Identifying Colorons at the LHC

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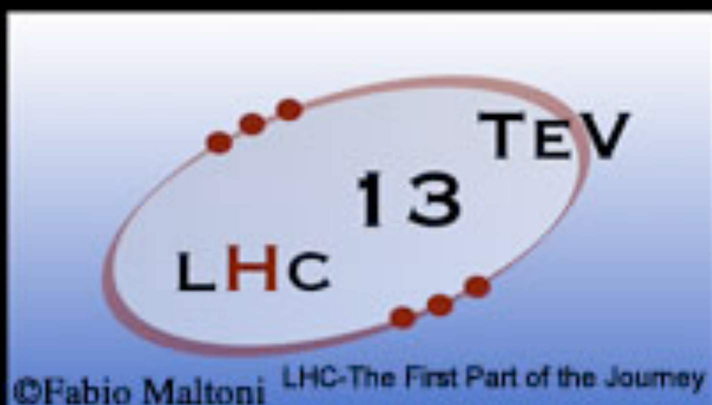
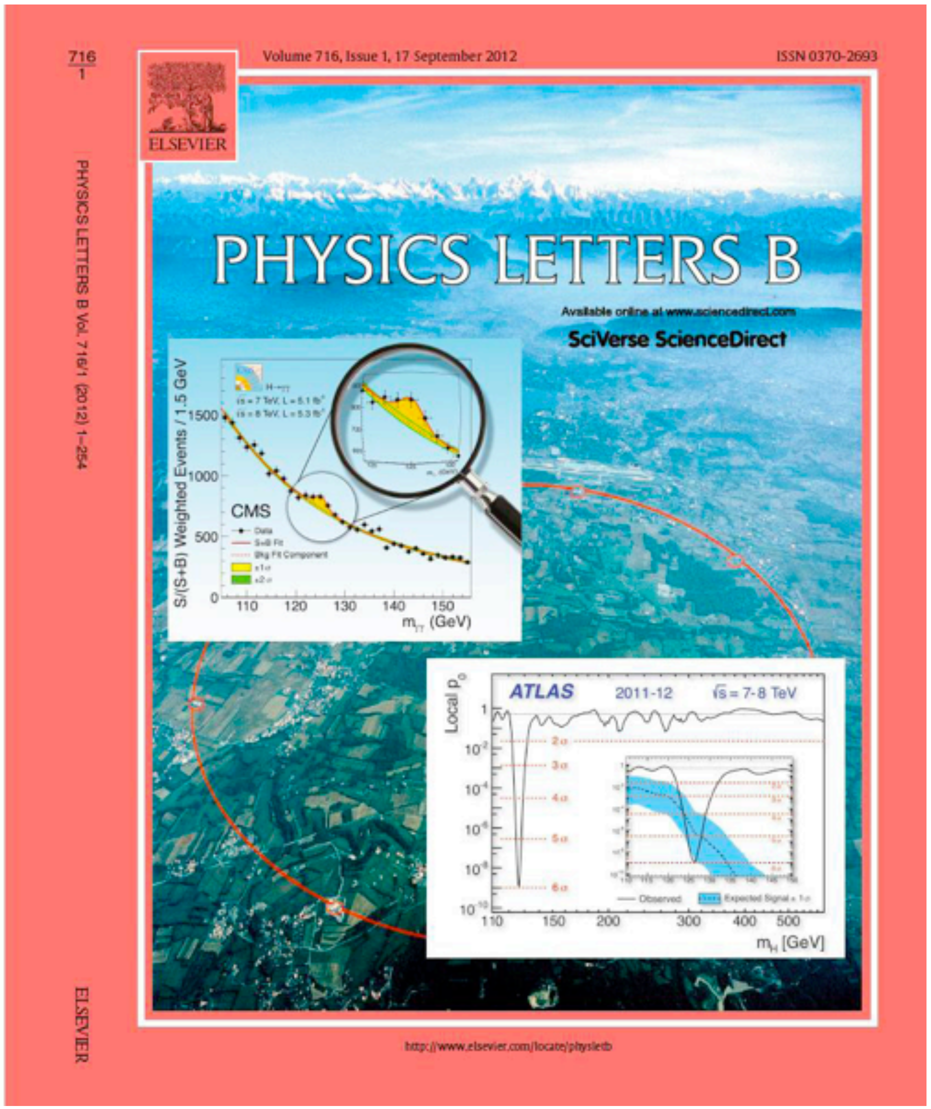
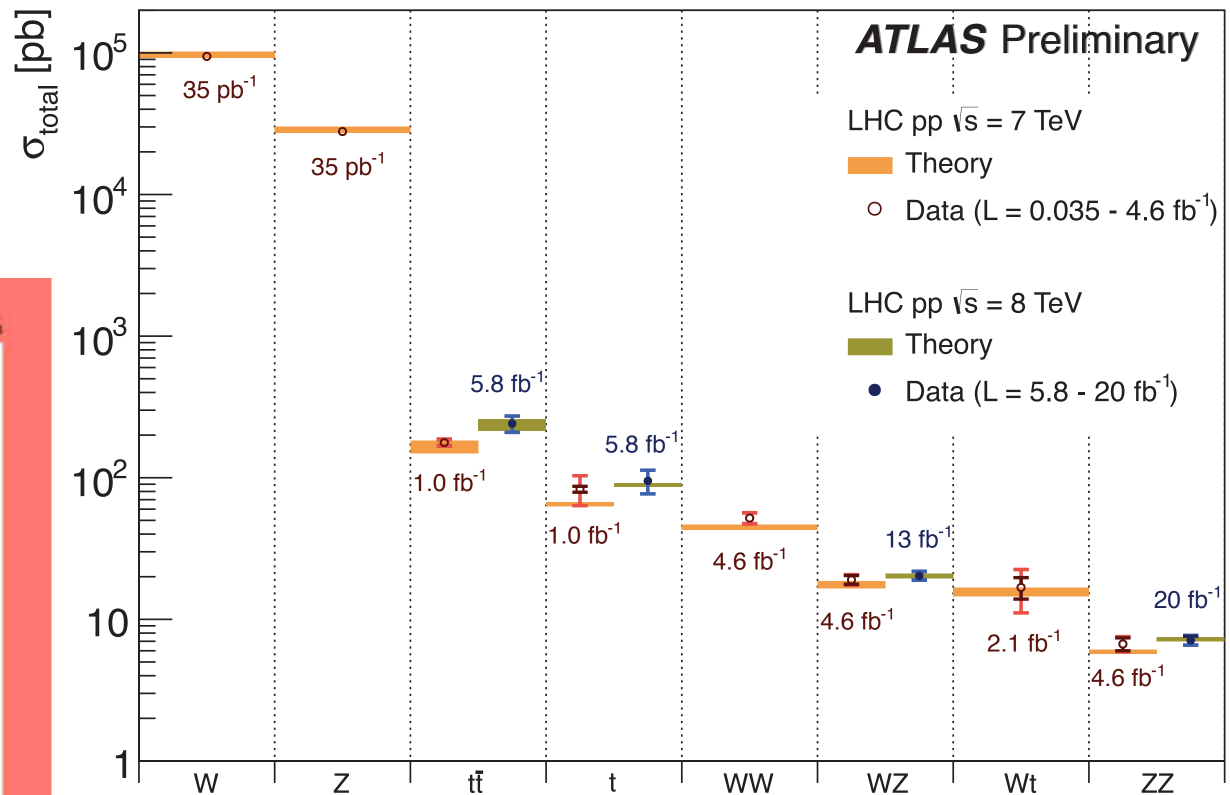


- New Strong Dynamics
- Model Components
- Indirect Effects
- LHC Searches at NLO
- Identification
- Conclusions

KITP, U.C. SANTA BARBARA JULY 10, 2013

After Years of Work Pay Off...





What Comes Next?

2015?

What May Leap Out?

New Colored States...

Gauge bosons from extended color groups:

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).

Still more possibilities:

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

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

...Which Might Connect to Top

E.g., colorons could impact A^t_{FB}

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.

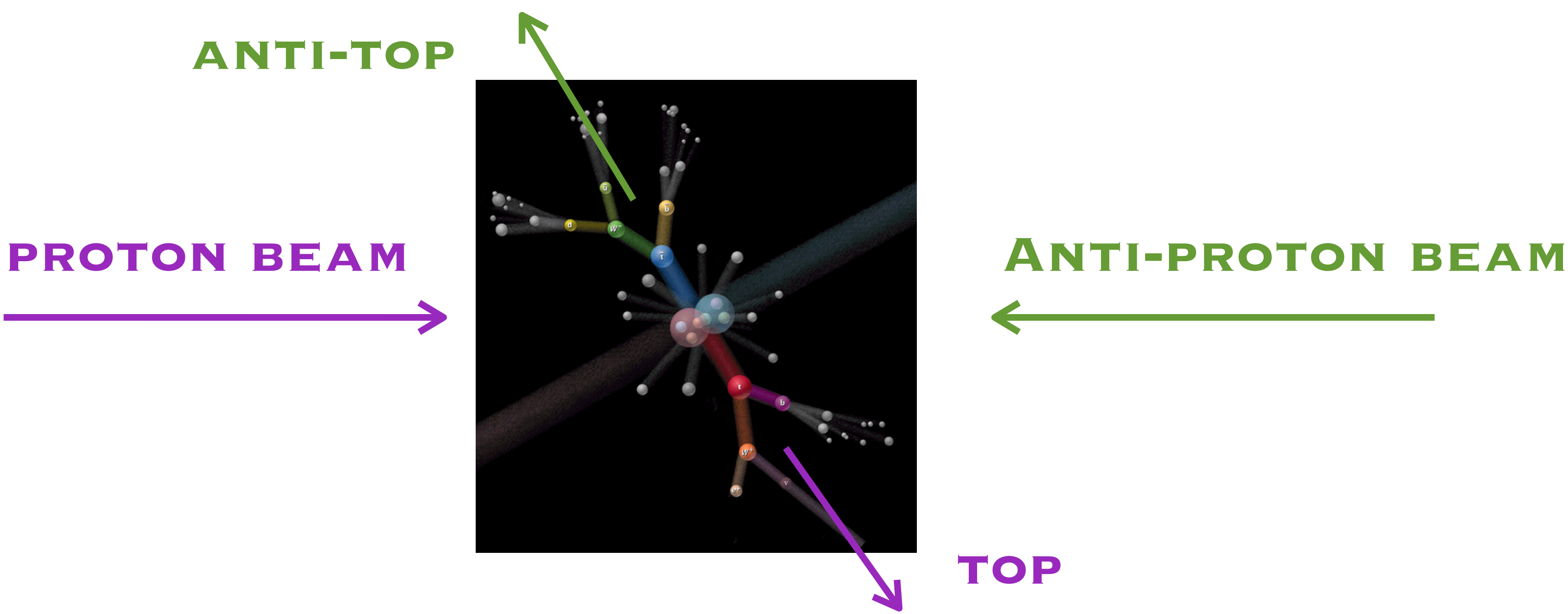
M.V. Martynov and A. D. Smirnov, arXiv:1006.4246.

Q. H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, and C. E. M. Wagner, Phys. Rev. D 81, 114004 (2010).

R.S. Chivukula, E.H. Simmons, and C.-P. Yuan, Phys. Rev. D82 (2010).

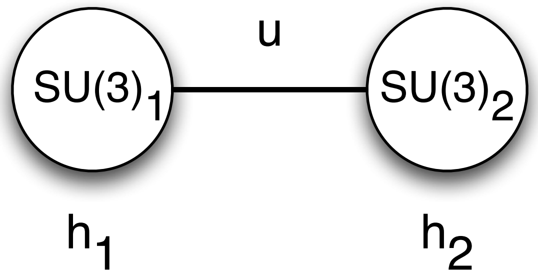
G. Rodrigo and P. Ferrario arXiv:1007.4328 [hep-ph]

... ***see also upcoming talk on Thursday by A. Kagan***



Model Basics

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

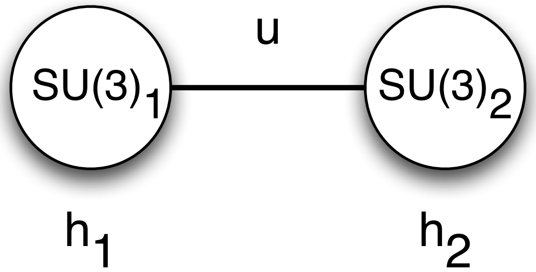
couples to: $g_S J^\mu_G \equiv g_S(J^\mu_1 + J^\mu_2)$ $\qquad M_G = 0$

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

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

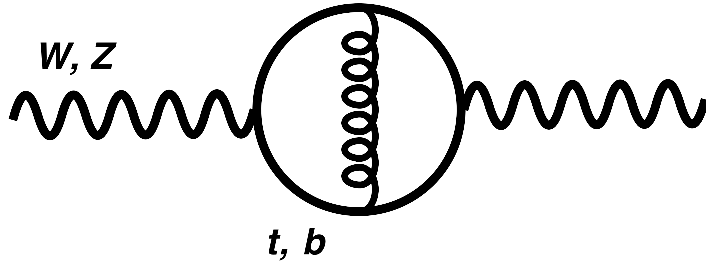
$SU(3)_1$	$SU(3)_2$	model	pheno.
	$(t,b)_L$ q_L t_R,b_R q_R	**coloron**	dijet
q_R	$(t,b)_L$ q_L t_R,b_R		
t_R,b_R	$(t,b)_L$ q_L q_R		
q_L	$(t,b)_L$ t_R,b_R q_R		
q_L t_R,b_R	$(t,b)_L$ q_R	**new axigluon**	dijet, A^t_{FB}, FCNC
q_L q_R	$(t,b)_L$ t_R,b_R	**topgluon**	dijet, tt, bb, FCNC, R_b...
t_R,b_R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

q = u,d,c,s

Indirect Effects

R.S. Chivukula, EHS, C.-P. Yuan   arXiv:1007.0260

- Coloron exchange can 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 if the coloron is heavy

- Likewise, coloron exchange across the $Zb\bar{b}$ vertex yields effects proportional to m_b^2 which are negligible

FCNC in Coloron Models

- Coloron exchange can produce FCNC if the coloron coupling to quarks are flavor non-universal
  [different flavors are charged under different SU(3) groups]

- The total rate of FCNC will depend quite <u>strongly</u> 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 an example [for another, see the talk by R.S. Chivukula]

New Axigluon Model

Pattern	$SU(3)_1$	$SU(3)_2$	model
5	**q_L t_R, b_R**	**$(t,b)_L$ q_R**	**new axigluon**

Since $g_A^t = -g_A^q = g_S \csc 2\theta$, the axigluon boosts A^t_{FB}

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

But axigluon exchange also induces an operator that causes B-meson mixing:

$$\frac{8\pi\alpha_s}{3M_C^2 \sin^2 2\theta}(V_{td}^* V_{tb})^2(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

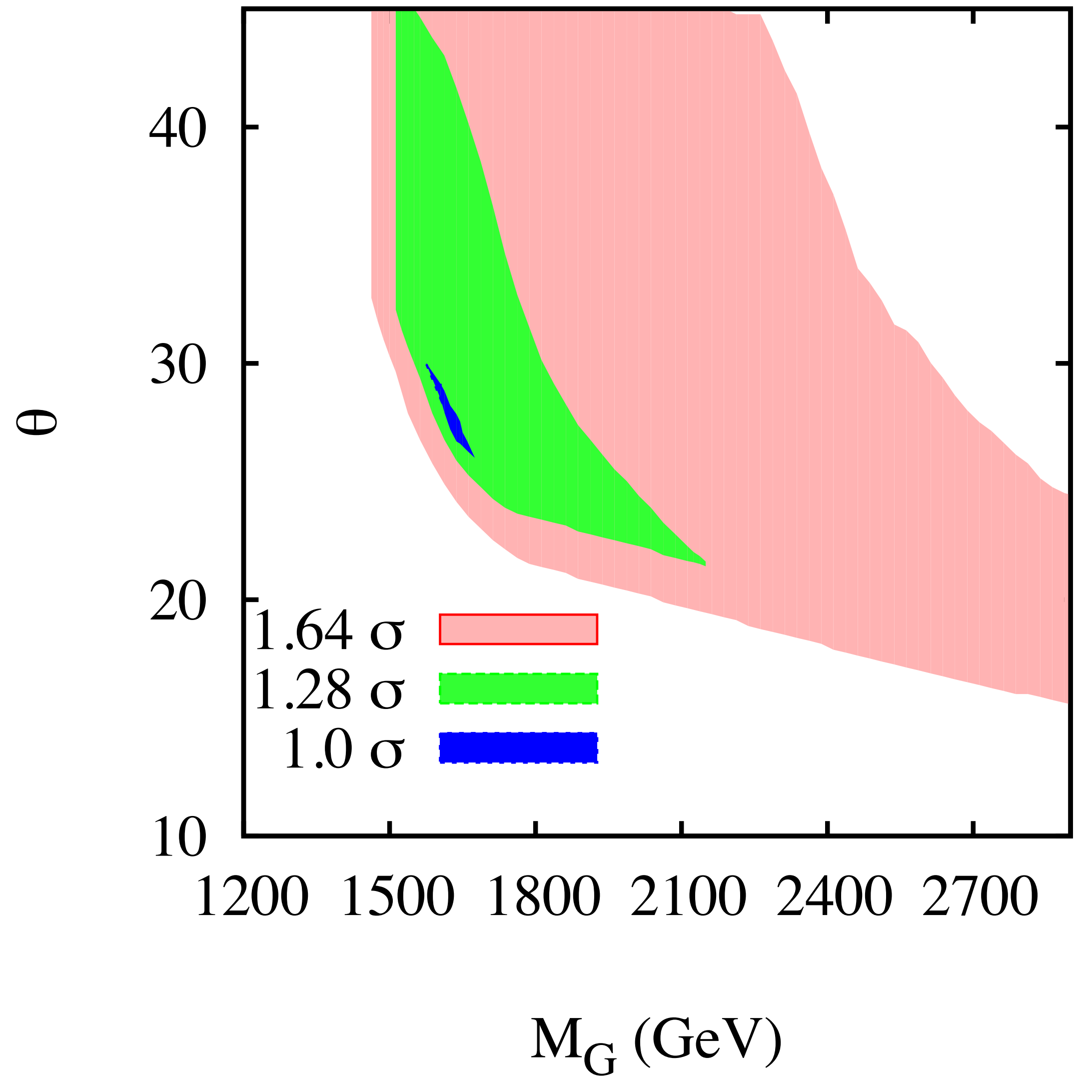
UTFit analyses set the limit: $M_C \sin 2\theta > 1800\,\mathrm{GeV}$

UTFit Collaboration arXiv:0707.0636

New Axigluon And A^t_{FB}

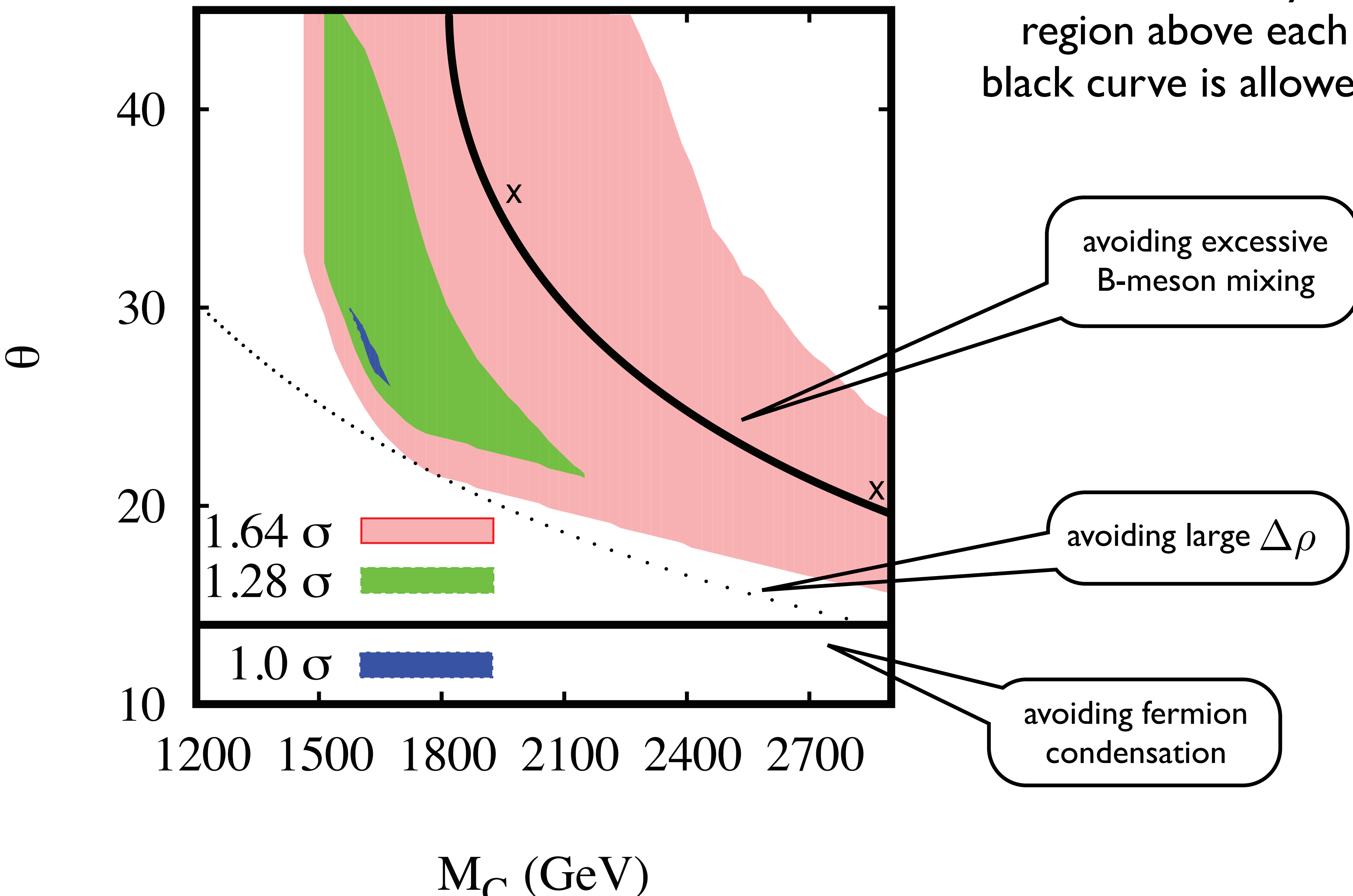
Here are the regions of model parameter space where A^t_{FB} and M_{tt} both agree with experiment to the given degree.

Theta is cut off at 10^o to keep h_1, h_2 perturbative.



Frampton, Shu, and Wang (2010)

Overlay of Precision Constraints



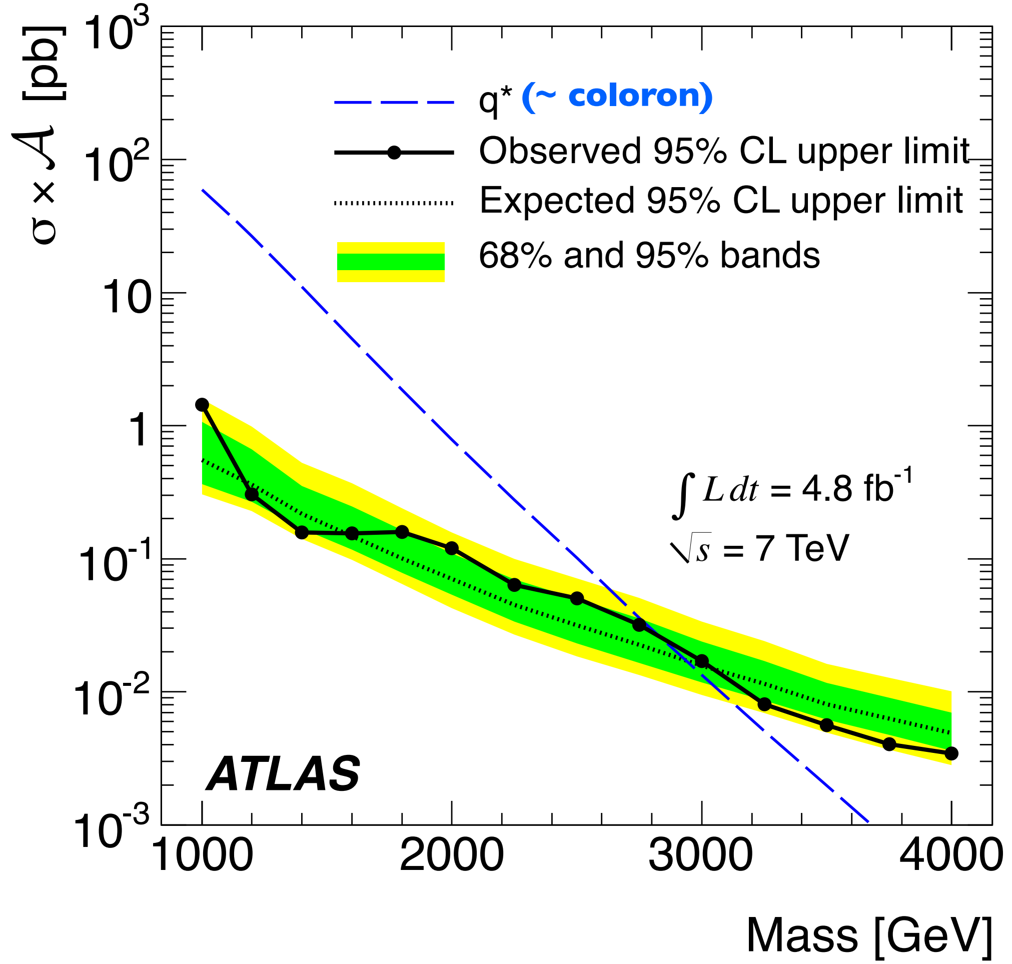
We find that only the region above each black curve is allowed.

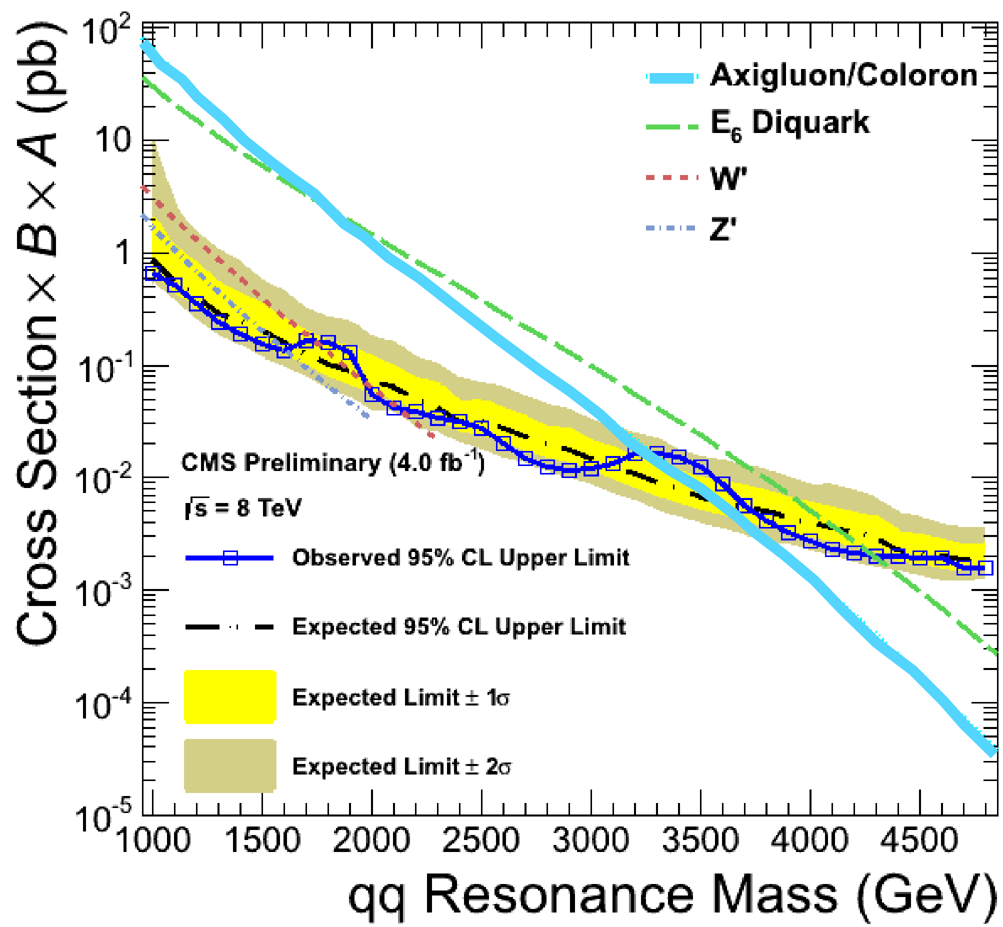
LHC Coloron Searches at NLO

R.S. Chivukula, A. Farzinnia, R. Foadi, EHS arXiv:1111.7261
R.S. Chivukula, A. Farzinnia, J. Ren, EHS arXiv:1303.1120

LHC Limits on Colorons

LHC searches for colorons in dijets constrain M_C



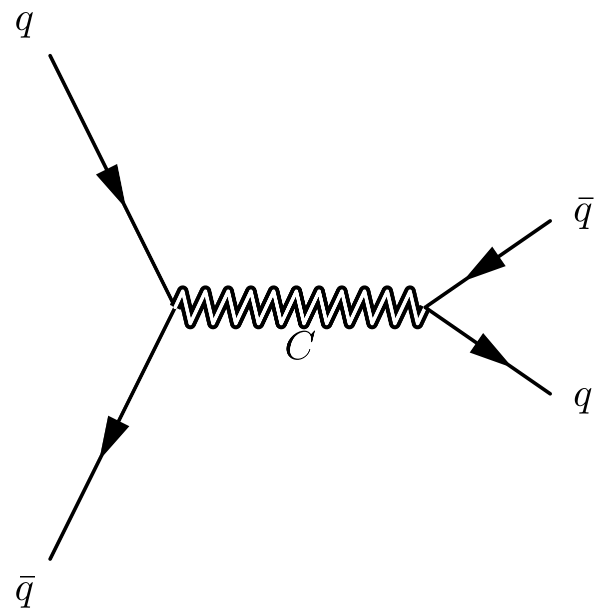


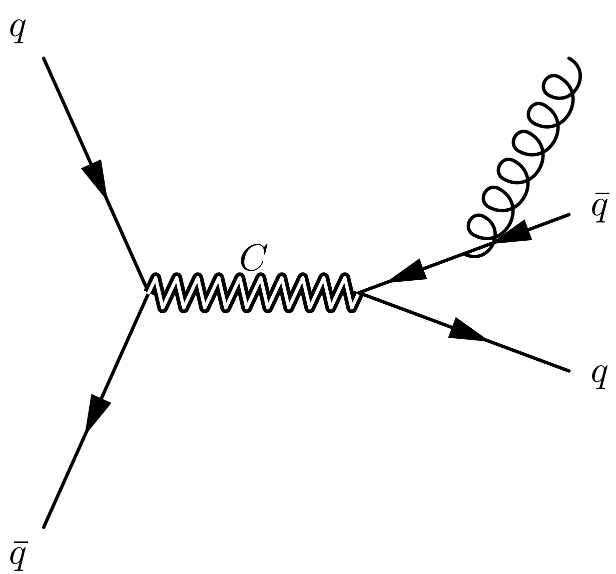
But these calculations have treated the colorons only at LO and QCD to NLO (or beyond) ... we can do better!

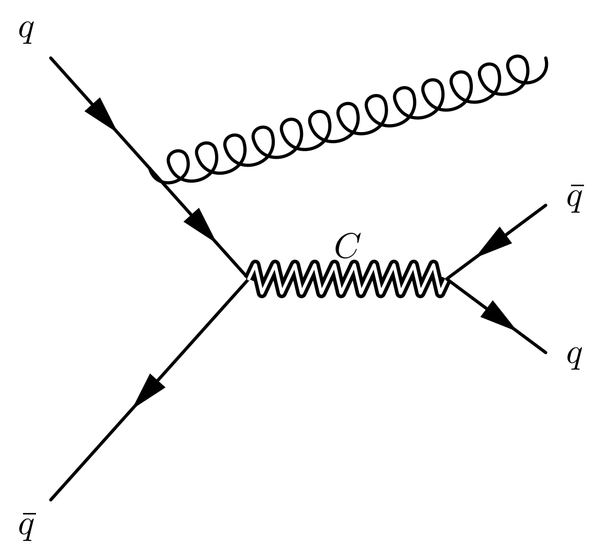
Coloron Production

LO vs NLO production

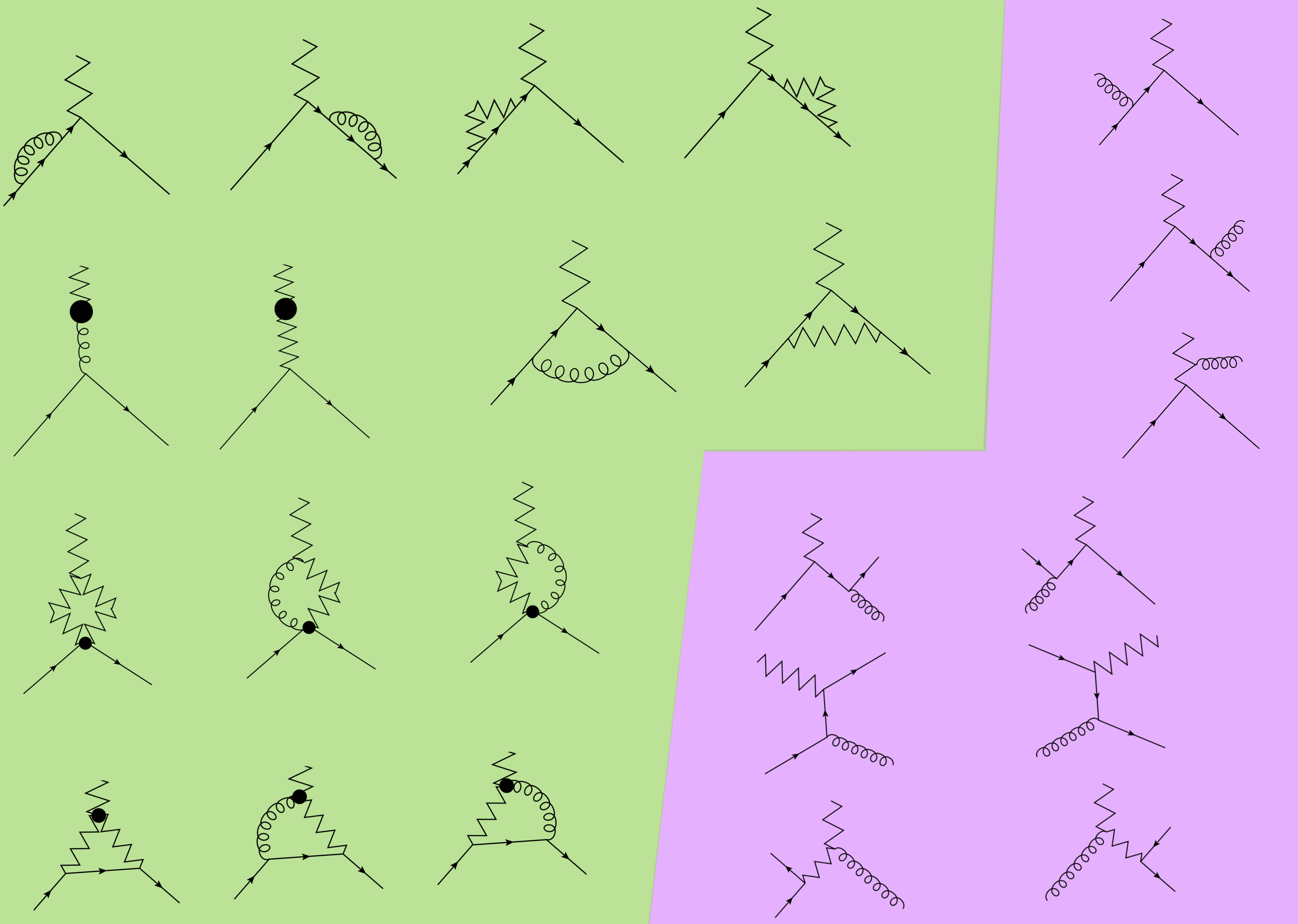
- cross-section
- scale-dependence
- p_T of coloron





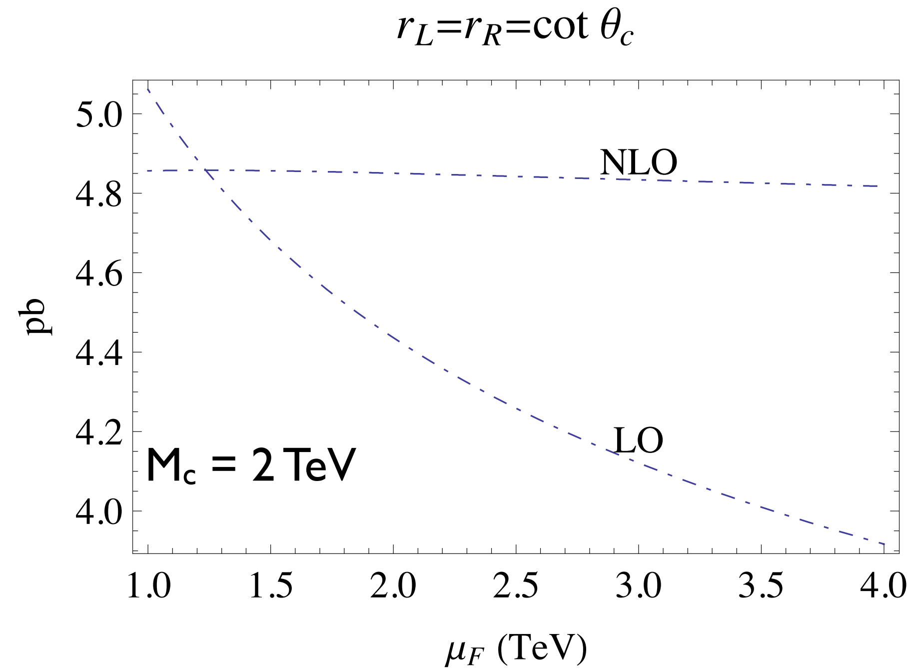


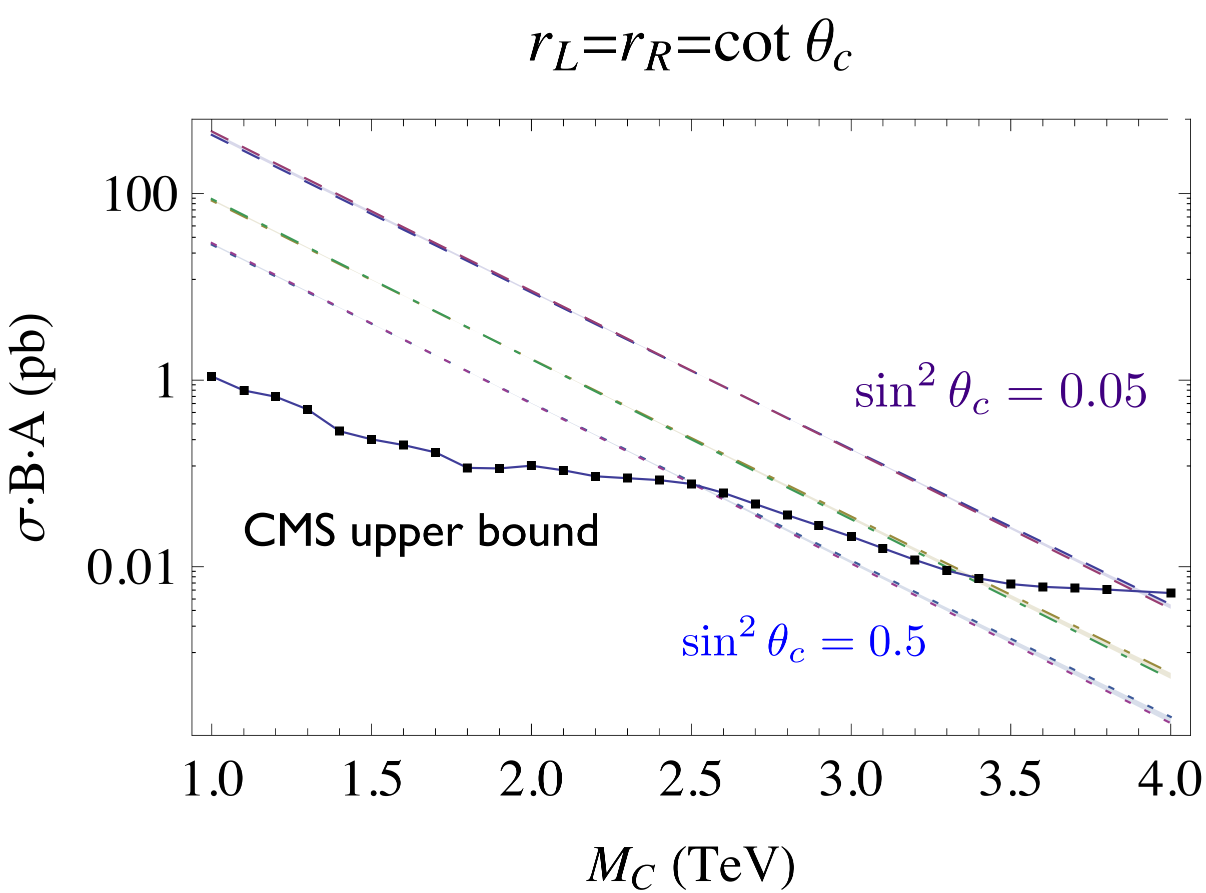
NLO Colorons: Virtual & Real Corrections



NLO Cross-Section

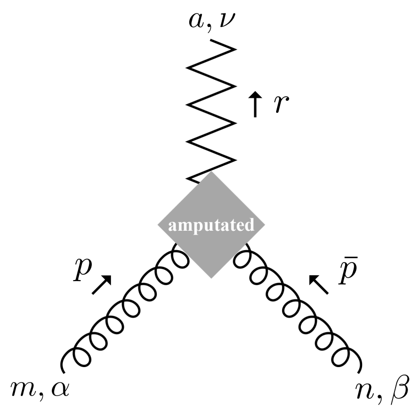
NLO coloron shows enhanced rate (below) and less scale-dependence (right) compared to LO

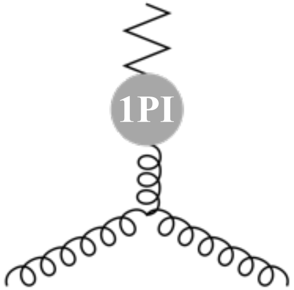


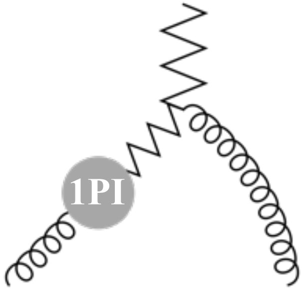


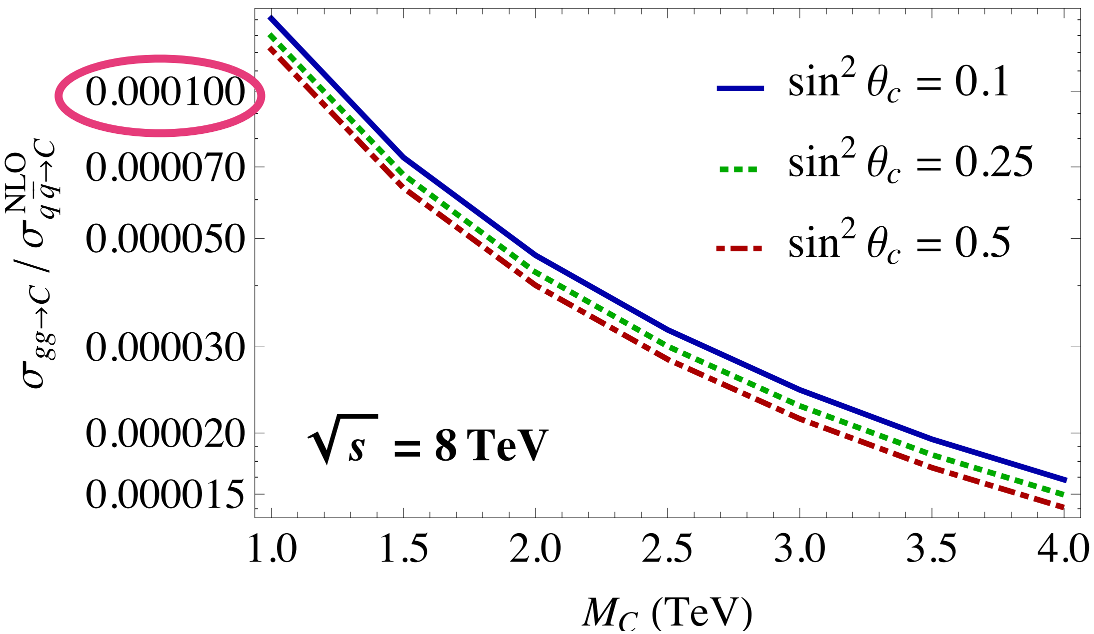
Cgg Vertex at NLO

Can we harness the incoming gluons at NLO?

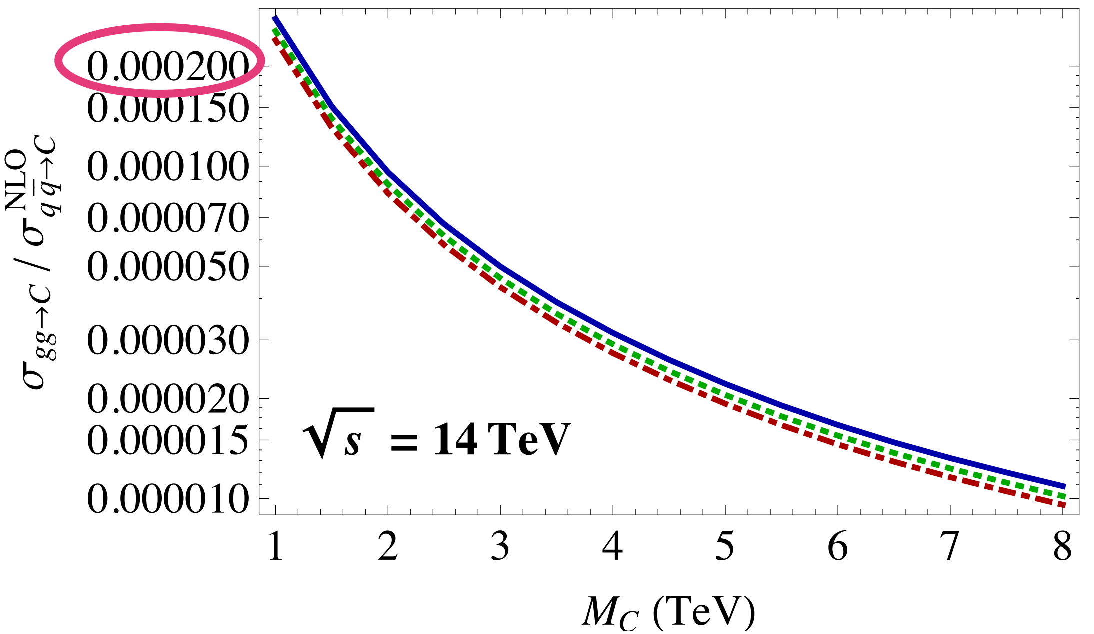






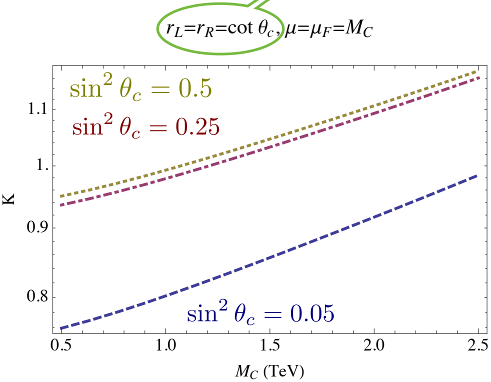


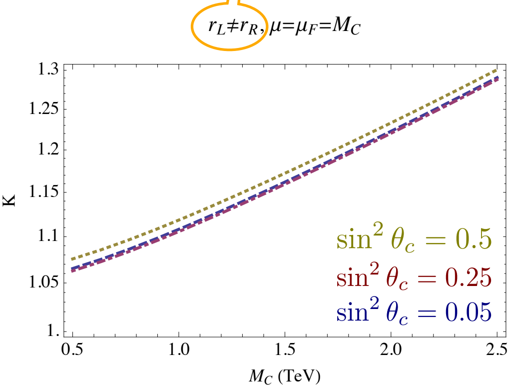
$r_L = r_R = \cot\theta_c$



K-factor for Coloron & Axi-gluon

$$K \equiv \frac{\sigma^{\rm NLO}_{q\bar{q}\to C}}{\sigma^{\rm LO}_{q\bar{q}\to C}}$$





Also: 30% of produced colorons have p_T > 200 GeV!

Suppose we discover a coloron:

A tremendous variety of chiral and flavor structures for the coloron coupling to quarks is open...

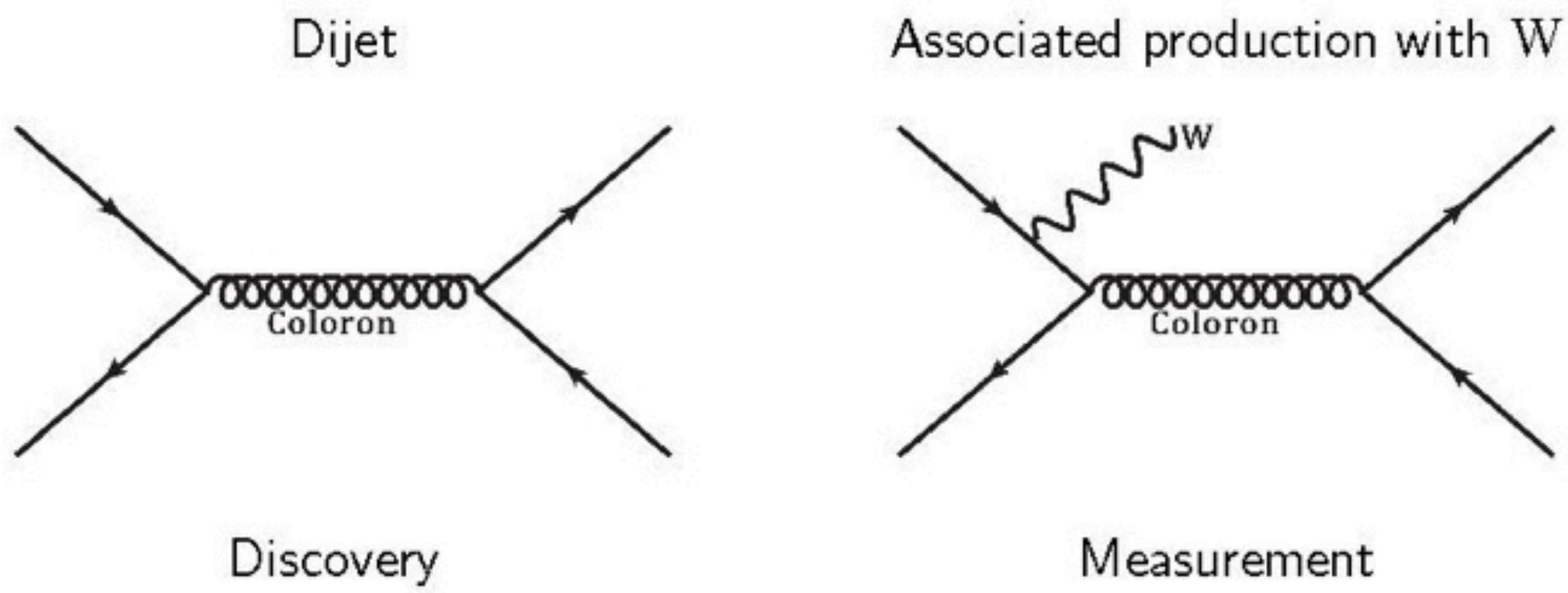
$$\underbrace{g_s \bar{q} C^\mu \gamma_\mu (g_V^q + g_A^q \gamma_5)\, q}_{q=u,d,c,s} \quad \text{and} \quad \underbrace{g_s \bar{T} C^\mu \gamma_\mu \left(g_V^T + g_A^T \gamma_5\right) T}_{T=t,b}$$

How to establish which coloron has been found?

Identification

A. Atre, R.S. Chivukula, P. Ittisamai, EHS, J.-H. Yu arXiv:1206.1661
A. Atre, R.S. Chivukula, P. Ittisamai, EHS arXiv:1306.4715

1. Study Associated Production:



Goal

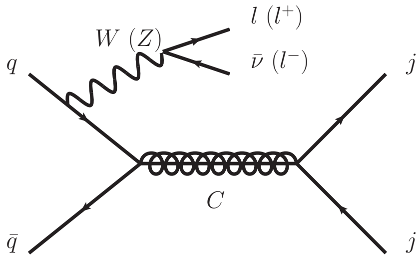
" Using associated production* with W and dijet resonance to determine colorons/axigluons couplings."

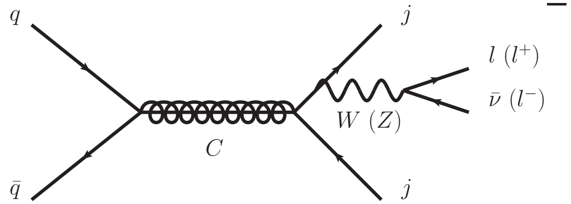
*Idea introduced by Cvetic and Langacker (1992) for measuring Z' couplings

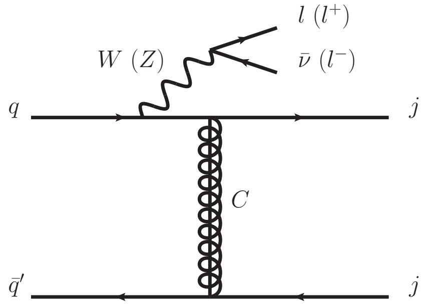
New Mode: W+C^A probes Chiral Couplings

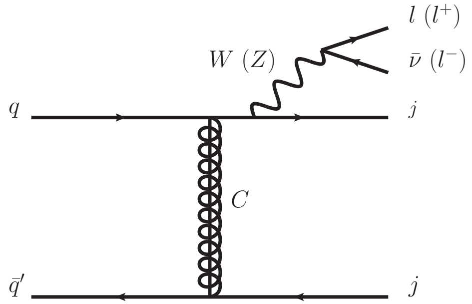
Different production modes probe several combinations of the coloron's couplings to RH and LH fermions:

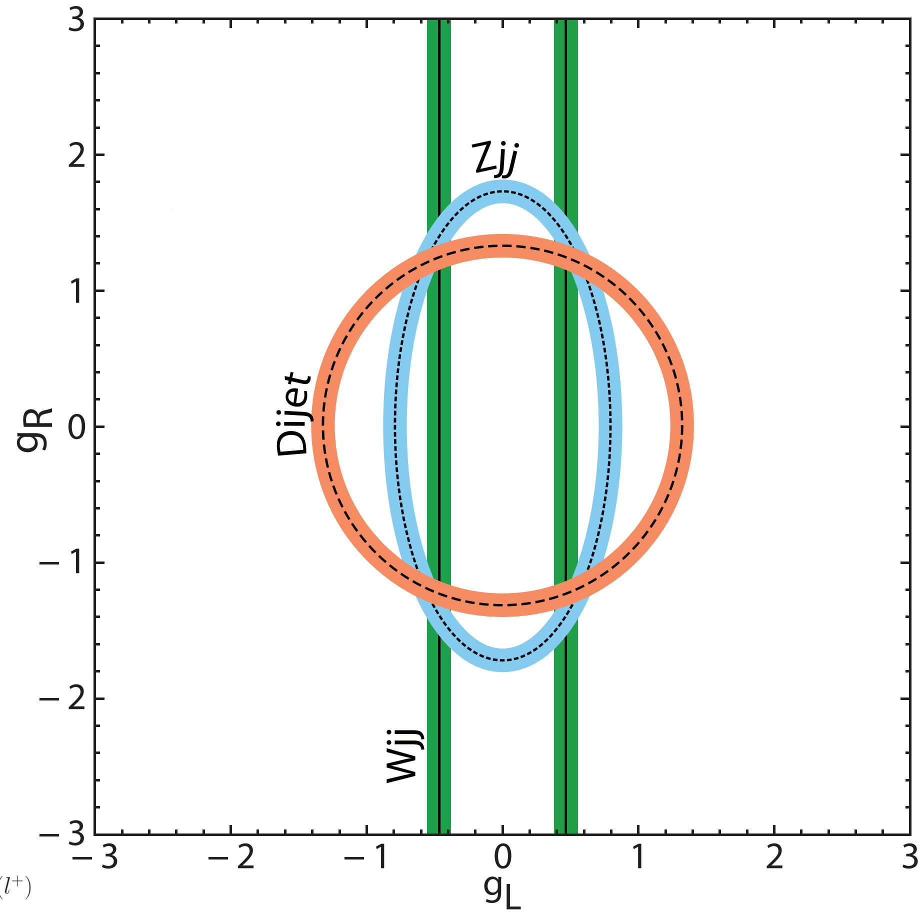
$$pp \to C^a + W[Z] \to jj\ell\nu[\ell\ell]$$











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

Simulation Details

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:

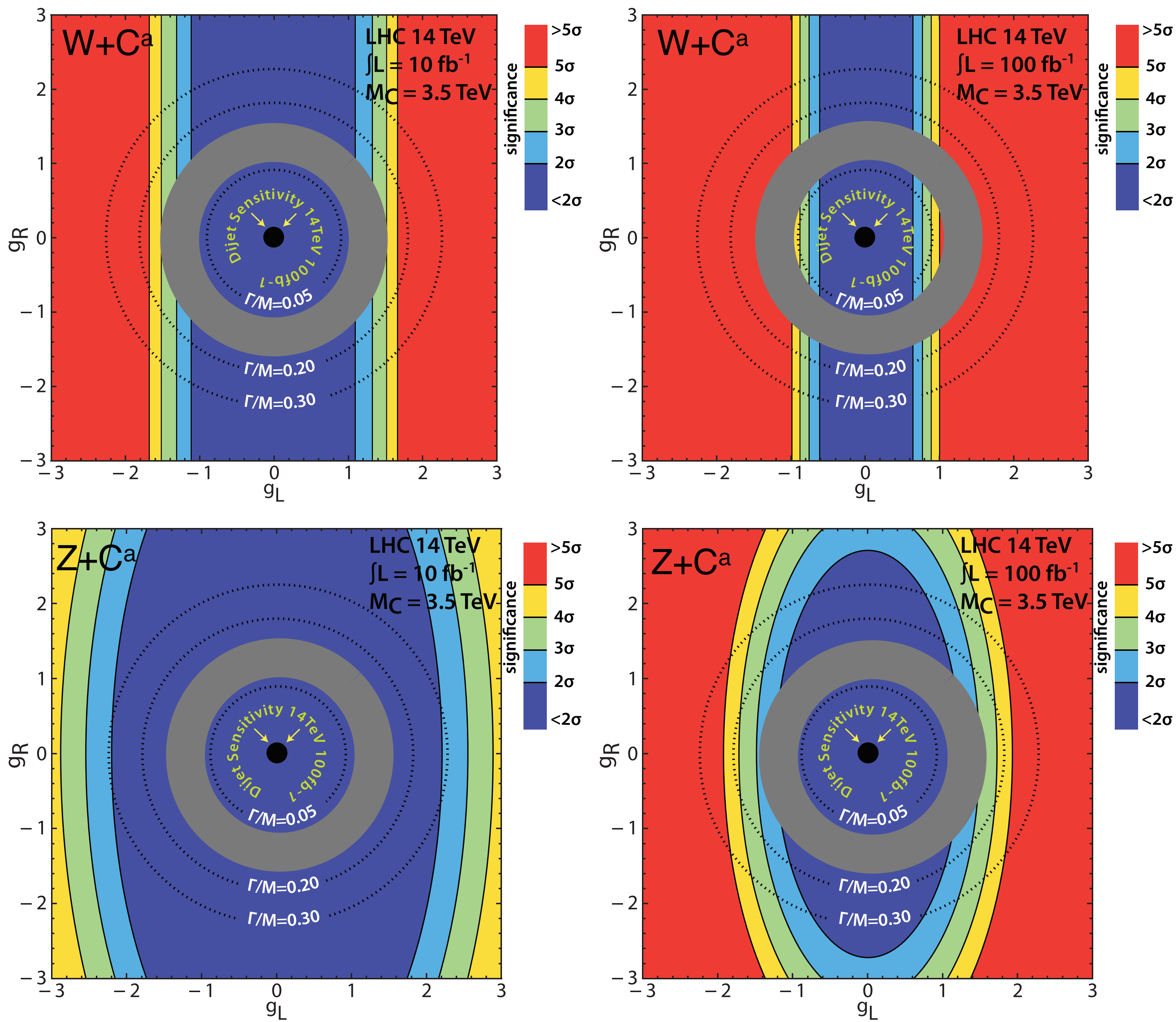
- p_T of leading jets
- total transverse jet energy ($H_T \simeq \sum p_T$)
- Invariant masss m_{jj} or m_{jjW}

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

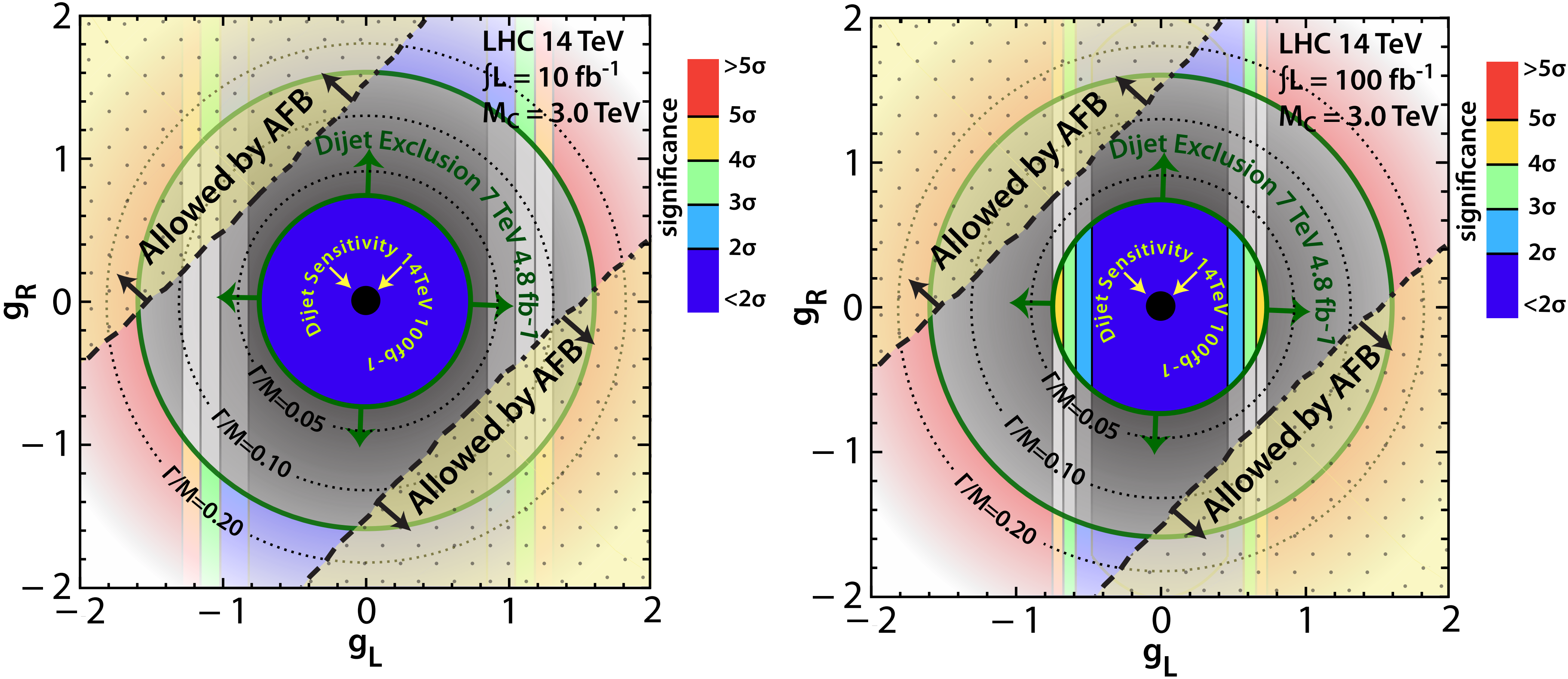
W+C^a: Heat Map of Significance

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 A^T FB range



2. Distinguish Dijet Resonances

Suppose a new dijet resonance is found. How to tell whether it is a coloron or a leptophobic Z'?

For a given measured mass M and cross-section σ_{jj}

$$\sigma(pp \to C \to jj) = \frac{8}{9}\frac{\Gamma_C}{M_C^3}\Sigma(pp \to C)Br(C \to jj)$$

must be equal

PDFs, phase space, kinematics

$$\sigma(pp \to Z' \to jj) = \frac{1}{9}\frac{\Gamma_{Z'}}{M_{Z'}^3}\Sigma(pp \to Z')Br(Z' \to jj)$$

Generalize Flavor Structure?

For more generality, allow $g^t \equiv \xi\, g^q$

As a result: $\Gamma \to \Gamma * \left(\frac{4+2\xi^2}{6}\right)$ $\quad Br(V \to jj) : \frac{5}{6} \to \left(\frac{4+\xi^2}{4+2\xi^2}\right)$

which changes the detail but not the substance of

$$\sigma(pp \to C \to jj) = \frac{8}{9}\frac{\Gamma_C}{M_C^3}\Sigma(pp \to C)Br(C \to jj)$$

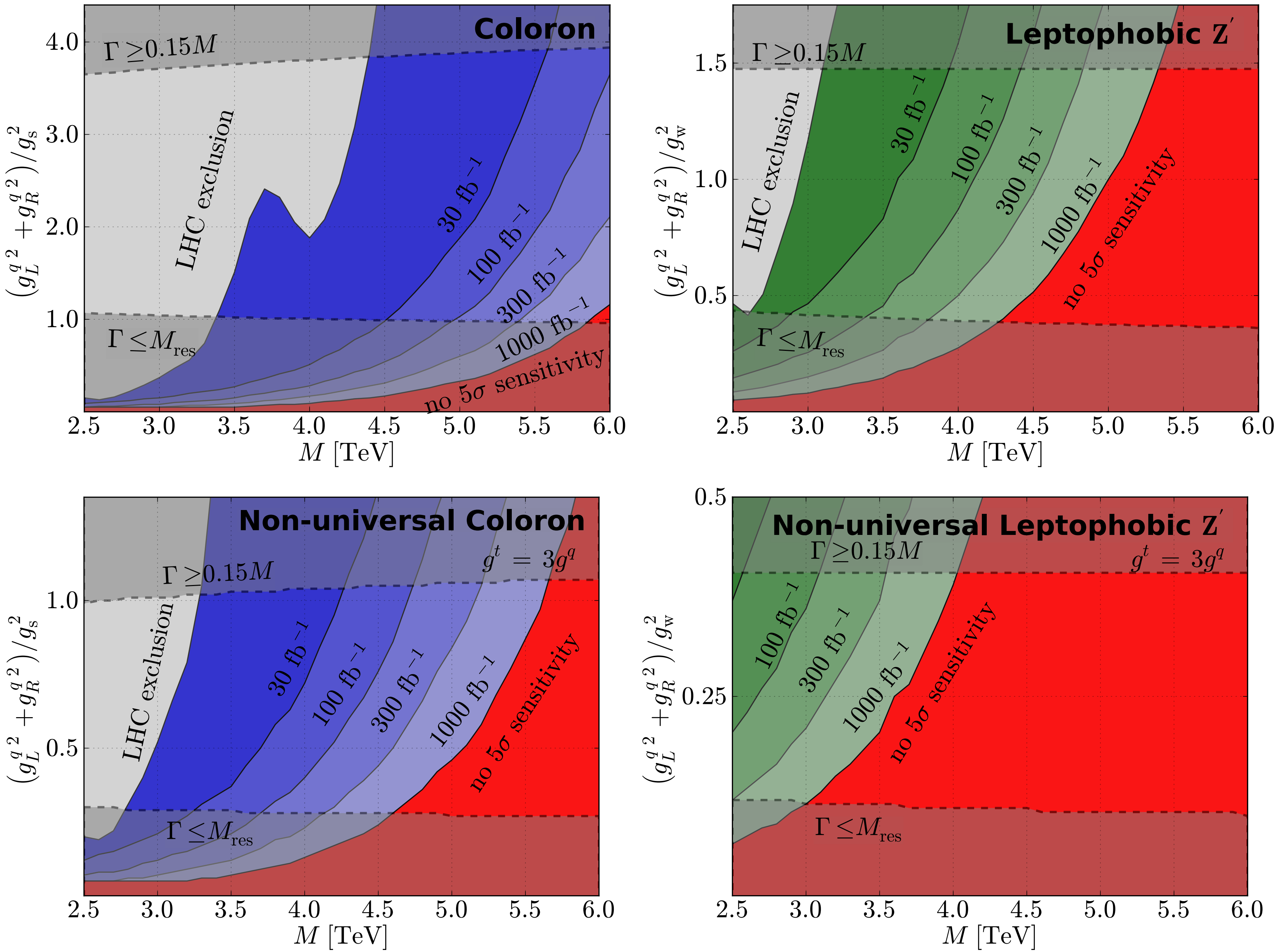
must be equal

PDFs, phase space, kinematics

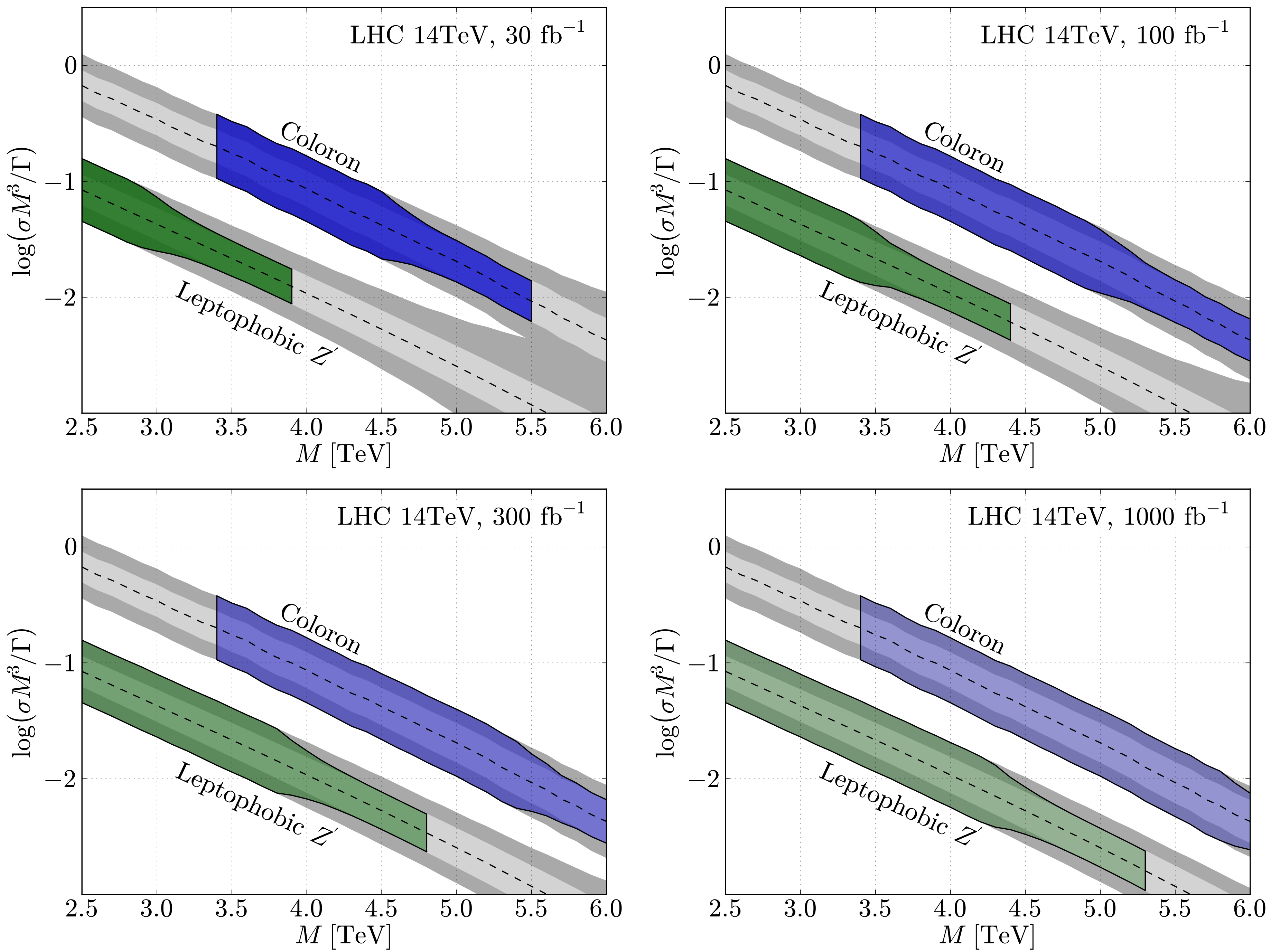
$$\sigma(pp \to Z' \to jj) = \frac{1}{9}\frac{\Gamma_{Z'}}{M_{Z'}^3}\Sigma(pp \to Z')Br(Z' \to jj)$$

Define a color discriminant variable: $D_{\rm col} \equiv \frac{M^3}{\Gamma}\sigma_{jj}$

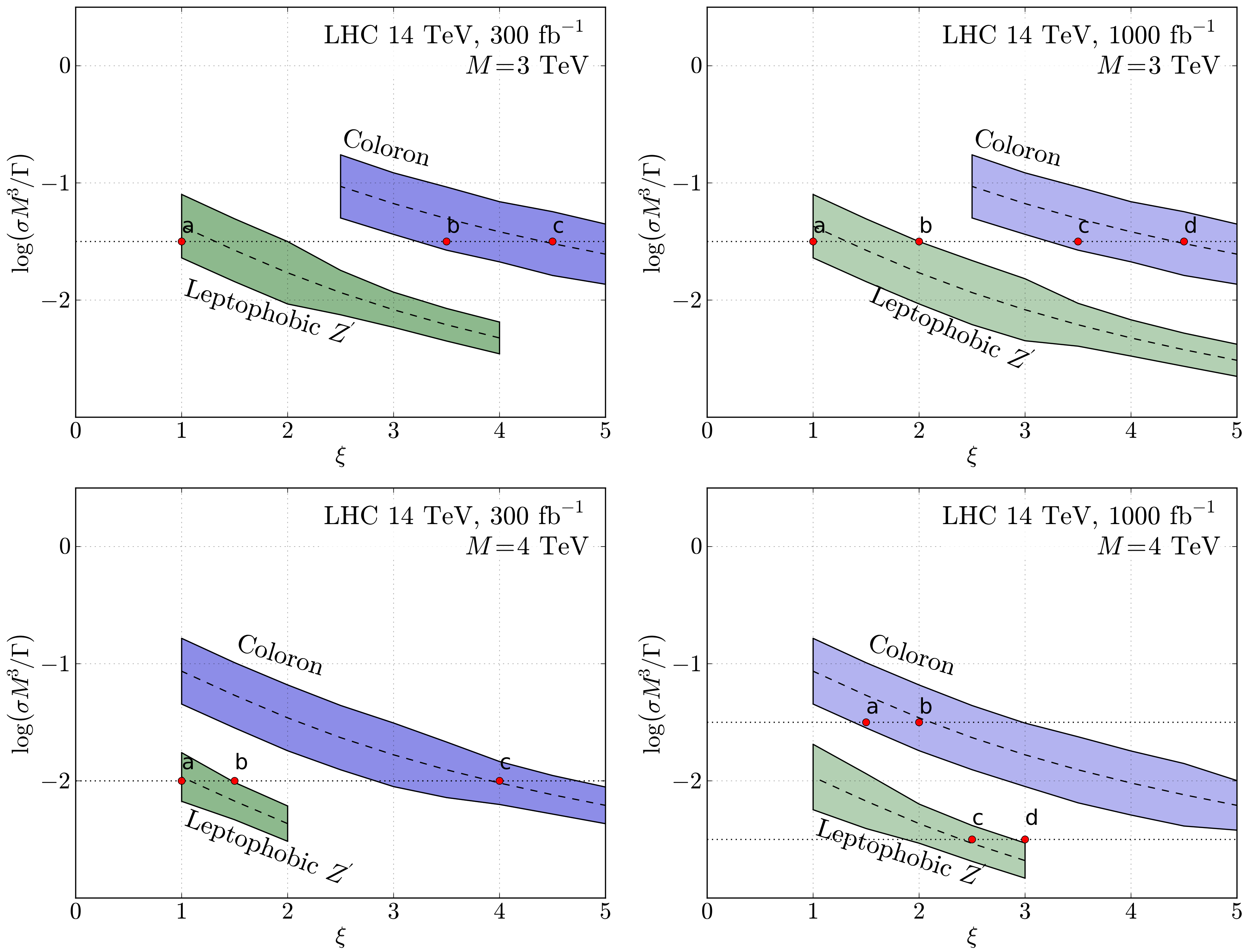
Establish Detection Range



Color Discriminant Variable in Action



Incorporating Flavor Non-Universality



Conclusions

Conclusions

BSM Physics may yet lurk in the strong interactions!

LHC can discover & identify colorons,

- incorporate NLO results for the coloron K-factor and p_T distribution into dijet searches
- use associated $W + C^a$ production to probe coloron's couplings
- use width to distinguish color structure of a new dijet resonance

Additional coloron effects?

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

Conclusions

Related Talks in this Conference:

- *A Flavorful Coloron Model*
  (Sekhar Chivukula)

- *Signatures of Pair-produced Massive Colored Bosons*
  (Yang Bai)

- *Top-quark F-B asymmetry and new strong interactions*
  (Alexander Kagan)