The ATLAS limits for the tBESS-like Lagrangian

Mikuláš Gintner and Josef Juráň

IEAP CTU in Prague

Z.Uni. in Žilina and S.Uni. in Opava

tBESS Lagrangian

- top-BESS Lagrangian – effective description of BSM physics
- BESS

  - R. Casalbuoni, S. De Curtis, D. Dominici, and R. Gatto, Phys. Lett. B 155, 95 (1985); Nucl. Phys. B282, 235 (1987);
  - R. Casalbuoni, P. Chiappetta, S. De Curtis, F. Feruglio, R. Gatto, B. Mele, and J. Terron, Phys. Lett. B 249, 130 (1990).

↓

top-BESS

  - M. Gintner, J. Juráň, and I. Melo, Phys. Rev. D 84, 035013 (2011);
  - M. Gintner, J. Juráň, Eur. Phys. J. C 73, 2577 (2013).

tBESS Lagrangian

- top-BESS Lagrangian – effective description of BSM physics

- BESS
  - R. Casalbuoni, S. De Curtis, D. Dominici, and R. Gatto, Phys. Lett. B 155, 95 (1985); Nucl. Phys. B282, 235 (1987);
  - R. Casalbuoni, P. Chiappetta, S. De Curtis, F. Feruglio, R. Gatto, B. Mele, and J. Terron, Phys. Lett. B 249, 130 (1990).

↓

top-BESS
  - M. Gintner, J. Juráň, and I. Melo, Phys. Rev. D 84, 035013 (2011);
  - M. Gintner, J. Juráň, Eur. Phys. J. C 73, 2577 (2013).

tBESS Lagrangian

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(2)_{HLS}$$

$$SU(2)_L \times U(1)_Y \times SU(2)_{HLS}$$

- NLσM of NGBs
- SM contained in tBESS
- Higgs: scalar singlet h
- Triplet of new vector resonances ρ_μ (GBs of $SU(2)_{HLS}$)

tBESS parameters

$$\text{SM parameters: } v, g, g', m_f, M_h, ...$$

$+$ extra parameters:

$g'', \alpha,$

$b_L, b_R, p, \lambda_L, \lambda_R,$

$a_V, a_\rho, a'_V, a'_\rho, ...$

$c_h, c_f, c'_h, c'_f, ...$

- Constraining the extra tBESS parameters by ...
  - a_v, a_ρ, c_i … Higgs measurements
  - g'', α … mass of new triplet (free)
  - g'' … GBs self-interactions
  - $g'', p, b_L - 2\lambda_L, b_R + 2\lambda_R$ … low-energy data (LEP, SLC, TVT)

Limits on Higgs-related parameters

- **ATLAS+CMS** Collaborations analysis (ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

based on the combination of decay modes $H \to \gamma\gamma,\, ZZ^*,\, WW^*,\, Z\gamma,\, b\bar{b},\, \tau\tau$ and $\mu\mu$
and the constraints on the associated production with a pair of top quarks
and on the off-shell coupling strengths of the Higgs boson.

- **Assumptions:**

One SM-like higgs boson state at about 125 GeV of a negligible decay width

Limits on Higgs-related parameters

- **ATLAS+CMS** Collaborations analysis (ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

based on the combination of decay modes $H \to \gamma\gamma,\, ZZ^*,\, WW^*,\, Z\gamma,\, b\bar{b},\, \tau\tau$ and $\mu\mu$
and the constraints on the associated production with a pair of top quarks
and on the off-shell coupling strengths of the Higgs boson.

- **Assumptions:**

One SM-like higgs boson state at about 125 GeV of a negligible decay width

- **Kappa framework**

-The LHC Higgs Cross Section Working Group, arXiv:1101.0593.
- kappas parametrize possible deviations of the Higgs interactions from their SM expectations

$$\kappa_W^2 \equiv \frac{\Gamma_{WW^*}}{\Gamma_{WW^*}^{\rm SM}} \qquad \kappa_Z^2 \equiv \frac{\Gamma_{ZZ^*}}{\Gamma_{ZZ^*}^{\rm SM}} \qquad \kappa_t^2 \equiv \frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{\rm SM}} \qquad \kappa_\gamma^2 \equiv \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}}$$

$$\mathrm{SM}\ \kappa_i^2 = 1$$

Scenario

Probing BSM contributions in tree and loop vertices

assumptions:

- new particles in loops are allowed
- no non-SM decays of the Higgs and BR of invisible/undetected decays are zero
- total 9 free κs.

6 tree level κ_i, $i = W, Z, t, b, \tau, \mu$,

3 loop level κ_j, $j = g, \gamma, Z\gamma$

(associated with the HO effective vertices $gg \to H$, $H \to \gamma\gamma$, $H \to Z\gamma$)

Combined analysis: ATLAS+CMS

Table 14: Fit results for the two parameterisations allowing BSM loop couplings, with $\kappa_V \leq 1$, where κ_V stands for κ_Z or κ_W, or without additional BSM contributions to the Higgs boson width, i.e. $BR_{BSM} = 0$. The measured results for the combination of ATLAS and CMS are reported together with their measured and expected uncertainties, as well as the measured results for each experiment. The uncertainties are not indicated when the parameters are constrained and hit a boundary, namely $\kappa_V = 1$ or $BR_{BSM} = 0$.

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $BR_{BSM} = 0$				
κ_Z	$1.03^{+0.11}_{-0.11}$	$^{+0.10}_{-0.11}$	$1.00^{+0.14}_{-0.14}$	$1.07^{+0.17}_{-0.18}$
κ_W	$0.91^{+0.10}_{-0.10}$	$^{+0.10}_{-0.11}$	$0.92^{+0.13}_{-0.13}$	$0.90^{+0.15}_{-0.15}$
κ_t	$1.43^{+0.23}_{-0.22}$	$^{+0.26}_{-0.32}$	$1.31^{+0.30}_{-0.32}$	$1.56^{+0.34}_{-0.32}$
κ_τ	$0.88^{+0.13}_{-0.12}$	$^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.17}$	$0.82^{+0.19}_{-0.17}$
κ_b	$0.60^{+0.18}_{-0.18}$	$^{+0.25}_{-0.24}$	$0.61^{+0.26}_{-0.26}$	$0.61^{+0.27}_{-0.26}$
κ_g	$0.81^{+0.11}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.15}$	$0.70^{+0.15}_{-0.13}$
κ_γ	$0.92^{+0.11}_{-0.10}$	$^{+0.12}_{-0.12}$	$0.88^{+0.15}_{-0.14}$	$0.96^{+0.17}_{-0.15}$

ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

15th September 2015

tBESS kappas predictions

@LO: $\kappa_W^2 = c_W^2, \quad \kappa_Z^2 = c_Z^2, \quad \kappa_t^2 = c_t^2.$

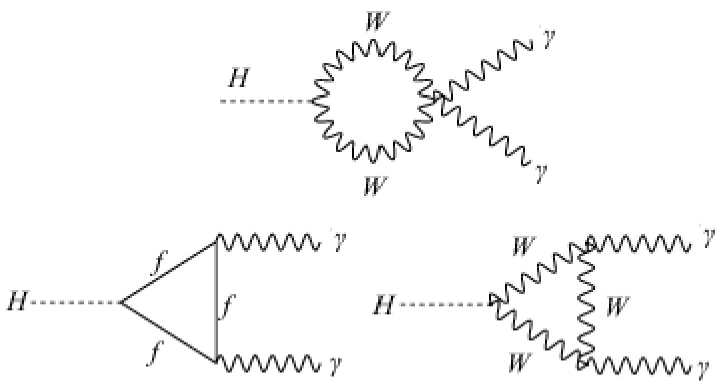
$$\mathcal{L}_{\rm ESB} \sim \frac{2h}{v}\Big[\frac{1}{2}c_Z M_Z^2 Z_\mu Z^\mu + c_W M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}c_{\rho^0} M_{\rho^0}^2 \rho_\mu^0 \rho^{0\mu} + c_{\rho^\pm} M_{\rho^\pm}^2 \rho_\mu^+ \rho^{-\mu}$$

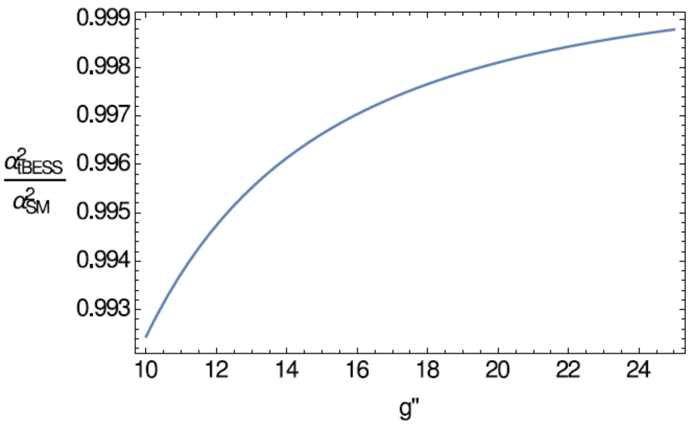
$$+ c_{Z\rho^0} M_Z M_{\rho^0} Z_\mu \rho^{0\mu} + c_{W\rho^\pm} M_W M_{\rho^\pm} (W_\mu^+ \rho^{-\mu} + \text{h.c.})\Big]$$

tBESS kappas predictions

κ_γ: tBESS prediction of $h \to \gamma\gamma$

Input parameters:
$m_W = 80.398$ GeV
$m_Z = 91.1876$ GeV
$G_F = 1.16637 \times 10^{-5}$ GeV^{-2}





$$\kappa_\gamma^2 \equiv \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}} = \left[\frac{\alpha_{\rm EM}(g'', M_\rho)}{\alpha_{\rm EM}^{\rm SM}}\right]^2 \left[\frac{c_\gamma(c_W, c_t, c_{\rho^\pm})}{c_\gamma^{\rm SM}}\right]^2$$

$$c_\gamma(M_\rho = 1\text{–}2\ {\rm TeV}) = -0.23\ c_t + 1.04\ c_W + 0.88\ c_{\rho^\pm}$$

$$c_\gamma^{\rm SM} = 0.81$$

tBESS kappas predictions

predictions of κ_γ, κ_W, κ_Z, and κ_t $(c_W, c_Z, c_\rho^\pm, c_t)$

$c_W(a_V, a_\rho)$, $c_Z(a_V, a_\rho)$, $c_\rho^\pm(a_V, a_\rho)$, and $c_\gamma(a_V, a_\rho, c_t)$

$$\mathcal{L}_2 = -v^2[\mathrm{Tr}(\bar{\omega}^\perp)^2(1 + 2a_V\frac{h}{v} + a'_V\frac{h^2}{v^2} + \ldots) + \alpha\mathrm{Tr}(\bar{\omega}^\parallel)^2(1 + 2a_\rho\frac{h}{v} + a'_\rho\frac{h^2}{v^2} + \ldots)]$$

splitting parameter: $r \equiv \frac{a_\rho}{a_V}$

... also c-dependency on g'' and M_{ρ^0}.
6 combinations, namely
$\{g'', M_{\rho^0}(\mathrm{TeV})\} = \{10, 1\}, \{10, 2\}, \{15, 1.5\}, \{20, 1\}, \{20, 2\}, \{25, 2\}$.

The 1st look: No-splitting assumption

$a_V = a_\rho \qquad r = 1$

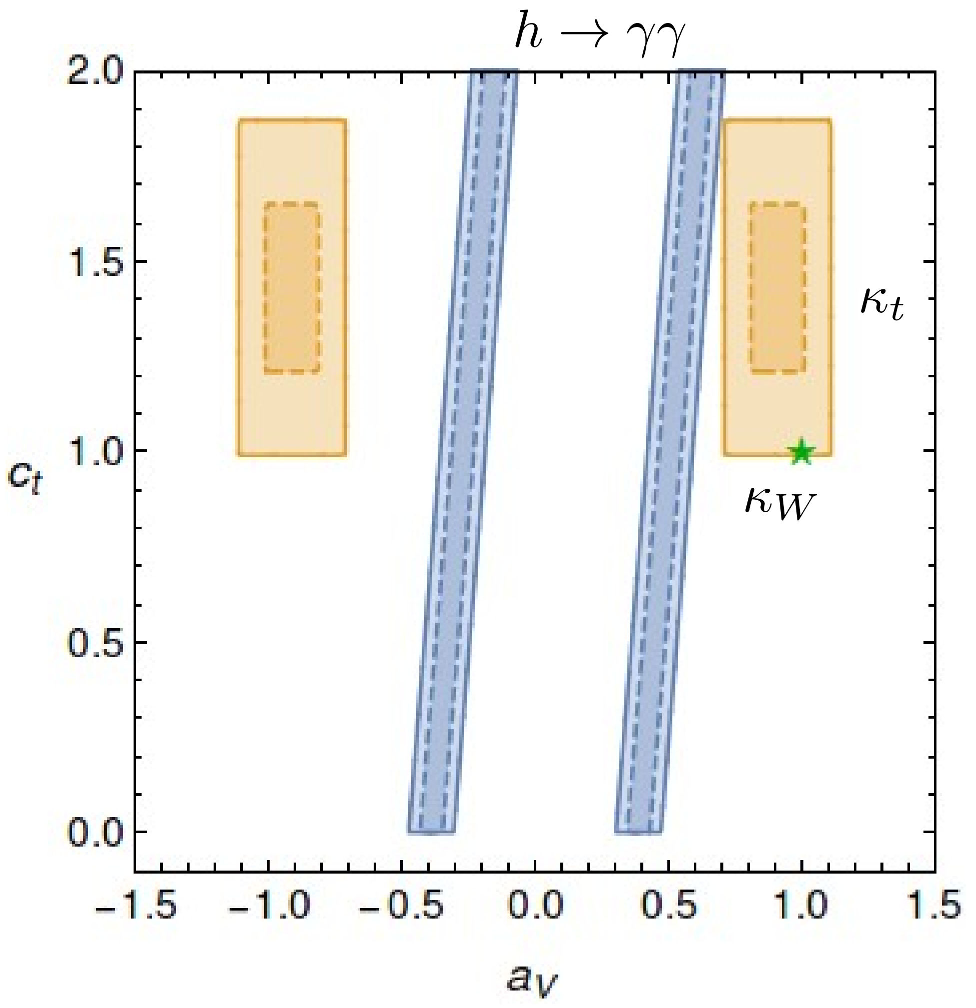
$c_W = c_Z = c_{\rho^\pm} = c_{\rho^0} = a_V$

$|\kappa_\gamma| = |2.37\, a_V - 0.28\, c_t|$

$\kappa_\gamma = 0.92 \pm 0.10$

$\kappa_W = 0.91 \pm 0.10$

$\kappa_t = 1.43 \pm 0.22$



Splitting assumption

$a_V \neq a_\rho \qquad r \neq 1$

$c_W \neq c_Z \neq c_{\rho^\pm} \neq c_{\rho^0}$

$$\tilde{\chi}^2(a_V, a_\rho, c_t) = \left\{ \frac{\kappa_\gamma^2 - [c_\gamma(a_V, a_\rho, c_t)/c_\gamma^{\rm SM}]^2}{\tilde{\sigma}_\gamma} \right\}^2 + \left(\frac{\kappa_t^2 - c_t^2}{\tilde{\sigma}_t} \right)^2 + \sum_{i=W,Z} \left[\frac{\kappa_i^2 - c_i^2(a_V, a_\rho)}{\tilde{\sigma}_i} \right]^2$$

$\tilde{\chi}^2_{\rm min} = 0.64$

Backing of 42% (d.o.f. = 4 - 3 = 1)

8 solutions $\{c_t, a_V, a_\rho\}$ (degenerate $\tilde{\chi}^2$-function)

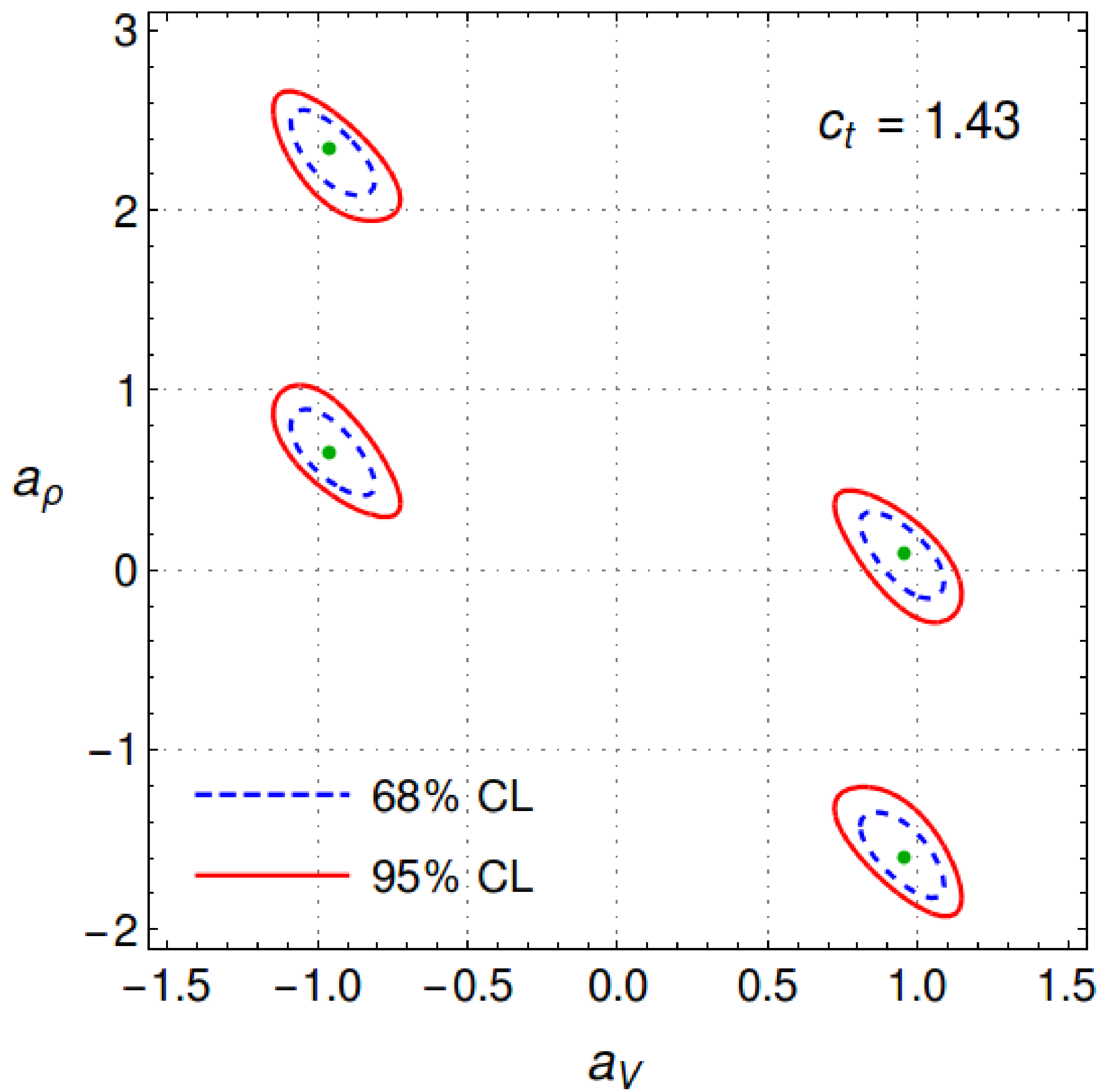
setting $c_t > 0 \rightarrow 4$ solutions

Constraints a_i versus c_j:

$c_W = c_Z = a_V$

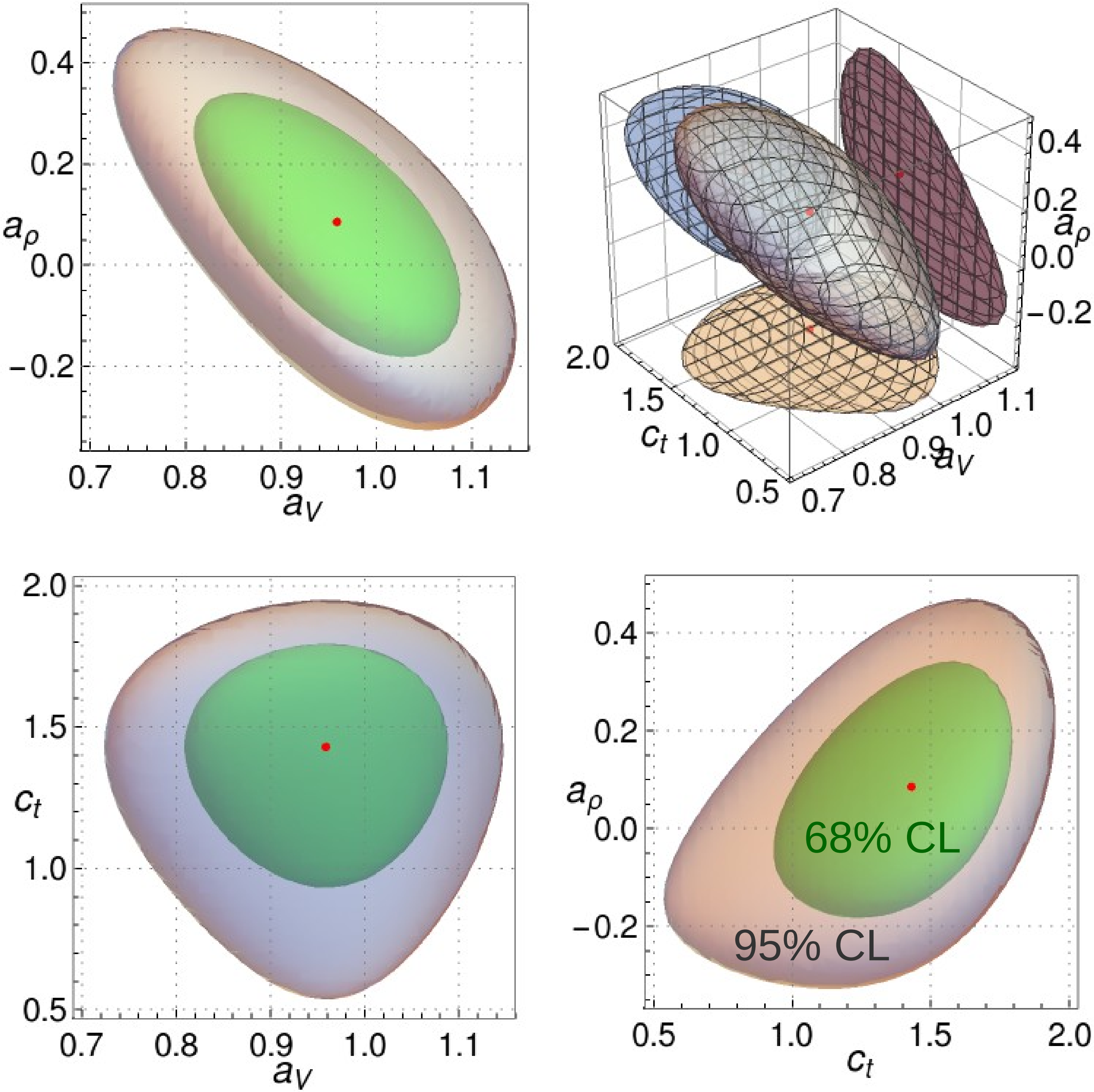
$c_\rho^\pm = a_\rho$

Contour plot: χ^2-cut for fixed c_t



The best-fit values

Constraint	parameter	sol1	sol2	sol3	sol4
20%CL	c_t	$1.43^{+0.21}_{-0.24}$	$1.43^{+0.21}_{-0.24}$	$1.43^{+0.21}_{-0.24}$	$1.43^{+0.21}_{-0.24}$
$\chi^2_{min} + 1$	a_V	$0.96^{+0.07}_{-0.08}$	$0.96^{+0.07}_{-0.08}$	$-0.96^{+0.08}_{-0.07}$	$-0.96^{+0.08}_{-0.07}$
	a_ρ	$0.09^{+0.13}_{-0.14}$	$-1.60^{+0.14}_{-0.14}$	$0.65^{+0.14}_{-0.14}$	$2.34^{+0.13}_{-0.14}$
68%CL	c_t	$1.43^{+0.36}_{-0.50}$	$1.43^{+0.36}_{-0.50}$	$1.43^{+0.36}_{-0.50}$	$1.43^{+0.36}_{-0.50}$
$\chi^2_{min} + 3.51$	a_V	$0.96^{+0.13}_{-0.15}$	$0.96^{+0.13}_{-0.15}$	$-0.96^{+0.15}_{-0.13}$	$-0.96^{+0.15}_{-0.13}$
	a_ρ	$0.09^{+0.25}_{-0.27}$	$-1.60^{+0.27}_{-0.26}$	$0.65^{+0.26}_{-0.26}$	$2.34^{+0.24}_{-0.28}$
95%CL	c_t	$1.43^{+0.52}_{-0.89}$	$1.43^{+0.52}_{-0.89}$	$1.43^{+0.52}_{-0.89}$	$1.43^{+0.52}_{-0.89}$
$\chi^2_{min} + 7.81$	a_V	$0.96^{+0.19}_{-0.24}$	$0.96^{+0.19}_{-0.24}$	$-0.96^{+0.24}_{-0.19}$	$-0.96^{+0.24}_{-0.19}$
	a_ρ	$0.09^{+0.38}_{-0.41}$	$-1.60^{+0.42}_{-0.38}$	$0.65^{+0.40}_{-0.40}$	$2.34^{+0.36}_{-0.43}$



parameter	sol1
c_t	$1.43^{+0.21}_{-0.24}$
a_V	$0.96^{+0.07}_{-0.08}$
a_ρ	$0.09^{+0.13}_{-0.14}$

Conclusion

- Current LHC constraints for tBESS-like Lagrangian
- ATLAS+CMS data, kappa framework with appropriate scenario
- Focusing on parameters a_V, a_ρ, and c_t

Conclusion

- Current LHC constraints for tBESS-like Lagrangian
- ATLAS+CMS data, kappa framework with appropriate scenario
- Focusing on parameters a_V, a_ρ, and c_t

- No-splitting versus splitting assumption
-

a_V	$0.96^{+0.07}_{-0.08}$	$0.96^{+0.07}_{-0.08}$	$-0.96^{+0.08}_{-0.07}$	$-0.96^{+0.08}_{-0.07}$
a_ρ	$0.09^{+0.13}_{-0.14}$	$-1.60^{+0.14}_{-0.14}$	$0.65^{+0.14}_{-0.14}$	$2.34^{+0.13}_{-0.14}$

- We find that the measurements admit tBESS-like kind of SM extensions with sizable values of the vector resonance couplings

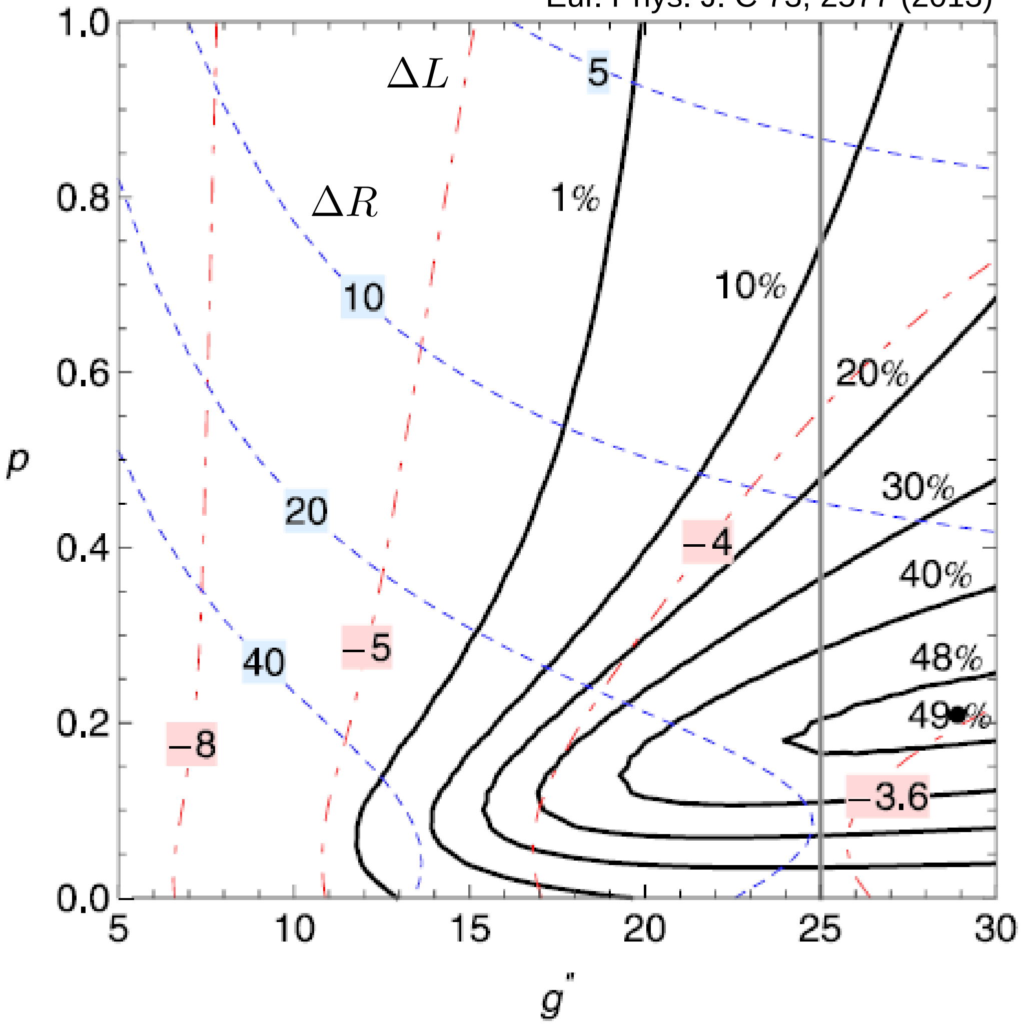
- … work still in progress, … looking for other constraints (mainly) of c_t

Thank you for your attention.

Low-Energy limits

LE limits on $g'', p, \Delta L \equiv b_L - 2\lambda_L, \Delta R \equiv b_R + 2\lambda_R$
using (pseudo-)observables: $\Gamma_b(Z \to b\bar{b} + X)$, $\mathrm{BR}(B \to X_s\gamma)$,
ϵ_1, ϵ_2, ϵ_3 (BO: M_W/M_Z, $\Gamma_l(Z \to l\bar{l} + photons)$, $\mathrm{A}_l^{FB}(M_Z)$)

Eur. Phys. J. C 73, 2577 (2013)



Fitting two parameters ΔL and ΔR: backing of the fit with given (g'', p) and the best-fit values of ΔL and ΔR (in thousandths)

95% CL limits of 4D fit (projections of 4D to 1D) ($\Lambda = 1$ TeV)

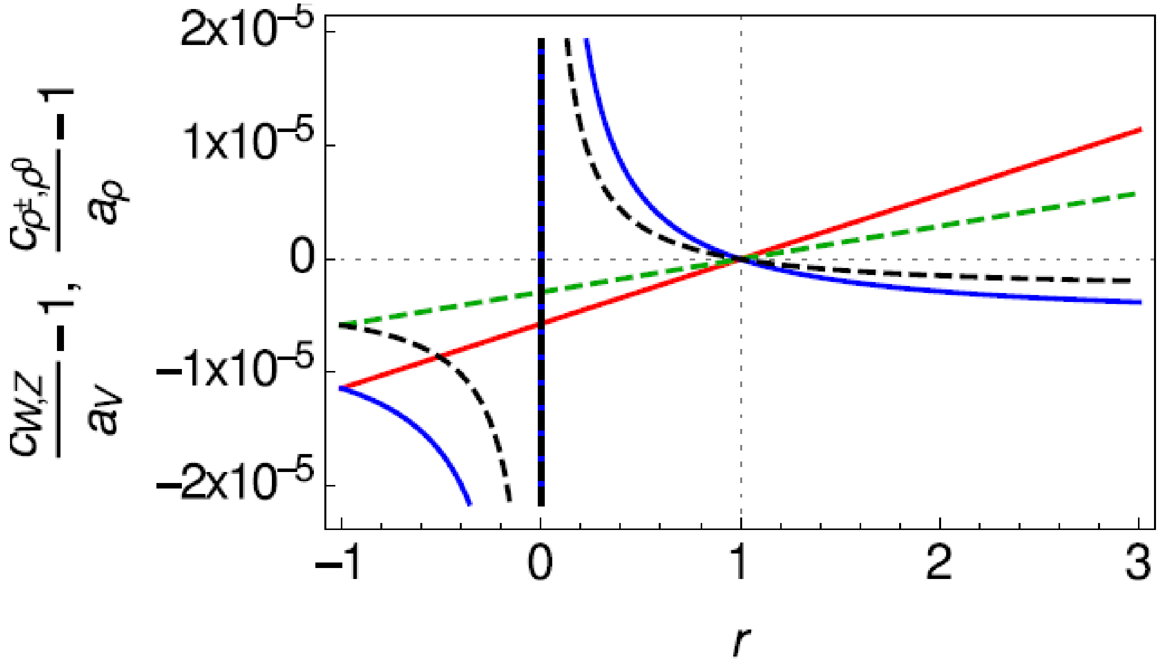
$12 < g''$
$-0.013 < \Delta L < 0.006$
$-0.006 < \Delta R < 0.056$
all interval $0 \leq p \leq 1$

Approximations

Approximations:

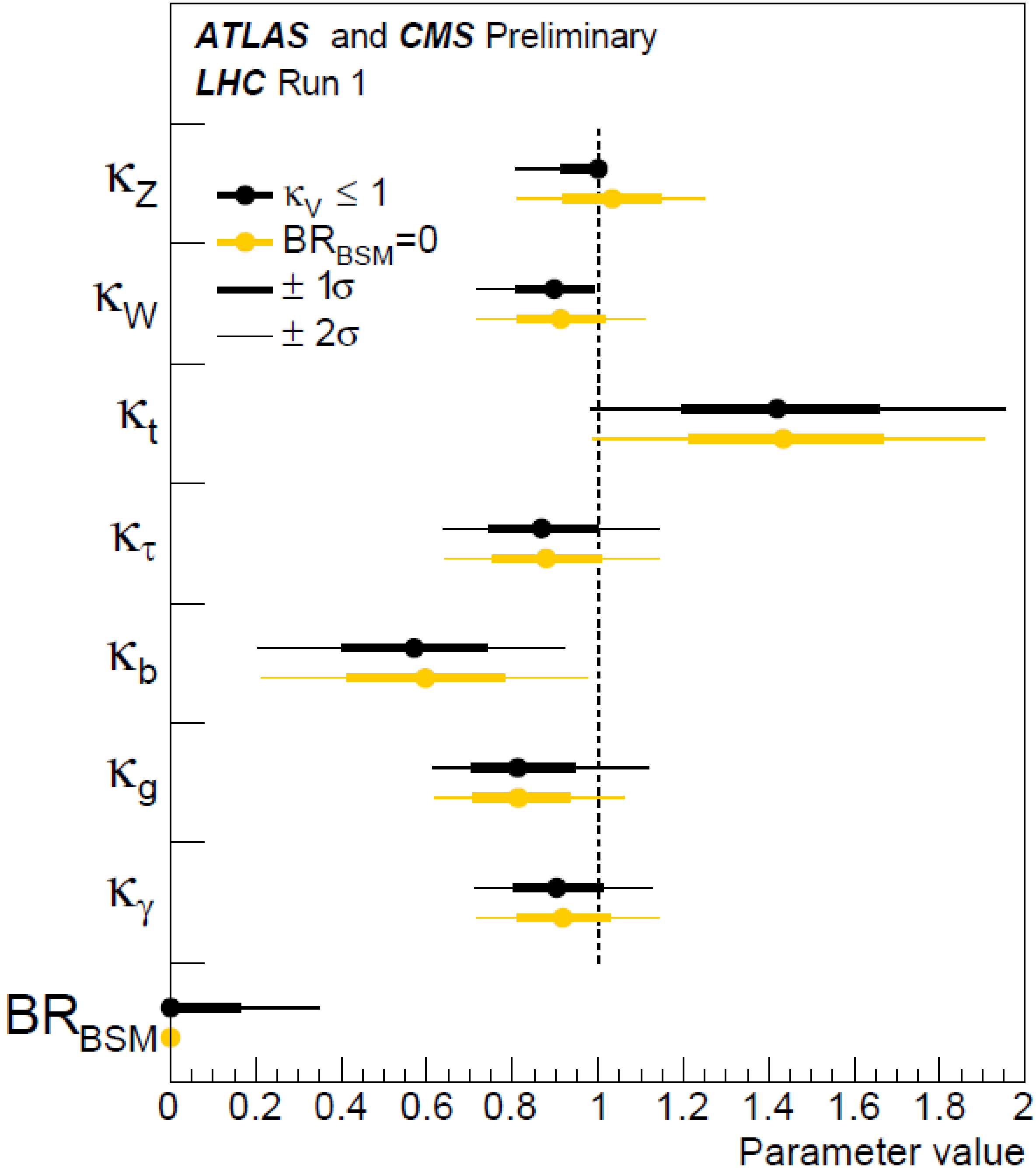
$c_W = c_Z = a_V$

$c_\rho^\pm = a_\rho$



$$\tilde{\chi}^2(a_V, a_\rho, c_t) = \left[\frac{\kappa_\gamma^2 - (1.28\ a_V + 1.09\ a_\rho - 0.28\ c_t)^2}{2\kappa_\gamma\sigma_\gamma}\right]^2 + \left(\frac{\kappa_t^2 - c_t^2}{2\kappa_t\sigma_t}\right)^2 + \left(\frac{\kappa_W^2 - a_V^2}{2\kappa_W\sigma_W}\right)^2 + \left(\frac{\kappa_Z^2 - a_V^2}{2\kappa_Z\sigma_Z}\right)^2$$

Combined analysis: ATLAS+CMS



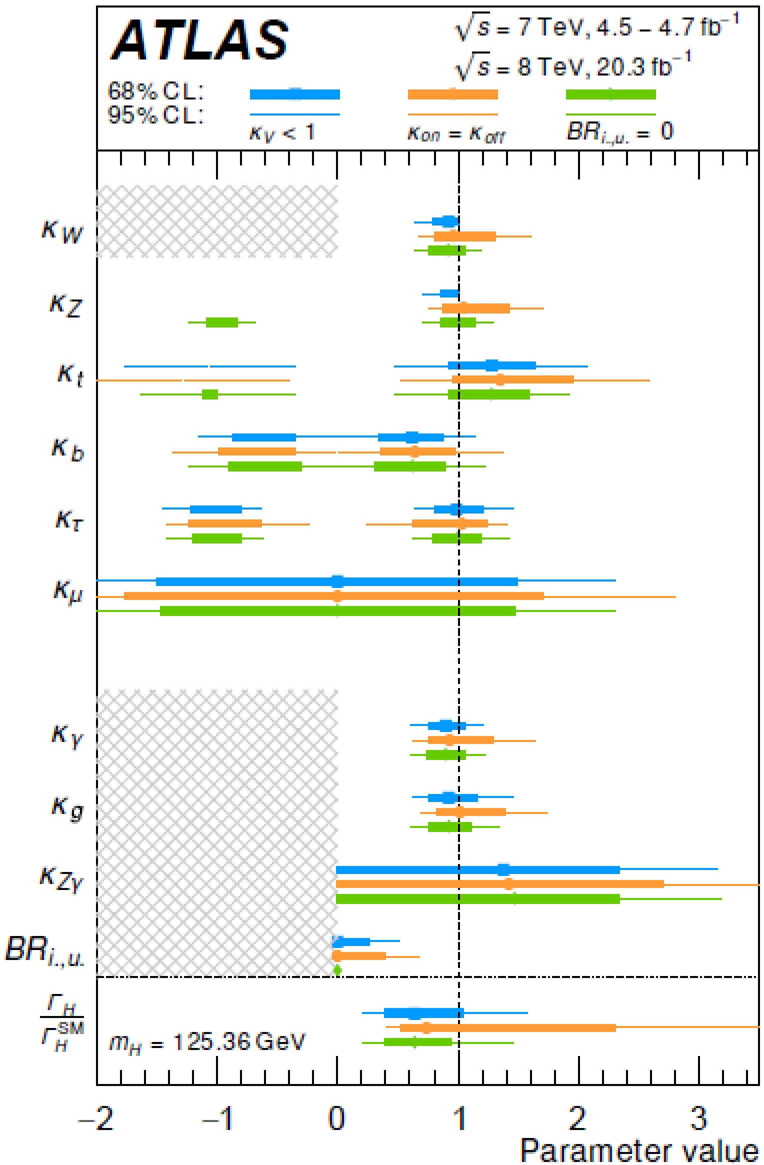
ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

15th September 2015

ATLAS data

our interest:
no new higgs decay channels,
ie., BRi.,u. = 0 (green, bottom)



Parameter		BI
		Fitted value
κ_W		$= 0.92^{+0.14}_{-0.15}$
κ_Z		$\in [-1.08, -0.84] \cup [0.86, 1.14]$
κ_t		$\in [-1.12, -1.00] \cup [0.93, 1.60]$
$\|\kappa_b\|$	=	$0.62^{+0.31}_{-0.27}$
$\|\kappa_\tau\|$	=	1.00 ± 0.20
$\|\kappa_\mu\|$	<	2.3 (95% CL)
κ_γ	=	0.90 ± 0.15
κ_g	=	0.92 ± 0.17
$\kappa_{Z\gamma}$	<	3.18 (95% CL)
$BR_{i.,u.}$	<	-
Γ_H/Γ_H^{SM}	=	$0.64^{+0.31}_{-0.25}$

arXiv:1507.04548 (16.7.2015)

Main parts of tBESS Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm GB} + \mathcal{L}_{\rm ESB} + \mathcal{L}_{\rm ferm}$$

$$\mathcal{L}_{\rm GB} = \frac{1}{2g^2}{\rm Tr}(\boldsymbol{W}_{\mu\nu}\boldsymbol{W}^{\mu\nu}) + \frac{1}{2g'^2}{\rm Tr}(\boldsymbol{B}_{\mu\nu}\boldsymbol{B}^{\mu\nu}) + \frac{2}{g''^2}{\rm Tr}(\boldsymbol{V}_{\mu\nu}\boldsymbol{V}^{\mu\nu})$$

$$\mathcal{L}_{\rm ESB} = \mathcal{L}_h + \mathcal{L}_2$$

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}M_h^2 h^2 - c_h\,\frac{M_h^2}{2v}h^3 - c'_h\,\frac{M_h^2}{8v^2}h^4$$

$$\mathcal{L}_2 = -v^2[{\rm Tr}(\bar\omega^\perp)^2(1 + 2a_V\frac{h}{v} + a'_V\frac{h^2}{v^2} + \ldots) + \alpha{\rm Tr}(\bar\omega^\parallel)^2(1 + 2a_\rho\frac{h}{v} + a'_\rho\frac{h^2}{v^2} + \ldots)]$$

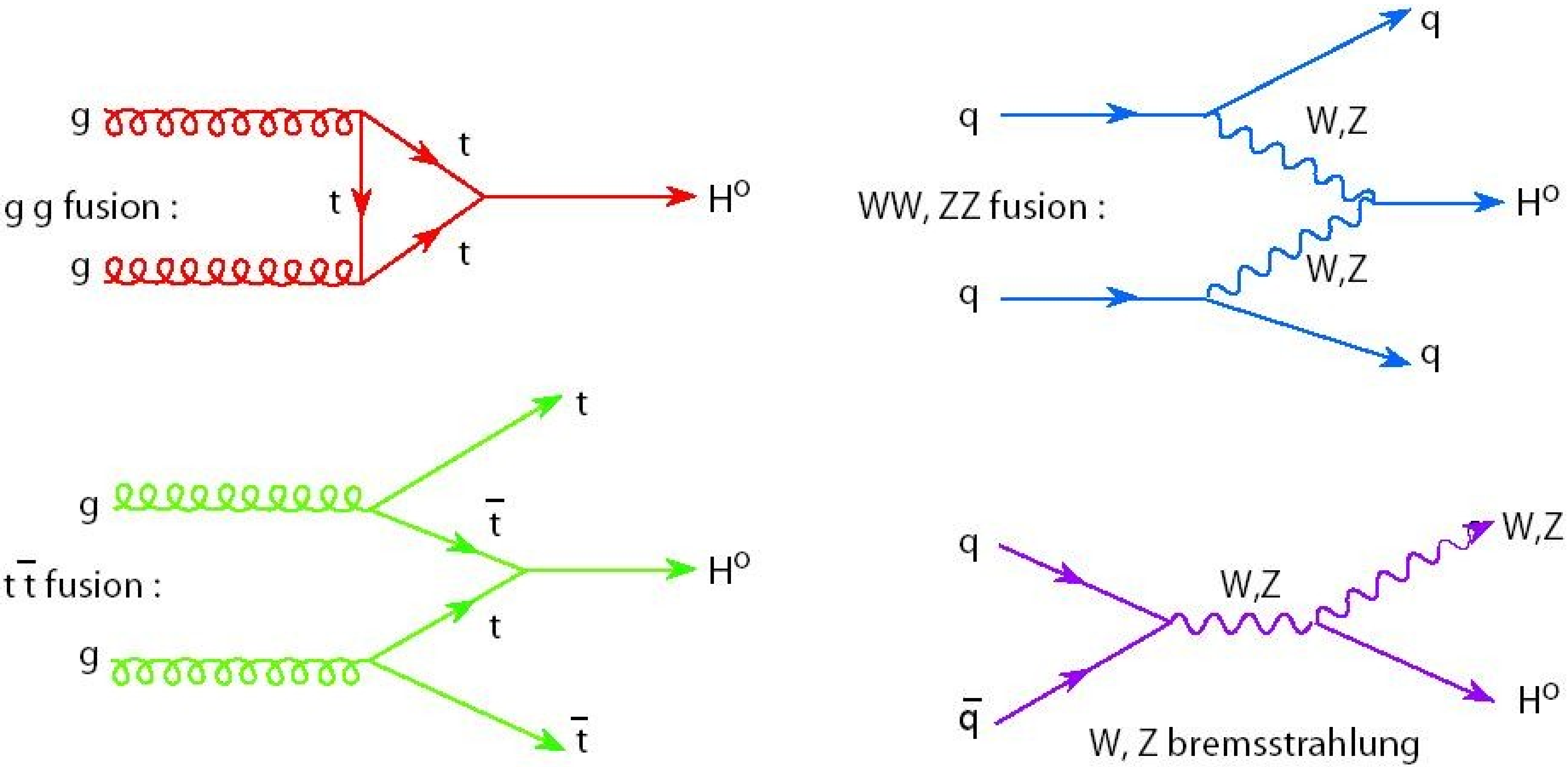
$$\mathcal{L}_{\rm ferm}^{\rm scalar} = -\sum_{k=1}^{6}\bar\psi_L^k U M_f^k(1 + c_f^k\frac{h}{v} + c_f'^k\frac{h^2}{v^2} + \ldots)\psi_R^k + {\rm h.c.}$$

$$\mathcal{L}_2 = \mathcal{M}(\alpha) + \frac{2a_V}{v}\mathcal{M}(\alpha r)h$$

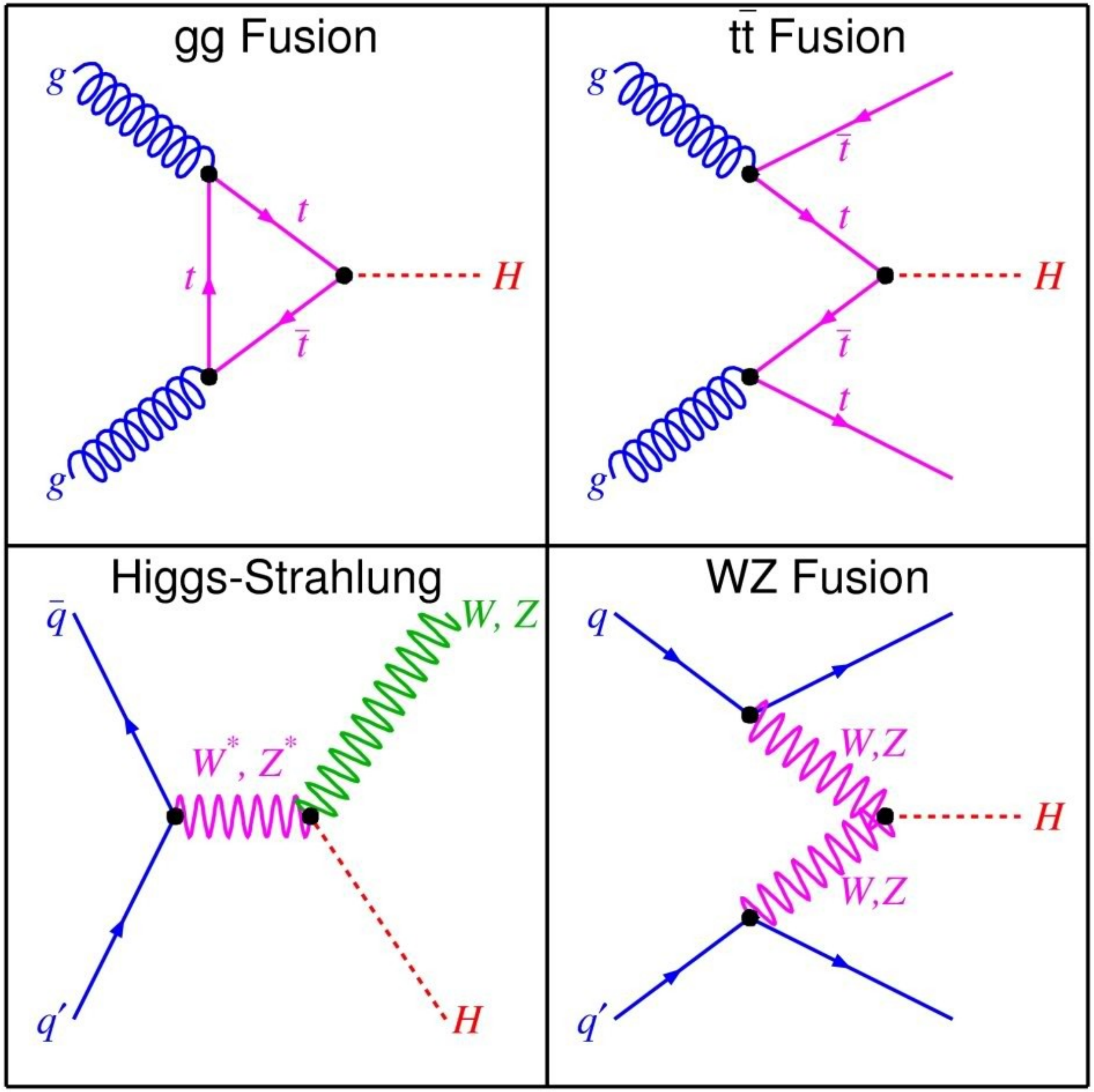
$$\frac{2a_V}{v}\mathcal{M}(\alpha r)h \;=\; \frac{2h}{v}\Big[\frac{1}{2}c_Z M_Z^2 Z_\mu Z^\mu + c_W M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}c_{\rho^0}M_{\rho^0}^2\rho_\mu^0\rho^{0\mu} + c_{\rho^\pm}M_{\rho^\pm}^2\rho_\mu^+\rho^{-\mu}$$

$$+ c_{Z\rho^0}M_Z M_{\rho^0}Z_\mu\rho^{0\mu} + c_{W\rho^\pm}M_W M_{\rho^\pm}(W_\mu^+\rho^{-\mu} + {\rm h.c.})\Big] \qquad (1$$

Main Higgs production modes



Main Higgs production modes



Main Higgs decay channels