Prospects for Higgs Physics at HL-LHC

Electrons for the LHC Workshop

Marumi Kado

Dipartimento di Fisica, Sapienza Università di Roma, INFN Sezione di Roma and LAL-IN2P3, Orsay

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The HL-LHC and HE-LHC Higgs YR

1. **Precision Higgs Physics**
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS

2. **The Higgs boson mass and width**
- Mass and width
- Off Shell couplings and width
- Interferometry

3. **Invisible decays of the Higgs boson**
- Portal to DM (invisible Higgs)
- Interplay with couplings measurements

4. **Higgs flavor, rare decays and rare production**
- LFV μτ, eτ
- J/Ψγ, ZY, WD
- Phiγ, rhoγ
- tH
- FCNC top decays

5. **High energy probes and EFT interpretation**
- Diboson EWK and diboson longitudinal scattering
- High mass DY
- Global EFT fits

6. **BSM Higgs**
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

7. **Di-Higgs production and Higgs self couplings**

CERN-LPCC-2018-04
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Higgs Physics
at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

Convenors:
M. Cepeda[1,2], S. Gori[3], P. Ilten[4], M. Kado[5,6,7], F. Riva[8]

Contributors:
R. Abdul Khalek[9,10], A. Aboubrahim[11], J. Alimena[12], S. Alioli[13,13], A. Alves[14], C. Asawatangtrakuldee[15], A. Azatov[16,17], P. Azzi[18], S. Bailey[19], S. Banerjee[20], E.L. Barberio[21], D. Barducci[16], G. Barone[22], M. Bauer[20], C. Bautista[23], P. Bechtle[24], K. Becker[25], A. Benaglia[26], M. Bengala[27], N. Berger[28], C. Bertella[29], A. Bethani[30], A. Betti[24], A. Biekotter[31], F. Bishara[15], D. Bloch[32], P. Bokan[33], O. Bondu[34], M. Bonvini[6], L. Borgonovi[35,36], M. Borsato[37], S. Boselli[38], S. Braibant-Giacomelli[35,36], G. Buchalla[39], L. Cadamuro[40], C. Caillol[41], A. Calandri[42,43], A. Calderon Tazon[44], J.M. Campbell[45], F. Caola[20], M. Capozi[46], M. Carena[45,47], C.M. Carloni Calame[48], A. Carmona[49], E. Carquin[50], A. Carvalho Antunes De Oliveira[51], A. Castaneda Hernandez[52], O. Cata[53], A. Celis[54], A. Cerri[55], F. Cerutti[56,57], G.S. Chahal[58,20], A. Chakraborty[59], G. Chaudhary[60], X. Chen[61], A.S. Chisholm[1,4], R. Contino[62], A.J. Costa[27], R. Covarelli[63,64], N. Craig[65], D. Curtin[66], L. D'Eramo[67], M. Dührssen[1], N.P. Dang[68], P. Das[69], S. Dawson[22], O.A. De Aguiar Francisco[1], J. de Blas[70,18], S. De Curtis[71], N. De Filippis[72,73], H. De la Torre[74], L. de Lima[75], A. De Wit[15], C. Delaere[34], M. Delcourt[34], M. Delmastro[28], S. Demers[76], N. Dev[77], R. Di Nardo[78], S. Di Vita[79], S. Dildick[80], L.A.F. do Prado[81,23], M. Donadelli[82], D. Du[83], G. Durieux[84,15], O. Eberhardt[85], K. El Morabit[86], J. Elias-Miro[1], J. Ellis[87,51,1], C. Englert[88], S. Falke[28], M. Farina[89], A. Ferrari[90], A. Ferroglia[91], M.C.N. Fiolhais[92], M. Flechl[93], S. Folgueras[94], E. Fontanesi[35,36], P. Francavilla[67,95], R. Franceschini[96,97], R. Frederix[98], S. Frixione[99], G. Gómez-Ceballos[100], A. Gabrielli[56,57], S. Gadatsch[1], M. Gallinaro[27], A. Gandrakota[101], J. Gao[102], F.M. Garay Walls[103], T. Gehrmann[61], Y. Gershtein[101], T. Ghosh[104], A. Gilbert[1], R. Glein[105], E.W.N. Glover[20], R. Gomez-Ambrosio[20], R. Gonçalo[27], D. Gonçalves[106], M. Gorbahn[107], E. Gouveia[27], M. Gouzevitch[108], P. Govoni[26,13], M. Grazzini[61], B. Greenberg[101], K. Grimm[109], A.V. Gritsan[110], A. Grohsjean[15], C. Grojean[15], J. Gu[111], R. Gugel[25], R.S. Gupta[20], C.B. Gwilliam[112], S. Höche[113], M. Haacke[103], Y. Haddad[58], U. Haisch[46], G.N. Hamity[114], T. Han[106], L.A. Harland-Lang[19], R. Harnik[45], S. Heinemeyer[44,115], G. Heinrich[46], B. Henning[8], V. Hirschi[43], K. Hoepfner[116], J.M. Hogan[117,118], S. Homiller[119,22], Y. Huang[120], A. Huss[1], S. Jézéquel[28], Sa. Jain[69], S.P. Jones[1], K. Köneke[25], J. Kalinowski[121], J.F. Kamenik[122,123], M. Kaplan[100], A. Karlberg[61], M. Kaur[60], P. Keicher[86], M. Kerner[61], A. Khanov[124], J. Kieseler[1], J.H. Kim[125], M. Kim[126], T. Klijnsma[43], F. Kling[127], M. Klute[100], J.R. Komaragiri[128], K. Kong[125], J. Kozaczuk[129], P Kozow[121], C. Krause[45], S. Lai[33], J. Langford[58], B. Le[21], L. Lechner[93], W.A. Leight[130], K.J.C. Leney[131], T. Lenz[24], C-Q. Li[132], H. Li[83], Q. Li[133], S. Liebler[134], J. Lindert[20], D. Liu[135], J. Liu[136], Y. Liu[137], Z. Liu[138,45], D. Lombardo[8], A. Long[139], K. Long[41], I. Low[140,135], G. Luisoni[46], L.L. Ma[83], A.-M. Magnan[58], D. Majumder[125], A. Malinauskas[19], F. Maltoni[141], M.L. Mangano[1], G. Marchiori[67,67], A.C. Marini[100], A. Martin[77], S. Marzani[142,99], A. Massironi[1], K.T. Matchev[40,143], R.D. Matheus[23], K. Mazumdar[69], J. Mazzitelli[61], A.E. Mcdougall[21], P. Meade[119], P. Meridiani[6], A.B. Meyer[15], E. Michielin[18], P. Milenovic[1,144], V. Milosevic[58], K. Mimasu[141], B. Mistlberger[145], M. Mlynarikova[146], M. Mondragon[147], P.F. Monni[1], G. Montagna[148,48], F. Monti[26,13], M. Moreno Llacer[1], A. Mueck[149], P.C. Muiño[27], C. Murphy[150], W.J.

https://arxiv.org/pdf/1902.00134.pdf

Modus Operandi for the YR

Goals

- Reappraise projections made for ECFA 2014, with the experience gained with Run 2 data analyses.
- Harmonise projections between LHC experiments and with the TH community
- Provide a robust basis to compare and emphasise complementarity with other Higgs precision colliders.

Modus Operandi HL/HE-LHC for the YR

- Extrapolations mostly from Run 2 analyses using 80 fb^{-1} datasets.
- Account for differences with correction factors:
  - Increased luminosity
  - Increased centre-of-mass energy from 13 or 14 TeV to 27 TeV
  - General assumption detector and reconstruction performance at 200 (HL) and 1k (HE) PU events similar to the current ATLAS and CMS detector performance. This has been the design goal of HL-LHC upgrades
  - In some specific cases, consider reconstruction performance with new detector and different PU conditions of 200 but not 1k

HE-LHC Comments

- HE running scenario: 27 TeV and 15 ab^{-1}
- Experiments have attempted very basic extrapolations (in energy and luminosity - without fancy corrections for high foreseen PU of ~800 and different detector performance) only for very few analyses (i.e. HH in the baby channel).
- YR projections have relied on a very limited number of projections (mostly from TH).
- HE-LHC projections however have received less scrutiny than HL-LHC and can only be considered as indicative and not as a result of an in depth scrutiny of each analysis.

Systematic Uncertainties

Projected Systematics

- Many experimental systematic uncertainties are limited by statistics (e.g. through DD calibrations). HL-LHC projection extrapolations of the experimental systematic uncertainties have been performed taking into account larger datasets.

- **Profiling**: Some improvements in systematic uncertainties are automatically taken into account through profiling. However for this the profiling model needs to be validated (a model valid for a low luminosity with some approximations might break at high luminosity) - this requires the scrutiny of the collaborations and is currently being done.

- Most impactful systematic uncertainties:

  - Signal modelling (at all level, predicted cross section, Monte Carlo, PDFs, etc…) - Discussed in coming slides.

  - Background modelling (WW, top and V+jets mostly)

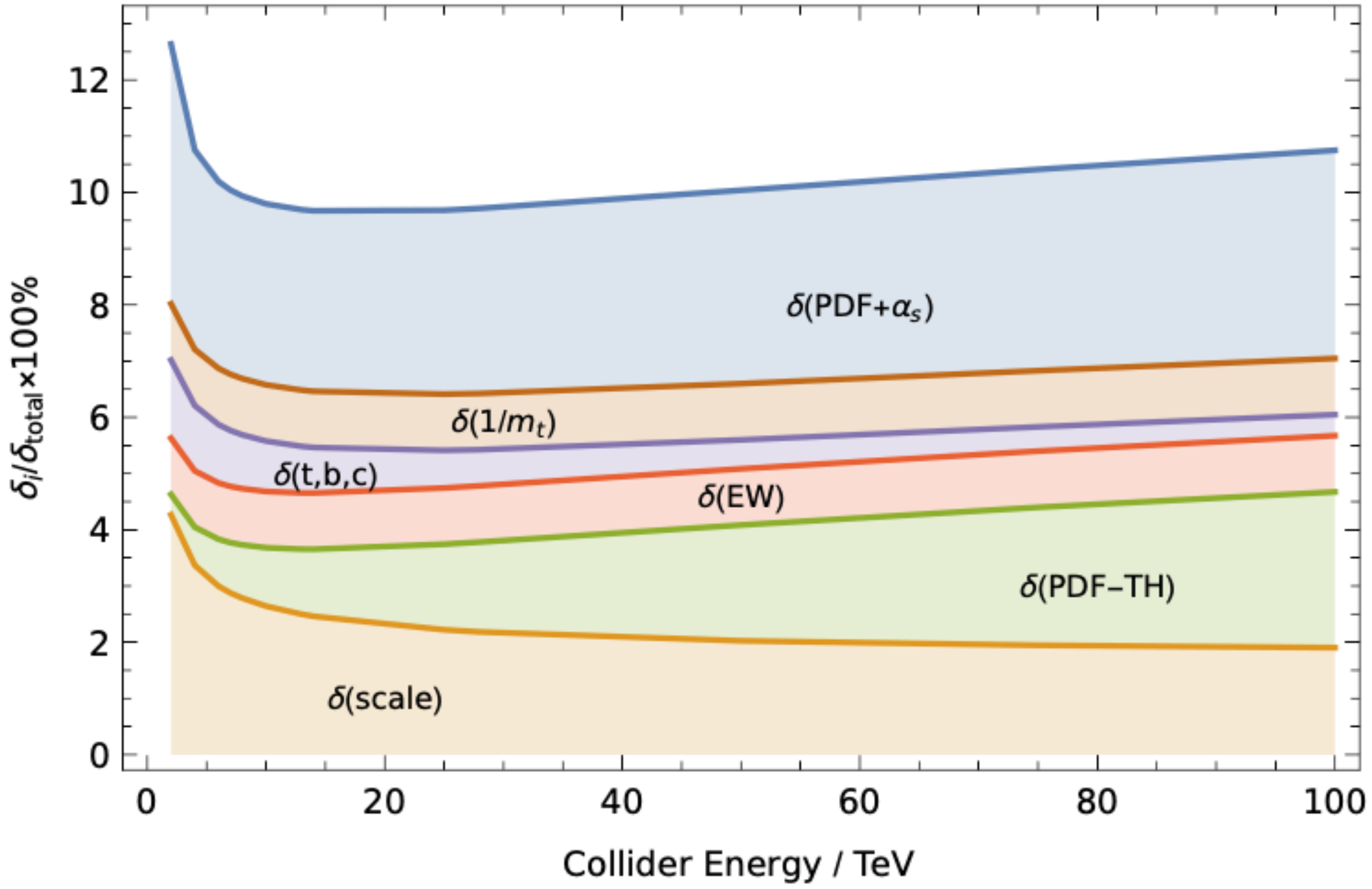
  - Jet Energy Scale and Resolution, Photon energy Resolution (and scale), flavor tagging.

Scenarios	In the YR document often refer to s1 and s2 scenarios, s1 corresponds to the current systematic uncertainties and is therefore not realistic (very conservative), and s2 is the baseline working scenarios for these projections. Systematic improvements (for S2) have been discussed in detail among experiments and with TH.

Precision Higgs Physics

Collaboration with LHC Higgs XS Working Group

- Provided cross sections (14 TeV and 27 TeV), with full estimate of uncertainties.
- Discussion to decide on TH systematics scenarios for HL/HE-LHC (taking into account, as accurately as possible future TH developments).
- Common decision to keep the same components and treat all uncertainties as uncorrelated, resulting in an approximate scenario where systematic uncertainty is divided by a factor of 2 w.r.t. to the current uncertainties.



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

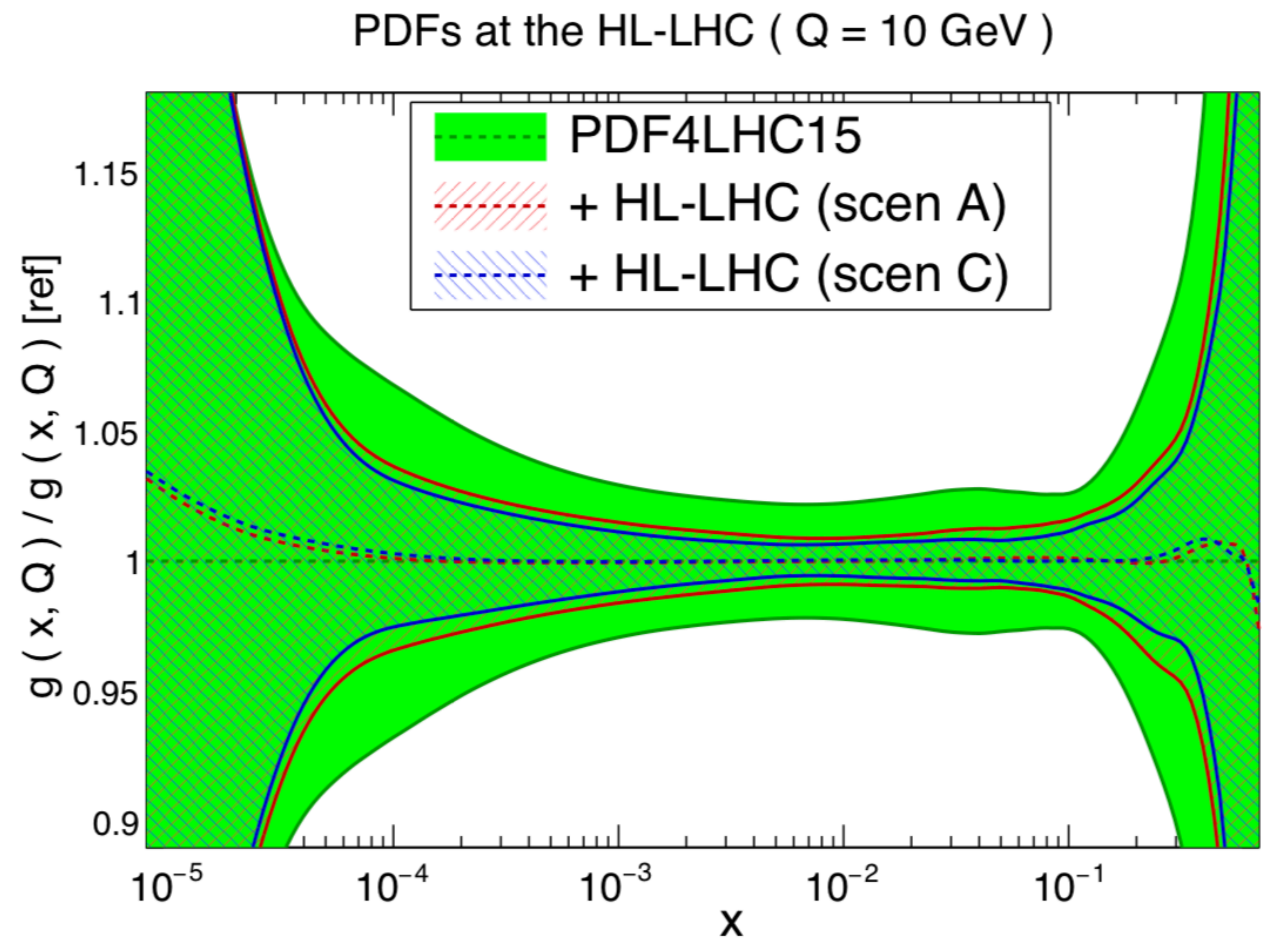
Cross sections for all processes have been computed by the LHC Higgs XS working group

PDFs

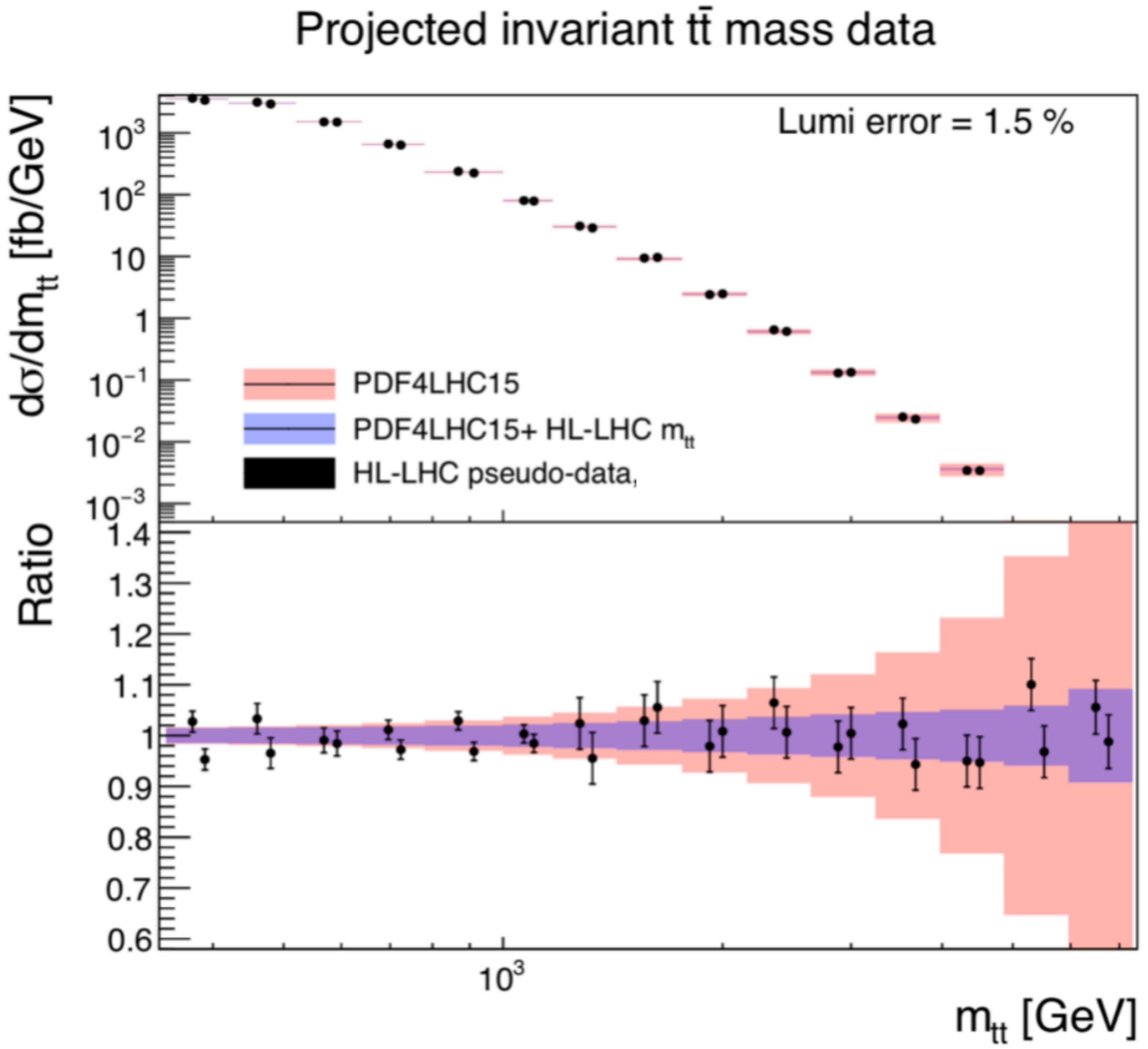
PDF uncertainties play an important role (see previous slide).

In depth analysis made taking into account HL-LHC measurements by:
Rabah Abdul Khalek, Shaun Bailey, Jun Gao, Lucian Harland-Lang, and Juan Rojo

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



e.g. top pair production differential cross section in tt-mass (with pseudo data).



Two scenarios considered:

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

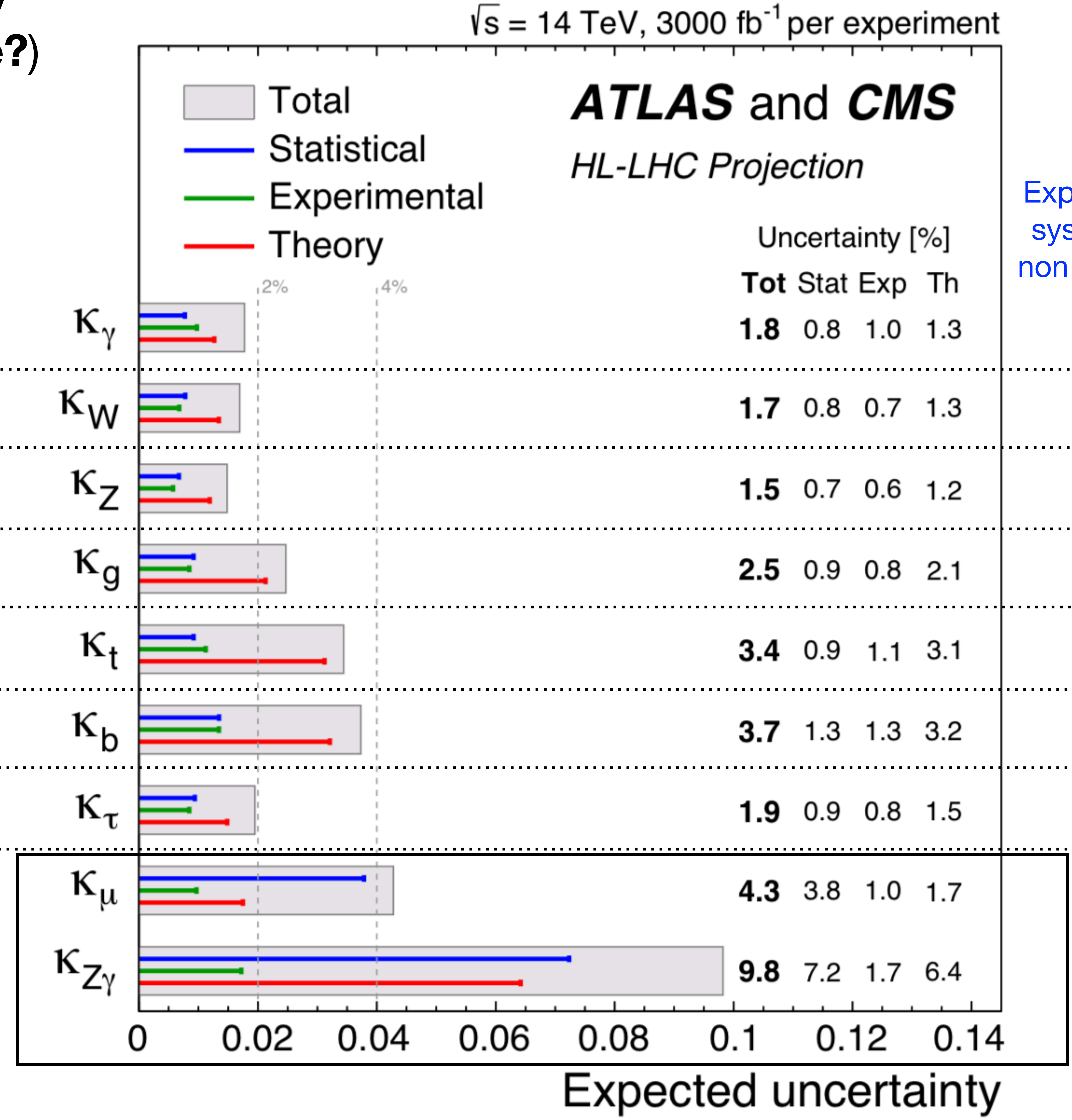
Ratio to baseline	10 GeV $\leq M_X \leq$ 40 GeV	40 GeV $\leq M_X \leq$ 1 TeV	1 TeV $\leq M_X \leq$ 6 TeV
gluon-gluon	0.50 (0.60)	0.28 (0.40)	0.22 (0.34)
quark-quark	0.74 (0.79)	0.37 (0.46)	0.43 (0.59)
quark-antiquark	0.71 (0.76)	0.31 (0.40)	0.50 (0.60)

Reduction w.r.t. PDF4LHC15

Combination of Main Decay and Production Channels Towards HL-LHC

Measurement of the couplings properties of the Higgs boson are key to further understand the nature of the Higgs boson (**is it composite?**)

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2
κ_γ	13%	9%	13%
κ_W	11%	8.6%	11%
κ_Z	11%	7.2%	11%
κ_g	14%	11%	14%
κ_t	30%	14%	30%
κ_b	26%	18%	26%
κ_τ	15%	14%	15%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134



Experimental systematics non negligible

Measurements here assume no BSM in Higgs width

Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)

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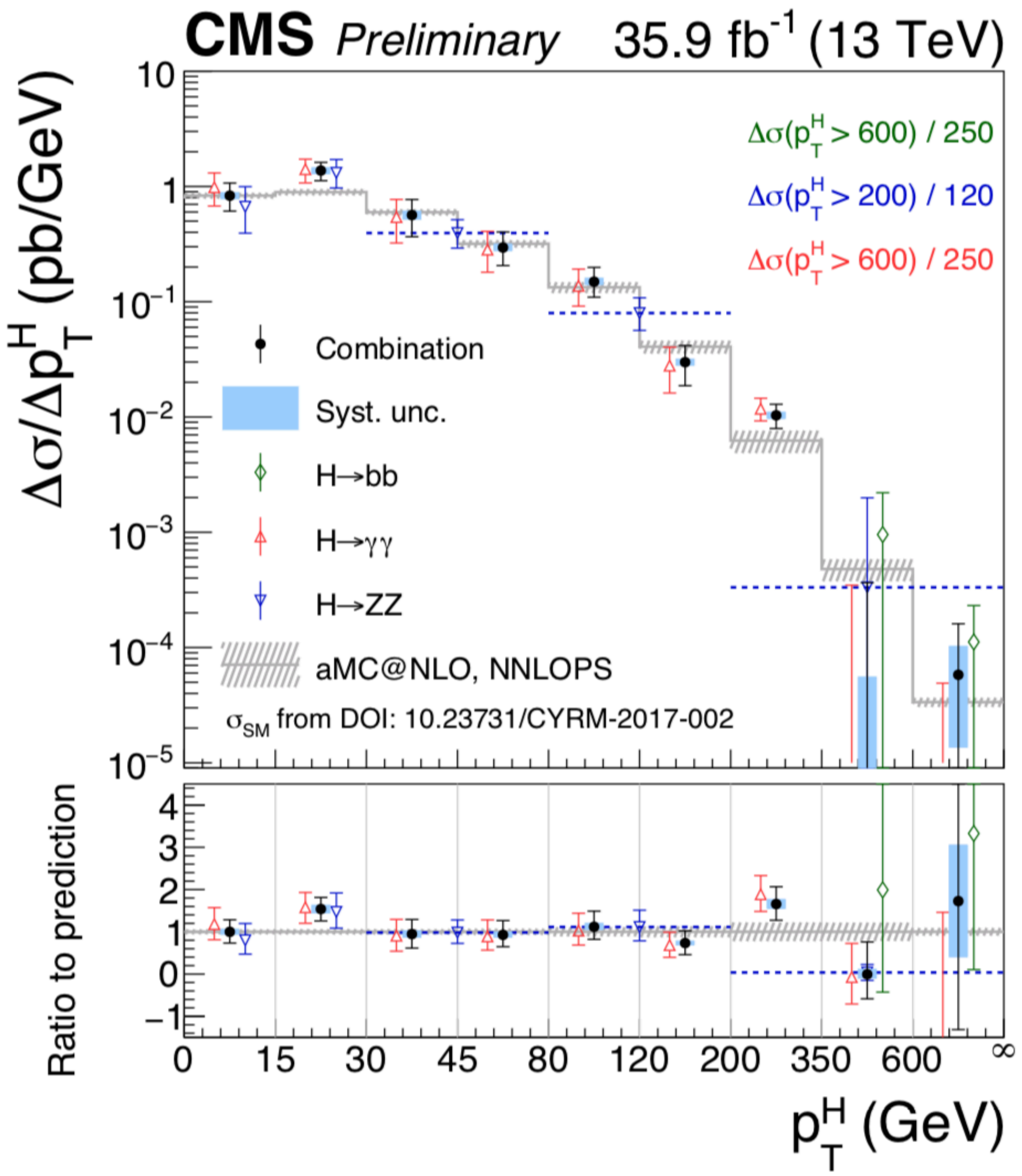
Towards HE-LHC

Coupling	S2	S2′
k_γ	1.6	1.2
k_W	1.5	1.0
k_Z	1.3	0.8
k_g	2.2	1.3
k_t	3.2	1.9
k_b	3.5	2.1
k_τ	1.7	1.1
k_μ	2.2	1.7
$k_{Z\gamma}$	6.9	4.1

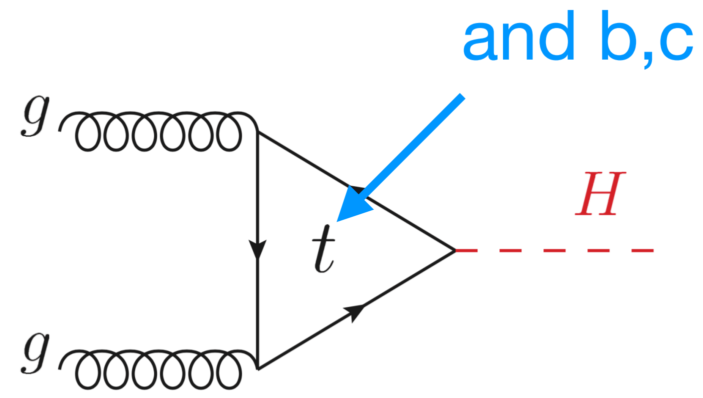
Estimated assuming that the statistical uncertainty is fully subdominant with an additional scenario S2’ where signal TH uncertainties are further divided by 2.

This further reduction of the TH uncertainty has no foundation on what improvements can be foreseen in TH predictions, S2’should be taken as an illustration of a possible improvement under an optimistic assumption.

Differential Cross Sections

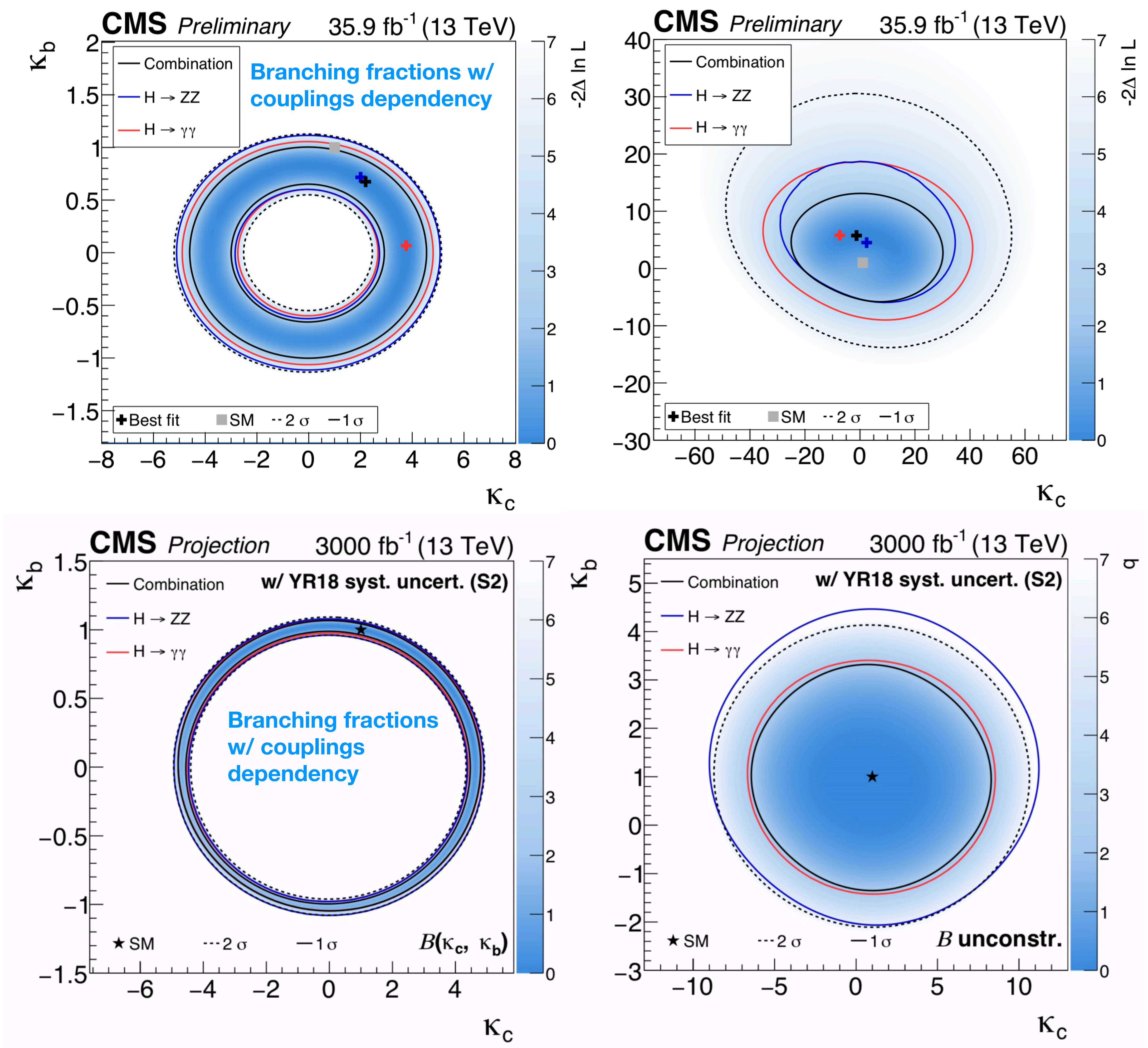


Recent indirect measurement of the b and c Yukawa couplings through their effect in the production loop.



Limits on Kc at HL-LHC

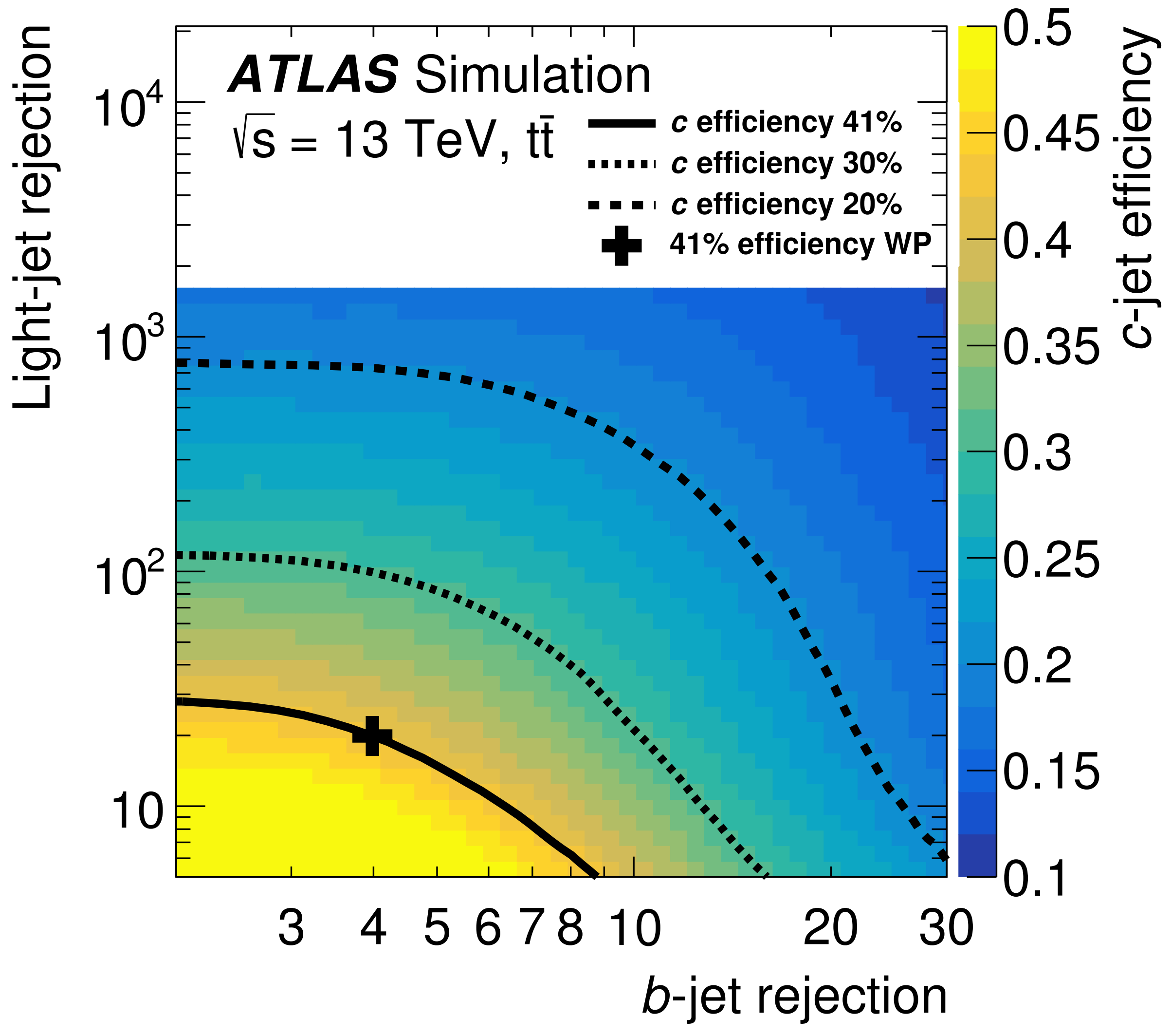
Cross section	**~4 x SM**
Shape only	**~8 x SM**



More on the 2d Generation (charm) Yukawa Couplings

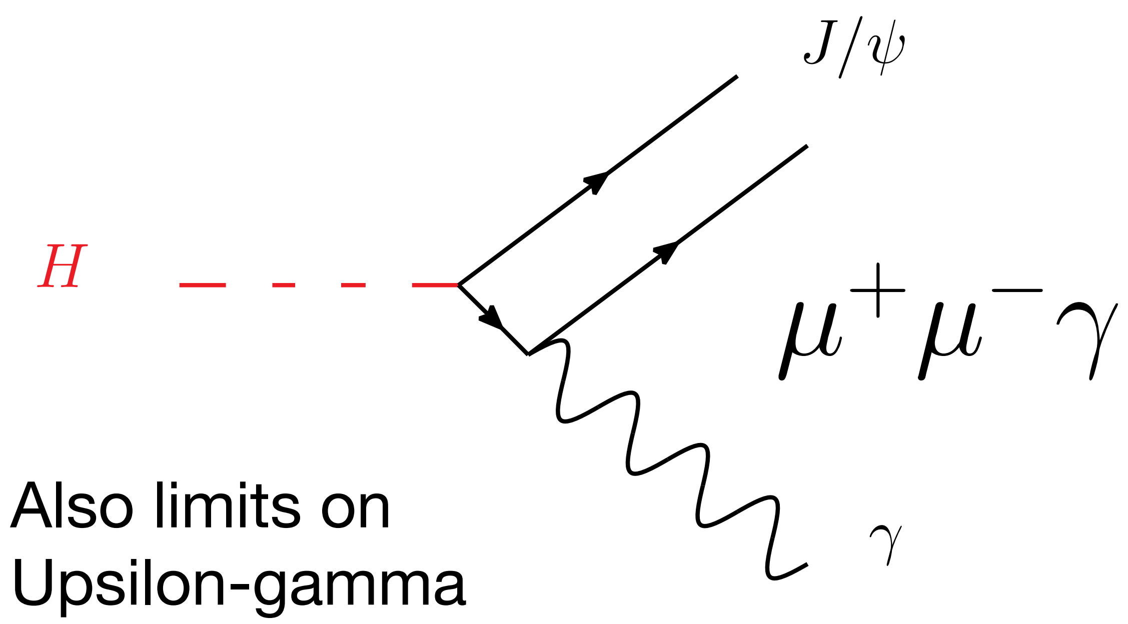
Very challenging, various ways to constrain

- VH(cc) direct detection (relies on ability to distinguish b and c jets)
- Differential cross sections
- Charmonium-photon exclusive decays
- WH production charge asymmetry (PDFs)
- Total width from the couplings fit



Run 2	HL-LHC
<100xSM	**<6xSM**

Potentially sensitive to charm Yukawa

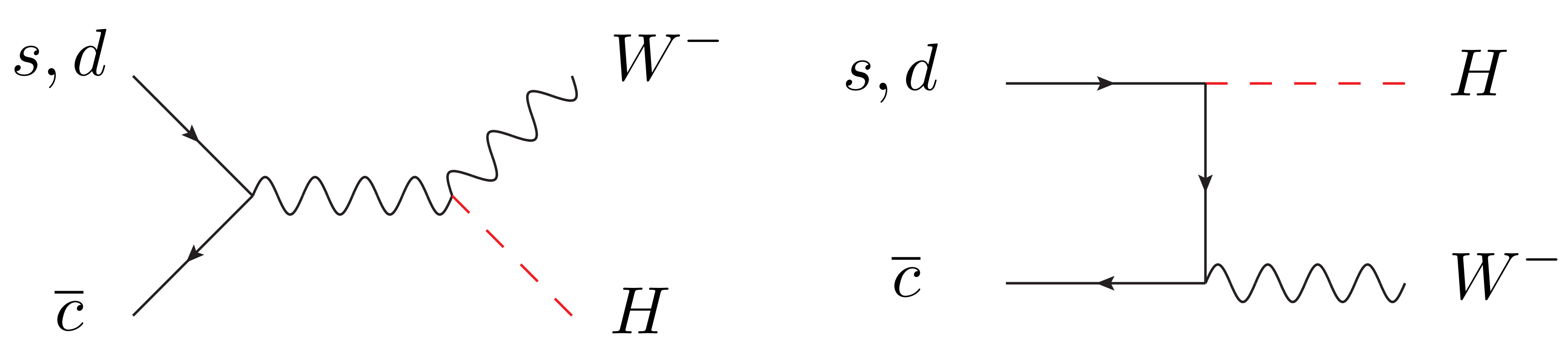


Also limits on Upsilon-gamma

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

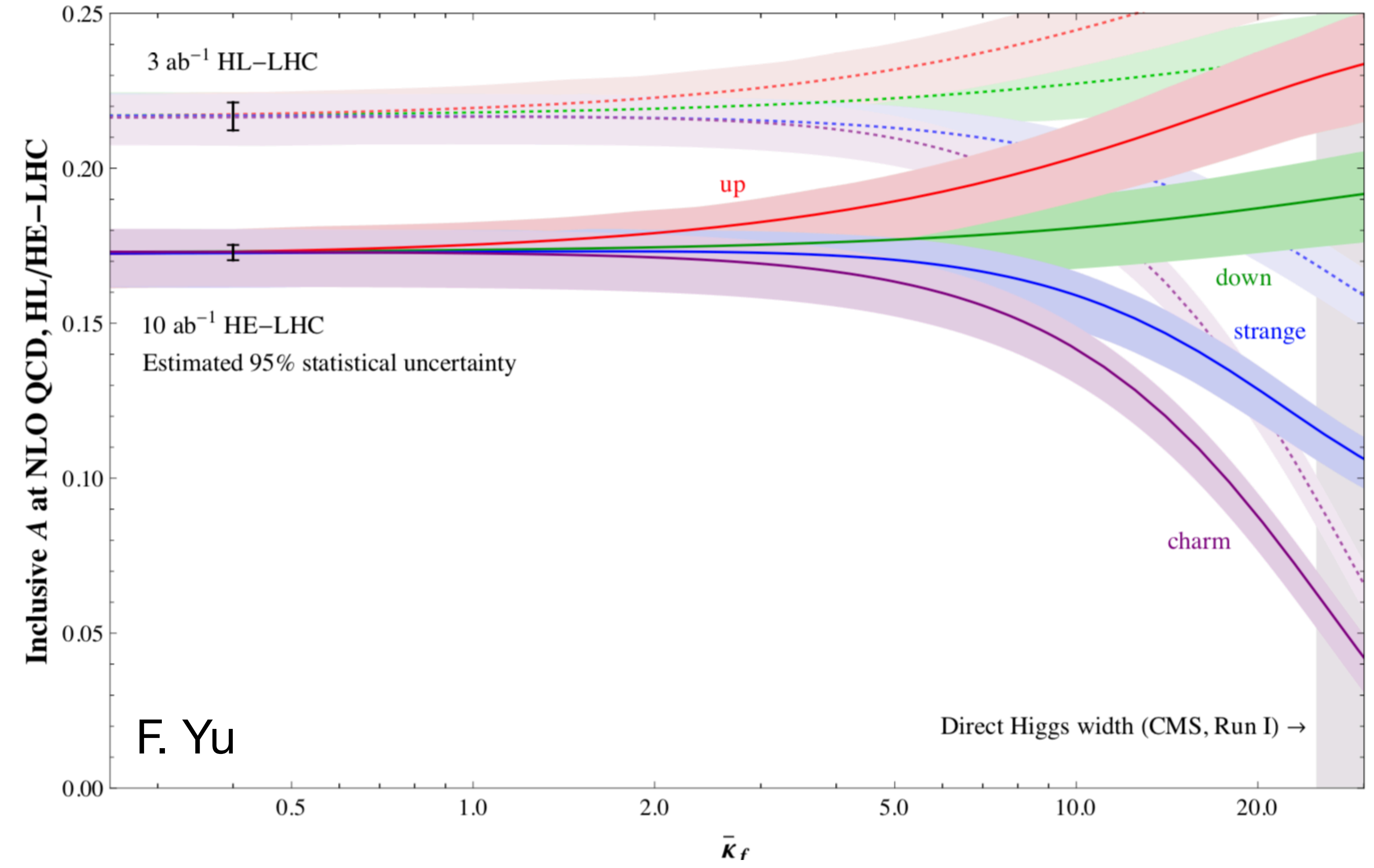
HL-LHC

<50xSM



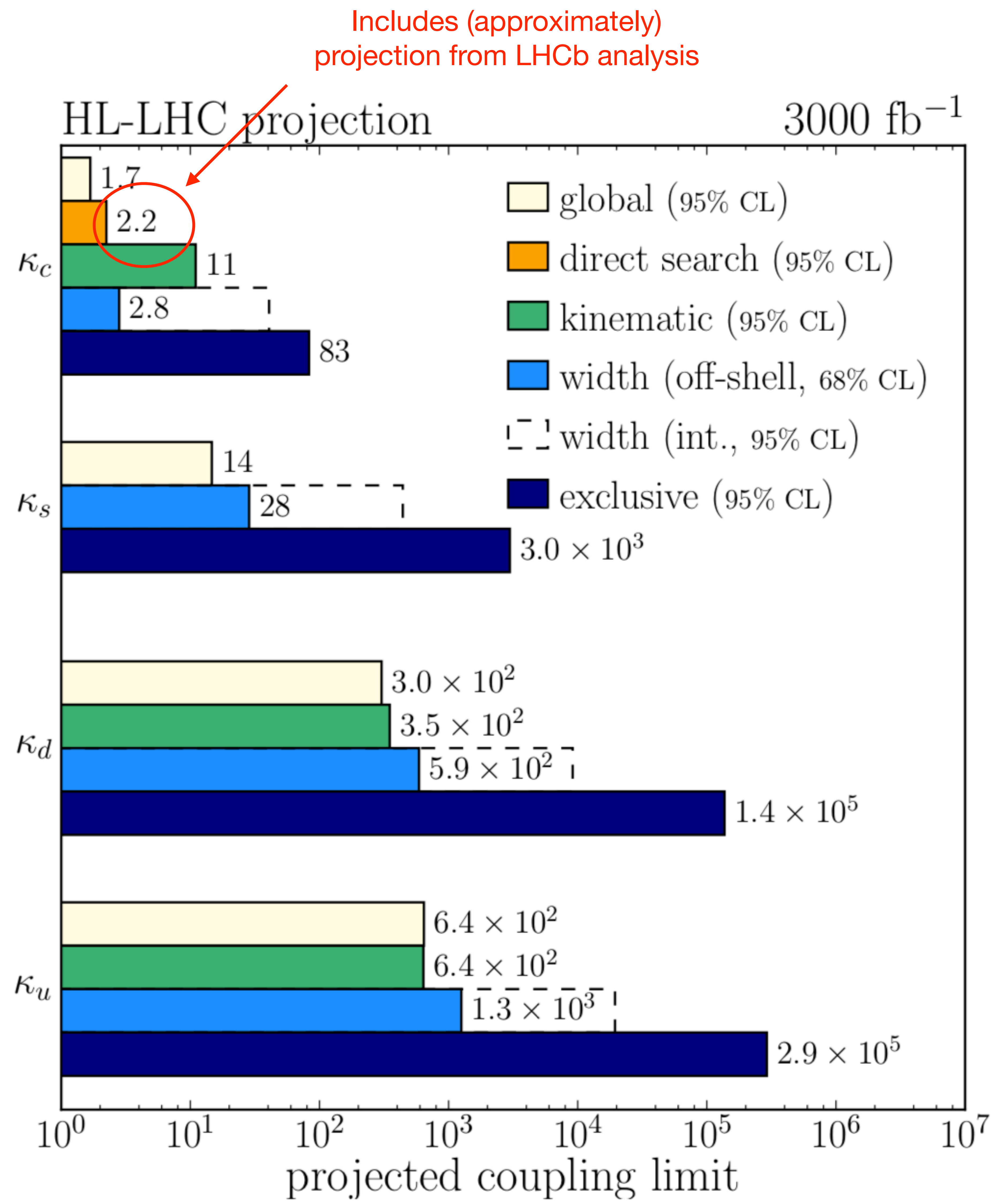
Based on d anti-d asymmetry in the PDFs

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



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

Summary On Flavors
(at HL-LHC with comments on HE-LHC)



First and Second generation Yukawas

- Extremely challenging at HL-LHC (most stringent constraint coming from the couplings fit assuming no BSM width).

- For the charm Yukawa direct search (using charm tagging) is not far behind!

- Then comes sensitivity to coupling combination through width offshell.

- Exclusive searches still only marginally sensitive.

- New emerging ideas to be explored with such large datasets.

Higgs Boson Mass and Width

Higgs boson mass

- Current measurement reached 0.1% precision with mostly 4-muon and 2e-2mu channel (with the Z mass constraint in the ee system):

$$m_H = 125.18 \pm 0.16 \text{ GeV}$$

- Very approximate estimate of the projection for HL-LHC: assuming that the analysis with high statistics will be further optimised to minimise impact of calibration systematic uncertainties. Precision reach:

$$10 - 20 \text{ MeV}$$

Interests (marginal?) of the mass measurement (little to no impact on EWK fit or Vacuum stability):

- Mild impact on coupling measurements.
- Potential impact on measurement of width through interference mass shift.
- On MSSM tuning.

Width from Lineshape measurements

- Current constraints from the measurement of the higgs line shape from 4-leptons and diphoton channels:

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

(CMS HIG-16-041 with 4l only and 36 fb-1)

SM expected width

(small i.e. potentially large relative variations from BSM couplings)

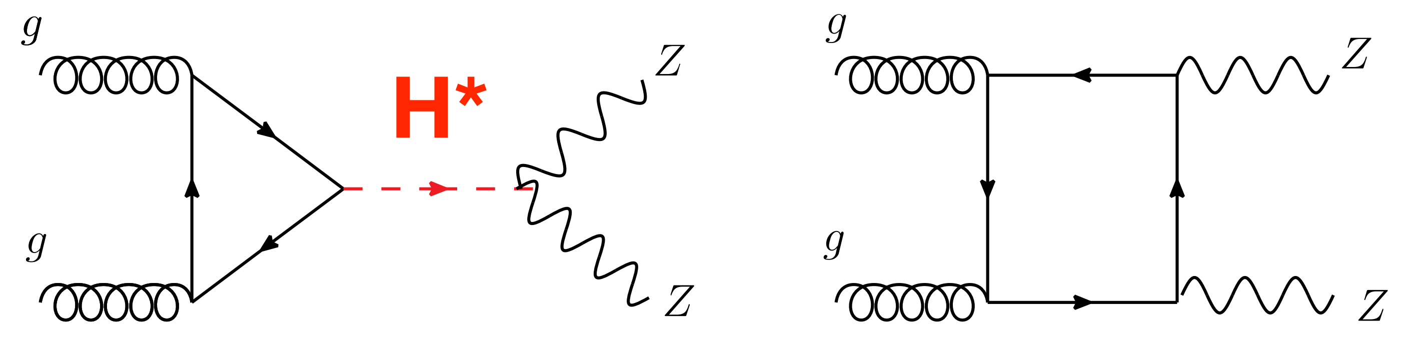
$$\Gamma^H_{SM} = 4.07 \pm 0.16 \text{ MeV}$$

With HL-LHC can probably reach O(50-100 MeVs), similar very approximate statement for HE-LHC

Higgs Boson Width

Offshell Higgs measurements

Study the 4-leptons spectrum in high mass regim[e] where the Higgs boson acts as **propagator**

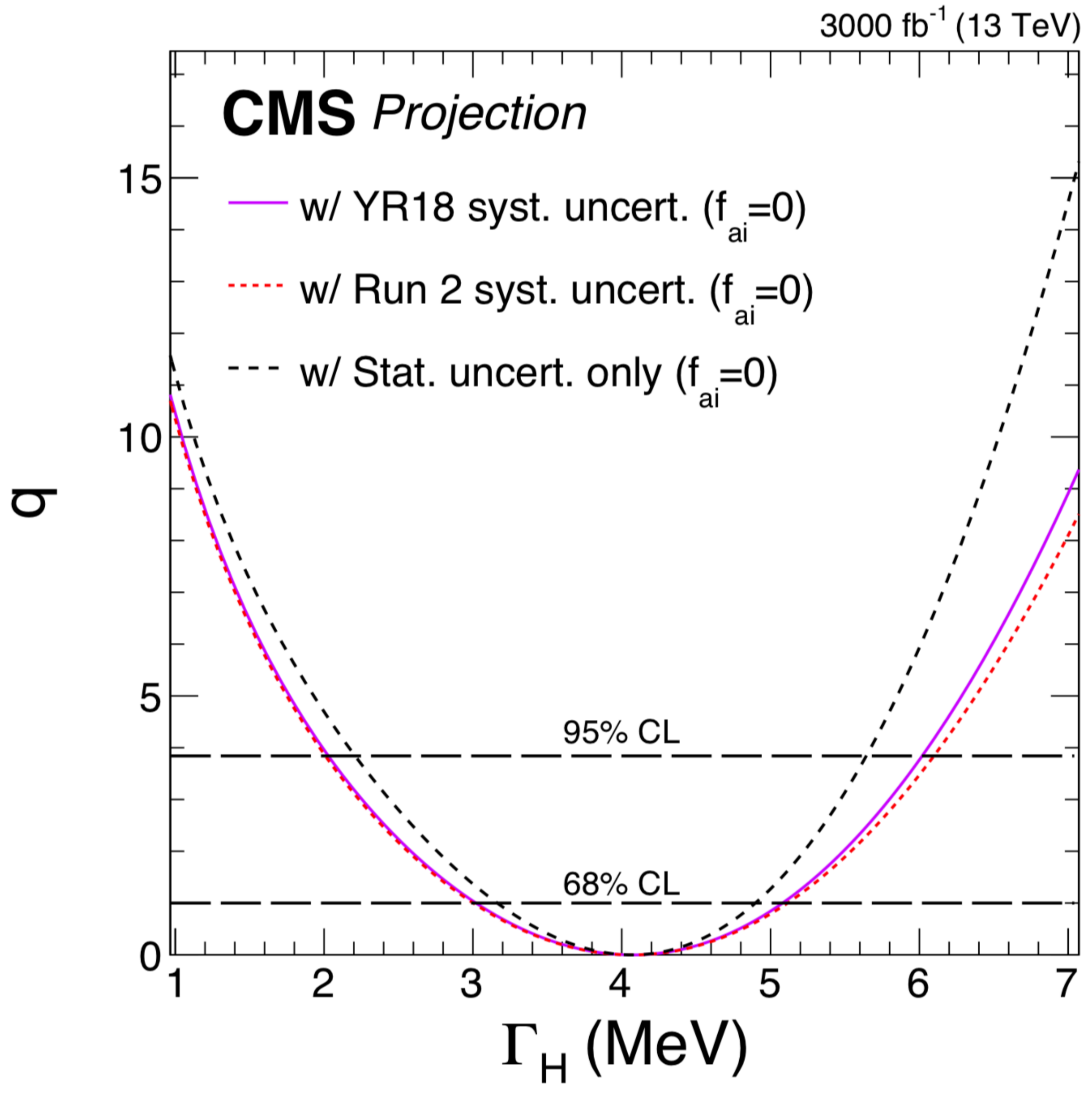


$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Results have been limited by statistics, however ggZZ (including interference term) systematic uncertainties become important at high luminosity!

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

Preliminary HL-LHC results with 3 ab-1:



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

HL-LHC (stat only): $\Gamma_H = 4.1^{+0.8}_{-0.9}$ MeV

Diphoton-continuum interference

- Mass shift: This interference has first been studied when noticing approximately 35 MeV with shift with dependence on Higgs pT

  $\Gamma^H_{SM} < 200$ MeV At HL-LHC

  Many more studies needed for HL-LHC sensitivity thus not trivial extrapolation to **HE-LHC**

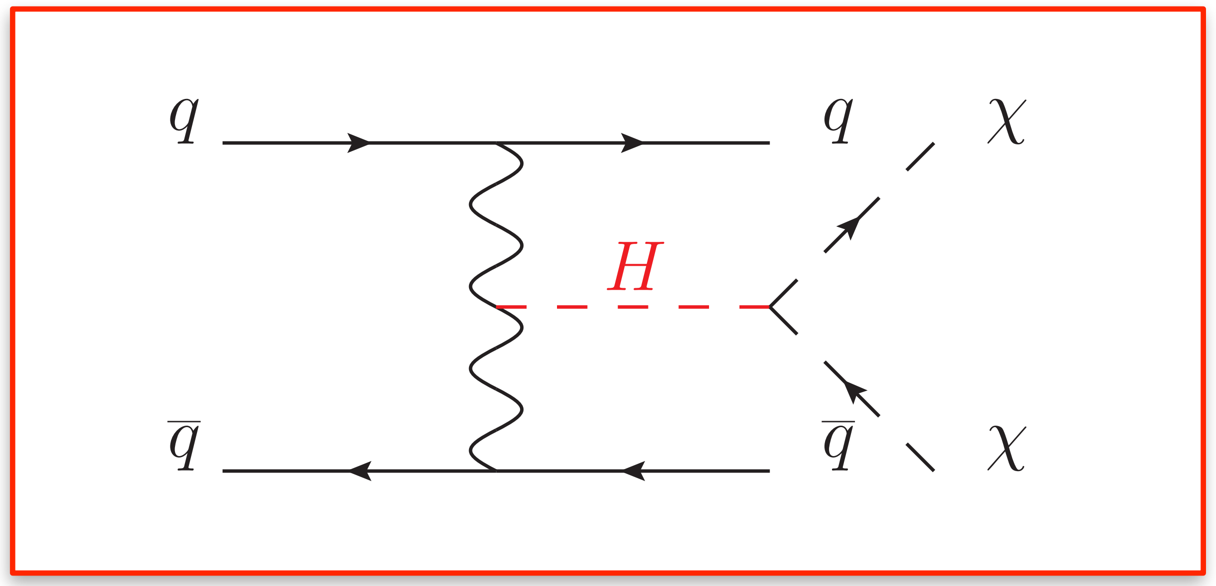
- Overall rate: affected by the interference by approximately 2%, can also yield constraints on the total width of the higgs.

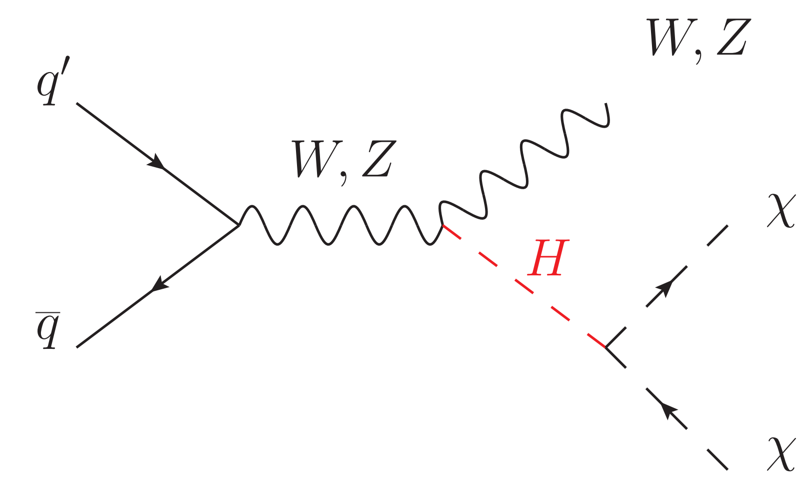
Coupling fit

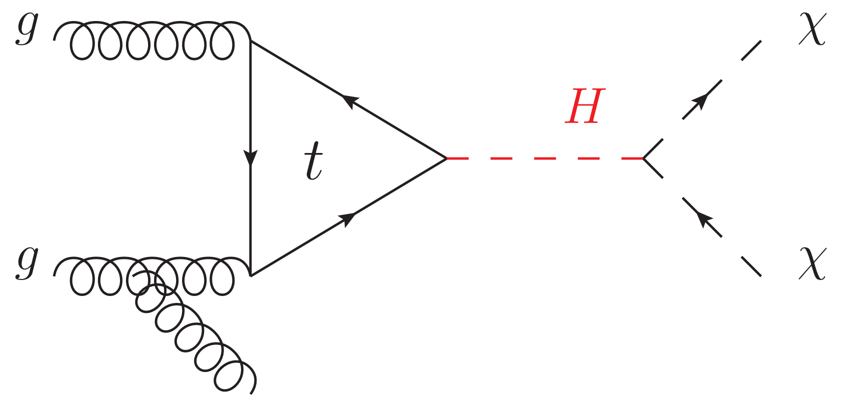
Assuming kV<1 allows to set a limit on Br(BSM) with run 2 data of 26% (ATLAS only with generic model)

At HL-LHC **Br(BSM) < 5%** (95% CL)

Invisible decays of the Higgs boson

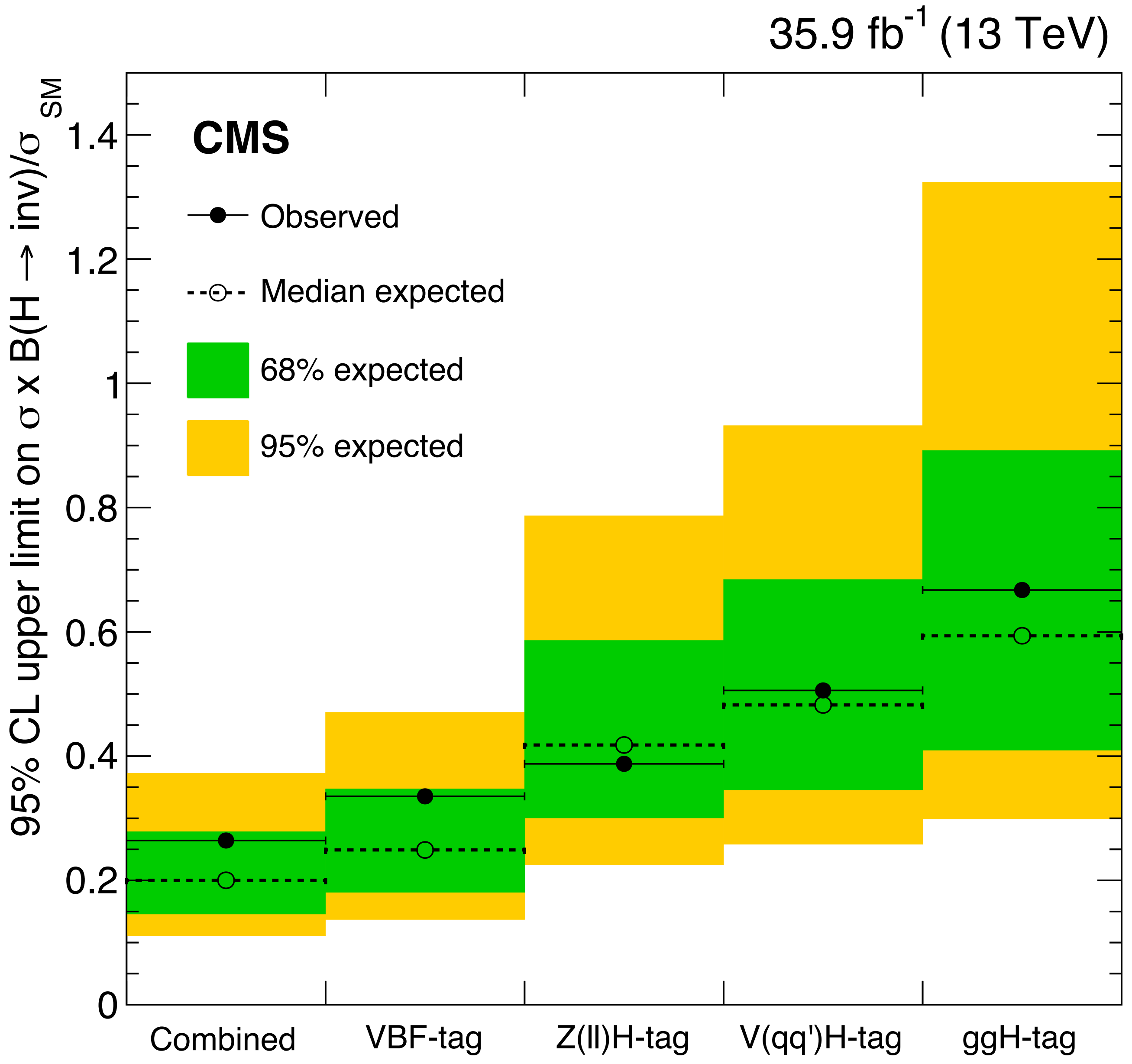


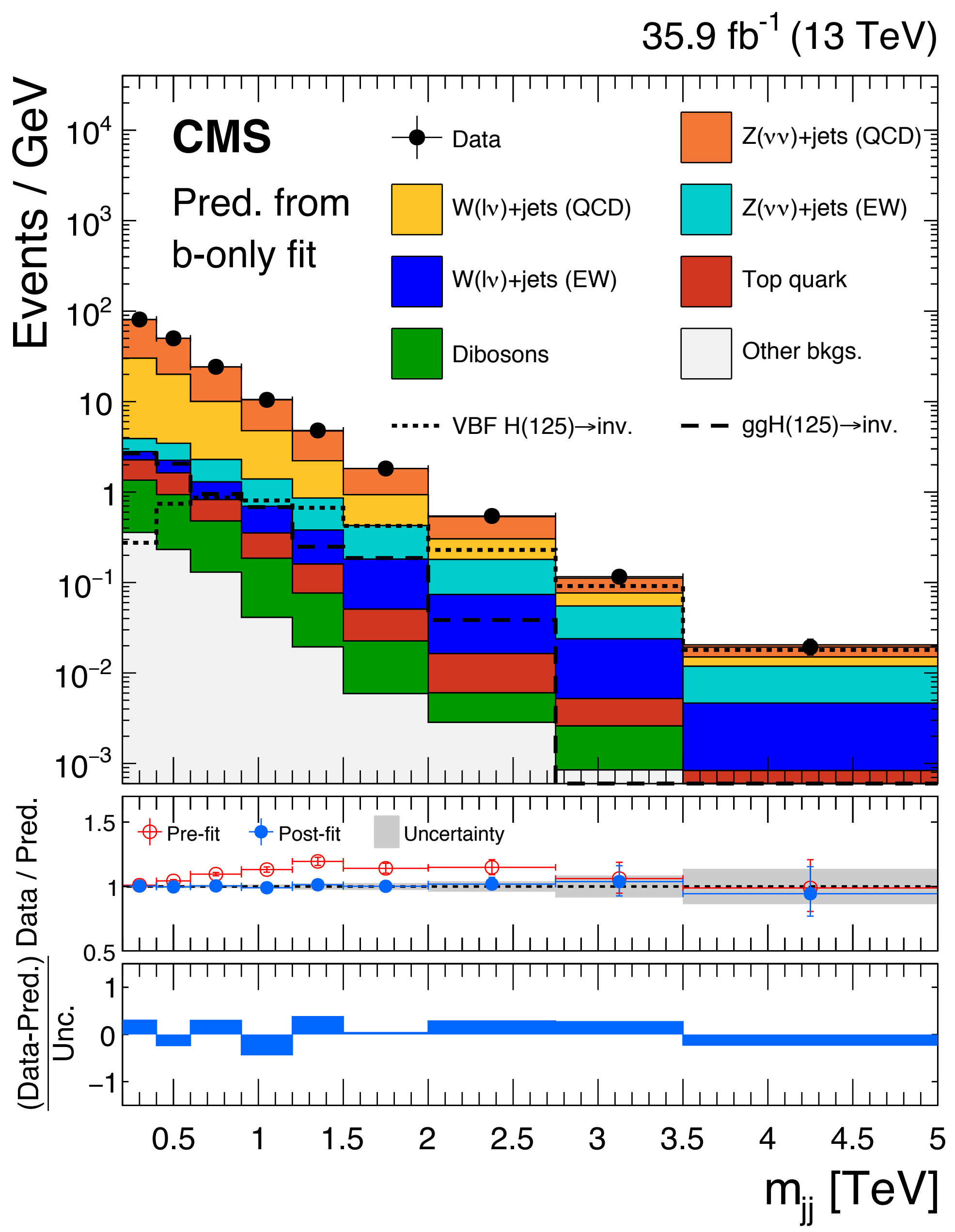




Comprehensive analysis of several channels and several datasets by CMS, to give current level of sensitivity on invisible branching fraction.

- Includes a mono-V hadronic boosted mode
- VBF is the most sensitive channel
- Challenge is the estimate of the V-jets backgrounds: estimated from control regions using W, Z and photon-jet events.

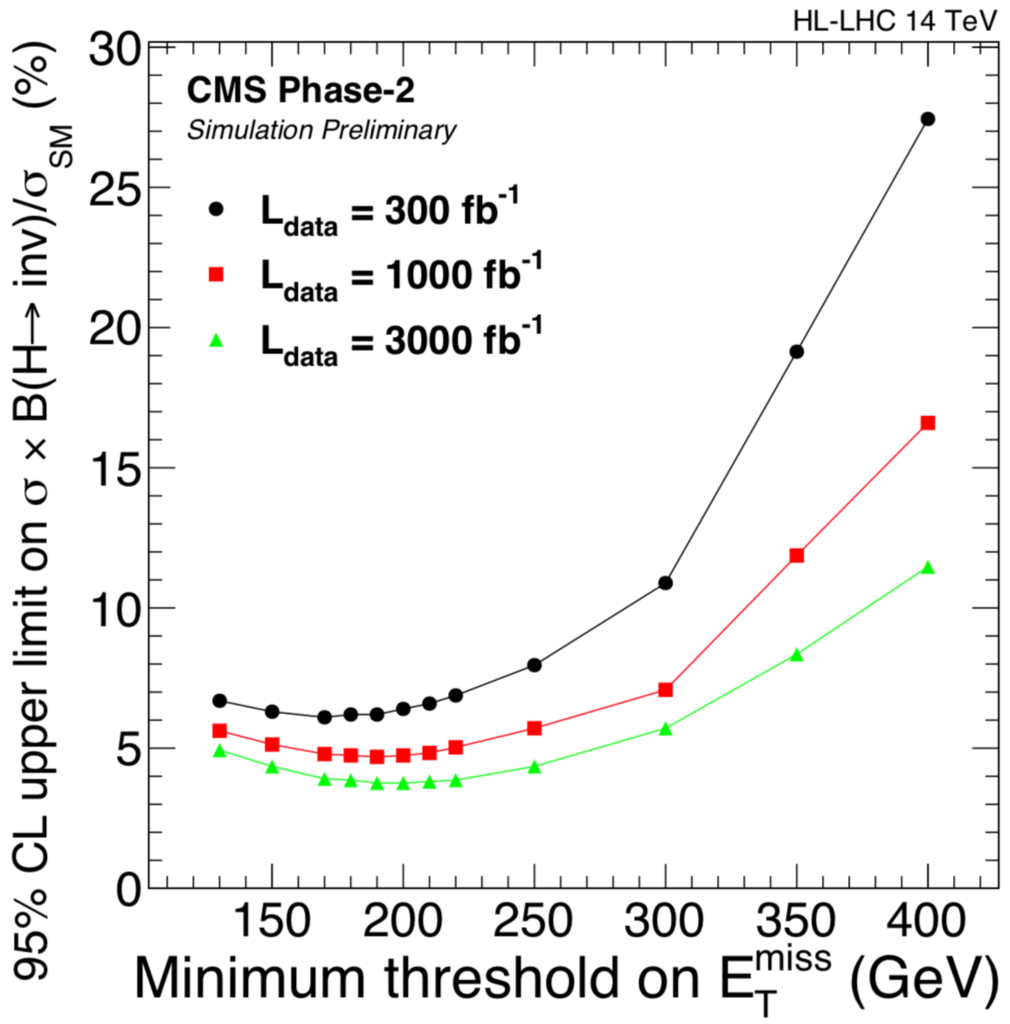




$$\mathrm{Br}_{\mathrm{inv.}} < 0.19\ (0.15)$$

These results are still with a **very small Run 2 dataset!**

Projection at HL-LHC in the VBF channel (single experiment):



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$$Br_{inv} < 3.8\%$$

Combination VH and VBF and consider ATLAS ~ CMS

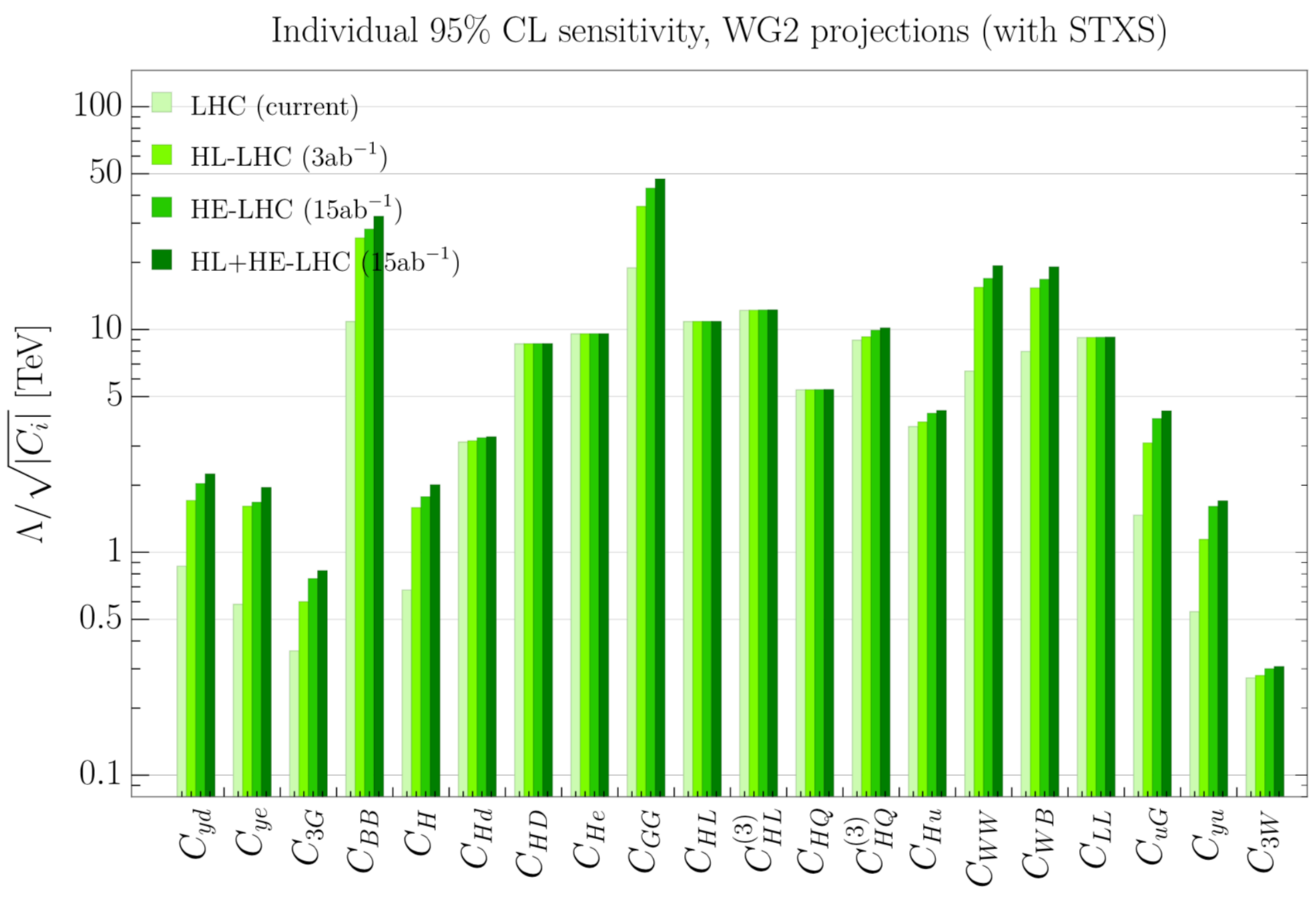
$$Br_{inv} < 2.5\%$$

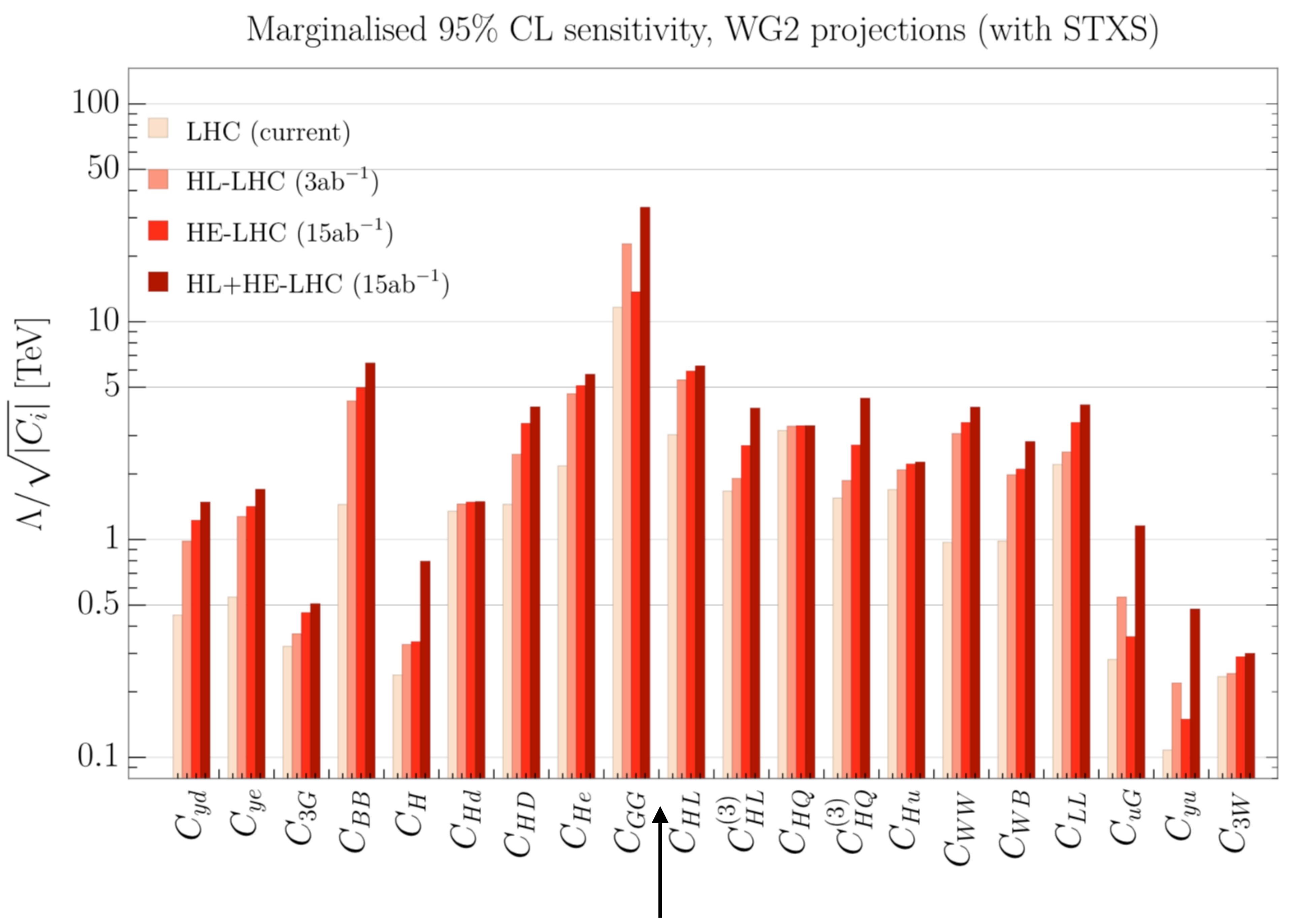
Still room for improvement but sensitivity already slower than pure statistics

Global EFT Fit (I): Partially Universal EFT fit

- 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.

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





Due to opening of flat direction

Only linear terms in parametrisation taken into account, fair approximation (taking only SM-BSM interference) for precise measurements (BSM small) - observables not growing with energy, less otherwise.

Global EFT Fit (II) for Universal New Physics

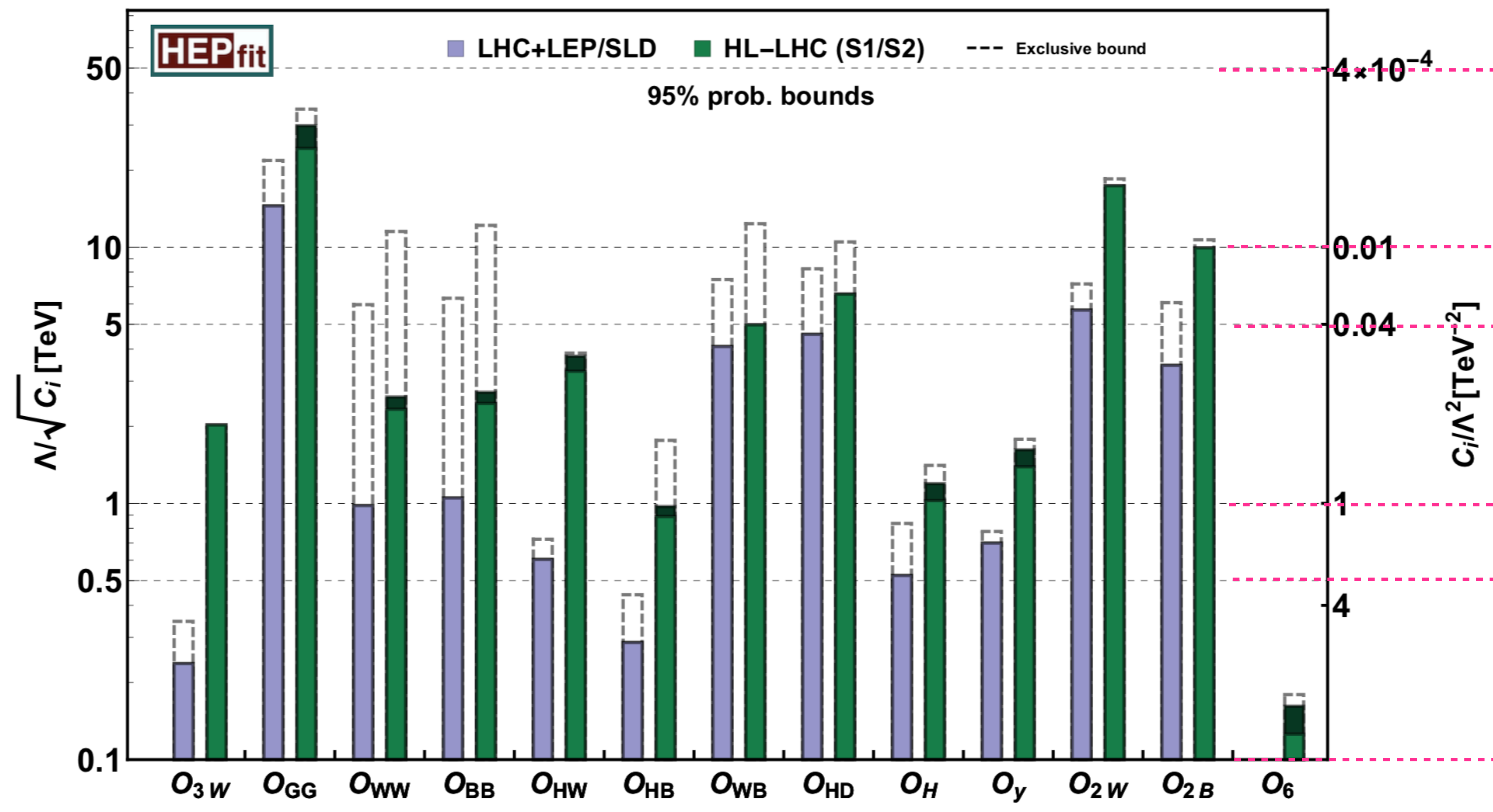
See section 4 of YR

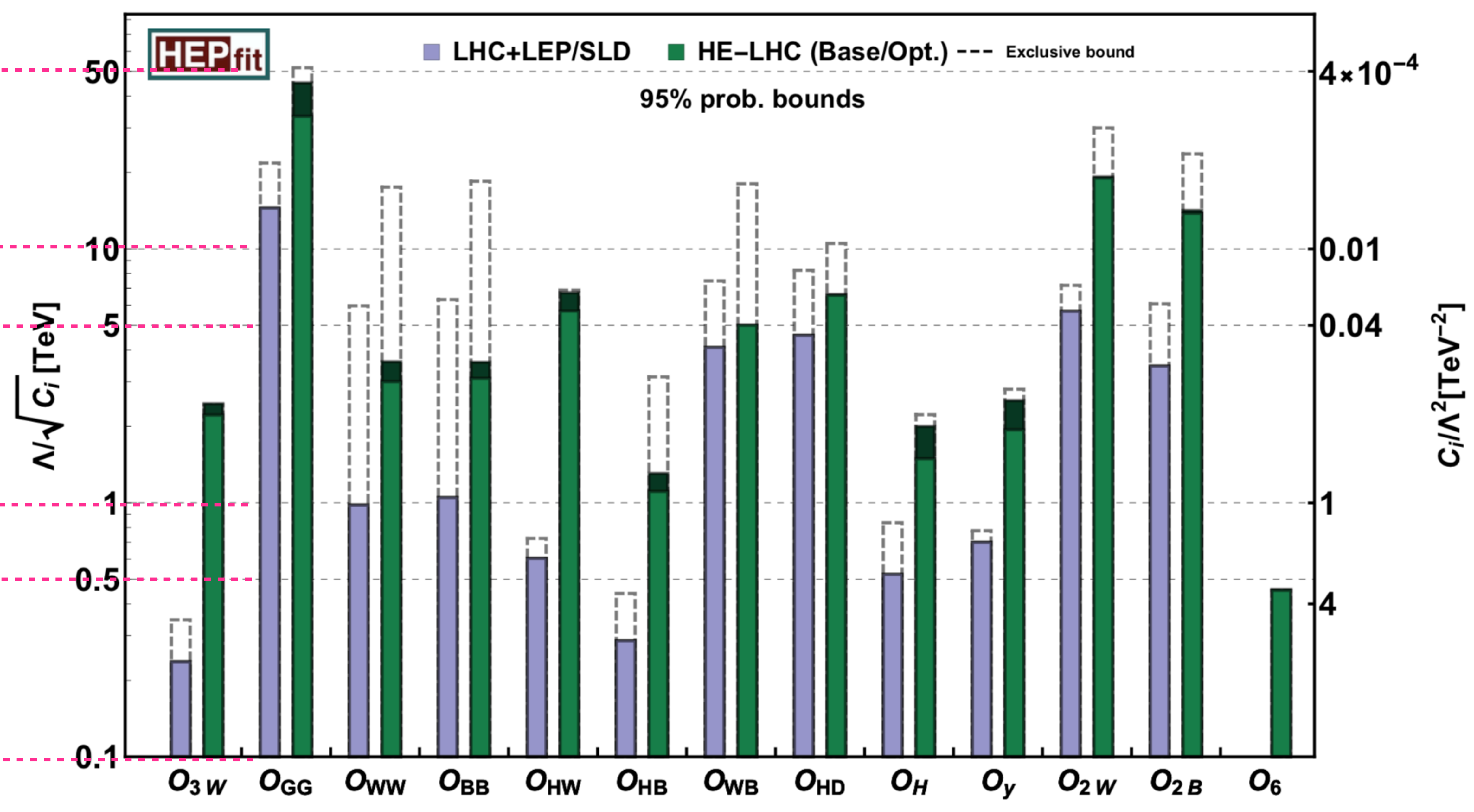
- SMEFT with dimension 6 operators in the Warsaw basis (as well).
- Assuming universality, which results in a slightly simpler model focussing on bosons and the following operators:

$$\{\mathcal{O}_H, \mathcal{O}_{HD}, \mathcal{O}_6, \mathcal{O}_{GG}, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{WB}, \mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{2B}, \mathcal{O}_{2W}, \mathcal{O}_{3W}, \mathcal{O}_y\}$$

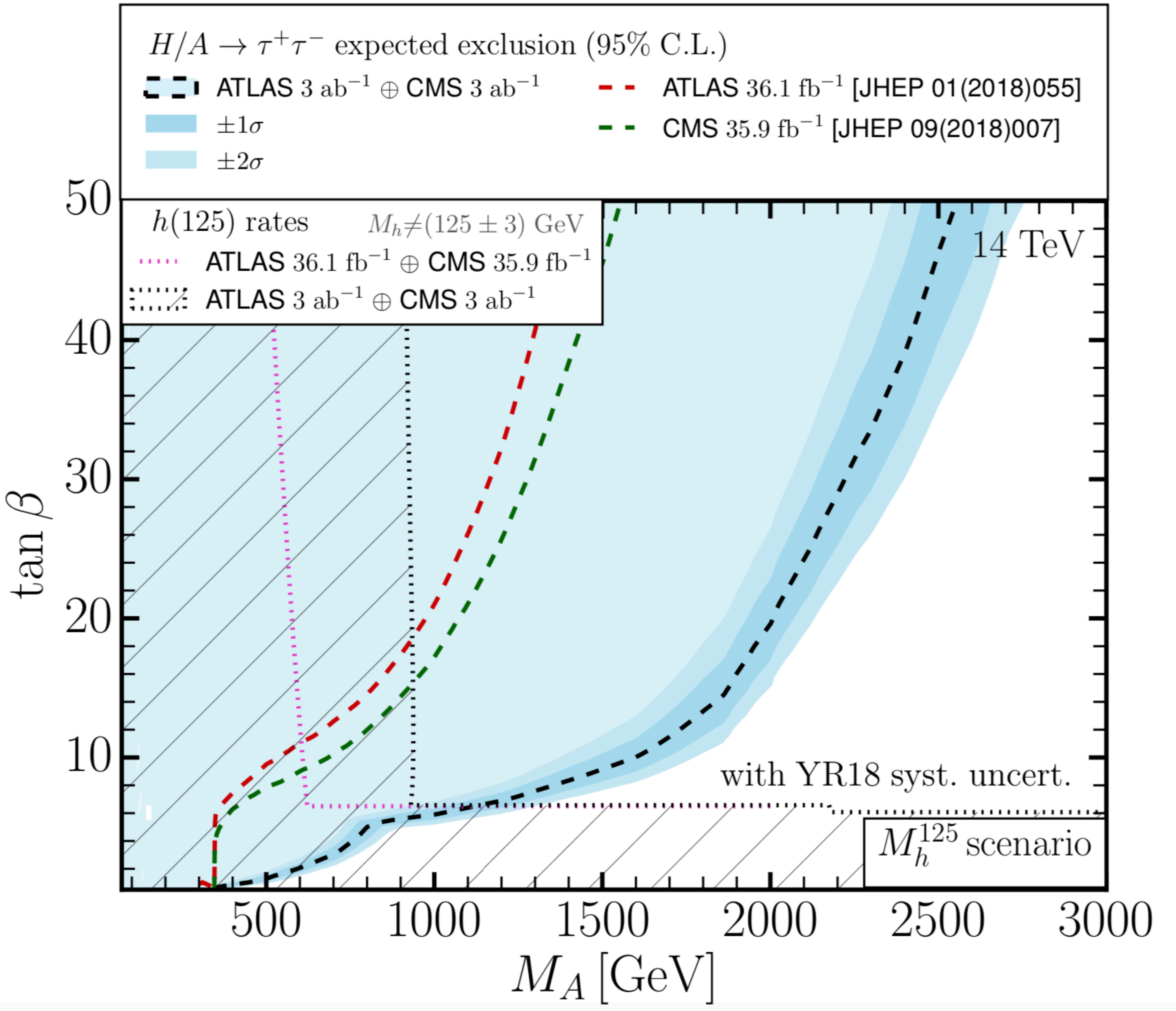
- **Inputs**:
  - LHC Higgs signal strengths (in part VH).
  - HH differential in baby
  - ZH in the high ZH mass regime
  - WZ (better than WW)
  - DY (high mass)

Quadratic terms taken into account where needed.





BSM Higgs Searches

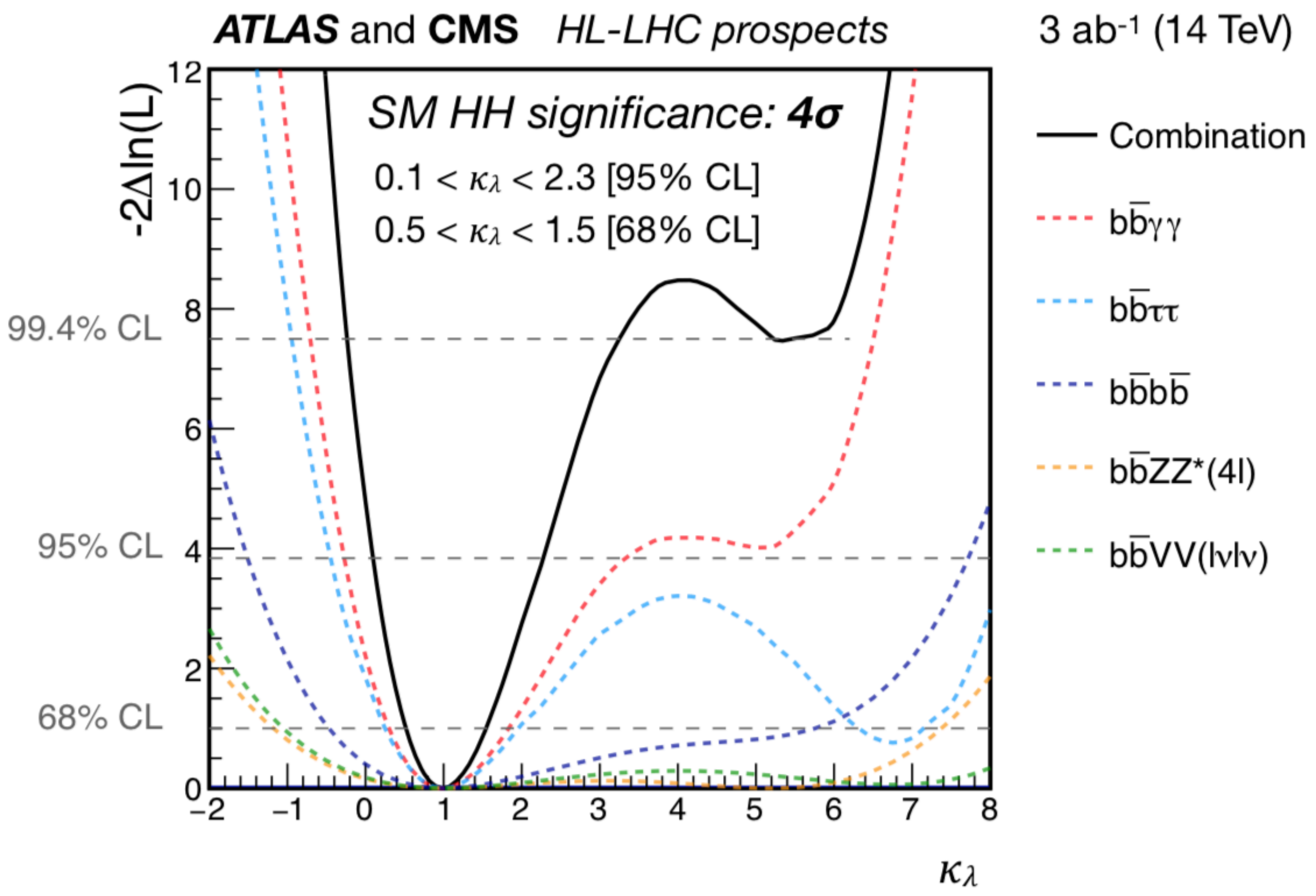


- **Define "BSM Higgs searches"** as any search having as principal goal to search for an extended Higgs sector (MSSM, 2HDM, NMSSM, Georgi-Machacek Triplets, additional singlets, etc…) not cases where the principal scope is a direct search for a BSM state with Higgs bosons in the final state.
- Because of their coupling properties and backgrounds in hadron collisions, searches for additional Higgs boson are typically in the intermediate mass range. Still large improvement in the sensitivity with the HL.
- Challenge: Extend the direct search coverage in the intermediate tan beta region and high mass requires improving searches such as top-pair (taking into account the interference with the continuum background), no conclusive prospect studies done so far.

Double Higgs Production and Higgs Self Coupling

At HL-LHC: Direct search

- Analyses completely reappraised.
- More channels investigated in detail.



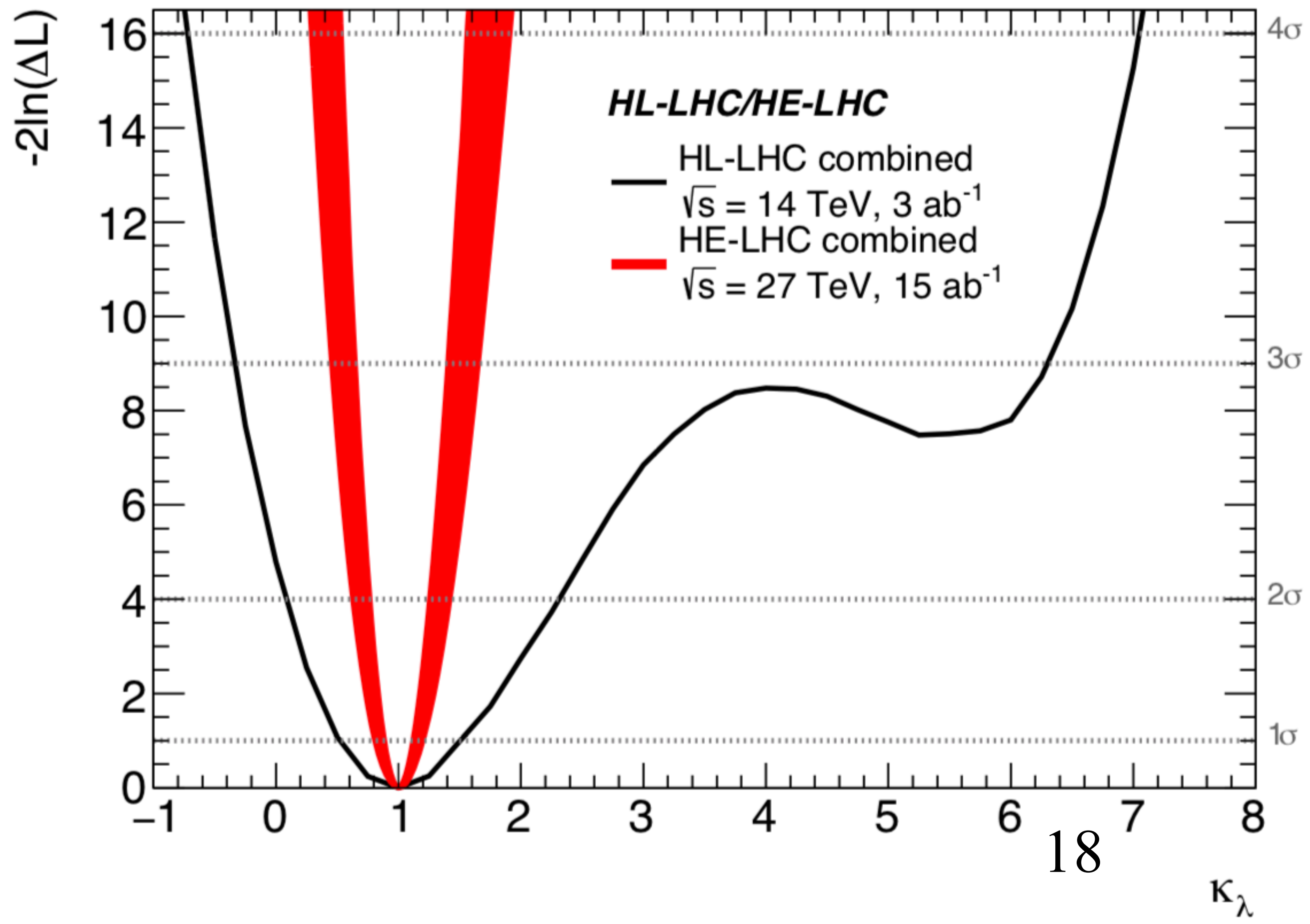
$$0.5 < \kappa_\lambda < 1.5$$

- Not quite 5 s.d. observation of HH signal.
- significant exclusion of the secondary minimum.
- Closing up on a measurement, but not decisive.

Huge progress made nevertheless! Probably still more (though not completely obvious).

At HE-LHC

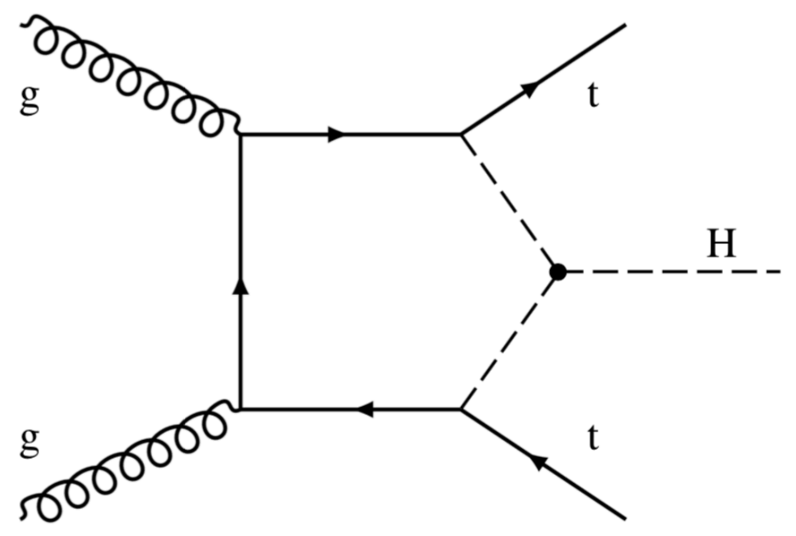
- Several single channel TH studies, compared with on EXP extrapolation of bbyy and bbtautau studies - One experiment reach at HE-LHC of 40% and 20% respectively on each channel.
- Some TH extrapolations provided a much improved sensitivity in the bbyy channel (15%) using HH with jet.
- Range of extrapolation given between 10% and 20% on the trilinear coupling.

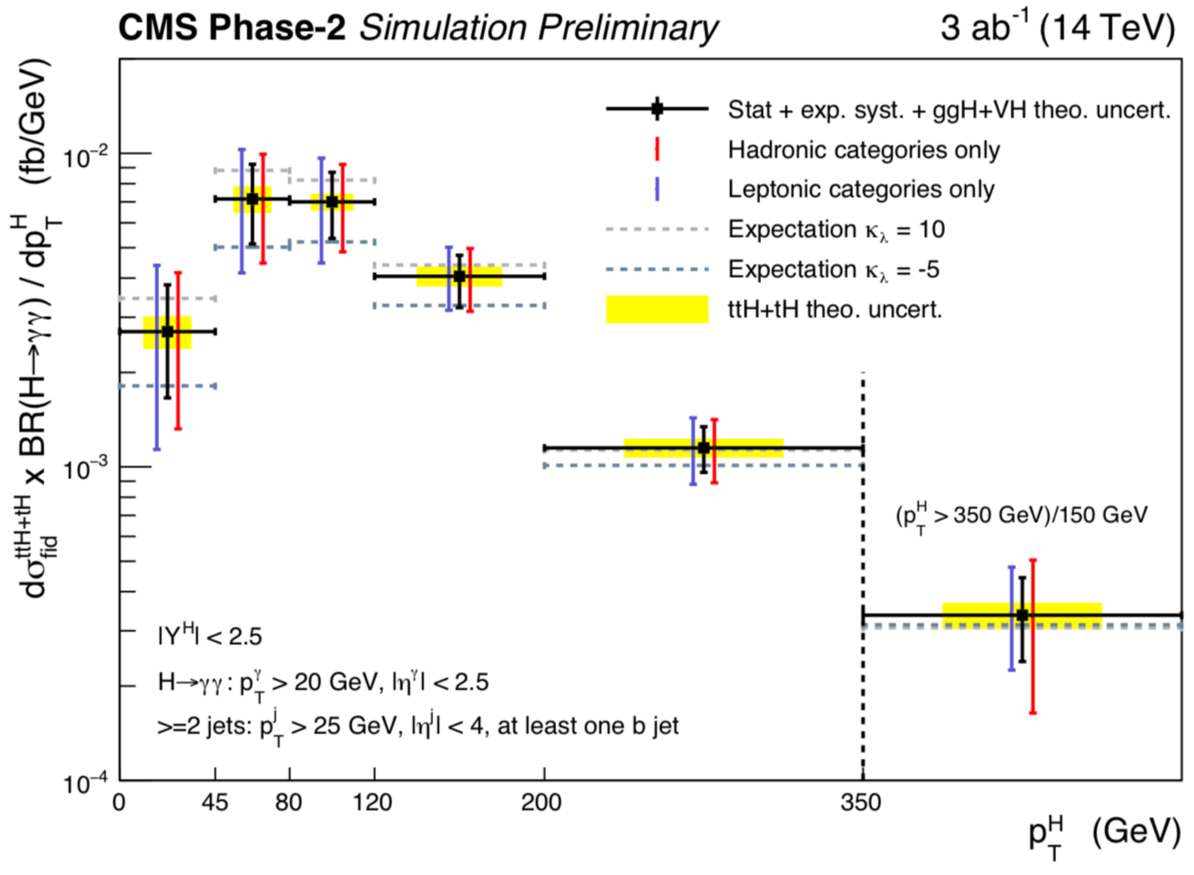


Indirect constraints on Higgs Self Coupling

Indirect constraints through differential cross sections

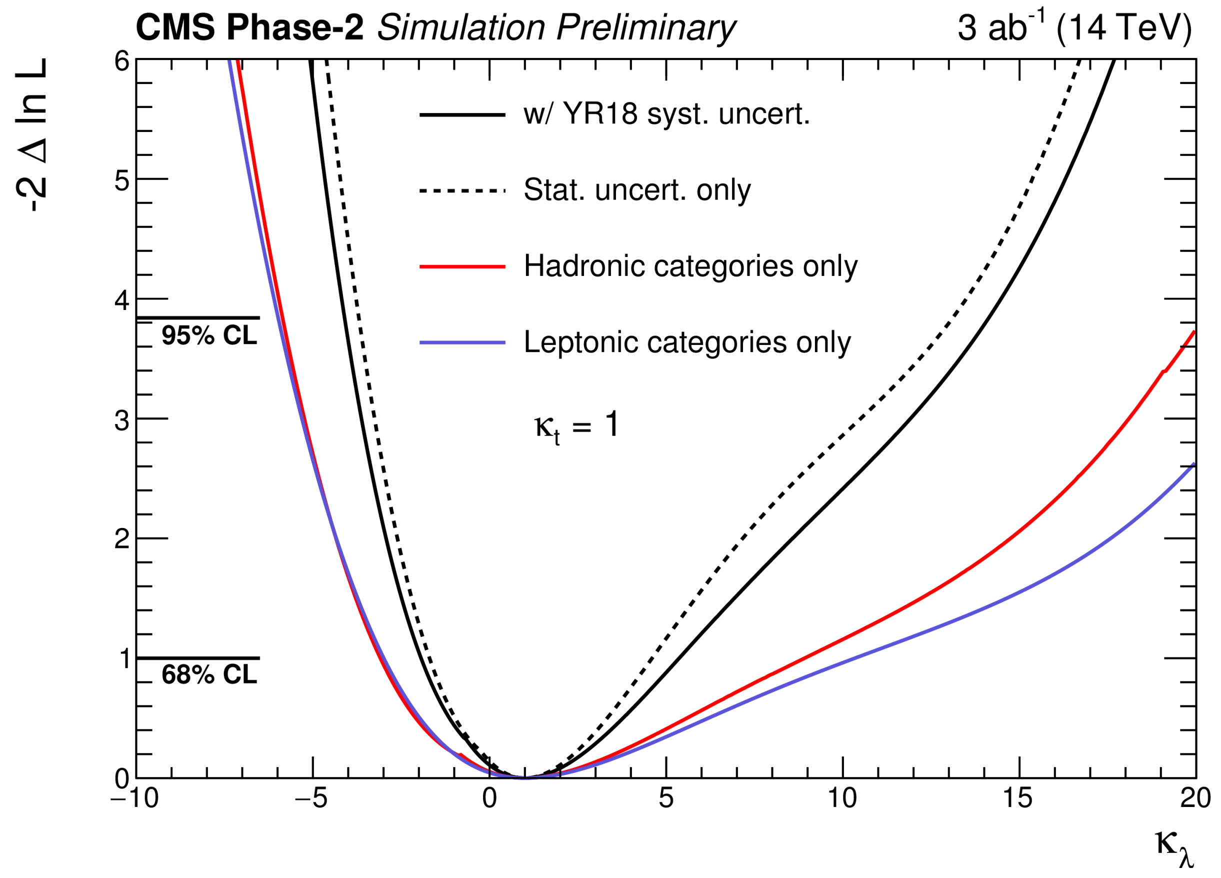
ttH Process (with subsequent decay to diphoton)





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

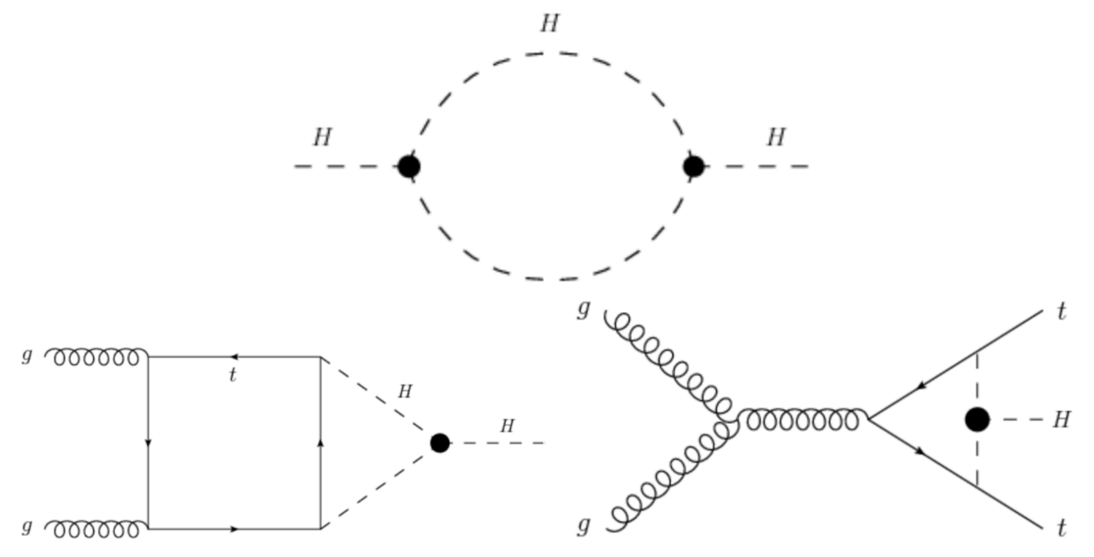
To some extent possible to disentangle effect of trilinear from other coupling modifications from the differential distribution



FTR-2018-020

Global fit 1704.01953

More complete TH study taking into account effects:



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

Fair constraints if varying trilinear only, however not realistic as a deviation would signal new dynamics and other Higgs couplings would be modified. A global fit is necessary.

Indirect constraints are significantly weaker, in the global case due to parameter degeneracies.

Summary and Conclusions

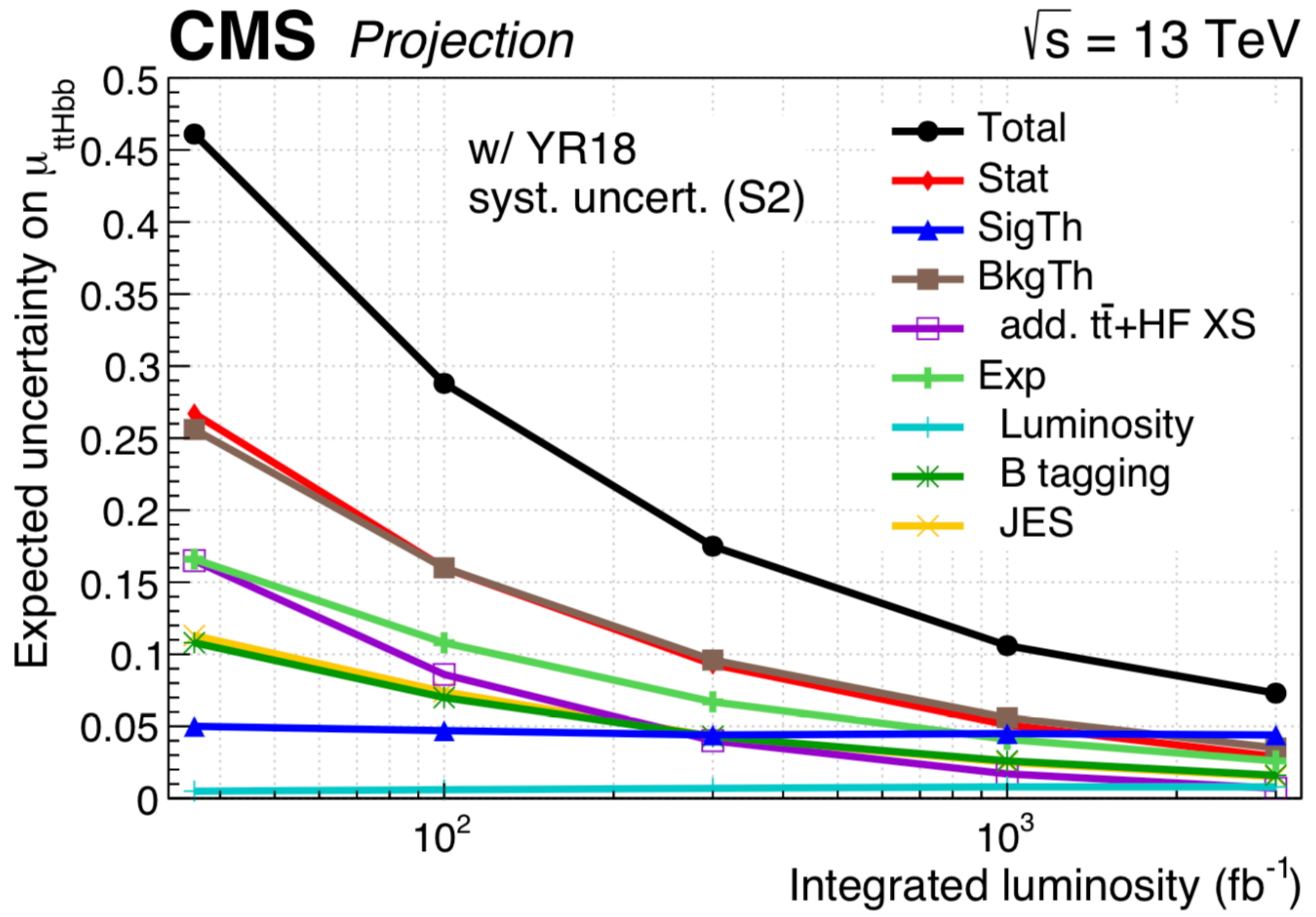
- Projected reach in precision Higgs physics has been fully reappraised in the light of the Run 2 optimised Higgs analyses.
- Consensus reached on foreseen projected systematic uncertainties (both experimental and TH).
- The landscape has changed reaching (few) percent level precisions on the couplings and new perspectives on constraining the trilinear coupling.
- However: the modus operandi for these projections did not include:
  - re-optimised analyses for approximately 40 times larger stats.
  - possible ancillary measurements to further restrict systematic uncertainties.
  - exploration of sensitive fiducial ratios.
  - This provides a improved basis for comparison and emphasising complementarity with future collider projects.
- Splendid opportunities for Higgs physics at the LHC!

Backup

A Closer Look at the ttH Case

HL-LHC projection

- Extrapolating expected sensitivity simply from available framework. 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).



Towards HE-LHC

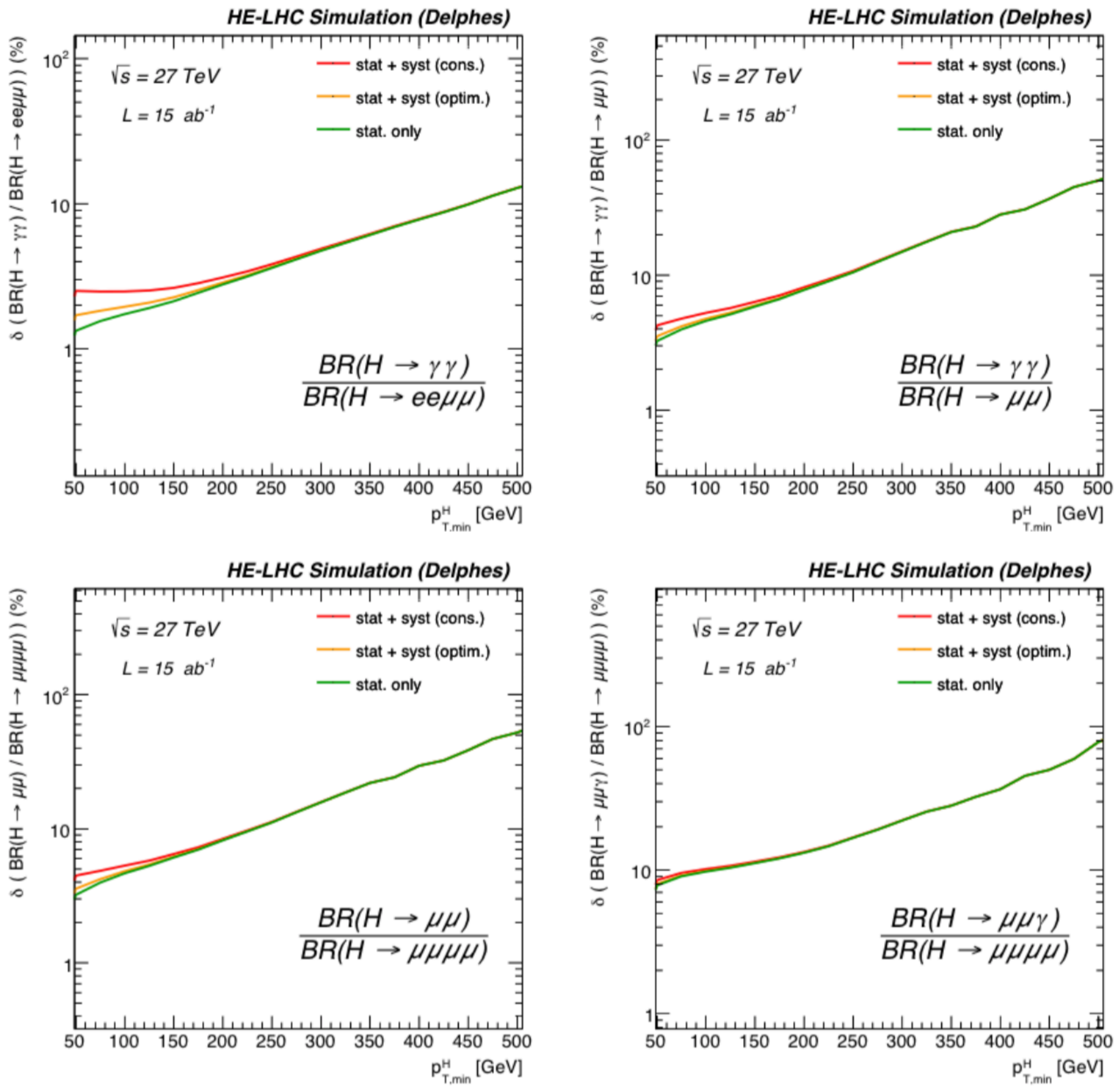
- Extrapolating current analyses does not give a fair estimate of the potential in this channel.
- Current ttH-yy and 4-lepton are not optimised at all for very high luminosities. There should be a fair margin of improvement in the analyses themselves.
- Ratio of ttH to ttZ measurements have been shown to reach approximately 1% on the couplings.

Approximation from ratio studies done in 1507/08169 (M. Mangano et al.), these studies can be extended to other channels.

More work needed to give an accurate assessment of the ultimate precision on the top Yukawa coupling

A Few Remarks

- The coupling measurements are already typically dominated by (TH) systematic uncertainties.
- In most cases improvements are marginal (even in this basic extrapolation scheme in the ttH case).
- Only in specific rare decay cases, the improvements are substantial. Please note that in the case of the dimuon and the Zgamma channels, the optimisation of the analyses and the assessment of systematic uncertainties were done for a case overwhelmingly dominated by statistical uncertainties. Further improvements should be possible.



Interesting example possible study of ratios

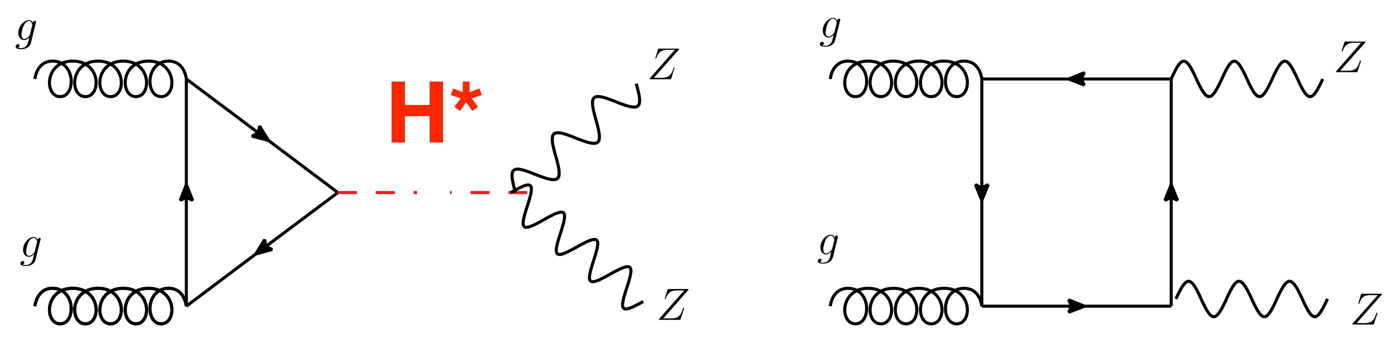
- Further reducing the impact of systematic uncertainties, both experimental and theoretical is possible in ratios, as for example:
  - Diphoton to 4-leptons (ee mumu)
  - Dimuon to 4-muons
  - mumu-gamma to four muons

- Reaching a percent level precision on the ratio of the relevant couplings.

Higgs Boson Width

Offshell Higgs measurements

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

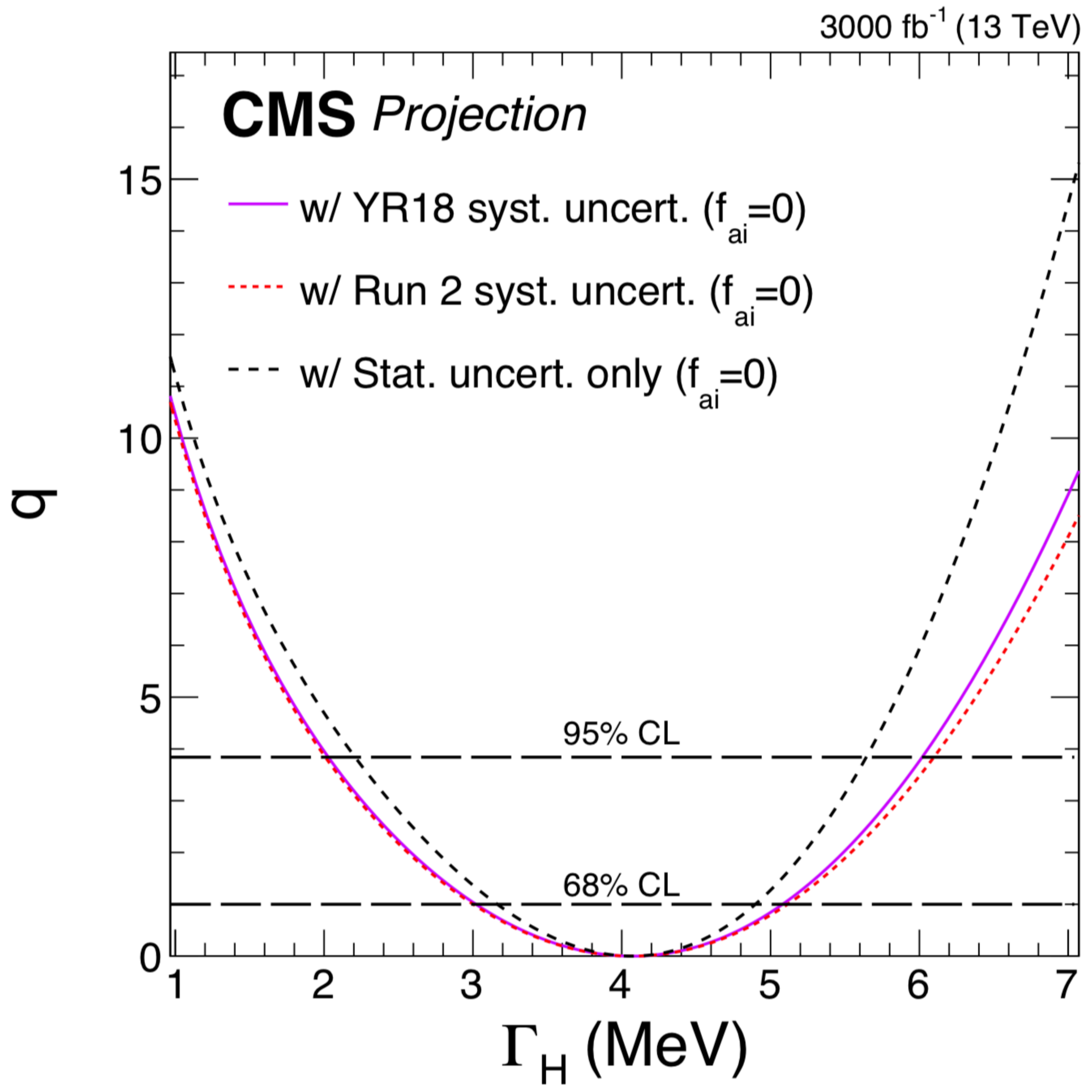


$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Results have been limited by statistics, however ggZZ (including interference term) systematic uncertainties become important at high luminosity!

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

Preliminary HL-LHC results with 3 ab-1:



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

HL-LHC (stat only): $\Gamma_H = 4.1^{+0.8}_{-0.9}$ MeV

Very approximate infinite stat approximation for **HE-LHC**:

$$\Gamma_H = 4.1 \pm 0.6\ \text{MeV}$$

Diphoton-continuum interference

- Mass shift: This interference has first been studied when noticing approximately 35 MeV with shift with dependence on Higgs pT

  $\Gamma^H_{SM} < 200$ MeV At HL-LHC

  Many more studies needed for HL-LHC sensitivity thus not trivial extrapolation to **HE-LHC**

- Overall rate: affected by the interference by approximately 2%, can also yield constraints on the total width of the higgs.

Similarly to couplings no significant improvement in naive extrapolation to **HE-LHC**

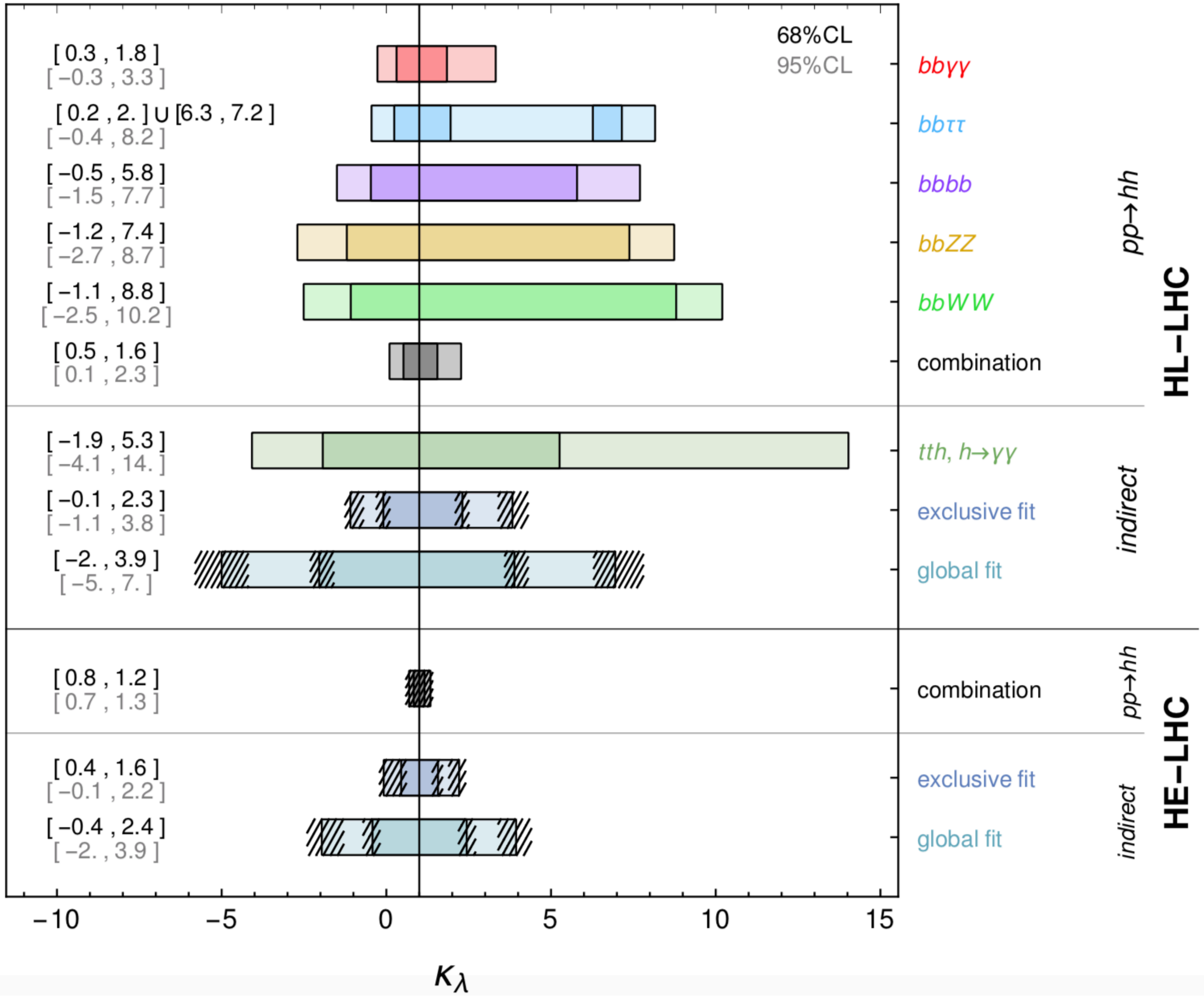
Coupling fit

Assuming kV<1 allows to set a limit on Br(BSM) with run 2 data of 26% (ATLAS only with generic model)

At HL-LHC **Br(BSM) < 5%** (95% CL)

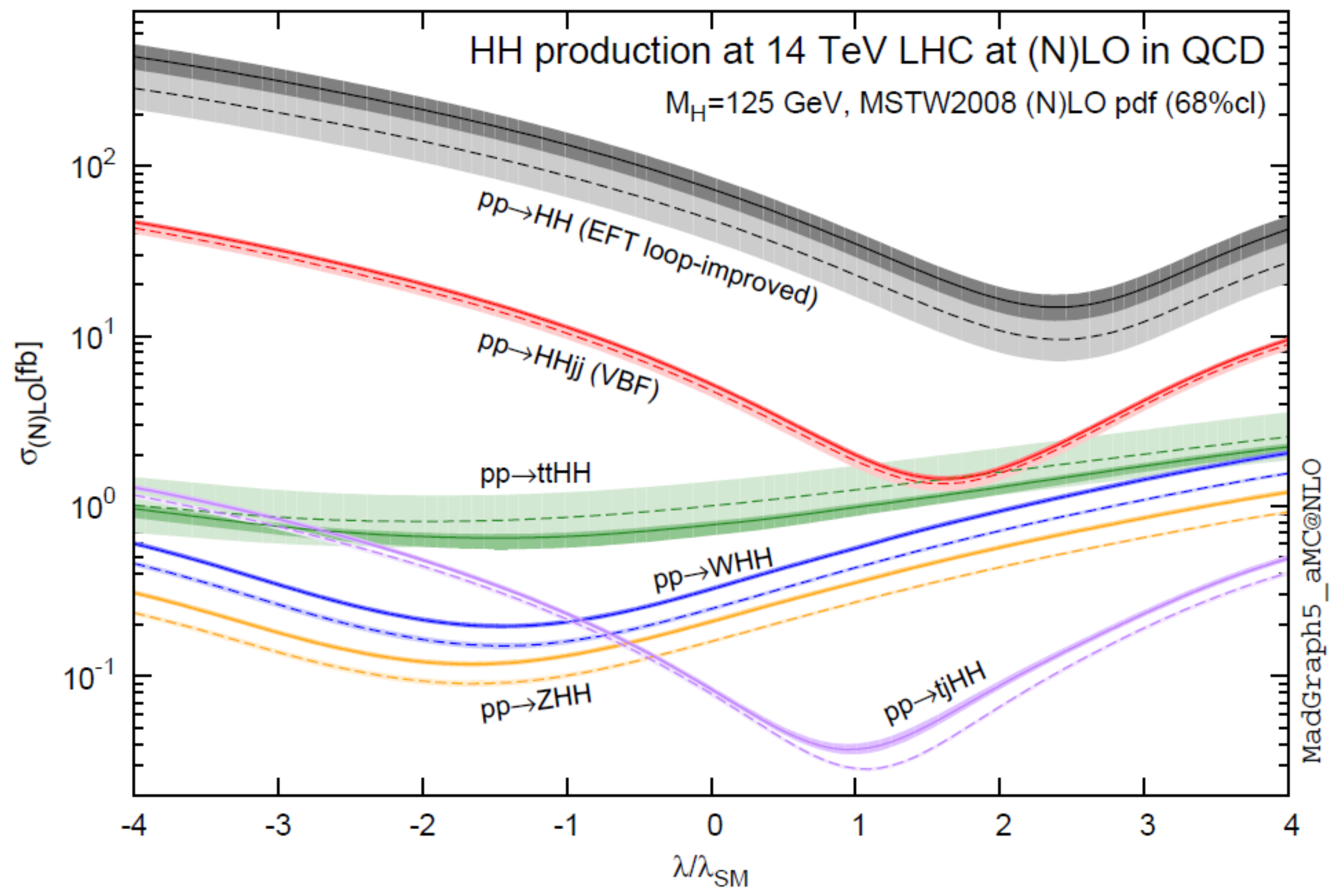
Idem to couplings extrapolating to **HE-LHC**

HH and Trilinear Coupling Summary



- Indirect constraints are interesting but in a realistic fit, the impact becomes very small relative to the direct HH measurements.

- More work can be done to explore using different production modes that can be very helpful in constraining the trilinear coupling.



- Most importantly, HE-LHC provides a strong case for a first assessment of the Higgs trilinear coupling.