Experimental SM and Higgs Physics at LHC

Lecture 4

More Higgs physics an global interpretation

Herbschule HEP - Bad Honnef

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Outline

Experimental SM and Higgs Physics at LHC

Lecture 1*: Basic Concepts, the LHC and precision measurements with Drell-Yan W and Z processes.*

Lecture 2*: Associated and multi- Vector boson production, and top quark*

Lecture 3*: Higgs Physics*

Lecture 4: *More Higgs Physics and Global interpretation*

- **Disclaimer:** These lectures will be focused mostly on ATLAS and CMS (LHCb covered by Marco Gersabeck and QCD and jet physics covered by Peter Uwer)
- **Excellent resources for keeping up-to-date with the latest results**: Physics Briefings from ATLAS and CMS.

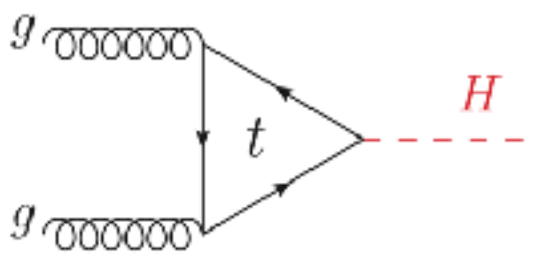
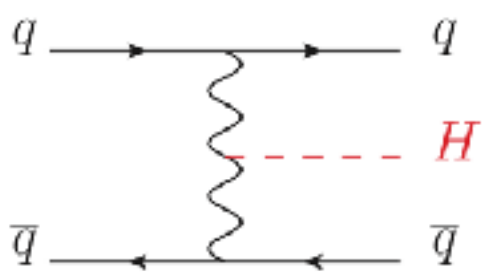
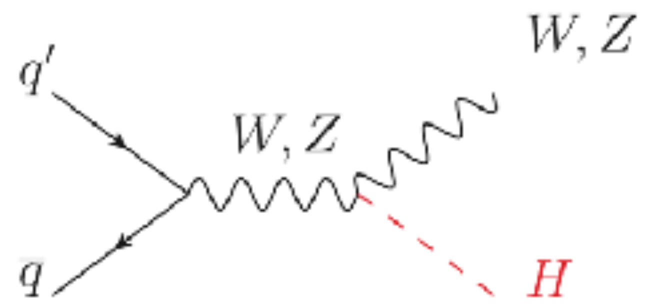
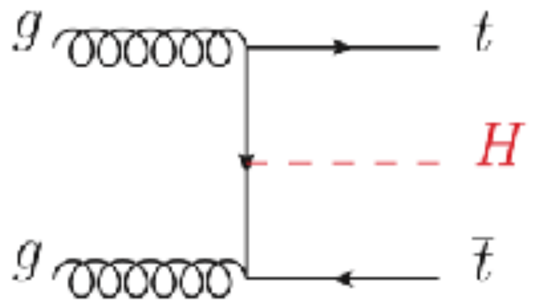
Review see latest PDG review

particle data group

Portrait of the Higgs Boson 10 Years after its Discovery

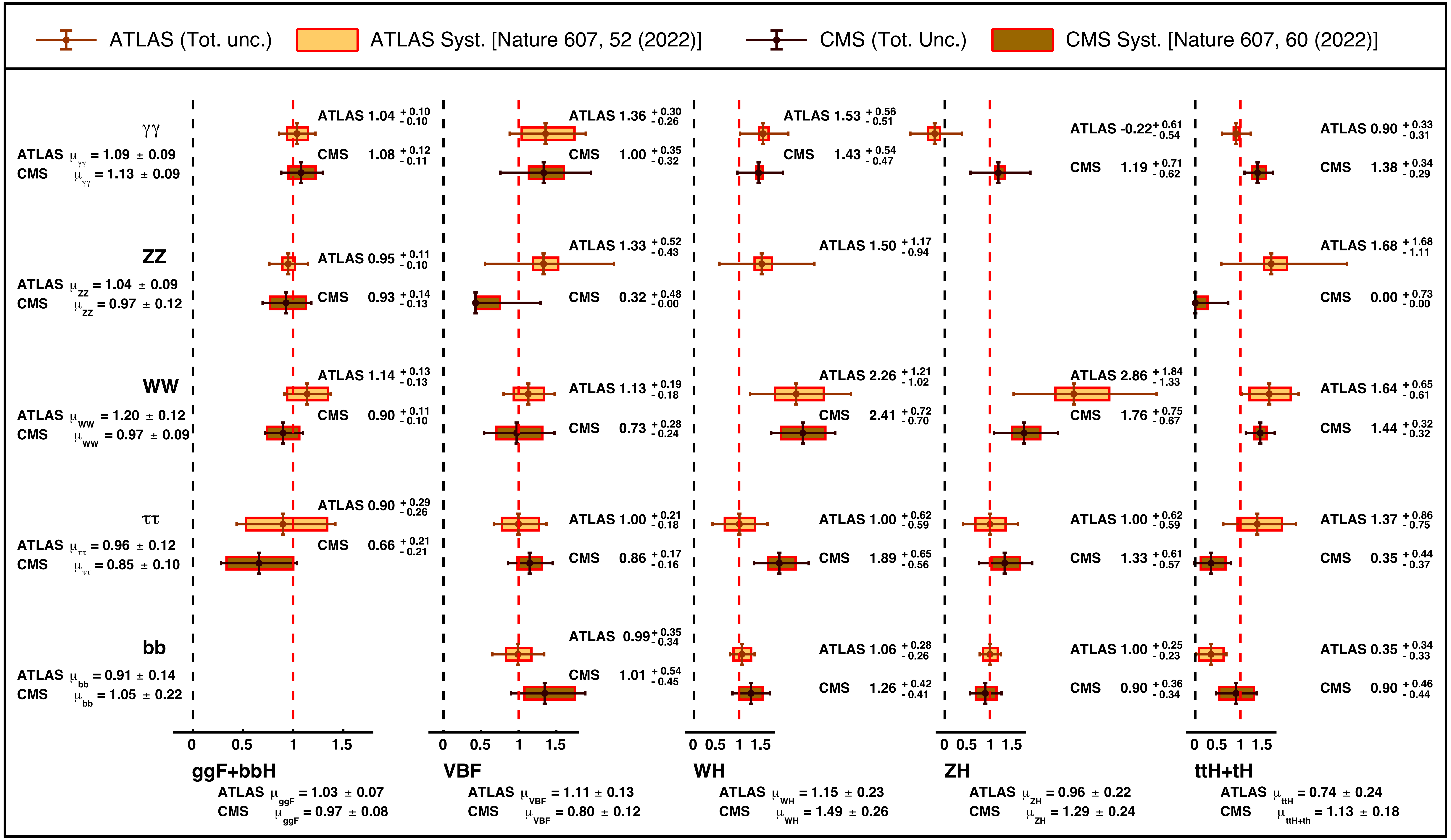
Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!

	Channel categories	Br	ggF  ~8 M vets produced	VBF  ~600 k vets produced	VH  ~400 k vets produced	ttH  ~80 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

Very broad overview!



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)	

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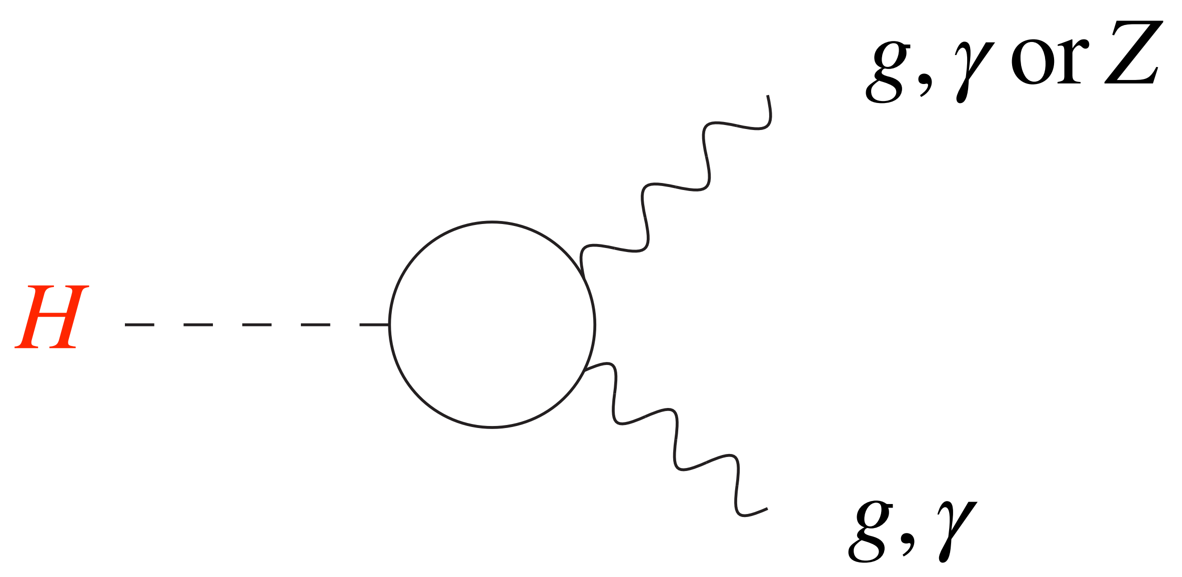
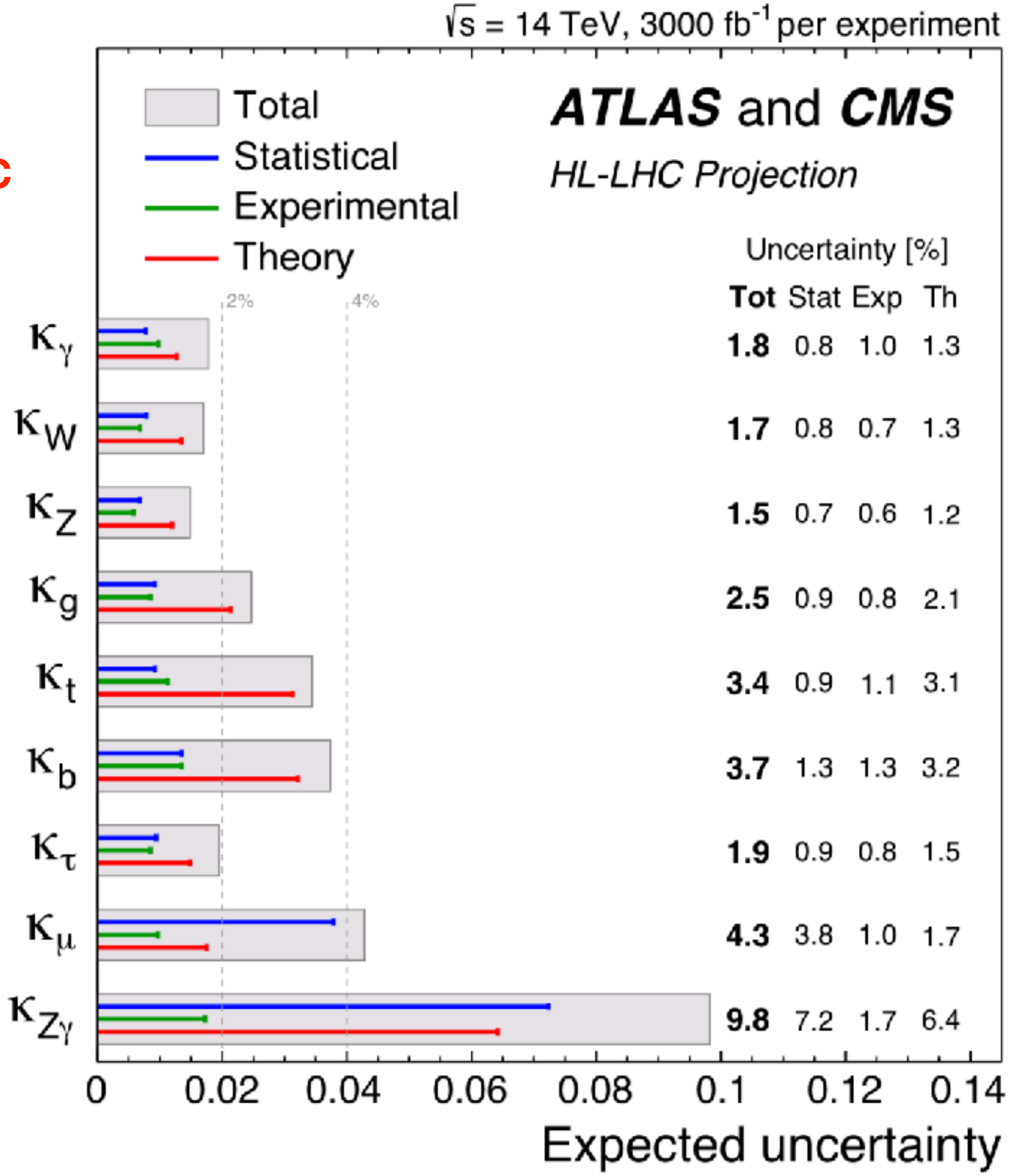
Probing new particles through loops



Precision Higgs Couplings Measurements

	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)

The Size of The Higgs boson

How to read these results?

One important example, is the $\mathcal{O}_H$ operator which represents the leading interaction term for a composite Higgs boson

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

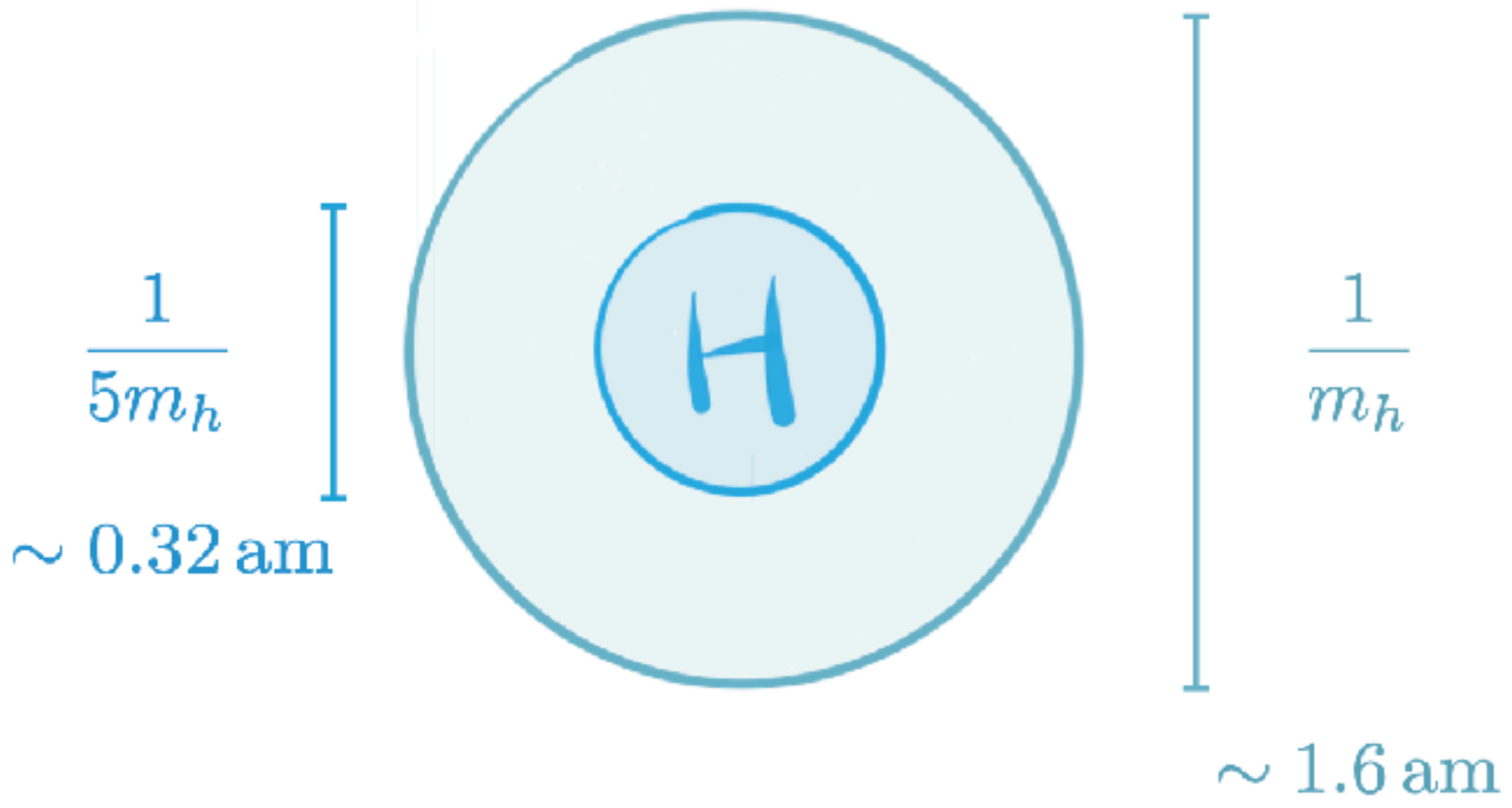
After EW symmetry breaking it normalises the kinetic term in the Lagrangian and thus **modifies all couplings simultaneously!**

$$\frac{c_H}{\Lambda^2}\cdot\frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \rightarrow \left(\frac{2c_H v^2}{\Lambda^2}\right)\cdot\frac{1}{2}\left(\partial_\mu h\right)^2$$

$$c_H \frac{v^2}{\Lambda^2} < 0.06$$

Taking $c_H = 1$ leads to $\Lambda > 1$ TeV

Comparing the Compton radius of the Higgs $1/m_H$ to its radius $1/\Lambda$ (as comparing the mass of the pion to that of the ρ meson!



The Higgs could very well be a pNGB as the pion!

More precision is needed to probe the compositeness of the Higgs boson!!

"A case for future lepton colliders" N. Craig (See paper)

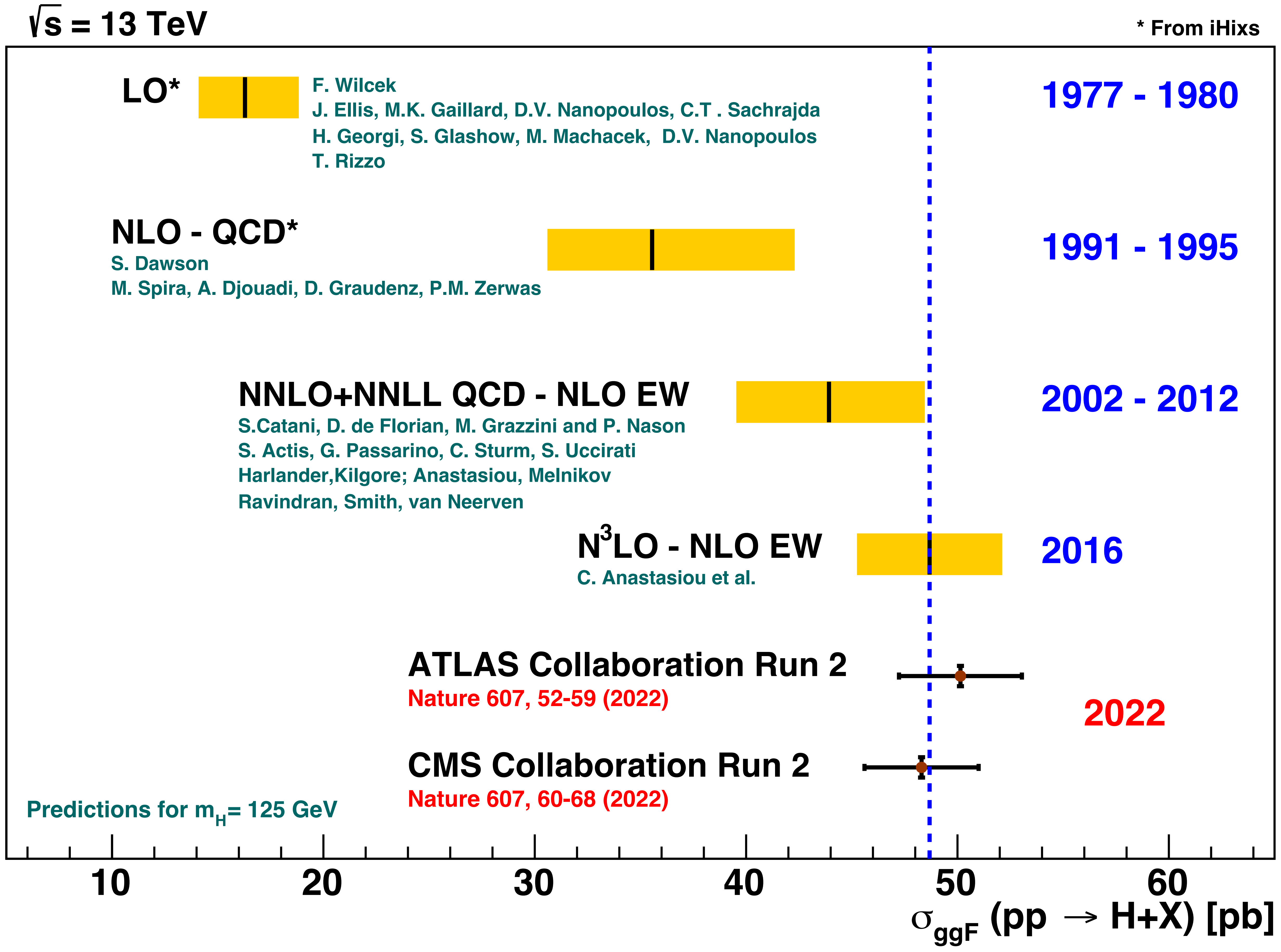
The Importance of Theory and Modelling

Predictions at hadron colliders are extremely complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…)

Most measurements at LHC are dominated by modelling and theory systematic uncertainties (with some notable exceptions).

The interpretability of our results relies on our ability to compute accurate and precise predictions!

The LHC has become a precision measurements machine, this would not have been possible without the **outstanding efforts of the TH community**.



Modelling and predictions - an overarching question!

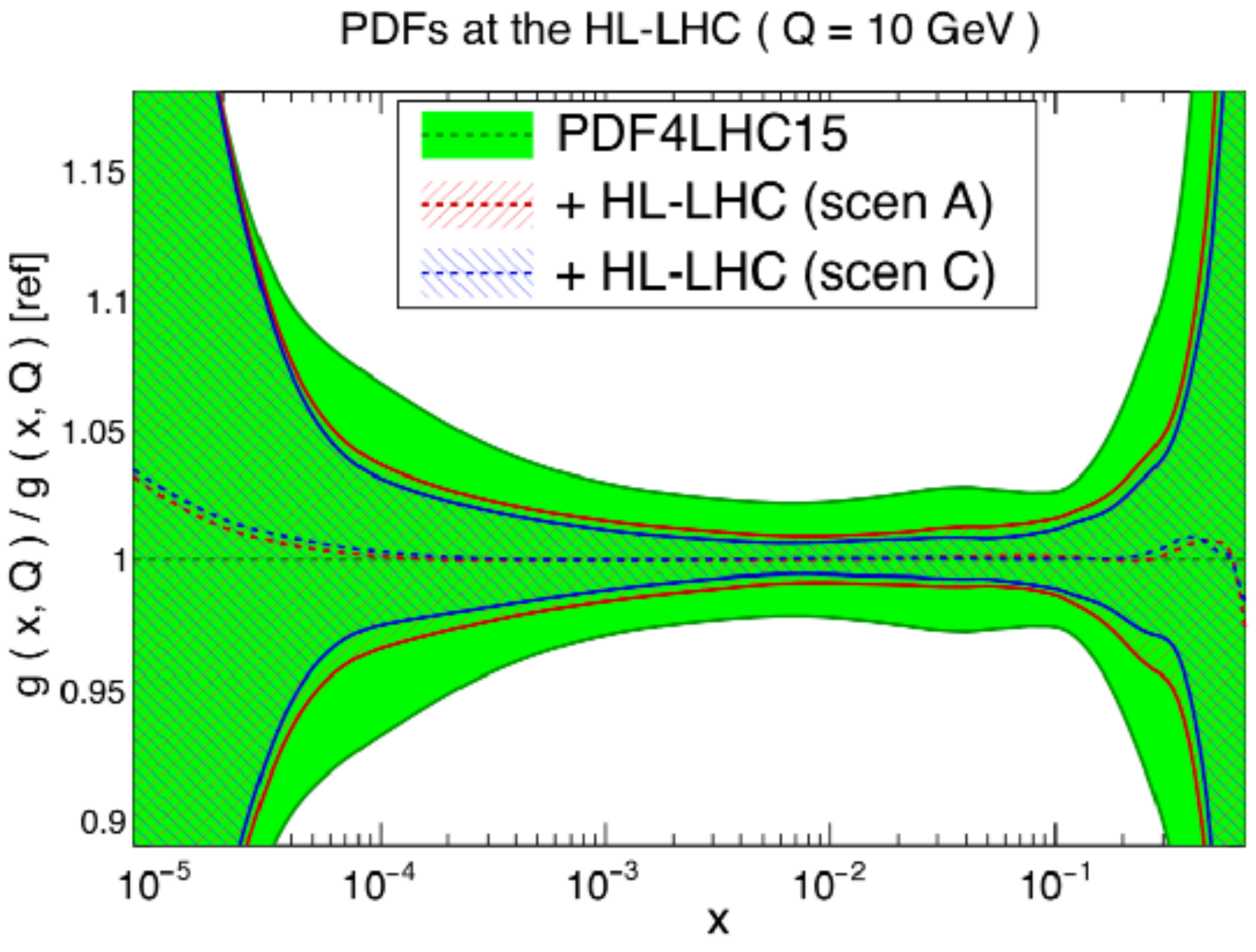
E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}} \left(^{+4.27\%}_{-6.49\%}\right)$	$\pm 0.89\,\text{pb}\,(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}} \left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}} \left(^{+4.28\%}_{-6.46\%}\right)$	$\pm 1.00\,\text{pb}\,(\pm 1.85\%)$	$^{+1.40\text{pb}}_{-1.41\text{pb}} \left(^{+2.60\%}_{-2.62\%}\right)$
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:

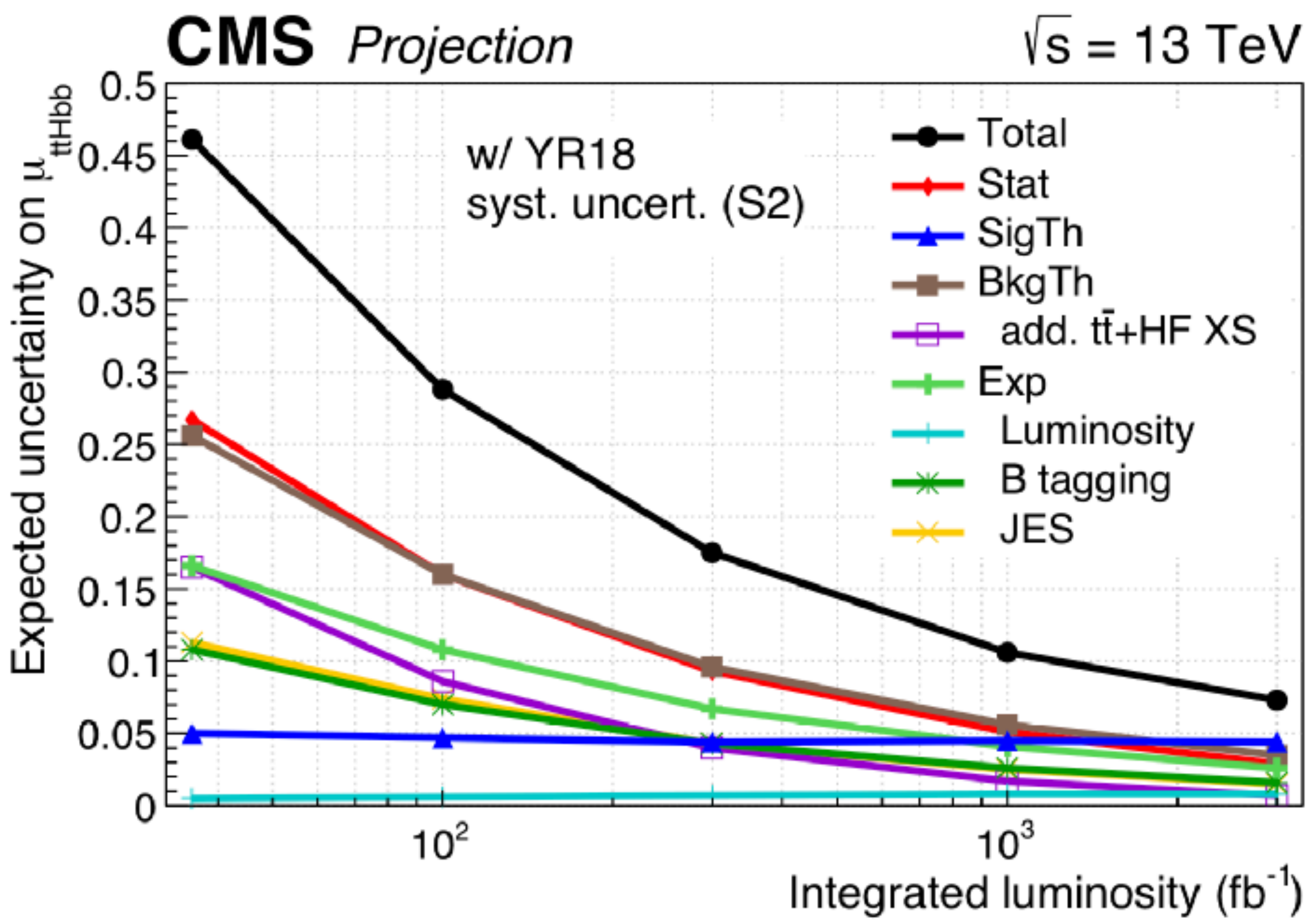
- Conservative (A): No reduction in systematics
- Optimistic (C): Reduction by a factor 2.5 of current systematic uncertainties.

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 the 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

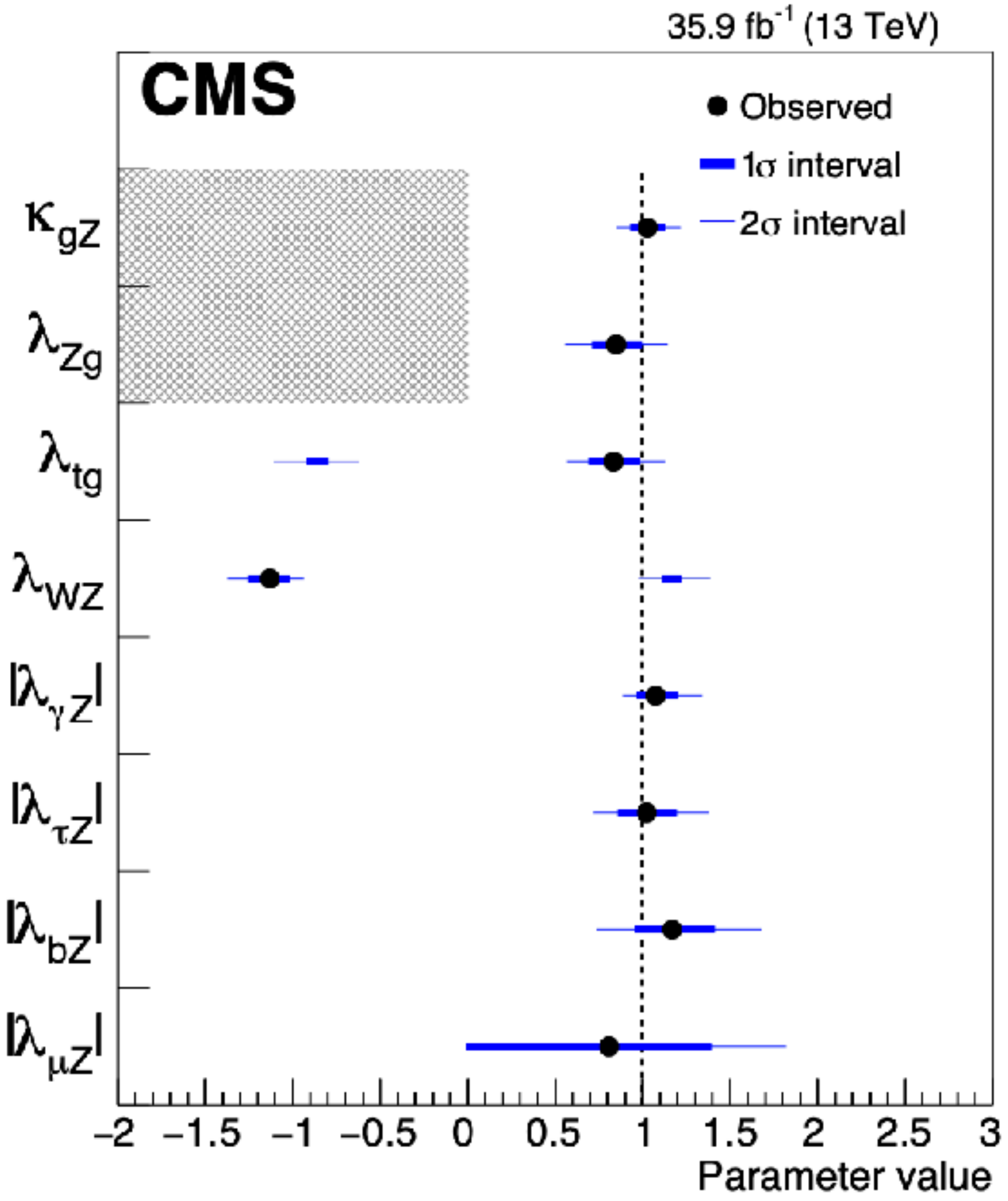
Run 2 Couplings Measurements

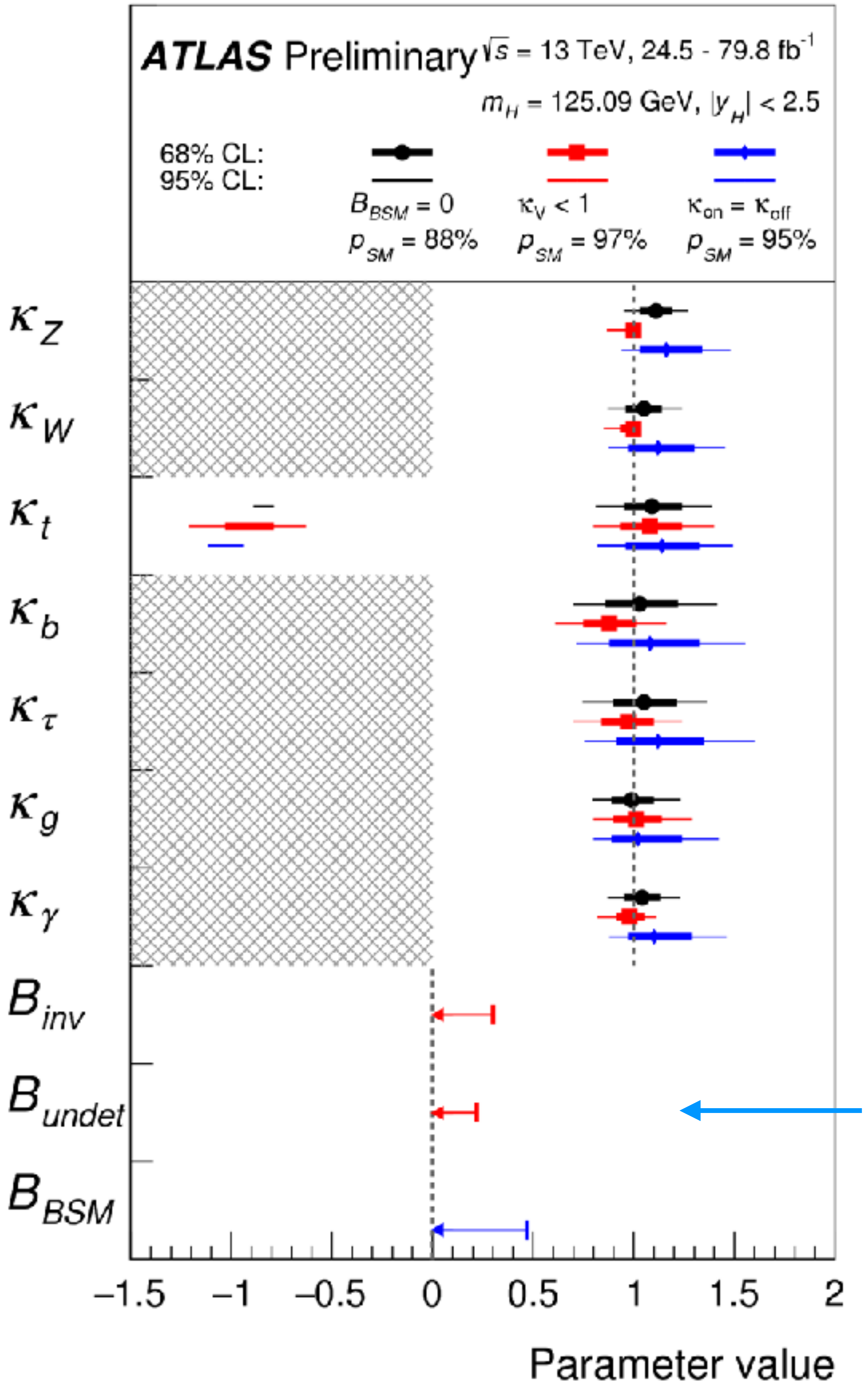
Previous measurements assume that the there is no additional contributions to the Higgs width than those from SM particles (see formulae in the backup).

What are the alternatives?

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

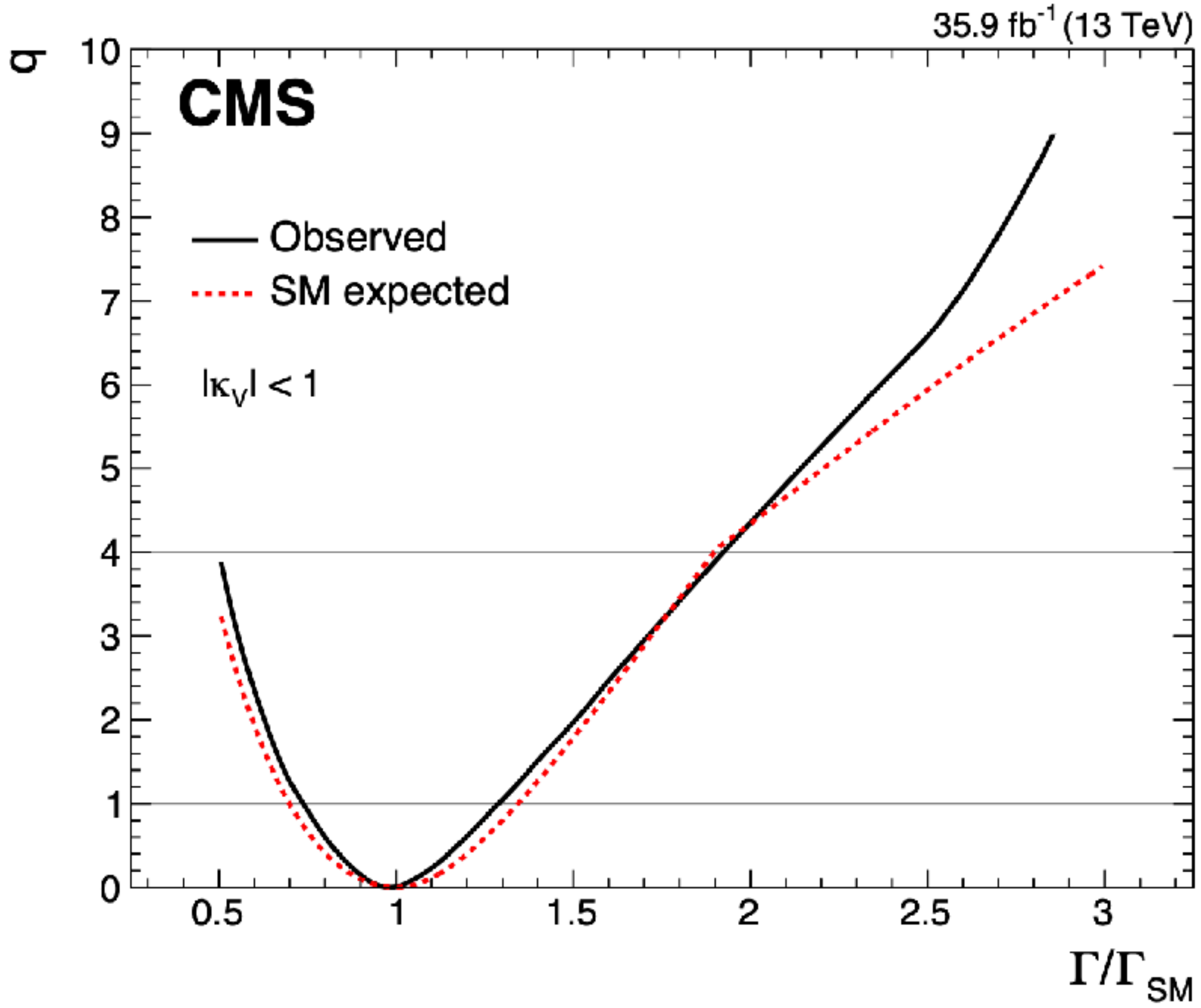
Measurement of ratios does not require any assumption on the natural width, parametrised as a function of one specific process $ggH \rightarrow ZZ$

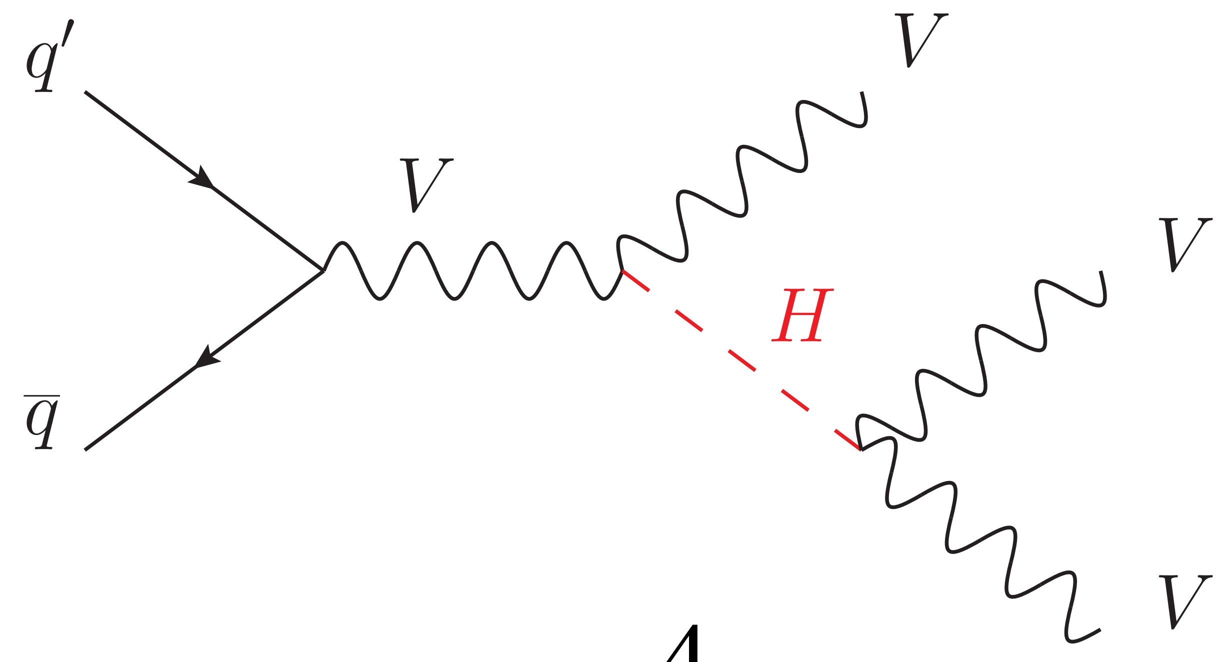




Couplings fit can constrain the total width with the assumption that kV<1

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)!

The Natural Width of the Higgs Boson

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

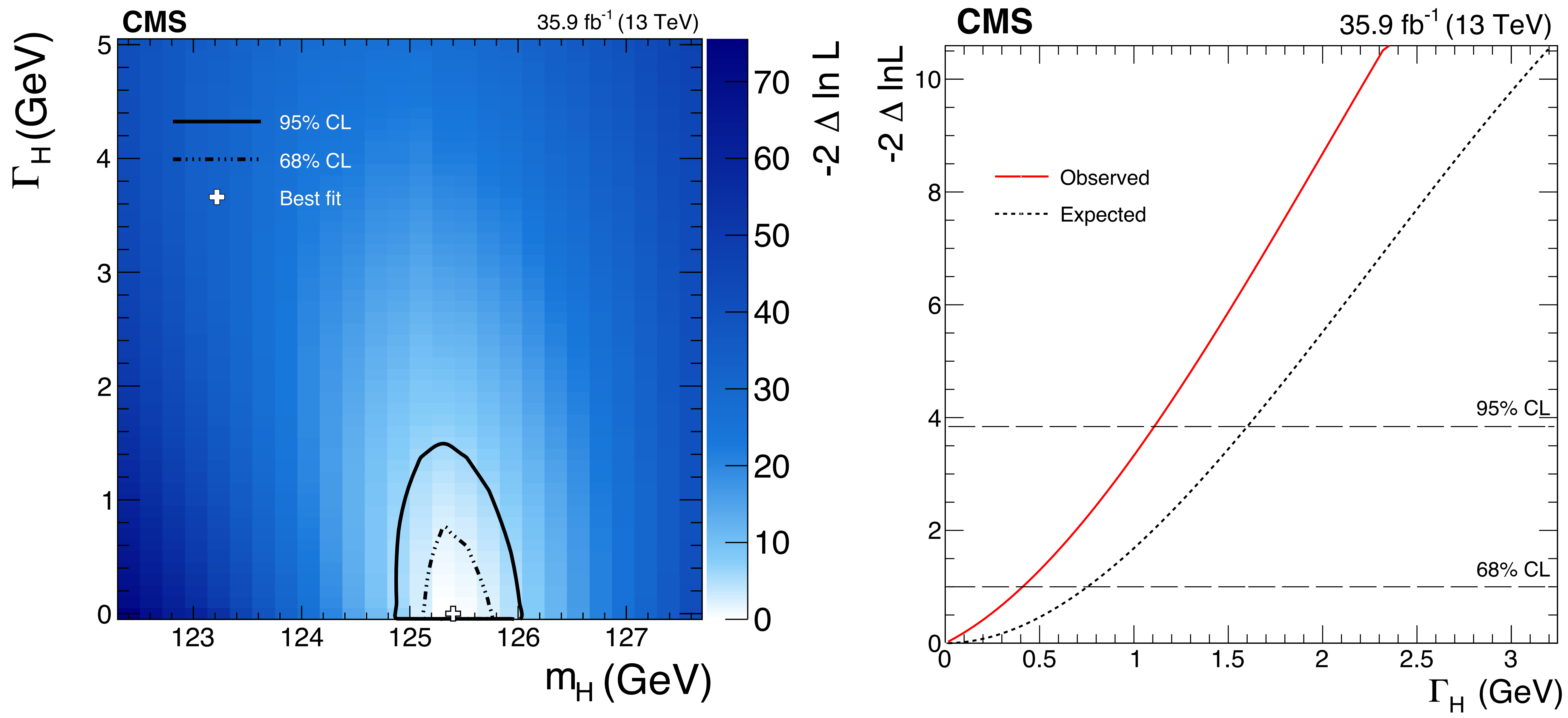
The Higgs total width in the SM is very small therefore small couplings to the Higgs can be easily visible: tool for discovery!

- **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.

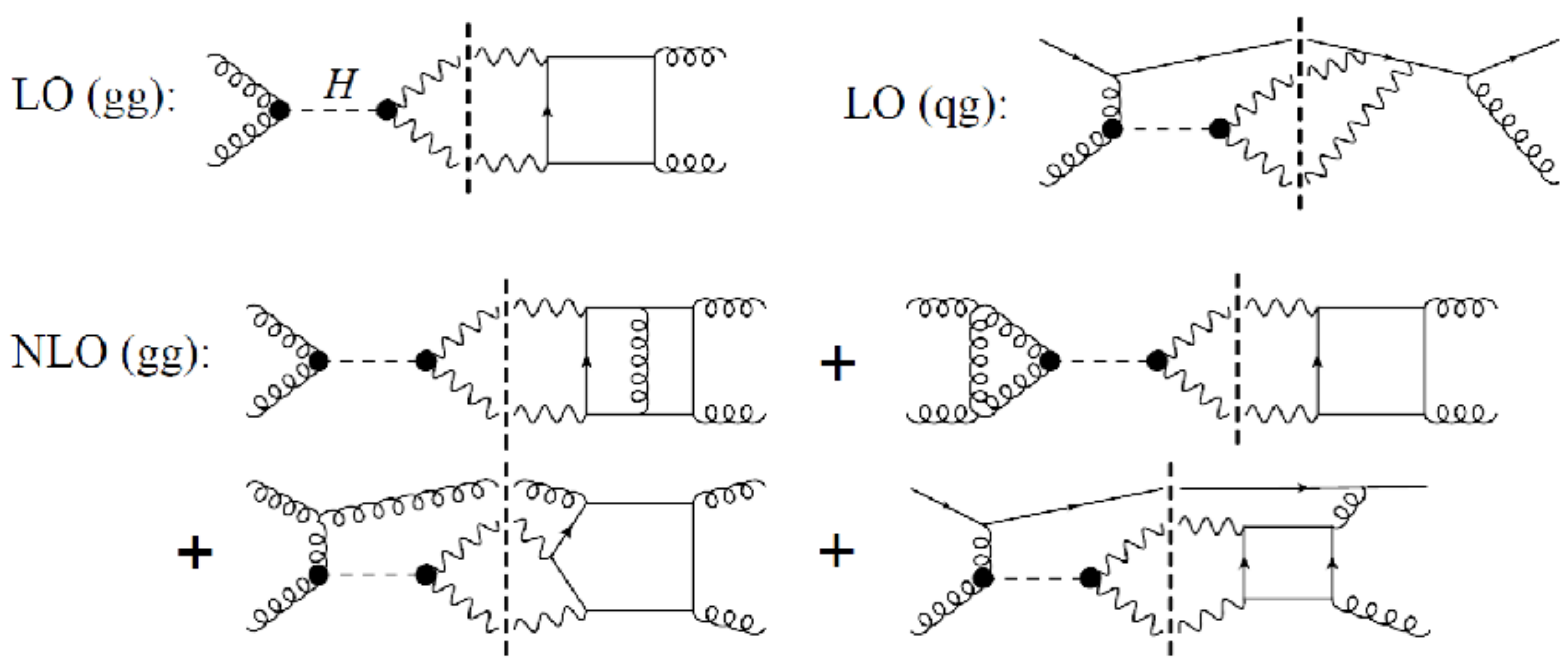


$$\Gamma^H_{SM} < 1.10 \text{ GeV at } 95\% \text{ CL}$$

Original Approaches to Constrain the Higgs boson Width

Diphoton signal-continuum background interference

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



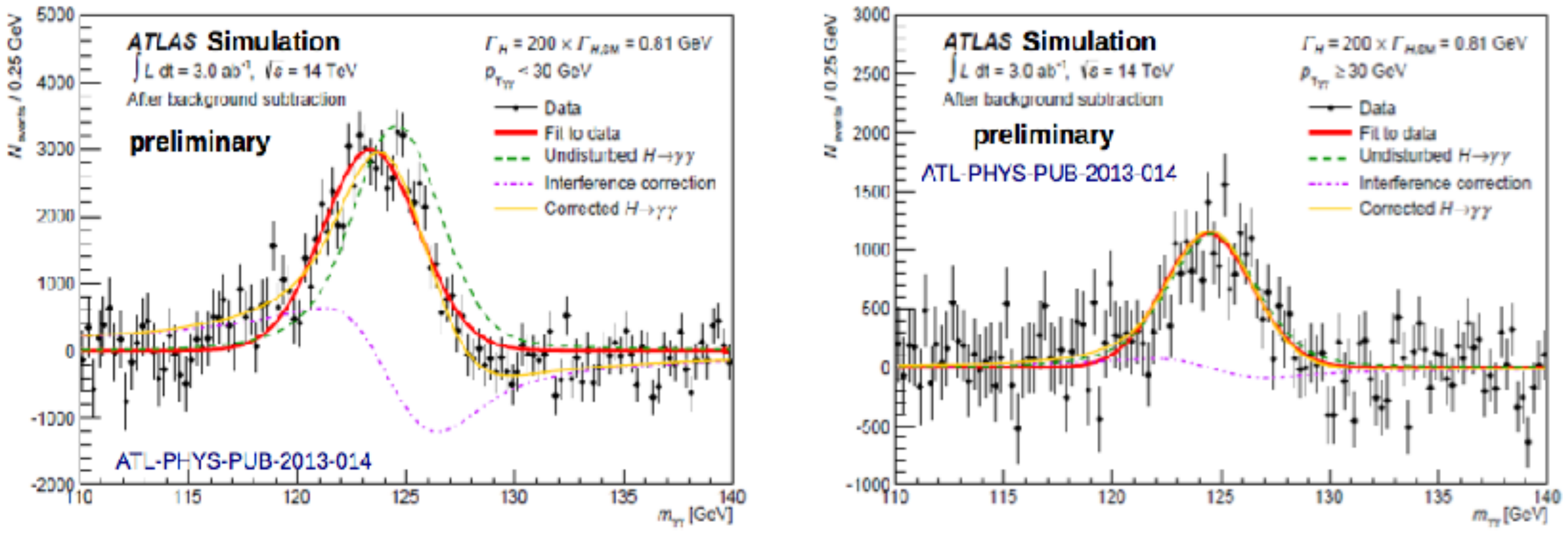
- **Rate**: the size of the interference inclusively is 2% and depends on the width of the Higgs boson. Comparing rates with other processes such as e.g. the four lepton channel in similar regions of phase space can constrain the total width.

- 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.

ATL-PHYS-PUB-2013-014



- 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

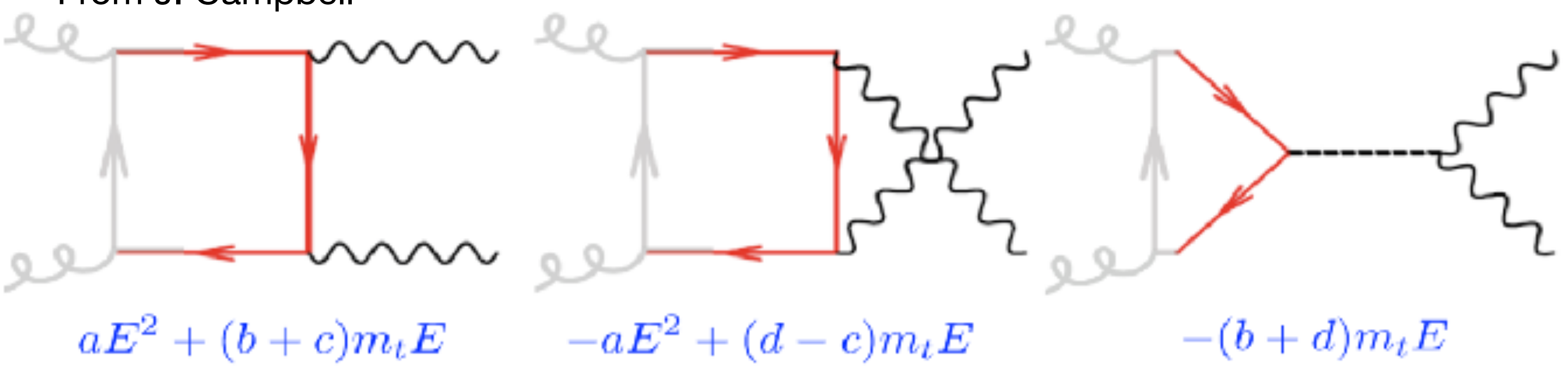
$\Gamma^{H}_{SM} < 200\ \mathrm{MeV}$ At HL-LHC

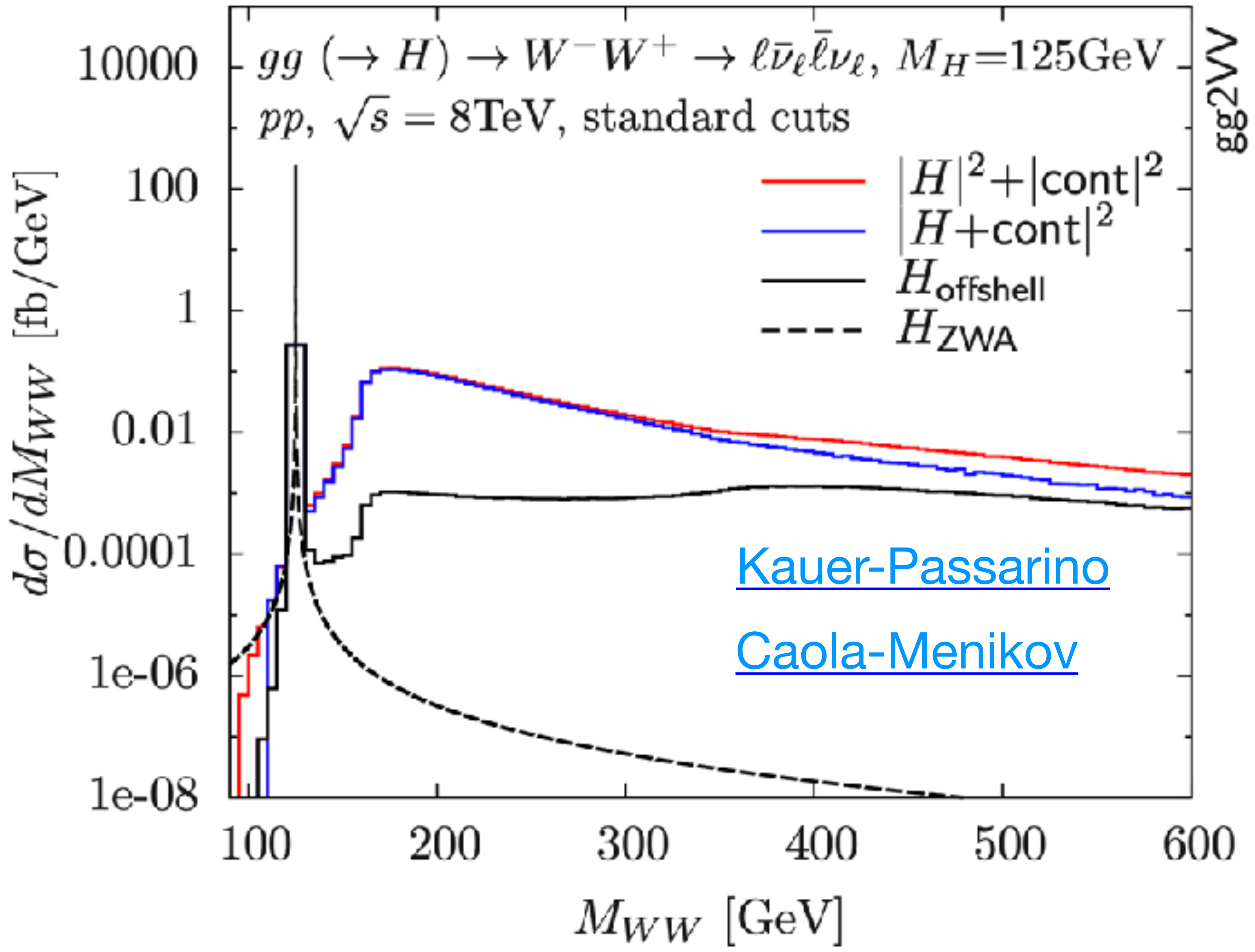
Off Shell Higgs

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





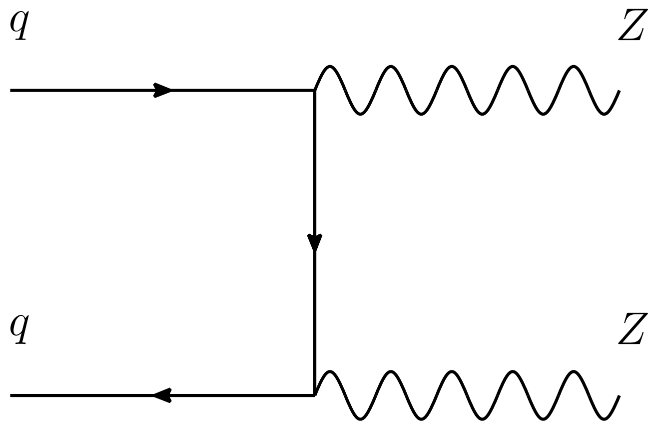
Kauer-Passarino

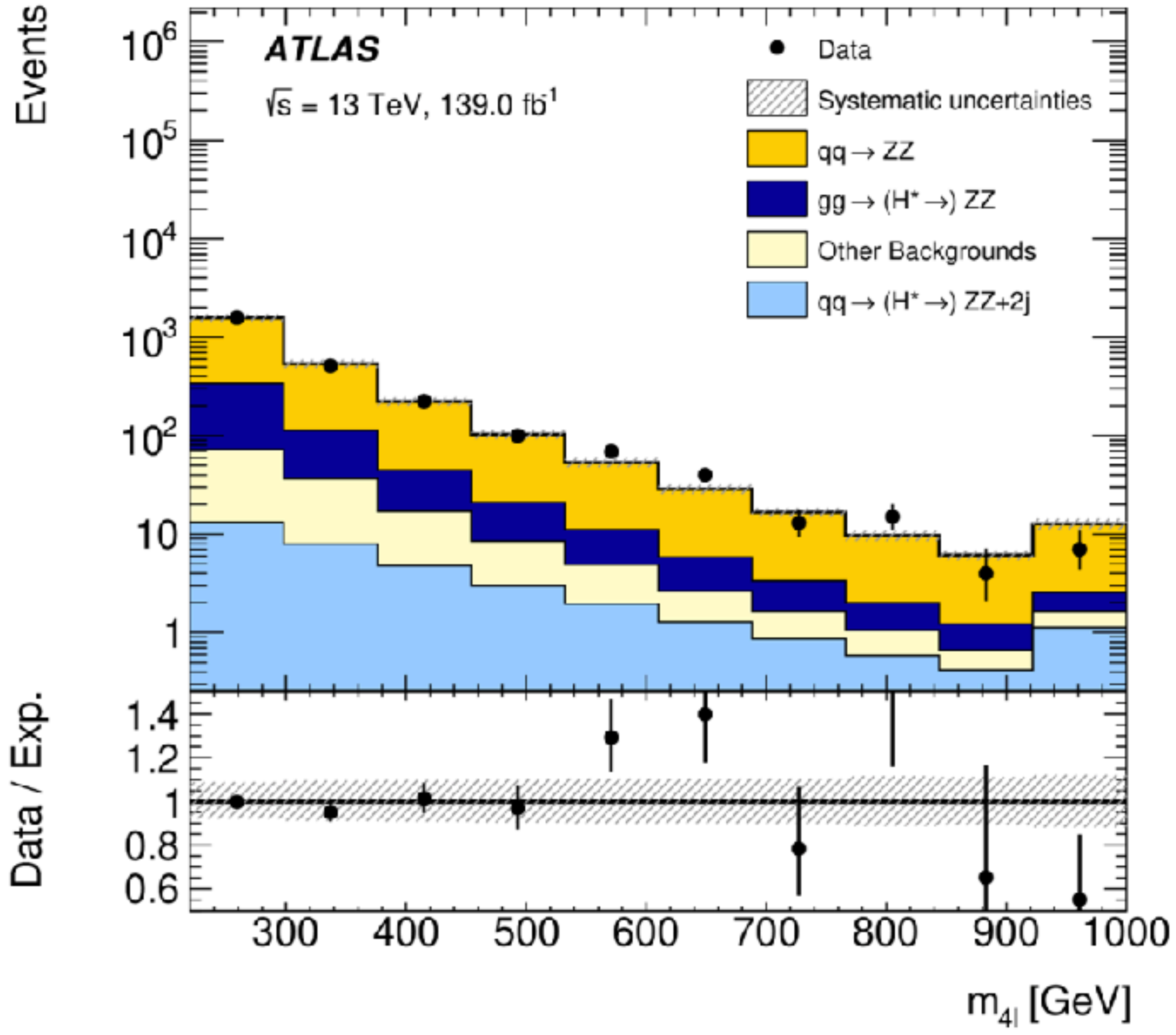
Caola-Menikov

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

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

Evidence for Off-Shell production at 3.6σ

ATLAS Result

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

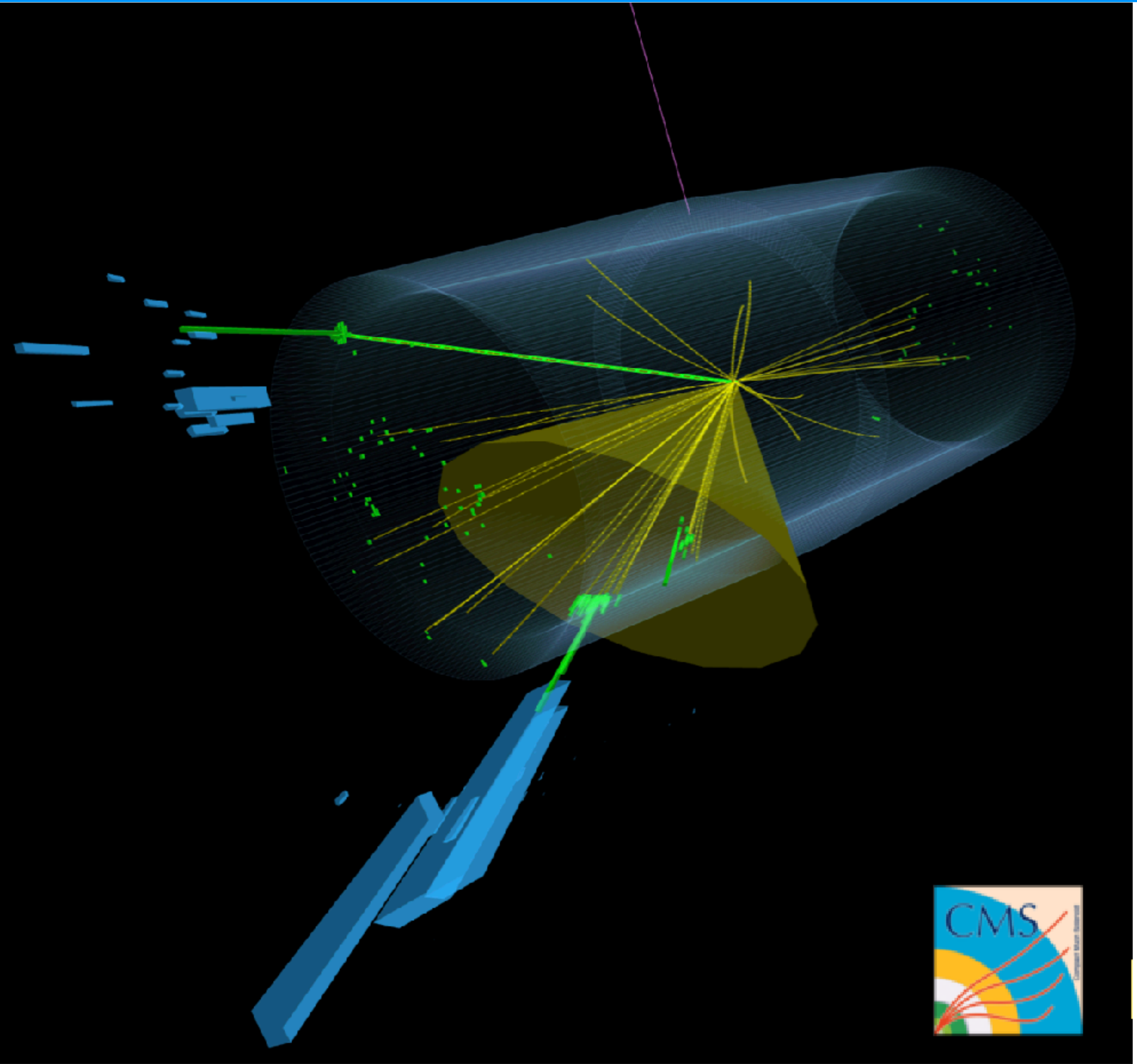
Evidence for Off-Shell production at 3.3σ

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?

The Yukawa coupling to charm



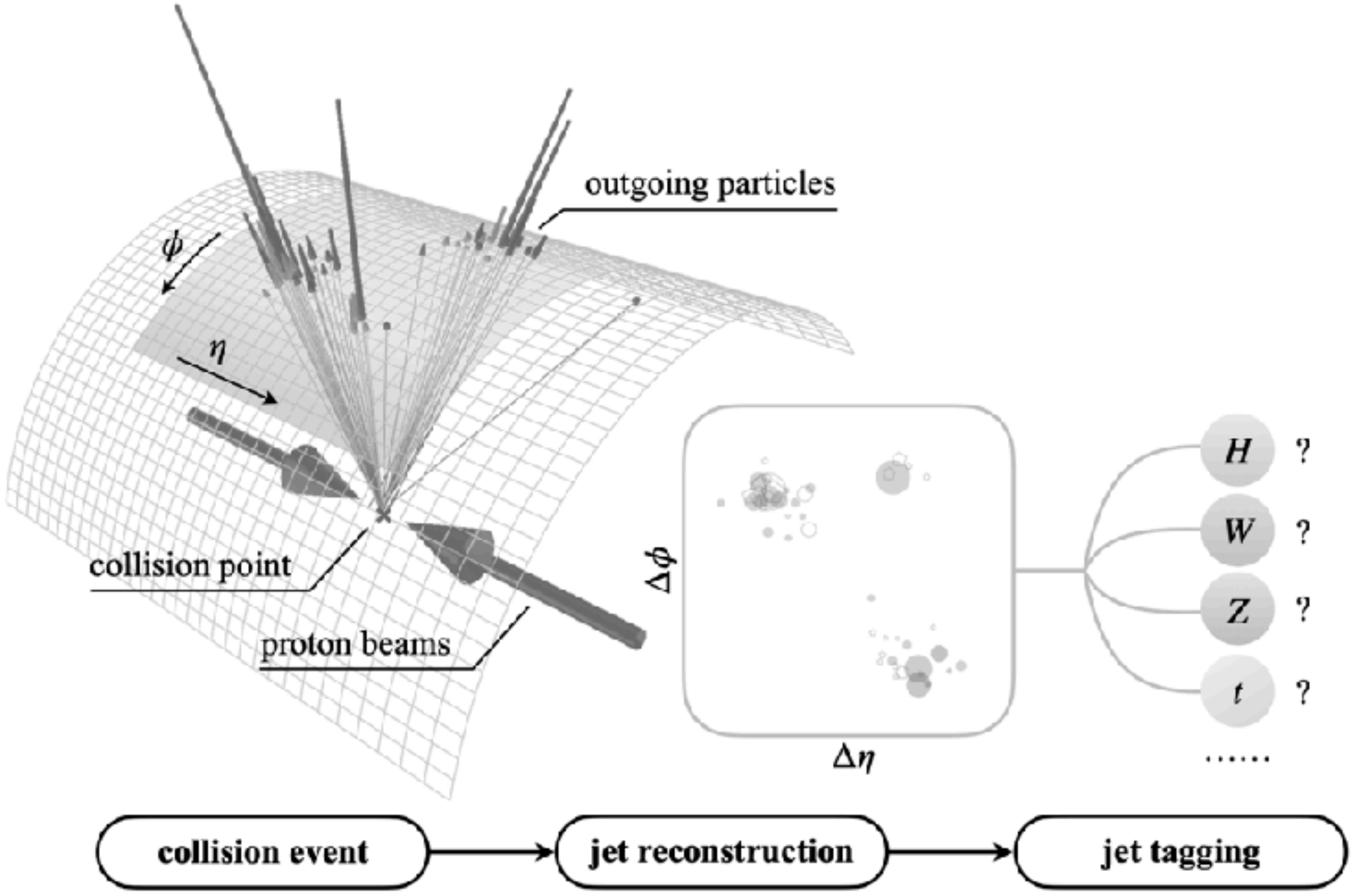


Illustration from [Particle Transformer]

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

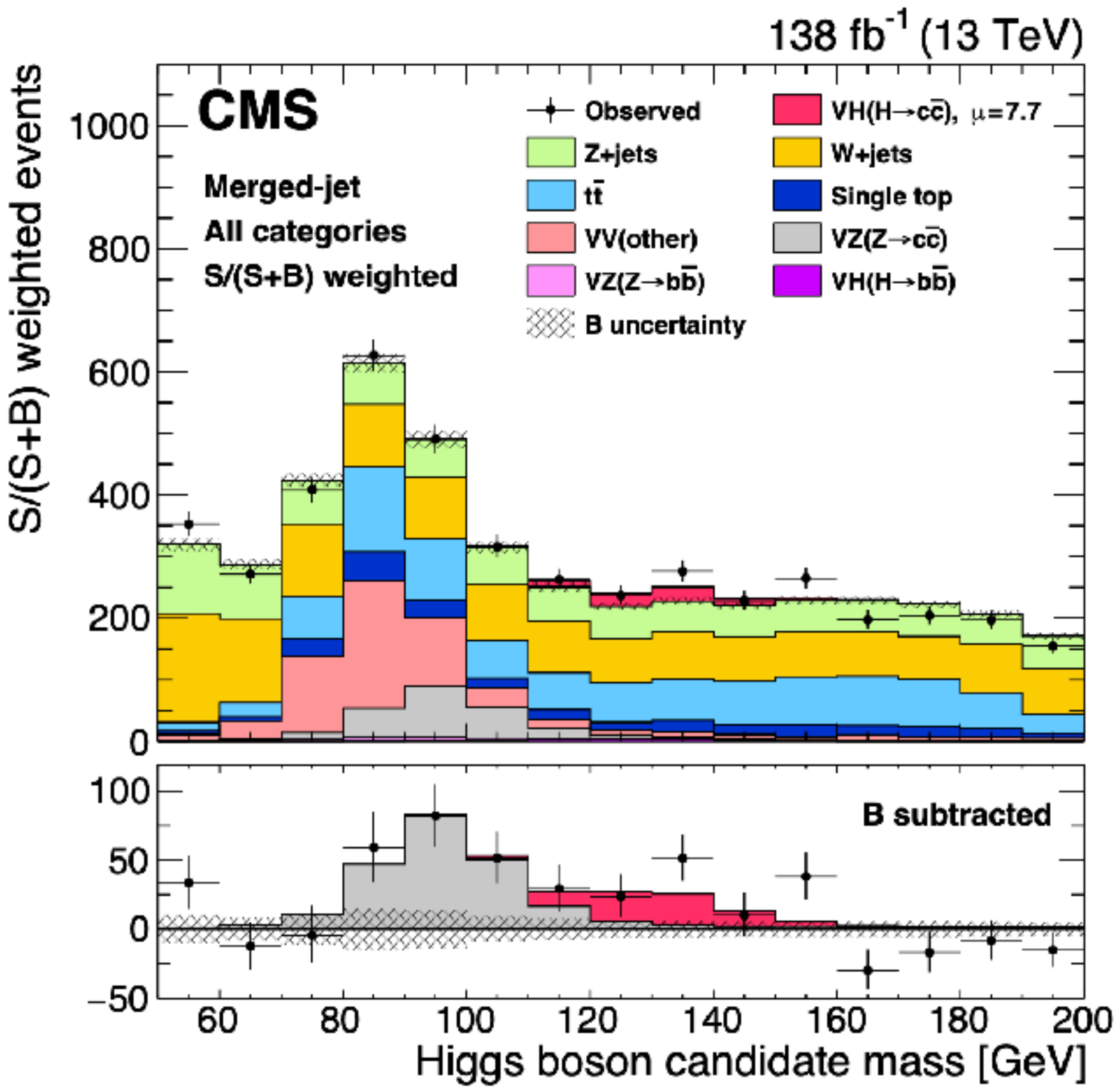
The challenging Yukawa coupling to charm

CMS analysis on full Run 2 data

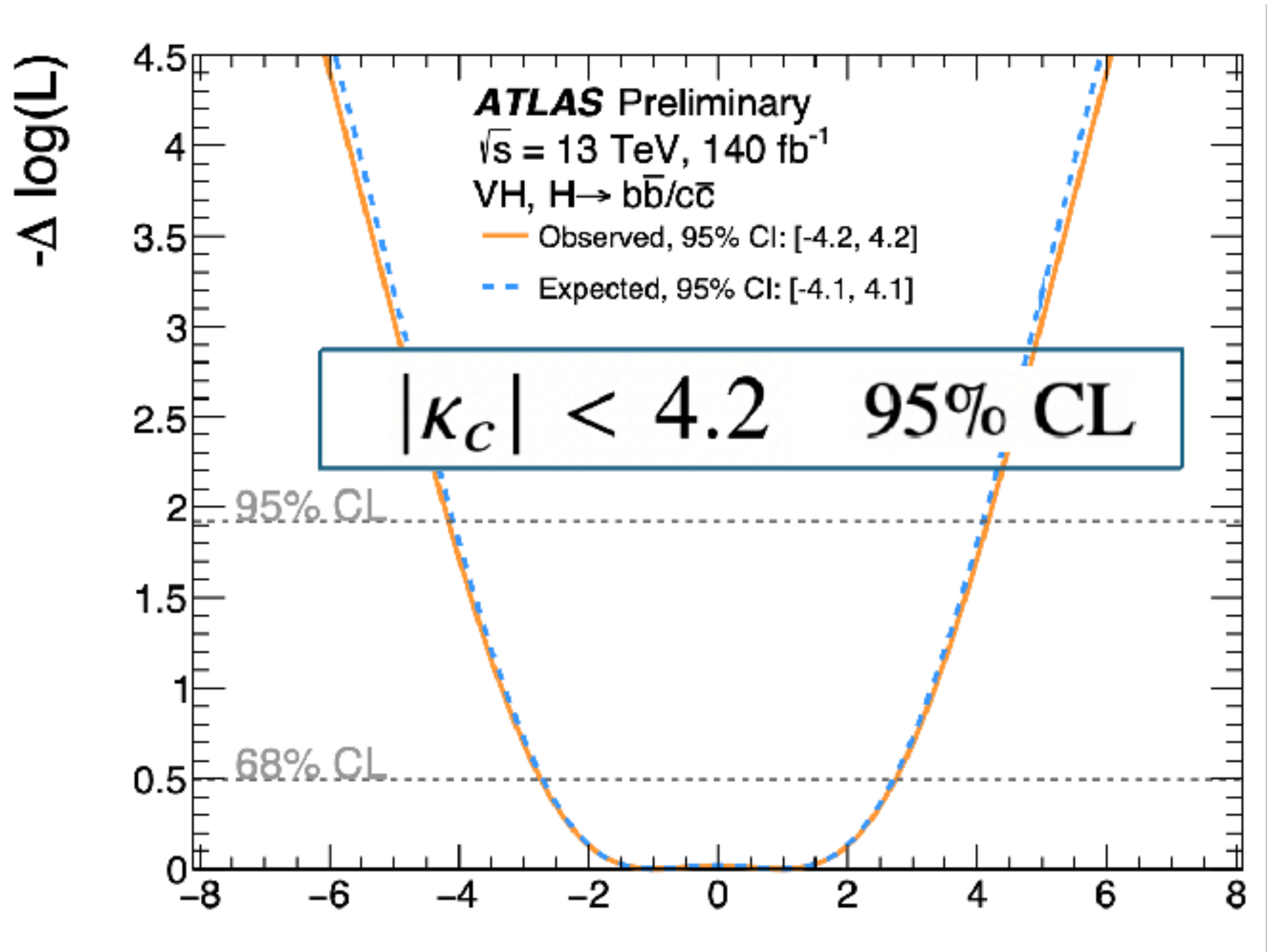
Signal strength:
$\mu < 14.4$

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

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



Refined analysis of Run 2 data with now Graph NN charm tagging!



kc < 8.5 in previous results

$$^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.6}_{-3.5}\,(\text{syst.}).$$

Improvement by a factor of 2 w.r.t. previous result

The challenging Yukawa coupling to charm

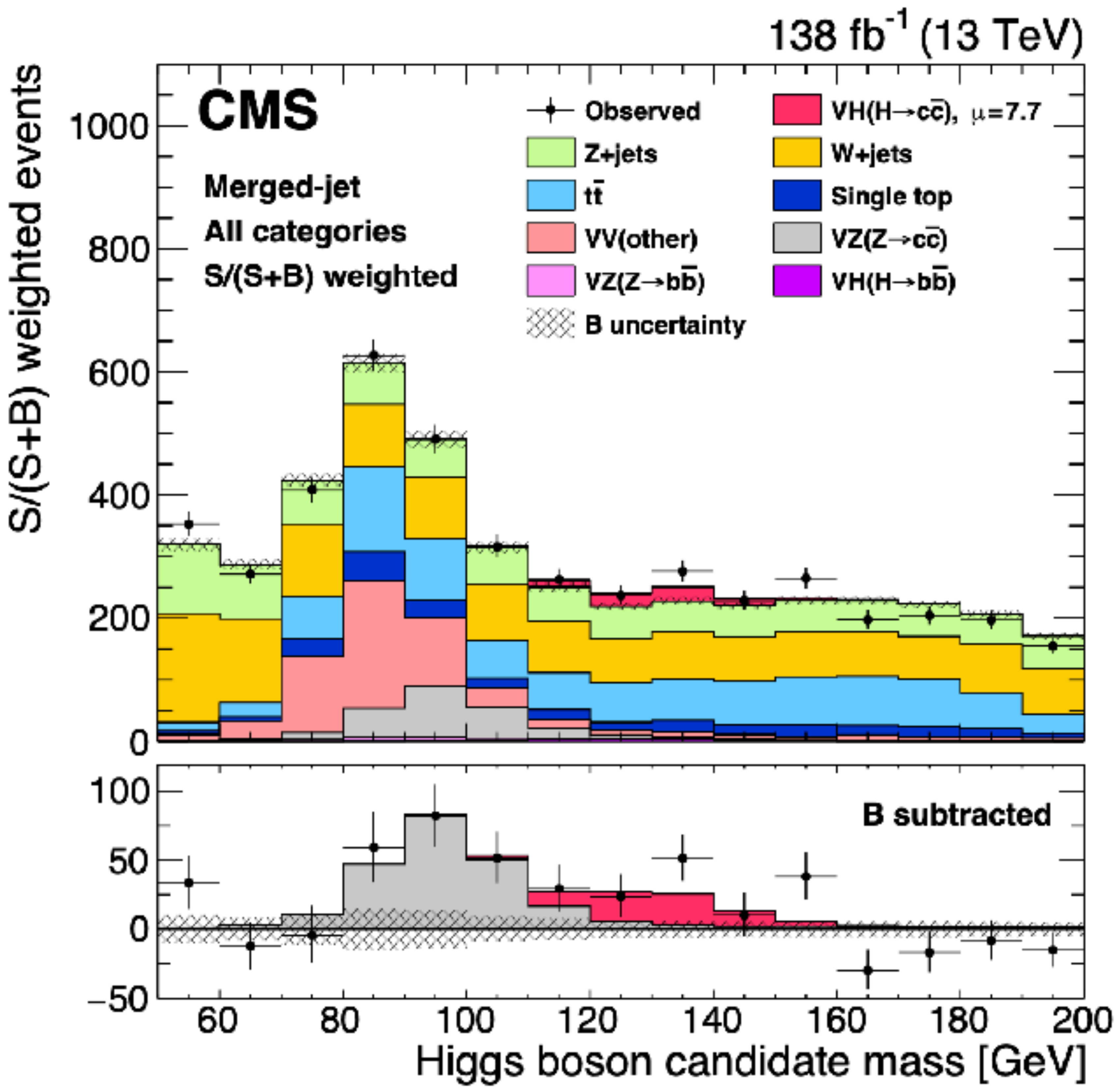
CMS analysis on full Run 2 data

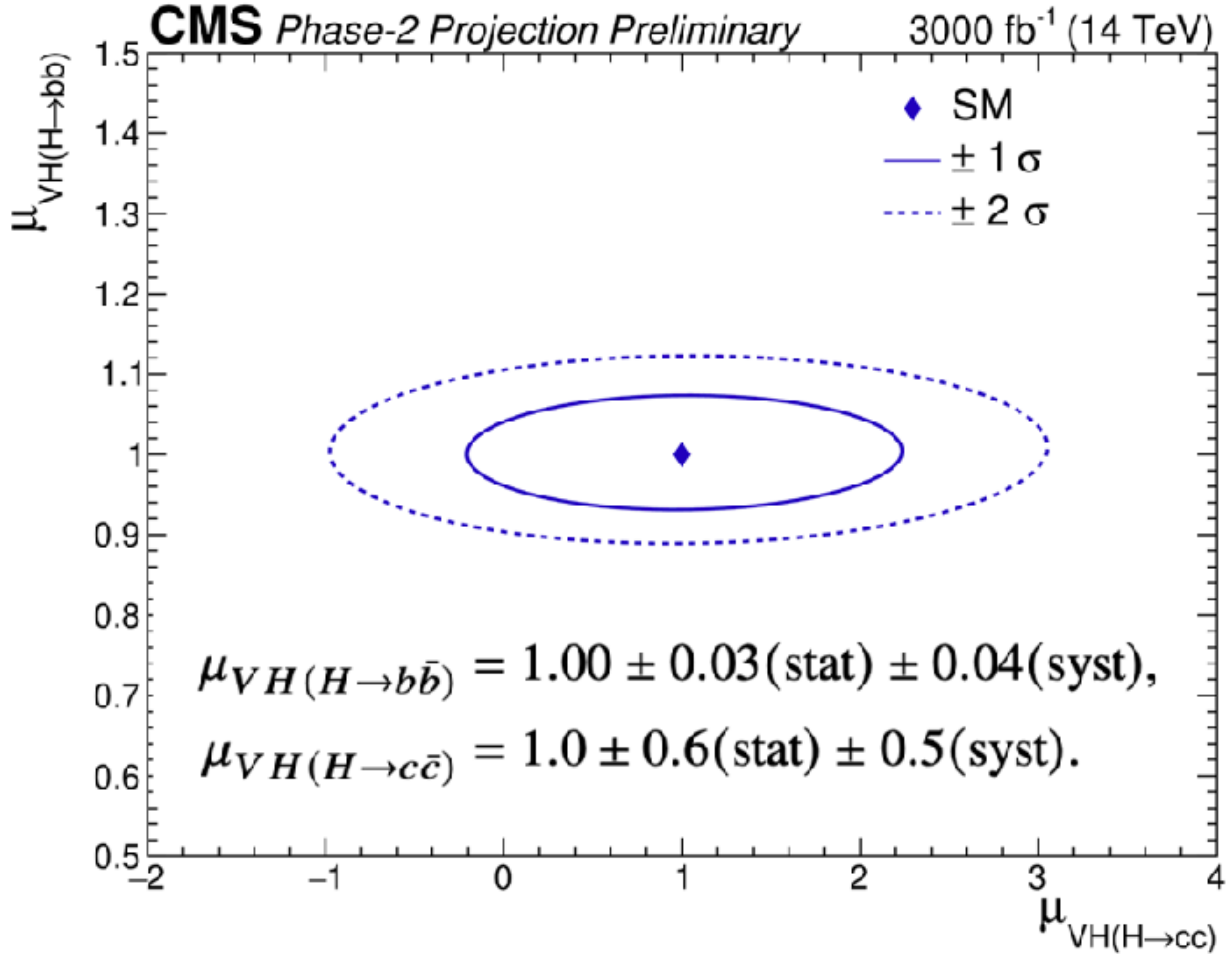
CMS Projection !

Signal strength:
μ < 14.4

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

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





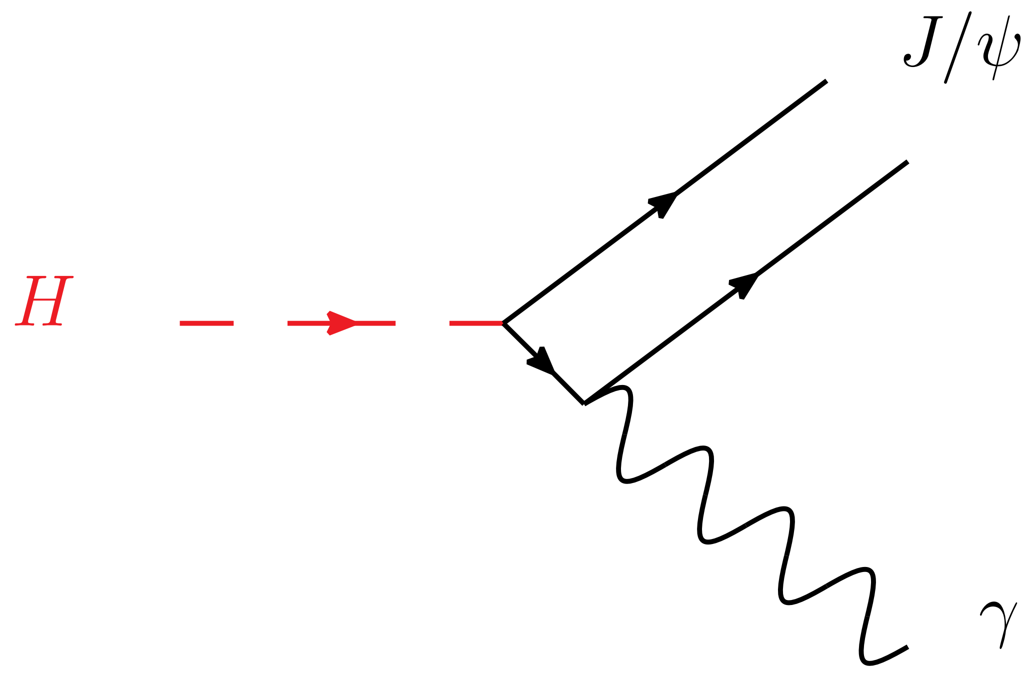
This result is very encouraging on the possibility of being sensitivity to this process at the LHC

More on the 2d Generation (charm) Yukawa Couplings

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

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

Discussed in Lecture 3



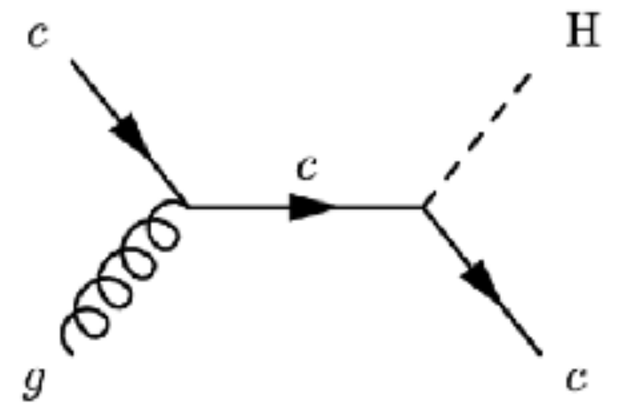
$\mu^+\mu^-\gamma$

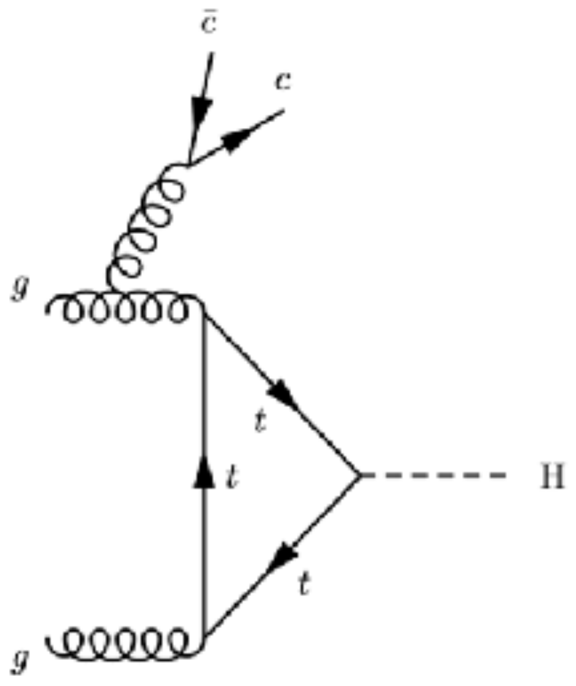
Sensitivity to gamma-gamma* (top loop) and interference

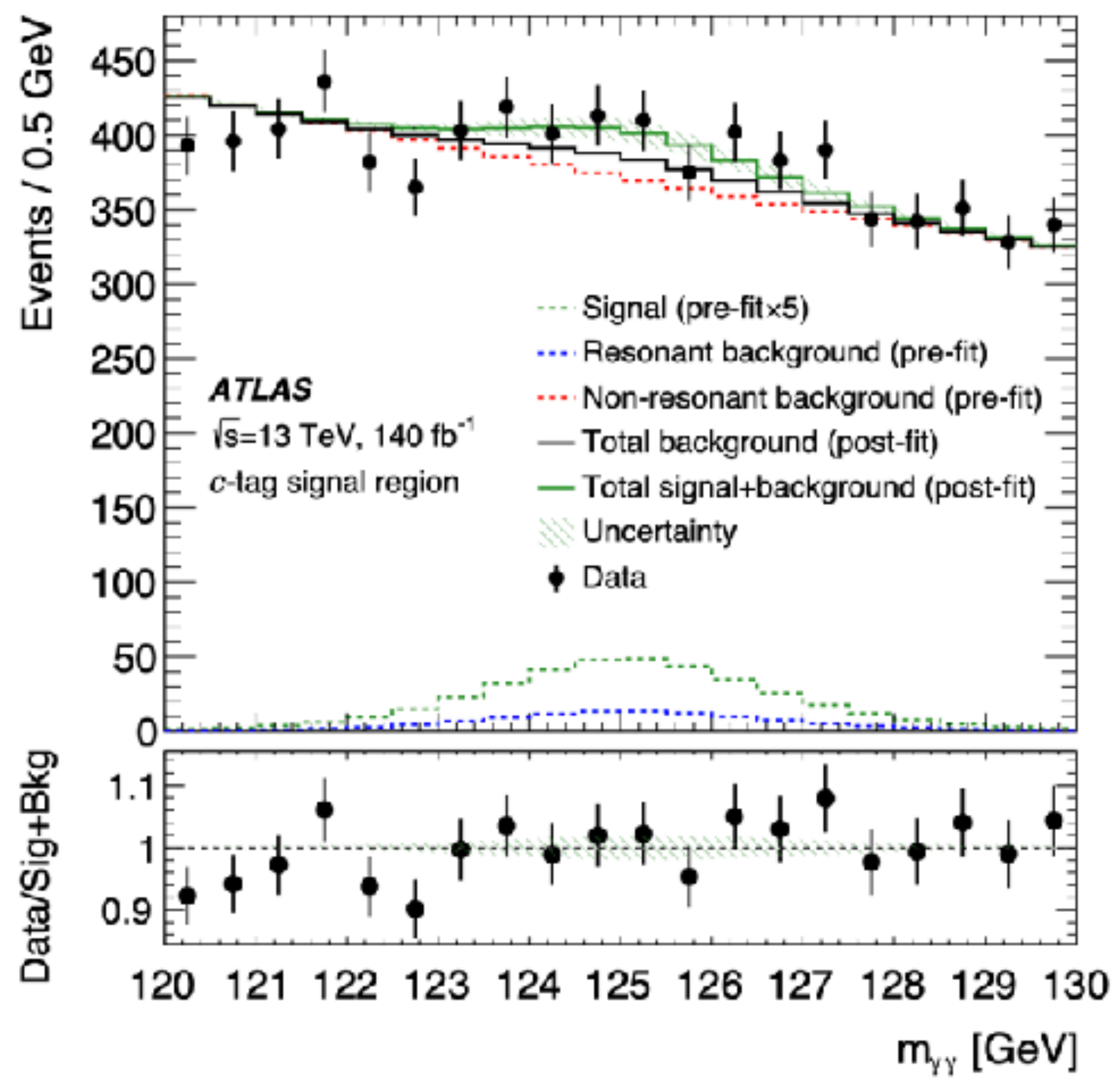
HL-LHC
<15xSM

Higgs and charm associated production

Charm Yukawa process subdominant (~1%)







ATLAS paper
CMS paper

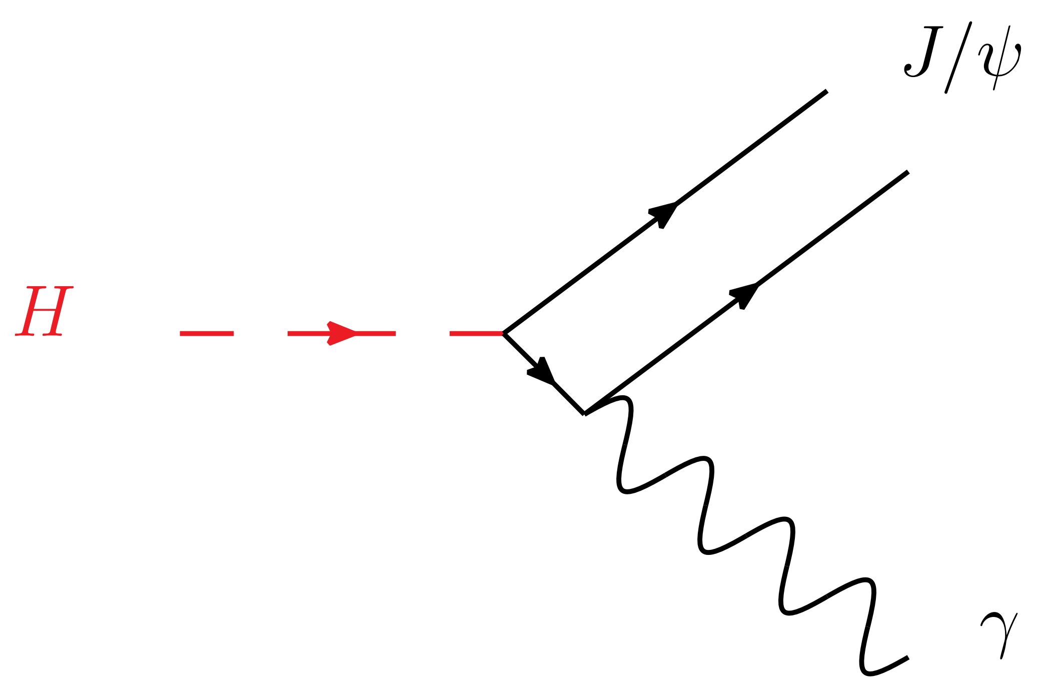
ATLAS and CMS analyses sensitive at the 1σ level, CMS places a limit on the charm Yukawa < 243 (355)

More on the 2d Generation (charm) Yukawa Couplings

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

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

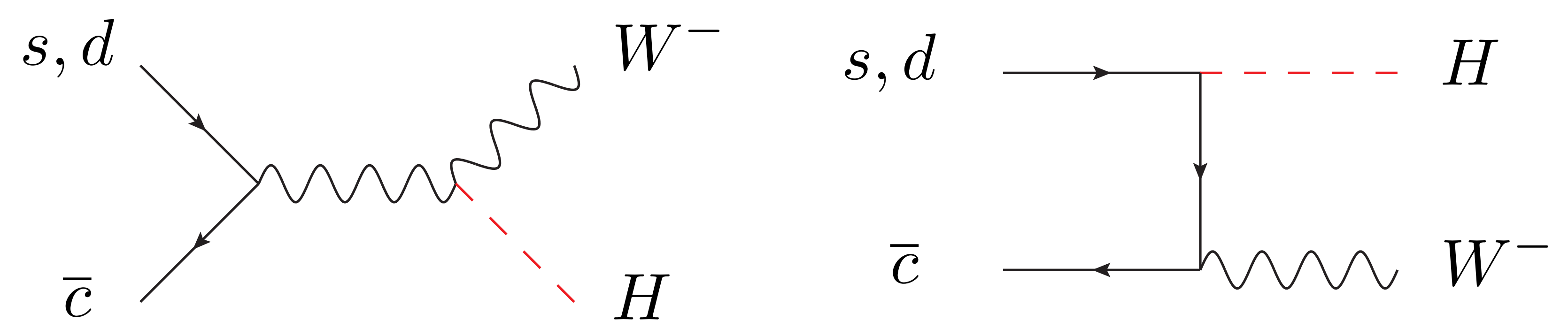
Discussed in Lecture 3



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

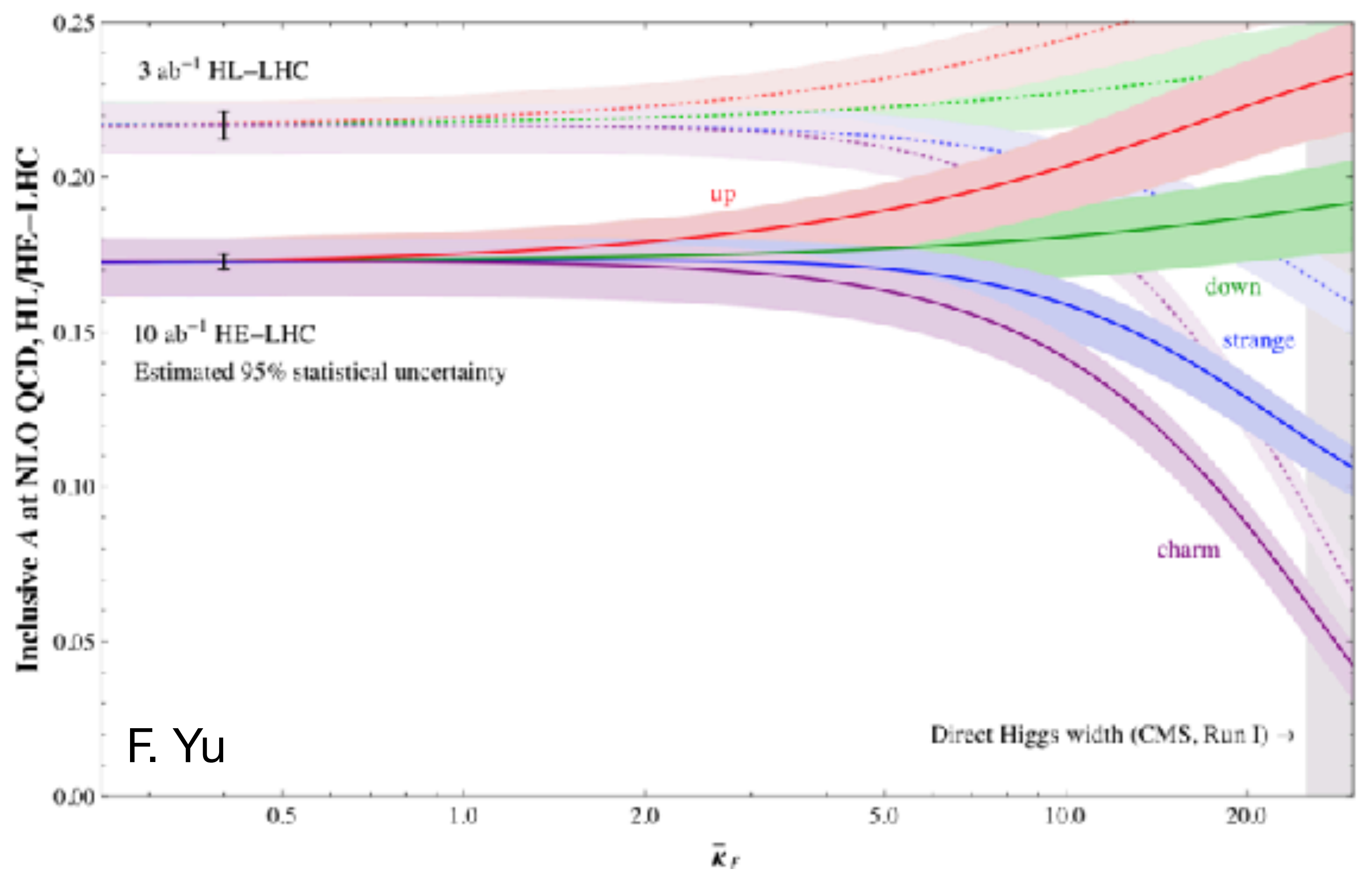
Sensitivity to gamma-gamma* (top loop) and interference

HL-LHC
<15xSM



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.

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

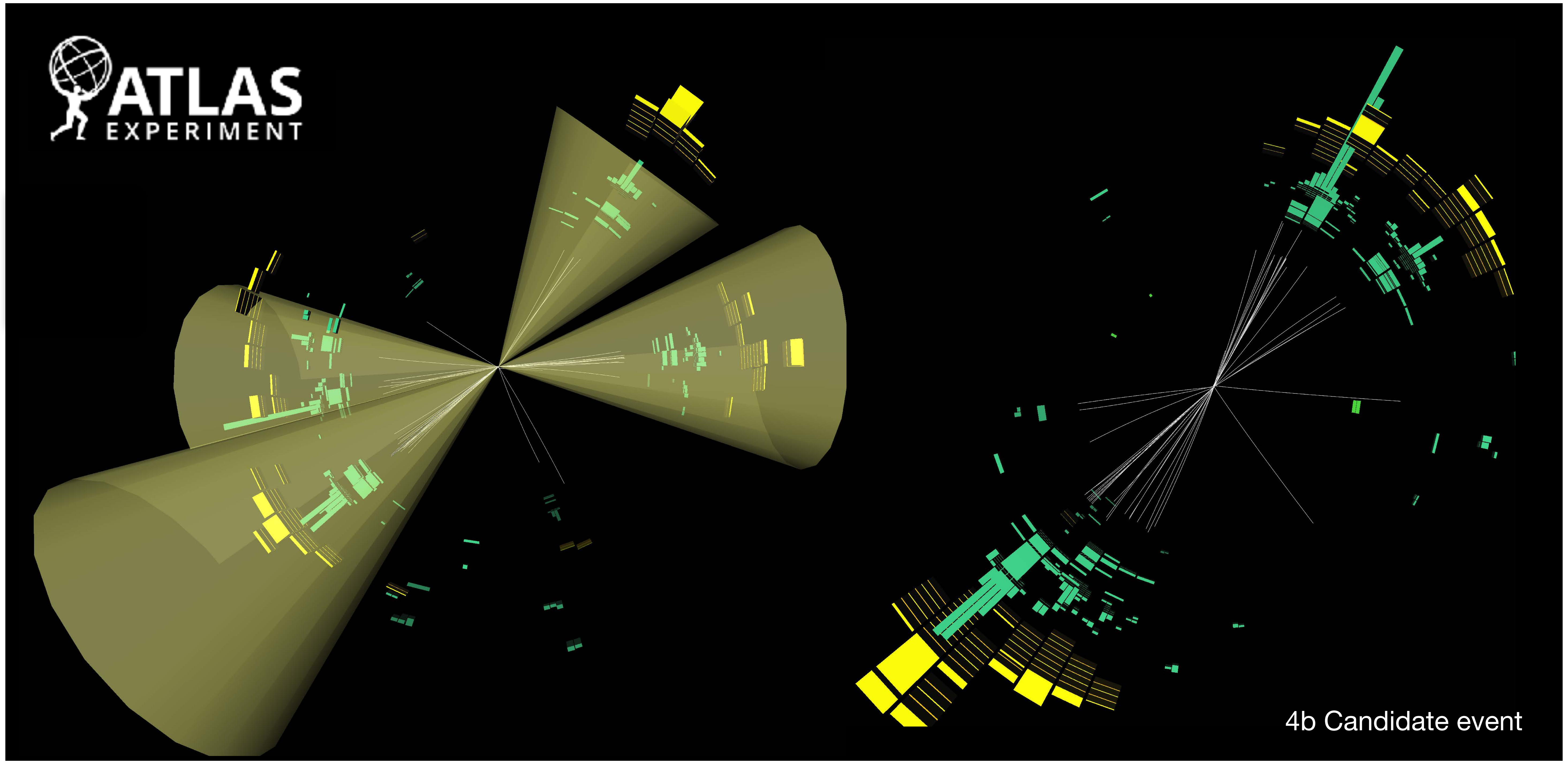
Very similar analysis as the Off-shell Higgs couplings!

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

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

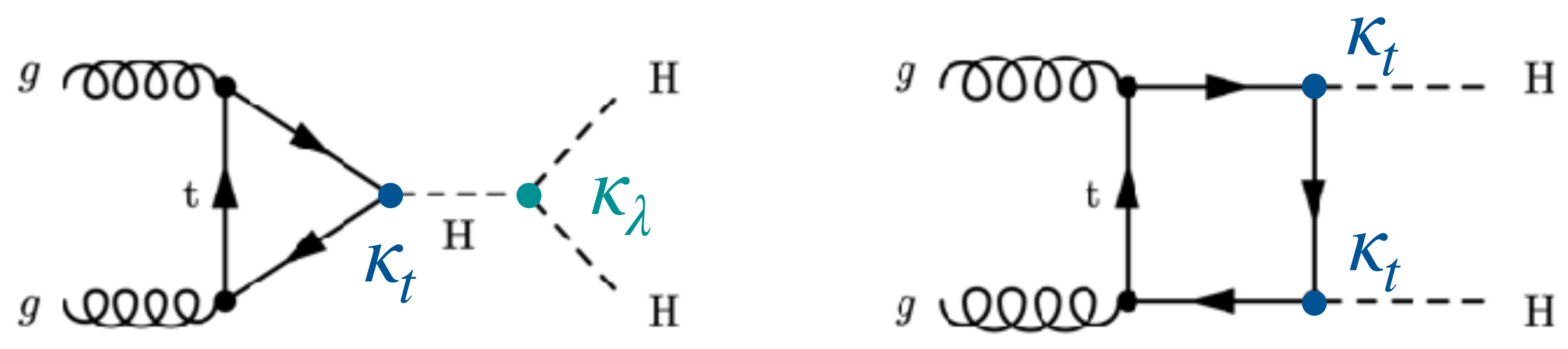
Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

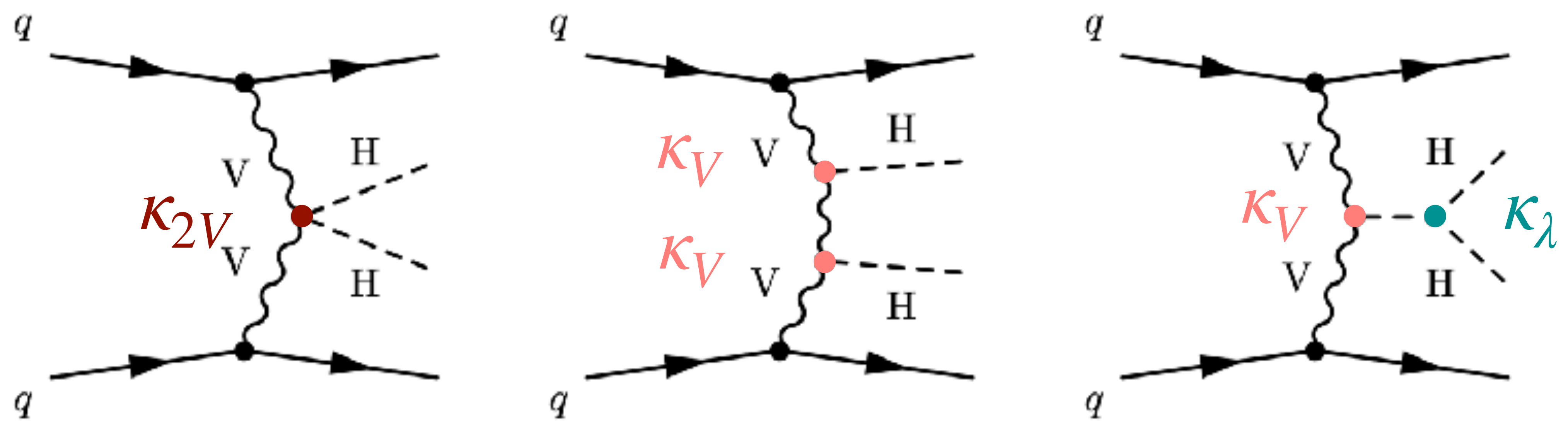
Fairly complex signatures (not outrageously so!)



HH Production and Higgs Self coupling

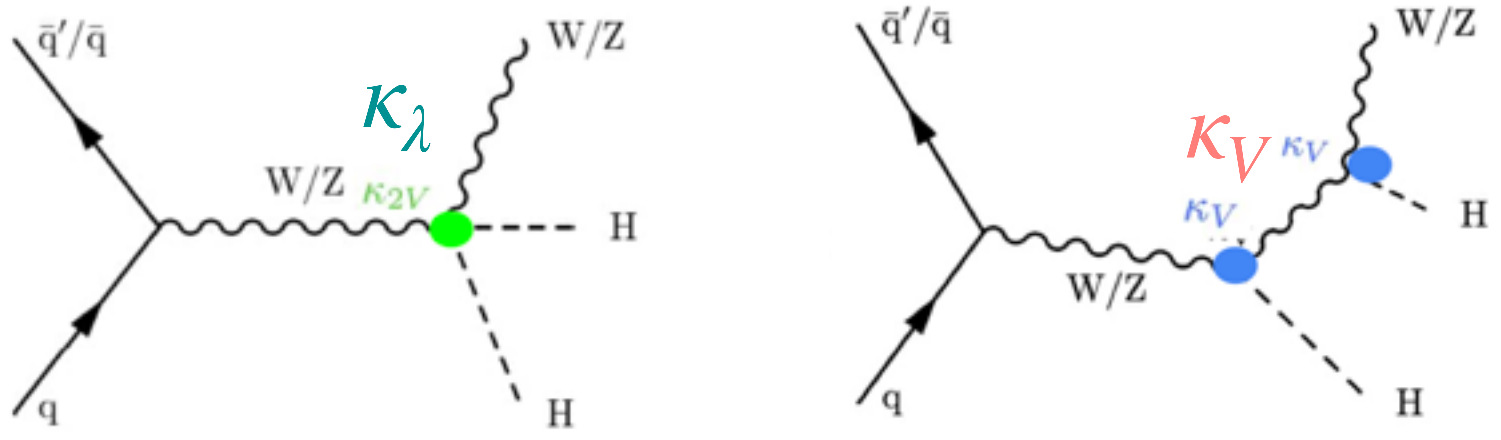
Higgs pair production through gluon fusion (VH and VBF)





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

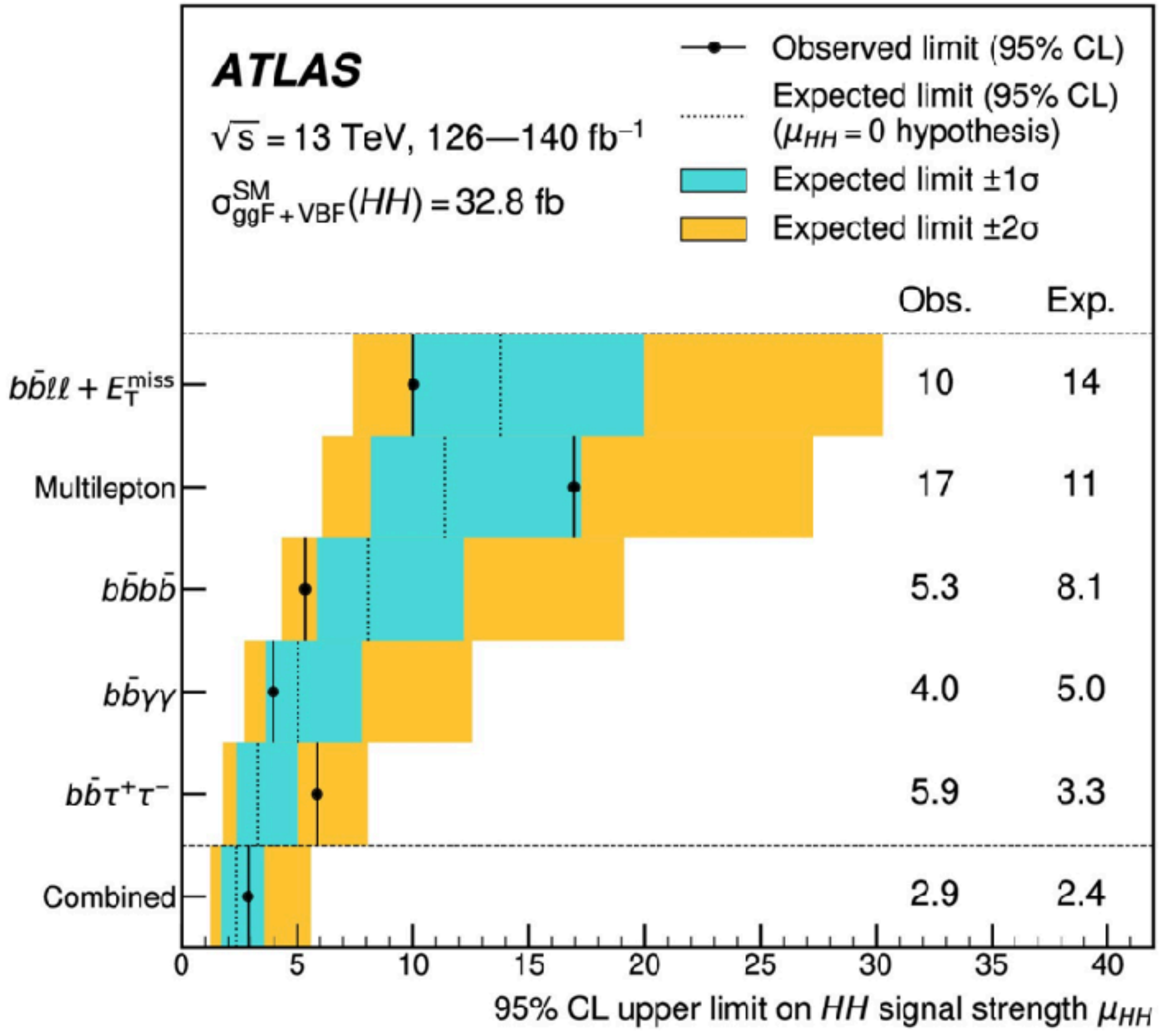
Bishara, Contino, Rojo



Most recent results from CMS

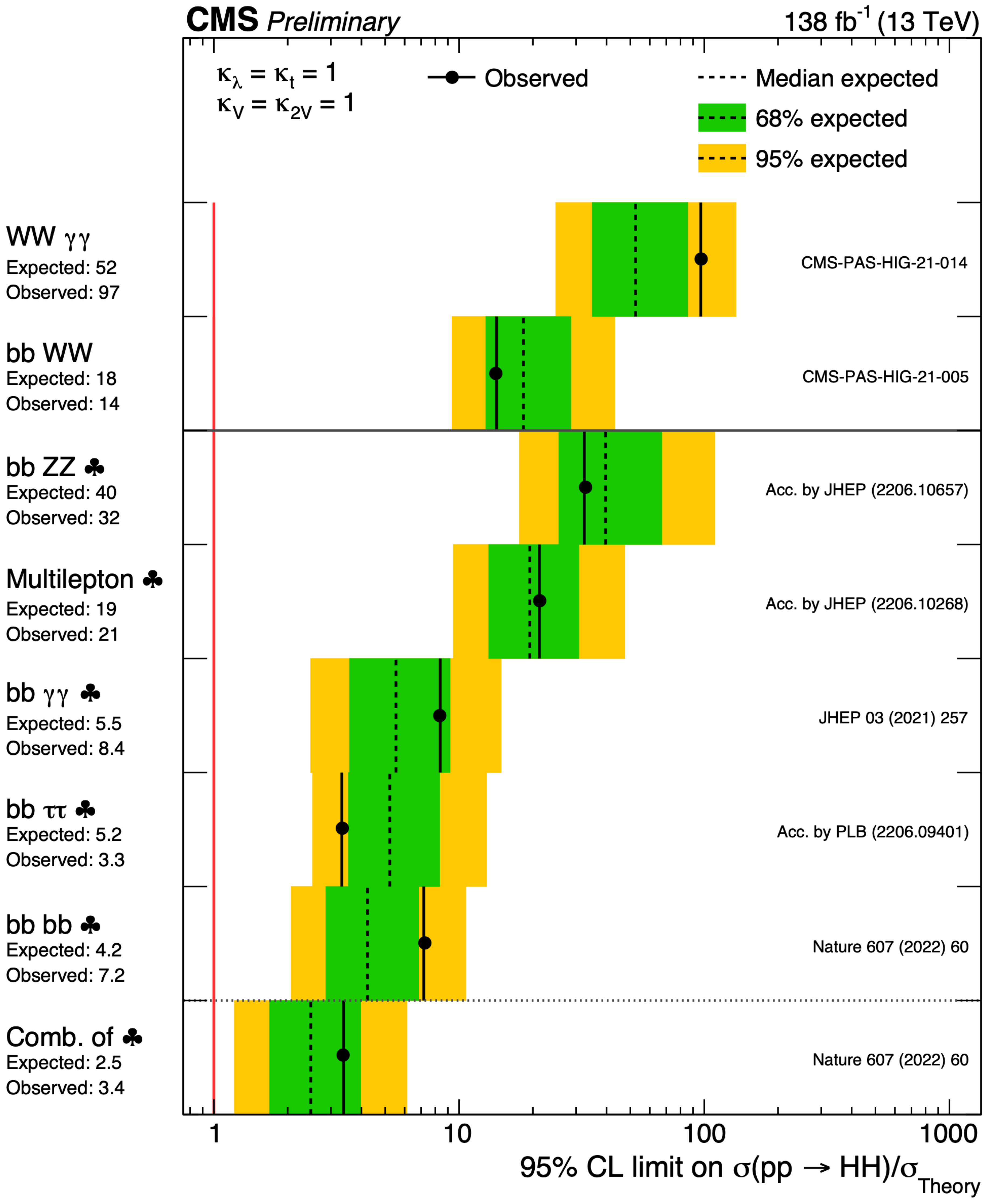
ttH not impossible (not done yet)

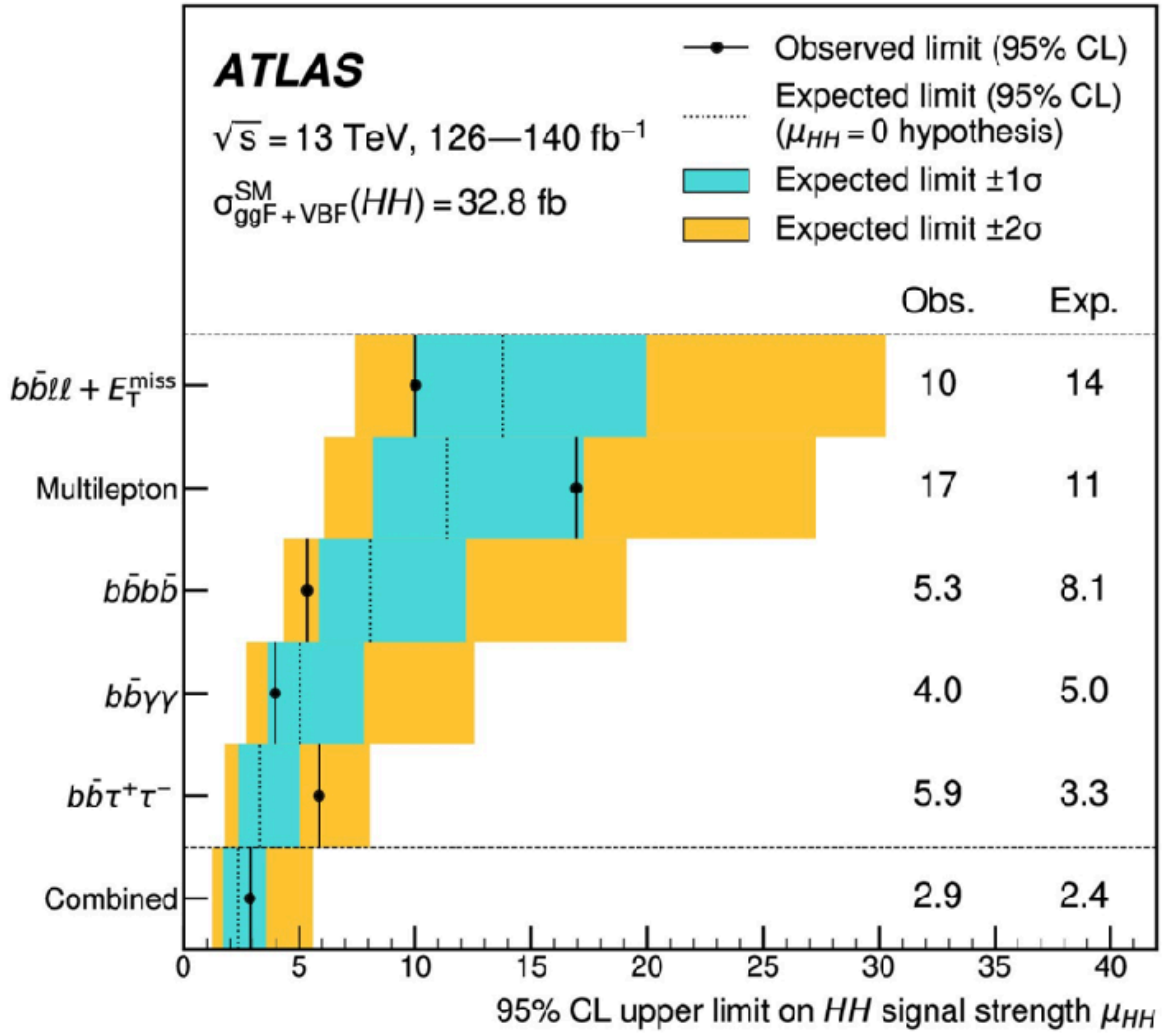
Multiple channels investigated: depending on both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!



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

Higgs Self Coupling and HH Production





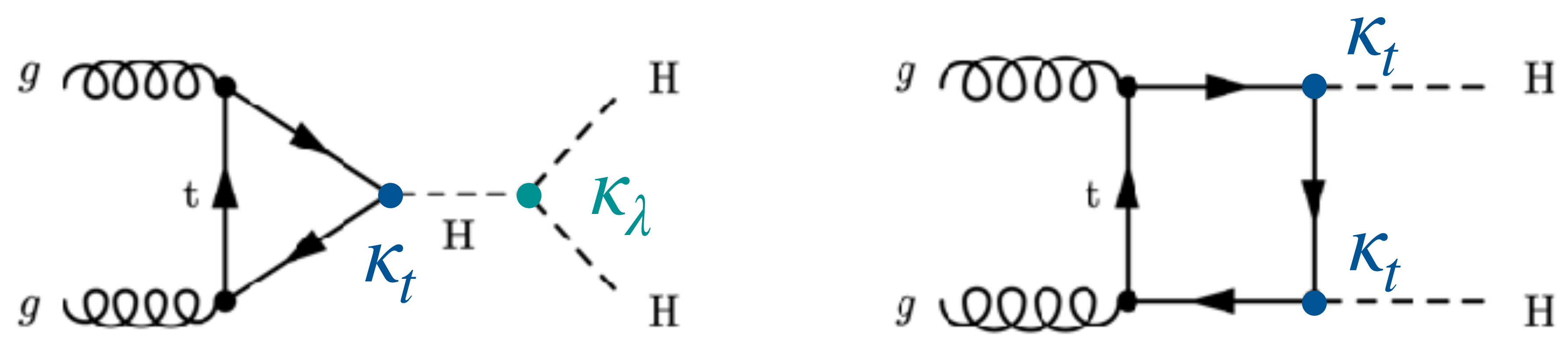
Observed limits start deviating from expectation!!

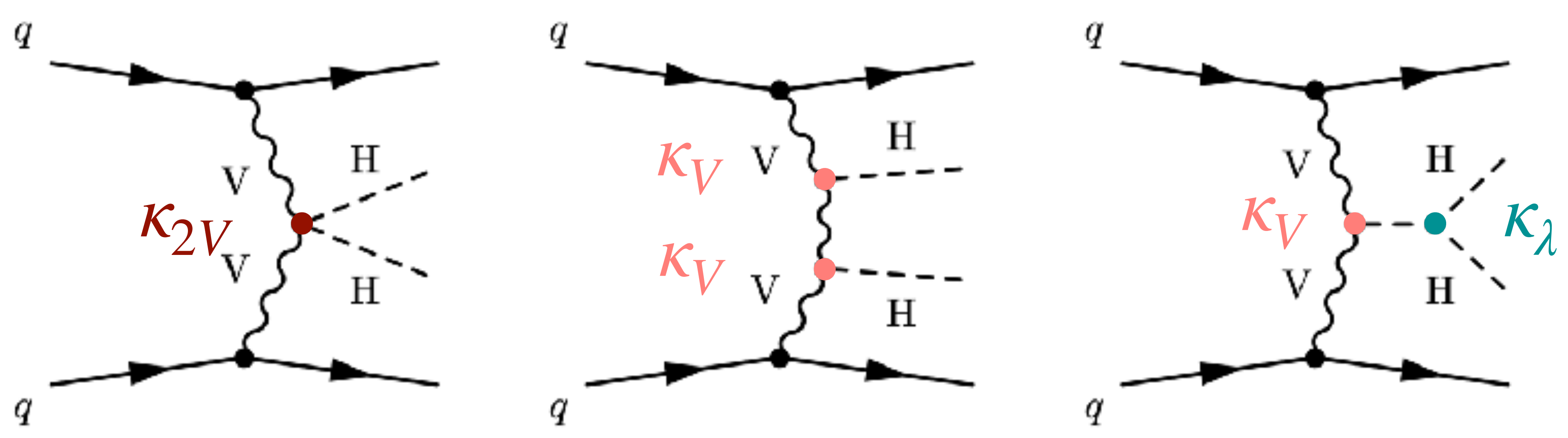
Both experiments have ~1σ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS ~1σ) with Run 2!!

Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3σ**

HH Production and Higgs Self coupling

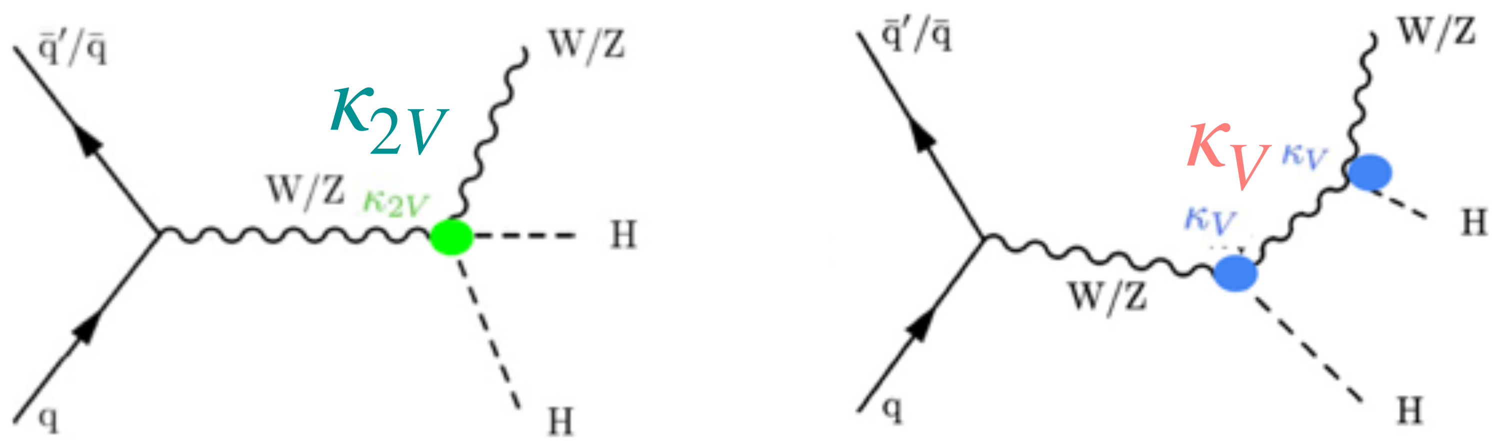
Higgs pair production through gluon fusion (VH and VBF)





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

[Bishara, Contino, Rojo]



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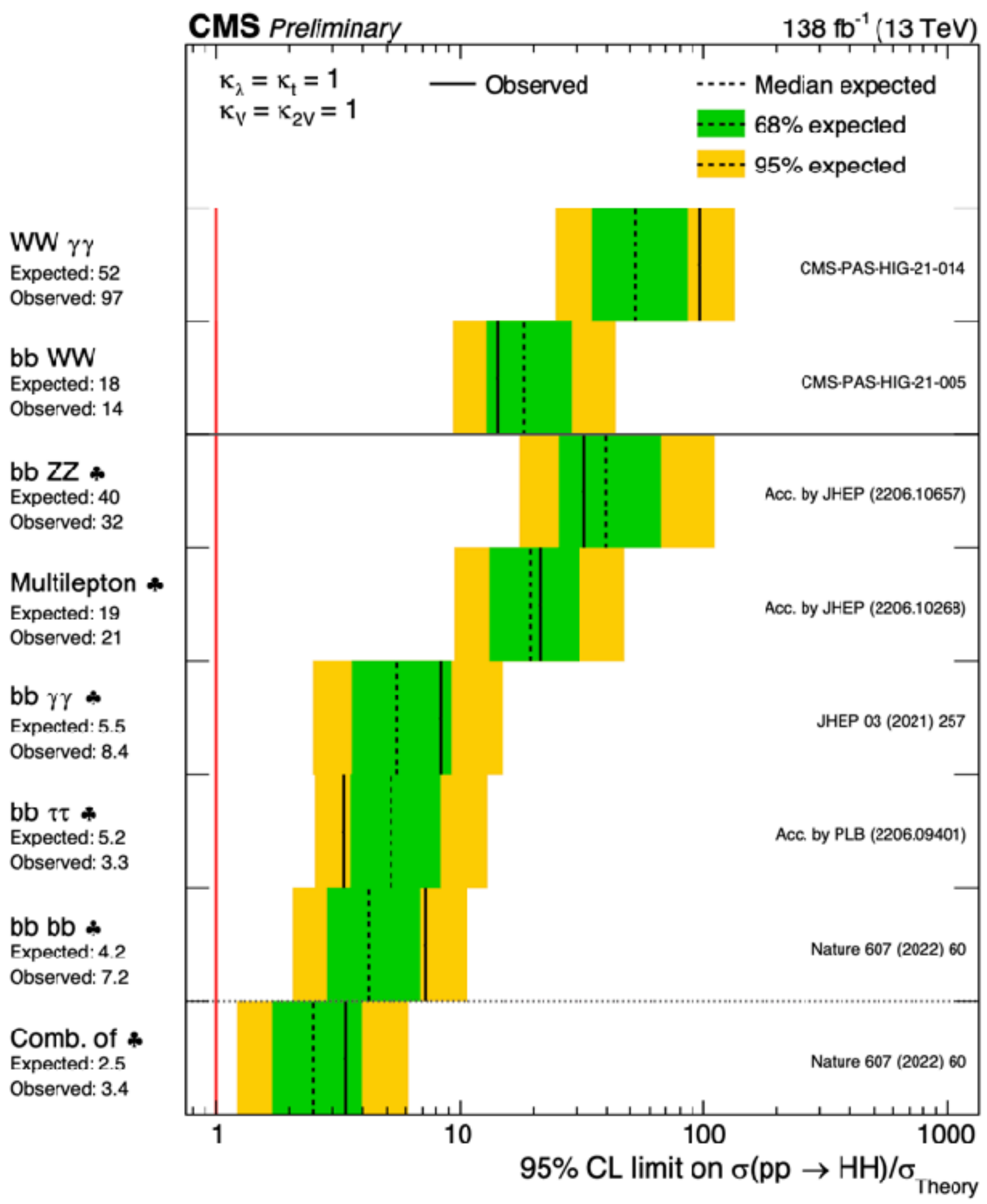

Observed limits start deviating from expectation!!

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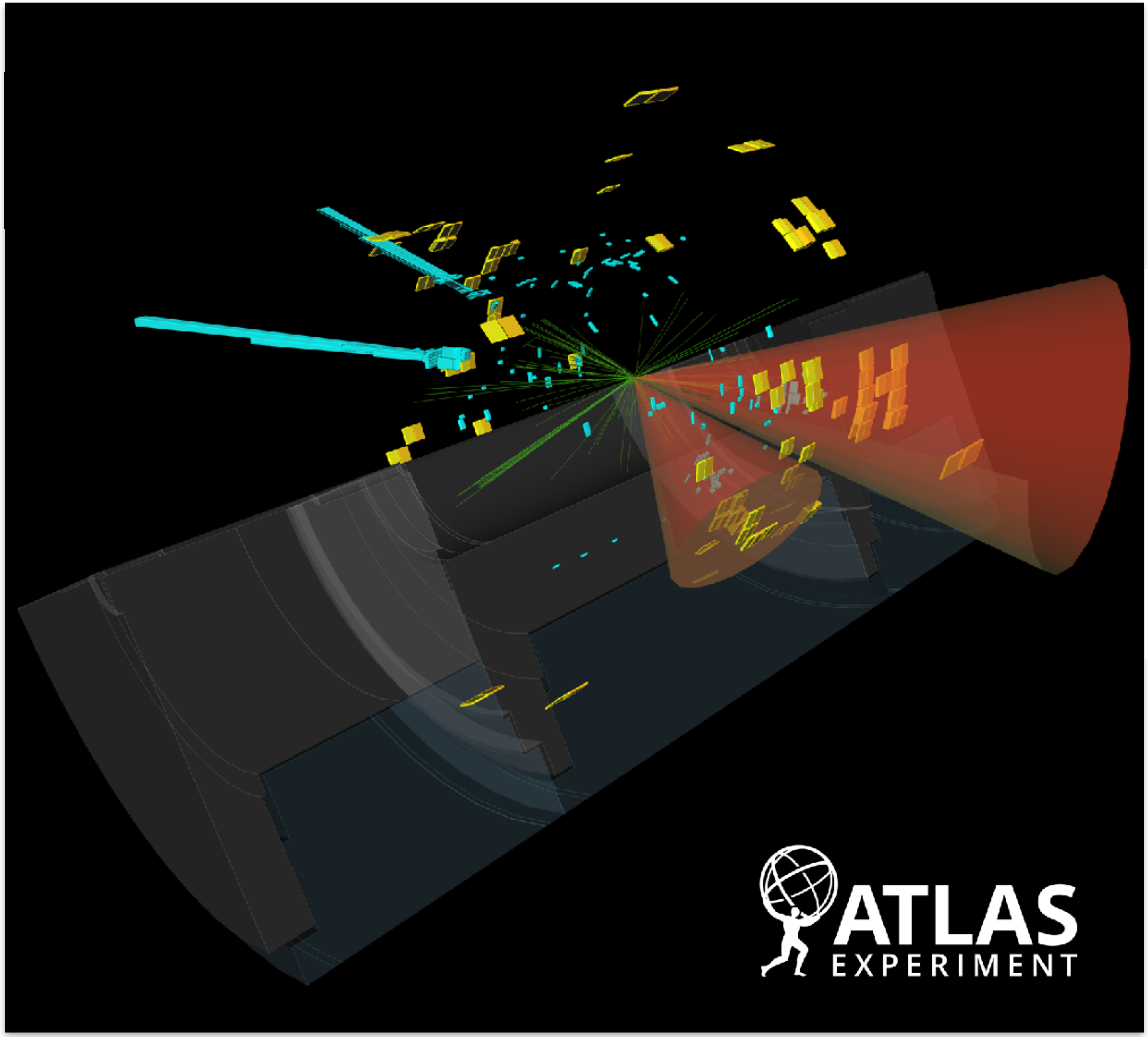
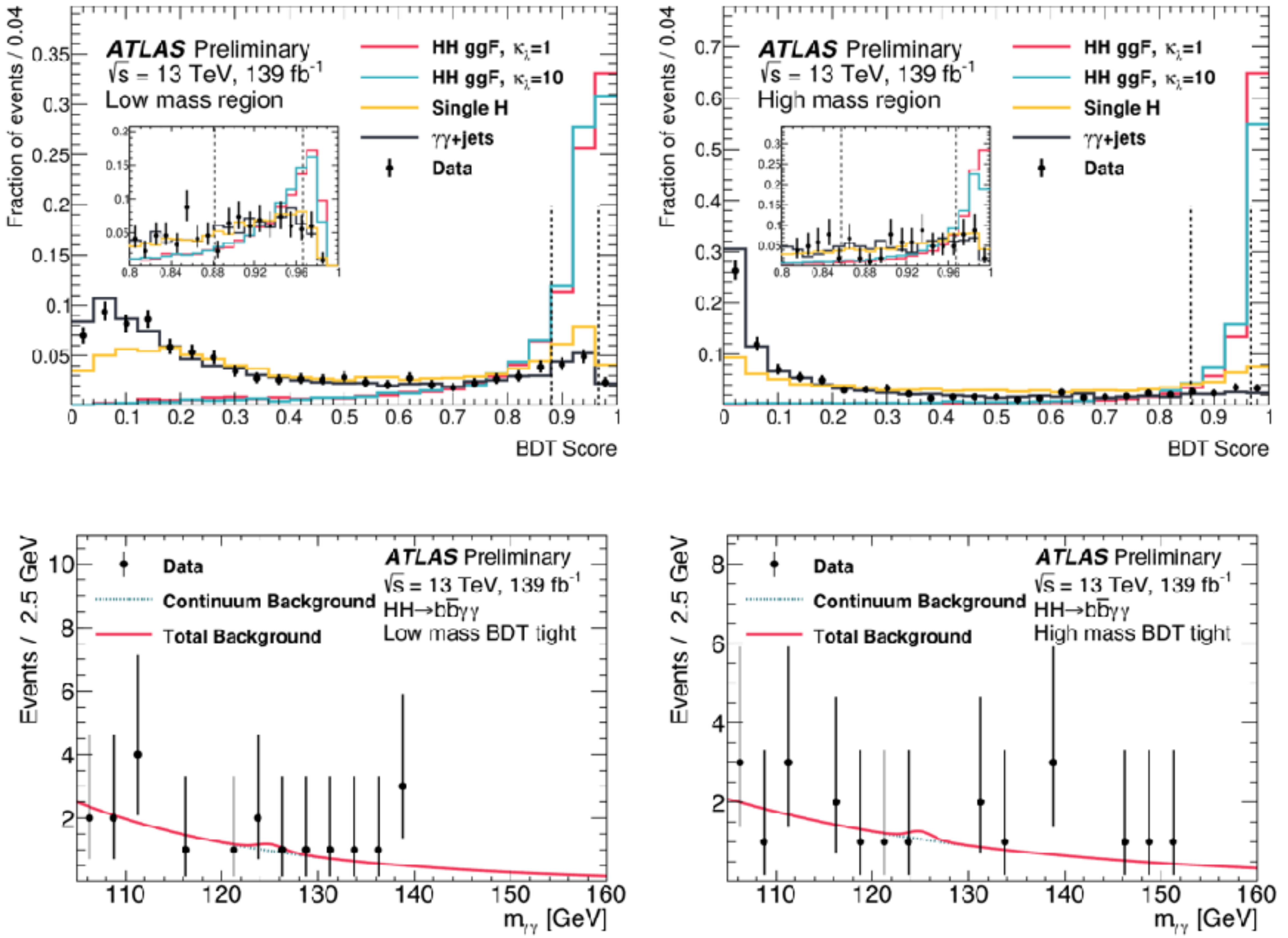
Di-Higgs boson production



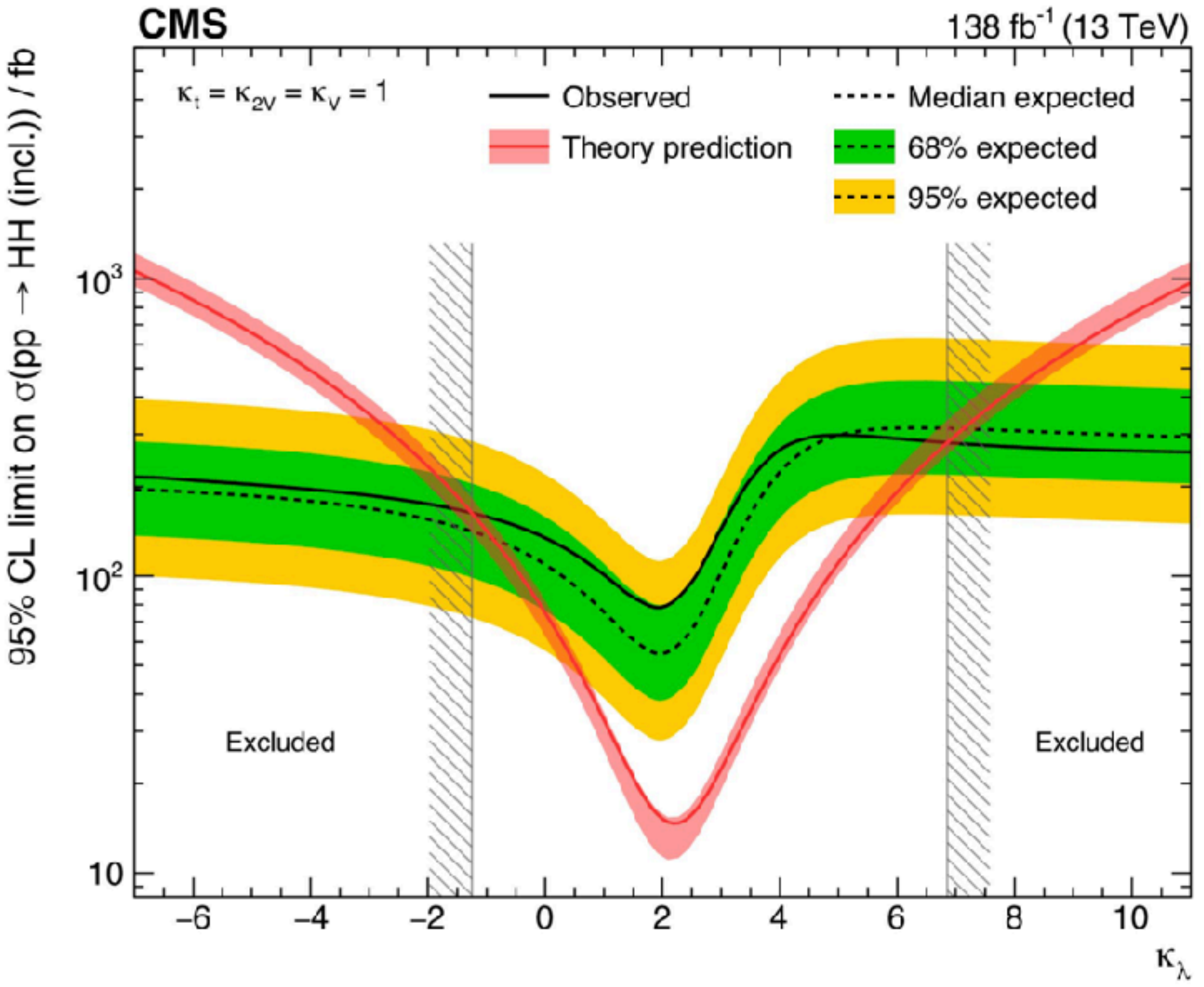
Example using the full Run 2 data set in the $b\bar{b}\gamma\gamma$ channel

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

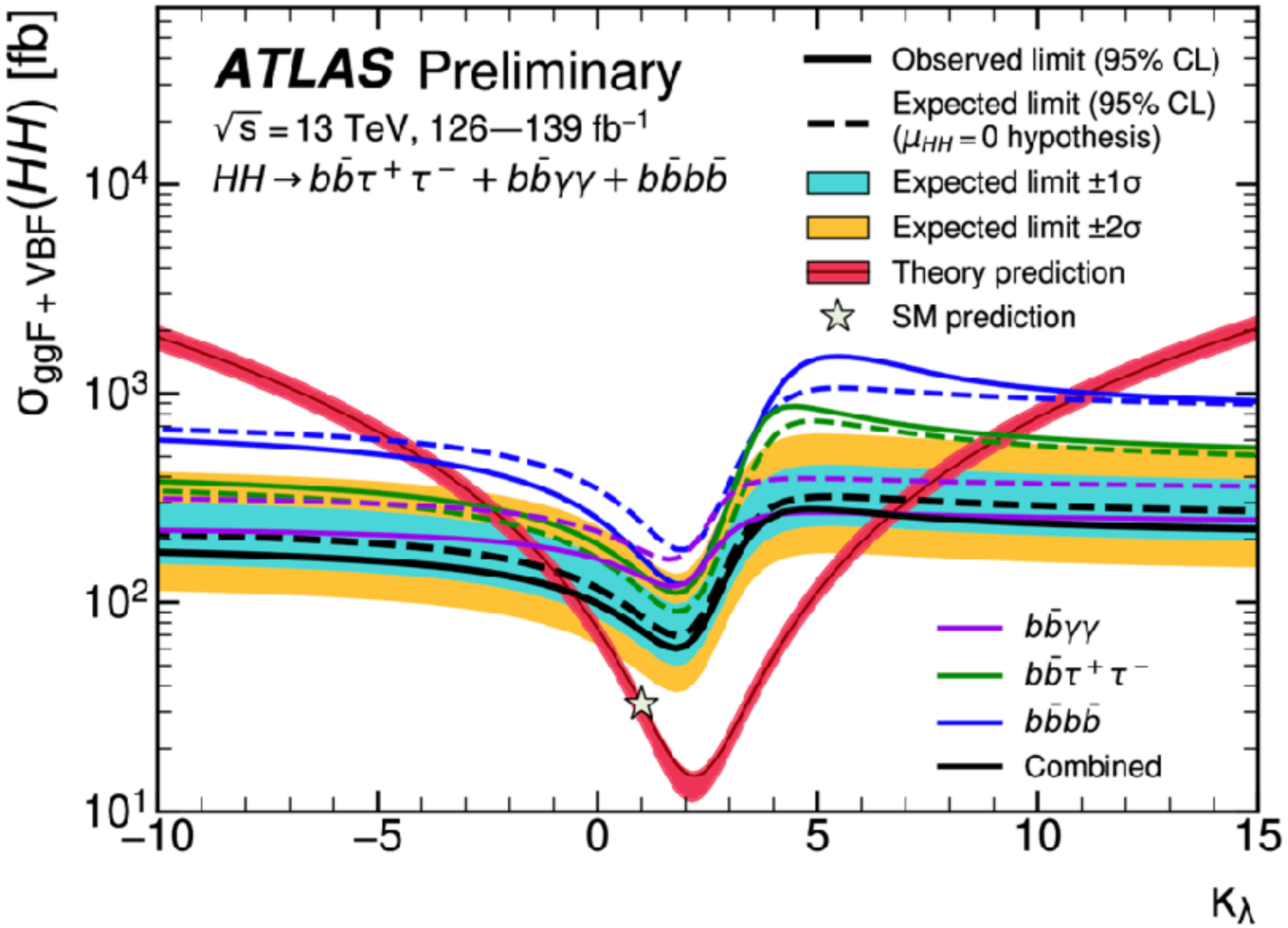
Partial combination in CMS



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

Expected interval similar

Partial combination in ATLAS



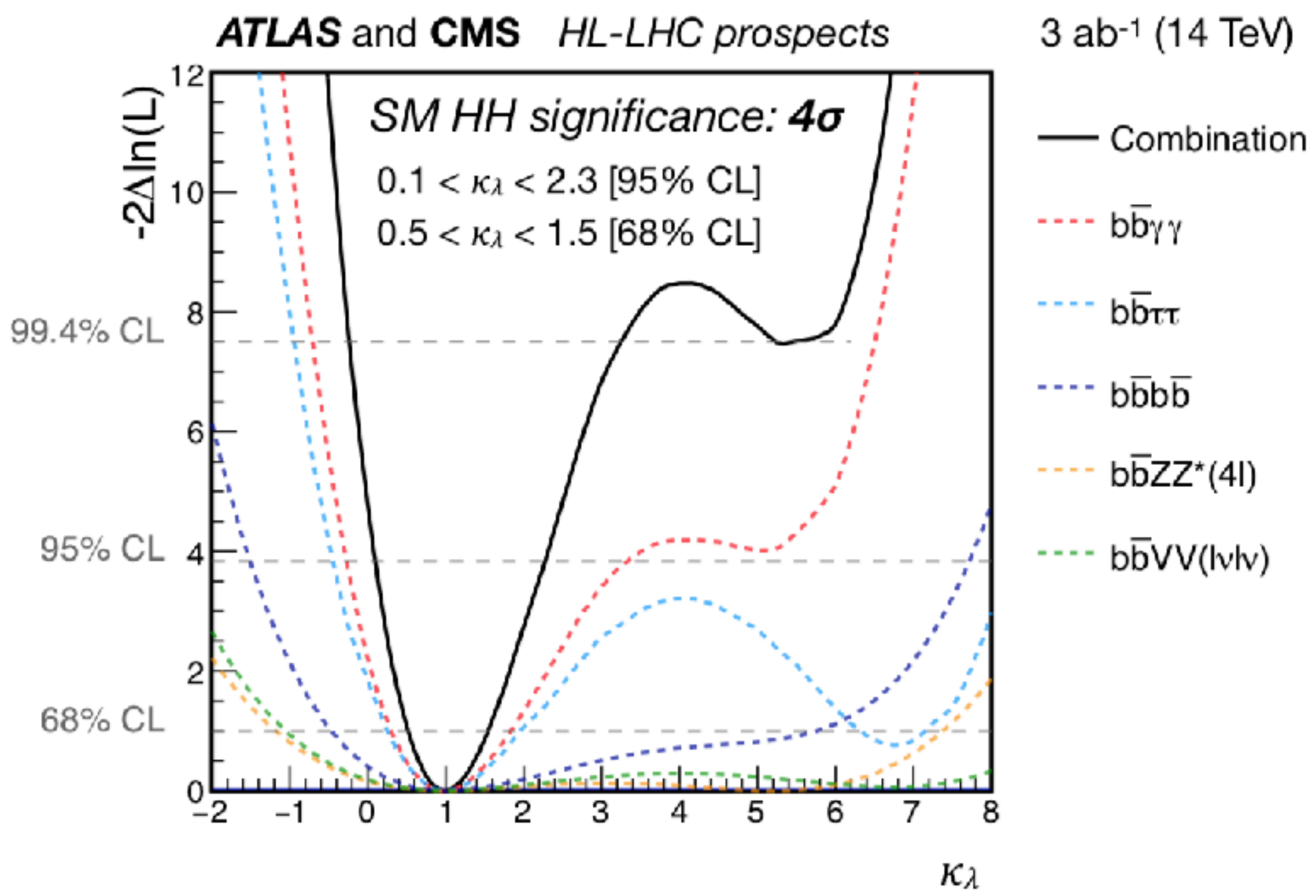
ATLAS

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



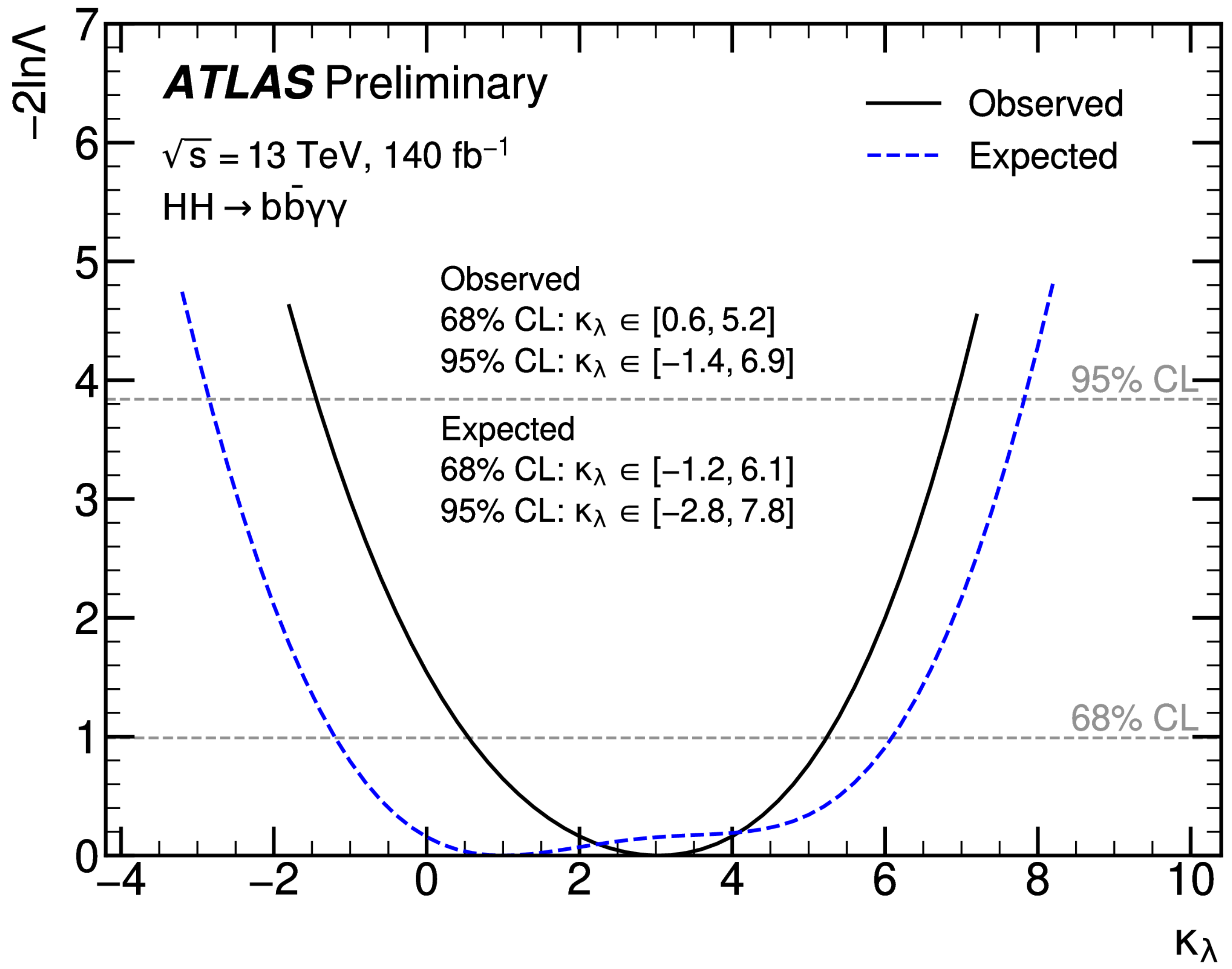
Current estimates yield an observation of an **HH signal at** 4σ

50% level constraints on the Higgs boson self coupling!

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

Already impressive!

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

Extrapolation based on partial Run 2, already significantly!

Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3**σ

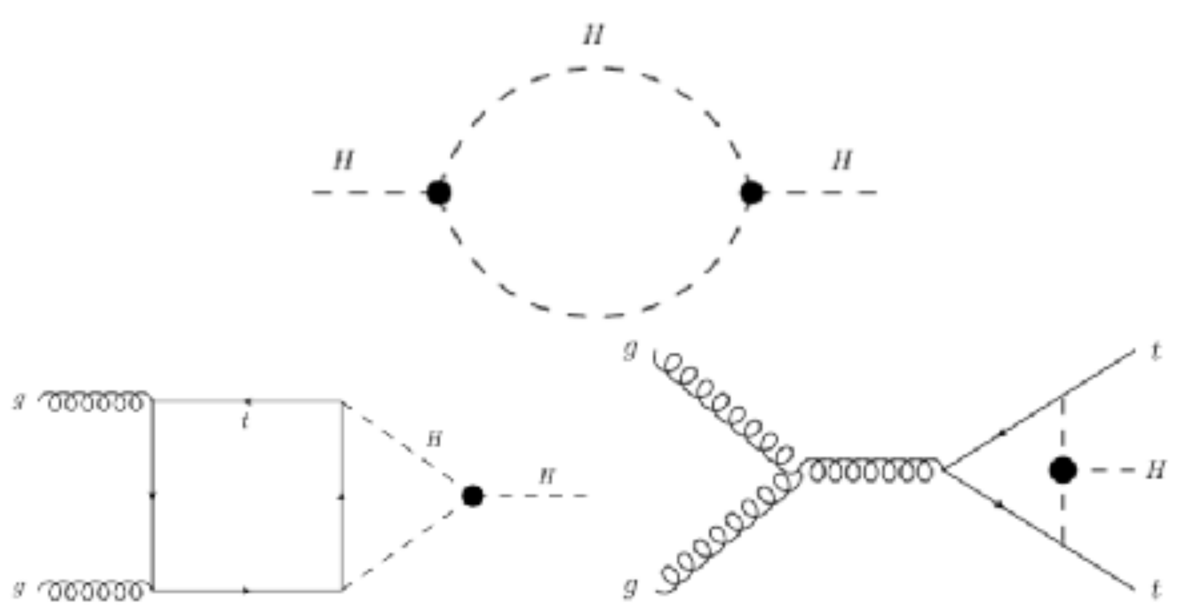
Indirect constraints on Higgs Self Coupling

ATLAS-CONF-2019-049

FTR-2018-020

Indirect constraints from combined STXS

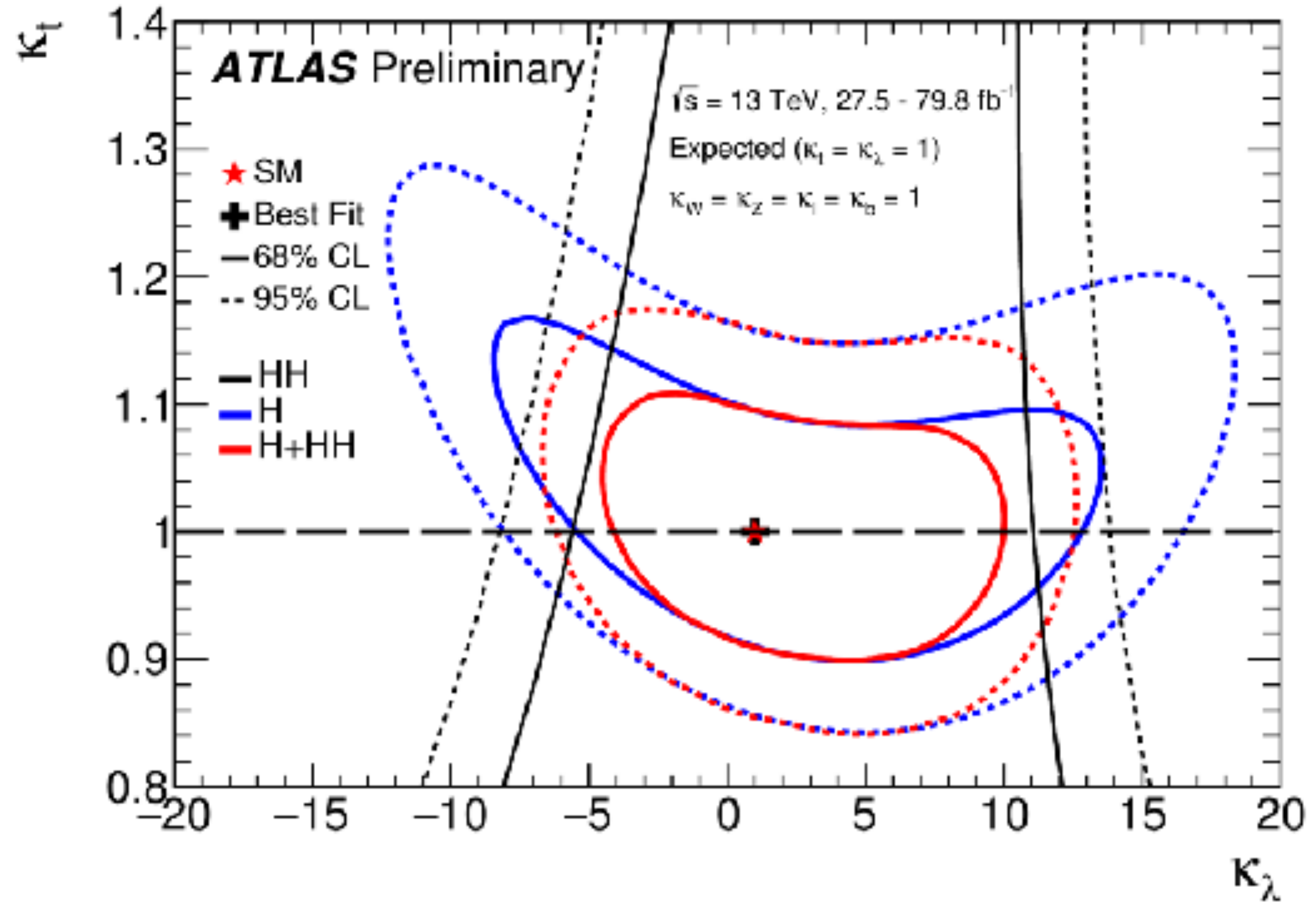
Combination with ATLAS STXSs



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

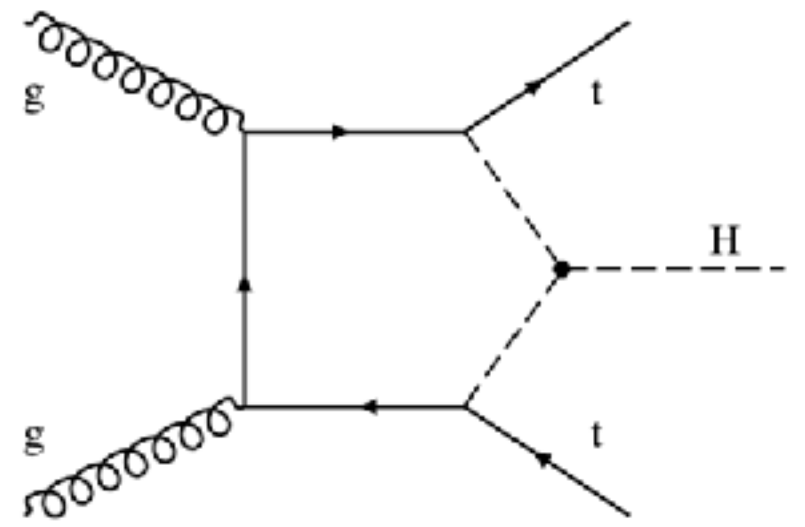
Direct/Indirect currently comparable, direct HH searches will dominate at higher luminosities, but complementarity still necessary to fix κ_t

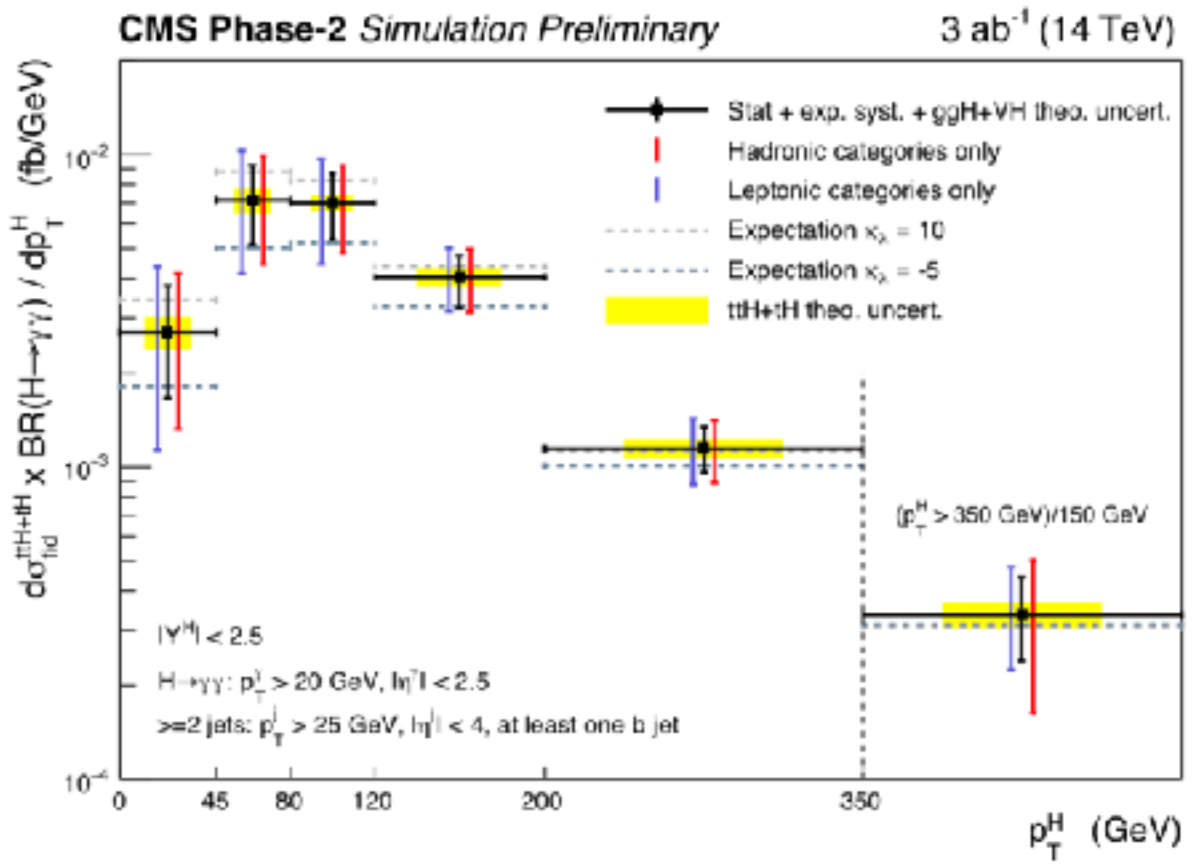
$$-2.3 < \kappa_\lambda < 10.3$$



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

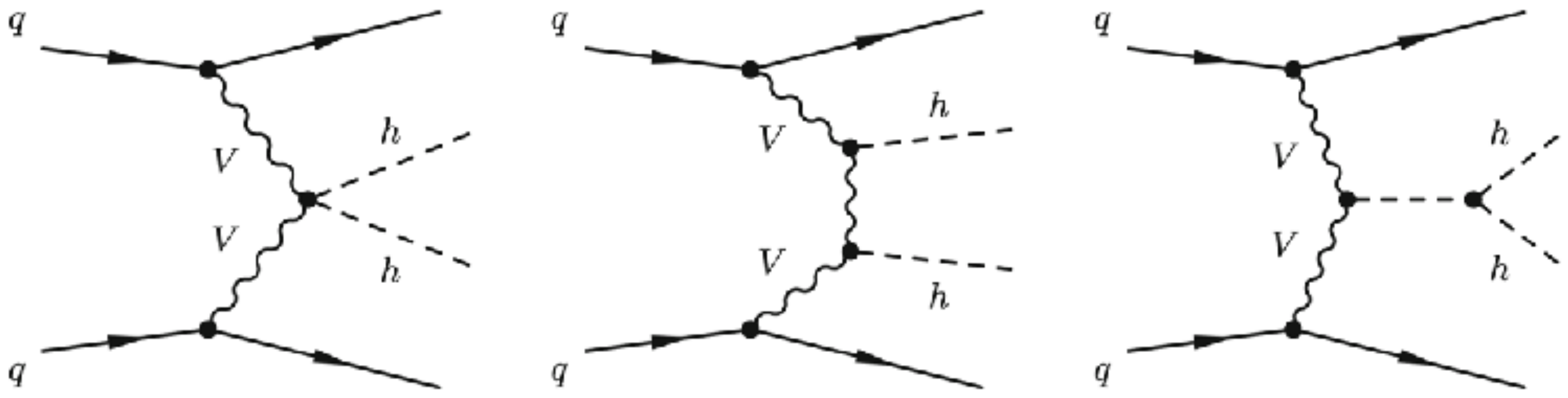
From P. Huang, A. Long and L.-T. Wang

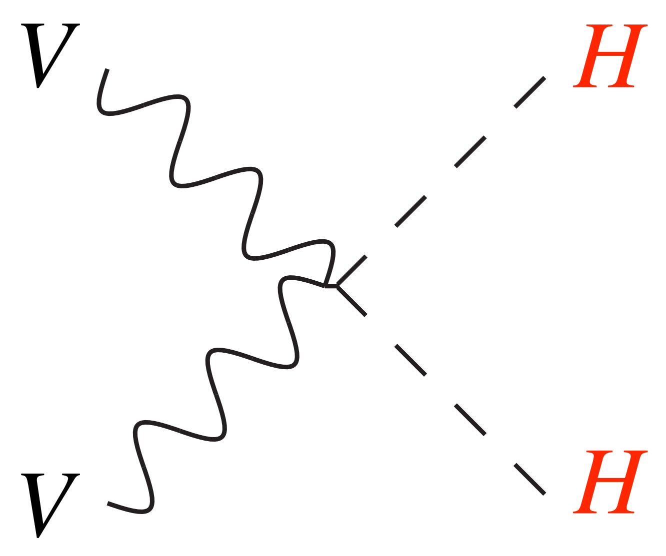
One more Higgs coupling measured!!

Non vanishing di-Higgs (to VV) coupling!

Without observing HH production

Done in VBF(HH) production with a significant negative interference with





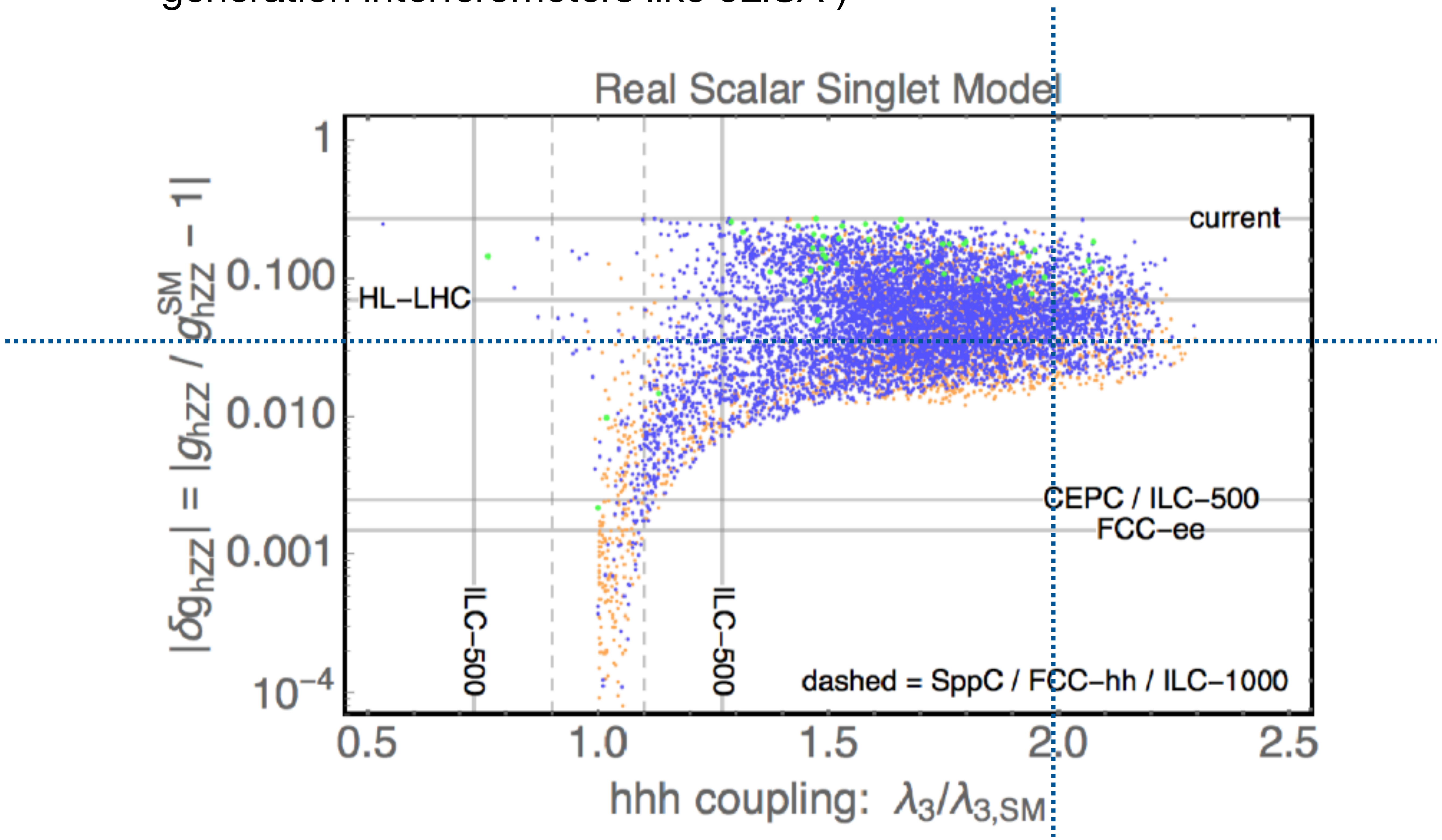
$$g_{HHVV} \sim \frac{2M_V^2}{v^2}$$

$\kappa_{2V} \in [0.67, 1.38]$ CMS result (ATLAS similar)

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.

$SU(2)_L \otimes U(1)_Y$ (from the Higgs mechanism)

$g \quad g' \quad v$

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:

$SU(2)_L \otimes U(1)_Y$ (from the Higgs mechanism)

$SU(2)_L \rightarrow g$, $U(1)_Y \rightarrow g'$, (from the Higgs mechanism) $\rightarrow v$

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 :

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

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

- The Fermi constant :

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

Determined from muon lifetime

- The Z mass :

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

Measured from the Z lineshape scan at LEP

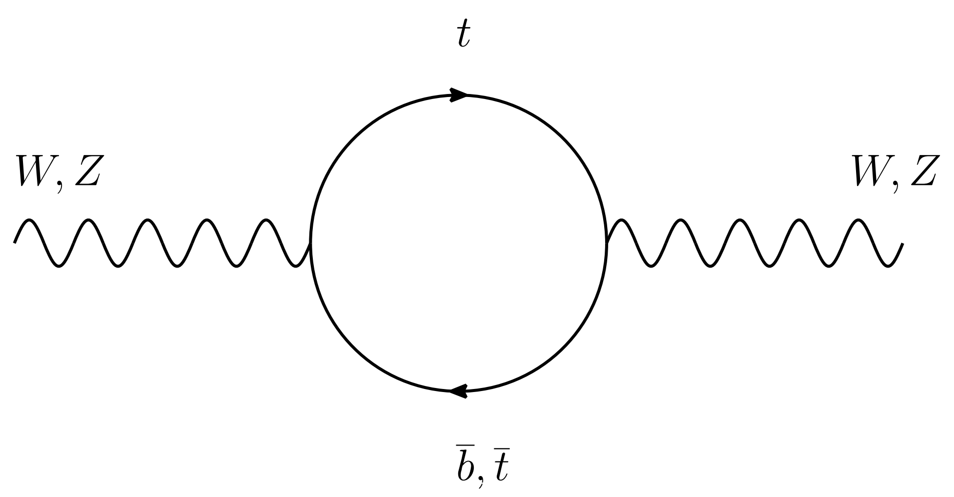
Note: we have assumed the existence of a Higgs field giving a vev (v) throughout (though we have not discussed the Higgs in detail yet)

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

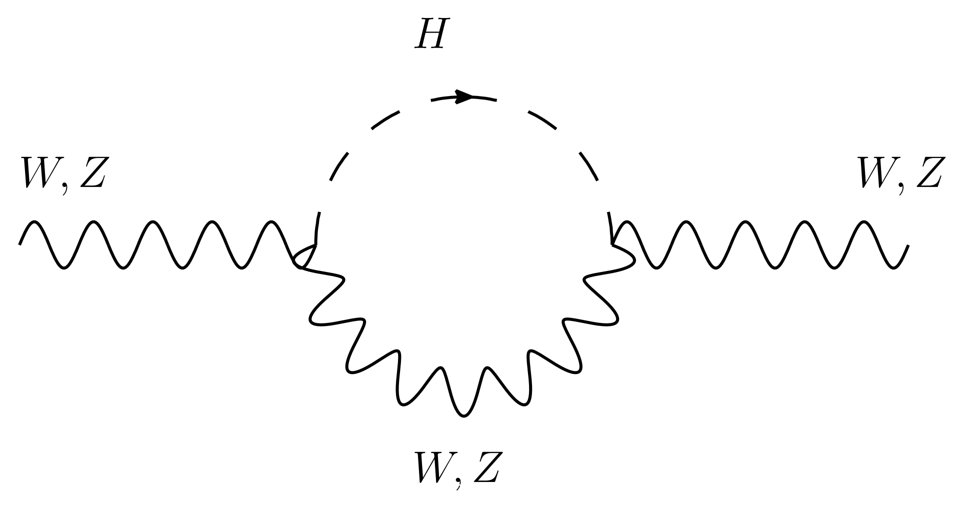
$$G_F = \frac{\pi\alpha}{\sqrt{2} M_W^2 (1 - \frac{M_W^2}{M_Z^2})}(1 + \Delta r)$$

$$\Delta r^{(\alpha)} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\mathrm{rem}}(M_H)$$

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

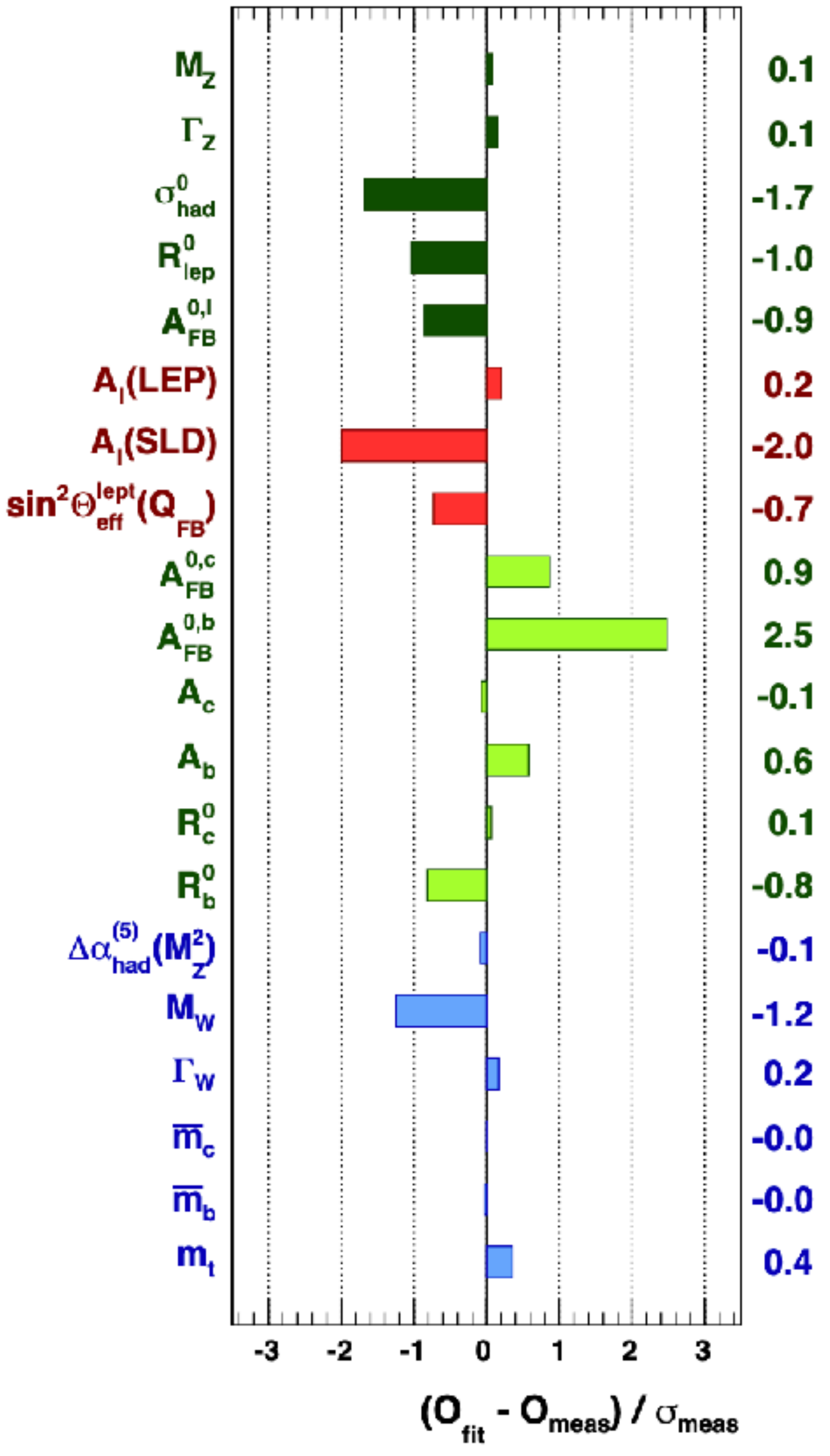
Fit Parameters

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	
σ^0_{had} [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	
$A^{0,b}_{\text{FB}}$	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
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	

Global Fit of the Standard Model

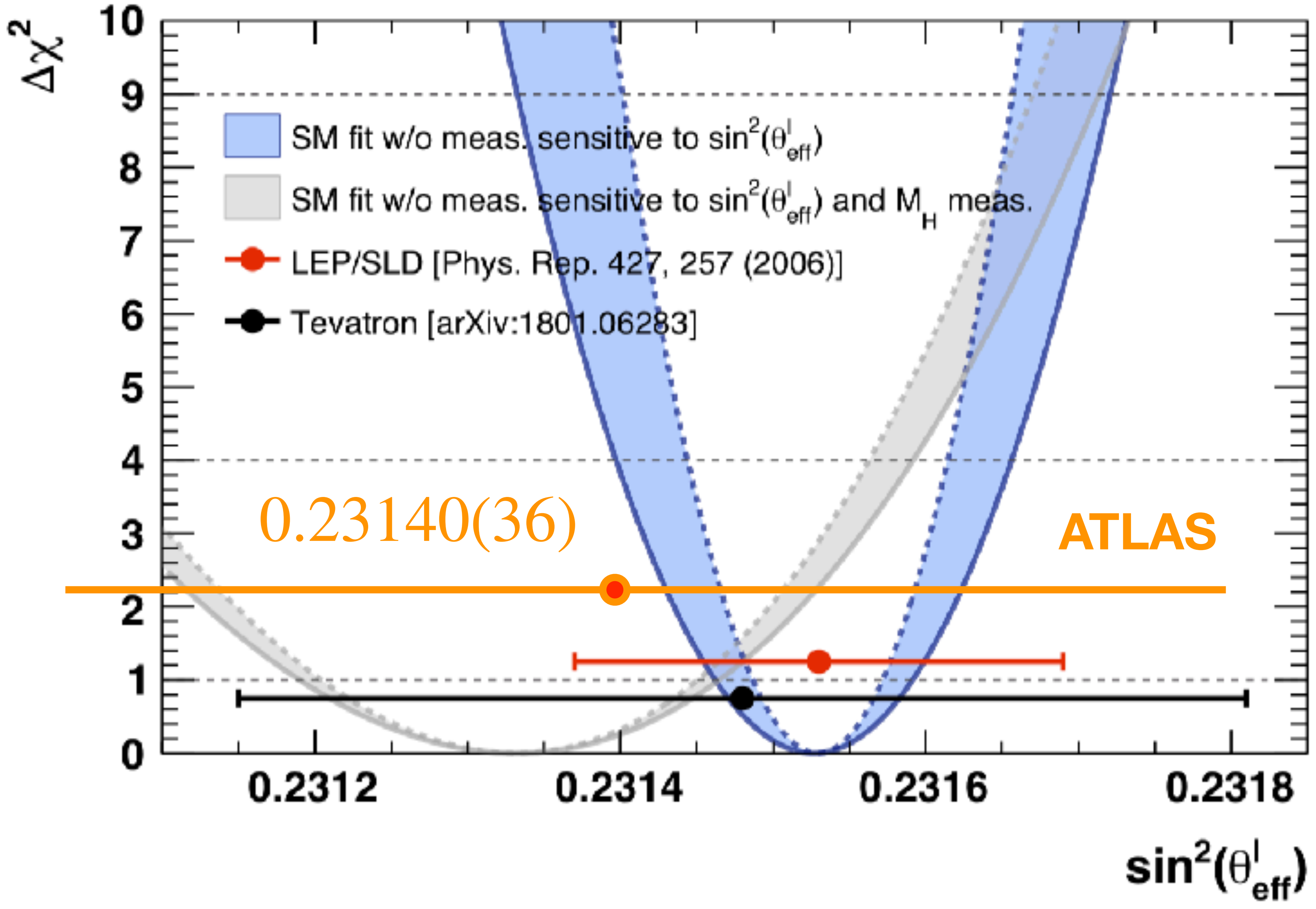
Parameter	Input value	Results from global EW fits: Standard fit	Complete fit	Fits w/o exp. input in given line: Complete fit	$M_H \equiv 120$ GeV
M_Z [GeV]	91.1875 ± 0.0021	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1959\,^{+0.0150}_{-0.0148}$	$91.1956\,^{+0.0141}_{-0.0136}$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959 ± 0.0015	2.4955 ± 0.0014	2.4952 ± 0.0017	2.4952 ± 0.0017
$\sigma^0_{\rm had}$ [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	$20.719\,^{+0.025}_{-0.028}$	$20.717\,^{+0.027}_{-0.026}$
$A^{0,\ell}_{\rm FB}$	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	$0.93469\,^{+0.00009}_{-0.00008}$	$0.93463\,^{+0.00007}_{-0.00005}$	$0.93462\,^{+0.00008}_{-0.00005}$	$0.93462\,^{+0.00008}_{-0.00003}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	$0.0741\,^{+0.0006}_{-0.0005}$	$0.0737\,^{+0.0005}_{-0.0004}$	$0.0738\,^{+0.0005}_{-0.0004}$	$0.0738\,^{+0.0005}_{-0.0004}$
$A^{0,b}_{\rm FB}$	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	$2157.6\,^{+0.5}_{-0.8}$	$2157.5\,^{+0.5}_{-0.8}$	$2157.5\,^{+0.5}_{-0.8}$	$2157.5\,^{+0.5}_{-0.8}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	$0.23141\,^{+0.00012}_{-0.00013}$	$0.23150\,^{+0.00008}_{-0.00010}$	$0.23148\,^{+0.00010}_{-0.00009}$	$0.23149\,^{+0.00009}_{-0.00010}$
M_H [GeV] $^{(\circ)}$	$\rm CL_{s+b}$	$91\,^{+30[+74]}_{-23[-42]}$	$120\,^{+12[+23]}_{-5[-6]}$	$91\,^{+30[+74]}_{-23[-42]}$	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
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.16}_{-0.07}$	$4.20\,^{+0.16}_{-0.07}$	–	–
m_t [GeV]	173.3 ± 1.1	173.4 ± 1.1	173.7 ± 1.1	$177.2 \pm 3.4^{(\triangledown)}$	$176.8\,^{+3.1}_{-3.0}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	2758 ± 11	2756 ± 11	$2729\,^{+57}_{-50}$	$2730\,^{+57}_{-46}$
$\alpha_s(M^2_Z)$	–	0.1193 ± 0.0028	0.1194 ± 0.0028	0.1194 ± 0.0028	0.1194 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	4	4	–	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	4.7	4.7	–	–

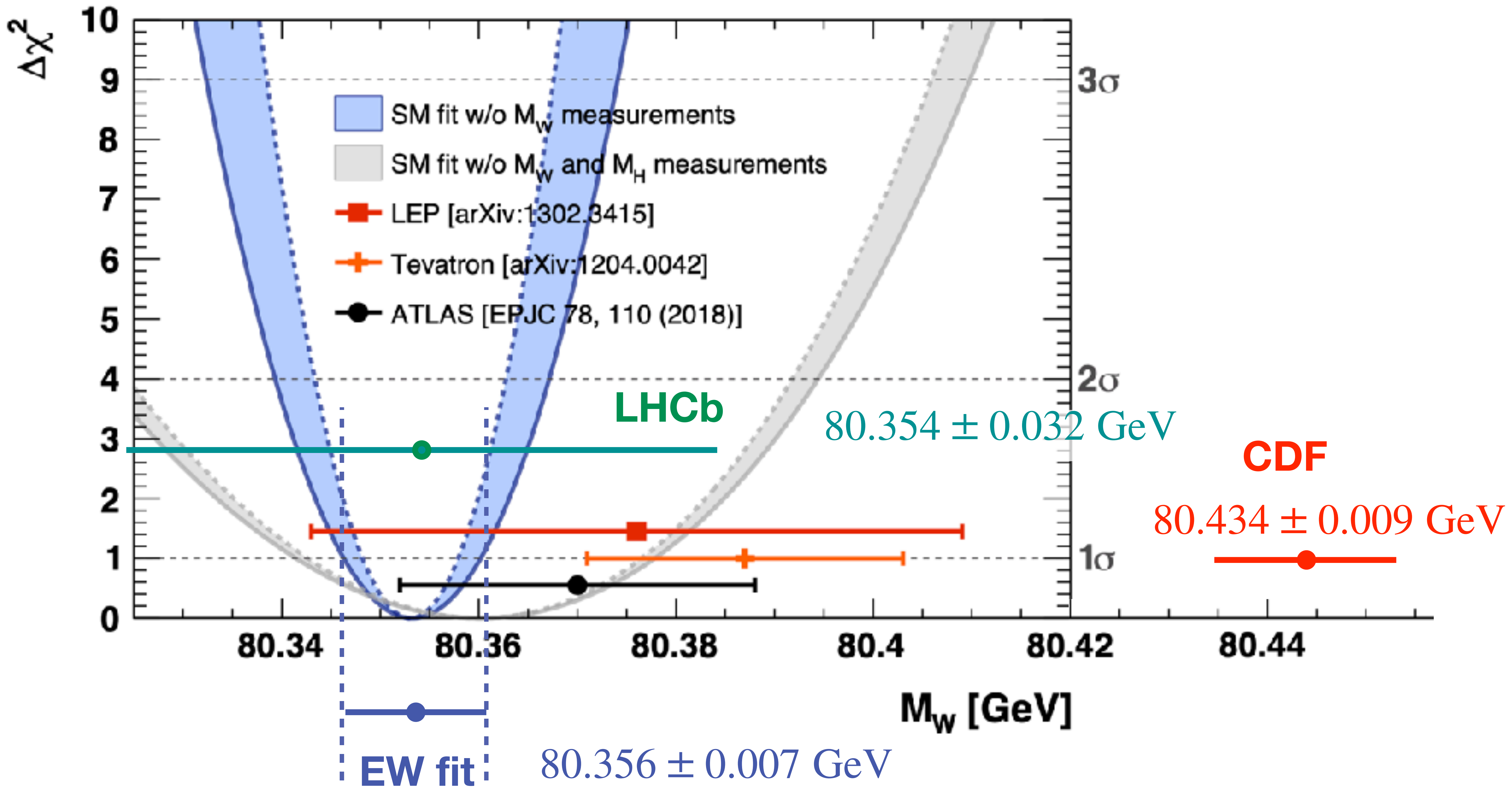


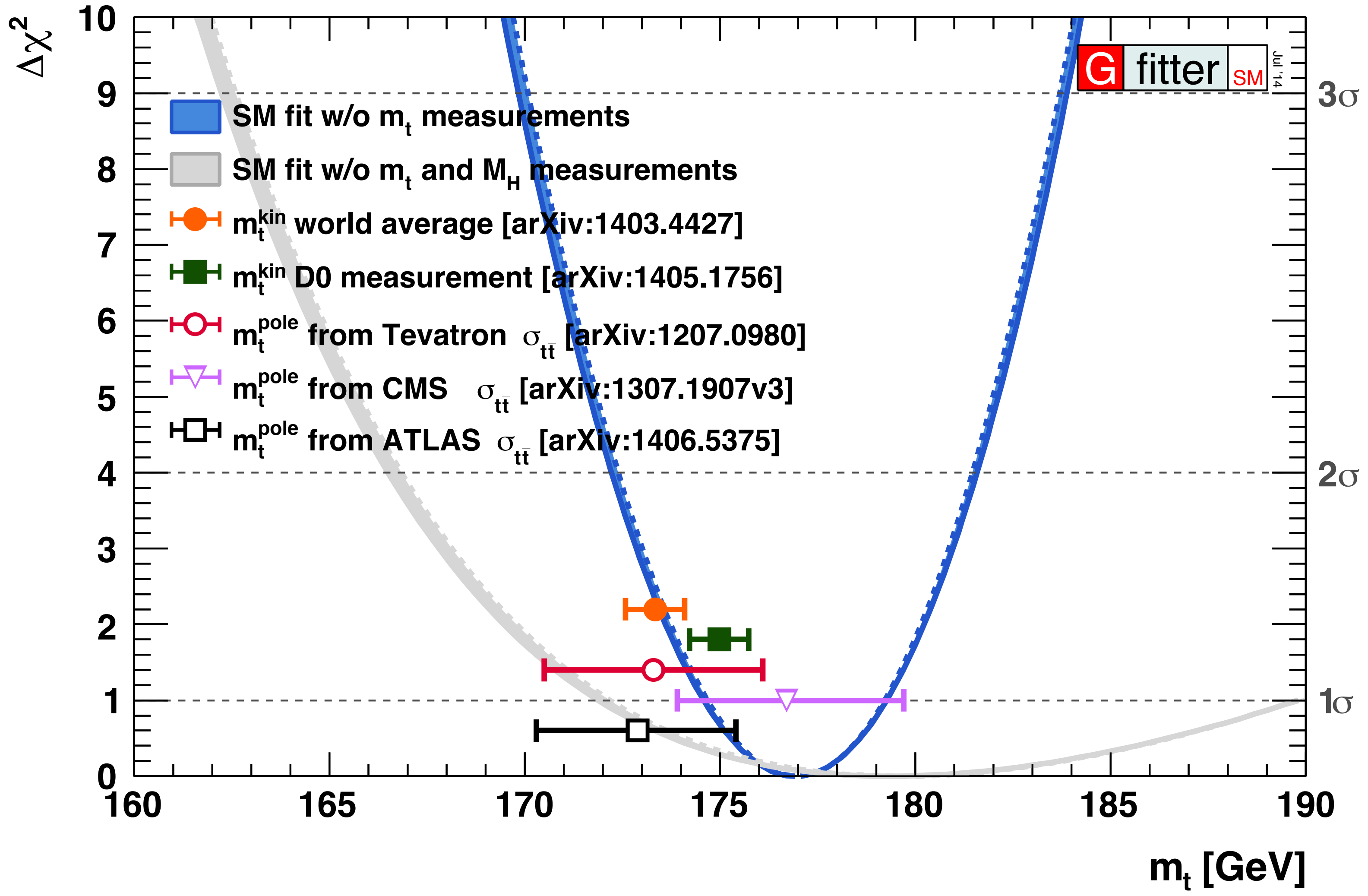
Fit with an overall $P(\chi^2, n_{dof})$ probability of ~20%

Largest tension known between A^b_{FB} (LEP) and A_ℓ (SLC).

Precision EW Observable: Effective Weak Mixing angle







- **Knowing the Higgs completely changes the picture!**
- Weak mixing angle and W mass the EW fit is more precise than the direct measurement
- For the top mass 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 : consider general (SM) 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):

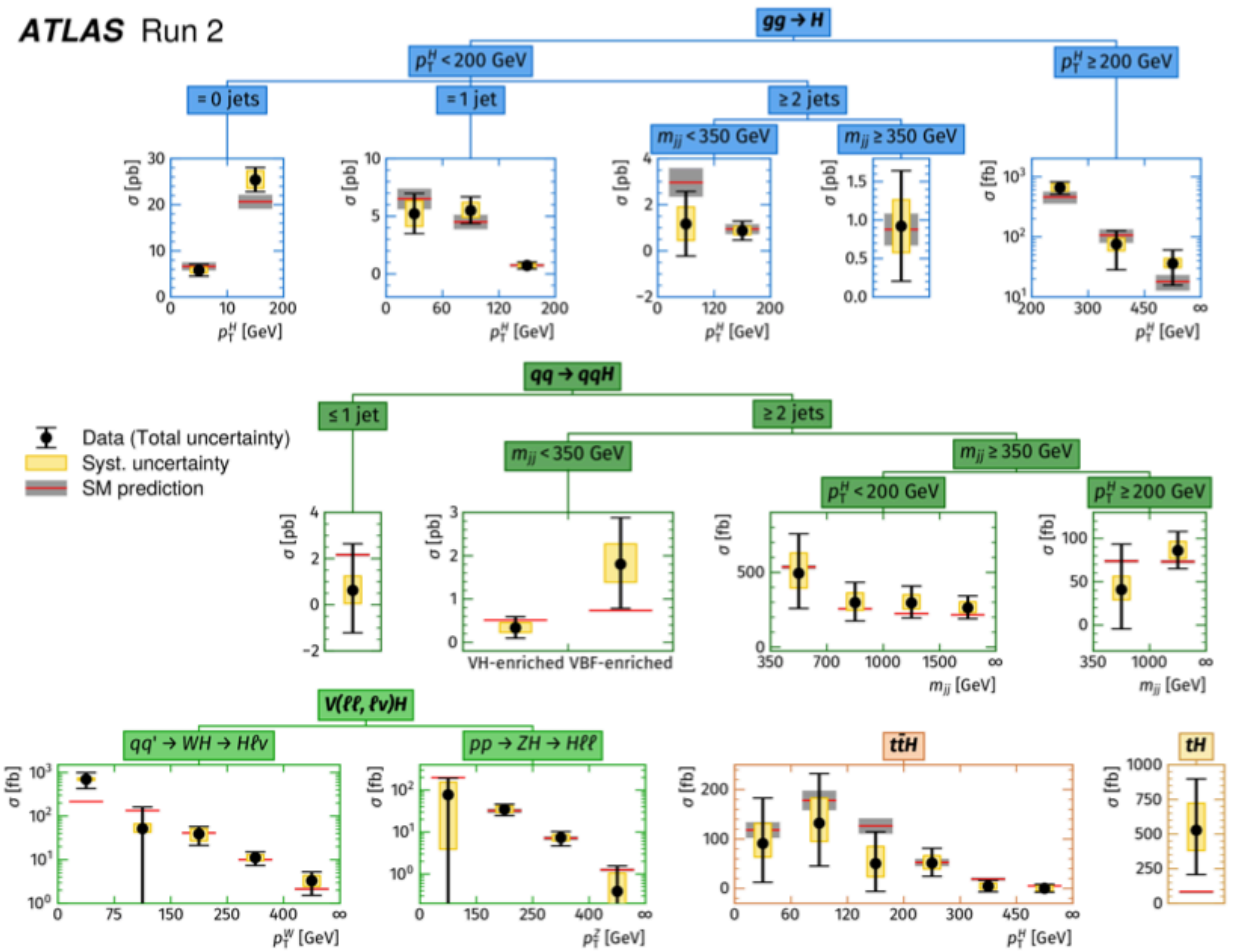
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

- **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**

Exploring further with STXS and SMEFT Interpretations

Simplified Template Cross Sections (STXS):

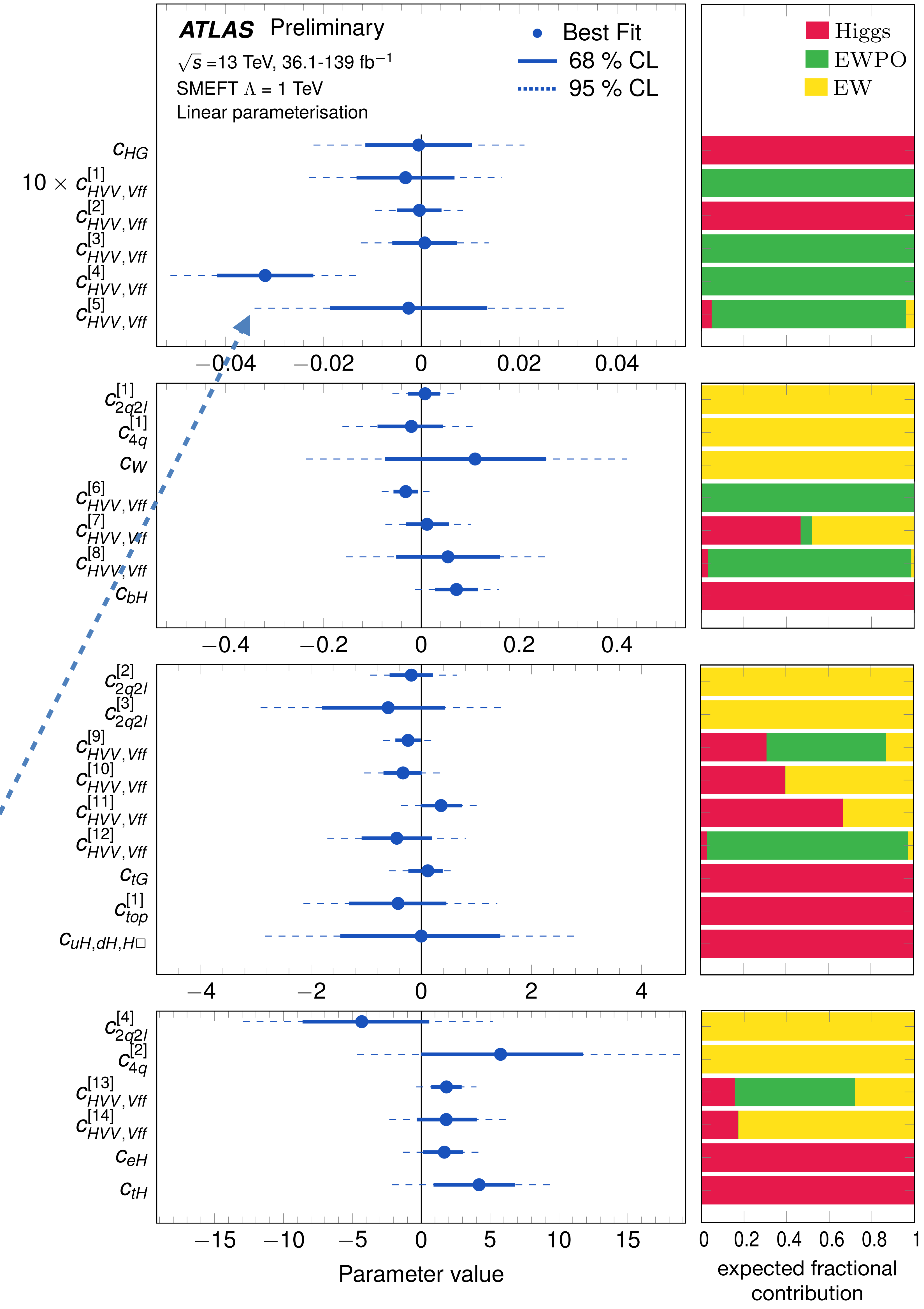
Combined measurements of Higgs boson production and decay in exclusive kinematic regions of the production phase space (and different production processes).



SMEFT Global Interpretation of our Data

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

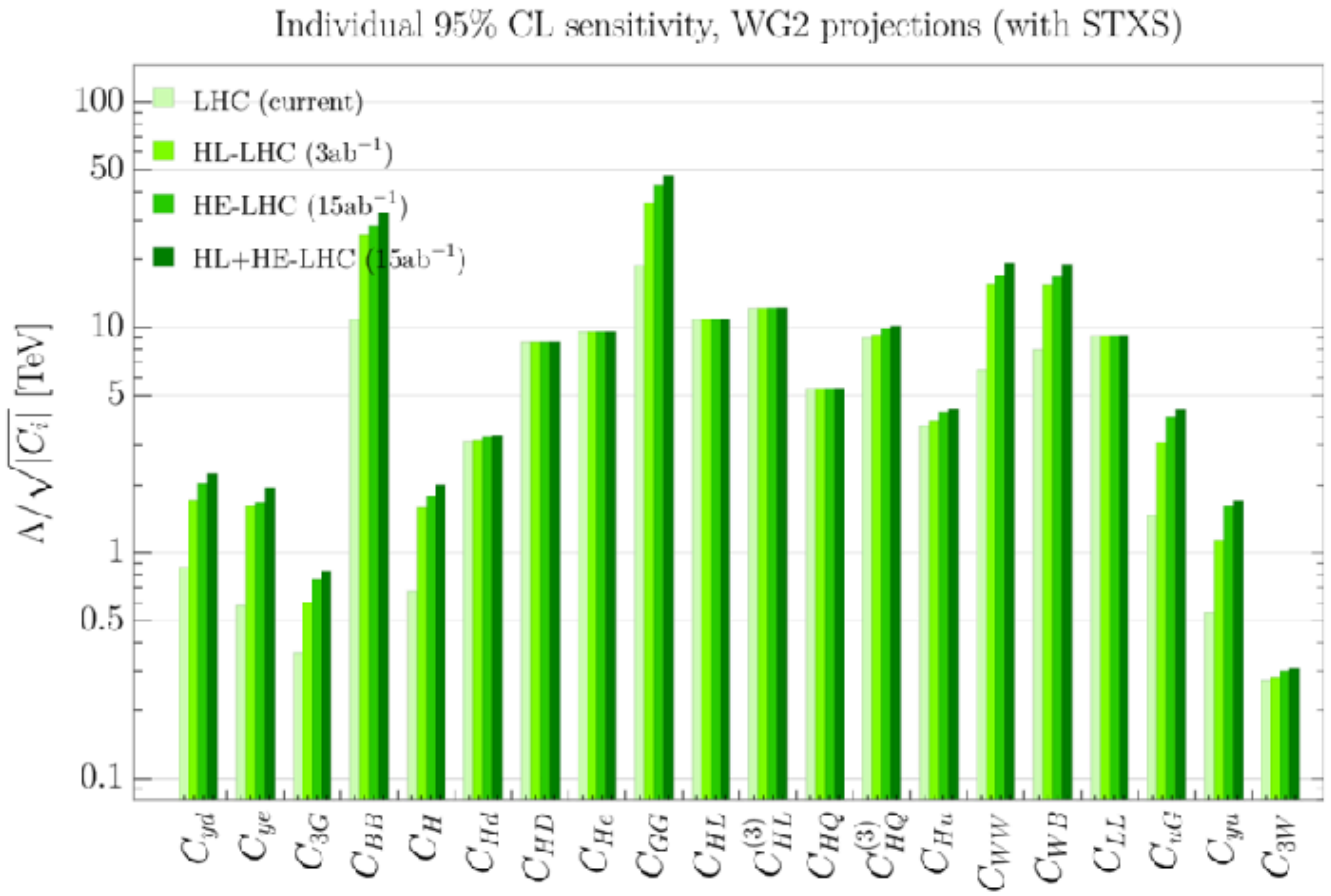
- Combined measurements of Higgs boson STXS.
- Differential cross-section measurements for diboson production and Z boson production via vector boson fusion (VBF).
- Electroweak precision data on the Z resonance from LEP and SLC.
- Uses **Principal Component Analysis** to group of Wilson coefficients.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



Largest discrepancy corresponding to the LEP $A_{FB}^{0,b}$ measurement

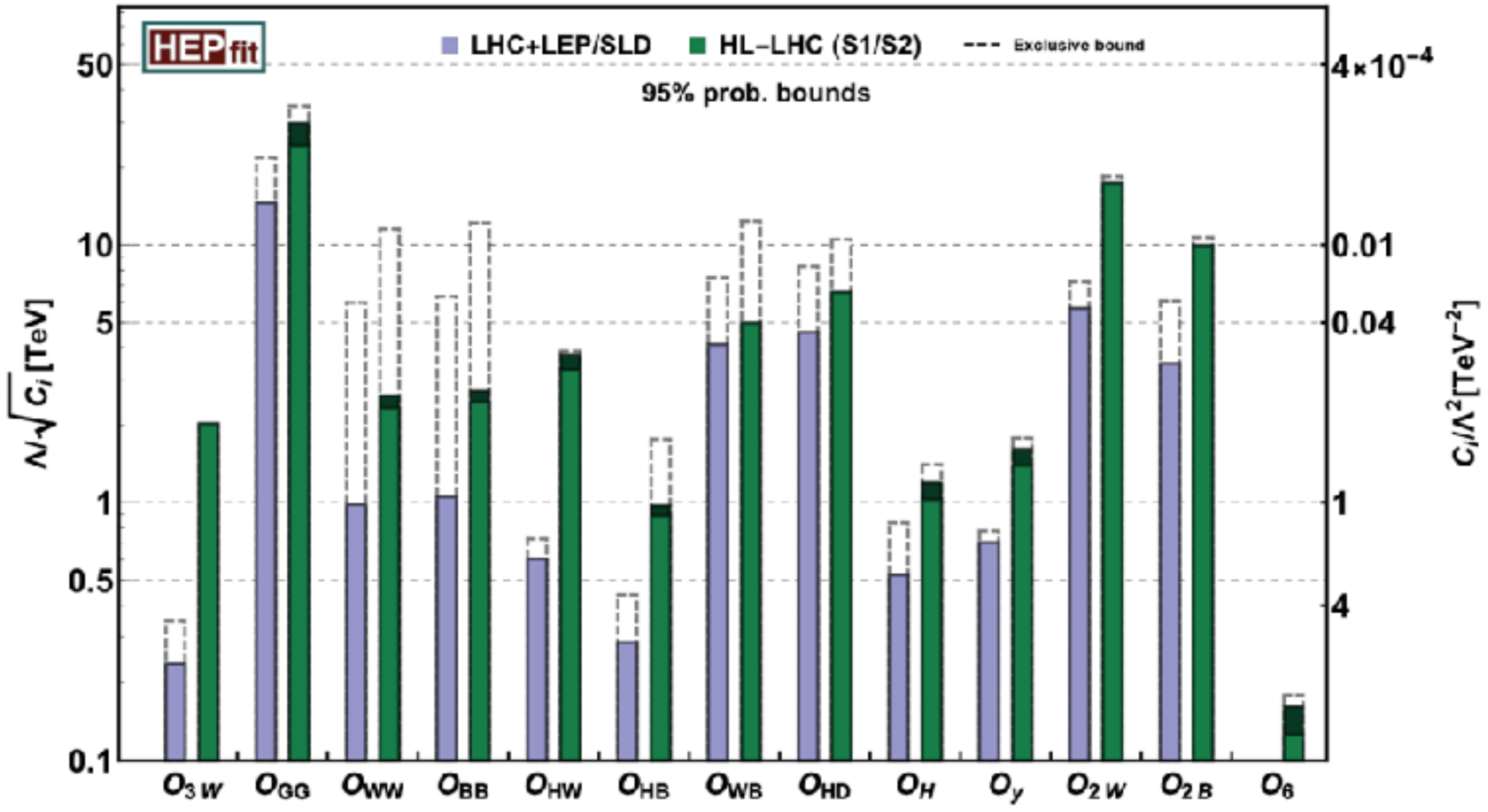
Global (SM) EFT Fit: Example Approaches and projections

- **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



Only linear terms in parametrisation

- **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)



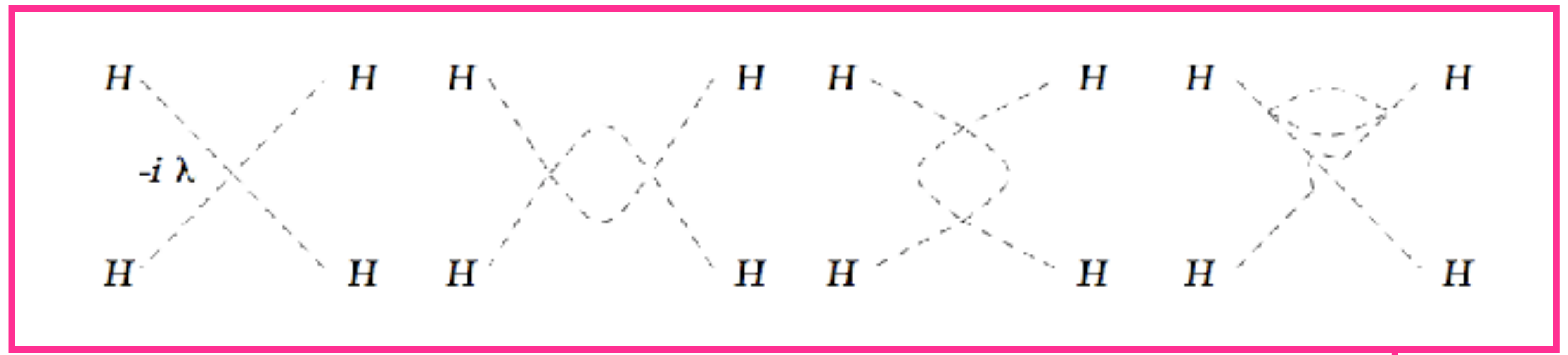
Quadratic terms taken into account where needed.

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

Implications – Vacuum Stability

Running of the Higgs self coupling:

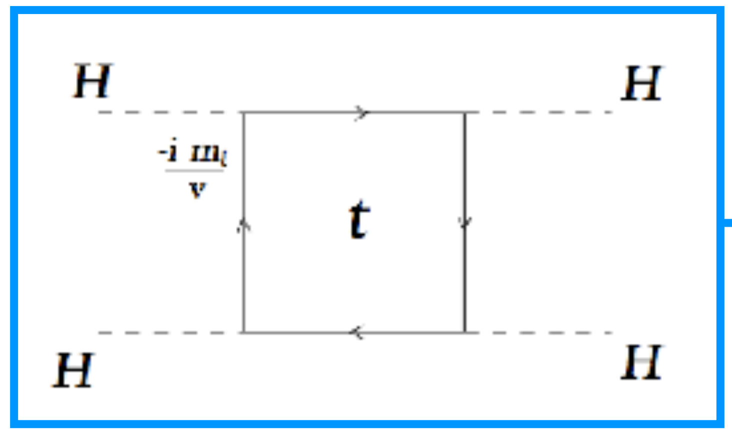
$$32\pi^2 \frac{\partial \lambda}{\partial \mu} = \boxed{24\lambda^2} - \boxed{6y_t^4}$$
$$-(3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4$$



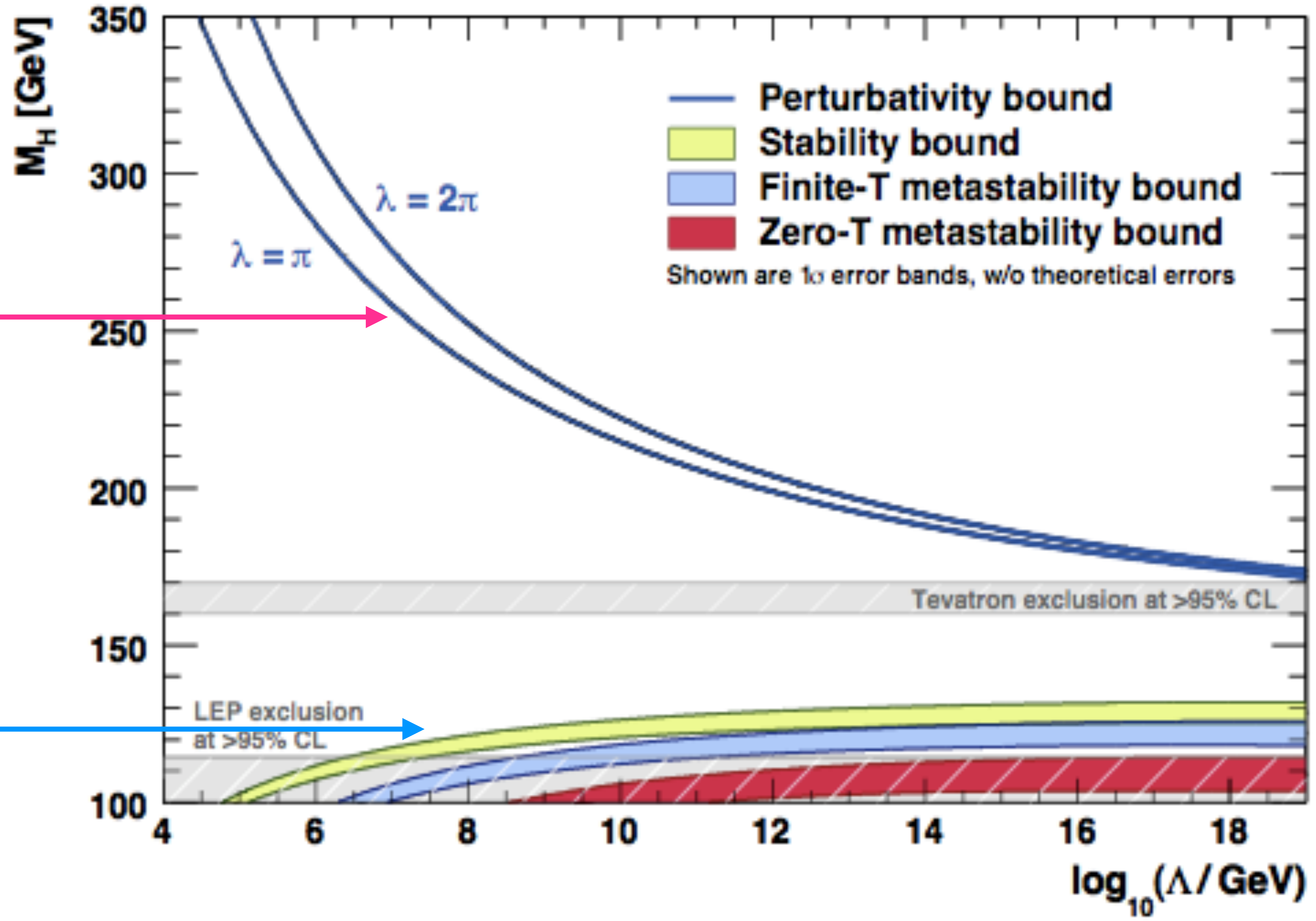
Dominant term for large values of the Higgs boson quartic coupling

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.

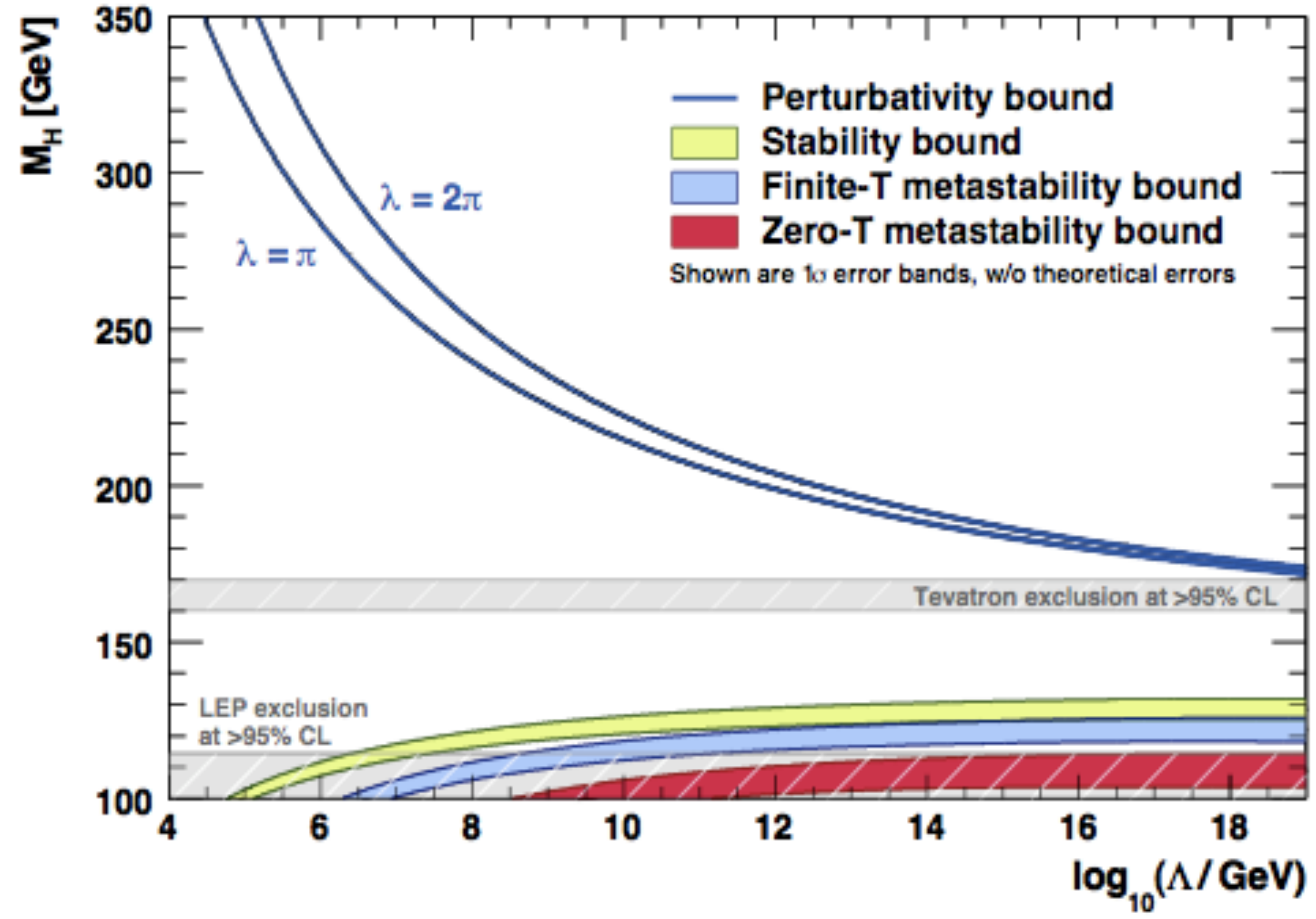


Implications – Vacuum Stability

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!

Comment on the Running of Couplings

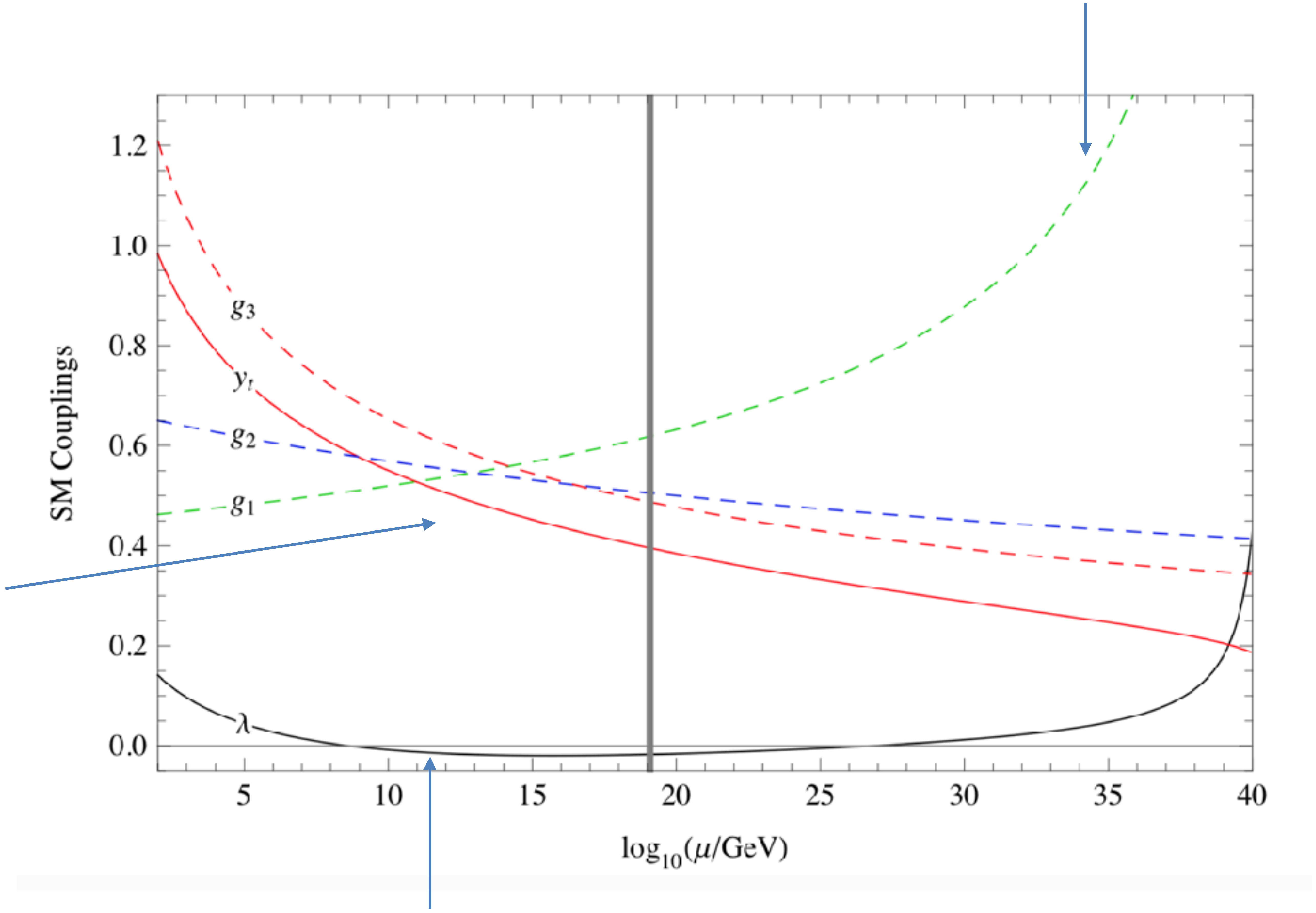
The running of the top Yukawa coupling

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

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

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).



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. (or more) sensitivity in HH 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

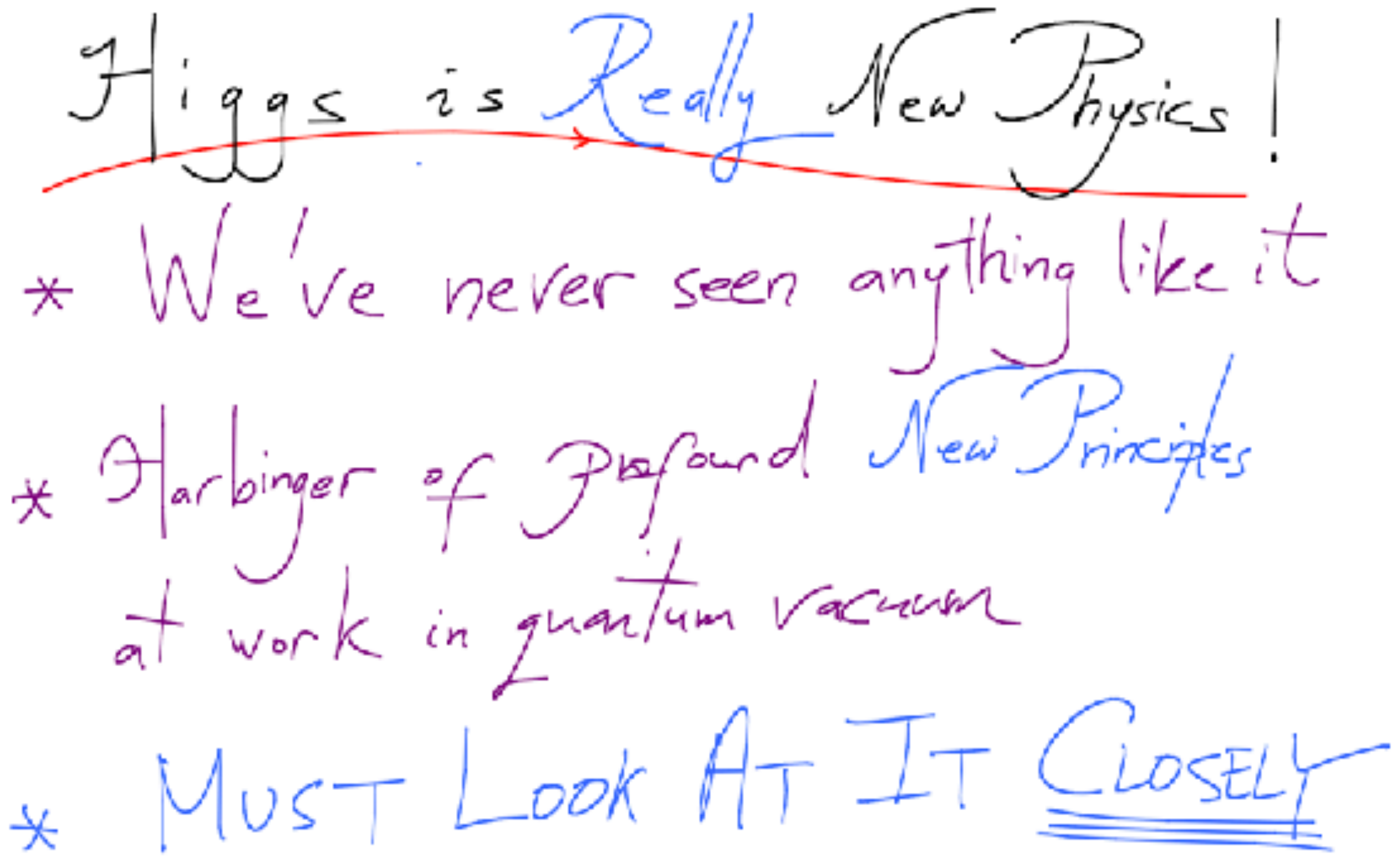
The SM and Higgs measurements program of the LHC physics is **vast** and **impressively diverse**.

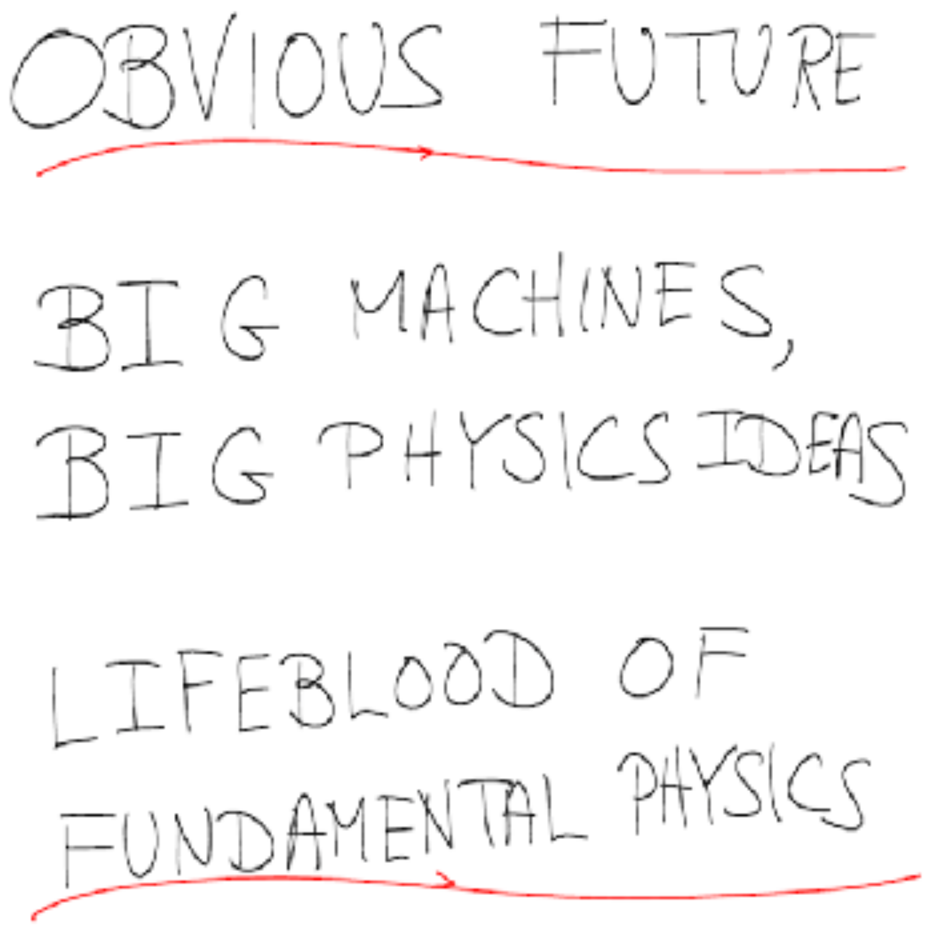
The LHC has already been **extremely successful** and has **surpassed many of its targeted results**.

Precision is the key for the success of the entire LHC program, both for measurements and searches!

Outlook

Opportunities at Future Colliders at the Energy Frontier





N. Arkani Hamed

Energy Frontier Vision in which the Higgs boson plays a very important role

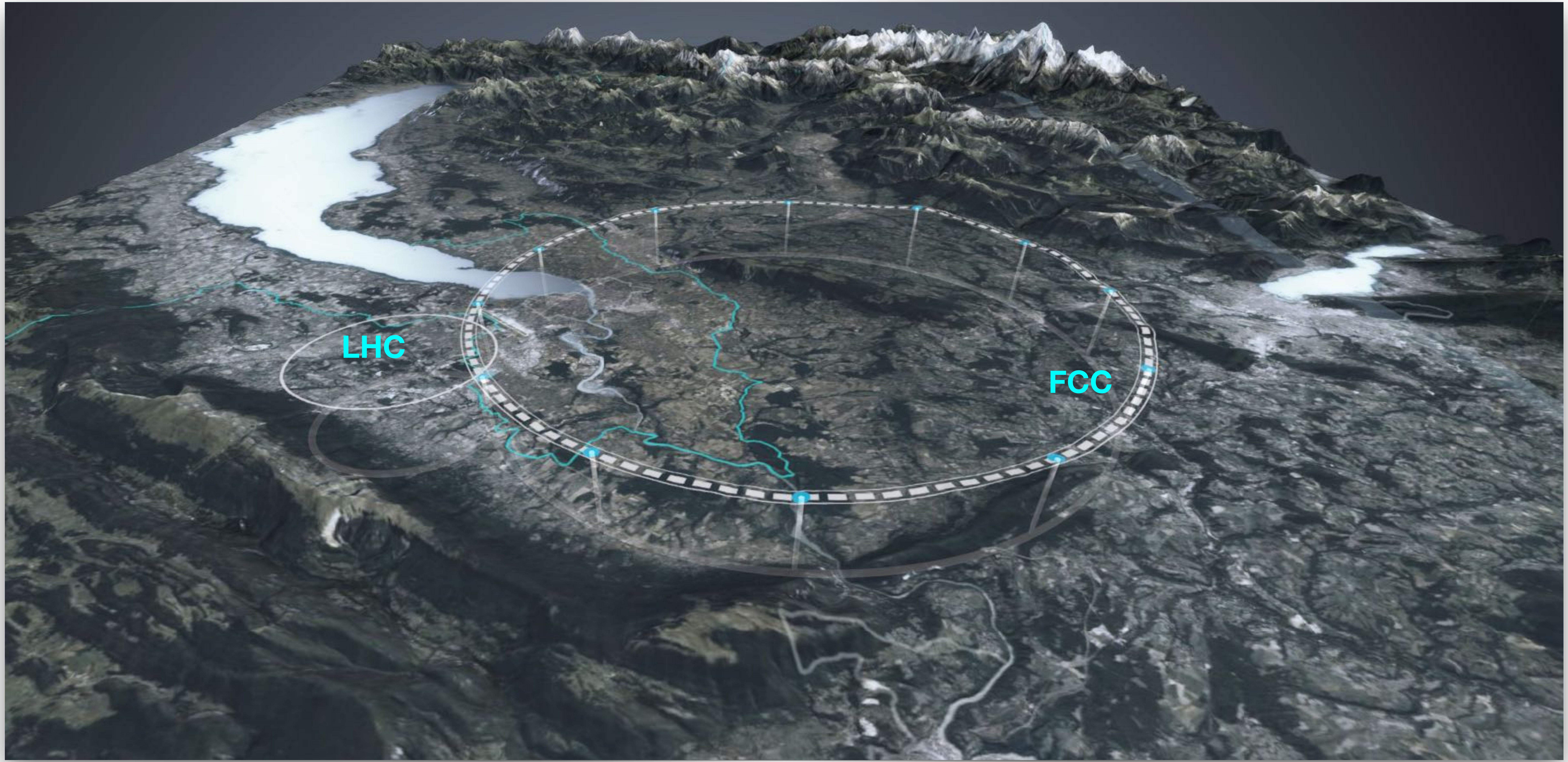
- **Short term**: immediate priority is the success of the HL-LHC (construction, operations, computing and software, and physics program)

- **Medium term**: e+e- Higgs factory, either based on a linear (ILC, C3, CLIC) or circular collider (FCC-ee, CepC) to enable an unprecedented precision investigation of the EW sector.

- **Long term**: a 100-TeV or more proton-proton collider (FCC-hh, SppC) or a 10-TeV muon collider to directly probe the order 10 TeV energy scale

A Scientific Mission for the 21st Century

Future Collider Projects



FCC-ee, the Ultimate Precision Machine!!

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

EW Precision Key measurements:

- $m_Z \sim 10^{-6}$, $m_W \sim 10^{-5}$, $m_{top} \sim 10^{-4}$
- $sin^2_{\theta_W} \sim 3.10^{-6}$, $\alpha_{QED}(m_Z^2) \sim 10^{-5}$, $\alpha_S \sim 10^{-4}$

FCC-ee is much, much more than a Higgs factory!

Superb precision achievable!

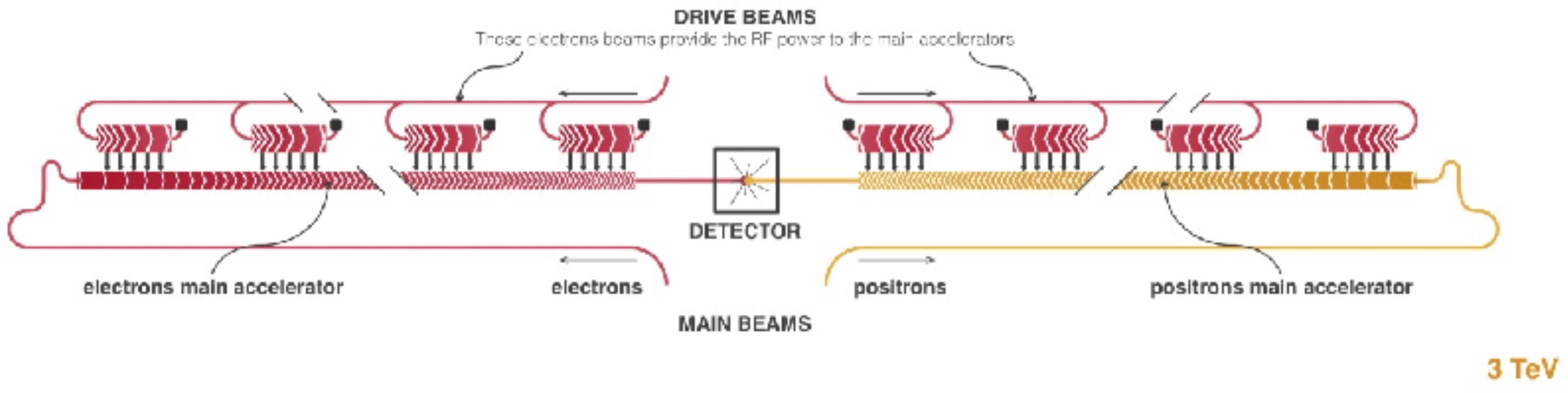
- x10-50 Improvement on all EW
- Up to x10 improvement on Higgs
- Indirect discovery **potential up to 70 TeV**

Backup

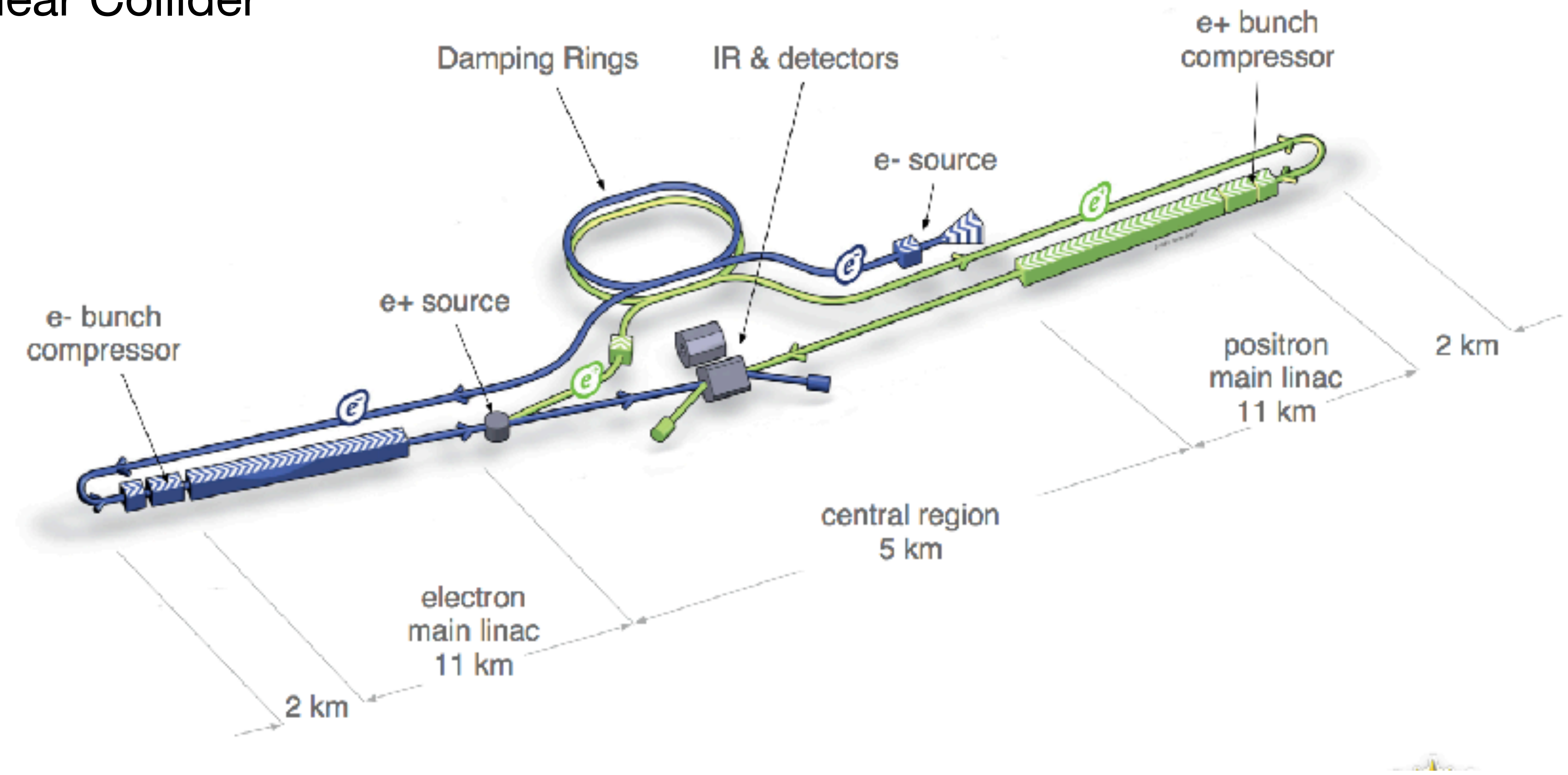
e^+e^- Collider Projects - Linear

Project	ILC	CLIC	FCC-ee	CepC	C3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

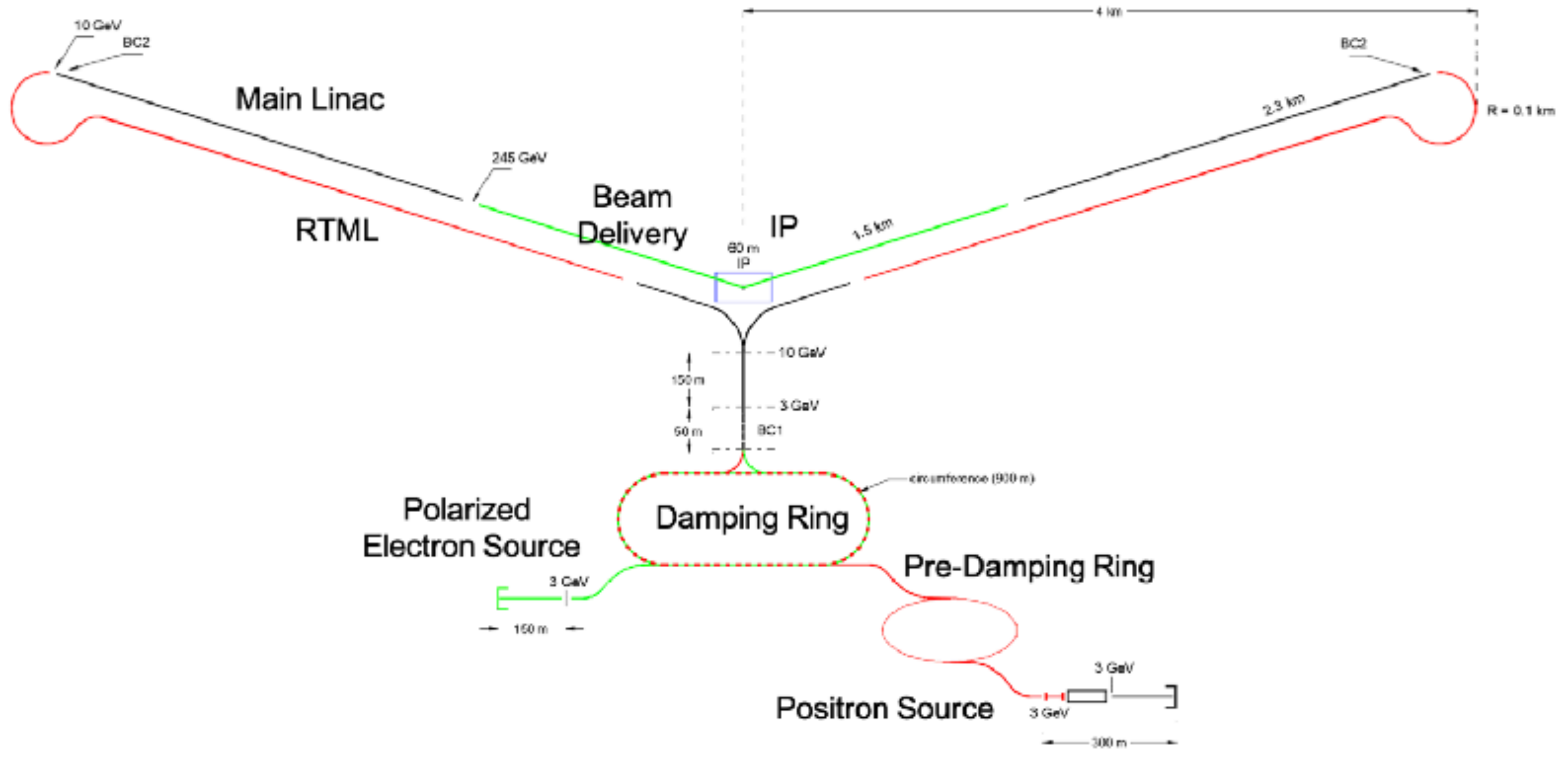
CLIC Compact Linear Collider



ILC International Linear Collider



C3
Cool Copper Collider

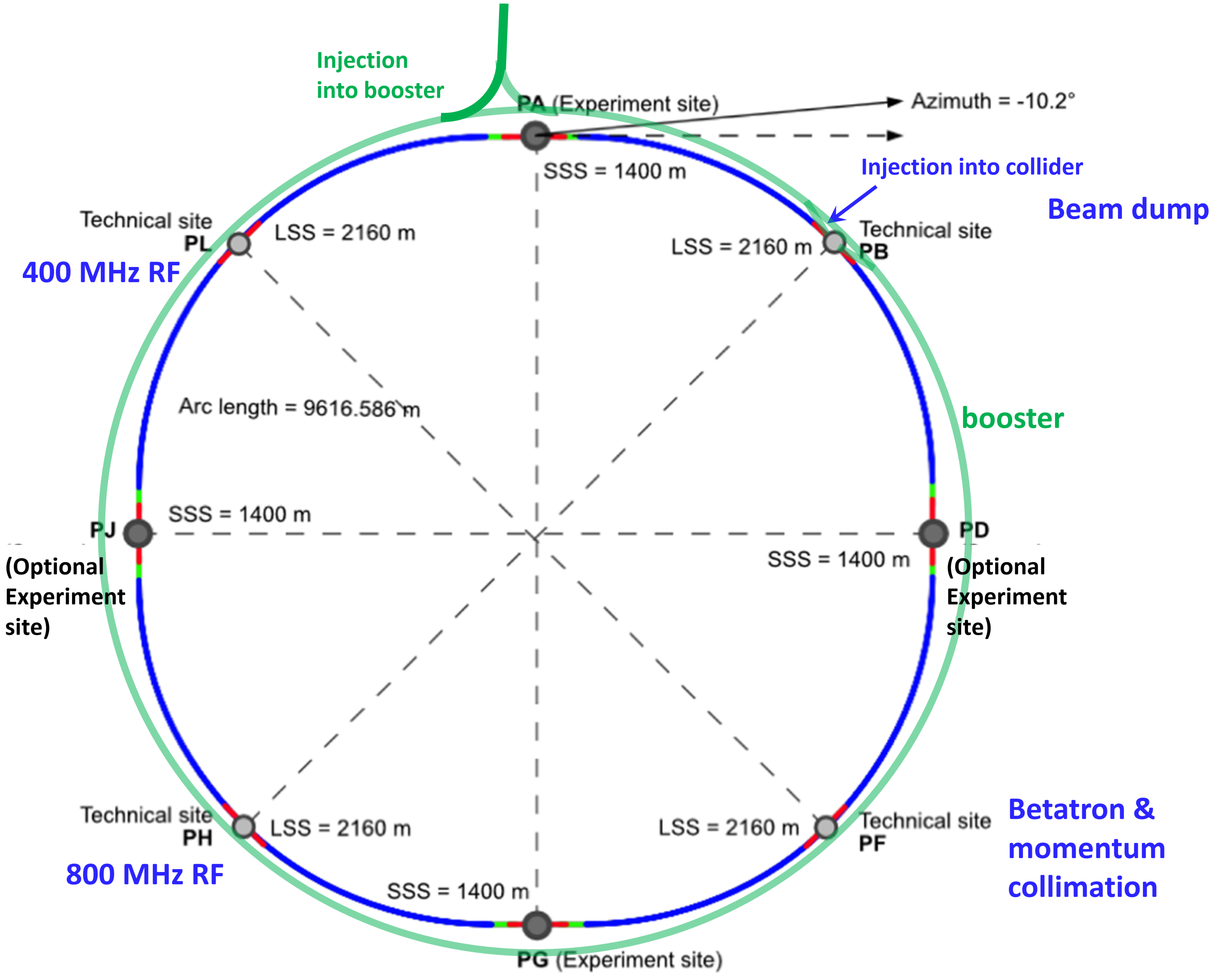


e+e- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



FCC-ee

Modern two-ring design (to reach amper currents): benchmark at ***KEK-B*** *and Super* ***KEK-B*** *with double-ring e+e– collider with multi-ampere stored currents with over than 1000 bunches, small β∗ of down to 0.8mm, top-up injection as well as a 22 mrad crossing angle at the IP with crab crossing!*

CepC similar design (in China)

e^+e^- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
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Lumi (10^{34} $cm^{-2}s^{-1}$)	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

Large amount of extremely useful data in a very clean environment!

- 100 000 Z / second
- 10 000 W / hour
- 1 500 Higgs bosons / day
- 1 500 top quarks / day

Event statistics (4IP)

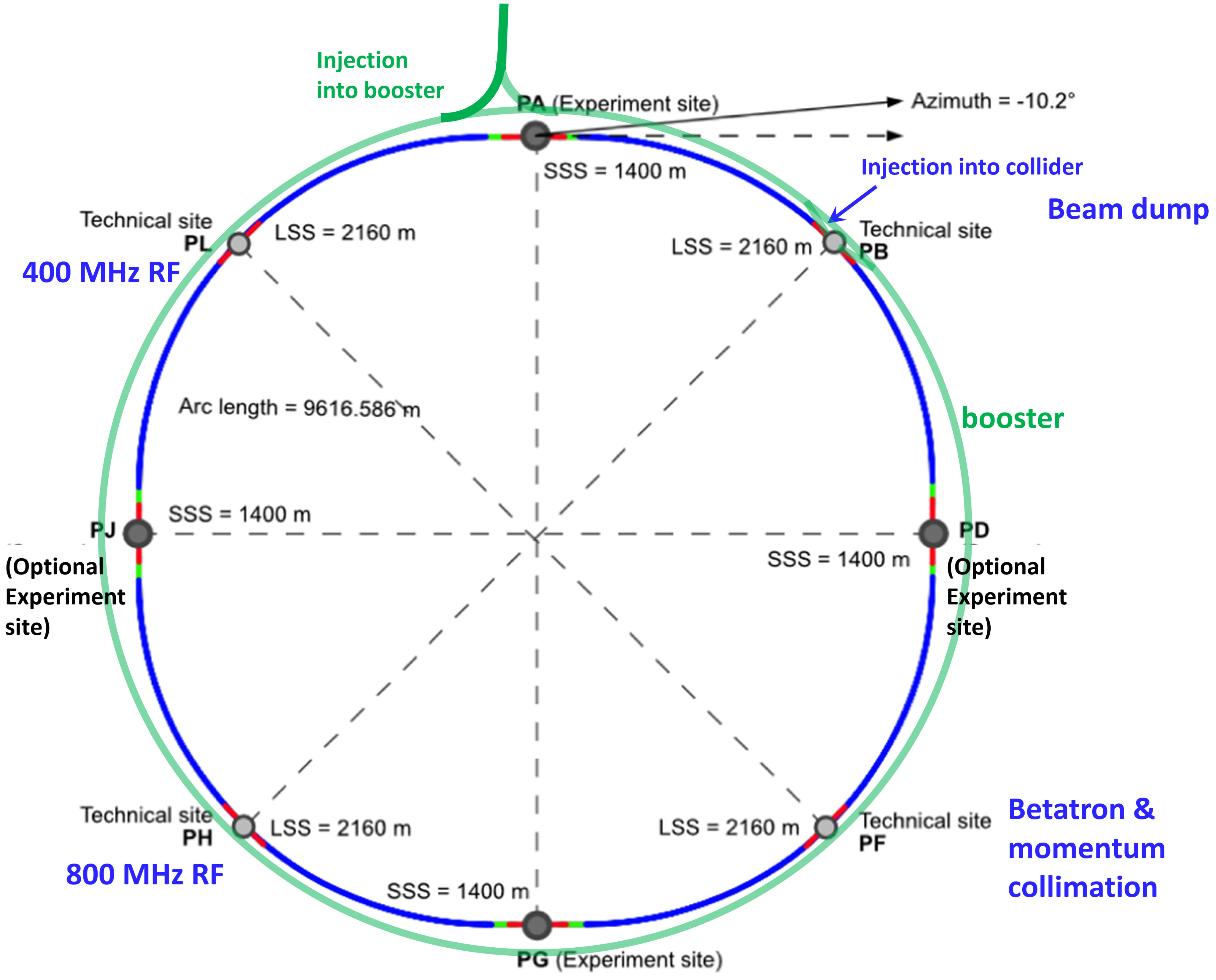
					E_{CM} errors	
Z peak	E_{cm} = 91 GeV	4yrs	6. 10^{12}	$e^+e^- \to Z$	<100 keV	LEP x 3.10^5
WW threshold	$E_{cm} \geq$ 157-161	2yrs	2. 10^8	$e^+e^- \to WW$	<300 keV	LEP x 2.10^3
ZH maximum	E_{cm} = 240 GeV	3yrs	1.5 10^6	$e^+e^- \to ZH$	1 MeV	Never done
s-channel H	$E_{cm} = m_H$	(3yrs?)	O(5000)	$e^+e^- \to H$	<< 1 MeV	Never done
Top production	E_{cm} = 340-365 GeV	5yrs	2. 10^6	$e^+e^- \to t\bar{t}$	2 MeV	Never done

*From A. Blondel

Precision on m_H of ~3 MeV

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



One LEP produced every 3 minutes!!

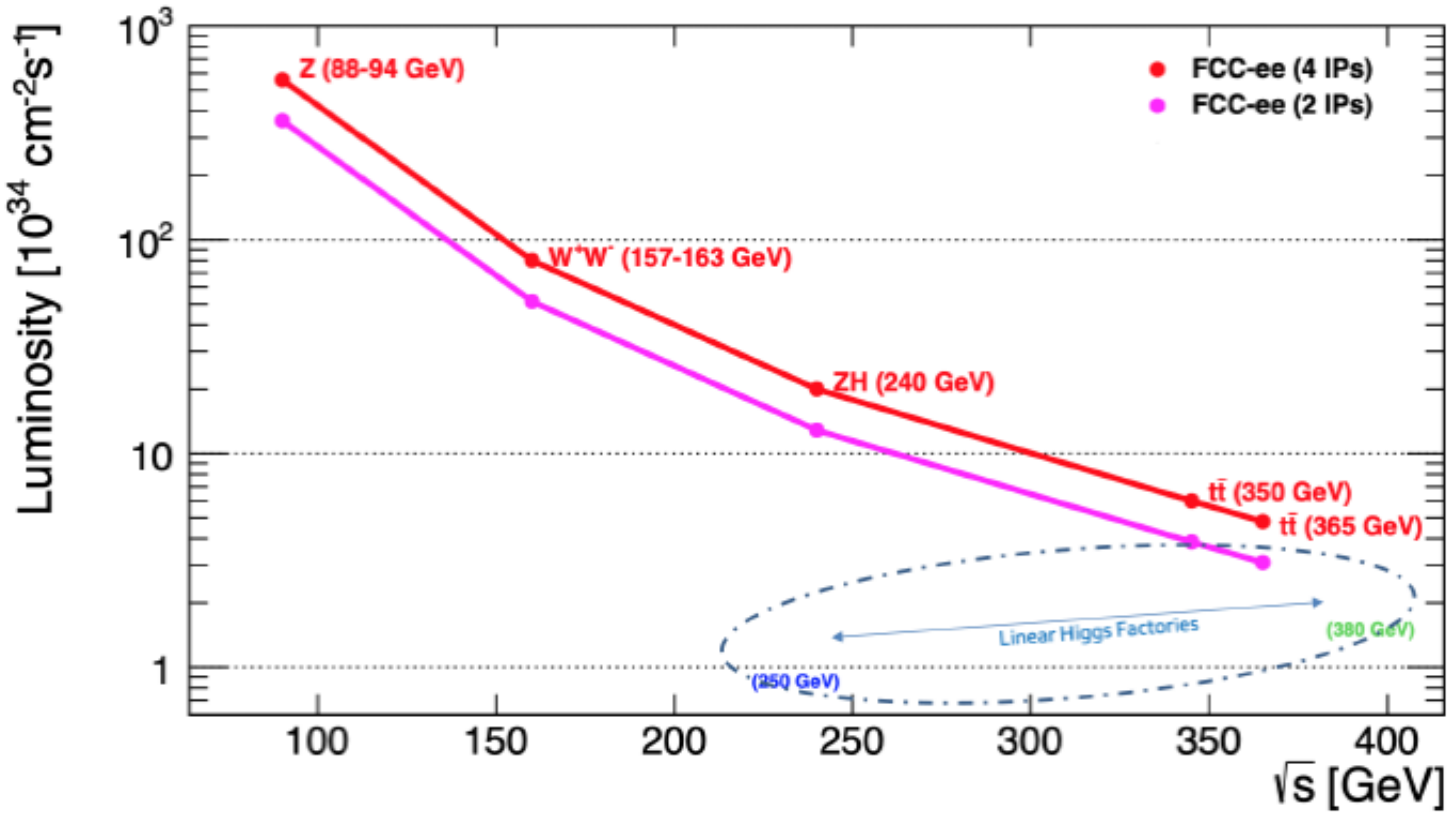
CepC similar design (in China)

e+e- Collider Projects

Future e+e- projects are complementary

- Circular colliders provide massive amount of data to address the Higgs and EW scale precision needs (1)
- Linear colliders could address specific questions more the need to explore higher energies (2)

FCC is an integrated program including FCC-hh phase - “The best project for CERN”



Clear advantage of circular and 4 IP in terms of luminosity!

FCC-ee intensity provides vast opportunities

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- x10 improvement on Belle II statistics for b, c and τ
- Huge direct discovery potential for feebly interacting particles in the 5-100 GeV range

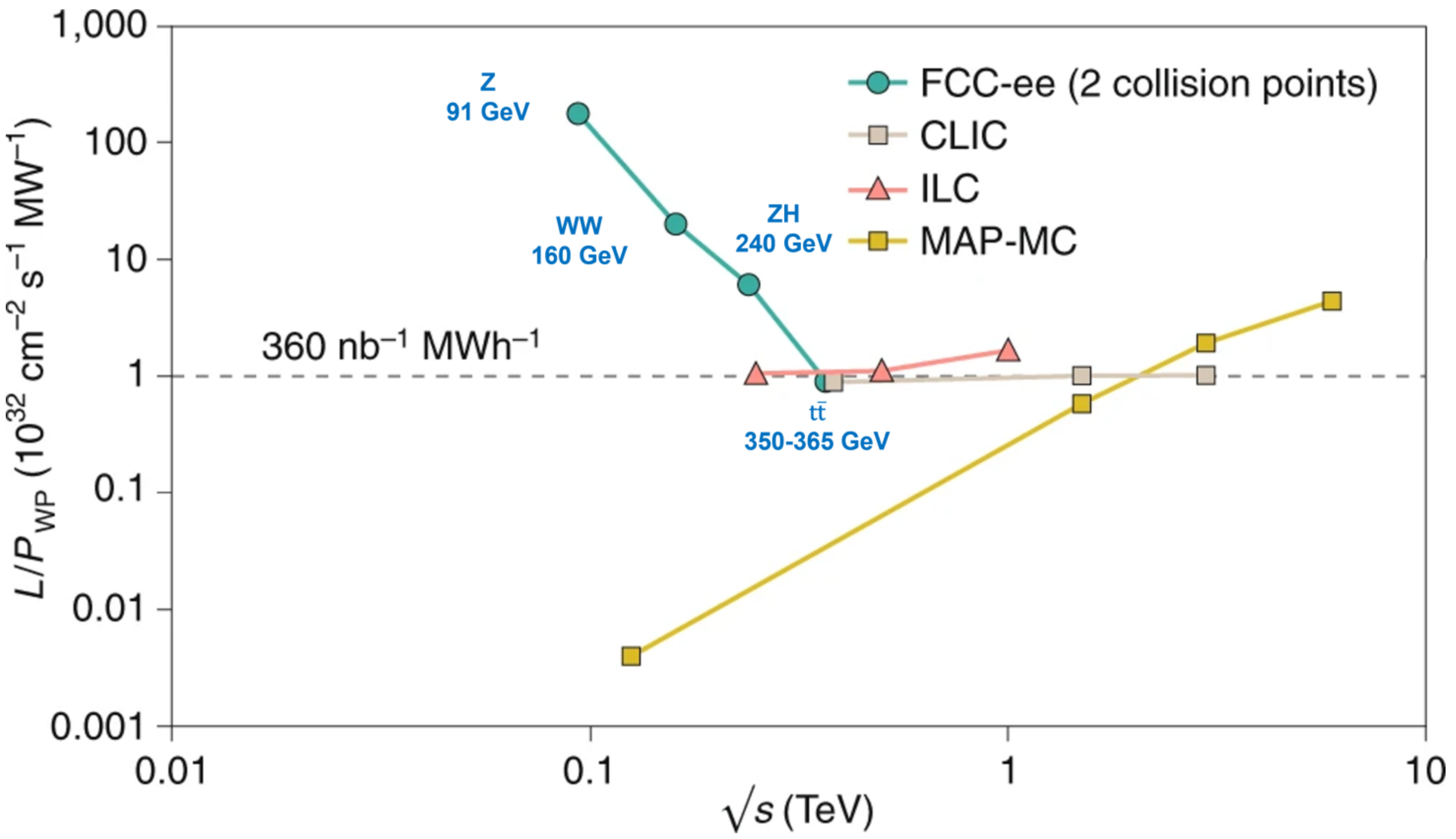
e+e- Collider Projects

Outstanding issues

- Timescales:
  - Projects outside CERN: ILC (**2038**) and CepC (**2035**)
  - Projects at CERN: FCC-ee and CLIC (**2048**)
- Sustainability, Energy and Power consumption are key parameters

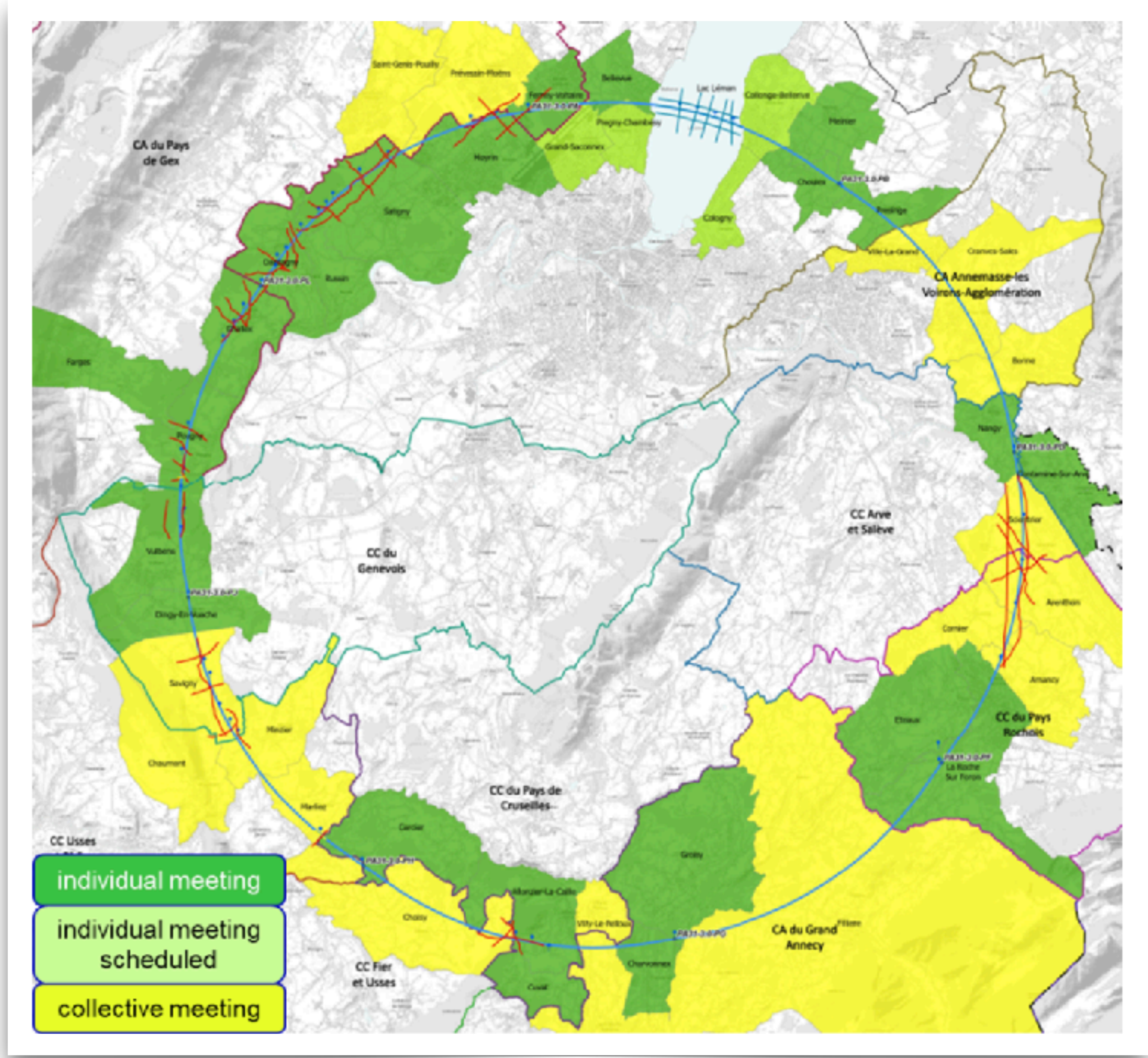
Challenging ideas to the FCC-ee

- An upgrade of e+e– collisions to higher energies, ~600 GeV or beyond, has been proposed through converting the FCC-ee into a few-pass ERL (Physics Letters B 804 (2020) 135394).
- Monochromatisation could give access to the s-channel Higgs production and thus the electron Yukawa! Understudy.

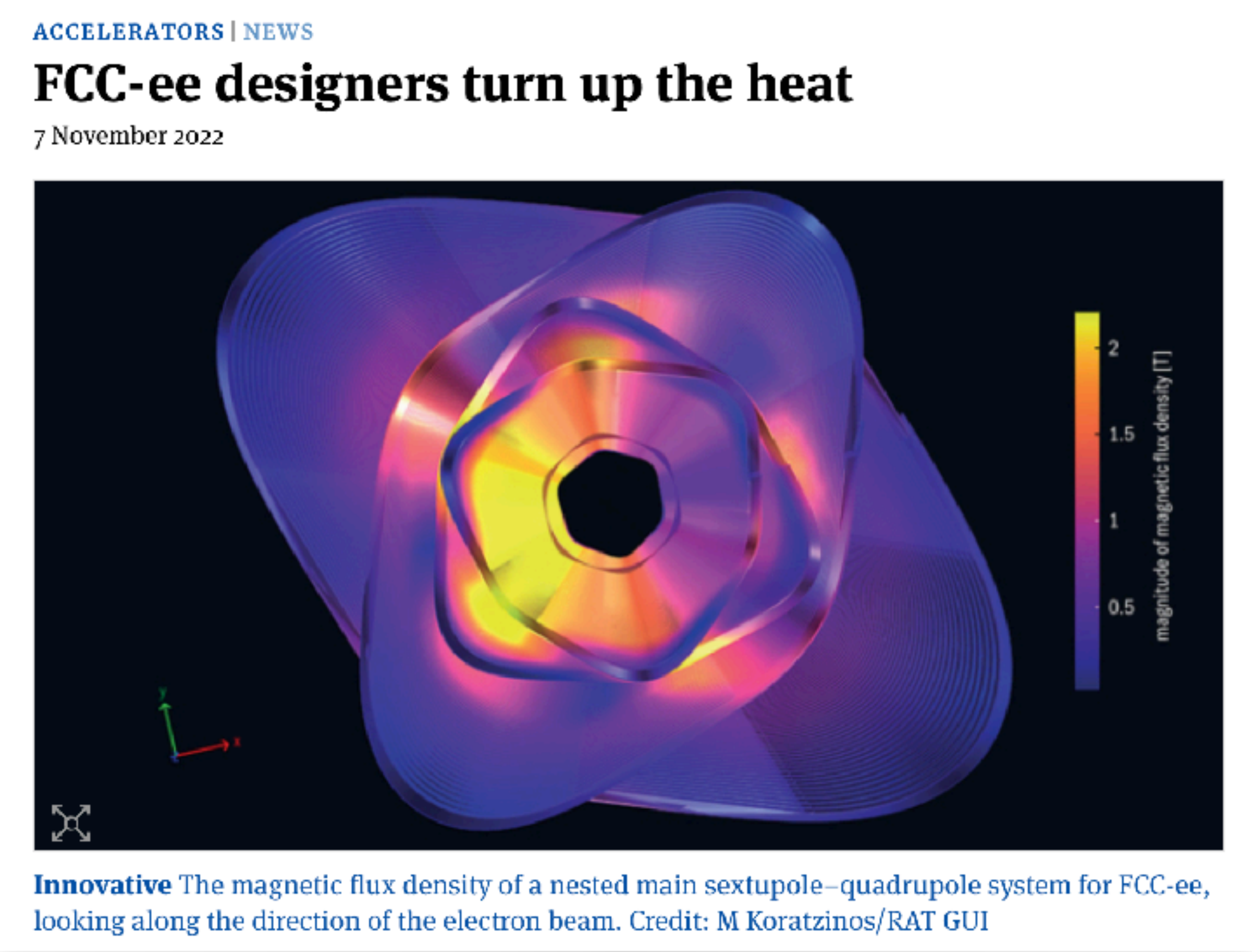


Large uncertainties see Snowmass white paper

Feasibility Studies



- Choice of baseline layout (90.7 km) - discussions with local authorities, environmental investigations and civil engineering designs well under way.
- In particular studies of possible injection schemes article


ACCELERATORS | NEWS

FCC-ee designers turn up the heat

7 November 2022

Innovative The magnetic flux density of a nested main sextupole–quadrupole system for FCC-ee, looking along the direction of the electron beam. Credit: M Koratzinos/RAT GUI

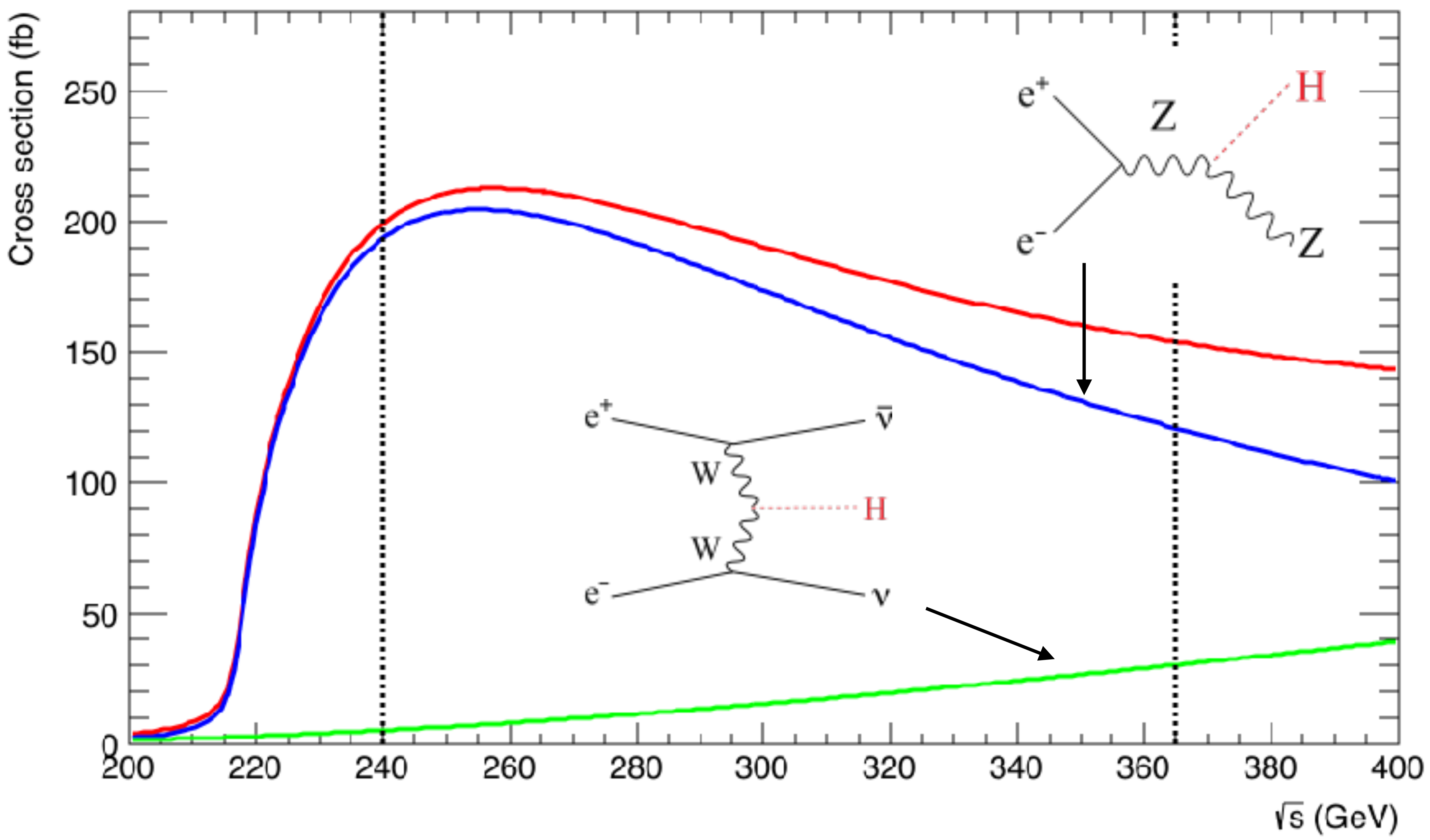
Power consumption

- 240 GeV the instantaneous power is 291 MW (compared to 140 MW for ILC and 110 MW for CLIC for less luminosity)
- Replace 5800 quadrupole and 4672 sextuple normal conducting magnets by HTS CCT magnets! article

Machine Parameters

Running mode	Z		W	ZH	$t\bar{t}$
Number of IPs	2	4	4	4	4
Beam energy (GeV)	45.6		80	120	182.5
Bunches/beam	12000	15880	688	260	40
Beam current [mA]	1270	1270	134	26.7	4.94
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	180	140	21.4	6.9	1.2
Energy loss / turn [GeV]	0.039	0.039	0.37	1.89	10.1
Synchr. Rad. Power [MW]			100		
RF Voltage 400/800 MHz [GV]	0.08/0	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	5.60	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	13.1	12.7	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	0.71	2.16	0.67	1.55
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	1.42	4.32	1.34	3.10
Longit. damping time [turns]	1158	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	110	200	300	1000
Vertical IP beta β_y^* [mm]	0.7	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	250	—	<28	<70
Beam lifetime (lum.) [min.]	35	22	16	10	13
	4 years		2 yrs	3 yrs	5 yrs

Higgs Physics at e+e- Colliders



1.5M per IP very clean ZH events produced at threshold

Approximately 1/3 of the number of ZH events at HL-LHC but in a much cleaner environment!

All final states can be very cleanly reconstructed.

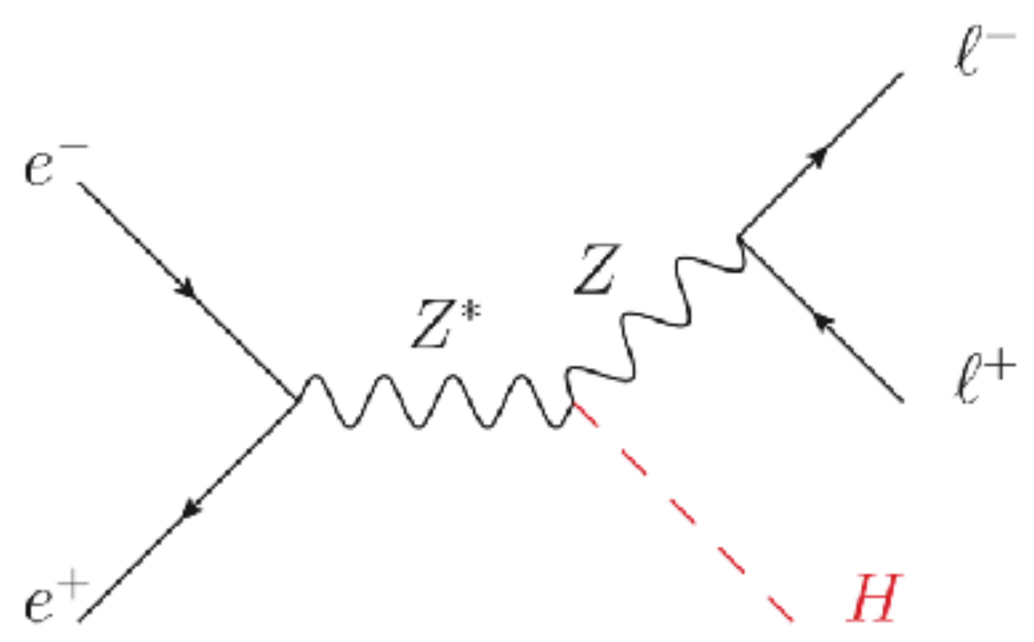
Additional 200k events at 350-365 GeV with approximately 30% from WW fusion which is interesting for the width measurement

- Measure $\sigma(e^+e^- \to HZ) \times Br(H \to bb, cc, gg, WW, \tau\tau, \gamma\gamma, \mu\mu, Z\gamma, \ldots)$ from each individual final state.
- Can also measure invisible decays from the reconstructed Z boson.

Fundamental difference with the LHC (and other hadron colliders): the width can be measured from the total HZ cross section! **Coupling measurements are less model dependent!**

Higgs Physics at e+e- Collider

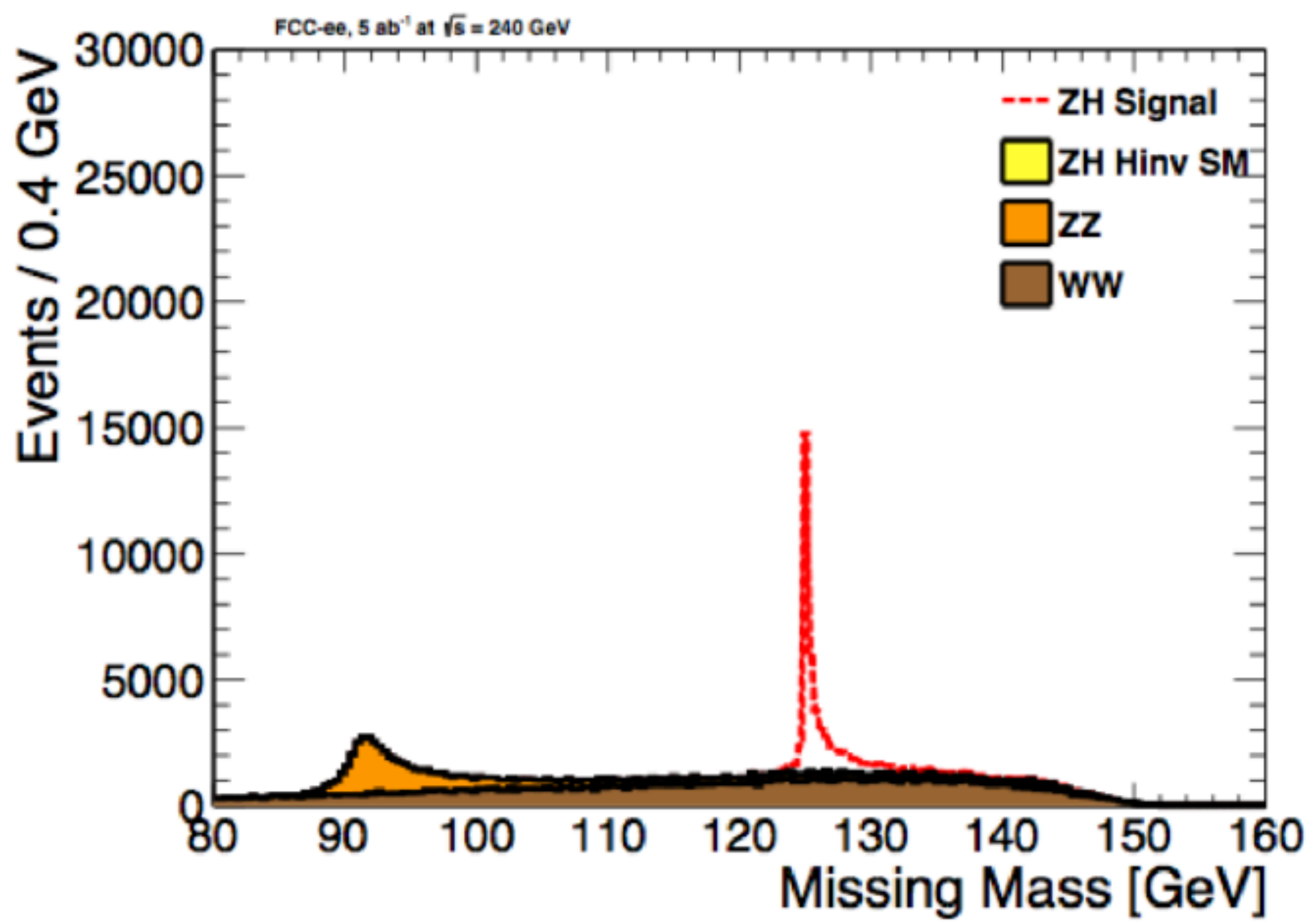
Threshold production of HZ provides a unique opportunity to measure the total HZ cross section through the recoil method



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |p_{\ell\ell}|^2$$

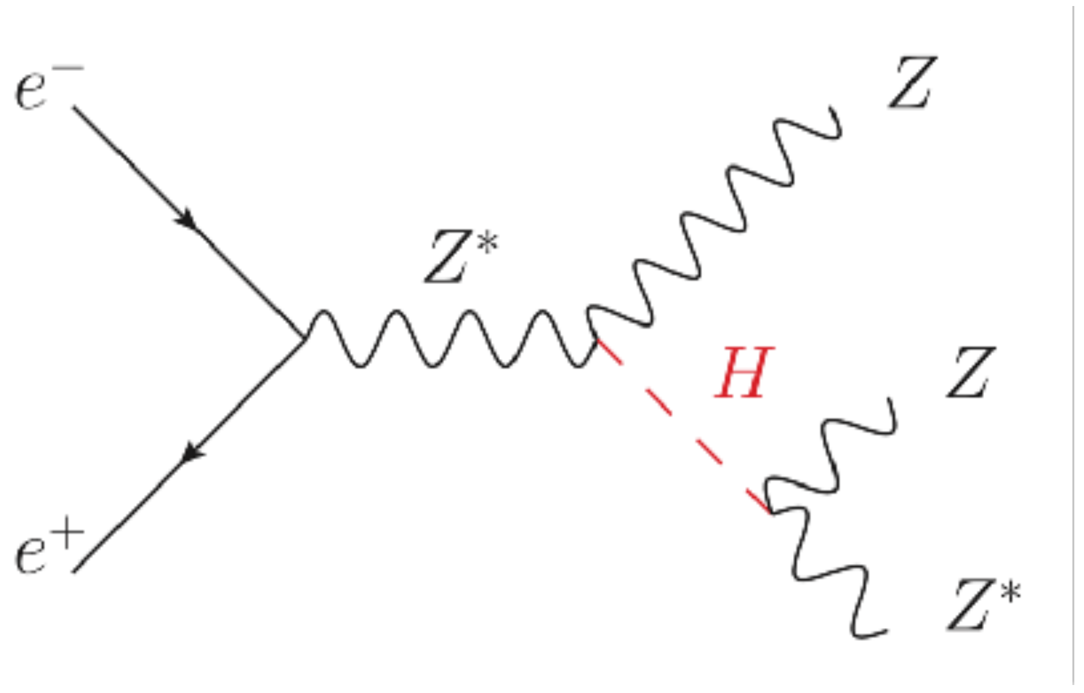
From conservation of energy and momentum, the energy and momentum of the Higgs is known from the Z without measuring the Higgs boson!

$$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$$



Measurement of the cross section at 240 GeV at 0.5% precision (0.9% at 365 GeV).

Then using the measurement of HZ with the Higgs to ZZ*:

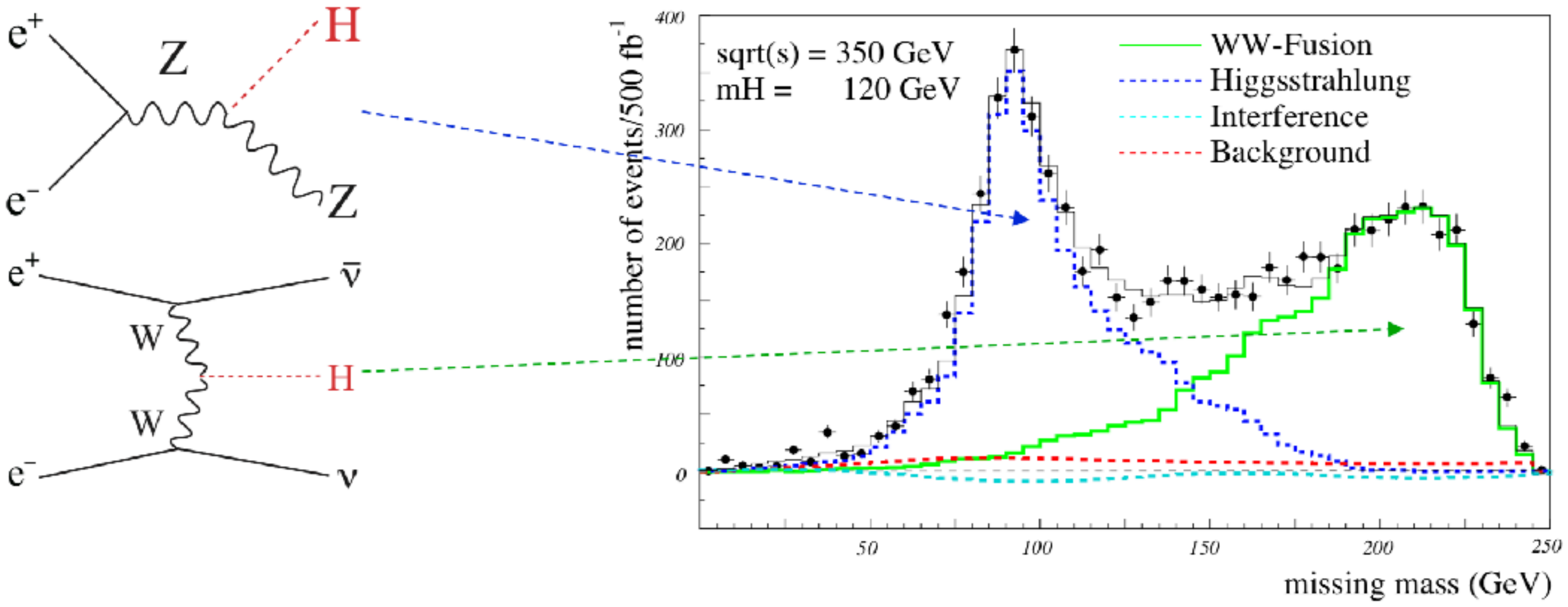


The total width of the Higgs can be measured at ~**2.5%** level with FCC-ee (240) alone.

$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

Higgs Physics at e+e- Collider

Further measurements of the width can be obtained using the WW fusion process as follows:



The WW fusion can be disentangled from the HZ process from the missing mass (which will not be peaked at the Z, but in this case at sqrt(s)-mH.

Then from the ratio of the following three measurements:

$$\frac{[\sigma(ZH) \times B(H \to WW)] \times [\sigma(ZH) \times B(H \to bb)]}{\sigma(\nu\nu H) \times B(H \to bb)}$$

Use different energy scale assumptions!

$$\propto \frac{\kappa_Z^2 \kappa_W^2}{\Gamma_H} \times \frac{\kappa_Z^2 \kappa_b^2}{\Gamma_H} \times \frac{\Gamma_H}{\kappa_W^2 \kappa_b^2} = \frac{\kappa_Z^4}{\Gamma_H}$$

Substantial gain in sensitivity to the total width, using higher COM energies and adding FCC-ee (365)!

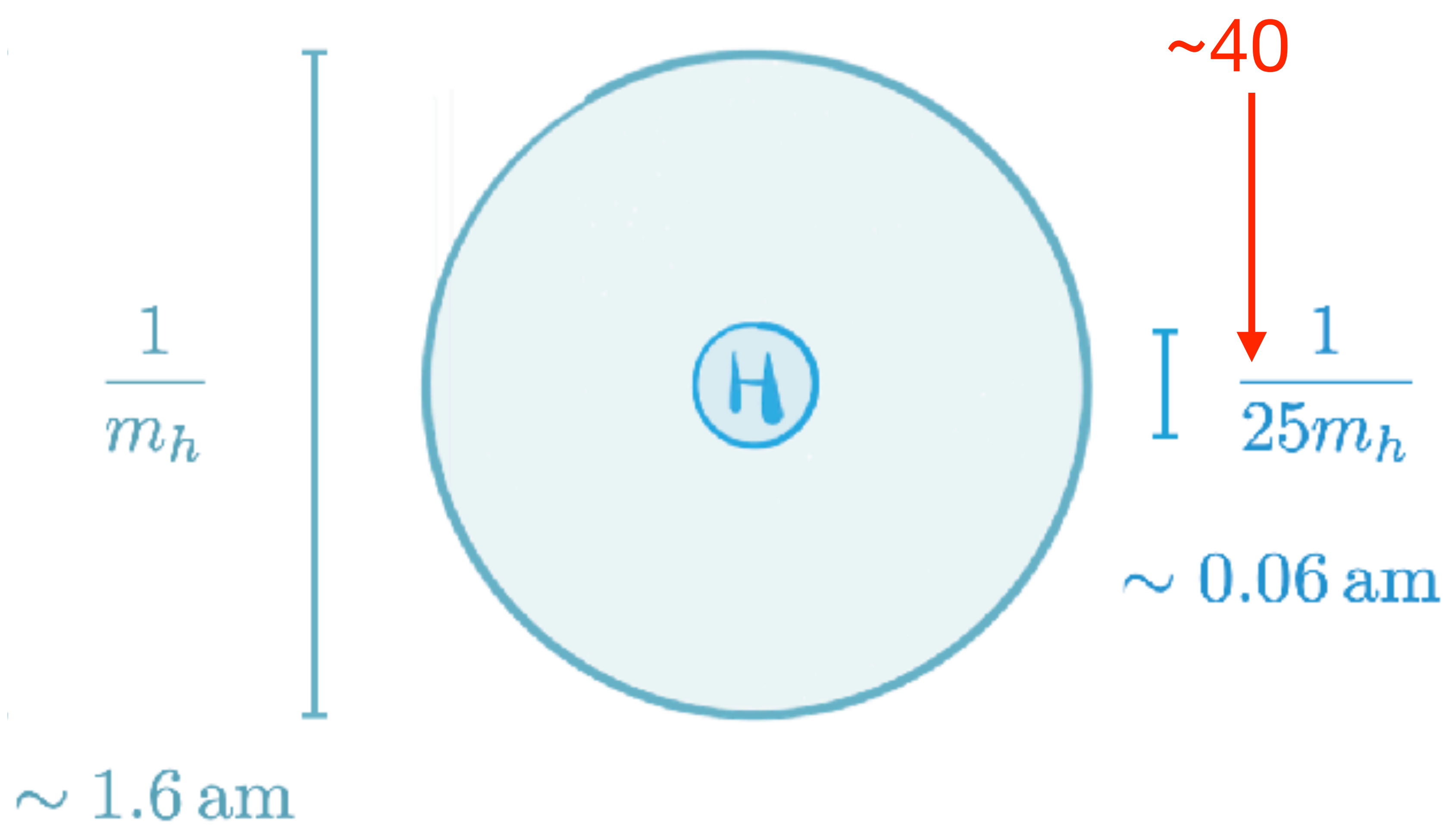
Precision on Γ_H of 1.1%

Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	Current precision	HL-LHC	FCC-ee (only)
κ_γ	13%	6%	1.8%	3.9%*
κ_W	11%	6%	1.7%	0.4%
κ_Z	11%	6%	1.5%	0.2%
κ_g	14%	7%	2.5%	1%
κ_t	30%	11%	3.4%	-
κ_b	26%	11%	3.7%	0.7%
κ_c	-	-	40%	1.3%
κ_τ	15%	8%	1.9%	0.7%
κ_μ	-	20%	4.3%	8.9%*
$\kappa_{Z\gamma}$	-	30%	9.8%	-*
B_{inv}		11%	2.5%	0.2%

***Of course not competitive on rare decays.**

Far more stringent constraint on the size of the Higgs boson!



$$c_H \frac{v^2}{\Lambda^2} < 0.002$$

Taking $c_H = 1$ leads to $\Lambda > 5.5$ TeV

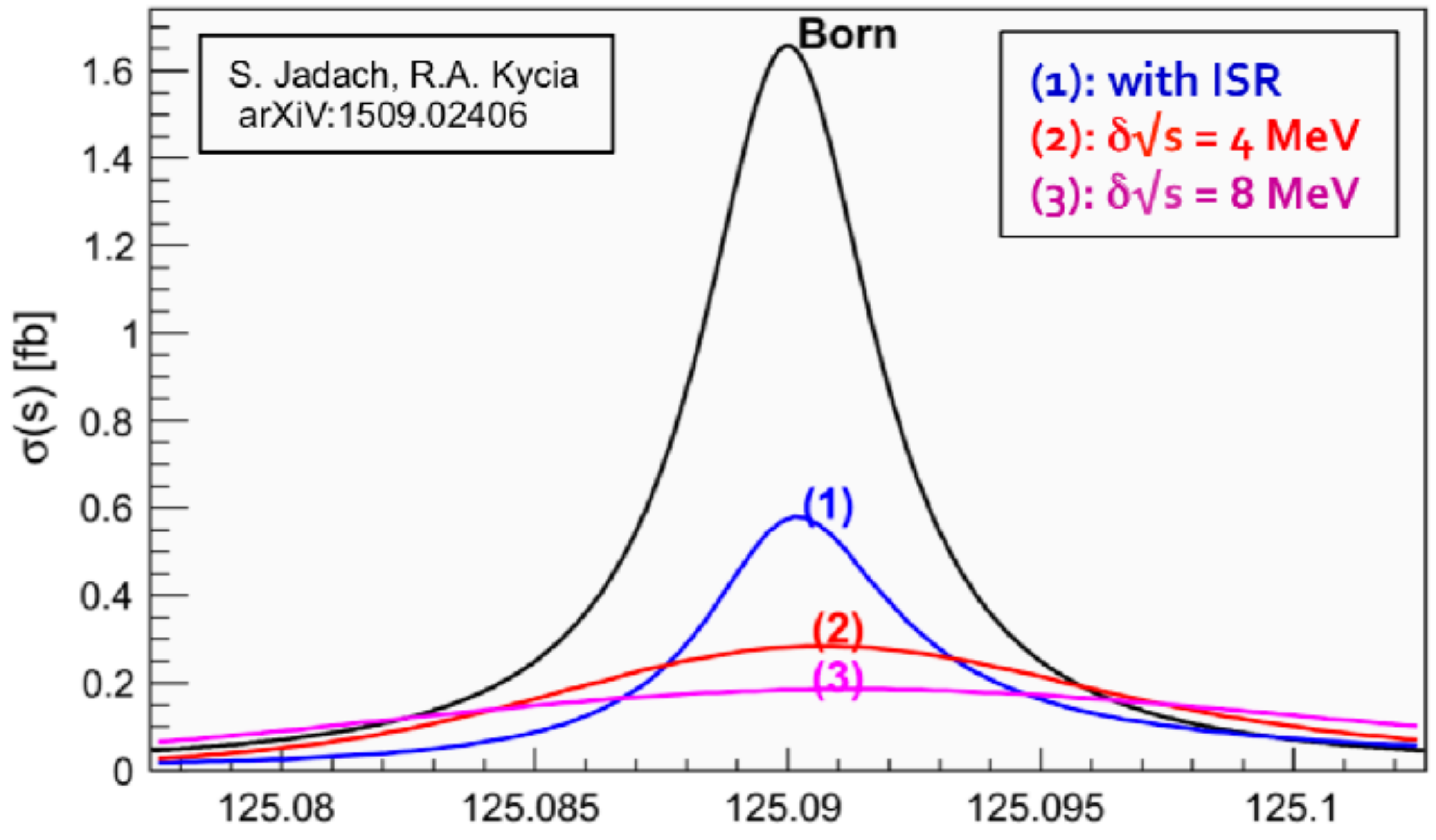
s-Channel Higgs production and e-Yukawa

Extremely challenging for several reasons:

1.- The production cross section is $\sigma(ee \to H) = 1.6 \text{ fb}$ will require extremely large luminosities

2.- Given the Higgs width of 4.2 MeV, and extremely small energy spread is necessary - require monochromatization.

- Default beam spread has delta ~ 100 MeV (no visible resonance)
- Requires beam monochromatisation
- Requires a prior knowledge of the Higgs boson mass of ~couple of MeV at most!
- Would require huge luminosity and therefore 4IPs.



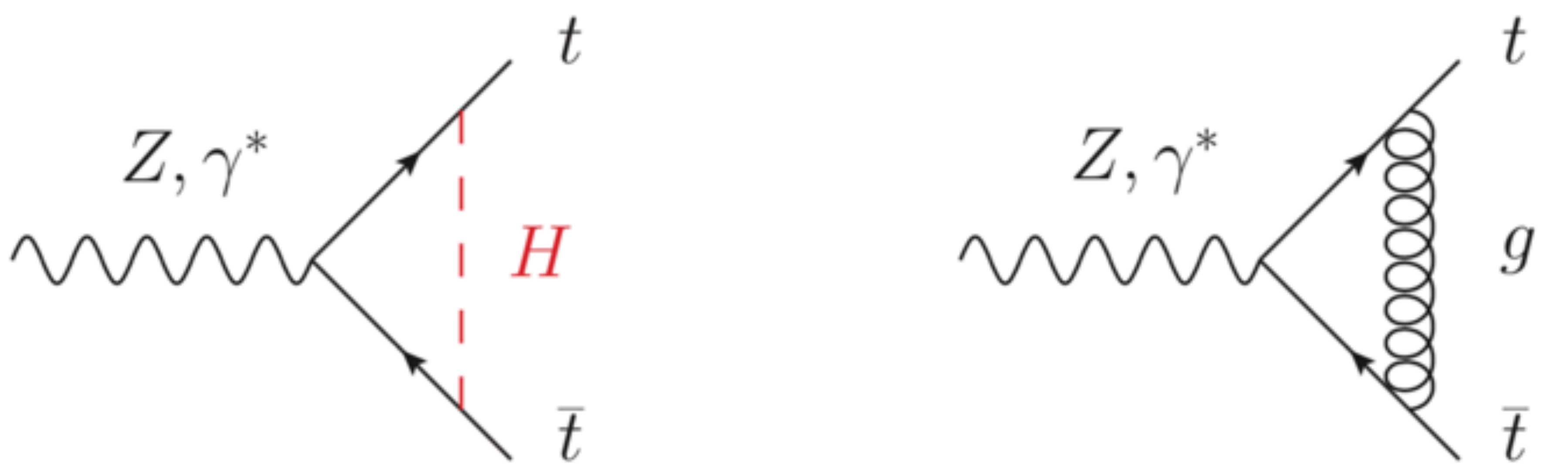
First studies indicate a sensitivity of 0.4σ per year and per detector (spread of ~6 MeV)

Monochromatization already considered but never used

Monochromatization uses opposite correlation between spatial position and energy.

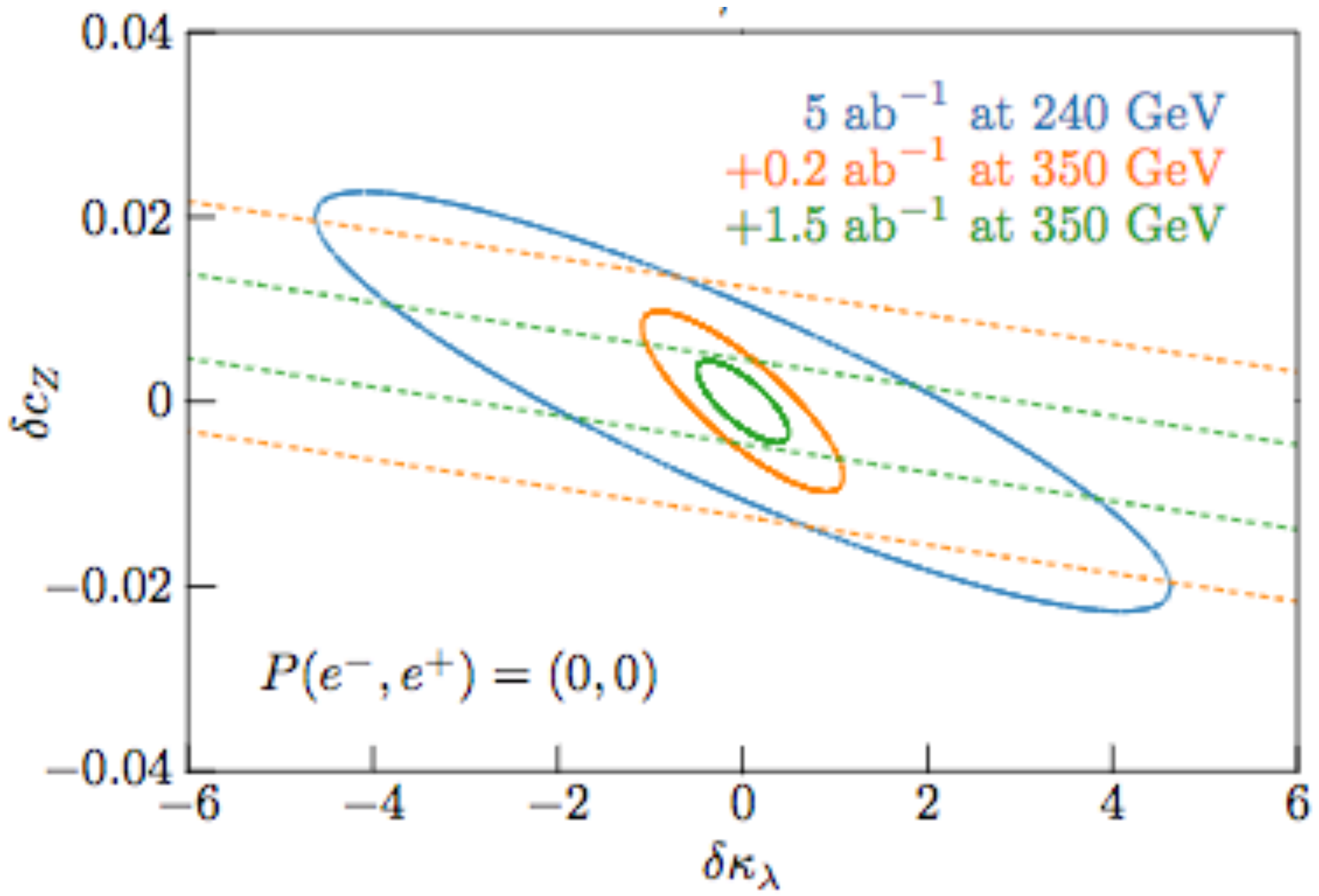
Model Dependent Measurements through Loops

Top pair cross section at threshold and above



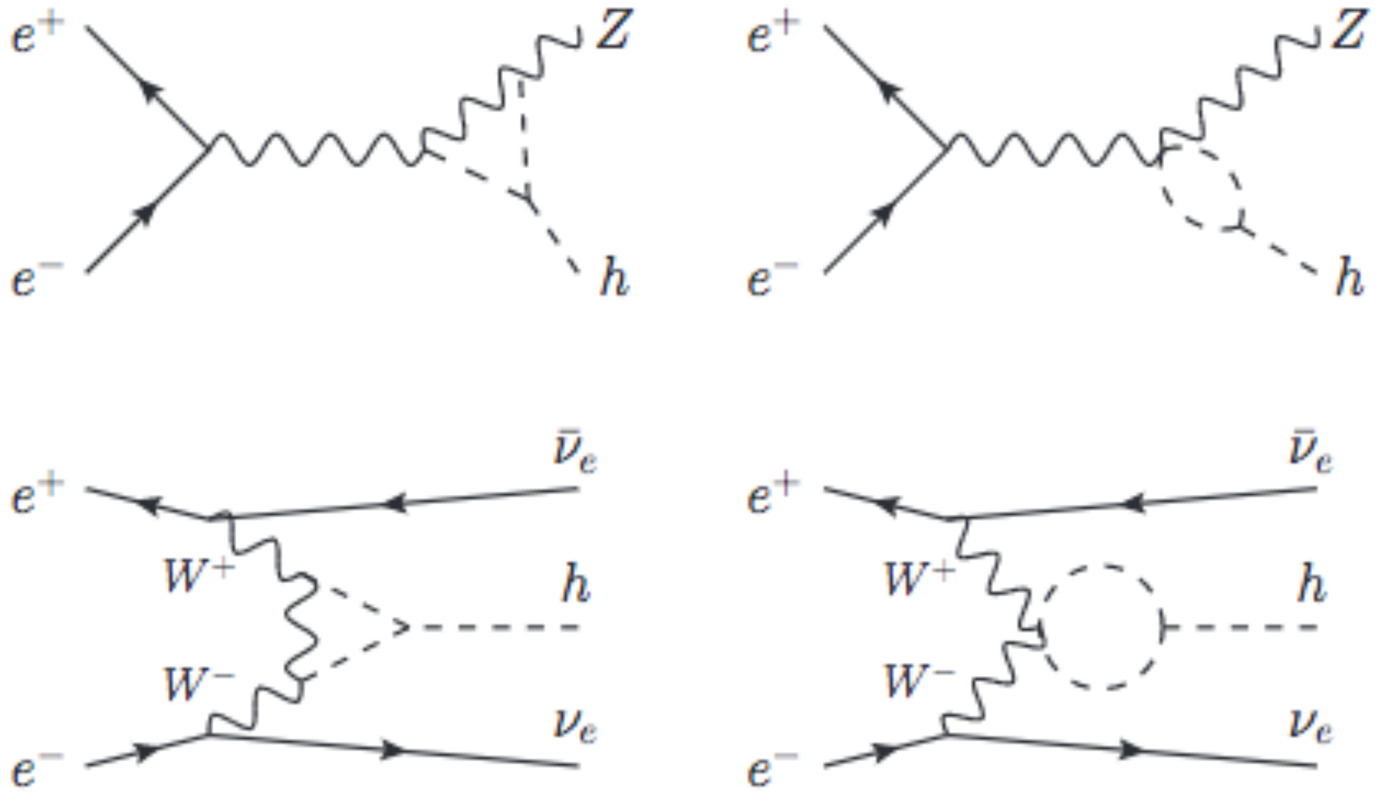
Precision on alphaS at FCC-ee will be important

Top Yukawa coupling precision from top pair cross section measurements **<10%**

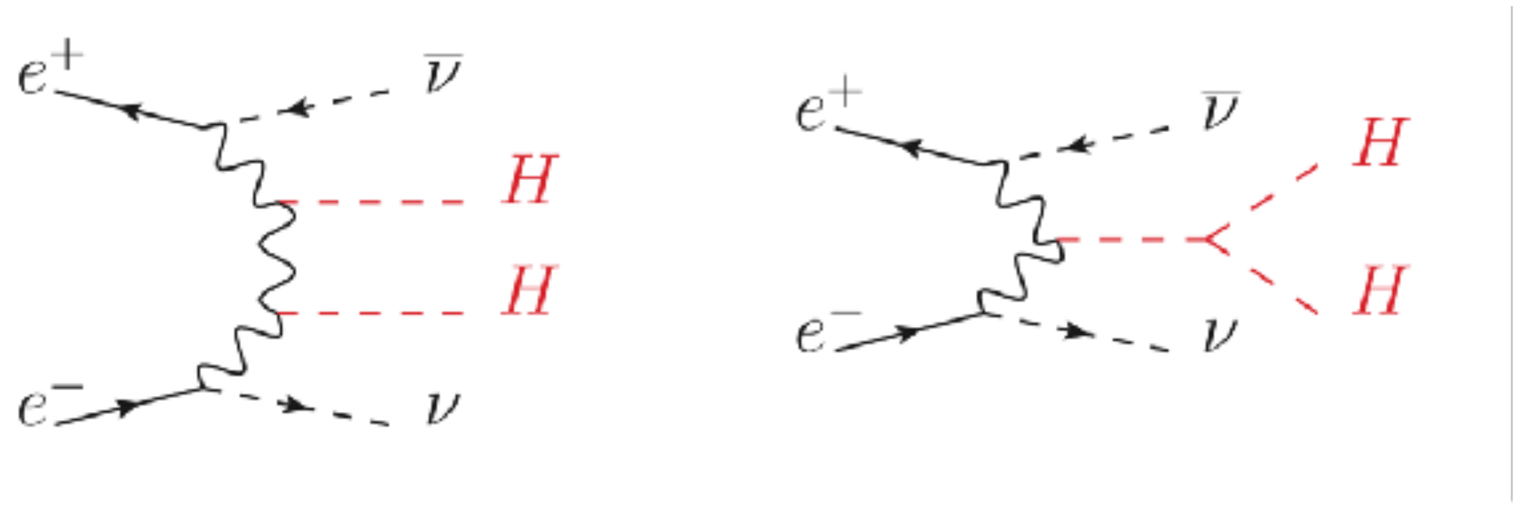


Higgs self coupling precision **~30%** - reduced to ~20% with kappaZ = 1 from SM

Higgs cross section at 240, 350, at 365 GeV



Similar precisions are obtained with double Higgs production at CLIC ($\sqrt{s}$ = 1.4 and 3 TeV)



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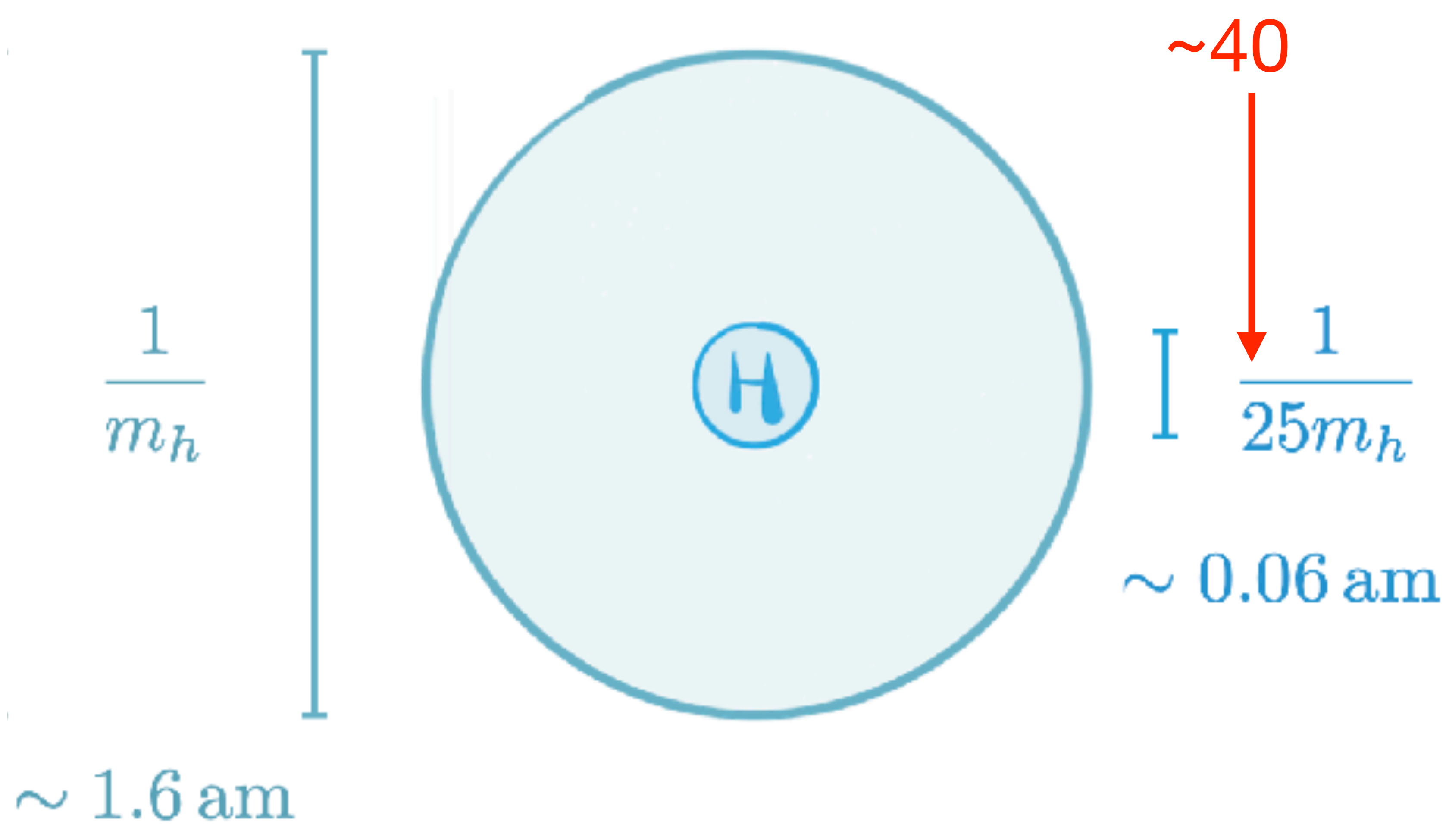
κ_t	30%	11%	3.4%	10%*
κ_b	26%	11%	3.7%	0.7%
κ_c	-	-	40%	1.3%
κ_τ	15%	8%	1.9%	0.7%
κ_μ	-	20%	4.3%	8.9%
$\kappa_{Z\gamma}$	-	30%	9.8%	-
B_{inv}	-	11%	2.5%	0.2%
κ_λ	-	-	50%	27%*

***Of course not competitive on rare decays.**

Far more stringent constraint on the size of the Higgs boson!



$$c_H \frac{v^2}{\Lambda^2} < 0.002$$

Taking $c_H = 1$ leads to $\Lambda > 5.5$ TeV

e^+e^- Ultimate Precision Machine!!

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

EW Precision

Key measurements:

- $m_Z \sim 10^{-6}$, $m_W \sim 10^{-5}$, $m_{top} \sim 10^{-4}$
- $sin^2_{\theta_W} \sim 3.10^{-6}$, $\alpha_{QED}(m_Z^2) \sim 10^{-5}$, $\alpha_S \sim 10^{-4}$

FCC-ee is much, much more than a Higgs factory!

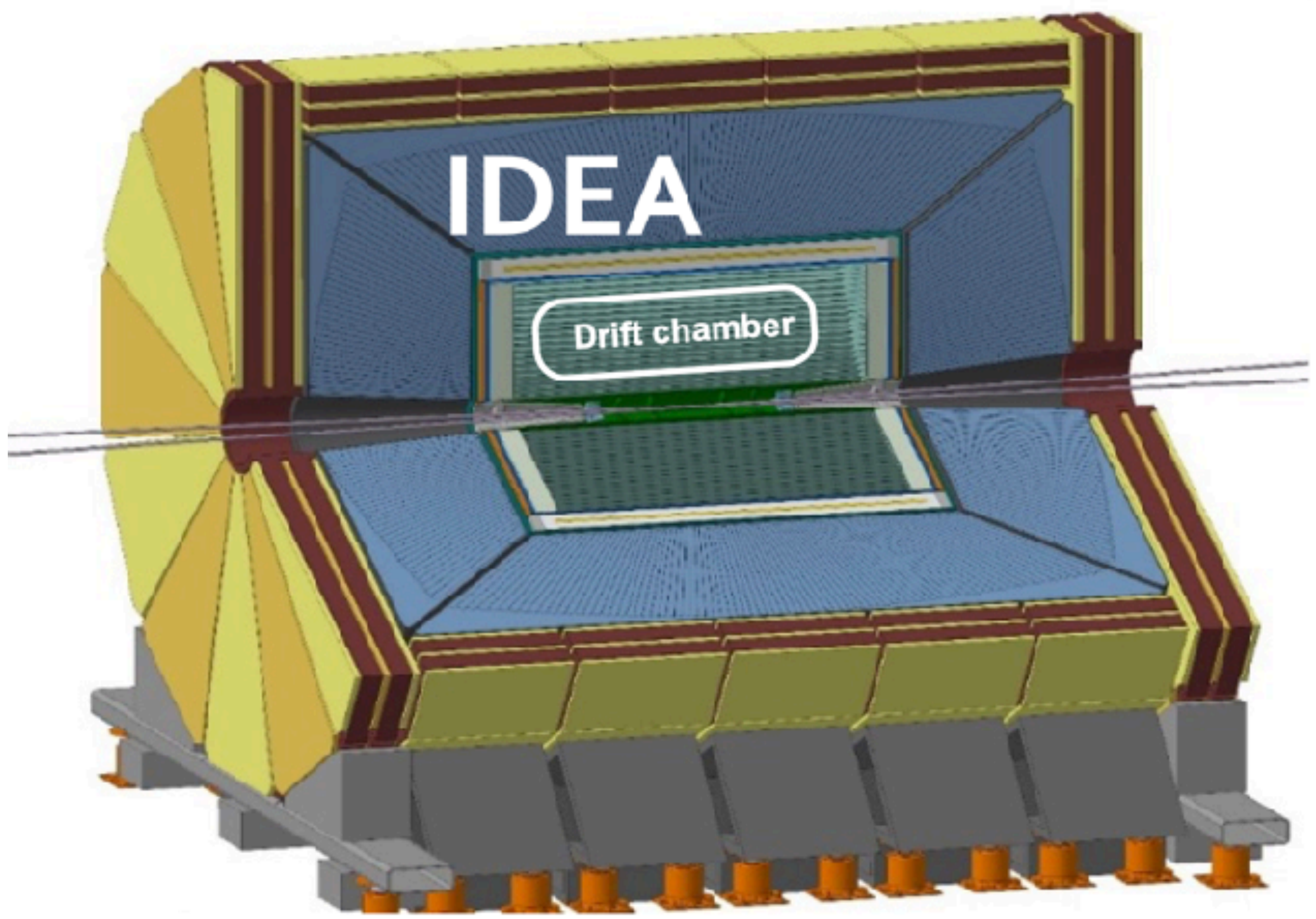
Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- Indirect discovery **potential up to 70 TeV**

e^+e^- Ultimate Precision Machine!!

Ultimate precision machine requires ultimate precision detectors!

Analysis work is now strongly oriented **towards detector requirements to achieve the design precision**



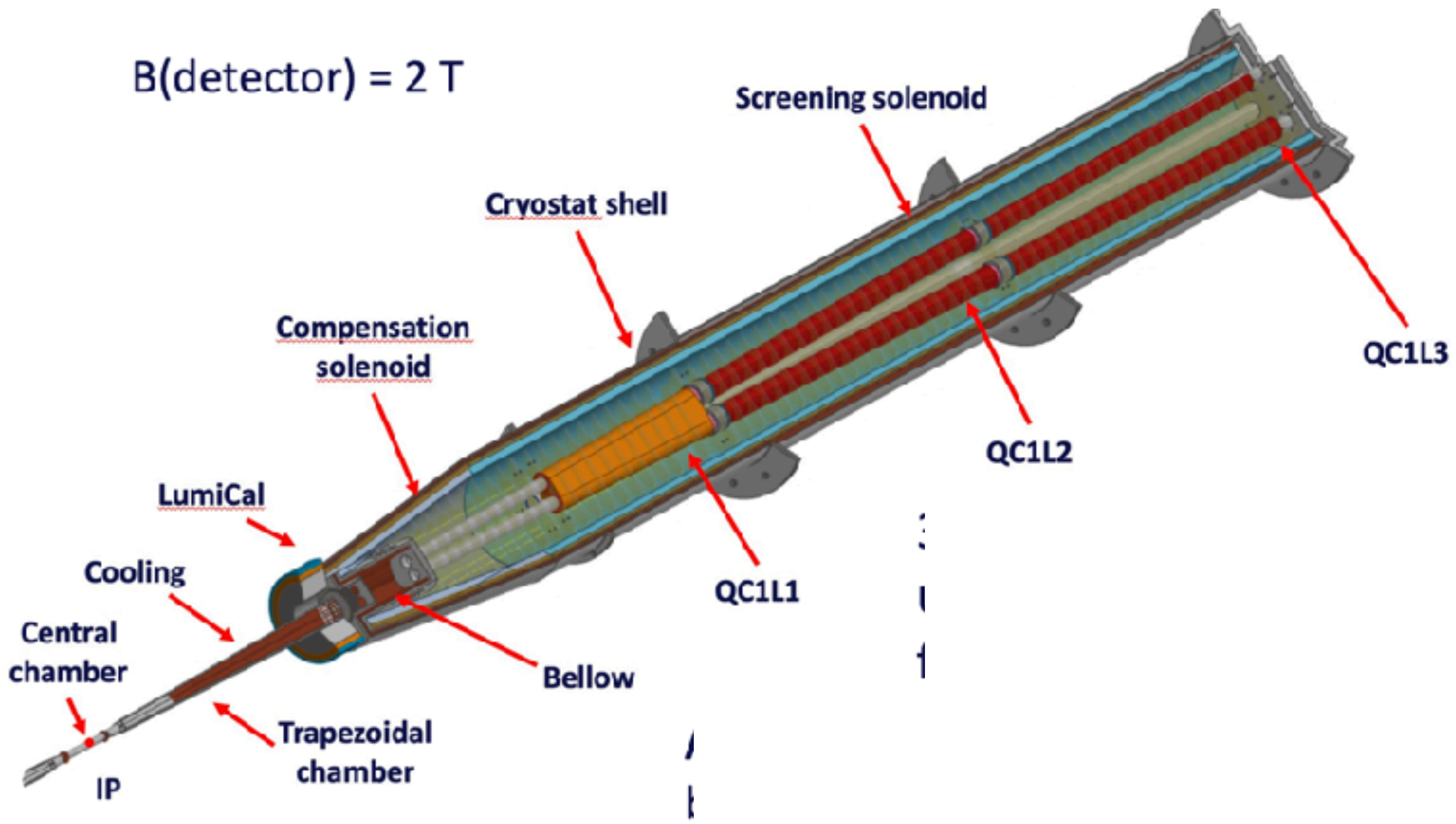
Several detector concepts: **CLD**, **IDEA** and **ALLEGRO** (Nobel Liquid concept)

Key aspects are very small amount of material in the inner detector region for precision track measurements and precise and highly granular calorimeter (numerous concepts)

See talk by Magnus Mager on MAPS!

The FCC-ee interaction region and final focus!

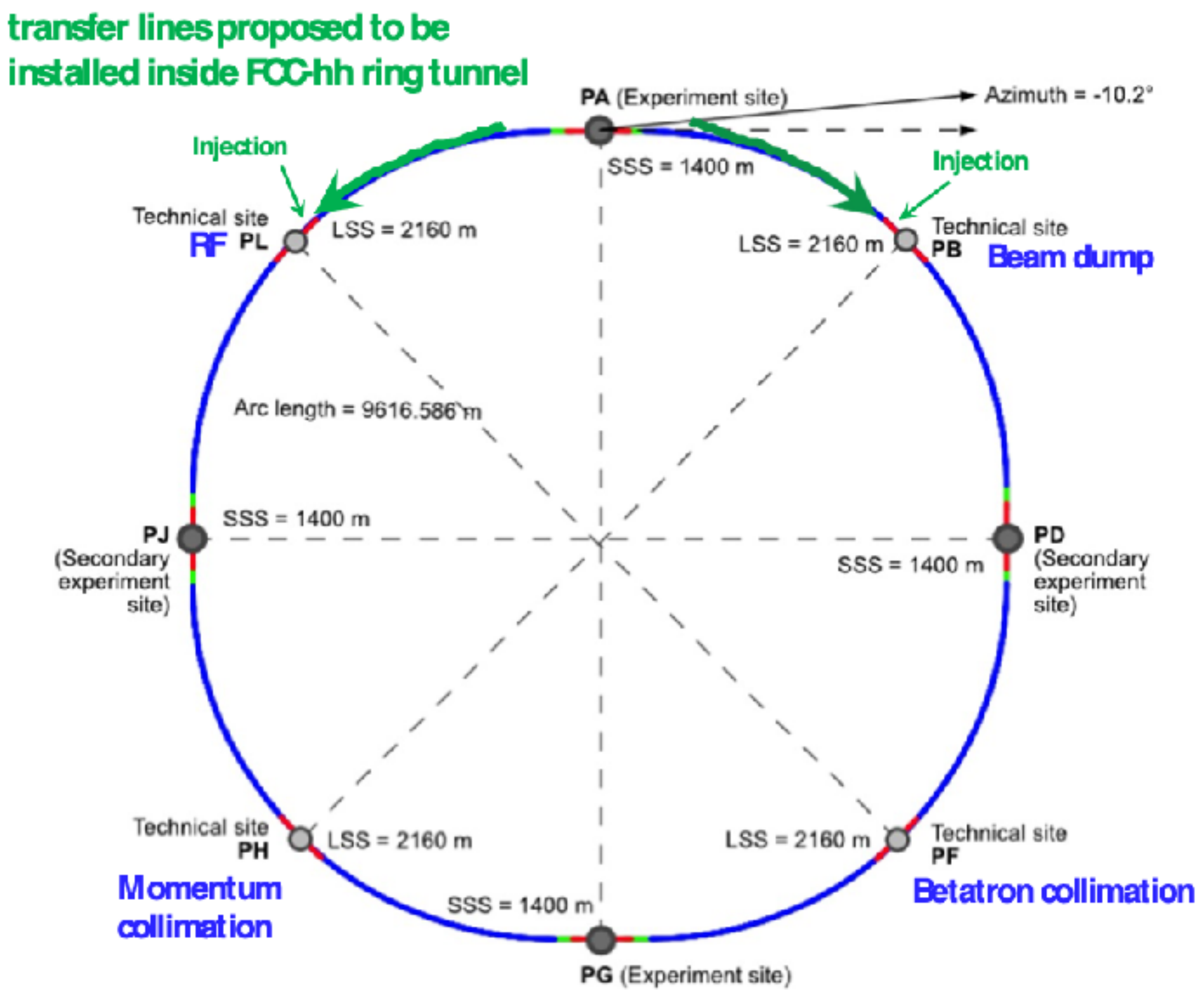
- Critical to reach highest possible luminosities
- Quadrupole magnets and final focus almost entirely inside the detector (at 8.4 m) - very strong requirements to reach **nano beams!**



Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh the second phase of the FCC program

Project	HL-LHC	FCC-hh	SppC
Location	CERN	CERN	China TBD
Circ.	27 km	90 km	55 - 100 km
COM energy	14 (15?) TeV	100 TeV	70 -140 TeV
Lum. (ab^{-1})	3	20-30	TBD
PU	200	1000	TBS
Field	8T	18T	20T



SppC similar design

Key technological challenges

- **High field magnets**, need 16T to reach 50 TeV/beam - Nb3Sn (FCC-hh) or Nb3Sn with HTS inserts (SppC) - exploration of HTS magnets
- Machine protection 30 W/m synchrotron radiation and **8GJ per beam (equivalent to Boing 747 at cruising speed)**

Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh program

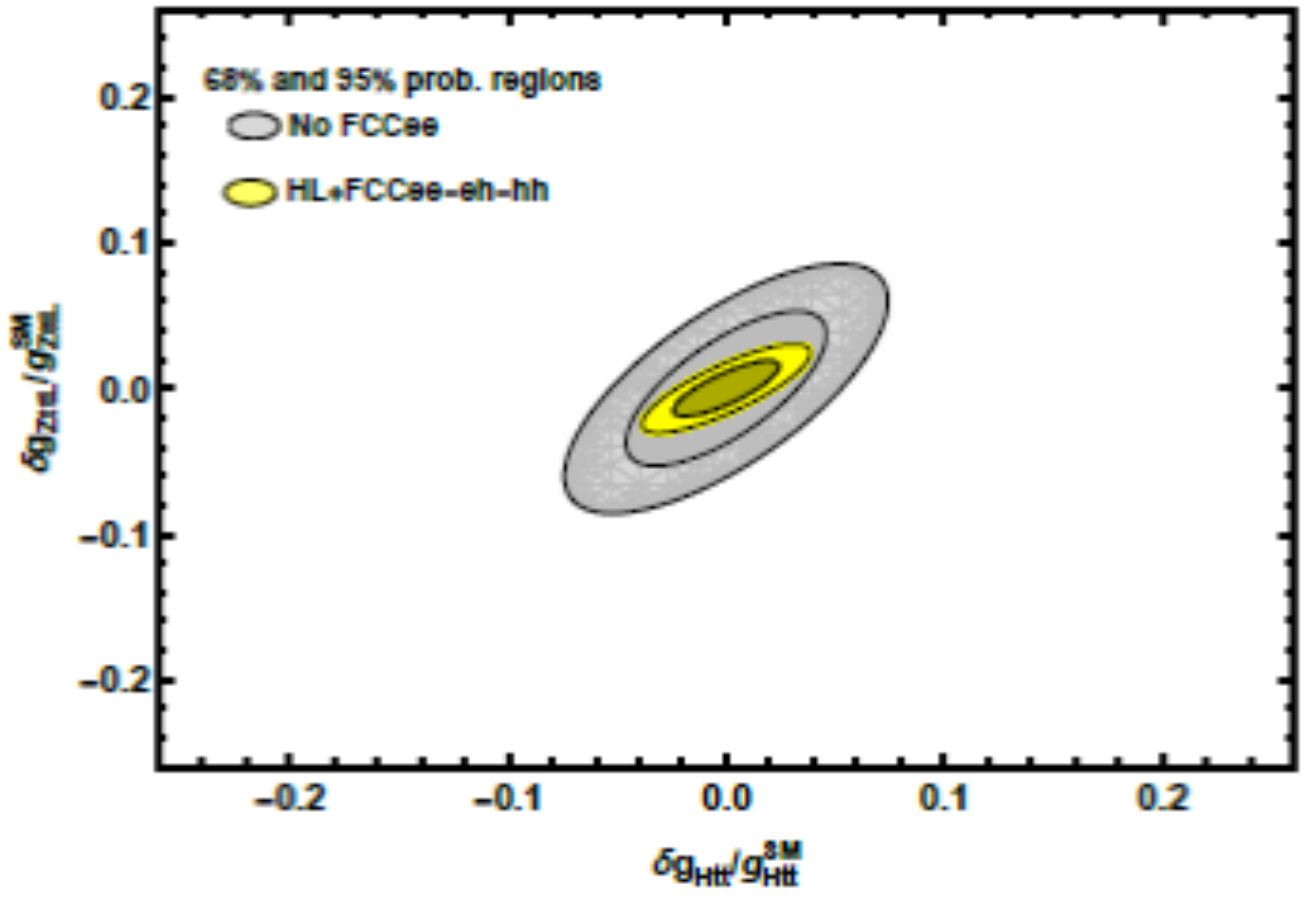
- **Primary goal is to explore the Multi-TeV scale with direct searches for new phenomena.**
- **Guaranteed deliverables**: completion of the missing key pieces in Higgs precision κ_H and κ_t

Essential complementarity with FCC-ee

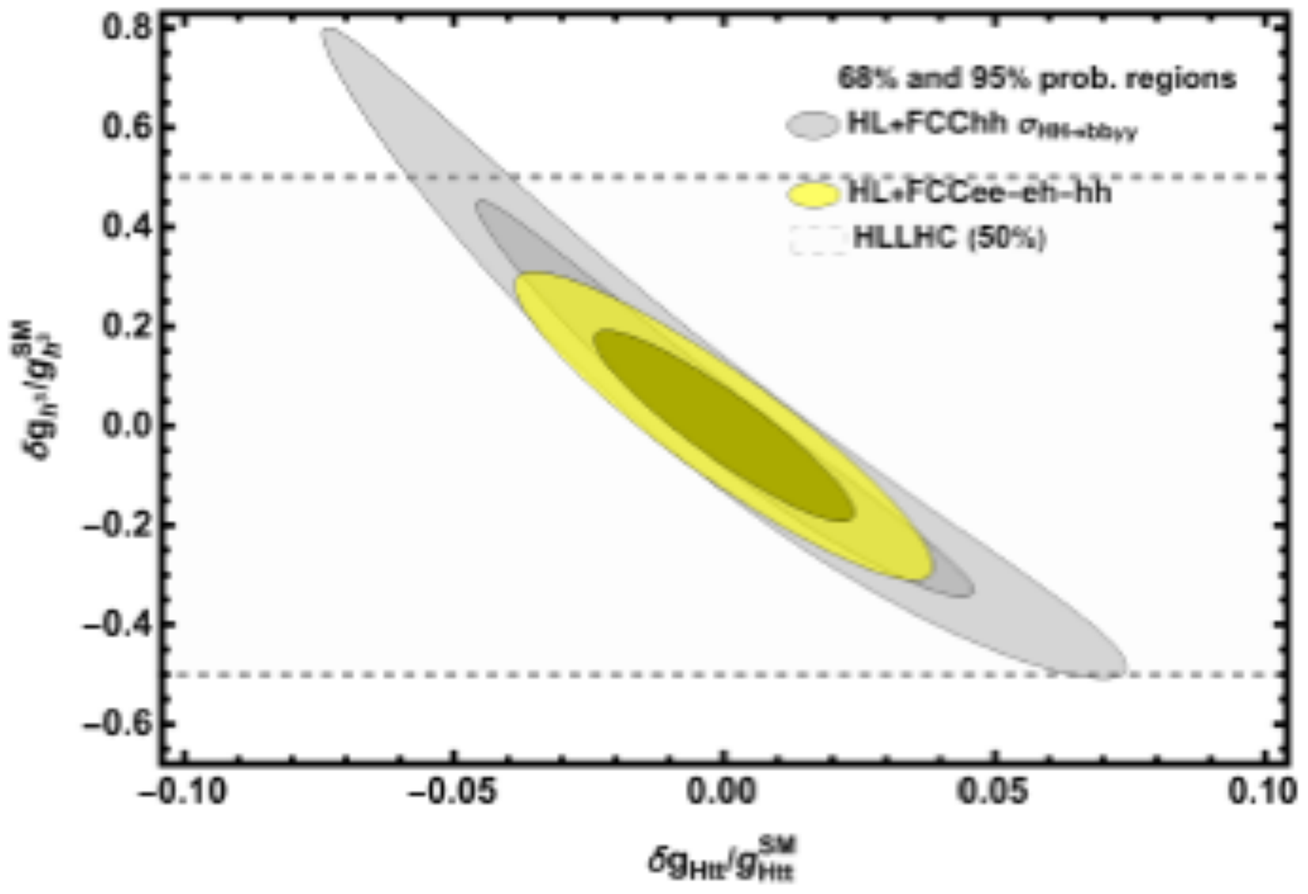
- FCC-hh is a very intricate environment (up to 1000 PU events), event reconstruction at its limits and large TH uncertainites
- Precision foreseen to be reached through ratios of cross sections.
- Key precision deliverables: top Yukawa coupling and Higgs trilinear coupling! FCC-ee and FCC-hh together are 2-3 times better than FCC-hh alone.

Ingredients

- FCC-ee measurement of the ttZ coupling ($e^+e^- \rightarrow t\bar{t}$ yields g_{ttZ})
- Measure the ratio ttH to ttZ at percent level!
- Then measure ratio HH to ttH



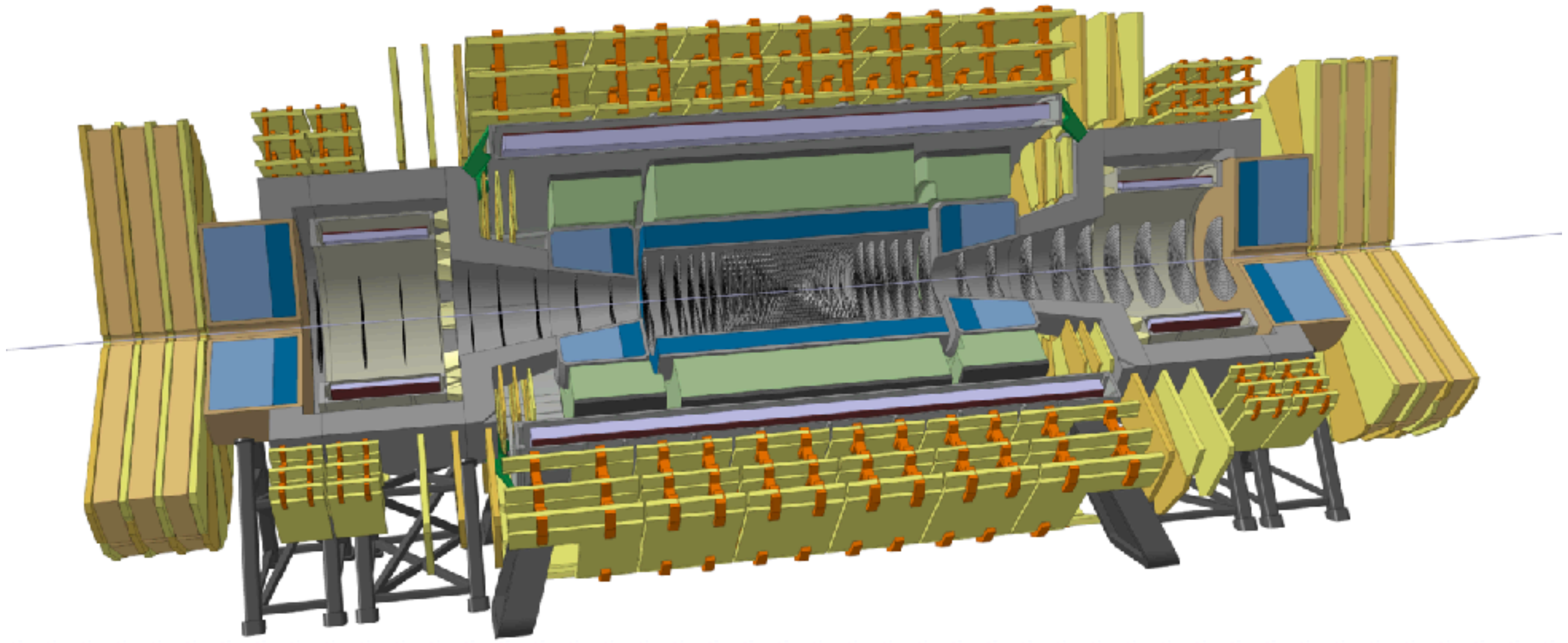
κ_t ~1%

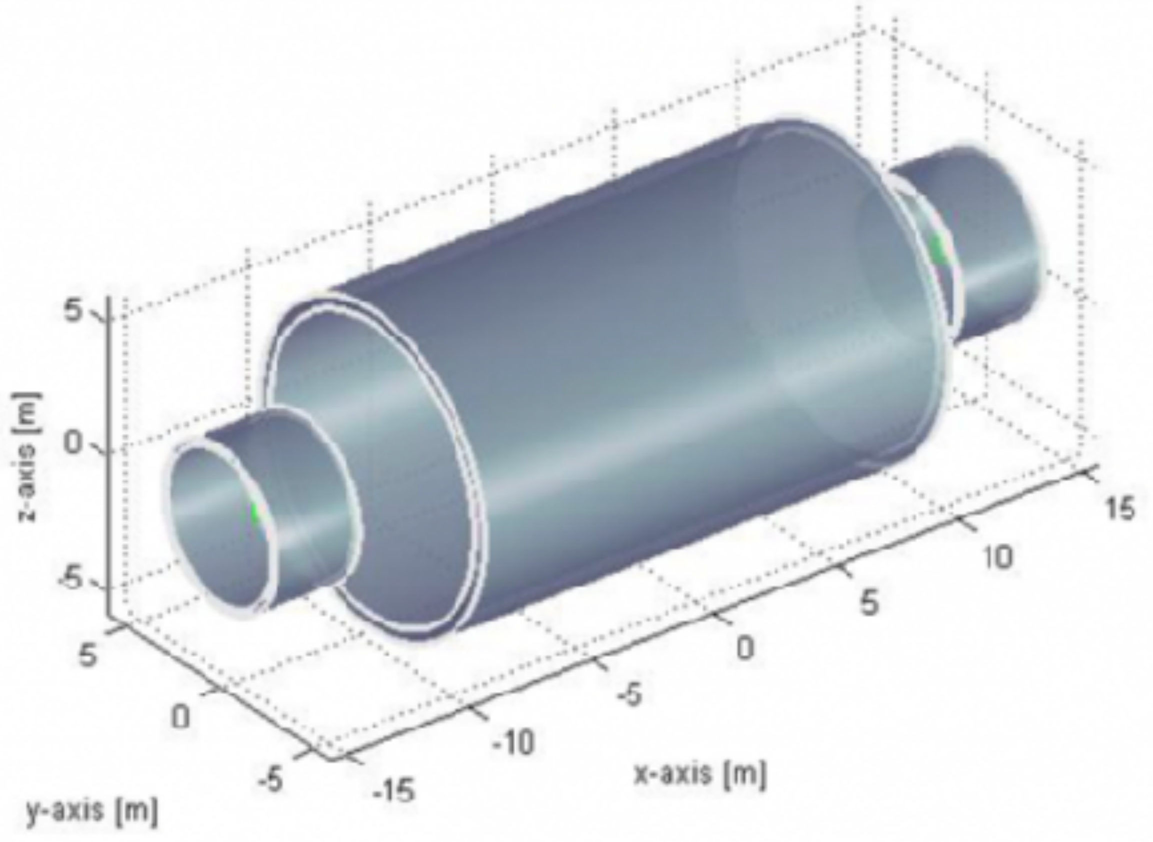


κ_λ ~5%

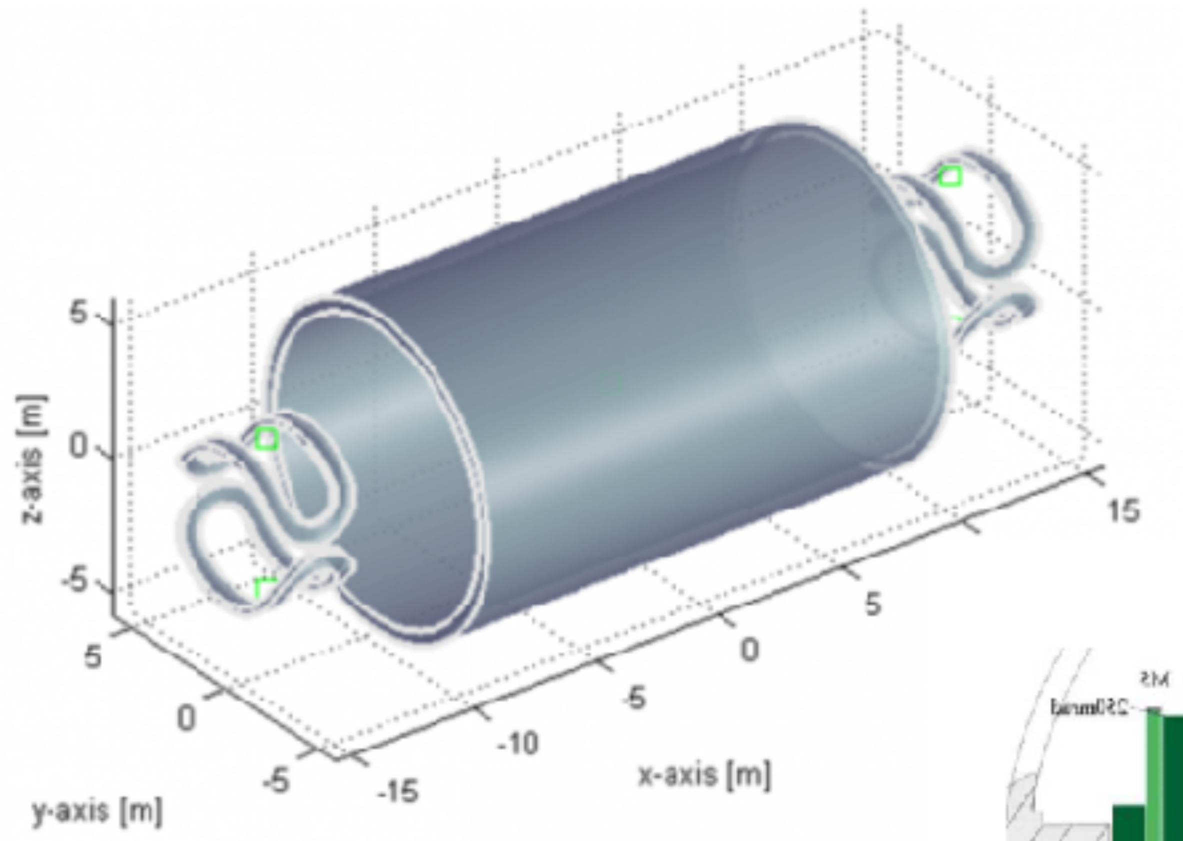
Hadron Collider Projects - Exploring the Multi-TeV scale

Dimensions commensurate (slightly larger) with current LHC experiments





Baseline



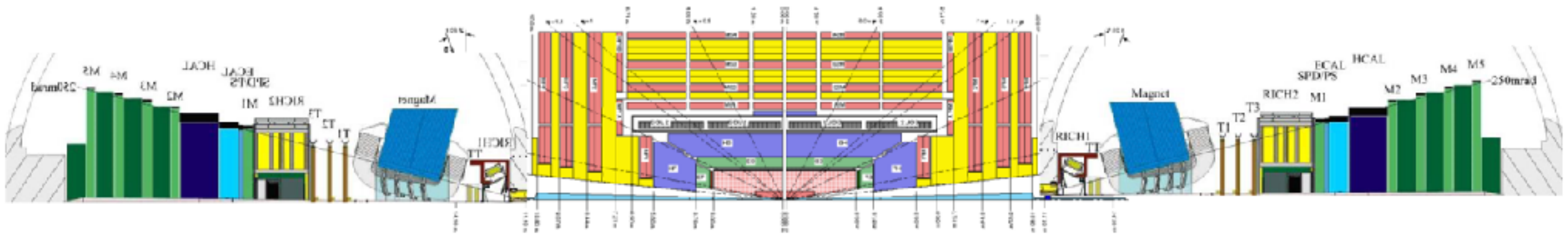
Alternative

FCC-hh key detector design challenges

- High luminosity - Extremely large PU, high occupancy and data rates, high trigger rates
- At FCC-hh Higgs produced up to rapidity of ~6.5 (up to 2.5 at LHC)
- Very high rates for triggering **Granularity** will be very important: decay product of a Z at 10 TeV separated by $\Delta R \sim 0.01$!!

Explore to improve on the resolution at high rapidity

Forward dipole magnet for high pseudo rapidity particles
Drawback: breaks the rotationally symmetric system…
Would be similar to a central CMS and two LHCbs in the forward directions!



Muon Collider Project - Exploring the Multi-TeV scale

Best of all worlds?

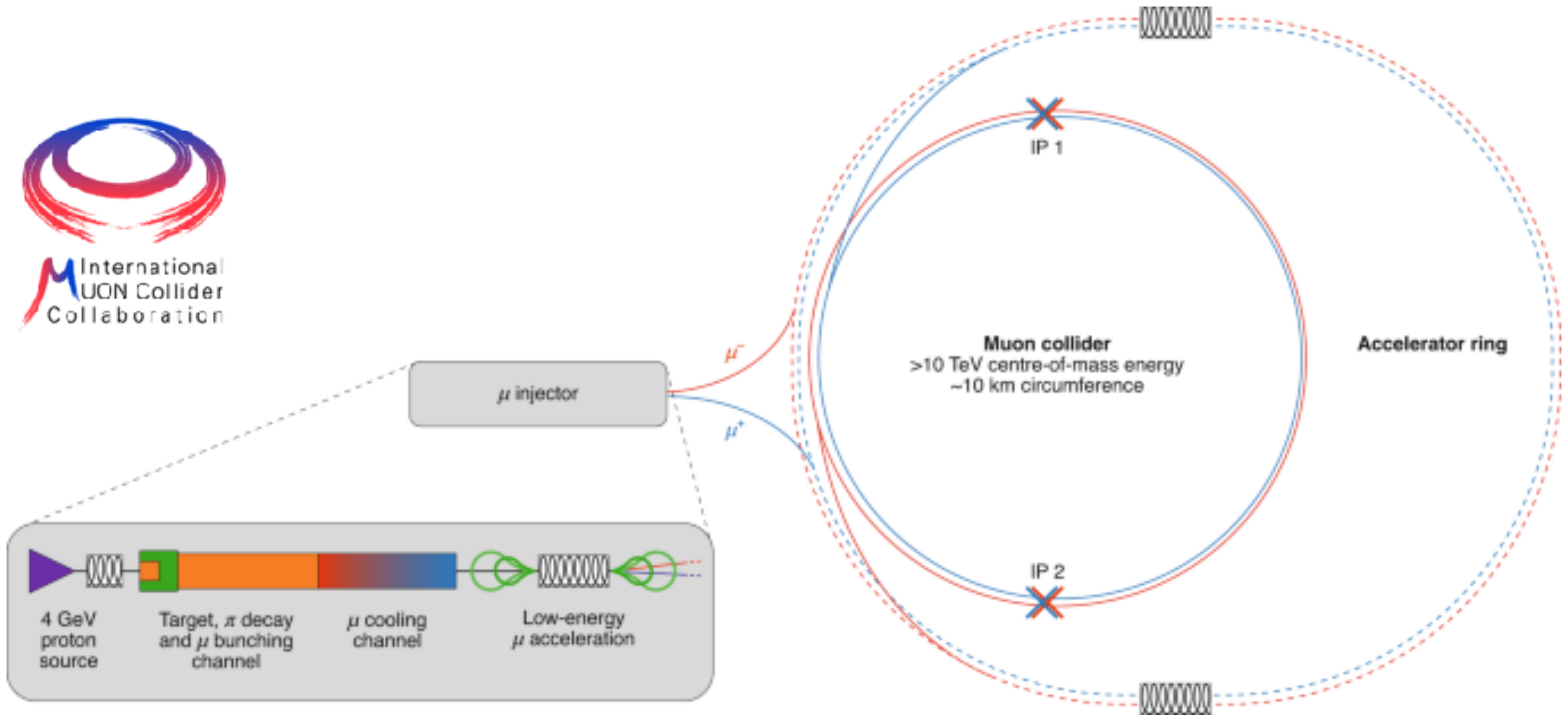
High energies, high luminosities with excellent lumi per MW ratio, (relatively) clean lepton collision events!

Mostly aimed at new physics searches in the Multi-TeV scale reach!

… incredibly challenging!

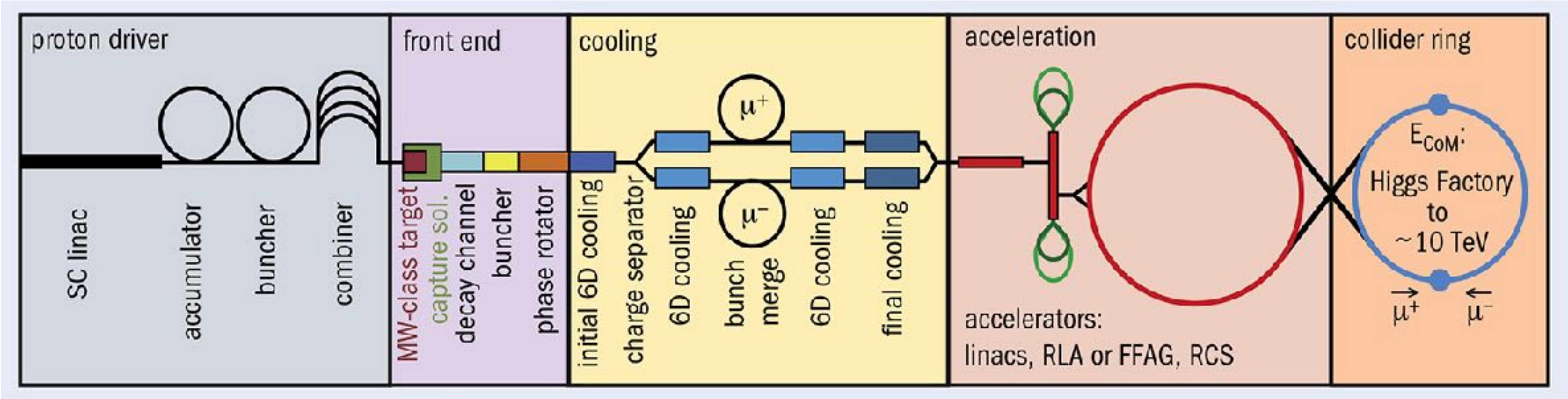
Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab−1 for 3, 10 and 14 TeV, **respectively**.

International MUON Collider Collaboration



MAP (Muon Accelerator Program)
Proton driven scheme

Reduction of the longitudinal and transverse emittance with a sequence of absorbers and RF cavities in a high magnetic field.



Muon Collider Project - Exploring the Multi-TeV scale

Muon collider as a Higgs Factory?

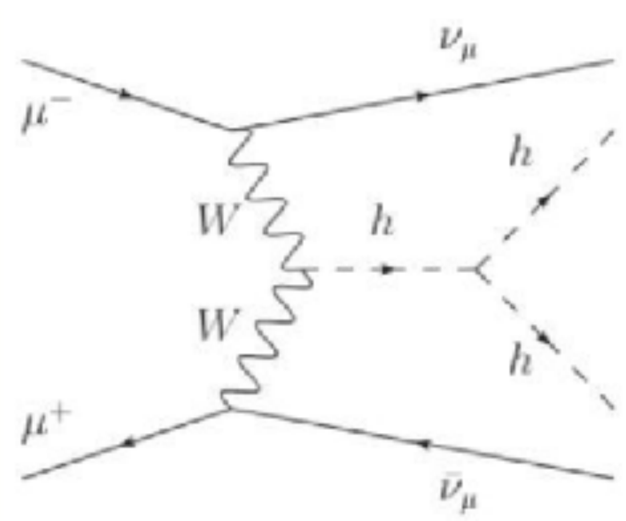
In principle could do everything as an e^+e^- collider with a much smaller ring! However the luminosity is estimated to be 2 orders of magnitude smaller at 240 GeV.

However at 125 GeV the s-channel production is 40,000 times larger (and a beam spread ~width).

Collider	μColl$_{125}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	0.005	5 + 0.2 + 1.5
Years	6 to 10	3 + 1 + 4
g_{HZZ} (%)	SM	0.17
g_{HWW} (%)	3.9	0.43
g_{Hbb} (%)	3.8	0.61
g_{Hcc} (%)	SM	1.21
g_{Hgg} (%)	SM	1.01
$g_{H\tau\tau}$ (%)	6.2	0.74
$g_{H\mu\mu}$ (%)	3.6	9.0
$g_{H\gamma\gamma}$ (%)	SM	3.9
Γ_H (%)	6.1	1.3
m_H (MeV)	0.1	10.
BR$_{inv}$ (%)	SM	0.19
BR$_{EXO}$ (%)	SM	1.0

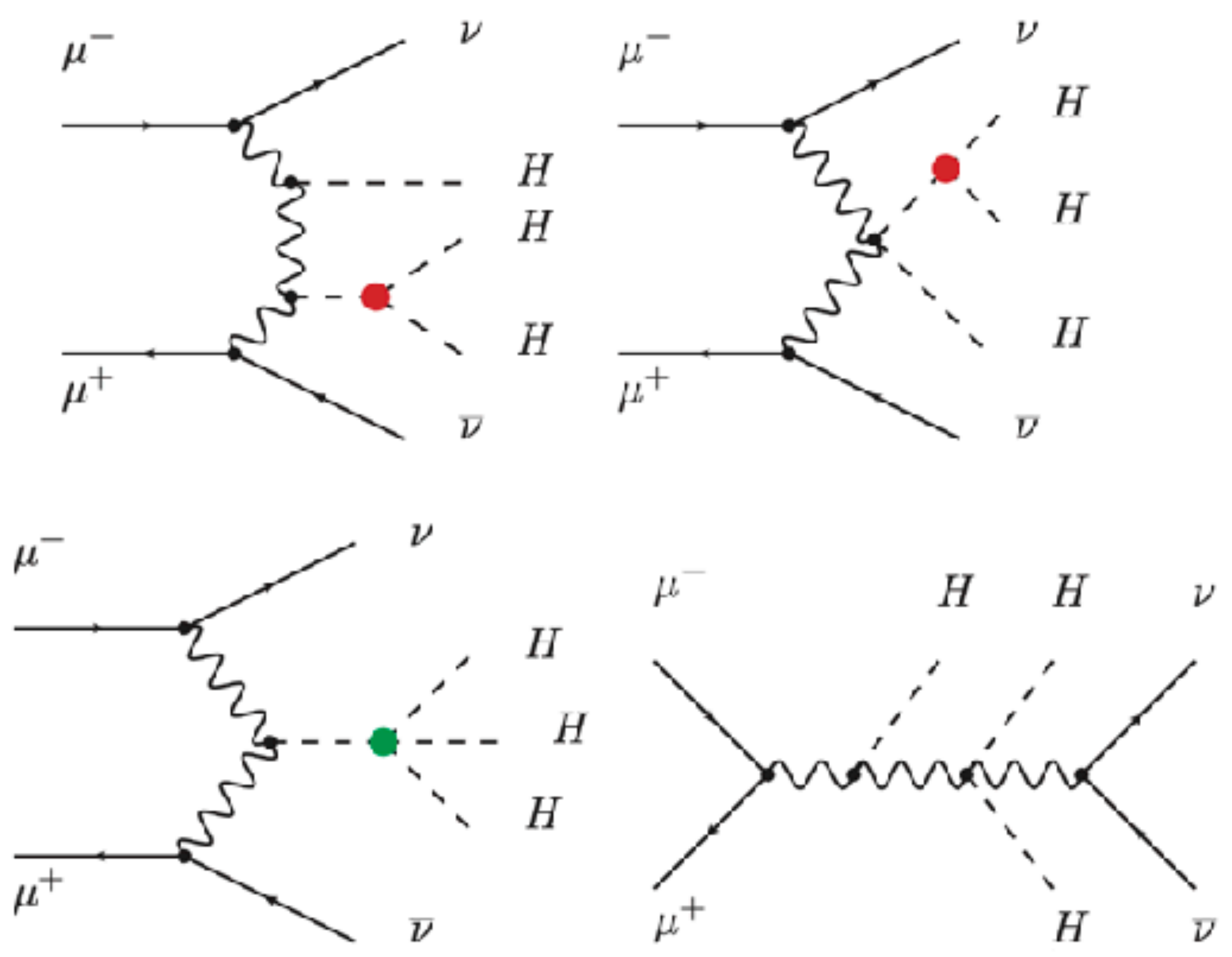
Muon Collider at 3 TeV

Notable result reach on trilinear coupling from di-Higgs production $\lambda_3 \sim 20\,\%$



Muon Collider at 14 TeV

Quartic couplings studies show (see paper)



Assuming $\lambda_3 = 1$ and $33\ ab^{-1}$ could reach **50%** precision of the Higgs boson quartic coupling.

Muon Collider Project - Exploring the Multi-TeV scale

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$g_{H\tau\tau}$ (%)	6.2	0.74
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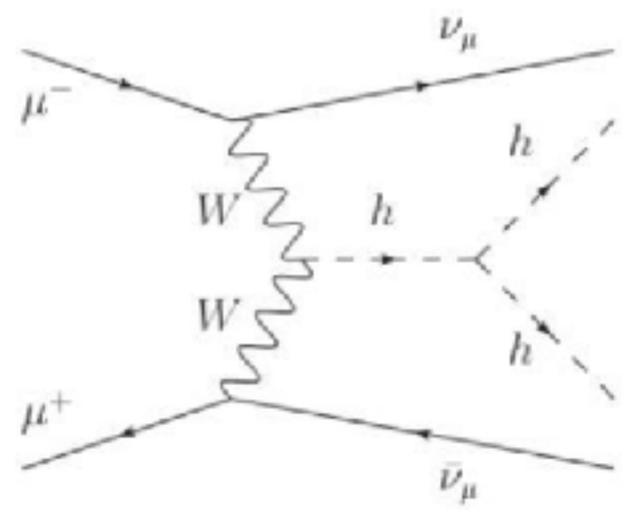
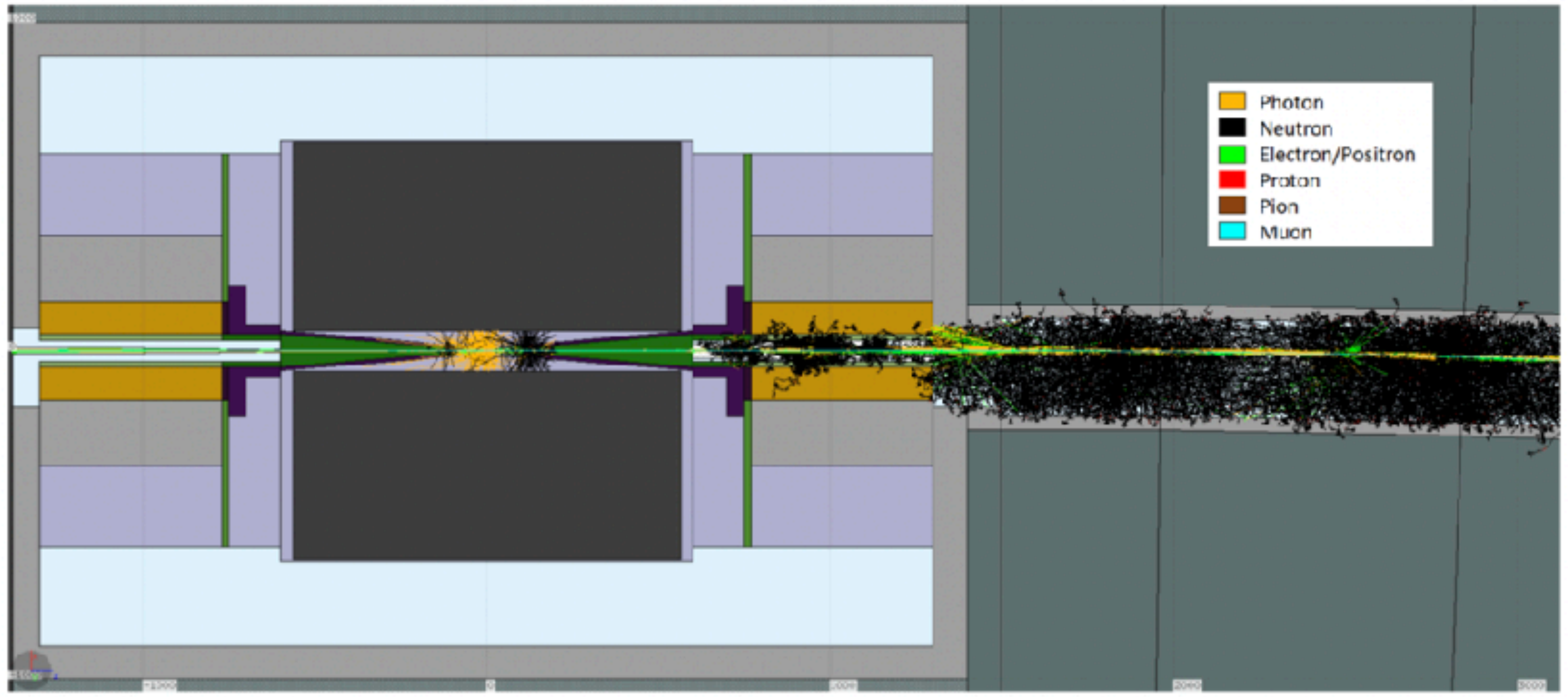


Conceptual and design challenges

- High neutrino flux (requires mitigation above 3 TeV)
- Beam backgrounds challenge to detector design.
- Production, cooling and preservation of the muons!

Constant muon decays bring beam backgrounds, and radiation levels similar to LHC!



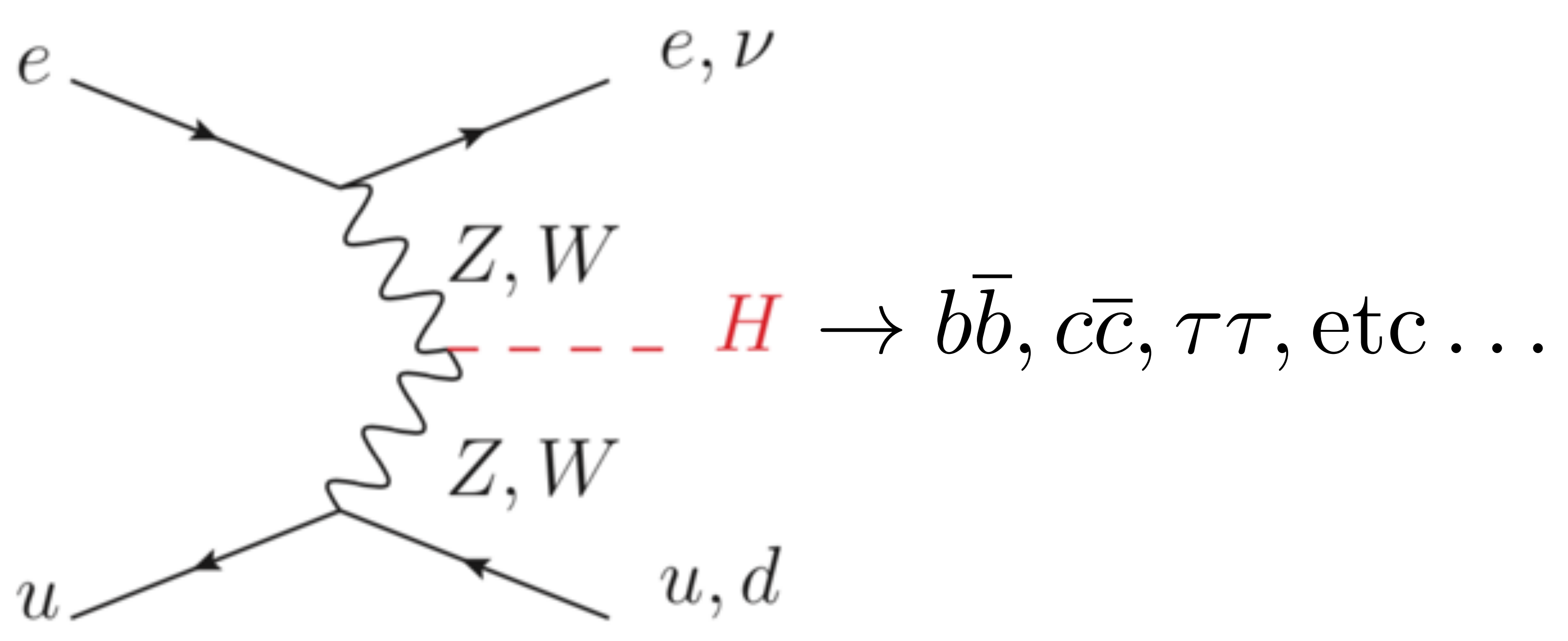
High Energy electron-proton Projects

The eh candidate machines

Project	LHeC	FCC-eh
Location	CERN	CERN
e energy	60 GeV	60 GeV
p energy	7 TeV	50 TeV
Lumi.	0.8 10^{34} $cm^{-2}s^{-1}$	1.5 10^{34} $cm^{-2}s^{-1}$

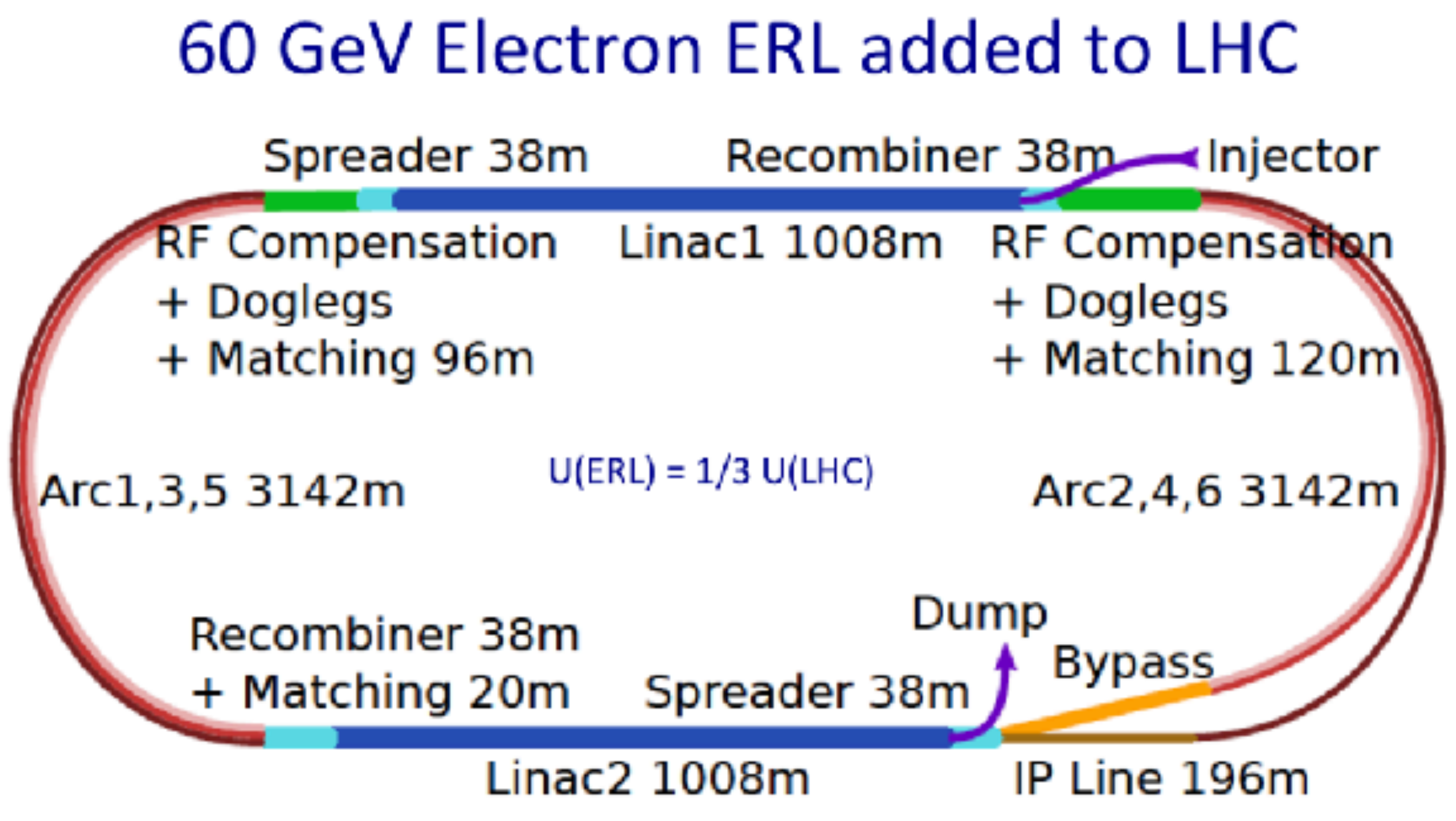
Primary program to measure proton PDFs, but also nice additional potential in Higgs physics

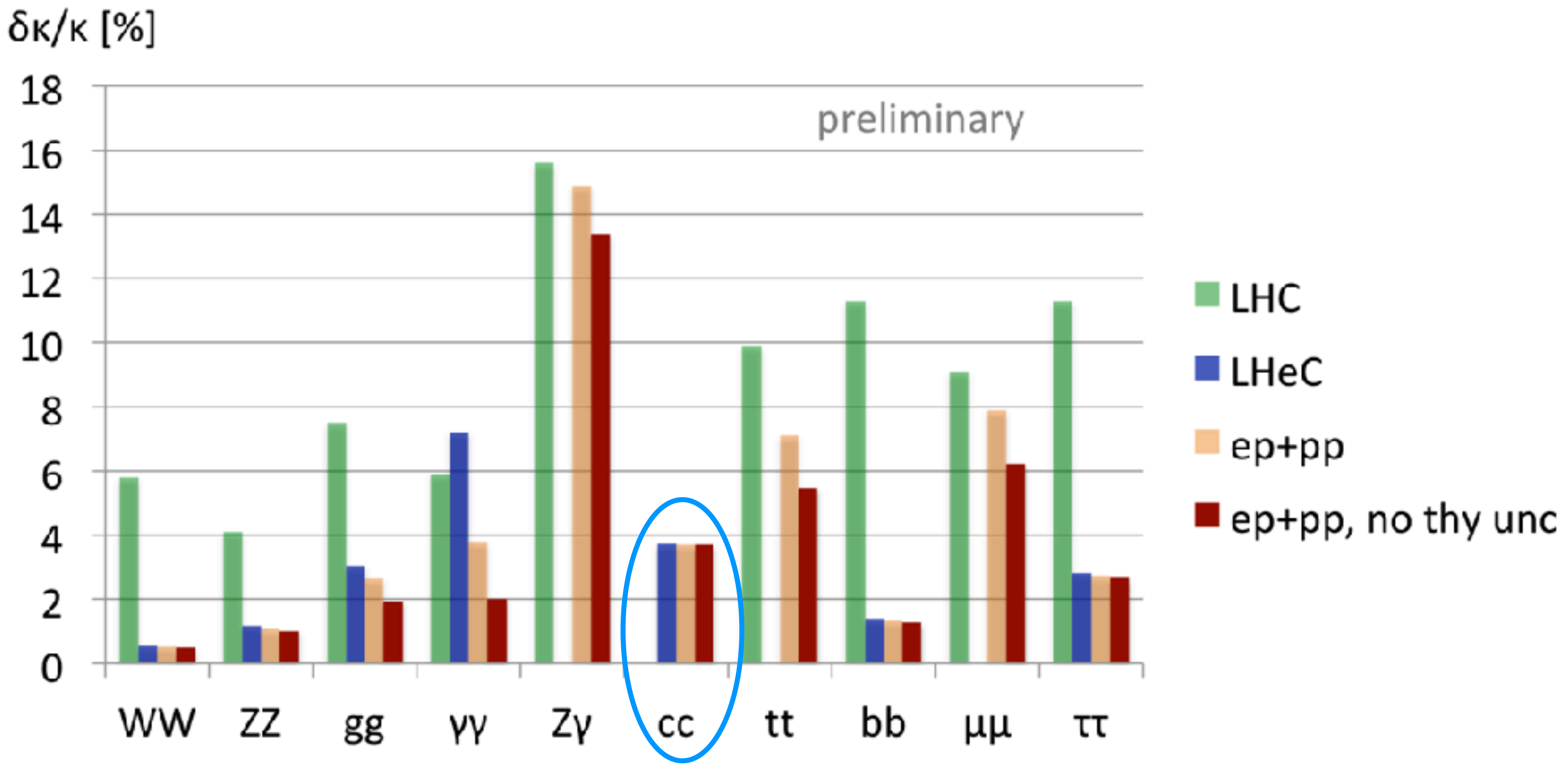
Main production process through vector boson fusion



Much cleaner environment than pure hadron!

Good reach in the WW channel.





Clean enough to make charm Yukawa at good precision and improvement in the b Yukawa as well w.r.t. HL-LHC.

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 — Extrapolated total cross section

$\mu_{if} = \mu_i \mu_f$ — Cross section times branching

$\mu_i \; (\mu_f = 1)$ — Cross sections

$\mu_f \; (\mu_i = 1)$ — 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).

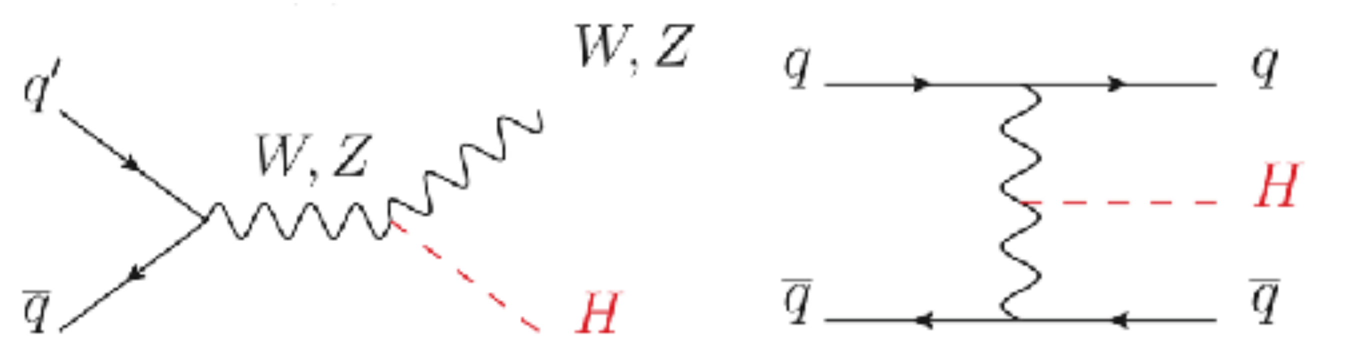
$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_\mathrm{Z}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_\mathrm{W}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f \bar{f}$$

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

More complete EFT and rigorous framework will be discussed later…

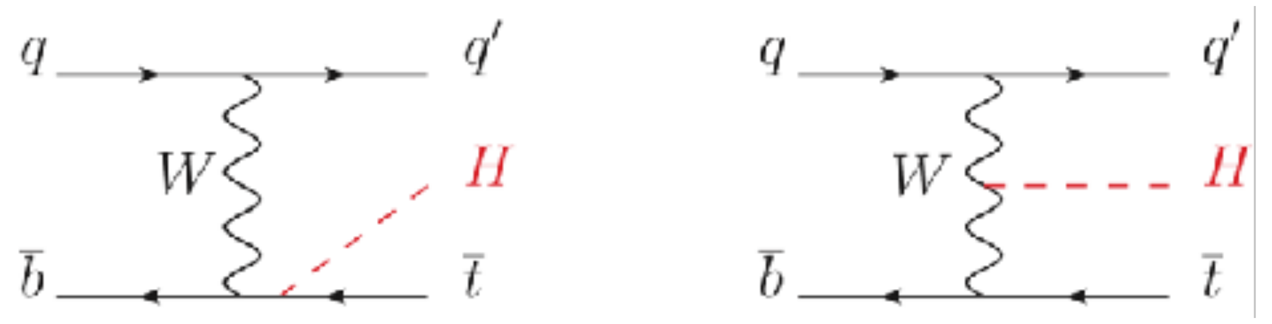
The Kappa Formalism

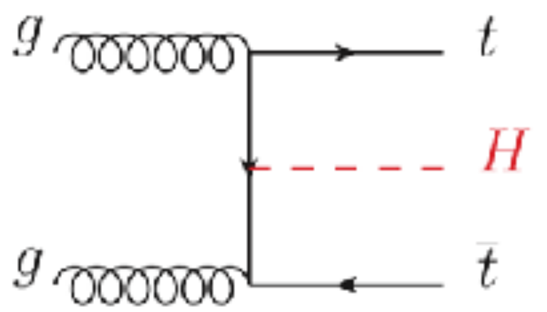
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

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

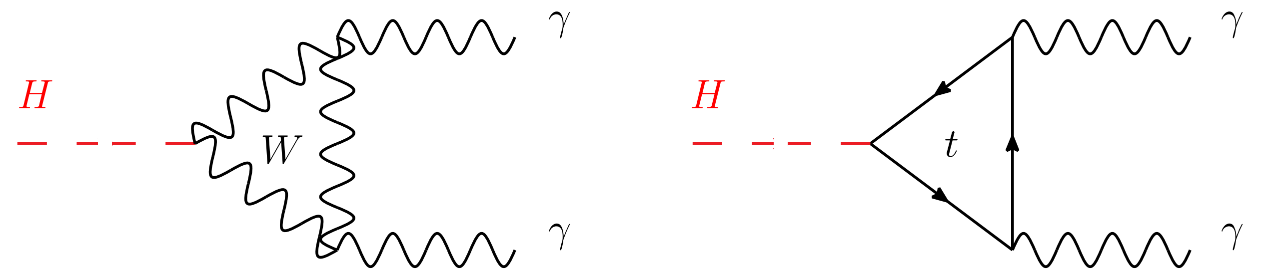




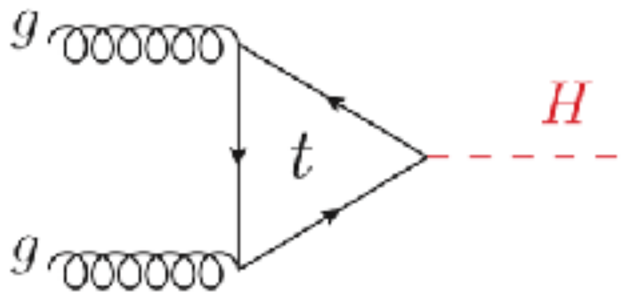
$\propto \kappa_t^2$

… 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:

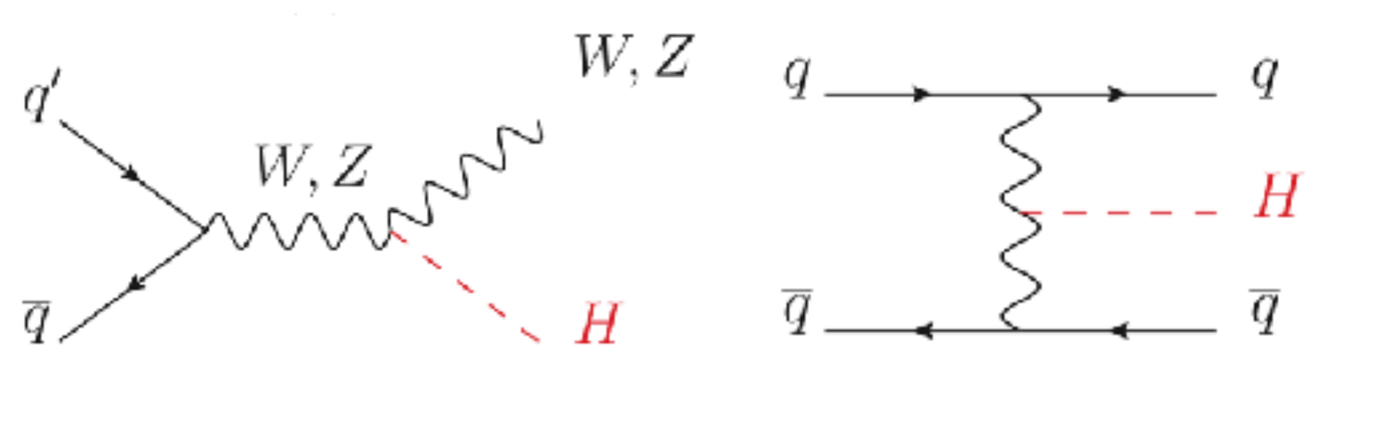
$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}$$

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

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

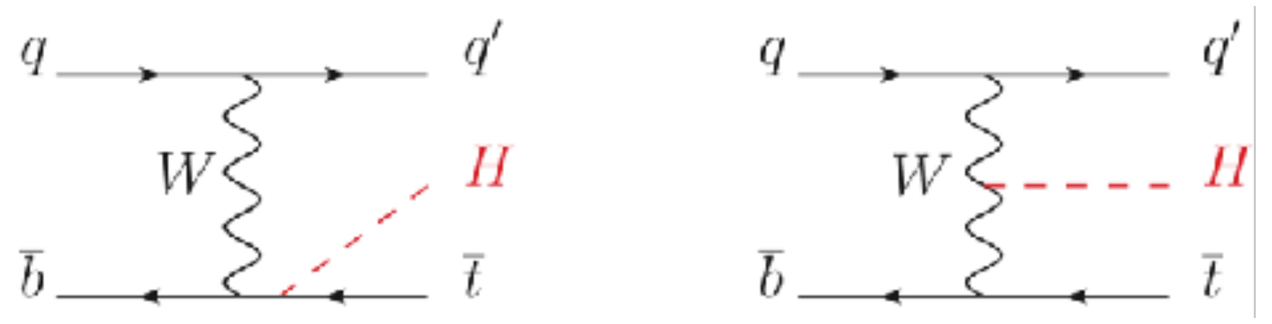
The Kappa Formalism

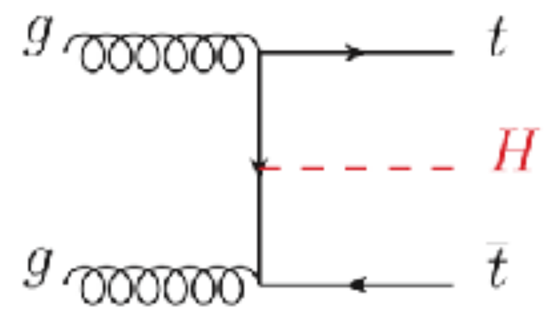
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

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





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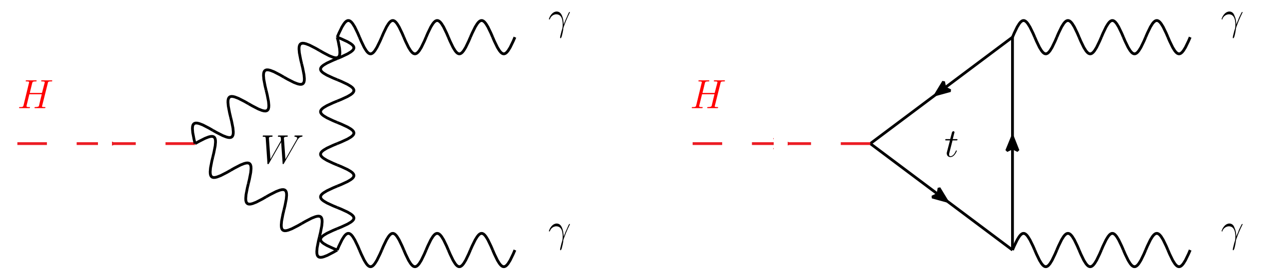
$\propto 1.6 \times \kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$



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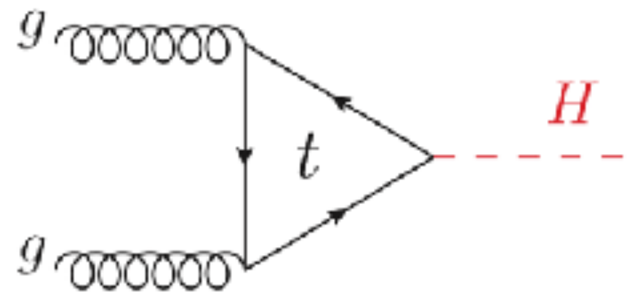

In order to measure the coupling modifiers (kappas) the signal strengths are re-parametrised as follows:

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

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

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