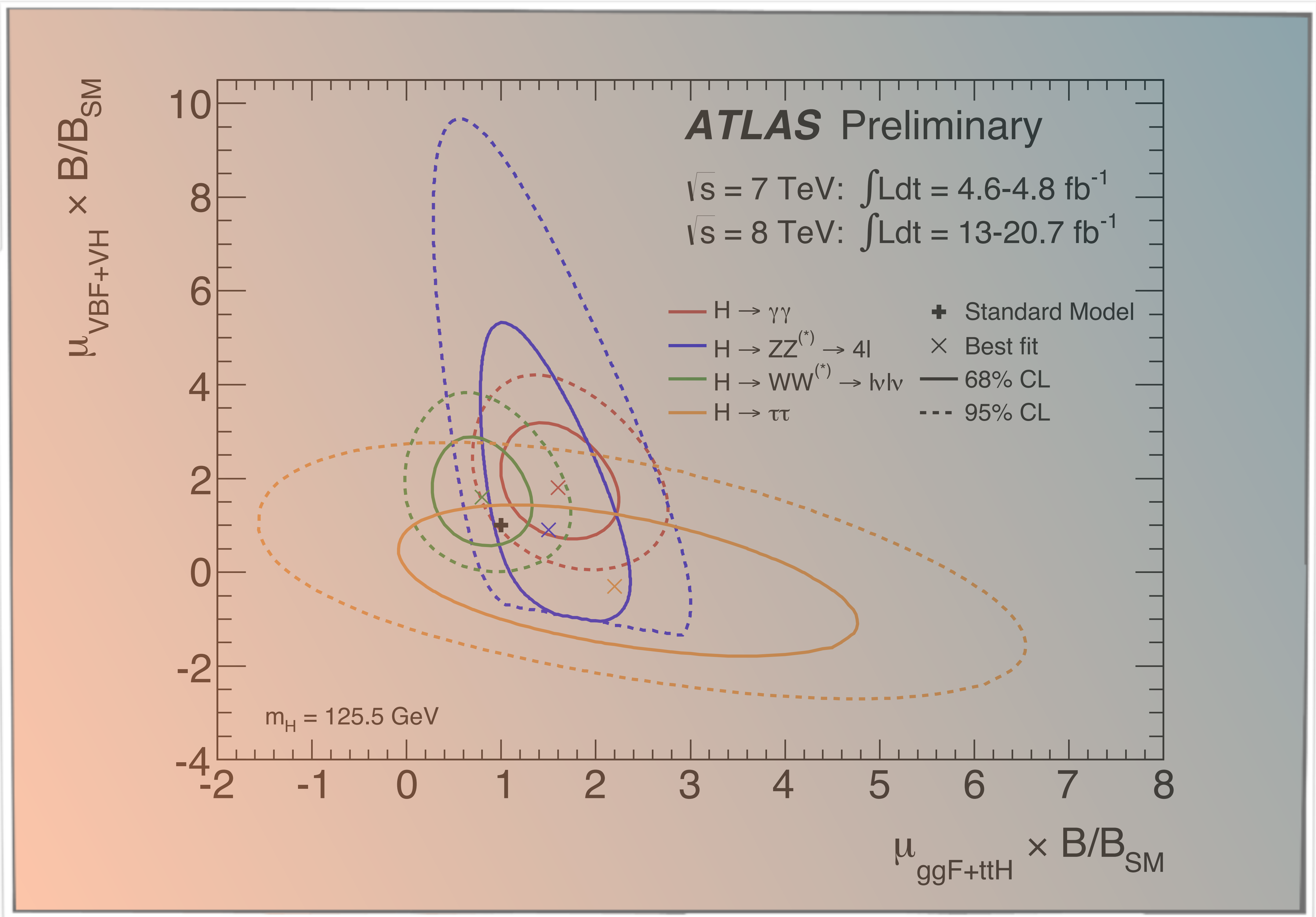
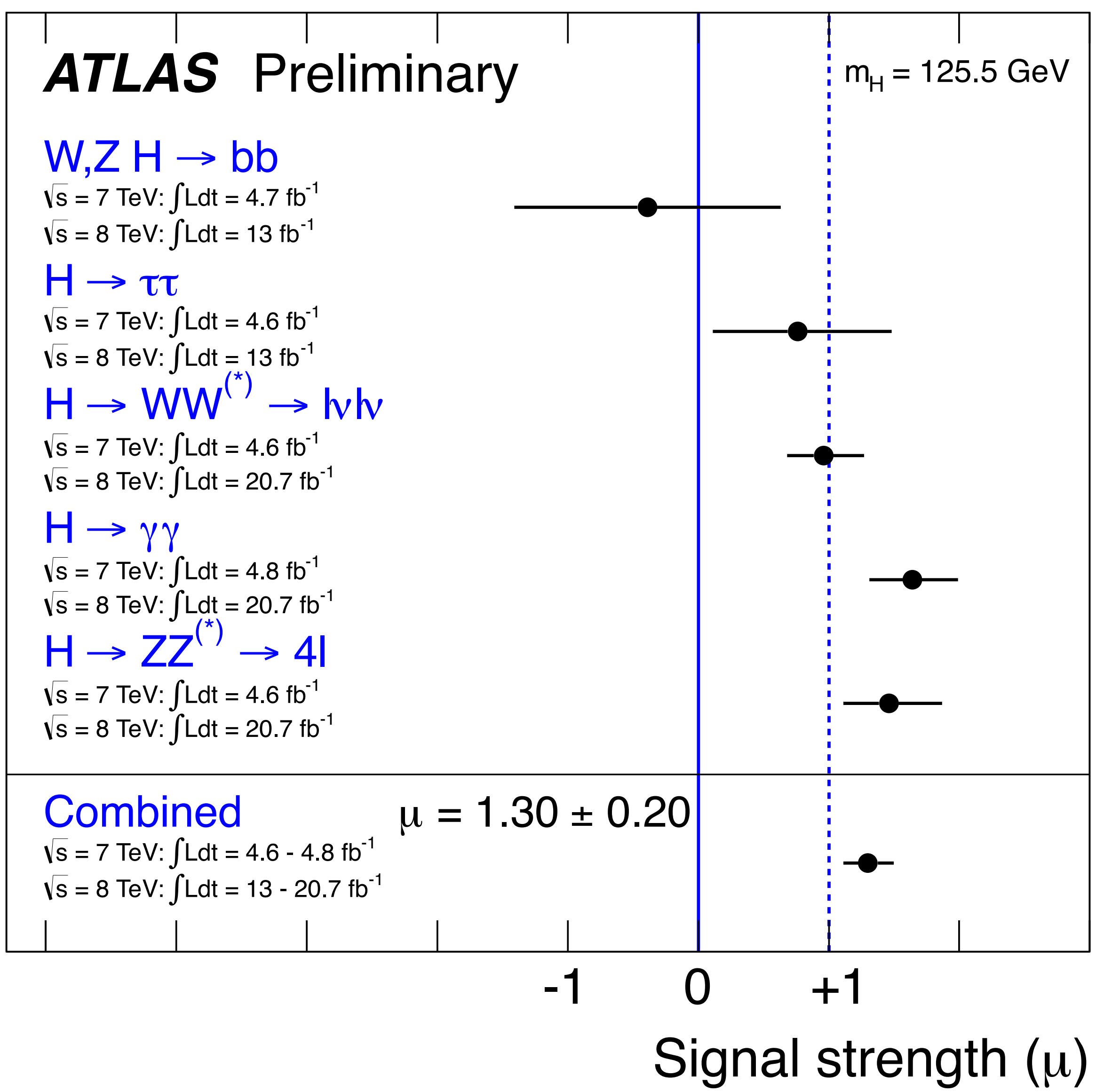
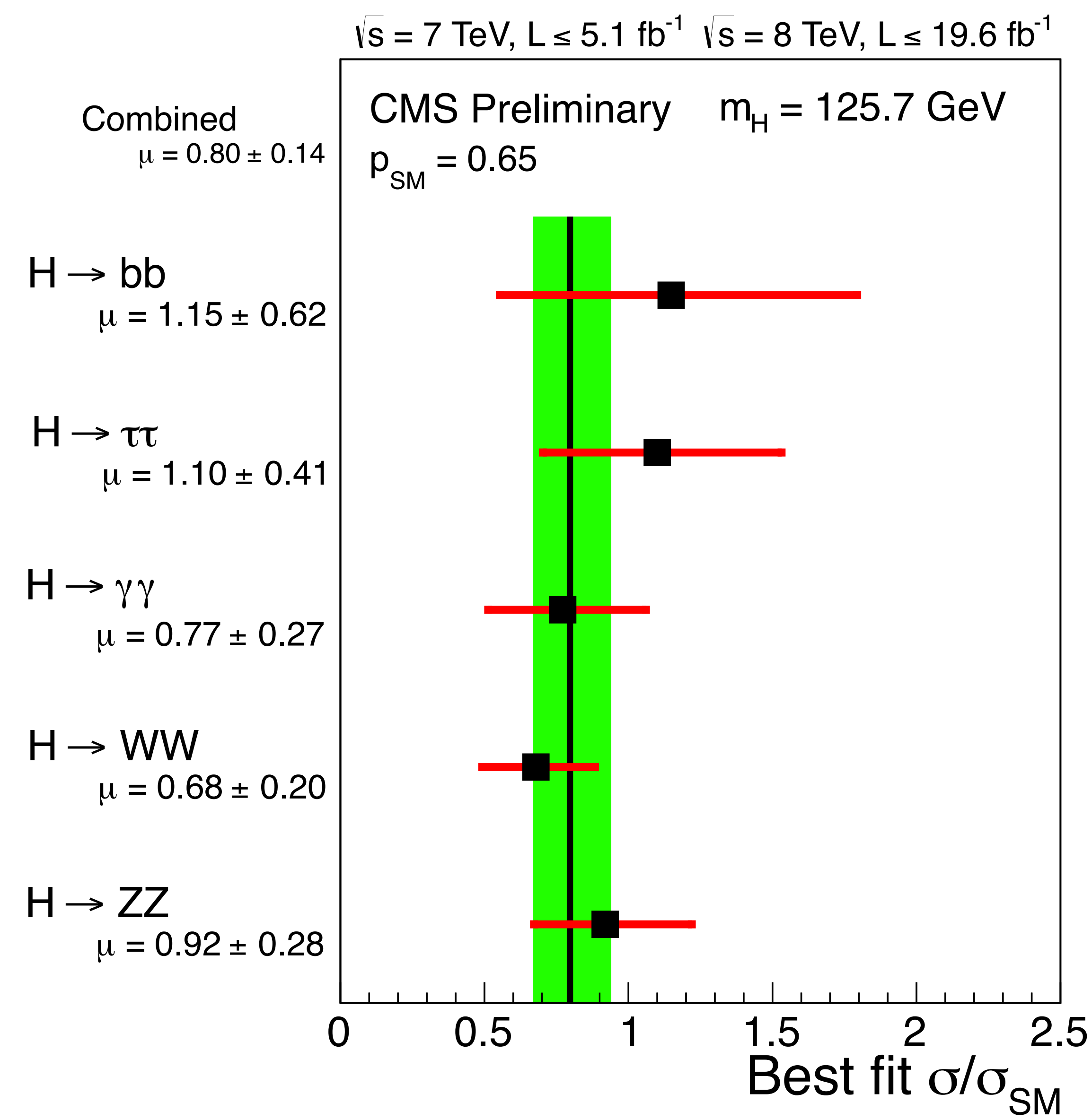
Experimental Aspects of
Higgs Coupling Determination



[ATLAS-CONF-2013-034]

Couplings – Present Status



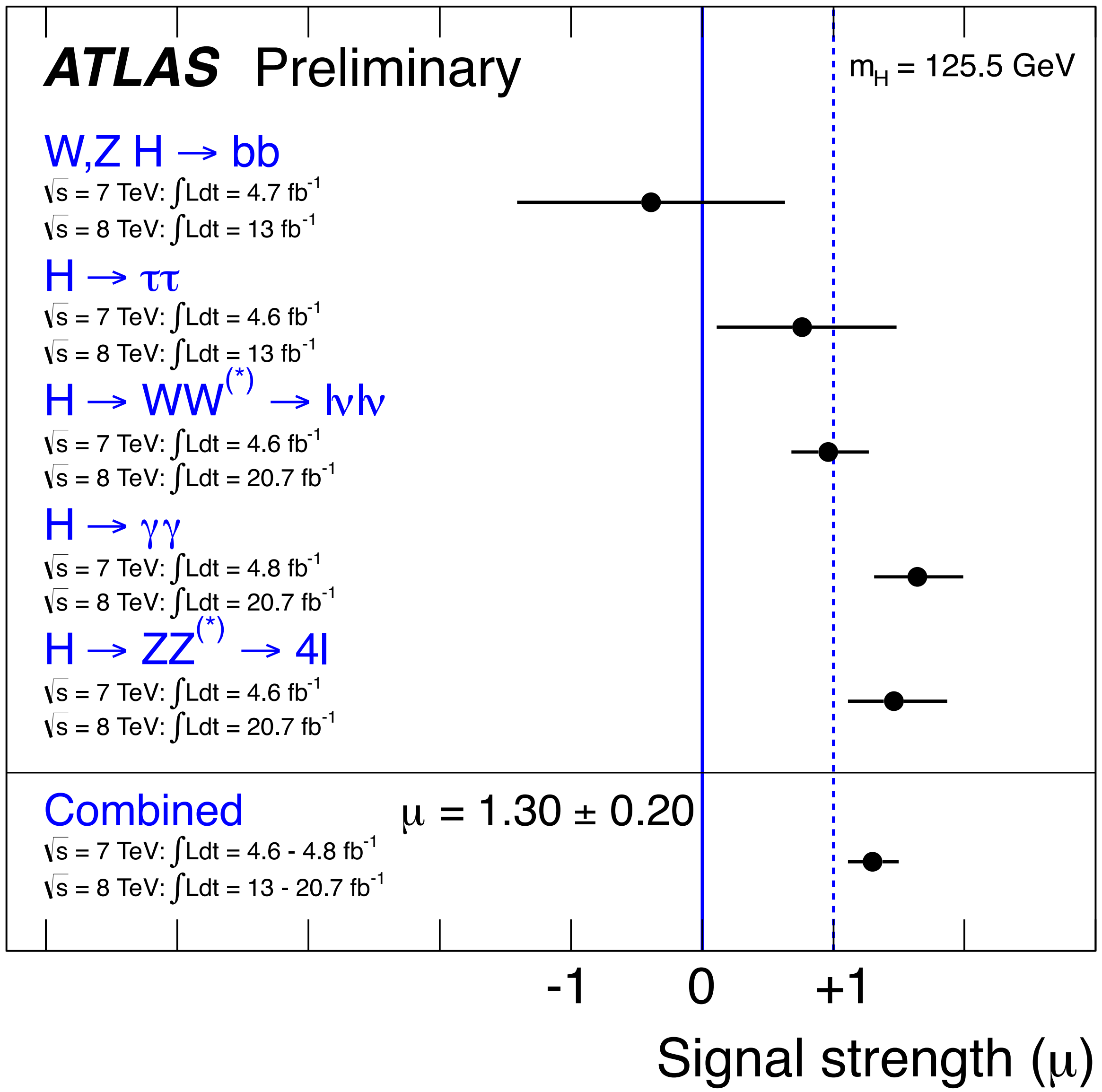


ATLAS: $\mu = 1.30 \pm 0.20$

CMS: $\mu = 0.80 \pm 0.14$

Couplings – Present Status

[ATLAS-CONF-2013-034]



ATLAS: μ = 1.30 ± 0.20

$$\mu_i = \sigma_i / \sigma_{i,\mathrm{SM}}$$

$$\mu_f = B_f / B_{f,\mathrm{SM}}$$

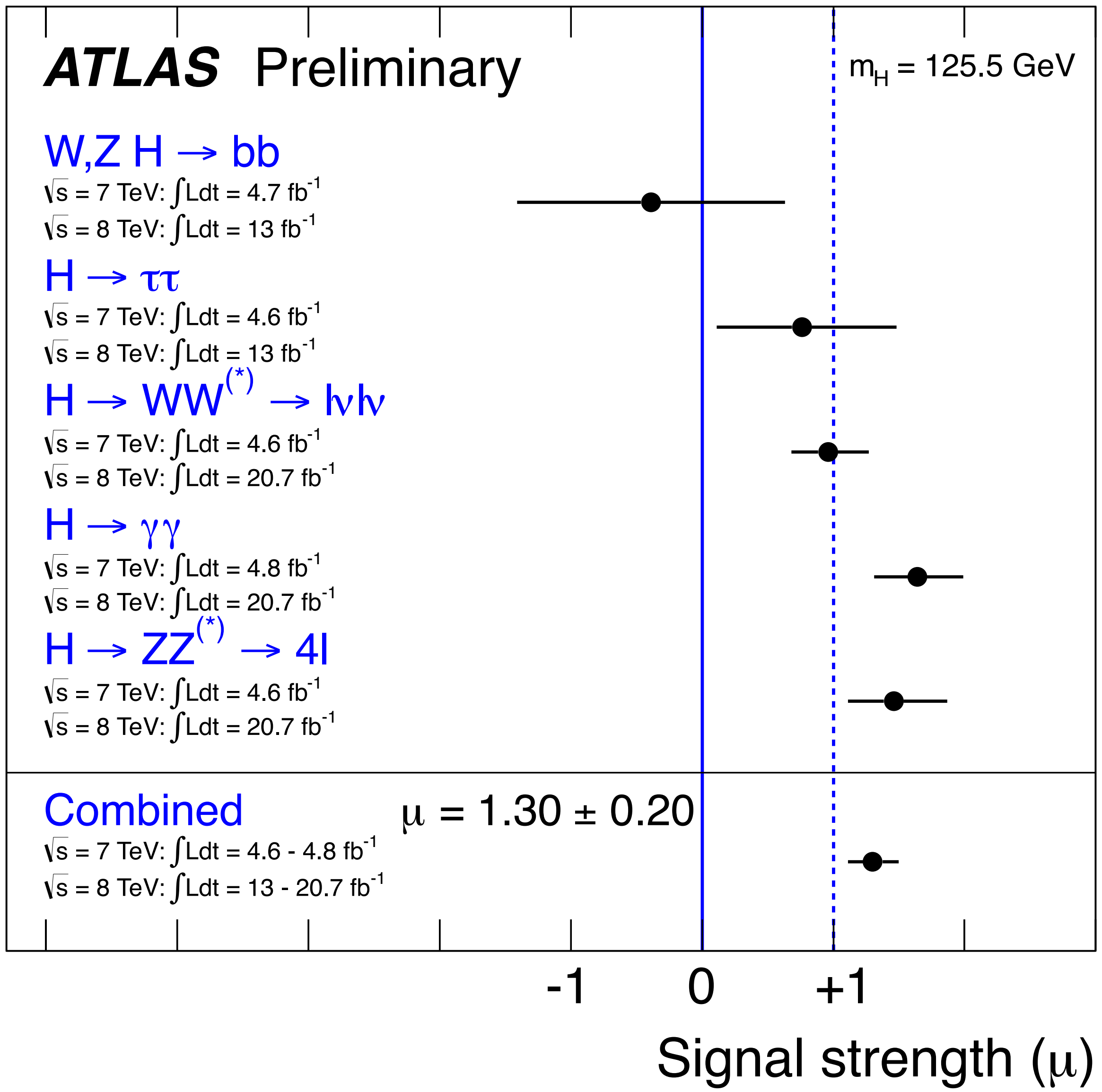
$$\mu = \mu_{if} = \mu_i \times \mu_f$$

Measurements of the signal strength parameter μ

for m_H = 125.5 GeV …
for the individual channels …
for their combination …

Couplings – Present Status

[ATLAS-CONF-2013-034]



ATLAS: μ = 1.30 ± 0.20

$$\mu_i = \sigma_i / \sigma_{i,\mathrm{SM}}$$

$$\mu_f = B_f / B_{f,\mathrm{SM}}$$

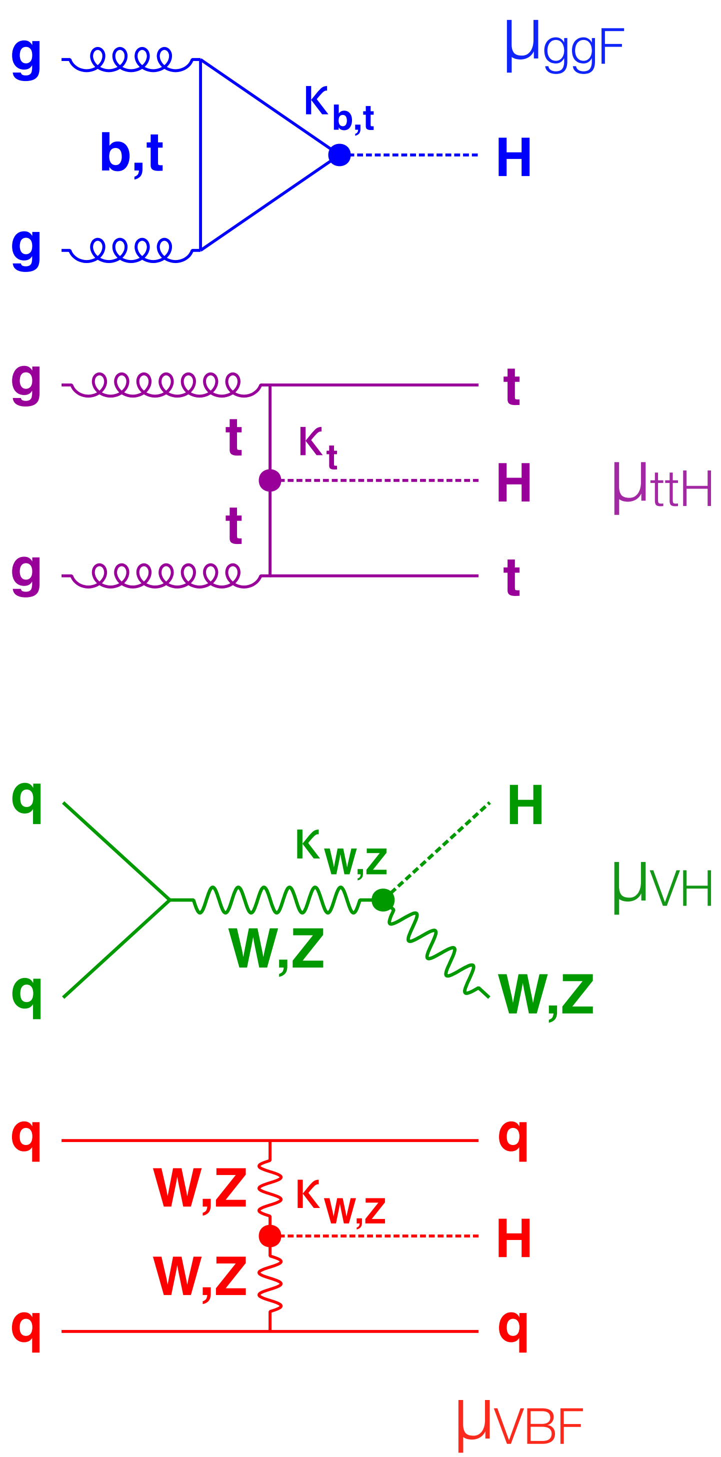
$$\mu = \mu_{if} = \mu_i \times \mu_f$$

Signal production strength
for individual decay modes …

Choose all μ the same …

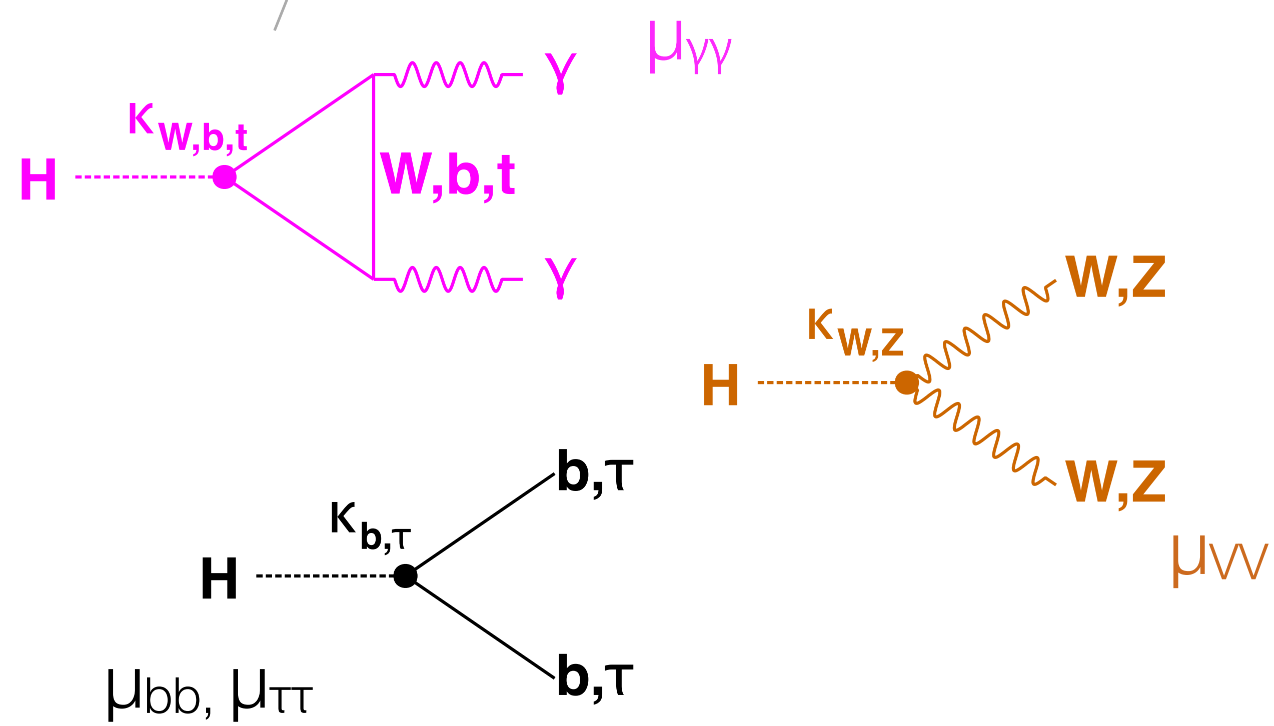
Combined: $\mu = \mu_i = \mu_f$ for all channels
Individual : $\mu = \mu_i = \mu_f$ for particular channel only

Higgs Boson Production and Decay



$$\mu_i = \sigma_i / \sigma_{i,\mathrm{SM}}$$

$$\mu_f = B_f / B_{f,\mathrm{SM}}$$



Higgs Boson Search Channels

[arXiv:1209.0040]

Channel	m_{H}(GeV)	ggH		VBF		VH		$\mathrm{t\bar{t}H}$	
		ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$\mathrm{H} \to \gamma\gamma$	110–150	√	√	√	√	-	-	-	-
$\mathrm{H} \to \tau^+\tau^-$	110–145	√	√	√	√	√	√	-	-
$\mathrm{H} \to \mathrm{b\bar{b}}$	110–130	-	-	-	-	√	√	-	√
$\mathrm{H} \to \mathrm{ZZ}^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	110–600	√	√	-	-	-	-	-	-
$\mathrm{H} \to \mathrm{WW}^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$	110–600	√	√	√	√	√	√	-	-

Higgs boson search channels in the ATLAS and CMS experiments by July 2012.

The √ symbol indicates exclusive searches targeting the inclusive gg ➛ H production, the associated production processes or the vector boson fusion production process.

Categories for Coupling Determination

[September 2012]

[ATLAS-CONF-2012-127]

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.8	[10]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8	[11]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet}\} \otimes \{\text{low, high pile-up}\}$	4.7	[12]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, VH\}$	4.7	[13]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet}\} \otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20\ \text{GeV}, E_{\mathrm{T}}^{\mathrm{miss}} \geq 20\ \text{GeV}\} \oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jet}\}$	4.7	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet}\}$	4.7	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \text{GeV}\}$	4.6	[14]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200\ \text{GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200\ \text{GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	5.8	[10]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9	[11]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet, 2-jet}\}$	5.8	[15]

Categories for Coupling Determination

[March 2013]

[ATLAS-CONF-2013-034]

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6	[8]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7	[8]
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	

Event Numbers – Example

[September 2012]
[ATLAS-CONF-2012-127]

Decay	Sub-channel	N_{obs}	$\langle N_B \rangle$	$\langle N_{ggF} \rangle$	$\langle N_{VBF} \rangle$	$\langle N_{WH} \rangle$	$\langle N_{ZH} \rangle$	$\langle N_{ttH} \rangle$
$H \to \gamma\gamma$	low-p_{Tt}	7013	6820	138	6.3	3.1	1.8	0.4
	high-p_{Tt}	320	291	14.0	2.9	1.8	1.0	0.4
	2-jet	36	24.2	1.3	3.4	0.0	0.0	0.0
$H \to ZZ^{(*)} \to 4\ell$	–	14	5.4	5.6	0.5	0.1	0.1	0.0
$H \to WW^{(*)} \to \ell\nu\ell\nu$	0-jet	667	573	75.3	0.8	0.3	0.4	0.0
	1-jet	183	141	16.7	1.7	0.3	0.2	0.0
	2-jet	3	3.7	0.3	1.3	0.0	0.0	0.0
$H \to \tau^+\tau^-$	0-jet	9277	9305	17.6	0.6	0.1	0.3	0.0
	1-jet	393	406	3.6	1.0	0.1	0.2	0.0
	2-jet	22	28.2	0.3	0.9	0.0	0.0	0.0
	VH	164	152	0.7	0.1	0.2	0.3	0.0
$H \to b\bar{b}$	ZH	322	321	0.0	0.0	0.0	4.0	0.0
	WH	1266	1311	0.0	0.0	11.1	0.0	0.0

Fall 2012 Analysis – Summary of the number of selected events, background and expected SM signal contributions for a 126 GeV Higgs boson

Statistical Procedure

Likelihood

[depends on μ_i, m_H …]

$$\mathcal{L}(\text{data}|\mu,\nu) = \prod_k \frac{(\mu_k s_k + b_k)^{n_k}}{n_k!} e^{-(\mu_k s_k + b_k)} \times \prod_j \pi_j(\tilde{\nu}_j|\nu_j)$$

Likelihood ratio …

[and test statistic …]

$$\Lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\nu}_\mu)}{\mathcal{L}(\mu', \hat{\nu}_{\mu'})} \qquad \& \qquad q = -2\ln\Lambda(\mu)$$

Asymptotically distributed as a χ^2 distribution with n degrees of freedom, where n is the dimensionality of the vector μ.

Statistical Procedure

Likelihood

[depends on μ_i, m_H …]

$$\mathcal{L}(\text{data}|\mu,\nu) = \prod_k \frac{(n^k_{\text{signal}} + b_k)^{n_k}}{n_k!} e^{-(n^k_{\text{signal}}+b_k)} \times \prod_j \pi_j(\tilde{\nu}_j|\nu_j)$$

Likelihood ratio …

[and test statistic …]

$$\Lambda(\mu) = \frac{\mathcal{L}(\mu,\hat{\nu}_\mu)}{\mathcal{L}(\mu',\hat{\nu}_{\mu'})} \qquad \& \qquad q = -2\ln\Lambda(\mu)$$

Asymptotically distributed as a χ^2 distribution with n degrees of freedom, where n is the dimensionality of the vector μ.

Higgs Boson Event Production

[ATLAS-CONF-2013-034]

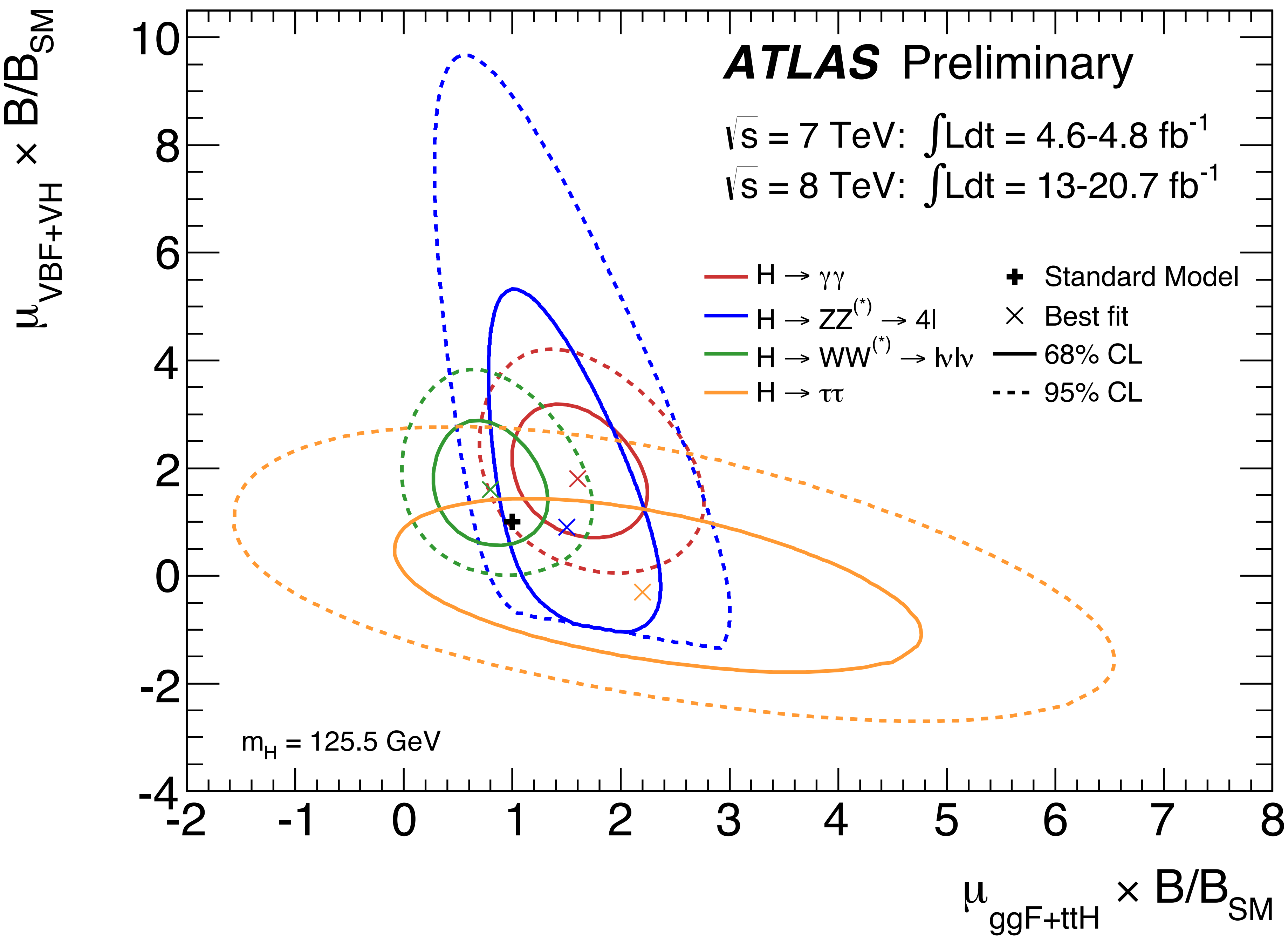
$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

k	=	analysis category
i	=	production mode
f	=	decay final state
n_k^{signal}	=	number of selected signal events in final state k
L	=	integrated luminosity
$\sigma_{i,SM}$	=	production cross section
$B_{f,SM}$	=	final state branching ratio
μ_i	=	production mode signal strength
μ_f	=	final state branching ratio strength
A	=	detector acceptance
ε	=	reconstruction and selection efficiency

Likelihood Contour – ($\mu_{ggF+ttH}$, μ_{VBF+VH}) Plane

[Note: μ_f = 1]

[ATLAS-CONF-2013-034]



Important:

BRs differ for different final states

Compatibility Test between Channels

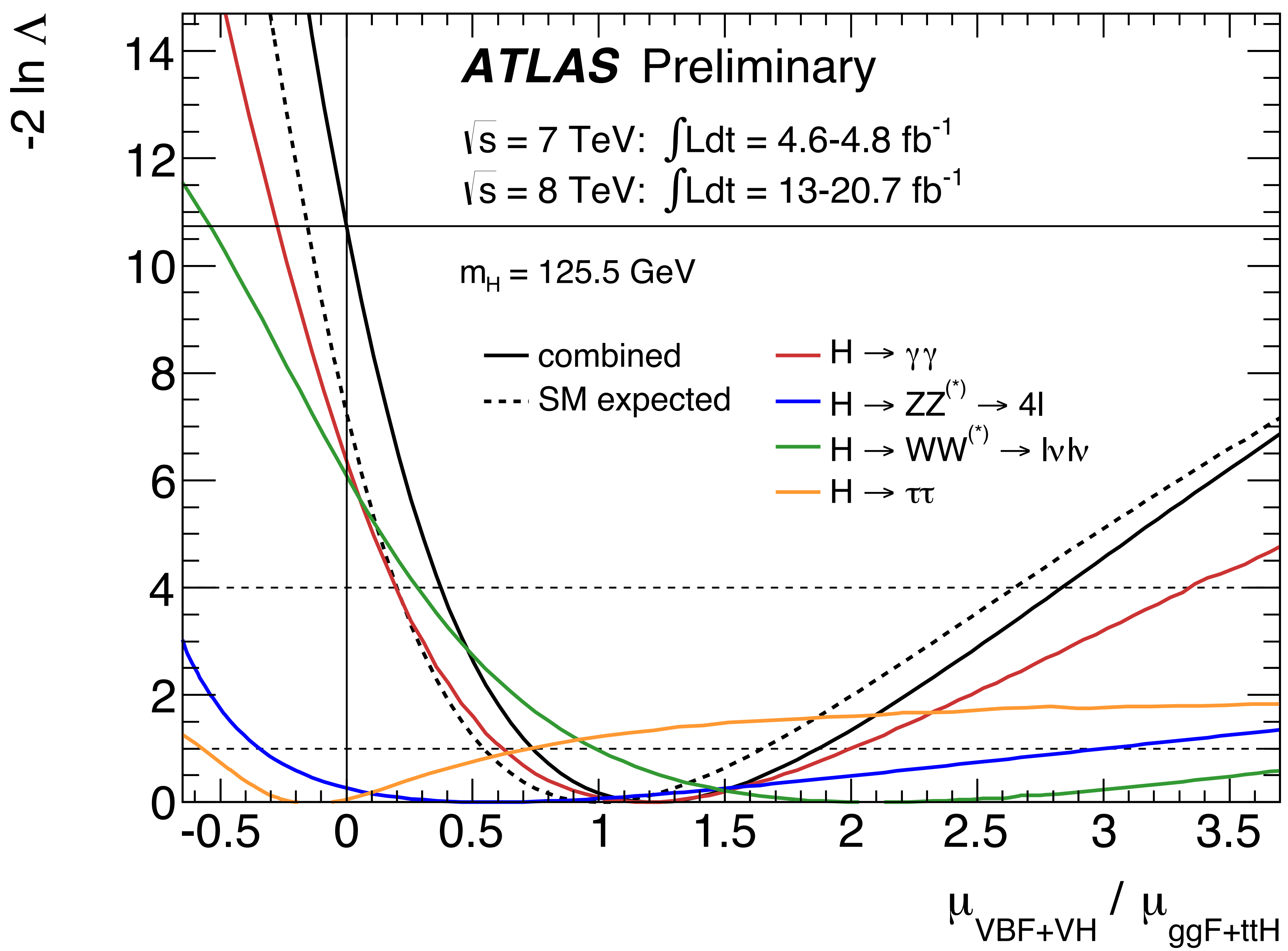
[ATLAS-CONF-2013-034]

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

$$\mu_{\mathrm{ggF}+t\bar{t}H;H\to XX} = \frac{\sigma(\mathrm{ggF}) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(\mathrm{ggF}) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)} = \frac{\sigma(t\bar{t}H) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(t\bar{t}H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)}$$

Compatibility Test between Channels

[ATLAS-CONF-2013-034]



Ratio of Relative Branching Ratios

[ATLAS-CONF-2013-034]

$$\sigma(gg \to H) * \mathrm{BR}(H\to\gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \rho_{\gamma\gamma/ZZ}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H\to\gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \cdot \rho_{\gamma\gamma/ZZ}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}$$

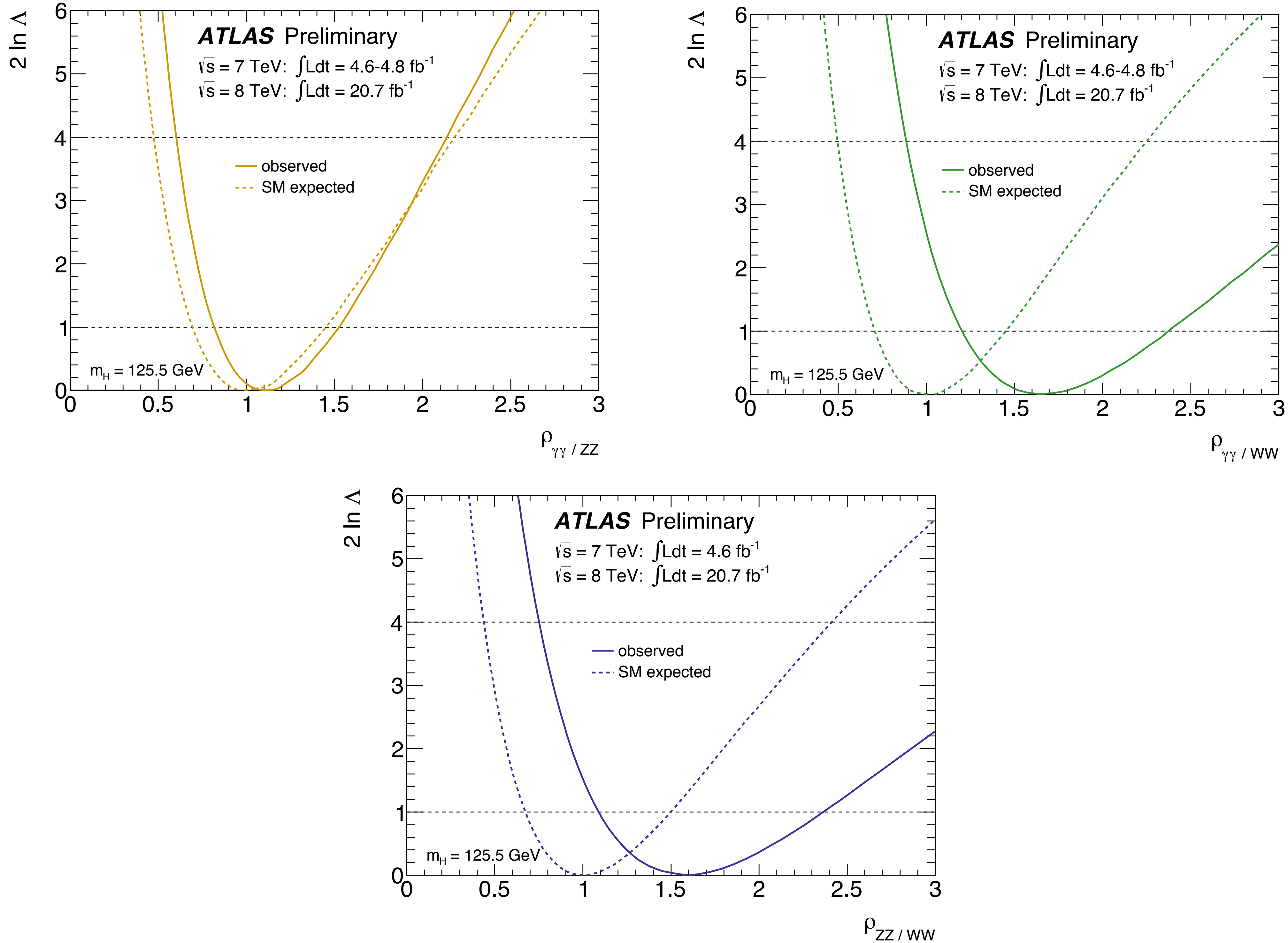
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H \to ZZ^{(*)})} \times \frac{\mathrm{BR}_{\mathrm{SM}}(H \to ZZ^{(*)})}{\mathrm{BR}_{\mathrm{SM}}(H\to\gamma\gamma)}$$

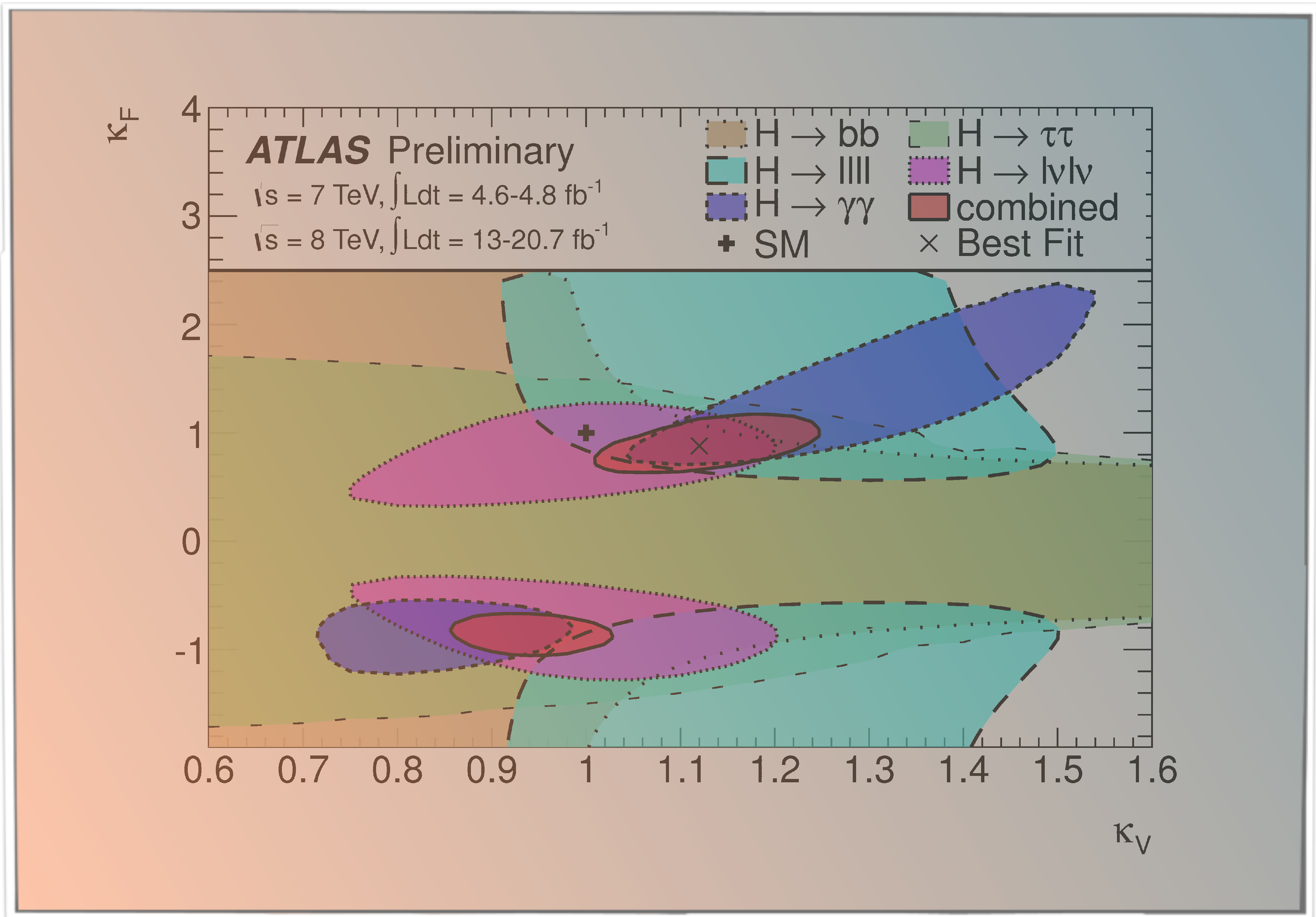
...

Ratio of Relative Branching Ratios

[ATLAS-CONF-2013-034]



Global Coupling Fits



[ATLAS-CONF-2013-034]

Signal Cross Section

$$(\sigma \cdot \mathbf{BR})\,(ii \to \mathrm{H} \to ff\,) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

σ_{ii}	=	production cross section
Γ_{ff}	=	partial decay width into final state *ff*
Γ_H	=	total Higgs decay width

Assumptions:

The signals observed in the different search channels originate from a single narrow resonance with a mass near 125 GeV. The case of several, possible overlapping, resonances in this mass region is not considered.

The width of the assumed Higgs boson near 125 GeV is neglected, i.e. the zero-width approximation for this state is used.

Signal Cross Section

$$(\sigma \cdot \mathbf{BR})\,(ii \to \mathrm{H} \to ff\,) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

σ_{ii}	=	production cross section
Γ_{ff}	=	partial decay width into final state *ff*
Γ_H	=	total Higgs decay width

Example:

Higgs boson production in the WH channel with decay to ZZ …

Dress SM predictions with scale factors κ_i
to parametrize possible coupling deviations …

$$\sigma_{WH} \times \mathrm{BR}(H \to ZZ) =$$

$$= \sigma_{WH}^{\mathrm{SM}} \times \mathrm{BR}^{\mathrm{SM}}(H \to ZZ) \times \frac{\kappa_W^2 \kappa_Z^2}{\kappa_H^2}$$

Scale factors
[SM: κ =1]

Scale factor
for total width …

Higgs Scale Factors

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

Production modes

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^2 \end{cases}$$

Total width

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Higgs Scale Factors

Interference term

Gluon Fusion Cross Section:

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

VBF Cross Section:

$$\kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) = \frac{\kappa_W^2 \cdot \sigma_{WF}(m_H) + \kappa_Z^2 \cdot \sigma_{ZF}(m_H)}{\sigma_{WF}(m_H) + \sigma_{ZF}(m_H)}$$

Partial γγ-Decay Width:

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Scale Factor for Total Higgs Width …

$$\kappa_{\mathrm{H}}^2(\kappa_i, m_H) = \sum_j \frac{\Gamma_j(\kappa_i, m_{\mathrm{H}})}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}(m_{\mathrm{H}})}$$

with j = WW, ZZ, bb, ττ, γγ …

But:

At LHC we do not measure the all Higgs boson production cross sections; and we don't measure the Higgs width, Γ_H !

Thus: need to use measured cross section to estimate κ_H …

Two possibilities:

Make assumptions on Γ_H ➛ model dependent measurement …
Make ratio of measurements, given that they are Γ_H independent …

Recommendations on
Benchmark Parameterization

[arXiv:1209.0040]

Benchmark parameterization without further assumptions and maximum degrees of freedom; not used.
[Black: common factors; blue: production factors; red: decay factors]

General parametrization allowing other couplings to float

Free parameters: $\kappa_{gZ} (= \kappa_g \cdot \kappa_Z/\kappa_H), \lambda_{\gamma Z} (= \kappa_\gamma/\kappa_Z), \lambda_{WZ} (= \kappa_W/\kappa_Z), \lambda_{bZ} (= \kappa_b/\kappa_Z), \lambda_{\tau Z} (= \kappa_\tau/\kappa_Z), \lambda_{Zg} (= \kappa_Z/\kappa_g), \lambda_{tg} (= \kappa_t/\kappa_g)$.

	$H \to \gamma\gamma$			$H \to ZZ^{(*)}$			$H \to WW^{(*)}$			$H \to b\bar{b}$			$H \to \tau^-\tau^+$		
ggH	κ_{gZ}^2	1	$\lambda_{\gamma Z}^2$	κ_{gZ}^2	1	1	κ_{gZ}^2	1	λ_{WZ}^2	κ_{gZ}^2	1	λ_{bZ}^2	κ_{gZ}^2	1	$\lambda_{\tau Z}^2$
$t\bar{t}H$	κ_{gZ}^2	λ_{tg}^2	$\lambda_{\gamma Z}^2$	κ_{gZ}^2	λ_{tg}^2	1	κ_{gZ}^2	λ_{tg}^2	λ_{WZ}^2	κ_{gZ}^2	λ_{tg}^2	λ_{bZ}^2	κ_{gZ}^2	λ_{tg}^2	$\lambda_{\tau Z}^2$
VBF	κ_{gZ}^2	$\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	$\lambda_{\gamma Z}^2$	κ_{gZ}^2	$\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	1	κ_{gZ}^2	$\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	λ_{WZ}^2	κ_{gZ}^2	$\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	λ_{bZ}^2	κ_{gZ}^2	$\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	$\lambda_{\tau Z}^2$
WH	κ_{gZ}^2	$\lambda_{Zg}^2\lambda_{WZ}^2$	$\lambda_{\gamma Z}^2$	κ_{gZ}^2	$\lambda_{Zg}^2\lambda_{WZ}^2$	1	κ_{gZ}^2	$\lambda_{Zg}^2\lambda_{WZ}^2$	λ_{WZ}^2	κ_{gZ}^2	$\lambda_{Zg}^2\lambda_{WZ}^2$	λ_{bZ}^2	κ_{gZ}^2	$\lambda_{Zg}^2\lambda_{WZ}^2$	$\lambda_{\tau Z}^2$
ZH	κ_{gZ}^2	λ_{Zg}^2	$\lambda_{\gamma Z}^2$	κ_{gZ}^2	λ_{Zg}^2	1	κ_{gZ}^2	λ_{Zg}^2	λ_{WZ}^2	κ_{gZ}^2	λ_{Zg}^2	λ_{bZ}^2	κ_{gZ}^2	λ_{Zg}^2	$\lambda_{\tau Z}^2$

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$

Simplest possible benchmark parametrization
where a single scale factor applies to all production and decay modes.

Common scale factor

Free parameter: $\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH					
$t\bar{t}H$					
VBF			κ^2		
WH					
ZH					

Recommendations on

Benchmark Parameterization

[arXiv:1209.0040]

Benchmark parametrization where custodial symmetry is assumed and vector boson couplings are scaled together (κ_V) and fermions are assumed to scale with a single parameter (κ_f).

Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH, $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF, WH, ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

Boson and fermion scaling without assumptions on the total width

Free parameters: $\kappa_{VV} (= \kappa_V \cdot \kappa_V / \kappa_H), \lambda_{fV} (= \kappa_f / \kappa_V)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH, $t\bar{t}H$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2$		$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \lambda_{fV}^2$	
VBF, WH, ZH	$\kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	κ_{VV}^2		$\kappa_{VV}^2 \cdot \lambda_{fV}^2$	

$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{SM}$

Fermion vs. Vector Coupling

Standard Model only contributions to total width

[ATLAS-CONF-2013-034]

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

Expressions for
Higgs production and decays:

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

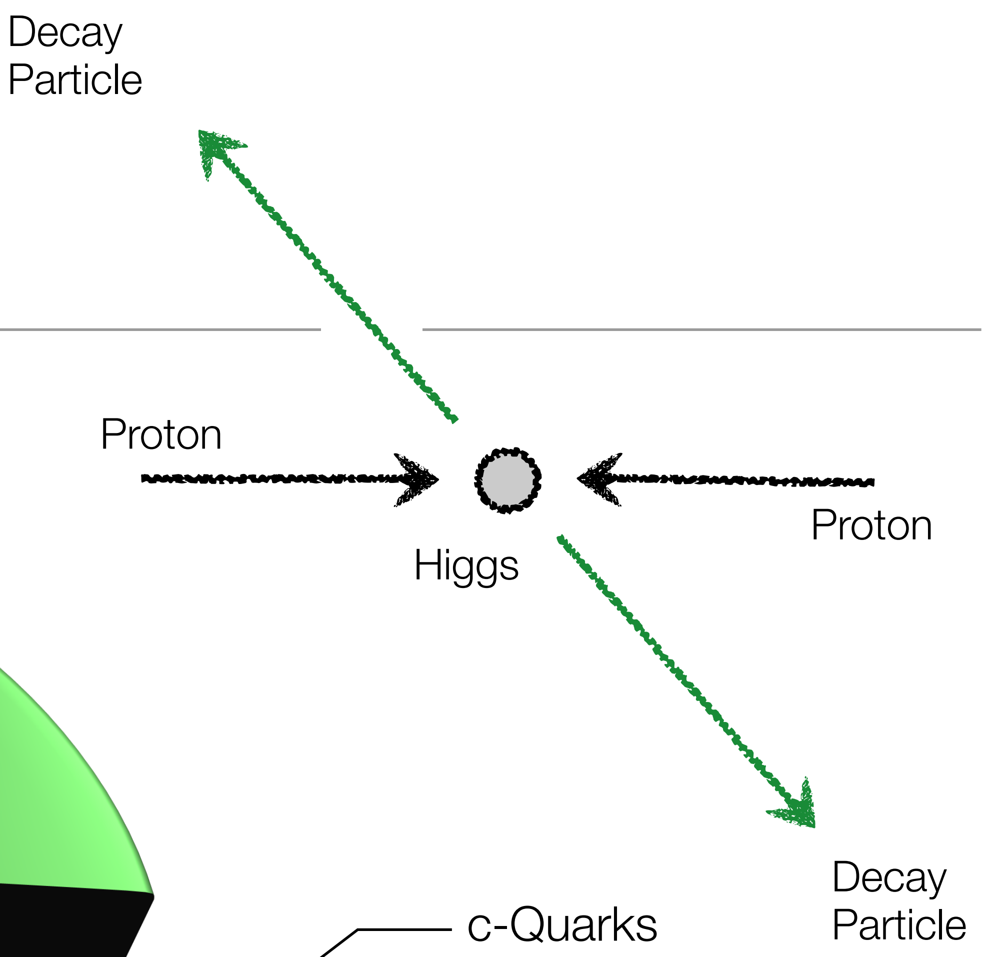
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

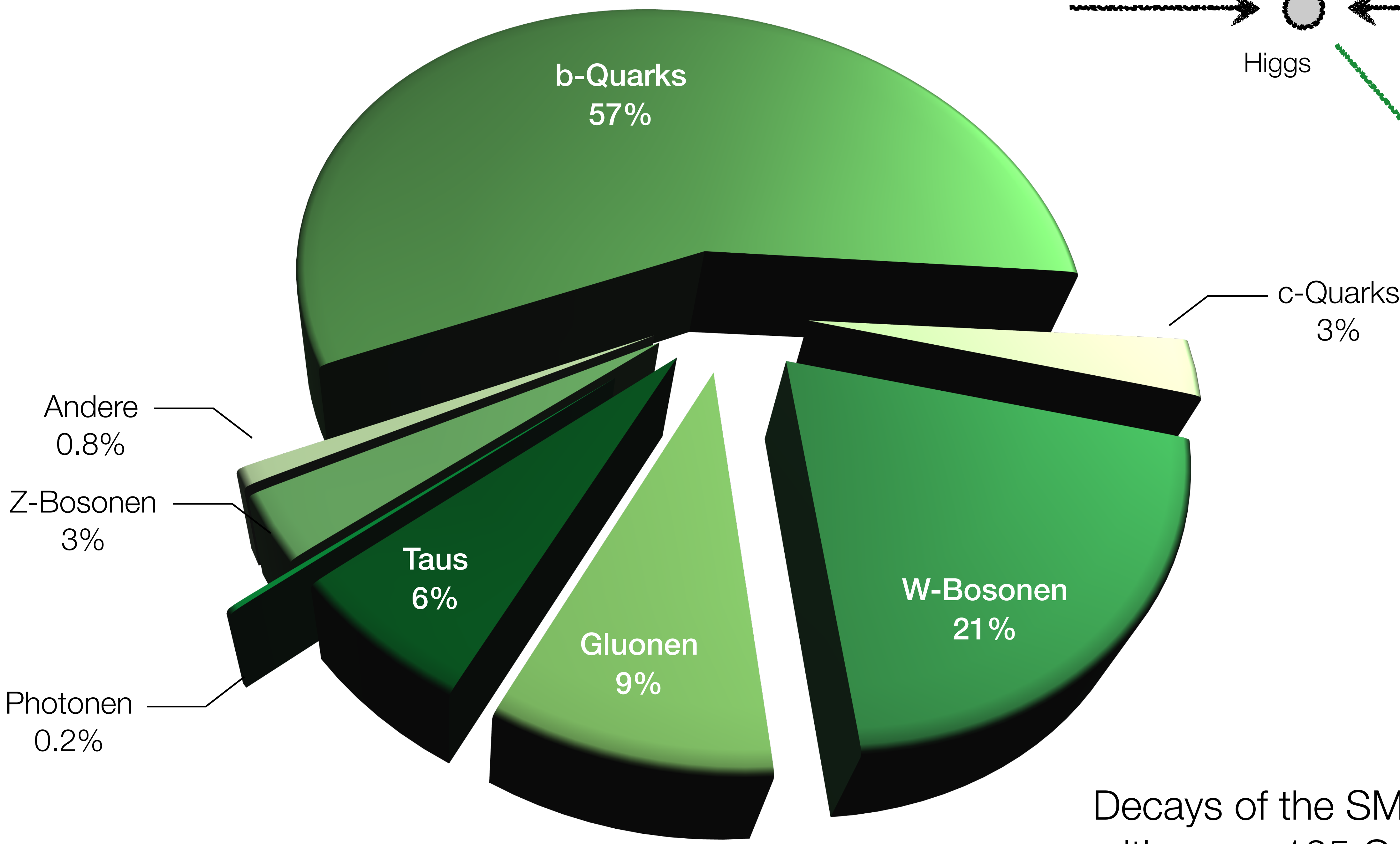
$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

Higgs Branching Ratios



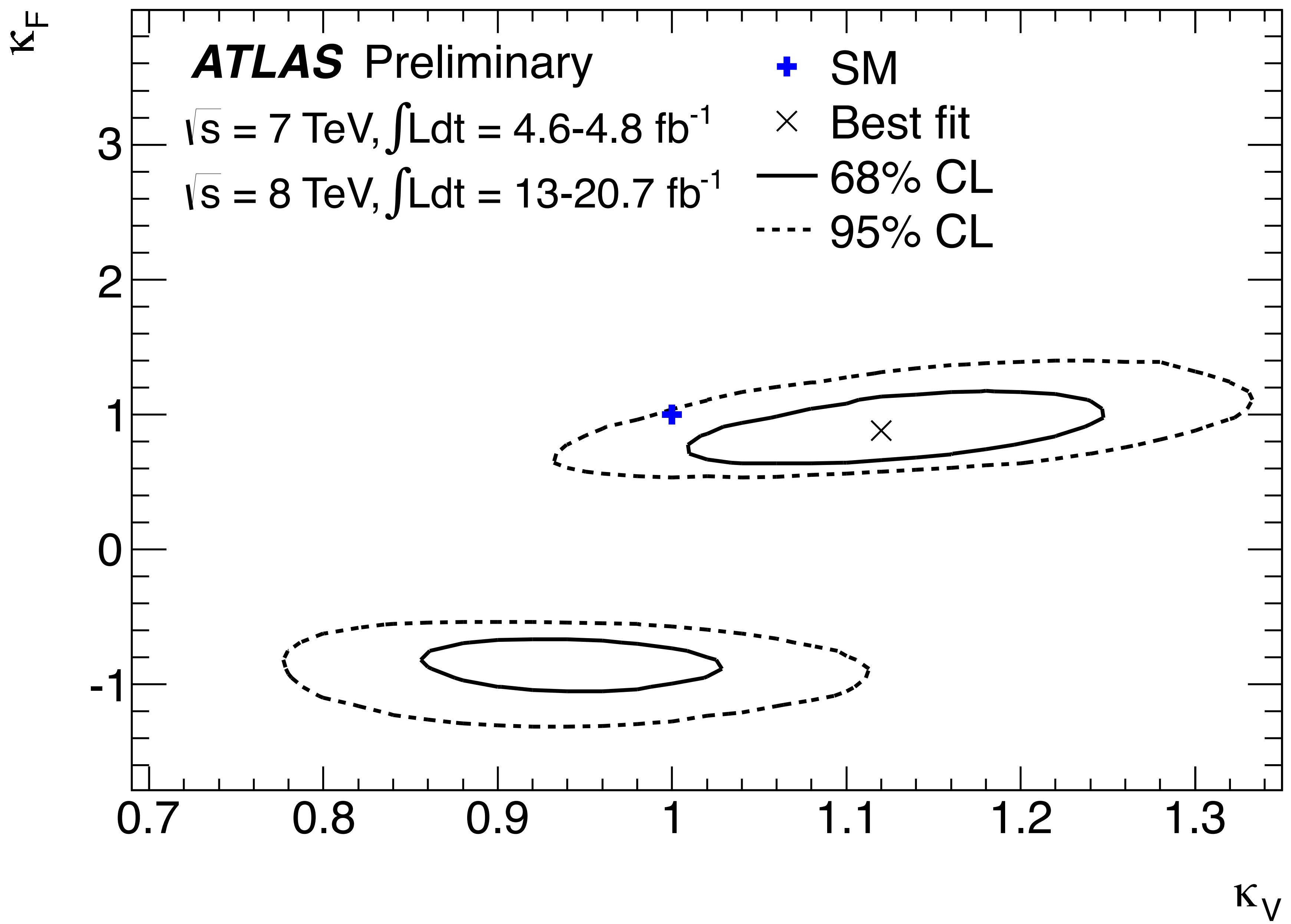


Decays of the SM-Higgs
with mass 125 GeV ...

Fermion vs. Vector Coupling

Standard Model only contributions to total width

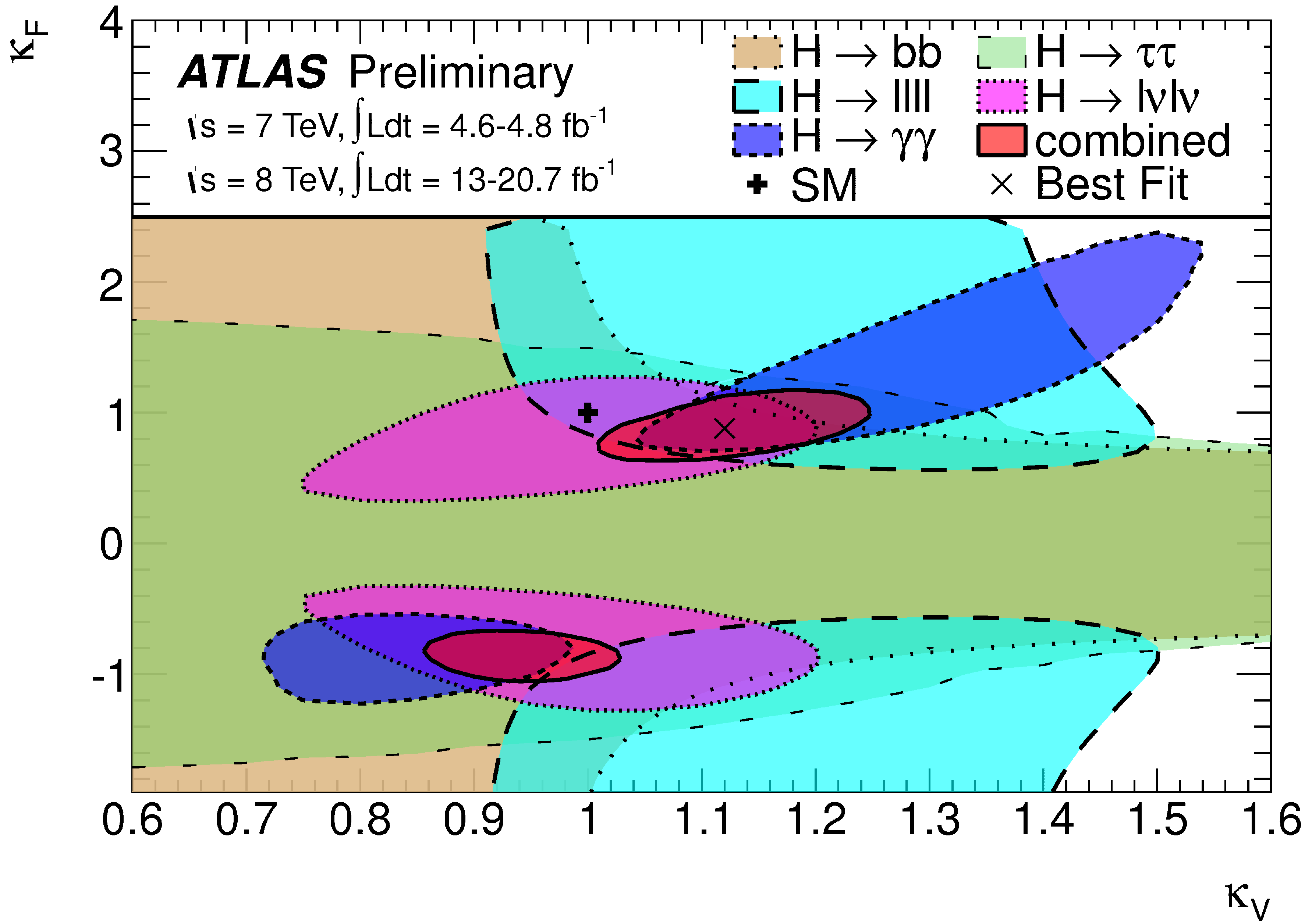
[ATLAS-CONF-2013-034]



Fermion vs. Vector Coupling

Standard Model only contributions to total width

[ATLAS-CONF-2013-034]



Probing BSM Contributions

Standard Model only contributions to total width

[ATLAS-CONF-2013-034]

scale factors κ_g and κ_γ
$\kappa_i = 1$ rest

Expressions for
Higgs production and decays:

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

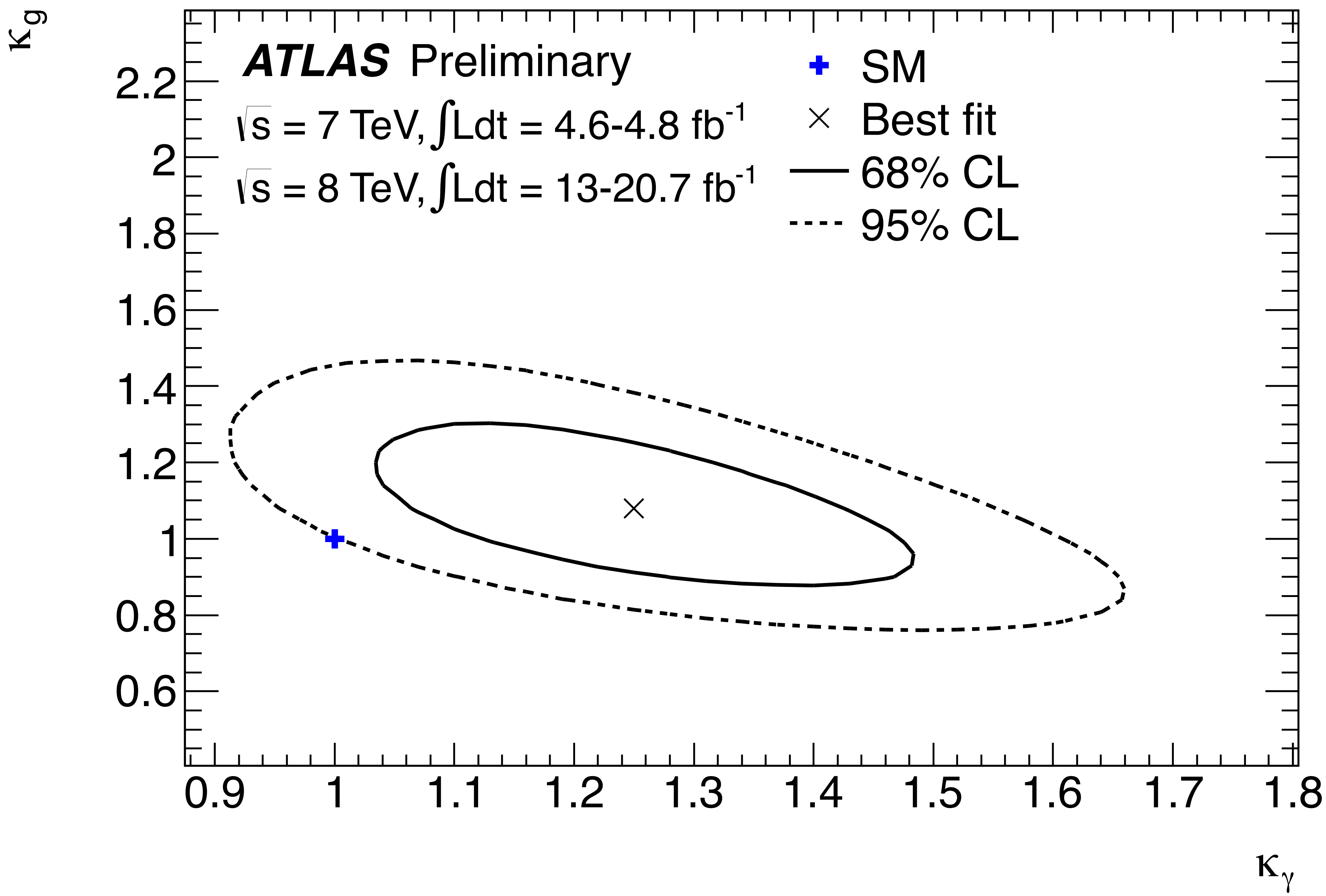
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

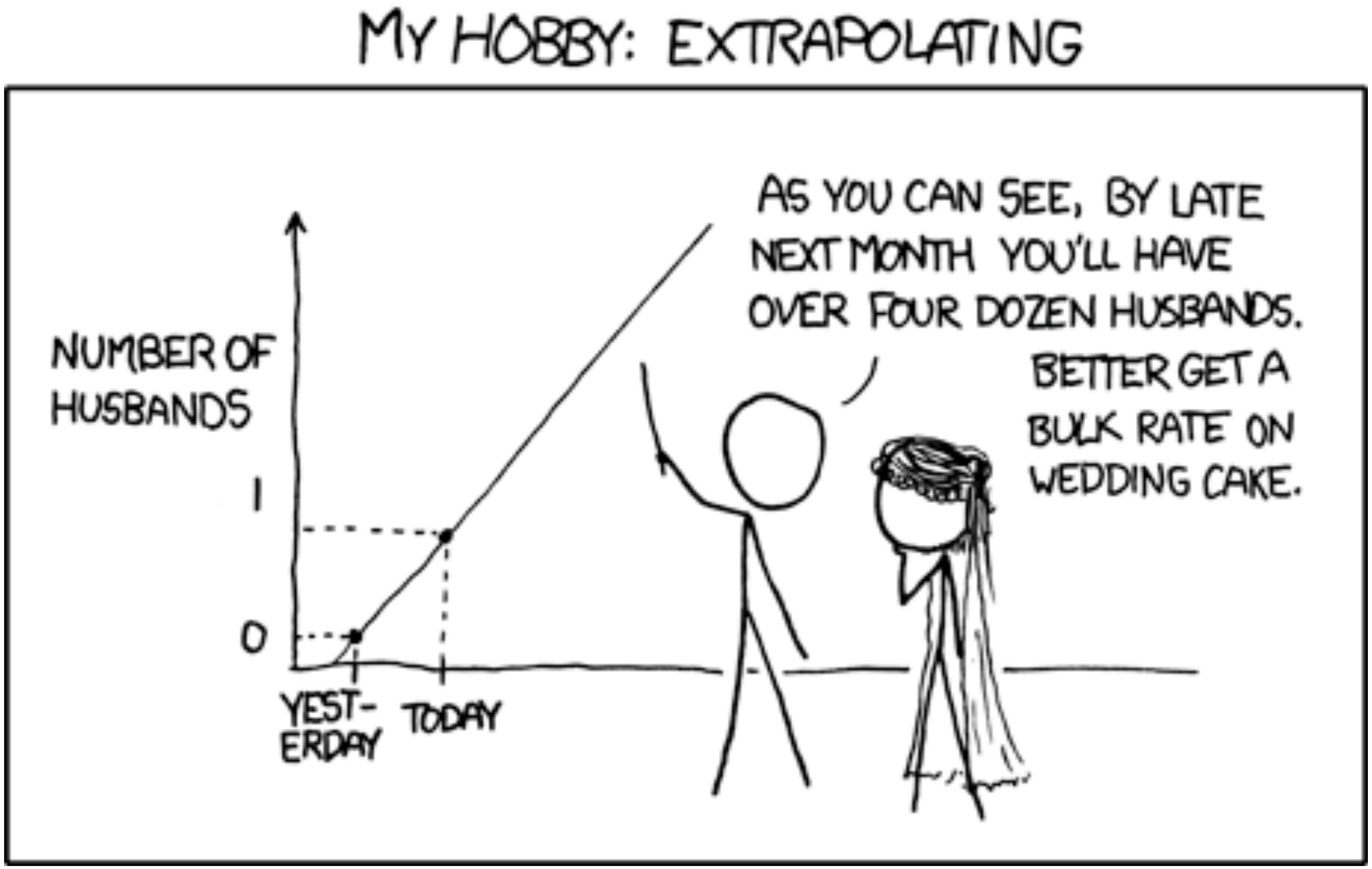
Probing BSM Contributions

Standard Model only contributions to total width

[ATLAS-CONF-2013-034]

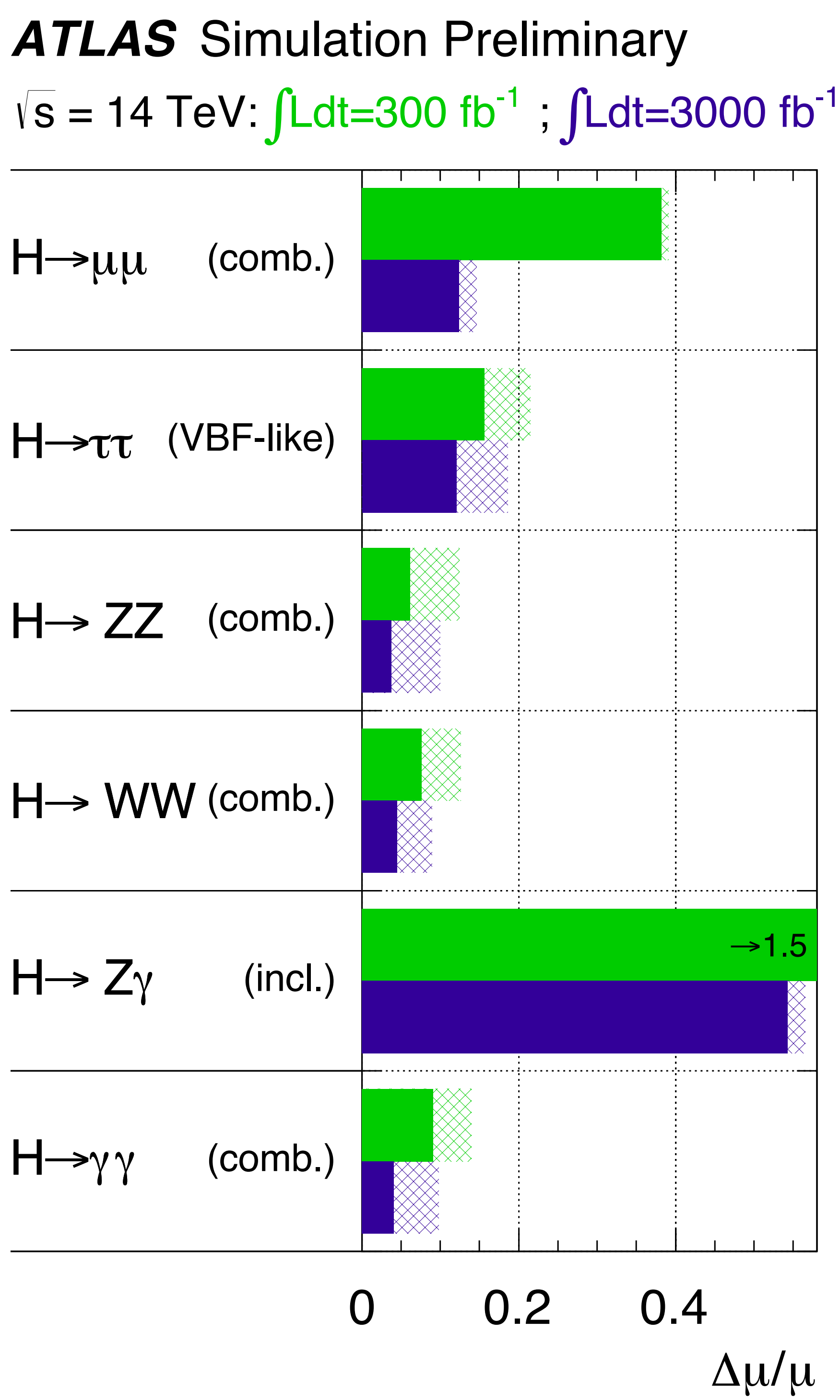


Future Prospects …



Higgs Coupling Prospects

[ATLAS-PHYS-PUB-2013-014]



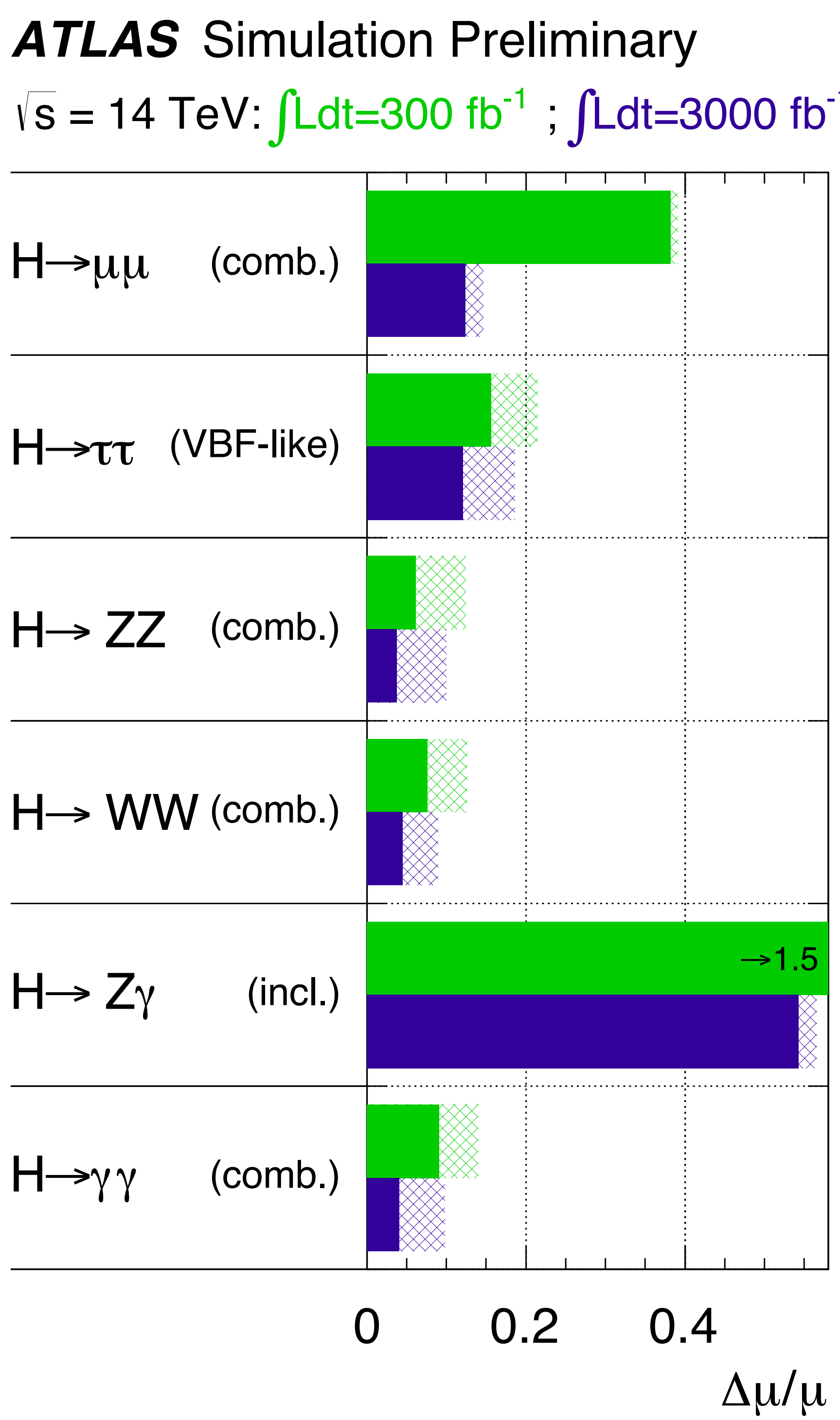
Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

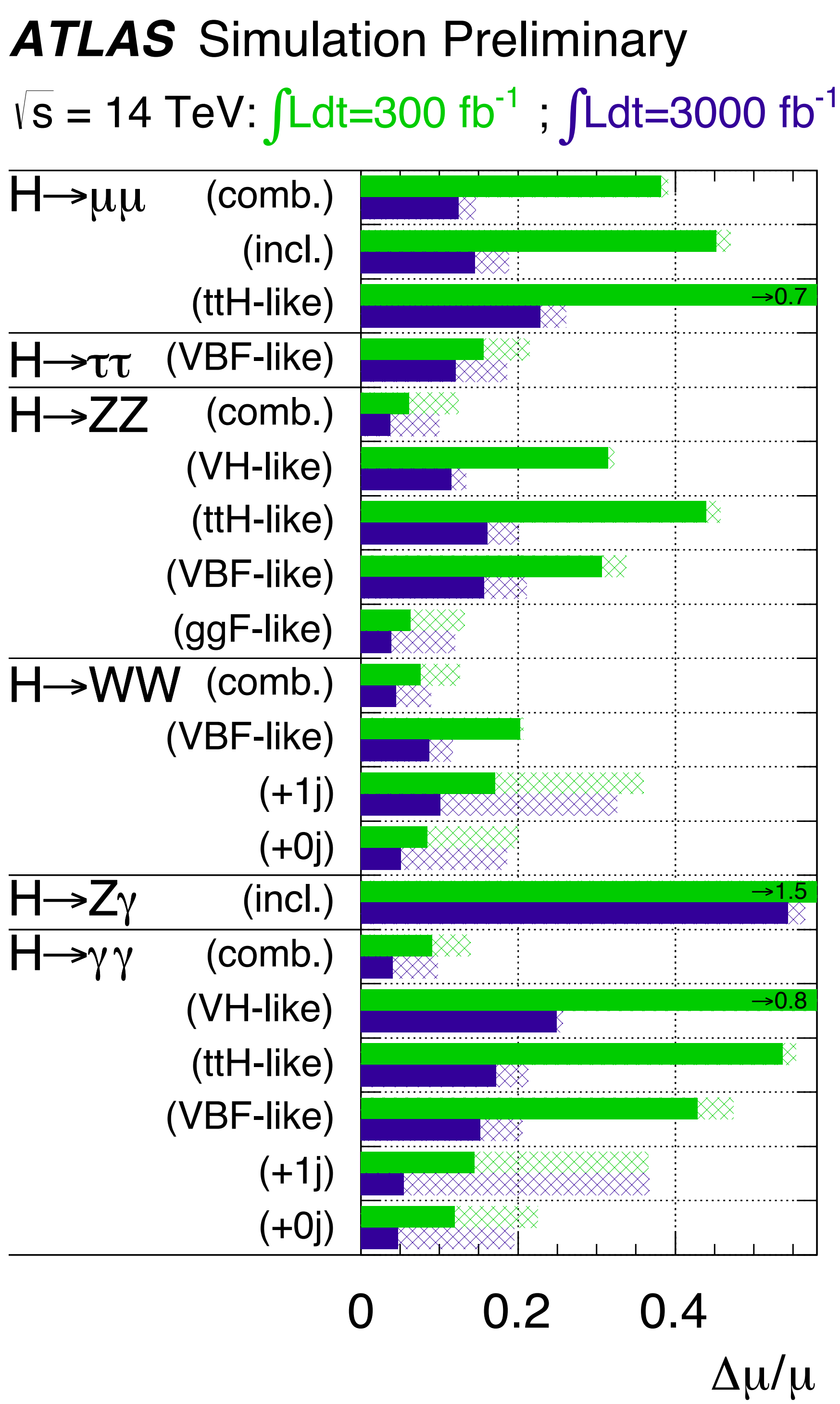
[ATLAS-CONF-2013-034]

Signal Strengths – Present Status

Higgs Coupling Prospects

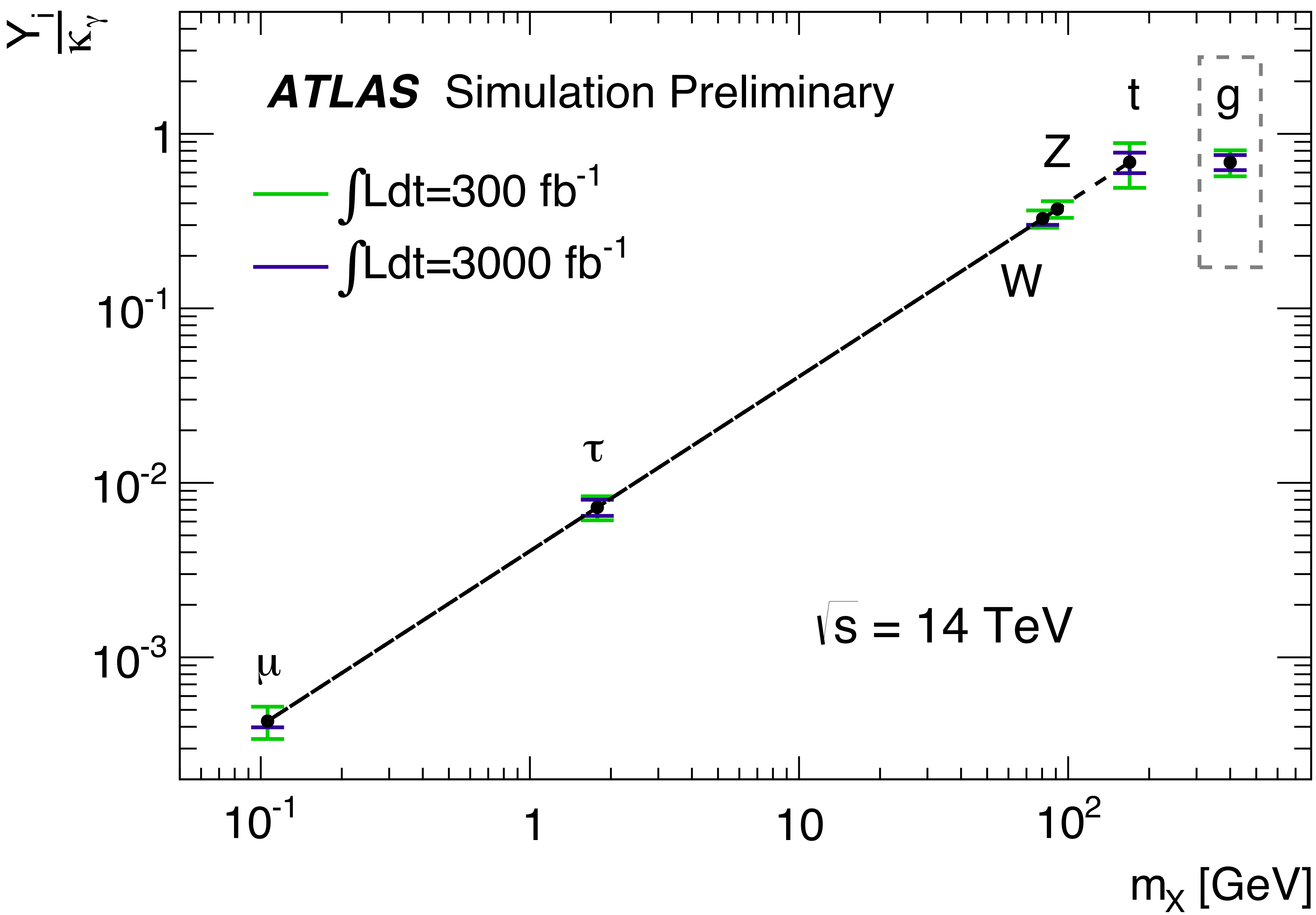
[ATLAS-PHYS-PUB-2013-014]





Higgs Coupling Prospects

[ATLAS-PHYS-PUB-2013-014]



Higgs Coupling Prospects

[Snowmass 2013; ILC Higgs White Paper]

Reconsideration of LHC projections by Snowmass 2013 …
[using different assumptions how systematics evolve …]

Best prospects given by CMS assuming …
decrease of theory errors by factor of 2 …
decrease of experimental systematics by $\sqrt{N}$ …

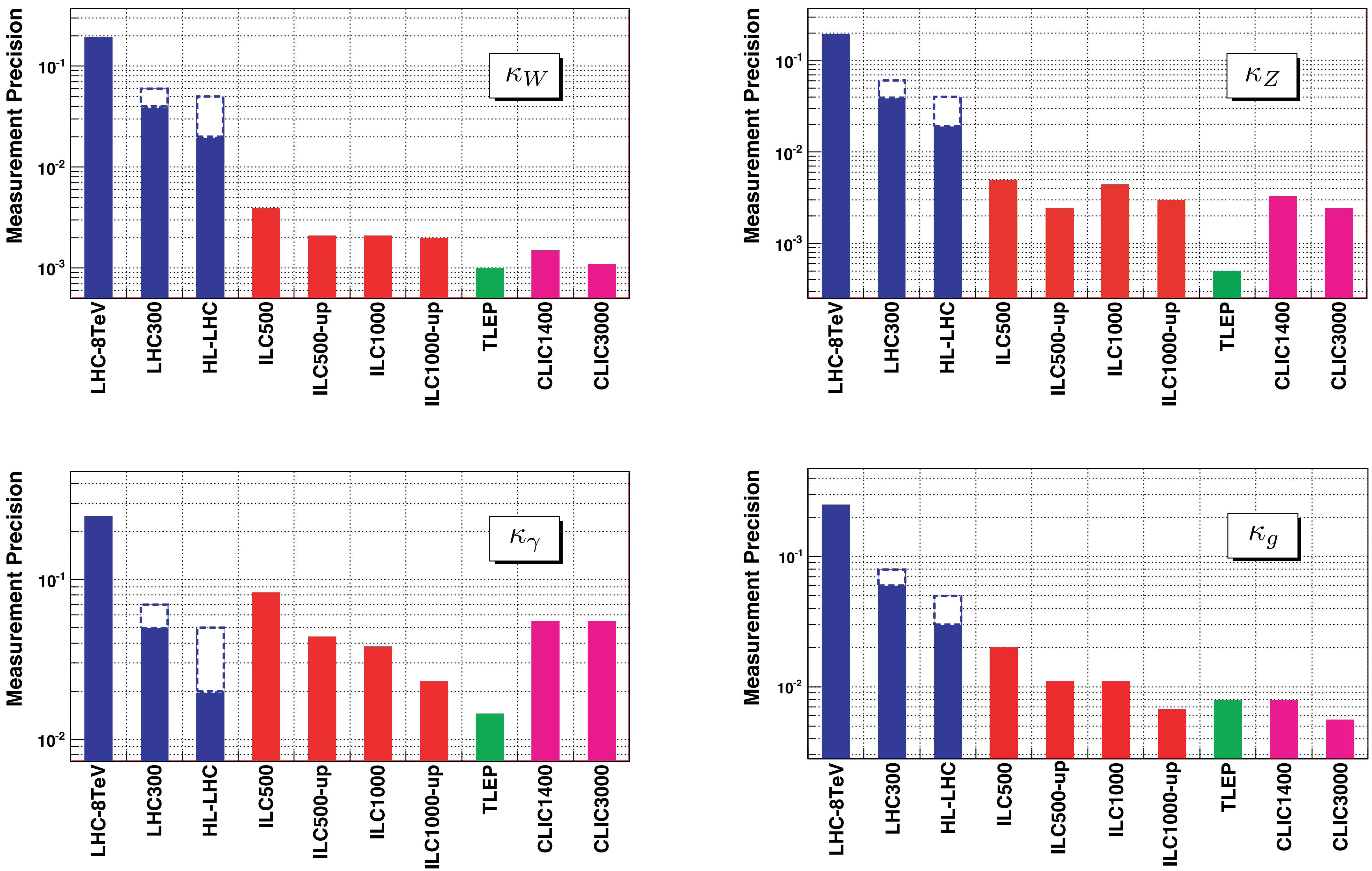
		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300 fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000 fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]
	ILC500	8.4	0.4	0.5	2.0	0.9	2.5	1.9	–	–
	ILC500up	4.4	0.2	0.3	1.1	0.6	1.3	1.0	–	–
	ILC1000up	2.3	0.2	0.3	0.7	0.4	0.9	0.7		

All numbers in percent.

Snowmass Higgs Working Group Report
ATL-PHYS-PUB-2013-007
CMS NOTE-13-002

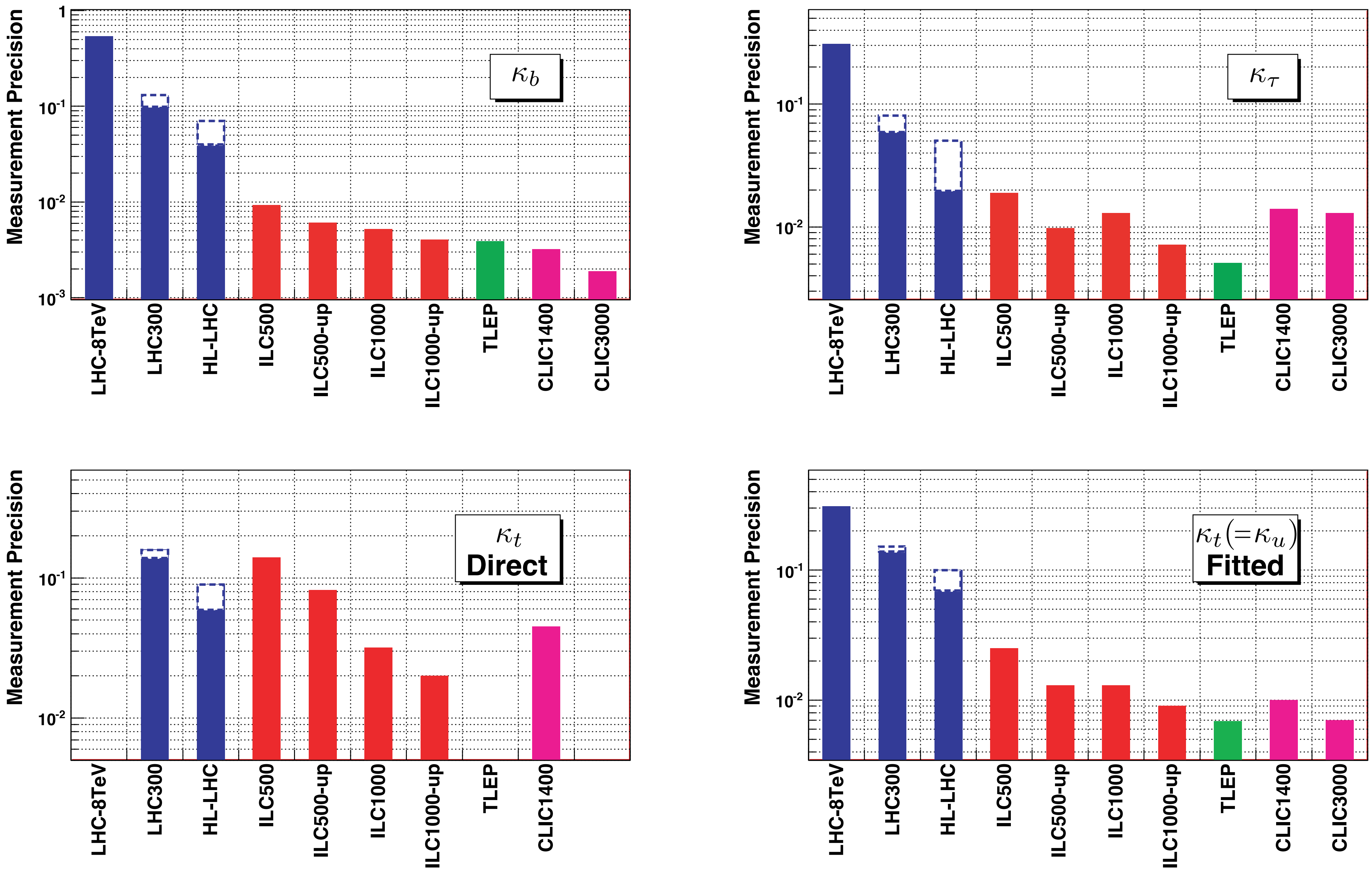
Higgs Coupling Prospects

[Snowmass 2013; ILC Higgs White Paper]



Higgs Coupling Prospects

[Snowmass 2013; ILC Higgs White Paper]



Physics Motivation

[Snowmass Higgs Working Group Report]

Non-Standard Higgs couplings possible due to new phenomena well beyond the present mass scales …

e.g. extra Higgs Bosons in a 2HDM …

Snowmass 2013: Survey of effects for M = 1 TeV …

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

[arXiv:1310.8361v1]

Generic size of Higgs coupling modifications for new physics at M = 1 TeV …

Higgs Self-Coupling Prospects

with
$m_H^2 = \eta v^2 / 2$ and $v^2 = -\mu^2 / \eta$

$$V_H = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2 \rightarrow \frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4$$

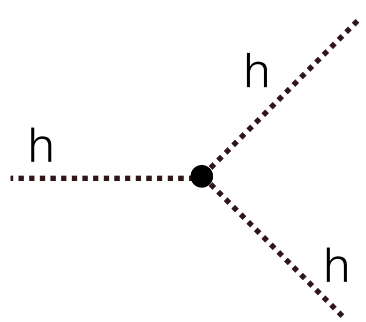
mass term

tri-linear coupling

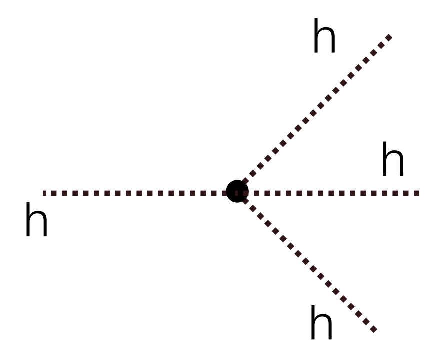
quartic coupling

Standard Model:

Higgs self couplings follow from the Higgs potential after expanding the Higgs doublet field Φ around the electroweak symmetry breaking vacuum expectation …

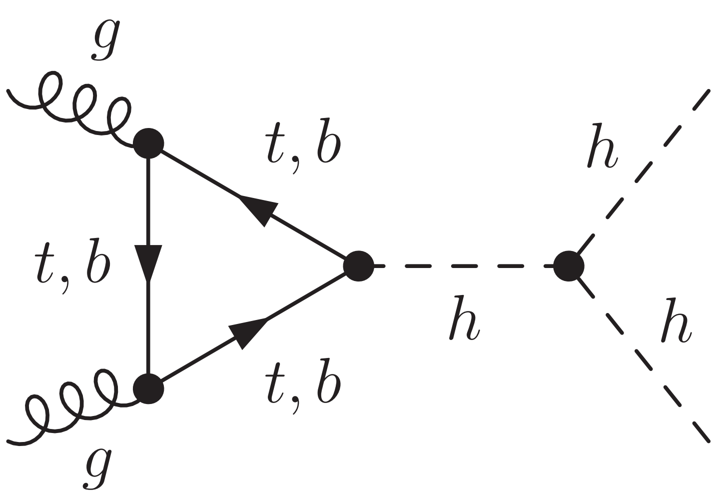


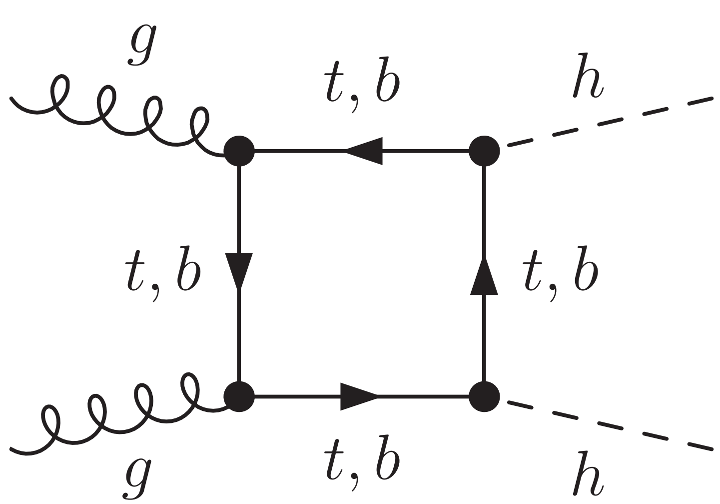
Trilinear coupling
via double Higgs production …



Quartic coupling
not accessible at LHC …

Higgs Self-Coupling Prospects



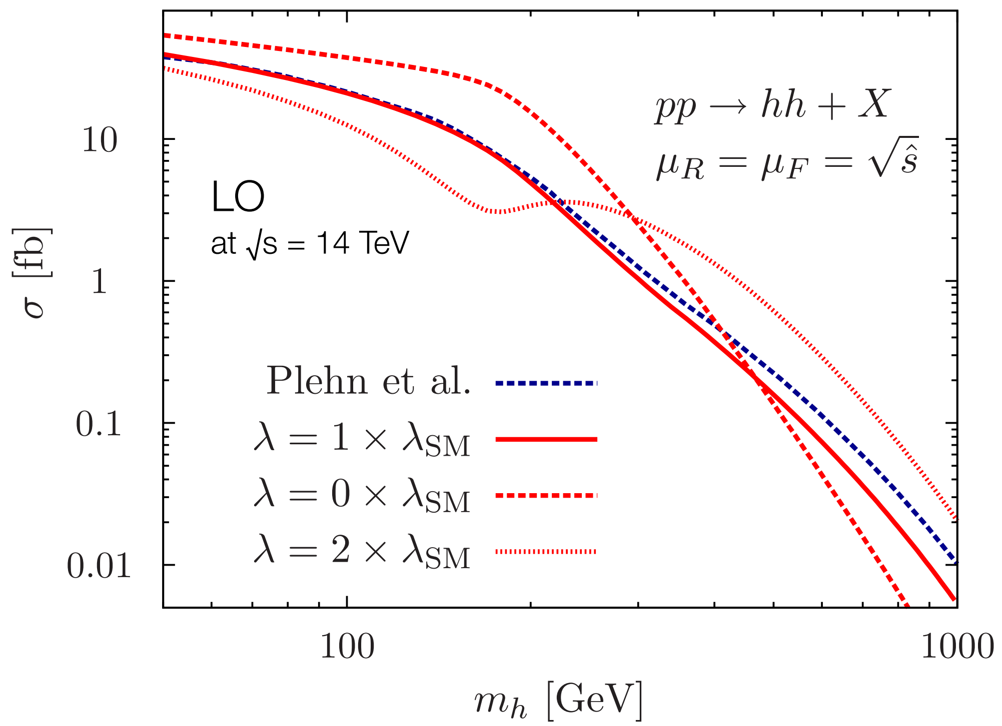


Destructive interference …

σ_{DH} depends on trilinear coupling $\lambda = m_H \cdot \sqrt{½}\eta$ …

relatively large λ-dependence
at $m_H \approx 125$ GeV …

[Dolan et al., arXiv:1206.5001]

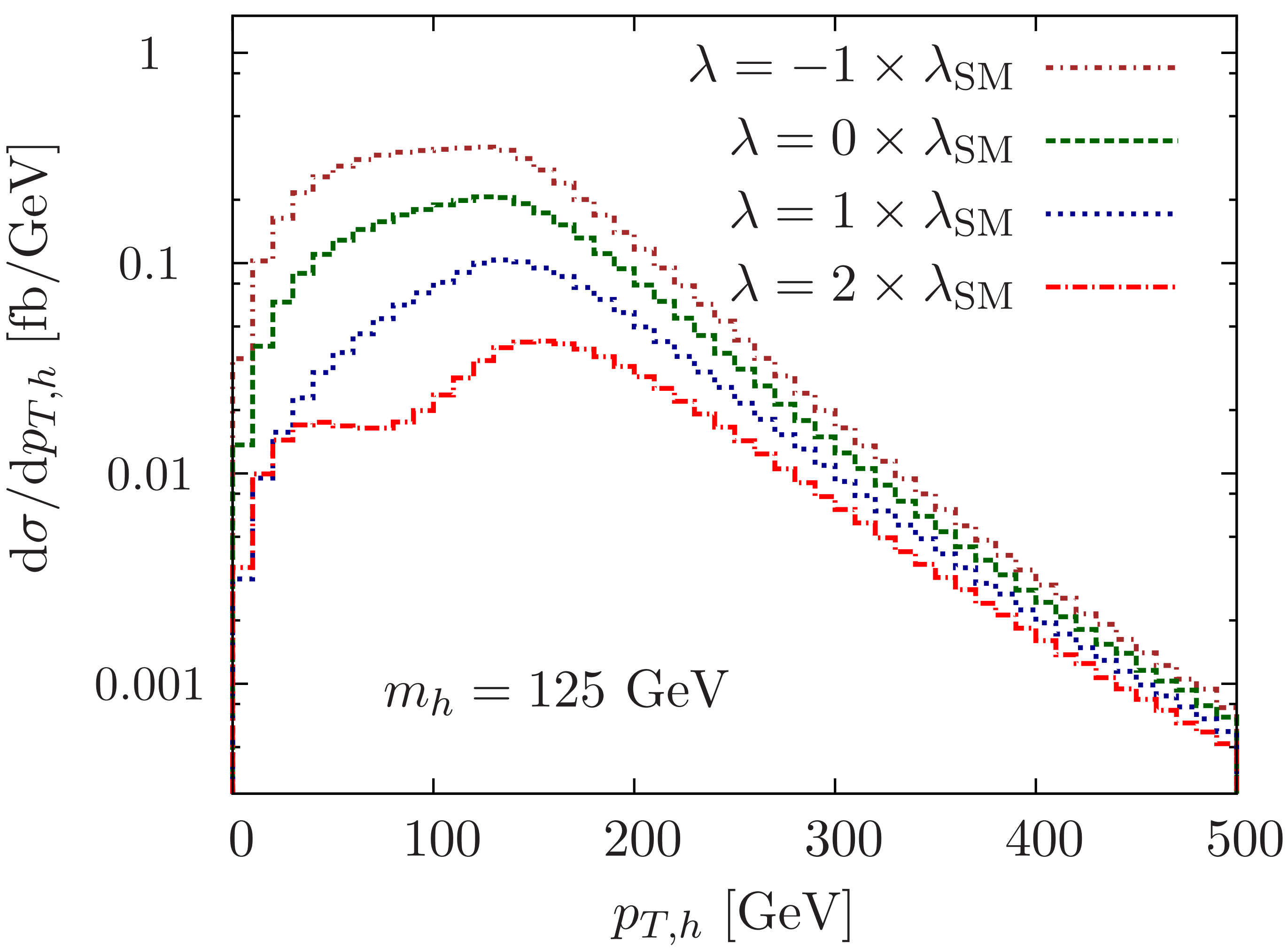


NLO: $\sigma = 34$ fb
[m_H = 125 GeV]

± 20 %
from QCD, PDF, EFT

Higgs Self-Coupling Prospects

[Dolan et al., arXiv:1206.5001]



Theory predicts:

Higgs bosons in
Di-Higgs production processes
naturally boosted $p_{T,h}$ ≥100 GeV …

Maximum sensitivity on
trilinear coupling λ expected for
transverse momenta of $p_{T,h}$ ~ 100 GeV …

Higgs transverse momentum $p_{T,h}$
good observable to identify kinematical region sensitive to different λ …

ATLAS Study on HH ➛ bbγγ

[E. Meoni, Aspen, March 2013]

Many channels to pursue, since m_H = 125 GeV …

Preliminary

Generator study
for HH ➛ bbγγ channel …

Tight $m_{\gamma\gamma}$ and b-tag p_T-cut
leave mostly ttH background …

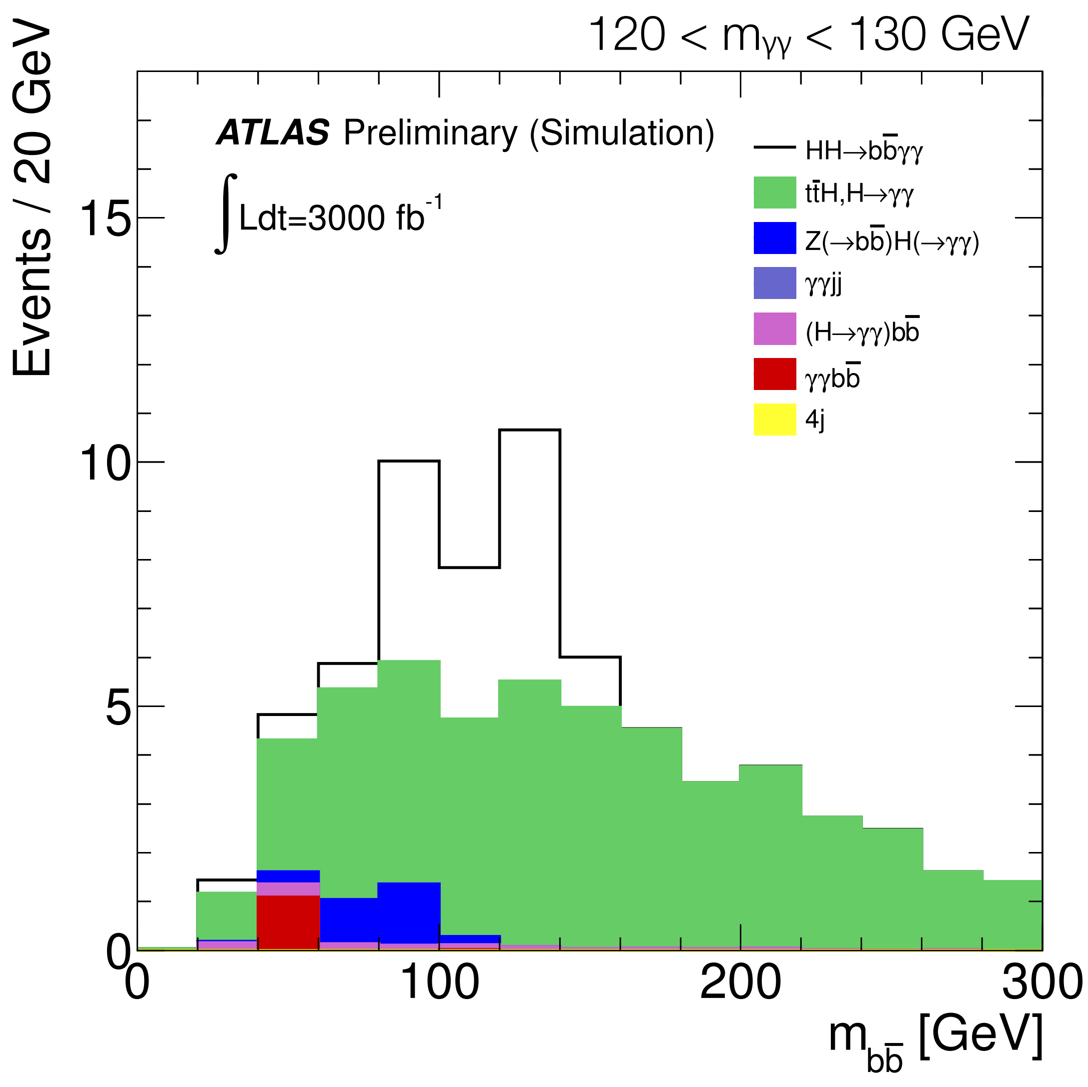
Selection:

2 b-jets with $p_T > 40$, 25 GeV
2 isolated photons, $p_T > 25$ GeV
Separation: $\Delta R_{\gamma b} > 0.4$

Expectation:

With additional channels and
two experiments: 30% measurement.

[see e.g. Barr et al. arXiv:1309.6318]



Higgs Self-Coupling Prospects

Decay channel	Branching ratio (%)	Events @ 14 TeV (L = 3,000 fb^{-1})
$b\bar{b} + b\bar{b}$	33.4084	33,976
$b\bar{b} + W^+W^-$	24.9696	25,394
$b\bar{b} + \tau^+\tau^-$	7.3638	7,488
$W^+W^- + W^+W^-$	4.6656	4,745
$ZZ + b\bar{b}$	3.0866	3,138
$ZZ + W^+W^-$	1.1534	1,174
$\gamma\gamma + b\bar{b}$	0.2658	270
$\gamma\gamma + \gamma\gamma$	0.0010	1