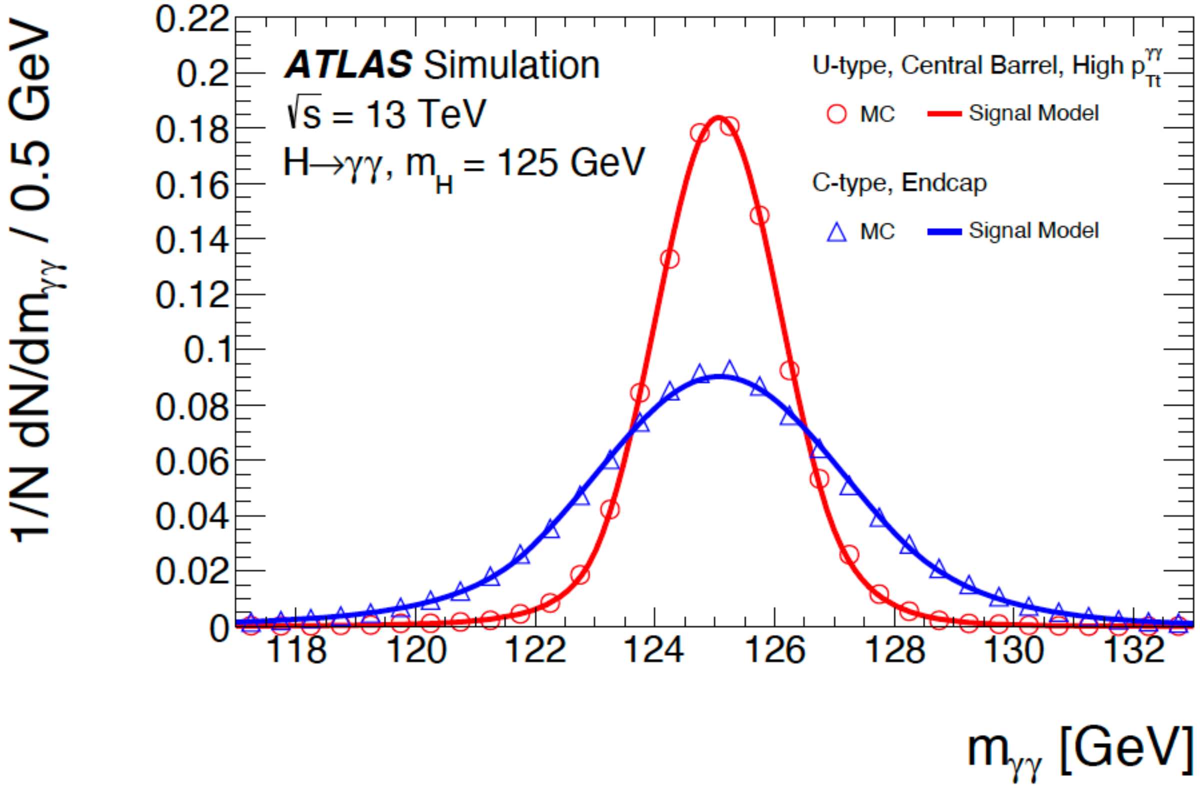
Coupling to itself?

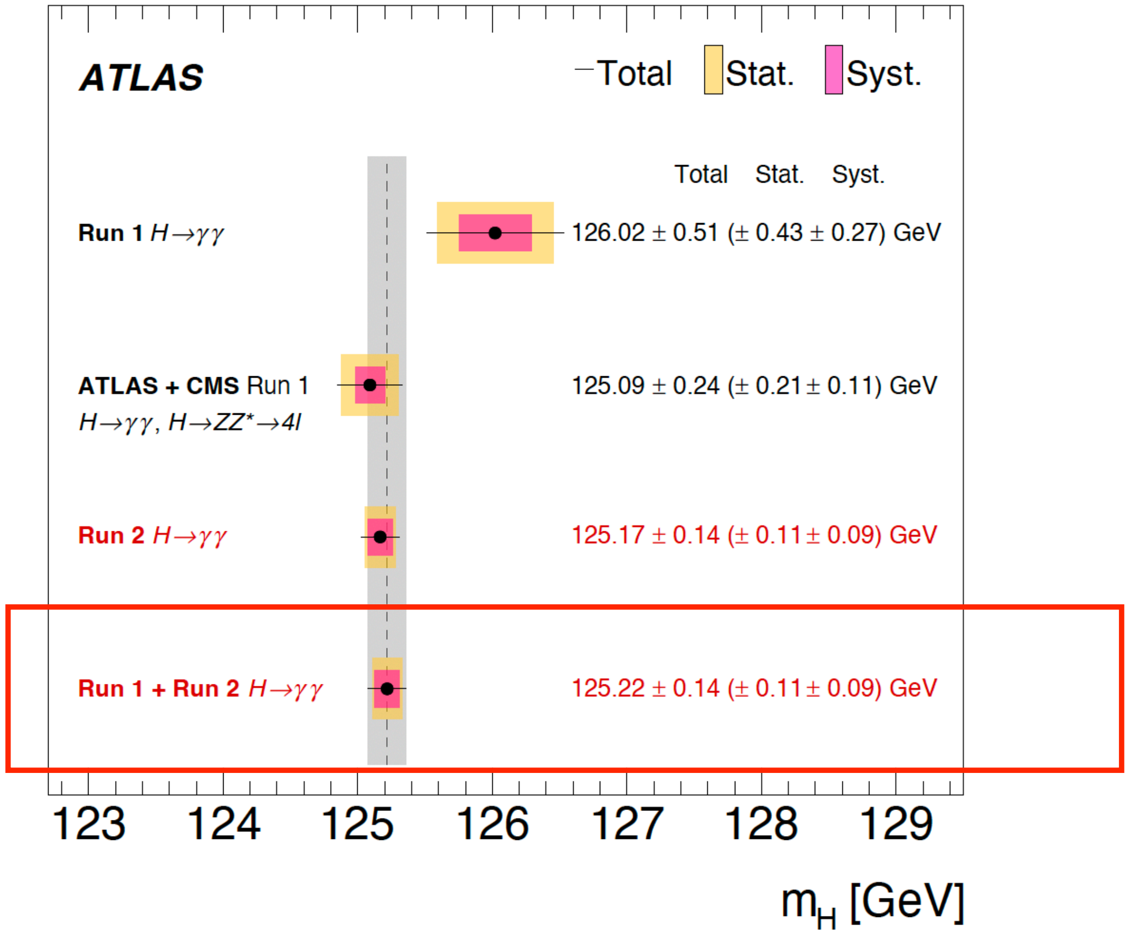
Coupling to invisible particles?
(neutrinos, dark matter)

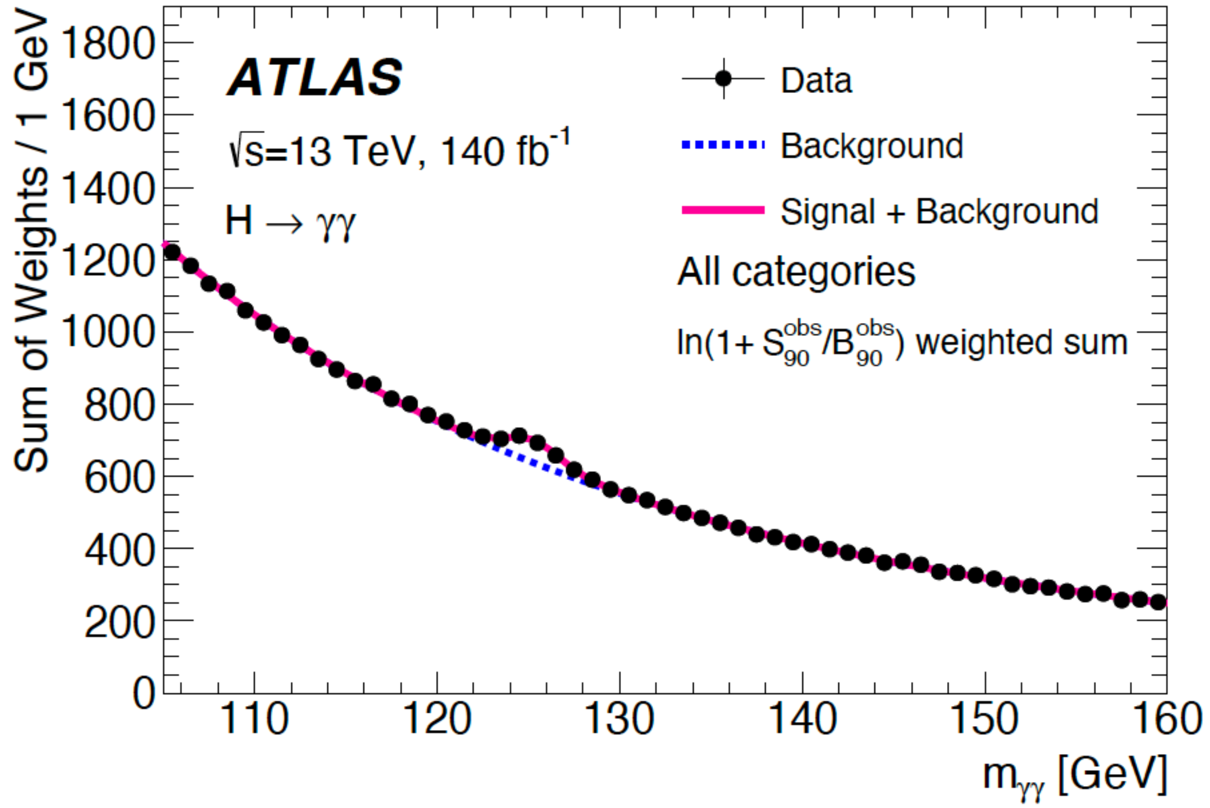
- Couplings:
  - Probe the Yukawa & BEH mechanisms
  - Higgs self-coupling ==> determines the shape of the Higgs potential ==> linked to a wide range of open questions in particle physics

[Phys. Lett. B 847 (2023) 138315]

Higgs boson mass measurement: Higgs ⇒ γ γ



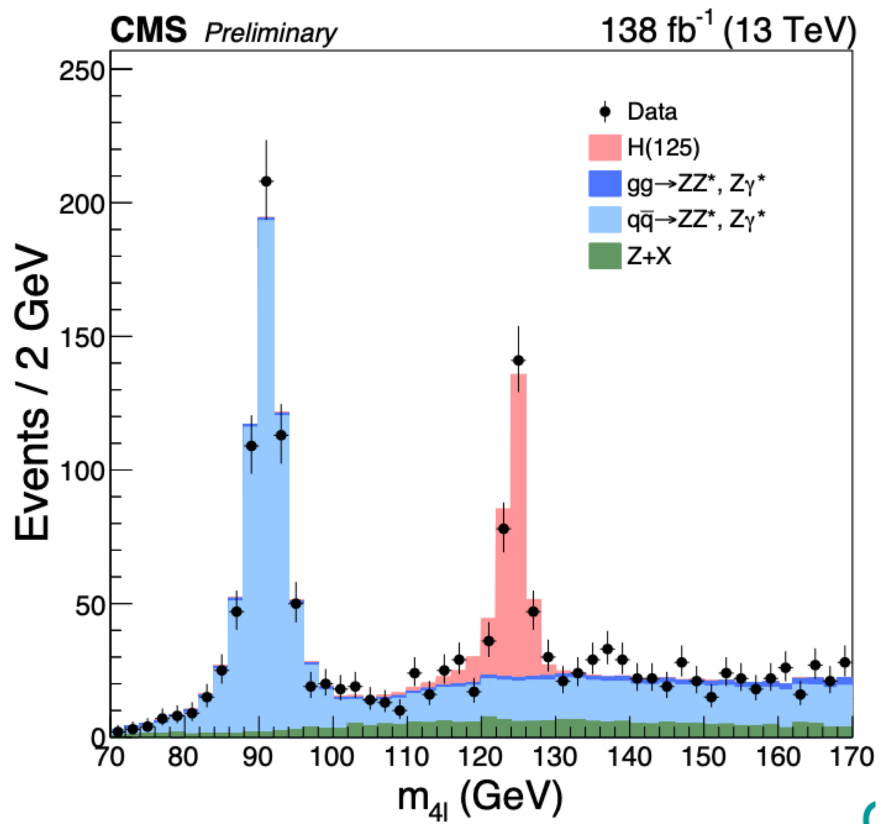




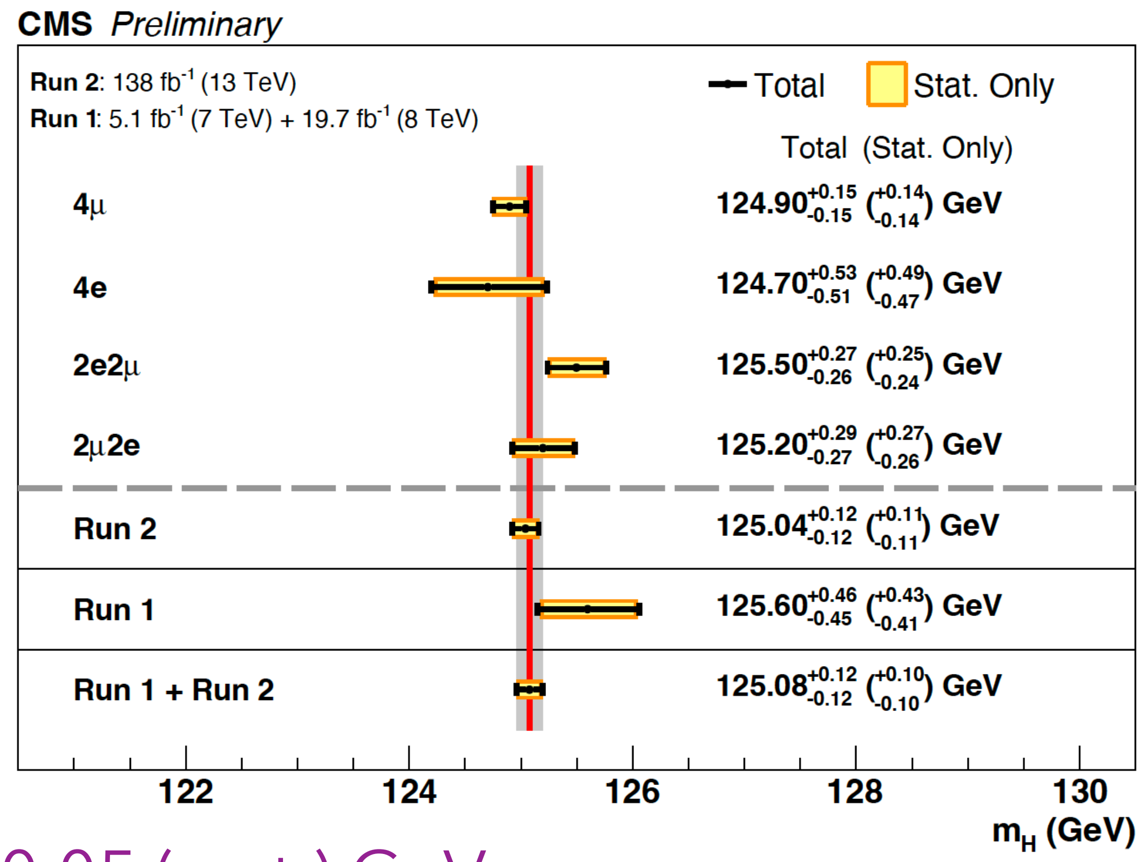
- Categorization by detector region, γ conversion type, and p_T improves total uncertainty **by 17% compared with inclusive case**
- Reduction of systematic uncertainty **by factor of 4** compared with previous iteration based on partial Run 2 data
  - Improved photon energy scale calibration
  - Better constraint one→γ extrapolation uncertainty using Z→ee data
- 0.1% precision from a single channel!

Higgs boson measurement: H->ZZ*->4l (CMS)

[CMS-PAS-HIG-21-019]



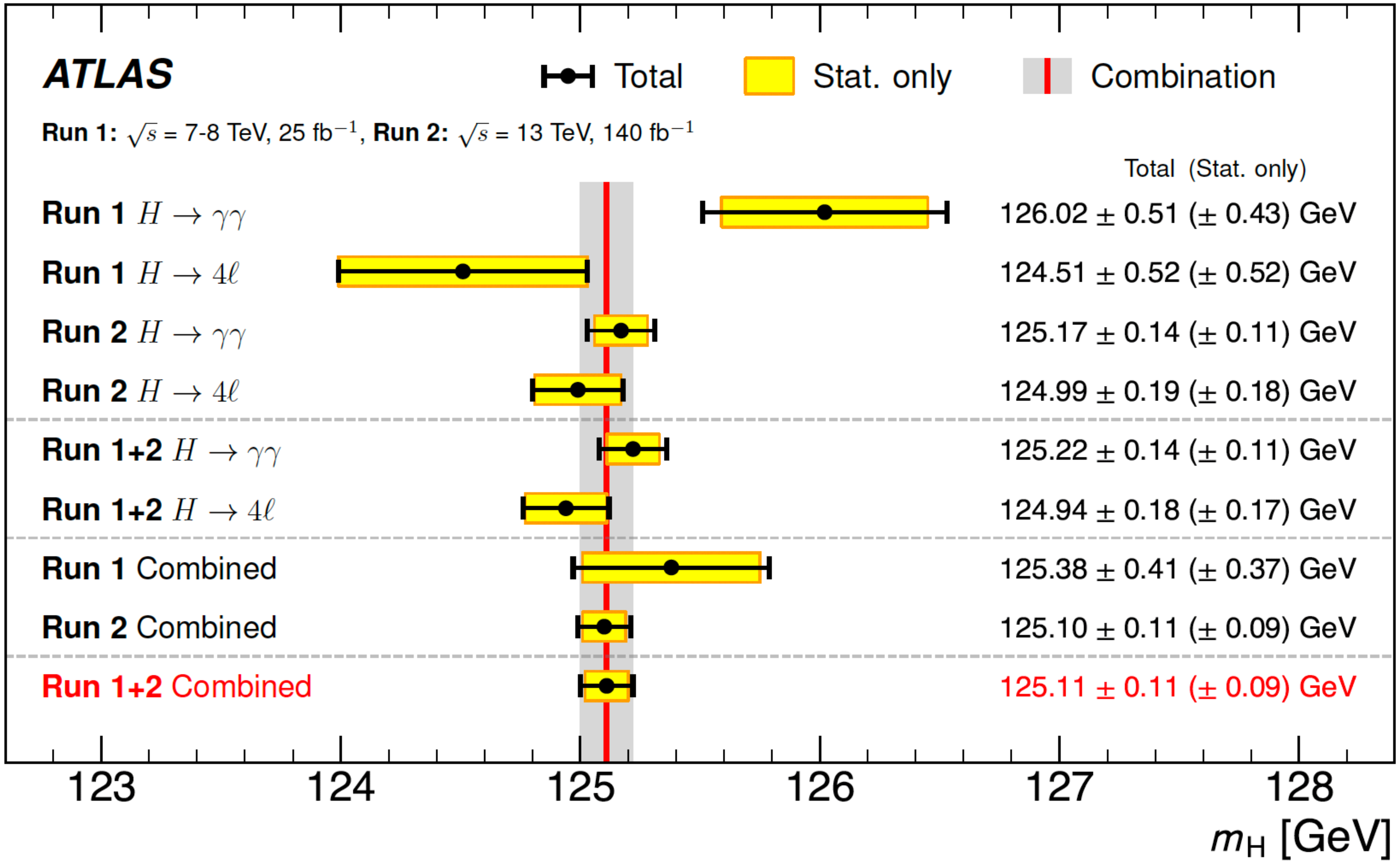
Most precise single-channel measurement!



$m_H = 125.04 \pm 0.11$ (stat.) ± 0.05 (syst.) GeV

- Beam-spot constraint in muon reconstruction + kinematic fit to Z-pole for on-shell lepton-pair candidate (+15% improvement in precision)
- Categorization based on per-event 4l mass resolution (+8%)
- 2D fit of m4l and matrix-element-based (MELA) discriminant (+4%)
- Measurement fully driven by data stat uncertainty
- Main syst from muon momentum and electron energy scale uncertainties

Current best Higgs mass measurement



[Phys. Rev. Lett. 131 (2023) 251802]

- *ATLAS Run 1+2: mH = 125.11 ± 0.11 (= ± 0.09 (stat) ± 0.06 (syst)) GeV*
- *CMS Run 1+2016: mH = 125.38 ± 0.14 (= ± 0.11 (stat) ± 0.08 (syst)) GeV [Phys. Lett. B 805 (2020) 135425*

→ 0.1% precision achieved with Run 1 + partial or full Run 2 measurement for ATLAS & CMS standalone!

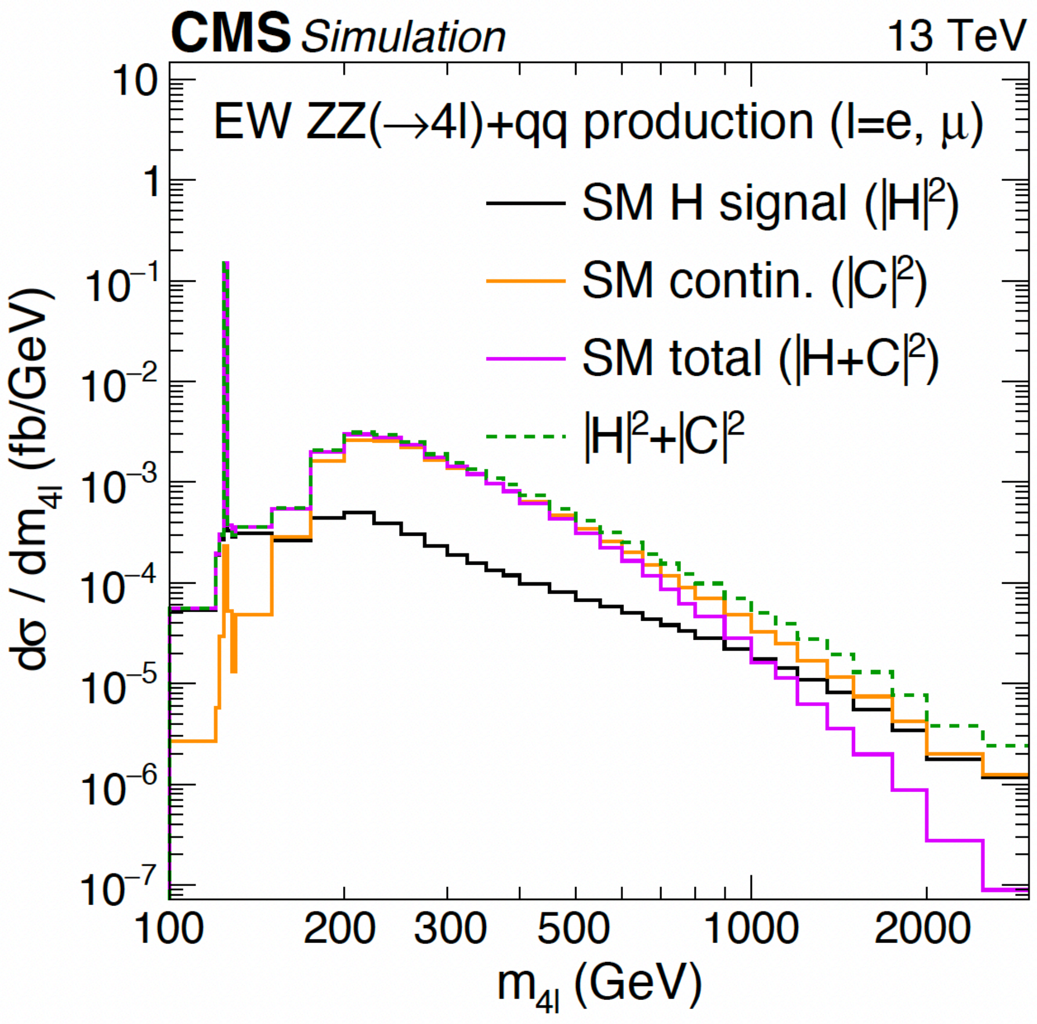
Higgs boson Width

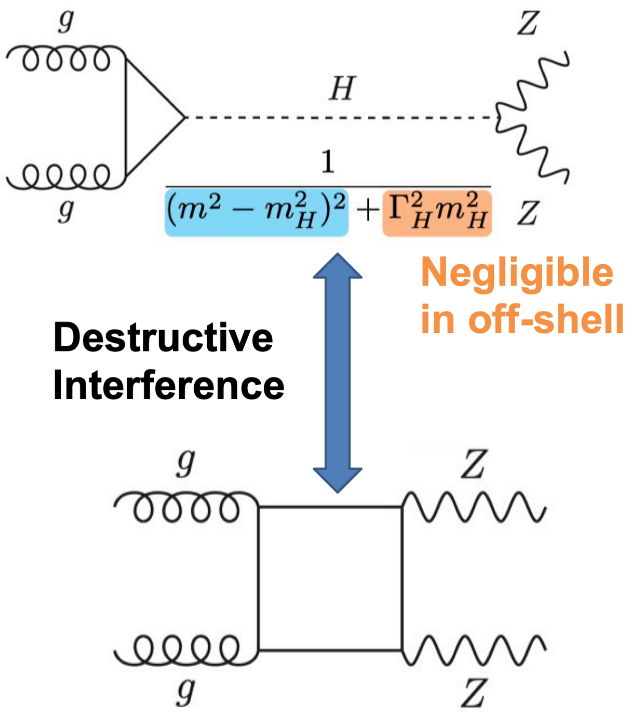
[Nat. Phys. 18 (2022) 1329]

- Width precisely predicted within the SM: [R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (20220] $\Gamma_{\text{SM}} = 4.1$ MeV
- Small value→difficult to measure due to detector resolution O (1-2 GeV)
- Measure in $H \to ZZ$ compare on- and off-shell production:

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}}$$

→ Use H→ZZ→4l & H→ZZ→2l2v events to enhance sensitivity



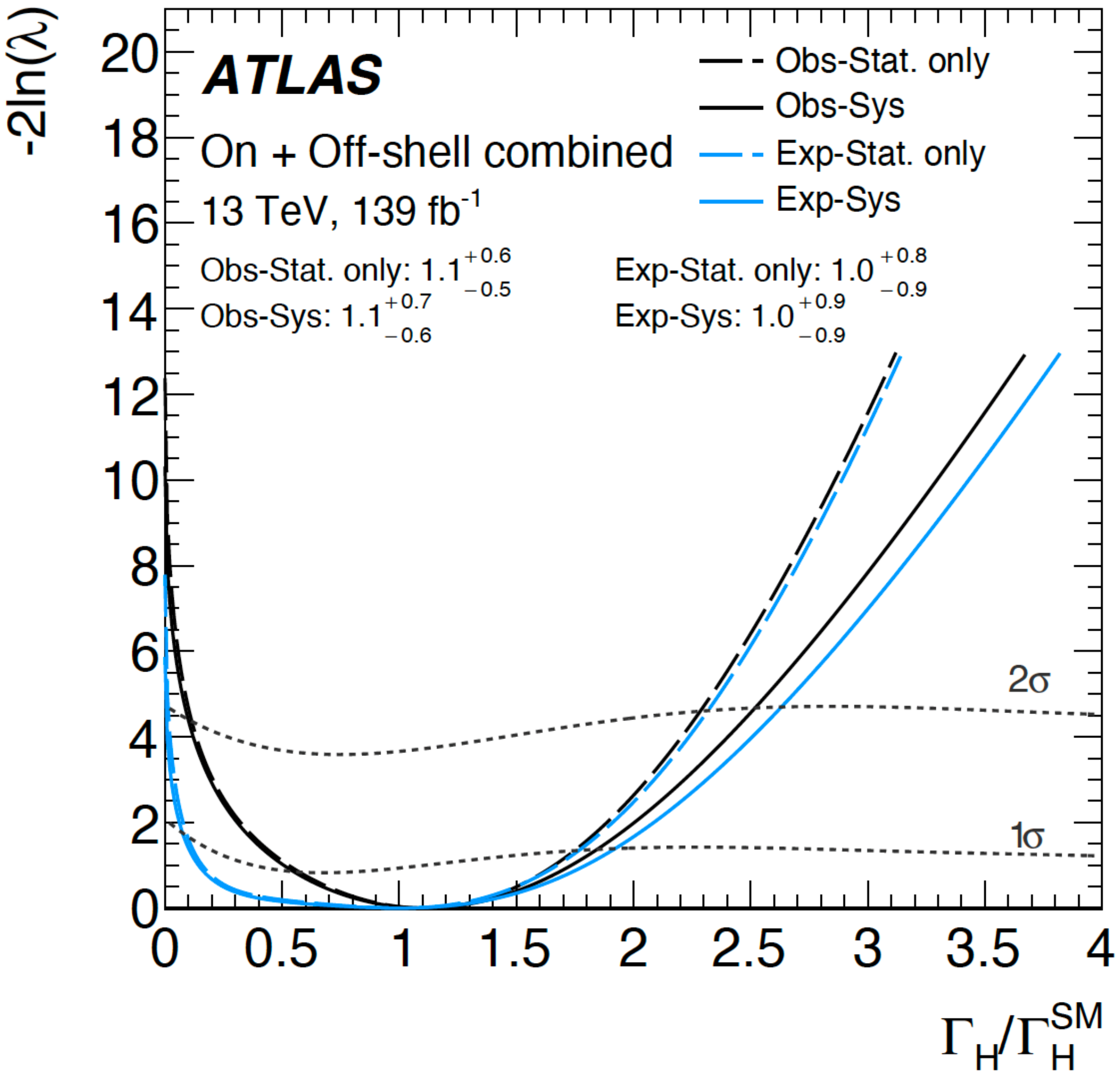


Negligible in off-shell

Destructive Interference

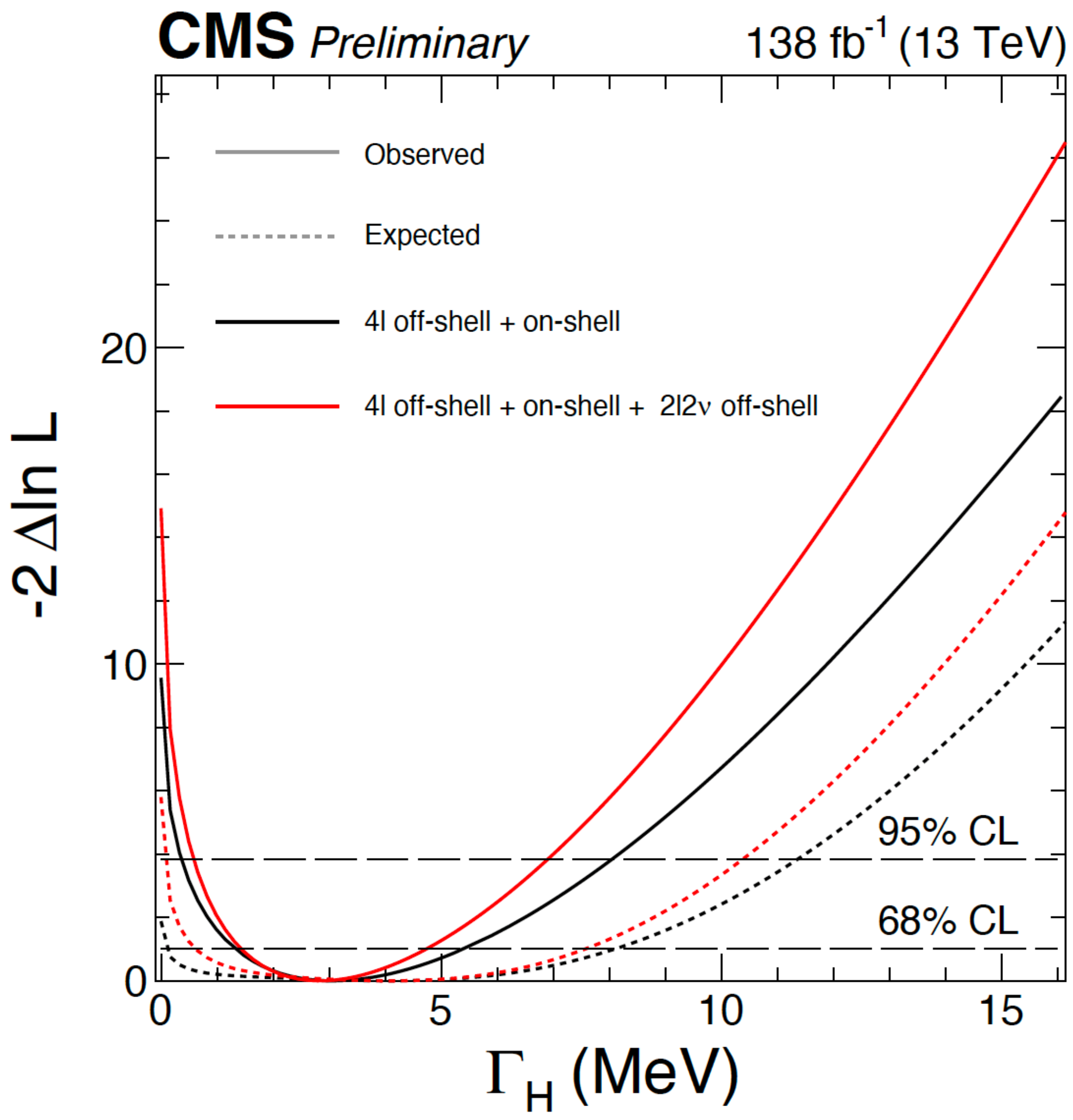
Higgs boson width

[Phys. Lett. B 846 (2023) 138223]



$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ MeV$$

[CMS-PAS-HIG-21-019]



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

What about HL-LHC?

- Mass measurements : mainly from H → 4μ, 2e2μ
  - Naive stat. uncertainty extrapolation for a CMS-like experiment ~ 24 MeV
  - Run II syst. uncertainty from muon energy scale ~ 30 MeV *CMS PAS FTR-21-007*
    - Might expect improvements from the huge calibration sample + decrease of stat. uncertainty from increased acceptance
    - ⇒ target $\mathcal{O}$(20 MeV) ?

- Width measurements : from off-shell measurement (+ on-shell/off-shell couplings as in SM)
  - CMS extrapolation from Run II, 78 fb^{-1} H → 4ℓ analysis ⇒ assuming theory uncertainties halved w.r.t. Run II
  - ⇒ ATLAS + CMS : $\Gamma = 4.1^{+0.7}_{-0.8}$ MeV

ATL-PHYS-PUB-2022-018

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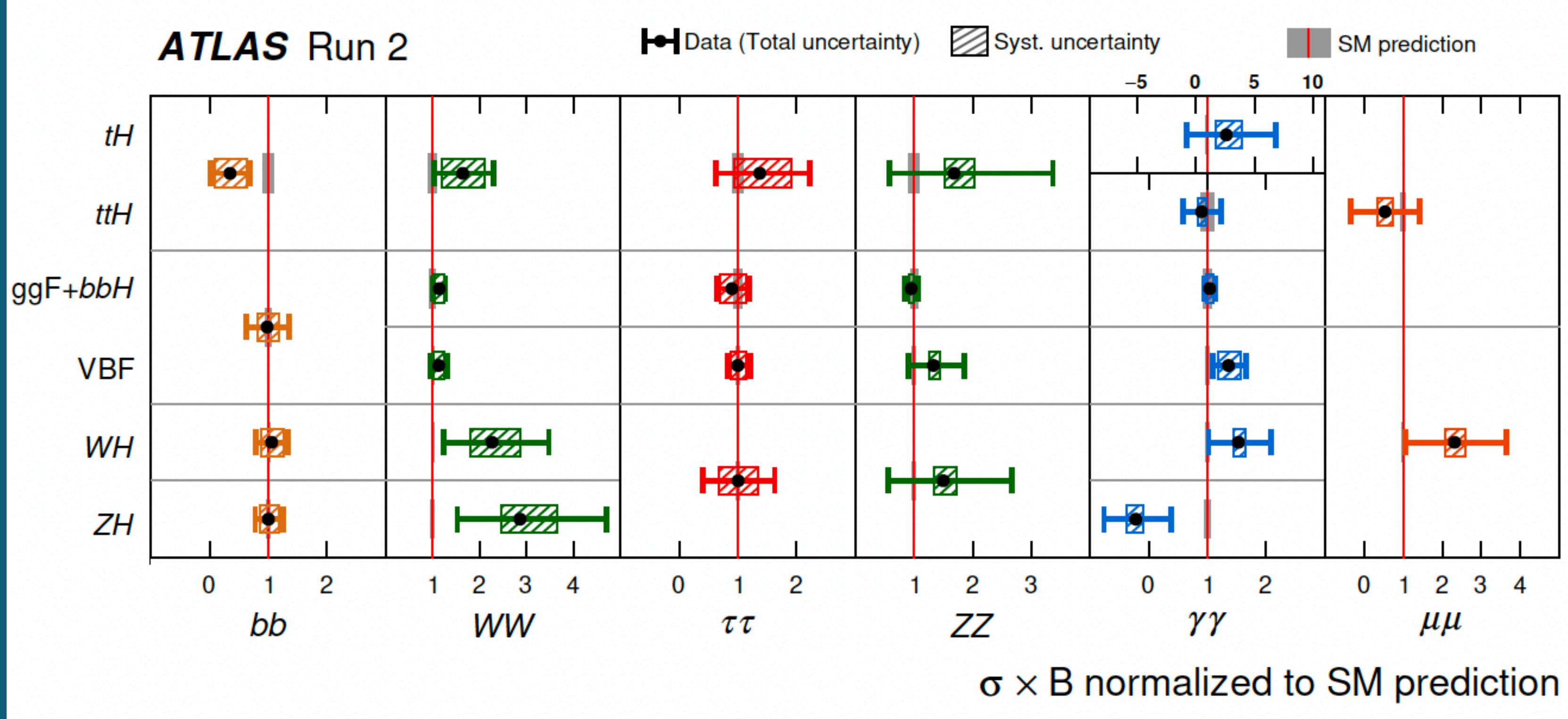
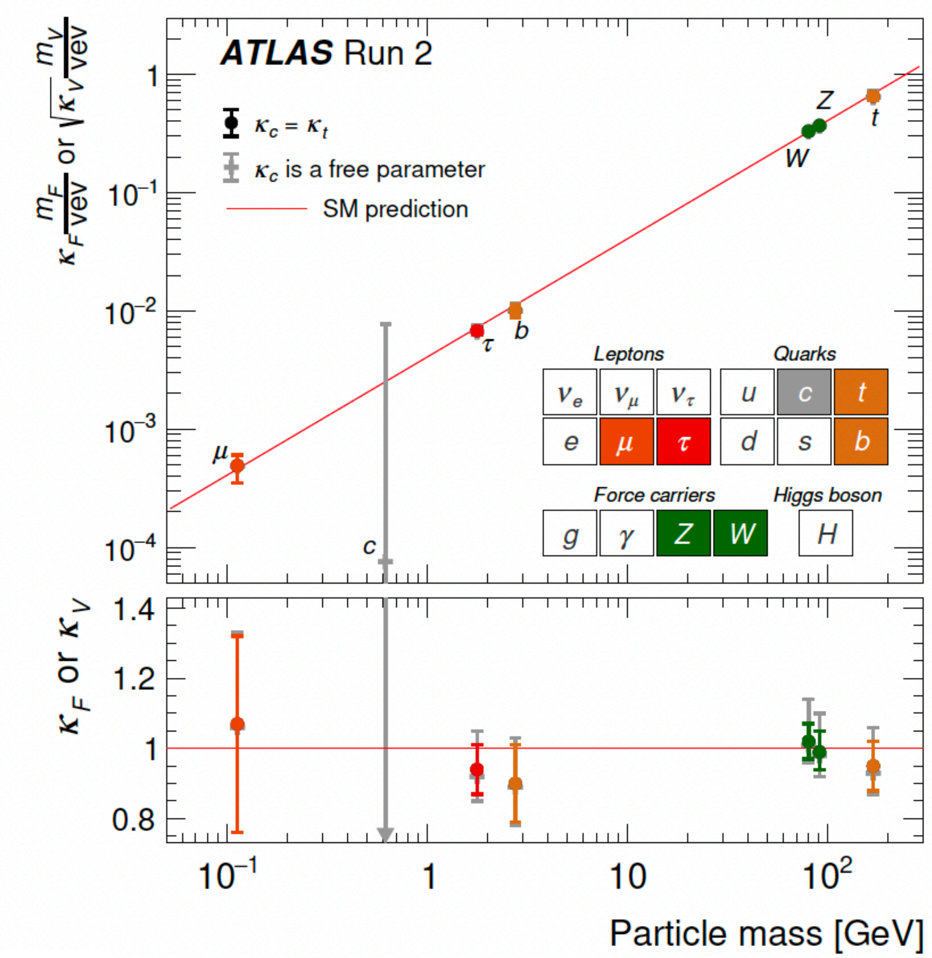
Cross section and coupling modifiers

[Nature 607, 52 (2022)]



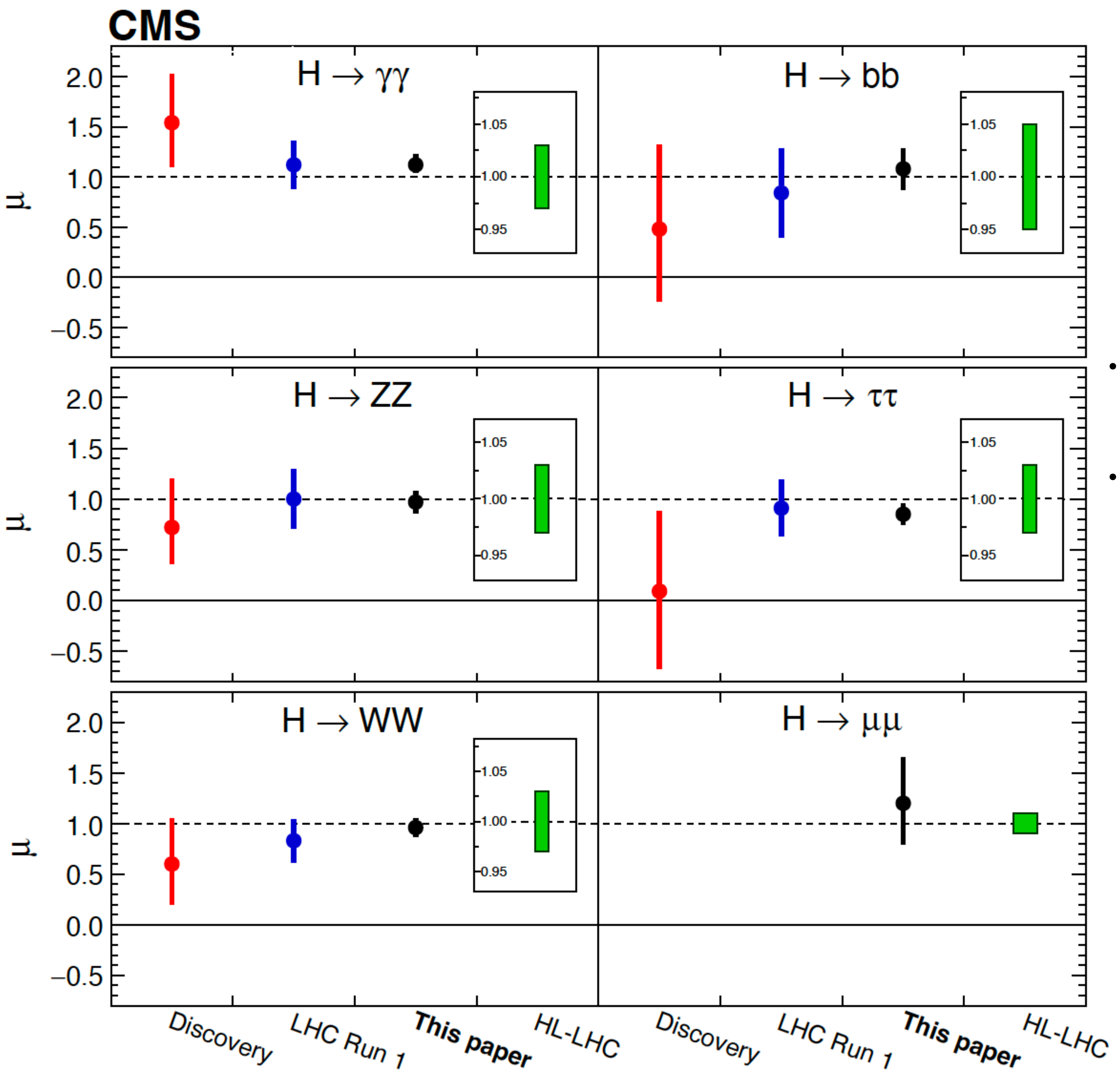


$$\kappa_X = \frac{\text{Higgs coupling to X}}{\text{SM prediction}}$$

($\kappa_X = 1$ in the SM)

Cross section and coupling modifiers

[Nature 607 (2022) 60-68]

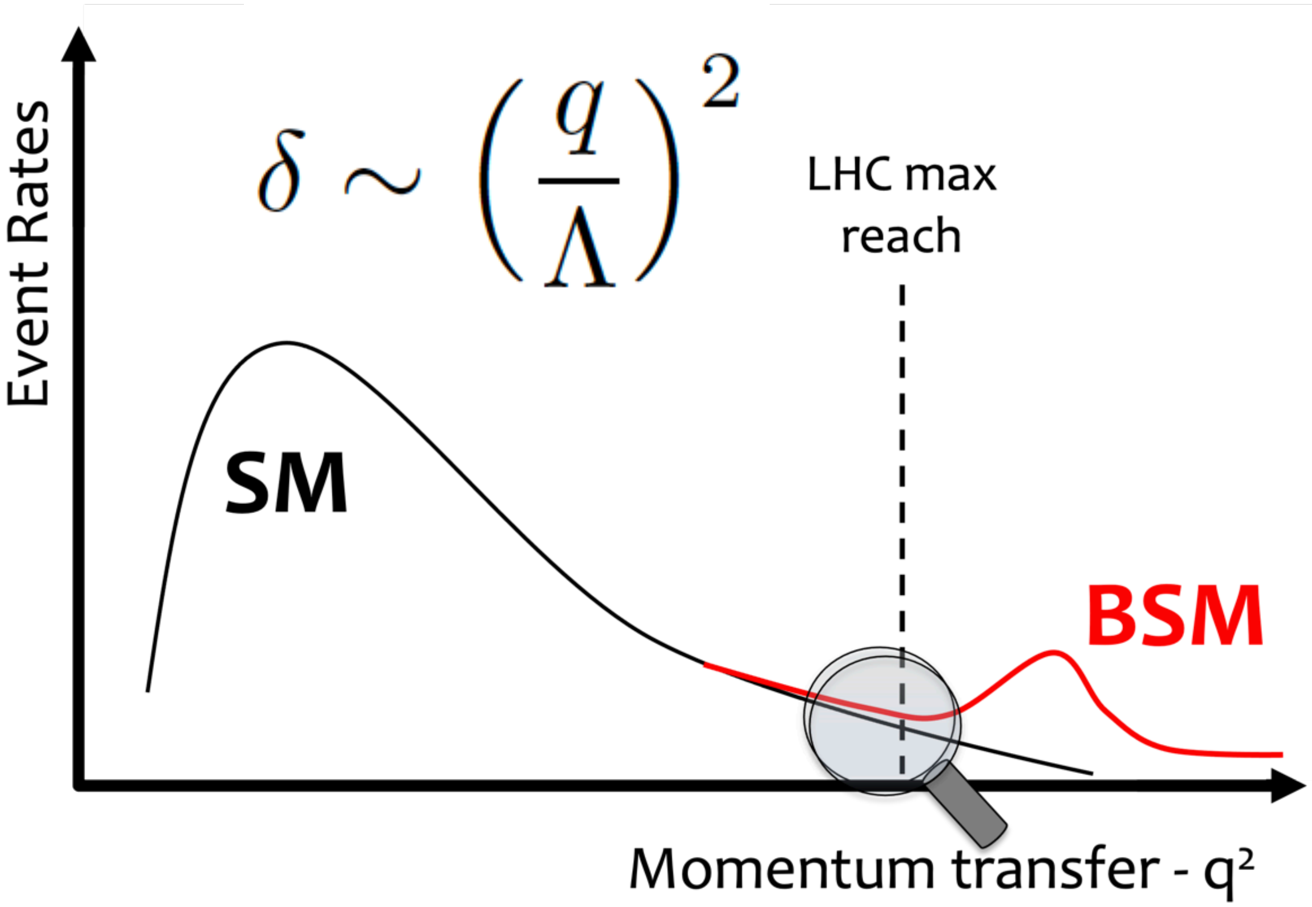


- High Luminosity LHC (HL-LHC)
- 3000 fb^{-1} @14 TeV

Dive into phase-space sensitive to BSM

- Shifting interest from static to dynamic properties of the Higgs boson
- Increased impact expected from new physics at high momentum

- Inclusive measurements: high-precision yields precision on new physics scale $\delta_\mu = 1\%$ ==> $\Lambda \sim 2.5$ TeV
- Differential: High momentum production sensitive to new physics $\delta_\sigma = 15\%$ (q=1TeV) ==> $\Lambda \sim 2.5$ TeV

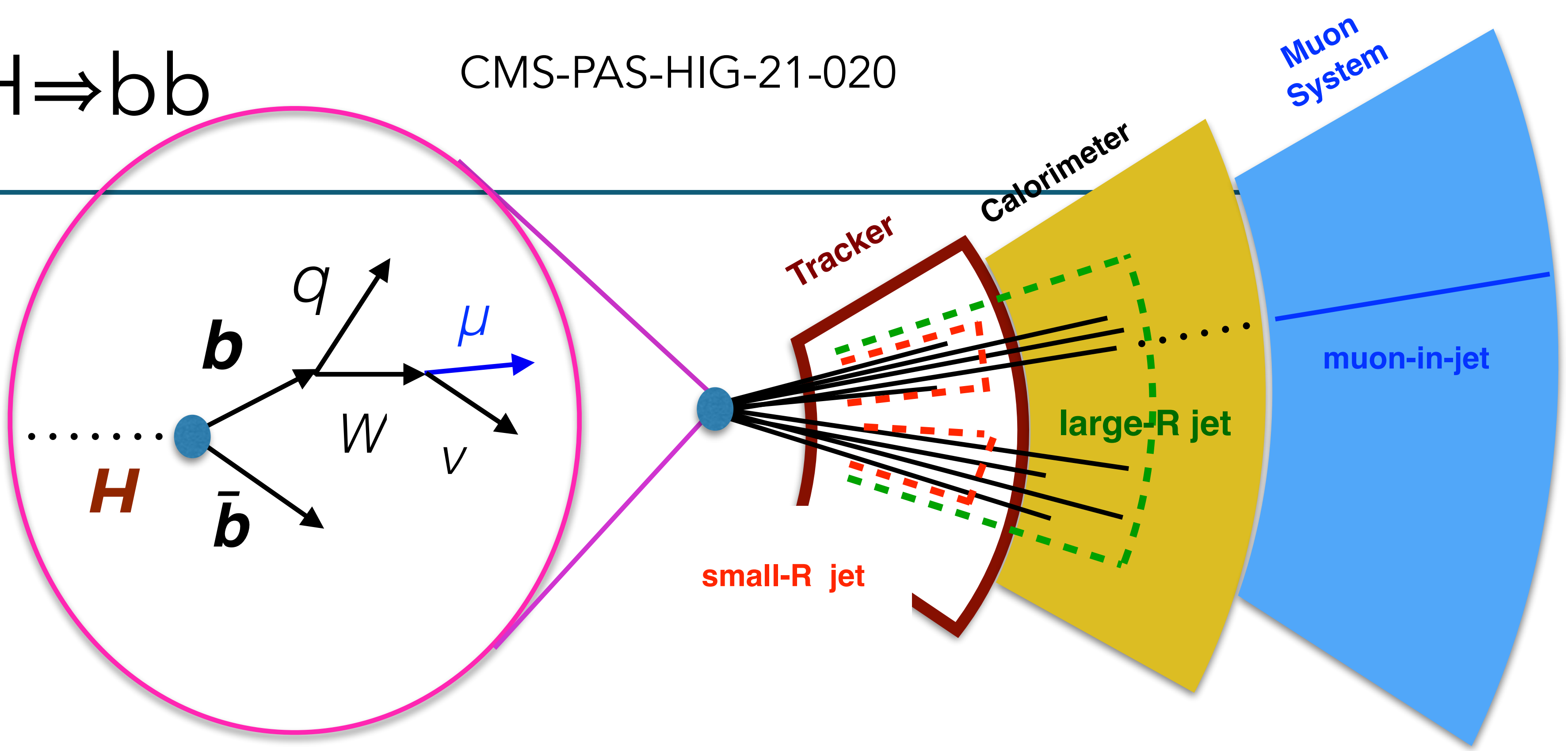


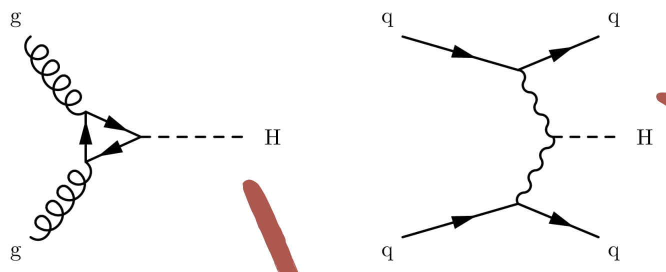
Fully hadronic final state expected to have more sensitivity in the tails of distributions

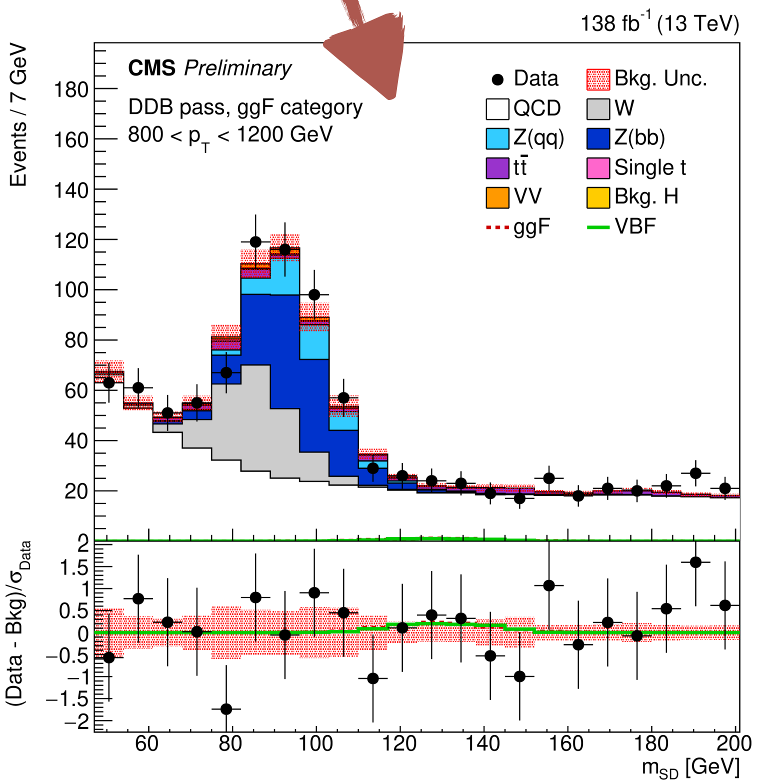
Boosted ggF/VBF, H⇒bb

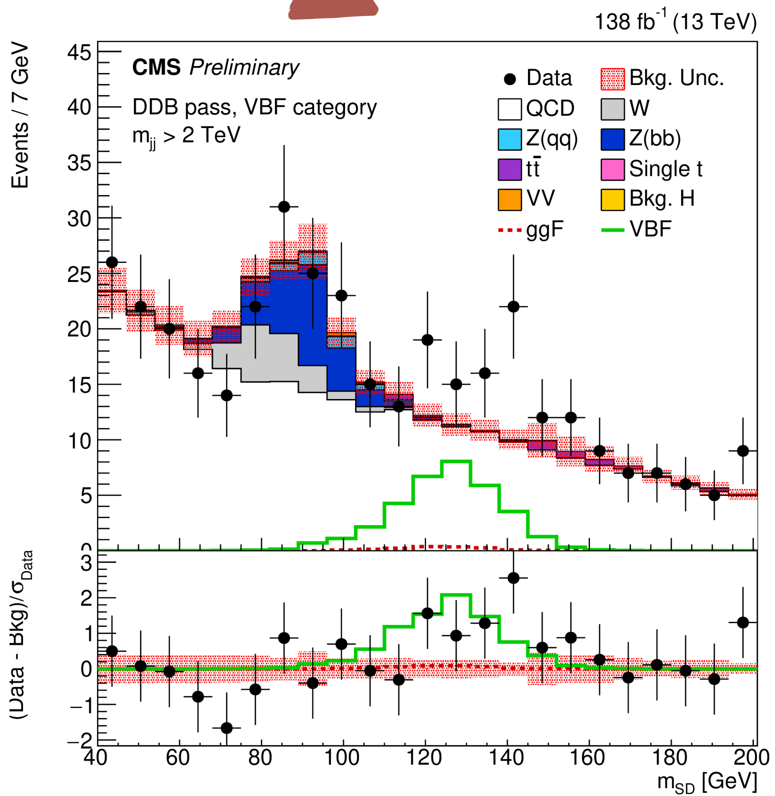
CMS-PAS-HIG-21-020

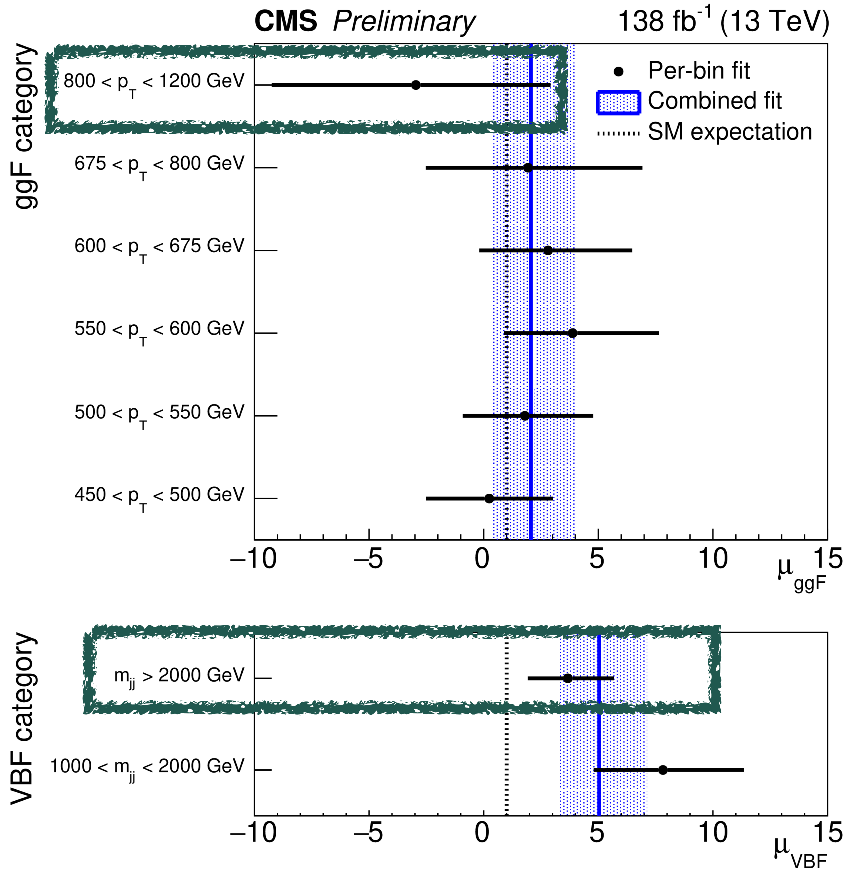
- Use boosted H(bb) reconstructed as large-R jet to explore **TeV-scale**







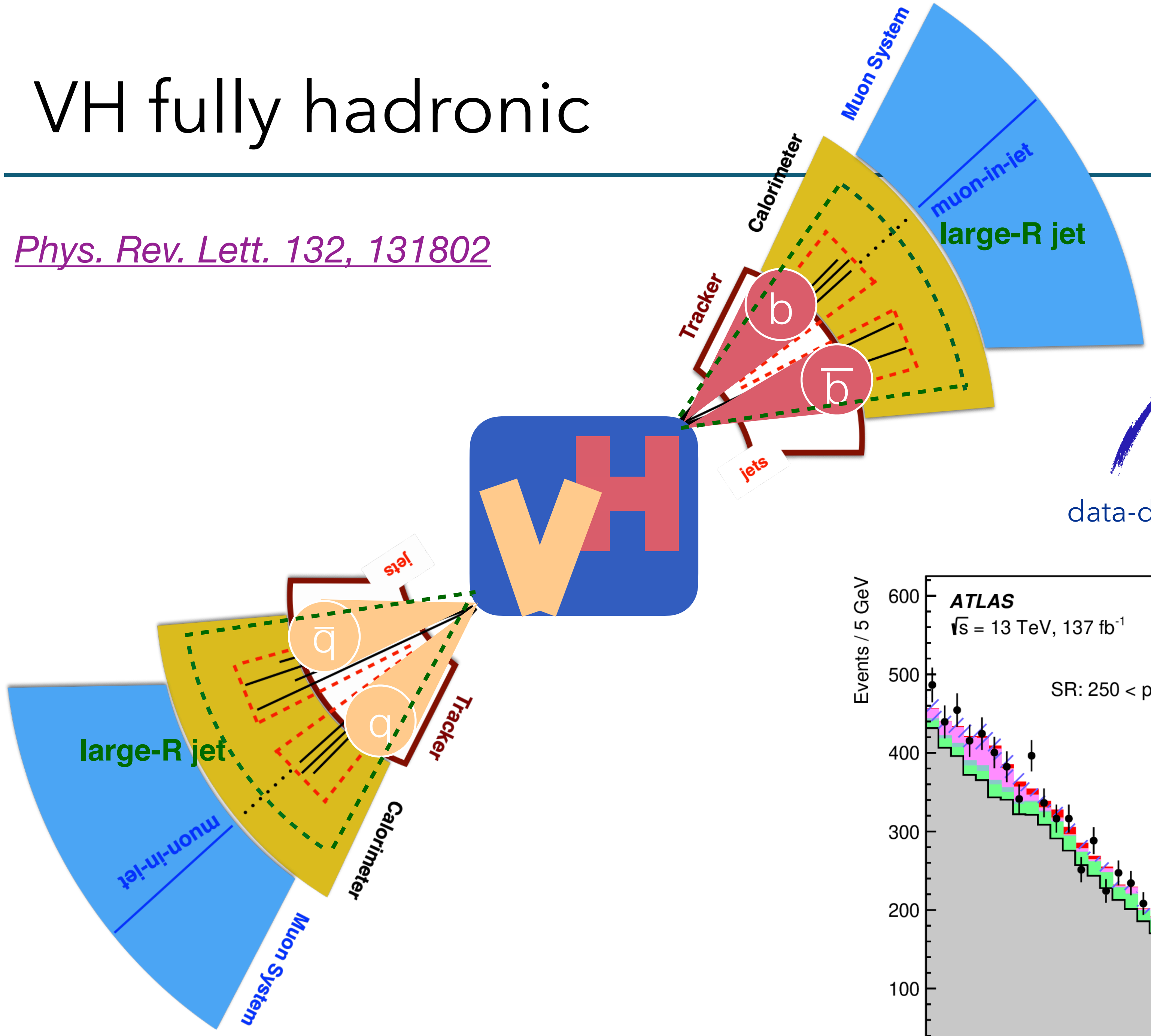


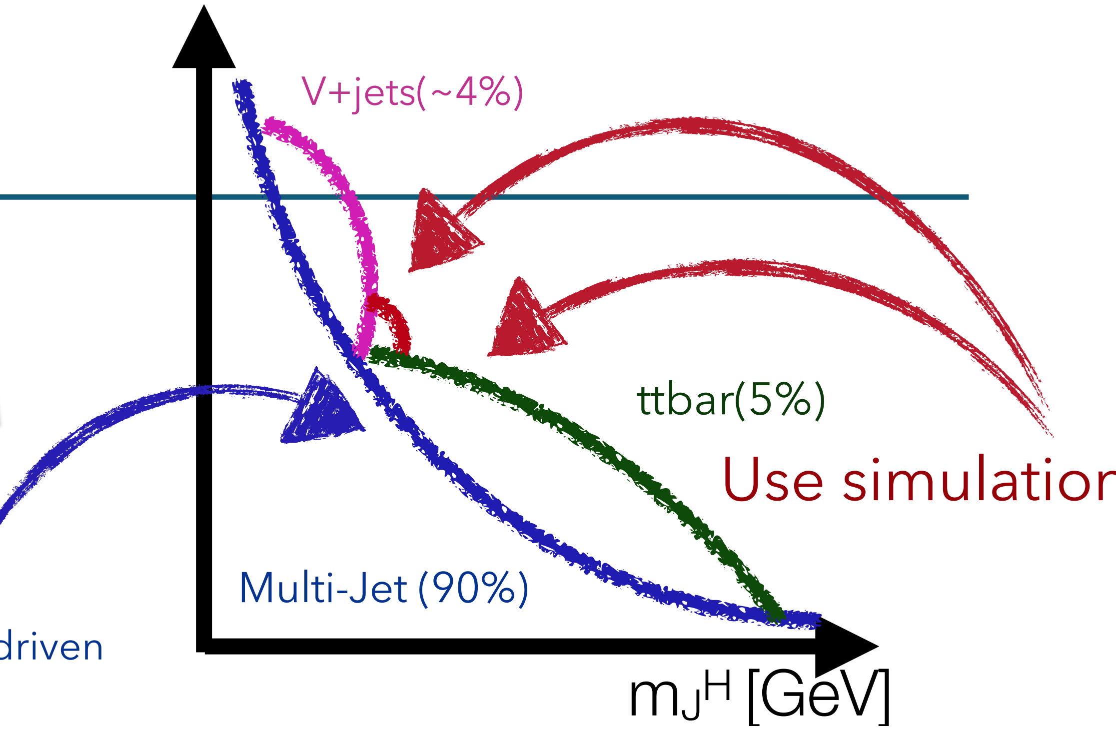


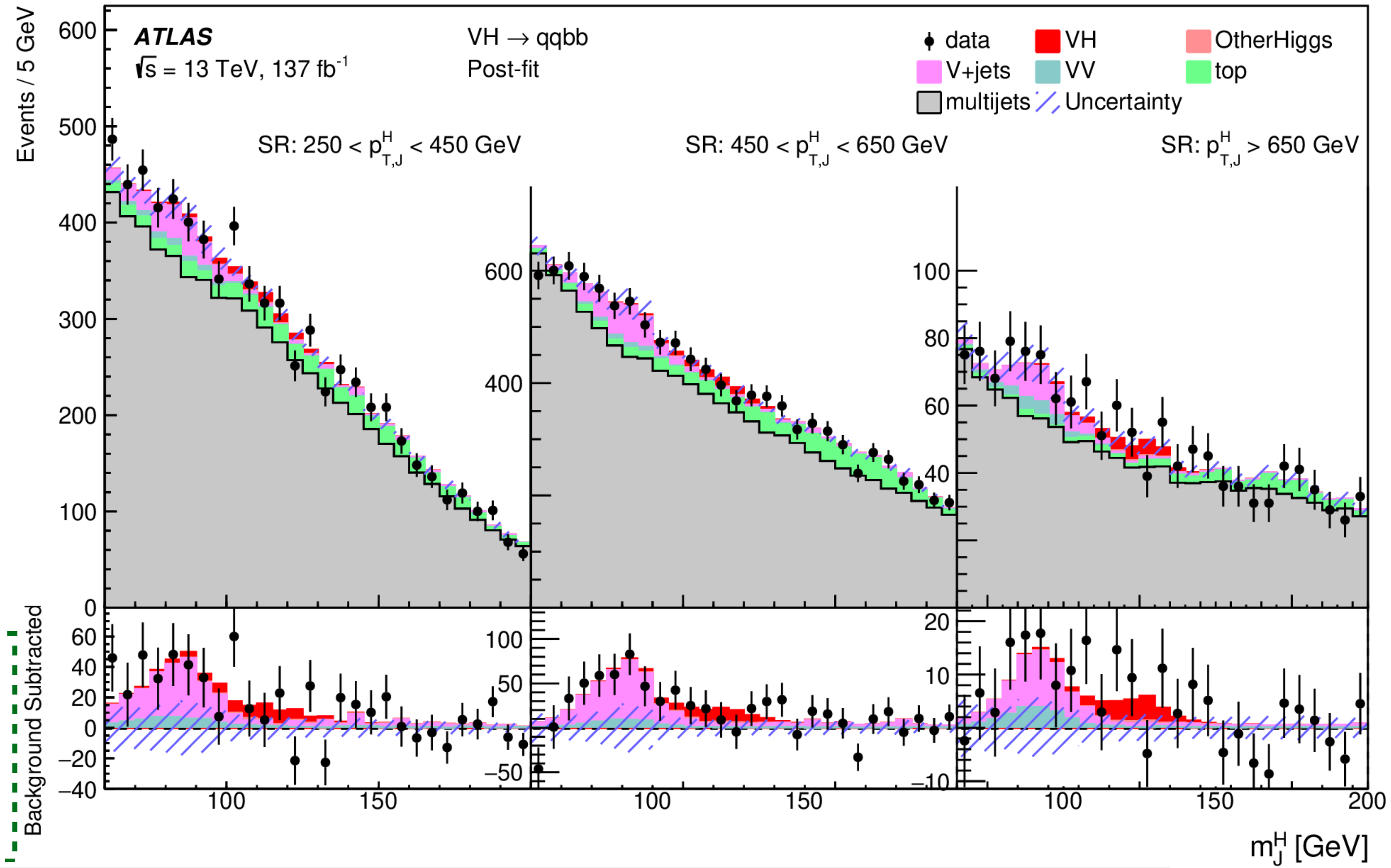
Observed significance 1.2(0.9σ exp) for ggF and 3.0 (0.9σ exp) for VBF

VH fully hadronic

Phys. Rev. Lett. 132, 131802







Observed significance 1.7σ (1.2σ expected) corresponding to an observed cross-section: 3.3±1.5(stat)+1.9-1.5(syst) pb

Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \leq p_T^H < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \leq p_T^H < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_T^H \geq 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2

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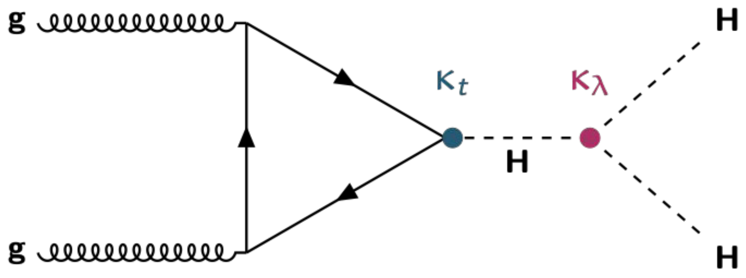
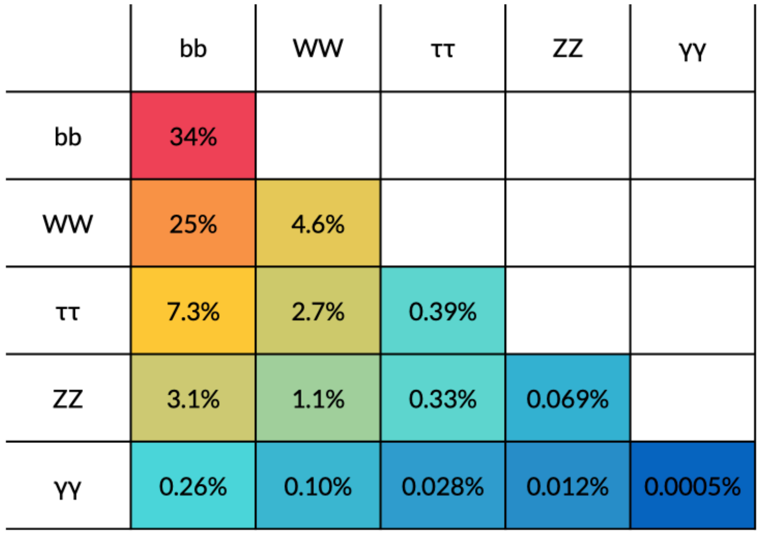
Coupling modifier constraints: self-coupling through HH

$\kappa_\lambda=\lambda/\lambda_{SM}$





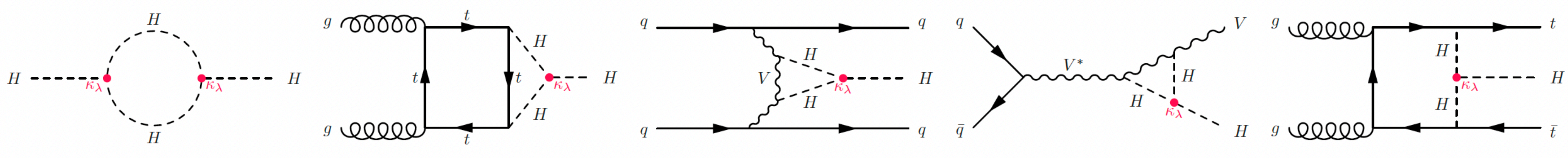
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Measure it by looking at HH pair production:

- **Very rare process**
- **~ 1000x smaller than single H**

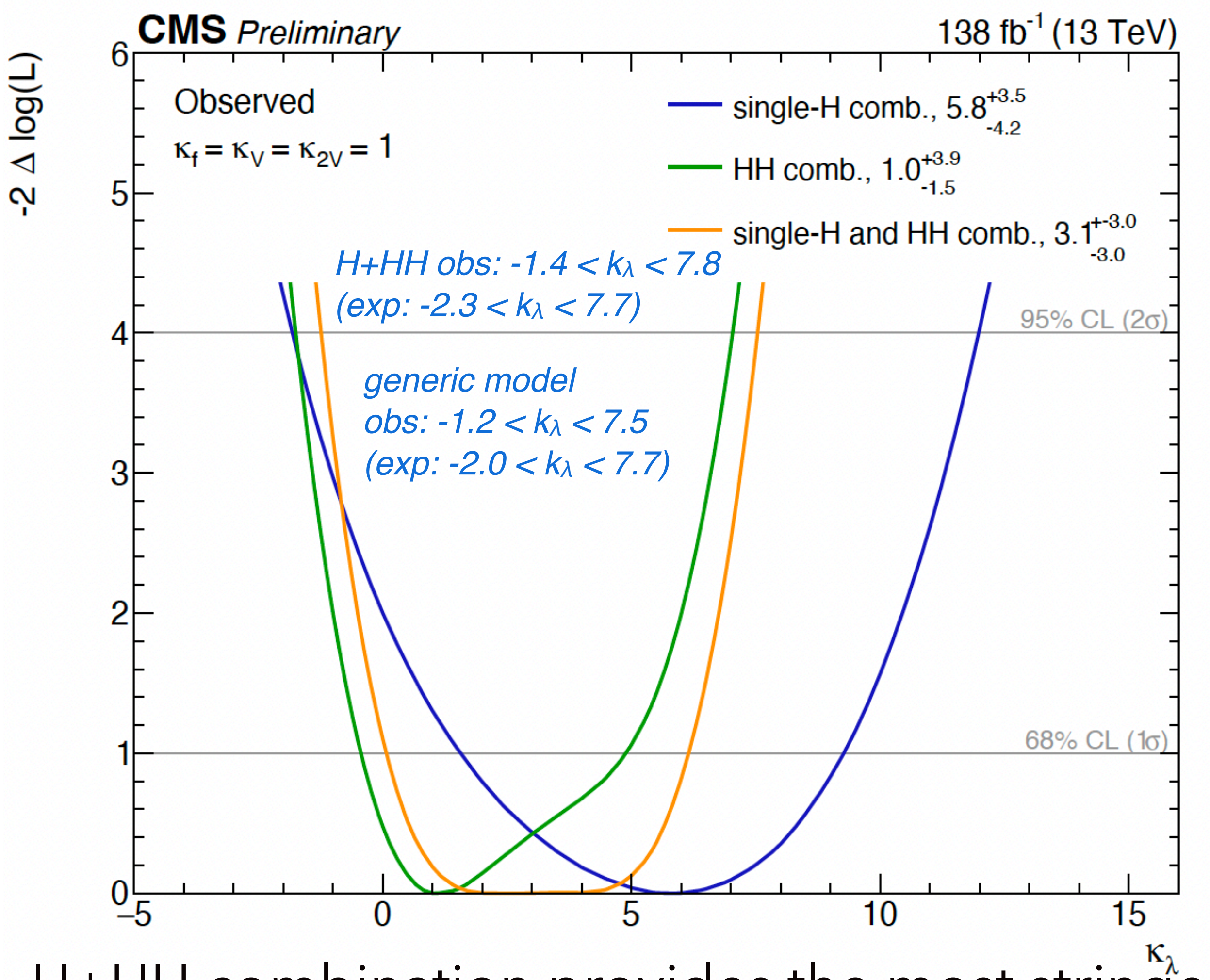
See talk by J. Veatch

κ_λ contributes to single-Higgs at NLO EW corrections (indirect constraint)

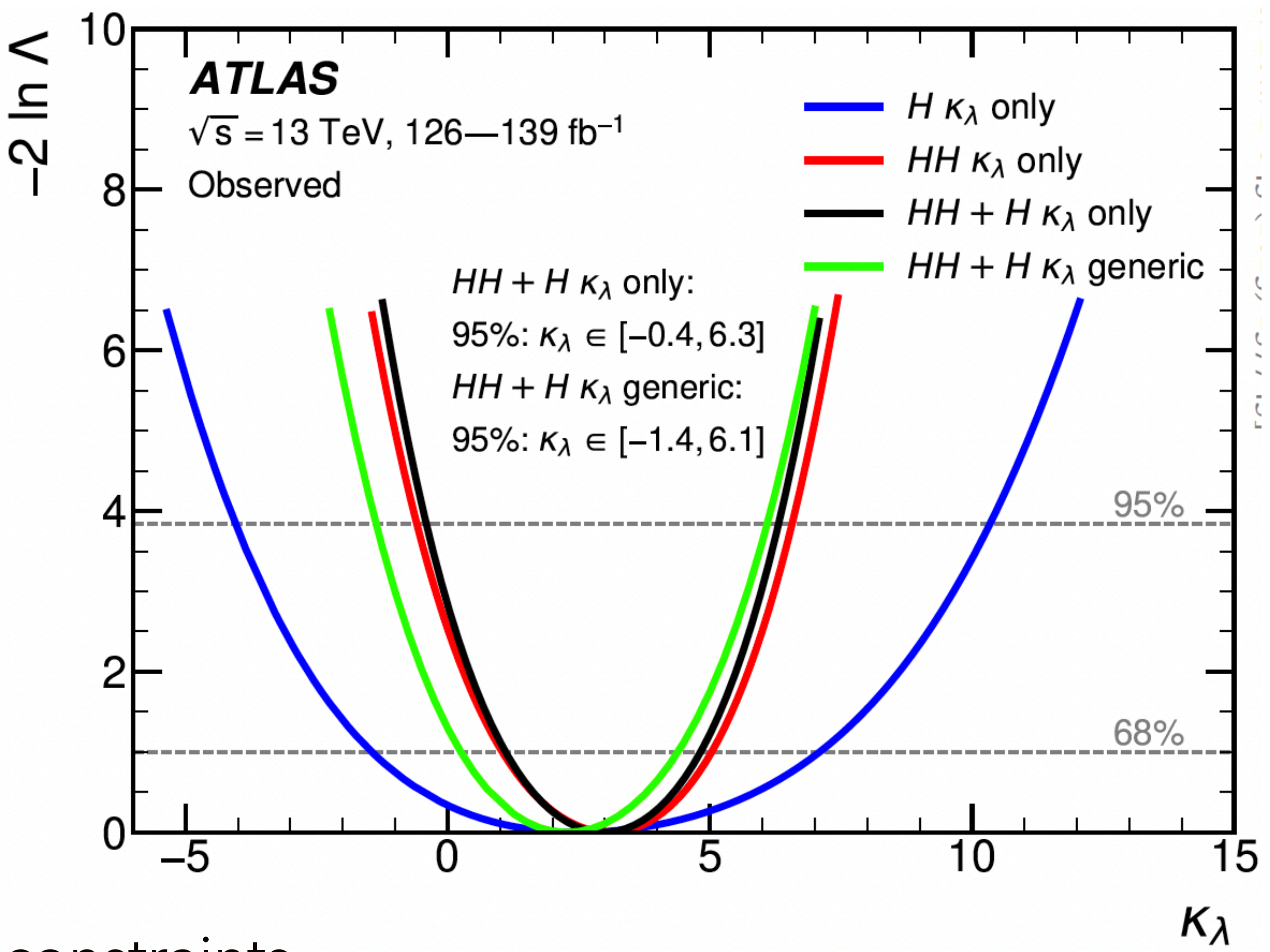


Coupling modifier constraints: self-coupling

[CMS-PAS-HIG-23-006]



[Phys. Lett. B 843 (2023) 137745]



- H+HH combination provides the most stringent constraints
  - Exp only confidence interval is 5% better than HH (most sensitive), 78% better than H (for ATLAS)
- Assumption on κ_t can be relaxed w/o losing sensitivity κ_λ
- More generic model (all coupling modifiers floating) still gives strong constraints

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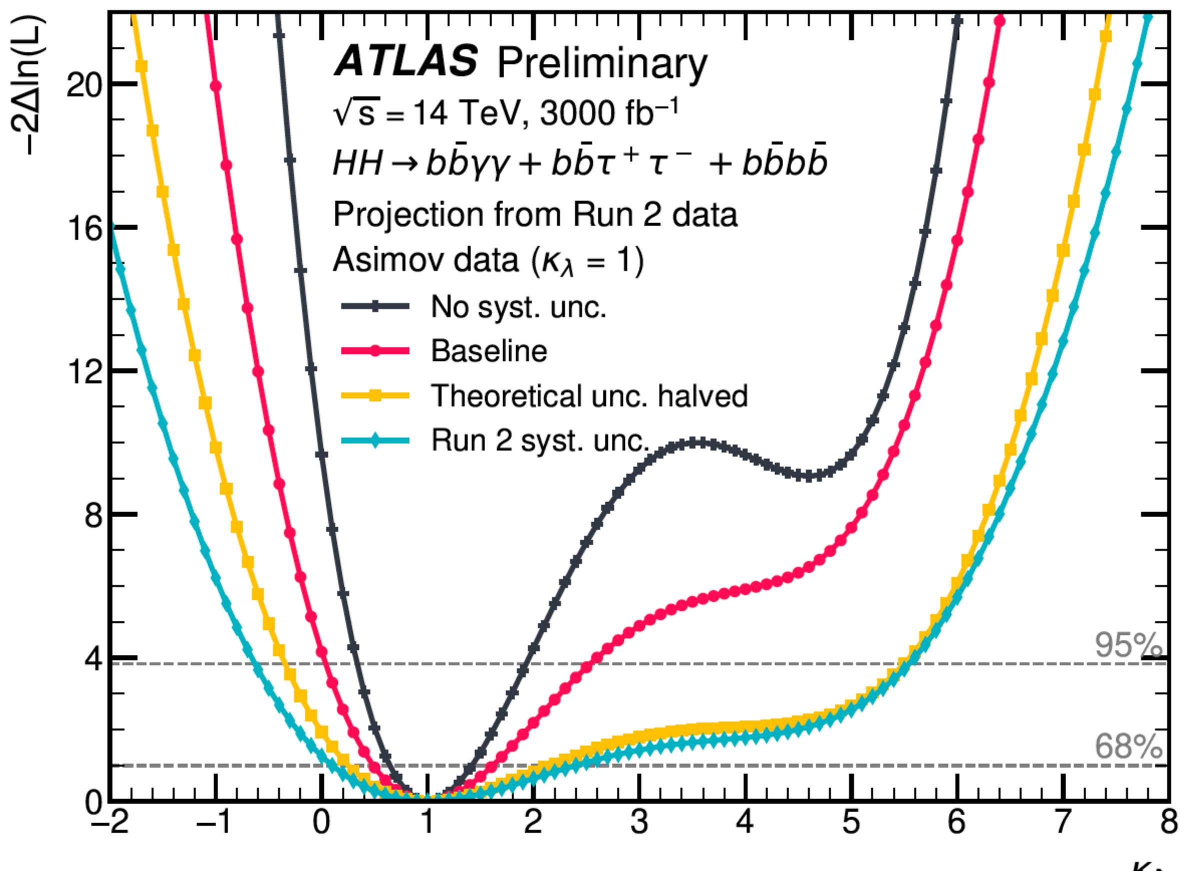
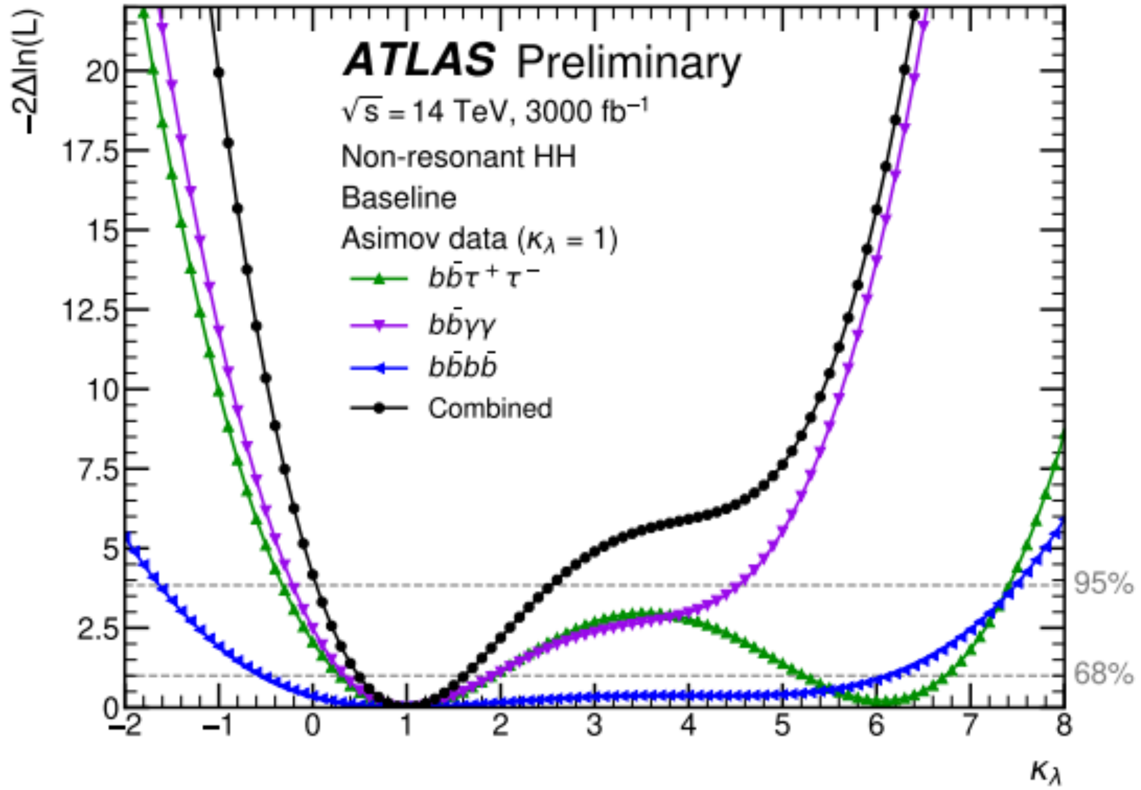
Higgs boson self-coupling projections

[ATL-PHYS-PUB-2022-053]

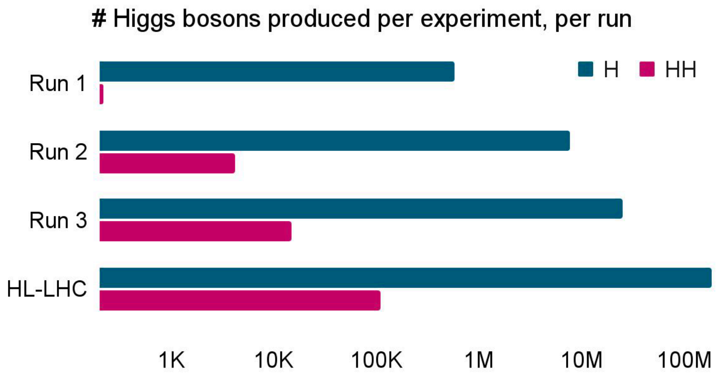




- ATLAS combination: Significance of 3.4 σ (4.9 σ), assuming the baseline scenario (no syst scenario).

- 5σ SM HH significance from back-of-the-envelope combination with CMS
- Can improve if we continue working on new things like trigger, event reconstruction, new techniques etc.

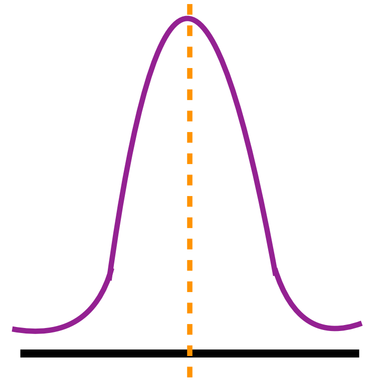
Combinations with precision differential measurements of Higgs production will push sensitivity even further!



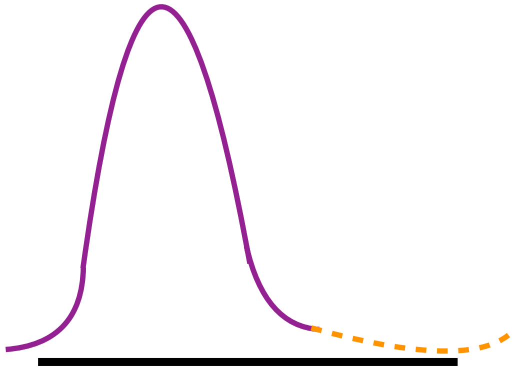
From Liza Brost

Summary

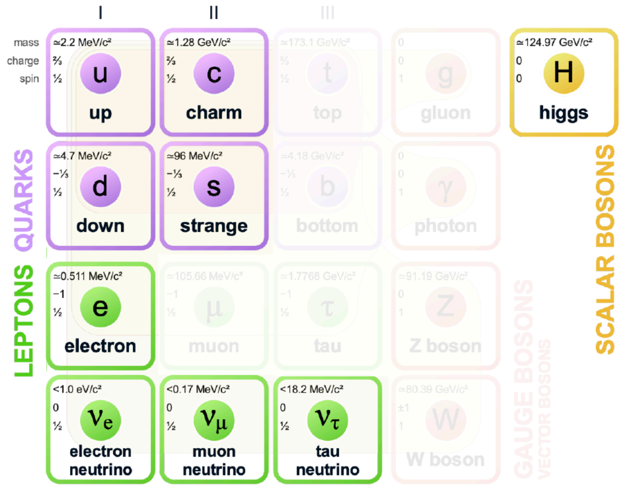
- Precision Higgs boson coupling measurements offer a unique insight into BSM physics & complimentary to direct searches
- With Run 1+2 data, we have
  - 0.09% precision on Higgs boson mass
  - ~50% precision on Γ_H from off-shell
  - ~10% precision on production cross-sections
  - Higgs self-coupling at ~3 times the SM
- Run 3 ongoing: will hopefully triple the stats
- Perfect time to explore new ideas!
- x 20 larger Higgs boson sample at HL-LHC ==> Will improve precision



Mass



Total width



Coupling to light quarks?

Coupling to electrons?

Coupling to itself?

Coupling to invisible particles? (neutrinos, dark matter)

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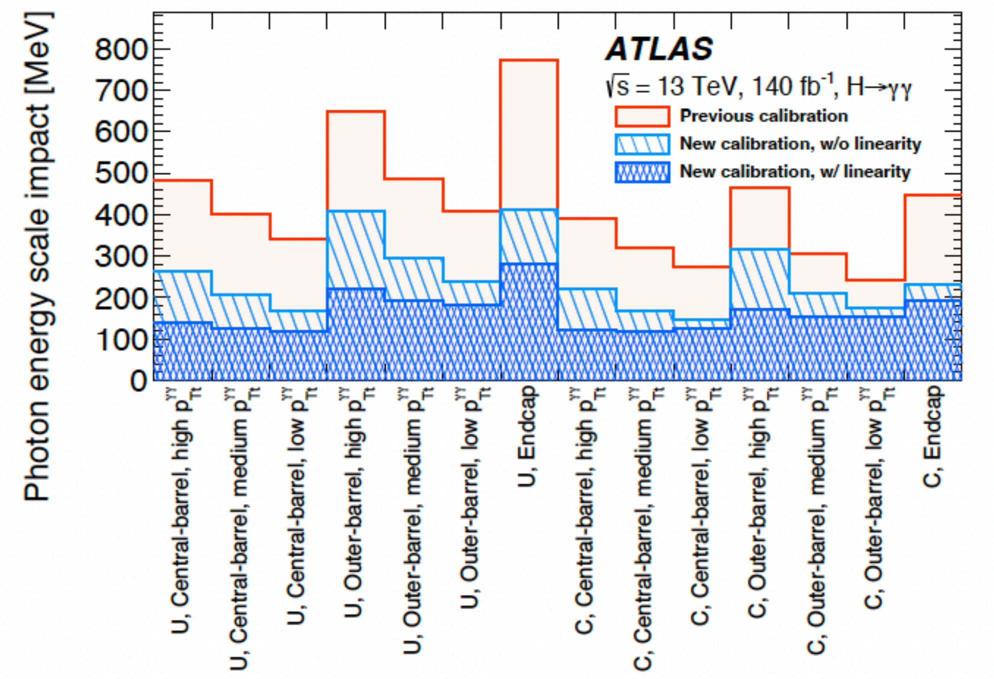
“Backup”

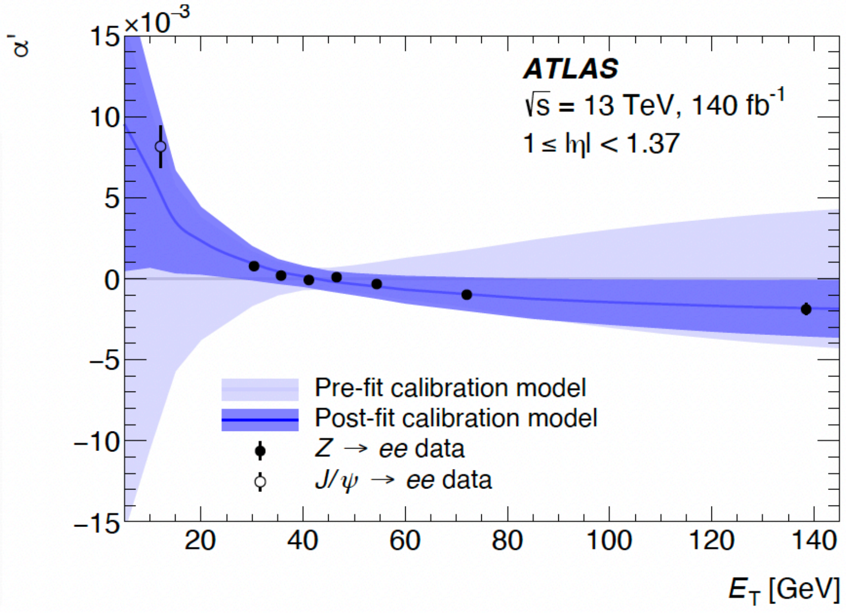


Large part of the work is about the photon energy scale calibration and its uncertainty ESU
Reconstruction/calibration changes w.r.t. previous measurement, among others

- better energy collection (especially for converted photons)
- refined ECAL layer inter-calibration ⇒ linearity and electron → photon extrapolation
- better understanding on electronics non-linearity
- dedicated correction for photon out-of-cluster energy leakage mis-modeling by simulation
  - ⇒ e.g. ~ 40% reduction in ESU for E_T = 60 GeV photon at η = 0.3

In addition measure the energy response linearity with the huge $Z \rightarrow ee$ sample available
⇒ use it to constrain the systematic uncertainties

~ 30% / ~ 50% *further* reduction of ESU for E_T = 60 GeV unconverted photon in barrel / endcap



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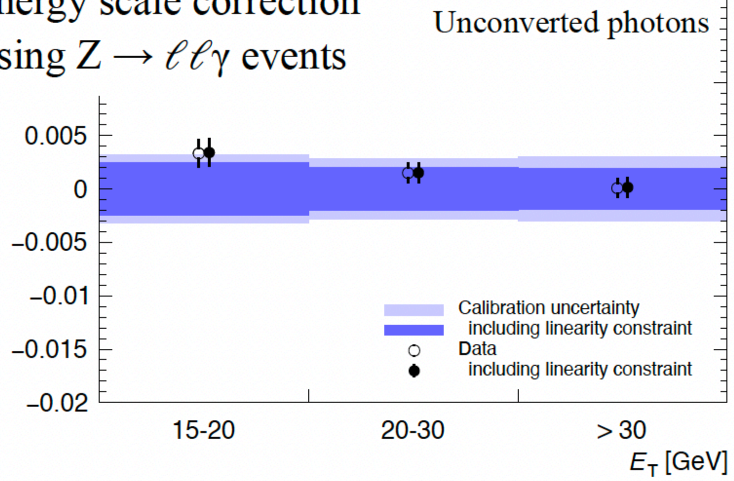
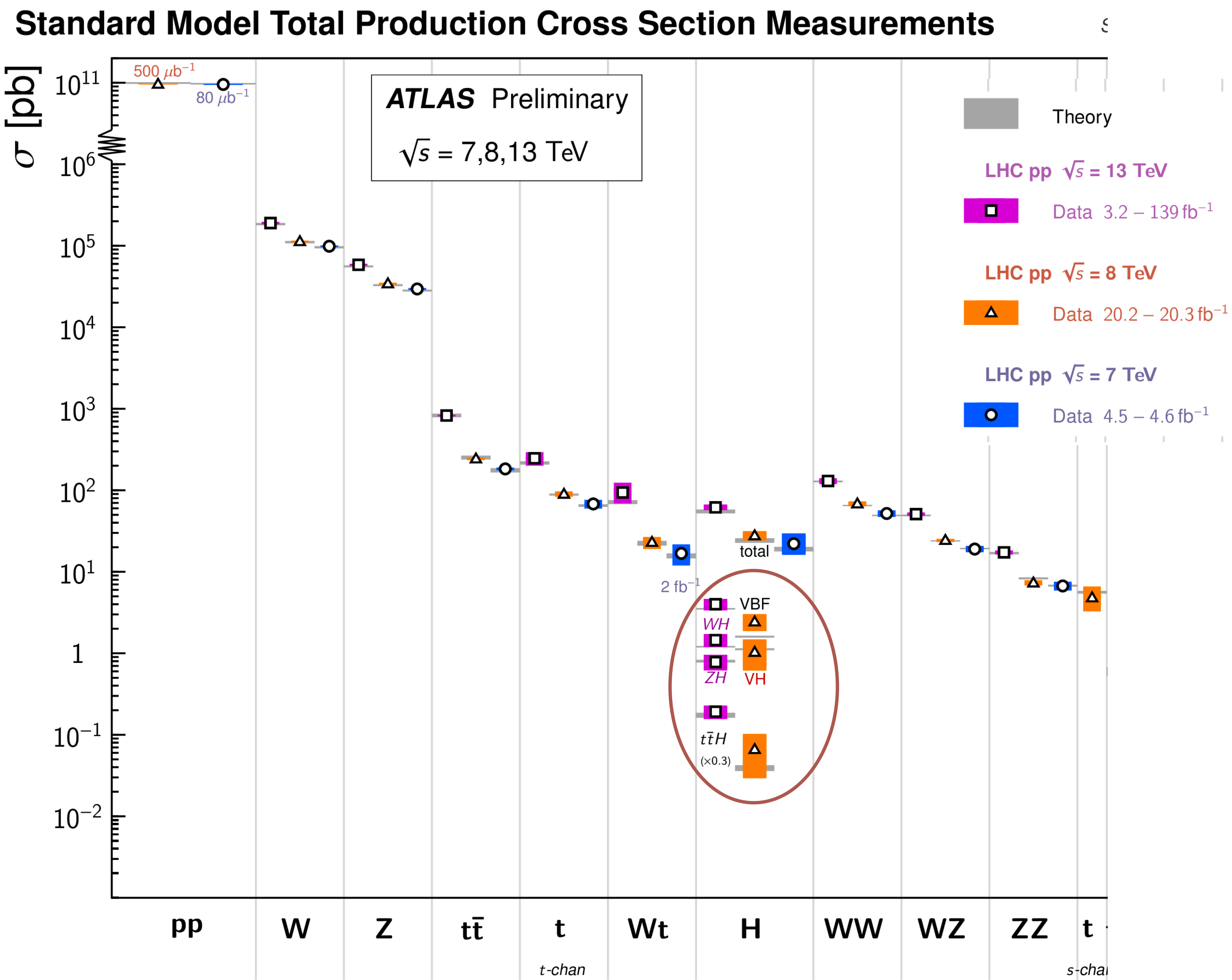
Cross-checked with direct residual energy scale correction using $Z \rightarrow \ell\ell\gamma$ events



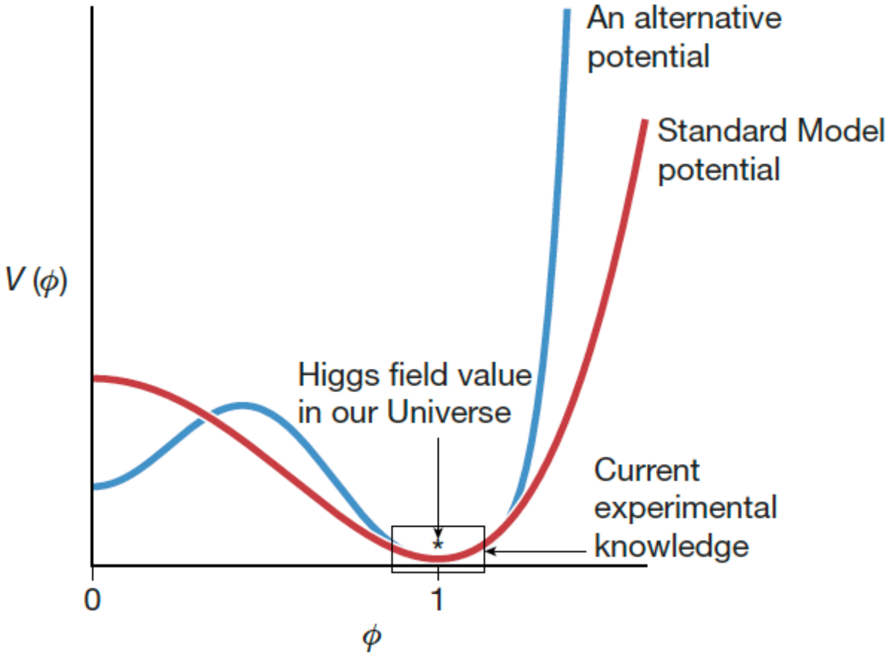
Huge Standard Model Backgrounds

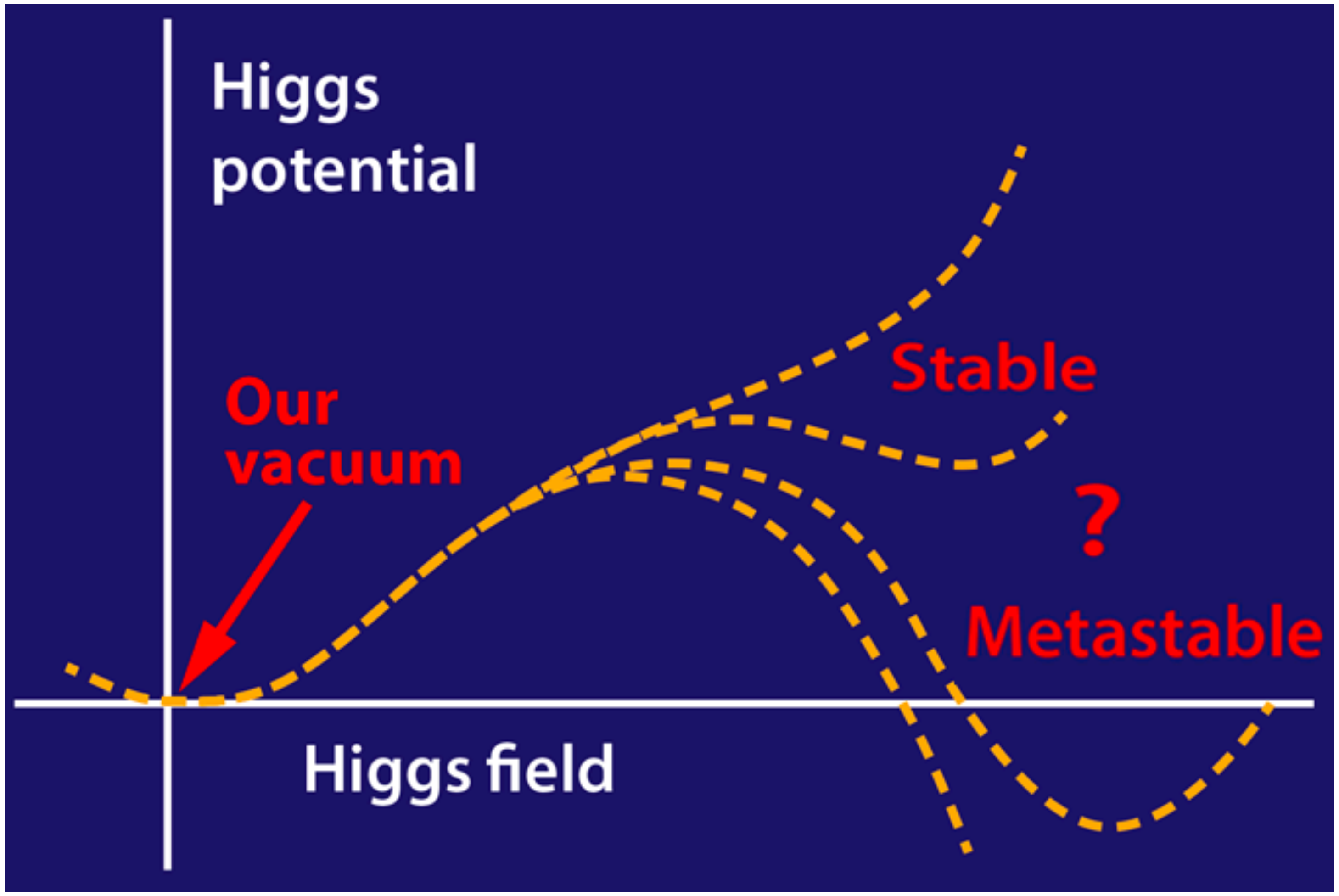


1 observed Higgs event in a trillion (10^{12}) pp collisions

The Higgs and the fate of our universe

- The Higgs boson was the missing of the SM and we've had it for more than 10 years now..
  - Is our universe stable or metastable?





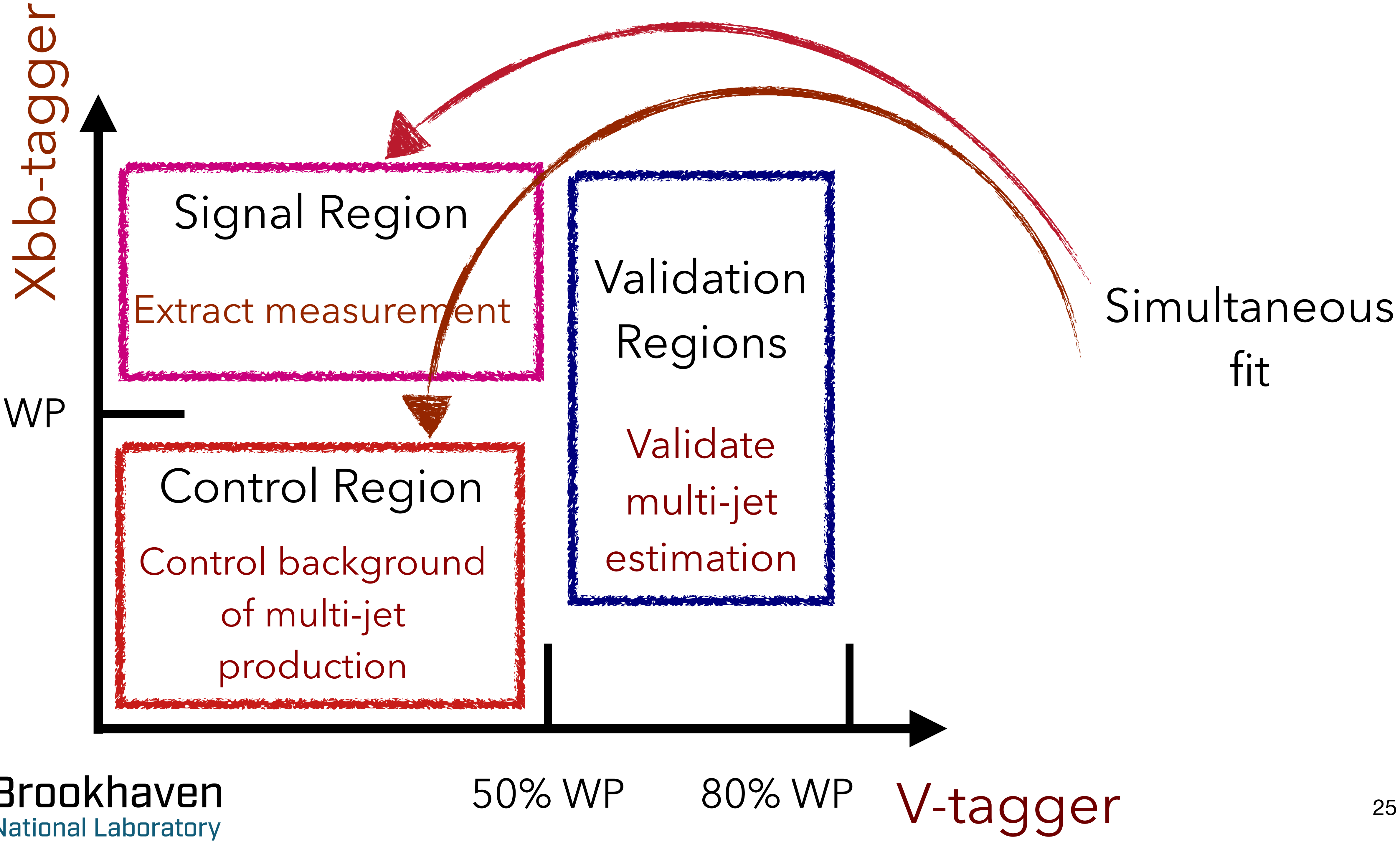
$$V(h) = 1/2\ m^2_H\, h^2 + \lambda_3 v h^3 + 1/4\ \lambda_4 v h$$

Higgs self-coupling

Analysis Strategy & Region Definitions

Higgs-candidate jet mass fit (m_{JH}) to SR and CR

- Reconstructed combining calorimeter & tracking measurements
- Corrected to account for muons from semileptonic b-hadron decays



Xbb-tagger

Signal Region

Extract measurement

Validation Regions

Validate multi-jet estimation

Simultaneous fit

50% WP

Control Region

Control background of multi-jet production

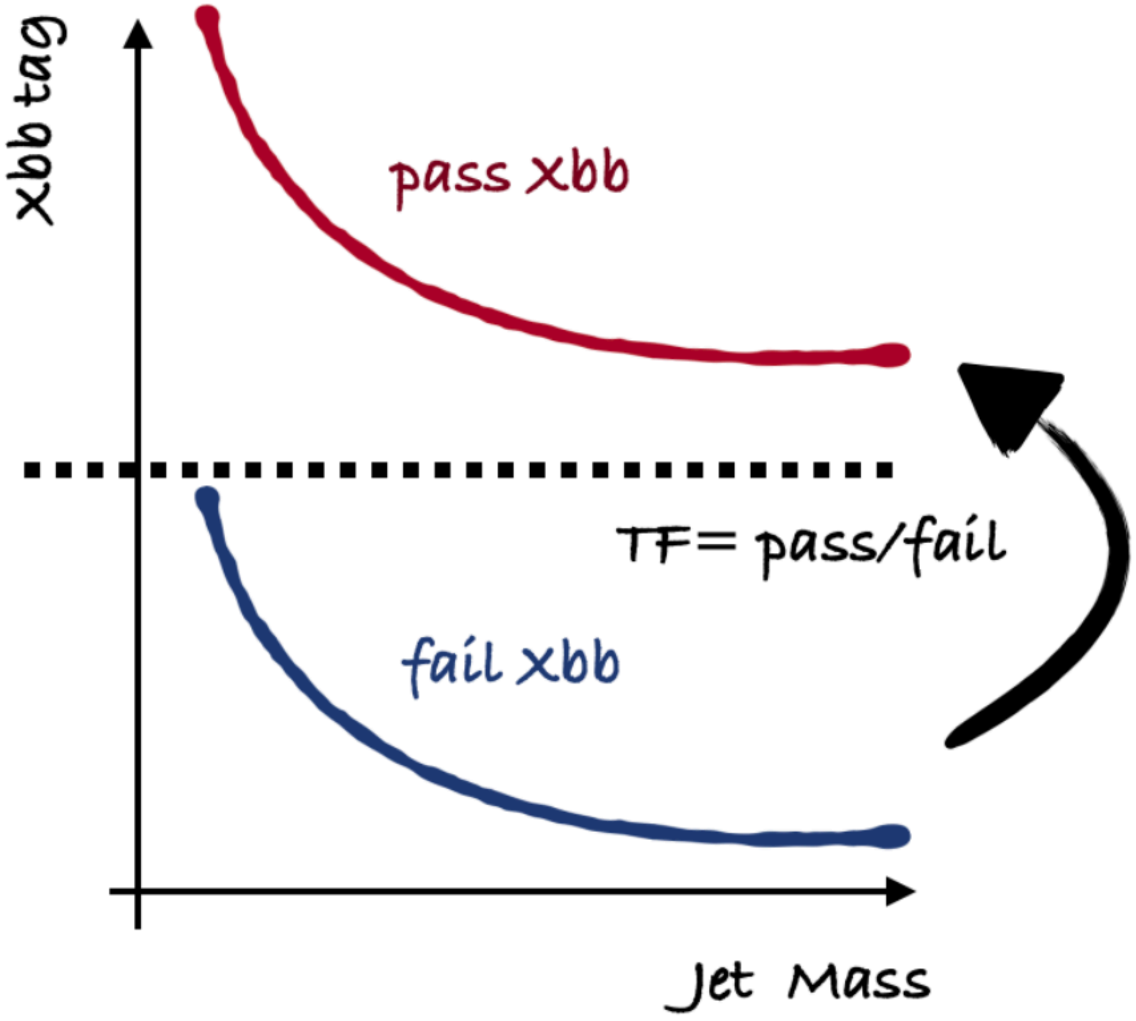
50% WP

80% WP

V-tagger

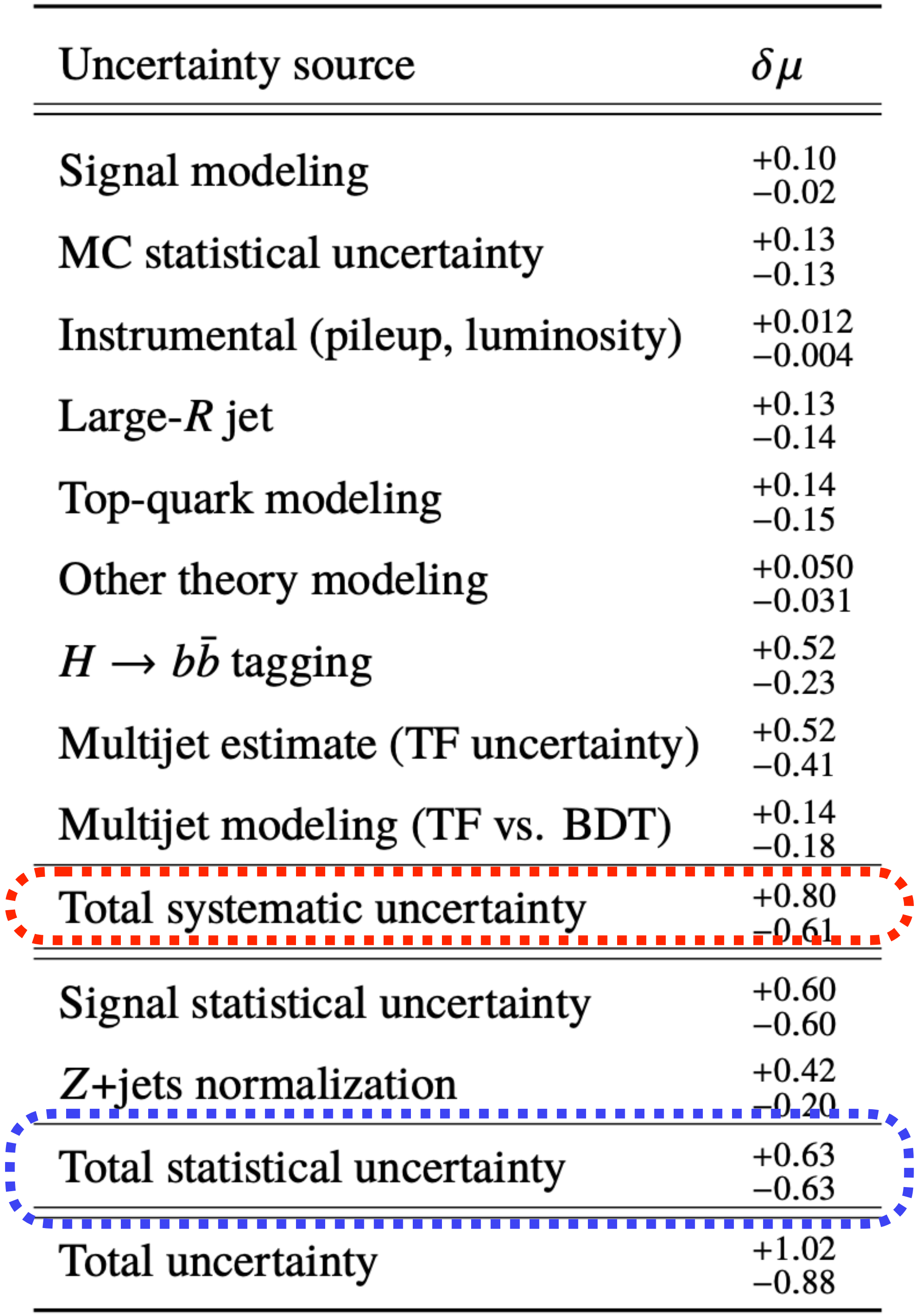
Multi-Jet Background Estimation

- Multi-jet background modeled from CR with Transfer Factor (TF) dependent on candidate-jet p_T & $\rho=\log(m_{J2}/p_{T2})$::
  - $TF(p_T, \rho) = \Sigma_{kl}\, a_{kl}\, \rho^k\, p_T{}^l$, where a_{kl} are polynomial coefficients
- TF scales CR events to yield number of multi-jet events in SR
- Polynomial order determined via Fisher F-tests in data
  - First order in both p_T & ρ proves to be sufficient, without inducing significant spurious signal



Alternate method: BDT which uses data from the CR and reweighs the kinematic to the SR

Challenges ahead

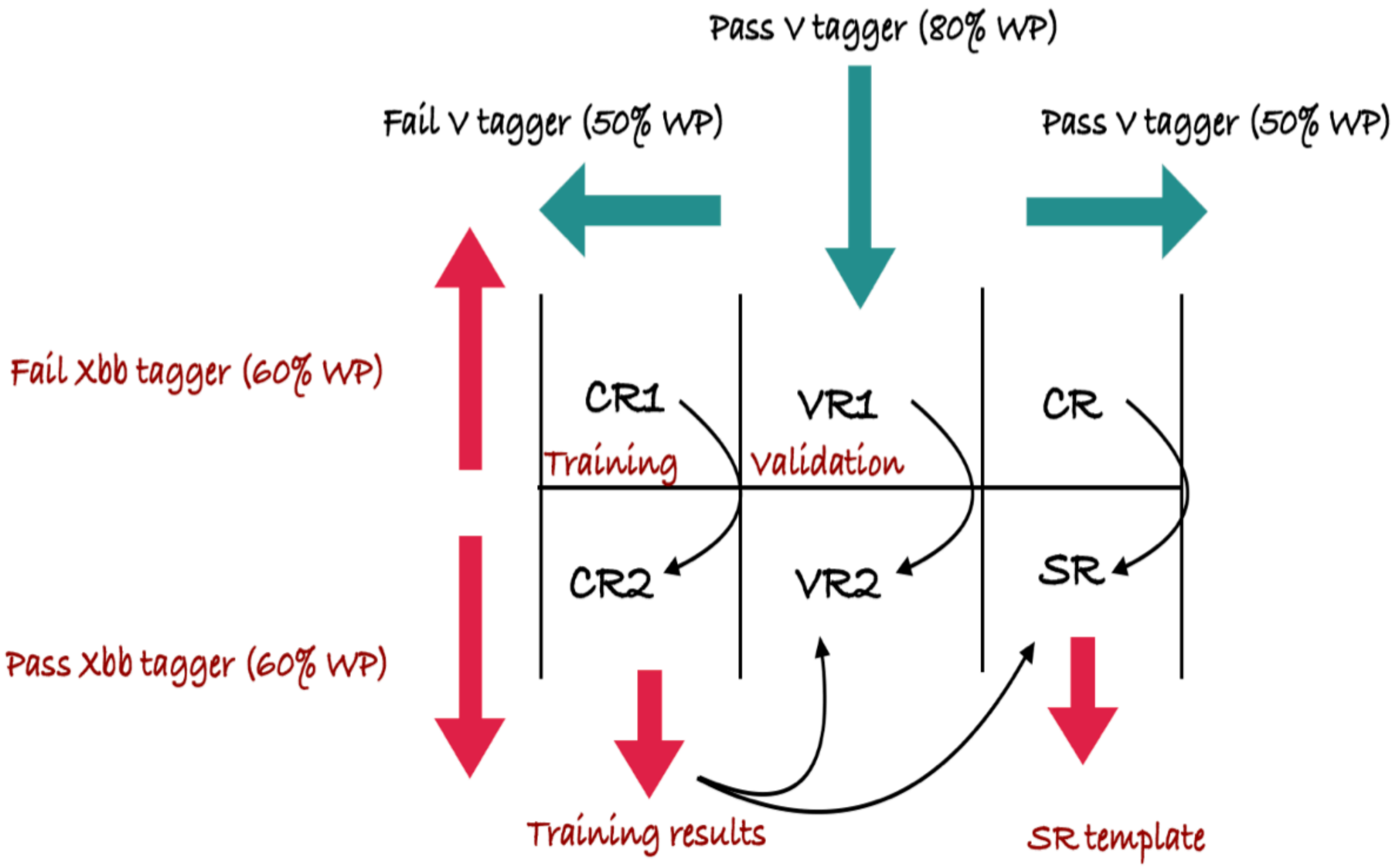


Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.050}_{-0.031}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs. BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
Z+jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

- Systematic and statistical uncertainty on the same level
- Systematic uncertainties dominated by shape of multi-jet data-driven estimate & Hbb-tagger scale factors

BDT method

- BDT method: extract background templates from events failing both V- and Hbb-tagger requirements
- MVA used to perform kinematic reweighting, by predicting event weights needed to bring shapes of kinematic distributions in CRs and SRs into agreement



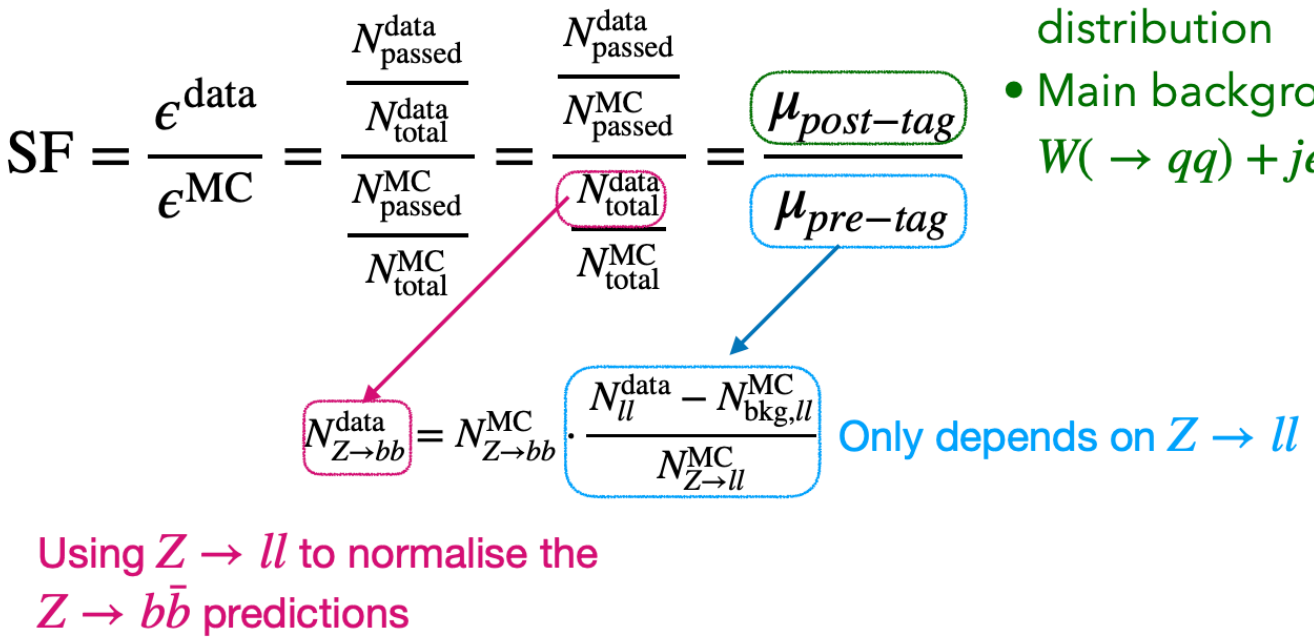
H->bb tagger and Calibration

The **Hbb Tagger** is used to tag boosted Higgs bosons decaying to bb using a NN with 3-class output: Higgs, multijet and top. The following discriminant is used:

$$D_{H_{bb}} = \ln \frac{p_{\text{Higgs}}}{f_{top} \cdot p_{\text{top}} + (1 - f_{top}) \cdot p_{\text{multijet}}} \qquad (1)$$

where f_{top} determines the weight of the top background shape in the final discriminant, set to $f_{top} = 0.25$ in this analysis.
Higher D scores correspond to jets more likely to originate from Higgs to $b\bar{b}$ decays.

- Calibration using large-R jets having at least two ghost-associated VR track jets
- Probe events: $Z(\rightarrow b\bar{b}) + jets$
- p_T -dependent calibration: 450-500, 500-600, 600-1000 GeV
- Methodology:



$$\text{SF} = \frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{data}}_{\text{total}}}}{\frac{N^{\text{MC}}_{\text{passed}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{MC}}_{\text{passed}}}}{\frac{\boxed{N^{\text{data}}_{\text{total}}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\boxed{\mu_{post-tag}}}{\boxed{\mu_{pre-tag}}}$$

$$\boxed{N^{\text{data}}_{Z\rightarrow bb}} = N^{\text{MC}}_{Z\rightarrow bb} \cdot \boxed{\frac{N^{\text{data}}_{ll} - N^{\text{MC}}_{\text{bkg},ll}}{N^{\text{MC}}_{Z\rightarrow ll}}}$$

Only depends on $Z \rightarrow ll$

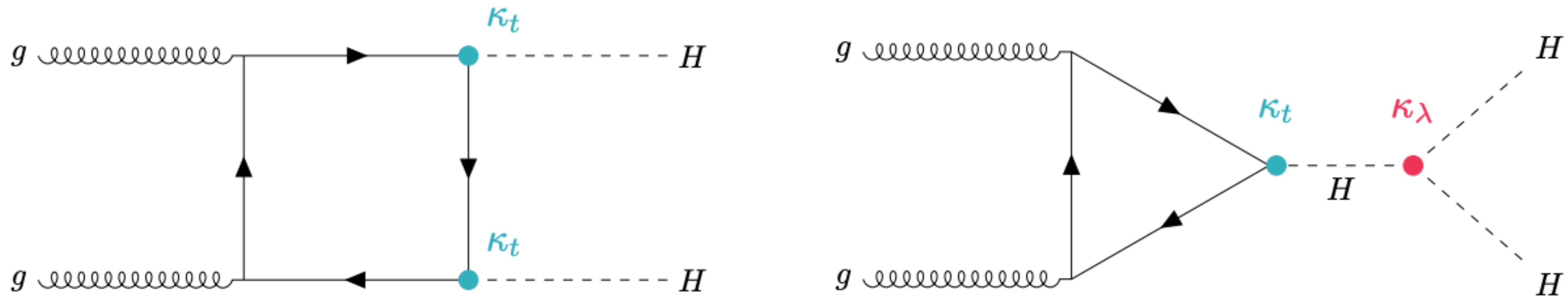
Using $Z \rightarrow ll$ to normalise the $Z \rightarrow b\bar{b}$ predictions

- Fit to the. large-R jet mass distribution
- Main backgrounds: dijet, $W(\rightarrow qq) + jets$, $t\bar{t}$

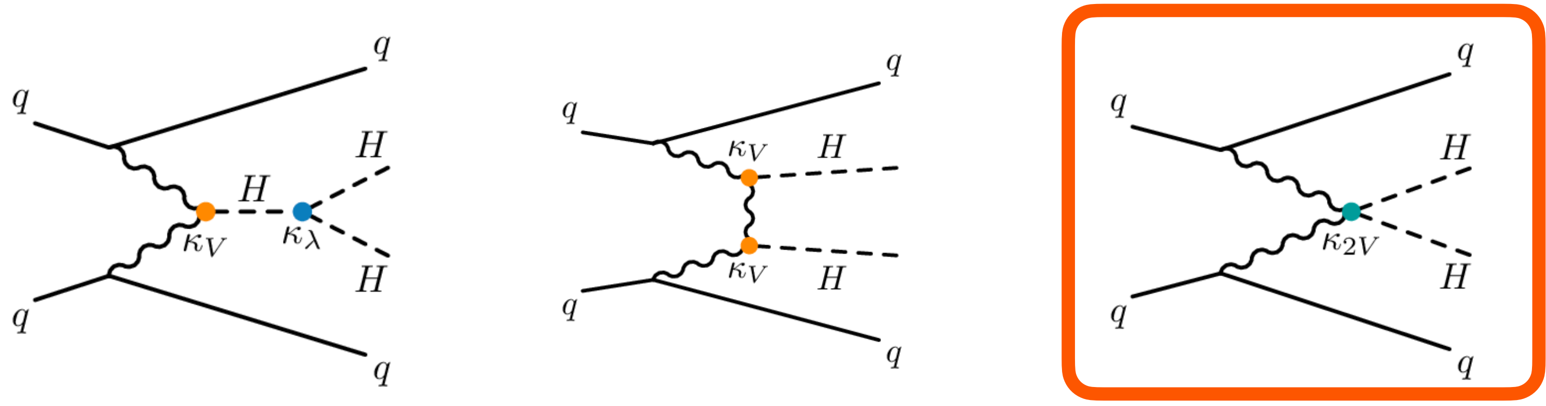
HH production modes

- **The HH leading production mode is gluon gluon fusion (ggF):**
- Destructive interference between the two diagrams results in a very small SM cross section of $\sigma^{HH}_{ggF}\sim 31.0$ fb at 13 TeV.

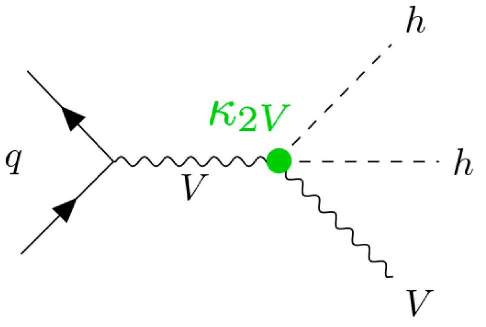
$\kappa_\lambda = c_{HHH}/c_{HHH}^{SM}$



- VBF production mode also very important σ ~ 1.72 fb
- Gives access to **$k_{2V} = C_{VVHH}/C_{VVHH}^{SM}$**

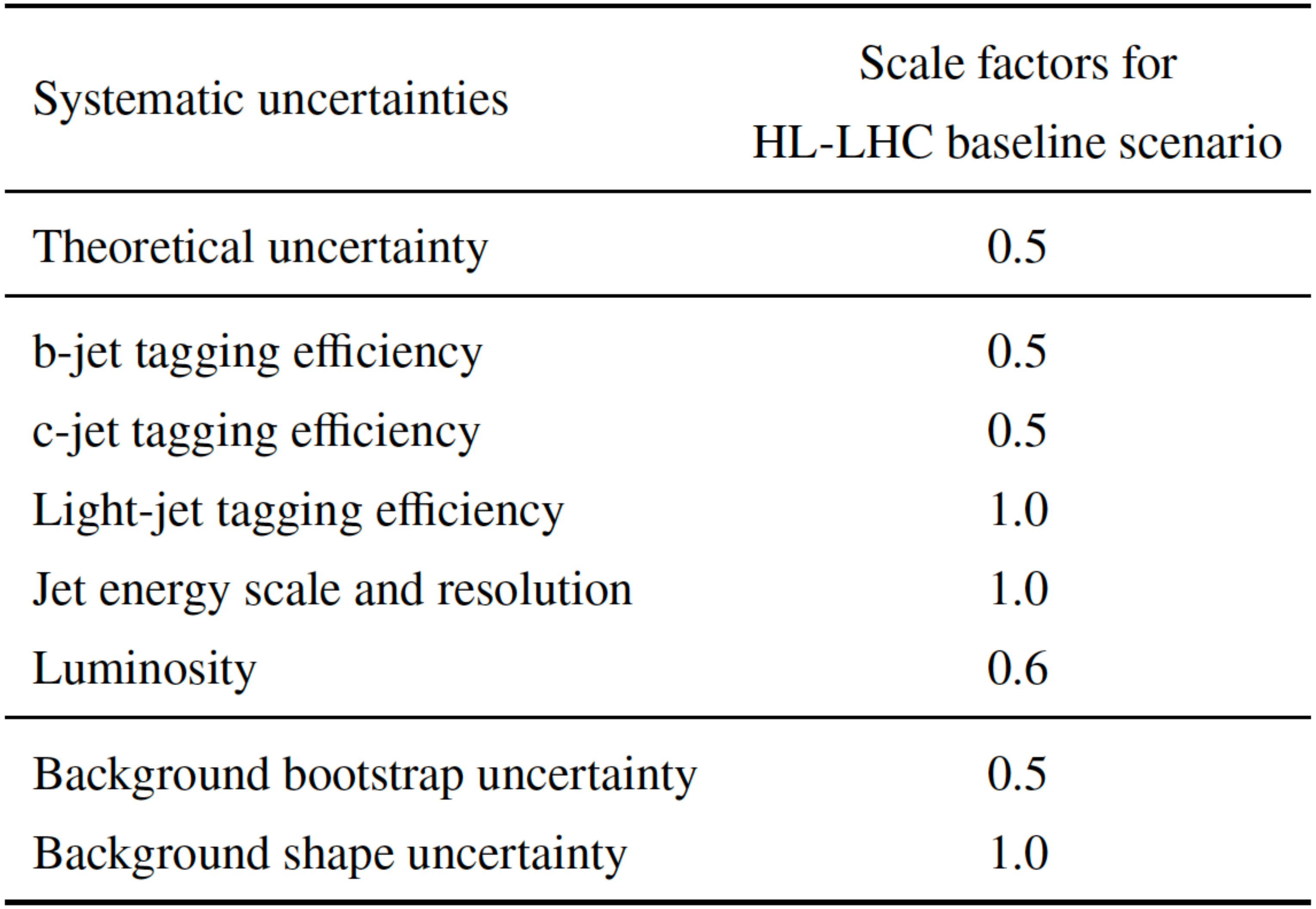


Vector Boson Associated (VHH) σ ~ 0.86 fb



HH@HL-LHC

Baseline Scenario



Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

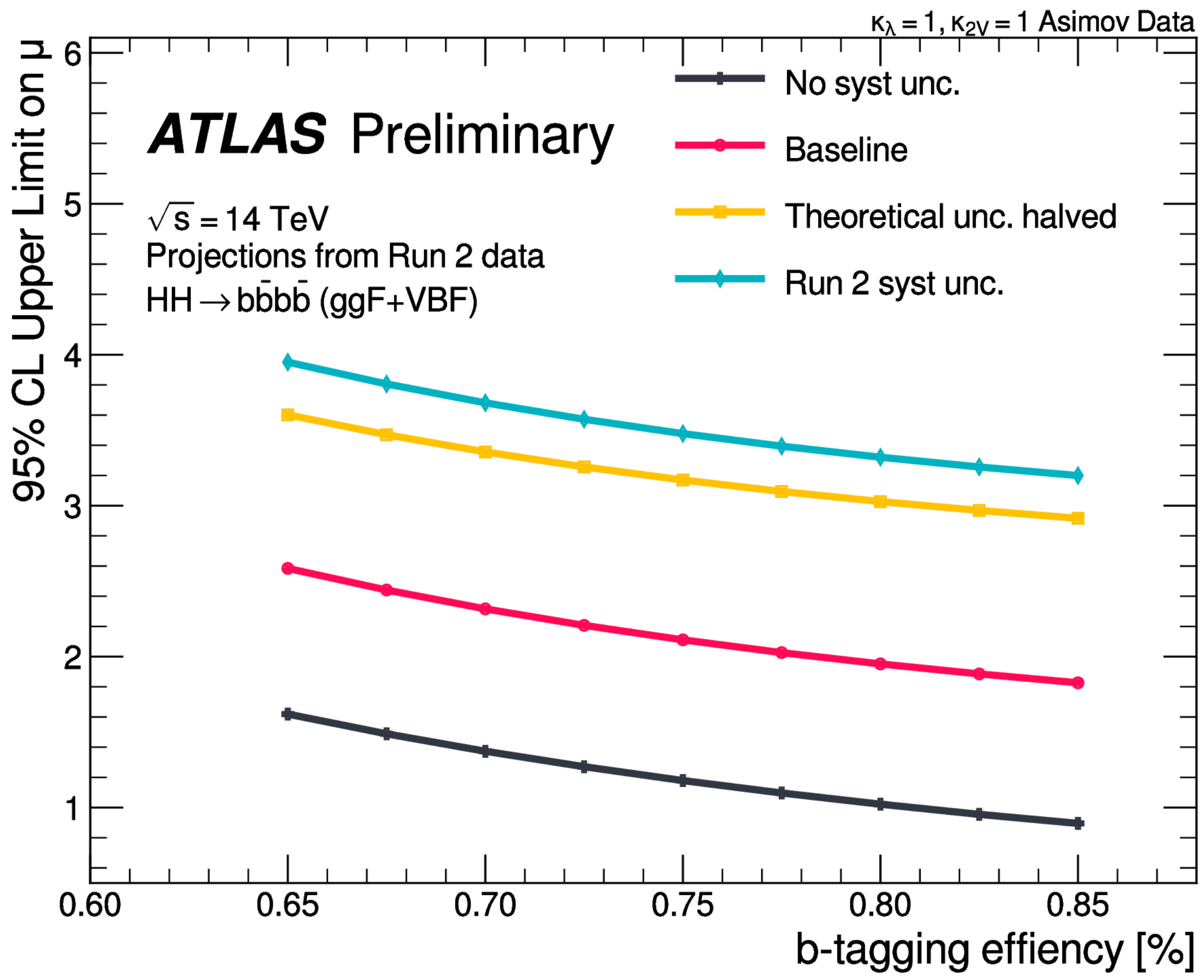
Other Scenarios:

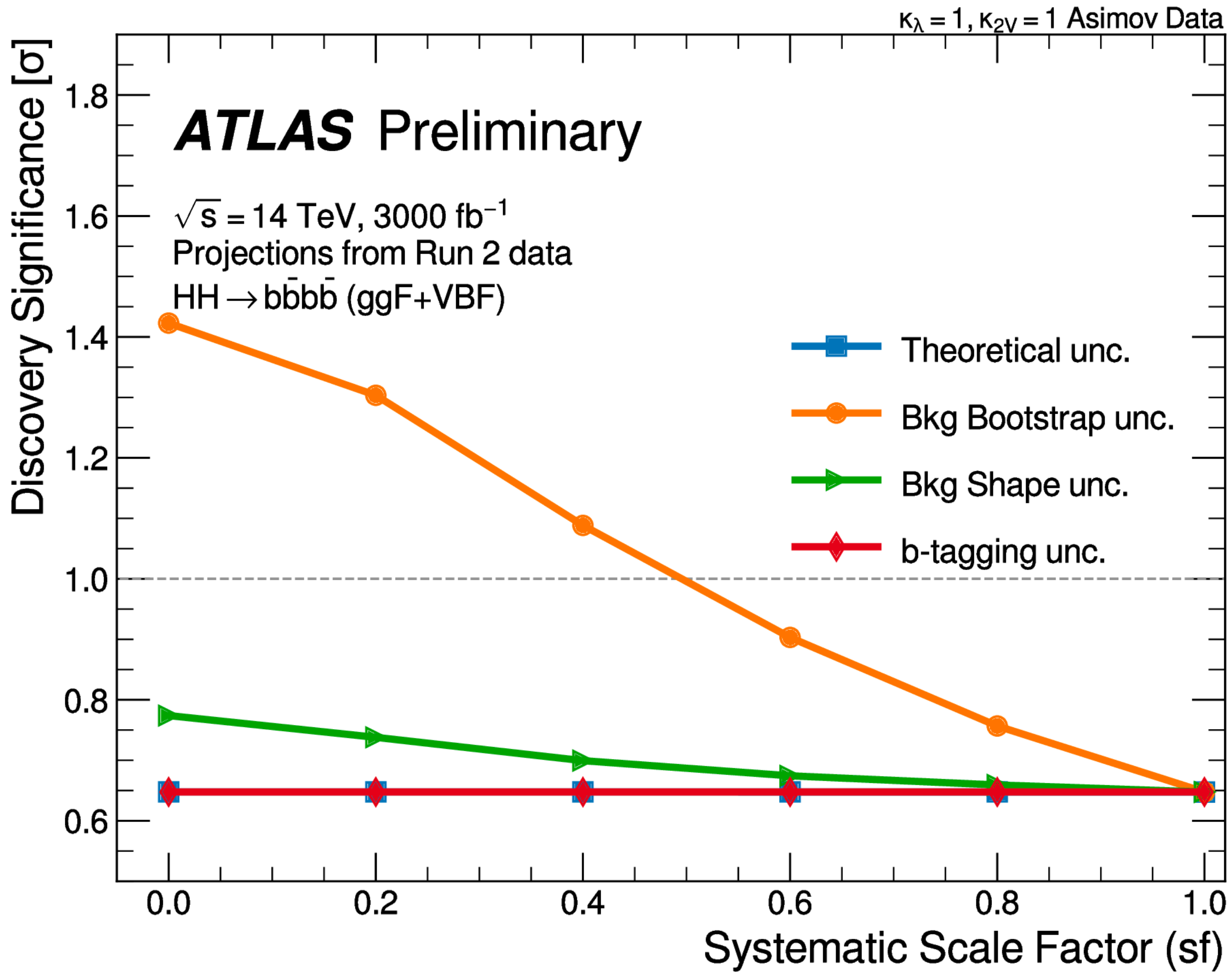
- No Systematic Uncertainties (Statistical Only)

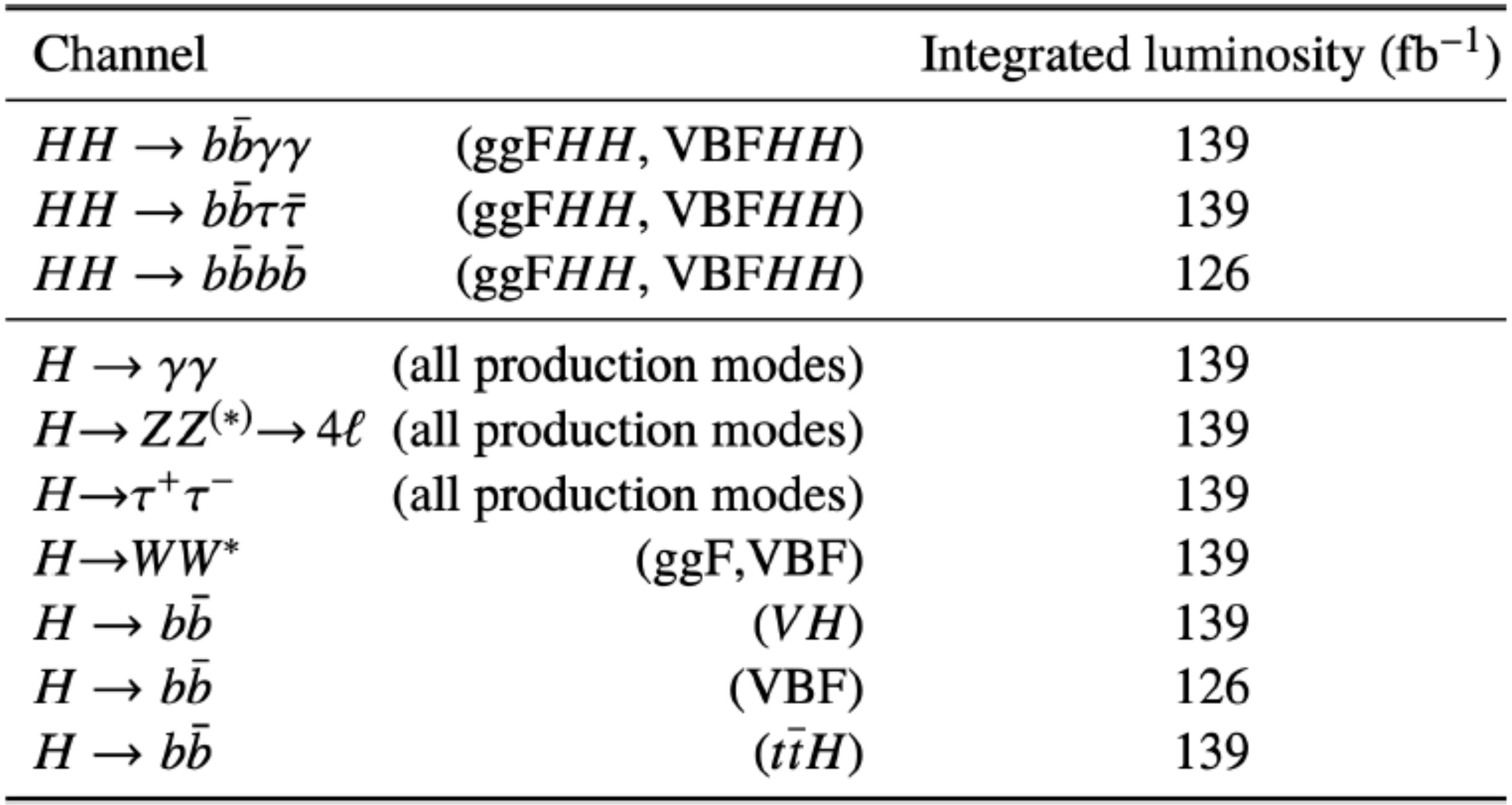
- Run 2 Systematic Uncertainties

- Run 2 Systematic Uncertainties, with theoretical uncertainties halved

Projections







Channel		Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	(ggFHH, VBFHH)	139
$HH \to b\bar{b}\tau\bar{\tau}$	(ggFHH, VBFHH)	139
$HH \to b\bar{b}b\bar{b}$	(ggFHH, VBFHH)	126
$H \to \gamma\gamma$	(all production modes)	139
$H \to ZZ^{(*)} \to 4\ell$	(all production modes)	139
$H \to \tau^+\tau^-$	(all production modes)	139
$H \to WW^*$	(ggF,VBF)	139
$H \to b\bar{b}$	(VH)	139
$H \to b\bar{b}$	(VBF)	126
$H \to b\bar{b}$	($t\bar{t}H$)	139