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A Light Higgs at the LHC and the B-Anomalies

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June, 6

Argonne National Laboratory

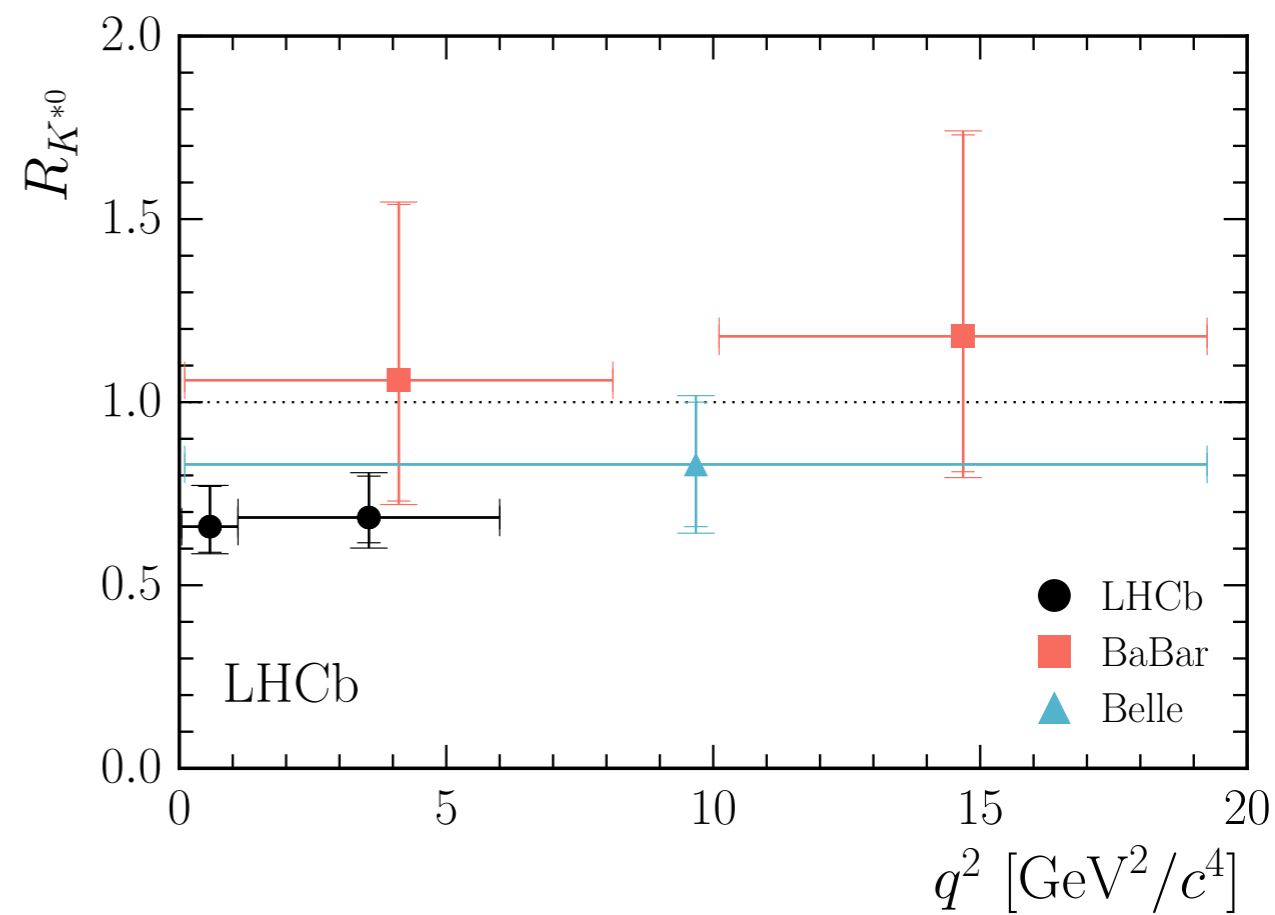
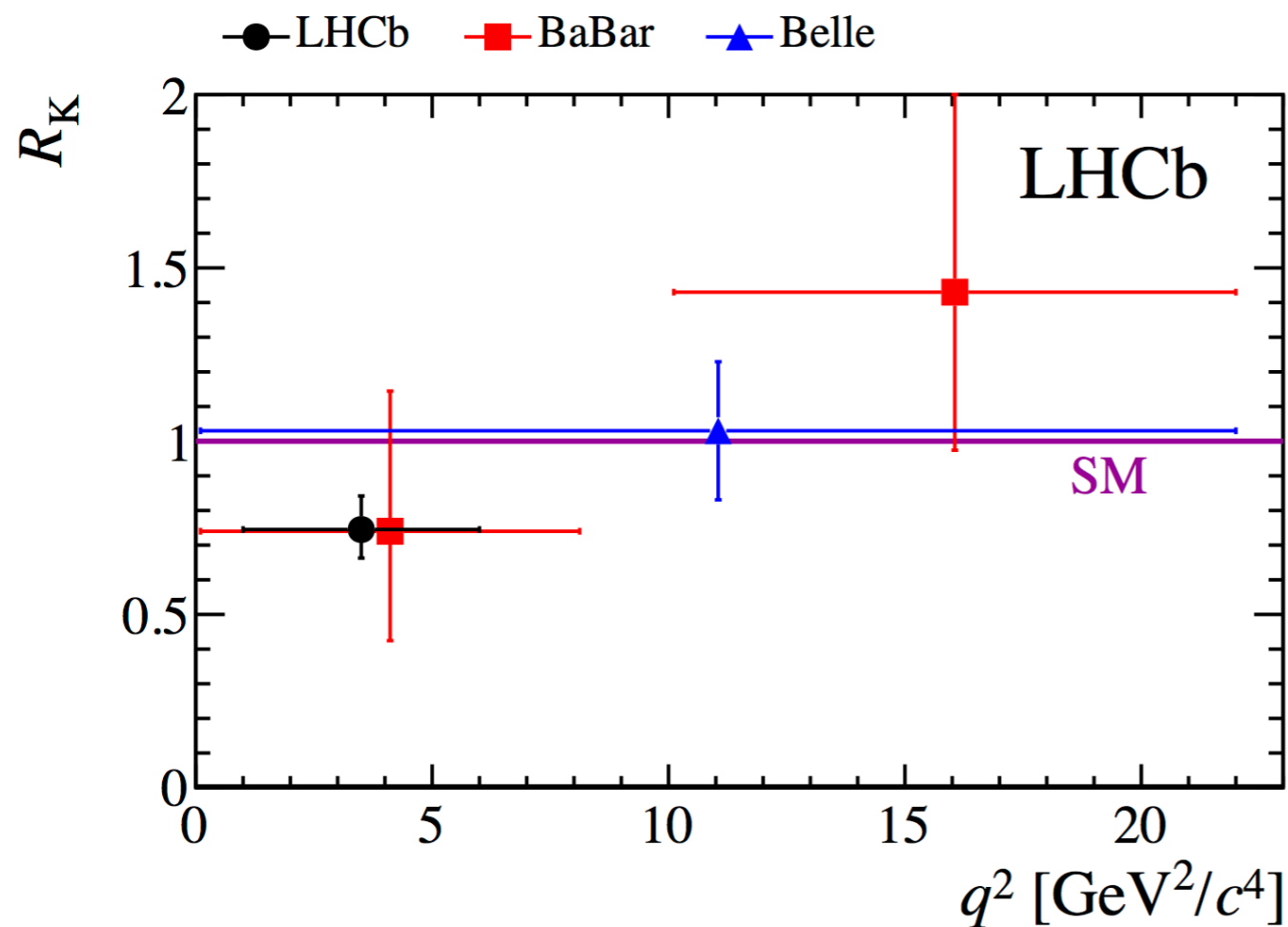
Collaborated with Da Liu, Jia Liu, and Carlos E.M. Wagner
[arXiv: 1805.01476]



R_K, R_{K^*} measurement

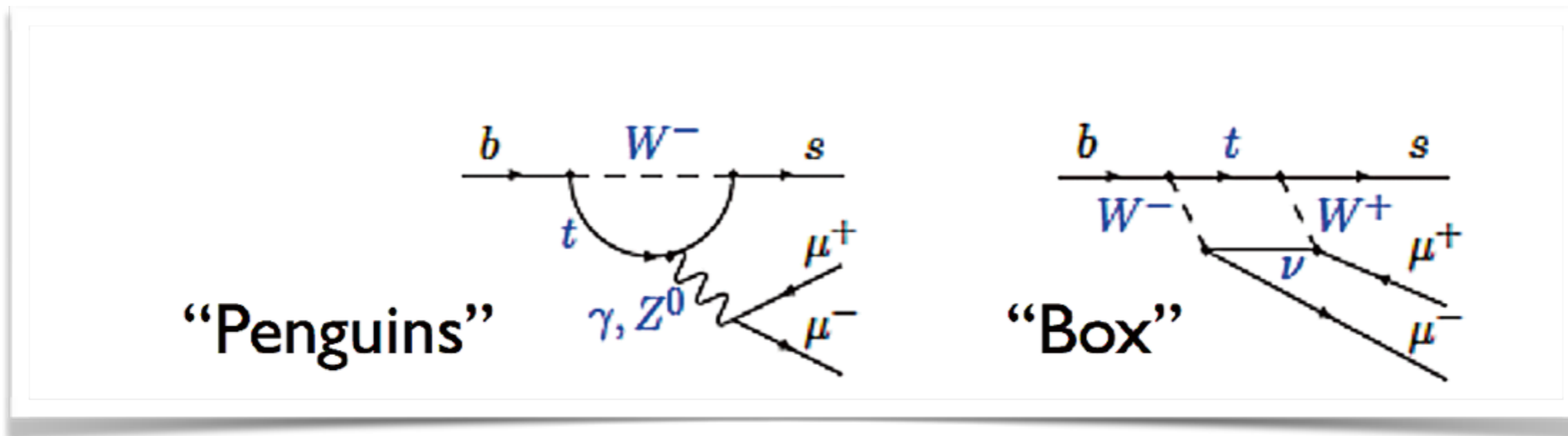
$$R_K = \frac{BR(B \rightarrow K \mu^+ \mu^-)}{BR(B \rightarrow K e^+ e^-)}$$

$$R_{K^*} = \frac{BR(B \rightarrow K^* \mu^+ \mu^-)}{BR(B \rightarrow K^* e^+ e^-)}$$





R_K, R_{K^*} measurement

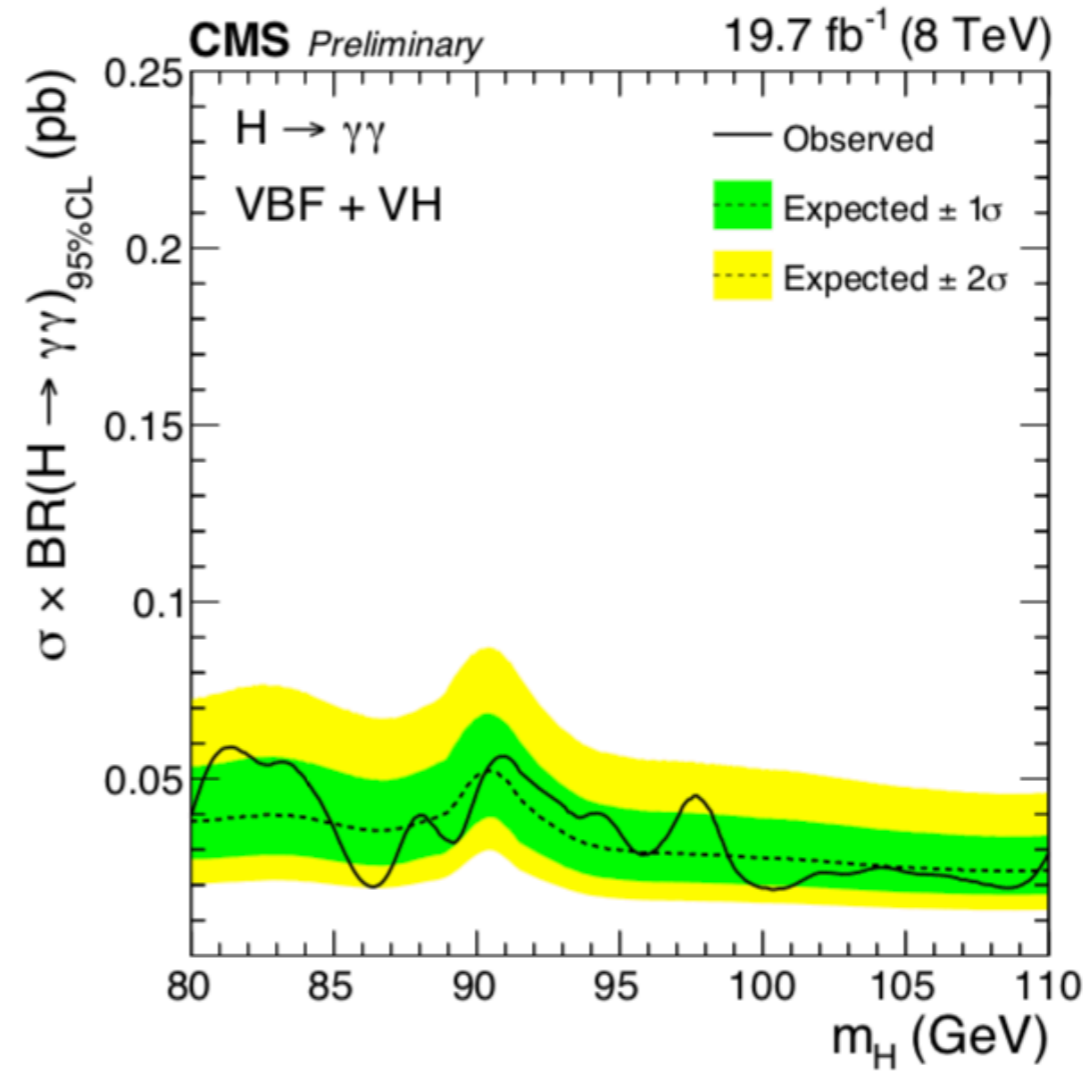
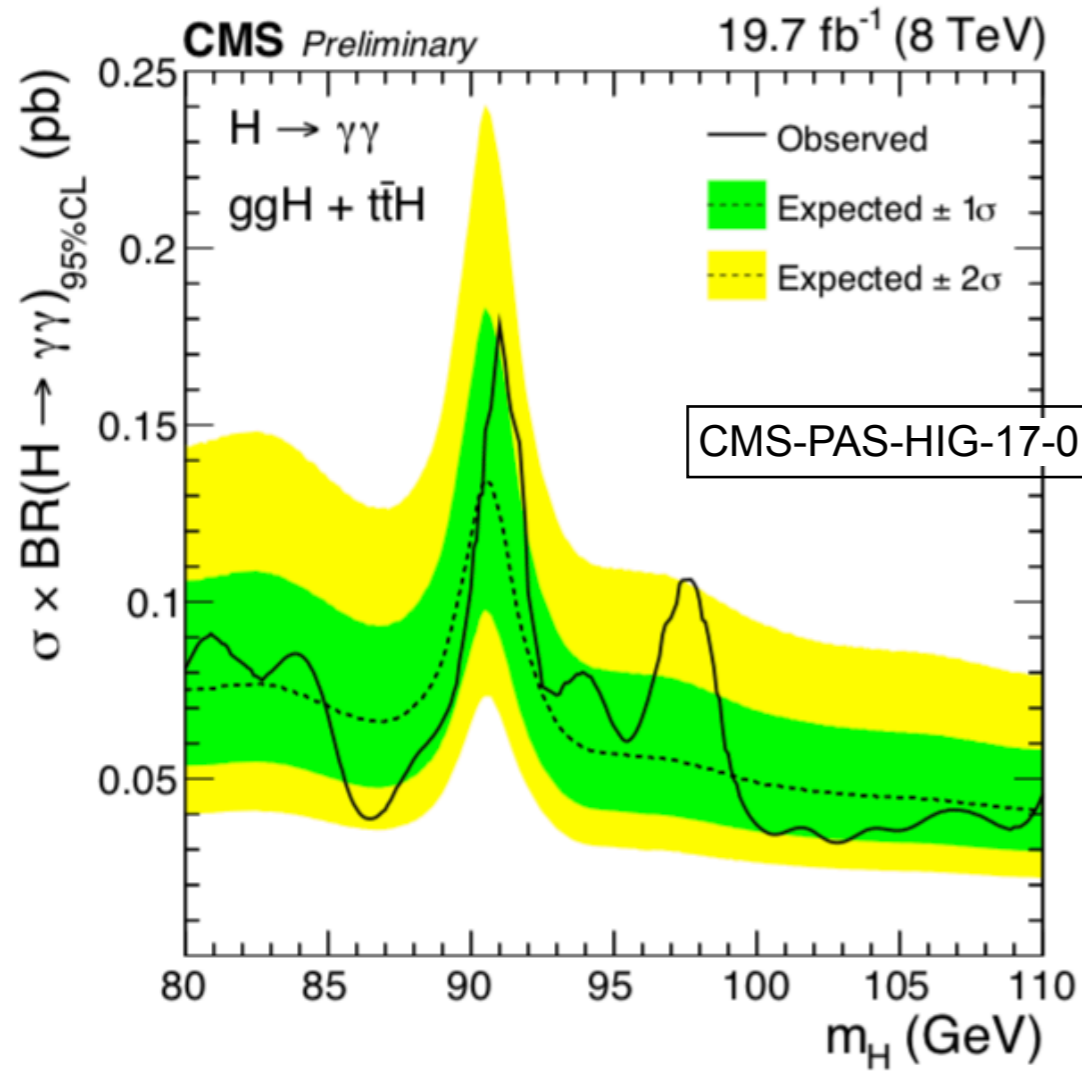


$$\mathcal{H}_{eff}^{NP} = -\mathcal{L}_{eff}^{NP} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha_{em}}{4\pi} (V_{tb}V_{ts}^*) C_9^{NP} \bar{b}_L \gamma_\mu \tilde{s}_L \bar{\mu} \gamma^\mu \mu + H.c.$$

$$C_9^{NP} = -1.59$$

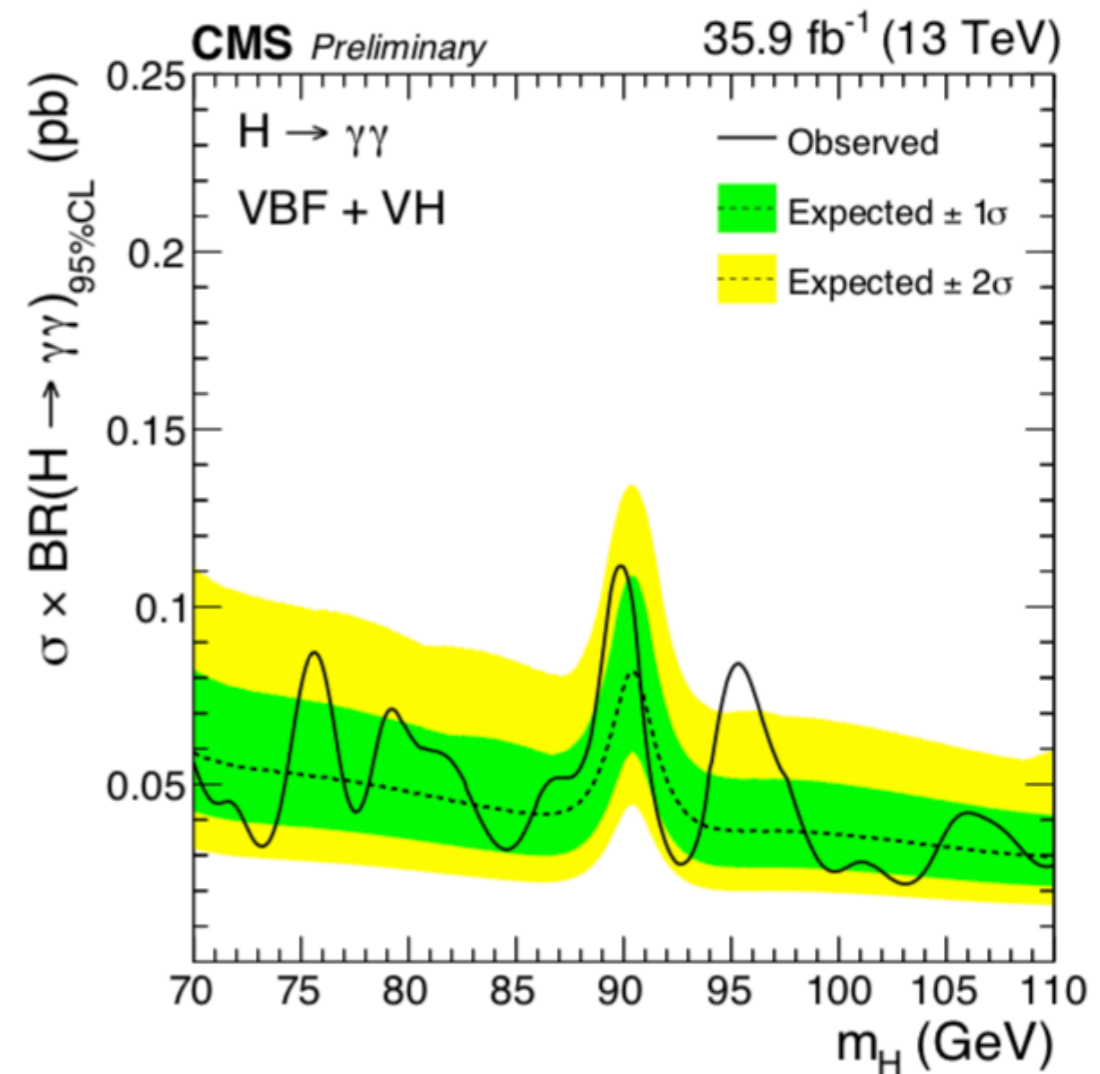
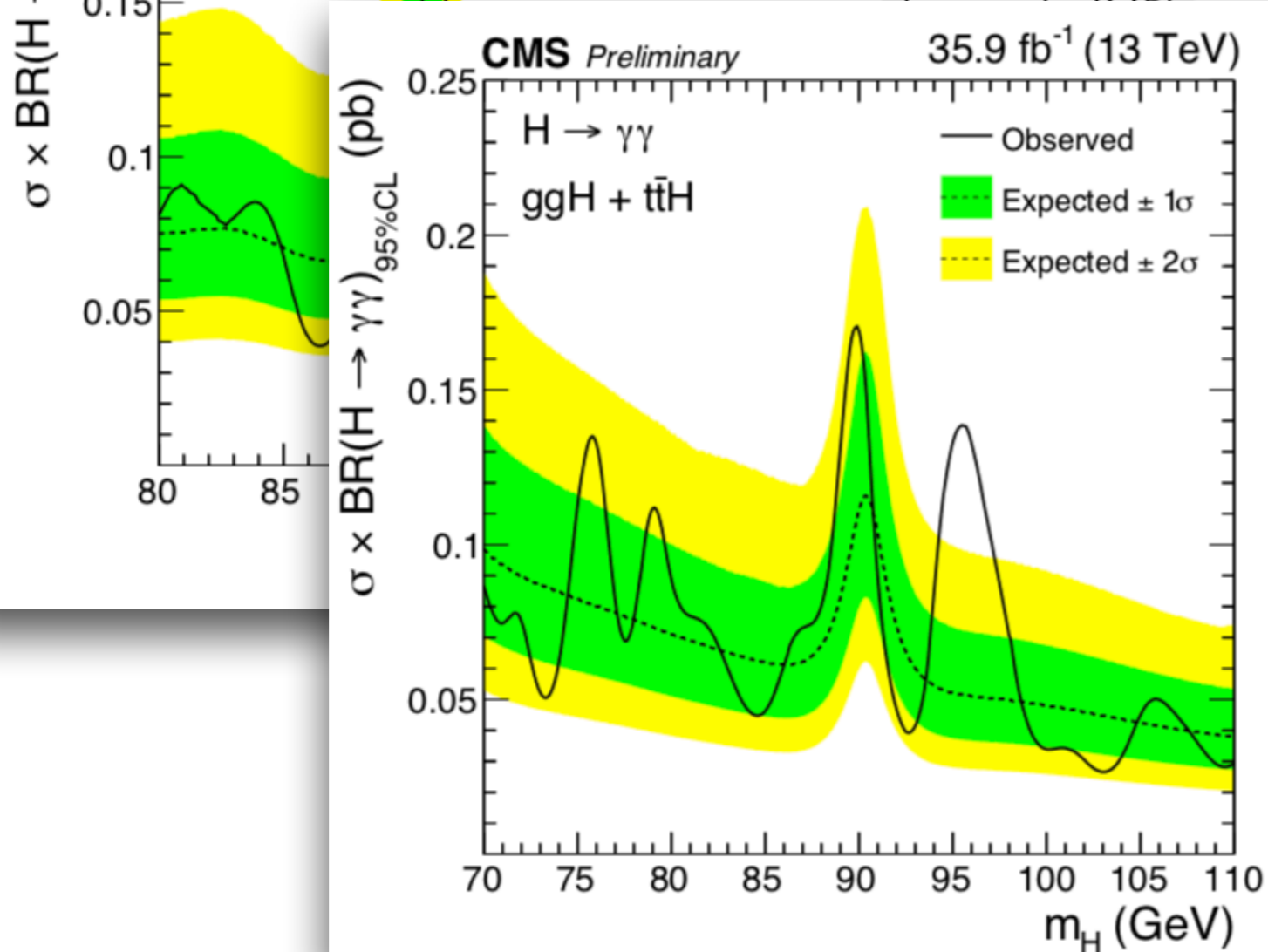
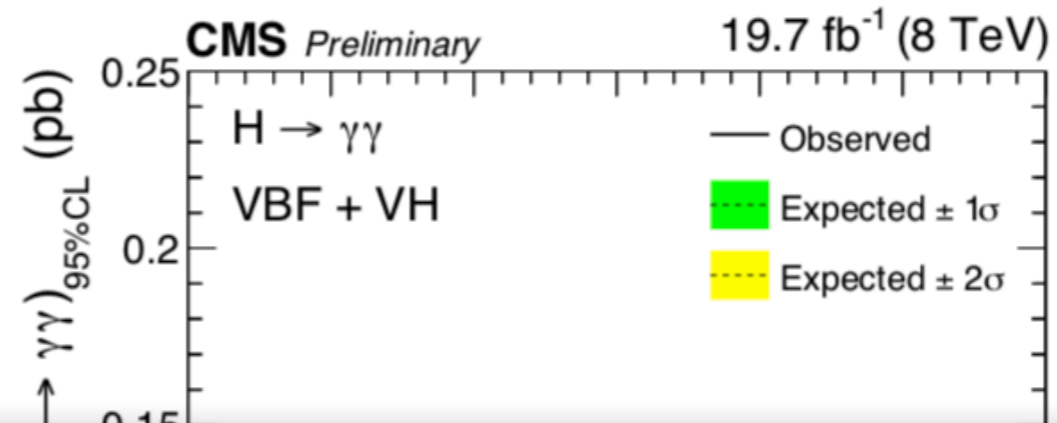
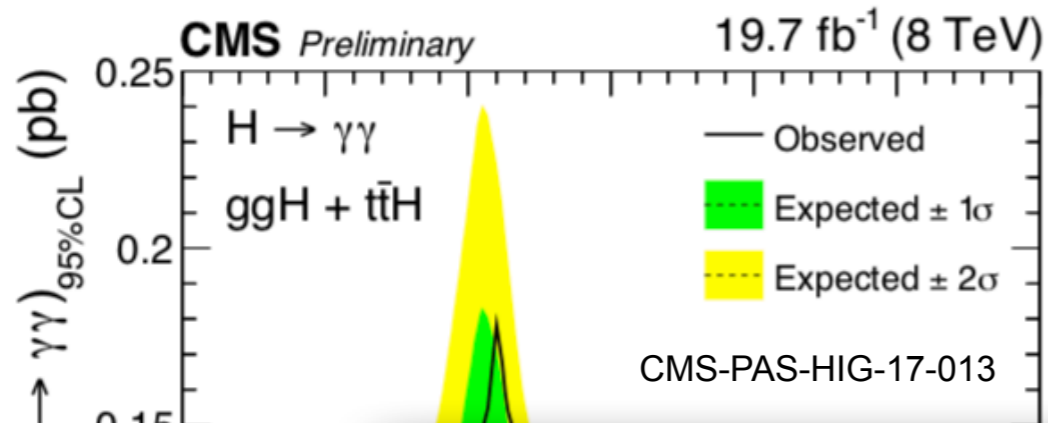


Light Higgs search at CMS





Light Higgs search at CMS





$$U(1)_{\mu-\tau}$$

Model

❖ Particles in Gauge fields

$$Z'_\mu$$

field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{L_\mu-L_\tau}$
H	1	2	$\frac{1}{2}$	0
q_L^i	3	2	$\frac{1}{6}$	0
u_R^i	3	1	$\frac{2}{3}$	0
d_R^i	3	1	$-\frac{1}{3}$	0
S	1	1	0	1
ϕ	1	1	0	$\frac{1}{2}$
$\psi_{L,R}$	3	2	$\frac{1}{6}$	$-\frac{1}{2}$

field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{L_\mu-L_\tau}$
ℓ^e	1	2	$-\frac{1}{2}$	0
ℓ^μ	1	2	$-\frac{1}{2}$	1
ℓ^τ	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	0
μ_R	1	1	-1	1
τ_R	1	1	-1	-1



Higgs Sector

❖ Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{Higgs}} = & (D_\mu \phi)^\dagger D^\mu \phi + (D_\mu S)^\dagger D^\mu S \\ & - \mu_\phi^2 \phi^* \phi - \lambda_\phi (\phi^* \phi)^2 - \mu_S^2 S^* S - \lambda_S (S^* S)^2 - \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 \\ & - \lambda_{\phi h} (\phi^* \phi) (H^\dagger H) - \lambda_{Sh} (S^* S) (H^\dagger H) - \lambda_{S\phi} (S^* S) (\phi^* \phi).\end{aligned}$$

❖ Mixing between mass eigenstates

$$\begin{pmatrix} h^0 \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix}$$



Fermion Sector

❖ Lagrangian

$$\mathcal{L}_q = i\bar{q}_L^i \not{D} q_L^i + i\bar{u}_R^i \not{D} u_R^i + i\bar{d}_R^i \not{D} d_R^i + i\bar{\psi} \not{D} \psi - m_\psi \bar{\psi} \psi$$

$$- \left(\bar{q}_L^i y_u^{ij} \tilde{H} u_R^j + \bar{q}_L^i y_d^{ij} H d_R^j + H.c. \right) - \left(\sqrt{2} \lambda_i \bar{q}_L^i \phi \psi_R + H.c. \right)$$

❖ The Mass and mixing matrixes are

$$\tan \theta_2 \equiv \frac{\lambda_2 v_D}{m_\psi}$$

$$\tan \theta_3 \equiv \frac{\lambda_3 v_D}{\sqrt{\lambda_2^2 v_D^2 + m_\psi^2 - m_{q_3}^2}}$$

$$m_{\tilde{q}_3}^2 \approx m_{q_3}^2 (1 - \tan^2 \theta_3),$$

$$m_{\tilde{q}_2}^2 \approx m_{q_2}^2 \cos^2 \theta_2,$$

$$m_{\tilde{\psi}}^2 \approx \lambda_2^2 v_D^2 (1 + \cot^2 \theta_2)$$

$$U_L^q \approx \begin{pmatrix} 1 + \frac{1}{2} t_{\theta_3}^2 & 0 & t_{\theta_3} \\ -s_{\theta_2} t_{\theta_3} & c_{\theta_2} \left(-1 + \frac{m_{\tilde{q}_2}^2}{m_{\tilde{\psi}}^2} t_{\theta_2}^2 \right) & s_{\theta_2} \left(1 + \frac{m_{\tilde{q}_2}^2}{m_{\tilde{\psi}}^2} - \frac{1}{2} t_{\theta_3}^2 \right) \\ -c_{\theta_2} t_{\theta_3} & s_{\theta_2} \left(1 + \frac{m_{\tilde{q}_2}^2}{m_{\tilde{\psi}}^2} \right) & c_{\theta_2} \left(1 - \frac{m_{\tilde{q}_2}^2}{m_{\tilde{\psi}}^2} t_{\theta_2}^2 - \frac{1}{2} t_{\theta_3}^2 \right) \end{pmatrix}$$



Interactions

❖ Higgs Interactions

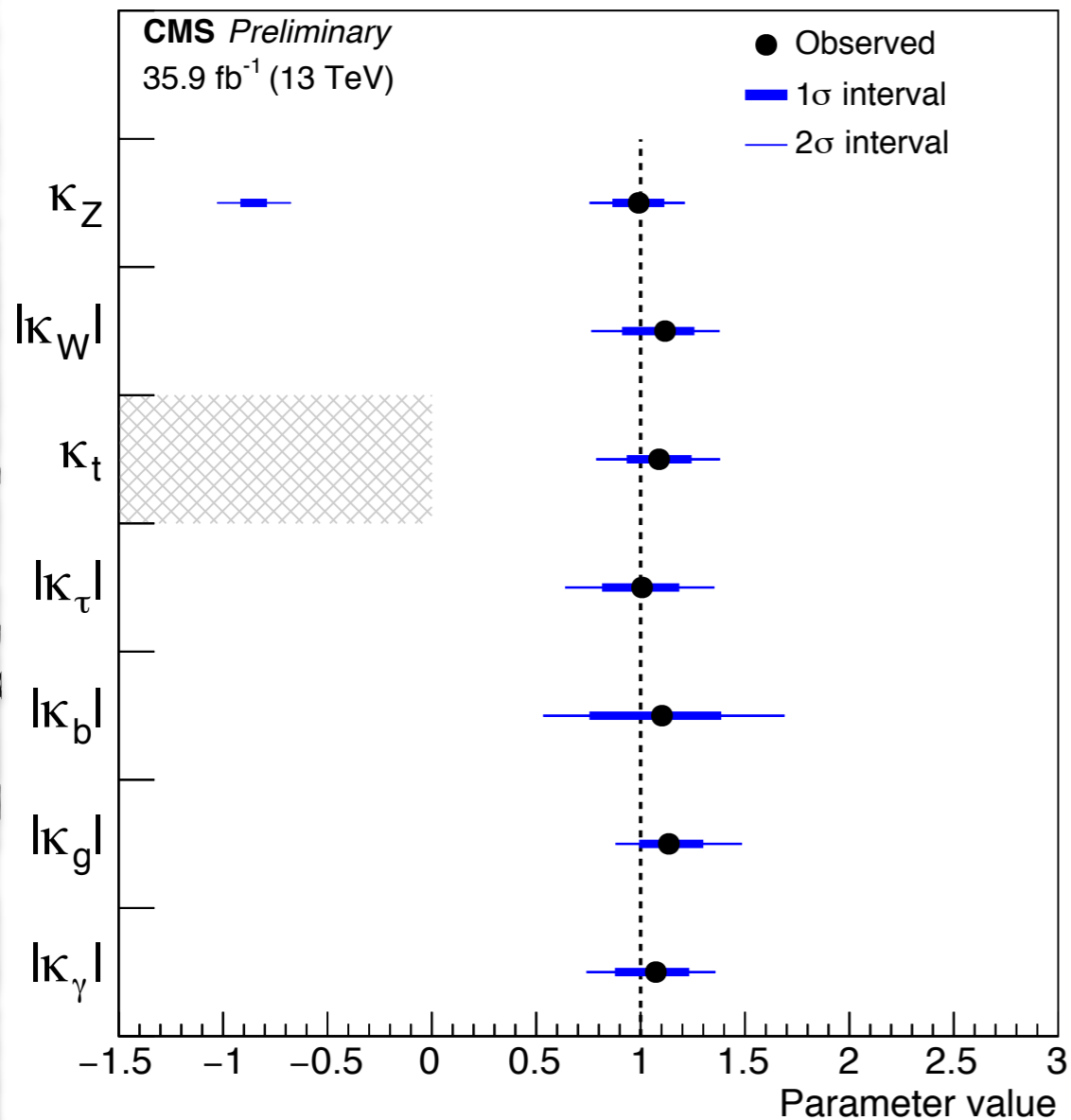
$$\begin{aligned}
 \mathcal{L}_{Higgs} \supset & \frac{m_{\tilde{b}}}{v} \left(\frac{v}{v_D} t_{\theta_3}^2 \left(\frac{m_{\tilde{b}}^2}{m_{\tilde{\psi}}^2} - c_{\theta_2}^2 \right) s_{\alpha} + \left(1 - \frac{t_{\theta_3}^2}{2} \right) c_{\alpha} \right) \tilde{h} \tilde{b} \tilde{b} \\
 & + \frac{m_{\tilde{b}}}{v} \left(\frac{v}{v_D} t_{\theta_3}^2 \left(\frac{m_{\tilde{b}}^2}{m_{\tilde{\psi}}^2} - c_{\theta_2}^2 \right) c_{\alpha} - \left(1 - \frac{t_{\theta_3}^2}{2} \right) s_{\alpha} \right) \tilde{\phi} \tilde{b} \tilde{b} \\
 & + \frac{m_{\tilde{s}}}{v} \left(\frac{v}{v_D} s_{\theta_2}^2 s_{\alpha} - c_{\alpha} \right) \tilde{h} \tilde{s} \tilde{s} + \frac{m_{\tilde{s}}}{v} \left(\frac{v}{v_D} s_{\theta_2}^2 c_{\alpha} + s_{\alpha} \right) \tilde{\phi} \tilde{s} \tilde{s} \\
 & + \frac{m_{\tilde{\psi}}}{v} \frac{v}{v_D} s_{\alpha} \left(s_{\theta_2}^2 + \frac{t_{\theta_3}^2}{2} (1 + c_{\theta_2}^2) \right) \tilde{h} \tilde{\psi} \tilde{\psi} + \frac{m_{\tilde{\psi}}}{v} \frac{v}{v_D} c_{\alpha} \left(s_{\theta_2}^2 + \frac{t_{\theta_3}^2}{2} (1 + c_{\theta_2}^2) \right) \tilde{\phi} \tilde{\psi} \tilde{\psi} \\
 & + (b \rightarrow t, s \rightarrow c) + \dots,
 \end{aligned}$$



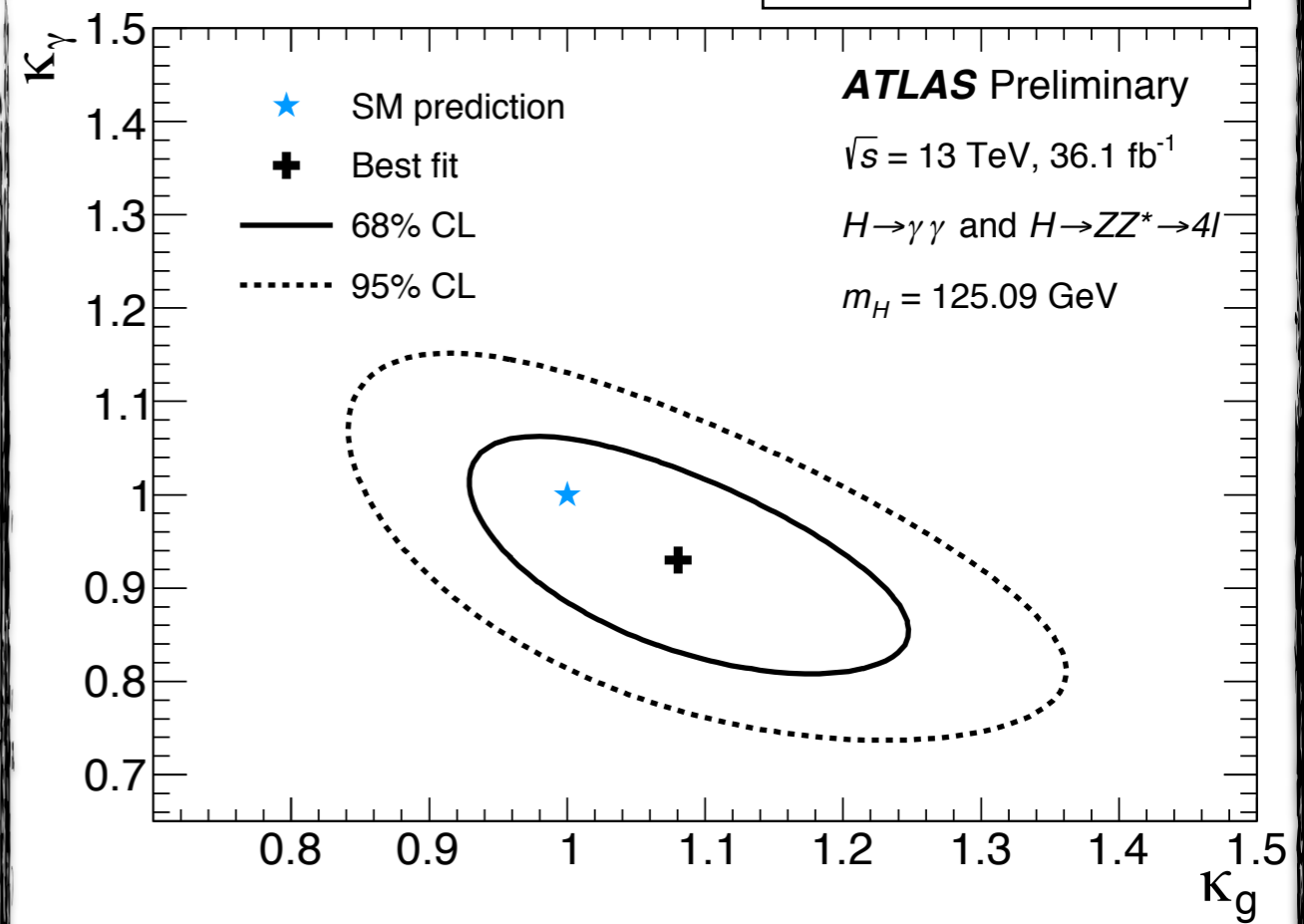
SM Higgs coupling measurement

$$\kappa = \frac{g_{\text{new}}}{g_{\text{SM}}}$$

HIG-17-031-pas



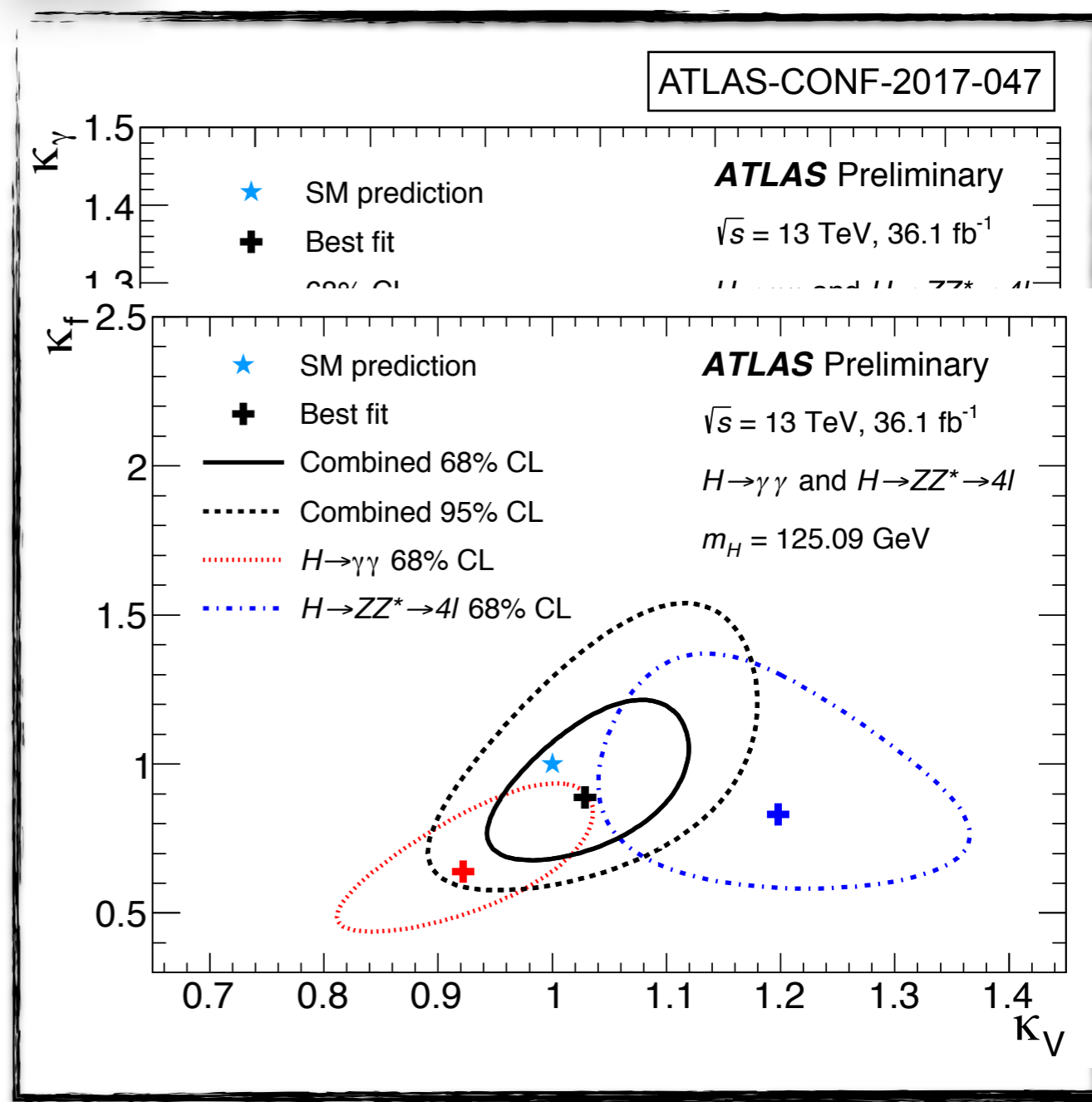
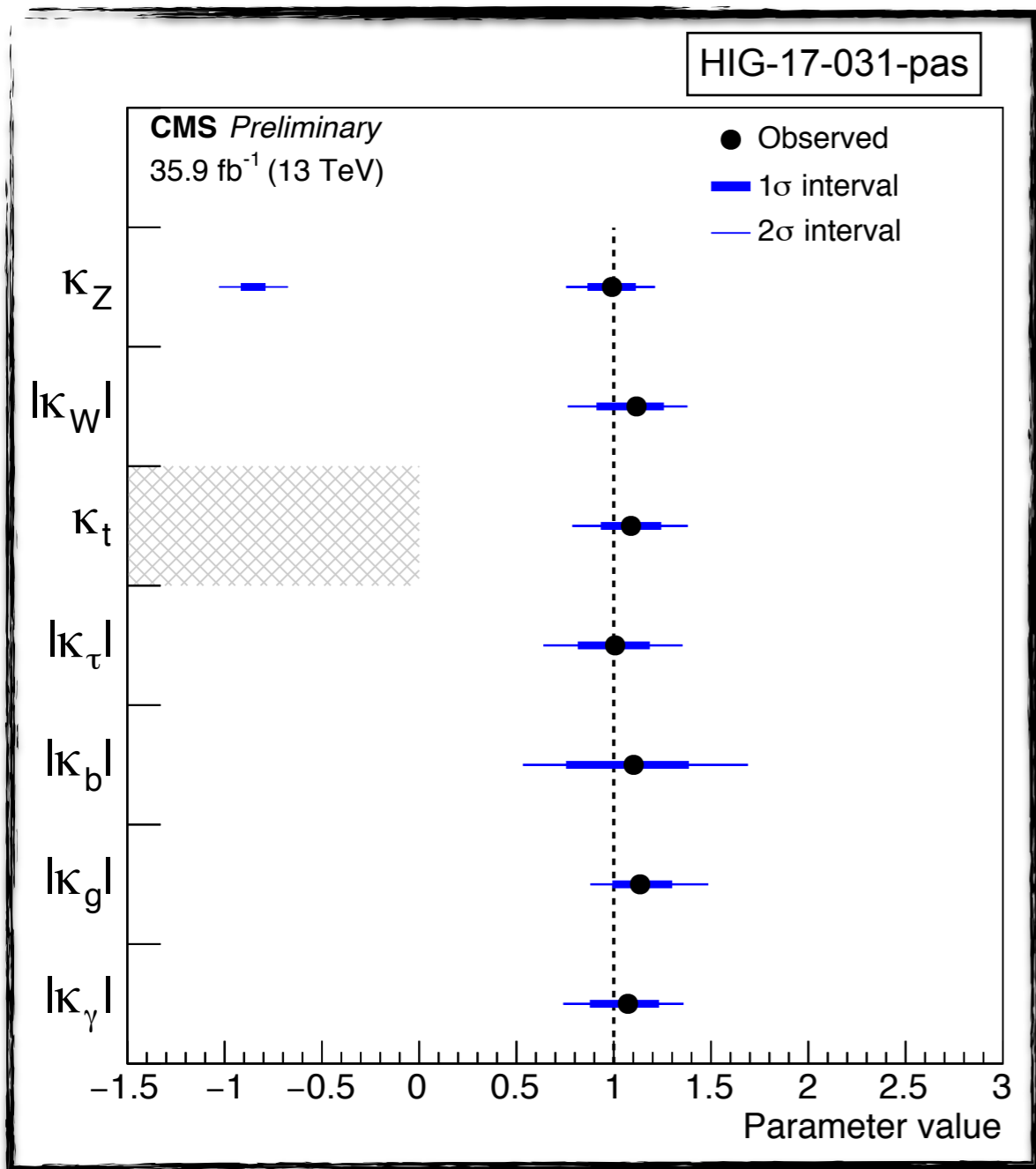
ATLAS-CONF-2017-047





SM Higgs coupling measurement

$$\kappa = \frac{g_{\text{new}}}{g_{\text{SM}}}$$

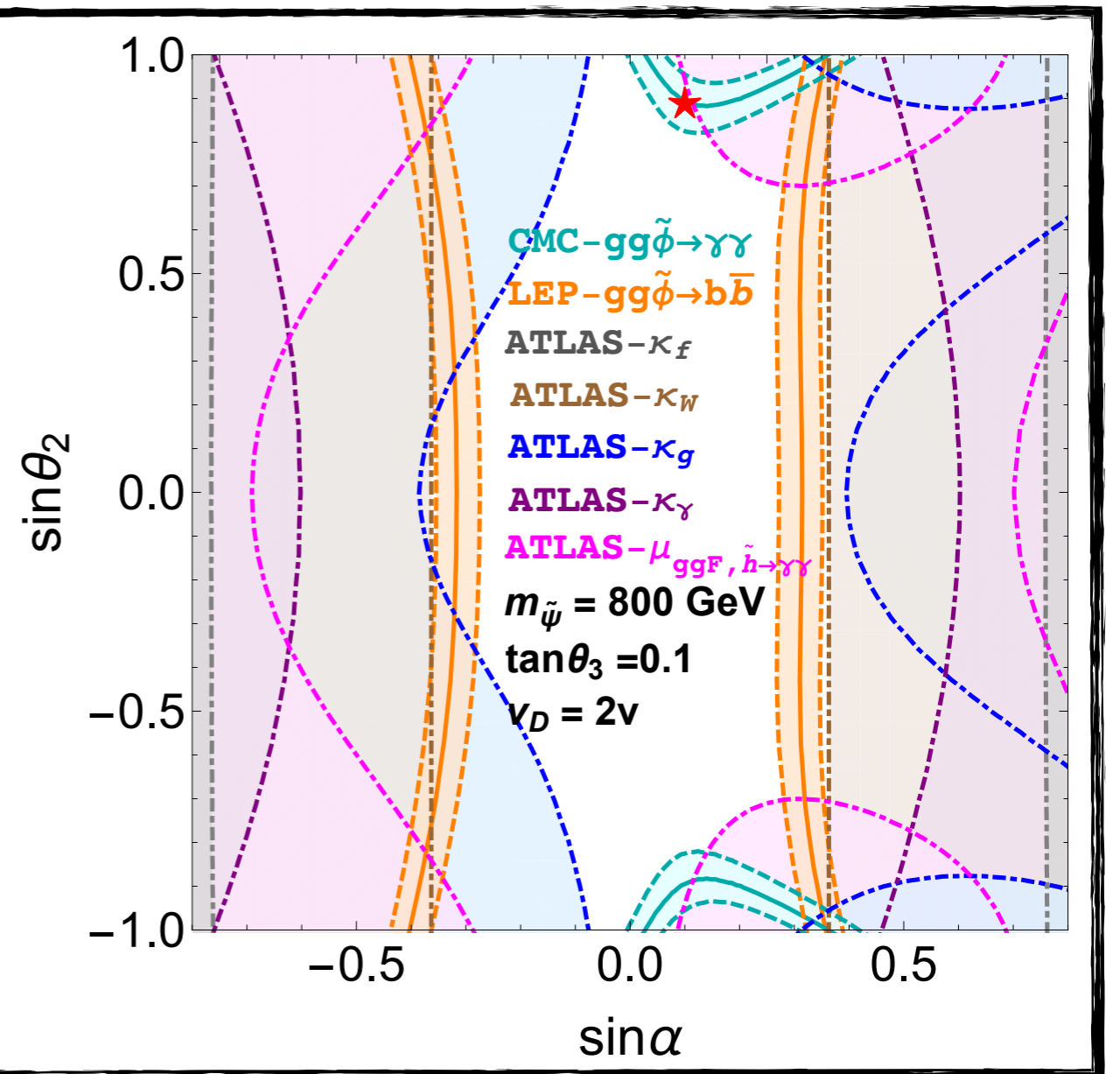
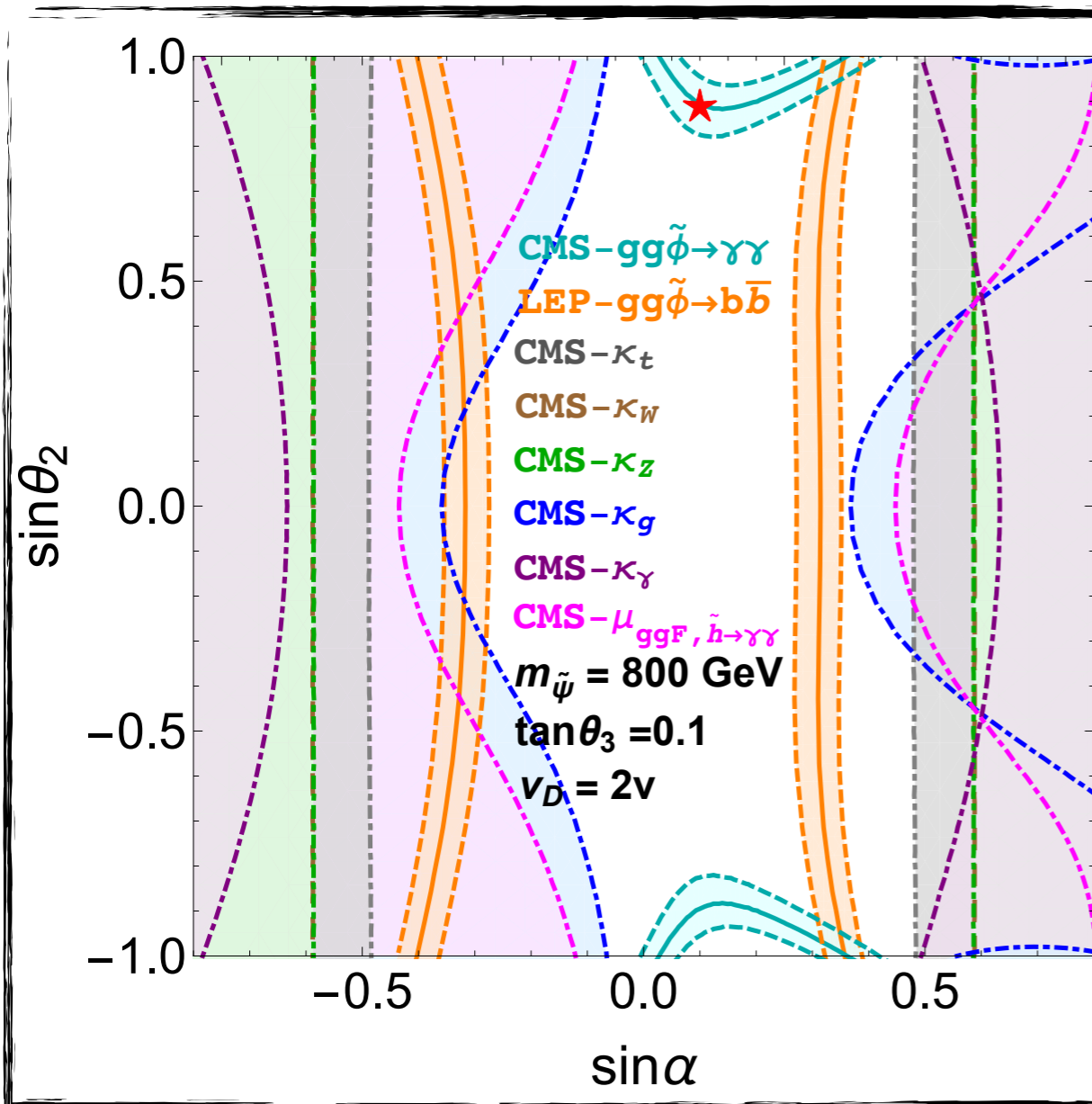




Higgs Constraint and CMS Excess

$$\kappa = \frac{g_{\text{new}}}{g_{\text{SM}}}$$

$$\mu = \frac{\sigma_{\text{new}}}{\sigma_{\text{SM}}}$$





Interactions

❖ Z' Interactions

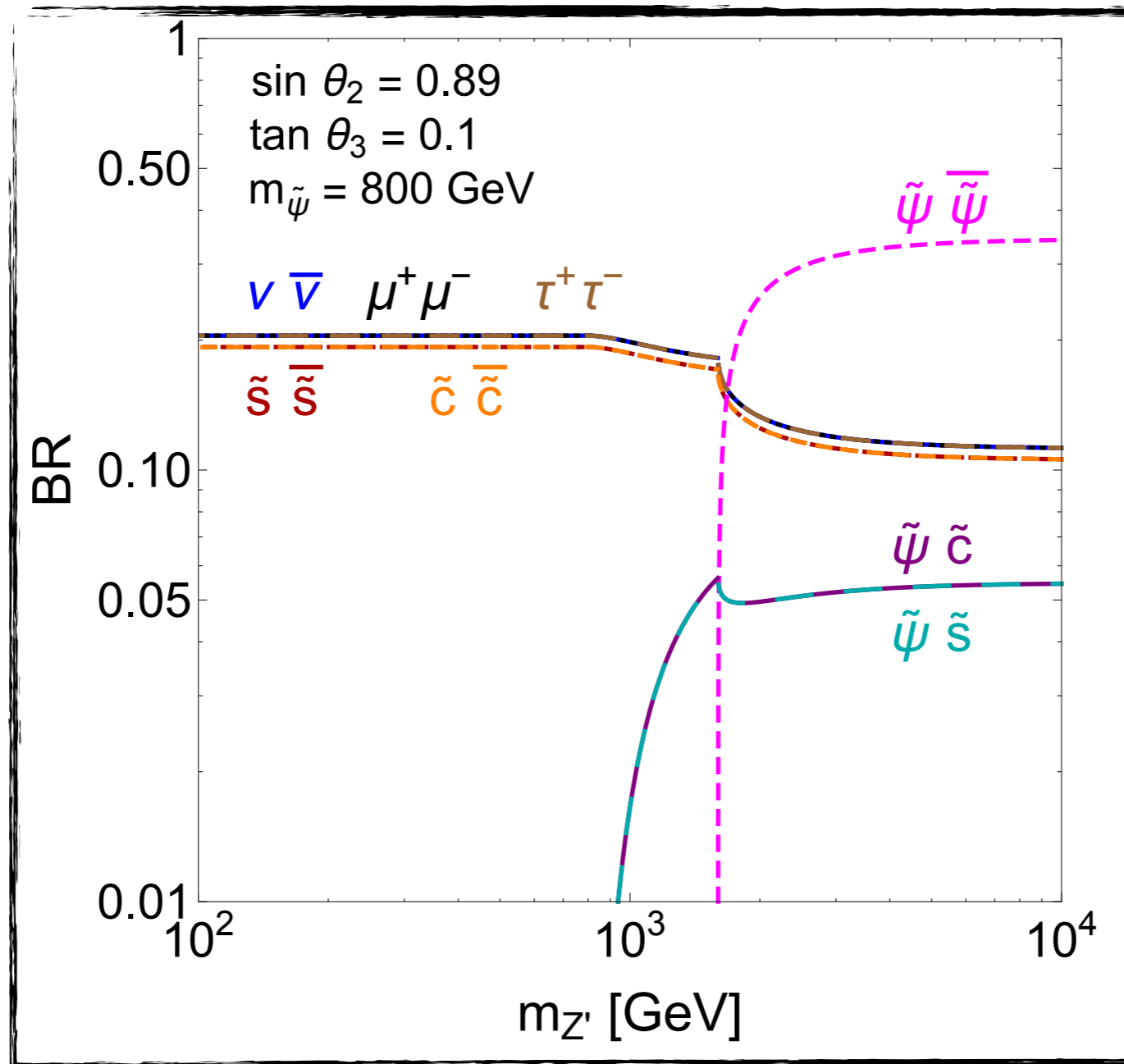
$$\begin{aligned}
 \mathcal{L}_{Z'}^{\text{quark}} &= -\frac{g_D}{2} t_{\theta_3}^2 c_{\theta_2}^2 Z'_\mu \bar{b}_L \gamma^\mu \tilde{b}_L - \frac{g_D}{2} Z'_\mu s_{\theta_2}^2 \bar{\tilde{s}}_L \gamma^\mu \tilde{s}_L \\
 &+ \frac{g_D}{2} Z'_\mu \left[(t_{\theta_3}^2 - 1) c_{\theta_2}^2 \bar{\tilde{\psi}}_L^d \gamma^\mu \tilde{\psi}_L^d + (t_{\theta_3}^2 - 1) \bar{\tilde{\psi}}_R^d \gamma^\mu \tilde{\psi}_R^d \right] \\
 &+ \frac{g_D}{2} Z'_\mu s_{\theta_2} c_{\theta_2} t_{\theta_3} \bar{b}_L \gamma^\mu \tilde{s}_L + H.c. \\
 &+ \frac{g_D}{2} Z'_\mu \left[-c_{\theta_2}^2 t_{\theta_3} \bar{b}_L \gamma^\mu \tilde{\psi}_L^d - \frac{m_{\tilde{b}}}{m_{\tilde{\psi}}} t_{\theta_3} \bar{b}_R \gamma^\mu \tilde{\psi}_R^d \right] + H.c. \\
 &+ \frac{g_D}{2} Z'_\mu \left[s_{\theta_2} c_{\theta_2} \left(\frac{t_{\theta_3}^2}{2} - 1 \right) \bar{\tilde{s}}_L \gamma^\mu \tilde{\psi}_L^d + \frac{m_s}{m_{\tilde{\psi}}} s_{\theta_2} \bar{\tilde{s}}_R \gamma^\mu \tilde{\psi}_R^d \right] + H.c. \\
 &+ (b \rightarrow t, s \rightarrow c),
 \end{aligned}$$

$$\mathcal{L}_{Z'}^{\text{lepton}} = g_D Z'_\mu [\bar{\mu} \gamma^\mu \mu - \bar{\tau} \gamma^\mu \tau + \bar{\nu}_{\mu L} \gamma^\mu \nu_{\mu L} - \bar{\nu}_{\tau L} \gamma^\mu \nu_{\tau L}] + H.c.$$



Z' Branching ratio

❖ Z' Branching ratio



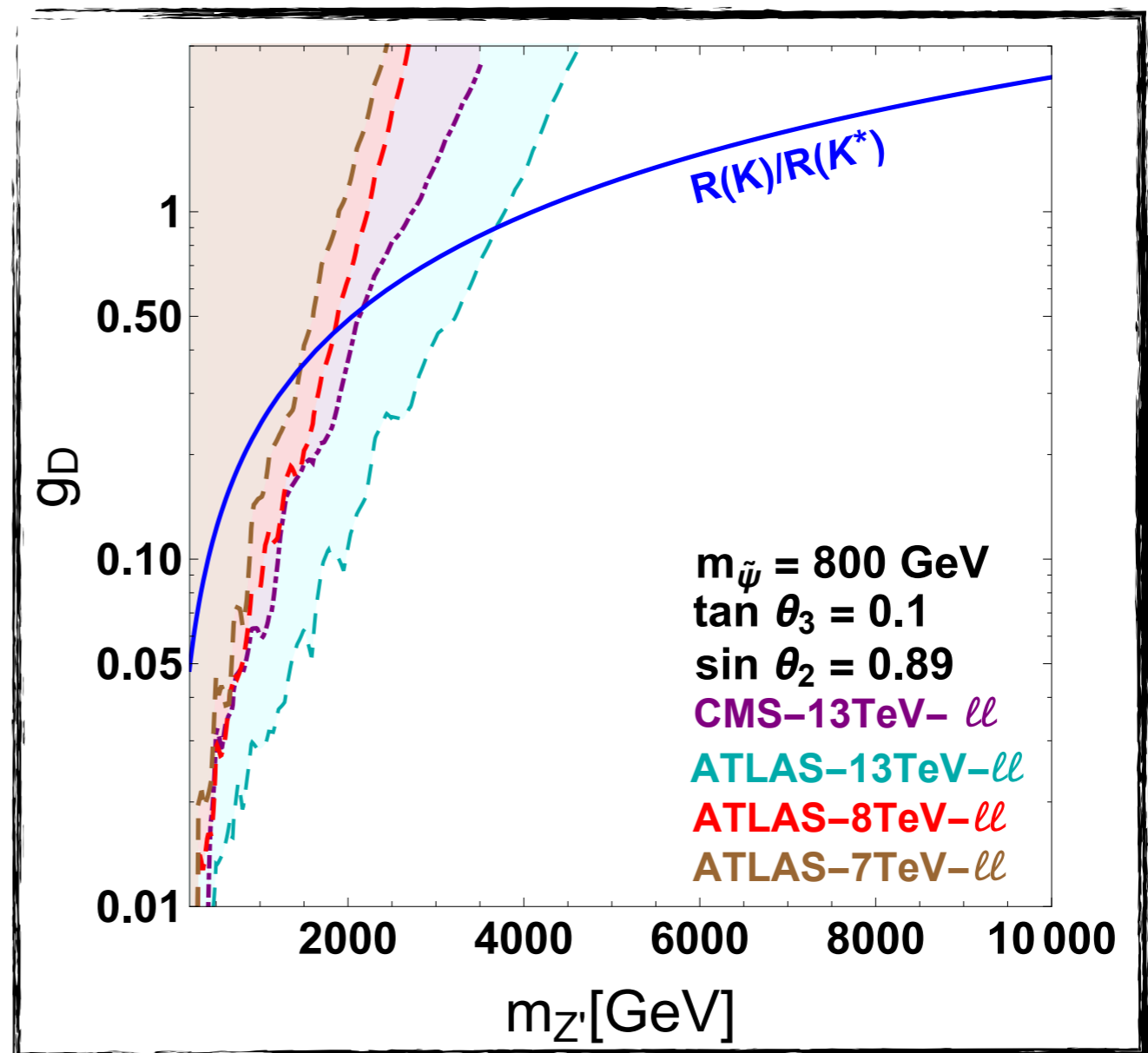


Z' Constraints from Collider

❖ Necessary for $R_K(R_{K^*})$

$$\frac{g_D^2}{m_{Z'}^2} s_{\theta_2} c_{\theta_2} t_{\theta_3} \sim 2.44 * 10^{-3} \text{TeV}^{-2}$$

❖ Z' search at LHC





Flavor Constraints

❖ Constraint from $b \rightarrow s\gamma$

0.548

$$\frac{\text{BR}(b \rightarrow s\gamma)}{\text{BR}(b \rightarrow ce\bar{\nu}_e)} = \frac{6\alpha}{\pi} \frac{\left[\eta^{\frac{16}{23}} A_\gamma + \frac{8}{3} (\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}) A_g + C \right]^2}{I(m_c/m_b) \left[1 - \frac{2}{3\pi} \alpha_s(m_b) f(m_c/m_b) \right]}$$

0.58

$$\frac{A_\gamma^Z}{A_\gamma^{SM}} \sim 5 \times 10^{-6}, \quad \frac{A_g^Z}{A_g^{SM}} \sim 4 \times 10^{-6}, \quad \frac{A_\gamma^{Z'}}{A_\gamma^{SM}} \sim 3 \times 10^{-4} t_{\theta_3} c_{\theta_2}^3 s_{\theta_2}, \quad \frac{A_g^{Z'}}{A_g^{SM}} \sim 4 \times 10^{-4} t_{\theta_3} c_{\theta_2}^3 s_{\theta_2}$$

❖ Constraint from mixing of $\bar{B}_s - B_s$

$$\mathcal{L}_{eff} = -\frac{g_D^2}{4m_{Z'}^2} s_{\theta_2}^2 c_{\theta_2}^2 t_{\theta_3}^2 \left(\bar{b}_L \gamma^\mu \tilde{s}_L \right)^2 - \frac{g^2}{4m_Z^2} \frac{m_{\tilde{b}}^2 m_{\tilde{s}}^2}{m_{\tilde{\psi}}^4} t_{\theta_2}^2 t_{\theta_3}^2 \left(\bar{b}_R \gamma^\mu \tilde{s}_R \right)^2$$

$$\frac{g_D^2}{4m_{Z'}^2} s_{\theta_2}^2 c_{\theta_2}^2 t_{\theta_3}^2 < 5.0 \times 10^{-5} \text{ TeV}^{-2}$$

$2.5 \times 10^{-5} \text{ TeV}^{-2}$



Flavor Constraints

❖ Constraint from top decay

$$\mathcal{L}_{tZ} = g \frac{m_{\tilde{t}} m_{\tilde{c}}}{2m_{\tilde{\psi}}^2} t_{\theta_2} t_{\theta_3} Z_{\mu} \tilde{t}_R^{\dagger} \gamma^{\mu} \tilde{c}_R + H.c.$$

$$\text{BR}(\tilde{t} \rightarrow Z\tilde{c}) \sim \frac{m_{\tilde{t}}^2 m_{\tilde{c}}^2}{2m_{\tilde{\psi}}^4} t_{\theta_2}^2 t_{\theta_3}^2 < 2.3 \times 10^{-4}$$

$$\frac{m_{\tilde{\psi}}}{\sqrt{t_{\theta_2} t_{\theta_3}}} > 102 \text{ GeV}$$



Summary

❖ $R_K(R_{K^*})$ Anomaly

★ Can be explained via a new $U(1)_{L_\mu-L_\tau}$ gauge boson.

❖ CMS di-photon resonance excess:

★ Can be explained by the light Higgs which charged under $U(1)_{\mu-\tau}$



Any Questions?