NON-STANDARD STRONG INTERACTIONS: THEORY AND PRACTICE

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1. Introduction
2. New Physics & Contact Interactions
3. Setting & Deciphering Limits
4. Conclusions

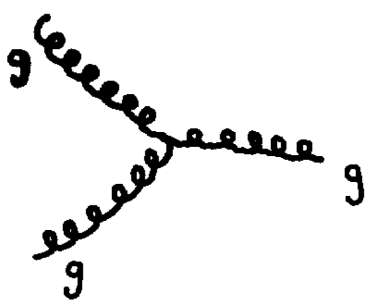
1. Introduction

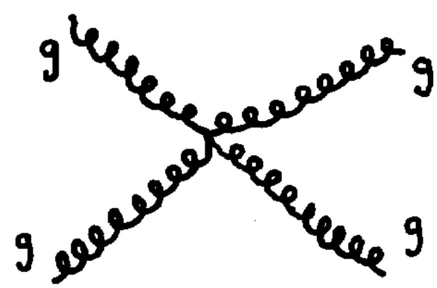
Standard 'color' or 'QCD' model of strong force:

SU(3) gauge force transmitted by gauge bosons (gluons) that are color-charged

gluons form an adjoint representation of SU(3)

$8 =$  $\qquad 8 \times 8 = 1 + 8 + 8 + 10 + \overline{10} + 27$



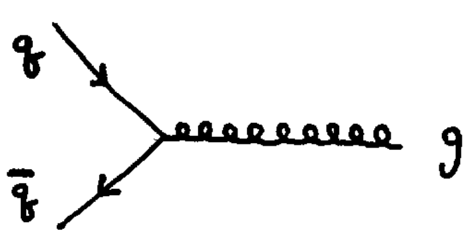


quarks (fermions) belong to fundamental (vector) representation of SU(3)

$3 =$ 

$\bar{3} =$ 

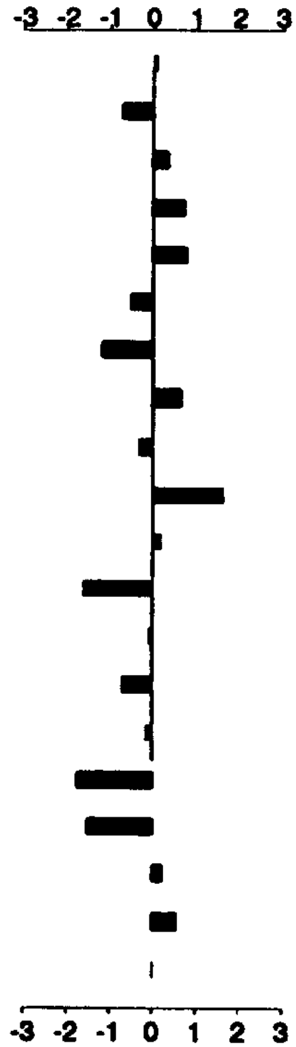
$3 \times \bar{3} = 8 + 1$



SLD / LEP data tightly constrains electroweak physics

Moriond 1998

m_Z [GeV]	91.1867 ± 0.0020	.05
Γ_Z [GeV]	2.4948 ± 0.0025	-.73
σ^0_{hadr} [nb]	41.486 ± 0.053	.34
R_e	20.775 ± 0.027	.72
$A^{0,e}_{fb}$	0.0171 ± 0.0010	.78
A_e	0.1438 ± 0.0071	-.52
A_τ	0.1400 ± 0.0063	-1.19
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.64
m_W [GeV]	80.350 ± 0.090	-.34
R_b	0.21732 ± 0.00087	1.64
R_c	0.1731 ± 0.0044	.19
$A^{0,b}_{fb}$	0.0998 ± 0.0022	-1.64
$A^{0,c}_{fb}$	0.0735 ± 0.0045	-.09
A_b	0.899 ± 0.049	-.73
A_c	0.660 ± 0.045	-.18
$\sin^2\theta^{lept}_{eff}$	0.23084 ± 0.00035	-1.78
$\sin^2\theta_W$	0.2198 ± 0.0021	-1.51
m_W [GeV]	80.400 ± 0.090	.22
m_t [GeV]	174.1 ± 5.4	.56
$1/\alpha$	128.894 ± 0.090	.01



Yet the presence of significant non-standard strong interactions is still possible.

Pulls + data from LEP Electroweak Working Group home page

Possible new strong physics includes:

- new colored fermions
  - 4th generation of conventional quarks
  - exotic quarks (mirror, weak singlet...)
  - quixes (color-sextet quarks)
- new colored scalars
- heavy colored gauge bosons
  - flavor-universal coloron
  - axigluon
  - topgluon
- compositeness of quarks or gluons
- unusual quark chromomagnetic moment
- CP-violating gluon interactions

...

Example: Quixes

Frampton + Glashow

ordinary quarks are color triplets ($\square$)

more exotic colored particles could transform

as color sextets ($\square\square$) or octets ($\begin{smallmatrix}\square&\square\\ \square&\end{smallmatrix}$)

QCD beta function

$$\beta(\alpha_s) \approx -\frac{\alpha_s}{2\pi}\left(11 - \frac{2}{3}N_3 - \frac{10}{3}N_6 - 4N_8 - 10N_{10}\ldots\right)$$

admits possibility of 2 quixes or 1 queight

Electroweak symmetry breaking ?

Marciano

suppose there are 2 flavors of quix

(LH weak doublet, RH weak singlets)

if color interactions break quix chiral

symmetries at high scale $\langle\bar{Q}Q\rangle \neq 0$,

breaks electroweak symmetry too

Chivukula,
Cohen, EHS

Example: Colorons

Modify the QCD strong interactions:

- gauge group: $SU(3)_1 \times SU(3)_2$
- gauge couplings $\xi_1 \ll \xi_2$
- quarks transform as (1,3)
- new scalar boson Φ transforming as $(3, \bar{3})$

When $\langle\Phi\rangle \neq 0$, SSB occurs:

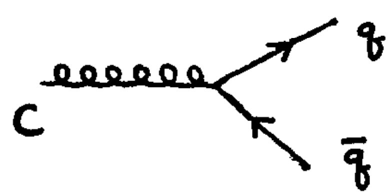
$$SU(3)_1 \times SU(3)_2 \;\Big\downarrow\; f \equiv \langle\Phi\rangle \;\; SU(3)_{QCD}$$

gauge bosons mix with angle $\cot\theta = \frac{\xi_2}{\xi_1}$ into

- massless gluons with coupling g_3
- colorons with mass $M_C = \left(\frac{g_3}{\sin\theta\cos\theta}\right) f$

  and vectorial coupling to all quarks

$-ig_3 \cot\theta T^a$



Axigluon and topgluon models are similar:

axigluon: Pati + Salam

- **separate SU(3) groups for LH, RH quarks**
- **massive bosons couple axially to all quarks**

topgluon: Hill

- **separate SU(3) groups for 3rd family, and for light family quarks**
- **massive bosons couple more to t and b**

2. New Physics & Contact Interactions

Suppose new strong interaction physics exists. How can one detect it ?

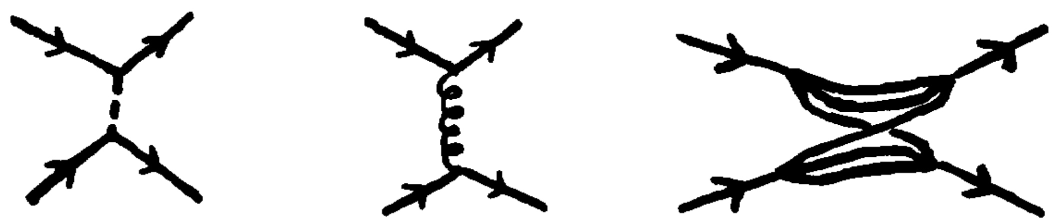
Sufficiently light new particles can be produced and detected directly:

- 4th family quarks through weak decays
- quixes in multi-jet final states
- colorons or axigluons as dijet resonances
- topgluons as $\bar{t}t$ or $\bar{b}b$ resonances

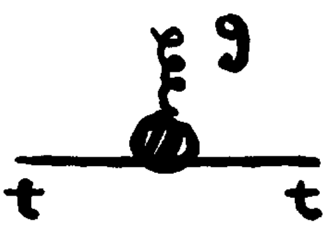
...

New physics at higher scales (Λ) generically causes additional (indirect) interactions among quarks and gluons.

- extra bosons, quark compositeness



- anomalous top chromomagnetic moment



- extra fermions, gluon compositeness

At scattering energies $E << \Lambda$, these interactions behave like contact interactions among quarks and gluons suppressed by powers of Λ:

Physically, Λ corresponds to the mass of the new particle being exchanged or to the compositeness scale or ...

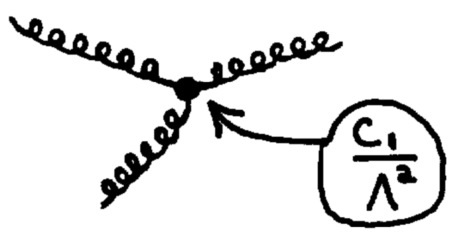
Contact interactions alter rates and kinematic distributions for hadronic scattering processes in predictable ways. Those suppressed by the fewest powers of Λ have the largest effects.

Efficient, model-independent way to study new strong physics is to search for all leading contact interactions.

EHS

For gluons:

$$\frac{1}{\Lambda^2} C_1 \; f_{abc} G^{\mu}_{a\nu} G^{\nu}_{b\rho} G^{\rho}_{c\mu}$$ [redacted]

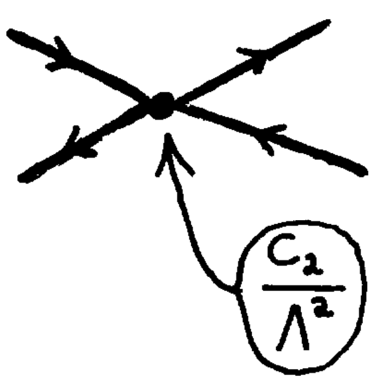


$$\frac{1}{\Lambda^2} C_2 \; D^{\mu} G_{a\,\mu\rho} D_{\nu} G^{\nu\rho}_{a}$$ [redacted]

equations of motion $\frac{\delta \mathcal{L}}{\delta A^{\mu}} = 0$

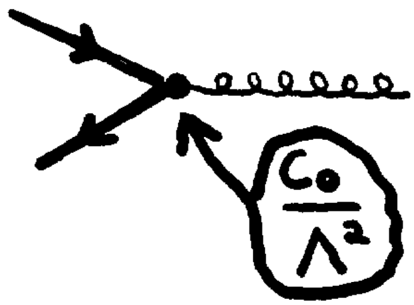
imply $D_{\mu} G^{\mu\nu}_{a} = \bar{\psi} \gamma^{\nu} T_a \psi$

this affects quark-quark scattering



For gluon-quark vertices:

$$\frac{m_q}{\Lambda^2} C_0 \; \bar{q}\sigma^{\mu\nu}T^a q G^a_{\mu\nu}$$ [redacted]



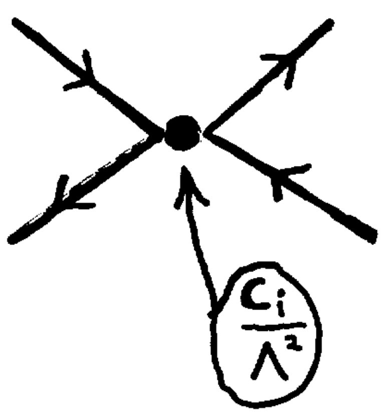
For quarks:

$$\frac{1}{\Lambda^2} C_2 \; (\bar{q}\gamma_\mu T^a q)^2$$

which is equivalent to $(DG)^2$ above

$$\frac{1}{\Lambda^2} C_3 \; (\bar{q}\gamma_\mu\gamma^5 T^a q)^2$$

$$\left.\begin{array}{l} \frac{1}{\Lambda^2} C_4 \; (\bar{q}\gamma_\mu q)^2 \\ \frac{1}{\Lambda^2} C_5 \; (\bar{q}\gamma_\mu\gamma^5 q)^2 \end{array}\right\} \rightarrow \left(\bar{\psi}_L \gamma^\mu \psi_L\right)^2$$



3. Setting & Deciphering Limits

Two case studies:

- color-octet quark contact interaction
- gluon contact interaction

FIRST CASE: $\frac{1}{\Lambda^2} C_2 \, (\bar{q}\gamma_\mu T^a q)^2$

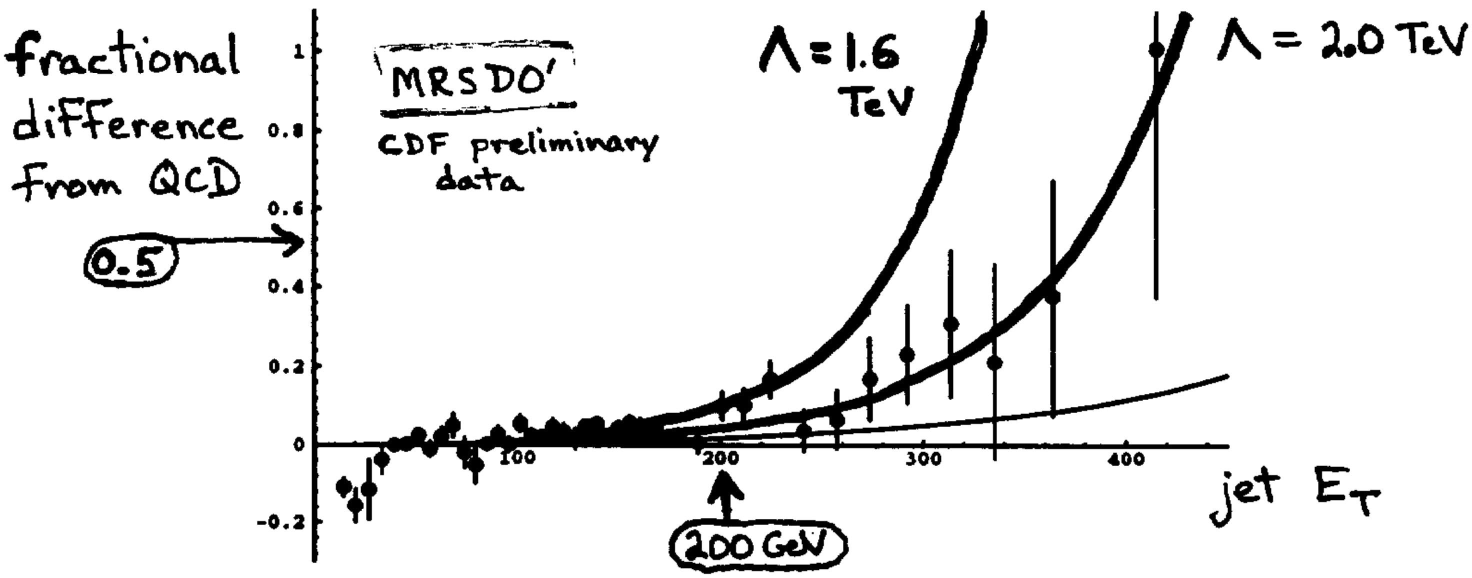
Chivukula, Cohen + EHS

which affects quark-quark scattering.

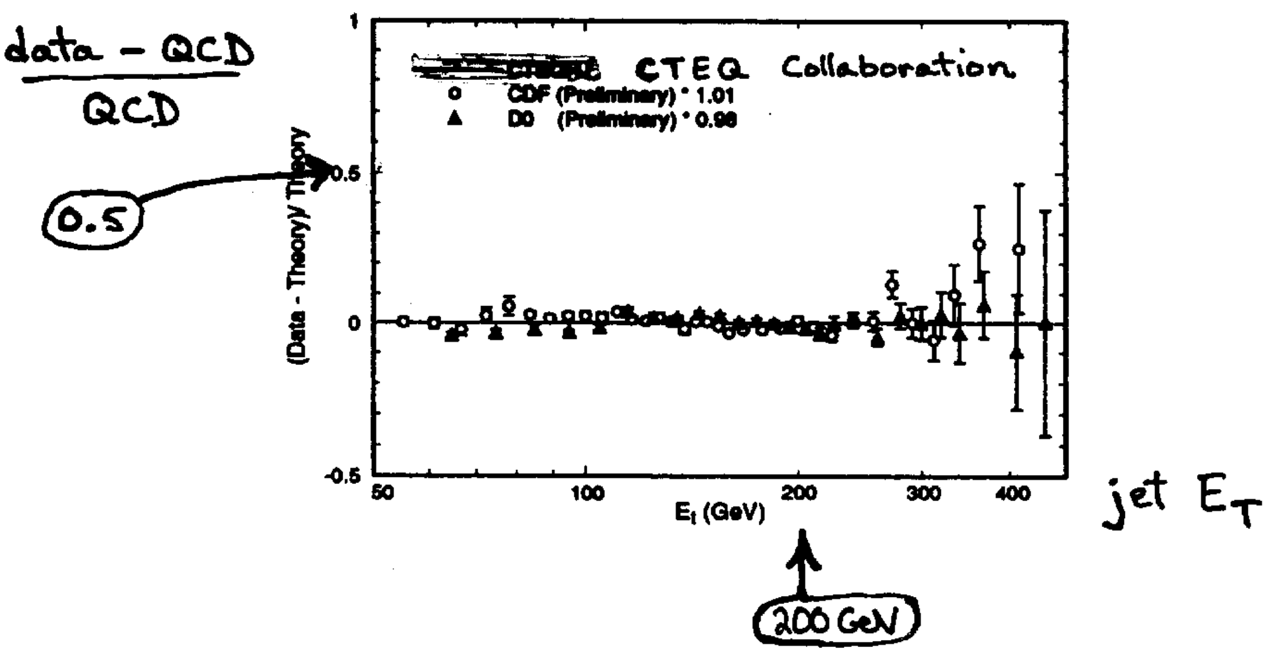
Consider $p\bar{p} \to \text{jet} + X$ at FNAL

- dijet production a leading contributor
- high p_T jets more likely to come from initial quarks
- σ for QCD+$(DG)^2$ falls more slowly with p_T than σ_{QCD}

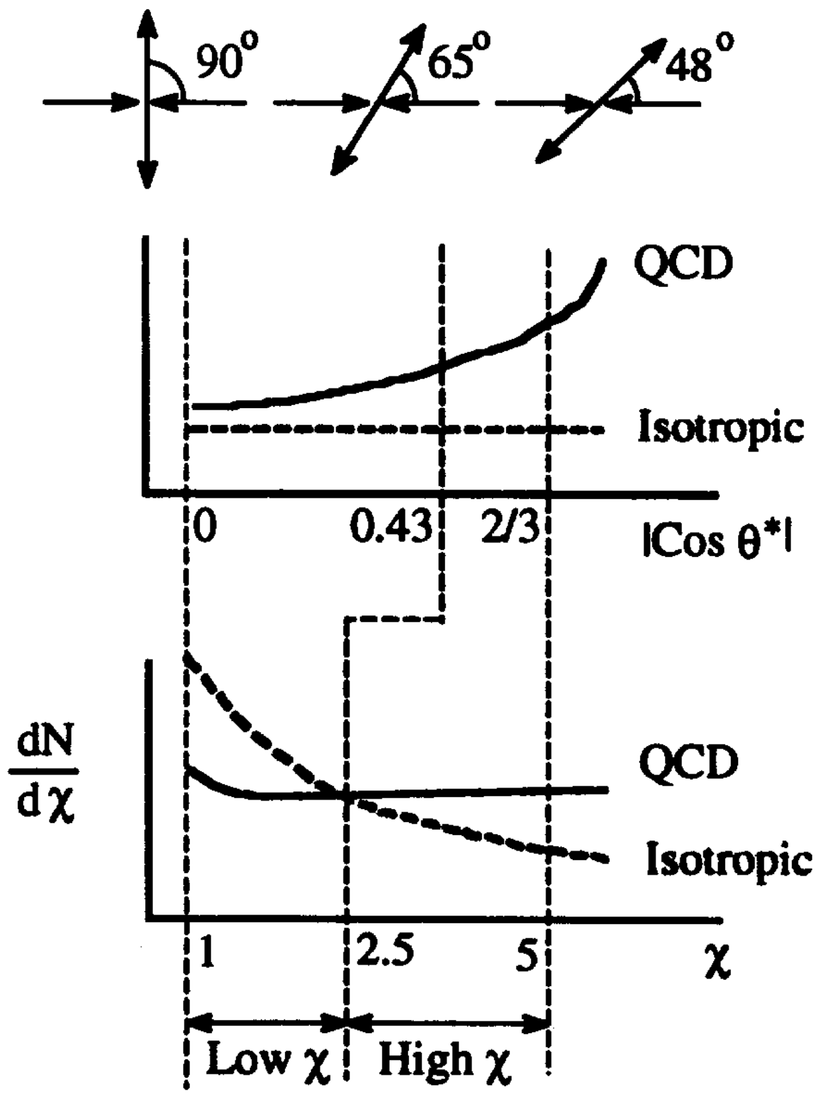
Inclusive jet spectrum can constrain $\left[C_2/\Lambda^2\right](\bar{\psi}\gamma_\mu T_a \psi)^2$



yet PDF's make precise limit uncertain.



- Variables used in Dijet Angular Distributions



θ* = Angle between jet and p in CMS

Most new physics is flat in $\cos\theta^* = \tanh\eta^*$

Most new physics peaks at low $\chi = \exp(2|\eta^*|)$

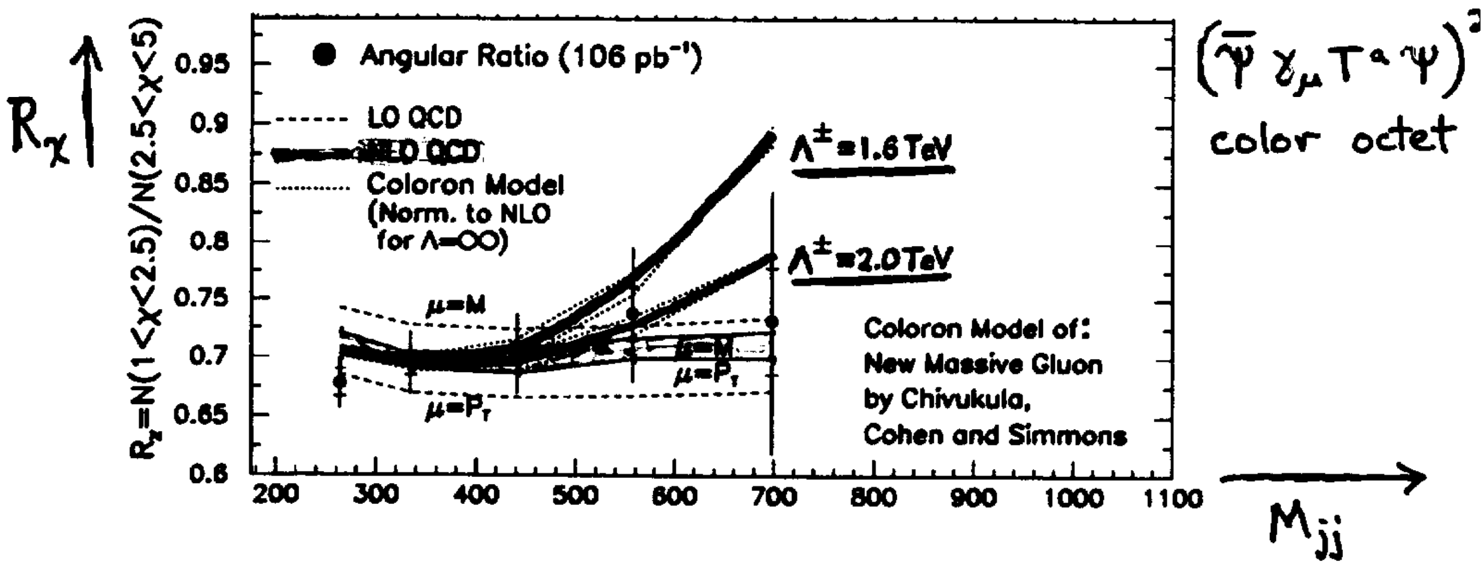
$$= \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

New physics has larger R_χ = N(Low χ)/N(High χ)

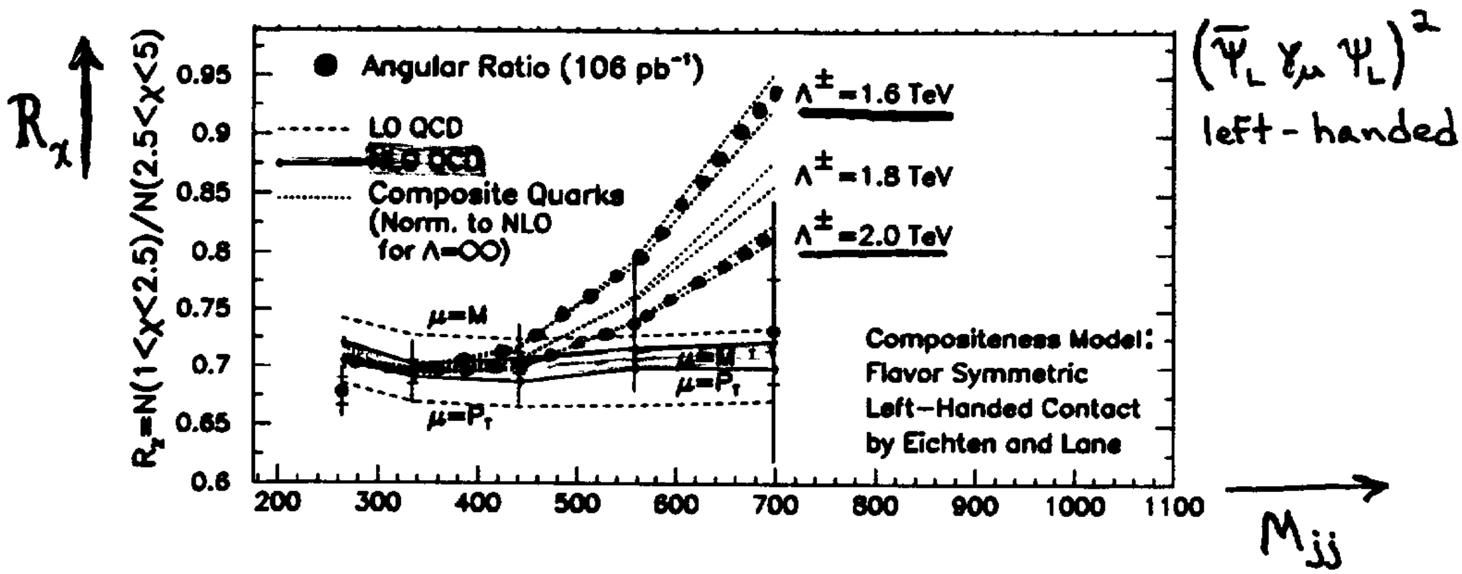
- For χ<5, the most sensitive variable is R_χ: the ratio of events with 1<χ<2.5 and 2.5<χ<5.

Courtesy of RM Harris

Dijet angular distribution less sensitive to PDF's



and can help distinguish among operators



$\chi \equiv (\mathbf{1}{+}\cos\theta)/(\mathbf{1}{-}\cos\theta)$ $\qquad$ $\mathbf{R}_\chi = \mathbf{N}(\mathbf{low}\chi)/\mathbf{N}(\mathbf{high}\chi)$

Plots courtesy of RM Harris

SECOND CASE: G^3

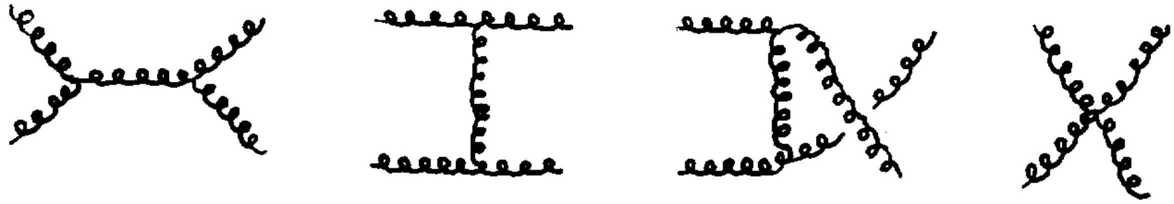
which alters multi-gluon vertices

Initial expectations:

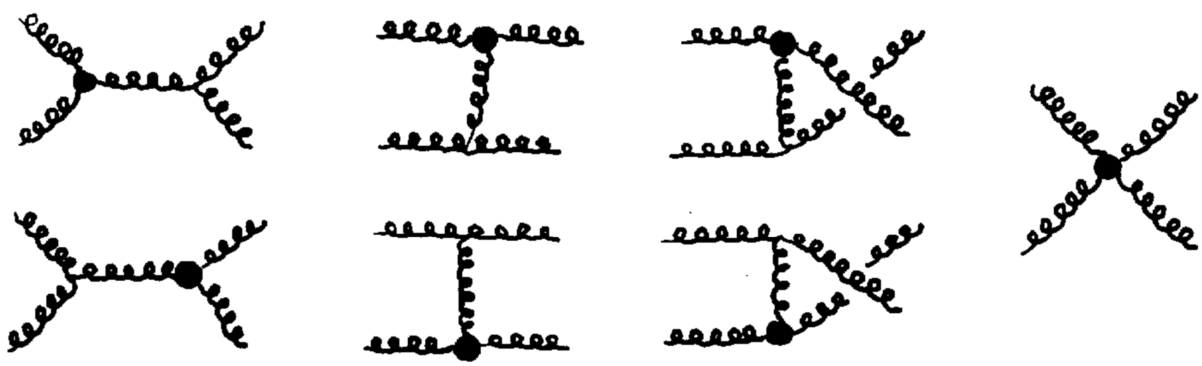
- hadron scattering at FNAL
  or LHC is dominated by gg collisions.
- non-standard gluon self-interactions may
  noticeably affect scattering rate
- inclusive jet production ($p\bar{p} \to \text{jet} + X$)
  well-measured at Fermilab already
- strong limits on C_1/Λ^2 anticipated

To assess effect of G^3 interaction on inclusive jet production, first calculate G^3 contribution to gluon-gluon scattering cross-section.

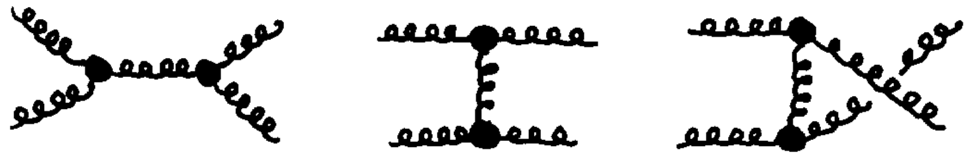
Feynman diagrams for QCD contribution:



- **Diagrams for leading G^3 contribution:**



- **•• Diagrams for sub-leading G^3 contribution:**



Scattering cross-section has the form

$$(\mathrm{QCD})^2 + \frac{2}{\Lambda^2}(\mathrm{QCD})(\bullet) + \frac{1}{\Lambda^4}[2(\mathrm{QCD})(\bullet\,\bullet) + (\bullet)^2]$$

$\bullet \equiv 1$ insertion of G^3

BAD NEWS: $O(\frac{1}{\Lambda^2})$ **tree graphs $\perp$ QCD graphs**

QCD diagrams are in [++++] helicity

$O(\frac{1}{\Lambda^2})$ **diagrams are [+++ −] or [++ − −]**

leading non-Standard effects are $O(\frac{1}{\Lambda^4})$

WORSE NEWS: similar cancellation holds for **$gq \to gq$ and all related (crossed) processes**

$\Longrightarrow$ **leading effects again are** $O(\frac{1}{\Lambda^4})$ $\Longleftarrow$

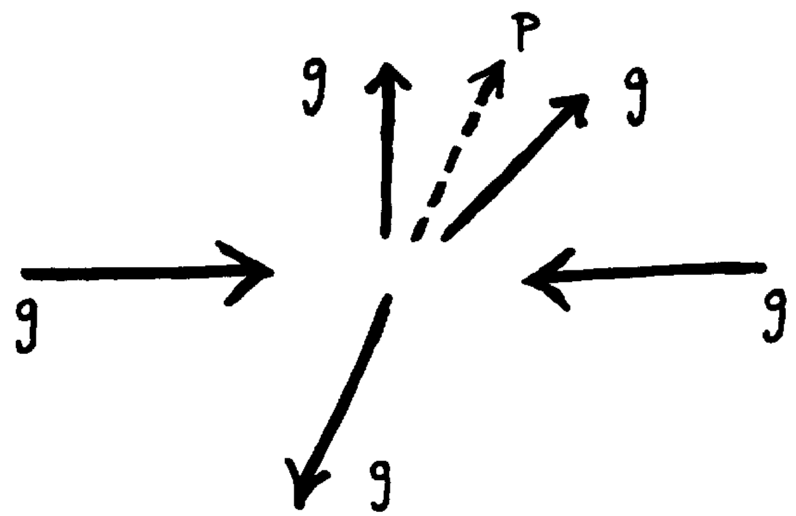
Hence, two-body scattering of massless partons does not put strong limits on G^3

- **numerical limits weak since gluons most prolific at low x where QCD background is largest**
- **interference between d=8 operators and QCD would also be** $O(\frac{1}{\Lambda^4})$**, muddying the waters**

Dixon
+ Shadmi

Study 3-jet production at hadron colliders ?

- if 2 outgoing gluons nearly collinear, replace by effective gluon with momentum p



- amplitudes for QCD, QCD+G^3 behave differently under rotations about p
- for QCD, [++++] helicity gives amplitude azimuthal symmetry
- when G^3 included, effective gluon can be linearly polarized $\Longrightarrow$ azimuthal dependence
- query: experimental difficulty of studying nearly-collinear 3-jet events ?

Cho + EHS

Heavy quark pair production ?

- use massive quarks to study G^3
- continue with 2-body scattering, produce heavy quarks via gluon fusion.

Cross-section for $gg \to Q\bar{Q}$ with G^3 included <u>does</u> have $O(\frac{1}{\Lambda^2})$ piece

$$\left[\sigma_{QCD+G^3} - \sigma_{QCD}\right] \propto$$

$$m_Q^2 \left(\frac{C_1}{\Lambda^2}\right) \frac{(t-u)^2}{(m_Q^2-t)(m_Q^2-u)}$$

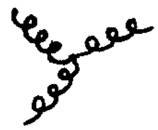
$$+ 6 \left(\frac{C_1}{\Lambda^2}\right)^2 (m_Q^2 - t)(m_Q^2 - u)$$

GOOD NEWS: sensitive to G^3 operator

BETTER NEWS: discrimination possible

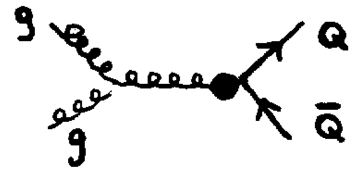
- $t\bar{t}$ production dominated by $gg \to t\bar{t}$ at LHC though not at FNAL
- however, $b\bar{b}$ produced from gg at FNAL

For production of massive quarks, G^3

- is only operator affecting  at $O(\frac{1}{\Lambda^2})$

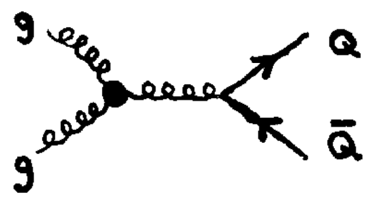
- is not only low-d operator affecting $gg \to Q\bar{Q}$
  - $m_Q \, \bar{Q}\sigma^{\mu\nu}T^a Q \, G^a_{\mu\nu}$

    chromomagnetic moment

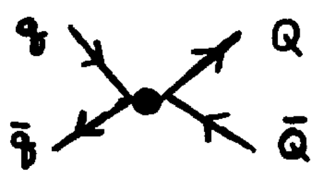


  - $f_{abc}G^{\mu}_{a\nu}G^{\nu}_{b\lambda}D^2G^{\lambda}_{c\mu}$

    d=8, no quark currents



Several operators other also contribute to $p\bar{p} \to Q\bar{Q}$ through quark annihilation



- $(DG)^2 \Longleftrightarrow (\bar{Q}\gamma^{\mu}T_a Q)^2$
- other four-quark operators like $(\bar{Q}\gamma^{\mu}Q)^2$

Must compare all operators' contributions to assess visibility of G^3. Comparison has been done for $t\bar{t}$, but not for $b\bar{b}$.

Most important operators at FNAL in $d\sigma/dp_T$?

✓✓ four-quark operators like $(DG)^2$ — Hill + Parke

enhance rate of top production,

especially at high p_T

also alter shape of distribution

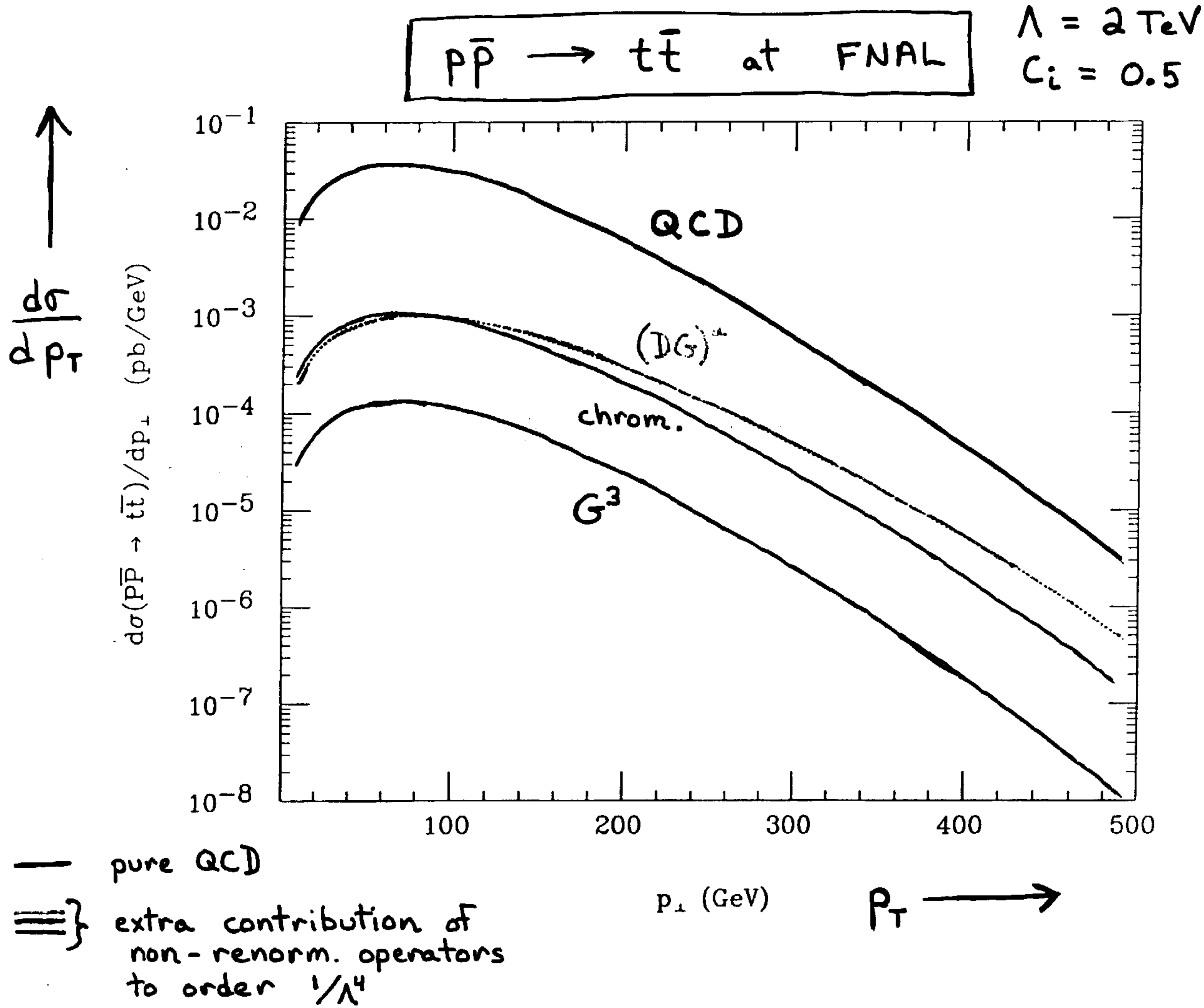
✓ chromomagnetic moment operator — Rizzo, Atwood + Kagan

enhances production rate

does not alter shape $\Longrightarrow$ less visible

✗ Effects of G^3 are an order of magnitude smaller

FNAL is unlikely to find G^3 in $t\bar{t}$ production.



pp̄ → tt̄ at FNAL
Λ = 2 TeV
Cᵢ = 0.5
dσ/dp_T
dσ(pp̄ → tt̄)/dp⊥ (pb/GeV)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
QCD
(DG)²
chrom.
G³
100
200
300
400
500
p⊥ (GeV)
P_T →
— pure QCD
} extra contribution of non-renorm. operators to order 1/Λ⁴

$$\frac{d\sigma}{dp_\perp} = \int_{-2.5}^{2.5} \left(\frac{d\sigma}{dp_\perp \, dy_3 \, dy_4} \right) dy_3 \, dy_4$$

<u>not</u> fiducial cut but

~~includes most produced $t\bar{t}$~~

$$\frac{C_i}{\Lambda^2} = \frac{.5}{(2)^2} \approx \frac{4\pi}{(10\,\text{TeV})^2}$$

e.g. use $.5 < p_T < 1$ TeV to

compare σ_{QCD} w/ σ_{EFT}

A different situation at the LHC:

Consider the p_T distribution:

Rate:

✓✓ at high p_T where QCD background lowest, most important new operator is G^3

✓ next is $(DG)^2$

✗ chromomagnetic moment effects 10× smaller

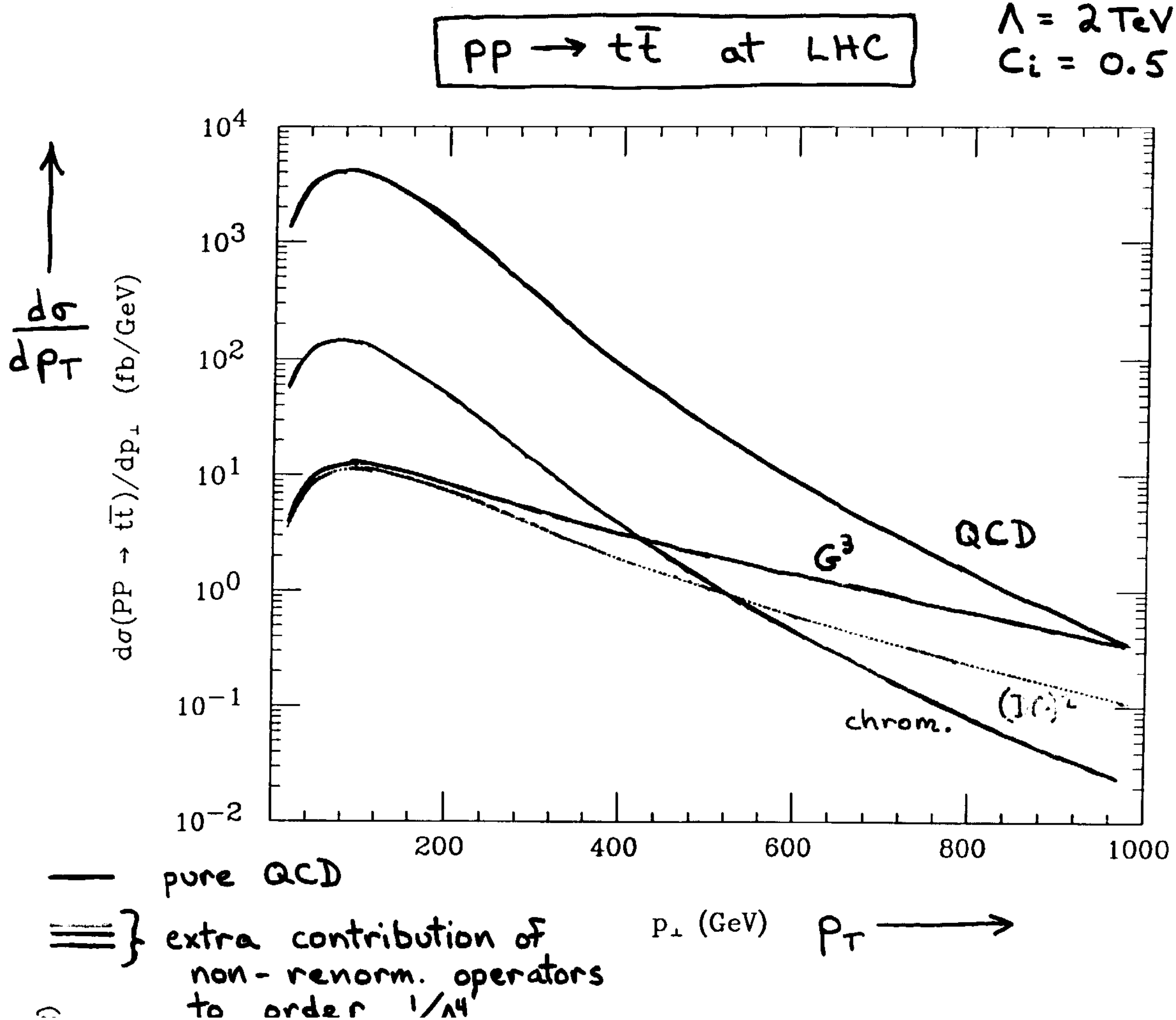
✗ d=8 operator smaller still

Shape

✓ curves for G^3 and $(DG)^2$ differ noticeably from QCD and one another

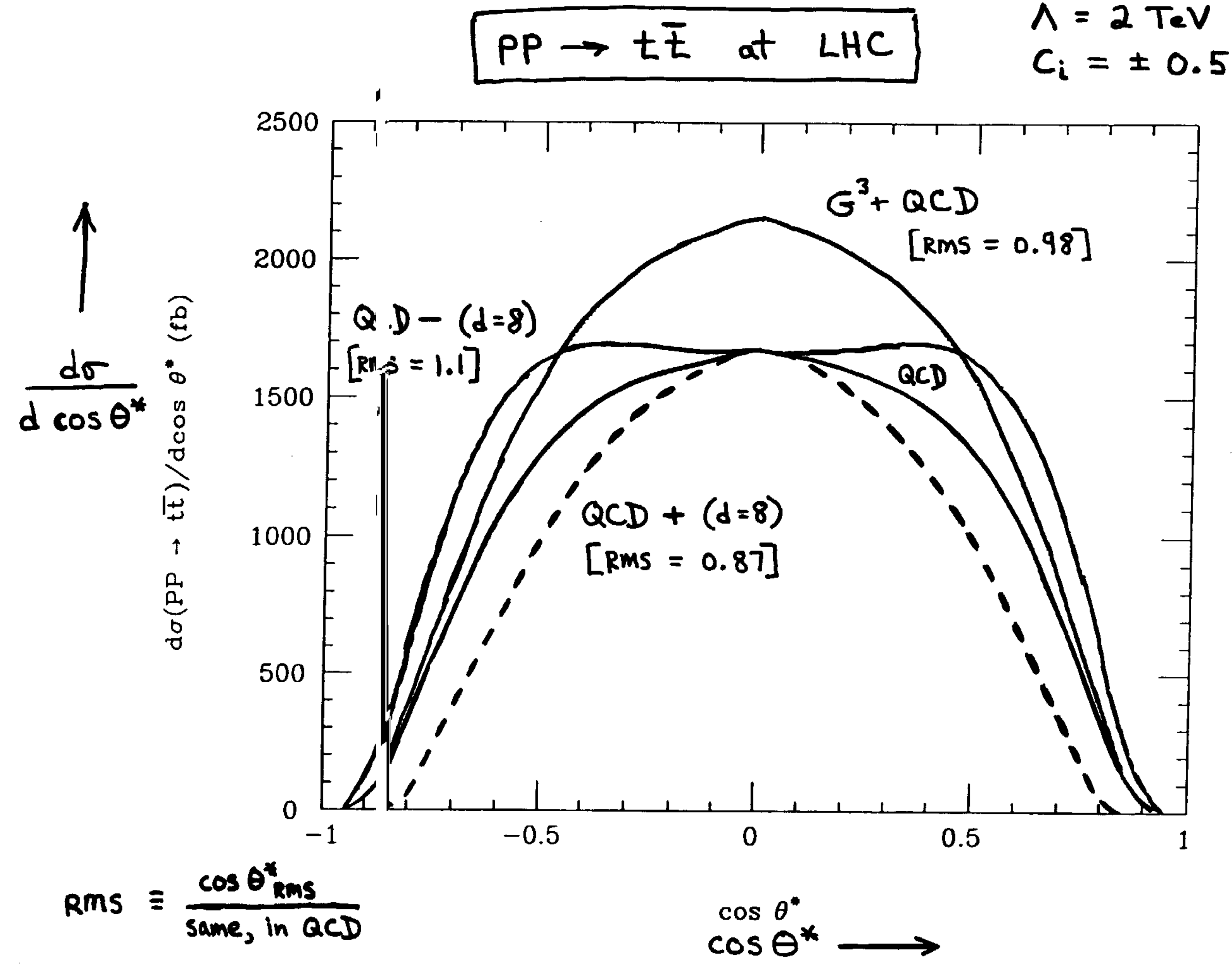
✗ chromomagnetic moment just like QCD

G^3 by far the most visible in the p_T distribution of the produced top quarks


pp → t t̄ at LHC
Λ = 2 TeV
C_i = 0.5
dσ / dp_T
dσ(PP → t t̄)/d$p_\perp$ (fb/GeV)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
QCD
G^3
chrom.
200
400
600
800
1000
$p_\perp$ (GeV)
p_T
pure QCD
extra contribution of non-renorm. operators to order $1/\Lambda^4$

Next, consider angular ($\cos\theta^*$) distribution of produced top quarks. Again, study alteration of rate and shape by new operators.

- ✗ chromomagnetic moment operator changes neither rate nor shape of $d\sigma/d\cos\theta^*$
- inclusion of G^3 or $(DG)^2$ noticeably alters rate, but changes shape only slightly
- ✓ presence of d=8 operator causes largest deviation from QCD in both rate and shape!


PP → $t\bar{t}$ at LHC
Λ = 2 TeV
C_i = ± 0.5
G^3 + QCD
[RMS = 0.98]
QCD
QCD + (d=8)
[RMS = 0.87]
QCD − (d=8)
[RMS = 1.1]
2500
2000
1500
1000
500
0
−1
−0.5
0
0.5
1
dσ(PP → $t\bar{t}$)/dcos θ* (fb)
$\frac{d\sigma}{d\cos\theta^*}$
cos θ*
cos Θ*
RMS ≡ $\frac{\cos\theta^*_{RMS}}{\text{same, in QCD}}$

$\cos\theta^*$: θ^* is angle b/twn angle of boost + of t in parton cm frame

cuts : $p_\perp \geq 500$ GeV

$\theta_{\overset{(-)}{t}\,\text{beam}} > 25.4°$ in lab frame to approx $|\eta| < 2.5$ for LHC

Operators have distinctive signatures

operator	FNAL	LHC p_T rate	p_T shape	θ^* rate	θ^* RMS
G^3		✓	✓	✓	
$(DG)^2$	✓	✓	✓	✓	
chrom.	✓	✓			
d=8				✓	✓

- $(DG)^2$ most visible at FNAL
- G^3 easiest to see at LHC

Back to the Physics:

Meaning of limits on these contact interactions?

$\frac{1}{\Lambda^2} C_2 \ (\bar{q}\gamma_\mu T^a q)^2$

- scale of quark compositeness
- mass/coupling of coloron
- scale of gluon compositeness (via $(DG)^2$)

$\frac{1}{\Lambda^2} C_1 \ f_{abc} G^{\mu}_{a\nu} G^{\nu}_{b\rho} G^{\rho}_{c\mu}$

- scale of gluon compositeness
- mass/charge of new fermion or scalar

4. Conclusions

Many distinct types of new strong physics remain possible. Direct searches for light exotic particles are useful but not exhaustive.

Low-energy effects of new physics at high scales can be generally described in terms of contact interactions among quarks and gluons.

Hadronic data contains information about all the leading contact interactions.

Limiting each distinct contact interaction corresponds to exploring the widest possible range of new physics.

Challenge: Can FNAL constrain G^3 ?

References:

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W.J. Marciano, PRD 21 ('80) 2425

J. Pati & A. Salam, PLB 58 ('75) 333

T. Rizzo, PRD 50 ('94) 4478 & hep-ph/9407366

E.H.S., PLB 226 ('89) 132; 246 ('90) 471; 259 ('91) 125

People:

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