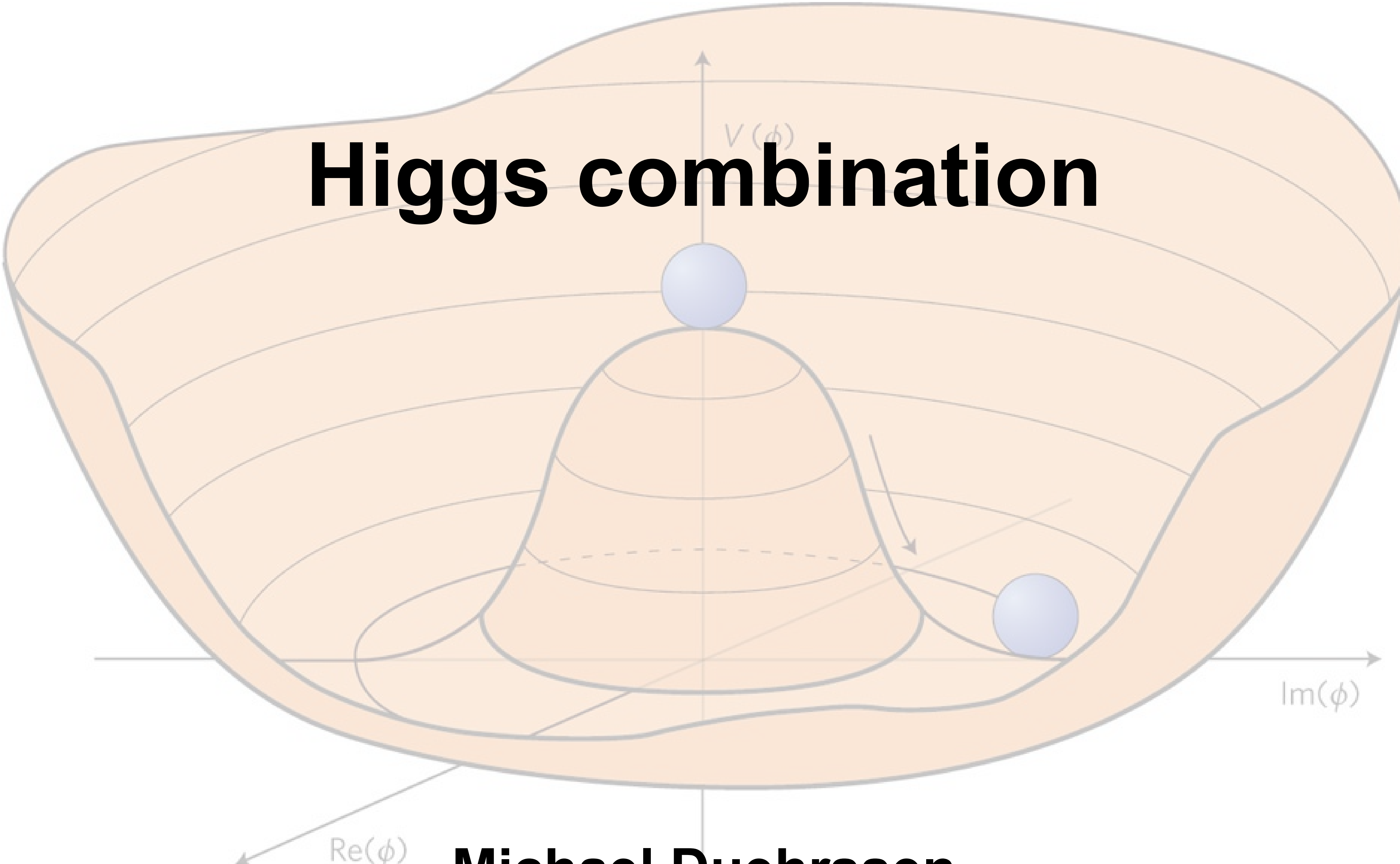
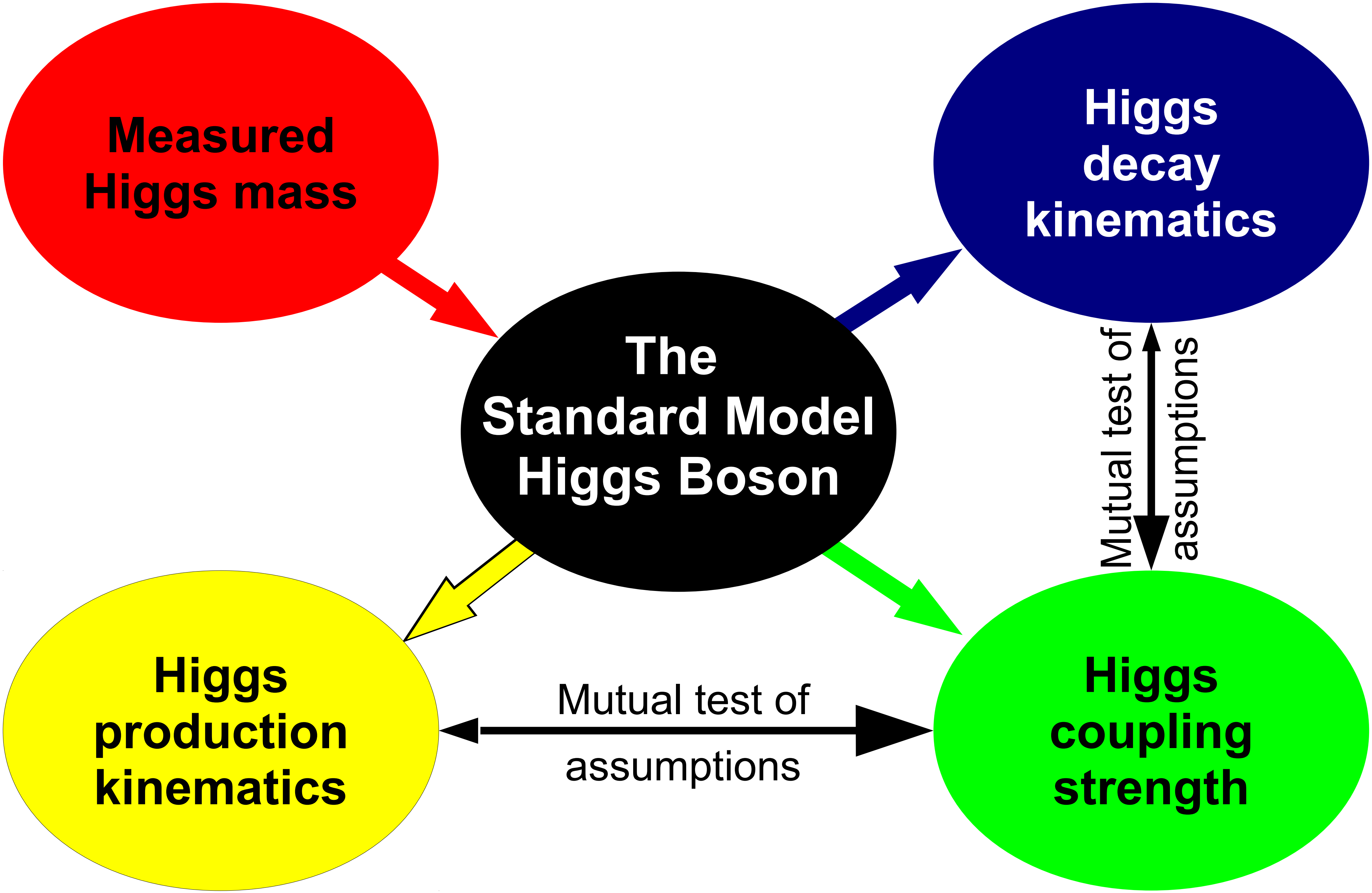
Higgs combination

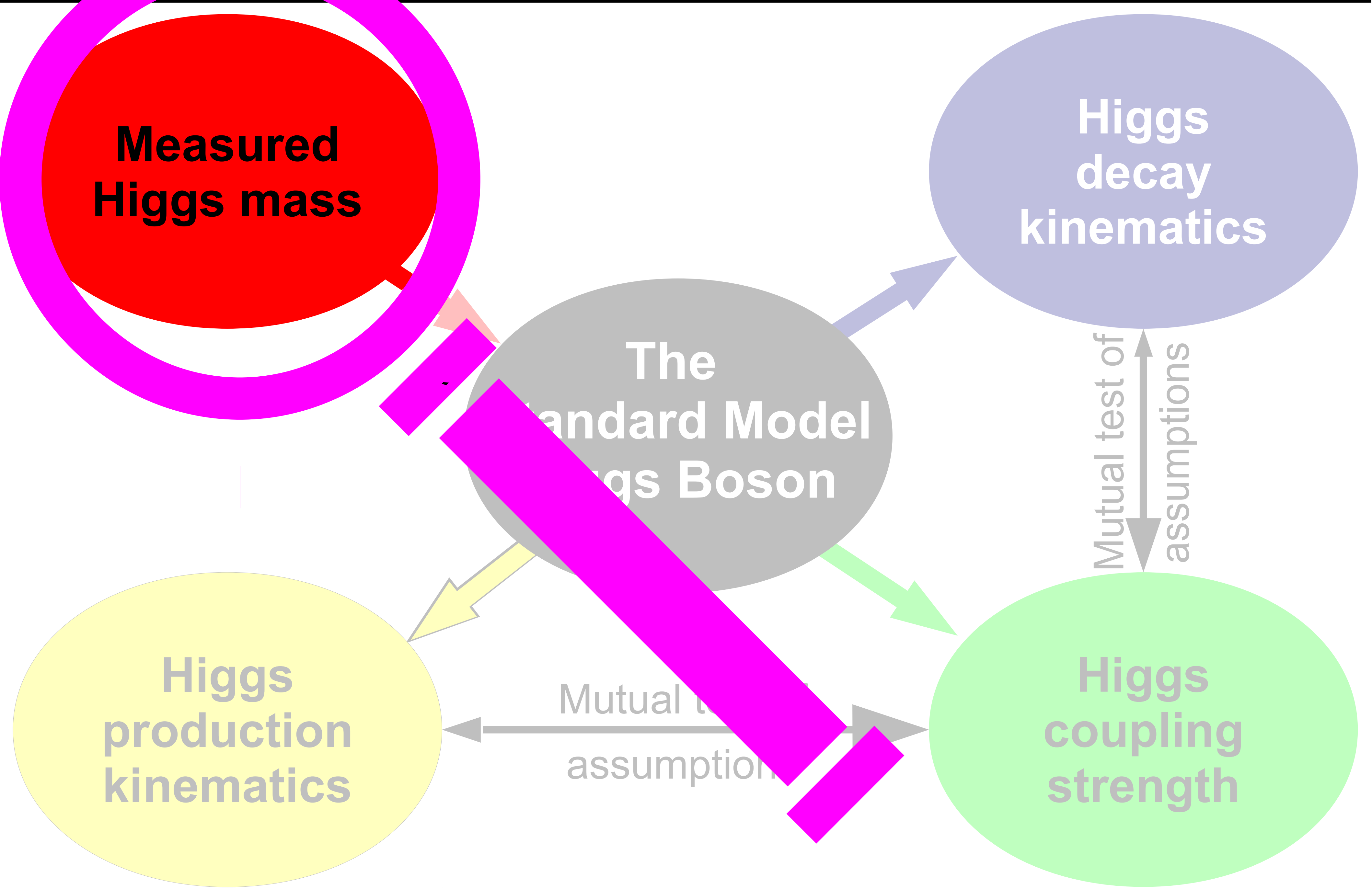


Michael Duehrssen
for the ATLAS and CMS collaborations
Moriond 2015

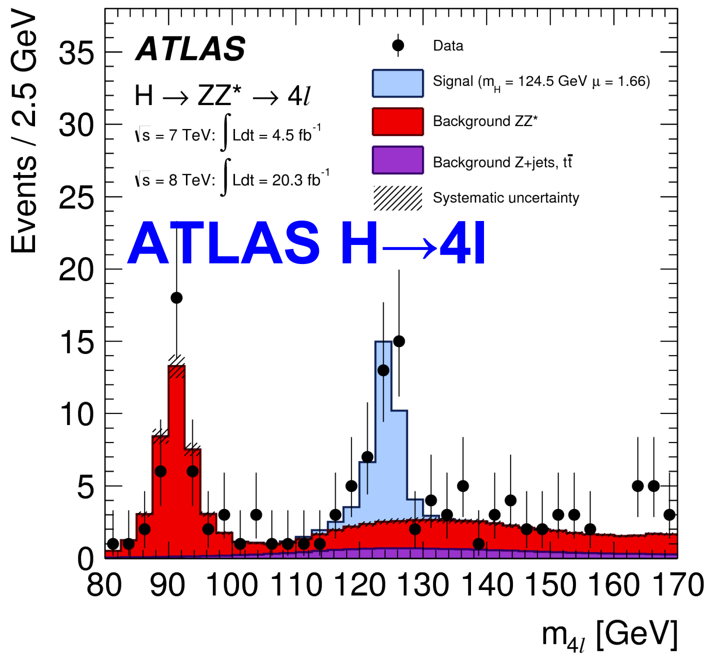
Higgs combination: testing the SM



Higgs combination: testing the SM



ATLAS+CMS Higgs mass combination

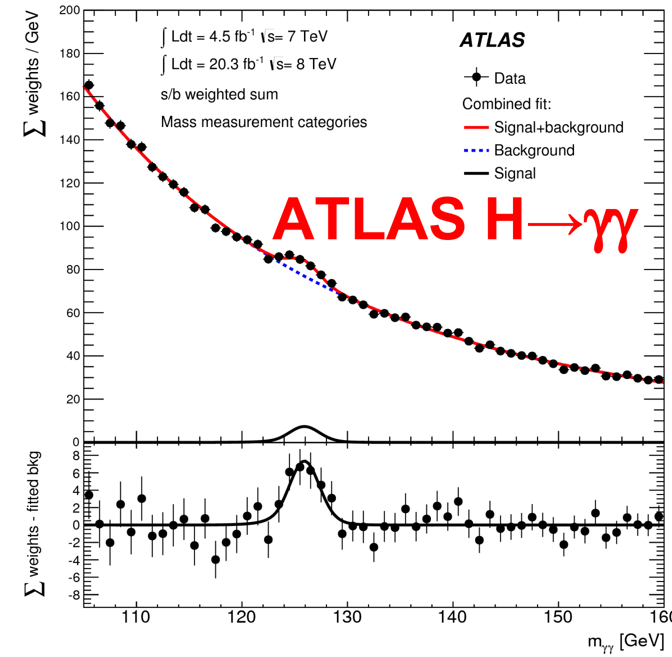


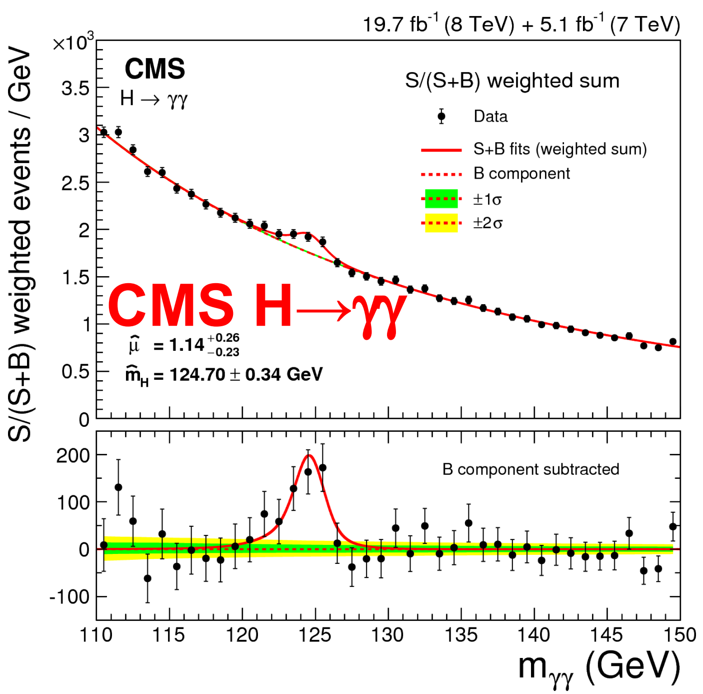
NEW

to be submitted to PRL

Combination of ATLAS+CMS mass measurements in

- **$H \rightarrow \gamma\gamma$**
- **$H \rightarrow 4l$**

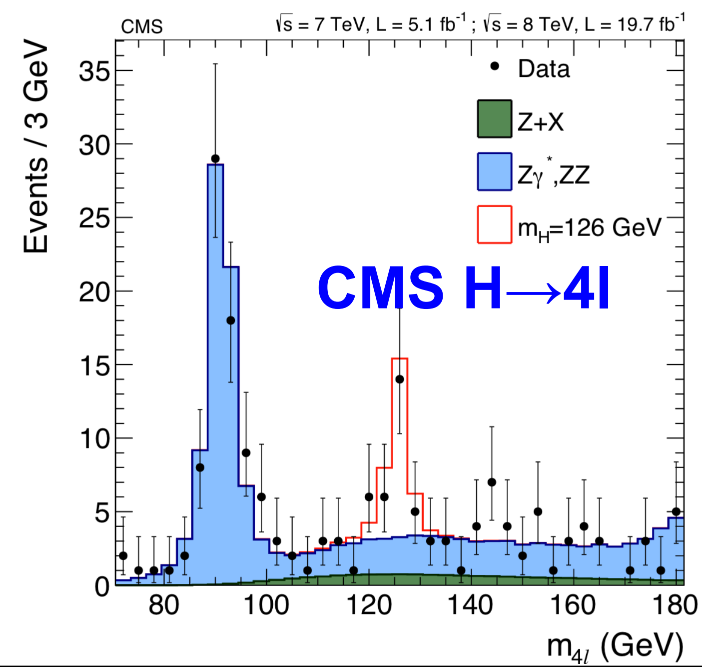




Aim to be agnostic to the signal yields: 3 signal strength parameter μ for

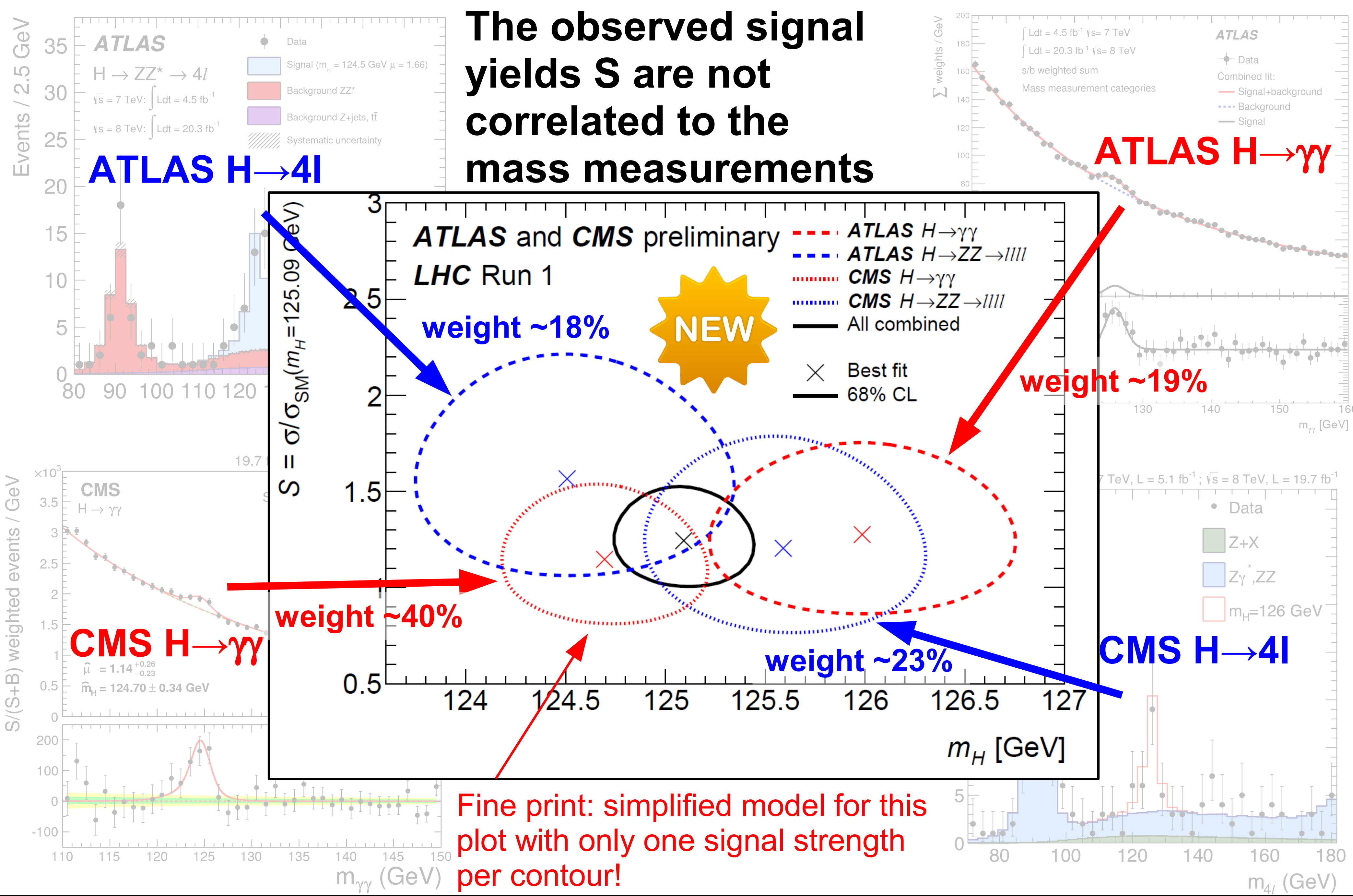
- **$gg \rightarrow H \rightarrow \gamma\gamma$**
- **VBF $H \rightarrow \gamma\gamma$**
- **$H \rightarrow 4l$**

simultaneously determined from data (profiled)



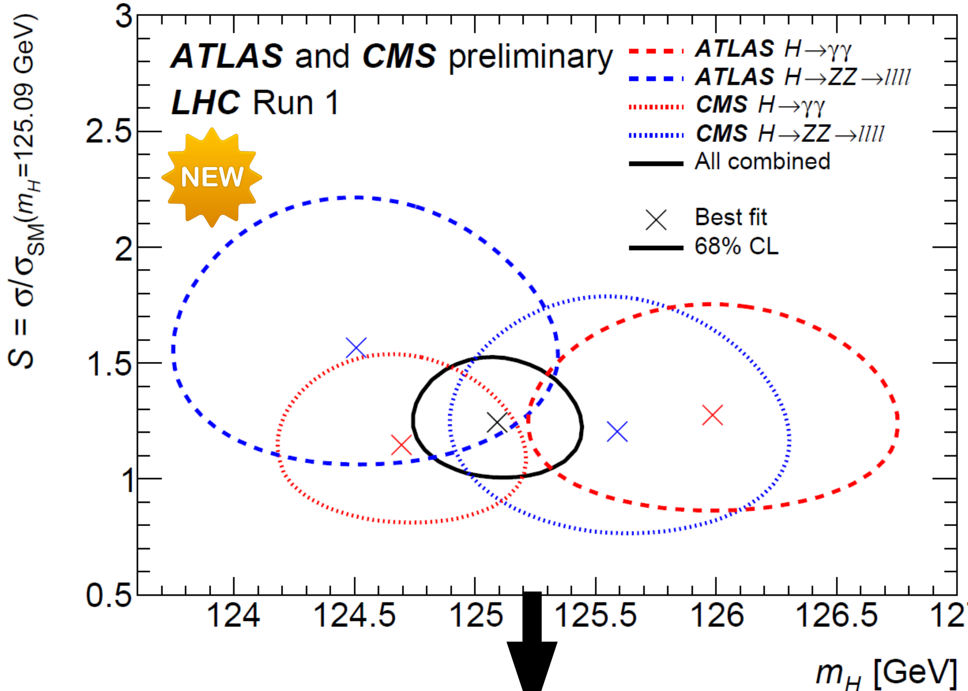
ATLAS+CMS Higgs mass combination

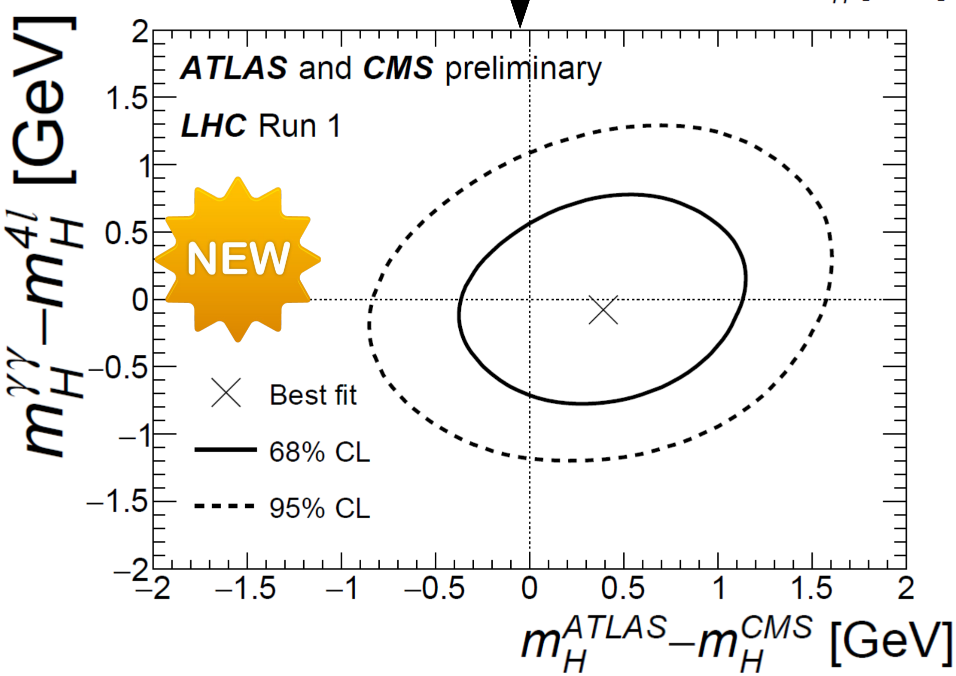
The observed signal yields S are not correlated to the mass measurements



Fine print: simplified model for this plot with only one signal strength per contour!

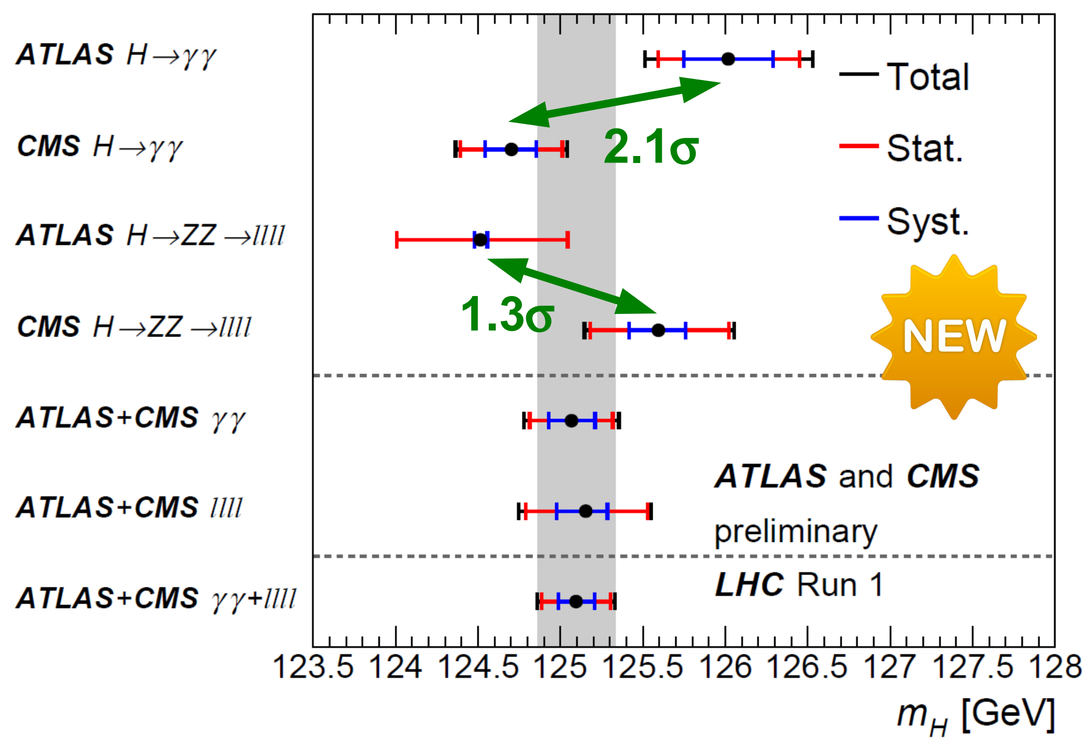
ATLAS+CMS Higgs mass combination





After combining the mass measurements in the H→γγ and the H → 4l channel and in ATLAS and CMS are very compatible with each other.

Tension only within the experiments

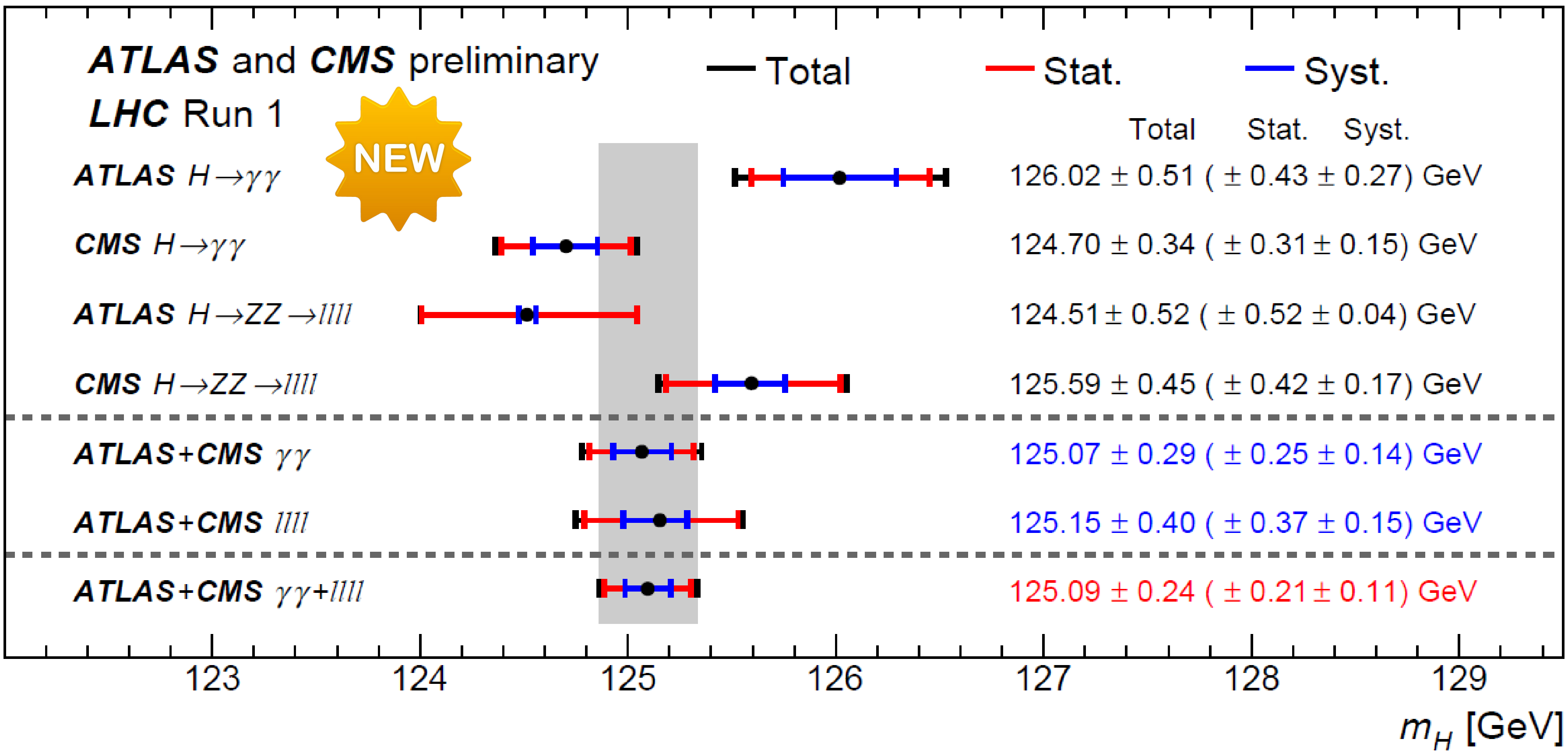


ATLAS+CMS Higgs mass combination

… and the ATLAS+CMS combined Higgs boson mass is:

$$m_H = 125.09 \pm 0.24\ \mathrm{GeV}$$ **(0.19% precision!)**

$$= 125.09 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{GeV}$$



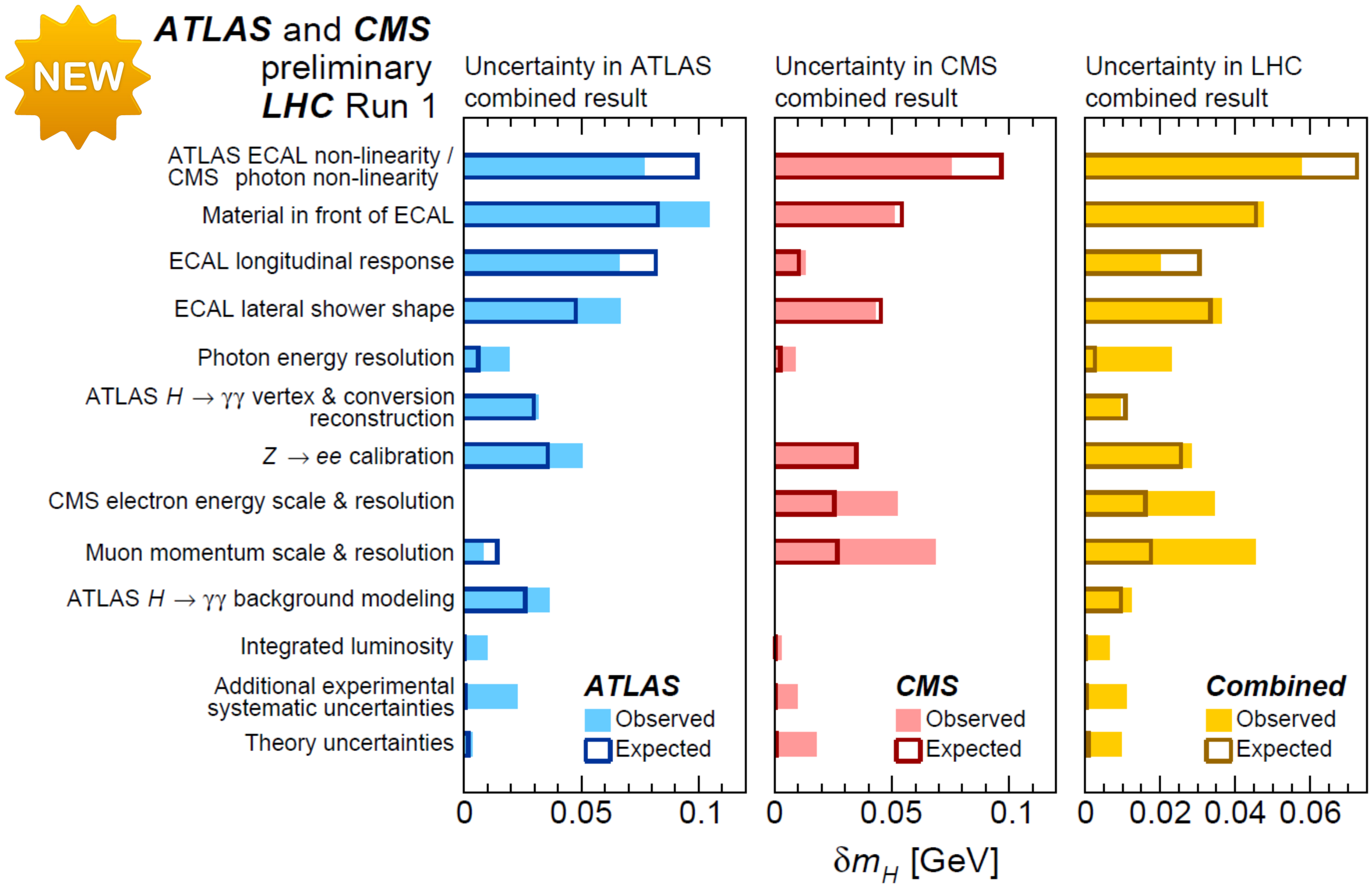
Compatibility of the 4 m_H measurements with the combined mass: 7-10%

ATLAS+CMS Higgs mass combination

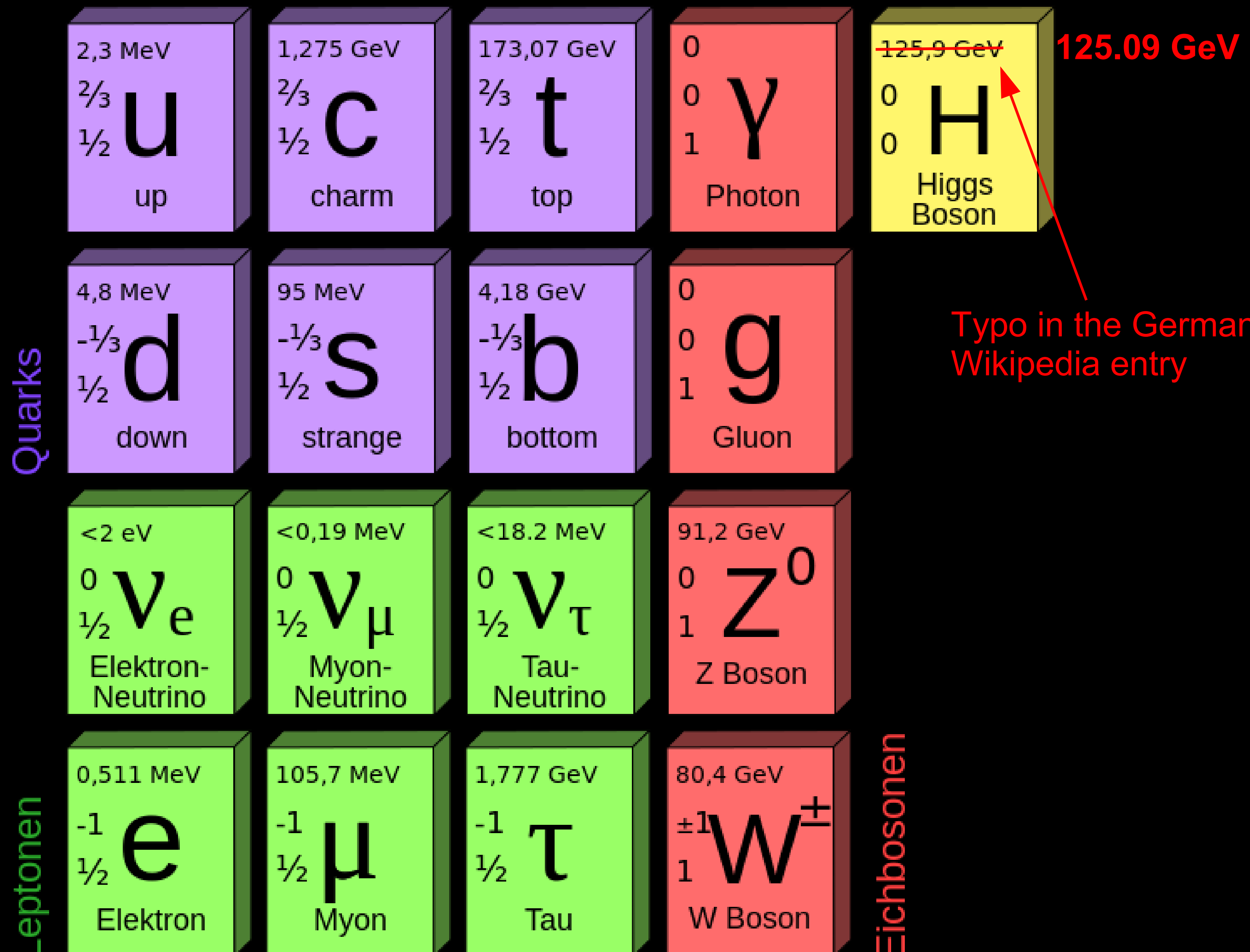
- **Measurement is dominated by the statistical uncertainty**
- **Very careful check of systematic uncertainties performed:**

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{scale}) \pm 0.02(\text{other}) \pm 0.01(\text{theory})\ \text{GeV}$$

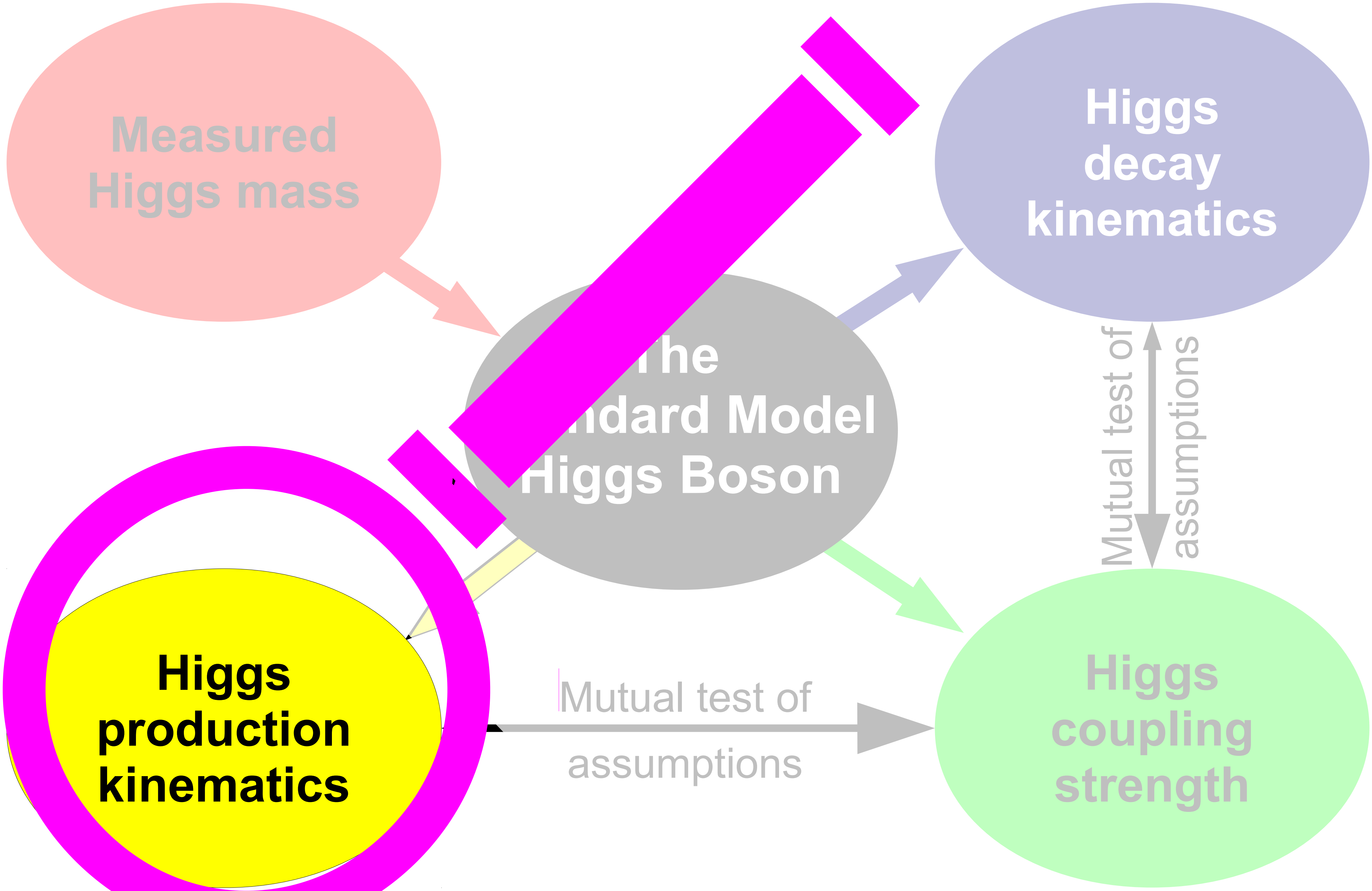
- **Energy scale and resolution systematic uncertainties dominate**



All parameters of the SM are now known

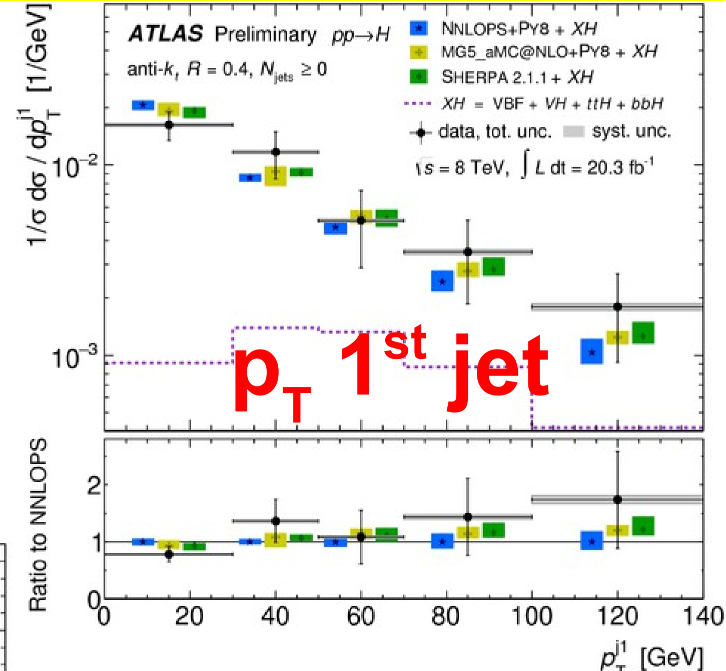


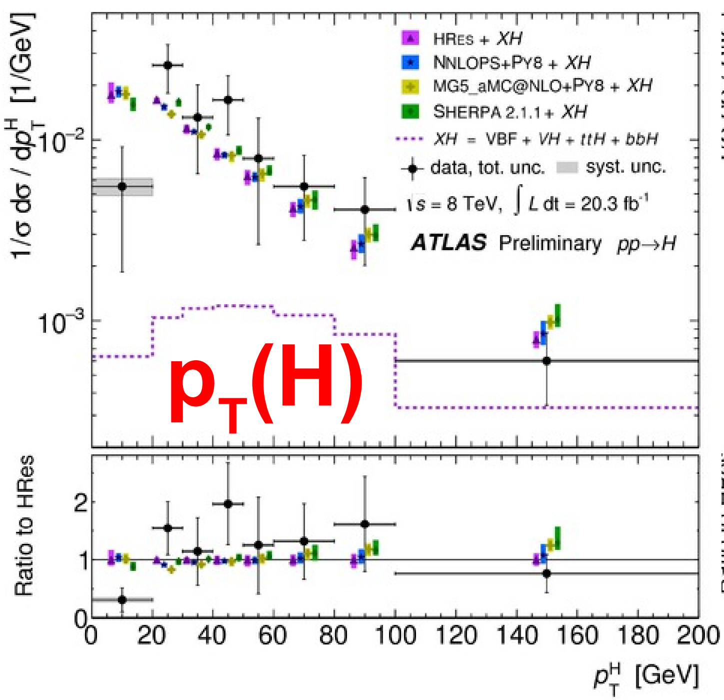
Higgs combination: testing the SM

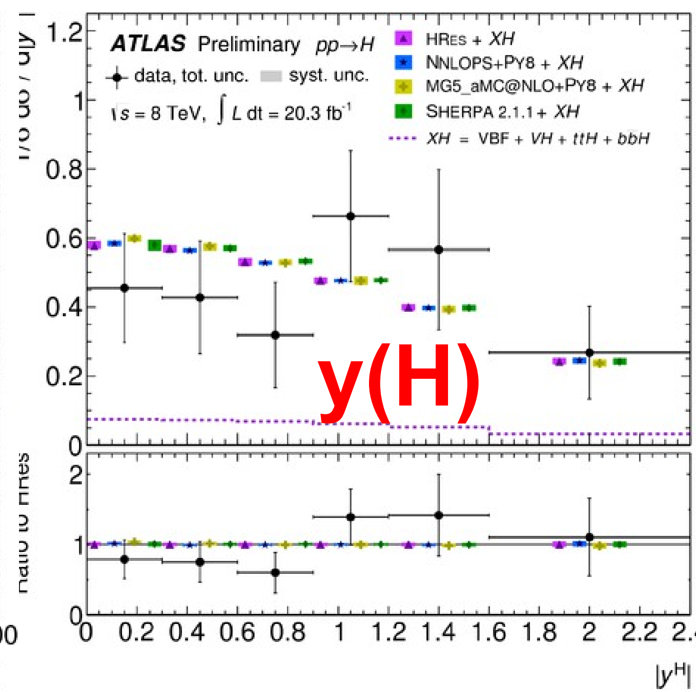


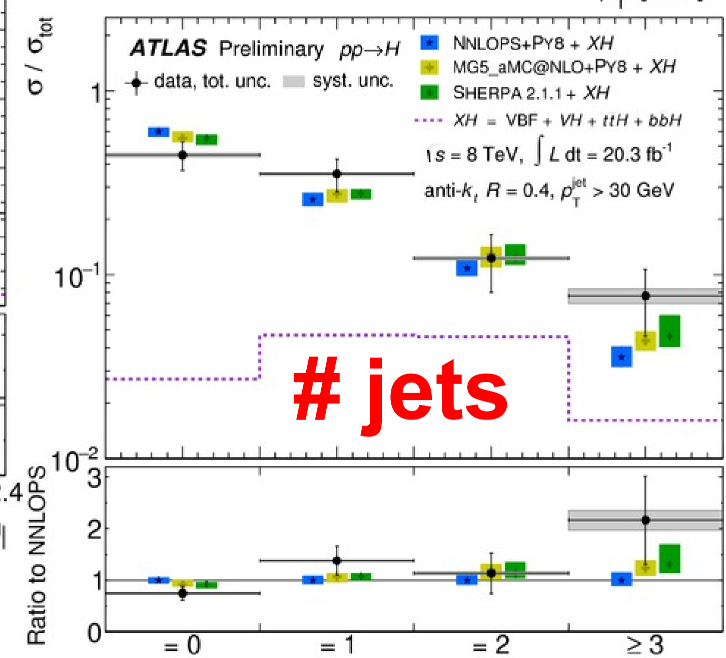
Higgs and associated jet kinematics

- Combination of differential measurements for the production kinematic distributions in $H \to 4l$ and $H \to \gamma\gamma$
- Here: combination of shapes in order to be independent of BR assumptions
- So far dominant sensitivity to $gg \to H$







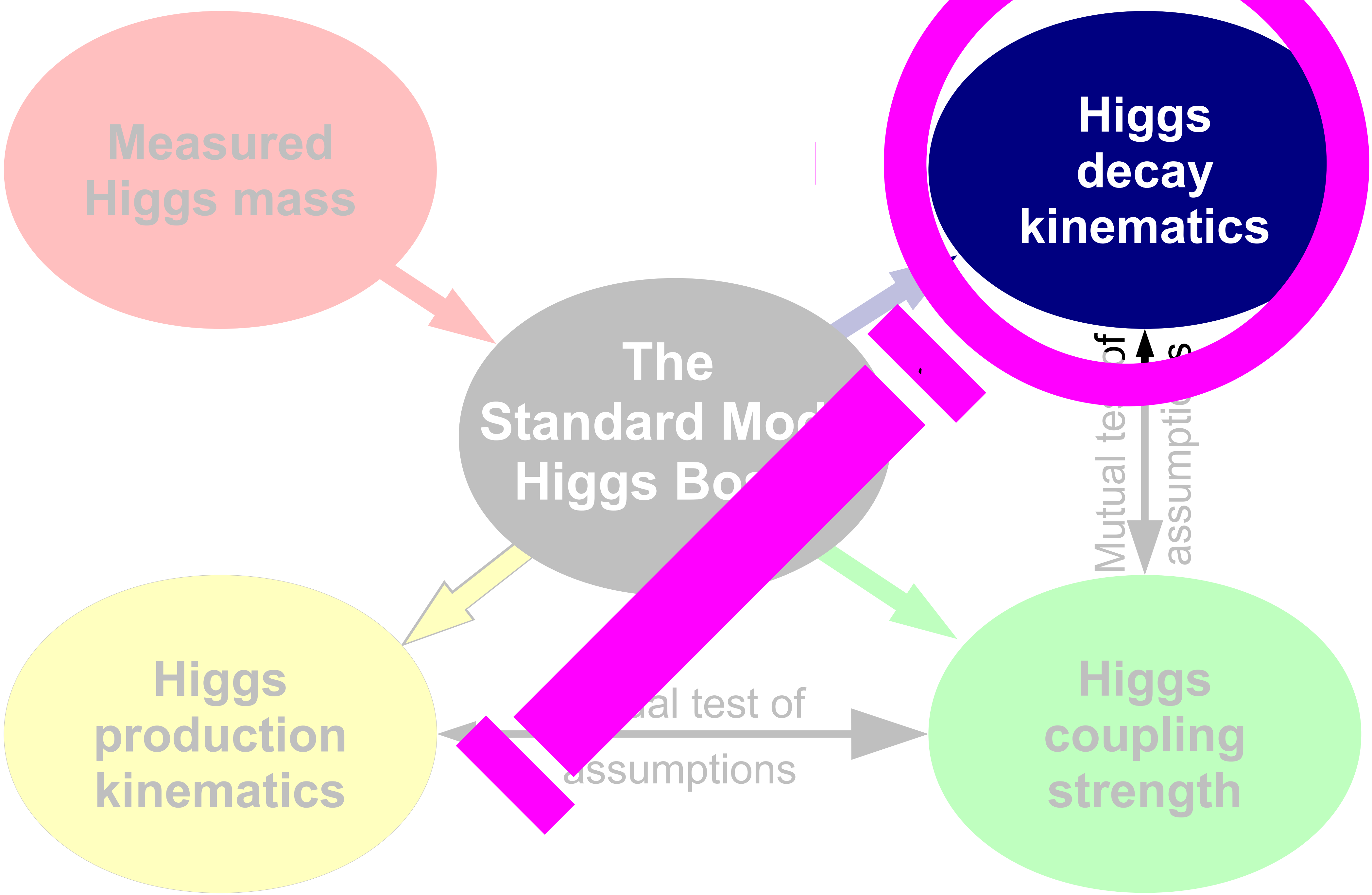


- Results are consistent with the SM !

to be submitted to PRL

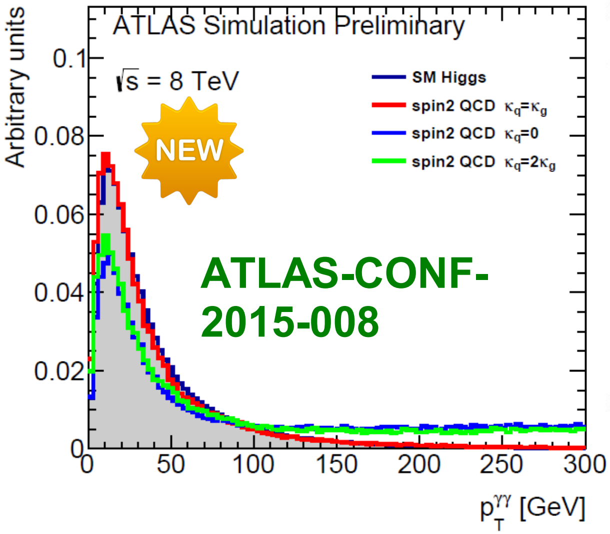
N_{jets}

Higgs combination: testing the SM



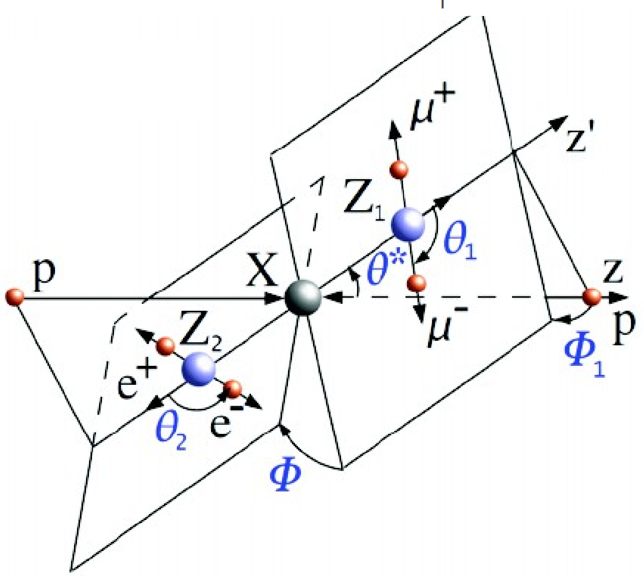
Decay kinematics in H→ZZ and H→WW

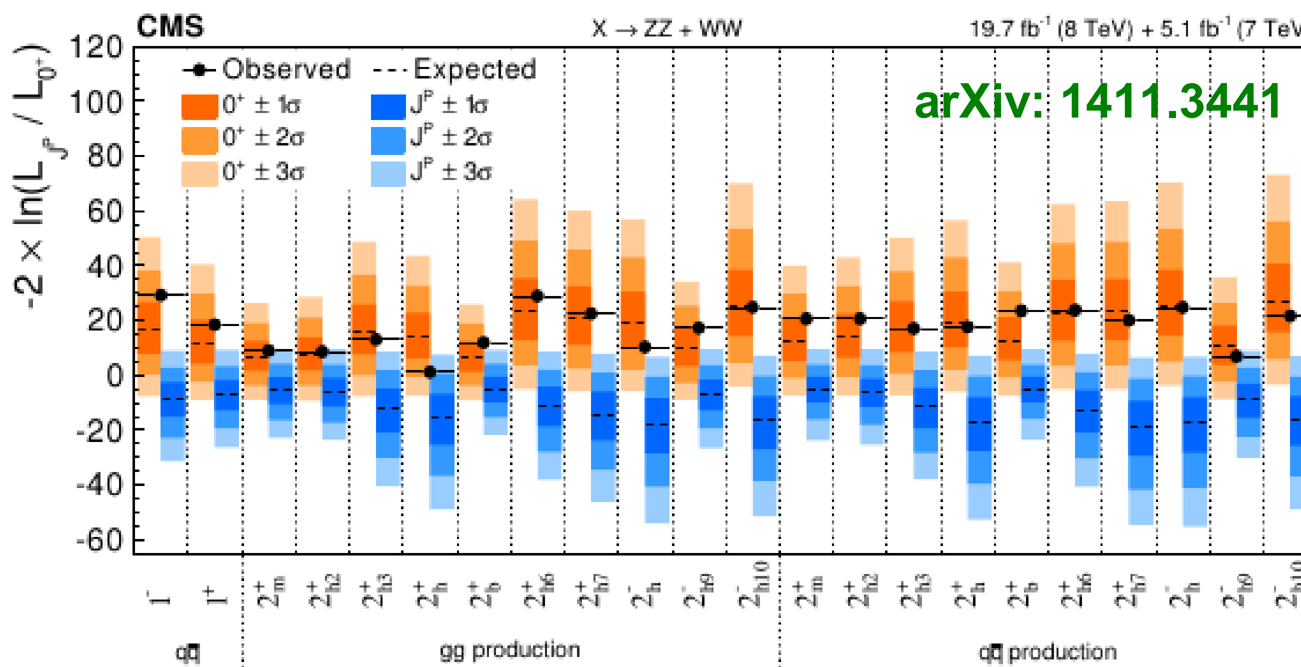
- **Deviations from the SM in the decay kinematics are currently probed through Spin/CP hypothesis tests and measurements**
- **Spin 1+2 hypothesis (in many variants) are excluded at >95%CL**



NEW ATLAS

Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$





Decay kinematics in H→ZZ and H→WW

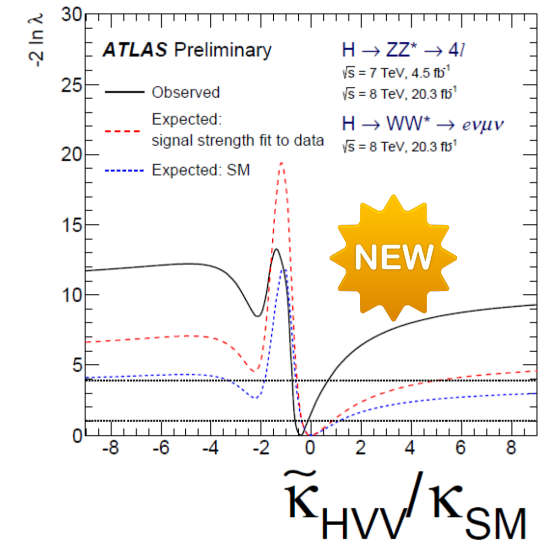
- **Measurement of anomalous couplings for the Spin 0 hypothesis, equivalent to EFT Lagrangian:**

$$L(HVV) \sim a_1 \frac{m_Z^2}{2} HZ^\mu Z_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 HZ_\mu \Box Z^\mu - \frac{1}{2} a_2 HZ^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 HZ^{\mu\nu} \tilde{Z}_{\mu\nu}$$

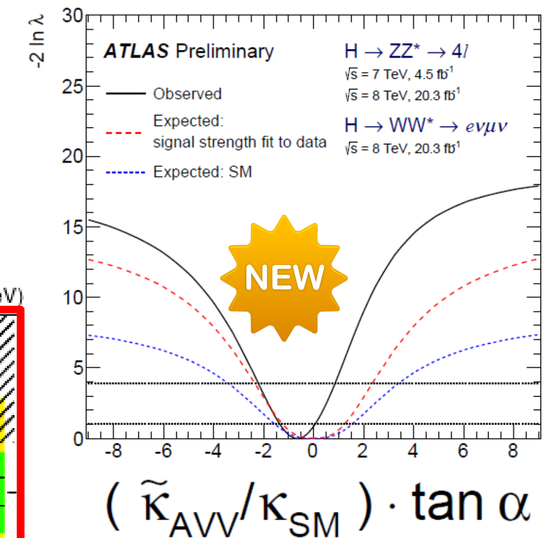
$$+ a_1^{WW} \frac{m_W^2}{2} HW^\mu W_\mu + \frac{1}{(\Lambda_1^{WW})^2} m_W^2 HW_\mu \Box W^\mu - \frac{1}{2} a_2^{WW} HW^{\mu\nu} W_{\mu\nu} - \frac{1}{2} a_3^{WW} HW^{\mu\nu} \tilde{W}_{\mu\nu}$$

$$+ \frac{1}{(\Lambda_1^{Z\gamma})^2} m_Z^2 HZ_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} HF^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} HF^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} HF^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} HF^{\mu\nu} \tilde{F}_{\mu\nu},$$

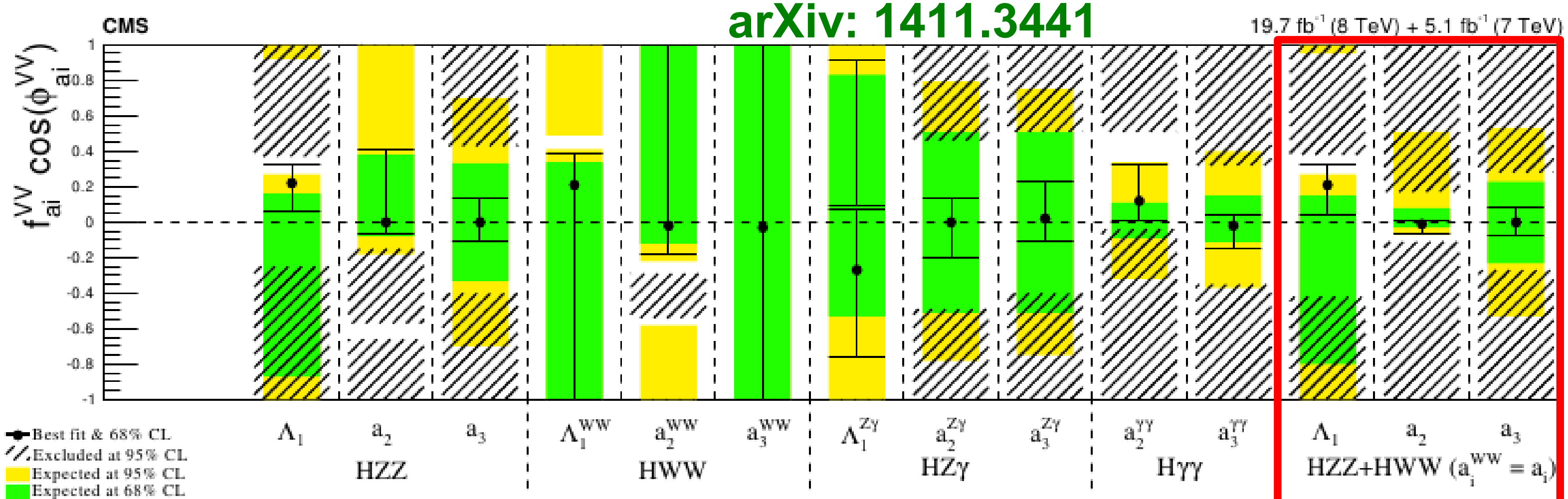
- **Combination: assume $a_i = a_i^{WW}$, $\kappa_i^{ZZ} = \kappa_i^{WW}$**
- **See Giacinto's and Josh's talks for details**
- **All results consistent with the SM !**



ATLAS-CONF-2015-008



arXiv: 1411.3441



Decay kinematics in H→ZZ and H→WW

- **Unfortunately ATLAS and CMS don't use the same convention for CP measurements**
- **Fortunately, its possible to translate → using CMS convention here**

$$f_{a_2} = \frac{|\tilde{k}_{HVV}|^2\sigma_{HVV}}{|k_{\rm SM}|^2\sigma_{\rm SM} + |\tilde{k}_{HVV}|^2\sigma_{HVV}},\ \phi_{a_2} = \arg\left(\frac{\tilde{k}_{HVV}}{k_{\rm SM}}\right)$$

$$f_{a_3} = \frac{|\tilde{k}_{AVV}\tan\alpha|^2\sigma_{AVV}}{|k_{\rm SM}|^2\sigma_{\rm SM} + |\tilde{k}_{AVV}\tan\alpha|^2\sigma_{AVV}},\ \phi_{a_3} = \arg\left(\frac{\tilde{k}_{AVV}\tan\alpha}{k_{\rm SM}}\right)$$

- BSM CP-even (95% CL)

CMS $f_{a2}\cos(\phi_{a2}) \in [-0.11, 0.17]$

ATLAS $f_{a2} < 0.12$ for $\phi_{a2} = 0$

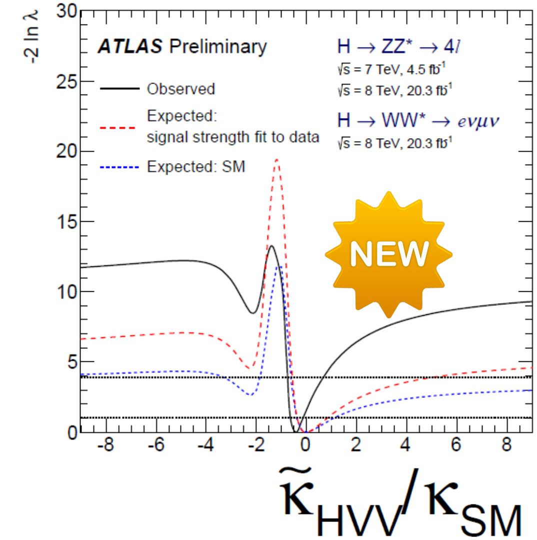
$f_{a2} < 0.16$ for $\phi_{a2} = \pi$

- BSM CP-odd (95% CL)

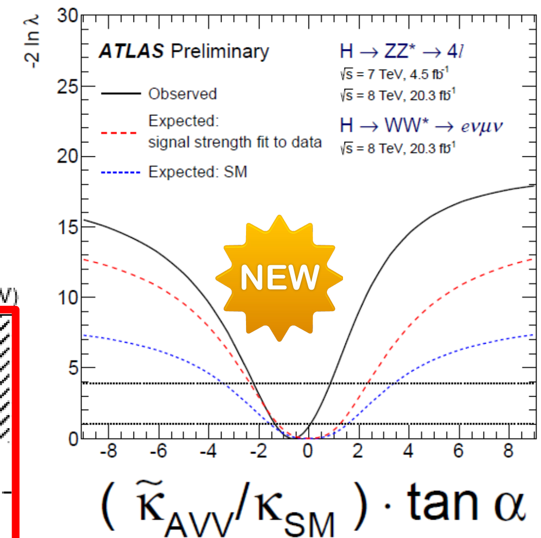
CMS $f_{a3}\cos(\phi_{a3}) \in [-0.27, 0.28]$

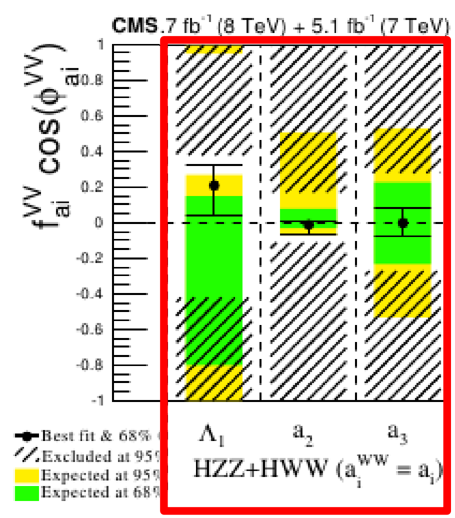
ATLAS $f_{a3} < 0.090$ for $\phi_{a3} = 0$

$f_{a3} < 0.41$ for $\phi_{a3} = \pi$

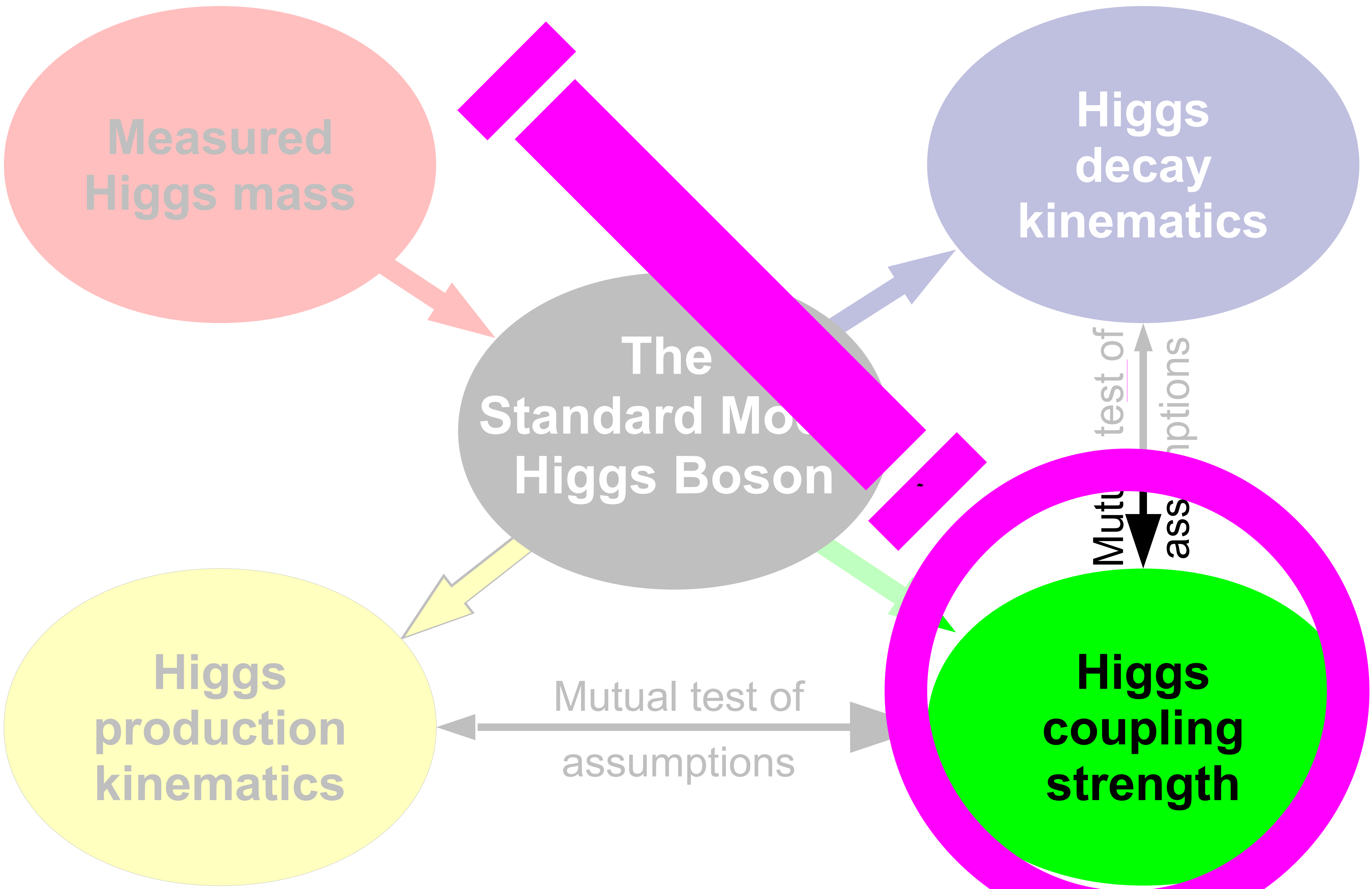


ATLAS-CONF-2015-008





Higgs combination: testing the SM

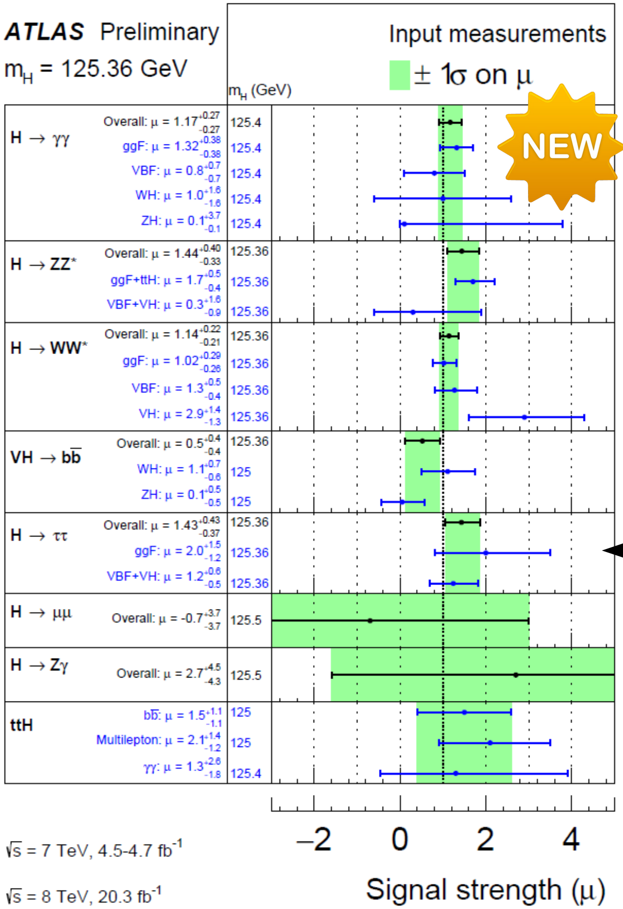


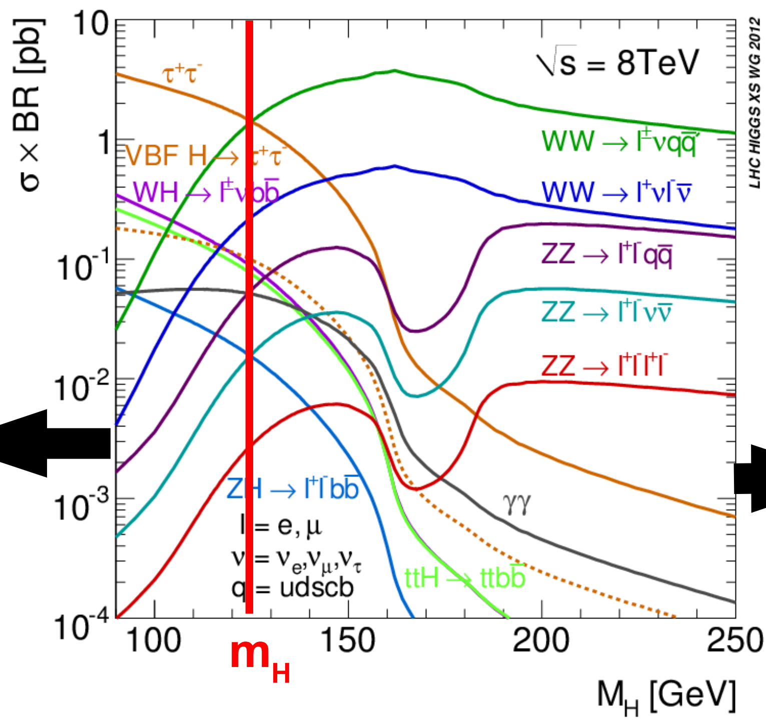
Combination: Measuring signal strength

- **Measure the ratio μ between the observed rate and the SM expectation for σ x BR in all Higgs analysis**
- **Assumes SM kinematics for production and decay !**

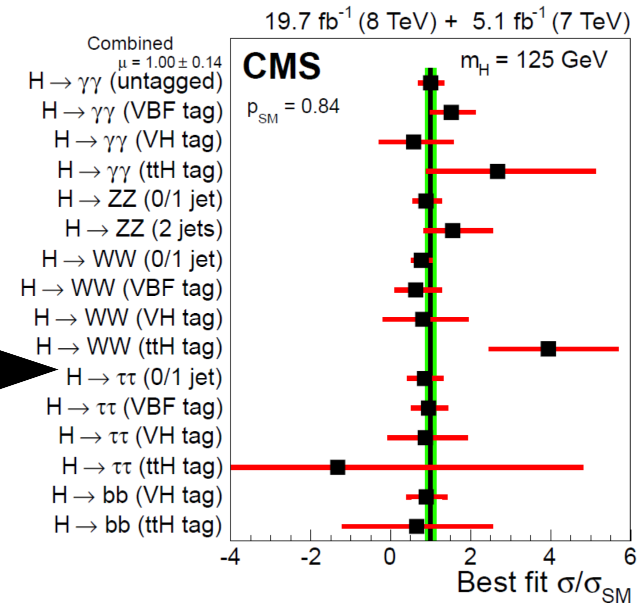
Main inputs to ATLAS combination
ATLAS-CONF-2015-007

Mass m_H:
ATLAS: 125.36 GeV, CMS: 125.02 GeV





Main inputs to CMS combination
arXiv: 1412.8662



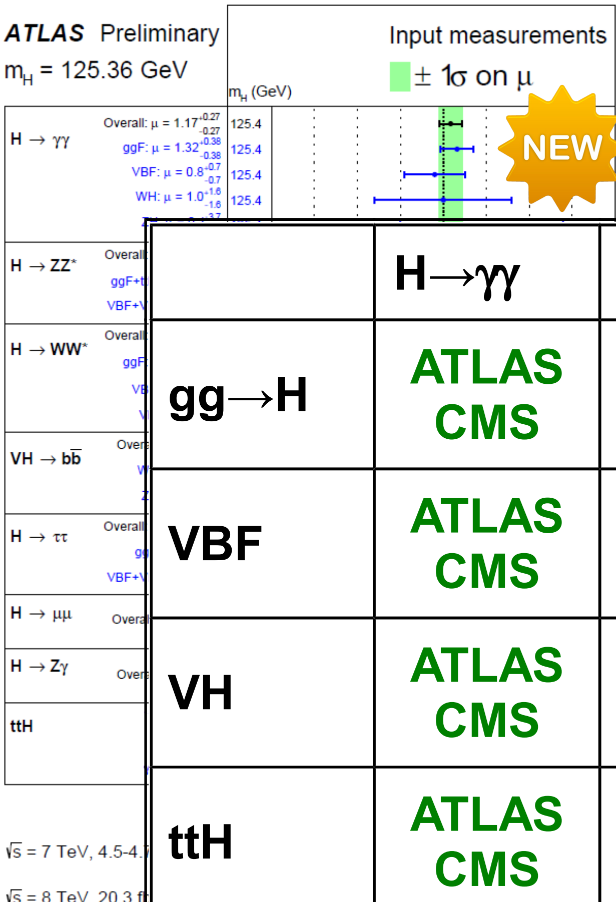
Combination: Measuring signal strength

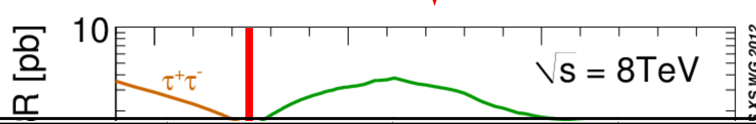
- Measure the ratio μ between the observed rate and the SM expectation for σ x BR in all Higgs analysis
- Assumes SM kinematics for production and decay !

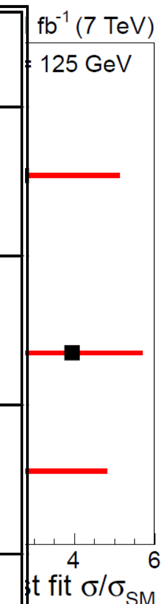
Main inputs to ATLAS combination
ATLAS-CONF-2015-007

Mass m_H:
ATLAS: 125.36 GeV, CMS: 125.02 GeV

Main inputs to CMS combination
arXiv: 1412.8662



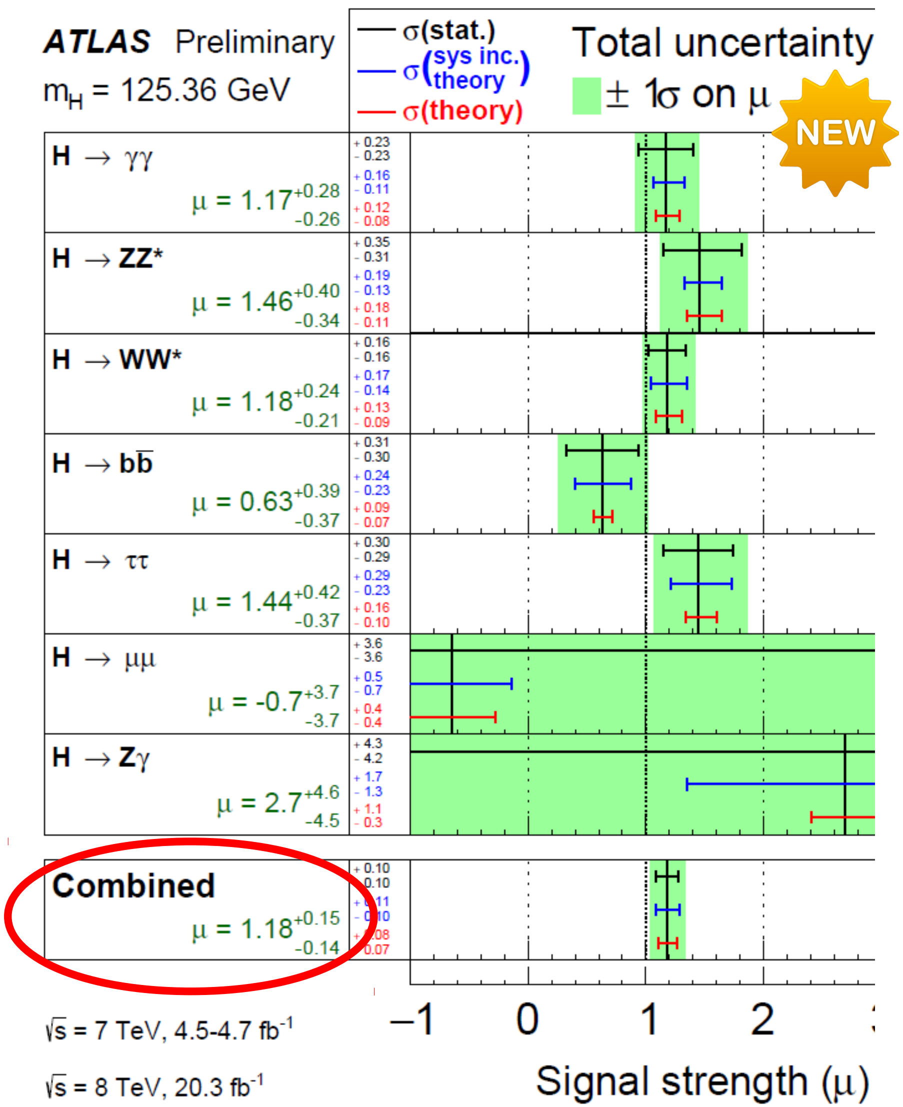


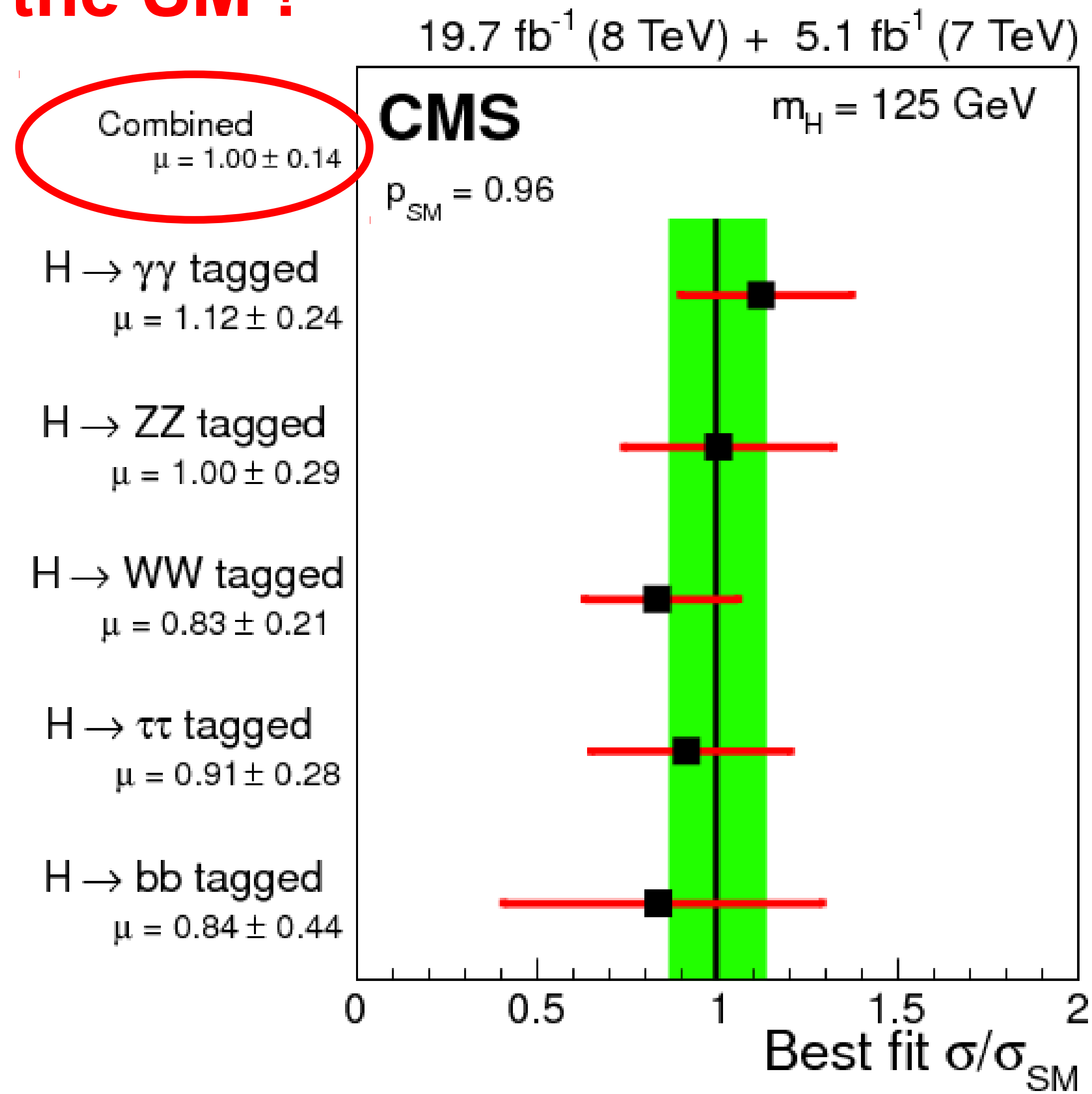


	H→γγ	H→ZZ	H→WW	H→ττ	H→bb	H→Zγ	H→μμ
gg→H	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VH	ATLAS CMS	ATLAS CMS	ATLAS CMS	- CMS	ATLAS CMS	ATLAS CMS	- CMS
ttH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		

Signal strength: grouping by decay

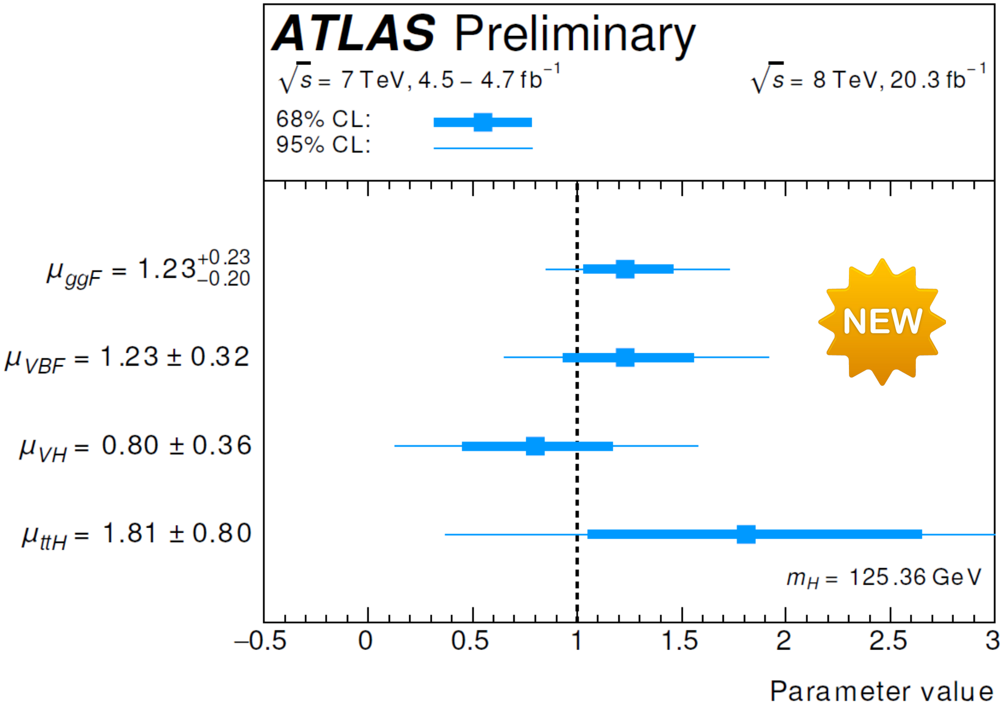
- **SM values for ratios between different production cross sections are assumed**
- **Results are consistent with the SM !**

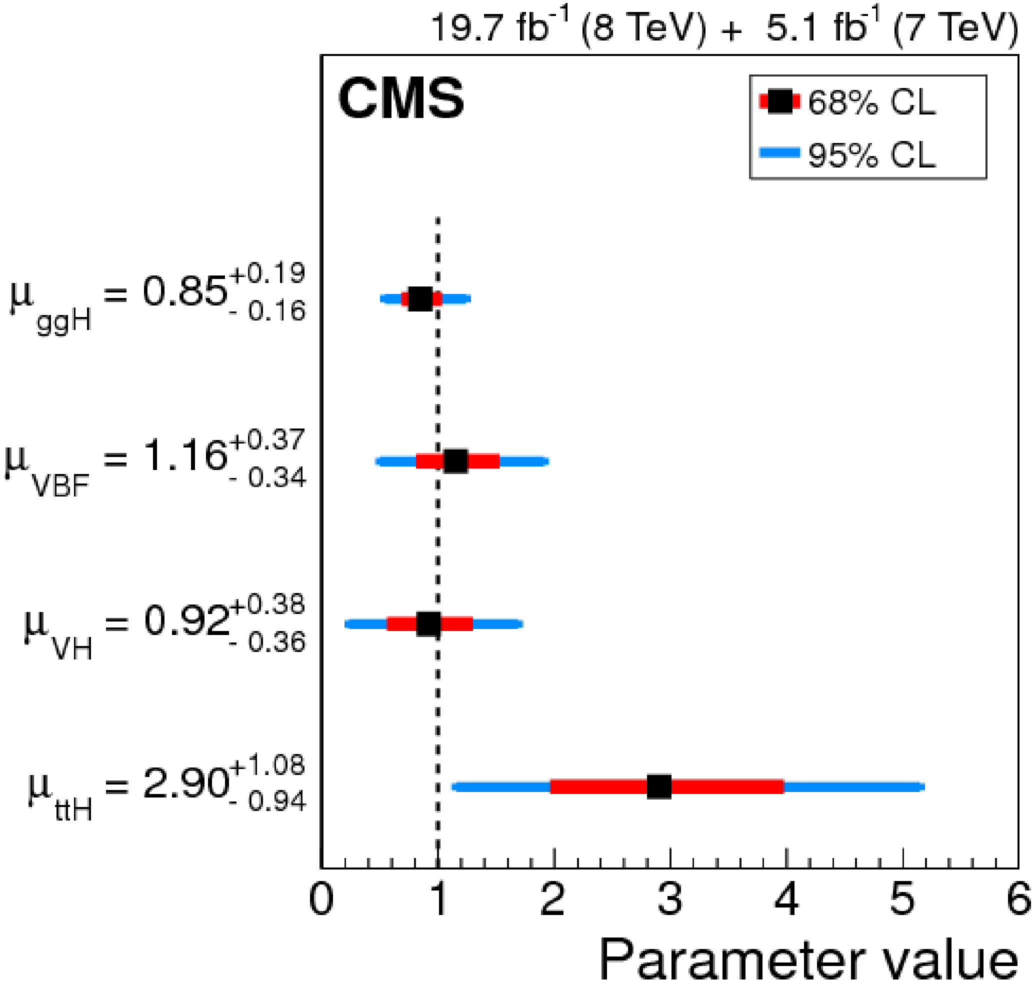




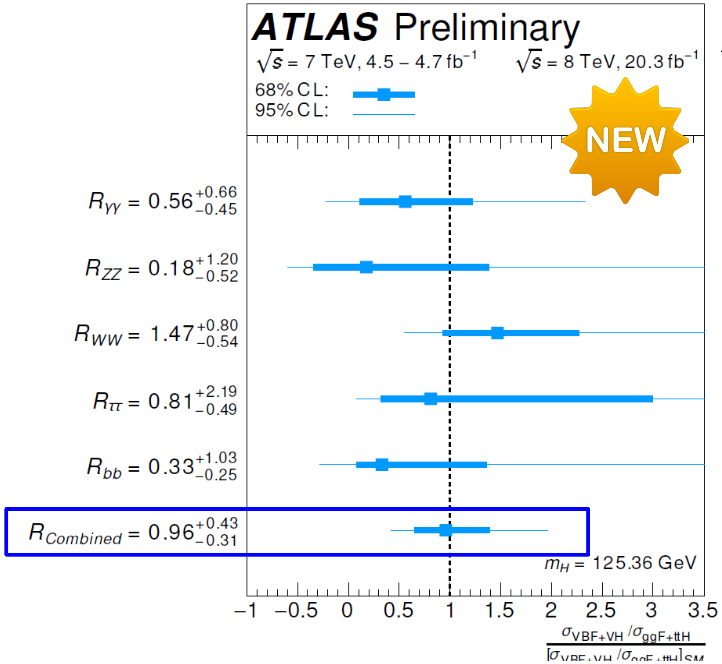
Signal strength: grouping by production

- **SM values for ratios between different branching fractions are assumed**
- **Results are consistent with the SM !**
  (but we can keep hoping for a ttH excess beyond the SM)



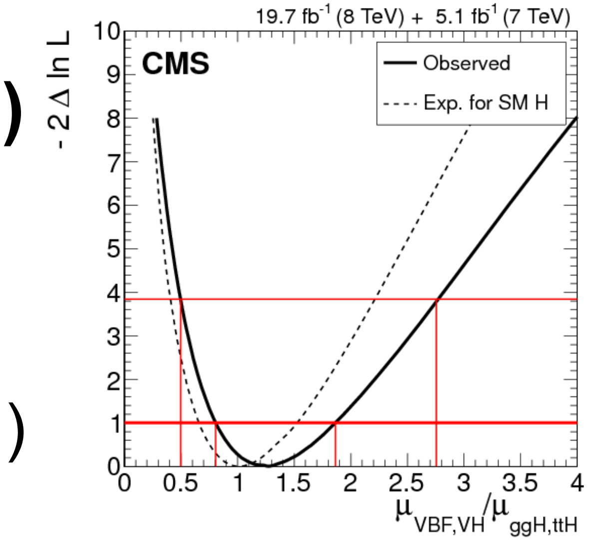


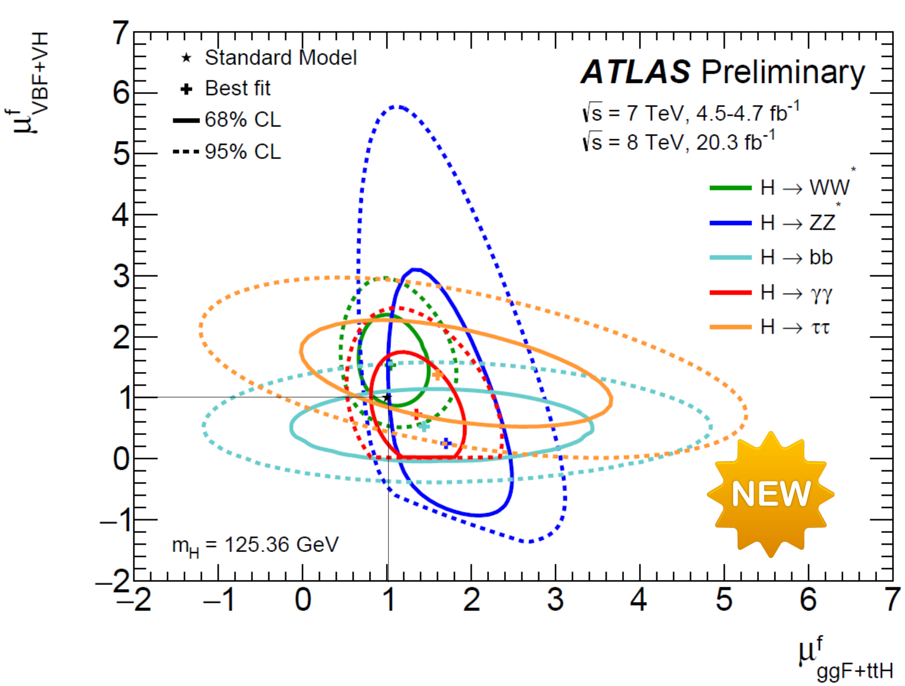
Signal strength: gg→H versus VBF



Avoids assumptions:

- **Separates gg→H (+ttH) from VBF (+VH) in each final state**
- **BR(H→ff) cancels in ratio** (VBF+VH)/(ggH+ttH)
- **Result consistent with the SM expectation**





Significance VBF:

ATLAS

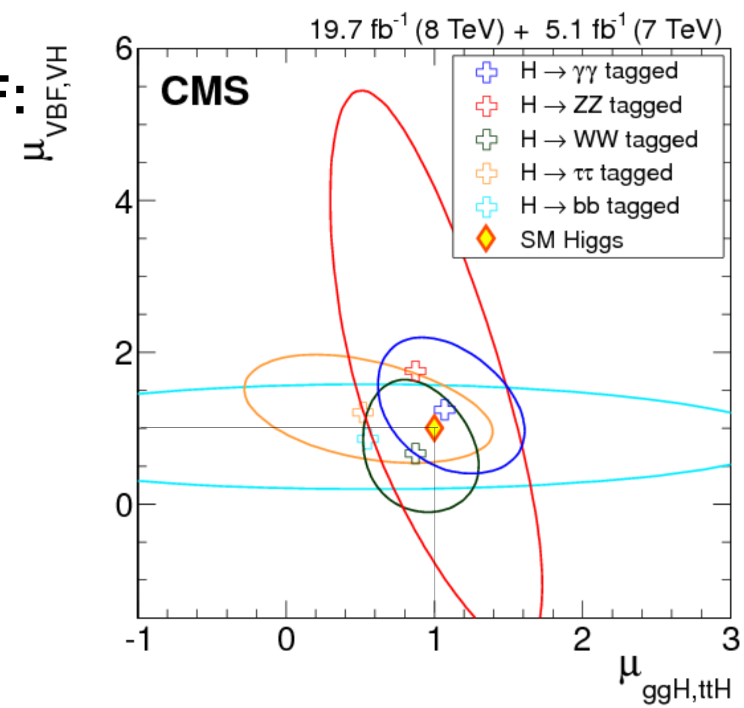
μ(VBF) / μ(ggH)

4.3σ (3.8σ exp.)

CMS (assuming BR as in SM)

μ(VBF)

3.7σ (3.3σ exp.)



κ-framework: coupling "measurements"

- **The coupling strength g of the Higgs to other SM particles is the most characteristic footprint. It scales with the mass:**

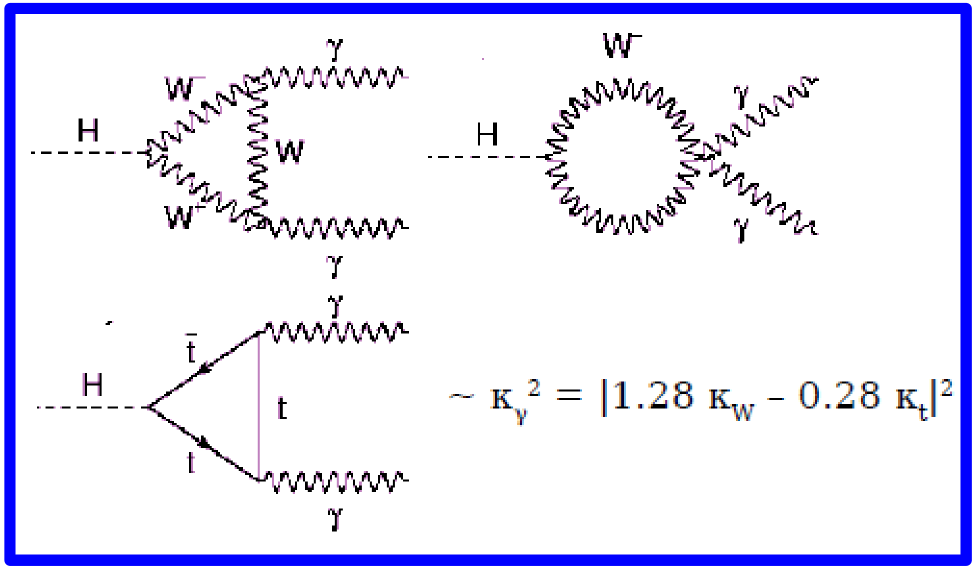
Fermions: $g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$ **Gauge bosons:** $g_V = \kappa_V \frac{2 m_V^2}{v}$

- **Encode deviations from SM with coupling scale factors κ_i**
  - **Production:** $\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$
  - **Decay:** $\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$
  - **Total width:** $\Gamma_H = \Sigma_i \, \kappa_i^2 \, \Gamma_i^{SM}$

Example:

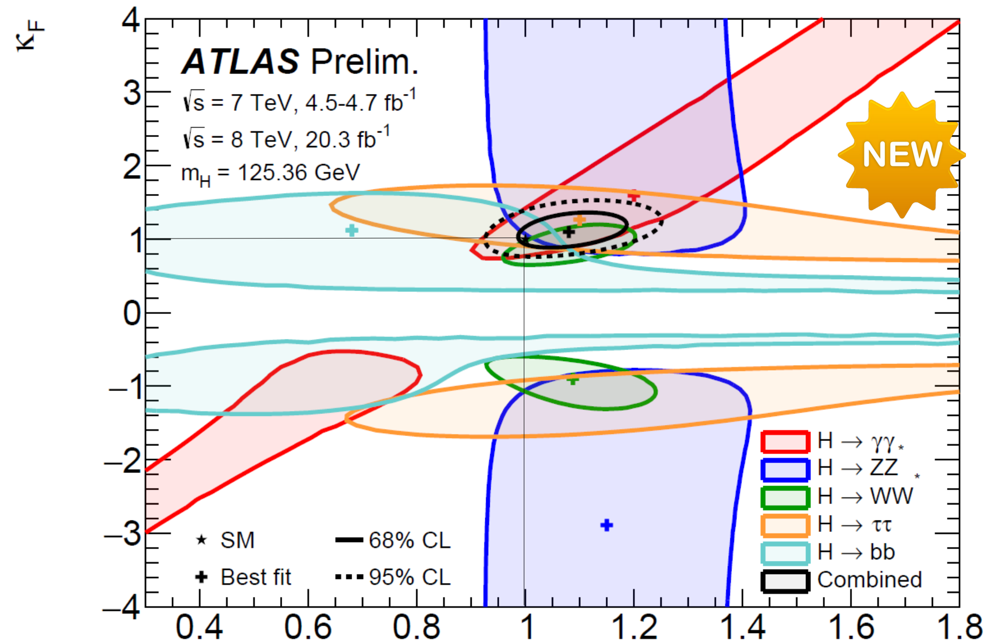
$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

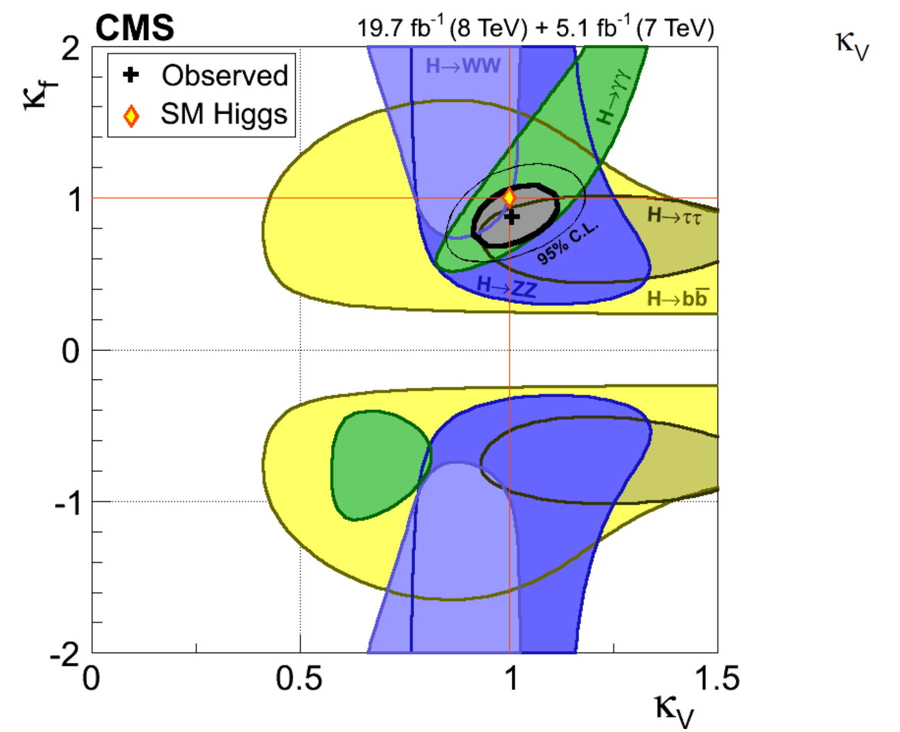
  - **SM: by definition for all $\kappa_i = 1$**
  - **Interference in H→γγ, gg→H, ...:**
    → some sign-ambiguities
- **Assumptions:**
  - Only one Higgs
  - <u>only scalar</u> modifications of the coupling strength: VH, VBF, gg→H, H→VV, ... kinematics as in SM



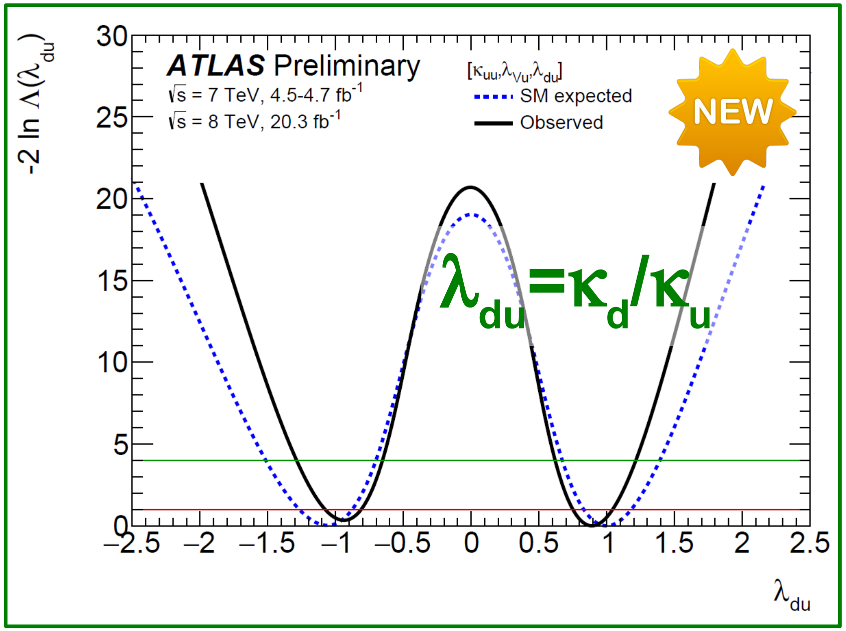
Couplings to fermions and gauge bosons

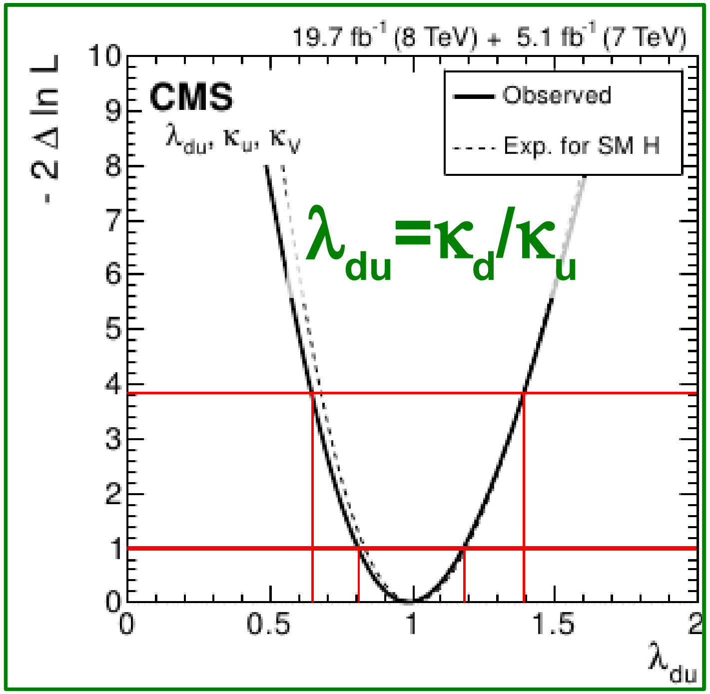
- **Test of fundamental difference between Yukawa and gauge couplings using independent scale factors for fermions and gauge bosons: κ_F and κ_V**
- **Assume: no BSM contributions to the total width Γ_H or to the $gg\rightarrow H$ + $H\rightarrow\gamma\gamma$ + $H\rightarrow Z\gamma$ loops beyond the effects from κ_F and κ_V**
- **κ_F sign ambiguity resolved from interference in $H\rightarrow\gamma\gamma$, tH, $gg\rightarrow ZH$**
- **Individual channels converge on the SM quadrant and agree well with each other and the SM within uncertainties**





Couplings in the fermion sector





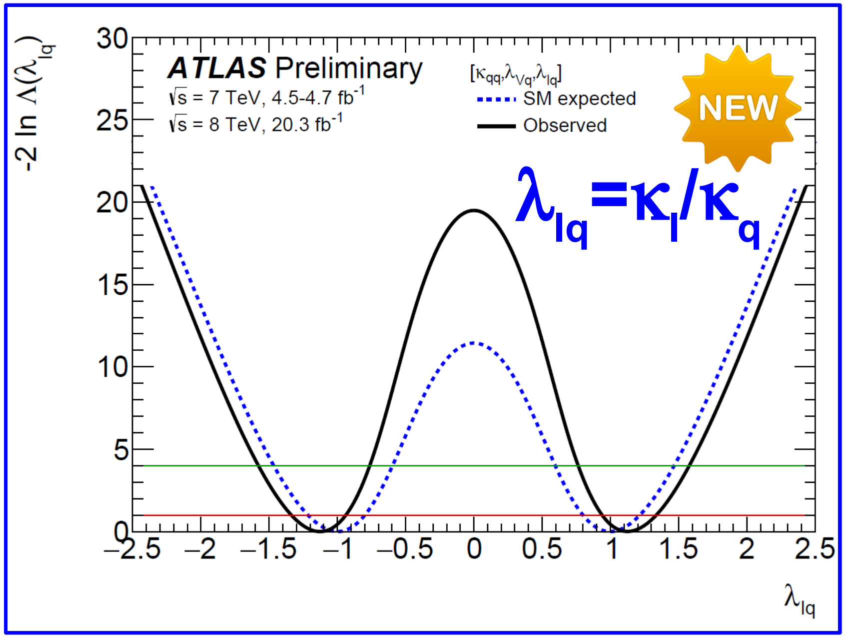
2HDM motivated: ratios of couplings in the fermion sector

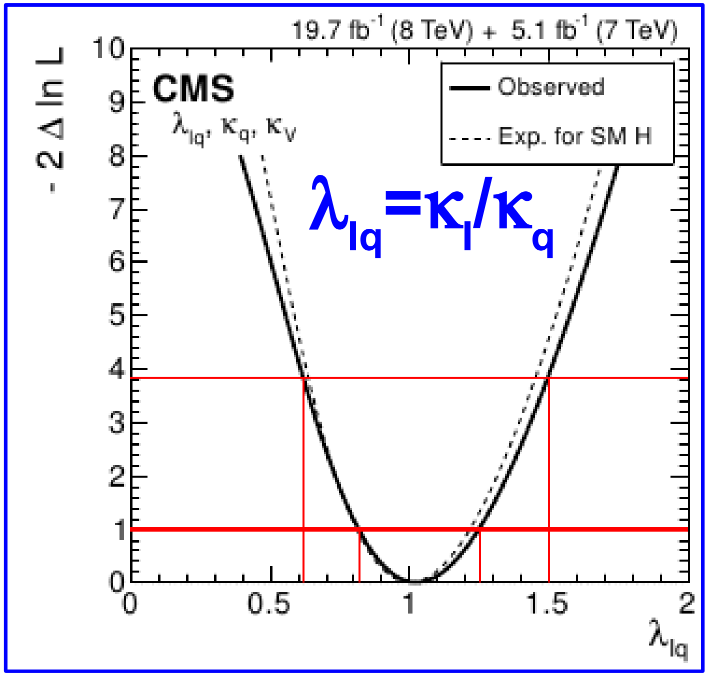
- **between down- and up-type fermions**

and

- **between leptons and quarks**

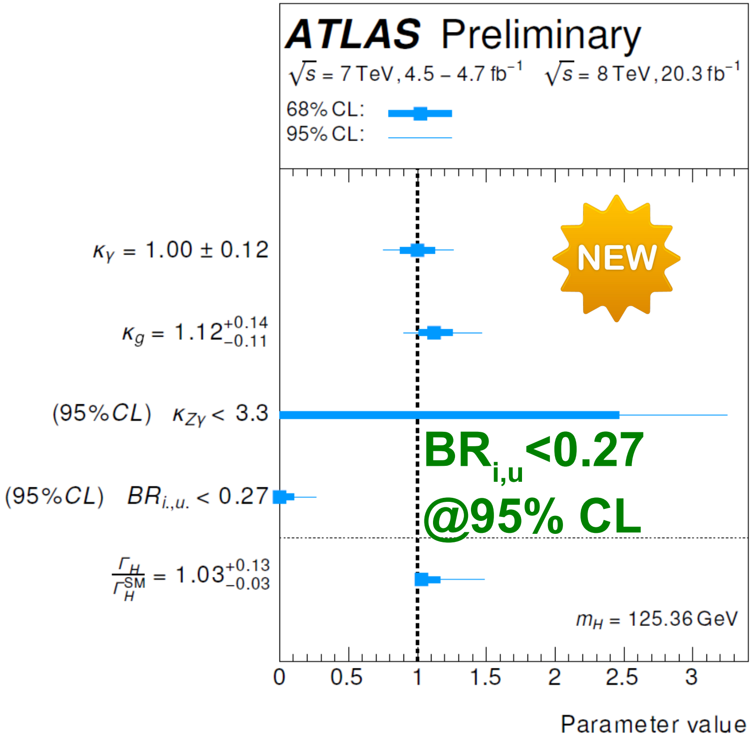
For both: very good agreement to the SM expectation!



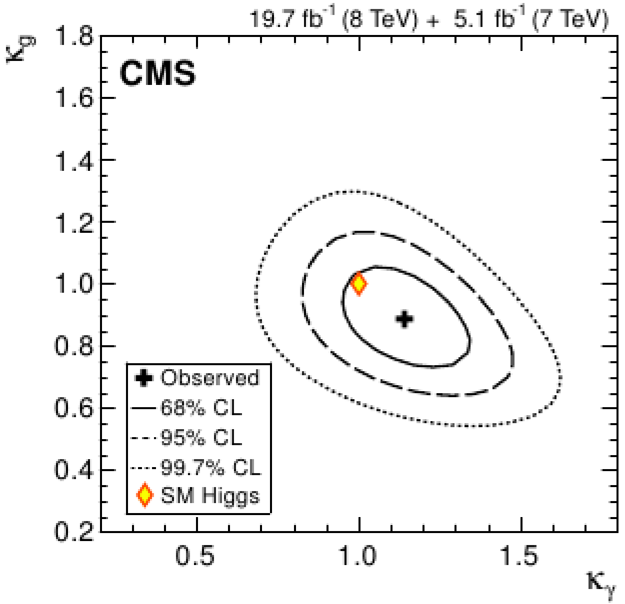


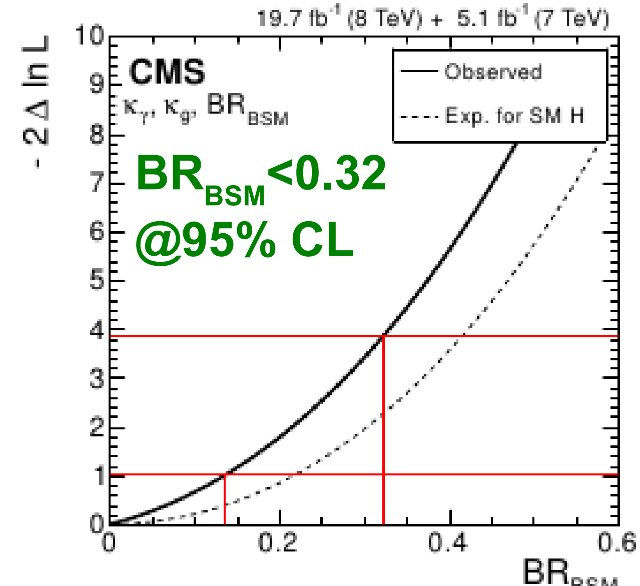
BSM contributions to gg→H and H→γγ loops

- The gg→H, H→γγ and H→Zγ loops are especially sensitive to BSM particles. Previous fits allowed only SM particles in these loops
- Determine effective coupling scale factors for these loop induced couplings: κ_g, κ_γ and $\kappa_{Z\gamma}$. Assume all other tree level couplings as in the SM: κ_i=1 for i=W, Z, t, b, τ, ...
- Can in addition fit a BSM Higgs branching ratio $B_{i,u}$ to invisible or undetectable final states (complementary to H→invisible searches)



- Results compatible with the SM expectation

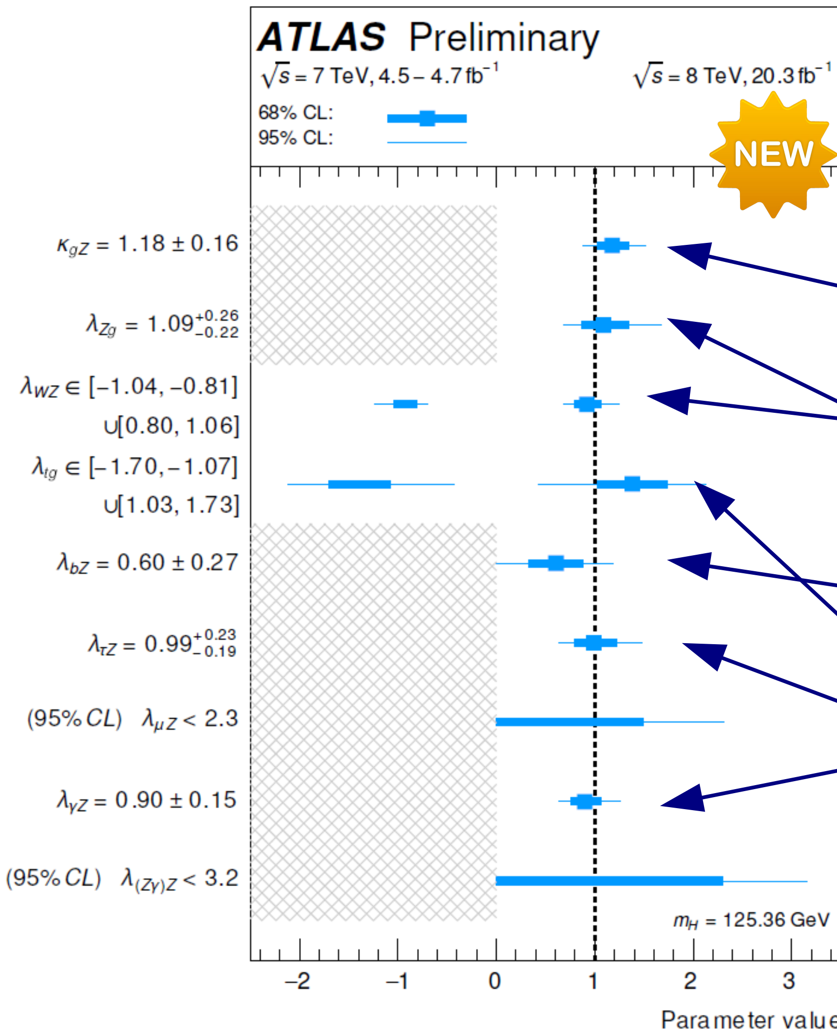




BR_{inv}<0.32 incl. H→inv. search

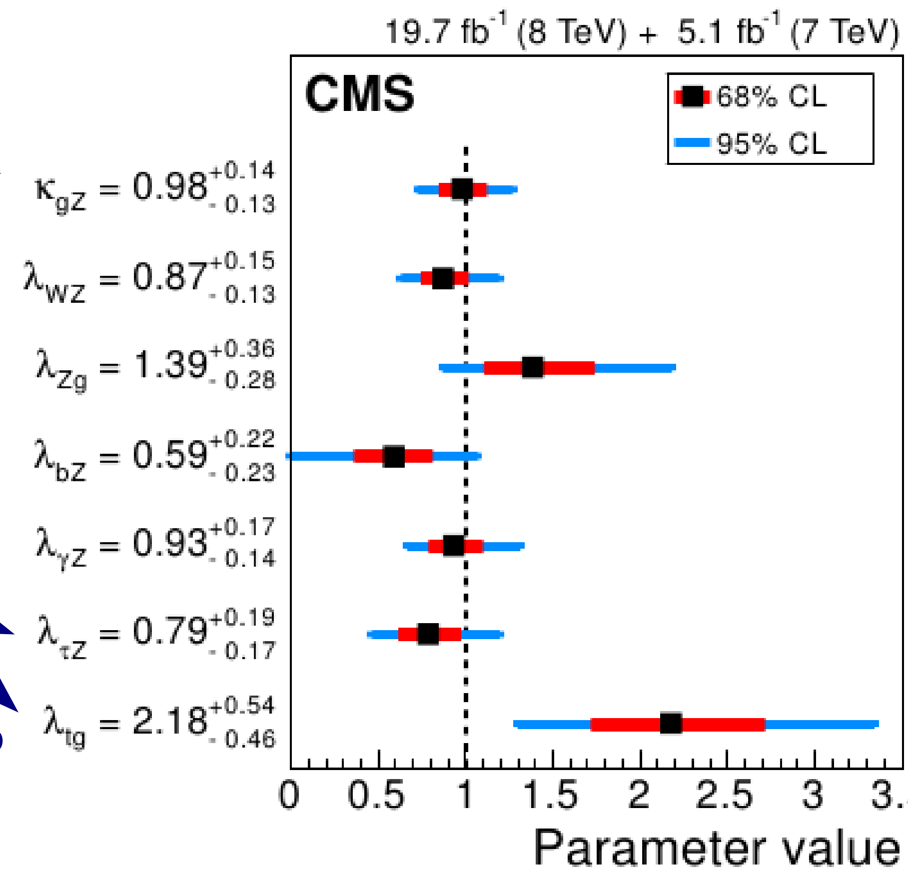
Generic fit to Higgs coupling ratios

- **Most general "measurement" within the κ-framework:**
  - **No assumption on particle content in gg→H, H→γγ, H→Zγ loops**
  - **No assumptions on BSM Higgs decay modes or total width**
- **Drawback at the LHC: can only fit ratios of couplings $\lambda_{XY}=\kappa_X/\kappa_Y$**

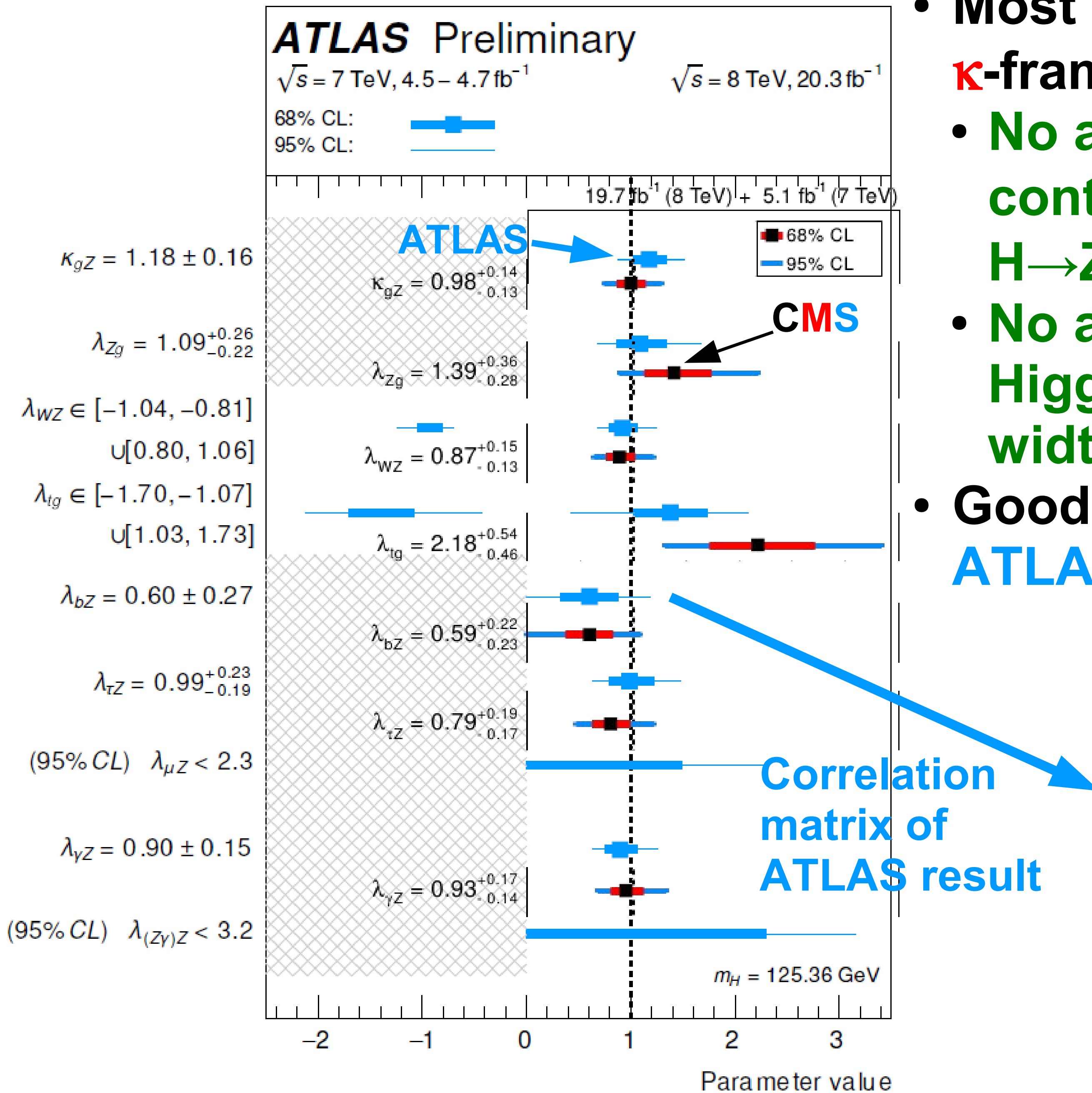


- **Results compatible with the SM expectation**

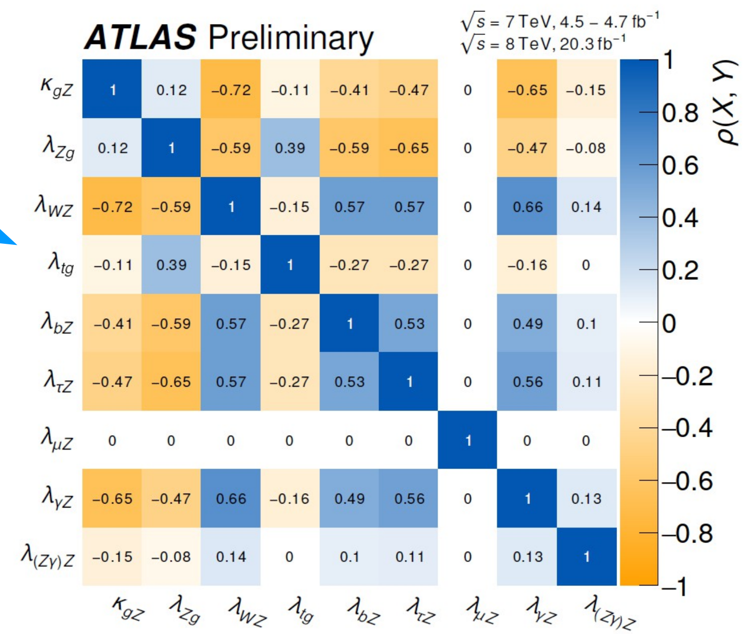
Rather difficult to compare



Generic fit to Higgs coupling ratios



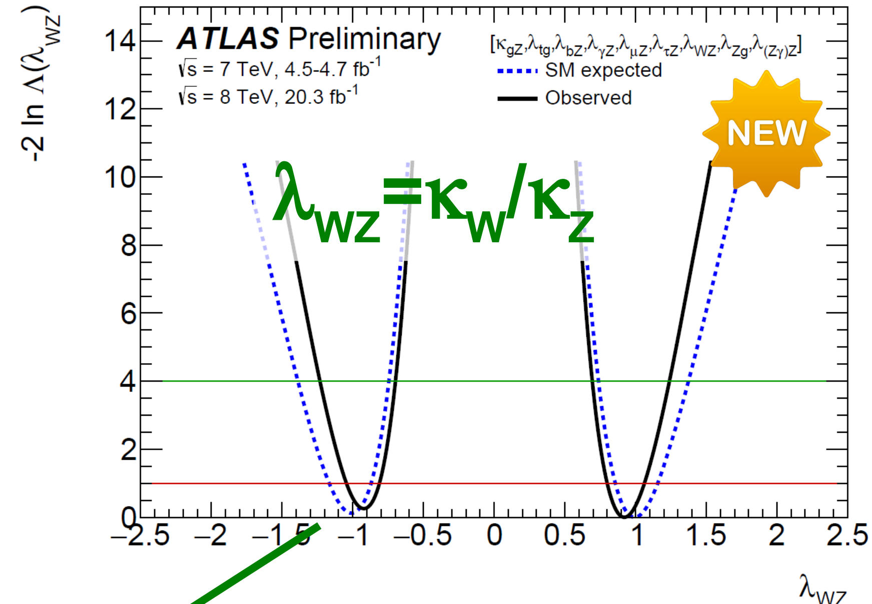
- **Most general fit within the κ-framework:**
  - **No assumption on particle content in gg→H, H→γγ, H→Zγ loops**
  - **No assumptions on BSM Higgs decay modes or total width**
- **Good agreement between ATLAS and CMS**



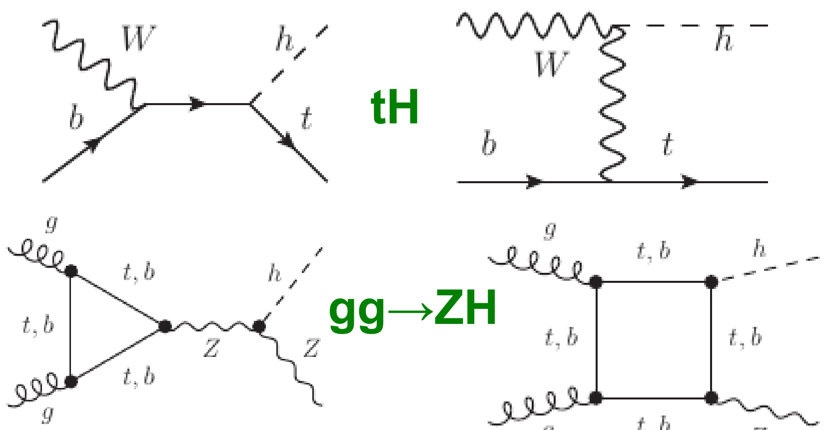
	κ_{gZ}	λ_{Zg}	λ_{WZ}	λ_{tg}	λ_{bZ}	$\lambda_{\tau Z}$	$\lambda_{\mu Z}$	$\lambda_{\gamma Z}$	$\lambda_{(Z\gamma)Z}$
κ_{gZ}	1	0.12	−0.72	−0.11	−0.41	−0.47	0	−0.65	−0.15
λ_{Zg}	0.12	1	−0.59	0.39	−0.59	−0.65	0	−0.47	−0.08
λ_{WZ}	−0.72	−0.59	1	−0.15	0.57	0.57	0	0.66	0.14
λ_{tg}	−0.11	0.39	−0.15	1	−0.27	−0.27	0	−0.16	0
λ_{bZ}	−0.41	−0.59	0.57	−0.27	1	0.53	0	0.49	0.1
$\lambda_{\tau Z}$	−0.47	−0.65	0.57	−0.27	0.53	1	0	0.56	0.11
$\lambda_{\mu Z}$	0	0	0	0	0	0	1	0	0
$\lambda_{\gamma Z}$	−0.65	−0.47	0.66	−0.16	0.49	0.56	0	1	0.13
$\lambda_{(Z\gamma)Z}$	−0.15	−0.08	0.14	0	0.1	0.11	0	0.13	1

Couplings to W- and Z- bosons

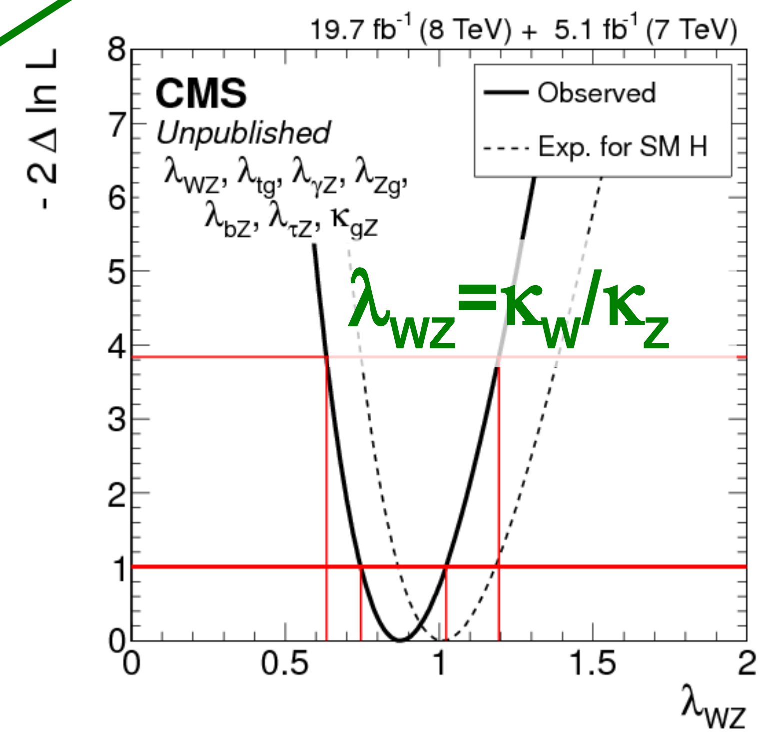
- **Custodial symmetry imposes the SM coupling ratio between the W and Z Higgs couplings (and ρ=1 as measured @ LEP)**
- **Measure coupling ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$ in the most generic model to avoid assumptions on other couplings**
- **Results consistent with the SM**



Some sensitivity to the relative sign between the W and Z coupling due to tH and gg→ZH production

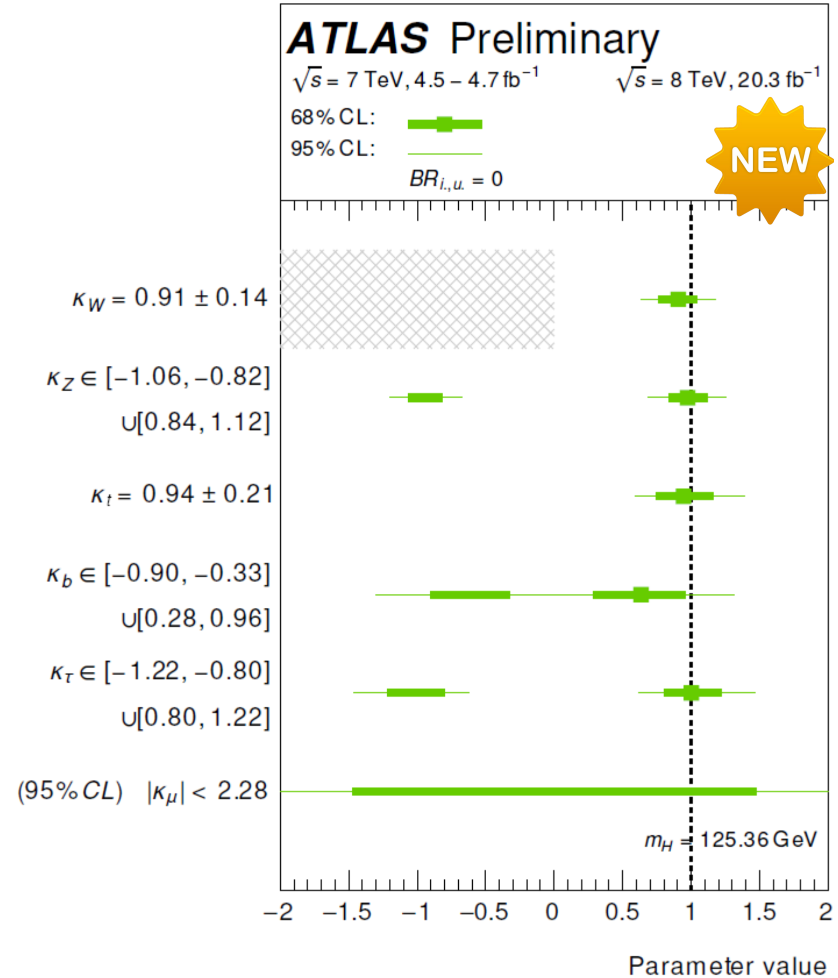


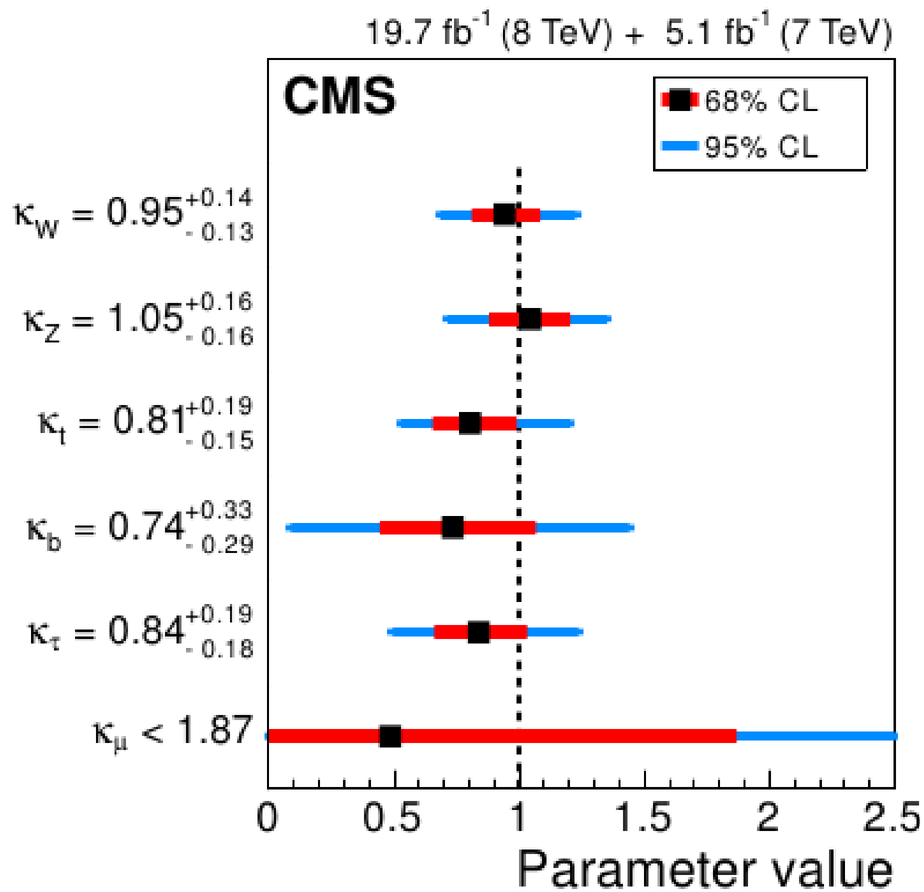
Warning: these interference effects show up in kinematic distributions. **Reaching the limit of the κ-framework!**



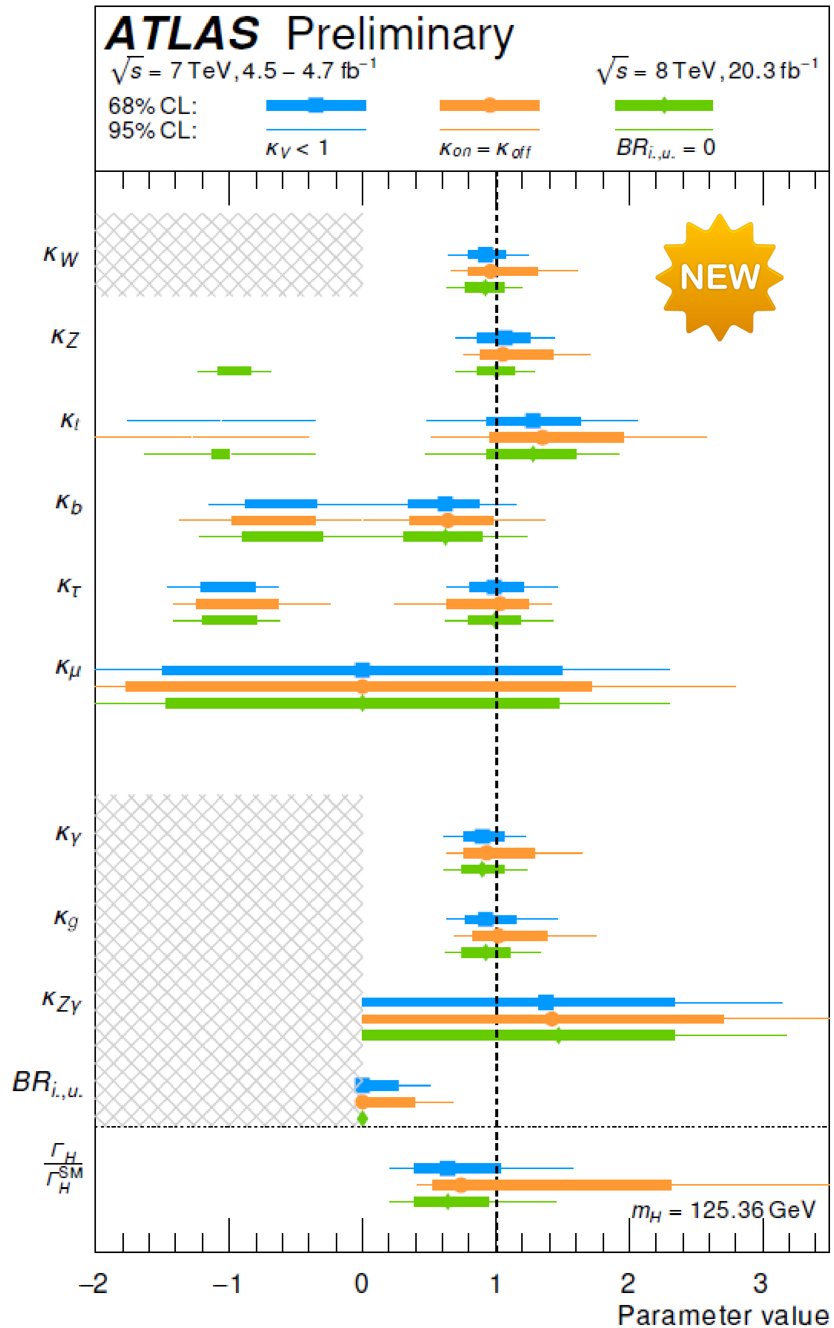
Determination of absolute Higgs couplings

- **Absolute Higgs coupling "measurements" need some theory assumptions at the LHC to provide an upper bound on one coupling or the width Γ_H. Usually: assume no BSM decays: $B_{i,u}=0$**
- **Here also assume only SM particles in $gg \rightarrow H$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ loops**
- **All results compatible between ATLAS and CMS and with the SM**



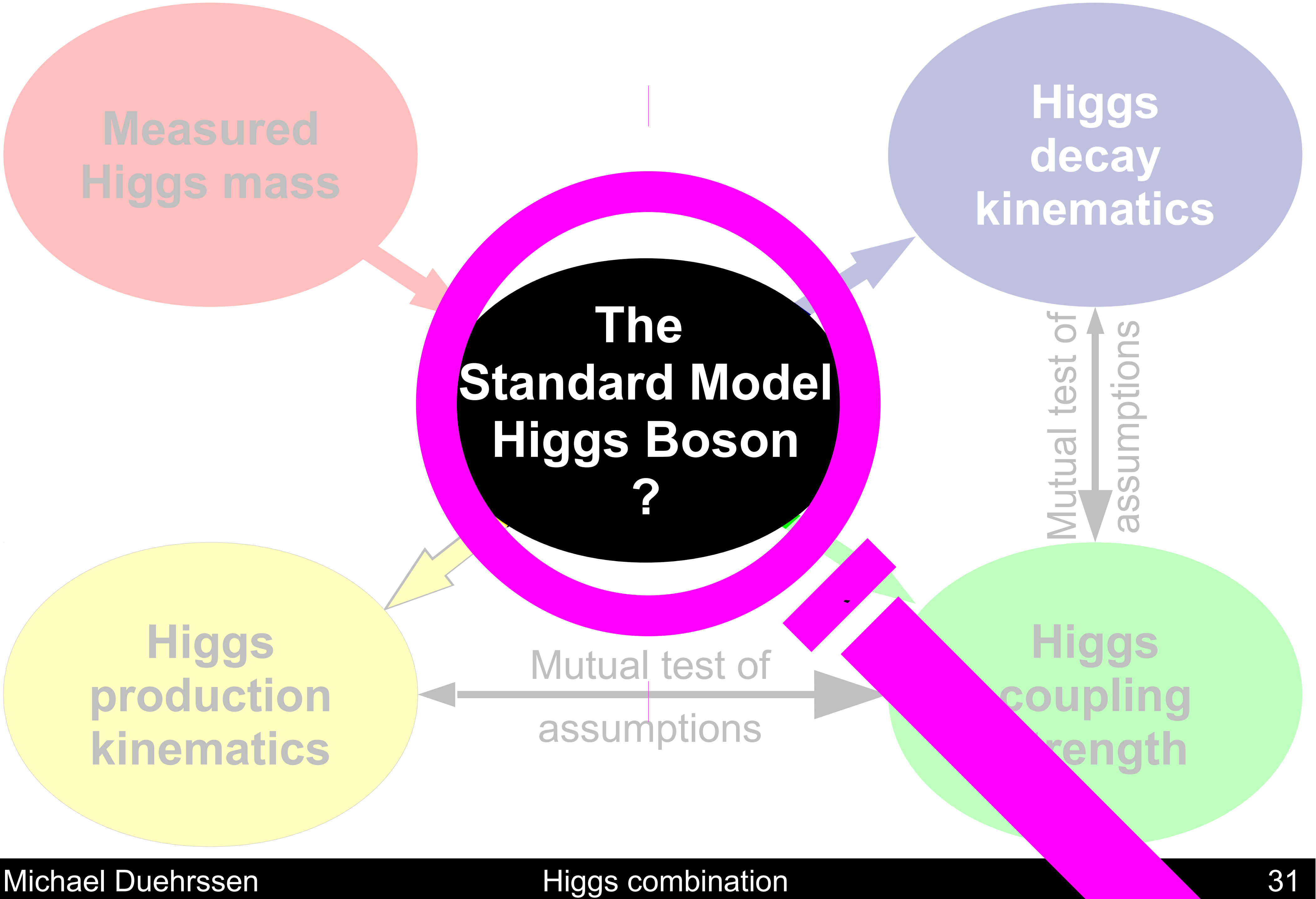


Generic fit to absolute Higgs couplings



- **Can impose several rather complementary assumptions for absolute Higgs coupling fits at the LHC:**
  - **Gauge couplings smaller than SM gauge couplings: $\kappa_V \leq 1$. This is valid for all theories with only Higgs singlets or doublets**
  - **Incorporate Higgs off-shell measurements and require no running of Higgs couplings: $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$ for κ_g, κ_W, κ_Z**
  - **No BSM Higgs decay modes: $BR_{i.u.} = 0$**
- **Also allow BSM contributions to the loops and the total width**
- **Nice agreement between different assumptions and with the SM**

Higgs combination: testing the SM



Summary

- Combined ATLAS+CMS measurement of the Higgs boson mass: m_H= 125.09 ± 0.24 GeV

- Combinations of Run 1 measurements in each experiment have been done for a majority of results
  - Combination of ATLAS+CMS Higgs coupling strength in preparation

- Extensive search for deviations from the SM prediction in
  - Higgs production kinematics
  - WW and ZZ Higgs decay kinematics
  - Signal strength in all categories of all observable final states and Higgs coupling strength

- Throughout, all results show very good consistency with the SM hypothesis