Overview of LHC Higgs physics & perspectives for the ILC

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Journées Collisionneur Linéaire
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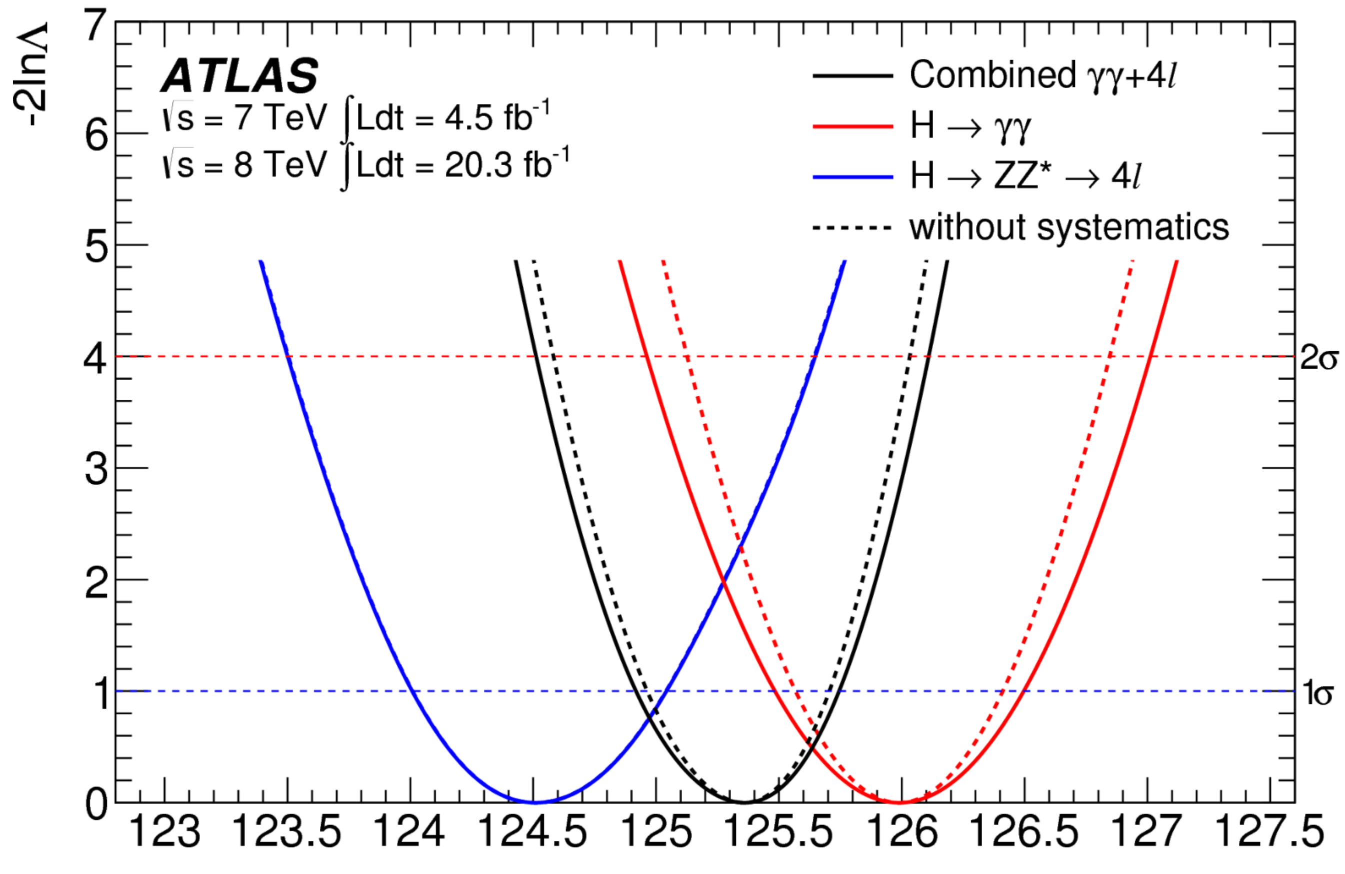
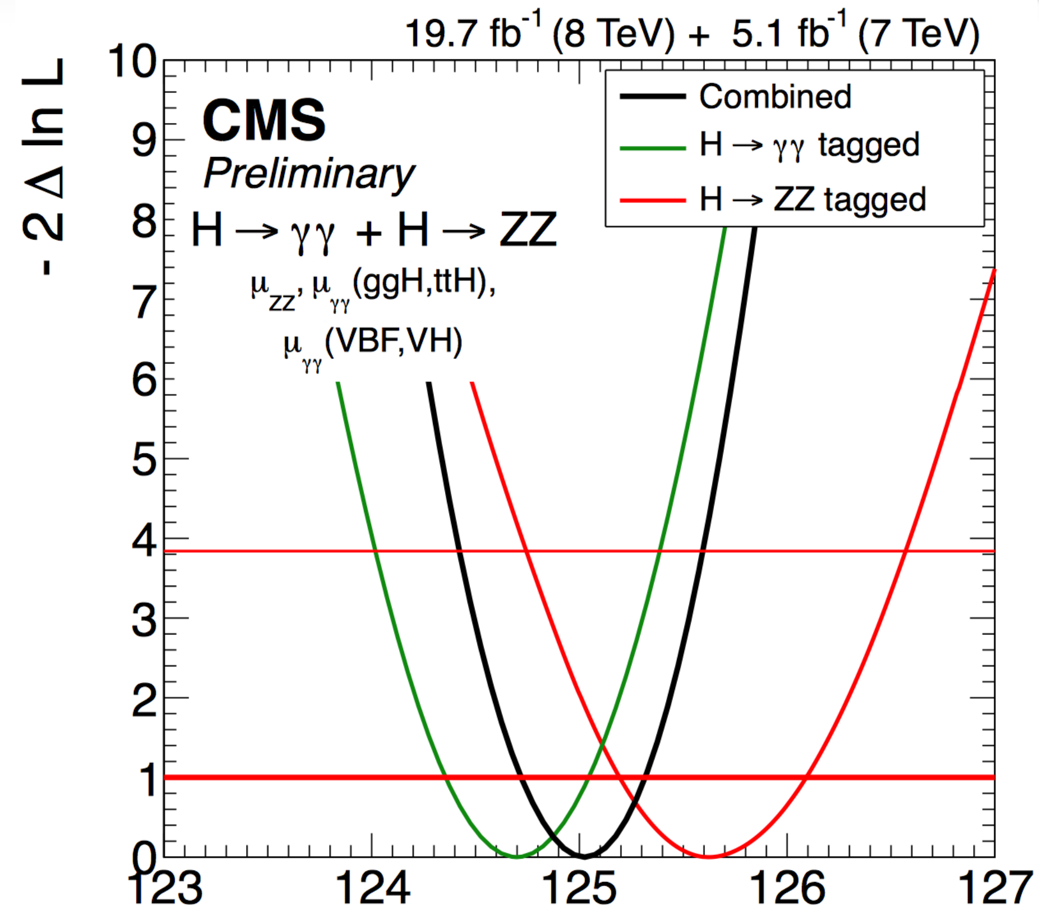
Higgs properties after LHC Run I

The last Standard Model free parameter ?



[ATLAS-HIG-2013-12]



[CMS-PAS-HIG-14-009]

$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})\ \text{GeV}$$

$$m_H = 125.03 \pm 0.27(\text{stat}) \pm 0.15(\text{syst})\ \text{GeV}$$

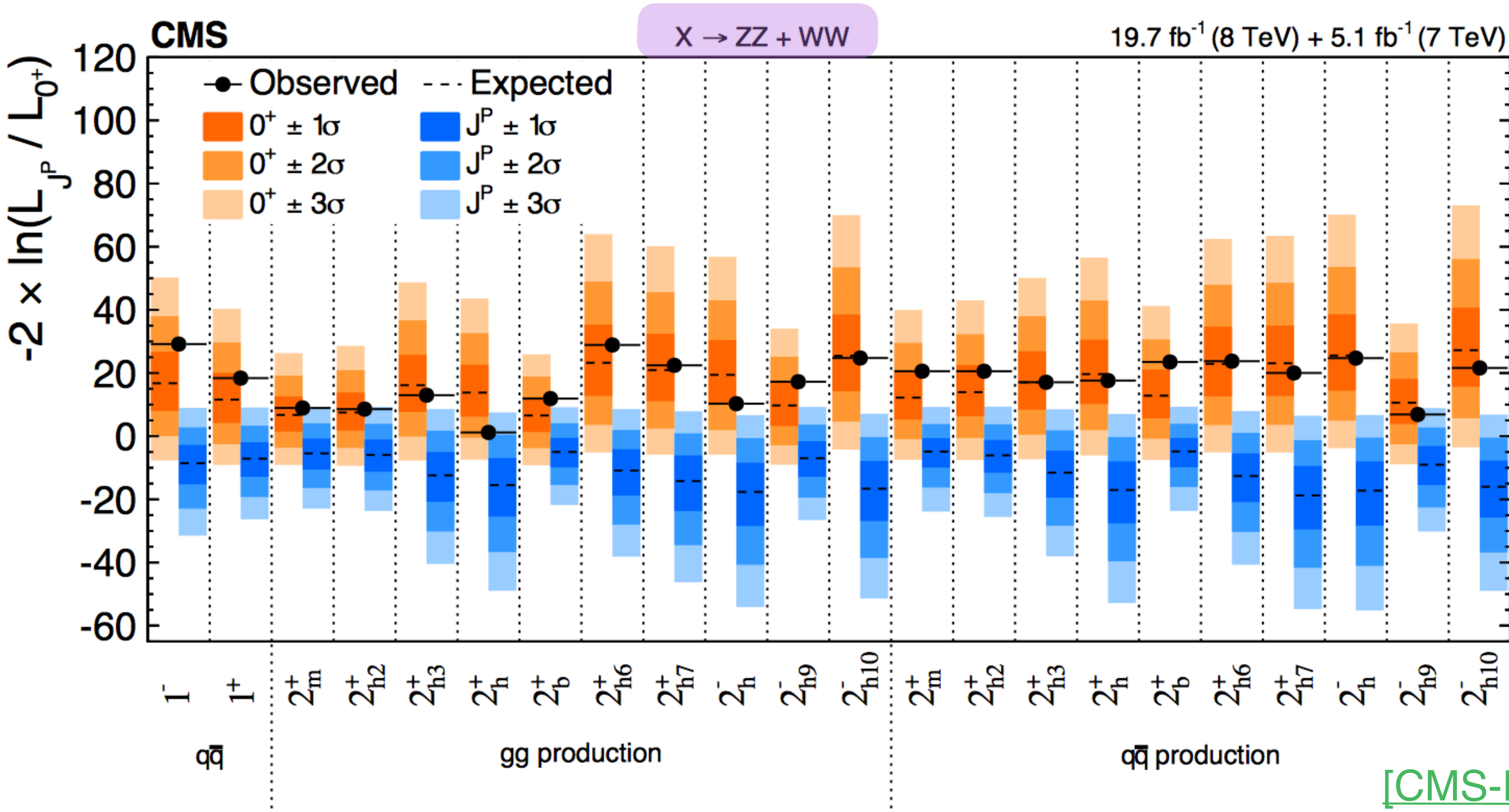
- « Maximizes » the number of accessible final states
- $\Gamma_H^{125,\text{SM}} = 4.1\ \text{MeV}$

J=1 & J=2 status

- SM prediction: $\mathrm{J}^{\mathrm{PC}} = 0^{++}$
- Test of spin alternatives in $H \to VV \to 4l, 2l2\nu$

e.g. for J=1: $A(\mathrm{X}_{J=1}\mathrm{VV}) \sim b_1^{\mathrm{VV}} \left[\left(\epsilon_{\mathrm{V}1}^{*} q\right) \left(\epsilon_{\mathrm{V}2}^{*} \epsilon_{\mathrm{X}}\right) + \left(\epsilon_{\mathrm{V}2}^{*} q\right) \left(\epsilon_{\mathrm{V}1}^{*} \epsilon_{\mathrm{X}}\right) \right] + b_2^{\mathrm{VV}} \epsilon_{\alpha\mu\nu\beta} \epsilon_{\mathrm{X}}^{\alpha} \epsilon_{\mathrm{V}1}^{*\mu} \epsilon_{\mathrm{V}2}^{*\nu} \tilde{q}^{\beta},$

- All J=1,2 tested models disfavored at at least 98% CL:

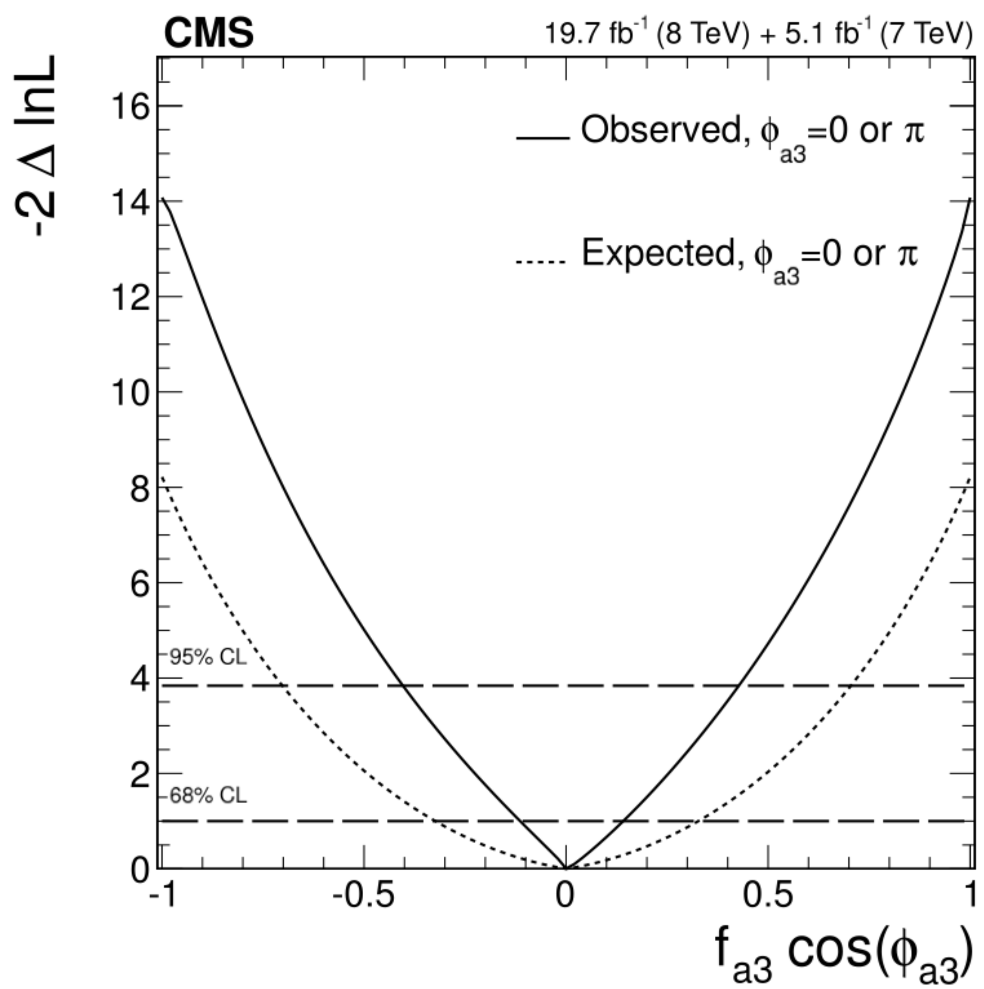


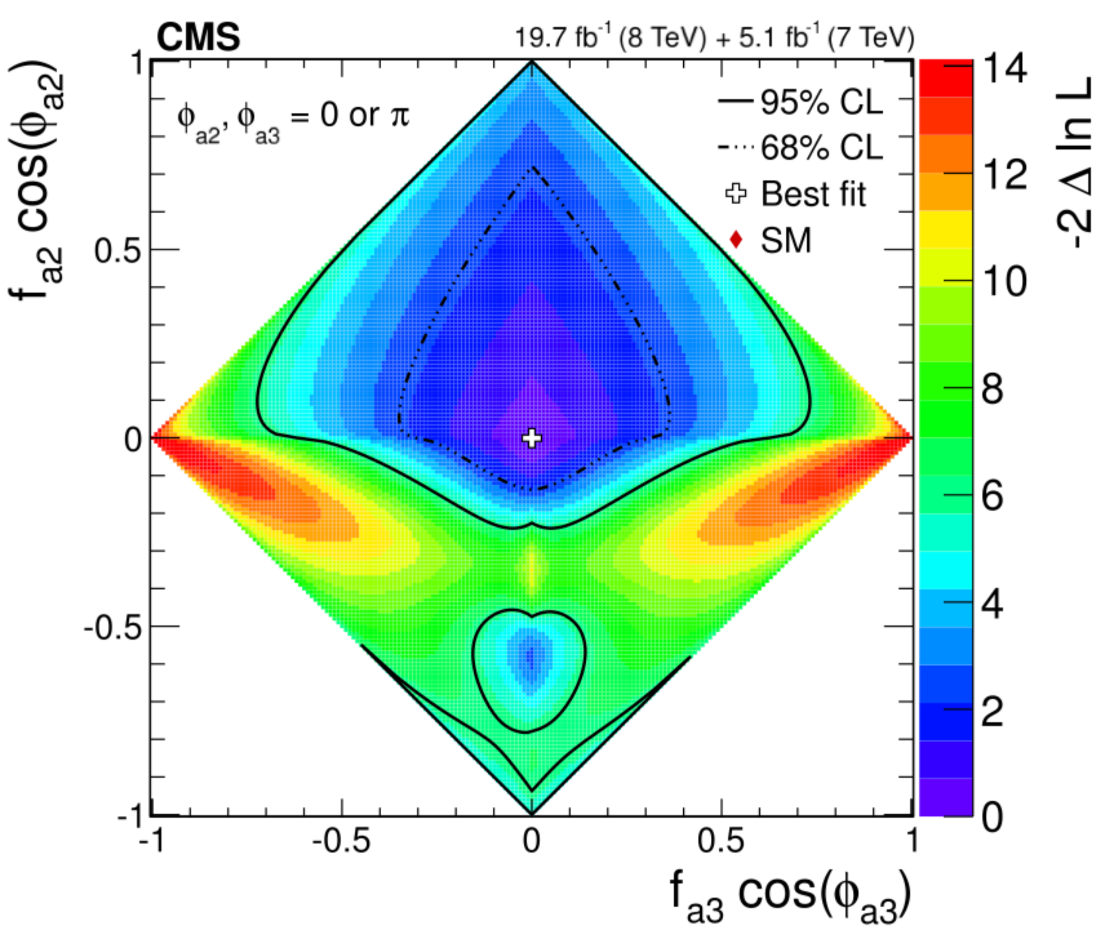
[CMS-PAS-HIG-14-008]

J=0 (from H->ZZ->4l)

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

- f_{a3} : pseudo-scalar fractional contribution to the ZZ cross-section





$$f_{a3} = 0.00^{+0.40}_{-0.44} \text{ @ } 95\% \text{ C.L.}$$

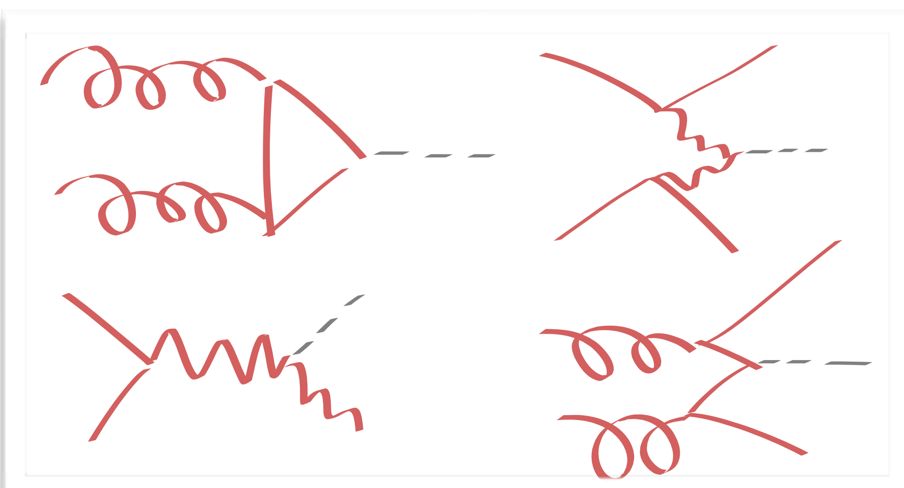
[CMS-PAS-HIG-14-008]

From signal strengths to couplings

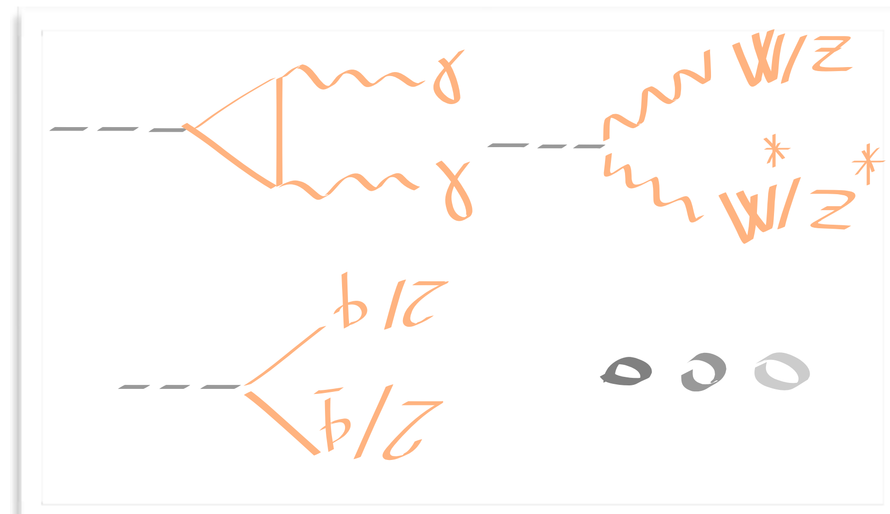
- Encode possible deviations in signal strengths:

$$\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X_{\mathrm{SM}})\mathcal{B}(H_{\mathrm{SM}} \to Y)} = \frac{{\kappa_X}^2 {\kappa_Y}^2}{\widetilde{\Gamma}_h}$$

$X \subset$

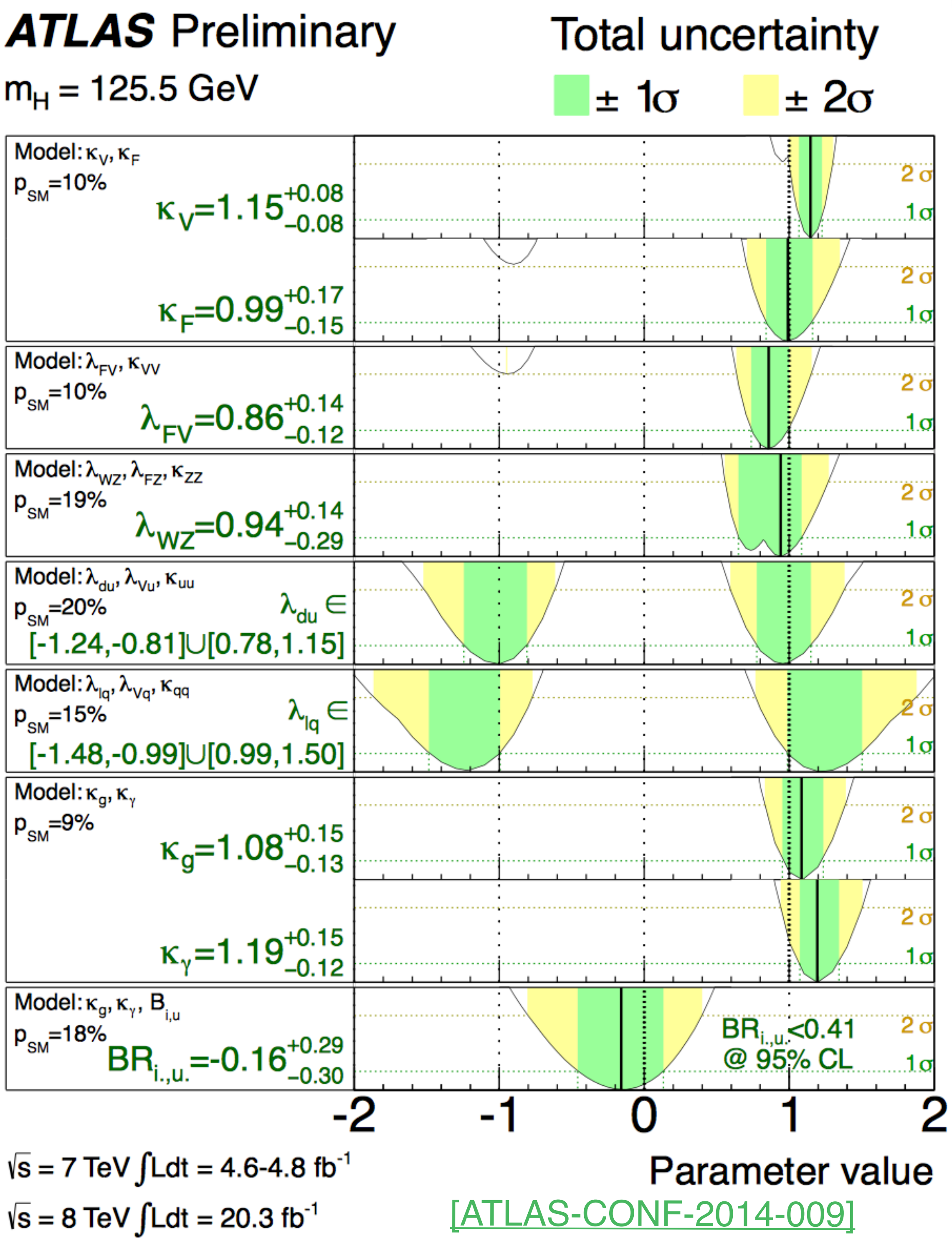


$Y \subset$

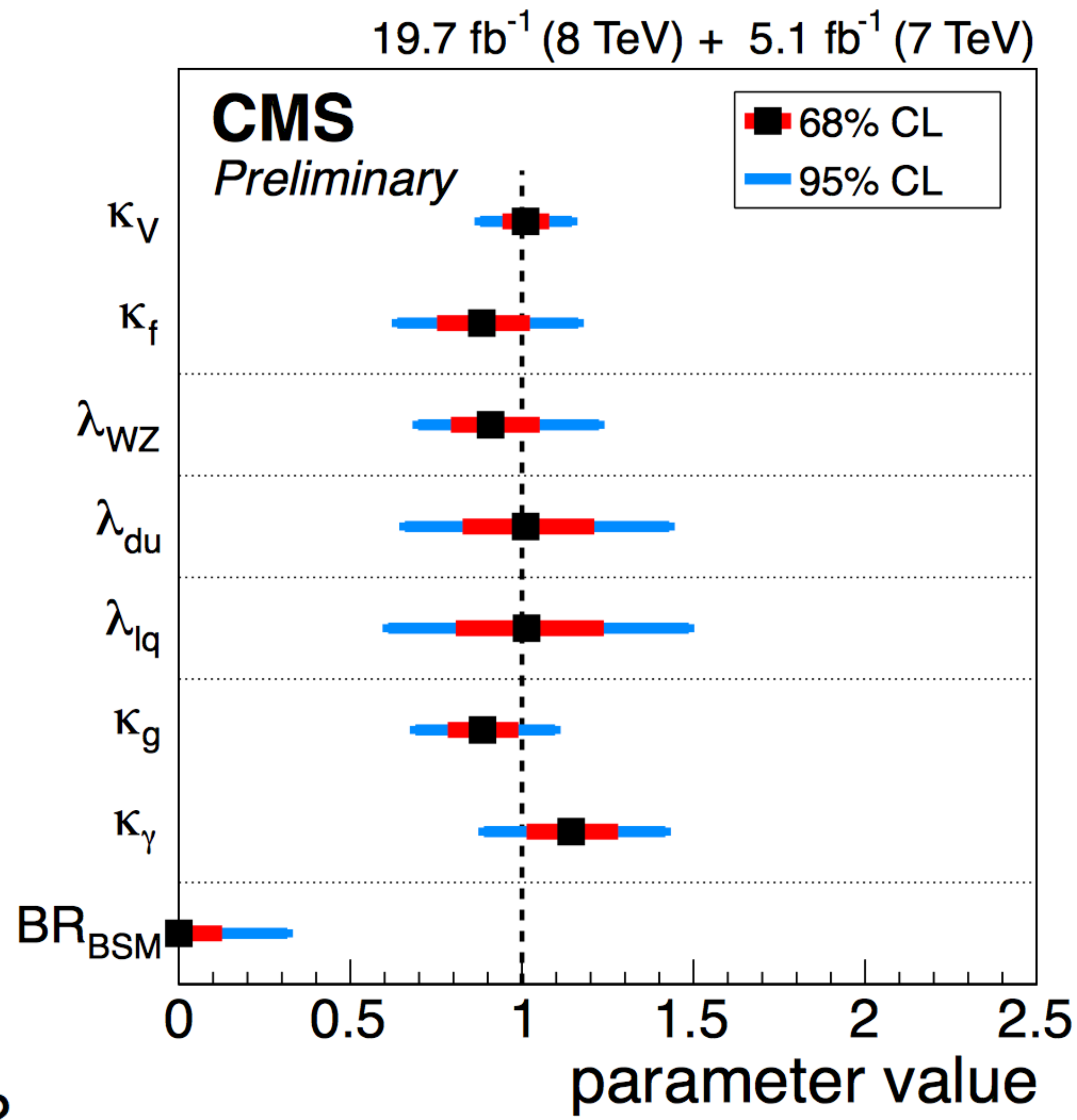


- Assumptions: only 1 Higgs state at 125 GeV, small width, 0^+ state
- Coupling determination: Predictions of signals strengths from SM inputs as functions of the couplings and fit to data

Couplings: ATLAS & CMS



[ATLAS-CONF-2014-009]



[CMS-PAS-HIG—2014-009]

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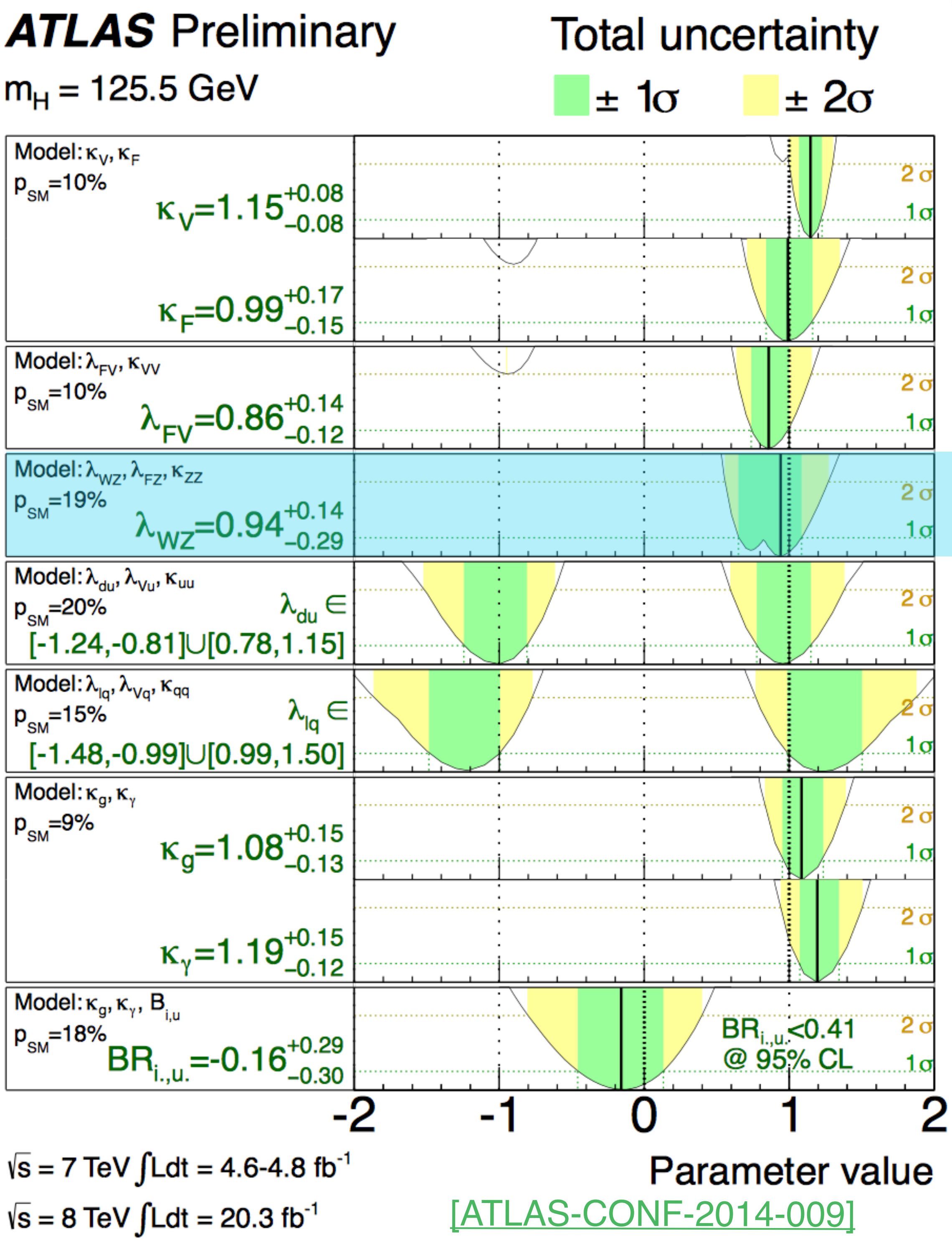
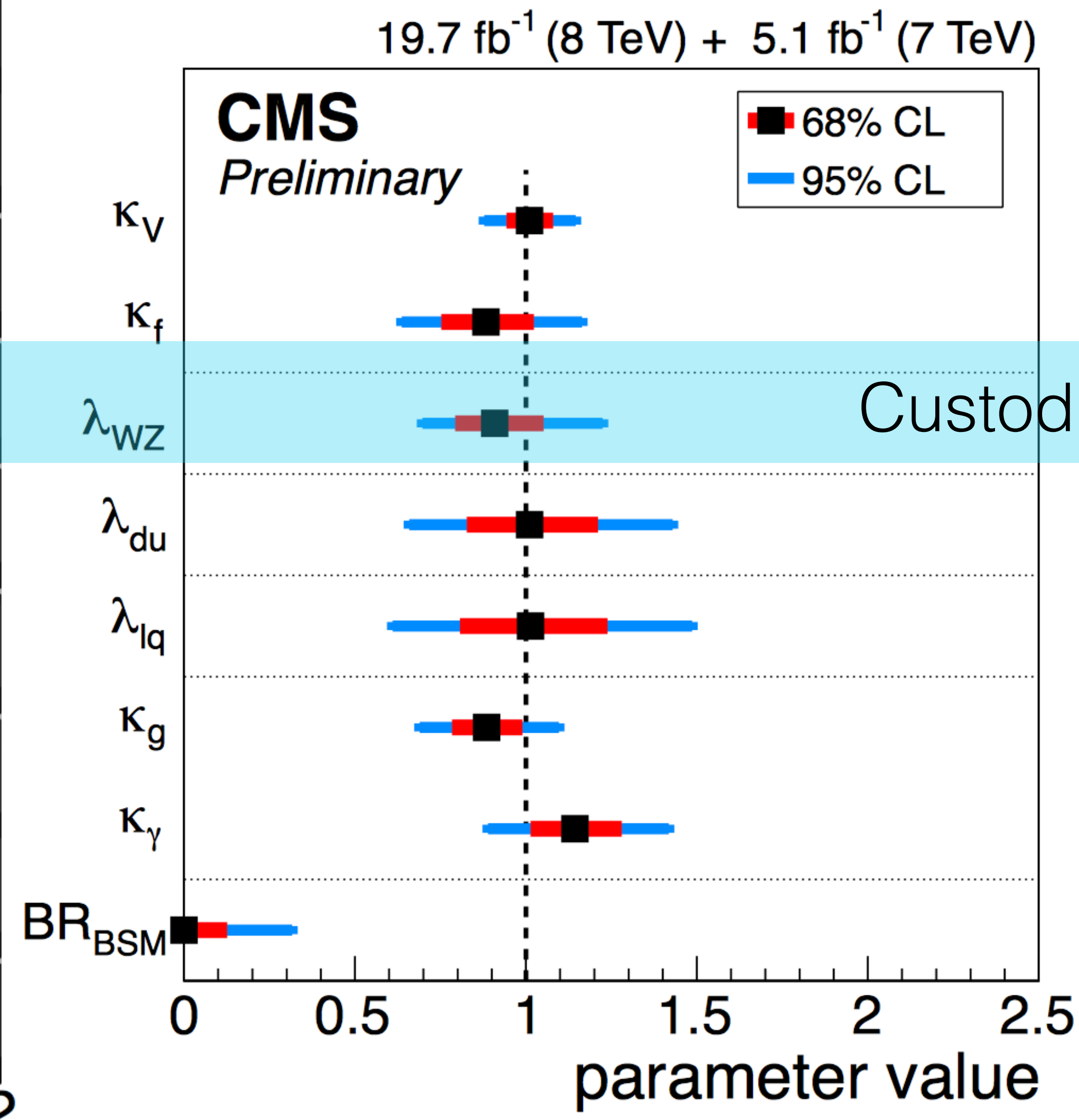


[ATLAS-CONF-2014-009]

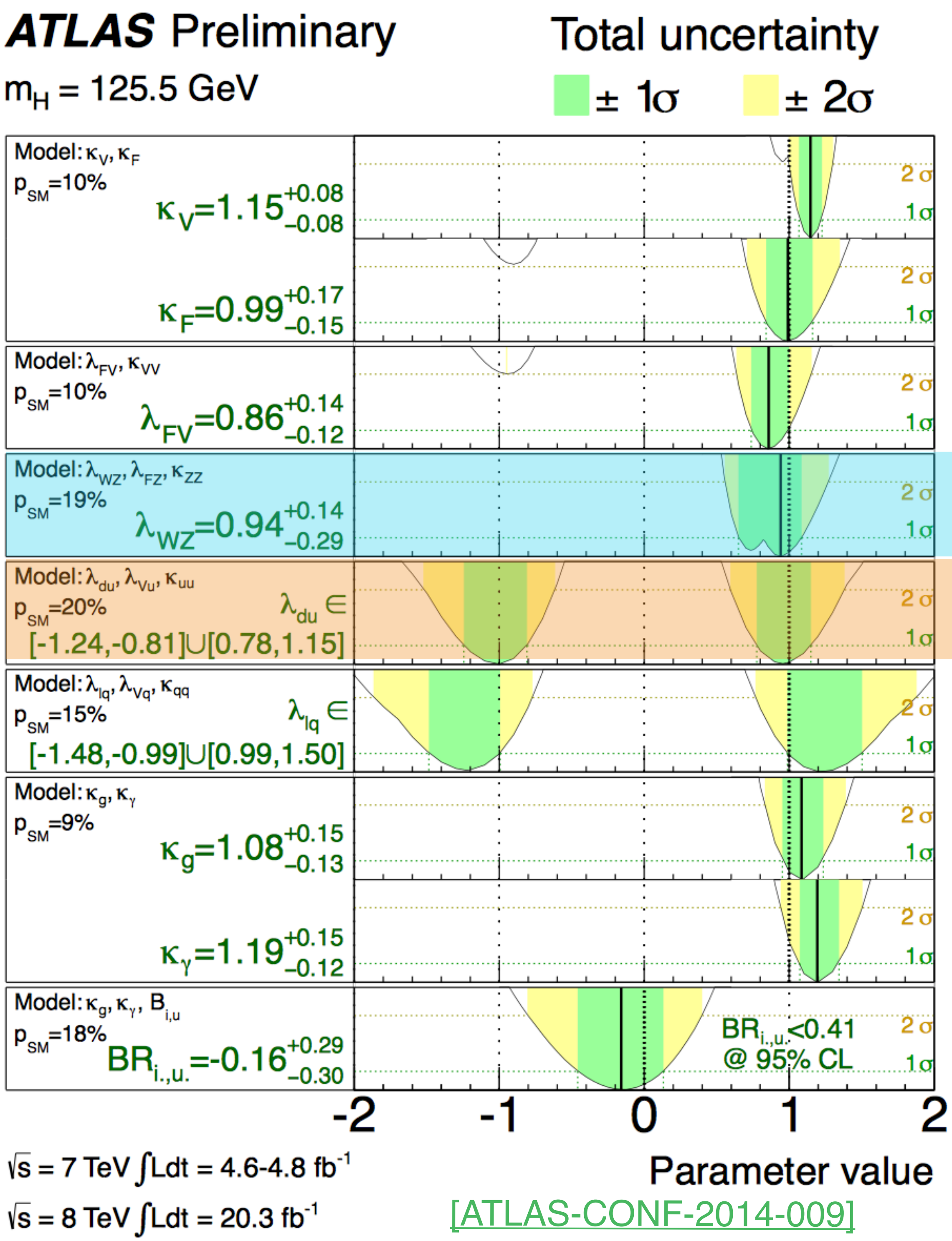


[CMS-PAS-HIG—2014-009]

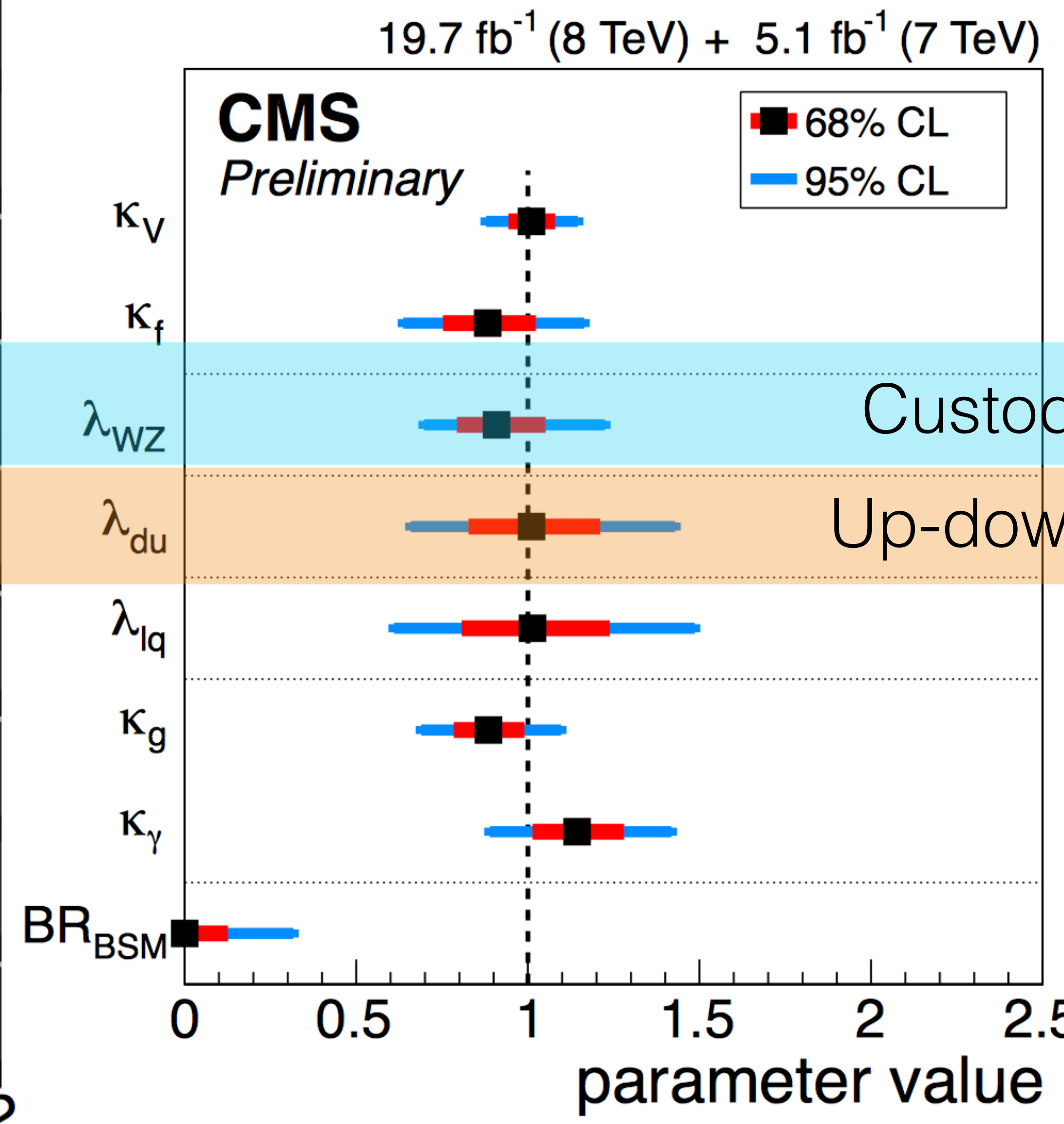
Test of:

Custodial symmetry

Couplings: ATLAS & CMS



[ATLAS-CONF-2014-009]



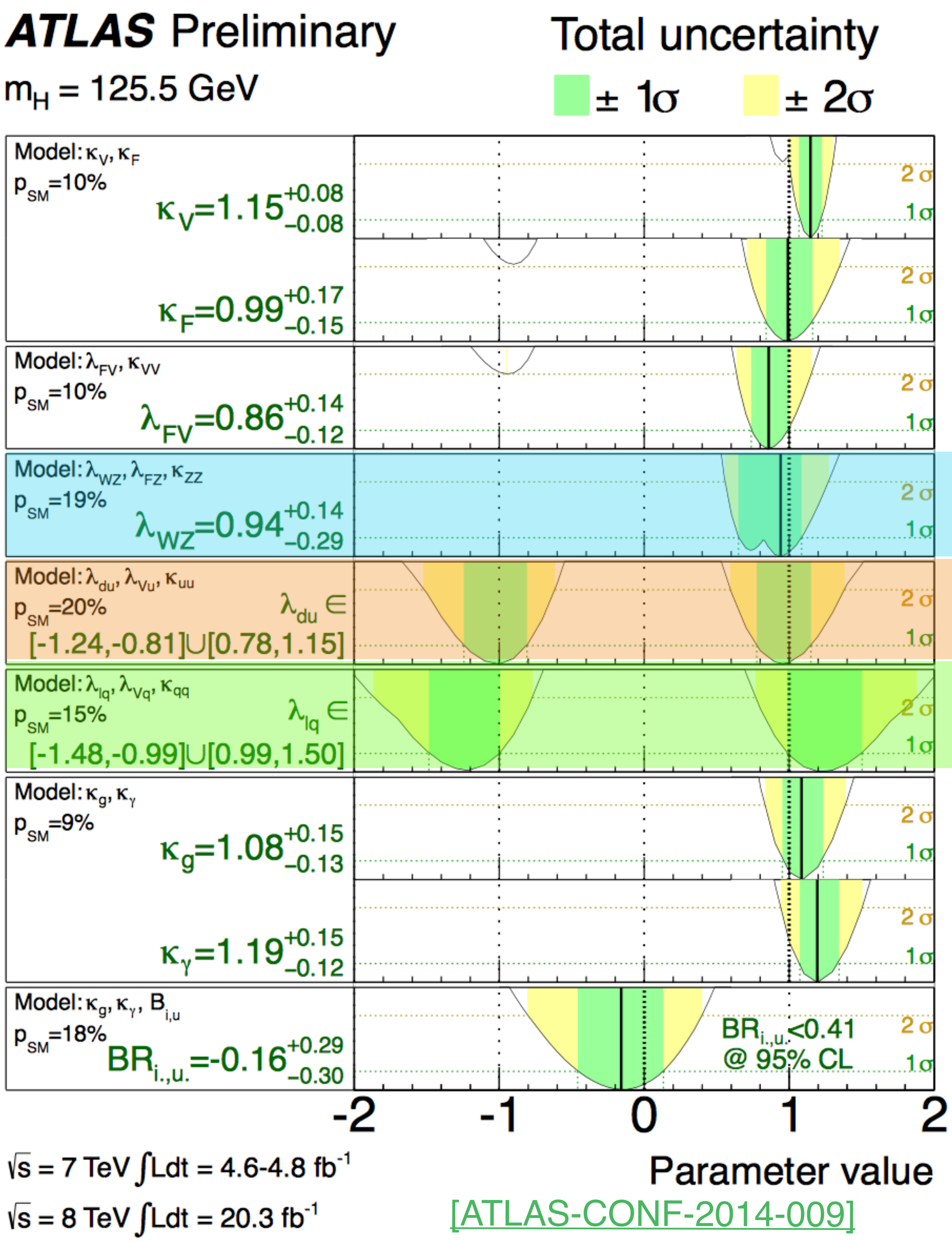
[CMS-PAS-HIG—2014-009]

Test of:

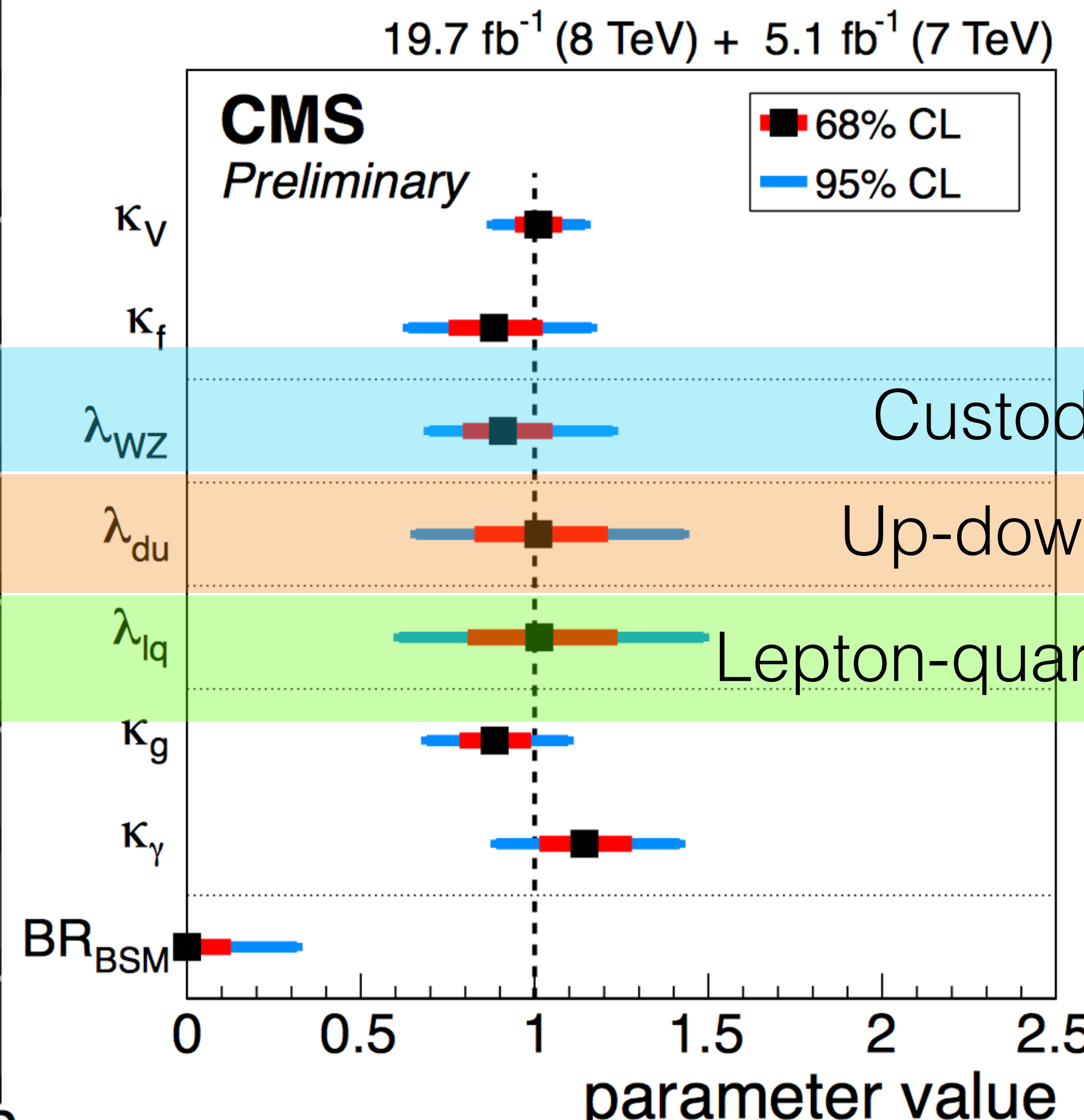
Custodial symmetry

Up-down universality

Couplings: ATLAS & CMS



[ATLAS-CONF-2014-009]



[CMS-PAS-HIG—2014-009]

Test of:

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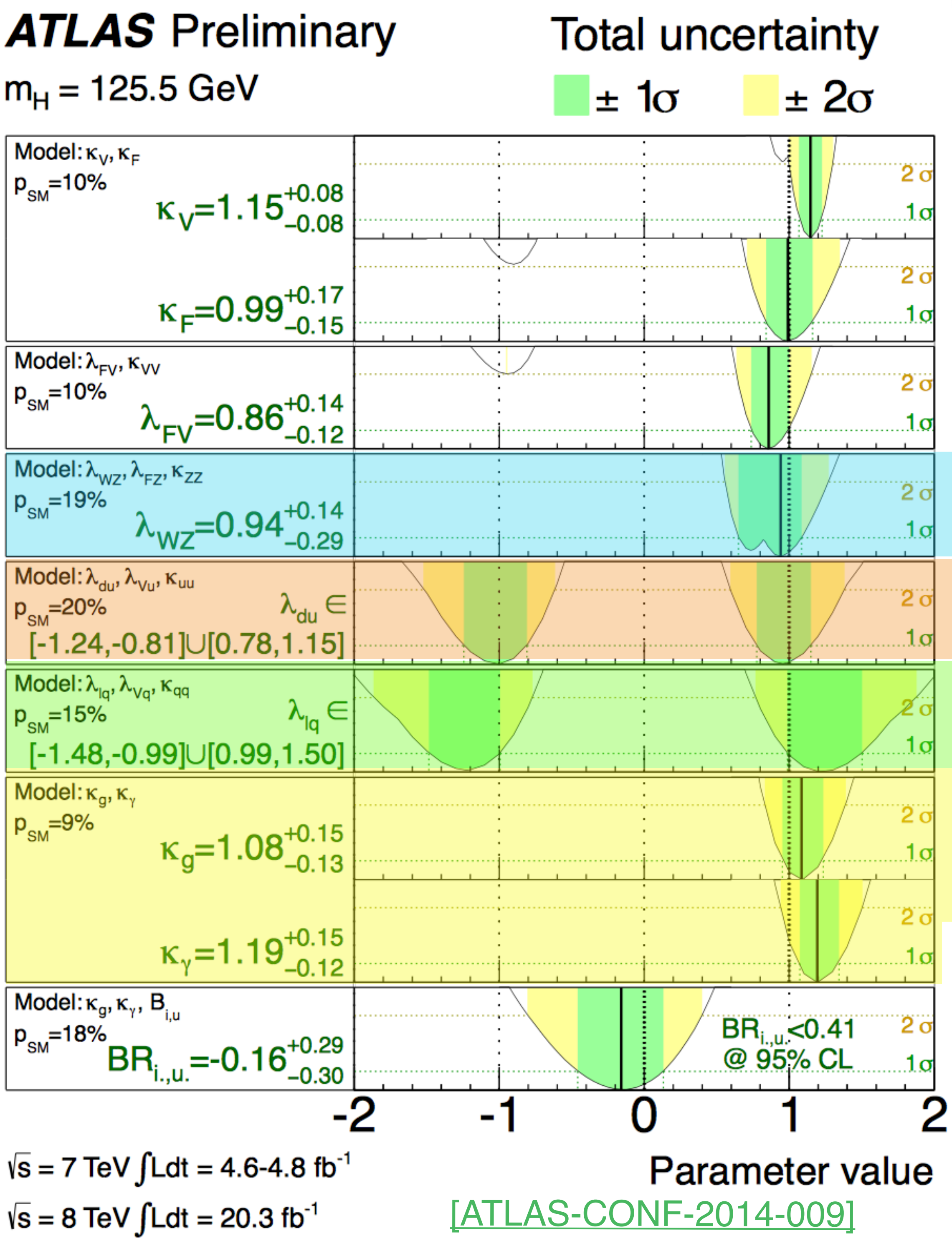
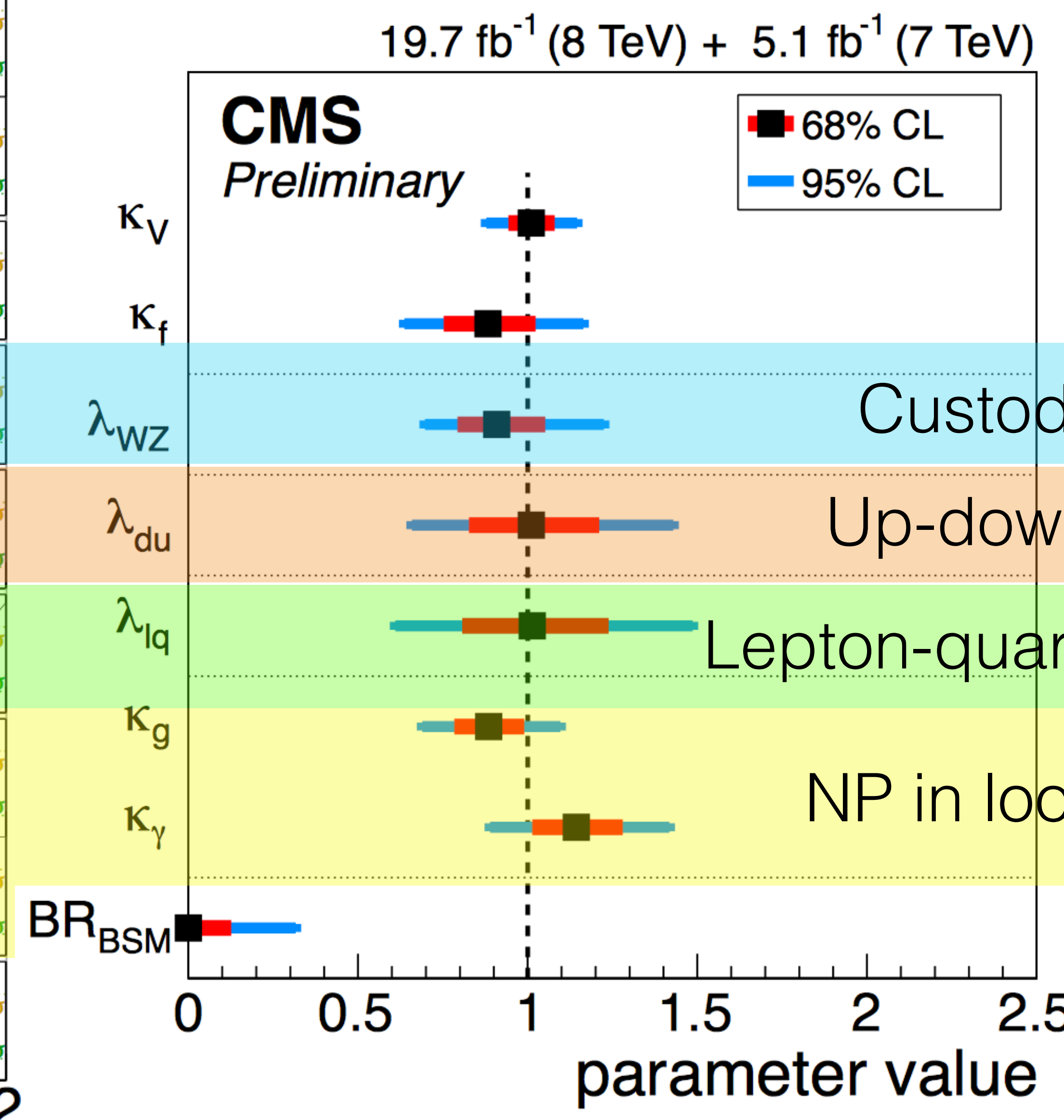
Up-down universality

Lepton-quark universality

Couplings: ATLAS & CMS



[ATLAS-CONF-2014-009]



[CMS-PAS-HIG—2014-009]

Test of:

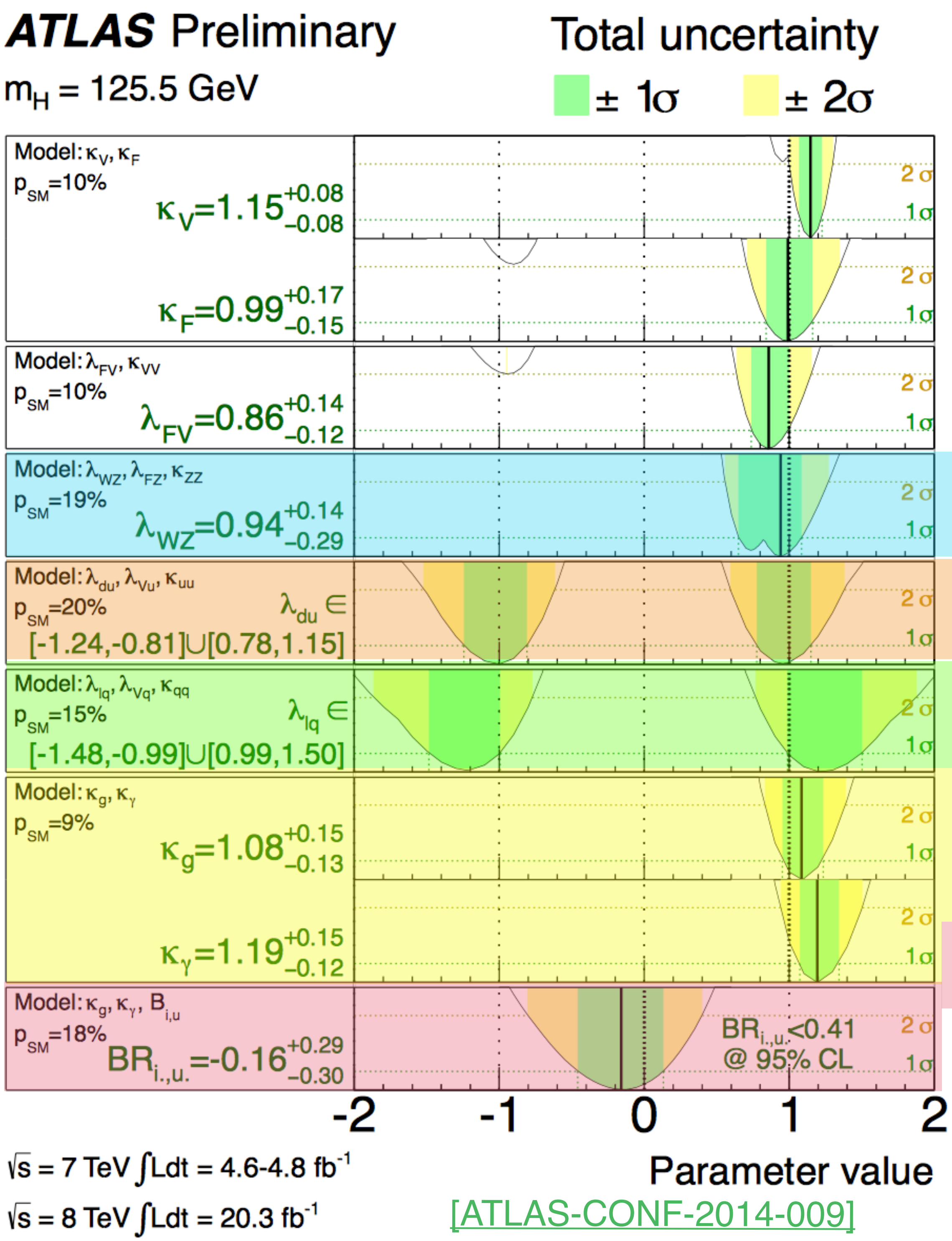
Custodial symmetry

Up-down universality

Lepton-quark universality

NP in loop processes

Couplings: ATLAS & CMS



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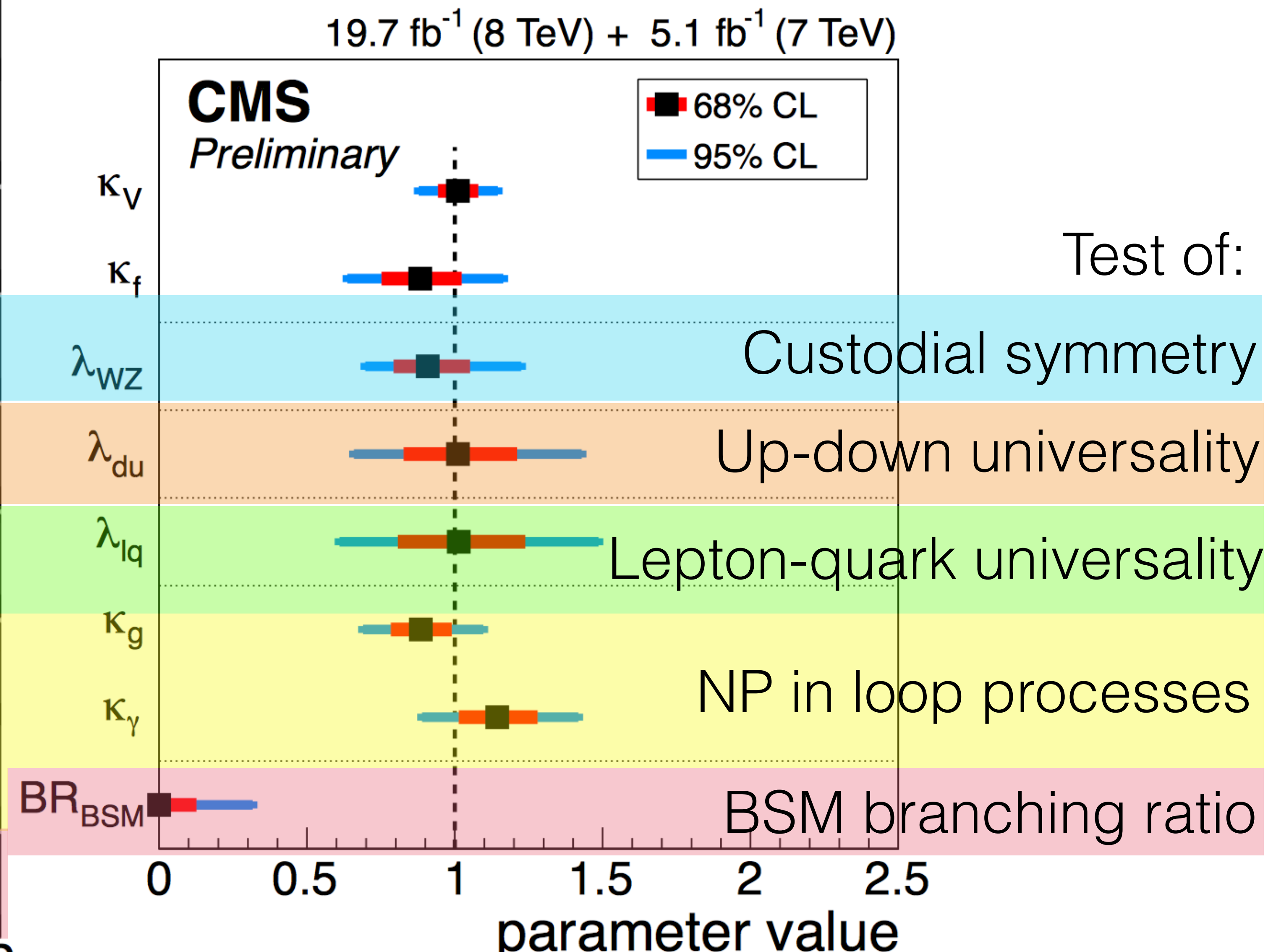


[CMS-PAS-HIG—2014-009]

Global couplings fit

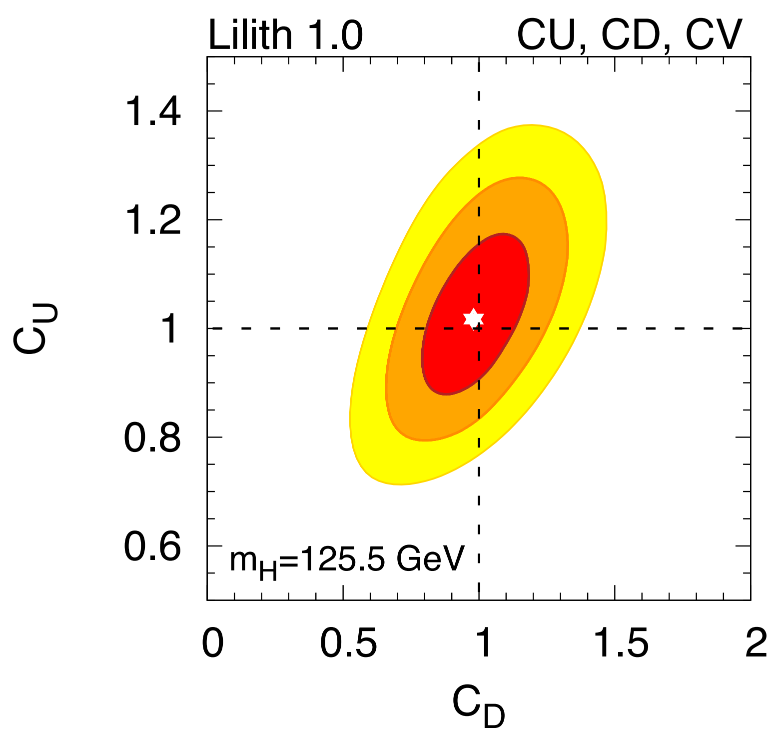
- Combination of the latest LHC and Tevatron results using Lilith

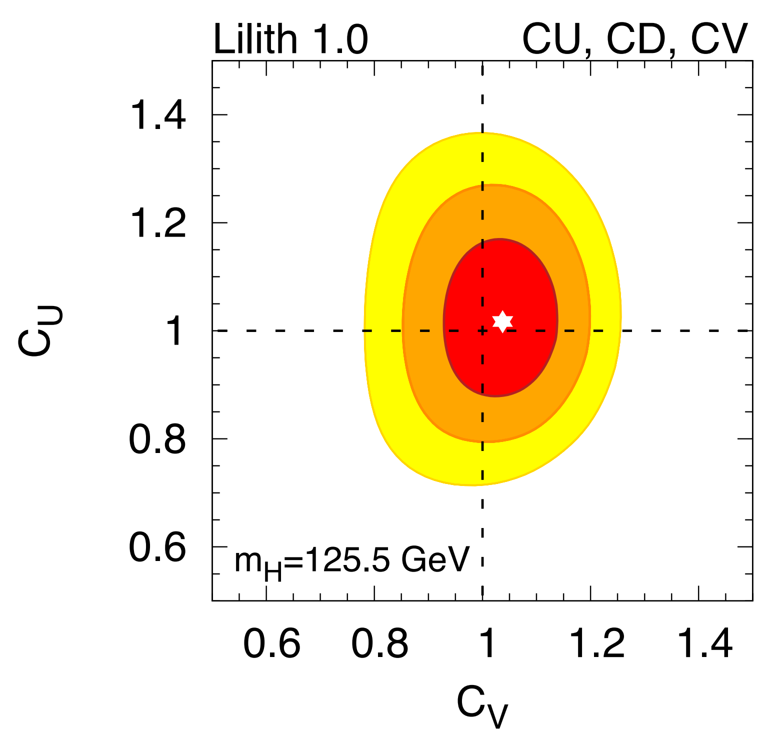
Lilith [JB, B. Dumont]

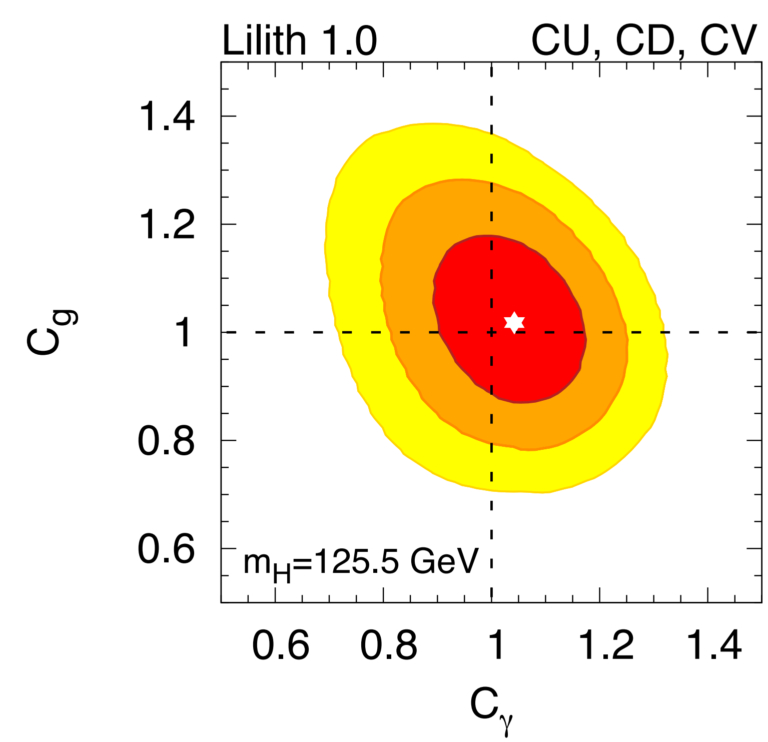
LIght LIkelihood fiT for the Higgs

(http://lpsc.in2p3.fr/projects-th/lilith/)

- **Fit:** C_U, C_D, C_V , assuming no extra BSM loop or width contributions







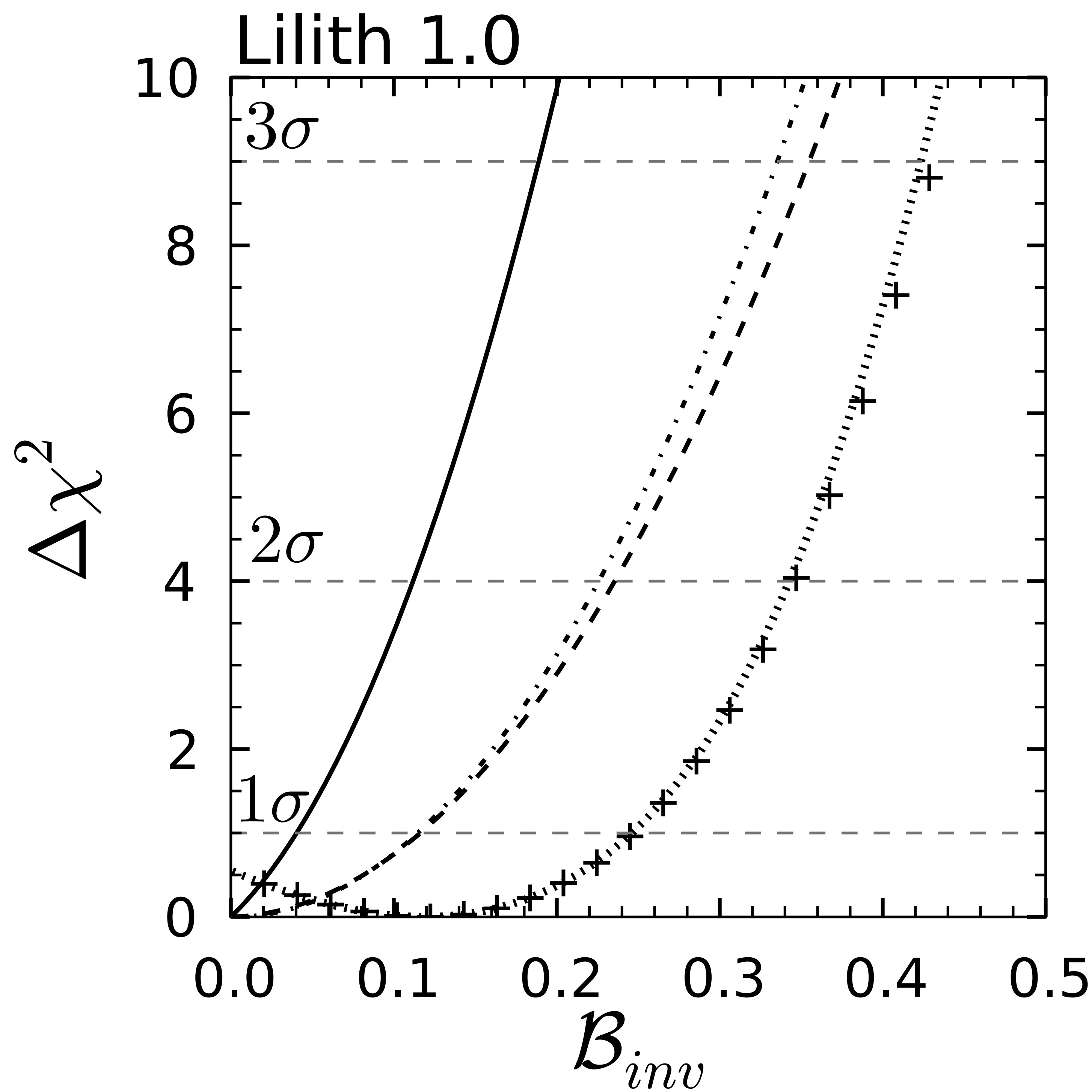
$$C_U = 1.02 \pm 0.10$$
$$C_D = 0.98 \pm 0.14$$

$$C_V = 1.04 \pm 0.07$$

$$C_\gamma = 1.04 \pm 0.11$$
$$C_g = 1.02 \pm 0.11$$

[JB, B. Dumont, S.Kraml, arXiv:1409.1588]

Invisible branching ratio fits



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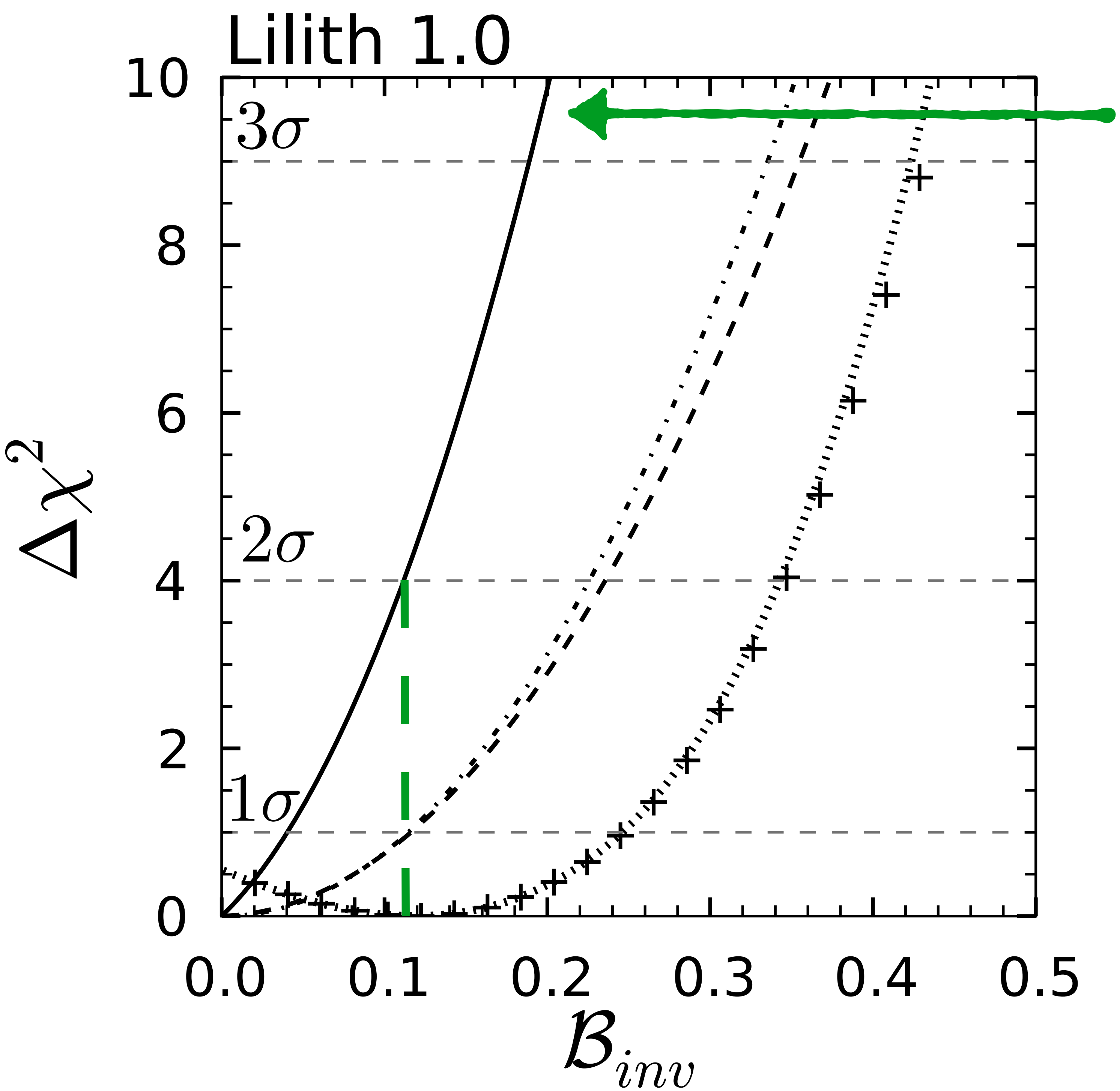
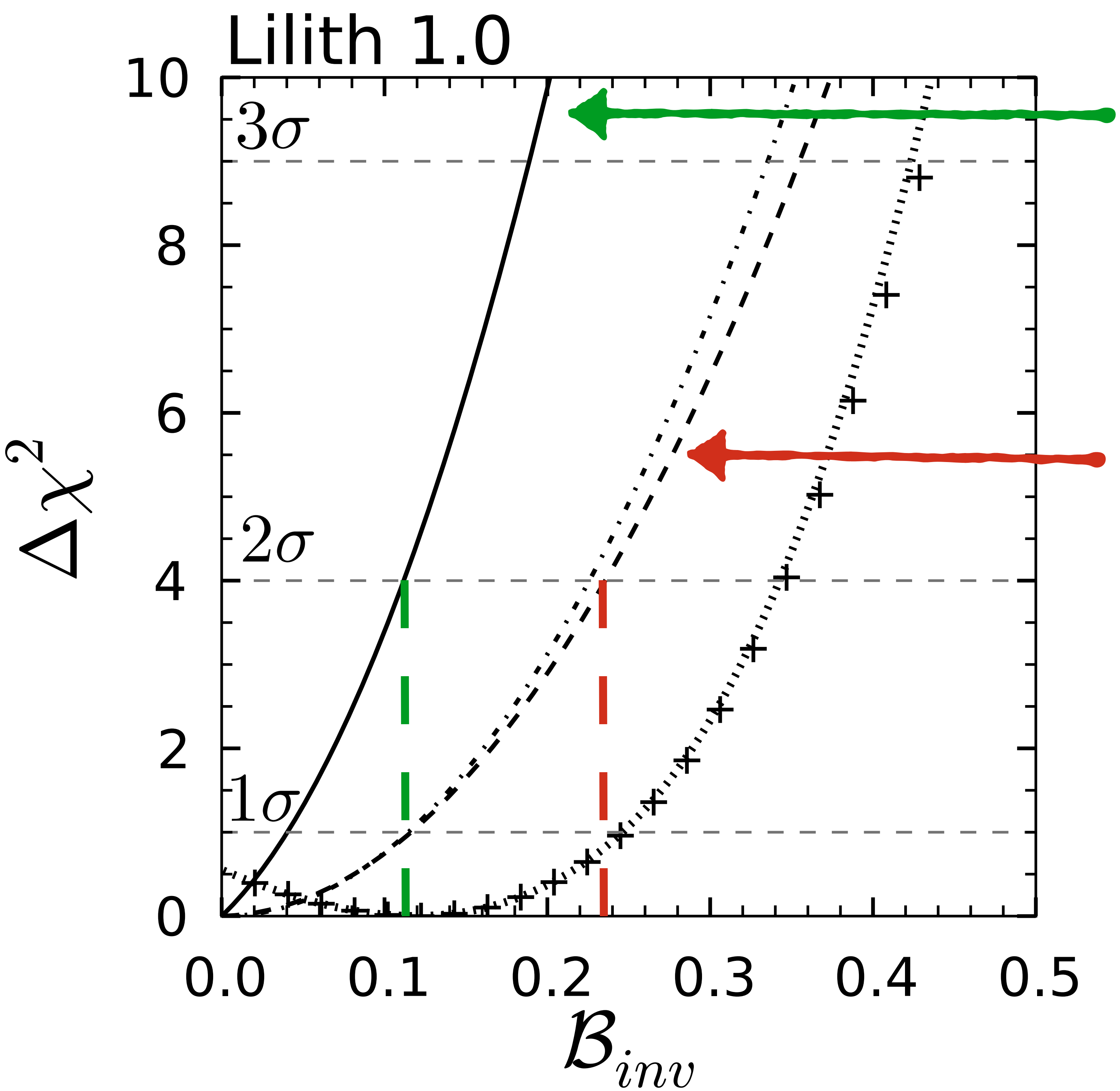


SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

Invisible branching ratio fits



SM+invisible

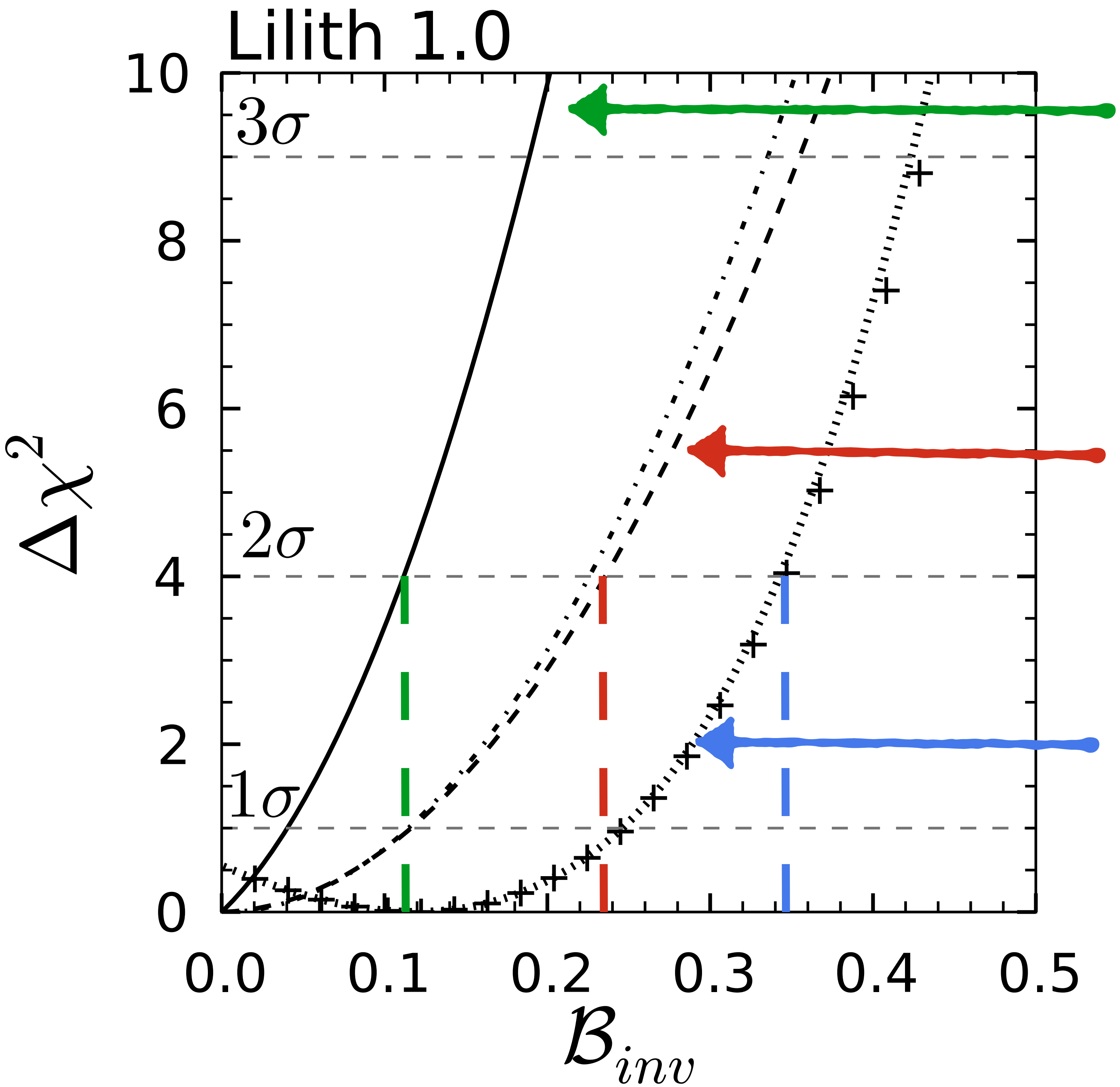
$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

C_U, C_D, C_V <1

SM+ΔC_γ, ΔC_g +invisible

$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

Invisible branching ratio fits



SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

CU, CD, CV <1
SM+ΔCγ, ΔCg +invisible

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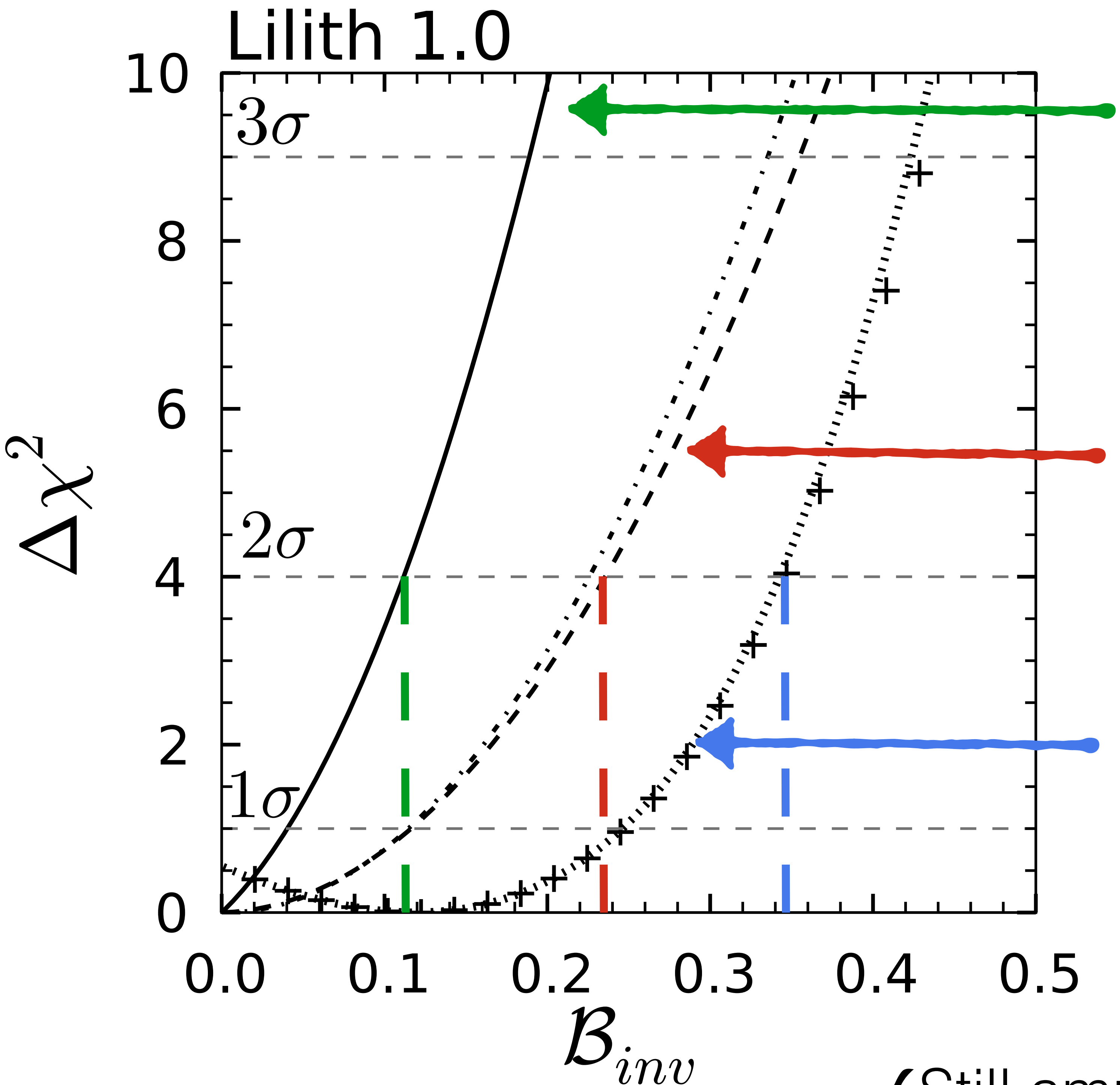
CU, CD, CV
CU, CD, CV, ΔCγ, ΔCg +invisible

$\mathcal{B}_{inv} \lesssim 0.34$ at 95.4% C.L.

Invisible branching ratio fits



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C_U, C_D, C_V
C_U, C_D, C_V, ΔC_γ, ΔC_g +invisible

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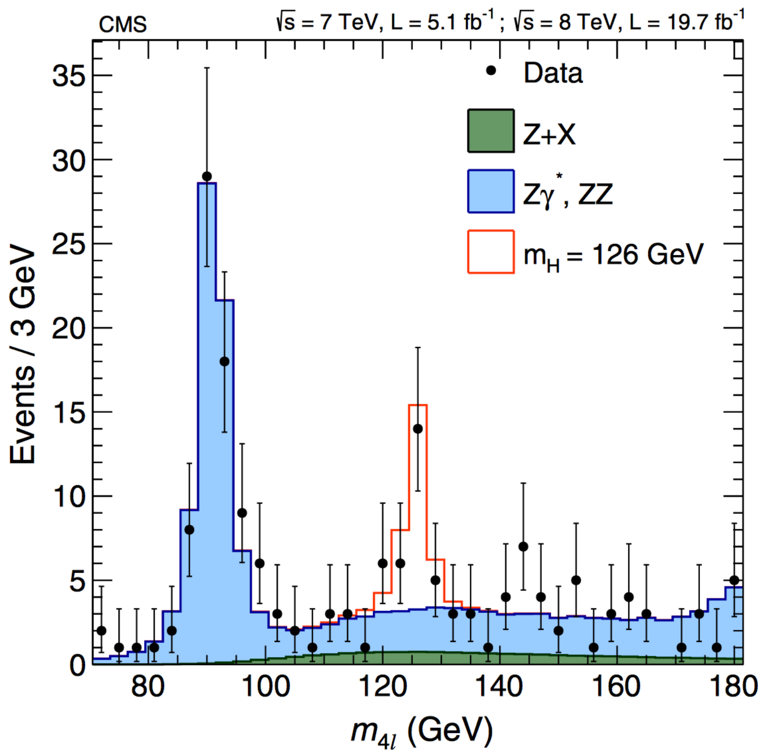
✓Still ample room for new decay modes

Width measurement

- Determination from H-> 4l, γγ lineshape:

$\Gamma_H^{95\%}$	ATLAS	CMS
4l	2.6 GeV	3.2 GeV
γγ	5.0 GeV	2.4 GeV

[ATLAS-HIG-2013-12]
[CMS-HIG-13-002]
[CMS-HIG-13-001]



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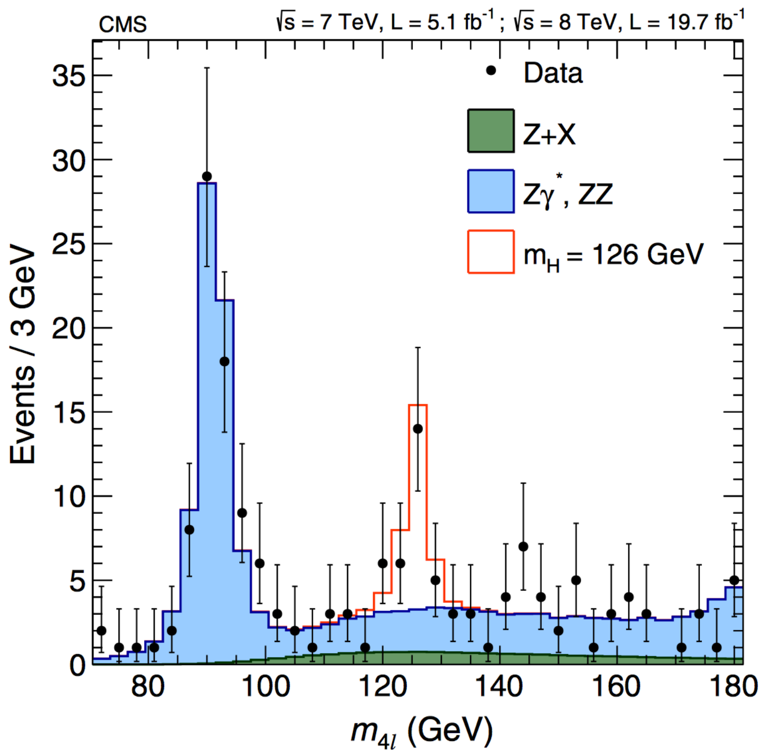
[CMS-HIG-13-001]

Limited by mass resolution



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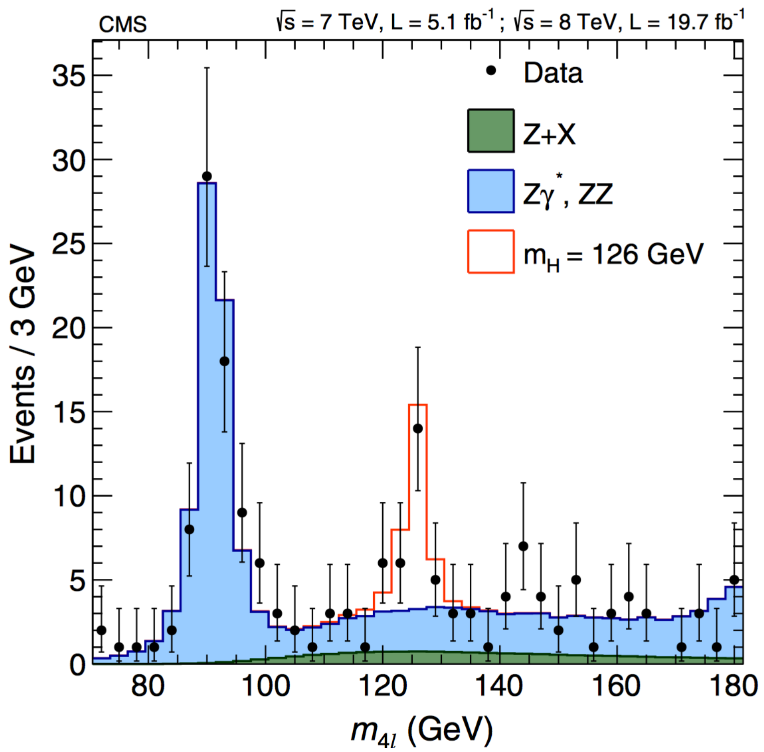


- From off-shell H*->ZZ production:

[Coala, Melnikov, arXiv:1307.4935]

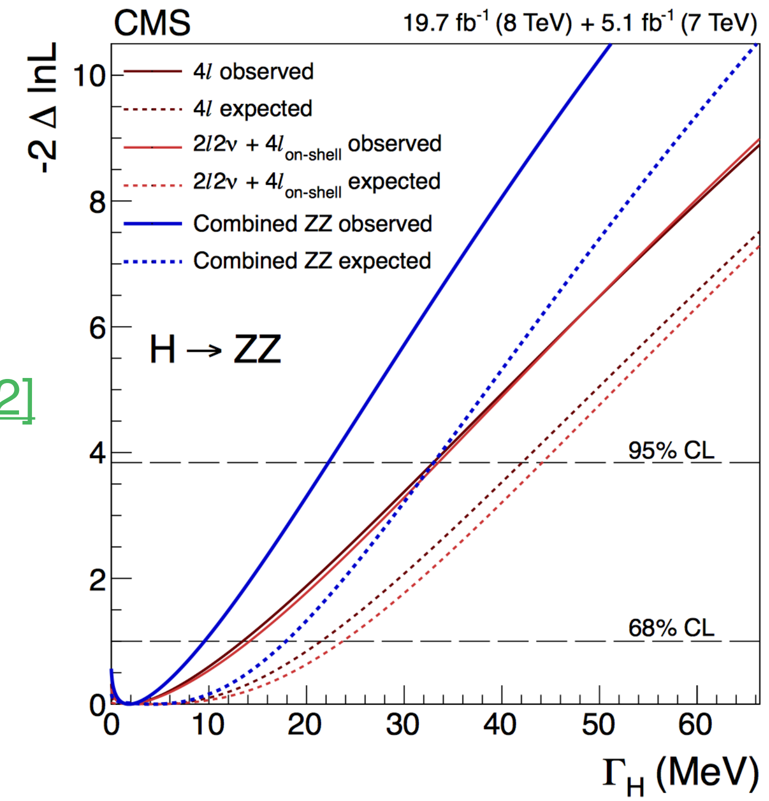
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{4l}^2} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\Gamma_H/\Gamma_H^{\rm SM} < 4.8 - 7.7 \text{ @ } 95\% \text{ C.L.}$$

[ATLAS-CONF-2014-042]

$$\Gamma_H/\Gamma_H^{\rm SM} < 5.4 \text{ @ } 95\% \text{ C.L.}$$

[CMS-HIG-14002]



- Also accessible from global fit

Summary after LHC Run I

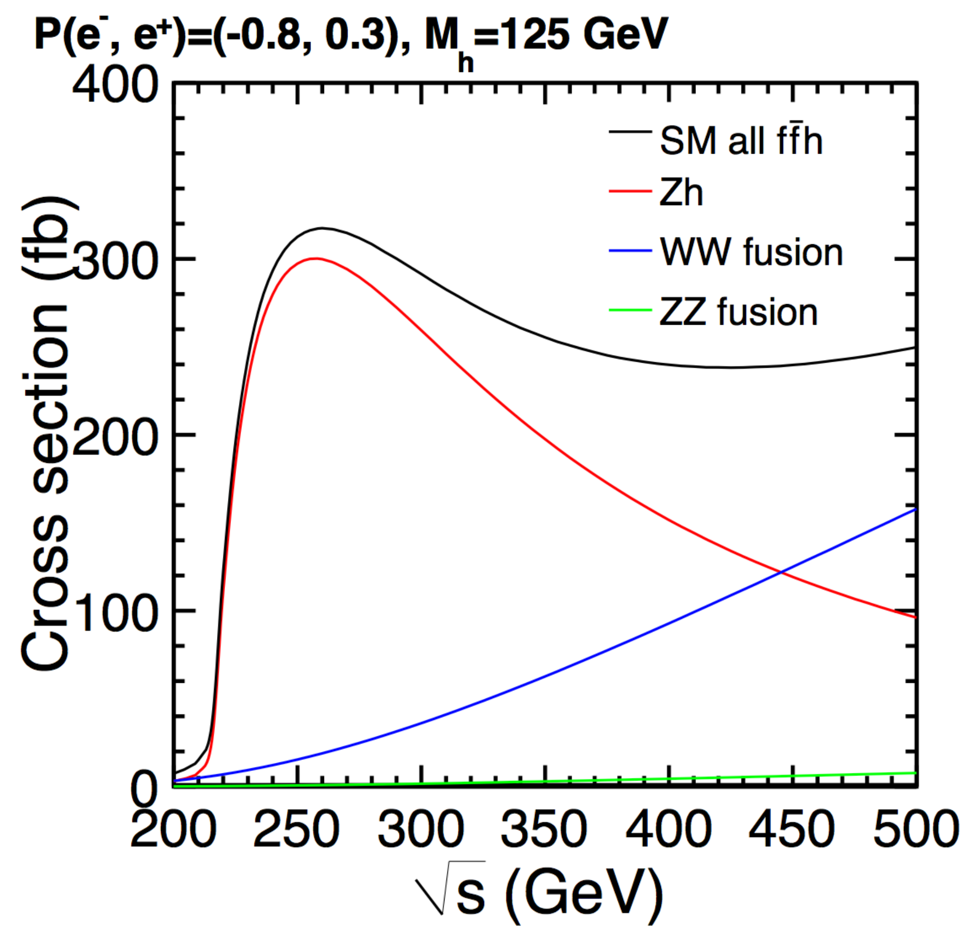
- No deviations… **yet** !
- There is large room for new decay channels (invisible, flavor violating…)
- Very small branching ratios are not a problem for observation (Higgs has been discovered in a channel with BR~10e-3)
- There is some room for new states in loop processes
- Uncertainties in the couplings are still of the order 15-20%

- What could the ILC tell us ?

Perspectives for the ILC

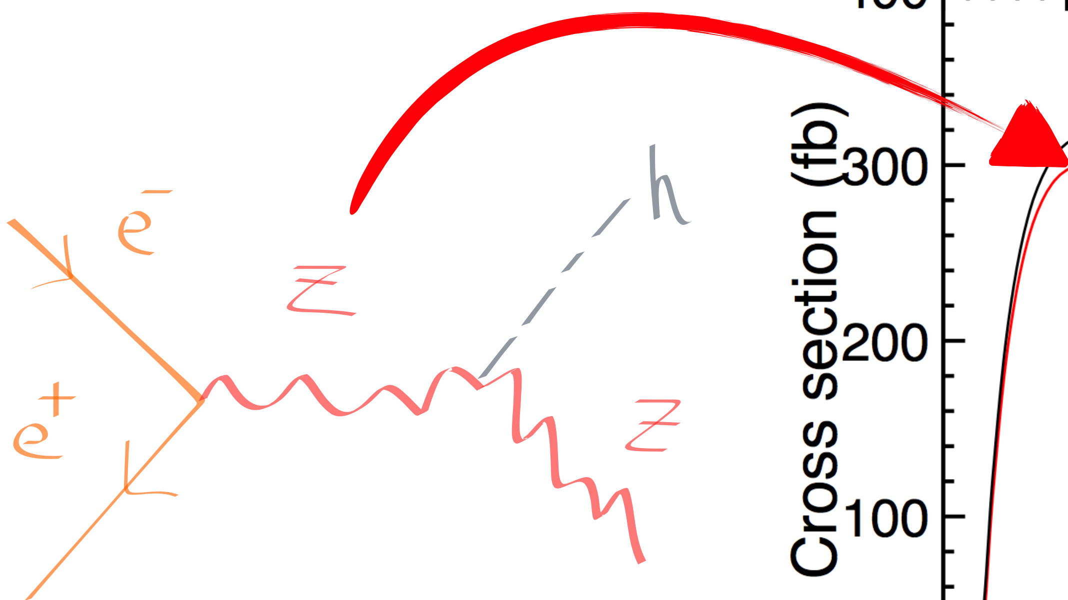
Based on the ILC Technical Design Report
and references therein

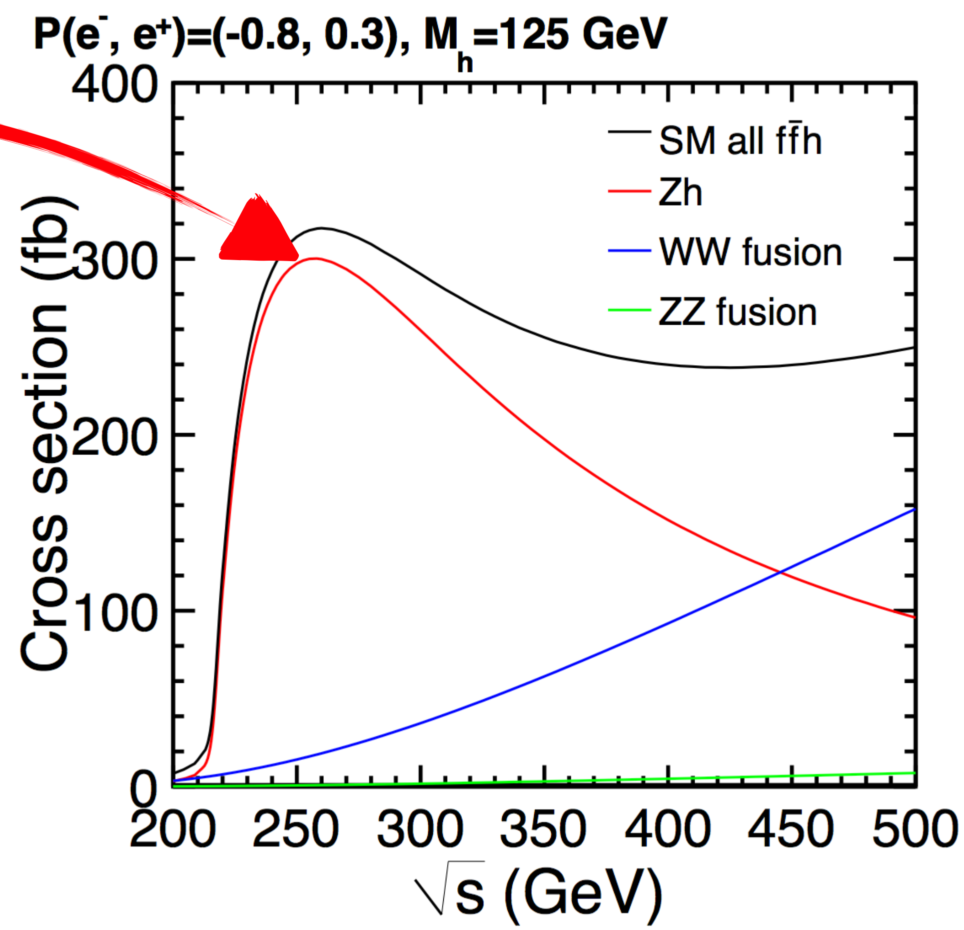
Higgs production at the ILC



- Maximum ZH cross-section at 250 GeV
- W-boson fusion (WBF) dominant after 450 GeV
- Higgs production is ~1% of the total cross-section !

Higgs production at the ILC





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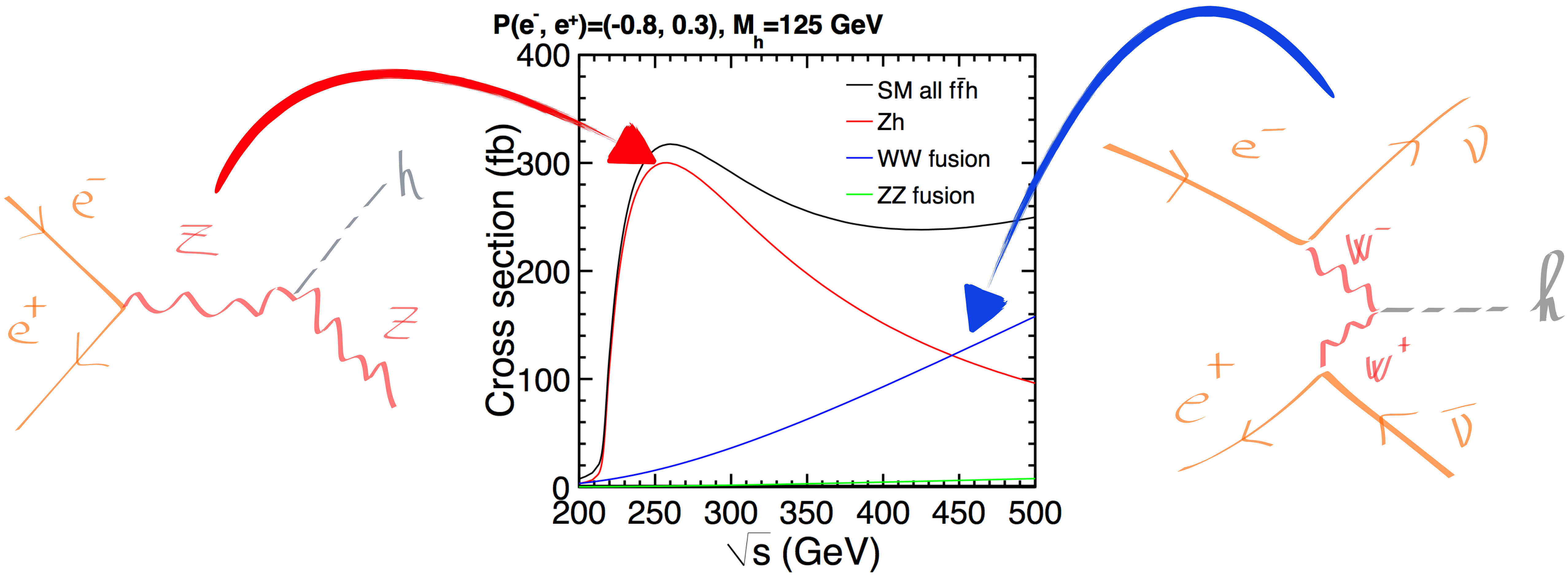

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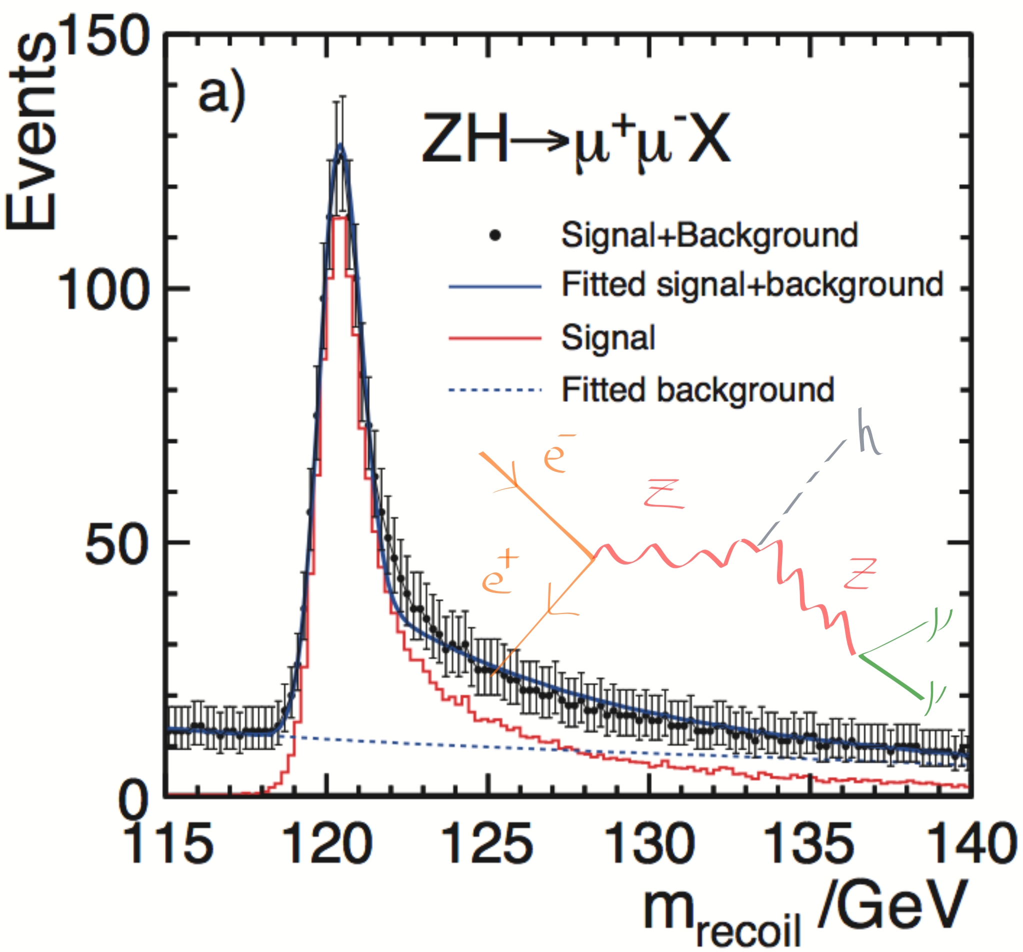
LC greatness: the ZH recoil method

- **Recoil method**: identify ZH production by tagging Z leptonic decays (***independently*** of the H decay mode) and select events in the recoil-mass peak(s):

$$m^2_{\text{recoil}} = (P_{e^+e^-} - P_Z)^2$$



Use this method to measure:

i. Higgs mass(es)
ii. Inclusive ZH cross section
iii. Absolute branching ratios (any)
iv. Total width

(SiD and ILD momentum resolution have been worked out to allow precise measurements with this method)

Mass, inclusive cross-section

For $250\ \mathrm{fb}^{-1}$ @ $250\mathrm{GeV}$

i. Mass: better precision in μμX than eeX (bremsstrahlung)

$$\Delta m_H(\mu\mu X) = 40\ \mathrm{GeV}$$

$$\Delta m_H(eeX) = 80\ \mathrm{GeV}$$

$$\Delta m_H(\mu\mu X + eeX) = 32\ \mathrm{GeV}$$

ii. Inclusive ZH cross-section: $\Delta\sigma_{\mathrm{incl}}^{ZH}/\sigma_{\mathrm{incl}}^{ZH} = 2.5\%$

$$\sigma_{\mathrm{incl}}^{ZH} = g_{HZZ}^2 \times \sigma_{\mathrm{incl,\ SM}}^{ZH} \quad \Rightarrow \quad \Delta g_{HZZ}/g_{HZZ} = 1.3\%$$

WBF at 500 GeV: $\Delta\sigma_{\mathrm{incl}}^{\mathrm{WBF}}/\sigma_{\mathrm{incl}}^{\mathrm{WBF}} = 2.7\% \Rightarrow \Delta g_{HWW}/g_{HWW} = 1.4\%$

Branching ratios, total width

iii. Branching ratios: events from ZY recoil at m_h $\Rightarrow$ $\mathcal{B}(h \to Y)$

Direct access to invisible branching-ratio, rare decays (μμ), LHC undetected branching ratio (cc, gg, …)

iv. Total width: $e.g.$ $\Gamma^H_{tot} = \frac{\Gamma(H \to ZZ)}{\mathcal{B}(H \to ZZ)} \propto \frac{\sigma^{ZH}_{\text{incl}}}{\mathcal{B}(H \to ZZ)}$

Precise model-independent extraction of the width (free of assumptions on couplings or new decay channels)

$$\mathcal{B}(H^{125.5}_{\text{SM}} \to WW) \simeq 10\,\mathcal{B}(H^{125.5}_{\text{SM}} \to ZZ)$$

$\Rightarrow$ use WBF at 500 GeV for better precision:

$$\Rightarrow \quad \Delta\Gamma^H_{tot}/\Gamma^H_{tot} = 5.0 - 6.0\%$$

[Snowmass13, arXiv:1310.8361v2]

σ.BR and couplings uncertainties

	ILC 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$
Inclusive	2.6/3.0/–%	–
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%
$H \to gg$	7/11/–%	–/4.1/2.3%
$H \to ZZ^*$	19/25/–%	–/8.2/4.1%
$H \to WW^*$	6.4/9.2/–%	–/2.4/1.6%
$H \to \tau\tau$	4.2/5.4/–%	–/9.0/3.1%
$H \to b\bar{b}$	1.2/1.8/–%	11/0.66/0.30%
$H \to c\bar{c}$	8.3/13/–%	–/6.2/3.1%
$H \to \mu\mu$	–	–/–/31%
	$t\bar{t}H$	
$H \to b\bar{b}$	–/28/6.0%	

Facility	ILC		
$\sqrt{s}$ (GeV)	250	500	1000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000
$P(e^-, e^+)$	(−0.8, +0.3)	(−0.8, +0.3)	(−0.8, +0.2)
Γ_H	12%	5.0%	4.6%
κ_γ	18%	8.4%	4.0%
κ_g	6.4%	2.3%	1.6%
κ_W	4.9%	1.2%	1.2%
κ_Z	1.3%	1.0%	1.0%
κ_μ	91%	91%	16%
κ_τ	5.8%	2.4%	1.8%
κ_c	6.8%	2.8%	1.8%
κ_b	5.3%	1.7%	1.3%
κ_t	–	14%	3.2%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$

[Snowmass13, arXiv:1310.8361v2]

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Facility	ILC		
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$P(e^-, e^+)$	(−0.8, +0.3)	(−0.8, +0.3)	(−0.8, +0.2)
Γ_H	12%	5.0%	4.6%
κ_γ	18%	8.4%	4.0%
κ_g	6.4%	2.3%	1.6%
κ_W	4.9%	1.2%	1.2%
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[Snowmass13, arXiv:1310.8361v2]

σ.BR and couplings uncertainties

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	$t\bar{t}H$	
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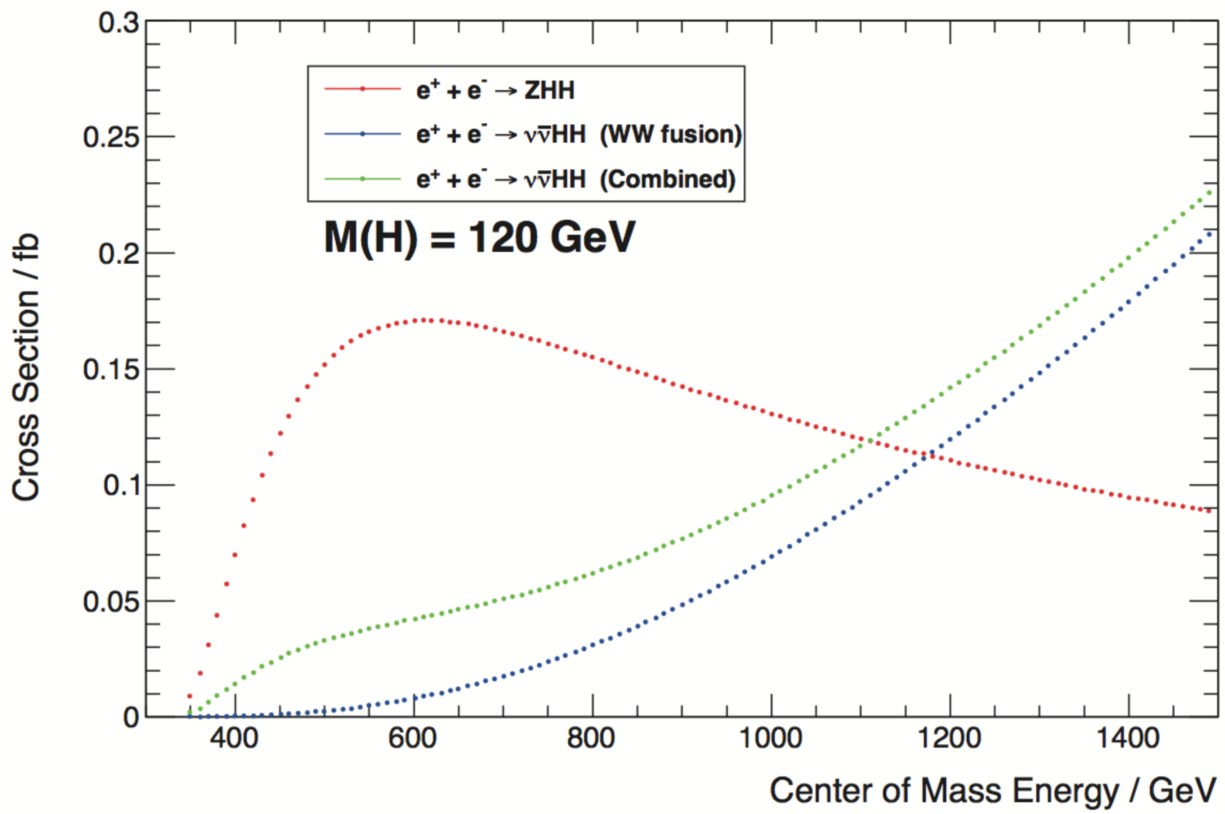
Trilinear coupling

- Fundamental parameter in the SM; dictates stability of the scalar potential $V(H^\dagger H) = -\mu^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2$



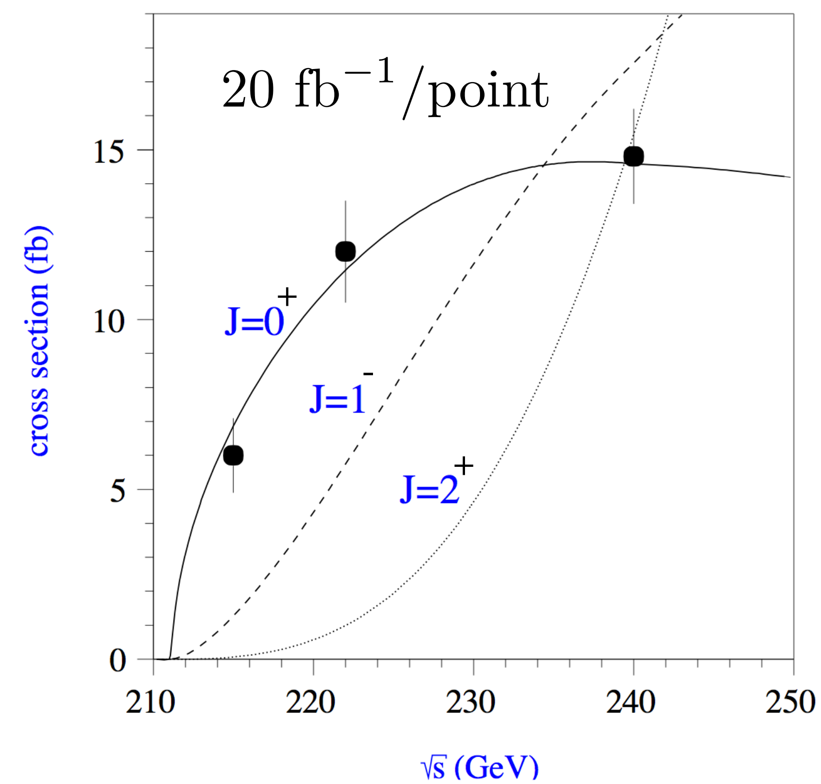
For these studies:

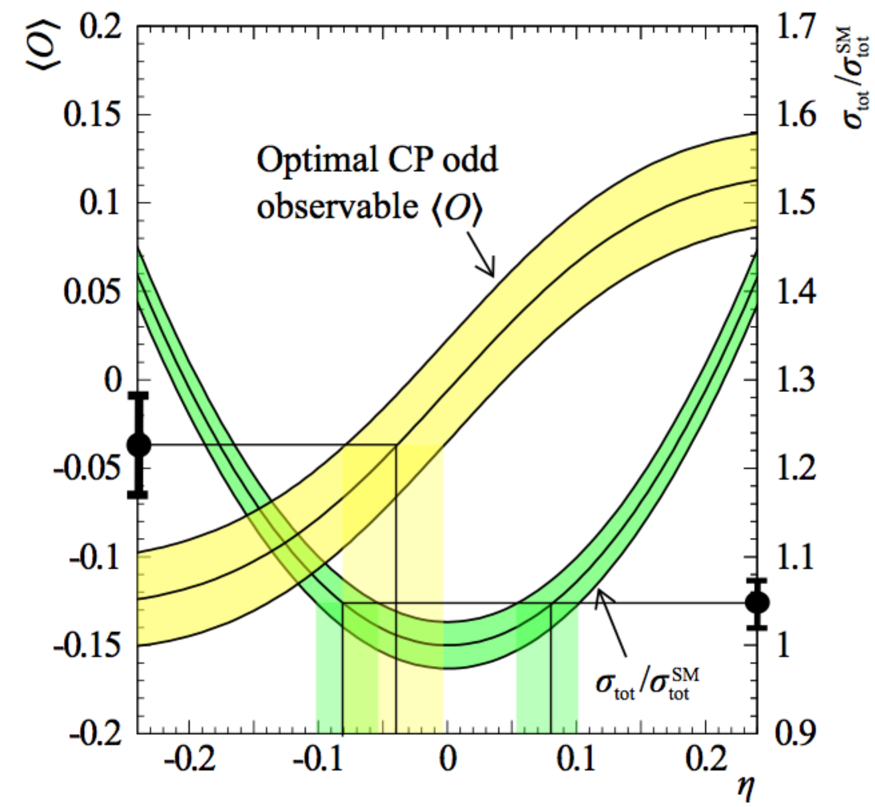
- HL-LHC: $gg \to HH \to b\bar{b}\gamma\gamma$
- ILC500(-up): $ZHH \to Xb\bar{b}b\bar{b}, Xb\bar{b}\gamma\gamma$
- ILC1000(-up): mostly $\bar{\nu}\nu HH \to \bar{\nu}\nu b\bar{b}b\bar{b}, \bar{\nu}\nu b\bar{b}\gamma\gamma$

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	$1600^\ddagger$	500+1000	$1600+2500^\ddagger$
λ	50%	83%	46%	21%	13%

Quantum numbers @ ILC

- Zh cross-section at threshold is sensible to **spin**





- **CP-even/odd admixture:** possible to test in threshold behavior of ZH (CP-odd is loop induced) or more precisely in couplings to fermions (CP-even/odd on the same foot):

$$g_{H\bar{f}f} \propto H\bar{f}(c_+ + i\gamma_5 c_-)f$$

Conclusion

- Run I of LHC was impressive, a lot of data has been collected, a lot of results have been produced
- A new state at ~125 GeV has been discovered, with so far, very SM-like properties
- LHC current results allow ample room for new phenomena in this Higgs sector
- Very precise measurements are needed to understand this new sector in details, and ultimately understand the dynamics of EWSB (and much more)
- The ILC could play this role perfectly (%-level measurements)

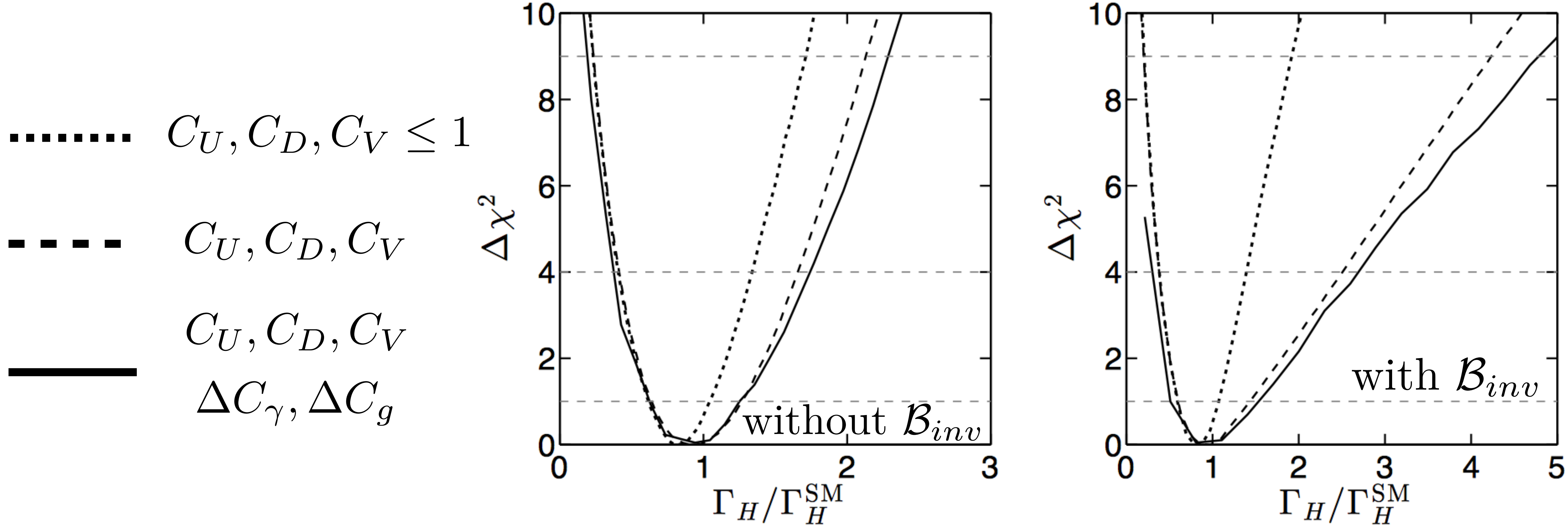
Backup

Width from global fit

Signal strength: $\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H\to Y)}{\sigma(X_{\rm SM})\mathcal{B}(H_{\rm SM}\to Y)} = \frac{{g_X}^2 {g_Y}^2}{\widetilde{\Gamma}_h}$

with $\widetilde{\Gamma}_h = \Gamma_h/\Gamma_h^{\rm SM} = \frac{1}{1-\mathcal{B}_{\rm BSM}} \sum_Y {g_Y}^2 \mathcal{B}(H_{\rm SM}\to Y)$

$\Longrightarrow$ access to the width

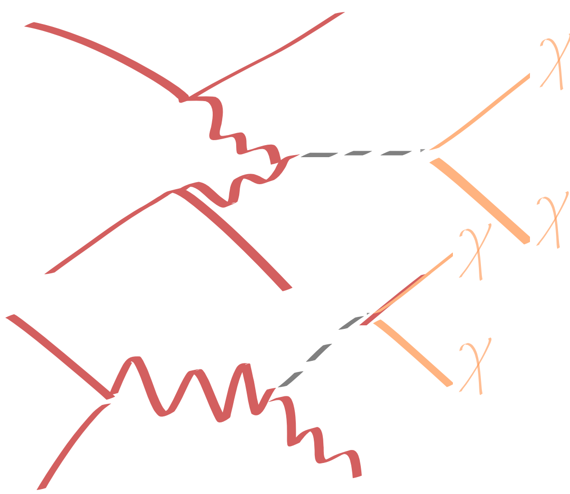


[Bélanger, Dumont, Ellwanger, Gunion, Kraml, arXiv:1306.2941]

Higgs global fit

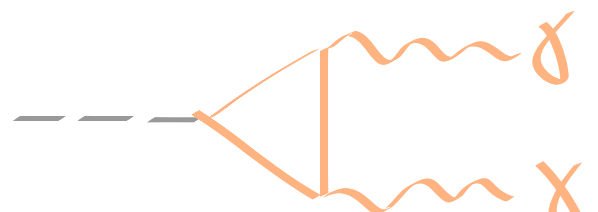
Recent results

- Considerable number of updated analyses released in the past few months



$VBF + VH, H \to \mathrm{inv}$

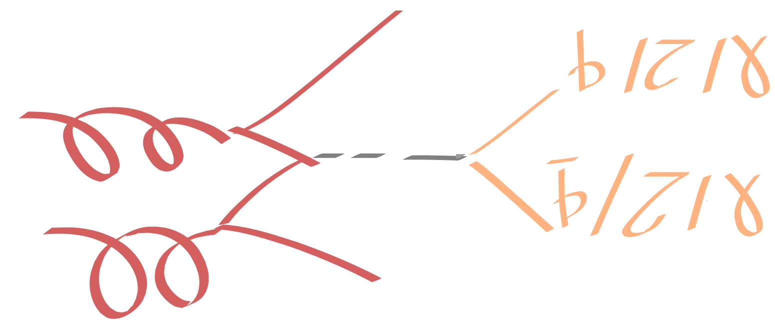
[CMS-HIG-13-030]



$H \to \gamma\gamma$

[CMS-HIG-13-001]

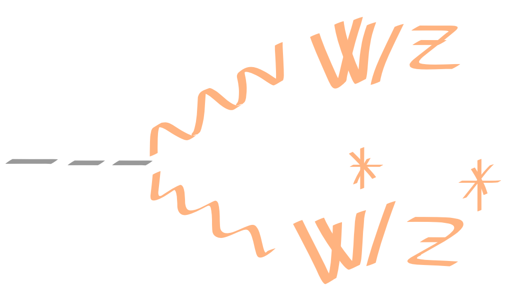
[ATLAS-HIGG-13-08]



$ttH, H \to \gamma\gamma, b\bar{b}, \tau\tau, \ldots$

[CMS-HIG-13-029]

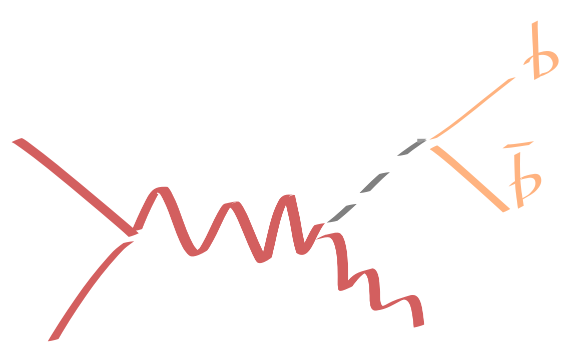
[ATLAS-HIGG-13-11,25]



$H \to WW^*/ZZ^*$

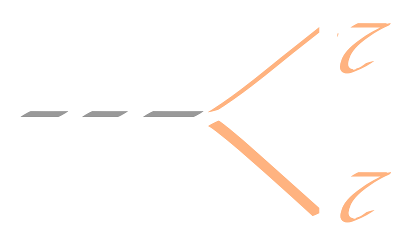
[ATLAS-CONF-14-060] *

[ATLAS-HIGG-13-21]



$VH, H \to b\bar{b}$

[ATLAS-HIGG-13-32] *



$H \to \tau\tau$

[ATLAS-CONF-14-061] *

* appeared after our analysis

Global fit

Based on previous work by G. Belanger, B. Dumont, U. Ellwanger, J.F. Gunion, S. Kraml in [arXiv:1212.5244, 1302.5694, 1306.2641]

- Define reduced couplings (« κ framework »):

$$\mathcal{L} = \left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu - C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b - C_D \frac{m_\tau}{2m_W} \bar{\tau}\tau \right] H$$

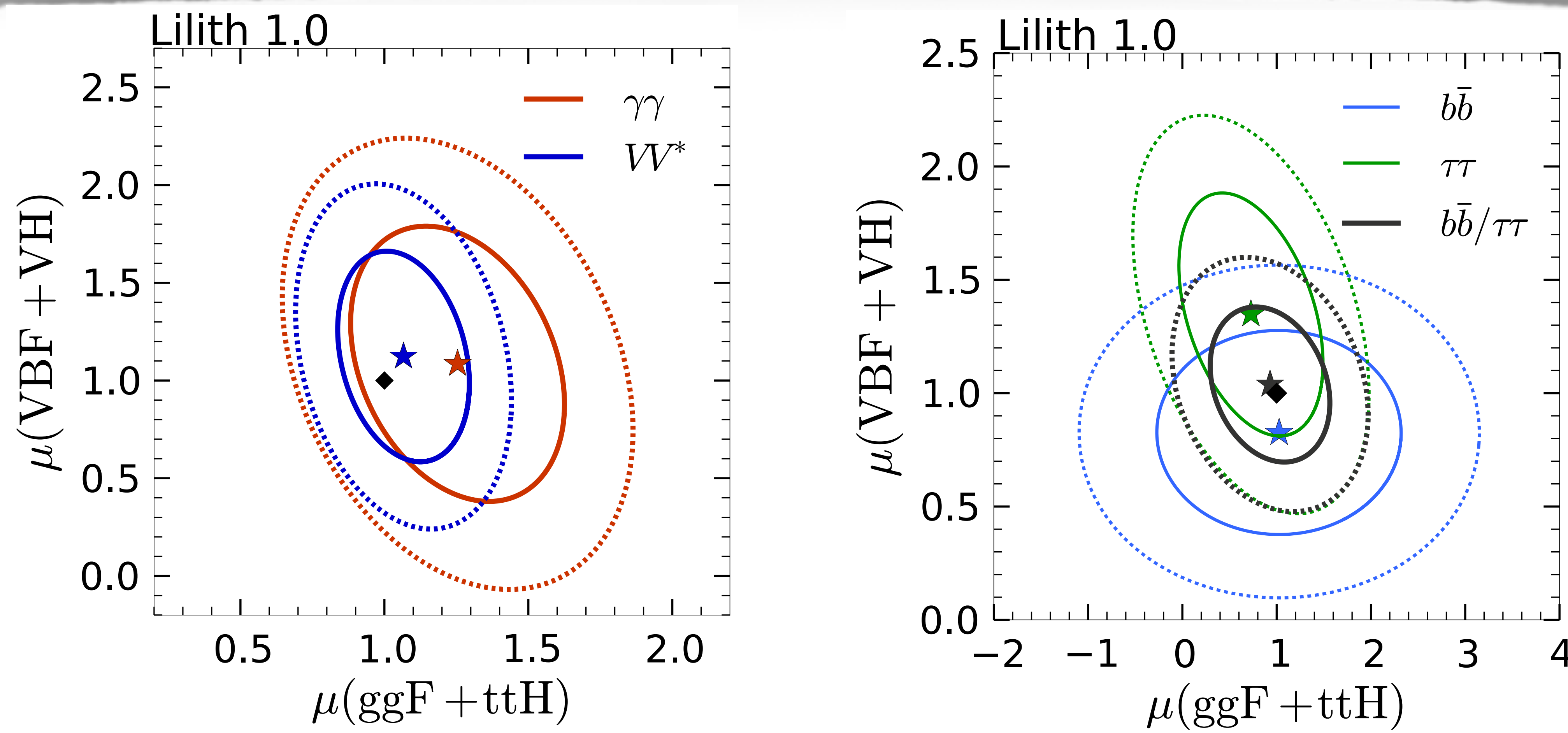
+ possible width extra-contribution (*e.g.* invisible BR)

- Effective loop-induced vertex: $C_{g,\gamma} = \overline{C}_{g,\gamma} + \Delta C_{g,\gamma}$

SM particles contribution

- Signal strengths predictions in terms of reduced couplings following LHC HXSWG recommendations [LHCHXSWG-2012-001]
- Construction of a combined likelihood
- If likelihood shape is available: no assumptions needed
- Otherwise: use the gaussian approximation
- Profile likelihood analysis

Signal strengths combination: LHC+Tevatron



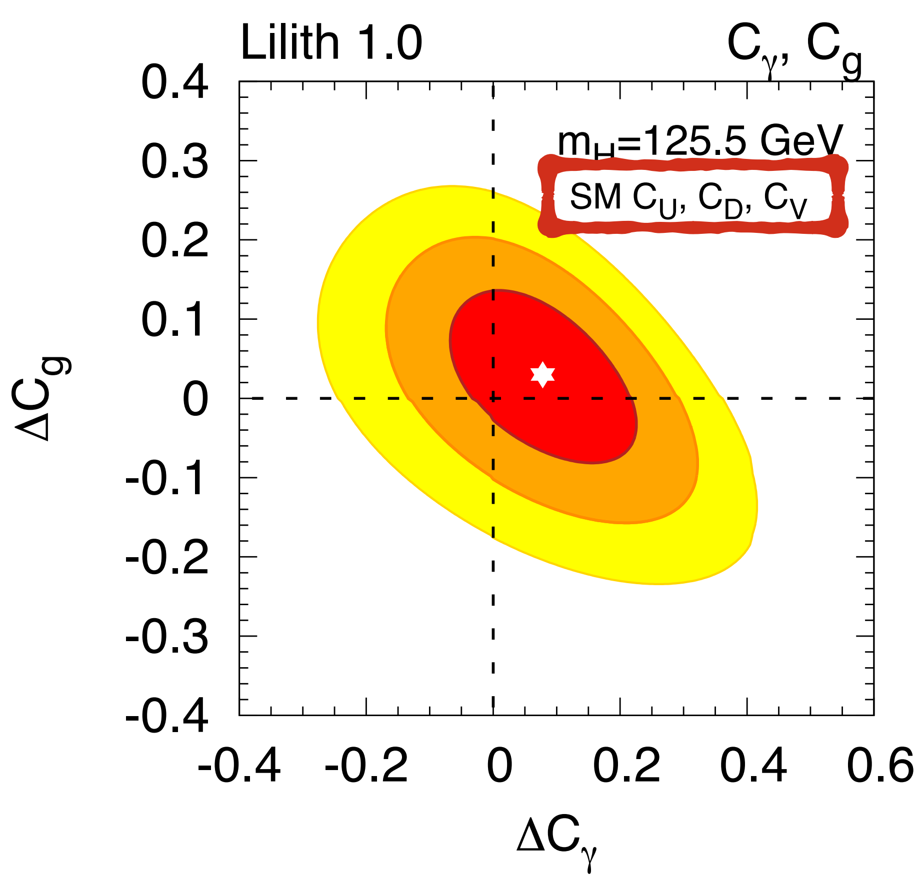
	$\hat{\mu}^{\mathrm{ggF+ttH}}$	$\hat{\mu}^{\mathrm{VBF+VH}}$	ρ
$\gamma\gamma$	1.25 ± 0.24	1.09 ± 0.46	-0.30
VV^*	1.07 ± 0.15	1.12 ± 0.36	-0.26
$b\bar{b}/\tau\tau$	0.93 ± 0.42	1.04 ± 0.23	-0.24
$b\bar{b}$	1.02 ± 0.85	0.83 ± 0.30	0
$\tau\tau$	0.73 ± 0.50	1.35 ± 0.35	-0.40

Perfectly well compatible with the SM

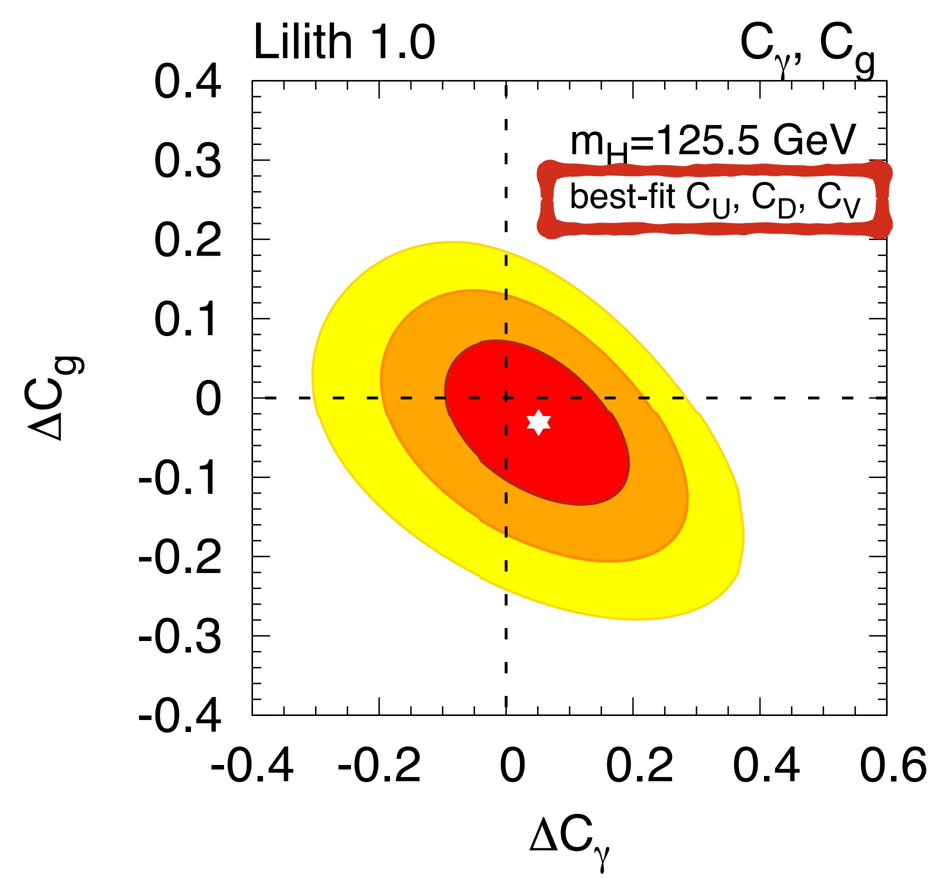
[JB, B. Dumont, S.Kraml, arXiv:1409.1588]

Loop-induced vertices fits: ΔC_γ, ΔC_g

- **<u>Fit:</u>** ΔC_γ, ΔC_g, assuming C_U, C_D, C_V fixed at their SM or best-fit values & no extra width contribution



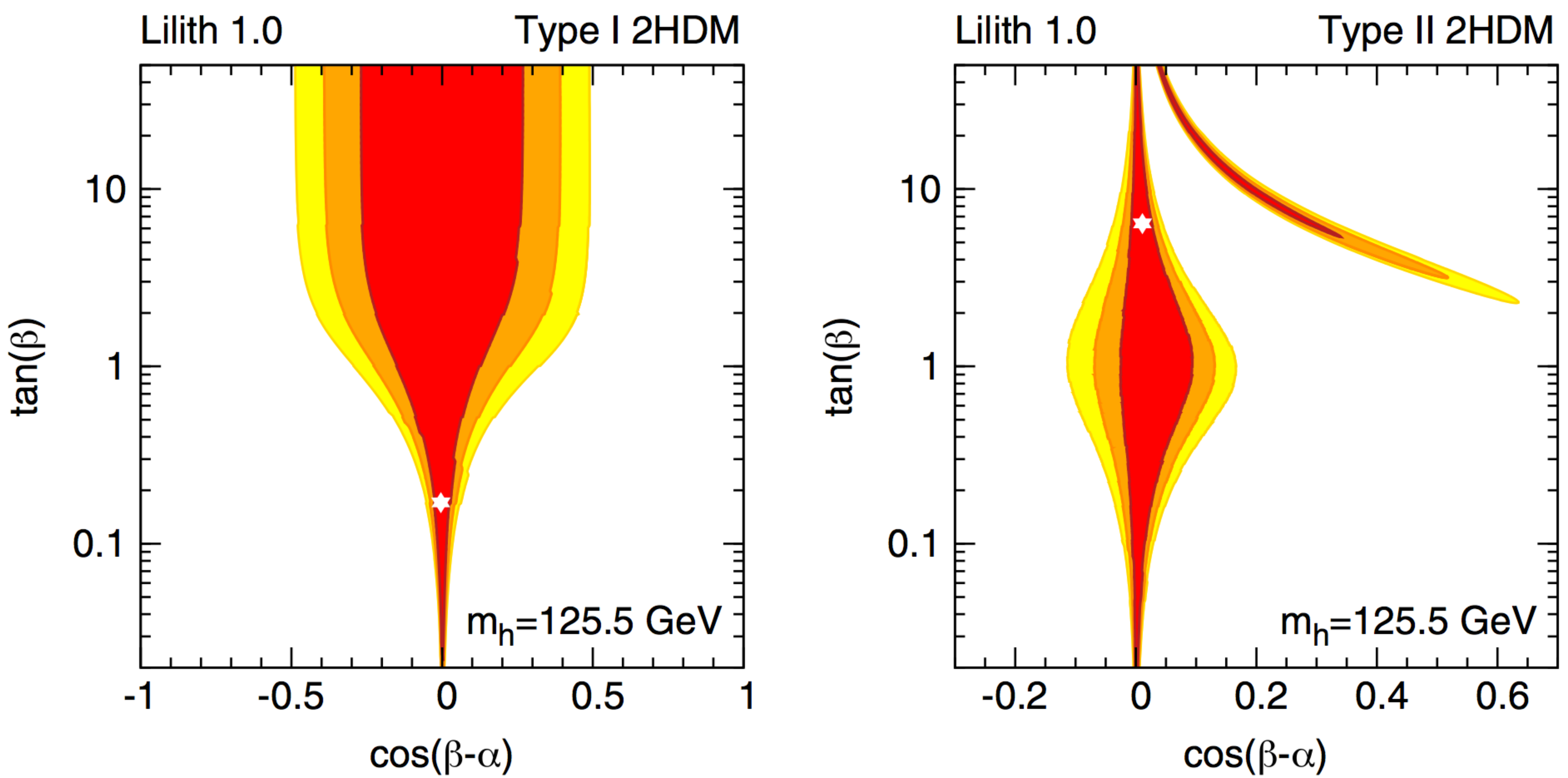
$$C_U = C_D = C_V = 1$$



$$C_U = 1.02\ , C_D = 0.98\ , C_V = 1.04$$

✓Loop-induced processes well compatible with SM particle contributions only

[JB, B. Dumont, S.Kraml, arXiv:1409.1588]



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