Coloron Models and LHC Phenomenology

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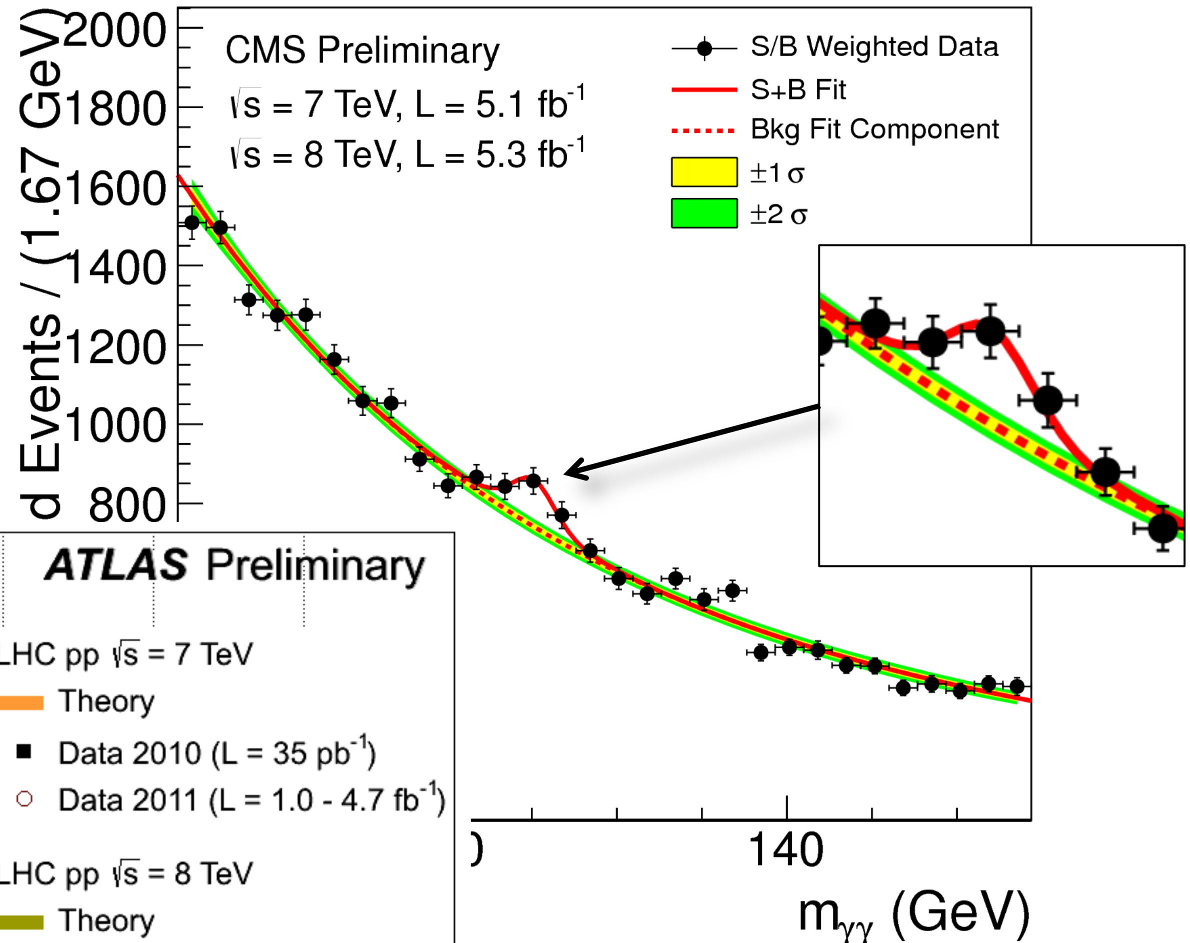
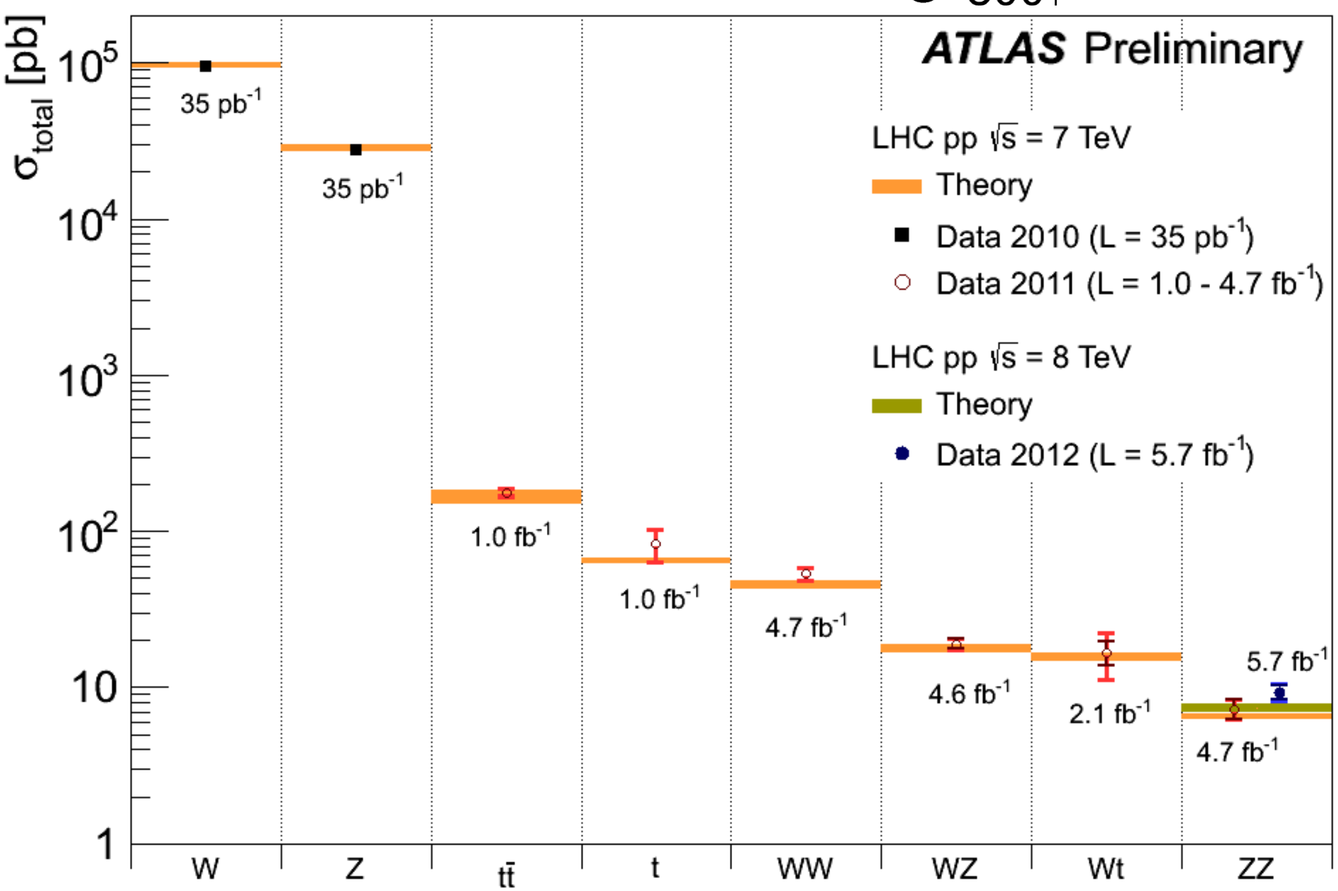
- New Strong Dynamics
- Models
- LHC Phenomenology
- Other Phenomenology
- Conclusions

SCGT 12 December 5, 2012

LHC's rediscovery and new particle

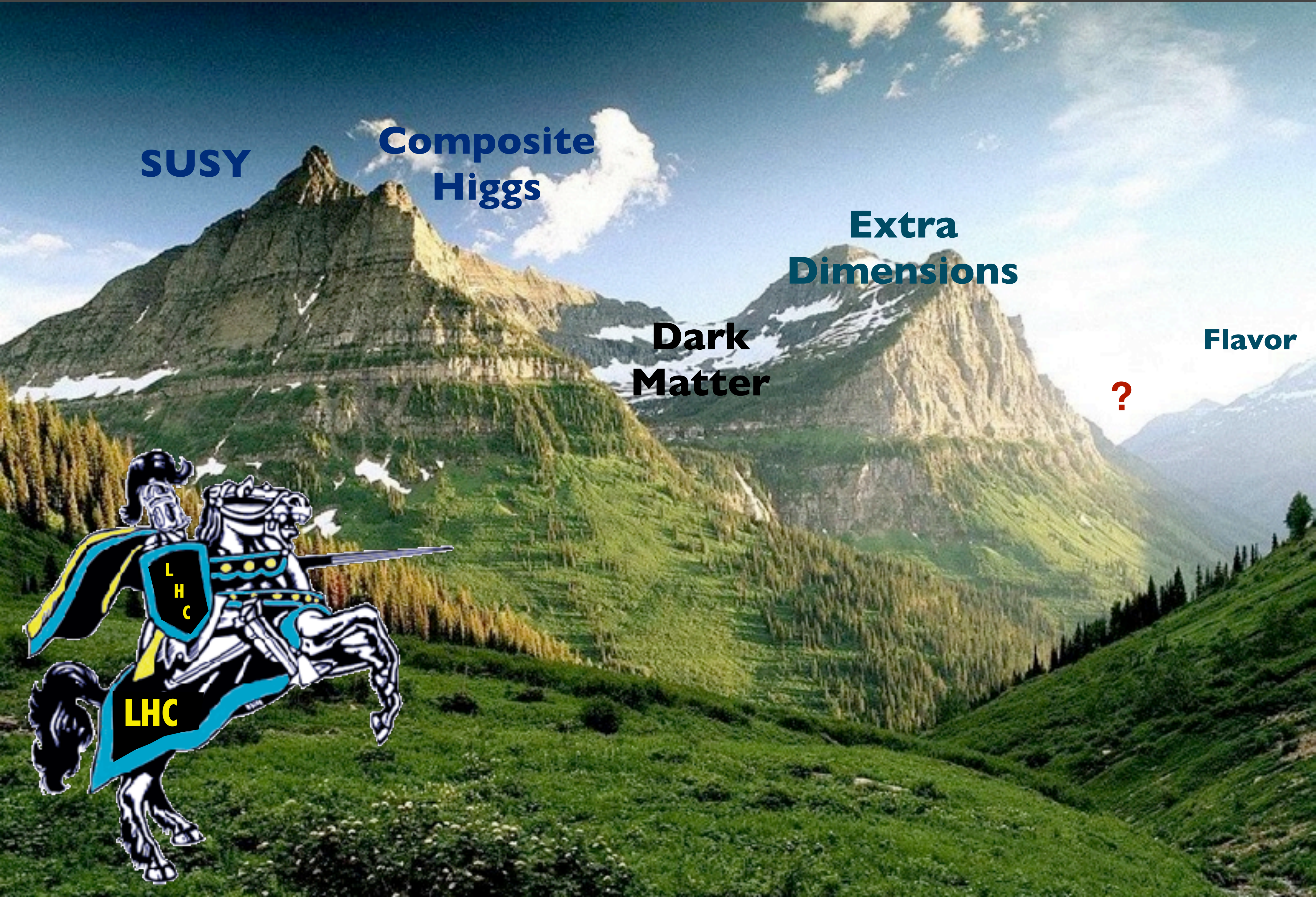
After years of work pay off ...





What's next?

Our Quest in The BSM Landscape



New Strong 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:

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).

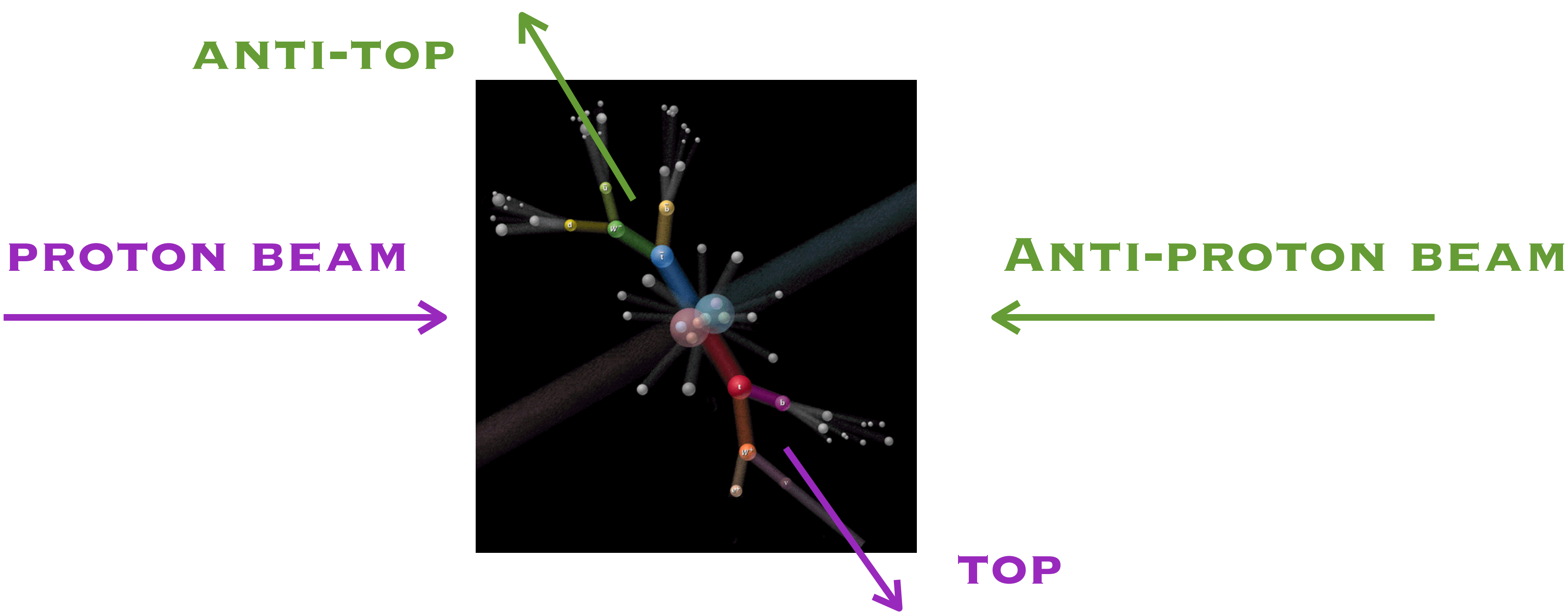
Recent catalog of colored states:

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

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

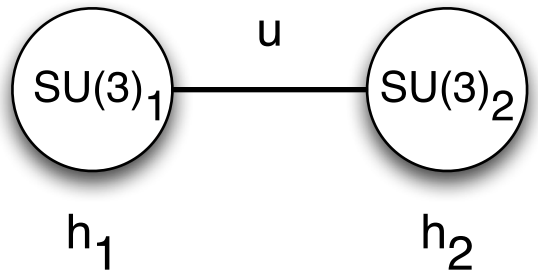
Coloron might impact A^{t}_{FB} at FNAL:

L. M. Sehgal and M. Wanninger, Phys. Lett. B 200, 211 (1988).
D. Choudhury, R.M. Godbole, R. K. Singh, and K. Wagh, Phys. Lett. B 657, 69 (2007).
P. Ferrario and G. Rodrigo, J. High Energy Phys. 02 (2010) 051.
M.V. Martynov and A. D. Smirnov, arXiv:1006.4246.
Q. H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, and C. E. M. Wagner, Phys. Rev. D 81, 114004 (2010).
P. Ferrario and G. Rodrigo, Proc. XVIII Int'l Workshop on Deep-Inelastic Scattering, April 19 -23, 2010, Firenze.
R.S. Chivukula, E.H. Simmons, and C.-P. Yuan, Phys. Rev. D82 (2010).
G. Rodrigo and P. Ferrario, 3rd Int'l Workshop on Top Quark Physics, Brugges, Belgium, 31 May to 4 Jun 2010.
G. Rodrigo and P. Ferrario arXiv:1007.4328 [hep-ph]
...



Models

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

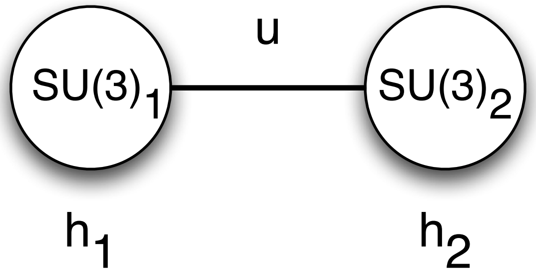
couples to: $g_S J^\mu_G \equiv g_S(J^\mu_1 + J^\mu_2)$

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

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: $\mathcal{L}^2_{FF} = -\dfrac{g_S^2}{2M_C^2} J^\mu_C J_{C\,\mu}$

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

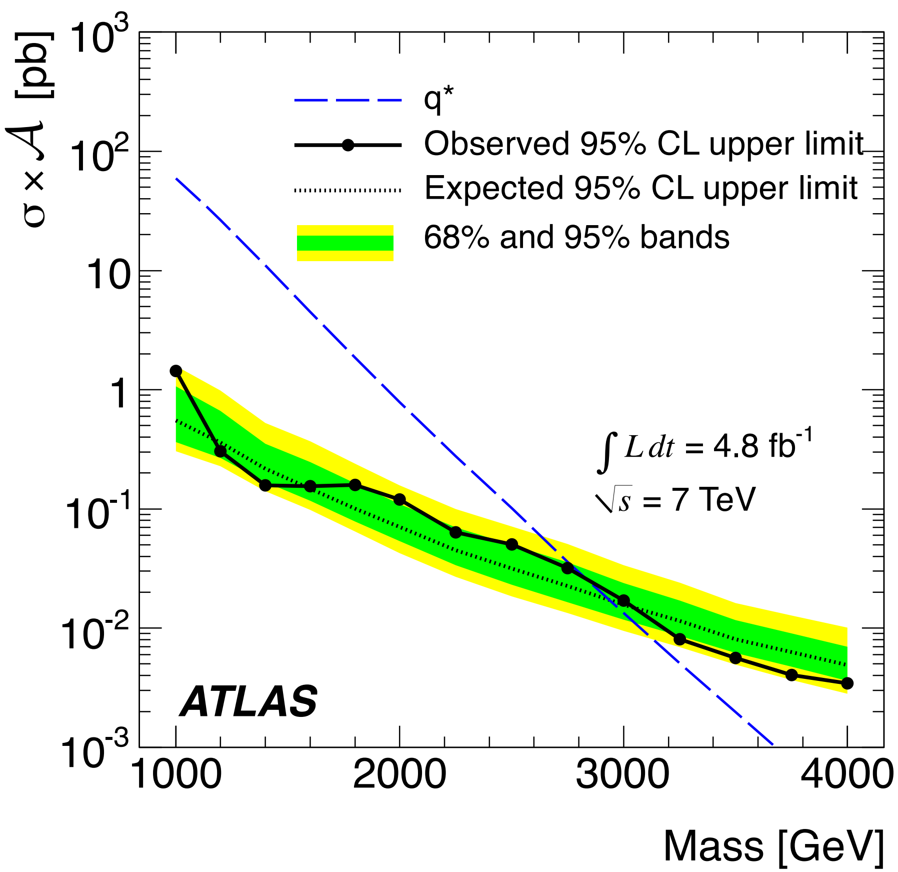
$SU(3)_1$	$SU(3)_2$	model	pheno.
	$(t,b)_L$ q_L t_R,b_R q_R	**coloron**	dijet
q_R	$(t,b)_L$ q_L t_R,b_R		
t_R,b_R	$(t,b)_L$ q_L q_R		
q_L	$(t,b)_L$ t_R,b_R q_R		
q_L t_R,b_R	$(t,b)_L$ q_R	**new axigluon**	dijet, A^t_{FB}, FCNC
q_L q_R	$(t,b)_L$ t_R,b_R	**topgluon**	dijet, tt, bb, FCNC, R_b...
t_R,b_R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

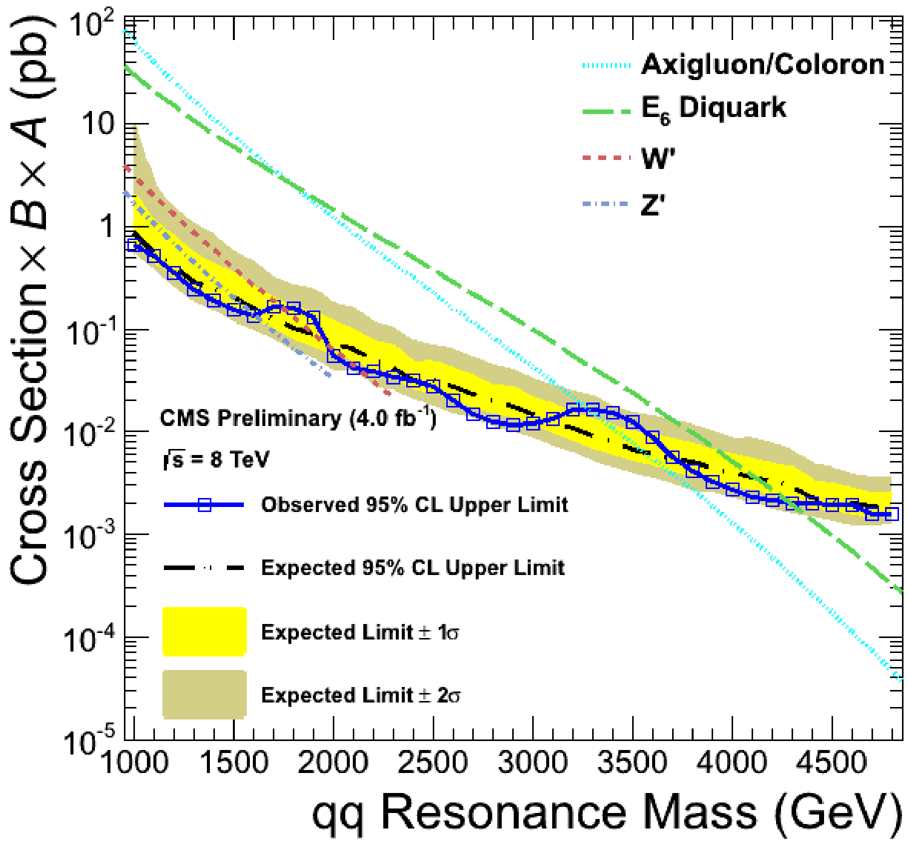
q = u,d,c,s

LHC Phenomenology

LHC Limits on Colorons

- LHC searches for colorons in dijet constrain $M_C > 3.5$ TeV



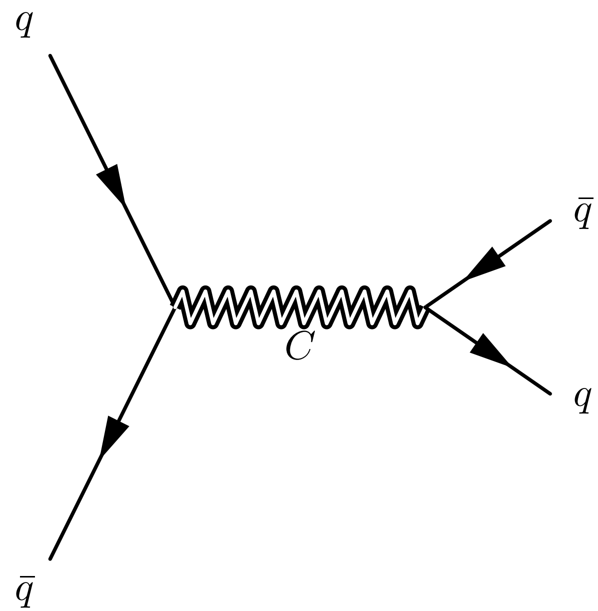


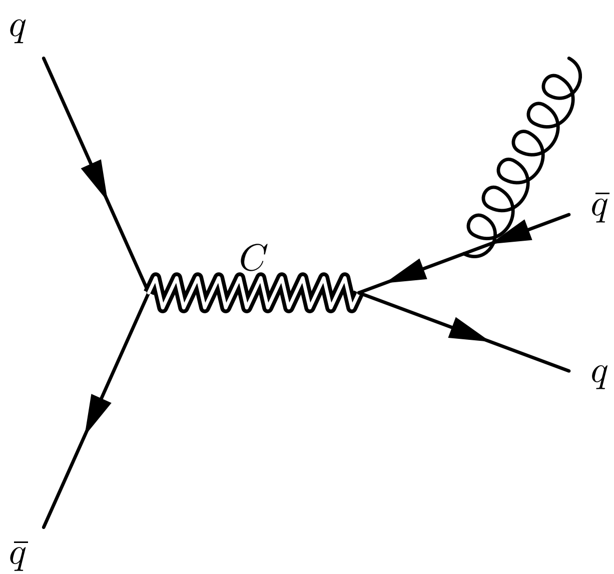
- But these calculations have treated the colorons only at LO and QCD to NLO (or beyond) ... we can do better!

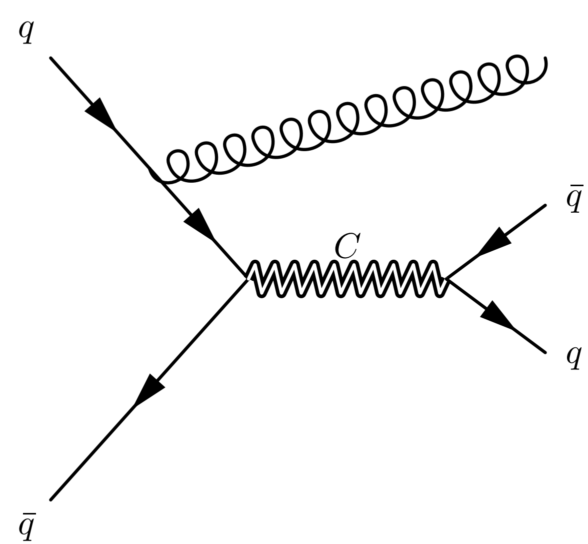
Coloron Production

LO vs NLO production

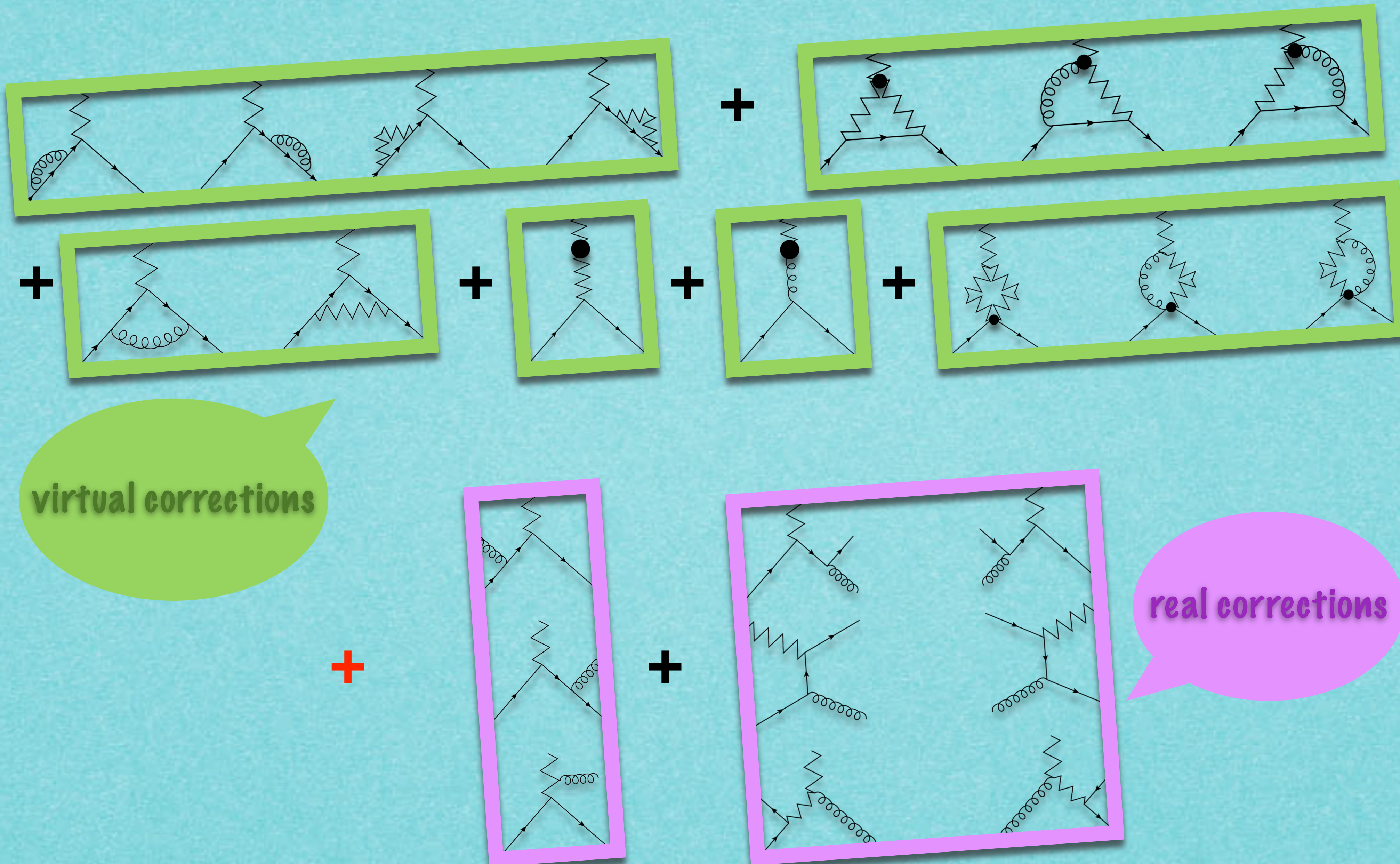
- cross-section
- pT of coloron





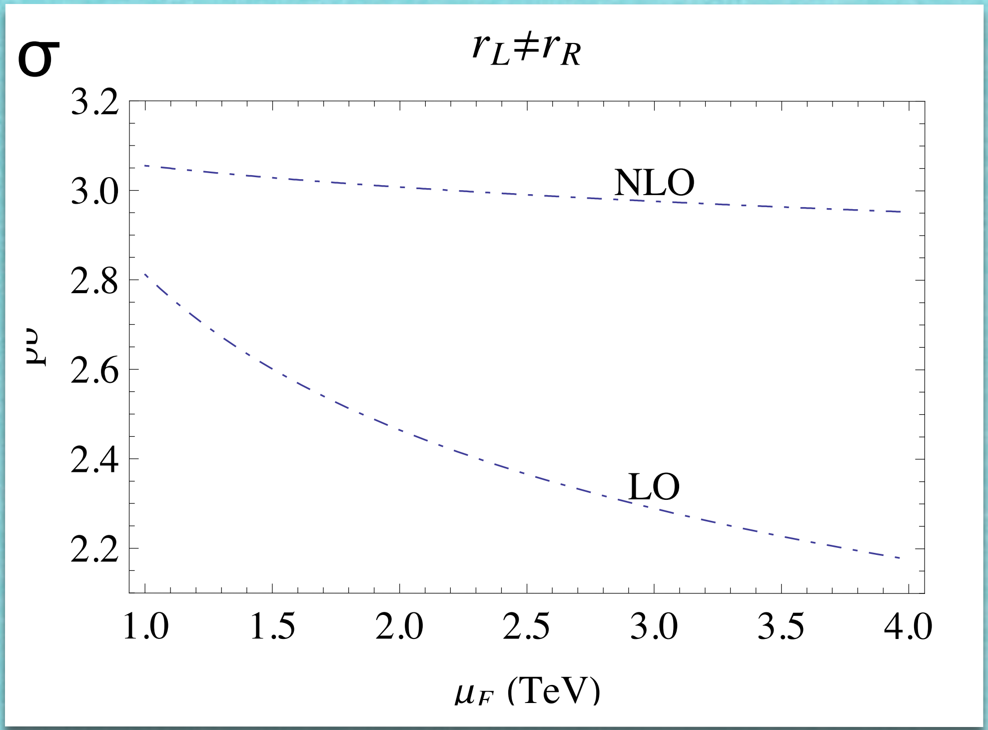


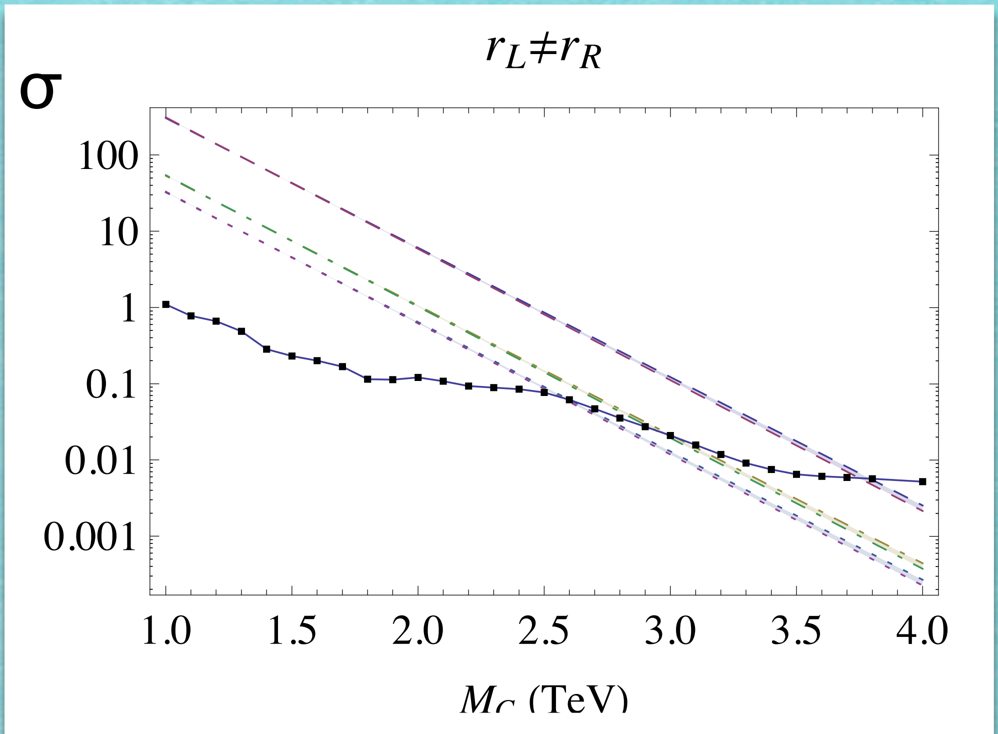
Colorons at NLO



R.S.Chivukula, A.Farzinnia, R.Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections

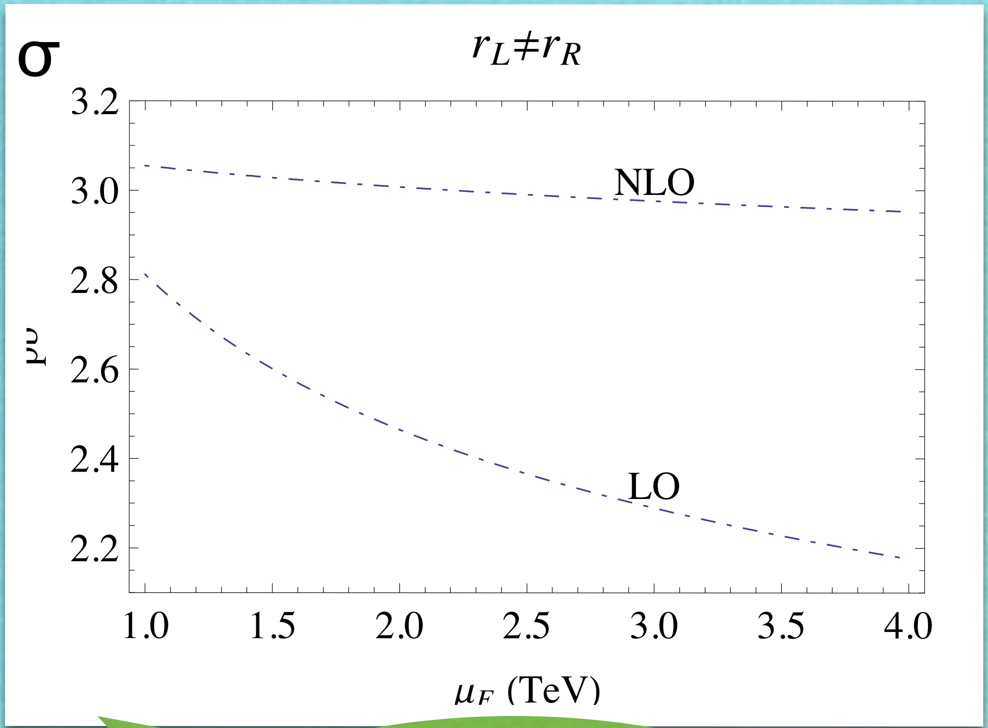


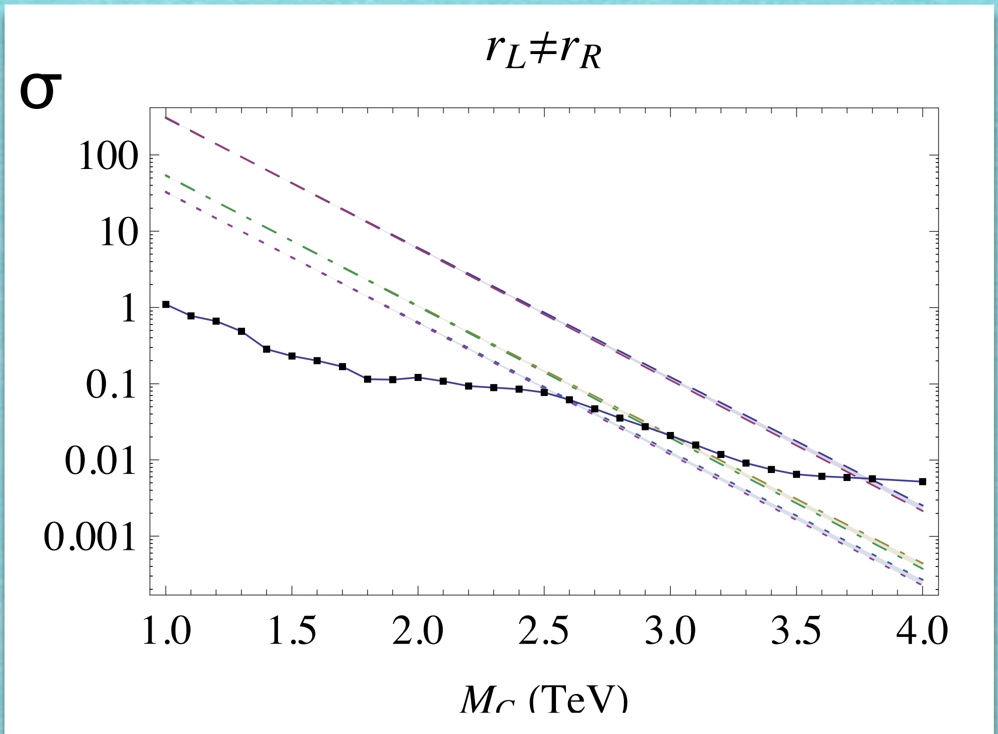


- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
- 30% of produced colorons have p_T > 200 GeV!

RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections





scale dependence
at LO: 30%
at NLO: 2%

- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
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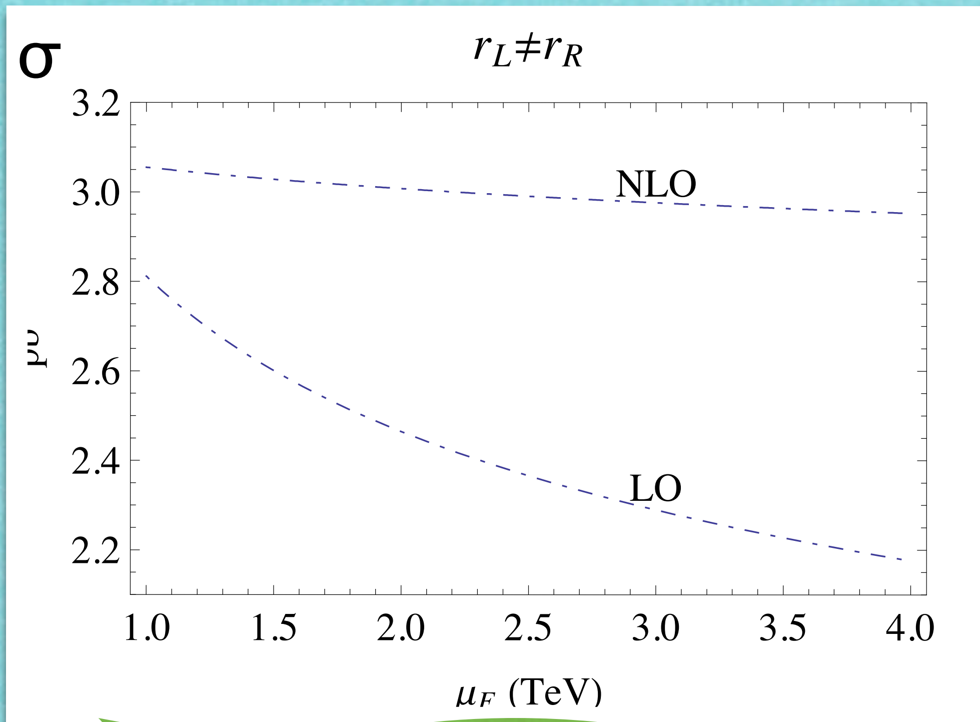
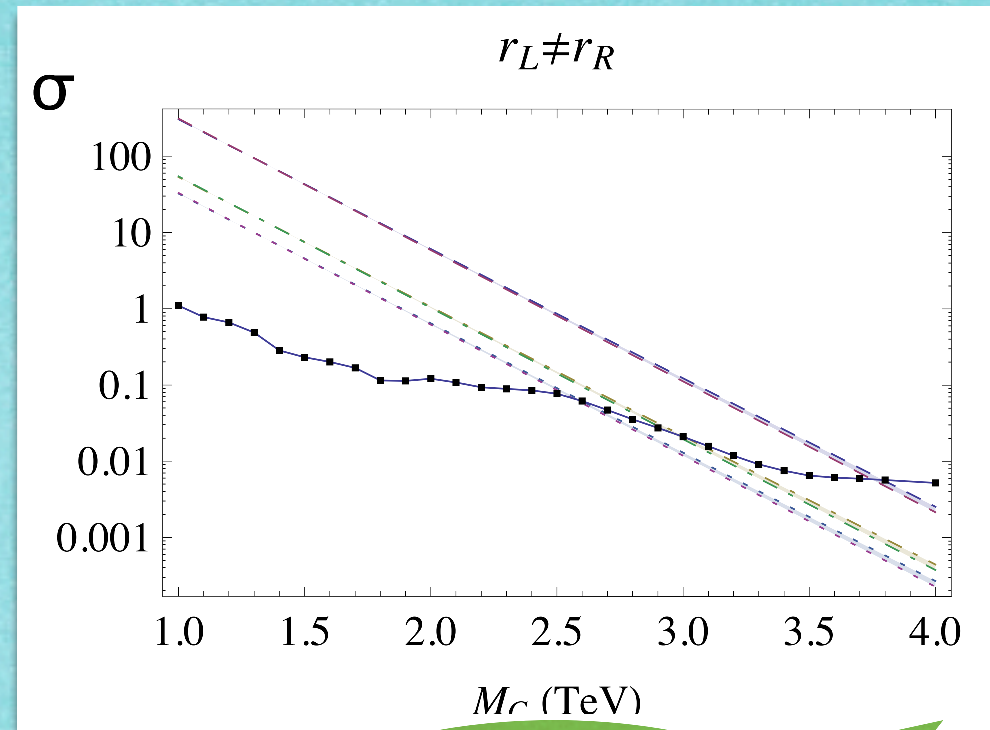
RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections





scale dependence
at LO: 30%
at NLO: 2%

Axigluon
mass limit from CMS
stronger when NLO
included

- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
- 30% of produced colorons have p_T > 200 GeV!

RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Beyond Production:

Suppose we discover a coloron... What then?

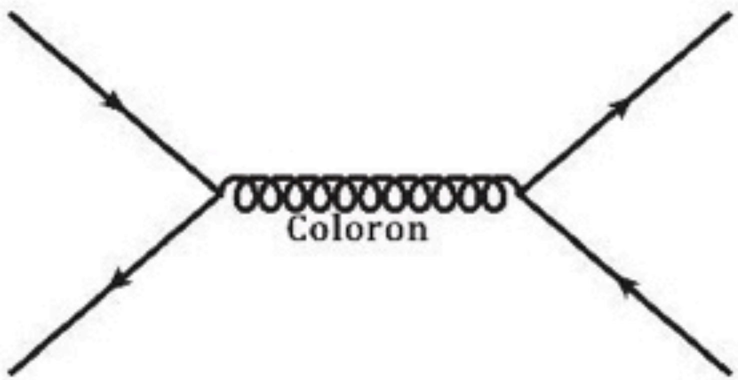
Remember the diversity of models:

$$\underbrace{g_s \bar{q}\, C^\mu \gamma_\mu \left(g_V^q + g_A^q \gamma_5\right) q}_{q=u,d,c,s} \quad \text{and} \quad \underbrace{g_s \bar{T}\, C^\mu \gamma_\mu \left(g_V^T + g_A^T \gamma_5\right) T}_{T=t,b}$$

How to establish which coloron has been found?

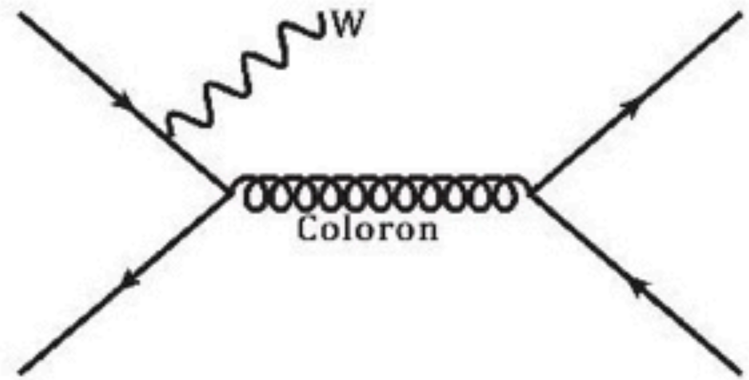
Goal

Dijet



Discovery

Associated production with W



Measurement

Goal

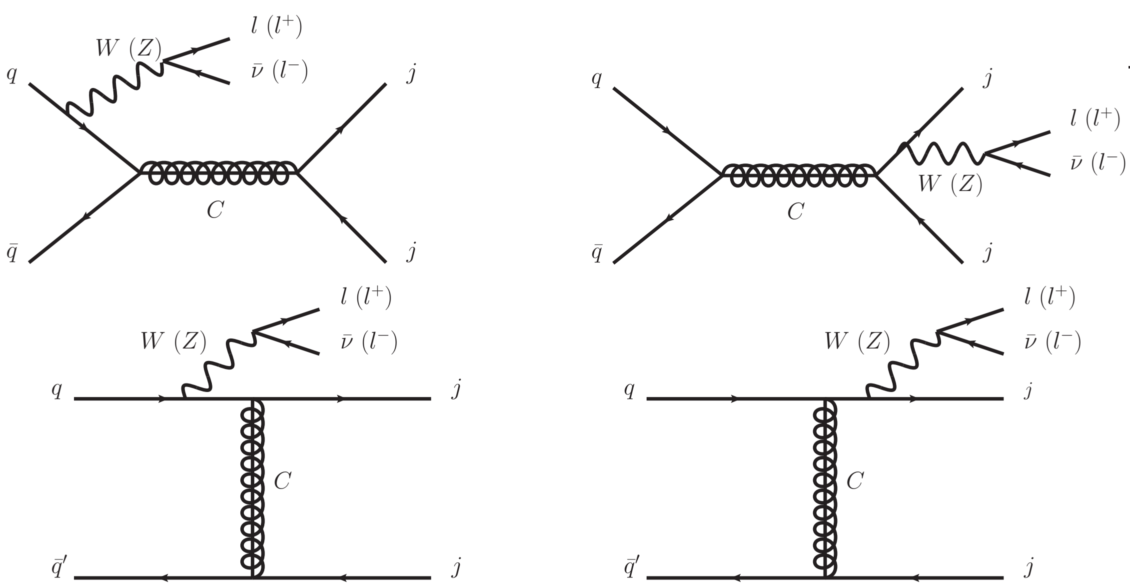
" Using associated production* with W and dijet resonance to determine colorons/axigluons couplings."

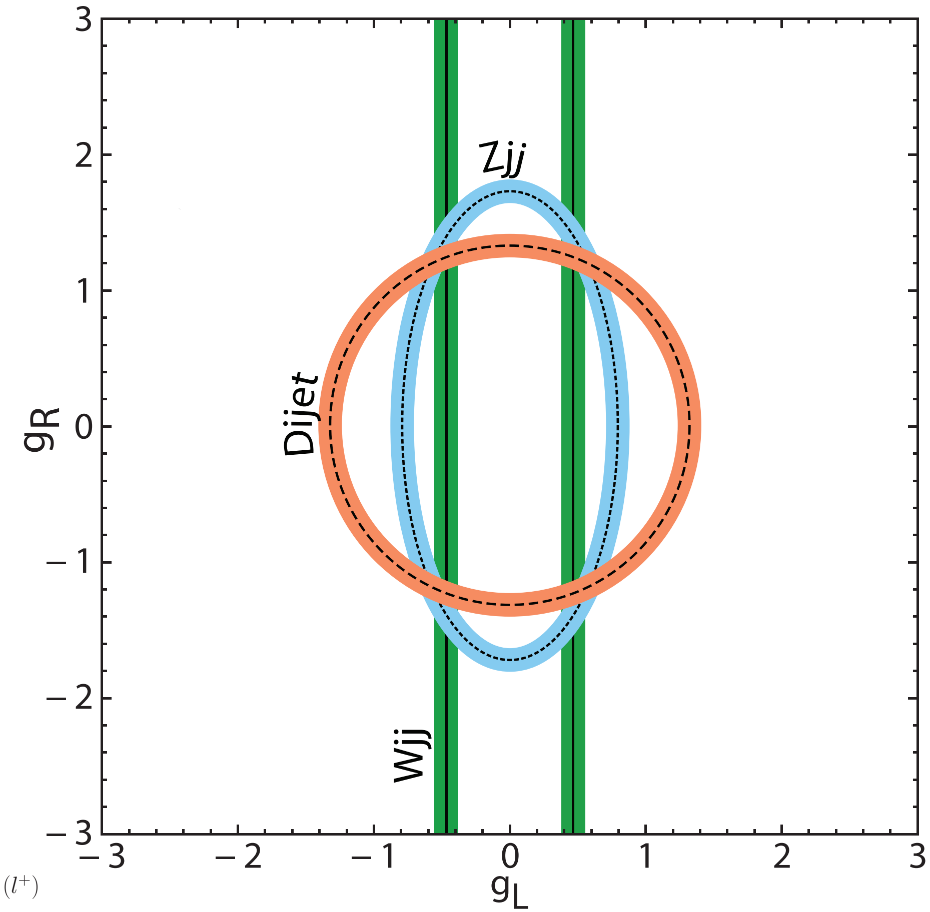
*Idea introduced by Cvetic and Langacker (1992) for measuring Z' couplings

New Mode: W+C^a probes Chiral Couplings

Different production modes probe several combinations of the coloron's couplings to RH and LH fermions:

$$pp \to C^a + W[Z] \to jj\ell\nu[\ell\ell]$$





A. Atre, R.S.Chivukula, P. Ittisamai, EHS arXiv:1206.1661

Event Generation and Event Selection

Event Generation: MadGraph 5.1.3 $\rightarrow$ Pythia 6.4 $\rightarrow$ PGS4

Event Selection ("Basic cuts"):

- At least two isolated jets
  - $p_T > 40\,\mathrm{GeV}$
  - $|\eta| < 2.5$
  - $\Delta R_{jj} > 0.4$
- One isolated electron or muon
  - $p_T > 25\,\mathrm{GeV}$
  - $\Delta R_{jl} > 0.4$, $\Delta R_{ll} > 0.2$
- Missing energy $> 25\,\mathrm{GeV}$

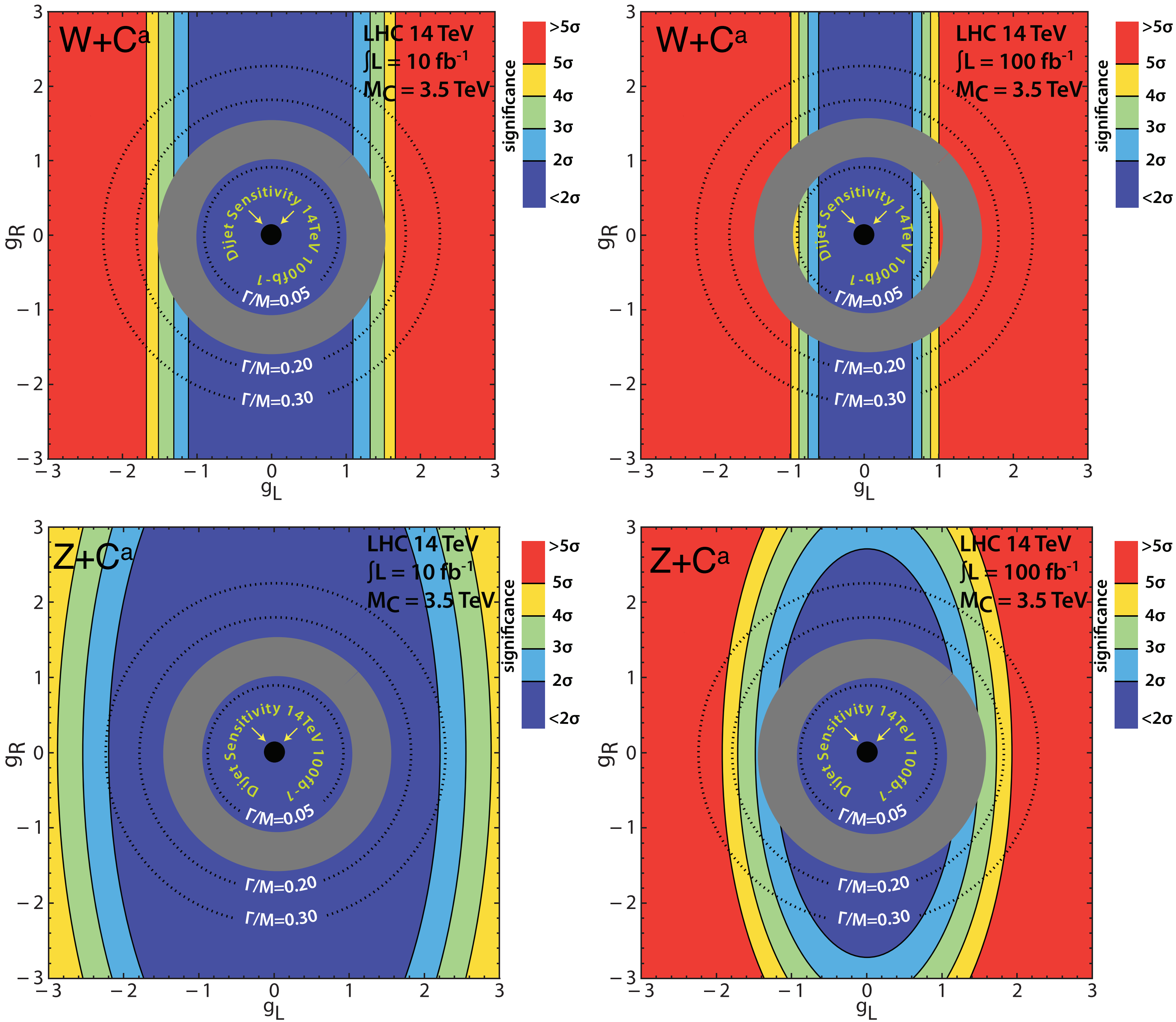
Optimization:

- p_T of leading jets
- total transverse jet energy ($H_T \simeq \sum p_T$)
- Invariant masss m_{jj} or m_{jjW}

maximize significance $\simeq \frac{s}{\sqrt{b}}$ at $10\,fb^{-1}$ and $100\,fb^{-1}$ for LHC $14\,\mathrm{TeV}$

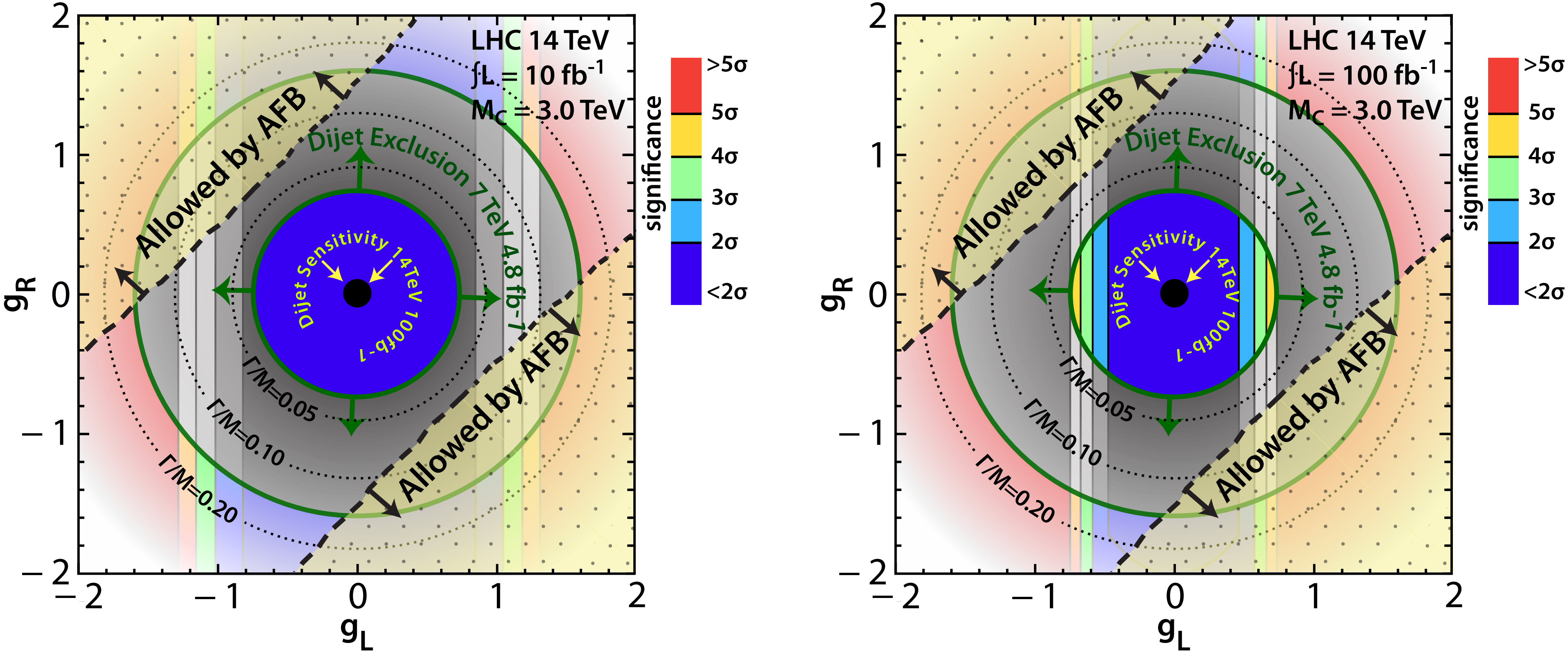
W+C^A: Heat Map of Significance

all of these heat maps are for M_C = 3.5 TeV at **14 TeV LHC**



grey ring is excluded by 7 TeV LHC dijet searches with 5 fb^{-1} of data

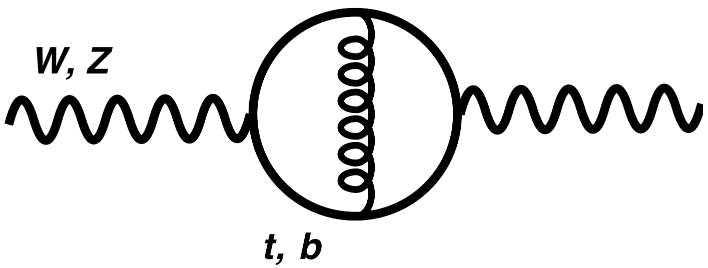
W+C^A: Heat Map and AFB range



Precision Phenomenology

Precision EW Tests

- Coloron exchange does impact $\Delta\rho$ at one-loop



but since

$$\Delta\rho_c \sim \frac{m_t^4}{M_W^2 M_C^2} \ln\left[\frac{M_c^2}{m_t^2}\right]$$

the size of the effect is small

- Likewise, coloron exchange across the $Zb\bar{b}$ vertex yields effects proportional to m_b^2 which are negligible
- New weak-charged states would give larger effects...

FCNC in Coloron Models

- Coloron exchange can produce FCNC if the coloron coupling to quarks are flavor non-universal

- The total rate of FCNC will depend quite strongly on how flavor is implemented overall in the model
  - Are there other states that quarks mix with?
  - Are there additional composite states made from quarks, whose exchange can boost FCNC's?

- Let's look at a specific implementation

A New Toy Topgluon Model

R.S. Chivukula, EHS, N. Vignaroli
(2012) in preparation

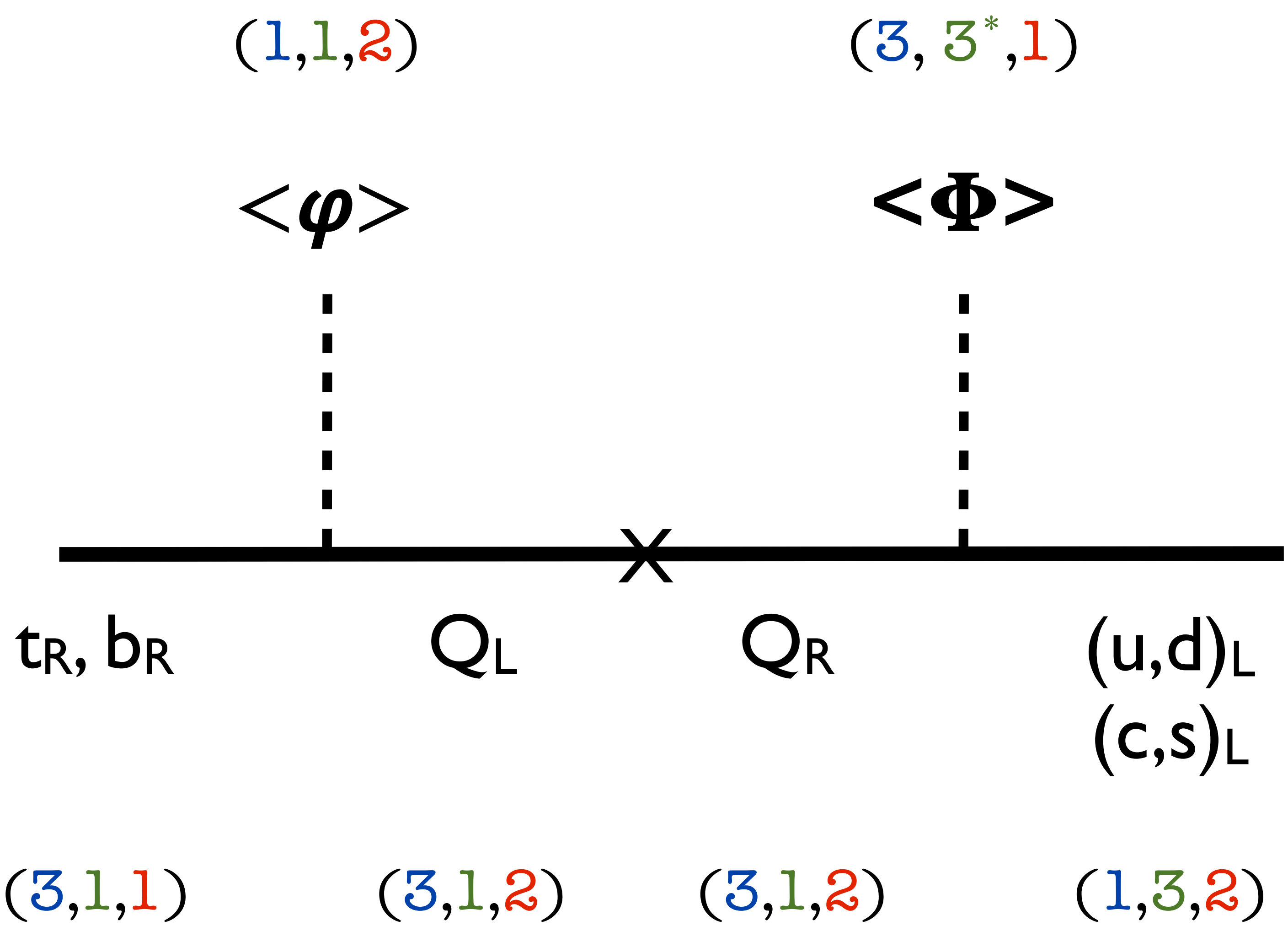
Our Toy Topgluon Model

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

R.S. Chivukula, EHS, N. Vignaroli (2012) in preparation

Generational Mixing in Toy Model

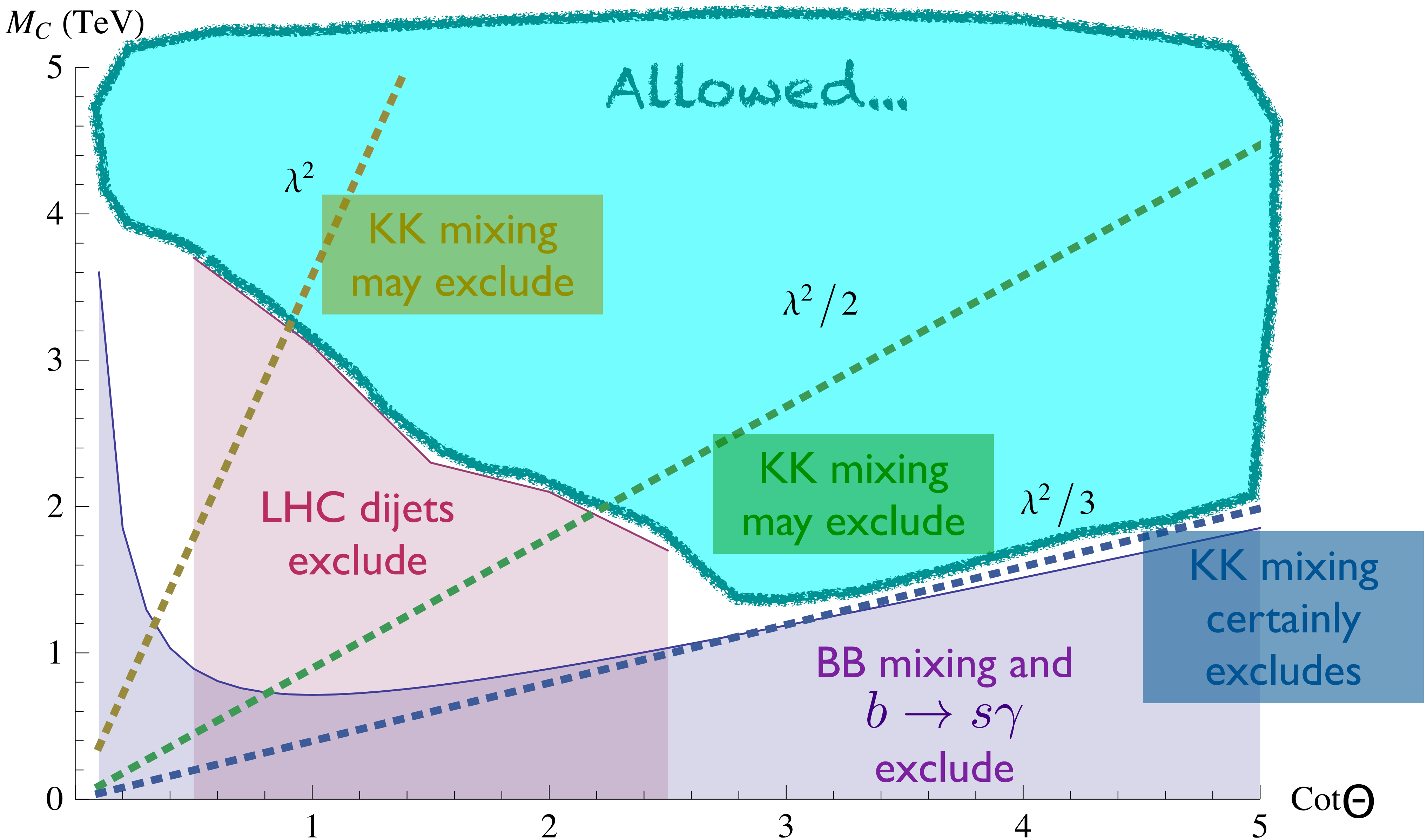
$SU(3)_1 \times SU(3)_2 \times SU(2)_W$



FCNC in Our Toy Topgluon Model

- 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
- Mixing among ordinary and heavy vector quarks also leads to flavor-changing b-quark decays: $b \to s\gamma$

Limits on Toy Topgluon Model



R.S. Chivukula, EHS, N. Vignaroli (2012) in preparation

Conclusions

Conclusions

Physics beyond the SM may lurk in the strong interactions

LHC can discover and study colorons,

- incorporate NLO results for the coloron K-factor and p_T distribution into dijet searches
- use associated $W + C^a$ production to probe the coloron's couplings.

Additional coloron effects?

- FCNC: yes, if couplings are flavor non-universal
- precision EW: negligible in $\Delta\rho$, $Zb\bar{b}$
- top-quark asymmetry: for some coupling values