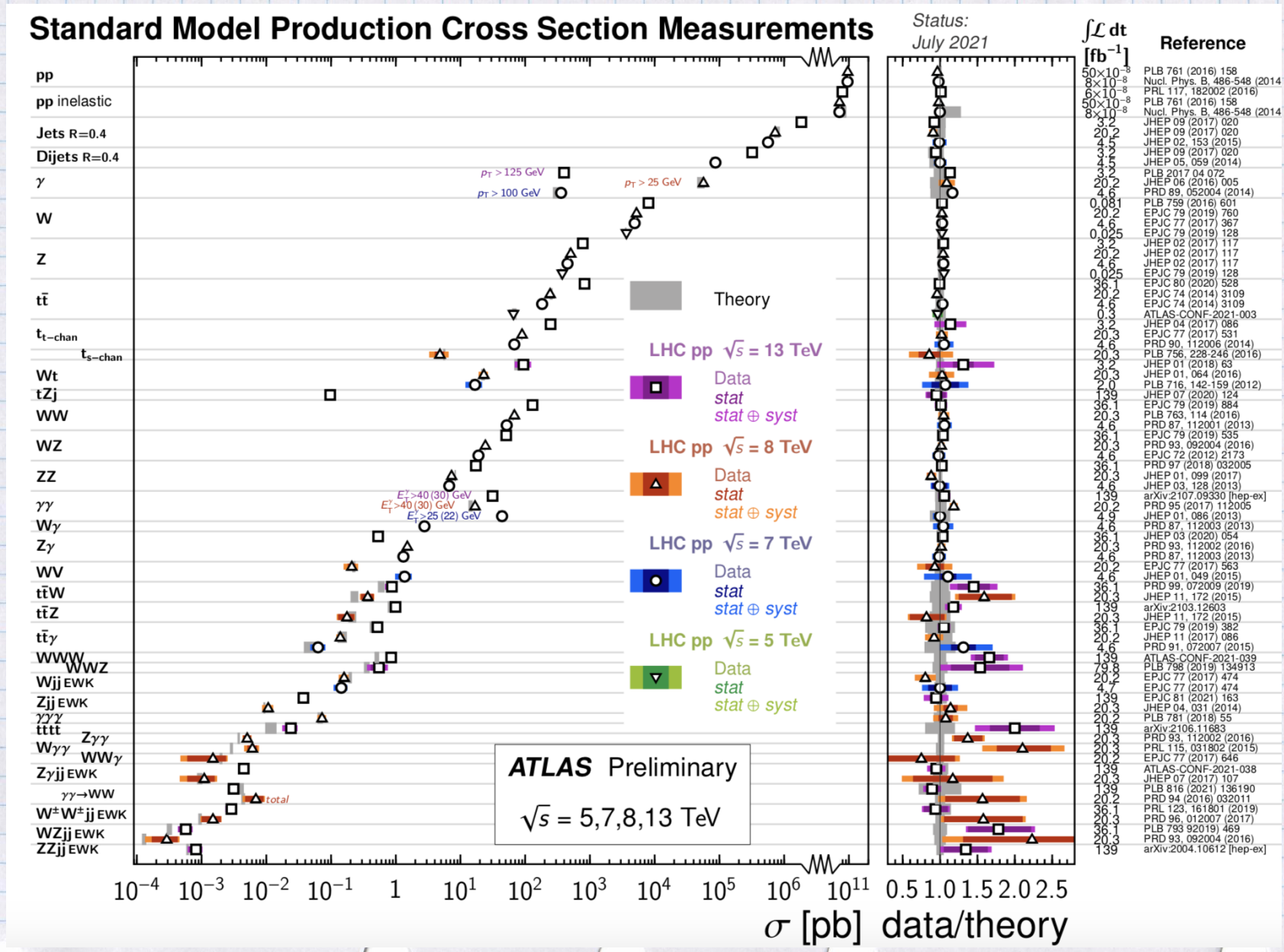
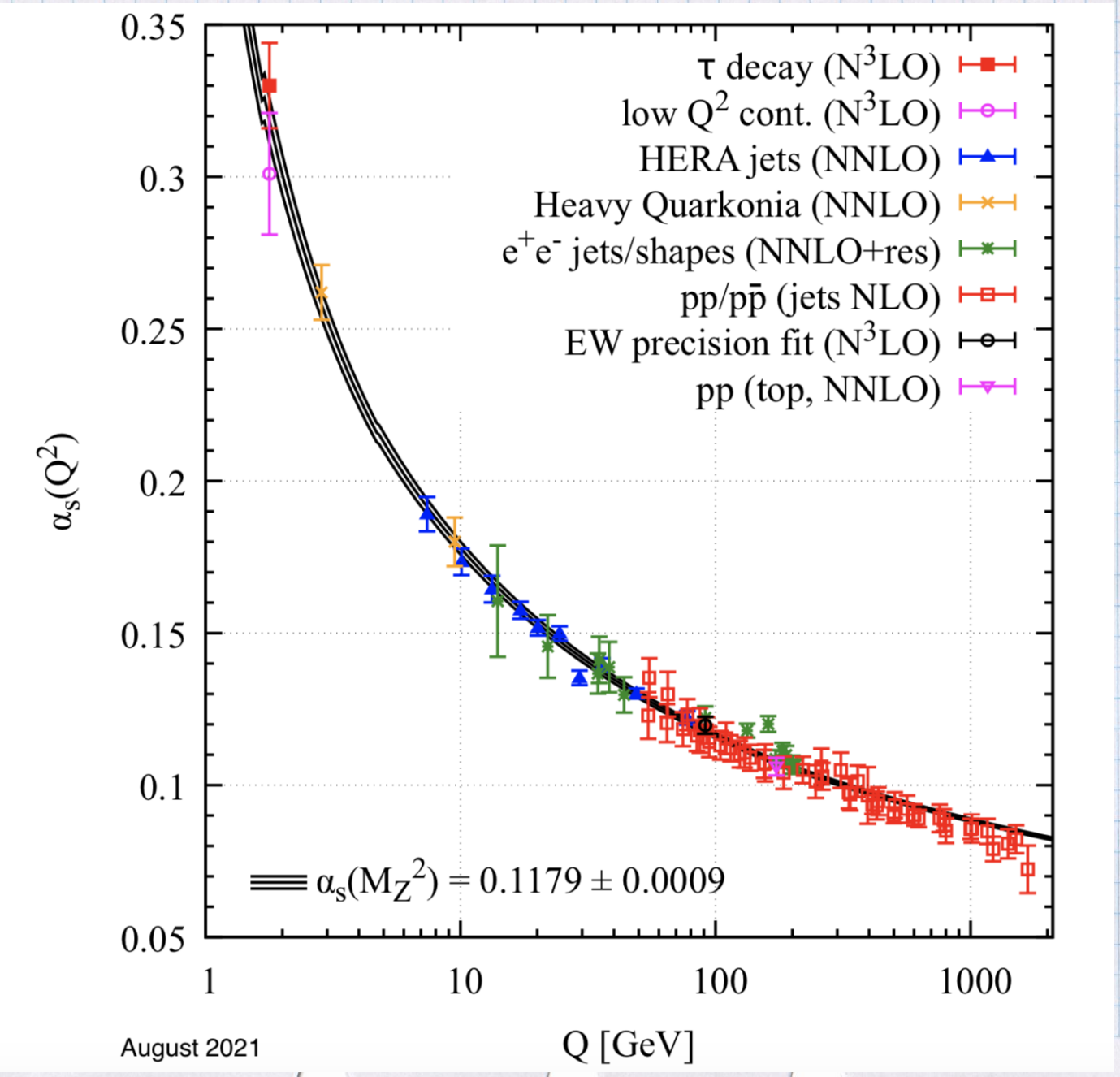
Experimental verification – QCD sector



Experimental verification – QCD sector



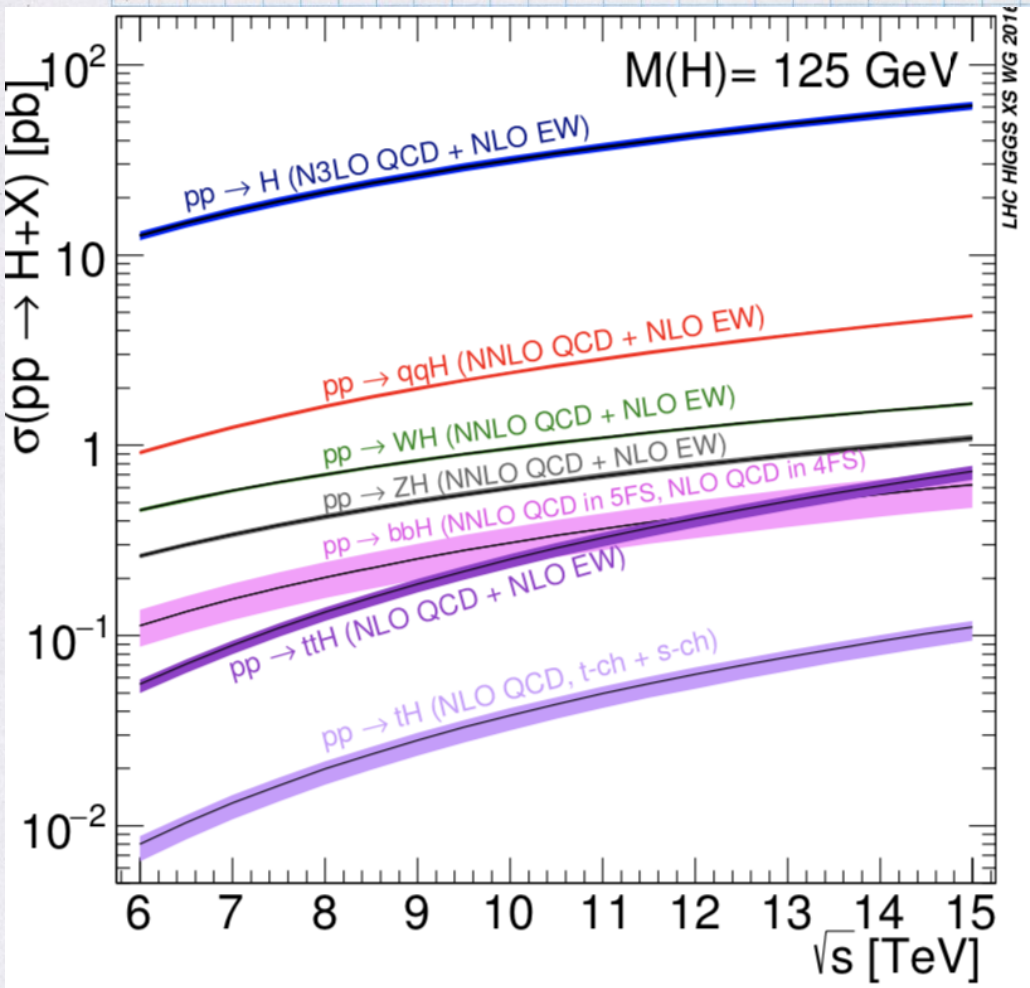
Experimental verification – Electroweak sector

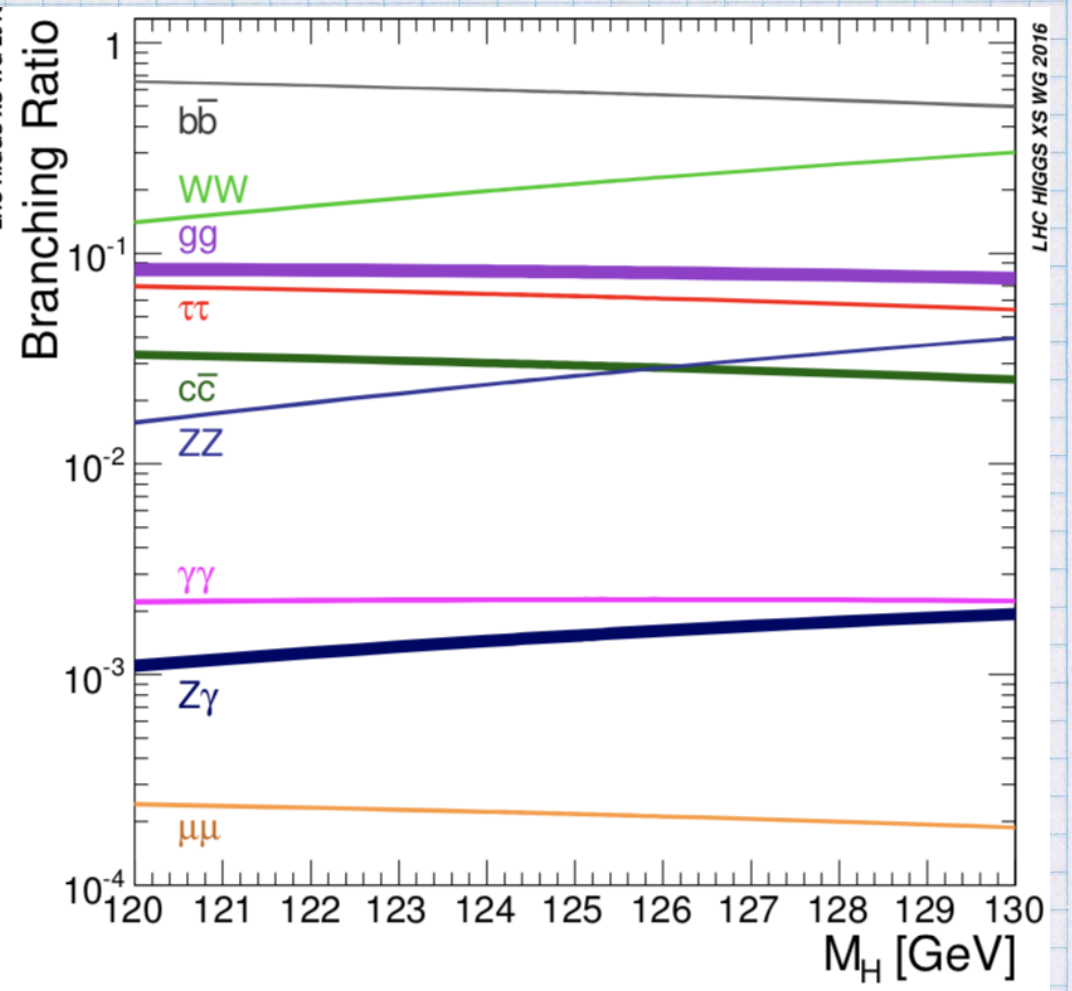
Quantity	Value	Standard Model	Pull
m_t [GeV]	172.83 ± 0.59	173.13 ± 0.56	-0.5
M_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	0.0
Γ_H [MeV]	$3.2^{+2.4}_{-1.7}$	4.12 ± 0.05	-0.4
M_W [GeV]	80.387 ± 0.016	80.360 ± 0.006	1.7
	80.376 ± 0.033		0.5
	80.366 ± 0.017		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
$\mathcal{B}(W \to \text{hadrons})$	0.6736 ± 0.0018	0.6751 ± 0.0001	-0.8
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0002	1.3
$Q_W(p)$	0.0719 ± 0.0045	0.0709 ± 0.0002	0.2
$Q_W(\text{Cs})$	-72.82 ± 0.42	-73.24 ± 0.01	1.0
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.90 ± 0.02	0.1
$\widehat{s}^2_Z(\text{eDIS})$	0.2299 ± 0.0043	0.23122 ± 0.00004	-0.3
τ_τ [fs]	290.75 ± 0.36	288.90 ± 2.24	0.8
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4510.88 \pm 0.60) \times 10^{-9}$	$(4508.61 \pm 0.03) \times 10^{-9}$	3.8

Experimental verification – Electroweak sector

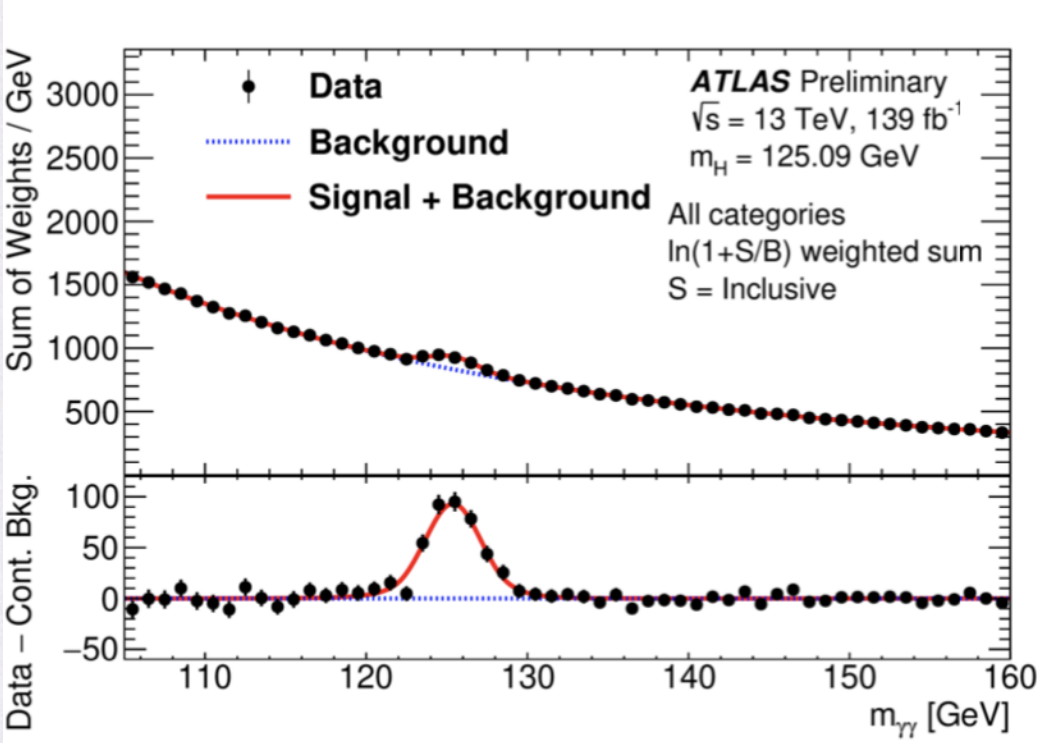
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.4941 ± 0.0009	0.6
σ_{had} [nb]	41.481 ± 0.033	41.482 ± 0.008	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.736 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01617 ± 0.00007	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1029 ± 0.0002	-2.0
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0002	-0.4
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23155 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.2
	0.23129 ± 0.00033		-0.8
A_e	0.15138 ± 0.00216	0.1468 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

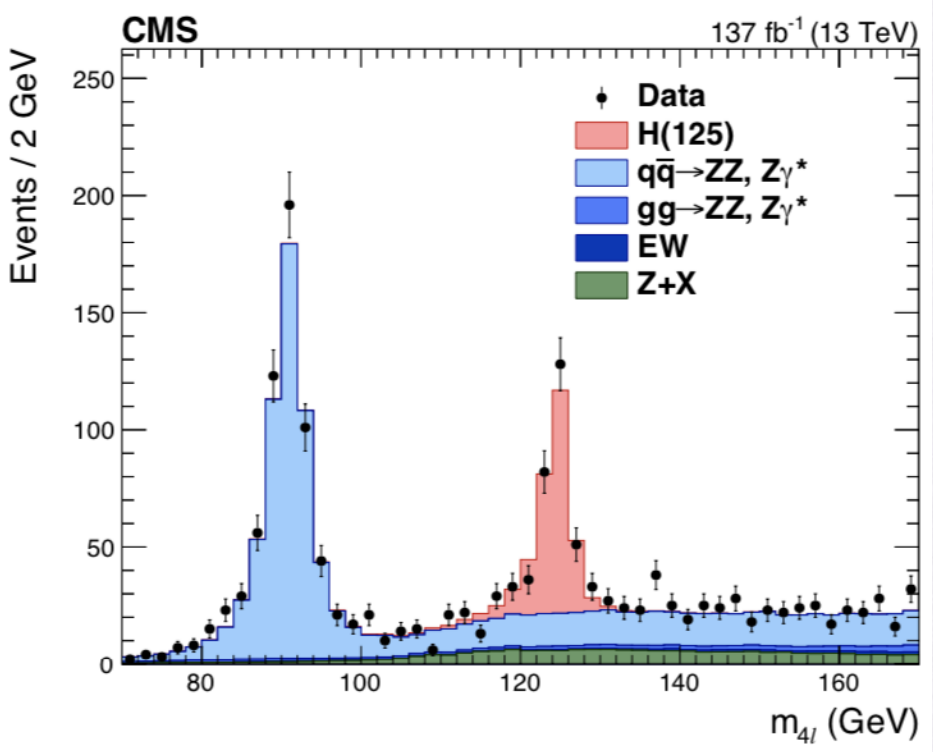
Experimental verification – Higgs Physics

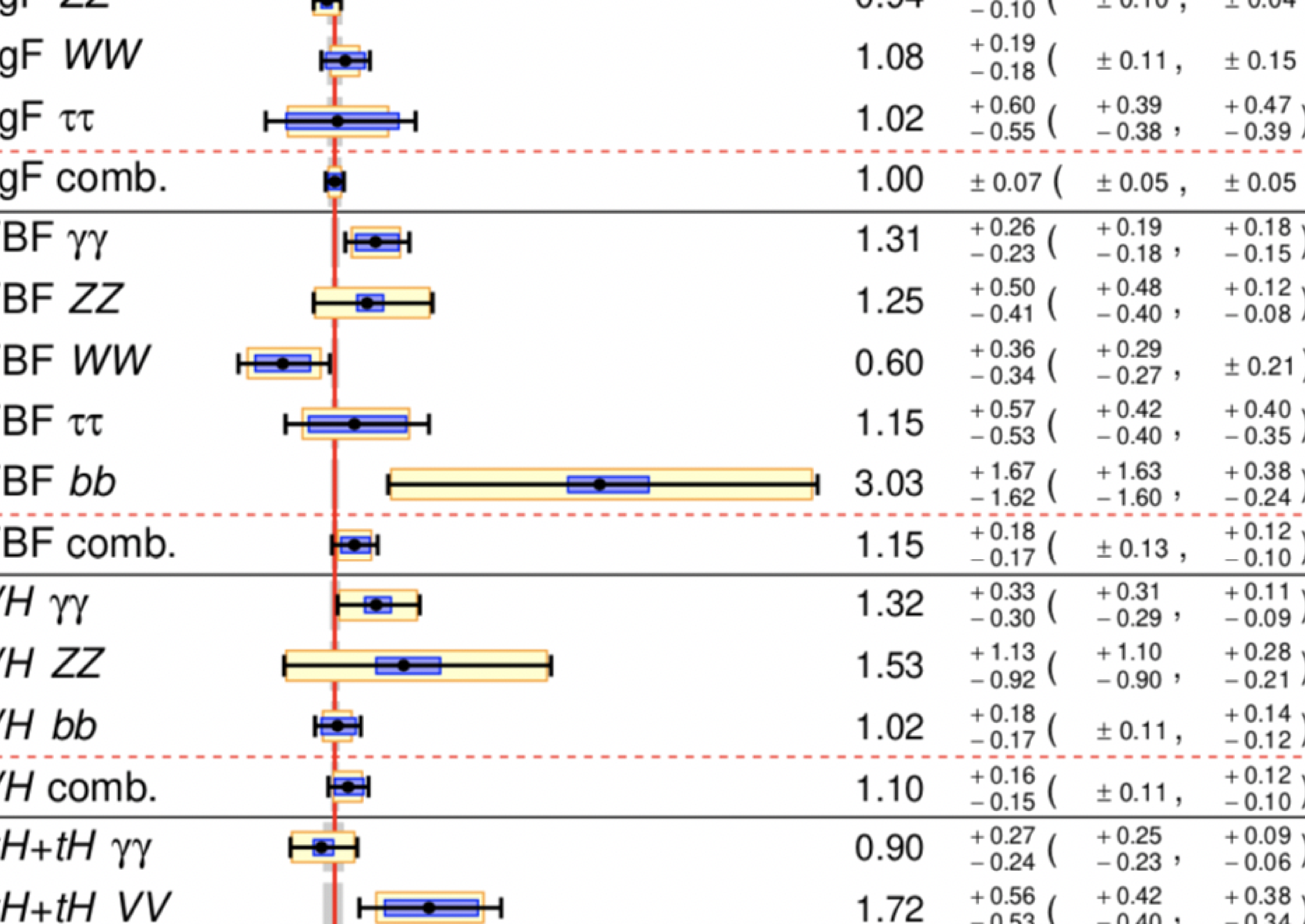




Experimental verification – Higgs Physics



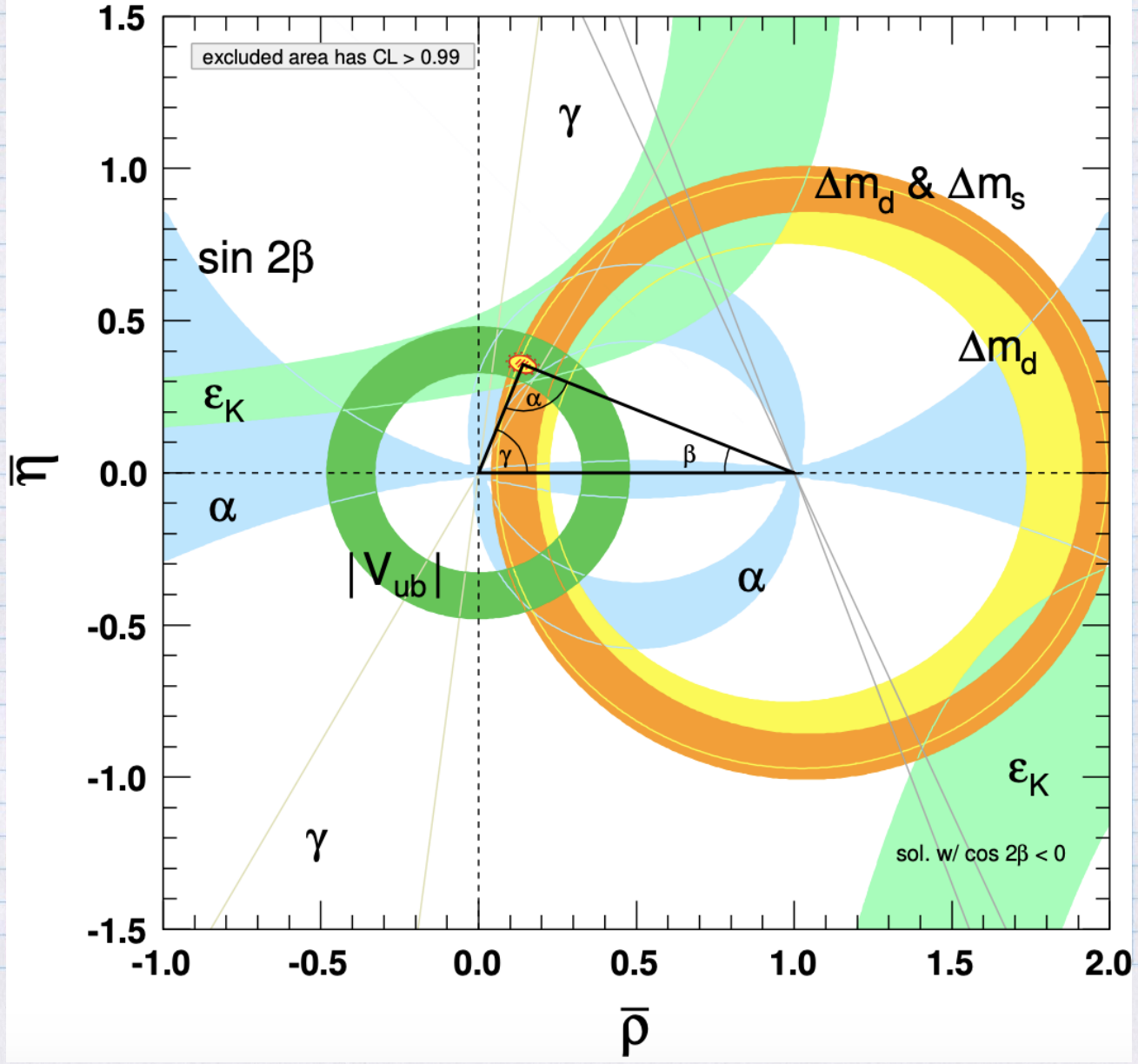




gF WW 1.08 +0.19 −0.18 (±0.11 , ±0.15
gF ττ 1.02 +0.60 −0.55 (+0.39 −0.38 , +0.47 −0.39
gF comb. 1.00 ±0.07 (±0.05 , ±0.05
BF γγ 1.31 +0.26 −0.23 (+0.19 −0.18 , +0.18 −0.15
BF ZZ 1.25 +0.50 −0.41 (+0.48 −0.40 , +0.12 −0.08
BF WW 0.60 +0.36 −0.34 (+0.29 −0.27 , ±0.21
BF ττ 1.15 +0.57 −0.53 (+0.42 −0.40 , +0.40 −0.35
BF bb 3.03 +1.67 −1.62 (+1.63 −1.60 , +0.38 −0.24
BF comb. 1.15 +0.18 −0.17 (±0.13 , +0.12 −0.10
H γγ 1.32 +0.33 −0.30 (+0.31 −0.29 , +0.11 −0.09
H ZZ 1.53 +1.13 −0.92 (+1.10 −0.90 , +0.28 −0.21
H bb 1.02 +0.18 −0.17 (±0.11 , +0.14 −0.12
H comb. 1.10 +0.16 −0.15 (±0.11 , +0.12 −0.10
H+tH γγ 0.90 +0.27 −0.24 (+0.25 −0.23 , +0.09 −0.06
H+tH VV 1.72 +0.56 (+0.42 , +0.38

Experimental verification - Flavour sector

$$V_{\rm CKM} = \begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$



... and yet the Standard Model is incomplete

Empirical evidence

- Neutrino oscillations (≡ neutrino masses) are firmly established in various experiments. They cannot be accommodated within SM ✶✶✶ (absolutely robust)

- No particle Dark Matter, which is "seen" in various astrophysical observations ✶✶ (Is DM a particle? gravity tricks?)

- Taking the measured values of M_t & M_h, the electroweak vacuum is not absolutely stable, unless additional physics intervens at energies $\lesssim 10^{10}$ GeV * (precision M_t / cosmology)

- The visible universe is composed of matter, as opposed to antimatter. Matter-antimatter asymmetry is left unexplained within the SM * (initial condition / cosmology)

Theoretical consistency at high-energy scales

- Standard Model cannot be extrapolated to arbitrary small scales (high energies) without taking into account quantum gravity effects

- If ~~the~~ Standard Model is valid only up to a scale Λ, the Higgs mass may receive large radiative corrections (the hierarchy problem).

$$m_h^2 = m_h^{(0)2} + c \cdot \Lambda^2 \quad (\simeq 125\ \text{GeV})$$

Aestetic consideration

- Too many free parameters in the Standard Model

  3 gauge couplings + 6 quark + 3 leptons masses
  + 1 Higgs mass + 1 VEV + 3 quark mixing angles
  + 1 CP-violating phase + 1 QCD θ-parameter
  = 19 parameters ... (modulo neutrino masses and mixings)

  Does not look like a 'final theory'.
  (reductionism, symmetries, unification)