Flavor and Scalar Signals of an Extended Color Sector

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SCGT14Mini

- Extended Color Dynamics
- A Top-Coloron Model
- Flavor Symmetries and Constraints
- Scalars: Same Sign Top Signature
- Flavor Independent Constraints
- Conclusions

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Extended Color Dynamics

New colored gauge bosons

Classic Axigluon: P.H. Frampton and S.L. Glashow, Phys. Lett. B 190, 157 (1987).

Topgluon: C.T. Hill, Phys. Lett. B 266, 419 (1991).

Flavor-universal Coloron: R.S. Chivukula, A.G. Cohen, & E.H. Simmons, Phys. Lett. B 380, 92 (1996).

Chiral Color with $g_L \neq g_R$: M.V. Martynov and A.D. Smirnov, Mod. Phys. Lett. A 24, 1897 (2009).

New Axigluon: P.H. Frampton, J. Shu, and K. Wang, Phys. Lett. B 683, 294 (2010).

Other color-octet states: (cf. “partial compositeness”)

KK gluon: H. Davoudiasl, J.L. Hewett, and T.G. Rizzo, Phys. Rev. D63, 075004 (2001)
B. Lillie, L. Randall, and L.-T. Wang, JHEP 0709, 074 (2007).

Techni-rho: E. Farhi and L. Susskind, Physics Reports 74, 277 (1981).

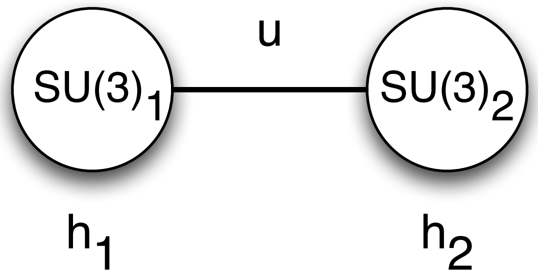
Recent catalog of colored states:

Color sextets, colored scalars, low-scale scale string resonances...

T. Han, I. Lewis, Z. Liu, JHEP 1012, 085 (2010).

Gauge Sector

Coloron Models: Gauge Sector



SU(3)₁ x SU(3)₂ color sector with $M^2 = \frac{u^2}{4}\begin{pmatrix} h_1^2 & -h_1 h_2 \\ -h_1 h_2 & h_2^2 \end{pmatrix}$

unbroken subgroup: $SU(3)_{1+2} = SU(3)_{QCD}$

$$h_1 = \frac{g_s}{\cos\theta} \qquad h_2 = \frac{g_s}{\sin\theta}$$

gluon state: $G^A_\mu = \cos\theta\, A^A_{1\mu} + \sin\theta\, A^A_{2\mu}$

couples to: $g_S J^\mu_G \equiv g_S(J^\mu_1 + J^\mu_2)$

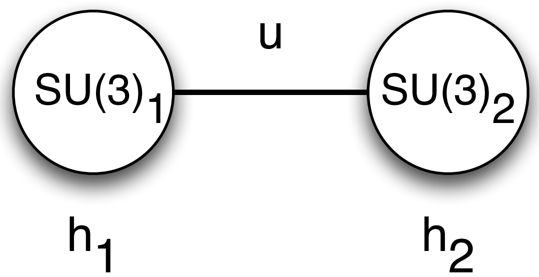
coloron state: $C^A_\mu = -\sin\theta\, A^A_{1\mu} + \cos\theta\, A^A_{2\mu}$ $\qquad M_C = \frac{u}{\sqrt{2}}\sqrt{h_1^2 + h_2^2}$

couples to: $g_S J^\mu_C \equiv g_S(-J^\mu_1 \tan\theta + J^\mu_2 \cot\theta)$

low-energy current-current interaction: $\mathcal{L}^2_{FF} = -\frac{g_S^2}{2M_C^2} J^\mu_C J_{C\,\mu}$

Fermions

Coloron Models: Quark Charges



$$g_S J^\mu_G \equiv g_S (J^\mu_1 + J^\mu_2)$$

$$g_S J^\mu_C \equiv g_S (-J^\mu_1 \tan\theta + J^\mu_2 \cot\theta)$$

low-energy current-current interaction: $\mathcal{L}^2_{FF} = -\frac{g_S^2}{2M_C^2} J^\mu_C J_{C\,\mu}$

Depending on how quarks transform under $SU(3)_1$ x $SU(3)_2$ the presence of colorons may impact

- LHC dijet mass distribution (or angular distribution)
- kinematic distributions of tt or bb final states
- asymmetry in top-quark production: A^t_{FB}
- FCNC processes: $K\bar{K}, D\bar{D}, B\bar{B}$ mixing, $b \to s\gamma$
- precision EW observables: delta-rho, R_b

Patterns of Quark Charges

$SU(3)_1$	$SU(3)_2$	model	pheno.
	$(t,b)_L$ q_L t_R,b_R q_R	**coloron**	dijet
q_R	$(t,b)_L$ q_L t_R,b_R		
t_R,b_R	$(t,b)_L$ q_L q_R		
q_L	$(t,b)_L$ t_R,b_R q_R		
q_L t_R,b_R	$(t,b)_L$ q_R	**new axigluon**	dijet, A^t_{FB}, FCNC
q_L q_R	$(t,b)_L$ t_R,b_R	**topgluon**	dijet, tt, bb, FCNC, R_b...
t_R,b_R q_R	$(t,b)_L$ q_L	**classic axigluon**	dijet, A^t_{FB}
q_L t_R,b_R q_R	$(t,b)_L$		

(No spectators required)

q = u,d,c,s

A Flavorful Top-Coloron Model

R.S.C., Elizabeth Simmons, N. Vignaroli
PRD 87 (2013) 075002

Flavorful Top-Coloron Model

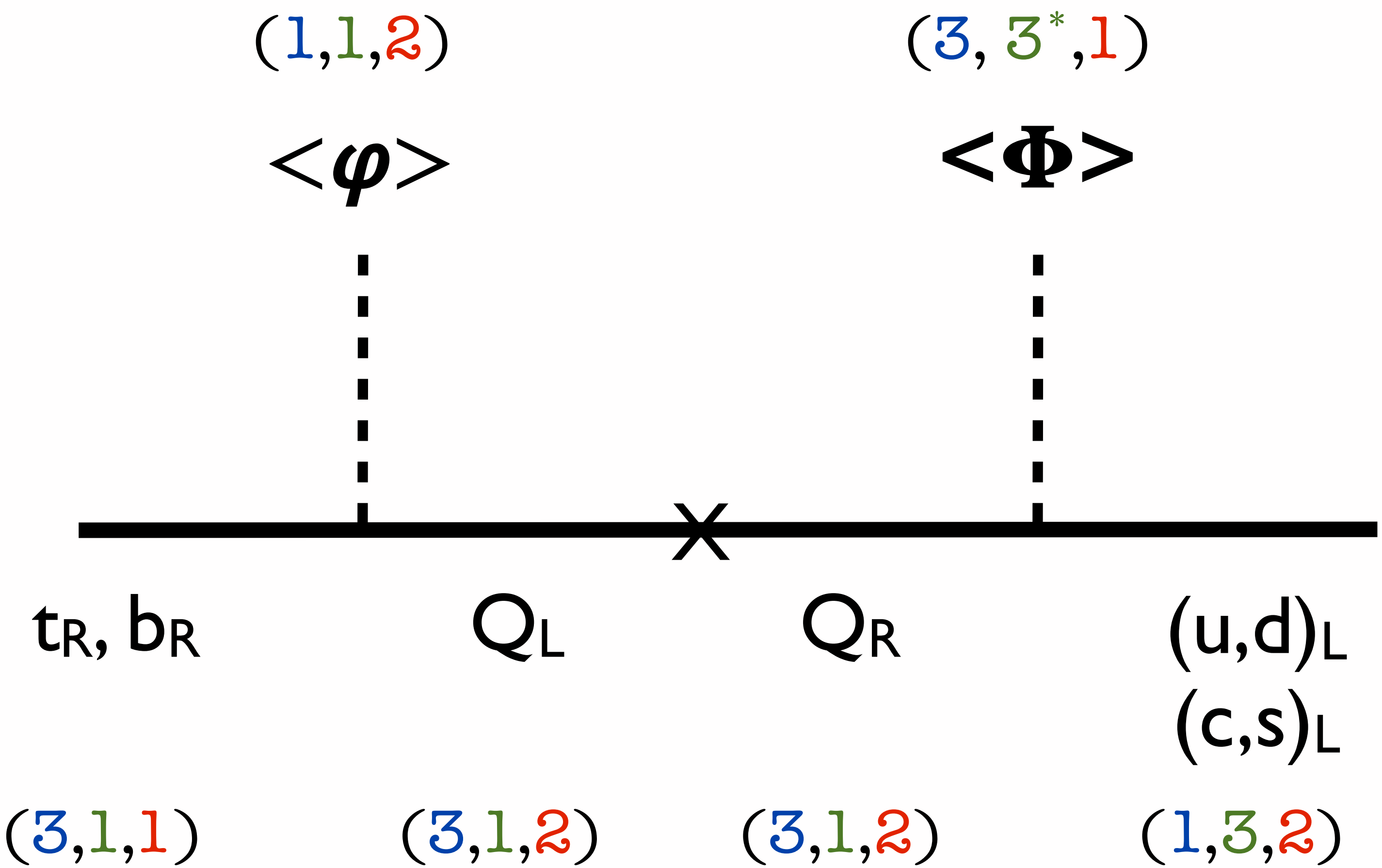
particles		$SU(3)_1$	$SU(3)_2$	$SU(2)_W$
3rd generation quarks	$(t,b)_L$	3	1	**2**
	t_R, b_R	3	1	1
light quarks	$(u,d)_L$ $(c,s)_L$	1	3	2
	u_R, d_R c_R, s_R	1	3	1
vector quarks	Q_L, Q_R	3	1	**2**
light scalar	$\boldsymbol{\varphi}$	1	1	**2**
heavy scalar	$\boldsymbol{\Phi}$	3	3*	1

Next to minimal flavor symmetry:

$$U(2)_{\vec{\psi}_L} \times U(2)_{\vec{u}_R} \times U(2)_{\vec{d}_R} \times U(2)_{\vec{\mathcal{Q}}_L} \times U(1)_{t_R} \times U(1)_{b_R} \times U(1)_{Q_R}$$

Generational Mixing

$SU(3)_1 \times SU(3)_2 \times SU(2)_W$



Mixing to third generation occurs <u>indirectly</u>, through mixing with vector quarks.

Generational Mixing

Light Generations

$$\mathcal{M}_u = M \cdot \begin{pmatrix} \Delta_u & \vec{0} & \vec{\alpha} \\ 0 \;\; 0 & \beta_t & 0 \\ 0 \;\; 0 & \lambda'_t & 1 \end{pmatrix} , \qquad \mathcal{M}_d = M \cdot \begin{pmatrix} \mathcal{C}\Delta_d & \vec{0} & \vec{\alpha} \\ 0 \;\; 0 & \beta_b & 0 \\ 0 \;\; 0 & \lambda'_b & 1 \end{pmatrix}$$

Third Generation

Vector Quarks

Weak Mixing ⇒ Cabbibo Matrix, $\mathcal{C}$, and

$$V_{ub} = \alpha_1 d = \alpha_1 \left(\frac{\lambda'_t}{\beta_t} - \frac{\lambda'_b}{\beta_b} \right) = A\lambda^3(\rho - i\eta) = 0.00131 - i0.00334$$

$$V_{cb} = \alpha_2 d = \alpha_2 \left(\frac{\lambda'_t}{\beta_t} - \frac{\lambda'_b}{\beta_b} \right) = A\lambda^2 = 0.0415 \,,$$

$$d = \mathcal{O}(1)$$
$$\alpha_1 = \mathcal{O}(\lambda^3)$$
$$\alpha_2 = \mathcal{O}(\lambda^2)$$

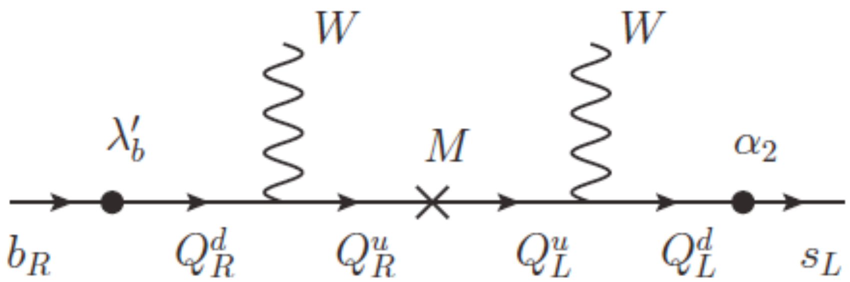
Constraints from Flavor Physics

R.S.C., Elizabeth Simmons, N. Vignaroli
PRD 87 (2013) 075002

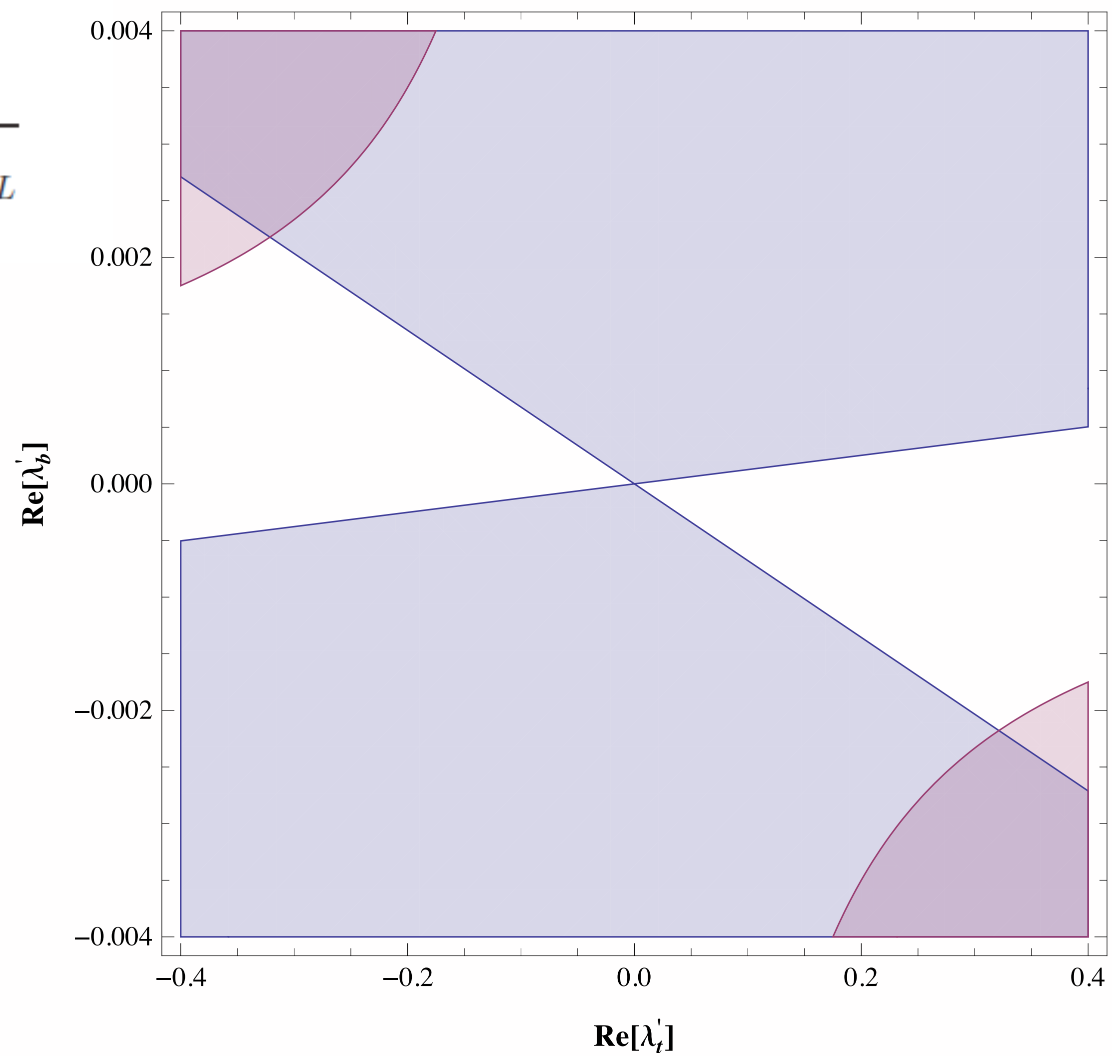
FCNC in Top-Coloron Model

- Mixing among ordinary and heavy vector quarks also leads to flavor-changing b-quark decays: $b \to s\gamma$
- Coloron exchange yields KK, DD, and BB mixing
  - quark charges under strong gauge groups are non-universal
  - the top and bottom mass eigenstate quarks are admixtures of ordinary and heavy vector gauge eigenstate quarks

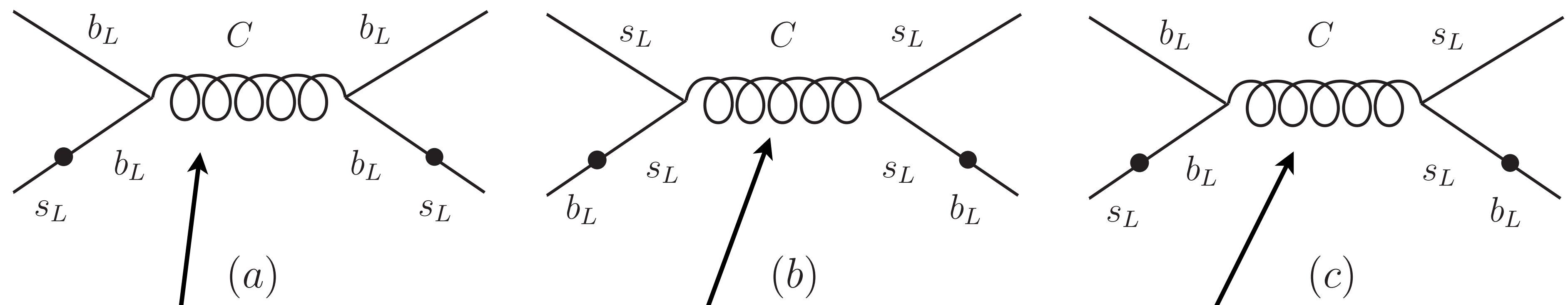
Constraints: b→sγ



Mixing with right-handed electroweak doublets enhances contributions to b→sγ



Constraints: B-Bbar Mixing



$$g_S^2 \left(\cot\omega J^{a\mu}_{bL}\right)^2 (D_L)^2_{32}$$

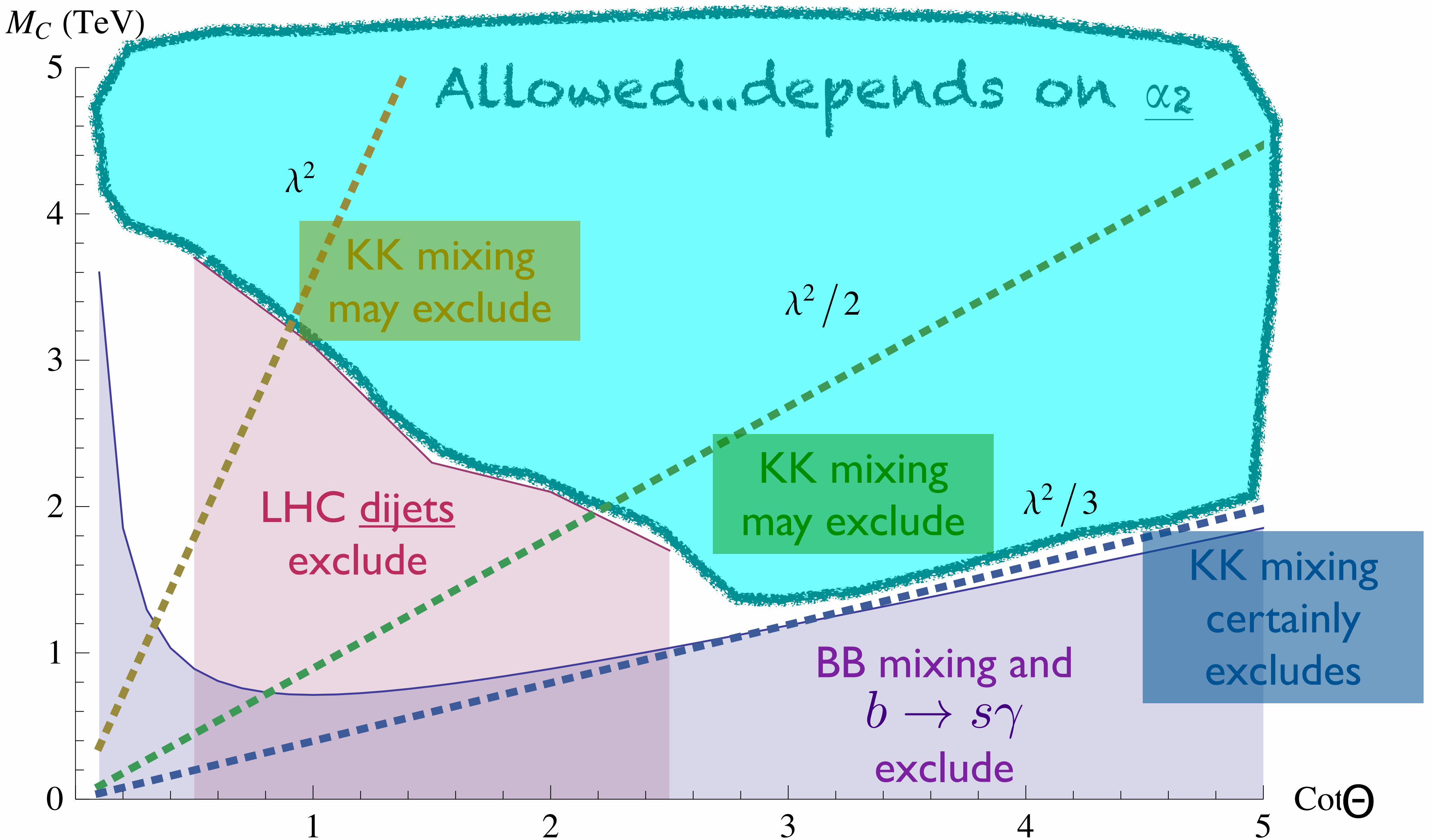
$$g_S^2 \left(-\tan\omega J^{a\mu}_{sL}\right)^2 (D_L^\dagger)^2_{32}$$

$$2g_S^2 \left(-\tan\omega J^{a\mu}_{sL}\right)\left(\cot\omega J^{a\mu}_{bL}\right)(D_L)_{32}(D_L^\dagger)_{32}$$

Flavor-changing Effects from Coloron Exchange:

<u>interplay between mixing and coupling strengths</u>

Flavor Limits on Top-Coloron Model



R.S. Chivukula, EHS, N. Vignaroli (2013)

Scalar Bosons

R.S.C., Elizabeth Simmons, N. Vignaroli
PRD 88 (2013) 034006
Bogdan Dobrescu and Yang Bai
JHEP 1107 (2011) 100

Colored Scalars and Their Potential

Most general renormalizable $(3,\bar{3})$ potential:

$$V(\Phi) = -m_\Phi^2 \mathrm{Tr}(\Phi\Phi^\dagger) - \mu(\det\Phi + \mathrm{H.c.}) + \frac{\xi}{2}\left[\mathrm{Tr}(\Phi\Phi^\dagger)\right]^2 + \frac{k}{2}\mathrm{Tr}(\Phi\Phi^\dagger\Phi\Phi^\dagger)$$

For an appropriate range of parameters:

vev

singlet fields

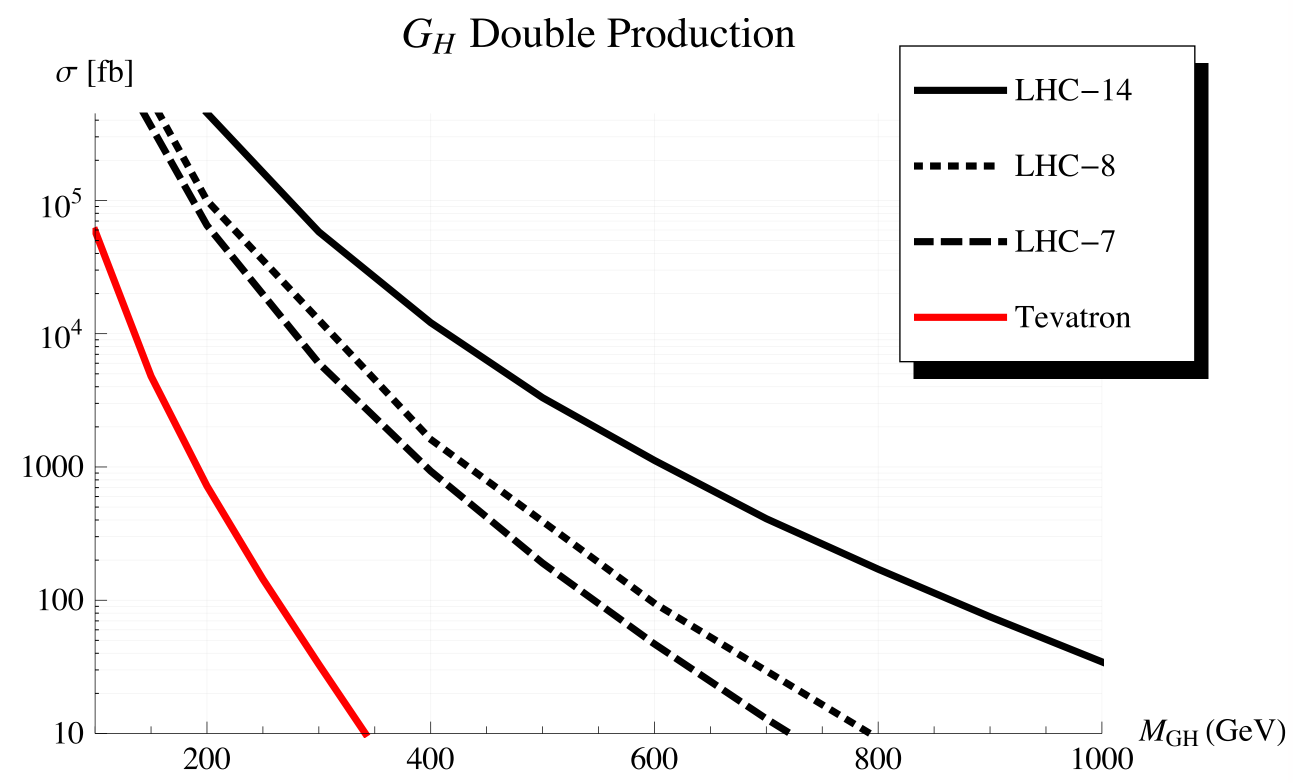
eaten by colorons

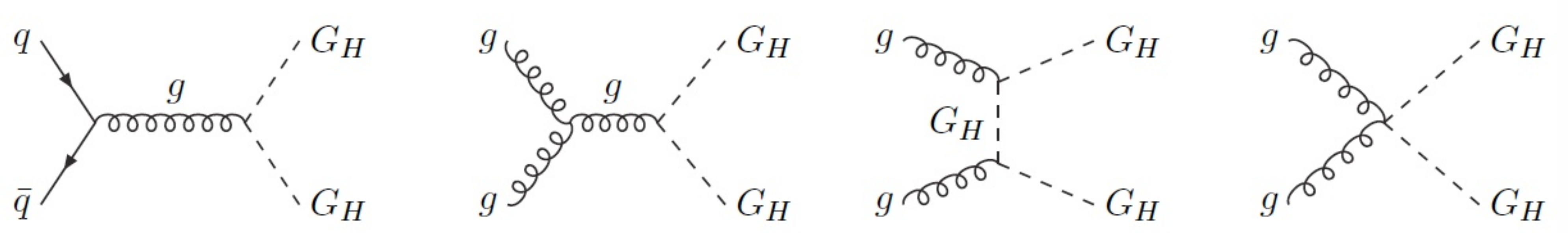
$$\Phi = u + \frac{1}{\sqrt{6}}(\phi_R + i\phi_I) + (G_H^a + iG_G^a)T^a$$

Color Octet Scalars

Quark couplings fixed from above!

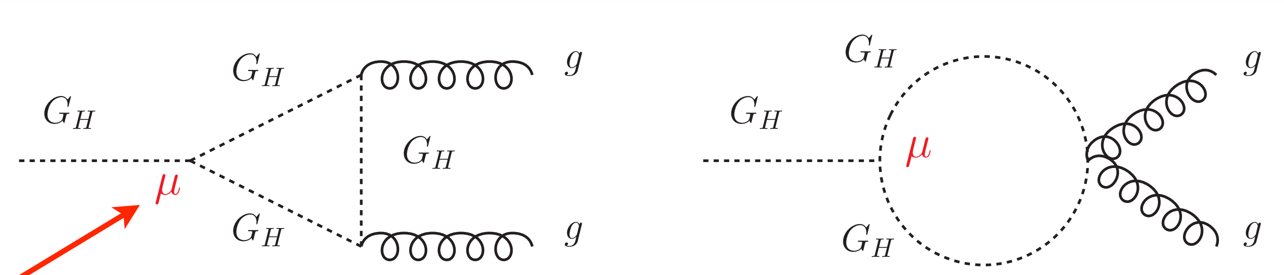
Octet Scalar Production





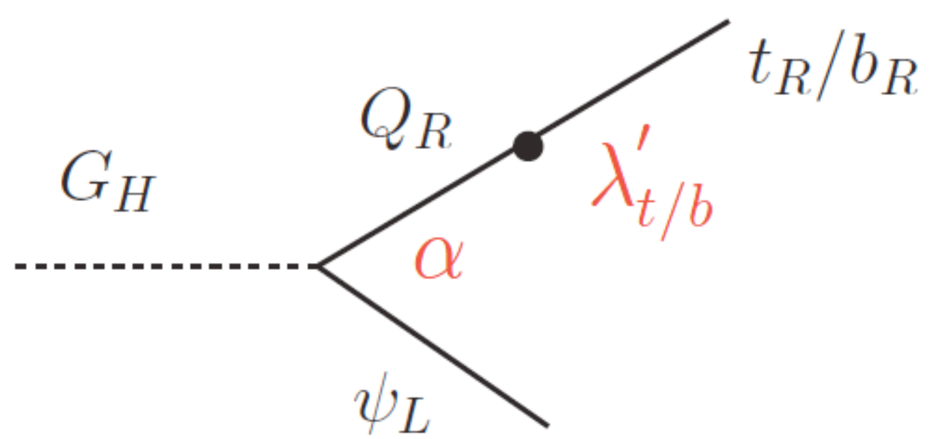
Octet Scalar Decay

Dijets:

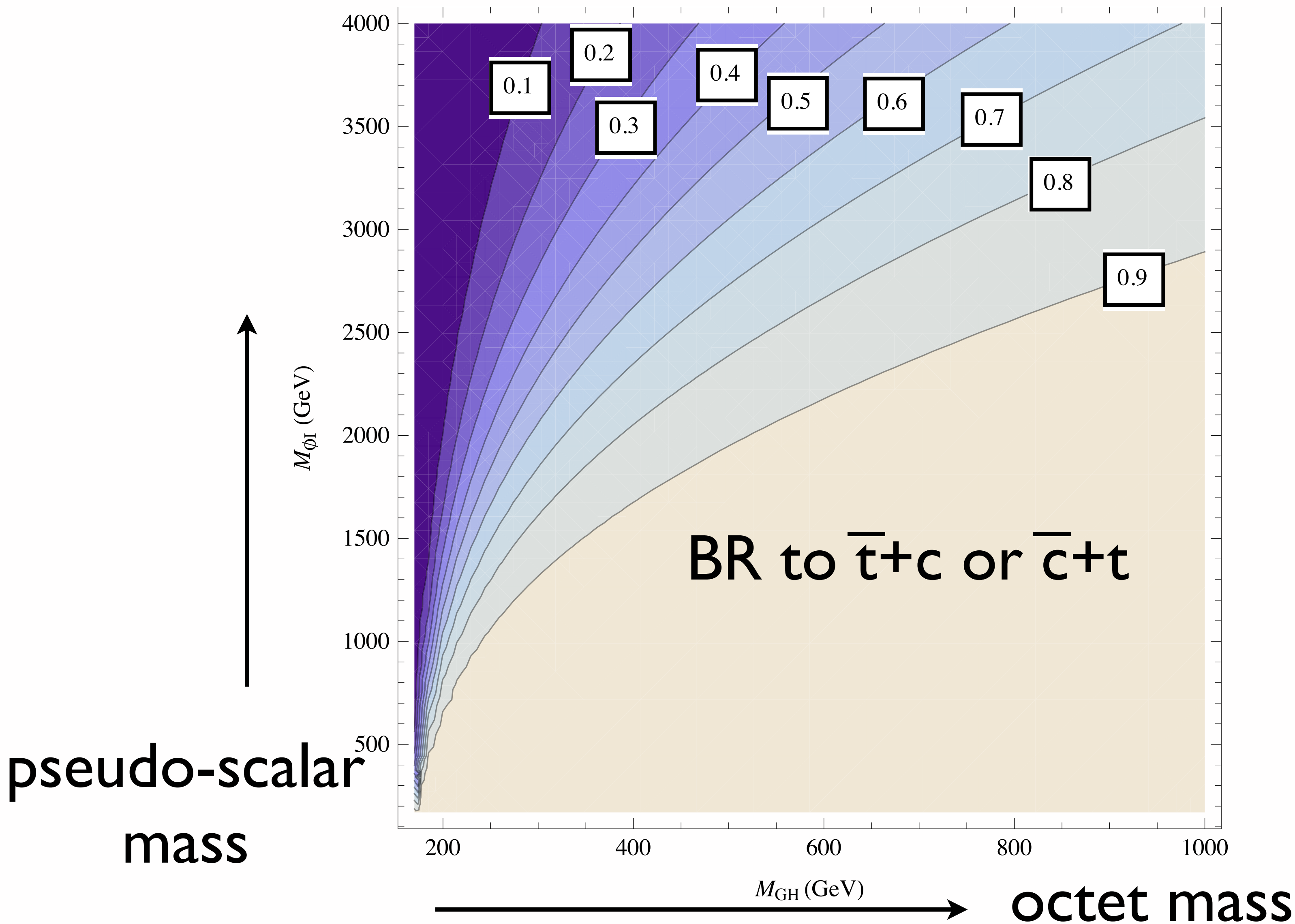


μ related to singlet pseudoscalar mass

$\bar{c}_L t_R + \bar{t}_R c_L$:

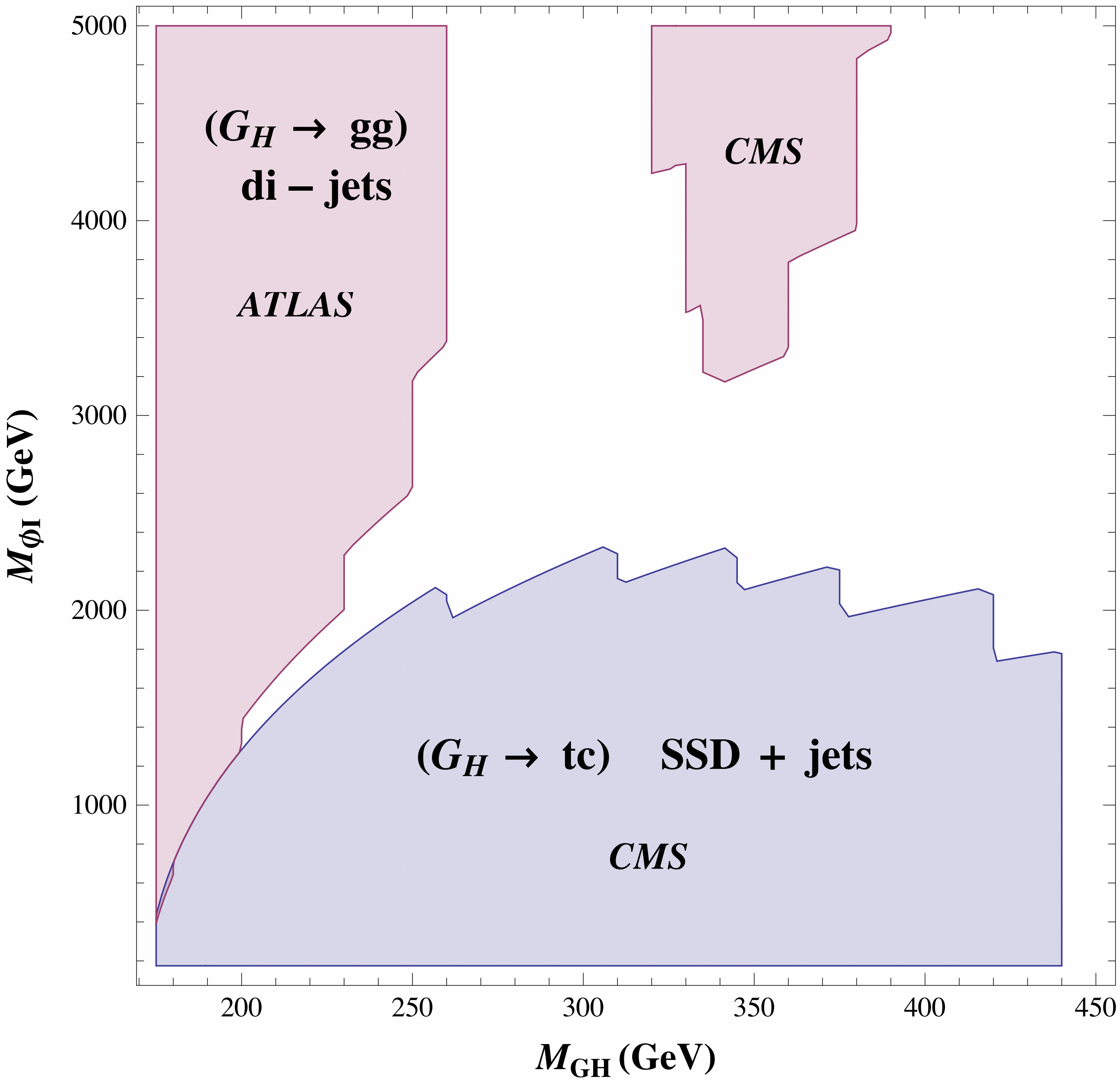


Top + Charm Often Very Large!



Octet pair production can lead to same-sign tops (dileptons)!

Experimental Constraints



Singlet mass dependence from behavior of BRs

References: CMS PAS SUS-12-029
ATLAS arXiv:1210.4826
CMS arXiv:1302.0531

Flavor-Universal Constraints On Scalars

R.S.C., Arsham Farzinnia, Jing Ren,
and Elizabeth Simmons

PRD 88 (2013) 075020 and in press

Scalar Potential: Higgs and Mixing

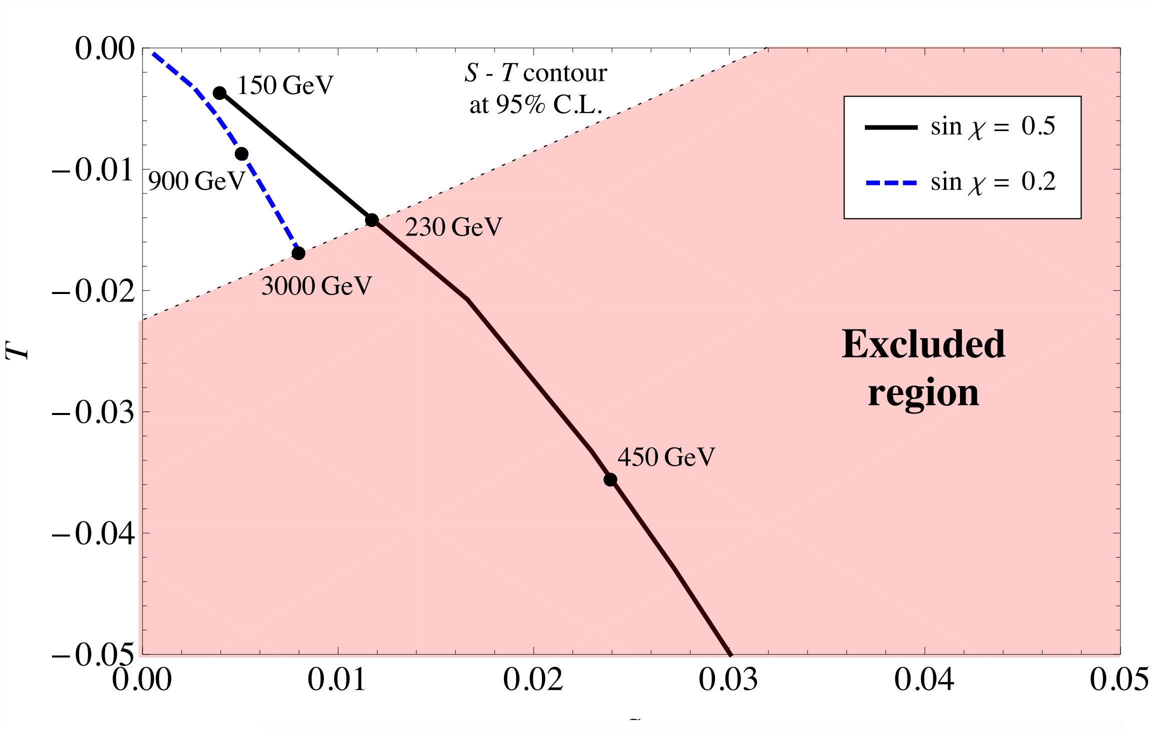
Scalar potential includes Higgs boson as well:

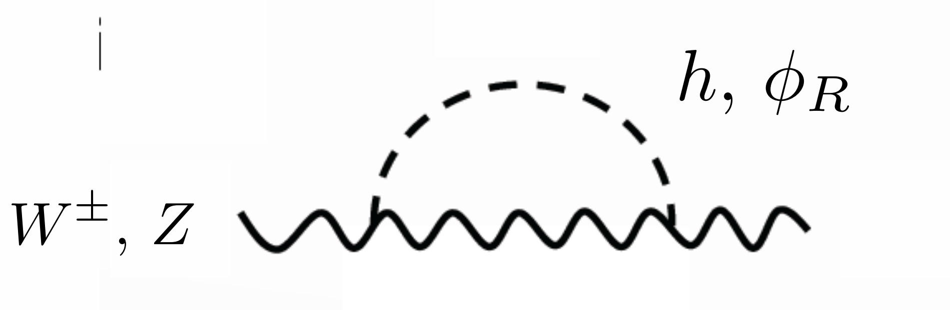
$$V(\phi,\Phi) \subset \frac{\lambda_h}{6}\left(\phi^\dagger\phi - \frac{v_h^2}{2}\right)^2 + \lambda_m \left(\phi^\dagger\phi - \frac{v_h^2}{2}\right)\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \frac{v_s^2}{2}\right)$$

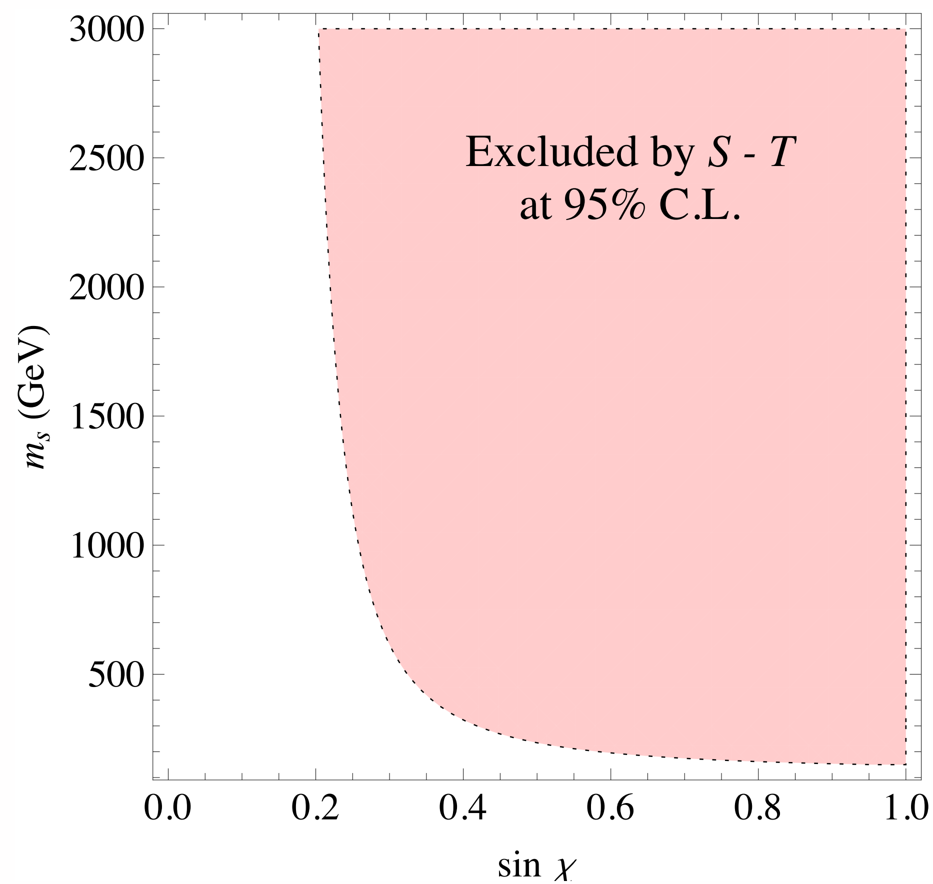
"Higgs portal" coupling: mixing between electroweak and color sectors

$$h = \cos\chi\, h_0 - \sin\chi\, \phi_{0R}$$

Precision Electroweak Constraints

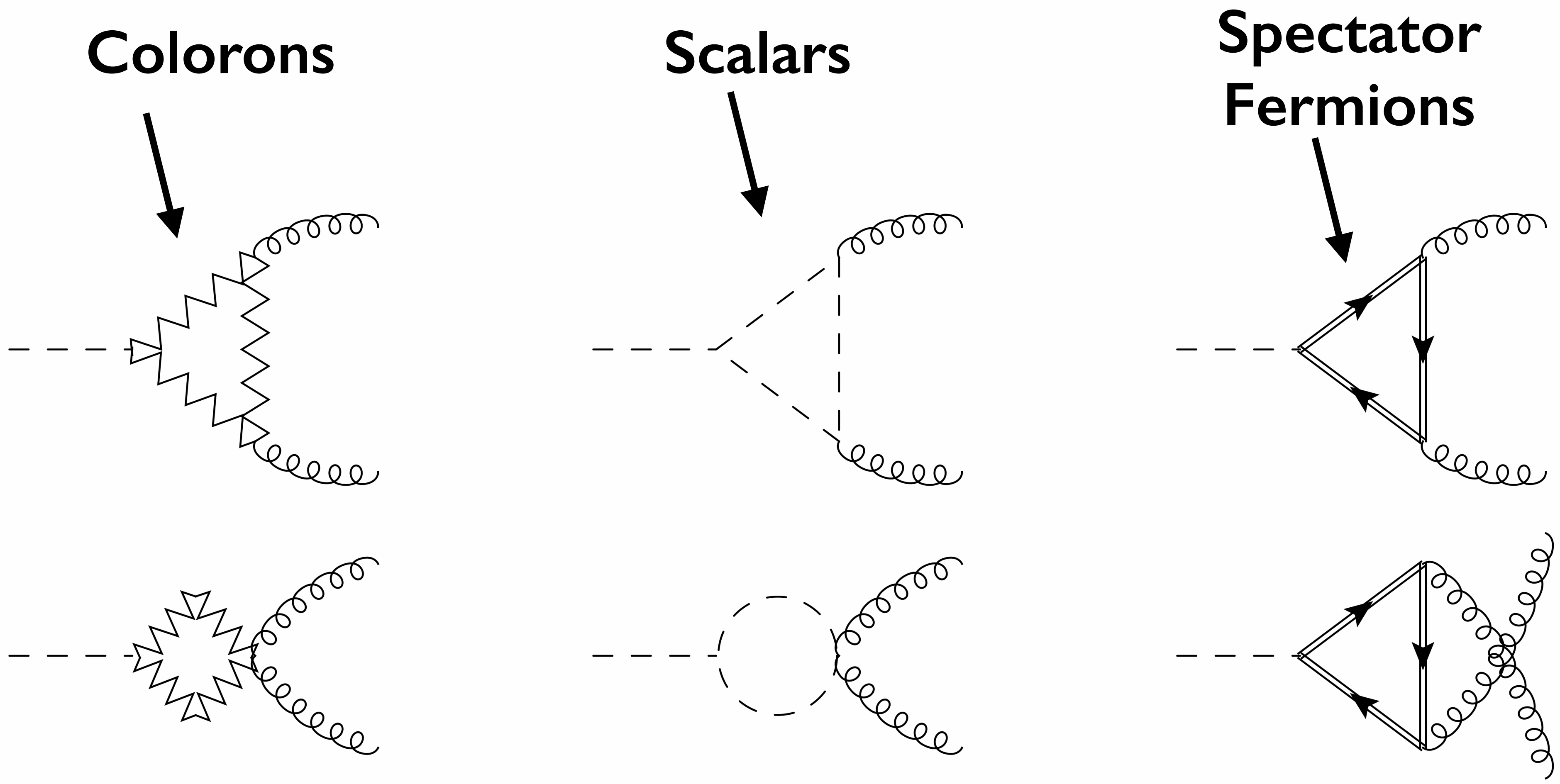




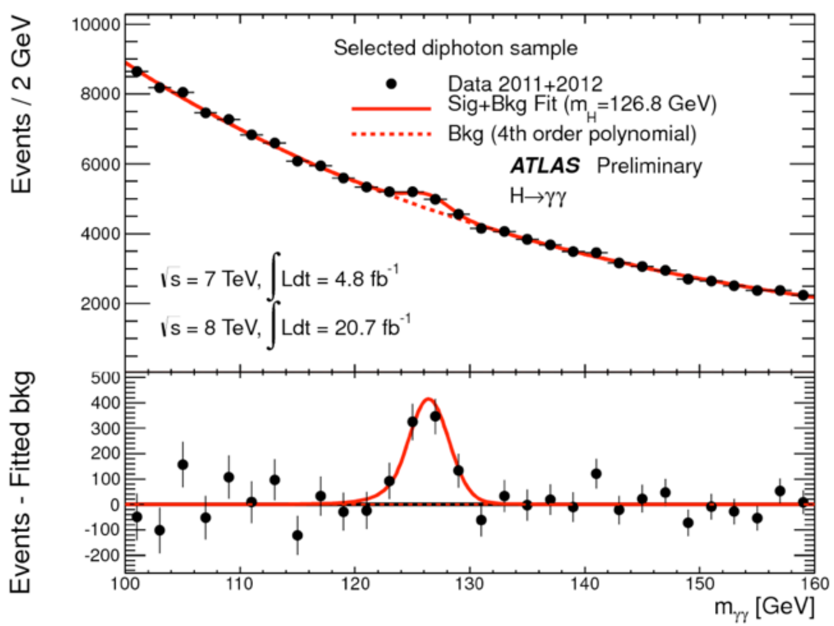


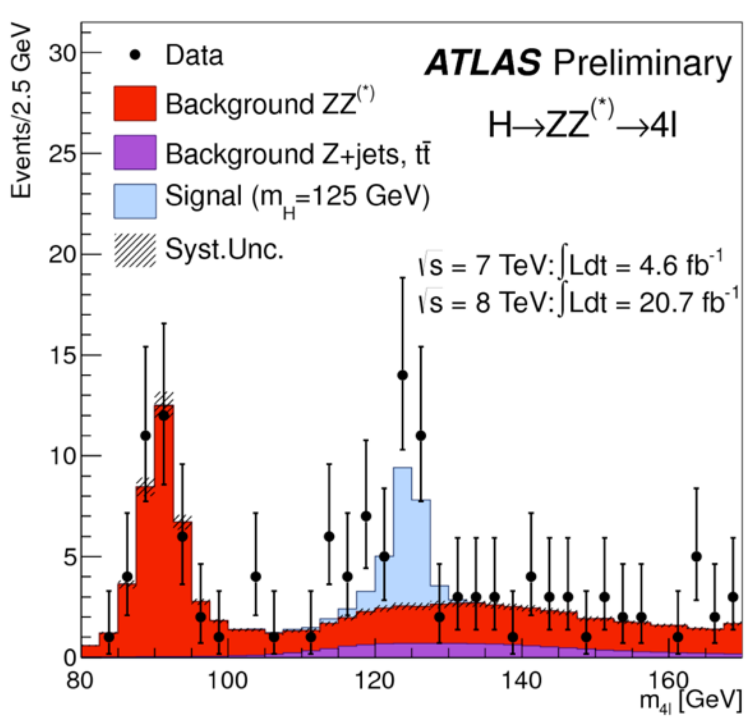
S-T contours from Gfitter, arXiv:1209.2716

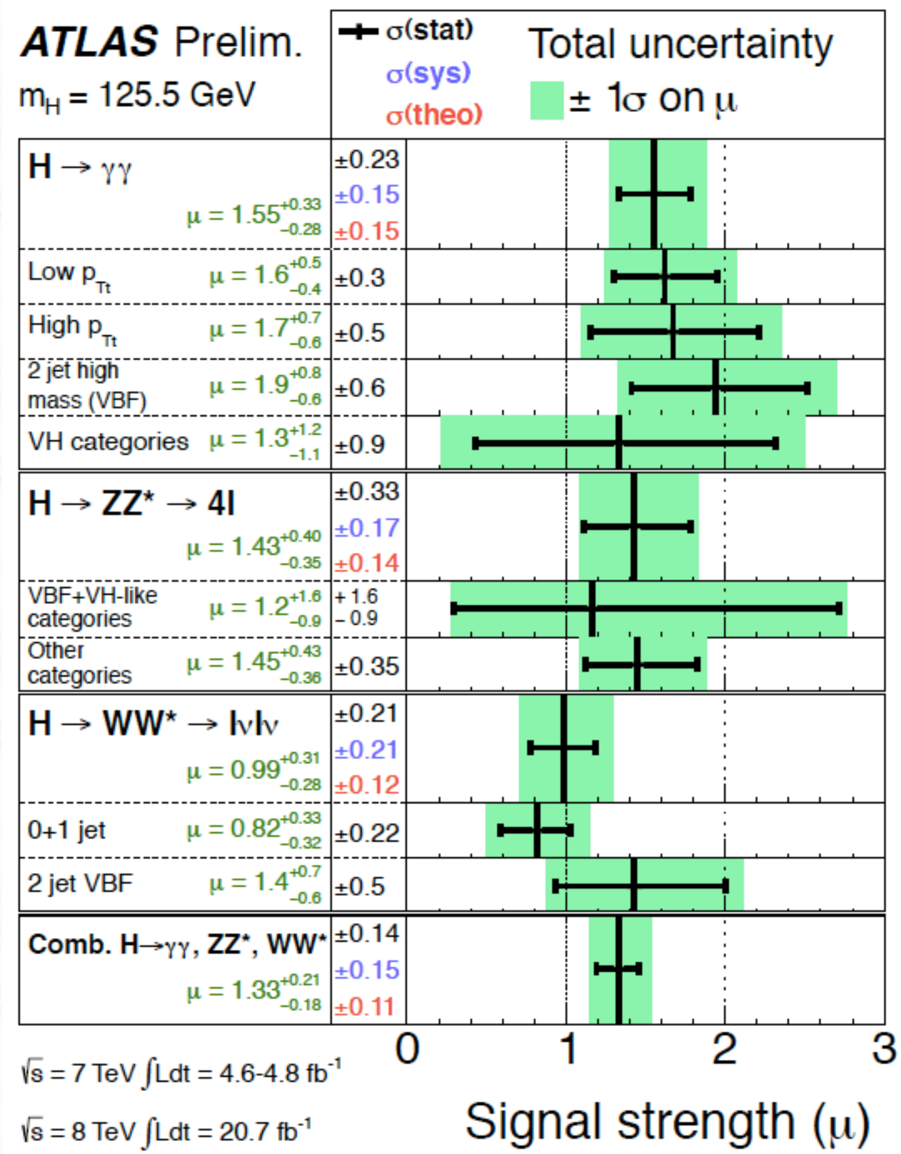
New States Contribute to Higgs Production!



ATLAS Higgs Observation

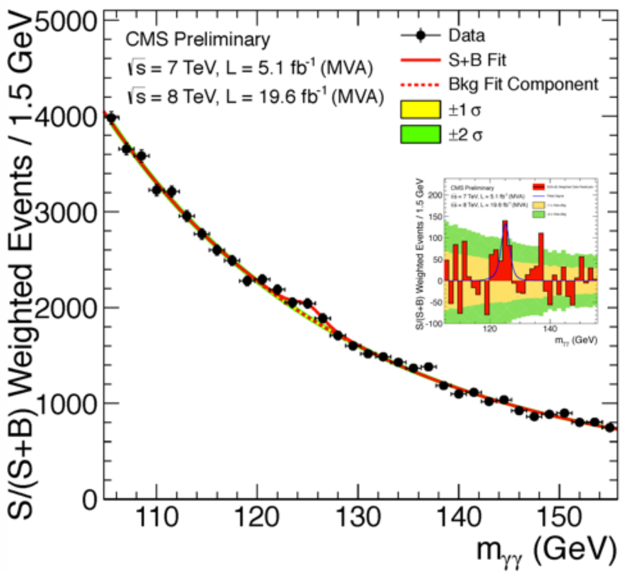


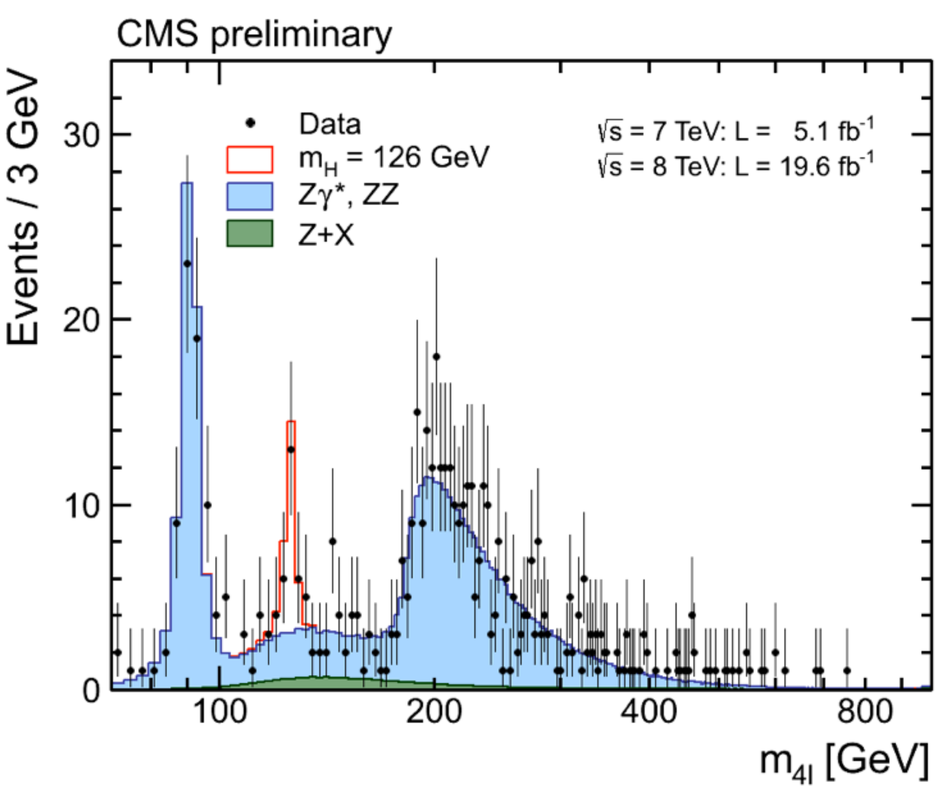


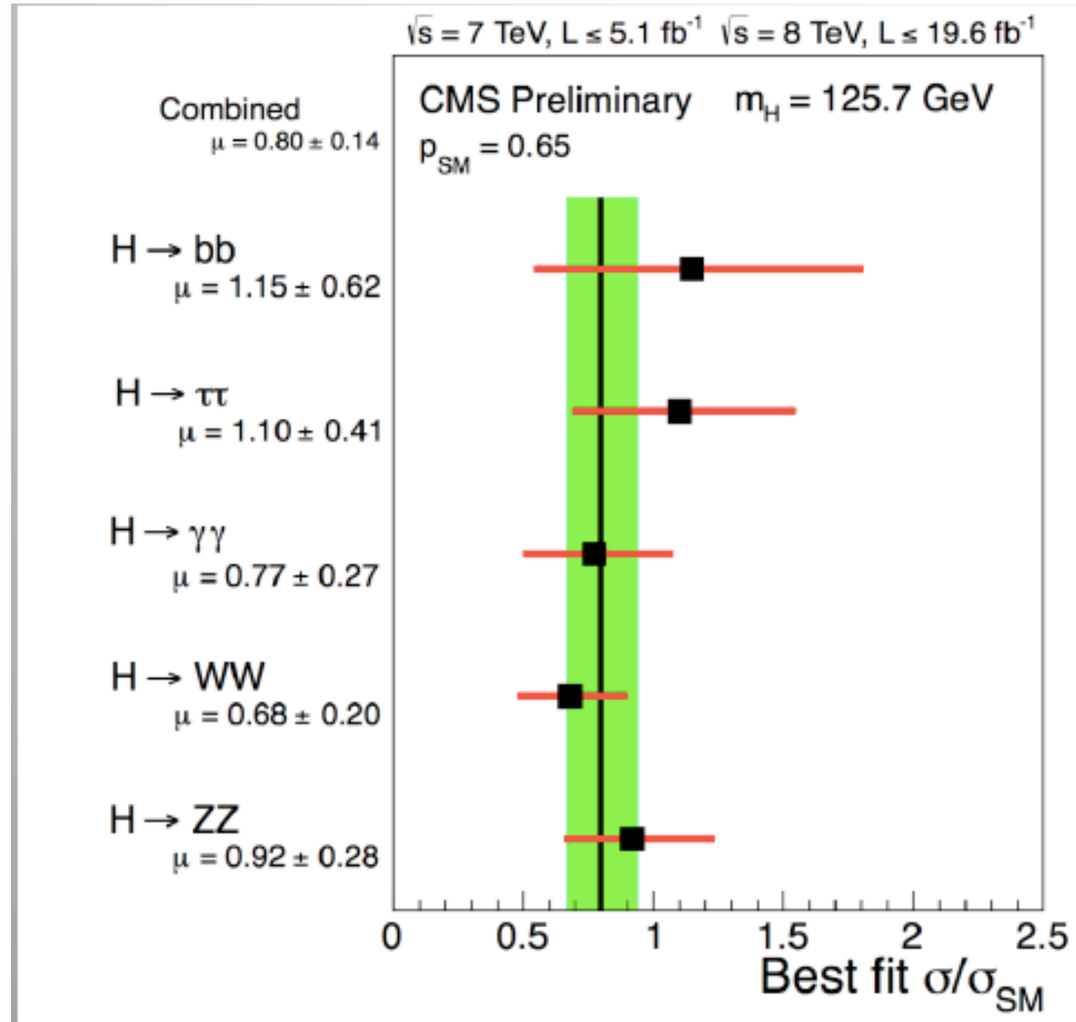


Moriond EW 2013, LP2013
ATLAS-CONF-2013-034,012,013

CMS Higgs Observation





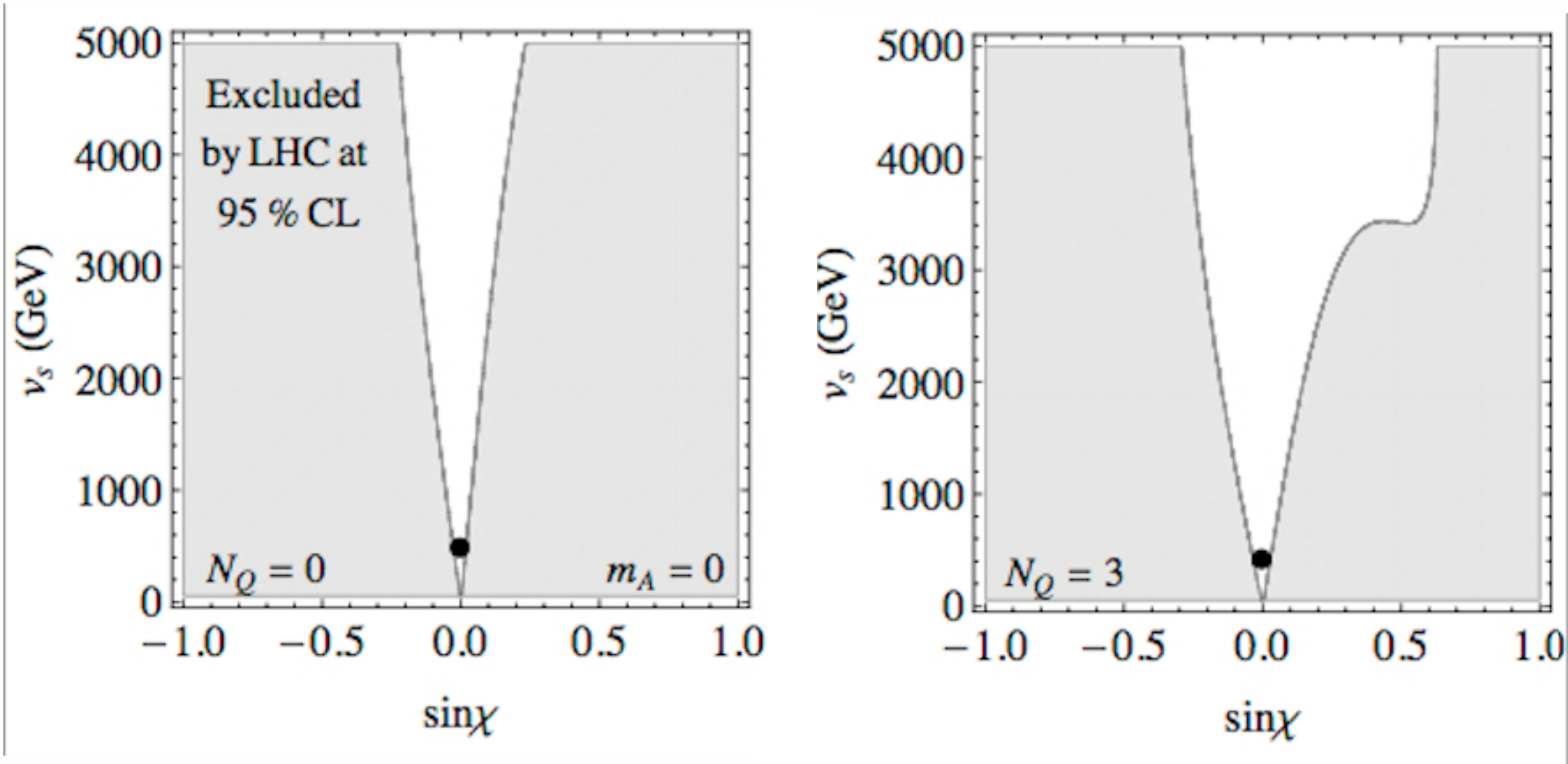


p-value= 0.65 w.r.t. μ=1

Moriond EW 2013, LP2013
CMS-PAS-HIG-13-001,2
CMS-PAS-HIG-12-045

Constraints from Higgs Observation

Coloron and colored scalar contributions to production...



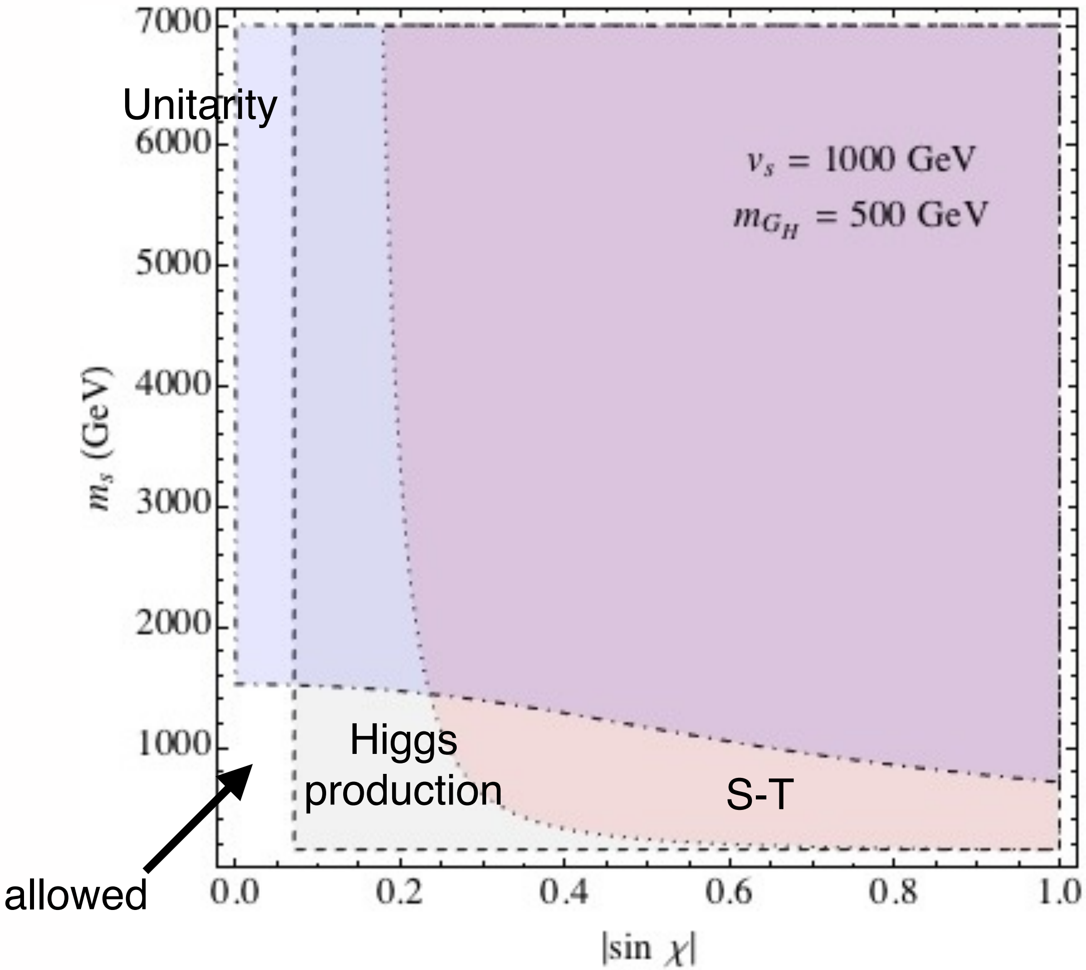
$h \to \phi_I \phi_I$ allowed

Note scale for v_s!

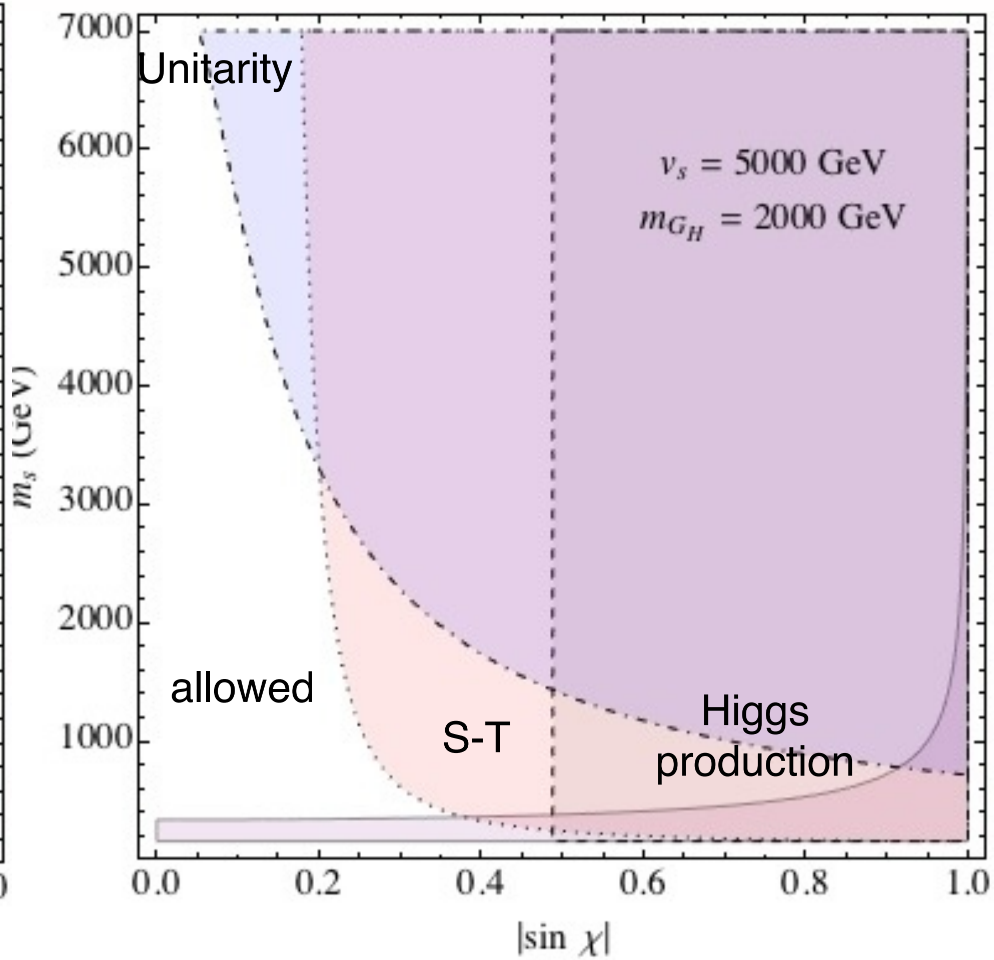
CMS-PAS-HIG-13-005
ATLAS-CONF-2013-034
Yao, Moriond EW 2013

Illustration of Combined Results

u=1000 GeV
m_{GH}= 500 GeV



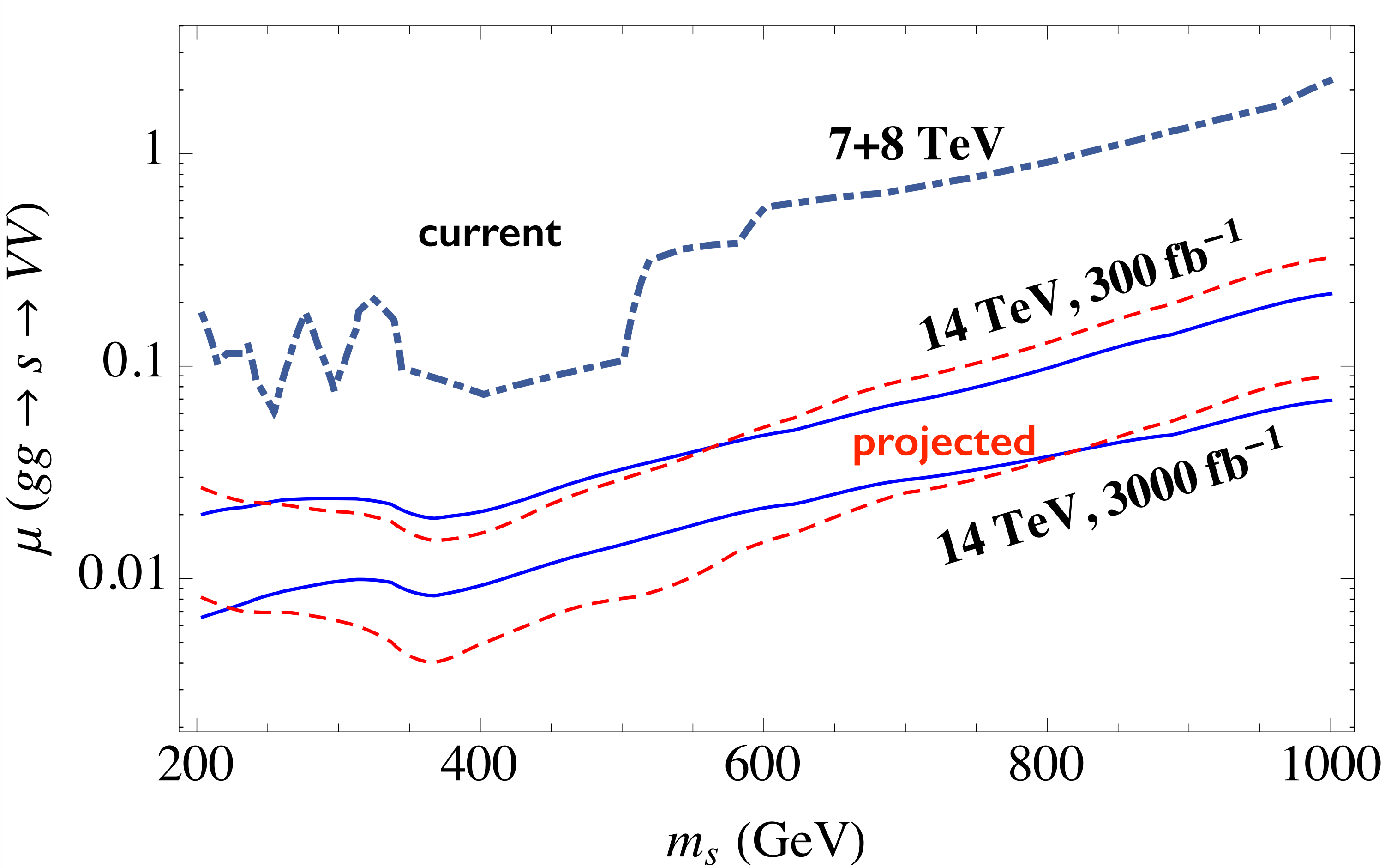
u=5000 GeV
m_{GH}= 2000 GeV



Illustrates interplay of different constraints ...
and of direct and indirect bounds

Heavy Singlet Boson

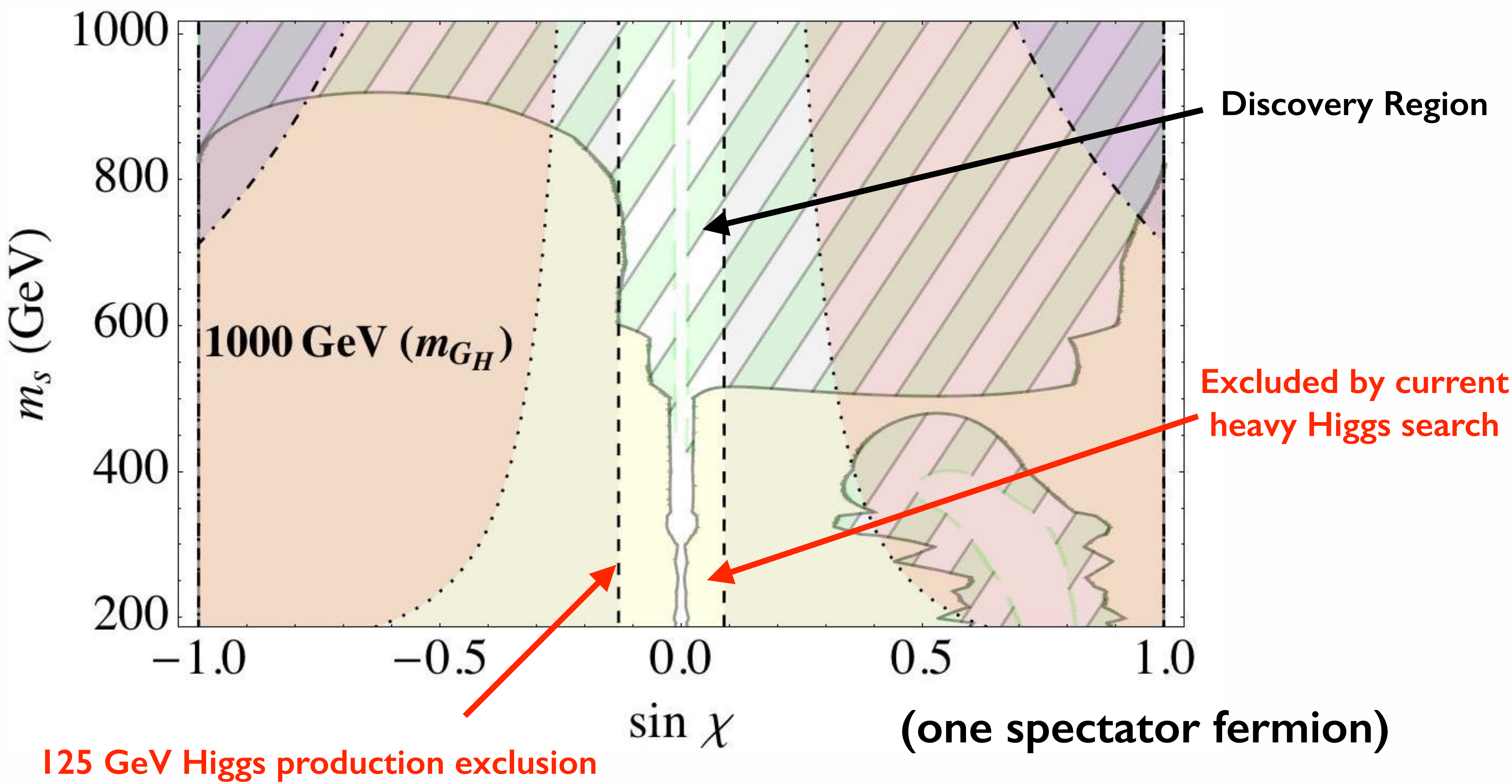
LHC Reach in σ*BR/(σ*BR)$_{\text{SM Higgs}}$



CMS-PAS-HIG-13-002/3
ATLAS-CONF-2013-013/030

LHC Singlet Boson Reach

Projection with 300 fb^{-1} @ 14 TeV



(one spectator fermion)

Illustrates that direct limits/searches will dominate!

Conclusions

Conclusions

Many models predict extended strong interactions

Is this extended dynamics flavor-universal or not?

- Introduced a flavorful top-coloron model
- Constraints from FCNCs favor NMFV.
- Same-sign tops, and therefore dileptons, an interesting signature for new colored scalars.

Additional effects of extended strong interactions?

- Color symmetry breaking sector can mix with EWSB
- Constraints on Higgs mixing and from observed properties of Higgs boson
- Discovery potential for heavy states at 14 TeV