QCD Corrections to Scalar Diquark Production

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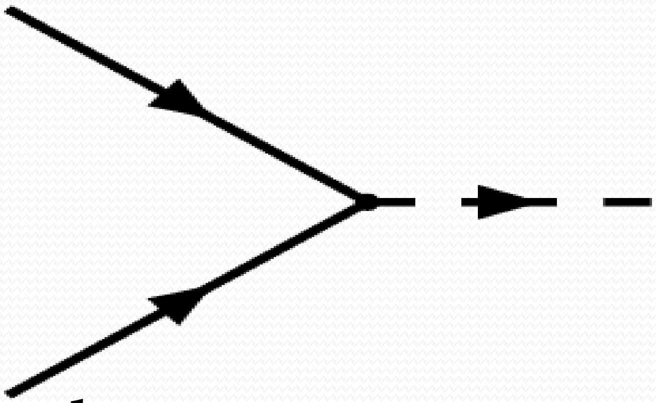
Motivation

- Hadron colliders (Tevatron, LHC) explore high energy frontier of physics beyond the Standard Model.
- Event rates dominated by strong interactions.
- Any new particle that participates in QCD interactions will be produced at favorable rates.
- For rather heavy particles, valence quarks are still the major contribution for their production.
- At *pp* colliders, such as the LHC, this means quark-quark scattering can dominate.

Quark-Quark Annihilation



- Color quantum numbers:

$$\mathbf{3} \times \mathbf{3} = \mathbf{6} + \bar{\mathbf{3}}$$

- EW quantum numbers:

$SU(2)_L$	$U(1)_Y$	$\|Q\| = \|T_3 + Y\|$	couplings to
$\mathbf{1}$	$1/3$	$1/3$	QQ, UD
$\mathbf{3}$	$1/3$	$1/3, 2/3, 4/3$	QQ
$\mathbf{1}$	$2/3$	$2/3$	DD
$\mathbf{1}$	$4/3$	$4/3$	UU

Exotic color states

- Examples of color sextet and antitriplet:
  - Color triplet scalar quarks in R-parity violating SUSY [Barbier *et al.*, hep-ph/0406039]
  - Color sextet scalars are present in some partial-unification models [Mohapatra *et al.*, 0709.1486 [hep-ph]]
- The pair production for color sextet states at the LHC was calculated in [Chen *et al.*, 0811.2105 [hep-ph]]
- We approach phenomenologically and do not assume any model.

Model

- The interaction Lagrangian is

$$\mathcal{L} = 2\sqrt{2}\left[\bar{K}_i{}^{ab} D^i \bar{q}_a \Big(\lambda_L P_L + \lambda_R P_R\Big) q_b^C + \text{h.c.}\right]$$

  - C is a charge conjugation matrix
  - *a*,*b*,*i* are color indices
  - $K^i{}_{ab}$ are Clebsch-Gordan coefficients

Born Level

- Leading order process: $q(p_1) + q(p_2) \rightarrow D(l)$
- Then the Born-level cross section is

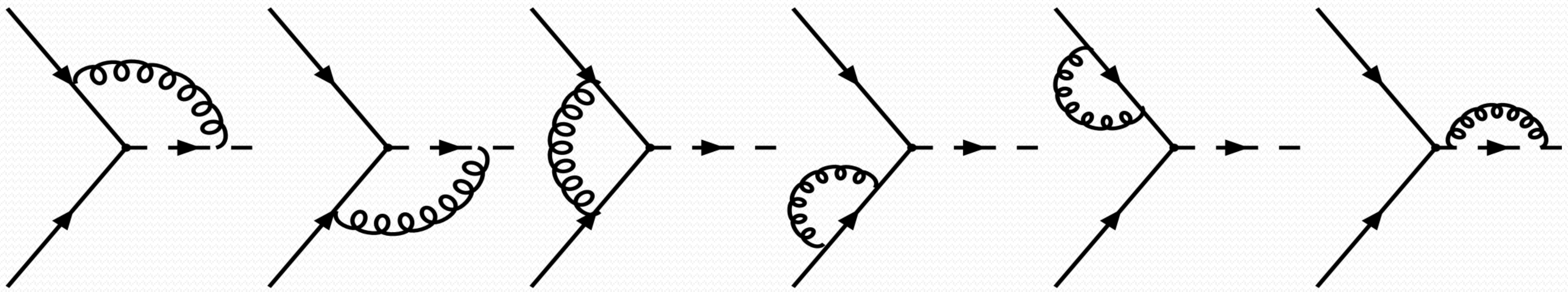
$$\sigma_{Born}(\hat{s}) = \frac{2\pi N_D \lambda^2}{N_C^2 \hat{s}} \delta(1 - \frac{m_D^2}{\hat{s}}) = \frac{\sigma_0}{\hat{s}} \delta(1 - \tau)$$

  - N_D is the dimension of the diquark representation
  - N_C is the dimension of the quark representation
  - m_D is the diquark mass
  - $\lambda^2 = \lambda_L^2 + \lambda_R^2$
  - $\hat{s}$ center of mass energy
  - $\tau = \frac{m_D^2}{\hat{s}}$

NLO Calculation

- At $O(\alpha_s)$ have contributions from loop diagrams, real gluon emission, and gluon initiated processes.
- Diagrams contain ultra-violet (UV), soft, and collinear divergences.
- All divergences are regulated using dimensional regularization in $d=4-2\varepsilon$ dimensions
- MS-bar scheme used to cancel UV and collinear divergences.
- Calculation done for stop production by Tilman Plehn [hep-ph/0006182]

Virtual Corrections



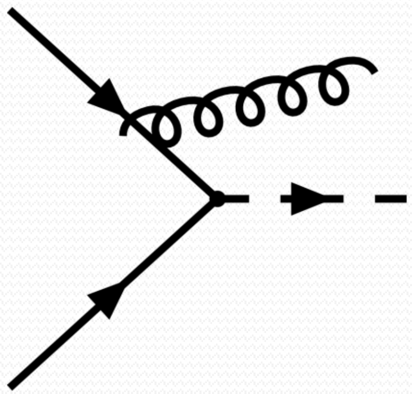
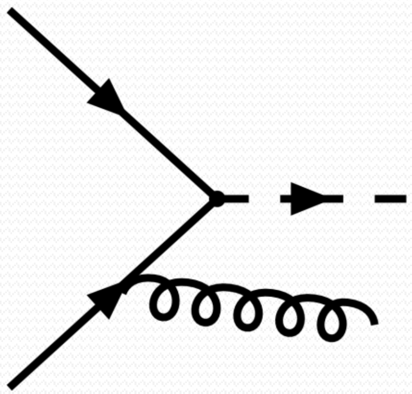
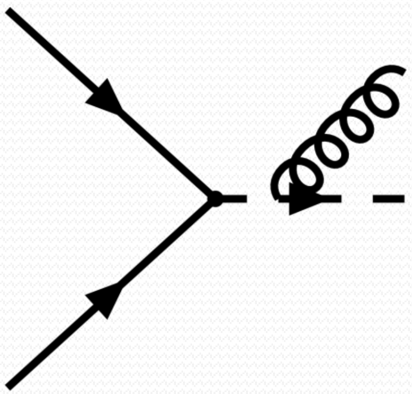
- One loop corrections:
  - Contain UV, soft, and collinear divergences.
  - Self-energy diagrams do not contribute.
  - Only vertex loops contribute

Renormalization

- Renormalization constants in MS-bar scheme:
  - Quark wave-function: $$Z_2^q = 1 - \frac{\alpha_s C_F}{4\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}$$
  - Diquark wave-function: $$Z_2^D = 1 + \frac{\alpha_s C_D}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}$$
  - Vertex: $$Z_\lambda = 1 - \frac{\alpha_s}{4\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}(4C_F - C_D)$$
- The scale dependence of the quark-diquark coupling is found to be

$$\lambda(\mu_R^2) = \frac{\lambda(Q^2)}{1 + \frac{3\alpha_s C_F}{4\pi}\ln\left(\frac{\mu_R^2}{Q^2}\right)}$$

Real Emission

- Contain soft and collinear divergences.
- Soft divergences cancel with soft divergences of virtual diagrams.
- Use MS-bar scheme to factorize collinear divergences.

qq Initial State

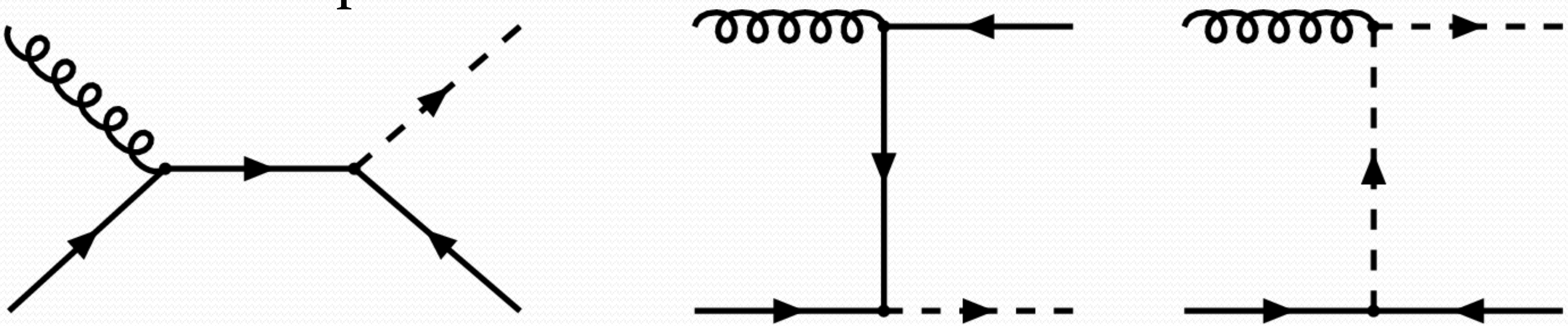
- Hadronic cross section for quark-quark initial states.

$$
\begin{aligned}
\sigma^{qq}_{NLO} &= \frac{2\pi\lambda^2}{S}\frac{N_D}{N_C^2}\int_{\tau_0}^{1}\frac{d\tau}{\tau}(q\otimes q)\left(\frac{\tau_0}{\tau}\right)\Big[\delta(1-\tau) \\
&+ \frac{\alpha_s}{2\pi}\Big\{2P_{qq}(\tau)\ln\frac{m_D^2}{\mu_F^2\tau} \\
&+ 2C_F\left[2(1+\tau^2)\left(\frac{\ln(1-\tau)}{1-\tau}\right)_+ + \left(\frac{\pi^2}{3}-\frac{3}{2}\ln\frac{m_D^2}{\mu_R^2}-1\right)\delta(1-\tau)+1-\tau\right] \\
&- C_D\left[\frac{1+\tau^2}{(1-\tau)_+}+\left(\frac{2\pi^2}{3}-1\right)\delta(1-\tau)\right]\Big\}\Big]
\end{aligned}
$$

- Where $P_{qq}(\tau) = C_F[(1+\tau^2)/(1-\tau)]_+$ is the DGLAP splitting function

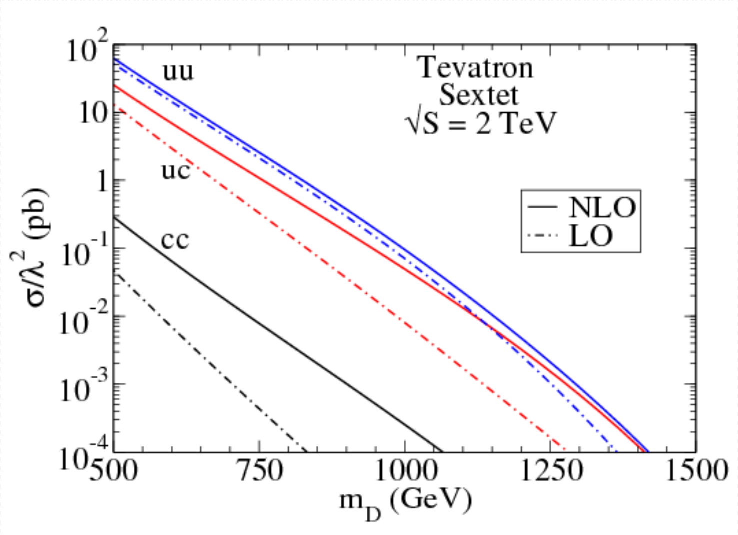
Gluon Initiated Process

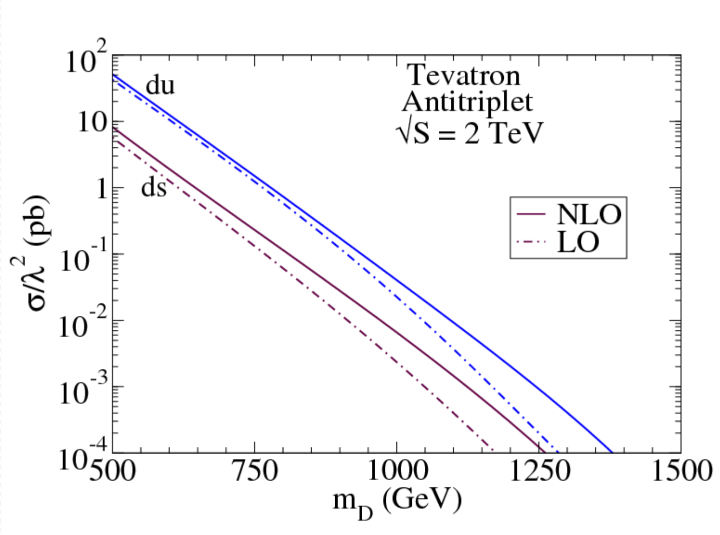
- NLO QCD corrections may also arise from gluon initiated processes:



  - Contains collinear divergences, but no soft divergences.
  - Use MS-bar scheme to factorize collinear divergences.

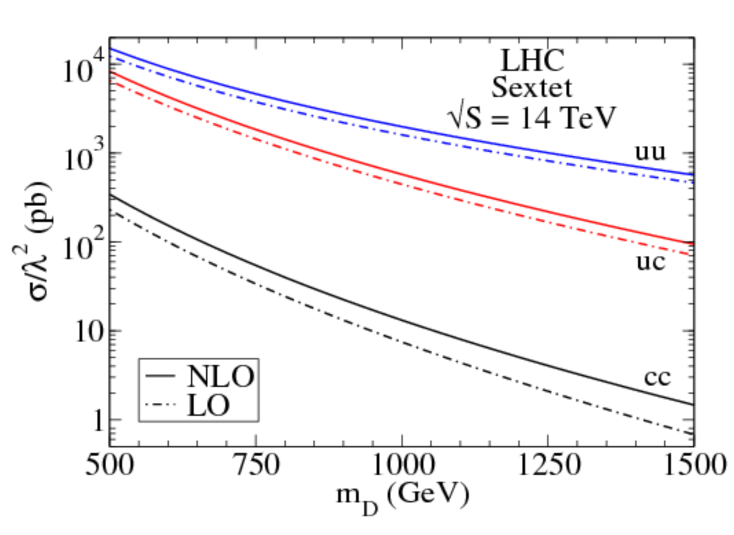
Tevatron Cross Section

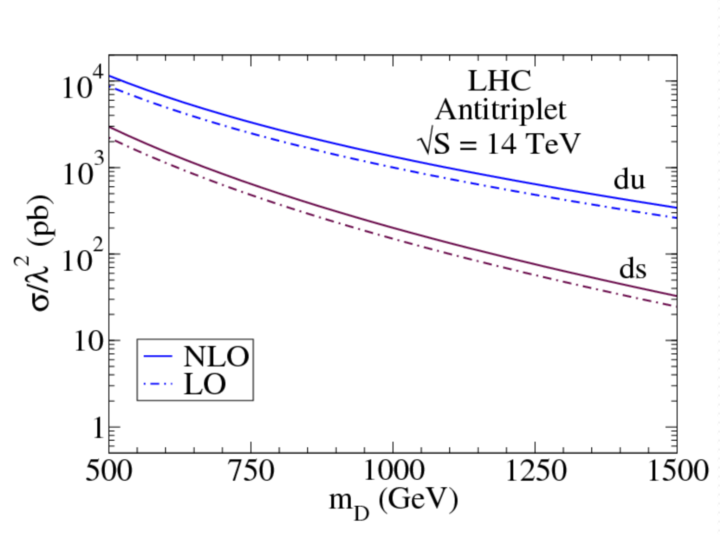




- p-pbar at 2 TeV
- $\mu_F=\mu_R=m_D$
- Scattering involving valence quarks dominates

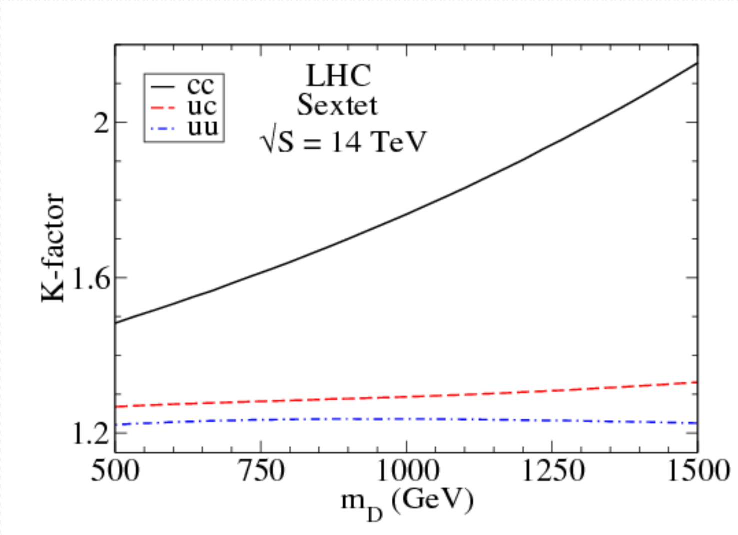
LHC Cross Section

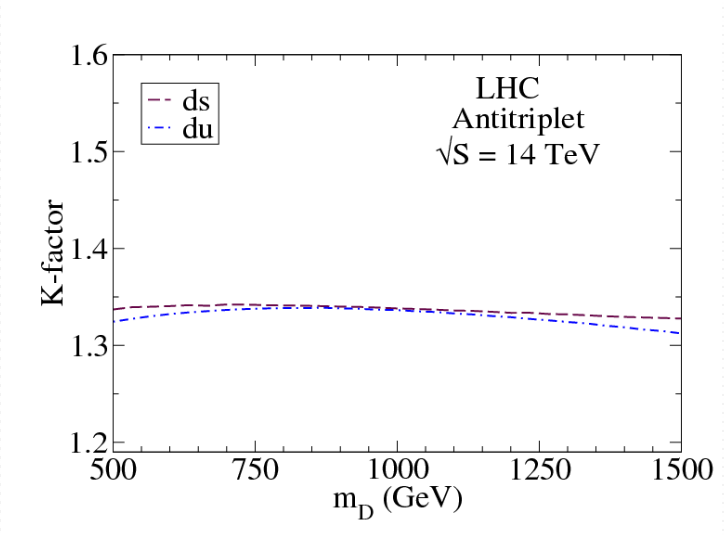




- pp at 14 TeV
- $\mu_F = \mu_R = m_D$
- Diquark is produced at favorable rates.

K-factors





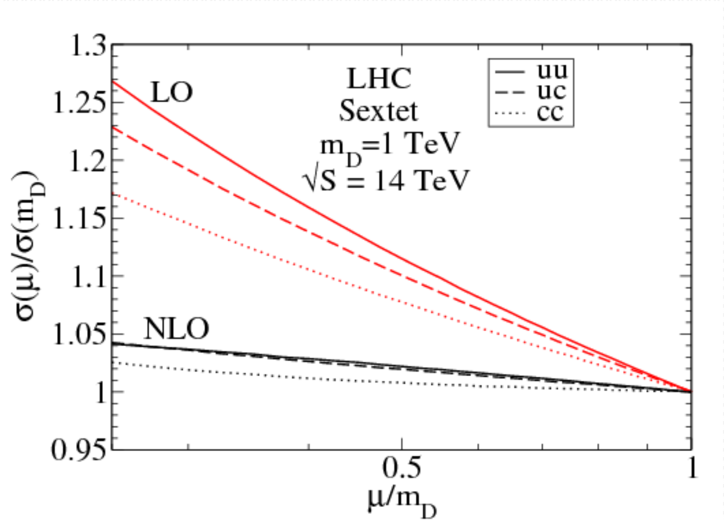
- The K-factor is the ratio of the NLO cross section to leading order cross section

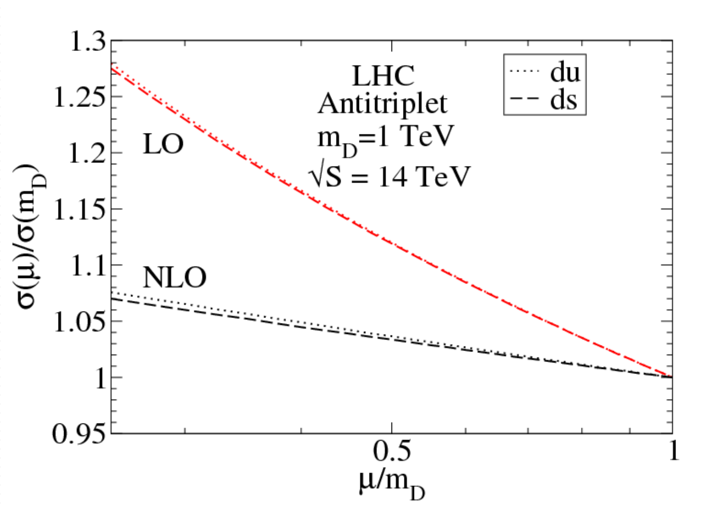
LHC Cross Section

	m_D	σ_{LO}^{CTEQ6L}	$\sigma_{LO}^{CTEQ6.1M}$	$\sigma_{NLO}^{CTEQ6.1M}$	$\sigma_{\Phi+q}^{CTEQ6.1M}$	$\sigma_{\Phi+g}^{CTEQ6.1M}$
du	500 GeV	8.71×10^3 pb	9.47×10^3 pb	1.15×10^4 pb	1.05×10^3 pb	3.48×10^3 pb
	1 TeV	1.00×10^3 pb	1.08×10^3 pb	1.34×10^3 pb	67.3 pb	573 pb
uu	500 GeV	1.23×10^4 pb	1.33×10^4 pb	1.51×10^4 pb	1.58×10^3 pb	4.07×10^3 pb
	1 TeV	1.60×10^3 pb	1.72×10^3 pb	1.98×10^3 pb	101 pb	784 pb

- Final state parton cross sections for p_T>20 GeV
- Final state gluon cross section dominant, especially for higher masses

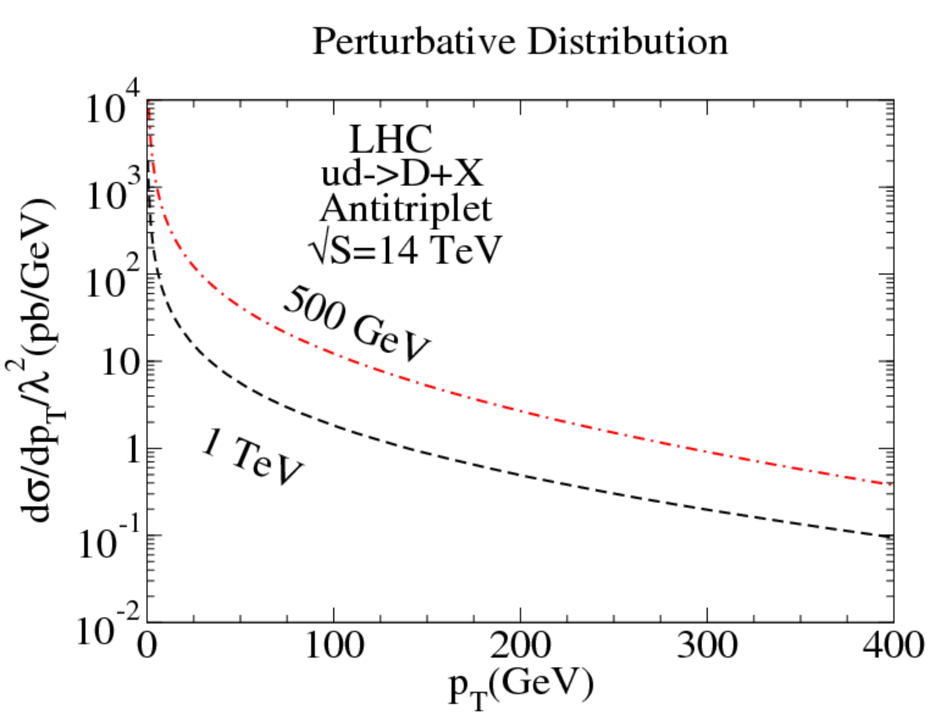
Scale Dependence

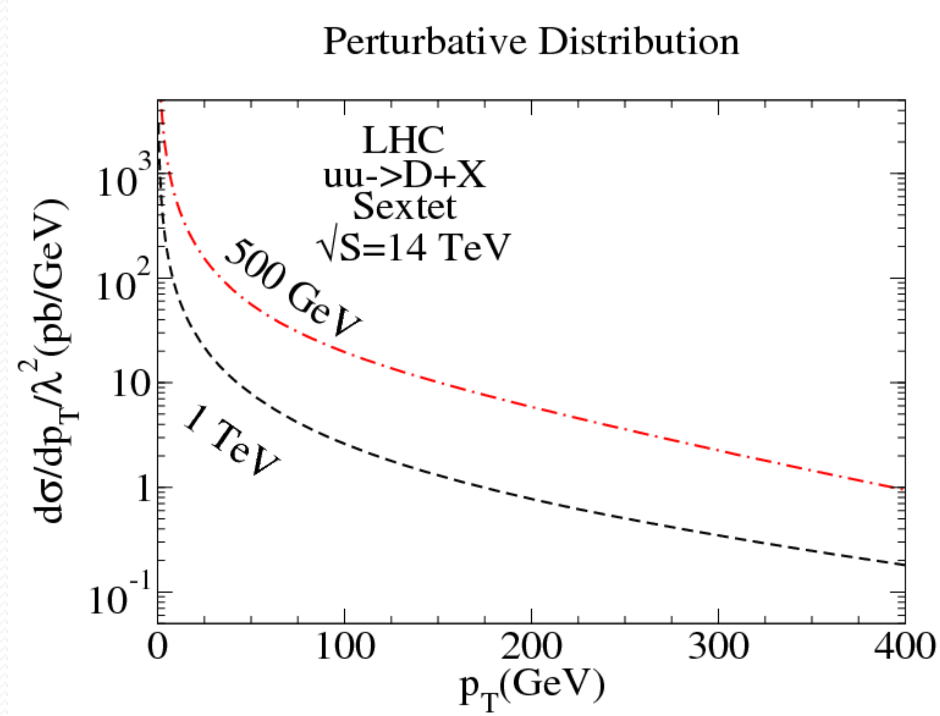




- Factorization and renormalization scales varied for $m_D/4<\mu_F=\mu_R<m_D$
- m_D=1 TeV
- Scale dependence of NLO cross section is less than that of the leading order cross section

Transverse Momentum Distribution





- Perturbative calculation diverges at p_T->0

Resummation, ct'd

- Resummation performed by Collins, Soper, and Sterman [Nucl. Phys. B 250, 199 (1985)]:
  - $$\frac{d^2\sigma^{resum}}{dp_T^2 dy} = \frac{\sigma_0}{S}\int \frac{d^2 b}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{p_T}} W(b^*) e^{-S_{np}}$$
  - $$\begin{aligned} W(b) &= \exp\left\{ -\int_{b_0^2/b^2}^{m_D^2} \frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\left[\ln\left(\frac{m_D^2}{q^2}\right)A^{(1)} + B^{(1)}\right]\right\} \\ &\times \left[f_q(x_1^0)_{q'}(x_2^0) + (x_1^0 \leftrightarrow x_2^0)\right] \end{aligned}$$
  - $$b_0 = 2e^{-\gamma_E}; \qquad b^* = \frac{b}{\sqrt{1 + b^2/b^2_{max}}}$$

$$A^{(1)} = 2C_F, \quad B^{(1)} = -(3C_F + C_D)$$

Non-perturbative Effects

- Parameterize non-perturbative effects following Davies, Webber, and Stirling [Nucl. Phys. B 256, 413 (1985)]

$$S_{np} = b^2 \left[g_1 + g_2 \log \frac{b_{max} m_D}{2} \right]$$

- From Tevatron data, g_1=0.14 GeV^2, g_2=0.54 GeV^2, and b_{max}=(2 GeV)$^{-1}$ [Landry et. al., hep-ph/0212159]

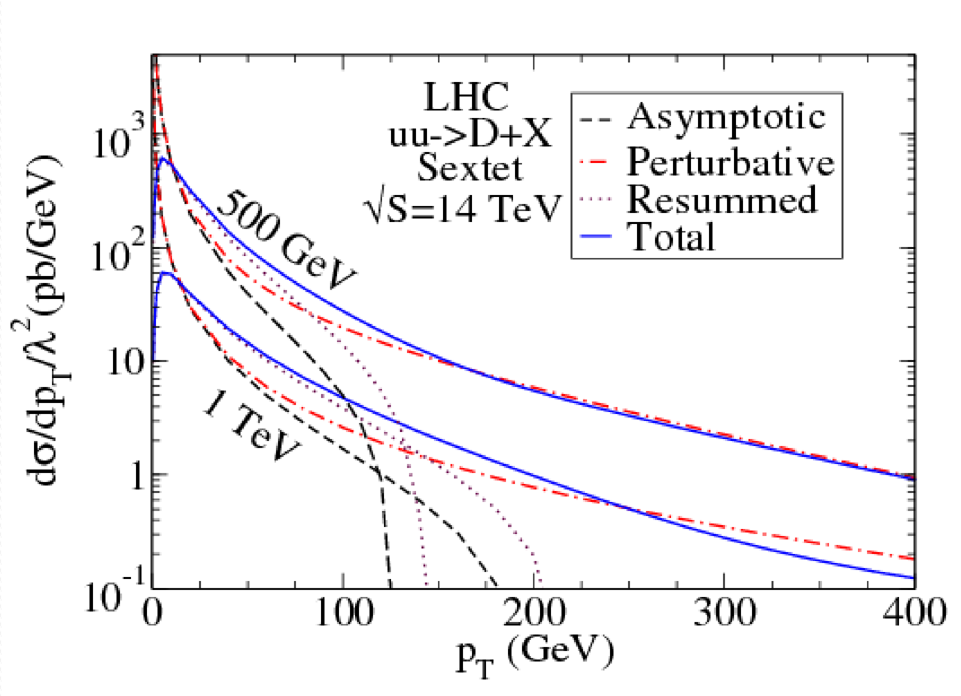
Matching

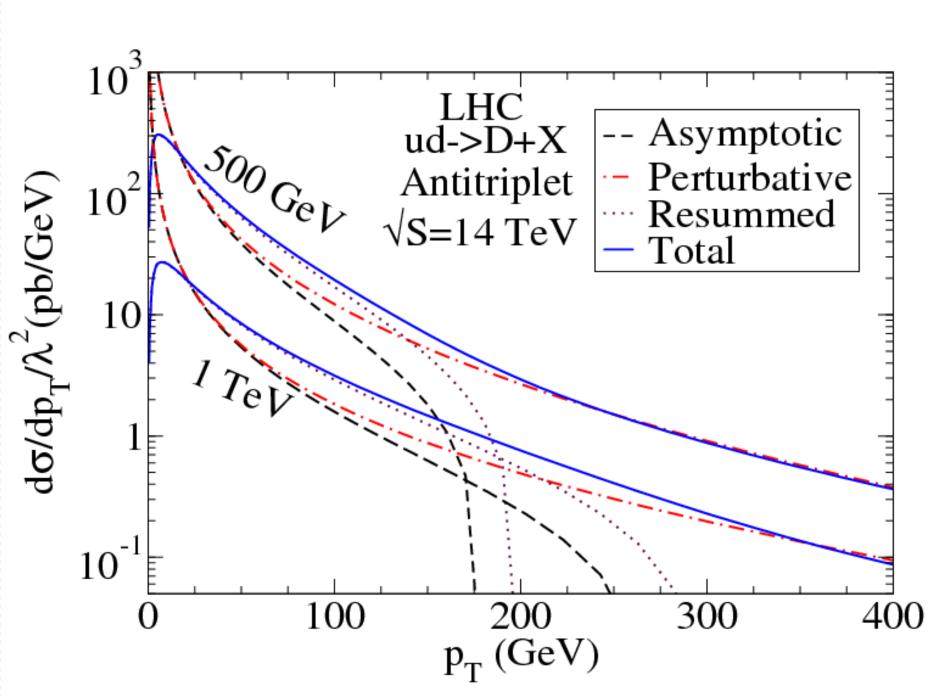
- To match the perturbative and resummed distributions:

$$\frac{d\sigma^{general}}{dp_T dy} = \frac{d\sigma^{pert}}{dp_T dy} + f(p_T)\left(\frac{d\sigma^{resum}}{dp_T dy} - \frac{d\sigma^{asym}}{dp_T dy}\right)$$

  - $f(p_T) = \dfrac{1}{1+(p_T/p_T^{match})^4}$ is an ad hoc function
  - p_T^{match} is the boundary line above which the the perturbative calculation is accurate

Resummation Results





- Results of transverse momentum resummation.
- At low p_T, asymptotic and perturbative distributions agree well.
- Distribution peaks at $p_T \sim 5$ GeV

Summary

- Diquarks produced at favorable rates and LHC.
- K-factors for production from initial state valence quarks:
  - 1.3-1.35 for antitriplet diquark
  - 1.2-1.3 for sextet diquark
- Much larger K-factors for pure sea quark scattering
- We performed the soft gluon resummation for small transverse momentum.
- Transverse momentum distribution peaks at $p_T \sim 5$ GeV

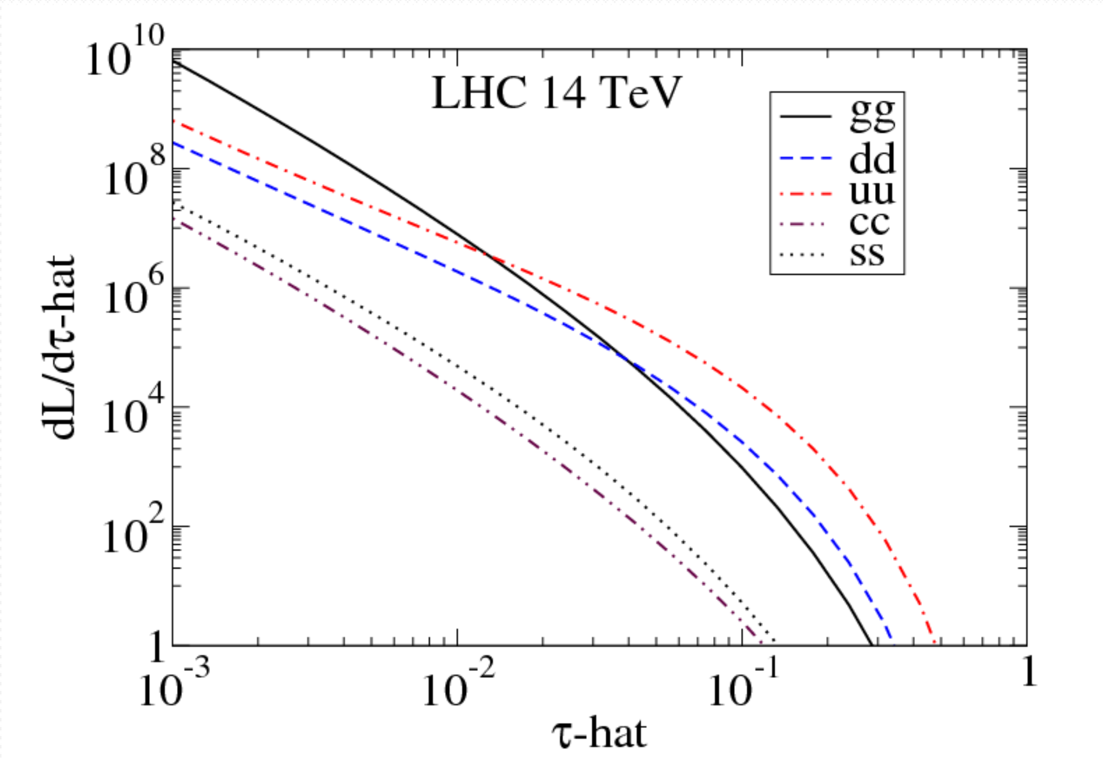
Extra Slides

Parton Luminosity

- Parton luminosity defined to be

$$\frac{d\mathcal{L}_{ij}}{d\hat{\tau}} = \int_{\hat{\tau}}^{1} \frac{dx_a}{x_a}[f_{a/A}(x_a) f_{b/B}(\hat{\tau}/x_a) + (A \leftrightarrow B \ if \ a \neq b)]$$

  - Where $\hat{\tau} = x_a x_b = \hat{s}/S$



Color Structure

- The generators of the diquark representation can be expressed as $$T_j^{Ai} = 2\mathrm{Tr}K^i t^A \bar{K}_j$$

- The quadratic casimir operator of the diquark representation is

$$T^A T_A = C_D = (N_C \mp 1)(N_C \pm 2)/N_C$$

- The generators satisfy the orthogonality relation

$$\mathrm{Tr}T^A T^B = T_D \delta^{AB} = \frac{1}{2}(N_C \pm 2)\delta^{AB}$$

Gluon Initiated Process

- Hadronic cross section for quark-gluon partonic channel:

$$\begin{aligned}\sigma^{gq}_{NLO} &= \frac{\lambda^2\alpha_s}{S}\frac{N_D}{N_C^2}\int_{\tau_0}^{1}\frac{d\tau}{\tau}(gq+qg)\left(\frac{\tau_0}{\tau}\right)\\ &\times \left\{P_{qg}(\tau)\ln\frac{m_D^2(1-\tau)^2}{\mu_F^2\tau}-\frac{1}{4}(1-\tau)(3-7\tau)\right.\\ &+ \left.\frac{C_D}{C_F}\left[\tau\ln\tau+\frac{1}{2}(1-\tau)(1+2\tau)\right]\right\}\end{aligned}$$

- Where $P_{qg}(\tau) = 1/2[(1-\tau)^2+\tau^2]$ is the DGLAP splitting function