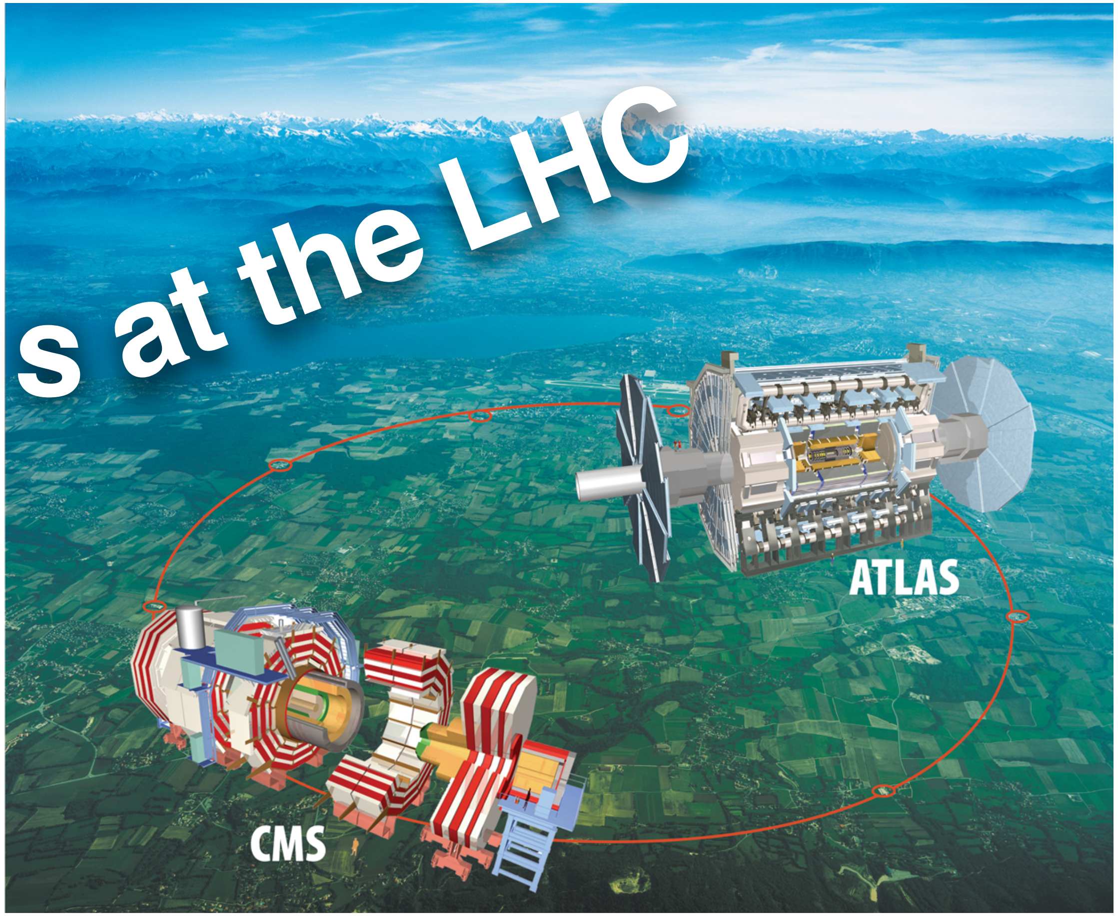
Higgs couplings at the LHC



June 3, 2015

http://blois.in2p3.fr/2015

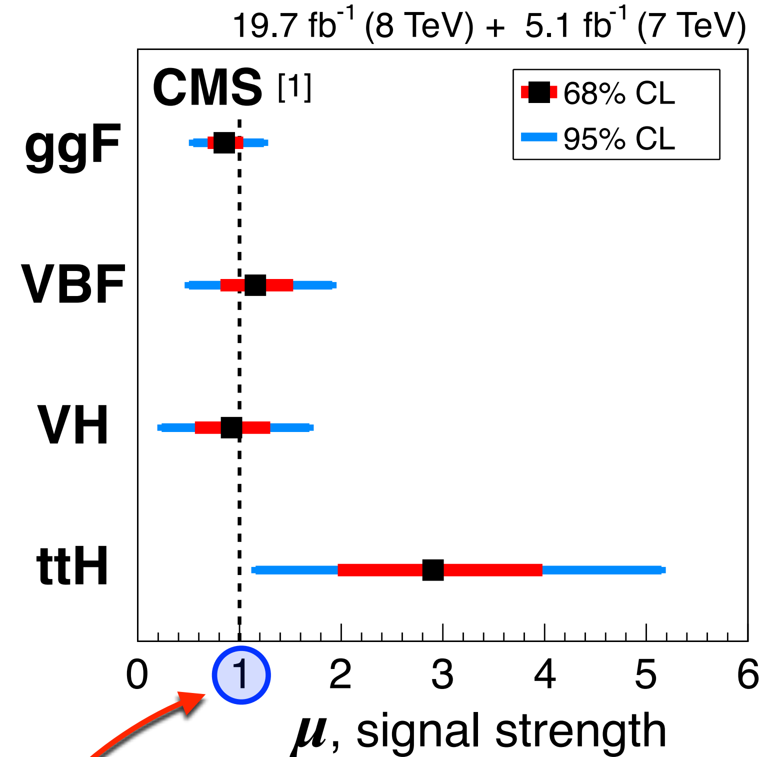
Tae Min Hong

U Pittsburgh

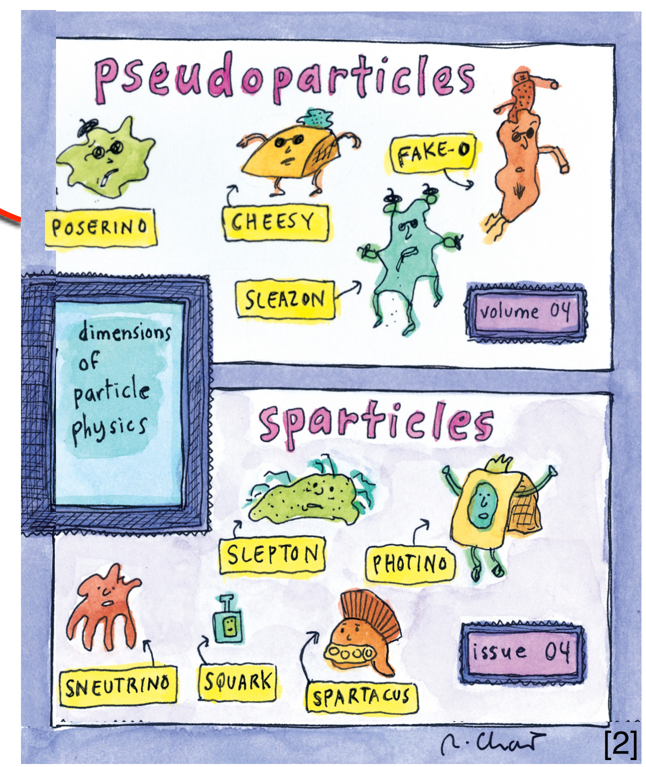
ATLAS

Outline

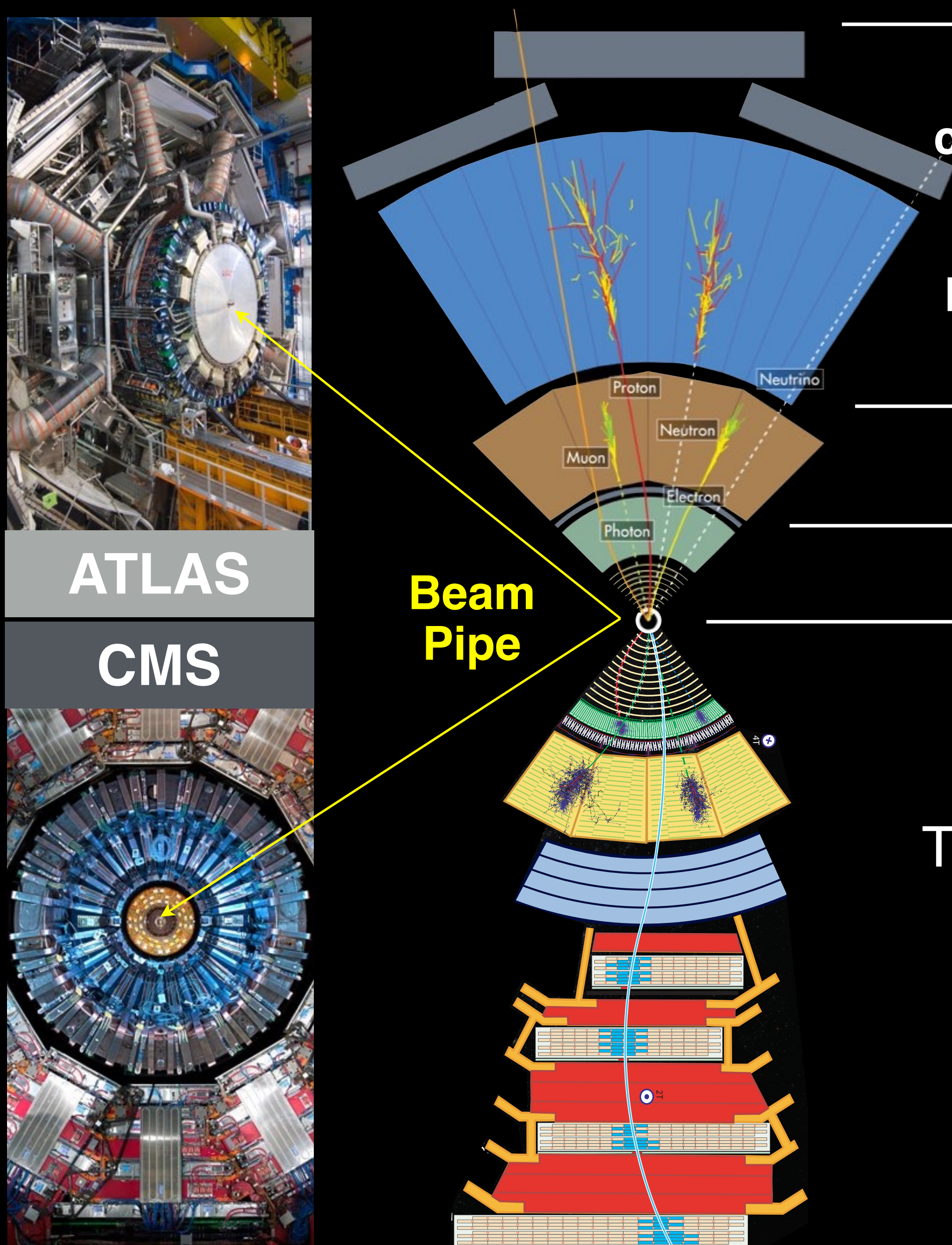
- ATLAS / CMS, LHC
- Higgs yield................. N
- Sig. strength......... $\mu = N_{\mathrm{obs}} / N_{\mathrm{exp}}$
- Coupling............. $\mu = \prod_i \kappa_i^2 / \kappa_H^2$
  - **New physics in vertices?**
  - **New physics in loops?**
  - **Fermion v. Boson?**
  - **Decay invisibly?**
- Summary
- Backup
  - References [1, 2] & model list

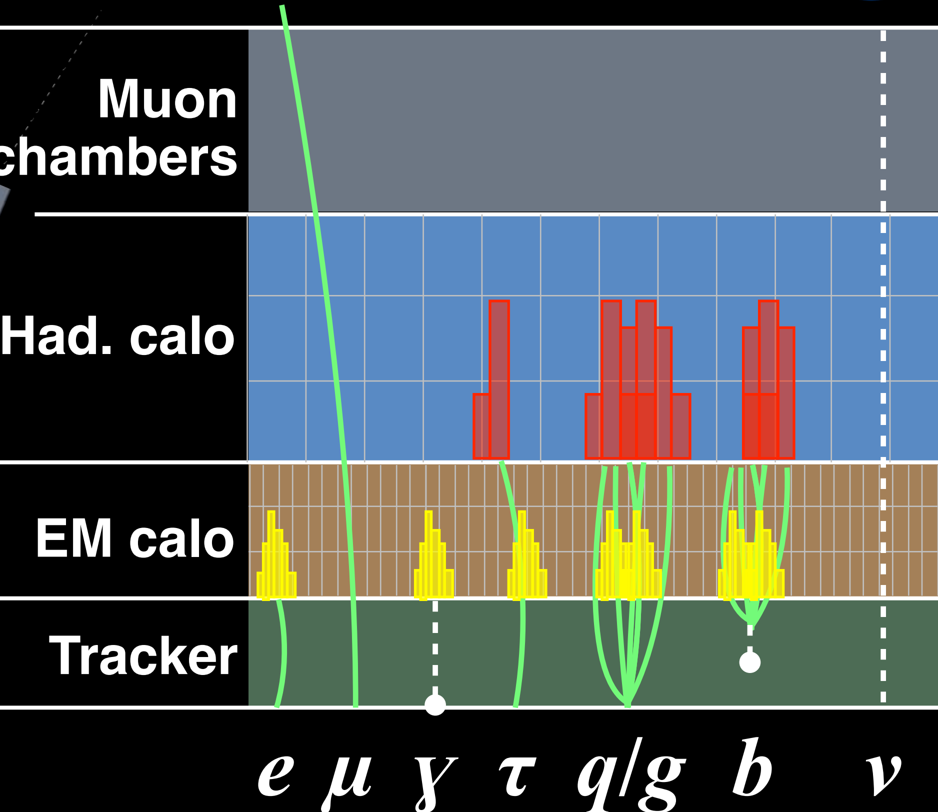


Does anything live in the error bars?



ATLAS & CMS detectors





Typical $\frac{\sigma}{P_T}$ for 60 GeV object is

- ones% for tracking
- ones% for EM calo
- tens % for jets

LHC is a Higgs factory

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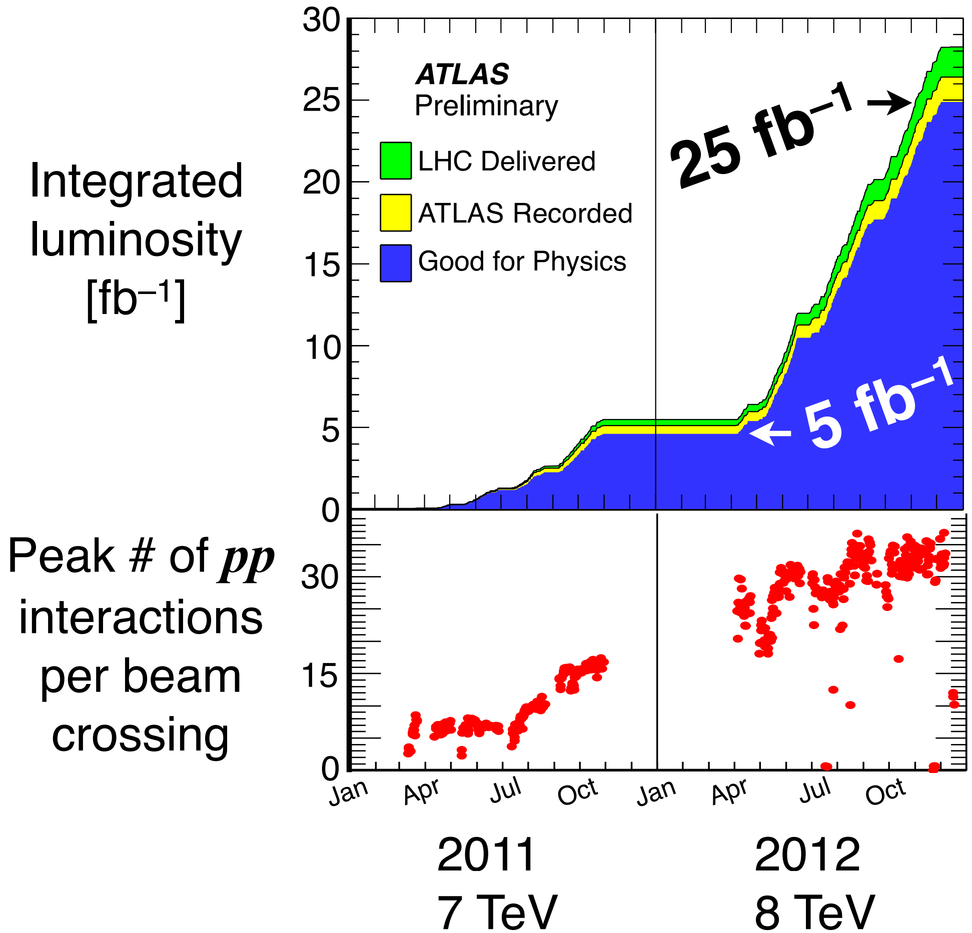

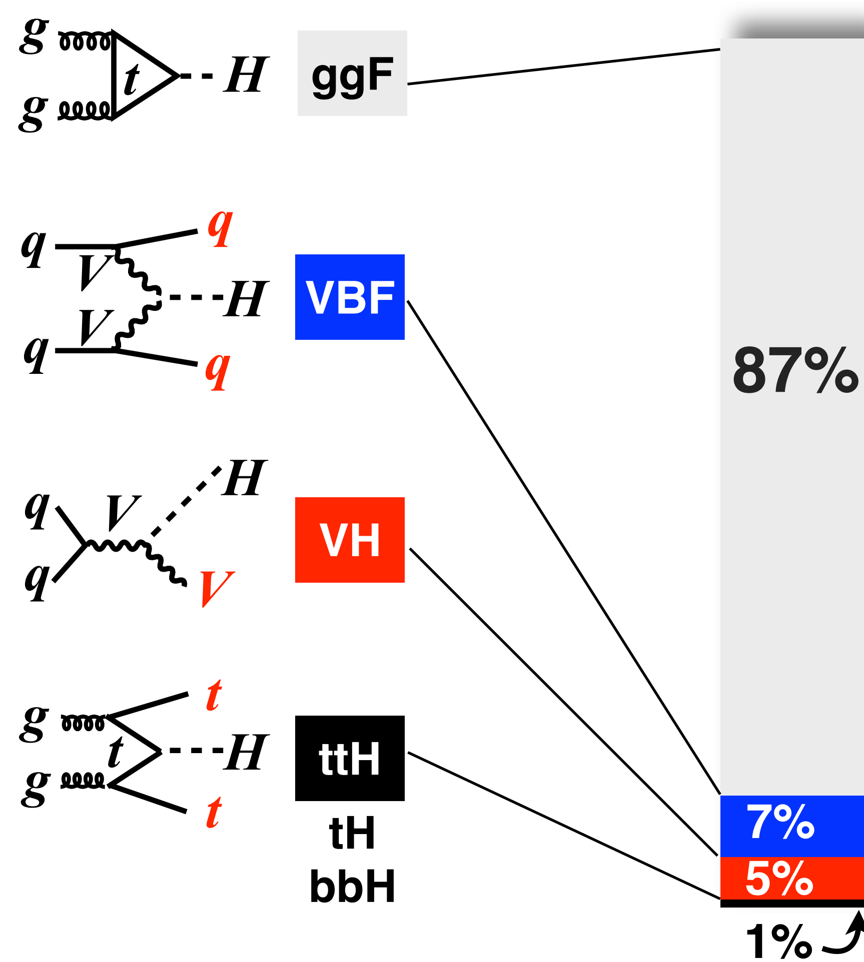

(Luminosity of 25 fb^{-1}) · (Cross-section of ≈ 20 pb) = (0.5M Higgs)

Produce 0.5M Higgs per exp’t → 10 - 20% measurements

Higgs yields

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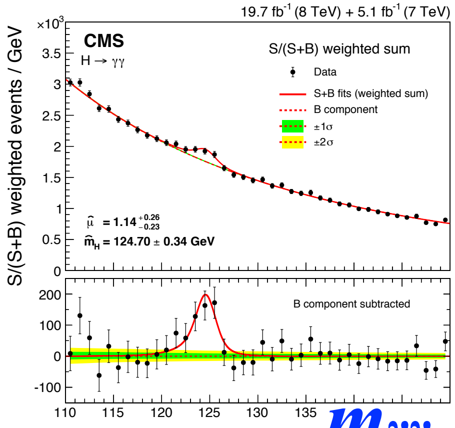
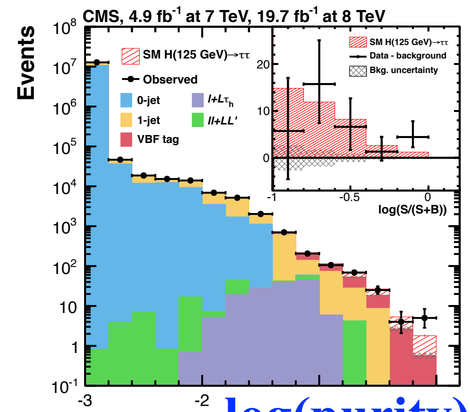
Yields below for rough idea. Categories / bins important.



$m_{\gamma\gamma}$

$\gamma\gamma$

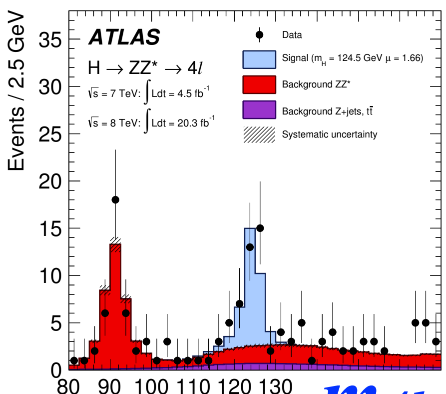
$N_{sig} \approx 170$
$N_{bkg} \approx 5000$
5 - 6σ obs.



log(purity)

$\tau\tau$

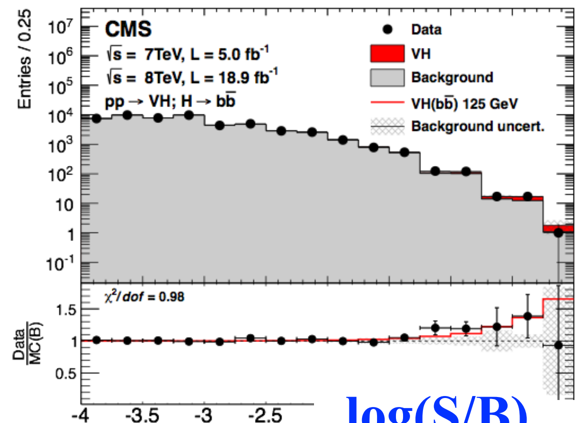
$N_{sig} \approx 650$
$N_{bkg} \approx$ huge
3 - 4σ observed



m_{4l}

ZZ

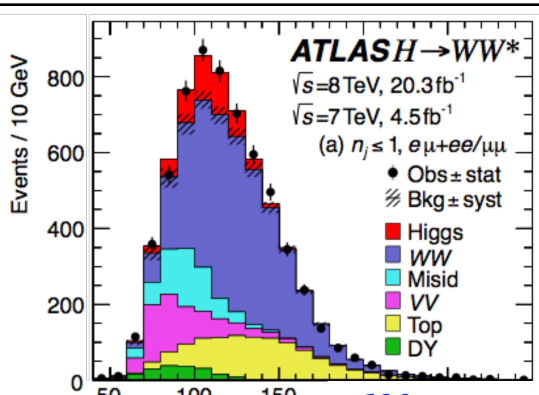
$N_{sig} \approx 16$
$N_{bkg} \approx 10$
6 - 7σ obs.



log(S/B)

bb

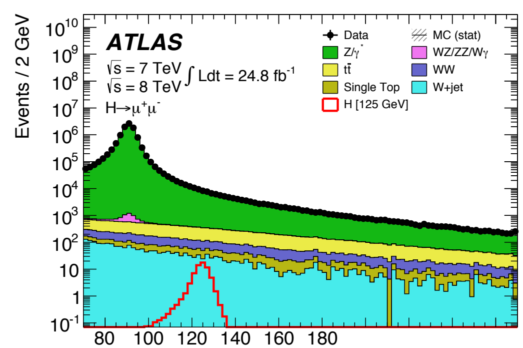
$N_{sig} \approx 60$
$N_{bkg} \approx$ huge
1 - 2σ observed



m_T

WW

$N_{sig} \approx 500$
$N_{bkg} \approx 7000$
5 - 6σ obs.



$m_{\mu\mu}$

$\mu\mu$

$N_{sig} \approx 30$
$N_{bkg} \approx$ huger
< 1σ expected

Signal strength

$$\mu = \frac{N_{\text{observed}}\ \text{Higgs}}{N_{\text{expected}}\ \text{Higgs}}$$

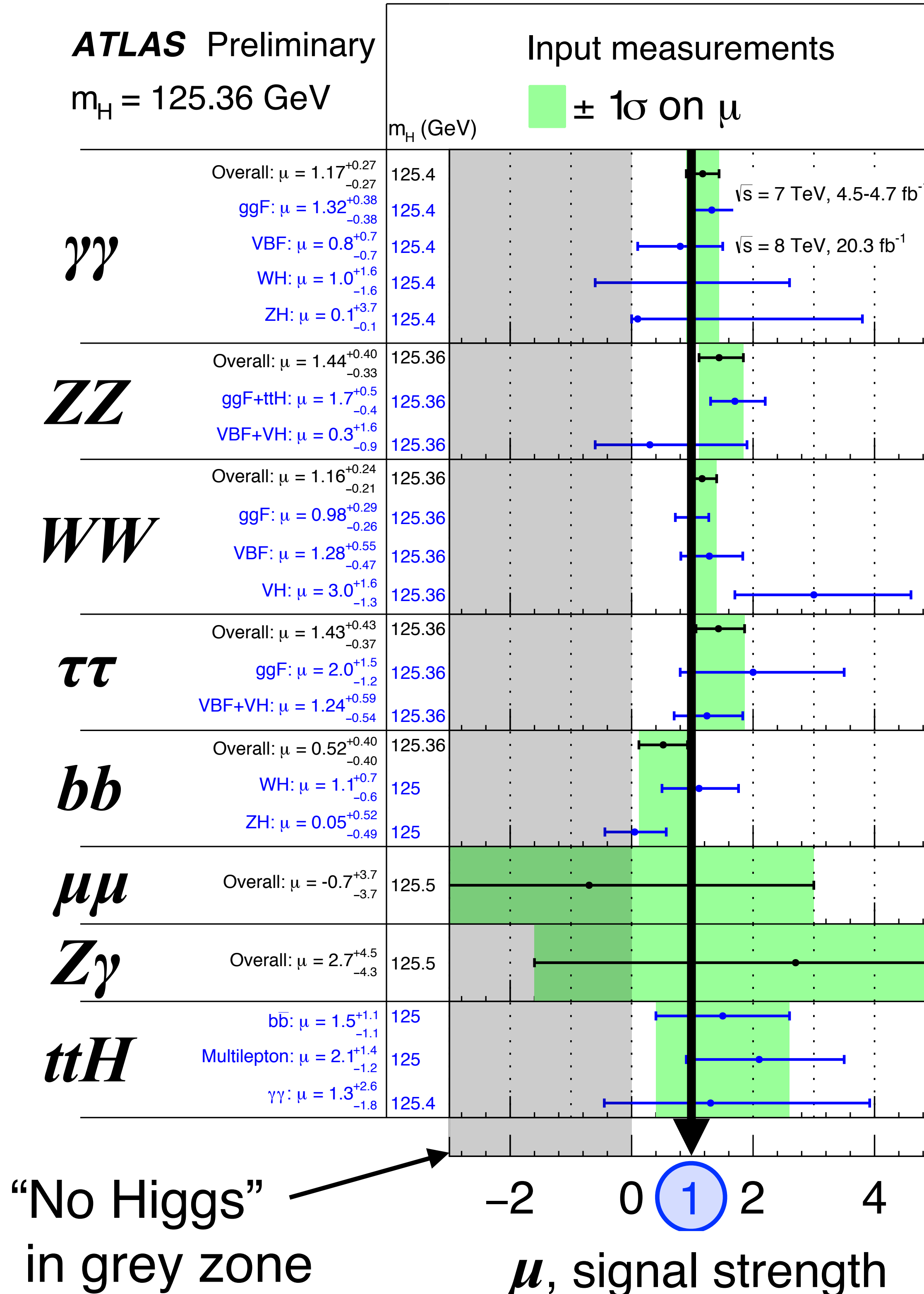
- Combined result

$$\mu_{\text{ATLAS}} = 1.18 \pm 0.15$$
$$\mu_{\text{CMS}} = 1.00 \pm 0.14$$

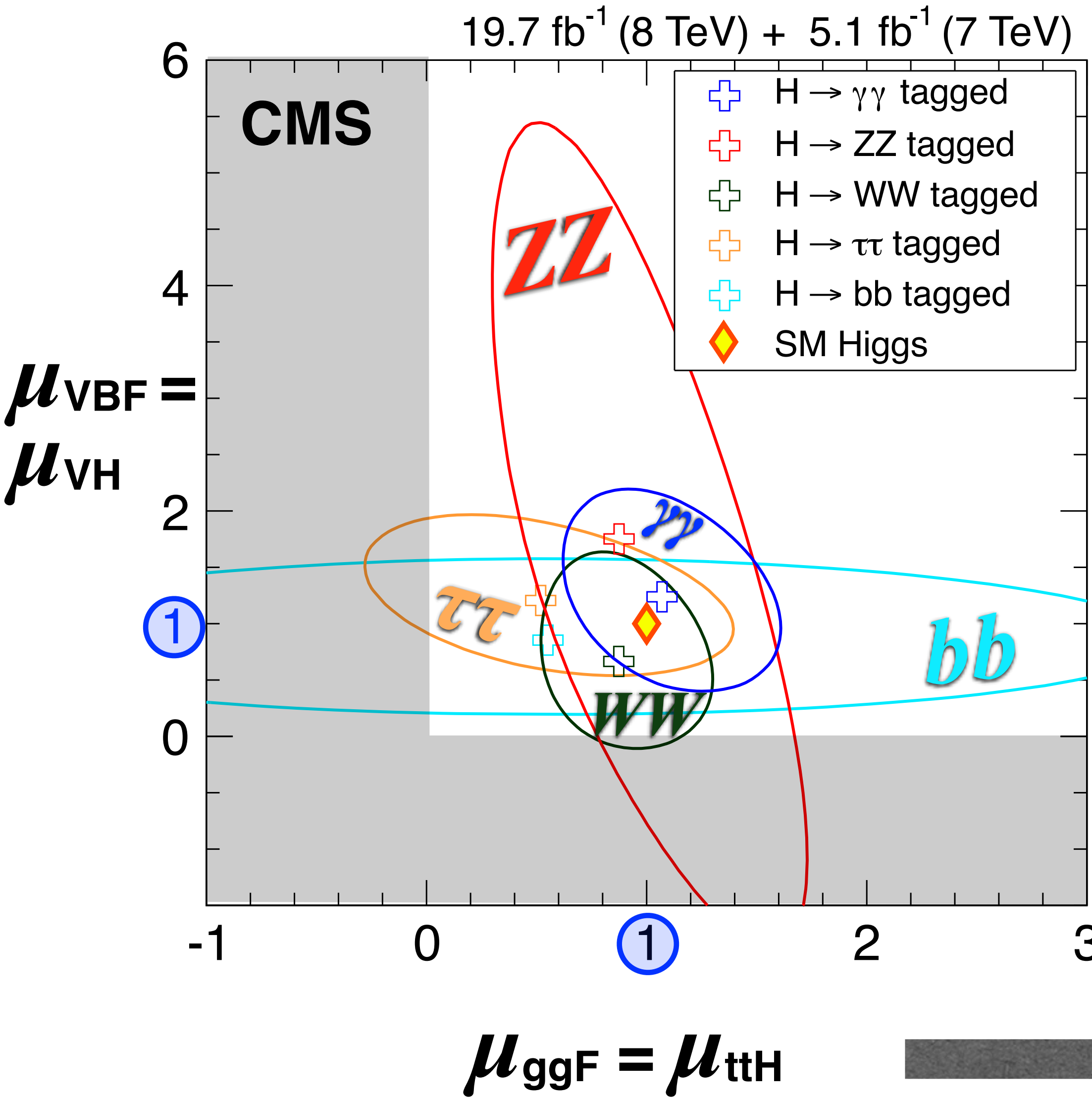
Statistical	0.09
Systematic	0.07
Higgs theory	0.07

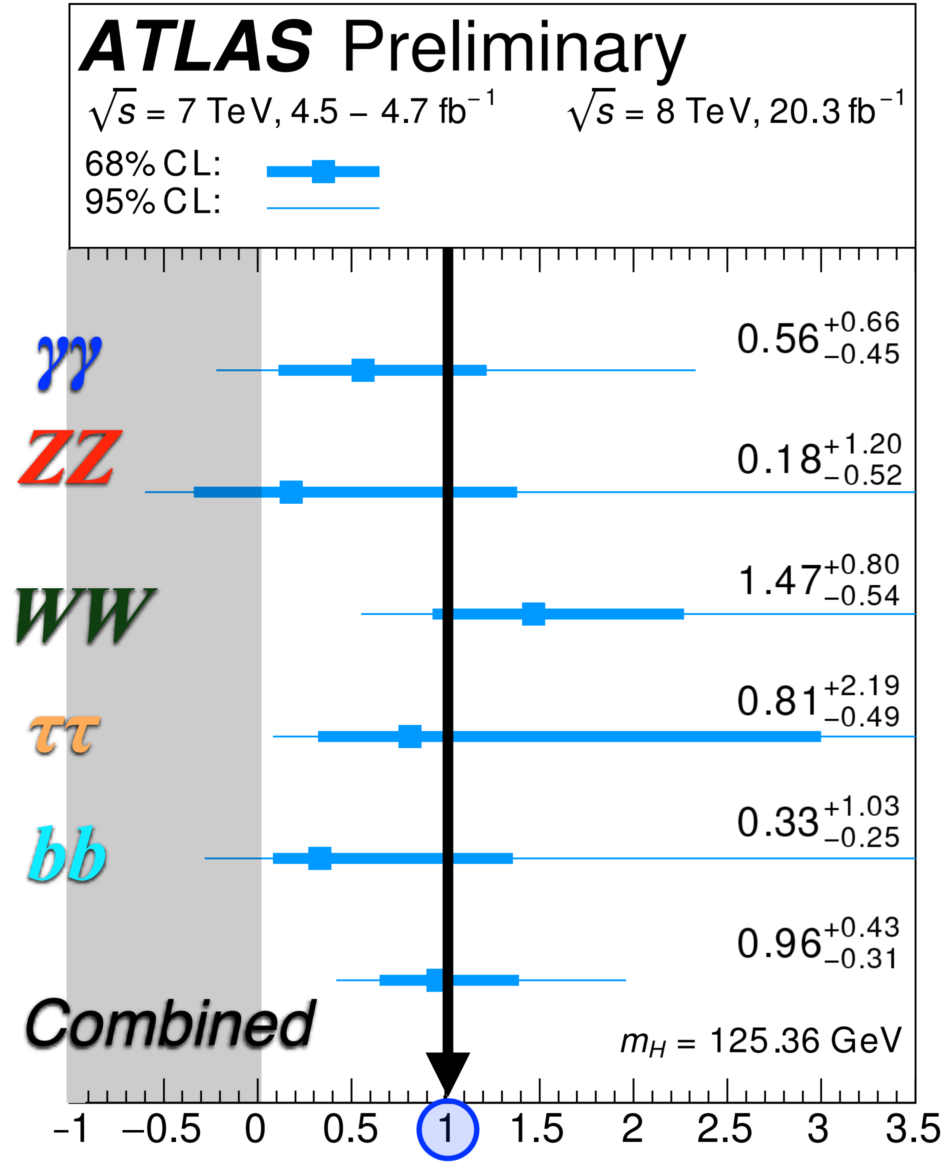
- Each decay & production

Consistent within errors



Compare ggF v. VBF





$$\frac{(\mu_{\text{VBF,VH}} / \mu_{\text{ggF,ttH}})\ \text{observed}}{(\mu_{\text{VBF,VH}} / \mu_{\text{ggF,ttH}})\ \text{expected}}$$

VBF-ggF consistent within **1σ**. Most stringent input from *WW*.

ATLAS + CMS

General relations for $\mu \leftrightarrow \kappa$

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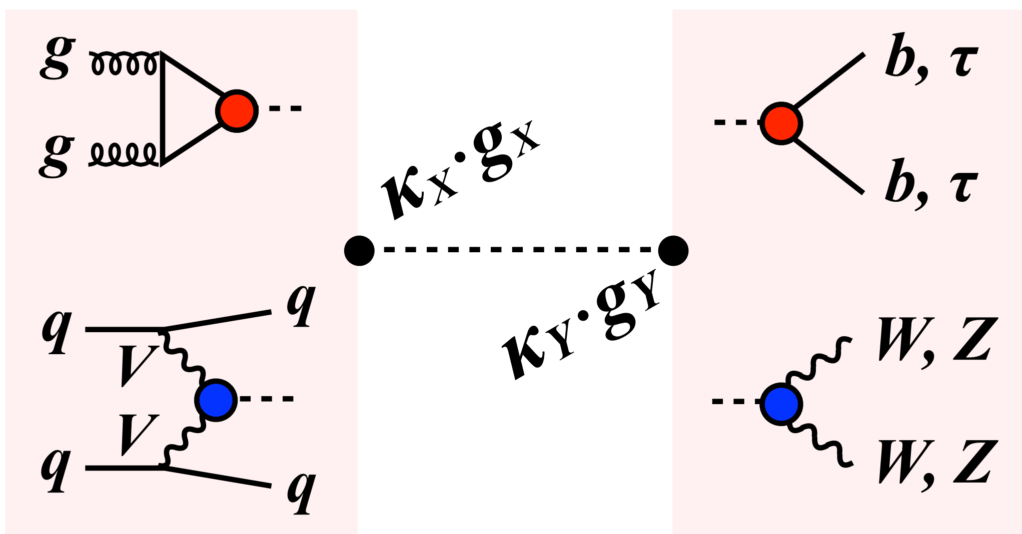
Diagrams



Production X Decay Y

Formulae

- Signal yield

$$N \propto \sigma_X \cdot B_Y \propto \sigma_X \cdot \frac{\Gamma_Y}{\Gamma_H}$$

- Signal strength

$$\mu = \frac{N_{\text{obs}}}{N_{\text{exp}}} = \frac{\kappa_X{}^2 \cdot \kappa_Y{}^2}{\kappa_H{}^2}$$

- Fit all κ simultaneously (assume fixed Γ_H)
- Better constraints with addt'l assumptions

Benchmark models

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Table for reference; will discuss a few models next

Couplings	Parameters	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $\gamma\gamma$ in ggF
Fermions / Bosons	κ_V, κ_F	✓	✓	✓	✓	✓	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
	$\lambda_{FV}, \kappa_{VV}$	✓	✓	✓	✓	–	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
Loops + BR$_{BSM}$	$\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$	=1	=1	–	–	✓	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$
	$\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, BR_{i.,u.}$	=1	=1	–	–	✓	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma) \cdot (1 - BR_{i.,u.})$
	$\kappa_F, \kappa_V, BR_{i.,u.}$	≤ 1 –	– –	✓ ✓	✓ ✓	✓ μ_{off}	$\frac{\kappa_F^2 \cdot \kappa_\gamma(\kappa_F, \kappa_V)^2}{\kappa_H^2(\kappa_F, \kappa_V)} \cdot (1 - BR_{i.,u.})$
U/D-type fermions	$\kappa_F, \kappa_V, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, BR_{i.,u.}$	≤ 1 –	– –	– –	– –	✓ μ_{off}	$\frac{\kappa_F^2 \cdot \kappa_\gamma(\kappa_F, \kappa_V)^2}{\kappa_H^2(\kappa_F, \kappa_V, \kappa_g, \kappa_\gamma)} \cdot (1 - BR_{i.,u.})$
	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$	✓	κ_u, κ_d	✓	✓	–	$\kappa_{uu}^2 \cdot \kappa_g^2(\lambda_{du}, 1) \cdot \kappa_\gamma^2(\lambda_{du}, 1, \lambda_{du}, \lambda_{Vu})$
Leptons / Quarks	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$	✓	κ_l, κ_q	✓	✓	–	$\kappa_{qq}^2 \cdot \kappa_\gamma^2(1, 1, \lambda_{lq}, \lambda_{Vq})$
Generic models	$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$	–	–	✓	✓	✓	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_\mu, \kappa_W)}{\kappa_H^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_\mu, \kappa_W, \kappa_Z)}$
	$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, BR_{i.,u.}$	≤ 1 – –	– – –	– – –	– – –	✓ ✓ μ_{off}	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_\mu, \kappa_W, \kappa_Z)} \cdot (1 - BR_{i.,u.})$
	$\lambda_{WZ}, \lambda_{tg}, \lambda_{bZ}, \lambda_{\tau Z}, \lambda_{gZ}, \lambda_{\gamma Z}, \lambda_{Z\gamma Z}, \kappa_{gZ}$	–	–	–	–	–	$\kappa_{gZ}^2 \cdot \lambda_{\gamma Z}^2$
Higgs → invisible	BR_{inv}			direct			

I added the last row to the list, not part of couplings papers.

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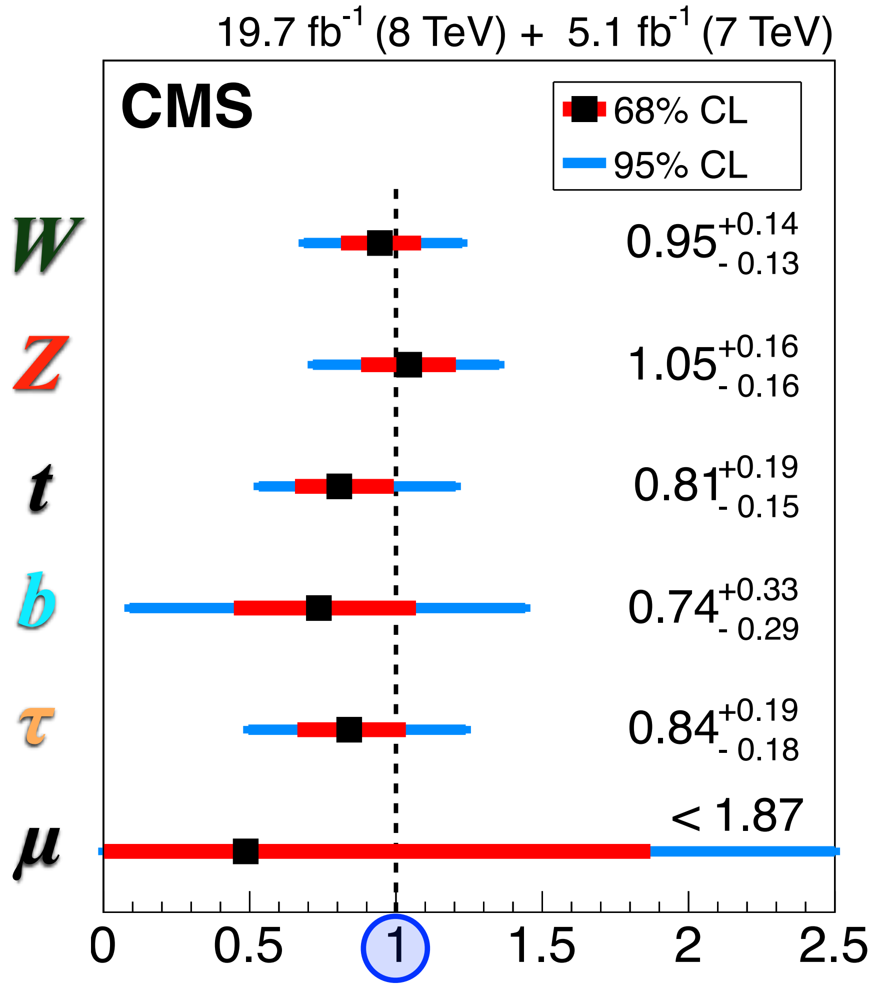
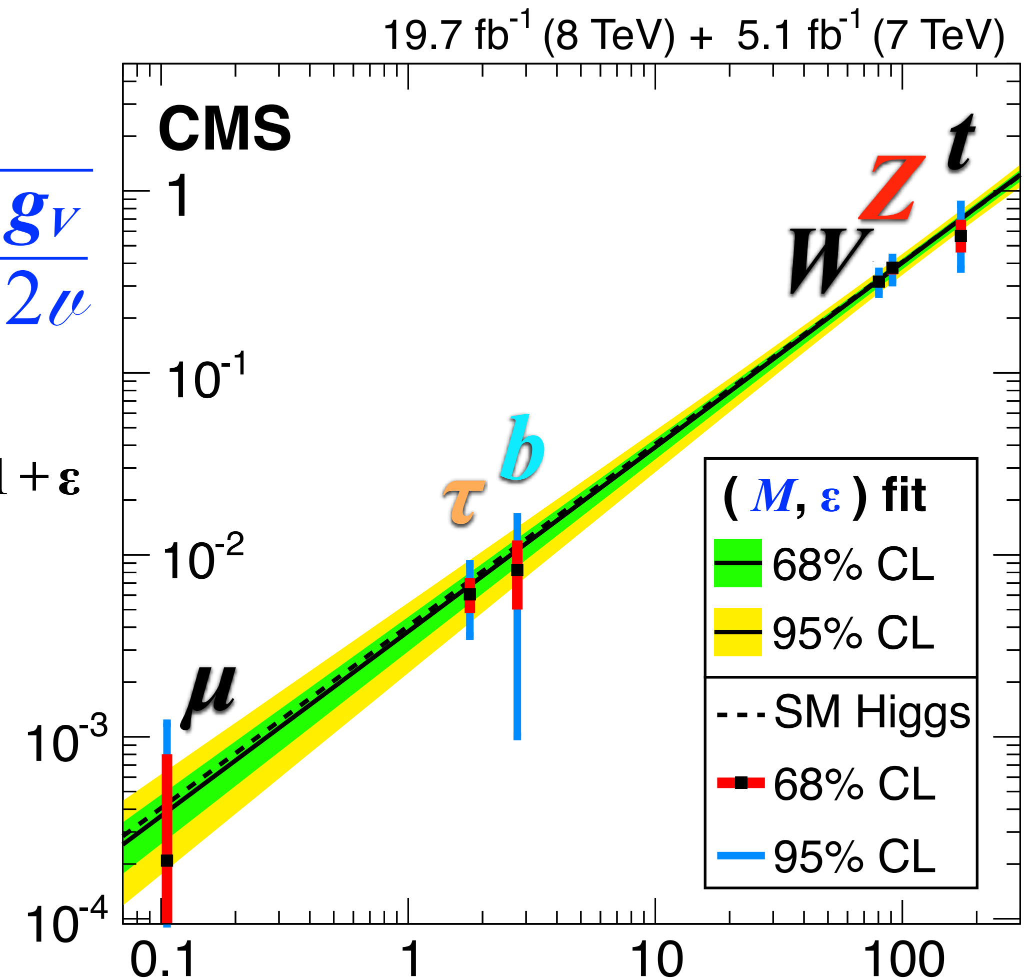
Higgs couplings

Higgs gives mass? Check vertices (assume SM loops)



κ, Higgs coupling relative to SM

$$\lambda_F\,,\ \sqrt{\frac{g_V}{2v}} \quad \updownarrow \quad \left(\frac{m}{M}\right)^{1+\varepsilon}$$



m, mass (GeV)

m or m^2 dependence in the Lagrangian consistent within ~1σ.

ATLAS + CMS

Higgs couplings

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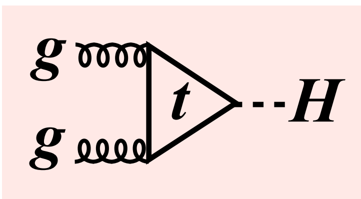
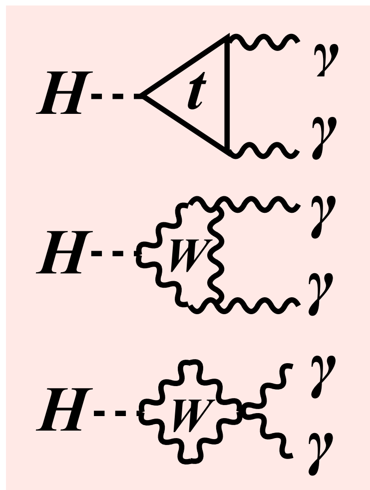
New physics in loops? Check loops.



Production

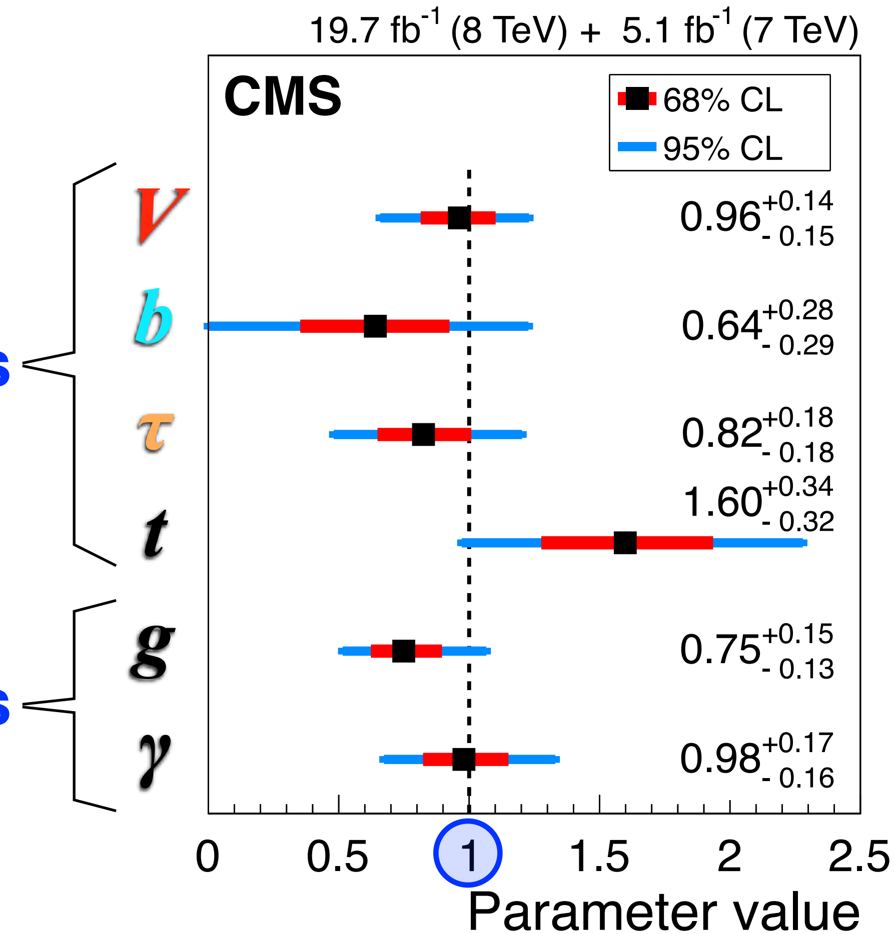
+



Decay

vertices

loops

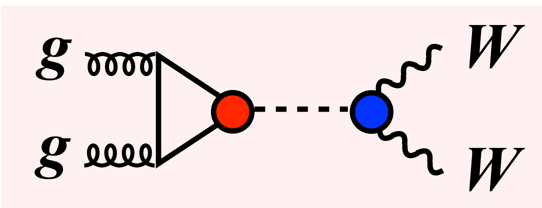


- Use κ_g and κ_γ to parametrize ⟶ **loops**
- Can reduce # of parameters per model. Here $V = (W, Z)$ & can, e.g., require $\kappa_V < 1$.
- SM for every κ included in **95%** confidence interval

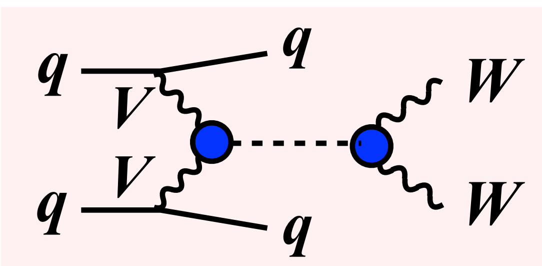
CMS

Example of κ_F - κ_V relations

Consider $H \to WW^*$

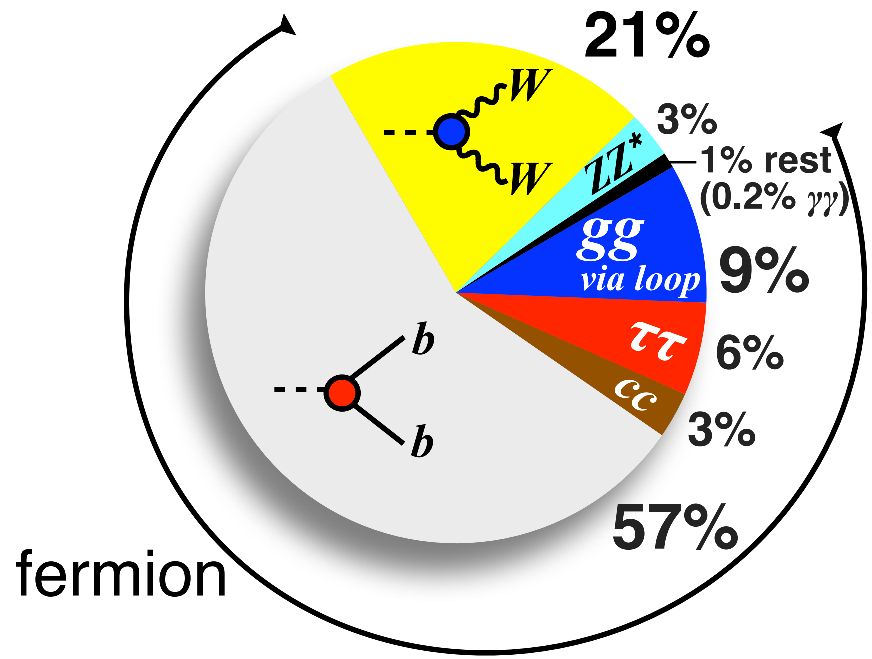


$$\mu^{\mathrm{ggF}}_{WW} = \frac{\kappa_t^2 \cdot \kappa_W^2}{\kappa_H^2} \approx \kappa_V^2$$



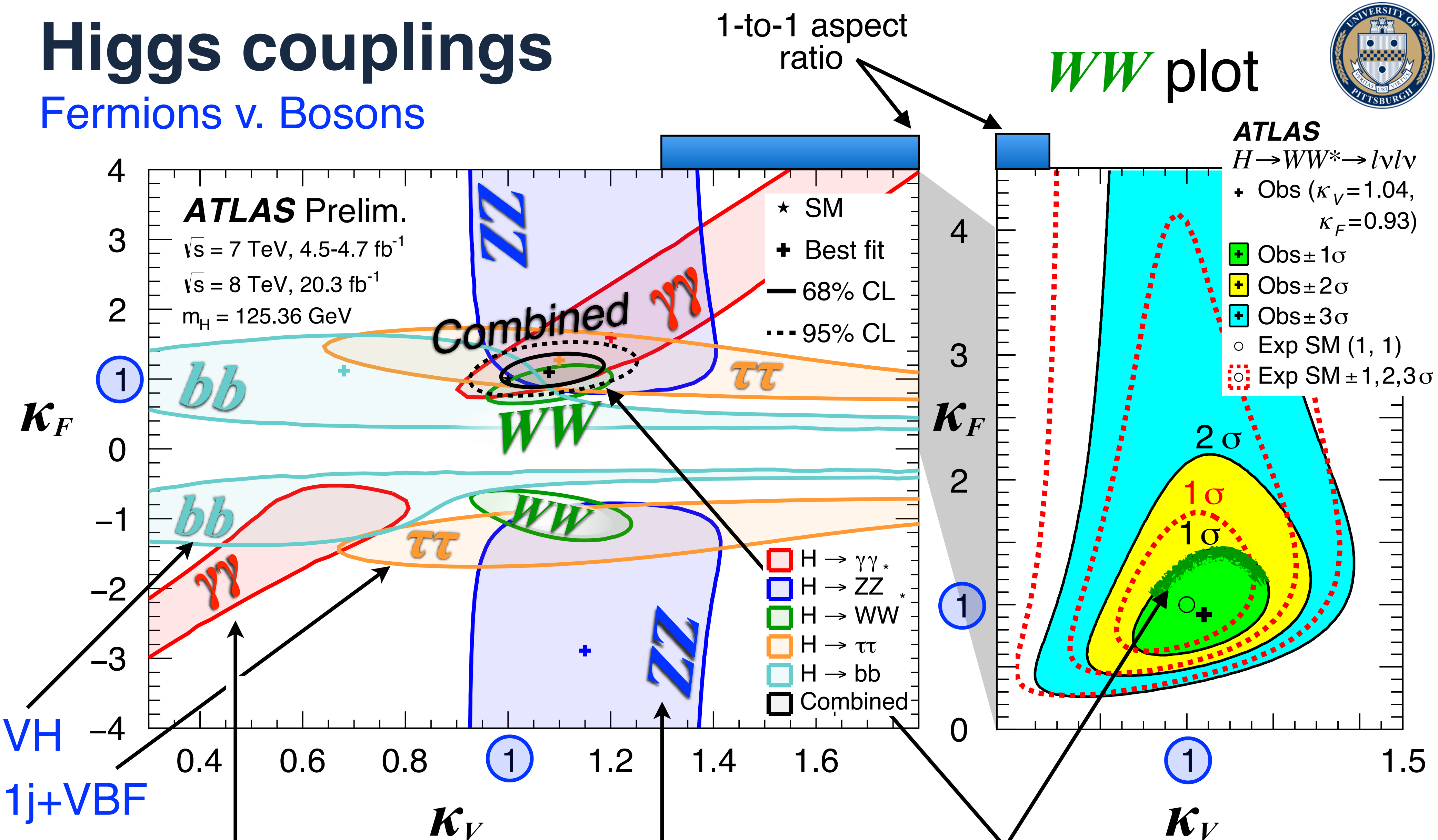
$$\mu^{\mathrm{VBF}}_{WW} = \frac{\kappa_V^2 \cdot \kappa_W^2}{\kappa_H^2} \approx \frac{\kappa_V^4}{\kappa_F^2}$$

- Simplest model is (κ_V, κ_F) where the denominator κ_H^2 is mostly κ_F^2



Higgs couplings

Fermions v. Bosons



Diagonal from $\gamma\gamma$ interference

VBF *ZZ* low stats, so κ_F bound open

VBF *WW* puts bound on κ_F since $\kappa_H \sim \kappa_F$

2-d compatibility test consistent at **41%**

ATLAS

VBF H → WW → eνμν*

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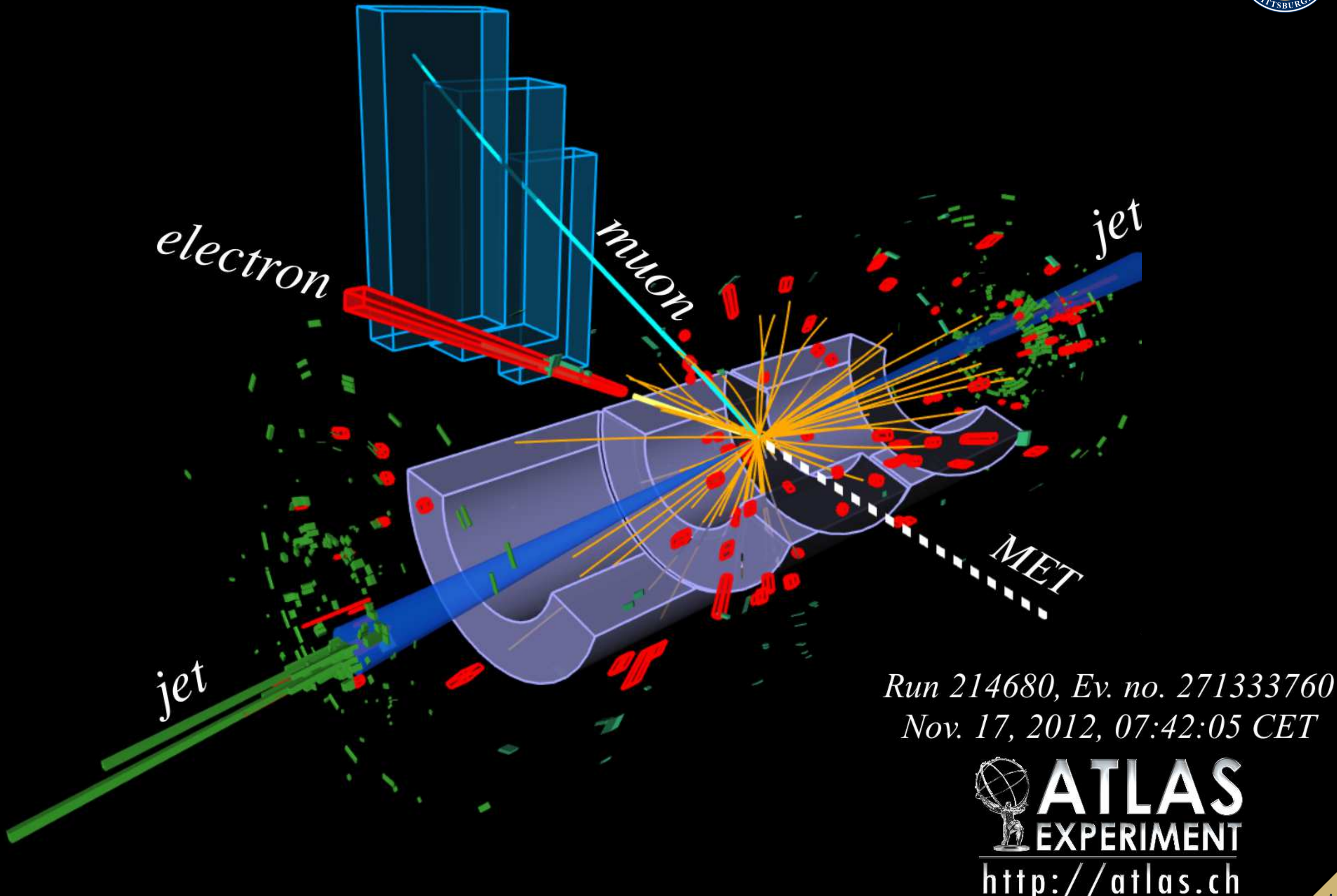

Higgs couplings

Summary of benchmarks

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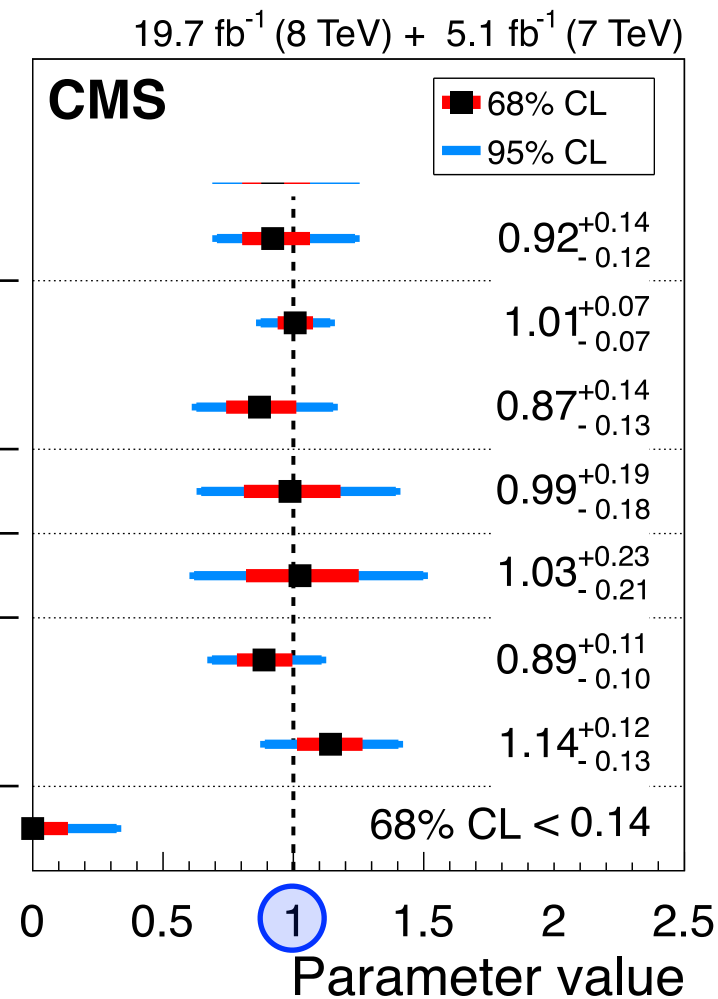
κ → κ ratios

Custodial symmetry	W/Z
Yukawa v. gauge	V F
MSSM, …	d/u
2HDM, …	ℓ/q
BSM in loops	g γ
Γ_H + (invisible or undetected)	$\mathrm{BR_{BSM}}$



denom

$$\mu = \frac{\kappa_X^2 \cdot \kappa_Y^2}{\kappa_H^2 \cdot (1 - \mathrm{BR_{BSM}})}$$

No statistically signficant deviations w.r.t. SM.

CMS

Higgs couplings

Higgs decays invisibly (SUSY, DM, etc.)?

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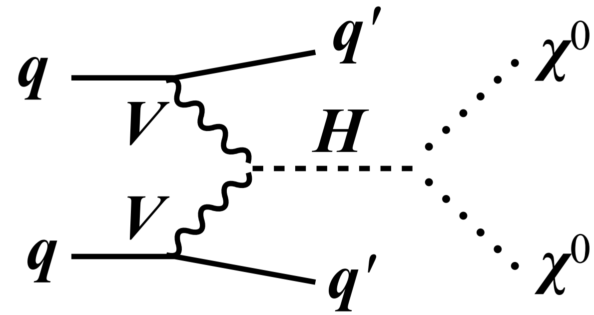
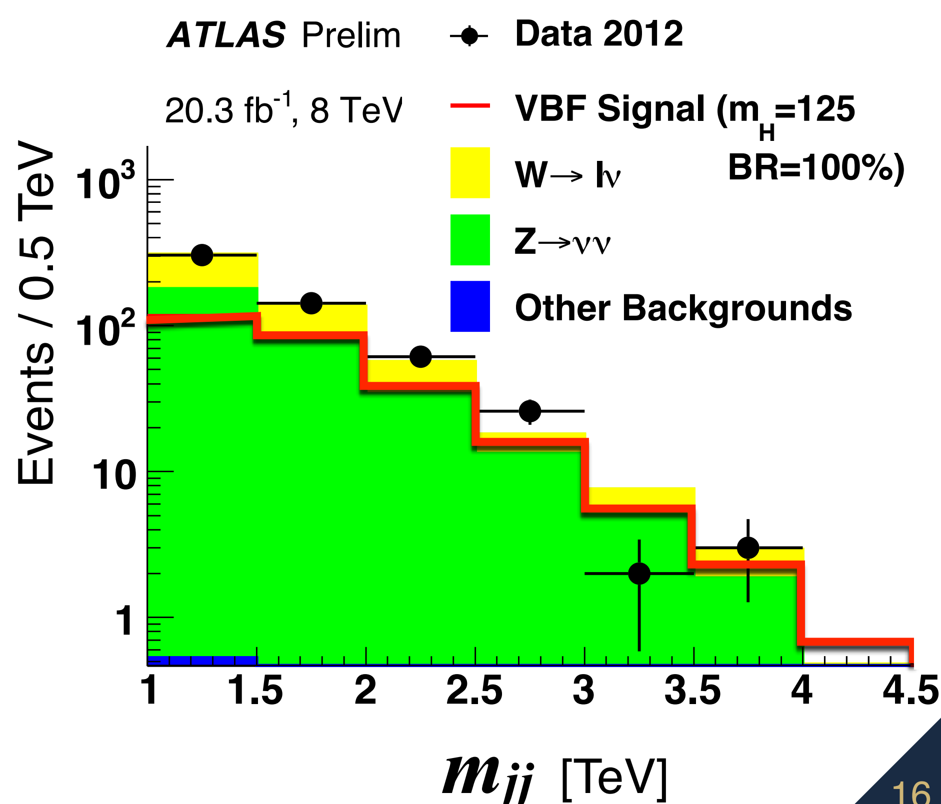
- Combined coupling limit on
  $\mathrm{BR_{BSM}} = \mathrm{BR_{undetected}} + \mathrm{BR_{invisible}}$
  ↕
- $H \rightarrow E_T^{miss}$ limit on $\mathrm{BR_{invisible}}$,
  most stringent from VBF, then VH

		obs.	exp.	
$\mathrm{BR_{CMS}}$	<	57%	40%	
$\mathrm{BR_{ATLAS}}$	<	29%	35%	at 95% CL

- Limits from indirect (couplings),
  direct (E_T^{miss})





Summary

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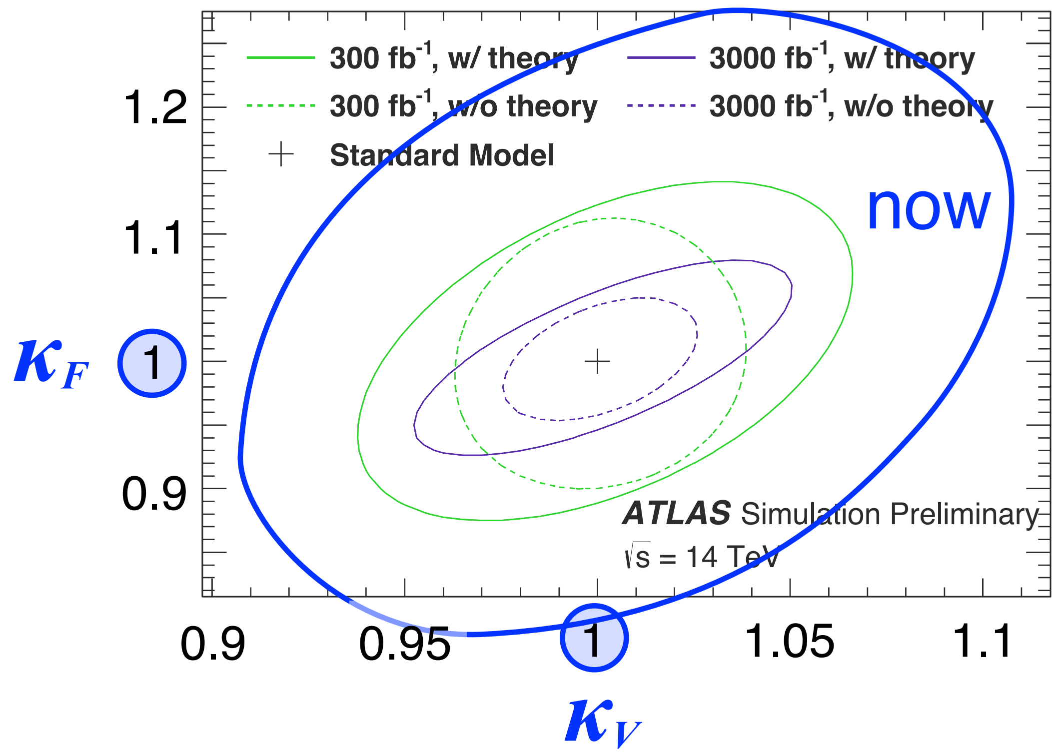
- Fermions v. Bosons?
  - Good to **10 - 20%**
- Vertices, loops?
  - Good to **10 - 20%**
- BSM decay?
  - $\mathbf{BR_{invisible}} \lesssim$ **40%**
- Corner Higgs with more data & better techniques

Future projections



Higgs is weird! Check if portal to non-SM physics.

Bibliography

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[1] All of the Higgs information is from

- https://cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- http://cms.web.cern.ch/org/cms-higgs-results

  I most heavily relied on the two couplings CONF notes.

[2] The cartoon from p1 and p17 is by Roz Chast from

- http://www.symmetrymagazine.org/sites/default/files/images/hi-res/cover_cropped.jpg

Summary table from CMS

Table 12: Tests of the compatibility of the data with the SM Higgs boson couplings. The best-fit values and 68% and 95% CL confidence intervals are given for the evaluated scaling factors κ_i or ratios $\lambda_{ij} = \kappa_i/\kappa_j$. The different compatibility tests discussed in the text are separated by horizontal lines. When one of the parameters in a group is evaluated, others are treated as nuisance parameters.

	Model parameters	Table in Ref. [169]	Parameter	Best-fit result 68% CL	Best-fit result 95% CL	Comment
1	κ_Z, λ_{WZ} (κ_f =1)	—	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61, 1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels.
2	$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.92^{+0.14}_{-0.12}$	[0.71, 1.24]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
3	κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.87, 1.14]	κ_V scales couplings to W and Z bosons.
			κ_f	$0.87^{+0.14}_{-0.13}$	[0.63, 1.15]	κ_f scales couplings to all fermions.
4	$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$0.99^{+0.19}_{-0.18}$	[0.65, 1.39]	$\lambda_{du} = \kappa_u/\kappa_d$, relates up-type and down-type fermions.
5	$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.03^{+0.23}_{-0.21}$	[0.62, 1.50]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relates leptons and quarks.
6	$\kappa_W, \kappa_Z, \kappa_t,$ $\kappa_b, \kappa_\tau, \kappa_\mu$	Extends 51	κ_W	$0.95^{+0.14}_{-0.13}$	[0.68, 1.23]	
			κ_Z	$1.05^{+0.16}_{-0.16}$	[0.72, 1.35]	
			κ_t	$0.81^{+0.19}_{-0.15}$	[0.53, 1.20]	Up-type quarks (via t).
			κ_b	$0.74^{+0.33}_{-0.29}$	[0.09, 1.44]	Down-type quarks (via b).
			κ_τ	$0.84^{+0.19}_{-0.18}$	[0.50, 1.24]	Electron and tau lepton (via τ).
			κ_μ	$0.49^{+1.38}_{-0.49}$	[0.00, 2.77]	κ_μ scales the coupling to muons.
7	M, ϵ	Ref. [202]	M (GeV)	245 ± 15	[217, 279]	$\kappa_f = v\frac{m_f^\epsilon}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$ (Section 7.4)
			ϵ	$0.014^{+0.041}_{-0.036}$	[−0.054, 0.100]	
8	κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.11}_{-0.10}$	[0.69, 1.11]	Effective couplings to gluons (g) and photons (γ).
			κ_γ	$1.14^{+0.12}_{-0.13}$	[0.89, 1.40]	
9	$\kappa_g, \kappa_\gamma, BR_{BSM}$	48 (middle)	BR_{BSM}	≤ 0.14	[0.00, 0.32]	Allows for BSM decays.
10	with H(inv) searches	—	BR_{inv}	$0.03^{+0.15}_{-0.03}$	[0.00, 0.32]	H(inv) use implies BR_{undet} =0.
11	with H(inv) and $\kappa_i = 1$	—	BR_{inv}	$0.06^{+0.11}_{-0.06}$	[0.00, 0.27]	Assumes $\kappa_i = 1$ and uses H(inv).
12	$\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$	50 (bottom)	κ_{gZ}	$0.98^{+0.14}_{-0.13}$	[0.73, 1.27]	$\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating κ_H.
			λ_{WZ}	$0.87^{+0.15}_{-0.13}$	[0.63, 1.19]	$\lambda_{WZ} = \kappa_W/\kappa_Z$.
			λ_{Zg}	$1.39^{+0.36}_{-0.28}$	[0.87, 2.18]	$\lambda_{Zg} = \kappa_Z/\kappa_g$.
			λ_{bZ}	$0.59^{+0.22}_{-0.23}$	≤ 1.07	$\lambda_{bZ} = \kappa_b/\kappa_Z$.
			$\lambda_{\gamma Z}$	$0.93^{+0.17}_{-0.14}$	[0.67, 1.31]	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$.
			$\lambda_{\tau Z}$	$0.79^{+0.19}_{-0.17}$	[0.47, 1.20]	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$.
			λ_{tg}	$2.18^{+0.54}_{-0.46}$	[1.30, 3.35]	$\lambda_{tg} = \kappa_t/\kappa_g$.
13	$\kappa_V, \kappa_b, \kappa_\tau,$ $\kappa_t, \kappa_g, \kappa_\gamma$	Similar to 50 (top)	κ_V	$0.96^{+0.14}_{-0.15}$	[0.66, 1.23]	
			κ_b	$0.64^{+0.28}_{-0.29}$	[0.00, 1.23]	Down-type quarks (via b).
			κ_τ	$0.82^{+0.18}_{-0.18}$	[0.48, 1.20]	Charged leptons (via τ).
			κ_t	$1.60^{+0.34}_{-0.32}$	[0.97, 2.28]	Up-type quarks (via t).
			κ_g	$0.75^{+0.15}_{-0.13}$	[0.52, 1.07]	
			κ_γ	$0.98^{+0.17}_{-0.16}$	[0.67, 1.33]	
	with $\kappa_V \leq 1$ and BR_{BSM}	—	BR_{BSM}	≤ 0.34	[0.00, 0.57]	Allows for BSM decays.
	with $\kappa_V \leq 1$ and H(inv)	—	BR_{inv}	0.17 ± 0.17	[0.00, 0.49]	H(inv) use implies $BR_{undet} = 0$.
	with $\kappa_V \leq 1$, H(inv),	—	BR_{inv}	0.17 ± 0.17	[0.00, 0.49]	Separates BR_{inv} from BR_{undet},
	BR_{inv}, and BR_{undet}	—	BR_{undet}	≤ 0.23	[0.00, 0.52]	$BR_{BSM} = BR_{inv} + BR_{undet}$.