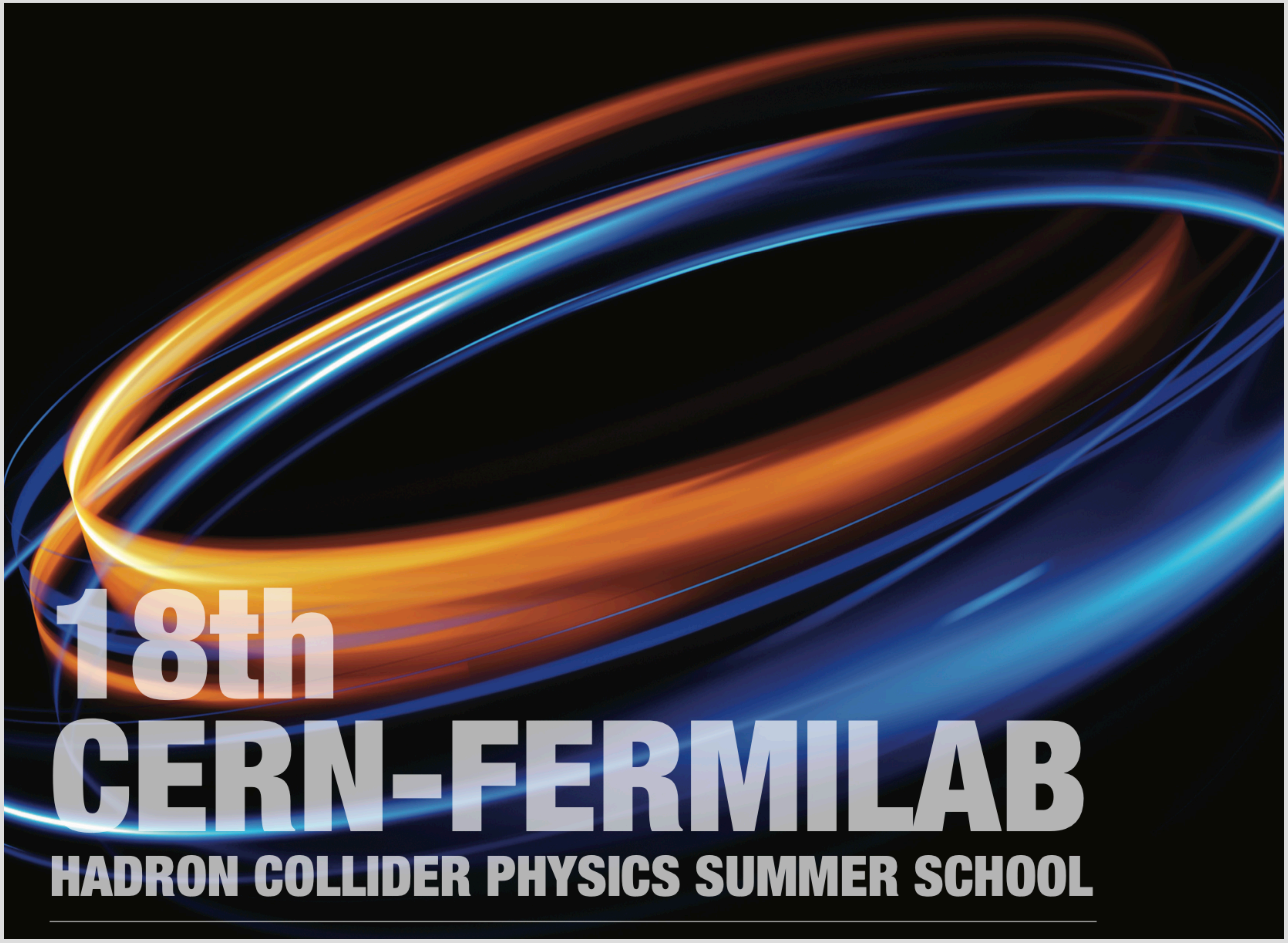
Experimental SM and Higgs Physics



CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Standard Model and Higgs

Lecture 4 *More Higgs Physics and Global Interpretation*

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Max Planck Institute for Physics

CERN-Fermilab School of Physics
August 29, 2023

Outline

***Lecture 1**: Basic concepts, QCD, jets and Z production*

- Introduction (rather long)
- Luminosity and total cross section
- Jet production measurements and the measurement of the strong coupling constant
- Drell-Yan Z production and the measurements of the weak mixing angle and the strong coupling constant

***Lecture 2**: EW Precision at Hadron Colliders*

- Drell-Yan W production and the W mass measurement
- Associated production of vector bosons and jets
- Multi-boson production (W, Z and photons)
- Top production and top properties measurements

***Lecture 3**: Higgs Physics*

- Diboson channels for Higgs measurements
- Measuring the Yukawa couplings of the Higgs boson
- Differential and Simplified Template cross sections
- CP properties of the Higgs boson
- Invisible Higgs boson decays
- Rare Higgs boson decays

***Lecture 4:** More Higgs Physics and Global interpretation*

- Higgs couplings measurements
- The Yukawa coupling of the Higgs boson to charm quarks
- Off shell Higgs boson coupling and Higgs width
- Di-Higgs boson production and Higgs boson trilinear self coupling
- Precision EW Fit
- SMEFT Global fits
- Challenges for Run-3 and the HL-LHC

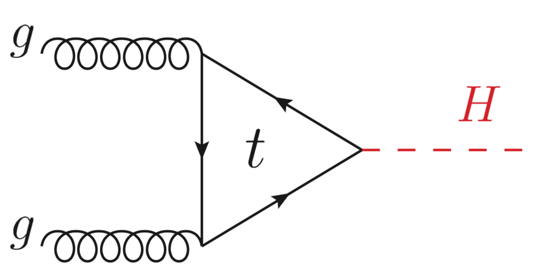
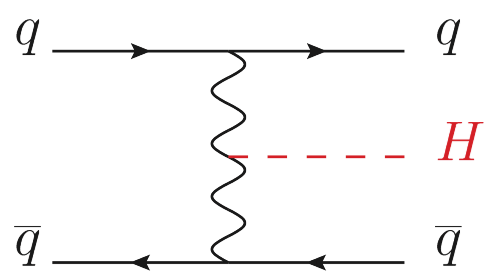
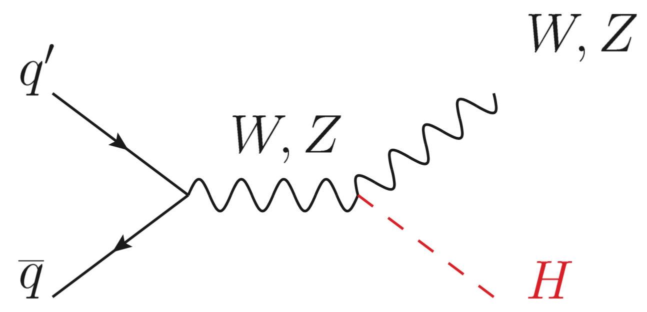
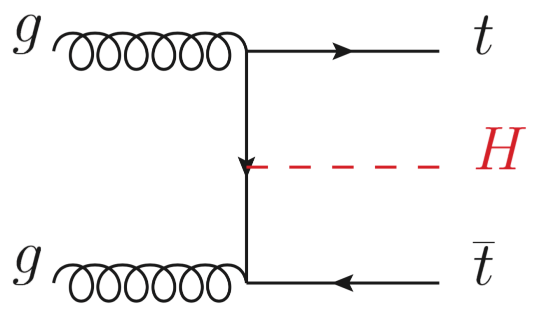
Review see latest PDG review

particle data group

Portrait of the Higgs Boson 10 Years after its Discovery

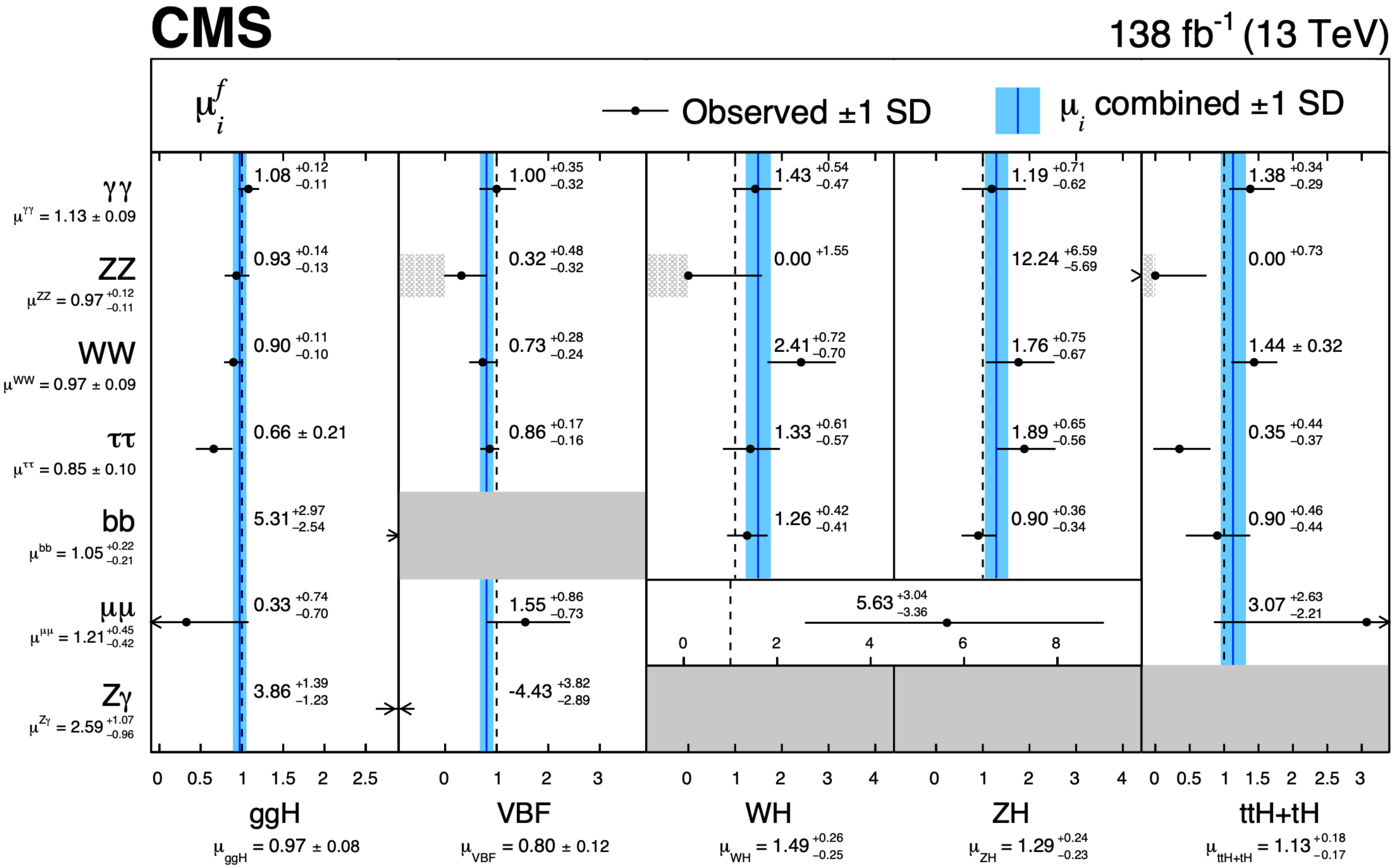
Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 3% (80 fb-1) of full HL-LHC dataset!

	Channel categories	Br	ggF	VBF	VH	ttH
			 ~4 M vets produced	 ~300 k vets produced	 ~200 k vets produced	 ~40 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

Portrait of the Higgs Boson 10 Years after its Discovery



*Similar results for ATLAS

Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%
B_{inv}		$< 11\,\%$	$< 16\,\%$	
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)	

How elementary is the Higgs Boson?

Minimal Composite Higgs scenarios

$$g_{HVV} = \frac{2m_V^2}{v}\sqrt{1 - v^2/f^2}$$

$$4\pi f \gtrsim 9\,\mathrm{TeV}$$

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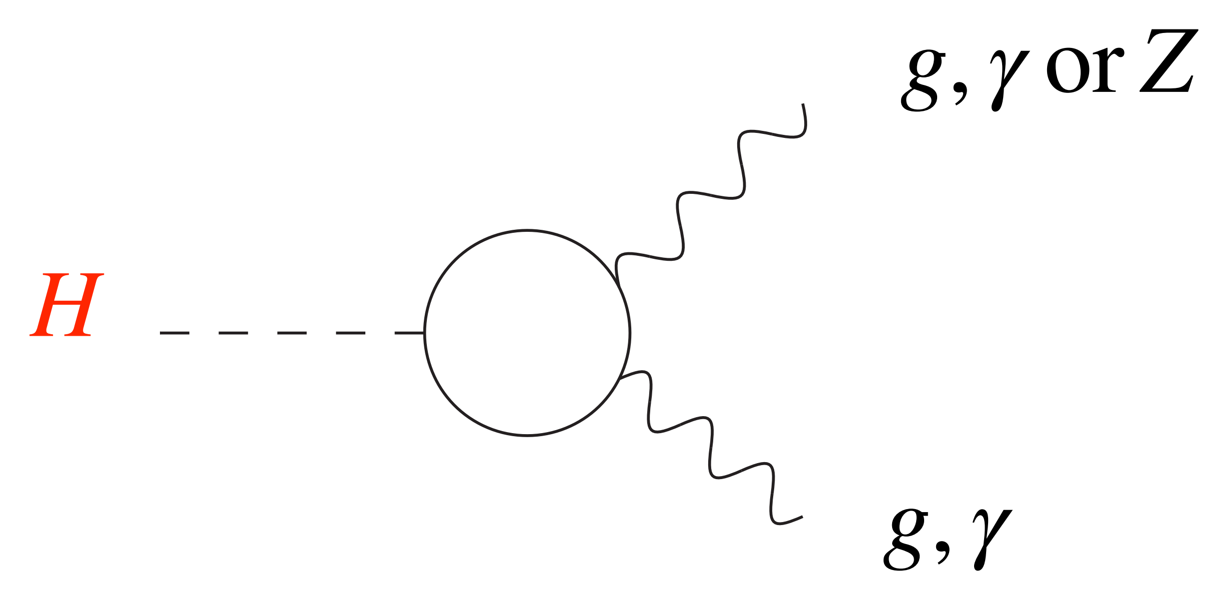
Probing new particles through loops



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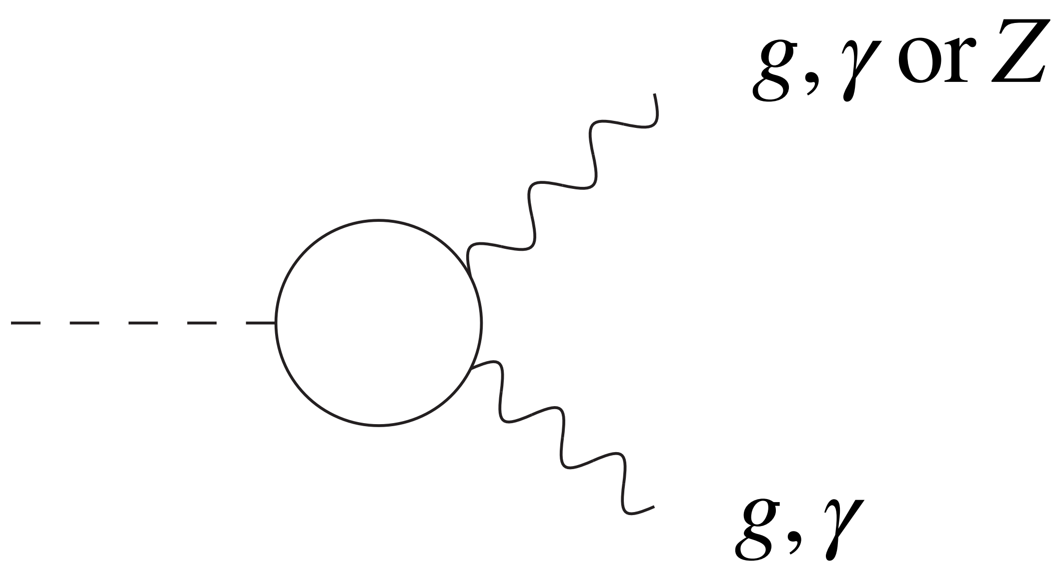
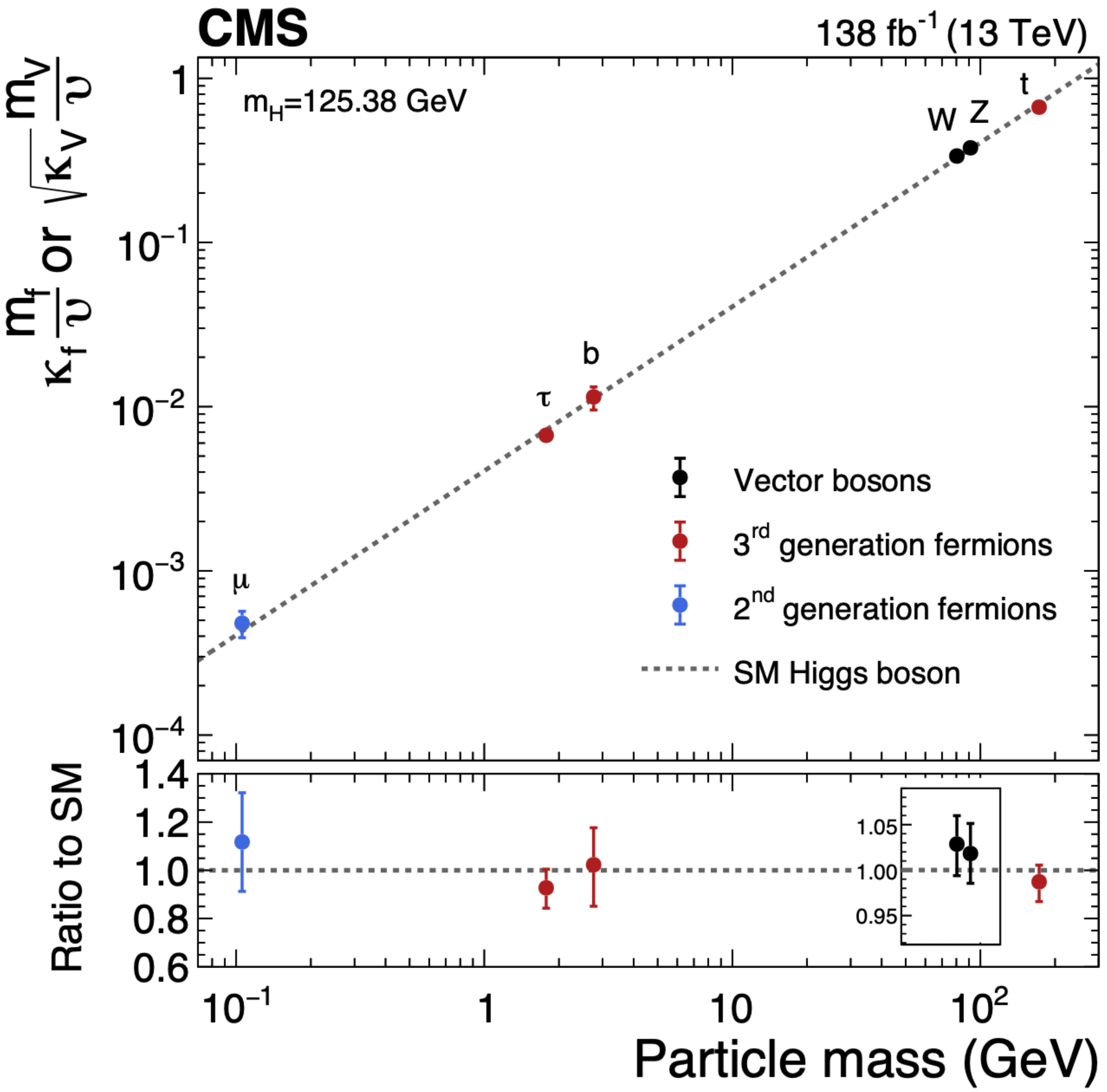


Probing the **Flavour Hierarchy** through the Yukawa couplings!

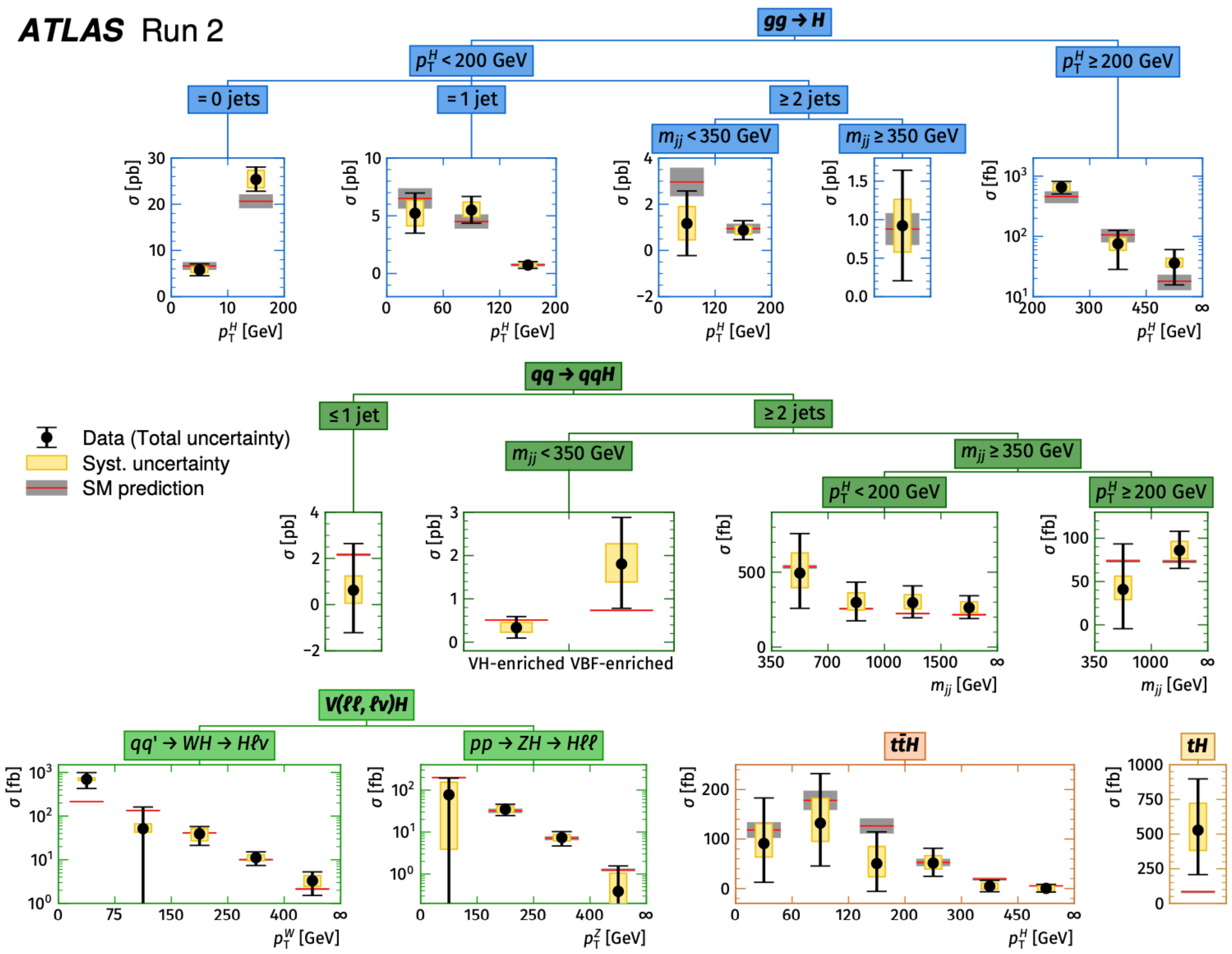
Portrait of the Higgs Boson 10 Years after its Discovery

Main coupling measurements



Caution not the same scale for gauge bosons and fermions

STXS measurement



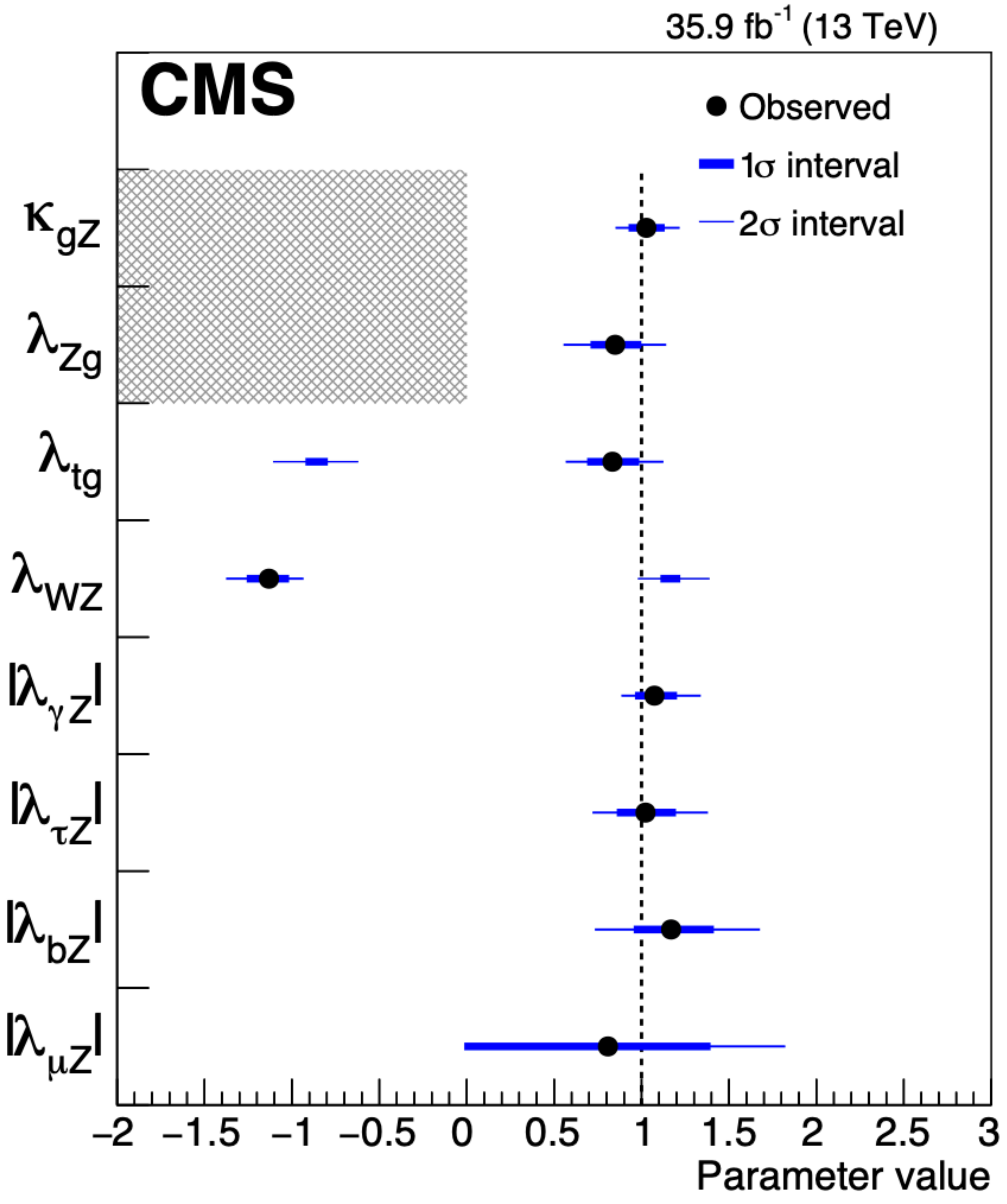
Run 2 Couplings Measurements

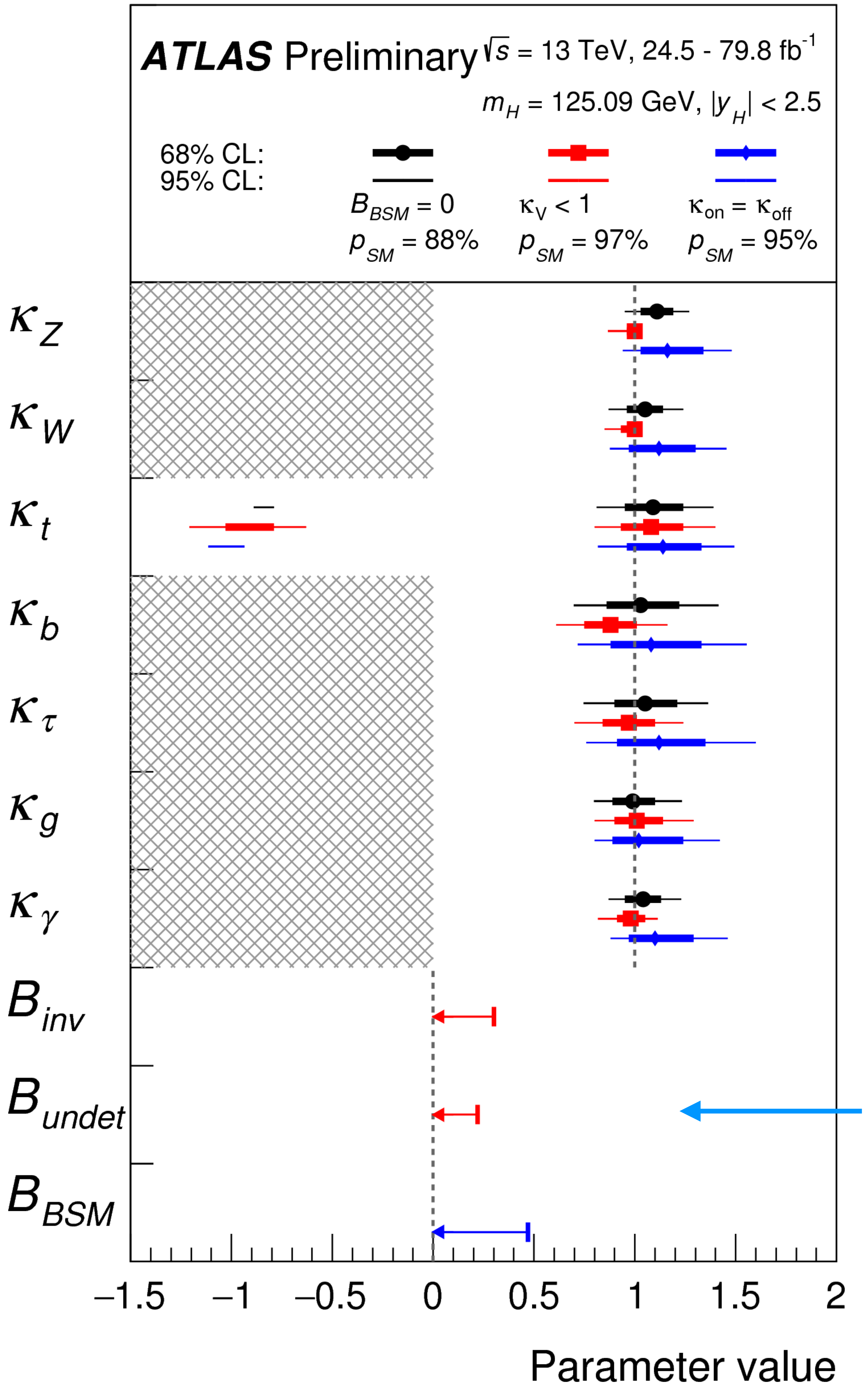
Previous measurements assume that the there is no additional contributions to the Higgs width than those from SM particles.

What are the alternatives?

$$\lambda_{kl} = \frac{\kappa_k}{\kappa_l}$$

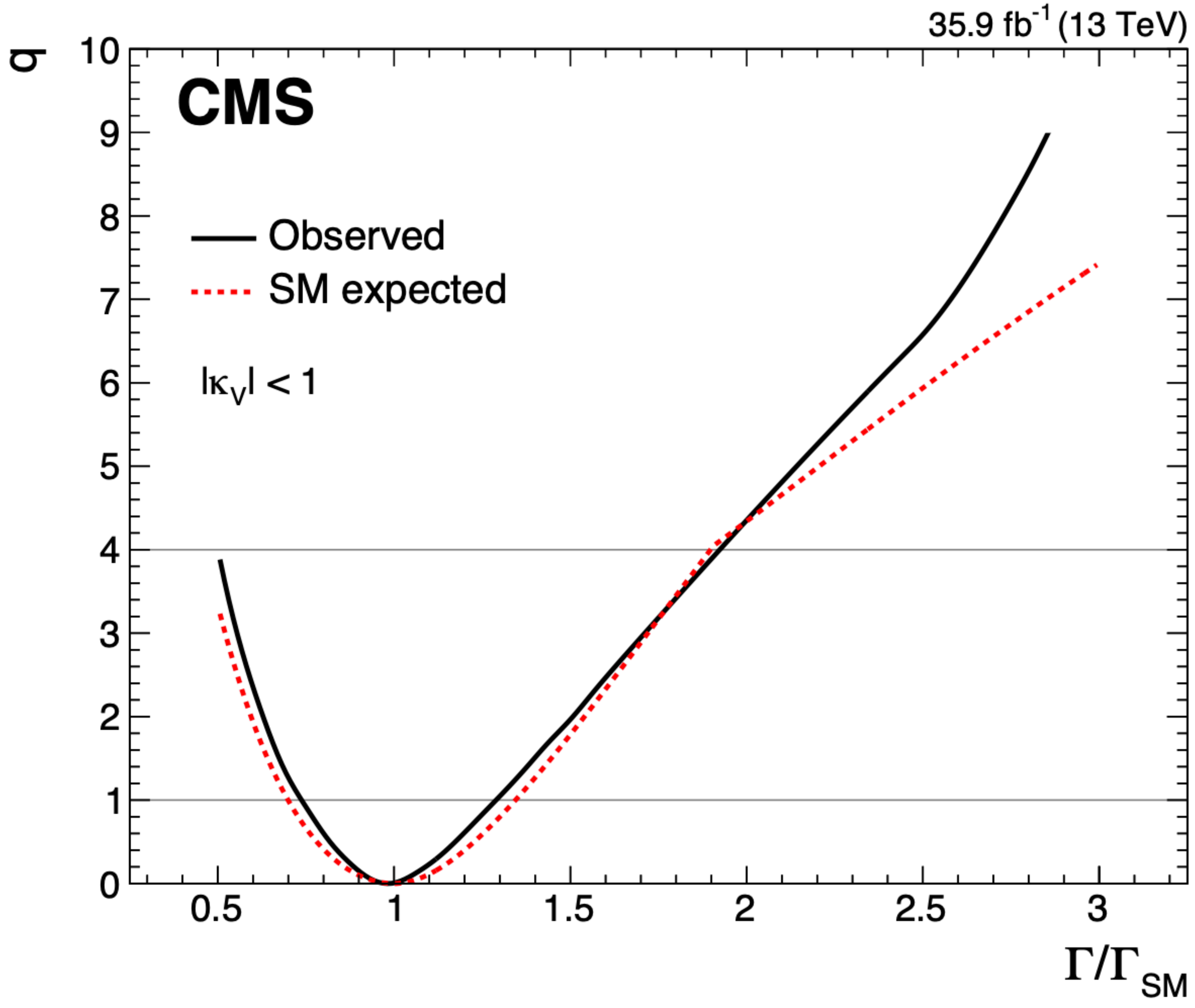
Measurement of ratios does not require any assumption on the natural width, parametrised as a function of one specific process $ggH \rightarrow ZZ$

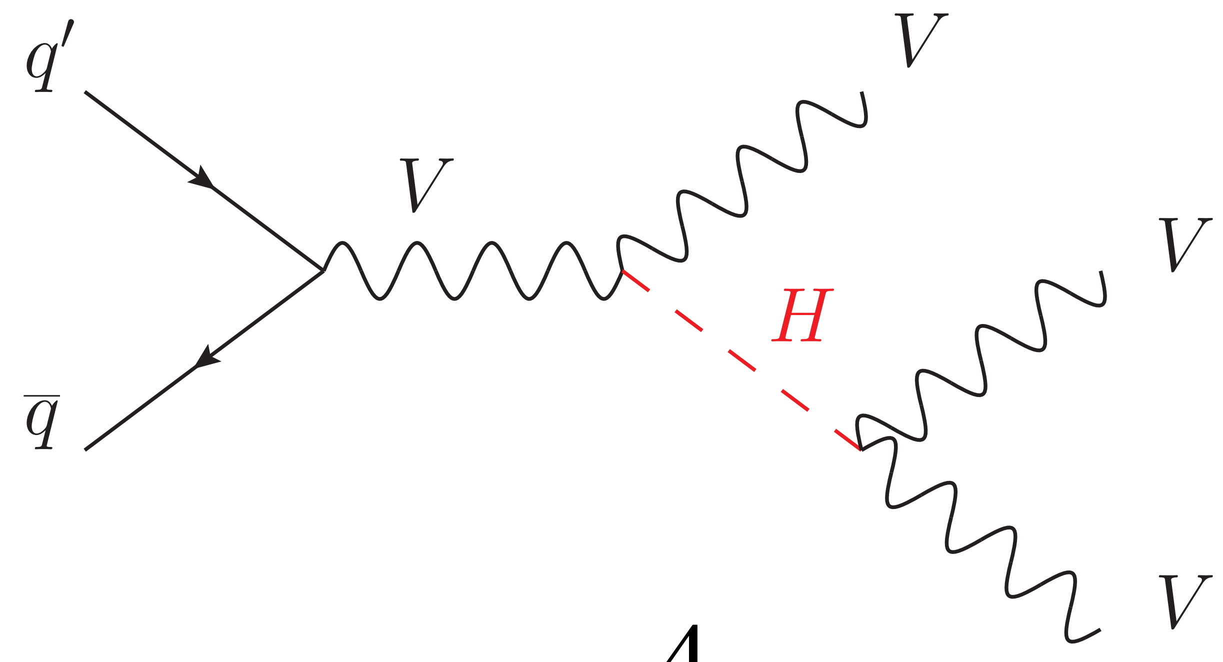




Couplings fit can constrain the total width with the assumption that kV<1

Why is kV < 1 sufficient to constrain the Higgs width?





$$\mu \propto \frac{\kappa_V^4}{\kappa_H^2}$$

A measurement of μ implies that $\mu \in [\mu_{min}, \mu_{max}]$ imposing $\kappa_V < 1$

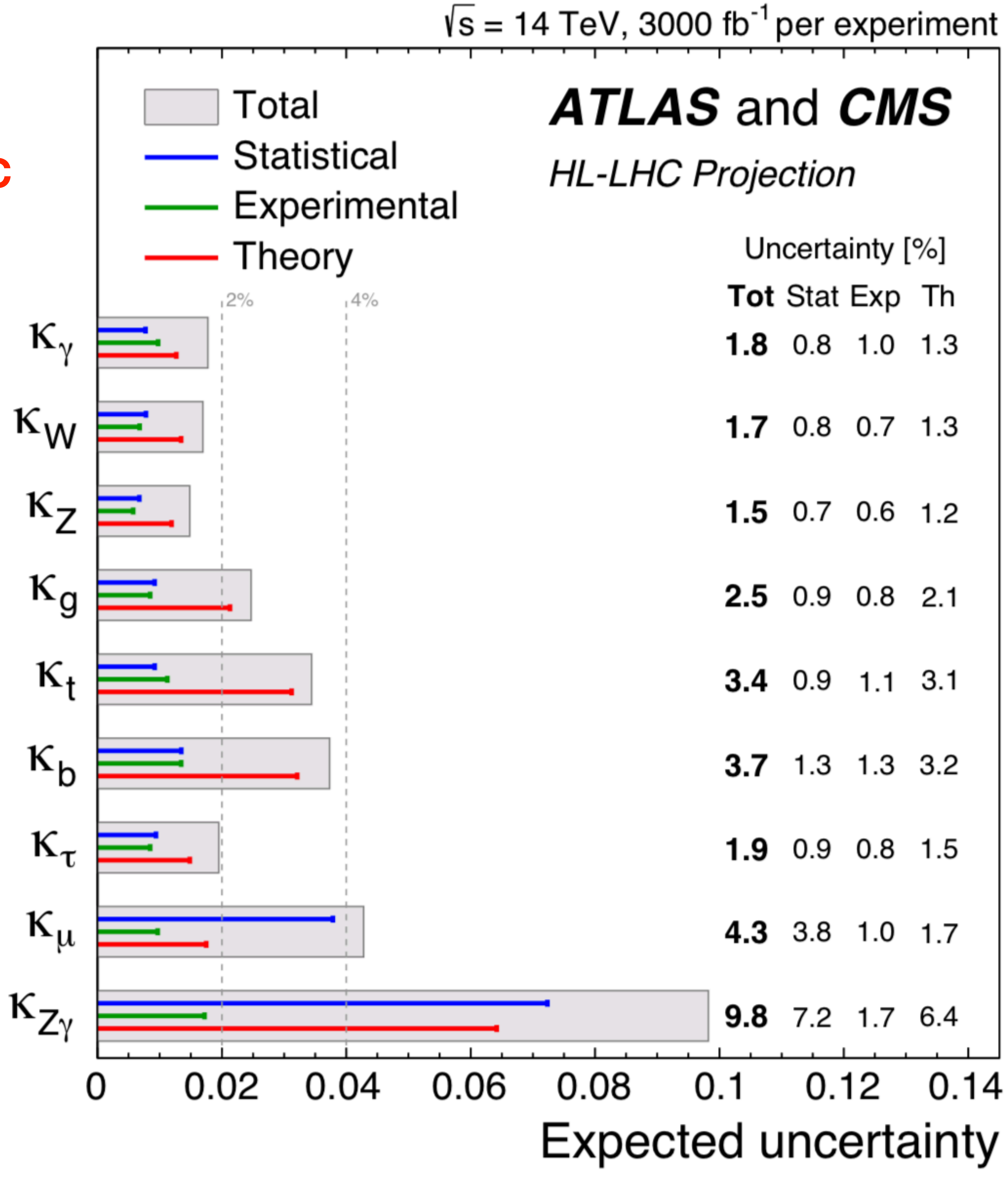
$$\mu > \mu_{min} \Rightarrow \frac{\kappa_V^4}{\kappa_H^2} > \mu_{min} \Rightarrow \kappa_H^2 < 1/\mu_{min}$$

Lower limit is more intuitive as $\kappa_H \to 0$ would require all other couplings to be very large to get SM rates (impossible with the different dependencies of couplings)!

How About this Picture at HL-LHC?

Portrait of the Higgs Boson 10 Years after its Discovery

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Modelling and predictions - an overarching question!

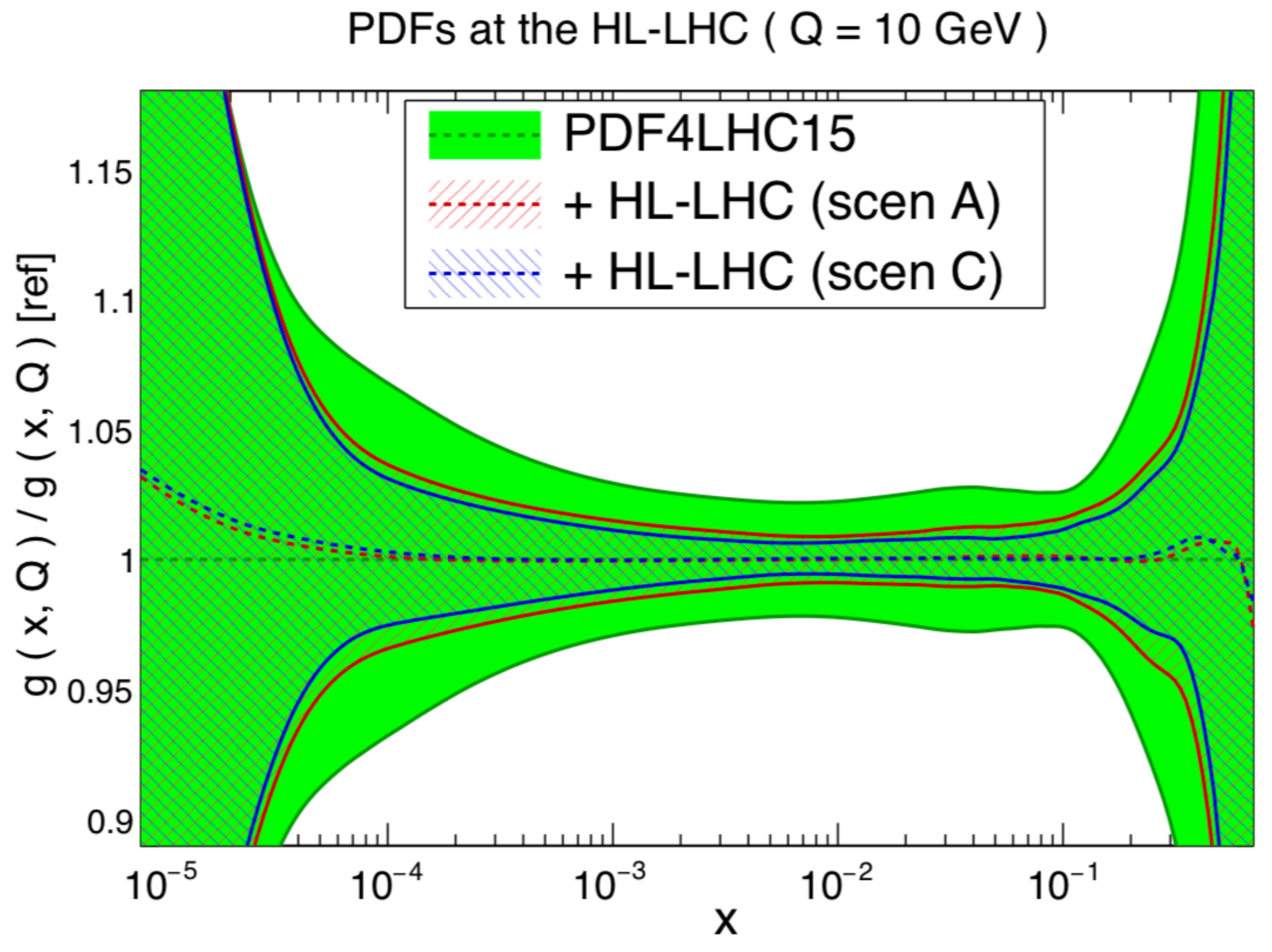
E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}\left(^{+4.27\%}_{-6.49\%}\right)$	$\pm 0.89\,\text{pb}\,(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}}\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}\left(^{+4.28\%}_{-6.46\%}\right)$	$\pm 1.00\,\text{pb}\,(\pm 1.85\%)$	$^{+1.40\text{pb}}_{-1.41\text{pb}}\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}\left(^{+4.53\%}_{-6.43\%}\right)$	$\pm 2.81\,\text{pb}\,(\pm 1.95\%)$	$^{+3.88\text{pb}}_{-3.82\text{pb}}\left(^{+2.69\%}_{-2.64\%}\right)$

Main assumptions for the projections

- Experimental systematic uncertainties reappraised in view of the larger dataset (many systematics dependent on data driven calibrations)
- TH systematic uncertainties on the Higgs signals divided by a factor of 2 w.r.t. current values according to the foreseen improvements in PDFs and alphaS (and the treatment of scale uncertainties as uncorrelated)
- Many uncertainties will also be reduced by the profiling (~equivalent to using control regions with higher statistics).

In depth PDF analysis made taking into account HL-LHC measurements by:

HL-LHC PDFs produced taking into account LHC cross sections for top, DY, W+charm, photon and jet production, etc…



Two scenarios considered:

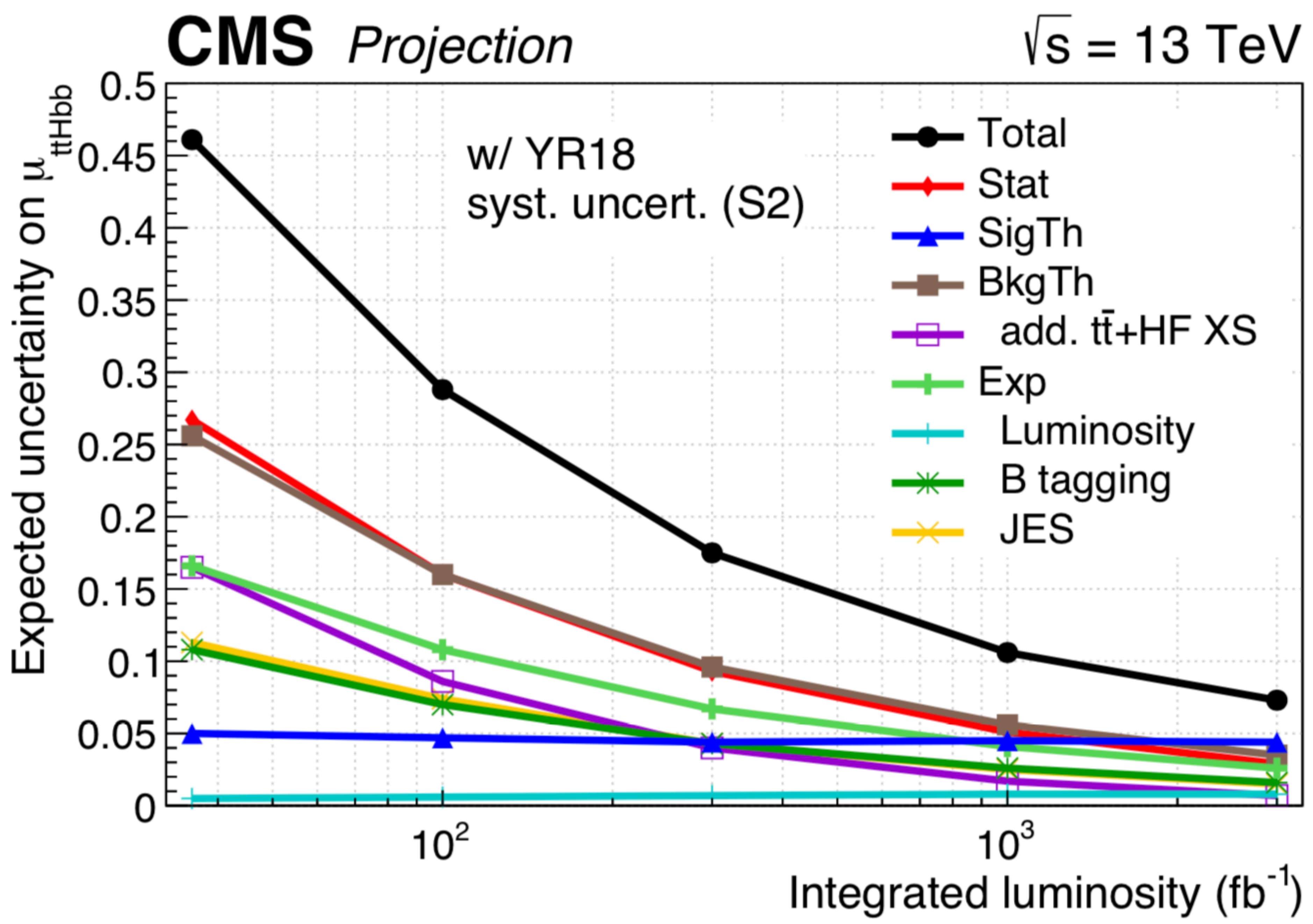
- Conservative (A): No reduction in systematics
- Optimistic (C): Reduction by a factor 2.5 of current systematic uncertainties.

Improvement by a factor of 2-3 w.r.t PDF4LHC15

A Closer Look at the ttH Case

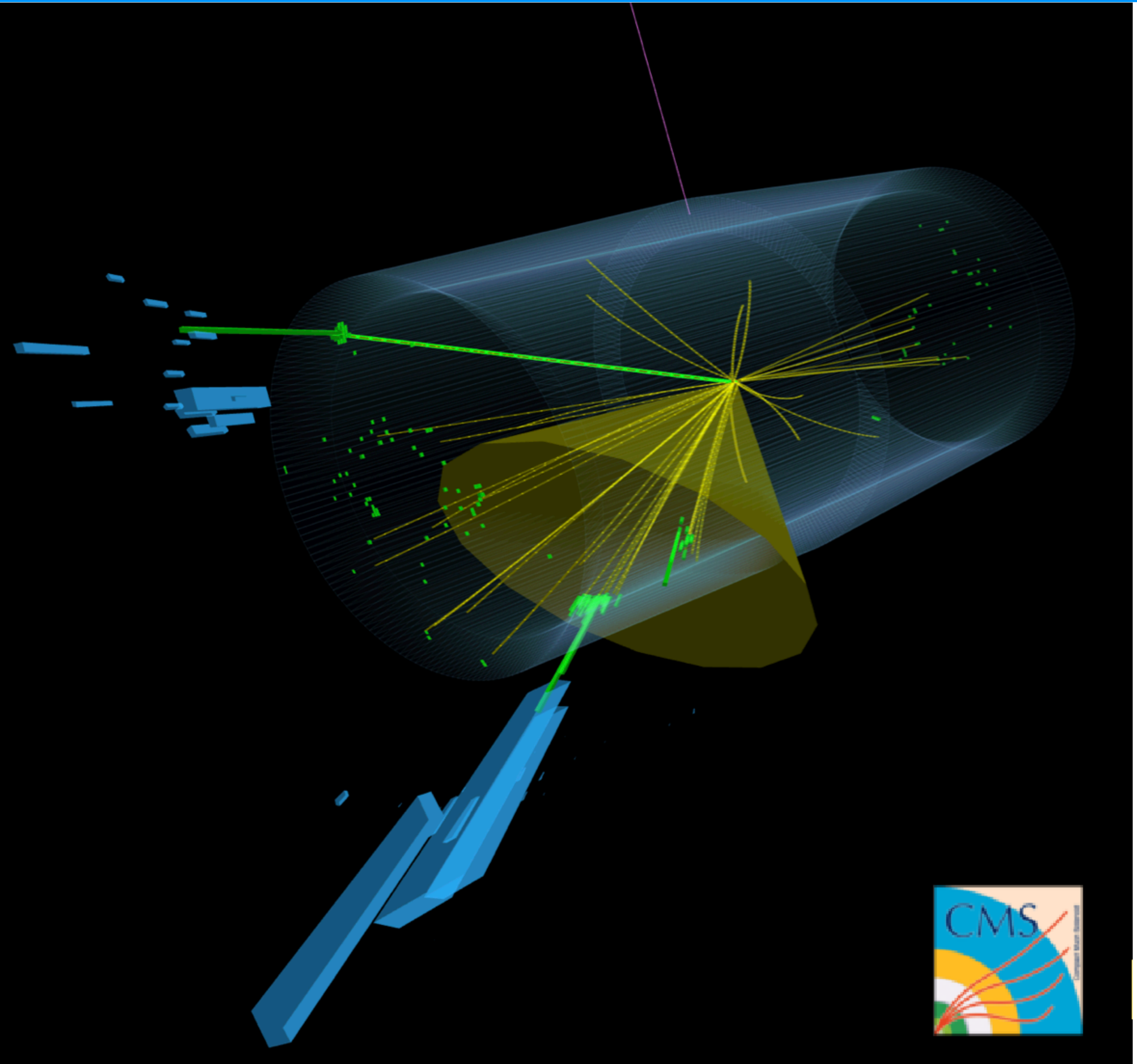
HL-LHC projection

- Extrapolating expected sensitivity simply from available frameworks. Already see that hierarchy of systematics can change with the luminosity.
- Uncertainties can be constrained by the data (it was important to verify that the constraints are justifiable).
- TH, EXP and Luminosity uncertainties were modified according to prescription.
- Harmonisation of the TH uncertainties on backgrounds (e.g. limiting the ttH(bb) sensitivity according to realistically reachable accuracy on the tt-HF background modelling).



Making the Impossible Possible

The Yukawa coupling to charm



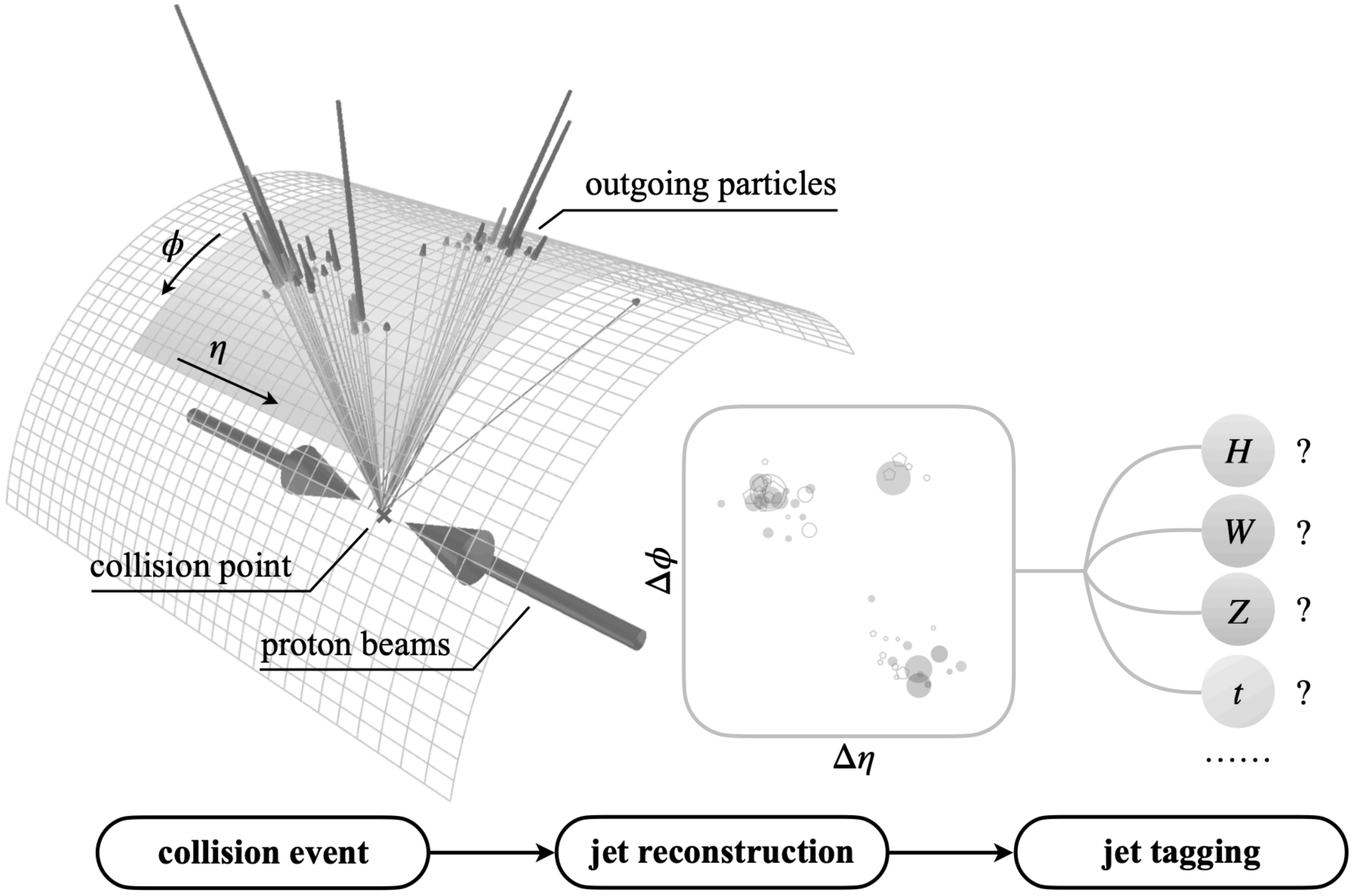


Illustration from [Particle Transformer]

Use of state-of-the-art ML techniques

Use “particle clouds” (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

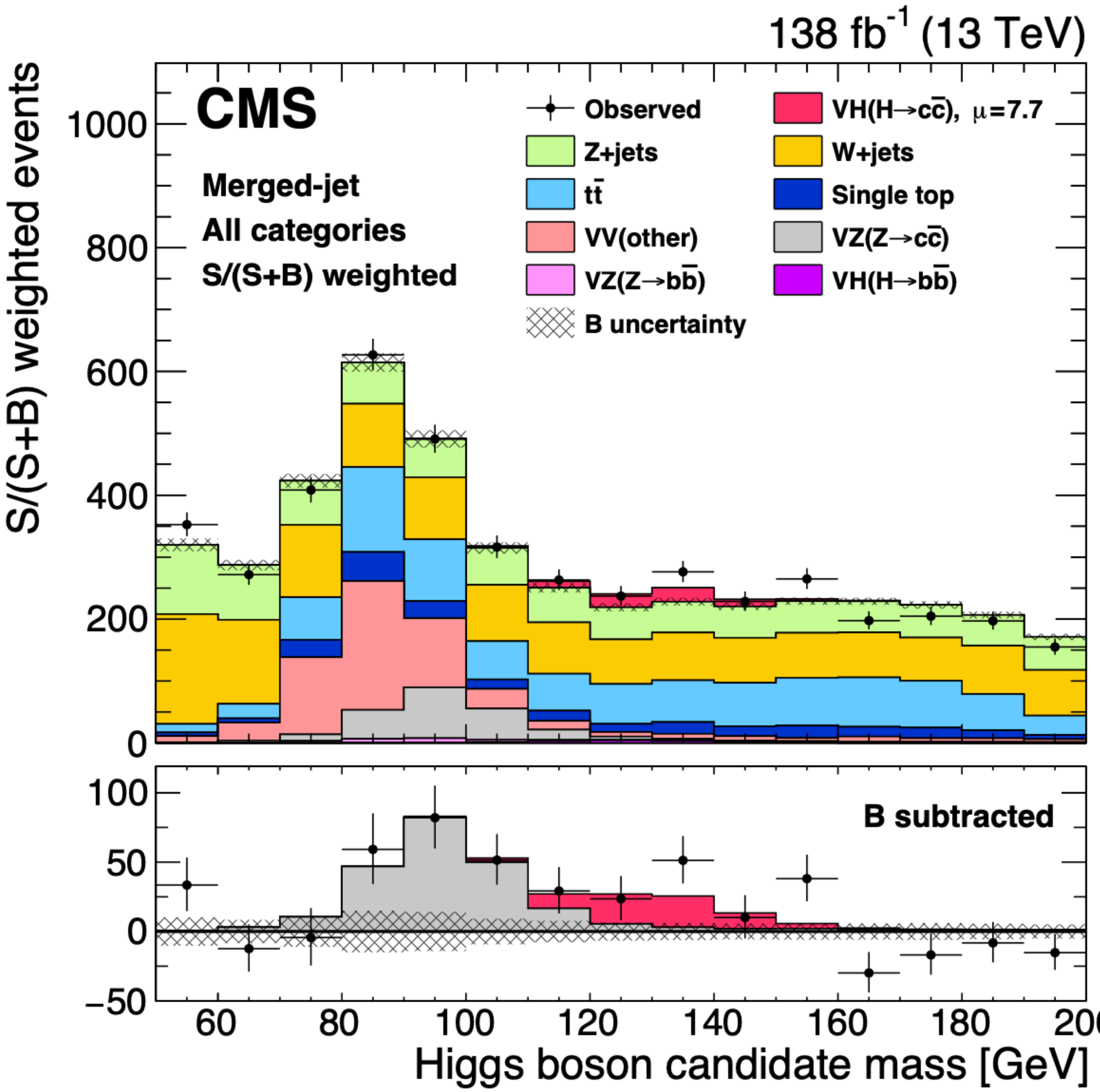
[Particle Net] uses Dynamic Graph CNN

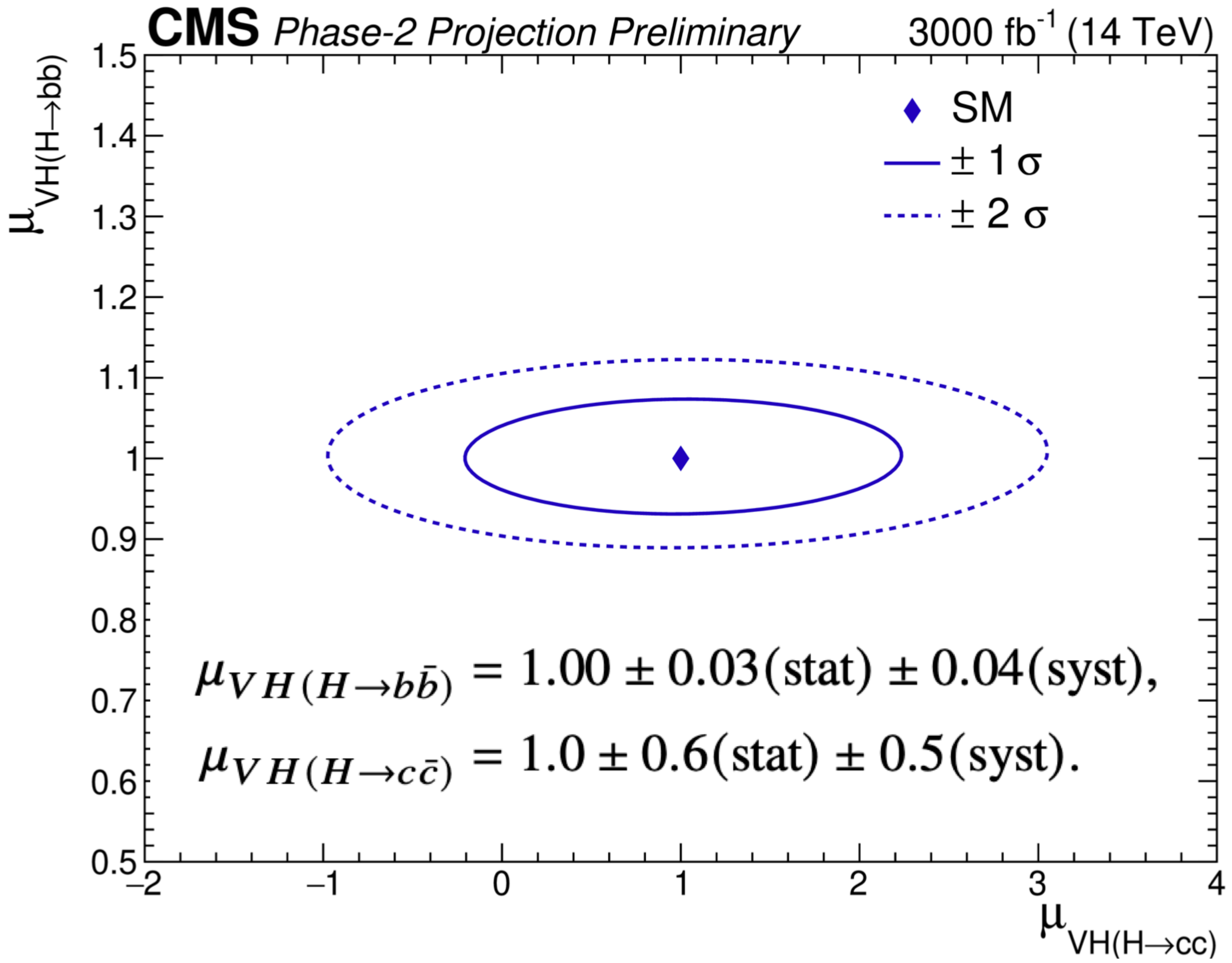
The challenging Yukawa coupling to charm

Signal strength:
μ < 14.4

Impact of boosted
Resolved: 19.0 (exp)
Boosted: 8.8 (exp)
Combined: 7.6 (exp)

Constraints on charm Yukawa
$1.1 < \kappa_c < 5.5$



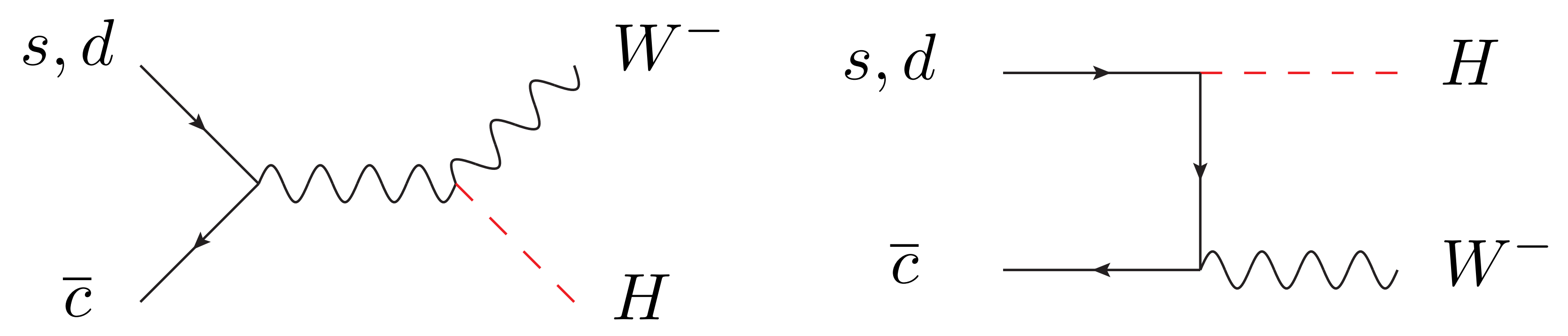


This result is very encouraging on the possibility of being sensitivity to this process at the LHC

More on the 2d Generation (charm) Yukawa Couplings

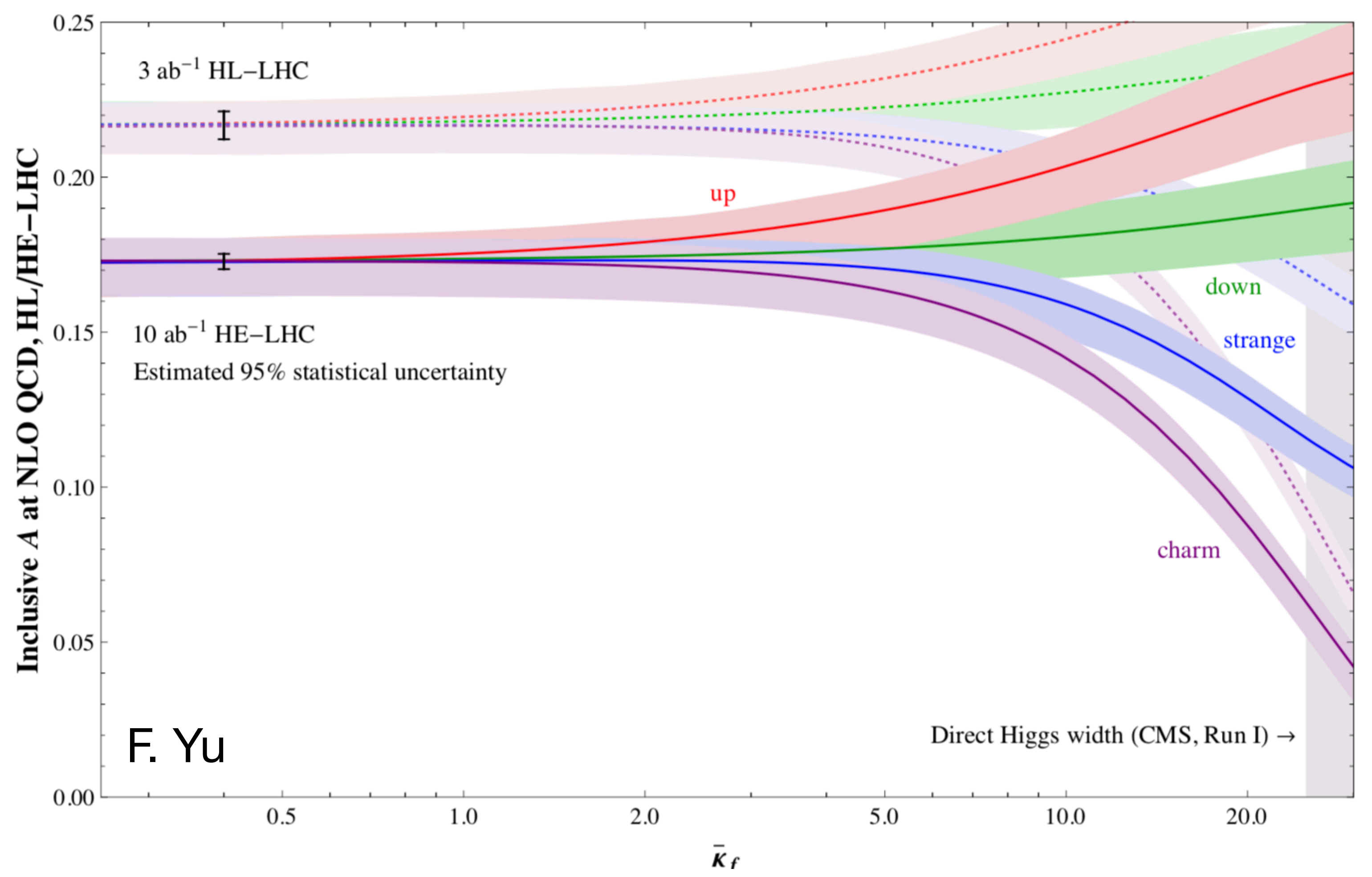
Other (even more) challenging ways to constrain the charm Yukawa coupling

- Differential cross sections (as discussed in the previous lecture)
- Charmonium-photon exclusive decays
- WH production charge asymmetry (PDFs)
- Total width from the couplings fit



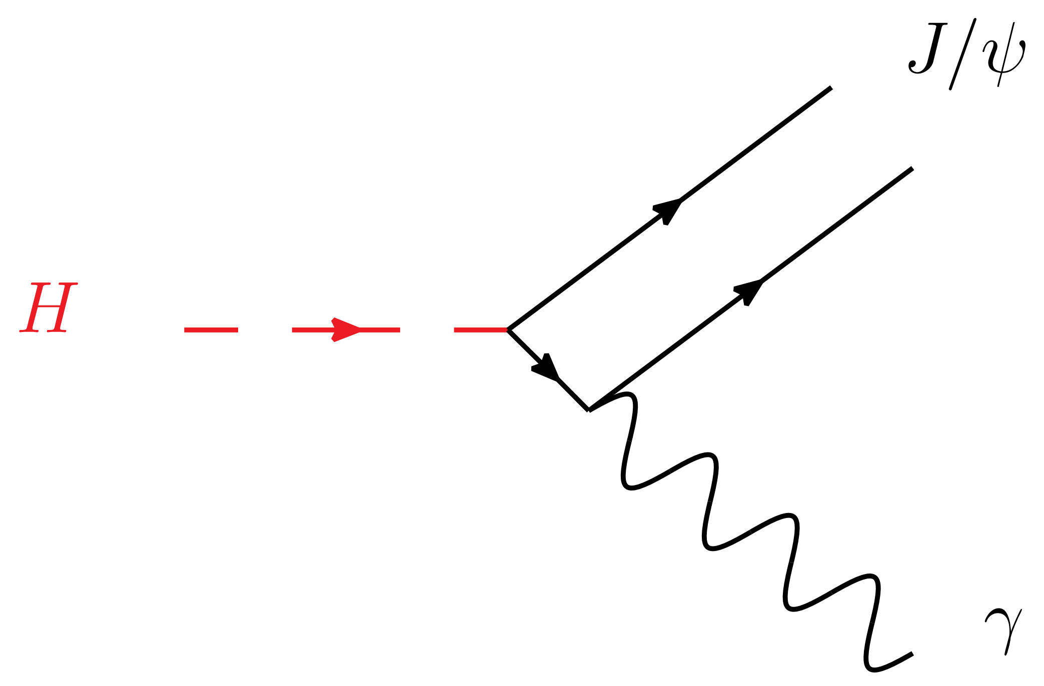
Based on d anti-d asymmetry in the PDFs

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$



Example of new idea in ratios where many TH uncertainties will cancel, of course in this case sensitive to PDFs.

Potentially sensitive to charm Yukawa



$\mu^+\mu^-\gamma$

Sensitivity to gamma-gamma* (top loop) and interference

HL-LHC

<15xSM

The Natural Width of the Higgs Boson

$$\Gamma^H_{SM} = 4.07 \pm 0.16 \text{ MeV}$$

The Higgs total width in the SM is very small therefore small couplings to the Higgs can be easily visible: tool for discovery!

- **At LHC only cross section x branching ratio**, no direct access to the Higgs total cross section (unlike e^+e^- collider from recoil mass spectrum).

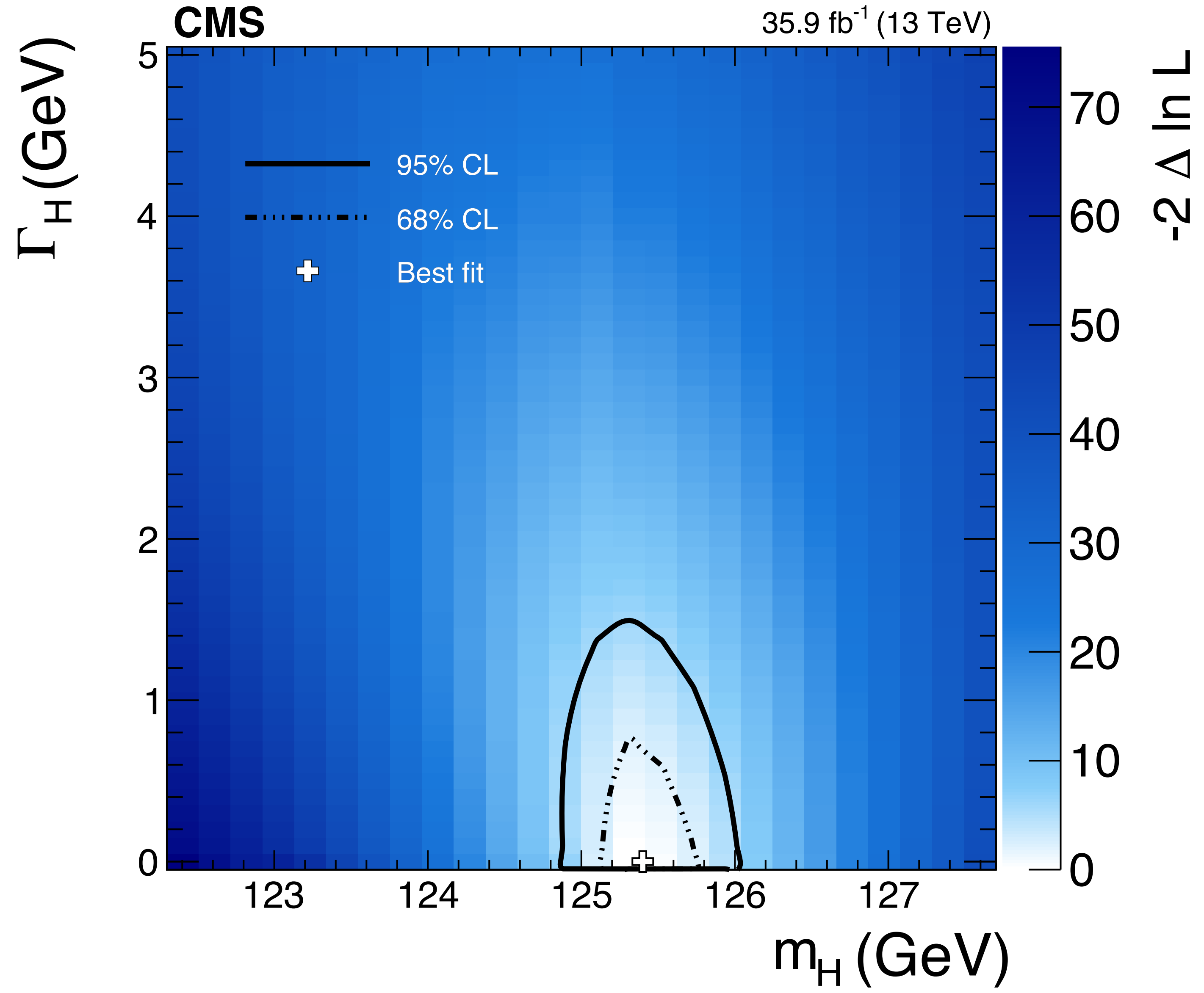
- At LHC direct measurements of ratios of couplings.

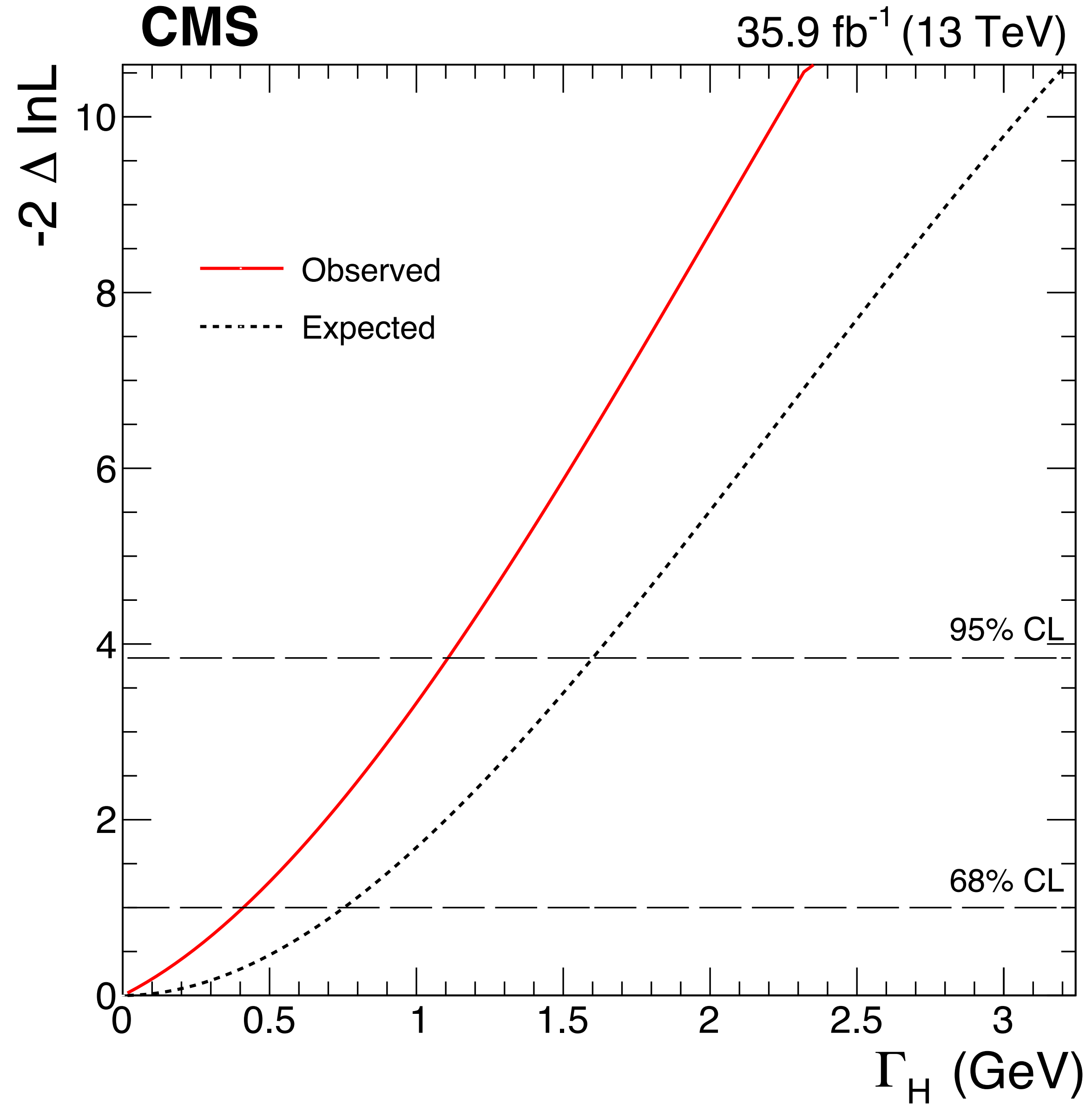
- In order to have absolute coupling measurements need to constrain the total width.

Thought to be impossible* prior to the Higgs discovery, a flurry of new ideas appeared to measure the Higgs boson width.

*Modulo weak constraints through the mass resonance line shape in the di-photon and the four leptons channels.

When fitting the Higgs signal line shape for the mass, also the total width can be fitted.



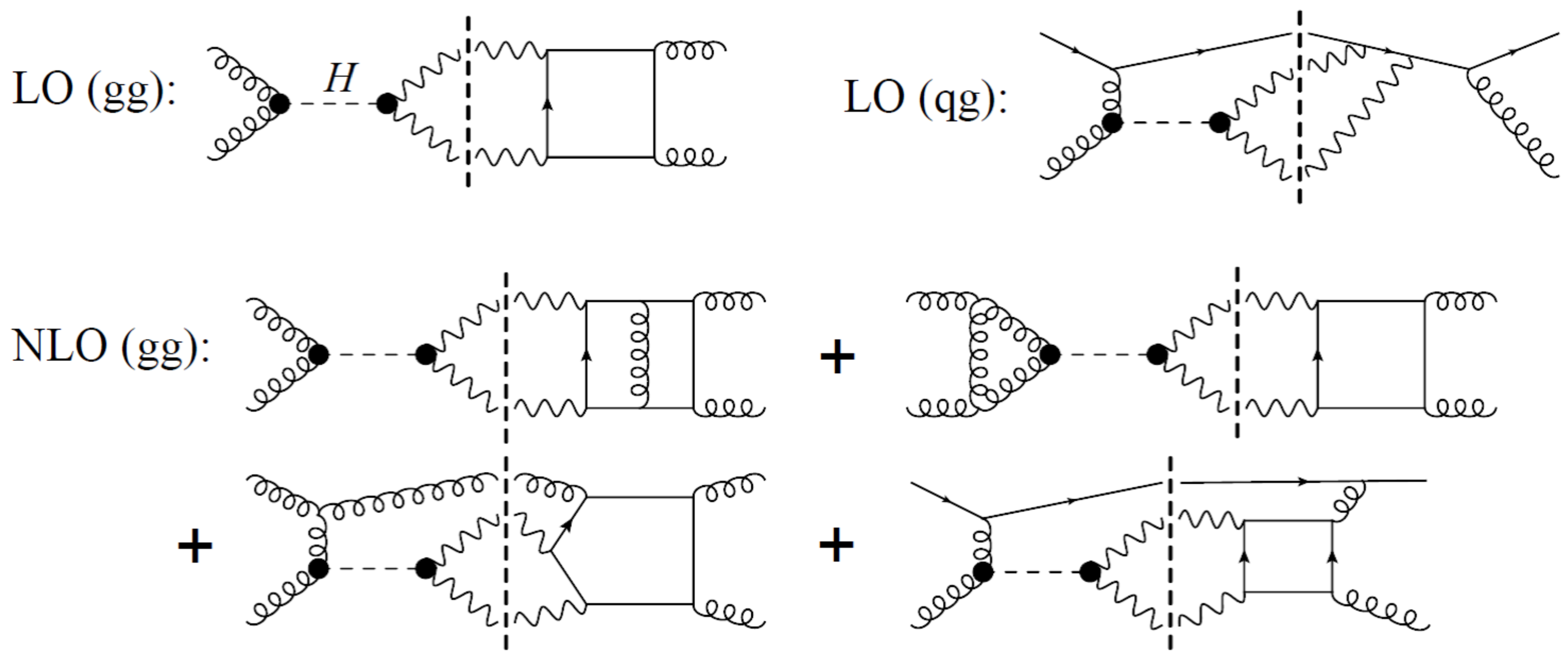


$$\Gamma^H_{SM} < 1.10 \text{ GeV at } 95\% \text{ CL}$$

Original Approaches to Constrain the Higgs boson Width

Diphoton signal-continuum background interference

Interference between the signal ggF production and the box diphoton production:



- **Rate**: the size of the interference inclusively is 2% and depends on the width of the Higgs boson. Comparing rates with other processes such as e.g. the four lepton channel in similar regions of phase space can constrain the total width.

- Worth exploring specific regions of phase space.

- **Mass shift**: This interference has first been studied when noticing (Martin, Dixon and Li) that the distortion in the reconstructed mass shape was sizeable (despite the very small width).

- Induced a mass shift of approximately 35 MeV.

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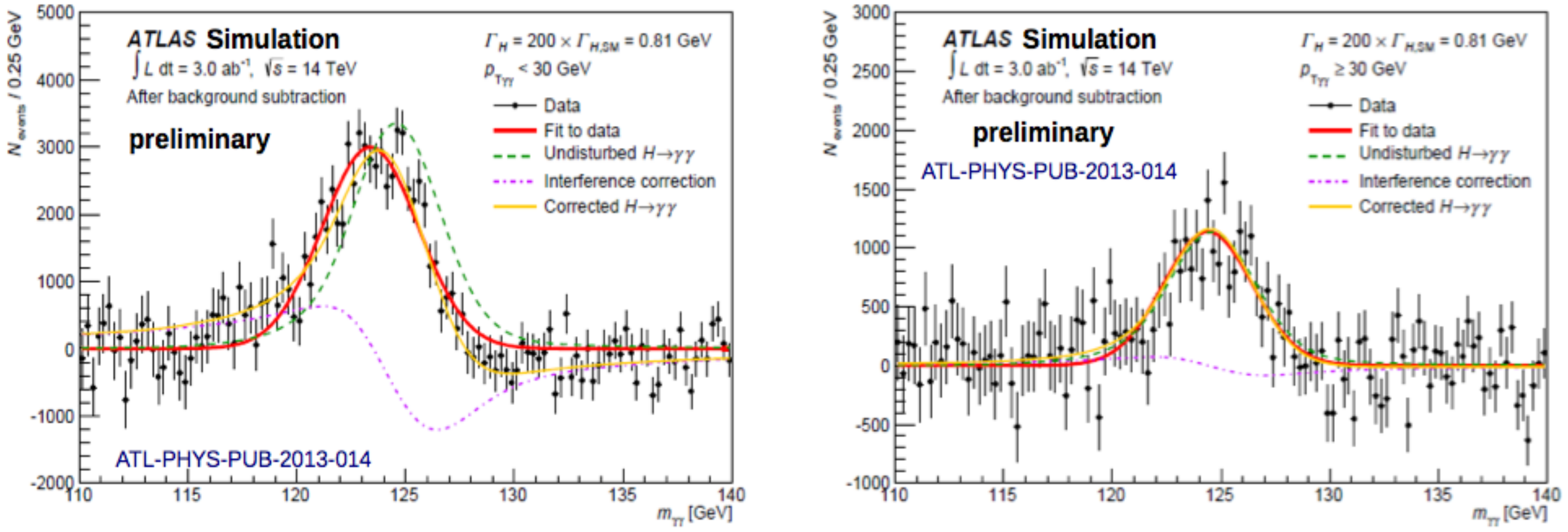


- The mass shift has an interesting dependence on the Higgs transverse momentum and on the Higgs width.
- Constraints using a Higgs boson mass measurements was proposed and carried out

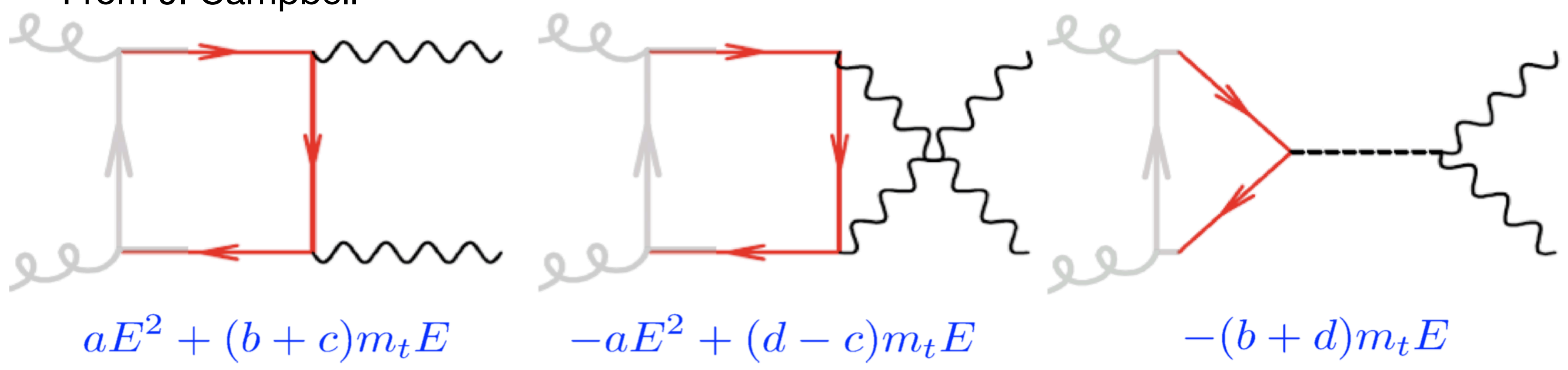
$$\Gamma^{H}_{SM} < 200 \text{ MeV}$$ At HL-LHC

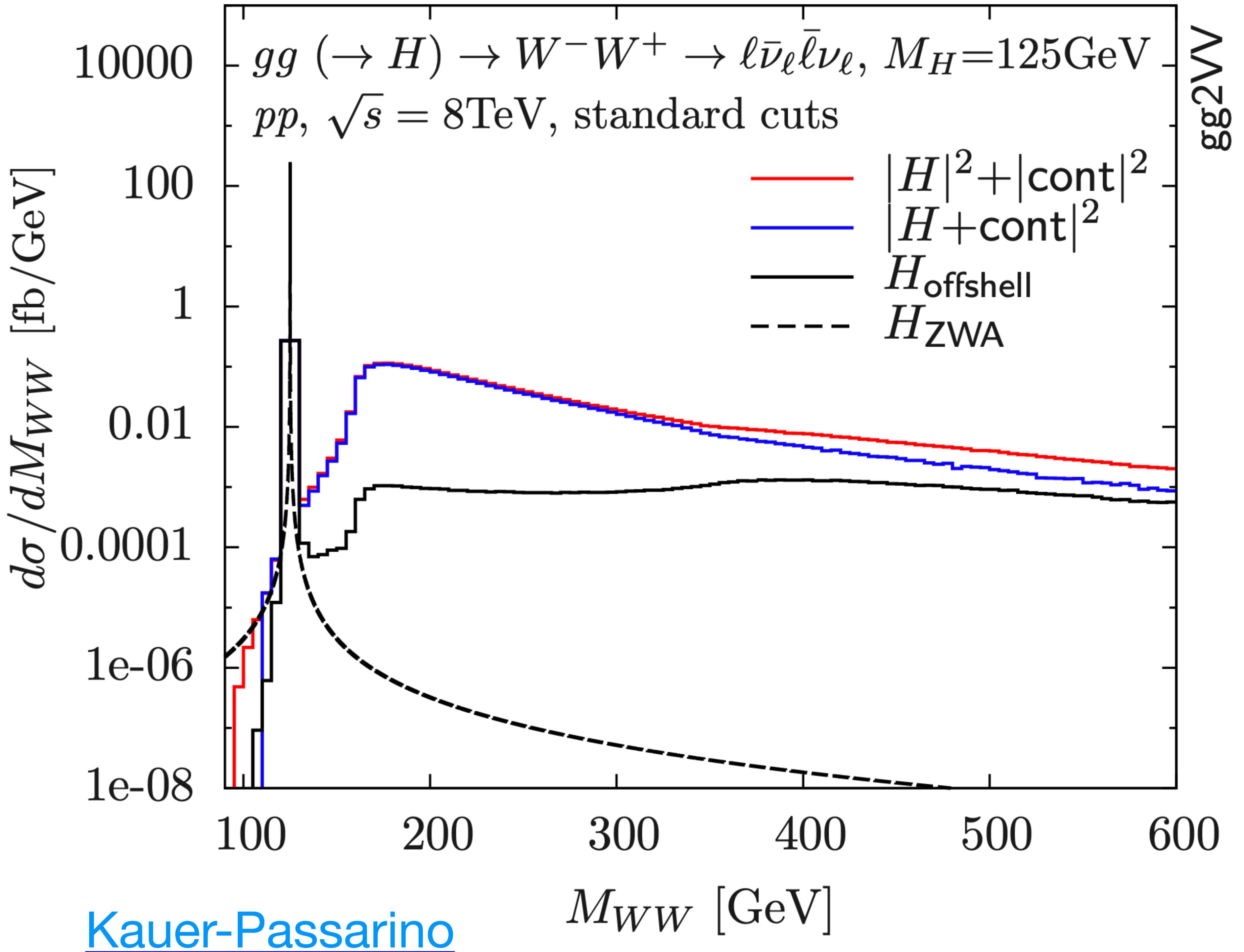
Off Shell Higgs

Study the Higgs boson as a propagator

Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a propagator

From J. Campbell



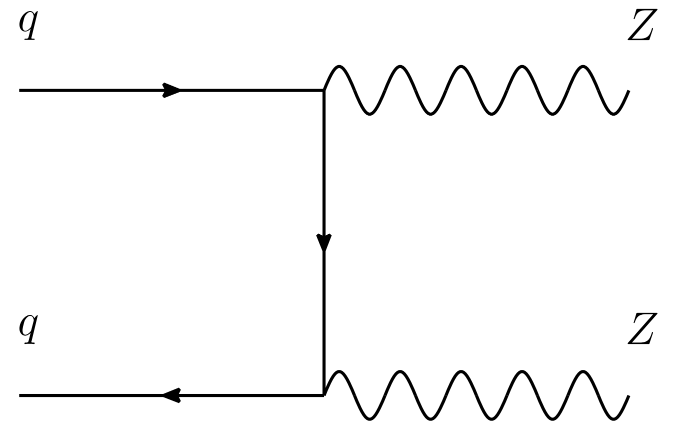


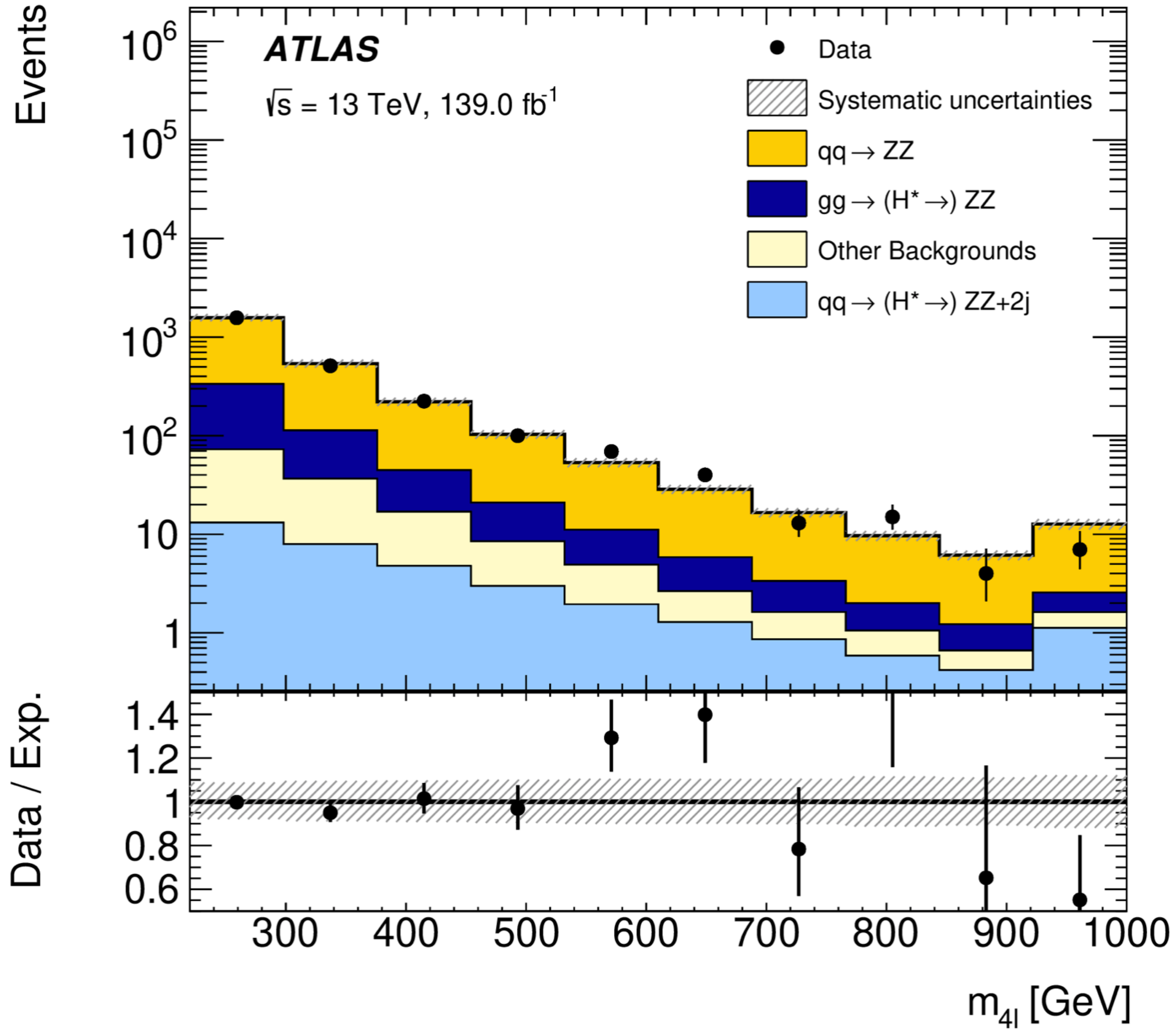
[Kauer-Passarino](#)

Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

Highly non trivial due to:

- The negative interference
- The large other backgrounds





Off Shell HVV Couplings and Width

Higgs Boson width

$$\sigma = \int \frac{g_i^2 g_f^2}{(s - m_H^2)^2 + \Gamma_H^2 m_H^2} ds$$

Assuming that these couplings run as in the Standard Model and measuring them on shell allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

$$(\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

CMS Result

$$\boxed{\Gamma_H = 3.2^{+2.4}_{-1.7}\ \mathrm{MeV}}$$

Evidence for Off-Shell production at 3.6σ

ATLAS Result

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

Evidence for Off-Shell production at 3.3σ

at HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$

Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Remarkable result to follow closely at Run 3! How much better can be done at HL-LHC?

Higgs Self Coupling

Outstanding goal of the LHC as <u>likely*</u> the next collider to provide a direct measurement would be a future radon collider!

*Possible at an e^+e^- collider but would require high c.o.m. energy

Di- Higgs Production

The Higgs self coupling is key in understanding the shape of the Higgs potential. Probing the potential would shed light, beside the electroweak symmetry breaking, on whether there could be an EW phase transition in the early universe, or the stability of the vacuum.

Measuring the di-Higgs production would provide a unique and direct probe of the Higgs boson self-coupling

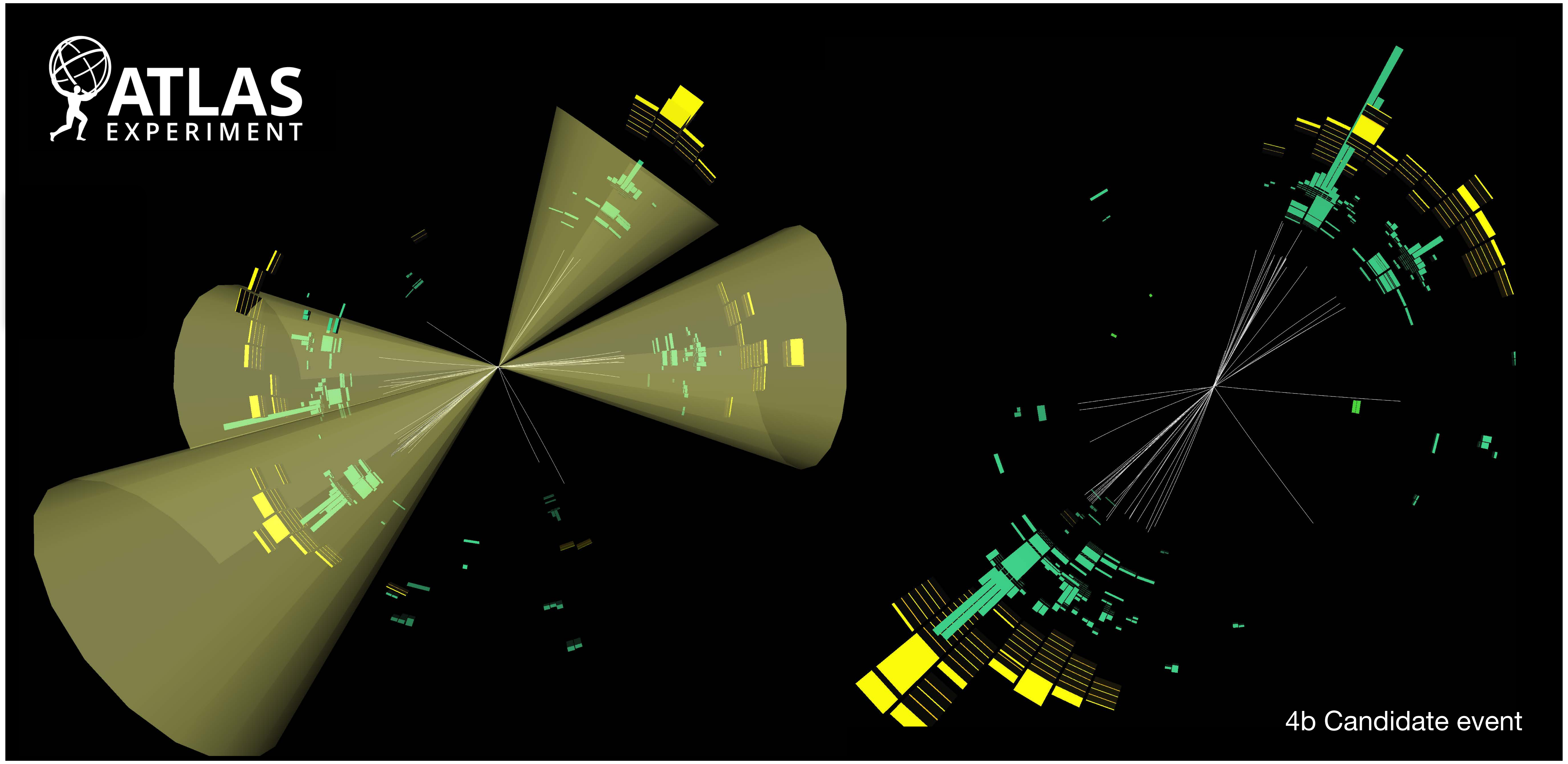
Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production!

Huge challenge! but still more than 100k event will be produced at HL-LHC!

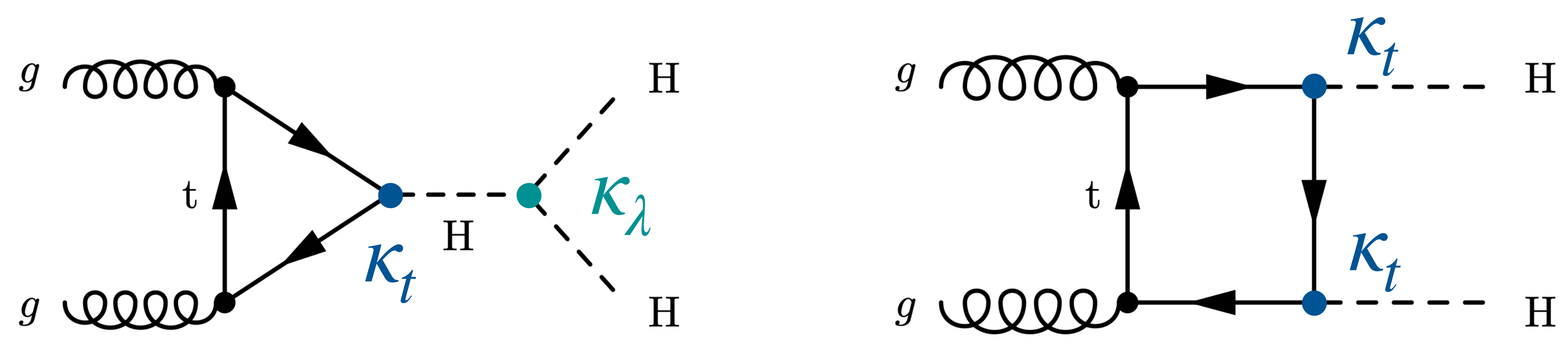
Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

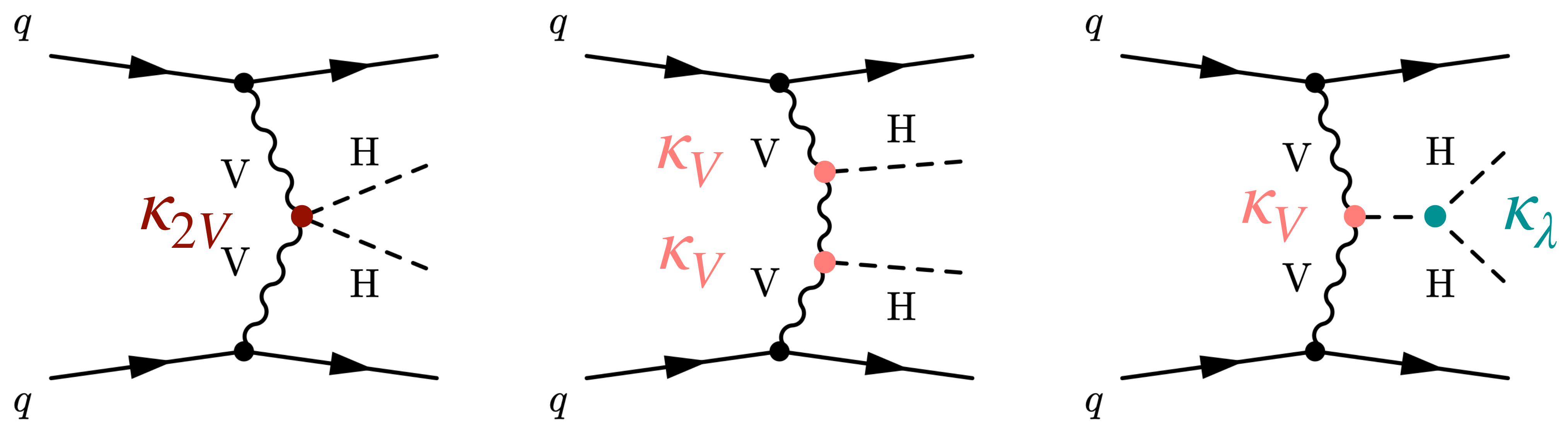
Fairly complex signatures (not outrageously so!)



HH Production and Higgs Self coupling

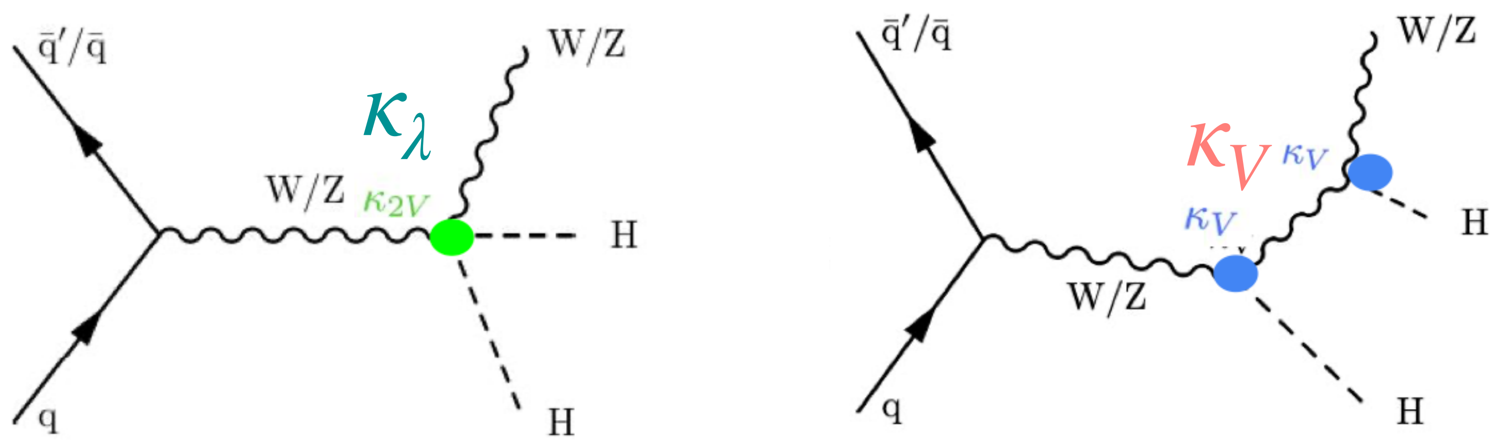
Higgs pair production through gluon fusion (VH and VBF)





With the VBF production mode not only limits on κ_λ also on κ_{2V}

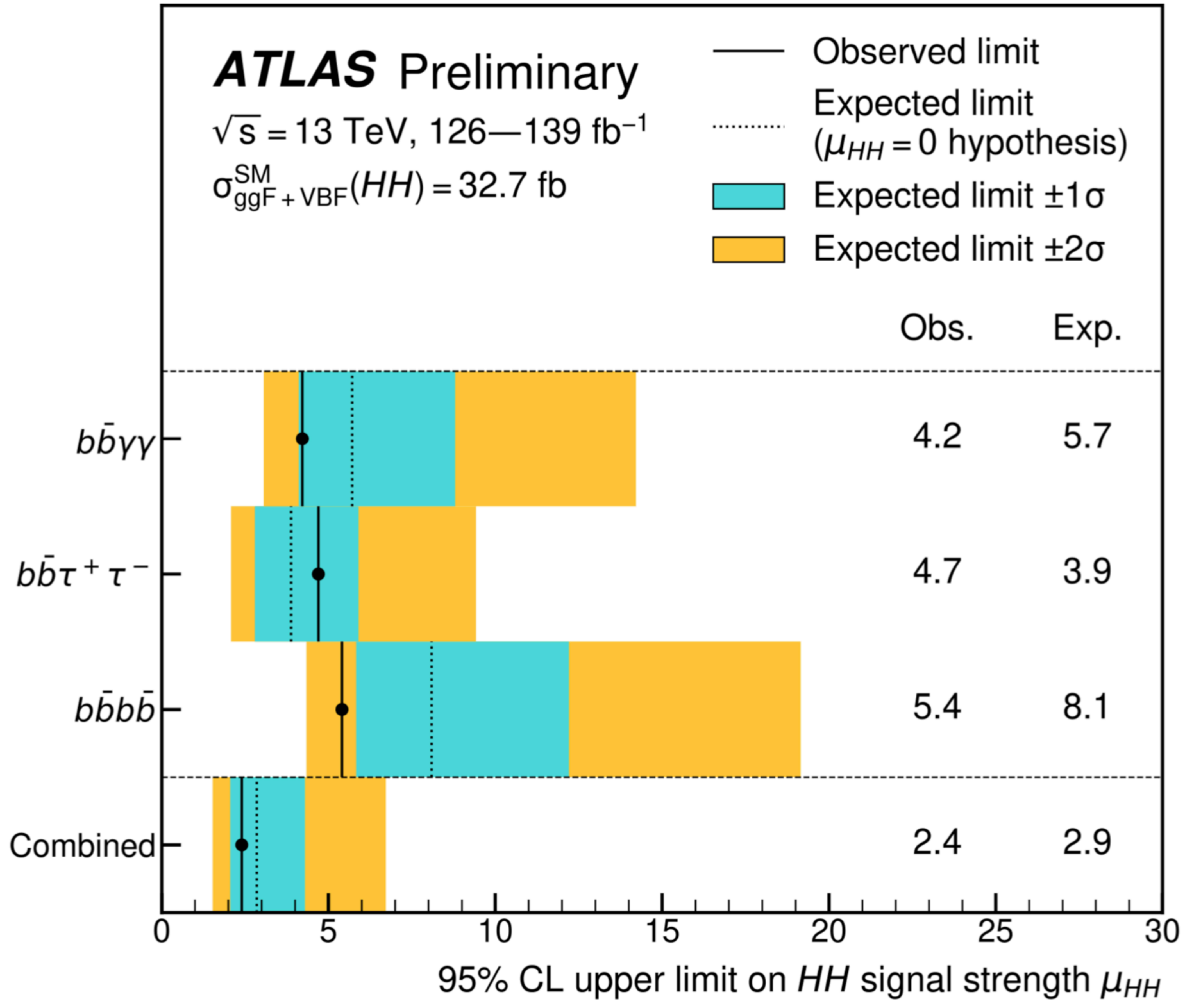
[Bishara, Contino, Rojo]



Most recent results from CMS

ttH not impossible (not done yet)

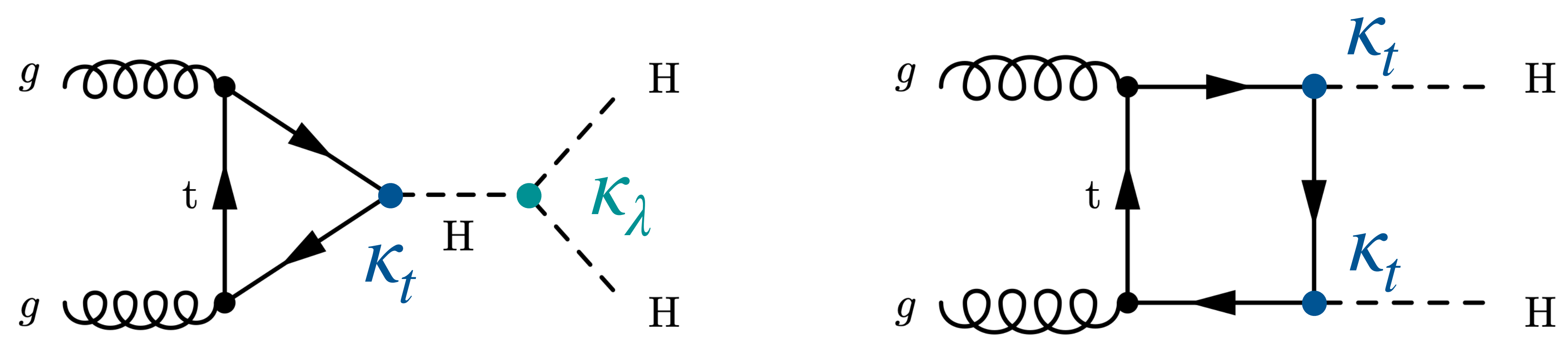
Multiple channels investigated: depending on both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

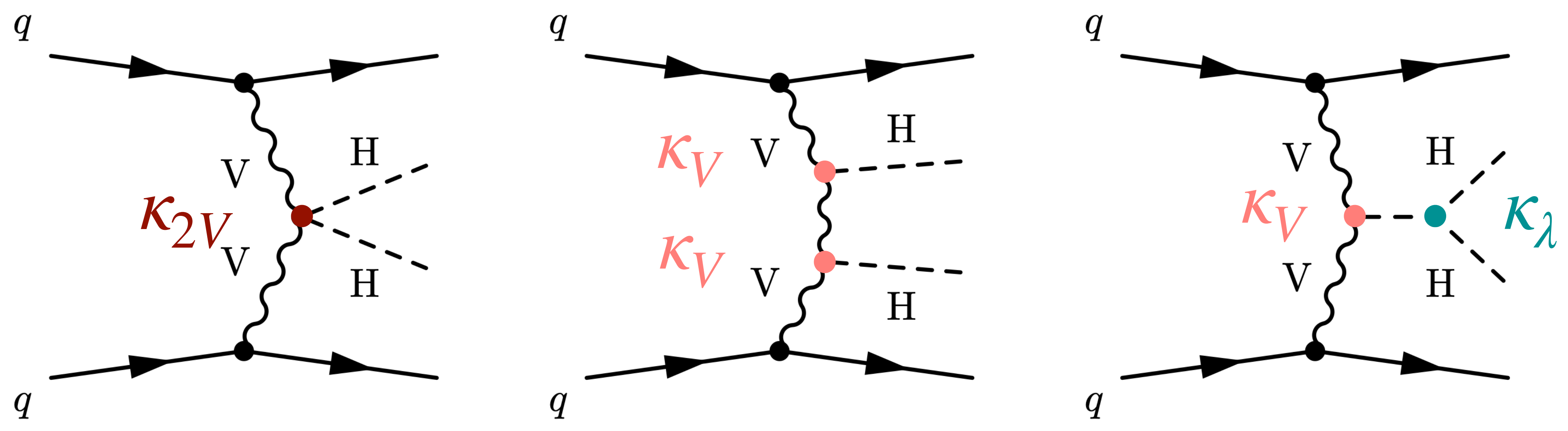


More than 3 times better limits than with 36 1/fb!!

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (VH and VBF)





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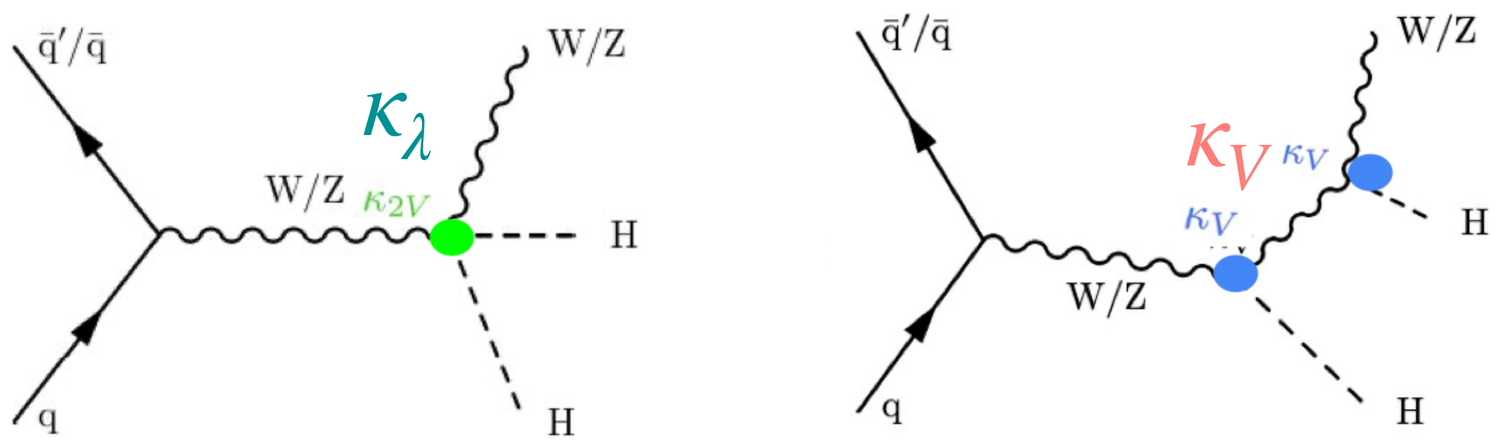
[Bishara, Contino, Rojo](#)



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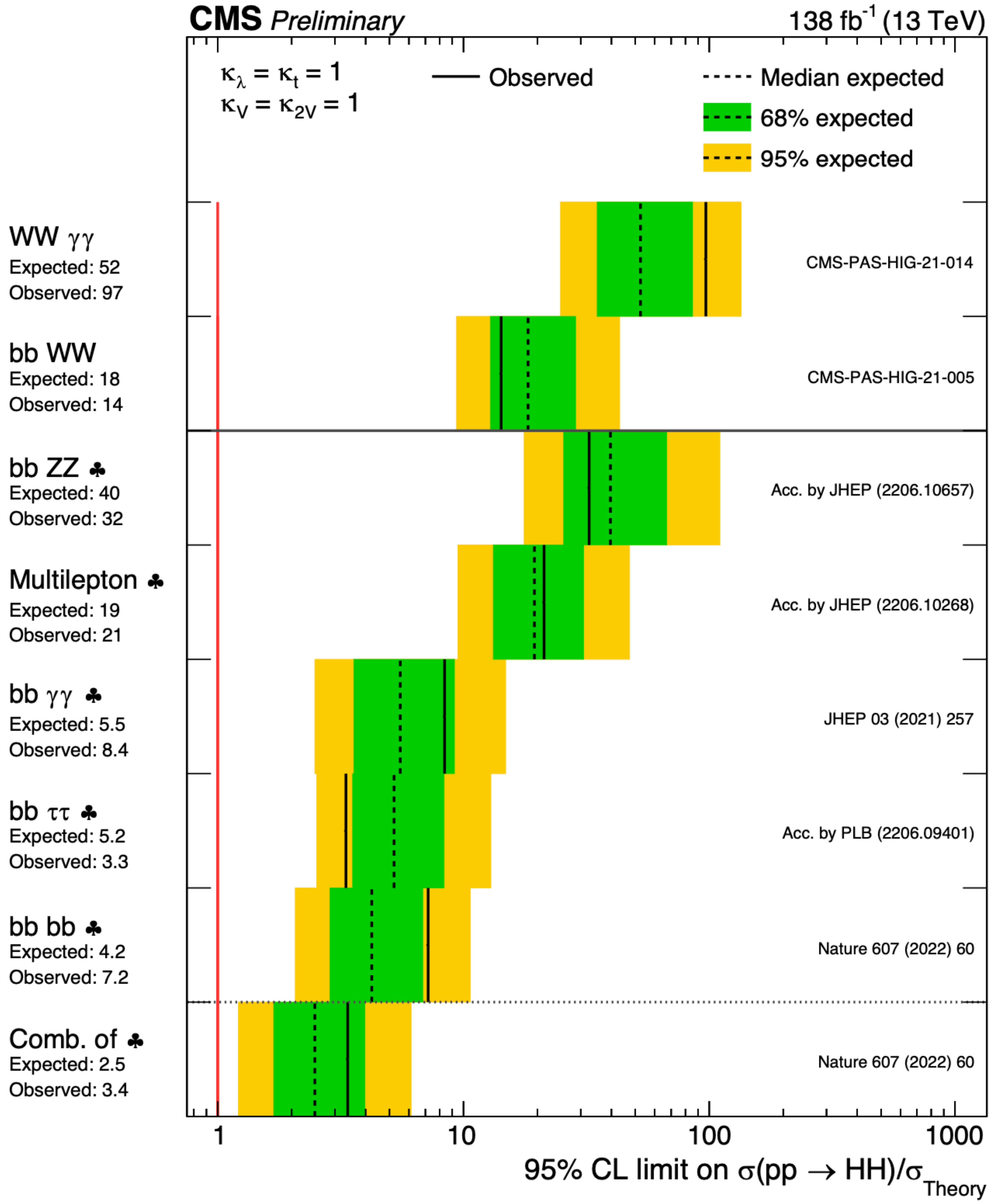
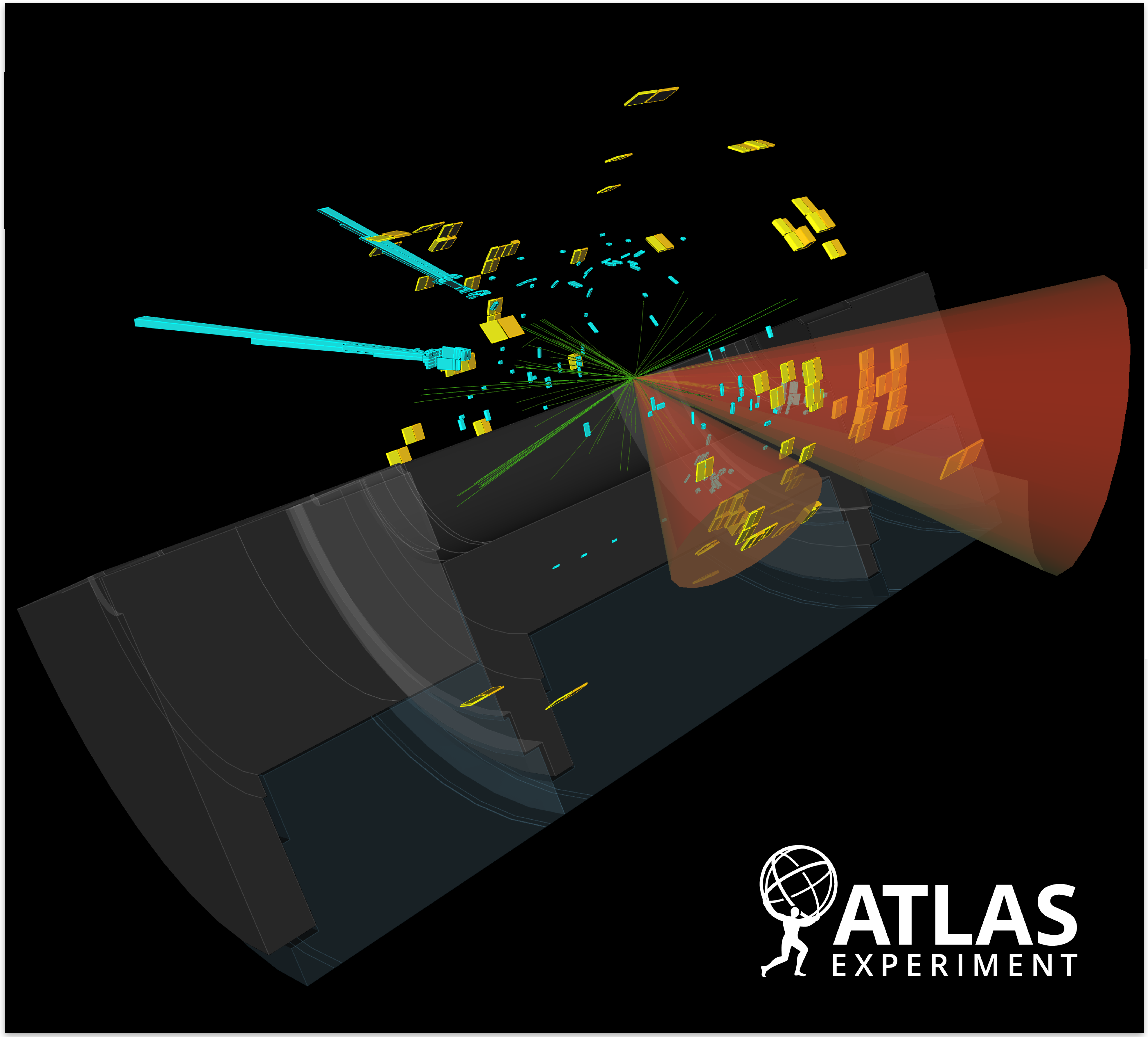


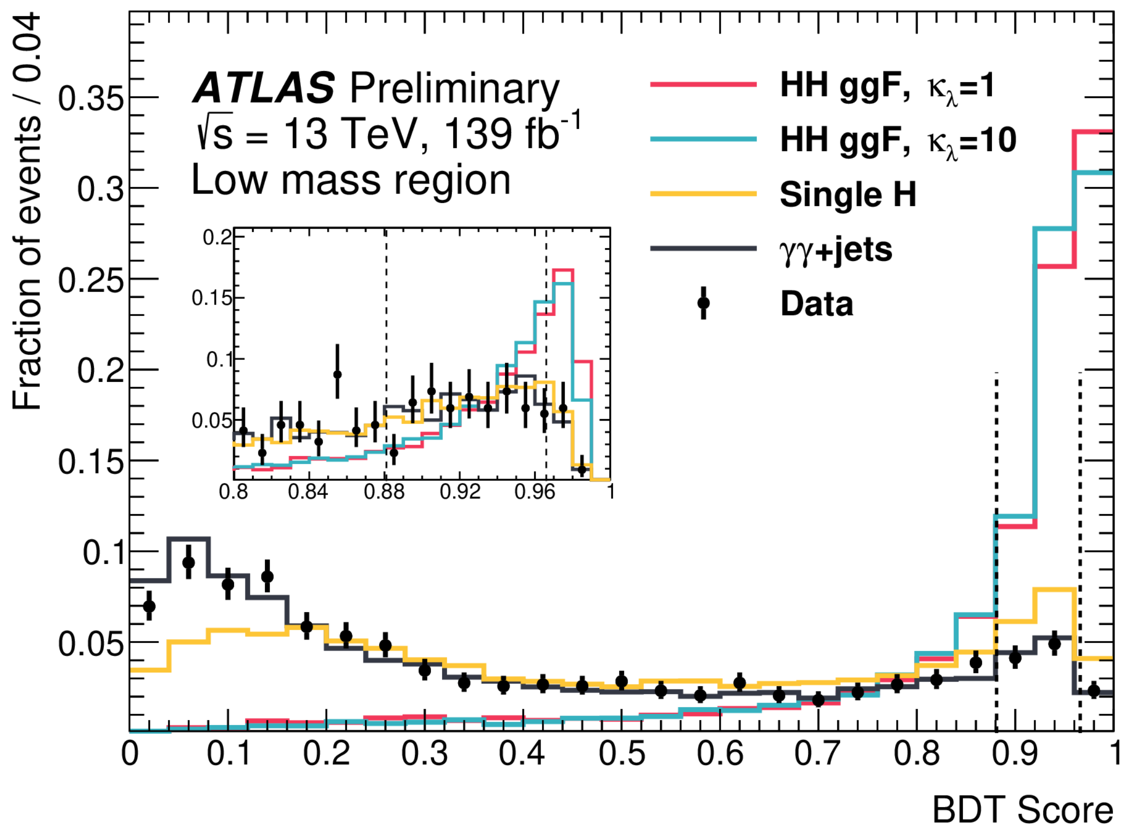
Most recent results from CMS

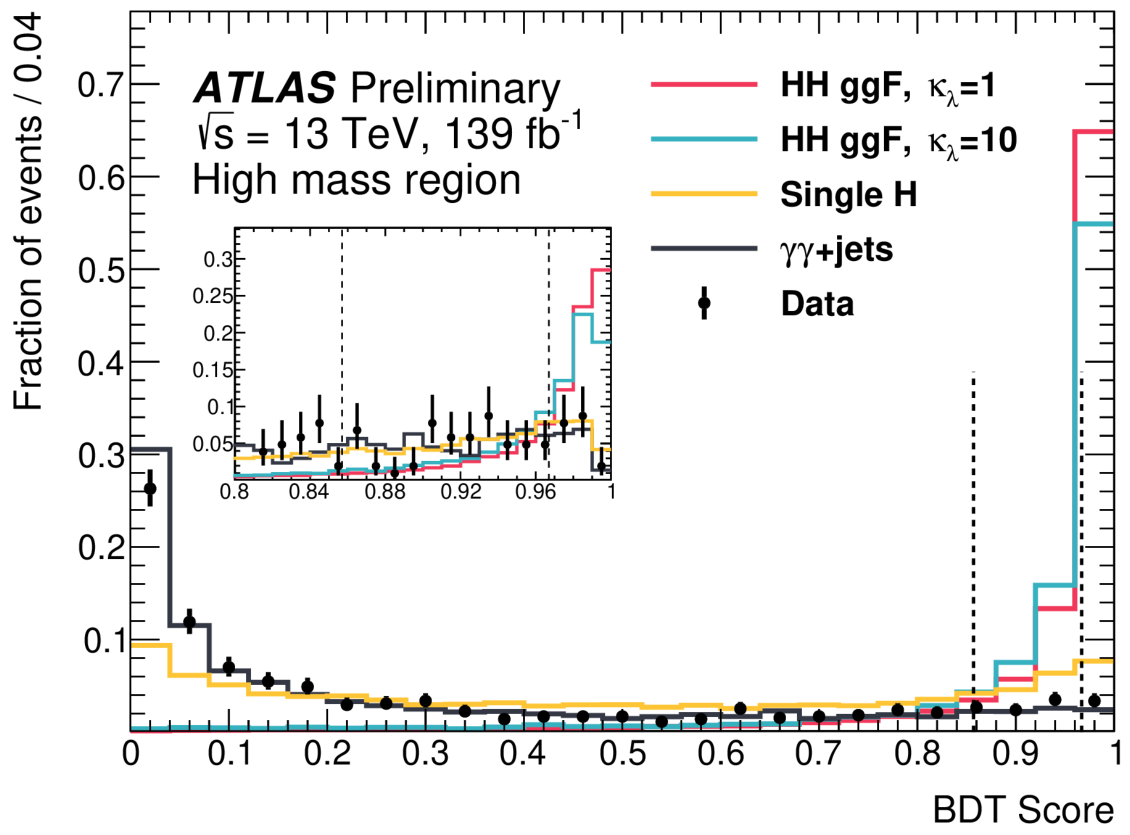
Di-Higgs boson production

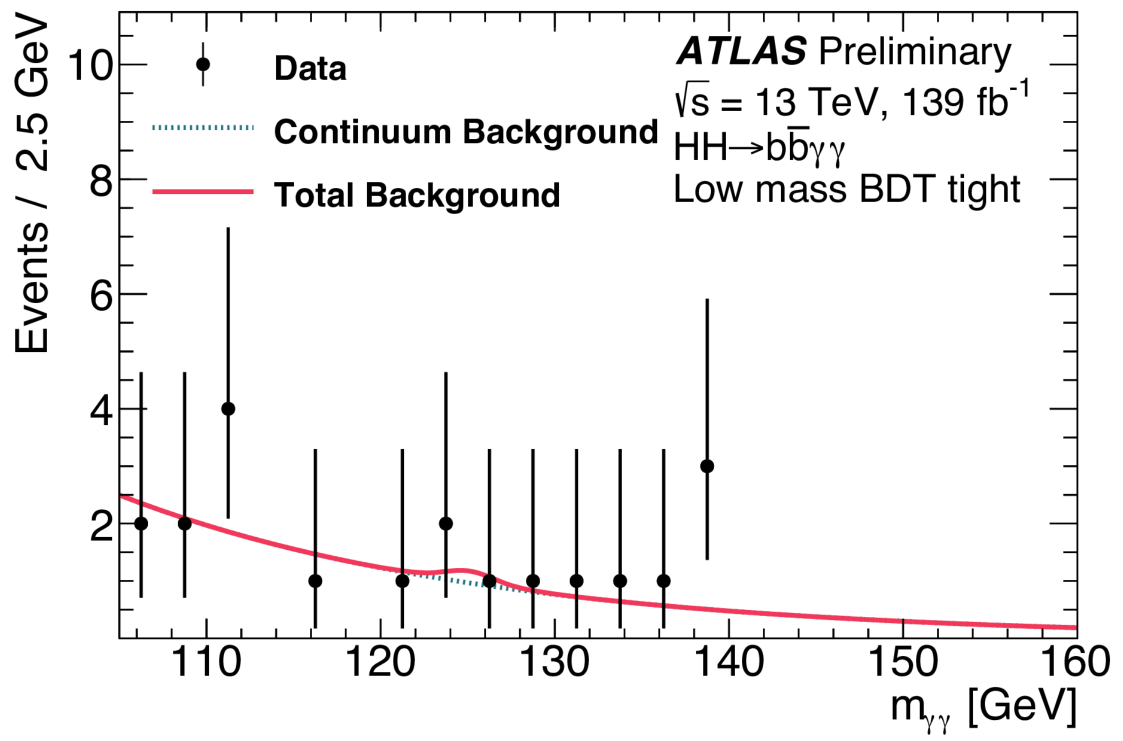


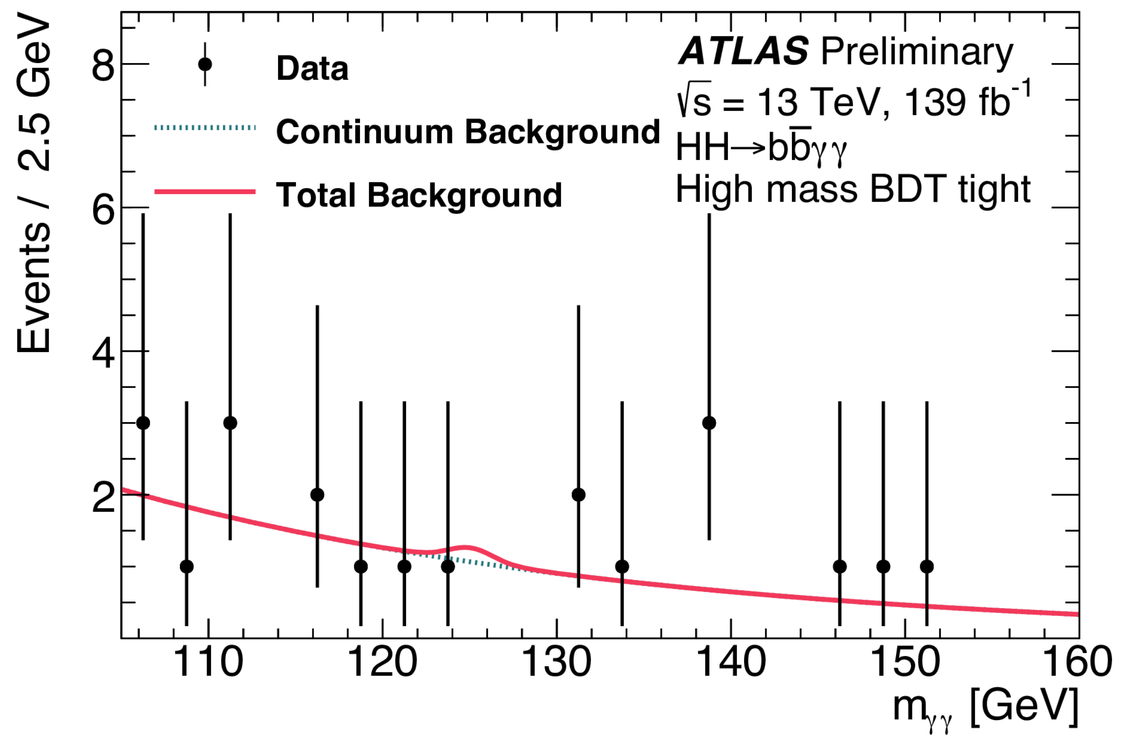
Example using the full Run 2 data set in the $b\bar{b}\gamma\gamma$ channel

Various regions defined from a BDT based on photon and jet kinematics, and separated in two regions in HH mass (high and low important to discriminate HH components and constrain the trilinear coupling).



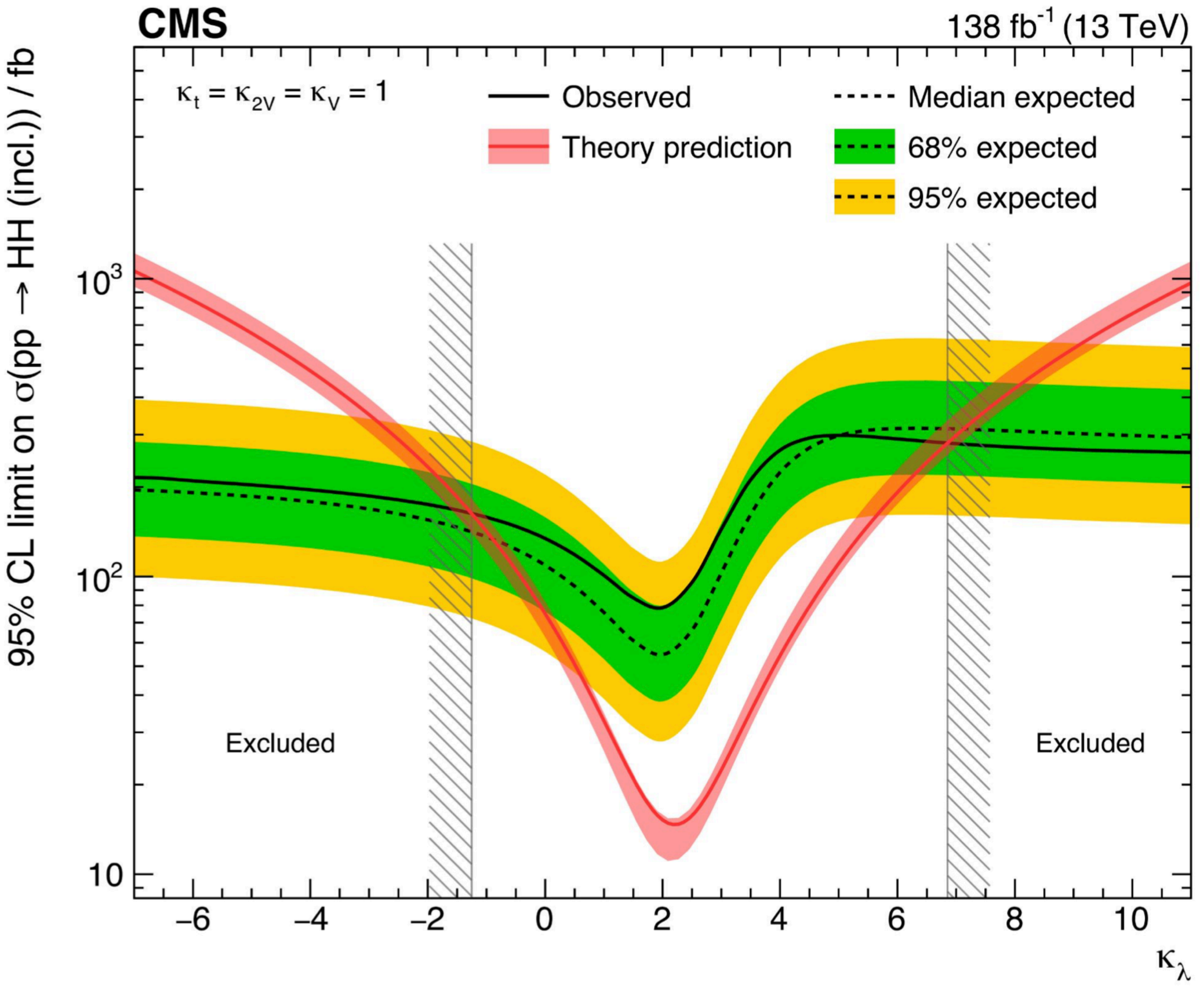






HH Production and Higgs Self coupling

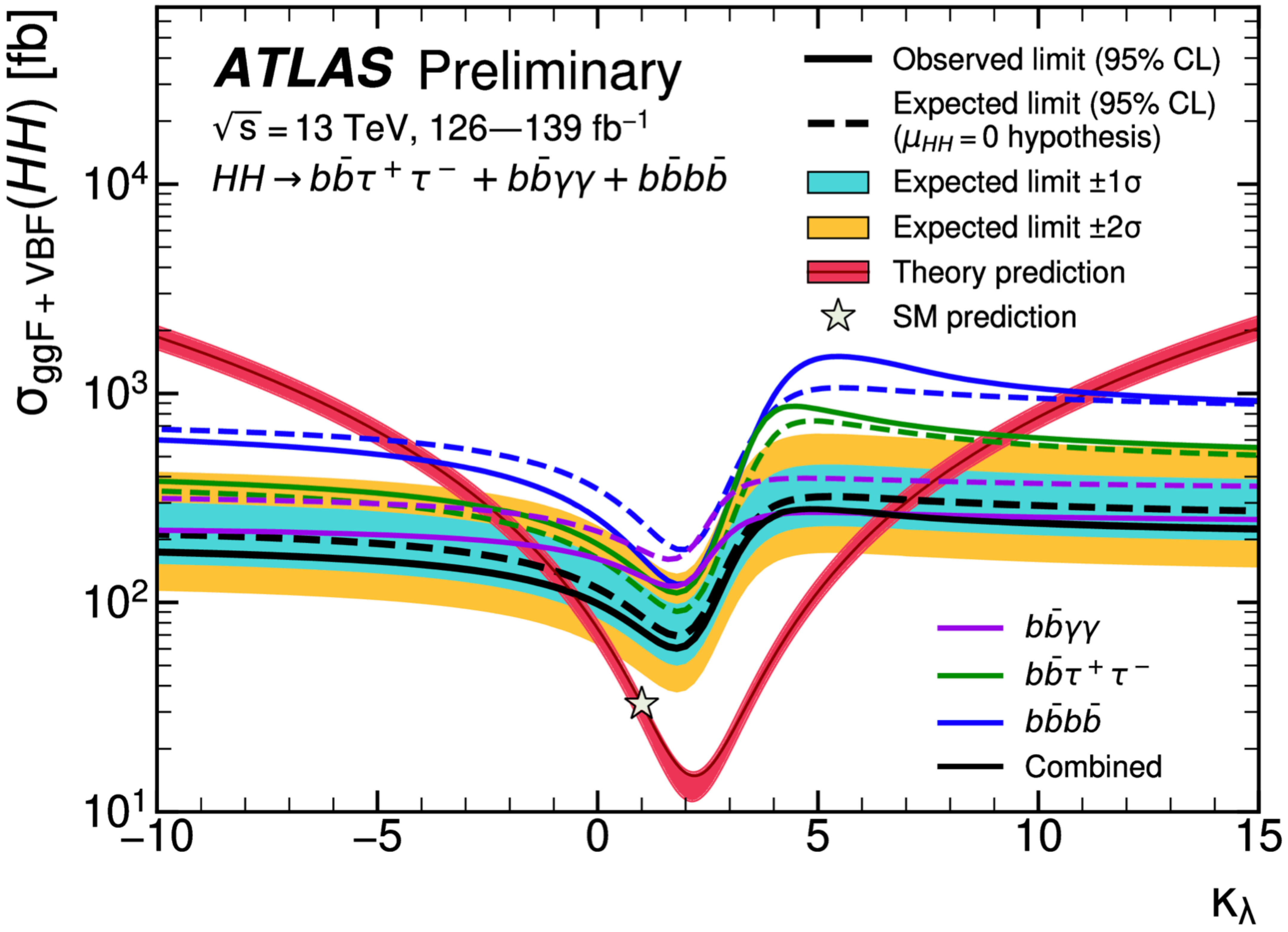
Partial combination in CMS



CMS $-1.24 < \kappa_\lambda < 6.49$

Expected interval similar

Partial combination in ATLAS



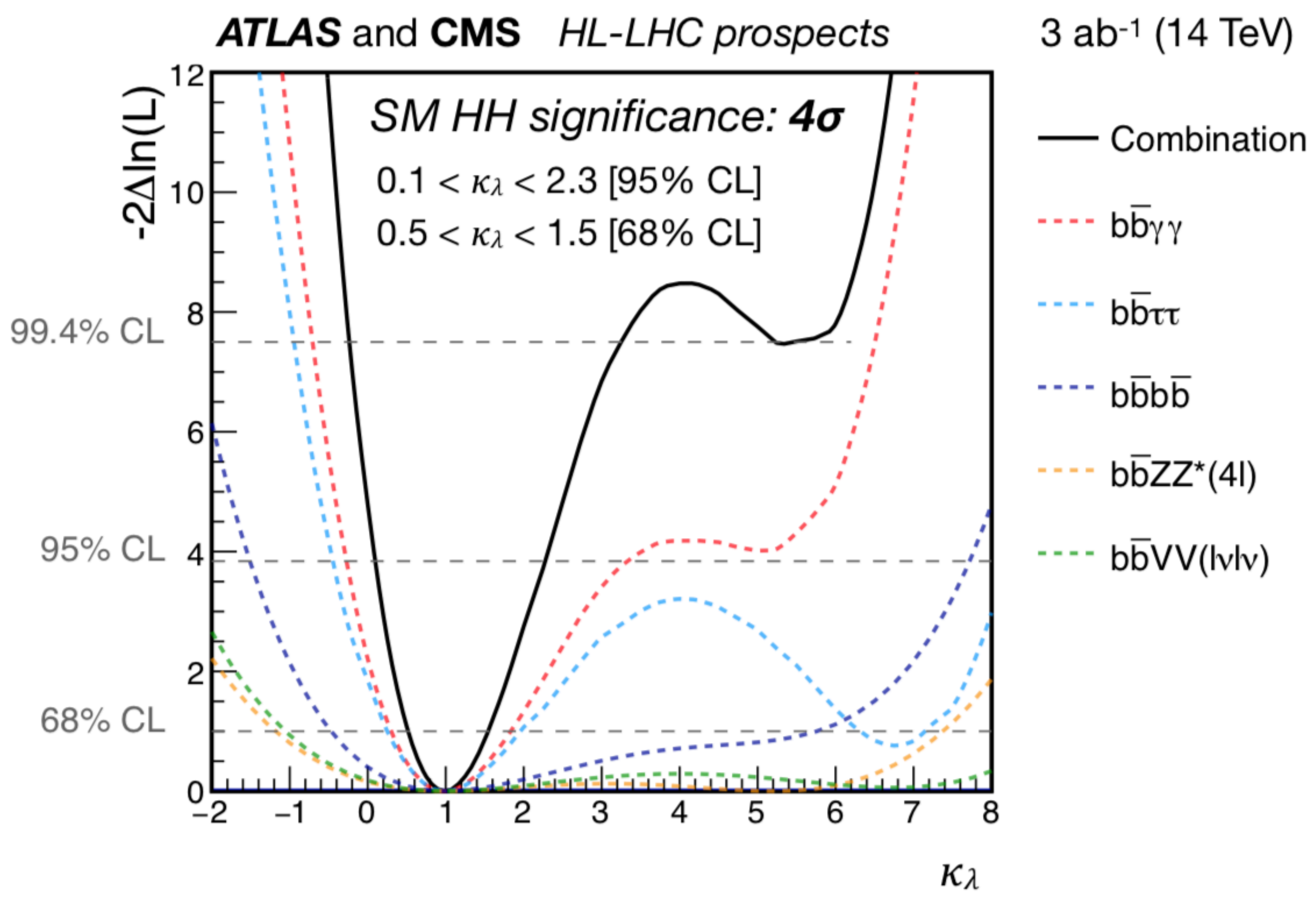
ATLAS

Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

Towards a Measurement of the Higgs Self Coupling

At HL-LHC



Current estimates yield an observation of an **HH signal at** 4σ

50% level constraints on the Higgs boson self coupling!

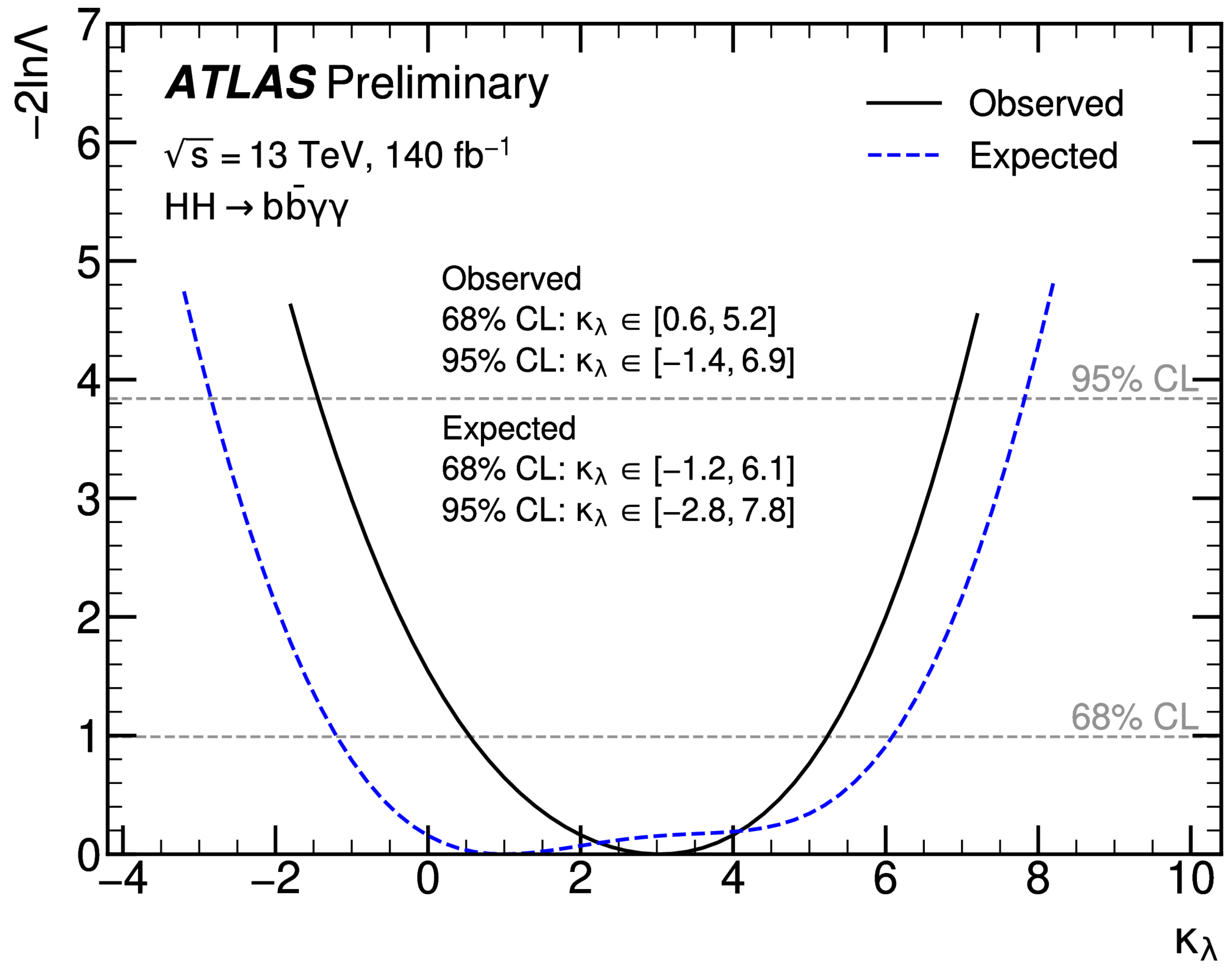
$$0.5 < \kappa_\lambda < 1.5$$

Already impressive!

Extrapolation was based on partial Run 2 analyses, already significantly improved on this result e.g. CMS expected sensitivity increased from 2.5 s.d. to 3.5 s.d.!

Should at least reach ~5 s.d. in combination of ATLAS and CMS

Where do we stand in the exclusion of the secondary minimum in the likelihood?



Single channel and experiment

Outstanding goal of Run 3 to improve on this and reach possible intermediate milesone1

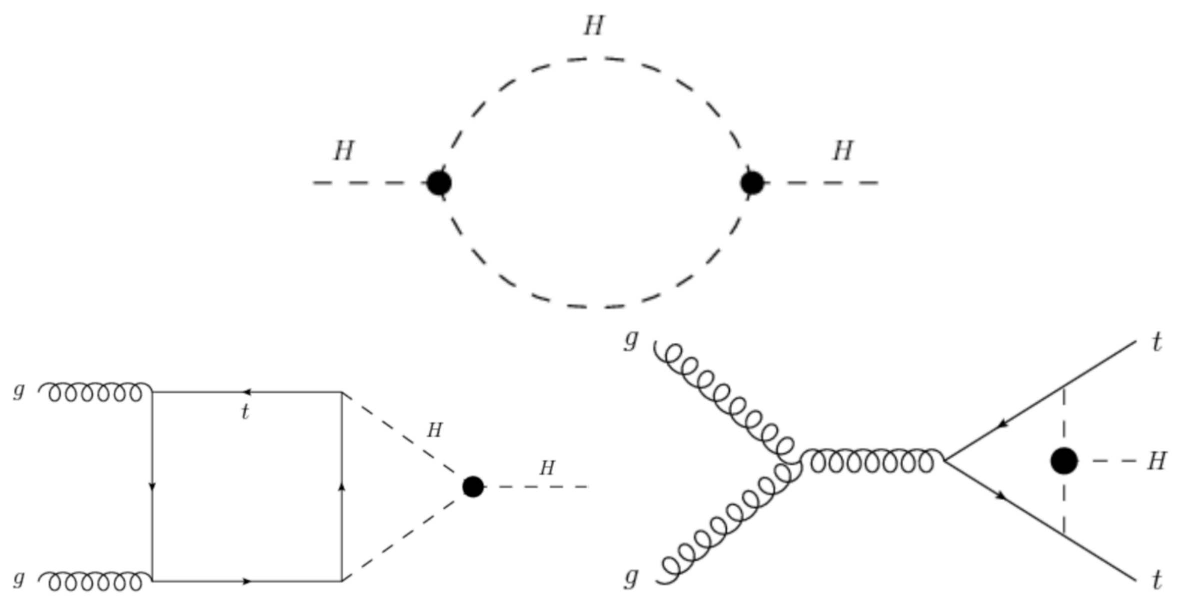
Indirect constraints on Higgs Self Coupling

ATLAS-CONF-2019-049

FTR-2018-020

Indirect constraints from combined STXS

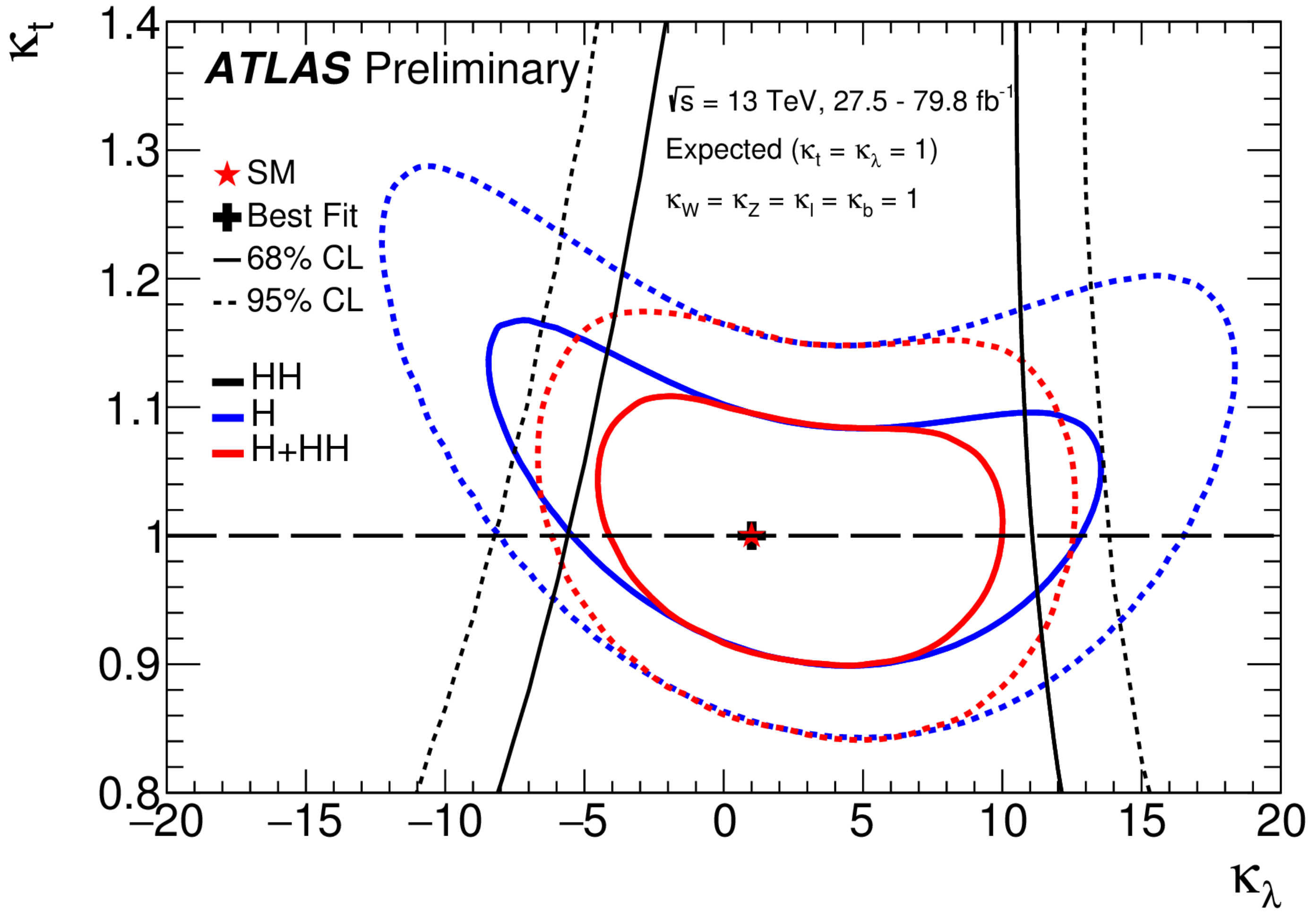
Combination with ATLAS STXSs



- Several production processes (ggF, VBF, VH, tHj)
- Several decay processes (diphoton, ZZ, yy)
- Trilinear coupling on wave function renormalisation

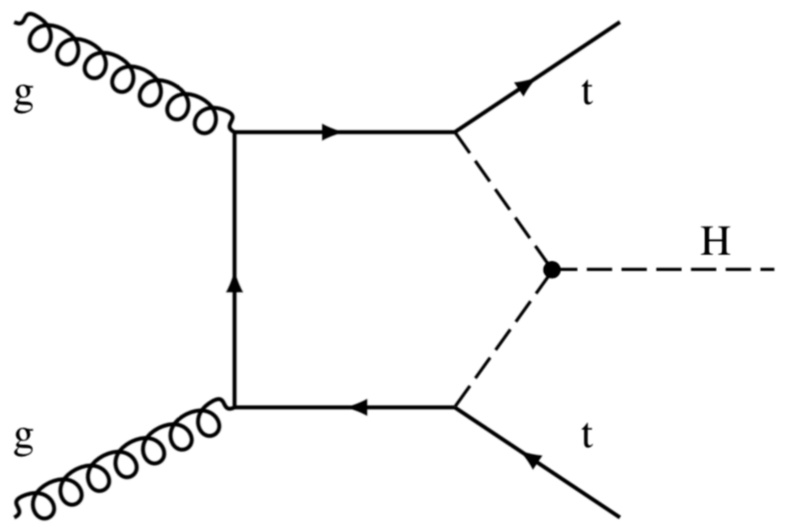
Direct/Indirect currently comparable, direct HH searches will dominate at higher luminosities, but complementarity still necessary to fix κ_t

$$-2.3 < \kappa_\lambda < 10.3$$

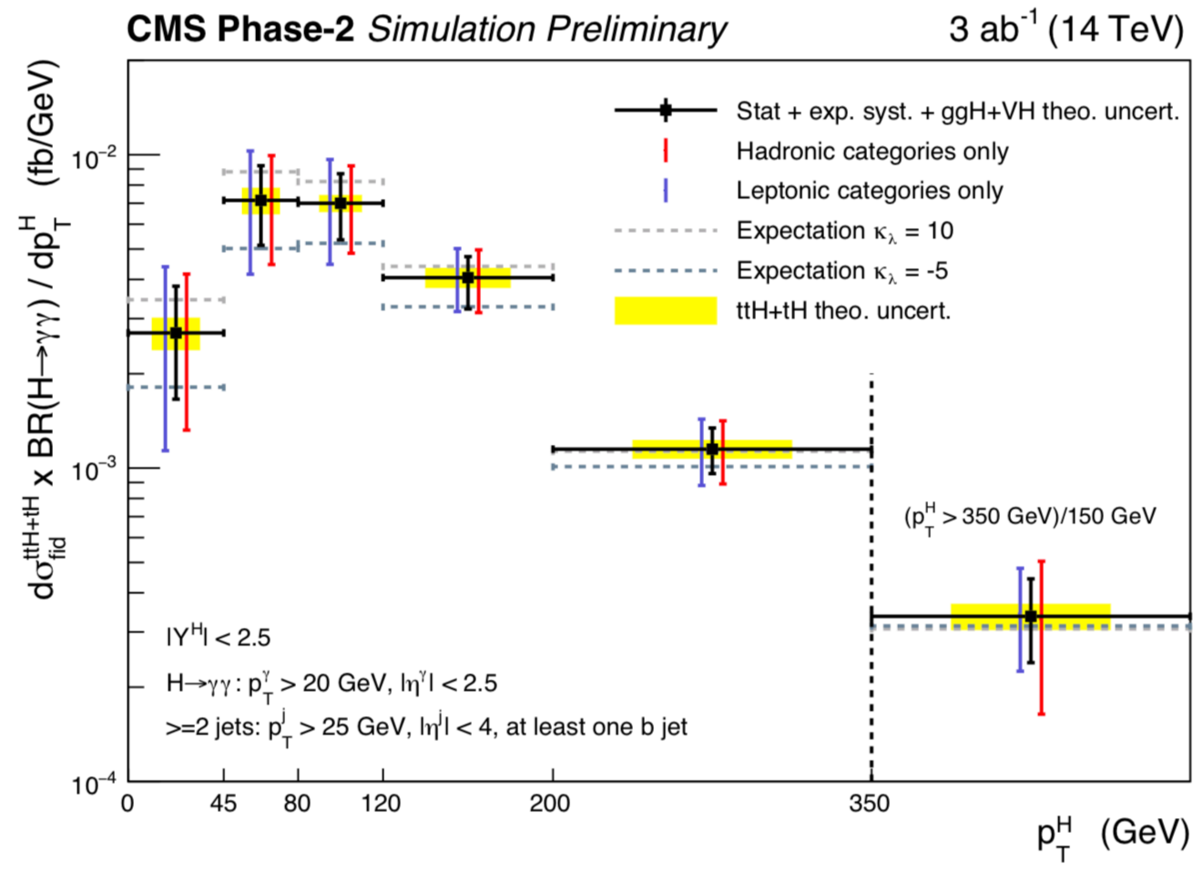


Indirect constraints from differential measurements (e.g. ttH)

ttH Process (with subsequent decay to diphoton)



$$-4.1 < \kappa_\lambda < 14.1$$



Possible to disentangle effect of trilinear from other coupling modifications from the differential ttH measurements!

Global fit

S. di Vita, C. Grojean et al.

In a global EFT Flat directions exist in the single-Higgs production (including all relevant operators) and the HH results are necessary to resolve them.

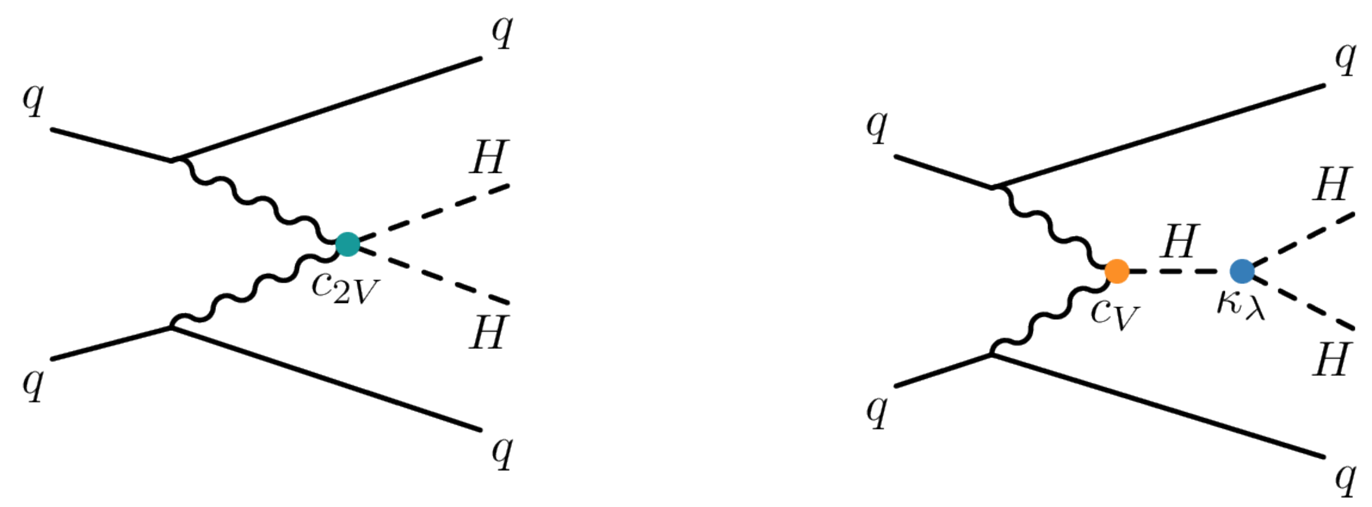
The inclusion of single-H differential measurements does not seem improve greatly the trilinear measurement with the full statistics.

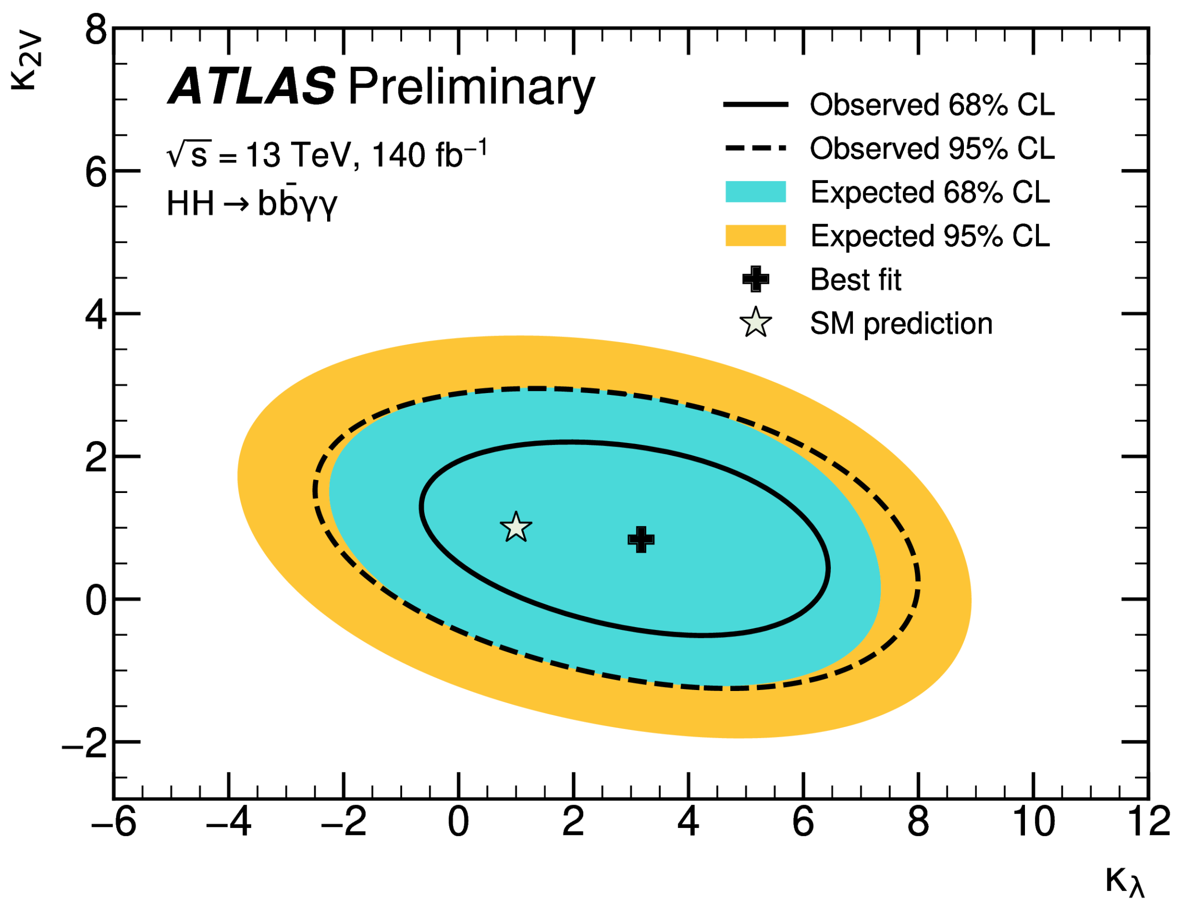
Towards a Measurement of the Higgs Self Coupling

From P. Huang, A. Long and L.-T. Wang

Current constraints on c2V

First specific VBF-HH search in the 4b final state, with as main interpretation a limit on the c_{2V}





Uses the latest N3LO-QCD estimate of the VBF-HH cross section!

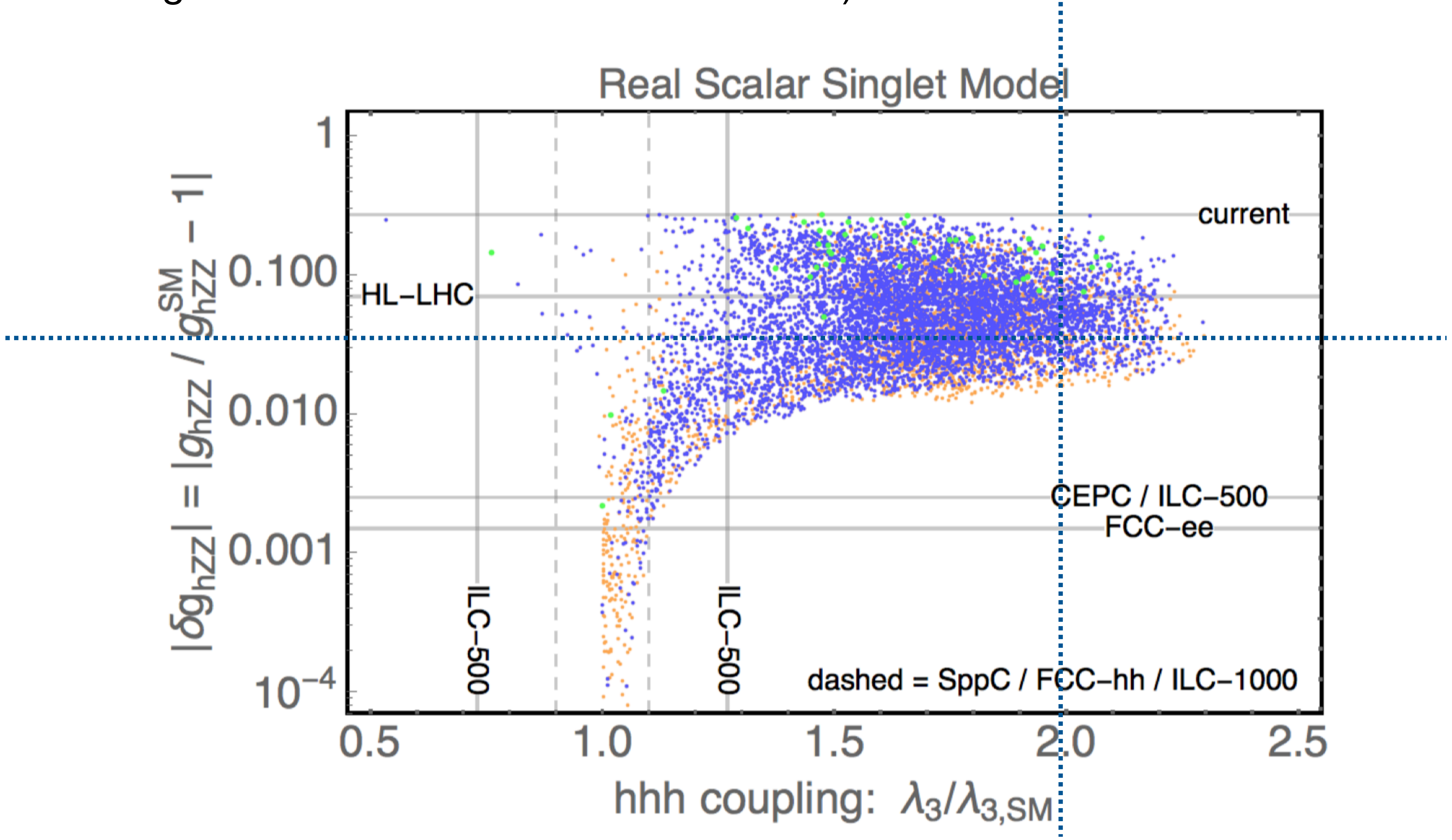
Strong variation of cross section (and acceptance) yield quite strong constraints at 95% CL:

$$-1.0 < c_{2V} < 2.7$$

Probing 1st order phase transition and GW signals

The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

In these cases, signals of stochastic background (e.g. collisions of bubbles) in the phase transition could potentially be detected by next generation interferometers like eLISA*)



*eLISA: evolved LISA

What Have we Learned?

Answer: **The Higgs boson mass!**

… and much more (of course)!!

The electroweak sector in a tiny nutshell

The elegant gauge sector (governed by symmetries and only three parameters for EWK and one parameter for QCD at tree level)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

QCD with its massless gluons discussed in detail by **Gregory Soyez**

The EW sector discussed by Tim Cohen…

Gauge bosons and fermions have masses!

Higgs mechanism is needed!

Higgs mechanism introduces predictive relations between gauge boson masses and their couplings.

$$SU(2)_L \otimes U(1)_Y \quad \text{(from the Higgs mechanism)}$$

$$g \qquad g' \qquad v$$

The one-to-one relation between the couplings and the masses of gauge bosons (at Tree level) introducing the week mixing angle!

$$\tan\theta_W = \frac{g'}{g}$$

$$m_W = \frac{gv}{2}$$

$$m_Z = \frac{gv}{2\cos\theta_W}$$

$$m_\gamma = 0$$

No additional parameter for the masses of the Gauge bosons!

The electroweak sector in a tiny nutshell

The elegant gauge sector (governed by symmetries and only three parameters for EWK and one parameter for QCD at tree level)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

Yesterday discussed unbroken QCD with its massless gluons

For the EW sector it is another story… Gauge bosons and fermions have masses!

Higgs mechanism is needed!

The Higgs is for tomorrow, but the mere presence of a Higgs mechanism introduces predictive relations between gauge boson masses and their couplings.

Expanding a bit on the Electroweak sector:

$$\begin{array}{cccc} SU(2)_L & \otimes & U(1)_Y & \text{(from the Higgs mechanism)} \\ \downarrow & & \downarrow & \downarrow \\ g & & g' & v \end{array}$$

The one-to-one relation between the couplings and the masses of gauge bosons (at Tree level) introducing the week mixing angle!

As a consequence, at tree level:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1$$

This parameter can be (and has been) measured experimentally well before the discovery of the Higgs.

Global Fit of the Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + h.c.$$

The Electroweak gauge sector

At tree level, fully described by three parameters

$$g,\ g',\ \text{and}\ v \qquad \rho = 1$$

Trade these parameters for precisely measured observables

- The fine structure constant :

$$\alpha = 1/137.035999679(94) \qquad 10^{-9}$$

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

- The Fermi constant :

$$G_F = 1.166367(5) \times 10^{-5}\,\mathrm{GeV}^{-2} \qquad 10^{-5}$$

Determined from muon lifetime

- The Z mass :

$$M_Z = 91.1876(21)\,\mathrm{GeV} \qquad 10^{-5}$$

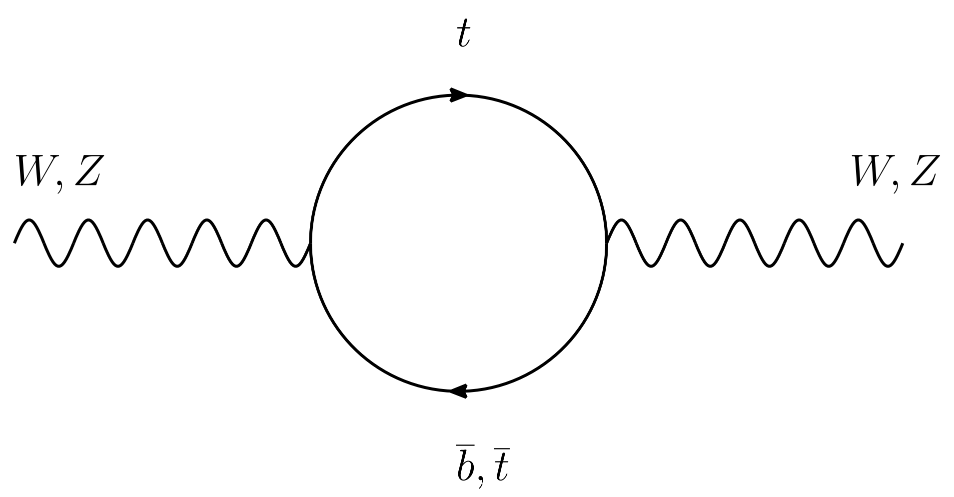
Measured from the Z lineshape scan at LEP

Note: we have assumed the existence of a Higgs field giving a vev (v) throughout (though we have not discussed the Higgs in detail yet)

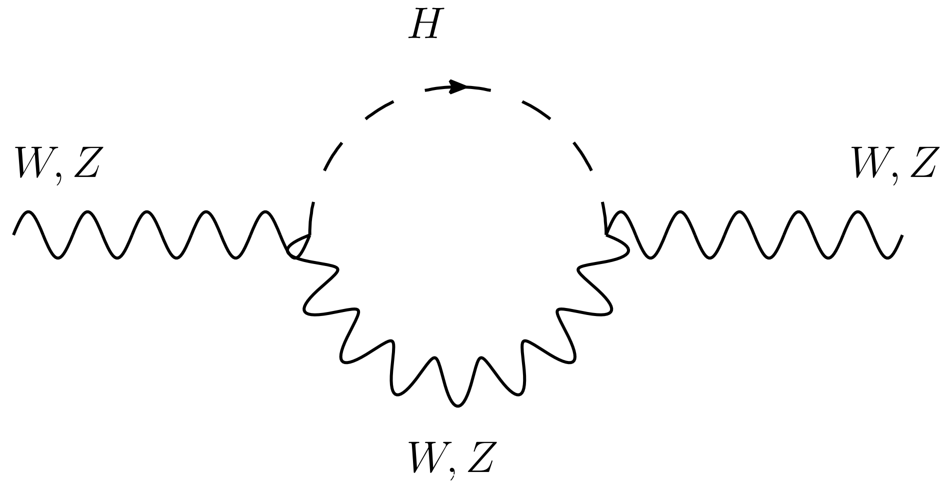
At loop level: all other fields enter the game through loop corrections which can be parametrized.

$$\boxed{\begin{aligned} G_F &= \frac{\pi\alpha}{\sqrt{2}M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}(1+\Delta r) \\ \Delta r^{(\alpha)} &= \Delta\alpha - \frac{c_{\mathrm{W}}^2}{s_{\mathrm{W}}^2}\Delta\rho + \Delta r_{\mathrm{rem}}(M_{\mathrm{H}}) \end{aligned}}$$

These corrections can then be computed as a function of all other parameters of the Standard Model



$$\propto m_t^2$$



$$\propto \log \frac{M_H}{M_Z}$$

Custodial symmetry

The Higgs potential is invariant under any rotations of the four components of the Higgs doublet

$$SO(4)$$

$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

$$\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$(H^\dagger H) = h_1^2 + h_2^2 + h_3^2 + h_4^2$$

$$V = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2$$

Under the $SU(2)_V$ symmetry, the weak gauge bosons (W^1,W^2,W^3) transforms as a triplet, this directly implies that ρ=1 and that all EWK bosons should be mass degenerate. This symmetry is approximate.

Radiative corrections from the Higgs:

$$\delta\rho = -\frac{11 G_F m_Z^2}{24\sqrt{2}\pi^2} \sin^2\theta_W \log(m_H^2/m_Z^2)$$

Are proportional to the weak mixing angle and therefore vanish with g'=0!

Radiative corrections from the fermions:

$$\delta\rho = m_t^2 + m_b^2 - 2 m_t m_b \frac{\log m_t^2/m_b^2}{m_t^2 - m_b^2}$$

Vanish if top and b are mass degenerate

For N iso-multiplets :

$$\rho = \frac{\sum_k v_k^2 [I^l(I^k+1) - (I_3^k)^2]}{\sum_k 2 v_k^2 (I_3^k)^2}$$

For the condition to be fulfilled any number of doublets is fine, but higher representations require fine tuning of the vev's

Main EW collider results before the LHC

Observables

- Z-pole observables: LEP/SLD results
- MW and ΓW: LEP/Tevatron
- mt :Tevatron
- $\Delta\alpha_{had}(5)$
- mc, mb: world averages

Comments

- Numerous observables O(40)
- Numerous experiments/analyses (with different systematics)
- Numerous TH inputs

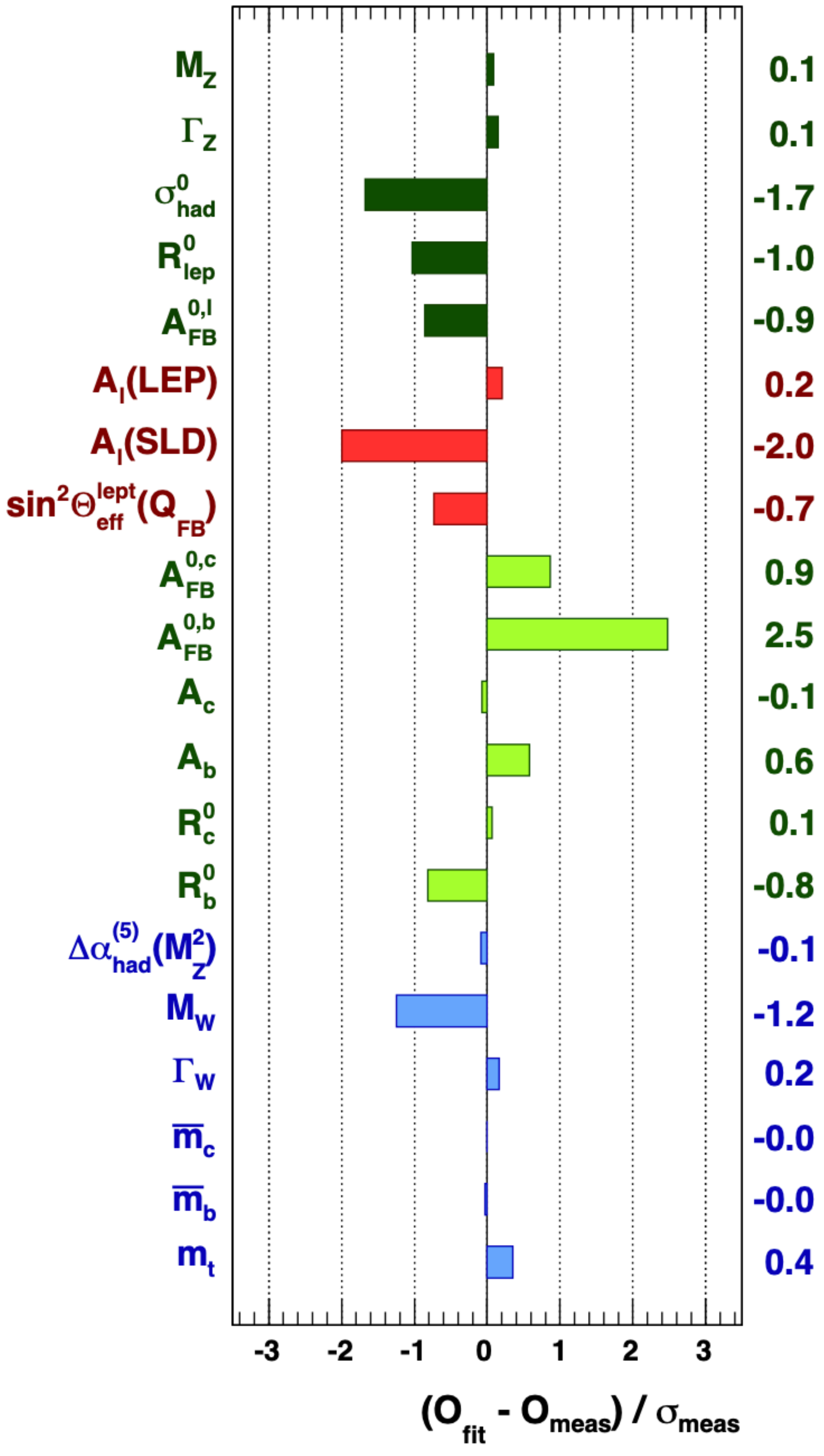
Fit Parameters

M_Z, M_H, $\Delta\alpha_{had}(5)$, α_s, m_c, m_b, m_t (and TH uncertainties)

M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	

Global Fit of the Standard Model

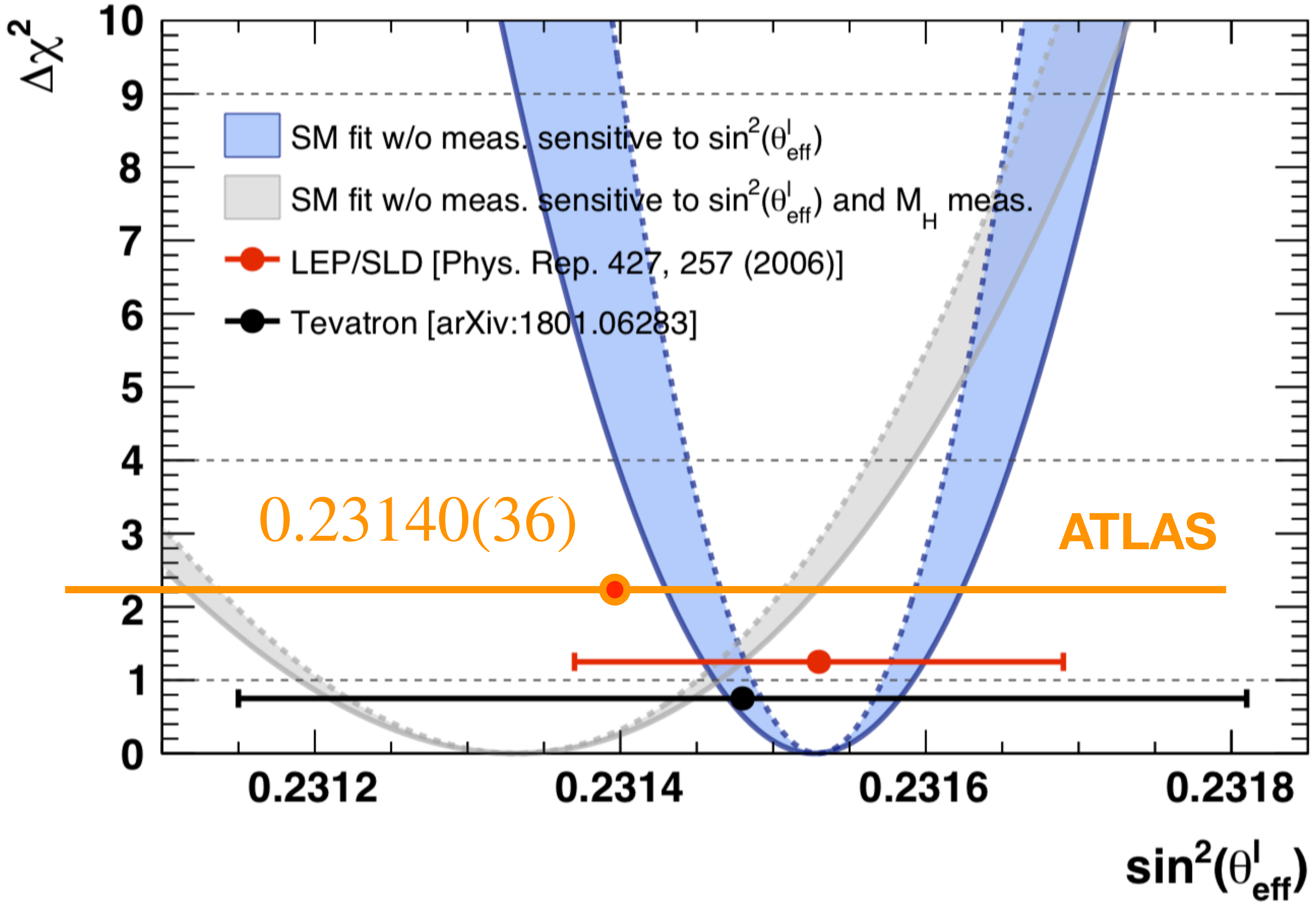
Parameter	Input value	Results from global EW fits: Standard fit	Complete fit	Fits w/o exp. input in given line: Complete fit	$M_H \equiv 120\,\mathrm{GeV}$
$\boldsymbol{M_Z}$ [GeV]	91.1875 ± 0.0021	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1959^{+0.0150}_{-0.0148}$	$91.1956^{+0.0141}_{-0.0136}$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959 ± 0.0015	2.4955 ± 0.0014	2.4952 ± 0.0017	2.4952 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	20.743 ± 0.018	20.741 ± 0.018	$20.719^{+0.025}_{-0.028}$	$20.717^{+0.027}_{-0.026}$
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	0.01640 ± 0.0002	$0.01624^{+0.0002}_{-0.0001}$	$0.01620^{+0.0002}_{-0.0001}$	$0.01620^{+0.0002}_{-0.0001}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	0.1479 ± 0.0010	$0.1472^{+0.0009}_{-0.0007}$	–	–
A_c	0.670 ± 0.027	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00040}_{-0.00028}$	$0.6679^{+0.00038}_{-0.00027}$	$0.6680^{+0.00038}_{-0.00026}$
A_b	0.923 ± 0.020	$0.93469^{+0.00009}_{-0.00008}$	$0.93463^{+0.00007}_{-0.00005}$	$0.93462^{+0.00008}_{-0.00005}$	$0.93462^{+0.00008}_{-0.00003}$
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	$0.0741^{+0.0006}_{-0.0005}$	$0.0737^{+0.0005}_{-0.0004}$	$0.0738^{+0.0005}_{-0.0004}$	$0.0738^{+0.0005}_{-0.0004}$
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.1037 ± 0.0007	$0.1032^{+0.0006}_{-0.0005}$	$0.1037^{+0.0003}_{-0.0005}$	$0.1037^{+0.0003}_{-0.0005}$
R^0_c $[10^{-4}]$	1721 ± 30	$1722.9^{+0.7}_{-0.6}$	1722.9 ± 0.6	1722.9 ± 0.6	1722.9 ± 0.6
R^0_b $[10^{-4}]$	2162.9 ± 6.6	$2157.6^{+0.5}_{-0.8}$	$2157.5^{+0.5}_{-0.8}$	$2157.5^{+0.5}_{-0.8}$	$2157.5^{+0.5}_{-0.8}$
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	$0.23141^{+0.00012}_{-0.00013}$	$0.23150^{+0.00008}_{-0.00010}$	$0.23148^{+0.00010}_{-0.00009}$	$0.23149^{+0.00009}_{-0.00010}$
$\boldsymbol{M_H}$ [GeV] $^{(\circ)}$	$\mathrm{CL_{s+b}}$	$91^{+30[+74]}_{-23[-42]}$	$120^{+12[+23]}_{-5[-6]}$	$91^{+30[+74]}_{-23[-42]}$	120 (fixed)
M_W [GeV]	80.399 ± 0.023	$80.383^{+0.014}_{-0.015}$	$80.370^{+0.007}_{-0.009}$	$80.360^{+0.014}_{-0.013}$	$80.359^{+0.015}_{-0.008}$
Γ_W [GeV]	2.085 ± 0.042	2.093 ± 0.001	2.092 ± 0.001	2.092 ± 0.001	2.092 ± 0.001
$\boldsymbol{\overline{m}_c}$ [GeV]	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–	–
$\boldsymbol{\overline{m}_b}$ [GeV]	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–	–
$\boldsymbol{m_t}$ [GeV]	173.3 ± 1.1	173.4 ± 1.1	173.7 ± 1.1	$177.2 \pm 3.4^{(\triangledown)}$	$176.8^{+3.1}_{-3.0}$
$\boldsymbol{\Delta\alpha^{(5)}_{\mathrm{had}}(M^2_Z)}$ $^{(\dagger\triangle)}$	2757 ± 10	2758 ± 11	2756 ± 11	2729^{+57}_{-50}	2730^{+57}_{-46}
$\boldsymbol{\alpha_s(M^2_Z)}$	–	0.1193 ± 0.0028	0.1194 ± 0.0028	0.1194 ± 0.0028	0.1194 ± 0.0028
$\boldsymbol{\delta_{\mathrm{th}} M_W}$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	4	4	–	–
$\boldsymbol{\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	4.7	4.7	–	–

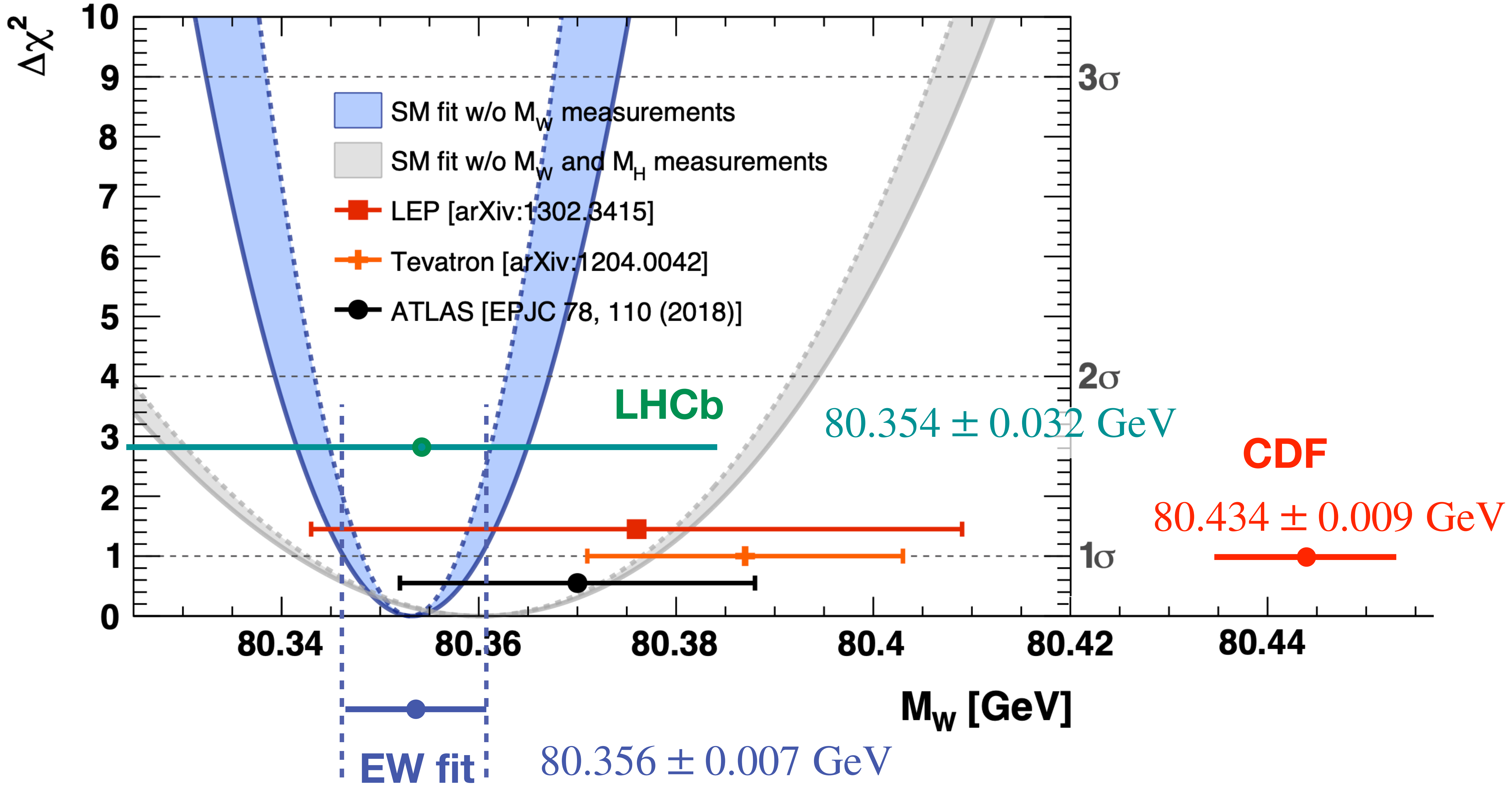


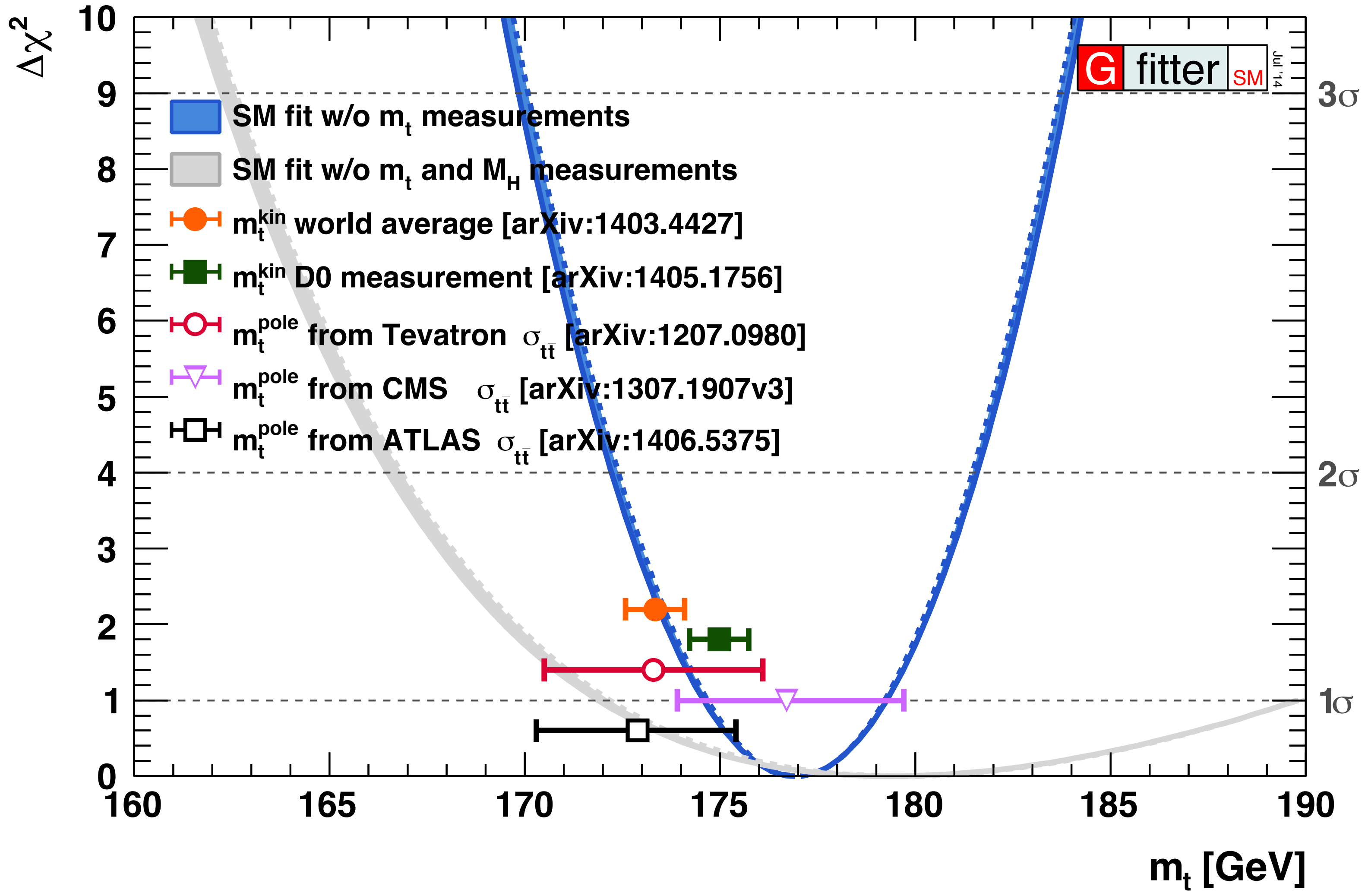
Fit with an overall $P(\chi^2, n_{dof})$ probability of ~20%

Largest tension known between A_{FB}^b (LEP) and A_ℓ (SLC).

Precision EW Observable: Effective Weak Mixing angle







- Weak mixing angle EW fit is more precise than the direct measurement, very important to pursue and improve the measurement. Within precision in agreement with SM prediction.
- Similar situation for the W mass, EW fit yields a precision of 7 MeV. We'll discuss the agreement with the SM once the consistency between measurements is settled!
- For the top mass the situation is different: direct measurements are significantly better already than the prediction (even more so for the Higgs mass!). **Still essential parameter!**
- **Knowing the Higgs mass precisely does not change the picture (important TH unc.)**

Global (SM) EFT Fit

With no **direct** or **indirect** indication for new physics beyond the Standard Model : also consider general EFT interpretation of the data!

- **SMEFT** has the same field content as the SM and respects the SM SU(3)xSU(2)XU(1) local symmetry, the difference is the presence of higher (mass) dimension operators, organised in dimension-6 and dimension-8 operators (assuming baryon number and lepton number conservation):

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

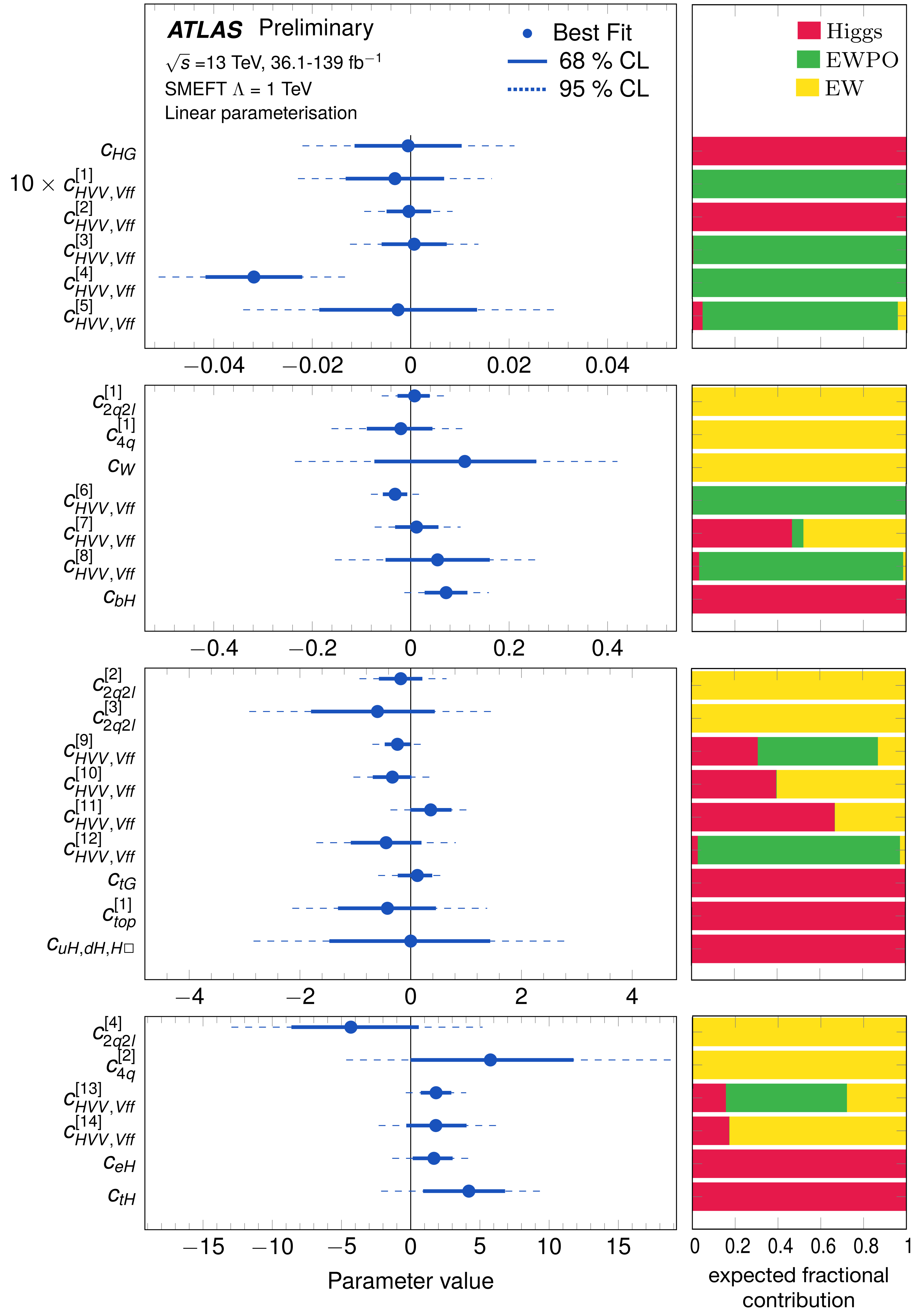
- **SMEFT with dimension 6 operators in the Warsaw basis**: Reduction of the (2499 baryon number preserving dim-6 Wilson coefficients) using U(3) flavour for the 5 light fermion fields (assuming $U(3)^5$ symmetry), reducing to 76 coefficient among which 20 relevant for di-boson, EWK precision and Higgs physics, i.e. with universality ~20 parameters

Much more in Tim's lectures!

SMEFT Global Interpretation of our Data

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots .$$

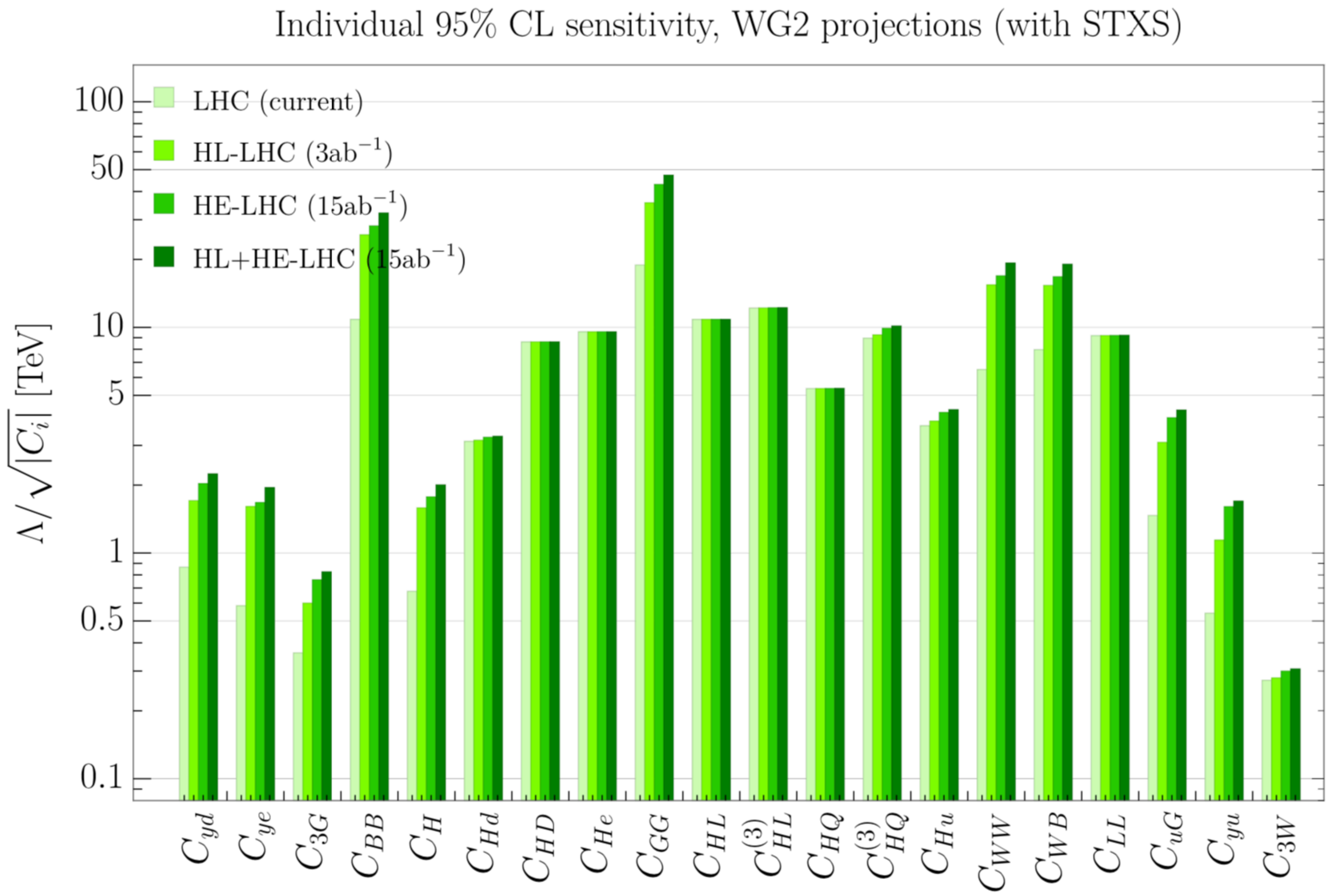
- Combined measurements of Higgs boson production and decay in exclusive kinematic regions of the production phase space (STXS).
- Differential cross-section measurements for diboson production and Z boson production via vector boson fusion (VBF).
- Electroweak precision data on the Z resonance from LEP and SLC.
- Uses Principal Component Analysis to group of Wilson coefficients.
- Perform both linear and quadratic fits.



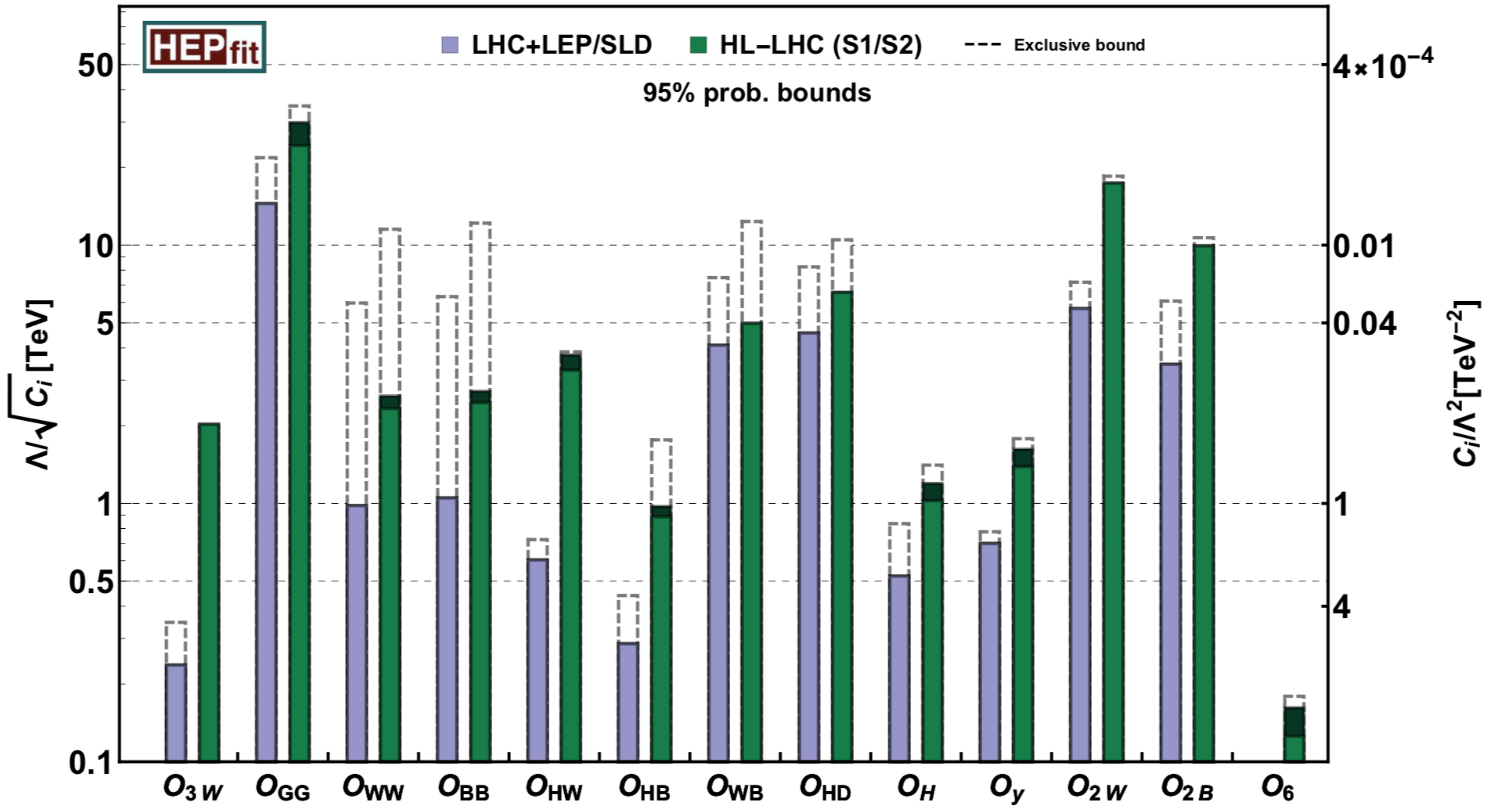
Global (SM) EFT Fit: Example Approaches and projections

- **Approach (a) inputs**:
  - Z pole (LEP, SLC) and WW (LEP)
  - LHC Higgs signal strengths (in part VH).
  - LHC WW (with pT>120 GeV)
  - Higgs STXSs

- **Approach (b) inputs**:
  - LHC Higgs signal strengths (in part VH).
  - HH differential in bbyy
  - ZH in the high ZH mass regime
  - WZ (better than WW)
  - DY (high mass)



Only linear terms in parametrisation



Quadratic terms taken into account where needed.

Indirect sensitivity to new phenomena of O(10 TeV) and up to O(50 TeV)

Implications

Of knowing the Higgs mass now…

Comments on the Running of Couplings

The running of the top Yukawa coupling

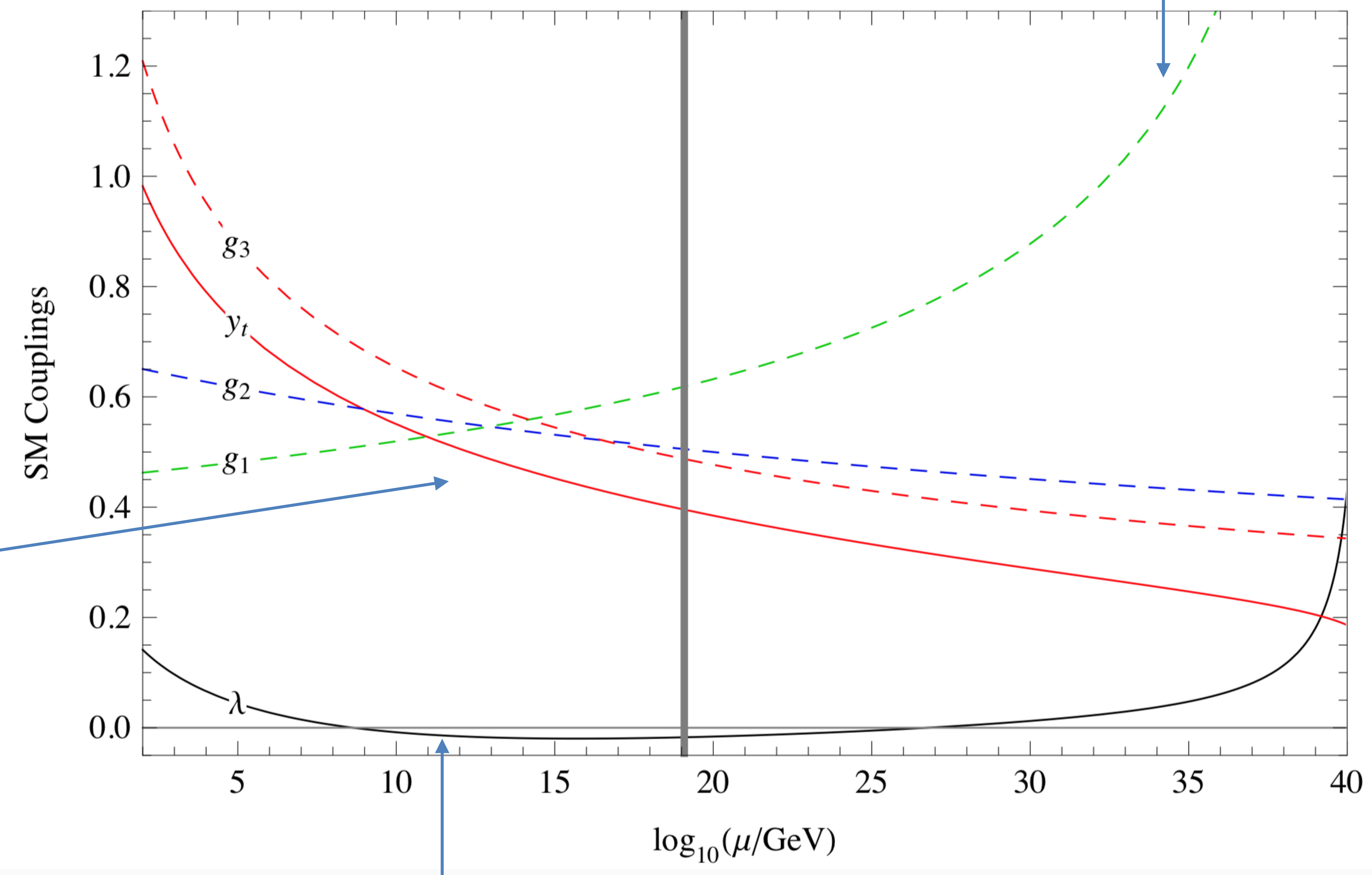
The Yukawa coupling is ~1, but perturbative because it is still small compared to 4π (very similar to QCD*)

$$\mu \frac{\partial y_t}{\partial \mu} \approx \frac{y_t}{16\pi^2} \left(\frac{9}{2} y_t^2 - 8 g_3 \right)$$

Two very important aspects in this RGE simple equation:

- With the observed top mass (and all the terms entering the RGE, including the Higgs quartic) the top mass smoothly decreases with energy.
- If the Yukawa is small w.r.t. strong coupling (and in general) at the high scale, it will stay small.
- If the Yukawa is larger in the high scale, then there is a fixed point (which yields a top mass slightly larger than the observed mass ~230 GeV).

Landau Pole

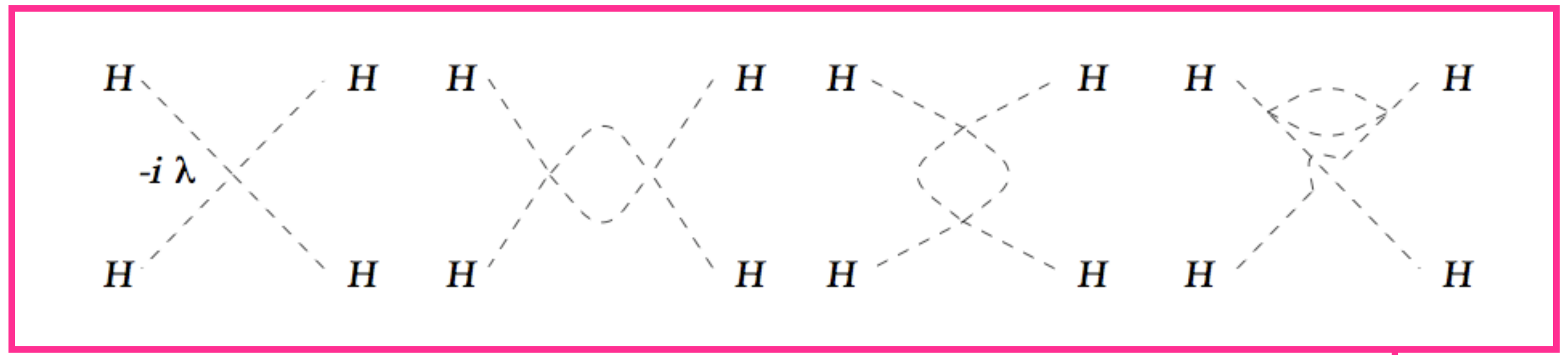


Running of the quartic coupling

Implications (II) – Global fit of the Standard Model

Running of the Higgs self coupling:

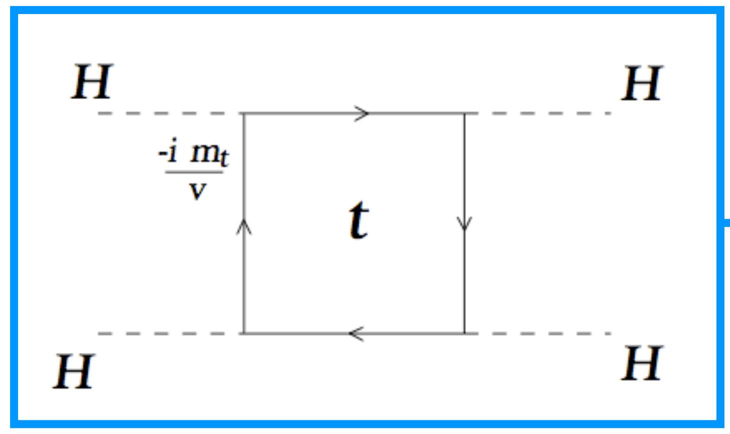
$$32\pi^2 \frac{\partial\lambda}{\partial\mu} = \boxed{24\lambda^2} - \boxed{6y_t^4} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4$$



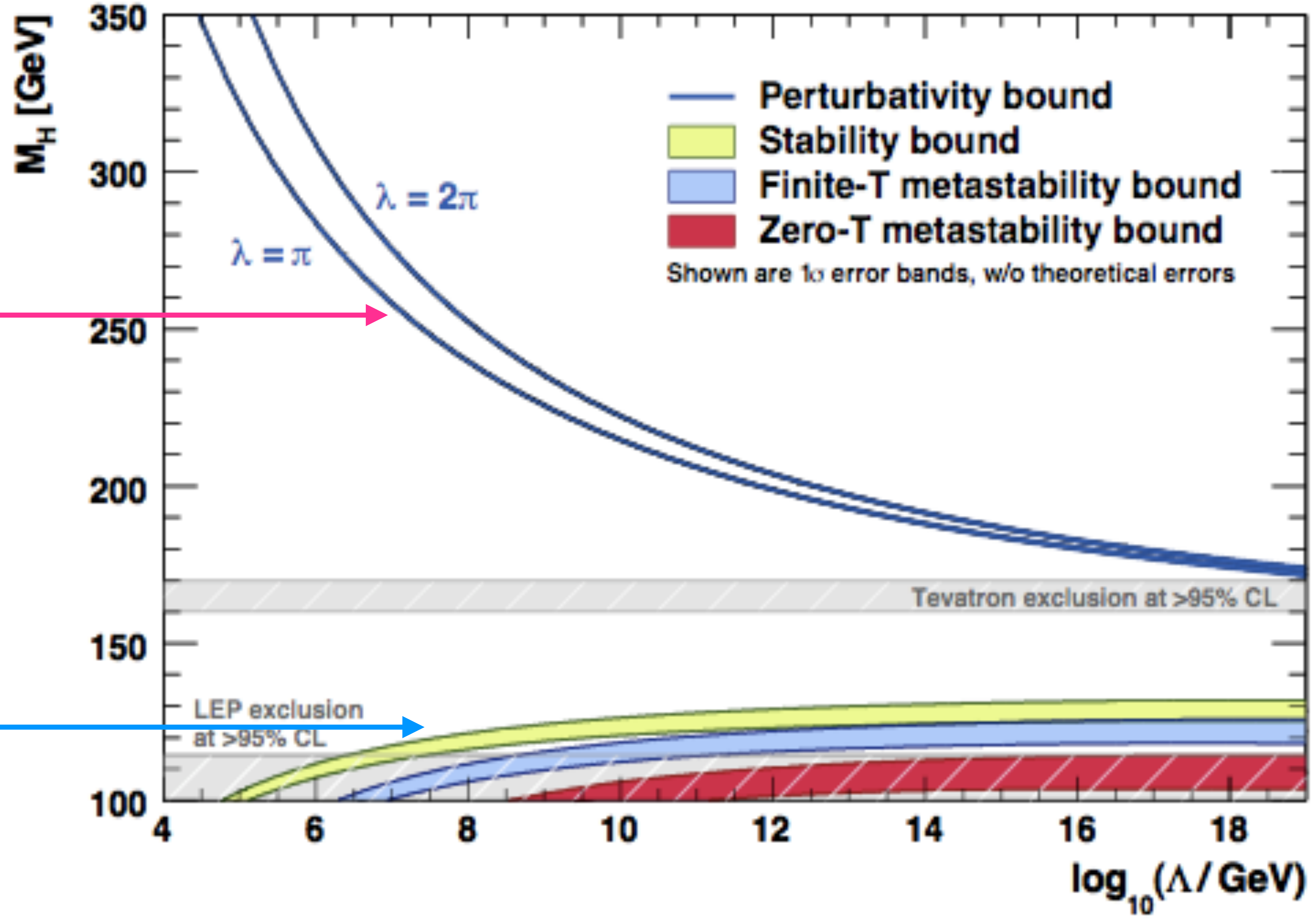
Dominant term for large values of the Higgs boson quartic coupling

The simplified differential equation can be solved and derive a so-called « triviality » bound.

Dominant term for small values of the Higgs boson quartic coupling



The simplified differential equation can be solved and derive a so-called « vacuum stability » bound.

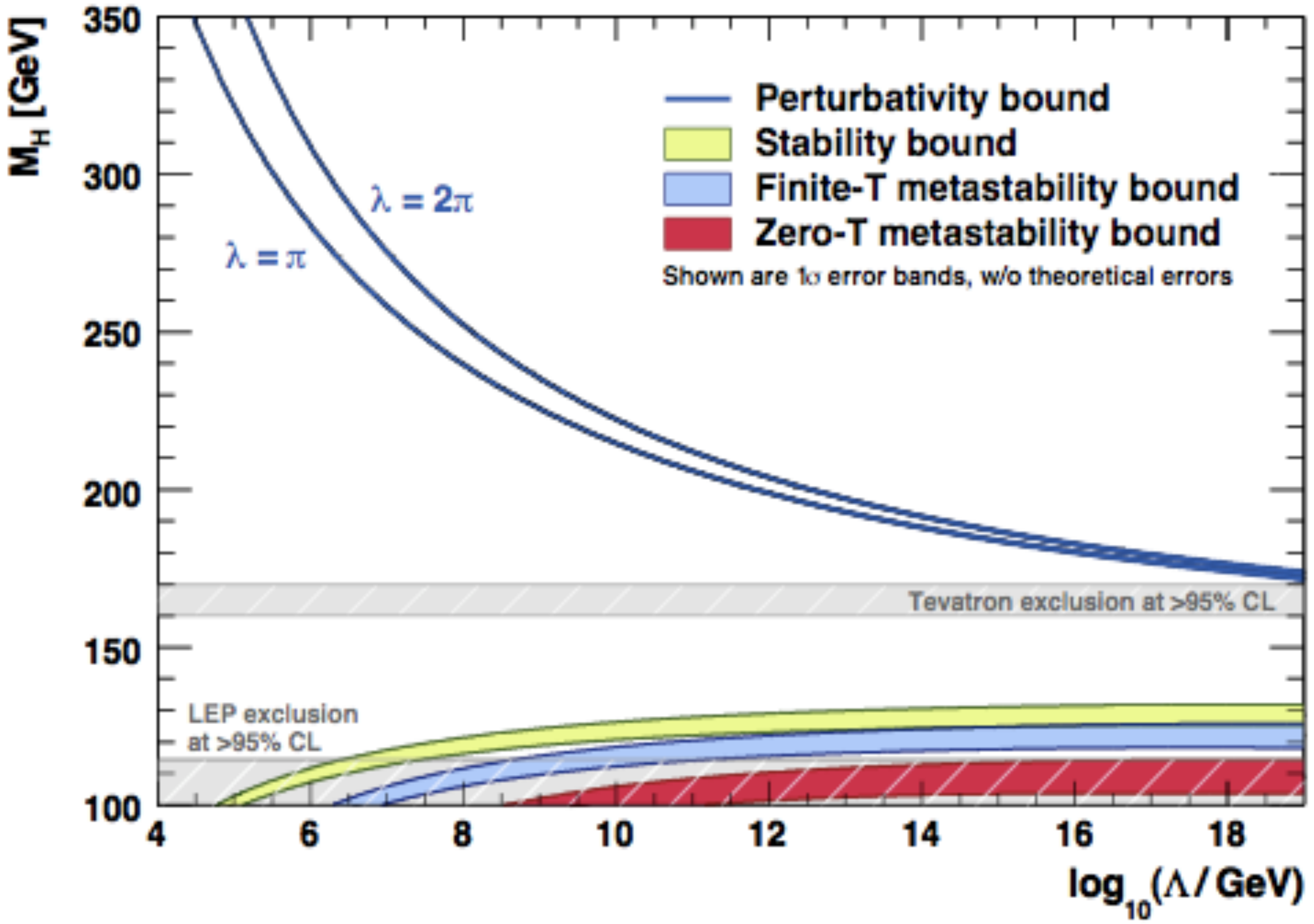


Implications (II) – Global fit of the Standard Model

Running of the Higgs self coupling:

$$32\pi^2 \frac{\partial\lambda}{\partial\mu} = 24\lambda^2 - 6y_t^4 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4$$

With the discovery of the Higgs,
for the first time in our history,
we have a self-consistent theory
that can be extrapolated to
exponentially higher energies.



Here as well, knowing the Higgs boson mass is very important, but knowing it precisely has small impact, the measurement and precision of the top mass is more important!

Concluding Remarks

Challenges for Run 3

We have discussed in some (too little) detail the prospects for the HL-LHC. What about the challenges for Run 3?

Intermediate milestones are key!

Recapping those mentioned during the lectures:

- Reach a close to first combined evidence across experiments for longitudinal VV EWK scattering?
- Observation (combined?) of Higgs boson coupling to muons.
- Could 2 s.d. sensitivity in combination of the two experiments be reached.
- Reach a 50% uncertainty on the Higgs width?

Intermediate milestones are of fundamental importance for all results, as improving in all areas important to move forward the entire LHC physics program!

Precision at the LHC: Three Pillars

Beside the analysis improvements and intermediate milestones mentioned in the previous slide!

1.- Modelling and TH systematic uncertainties.

The level of precision reached so far **relies** on a number of **TH breakthroughs**

- The « Next-to… » revolutions, and novel tools for automated calculations at higher orders
- Reaching N3LO-QCD precision (DY, ggF, VBF, VBF-HH..)
- NNLO Monte Carlos (requiring NNLO-PS matching!)
- Up to N4LL resummation matched to fixed order
- IR and Collinear safe fast Jet reconstruction algorithms

2.- In Situ calibration

Measurements such as the W or the Higgs mass have shown how precise calibrations are possible! Could a Z boson mass measurement be made at the LHC?

3.- Ancillary measurements

Essential ingredient to improve TH and modelling precision as well as probing the experimental calibrations

Conclusions

The SM and Higgs measurements program of the LHC physics is **vast** and **impressively diverse**.

In its main physics goals, the LHC has already been **extremely successful** and has **surpassed many of its targeted results**.

With its busy environment but high statistics the measurements carried out at LHC compete with the measurements done at LEP and are setting very high standards for future e^+e^- colliders for

The LHC entered the precision frontier! Hadron colluders which were formerly perceived as ‘discovery machines’ are delivering precision measurements!

The potential of hadron colliders as discovery machines and as probes for rare processes and the complementarity with future e^+e^- colliders remains!

Precision is the key for the success of the entire LHC program, both for measurements and searches (see Greg’s lectures)!

Further Reading on Parametrisation

Combination Procedure and Master Formula

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Same formula as the total cross section measurement formula

These « mu » or signal strength factors cannot be fitted simultaneously, typical fit models include:

μ	$\mu_{if} = \mu_i \mu_f$	$\mu_i \; (\mu_f = 1)$	$\mu_f \; (\mu_i = 1)$
Extrapolated total cross section	Cross section times branching	Cross sections	Branching fractions

Manifest in this formula why absolute couplings cannot be measured with this procedure: μ_i, μ_f cannot be fitted simultaneously.

For a complete description see (link) - Chapter 10

Combination Procedure and Master Formula

These measurement correspond to cross sections times branching fractions

$$\mu \ (\text{fit}) \quad \mu_i = 1 \quad \mu_f = 1$$

Signal strengths illustrates the agreement of measurements with the SM and the importance of the TH input.

A quick word on the kappa formalism

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian (assumes that the tensor structure of is that of the SM).

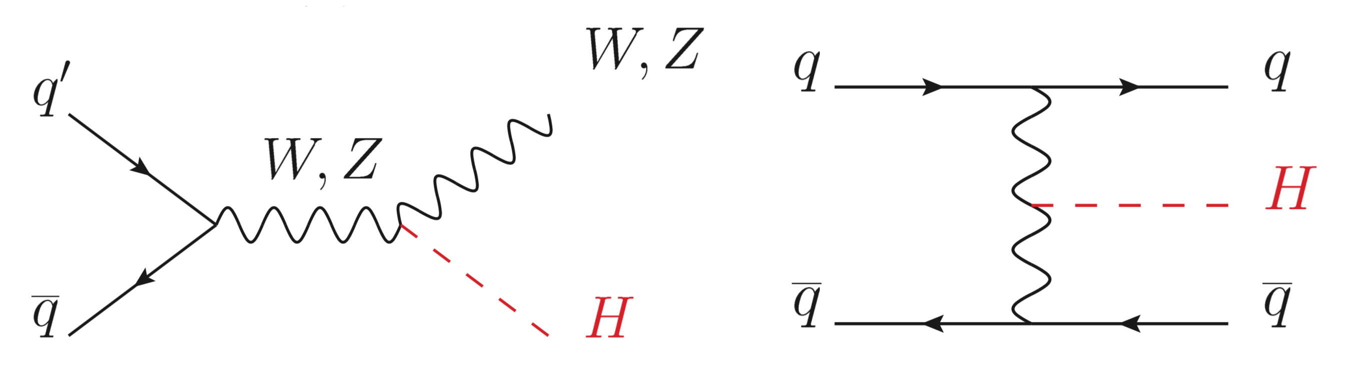
$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_{\mathrm{Z}}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_{\mathrm{W}}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f \bar{f}$$

Not gauge invariant and partial but very useful to illustrate coupling measurement concepts.

More complete EFT and rigorous framework will be discussed later…

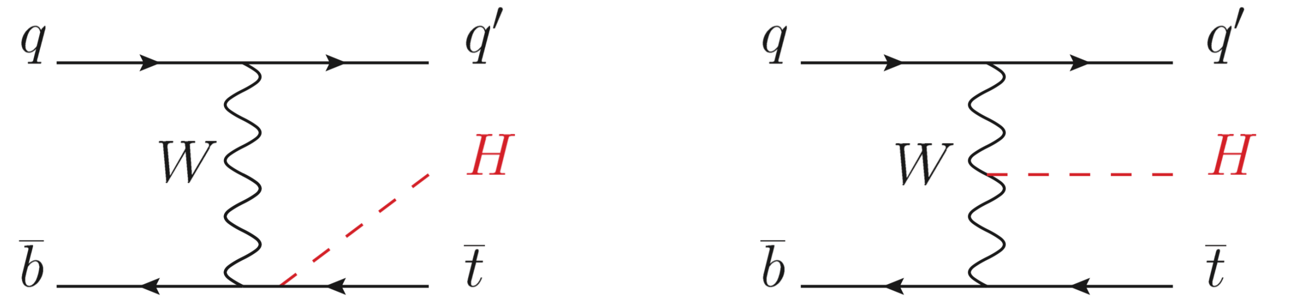
The Kappa Formalism

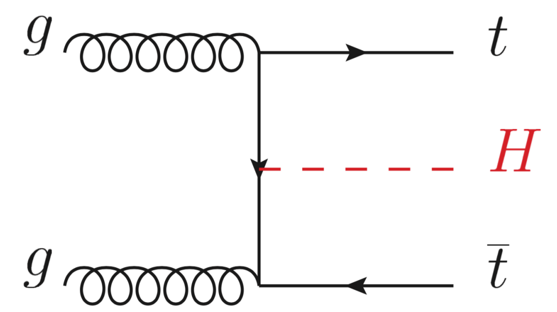
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

$\propto 3.3 \times \kappa_W^2 - 5.1\kappa_W\kappa_t + 2.8\kappa_t^2$

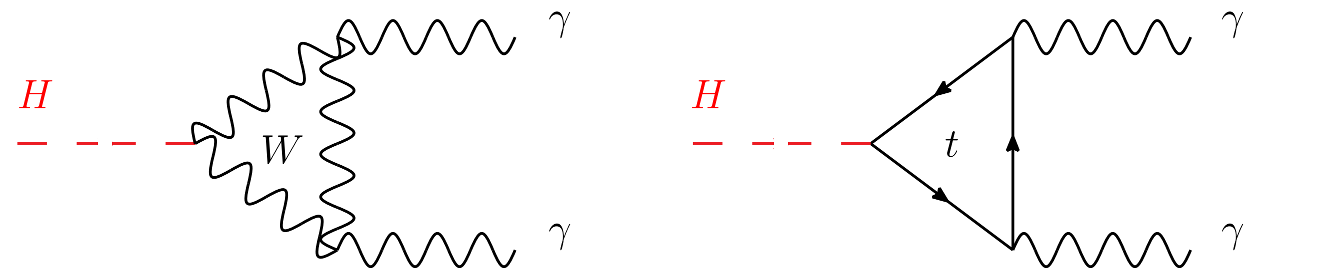




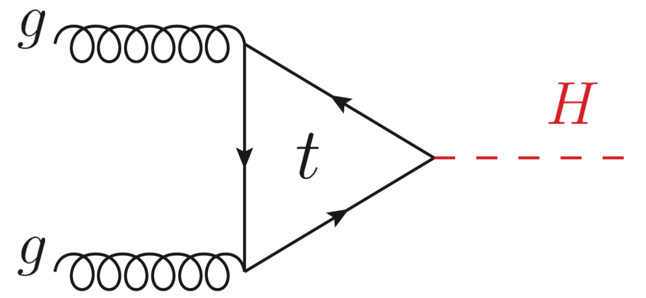
$\propto \kappa_t^2$

… and in loops (as a function of the know SM field content)

$\propto 1.6 \times \kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$



$\propto 1.06 \times \kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$



In order to measure the coupling modifiers (kappas) the signal strengths are re-parametrised as follows:

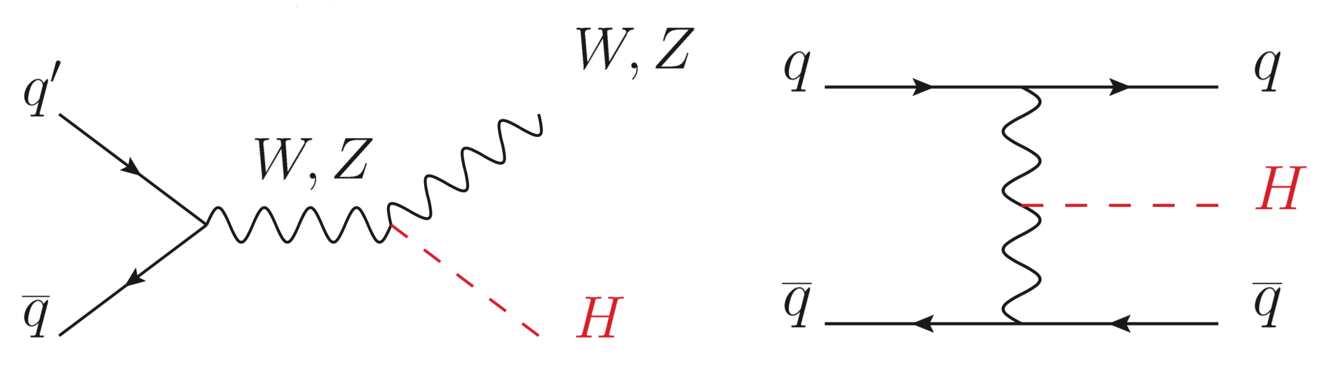
$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\mu_f = \frac{\Gamma_f}{\Gamma_H} \quad \text{so} \quad \mu_f = \frac{\kappa_f^2}{\kappa_H^2} \quad \text{where} \quad \kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_H^{SM}}$$

κ_H can be parametrised as a function of other couplings assuming no new BSM decays of the Higgs

The Kappa Formalism

Then parametrise the production and decays at tree level



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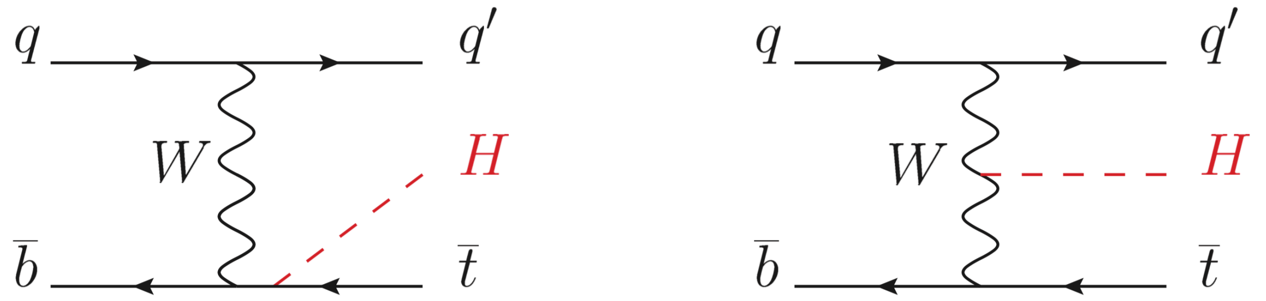

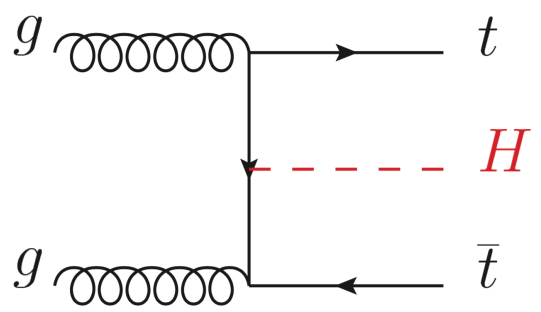

$\propto \kappa_t^2$

… and in loops (as a function of the know SM field content)

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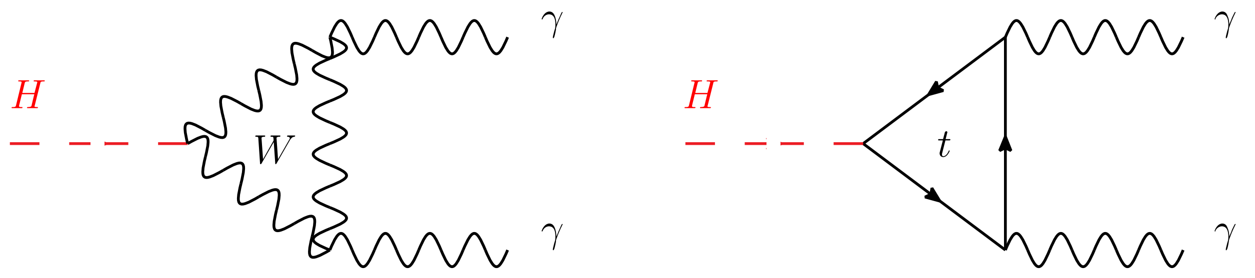
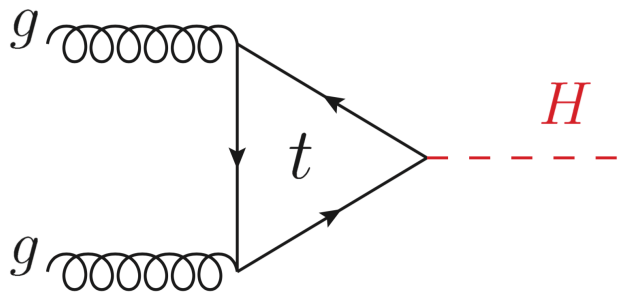


$\propto 1.06 \times \kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$



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$$\kappa_H^2 \sim 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + 0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.00022\kappa_\mu^2$$