QCD Corrections to Scalar Di-quark Production

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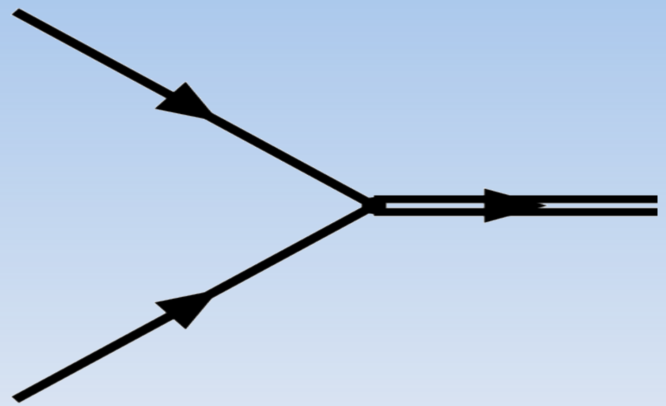
Motivation

- 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



- $\mathbf{3} \times \mathbf{3} = \mathbf{6} + \bar{\mathbf{3}}$
- Examples of color sextet and anti-triplet:
  - 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]]
- We approach phenomenologically and don't assume any model.

Model

- The SM-gauge invariant Lagrangian

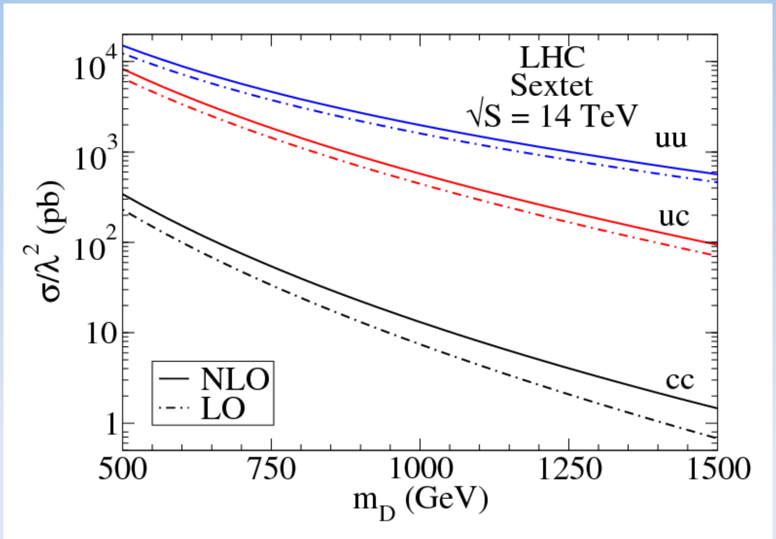
$$\mathcal{L} = (D_\mu\Phi)^\dagger(D^\mu\Phi) - M_\Phi^2\Phi^\dagger\Phi$$
$$+2\sqrt{2}\Big[K_{c_2c_3}^{c_1}\Phi_{c_1}^\dagger q_i^{c_2\,T}C^{-1}(\lambda_L^{ij}P_L + \lambda_R^{ij}P_R)q'^{c_3}_j + h.c.\Big]$$

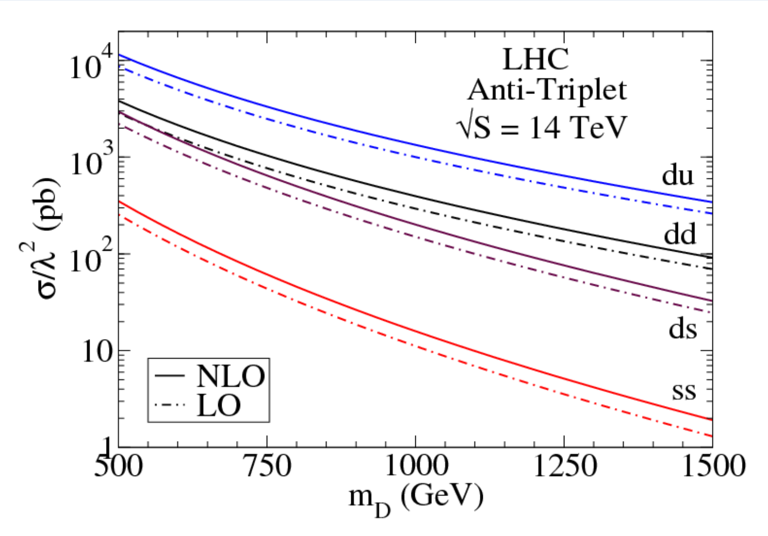
  - $D_\mu = \partial_\mu - ig_sG_\mu^aT^a$ is the QCD covariant derivative
  - C is a charge conjugation matrix
  - c_1,c_2,c_3 are color indices
  - *i,j* are flavor indices
  - $K_{c_2c_3}^{c_1}$ are Clebsch-Gordan coefficients

NLO Calculation

- At $\mathcal{O}(\alpha_s)$ 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]

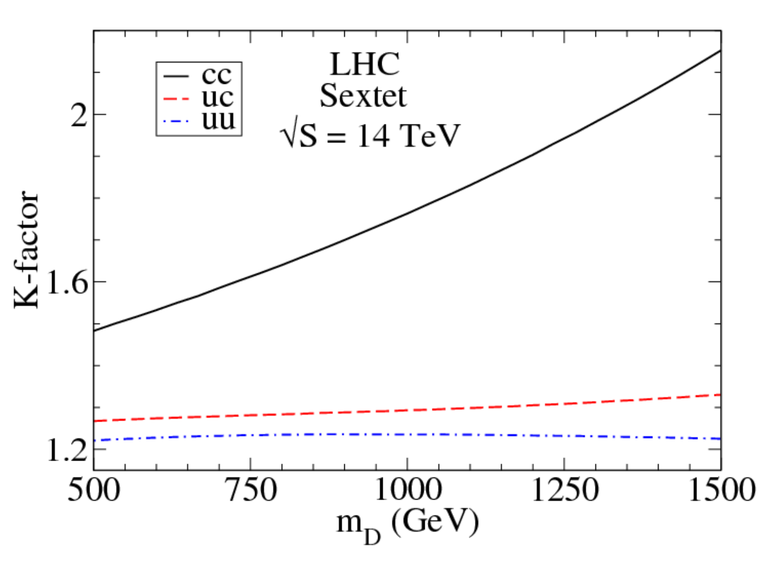
LHC Cross Section

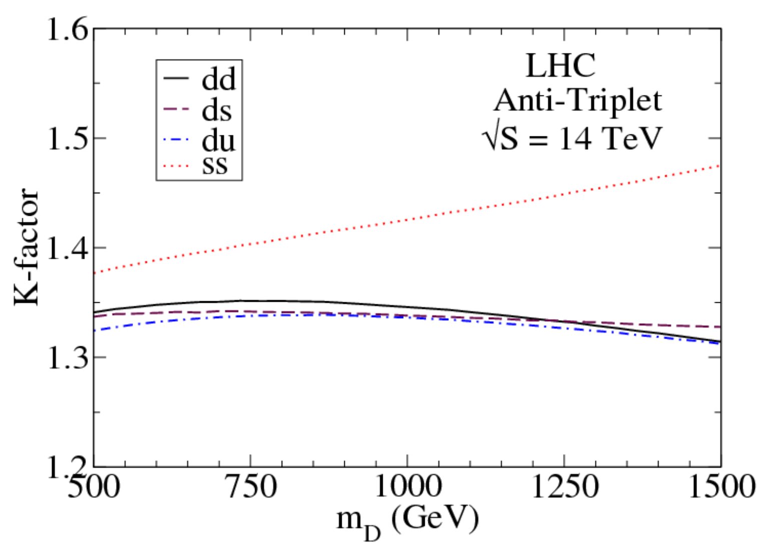




- pp at 14 TeV
- $\mu_F = \mu_R = m_D$
- Di-quark is produced at favorable rates.

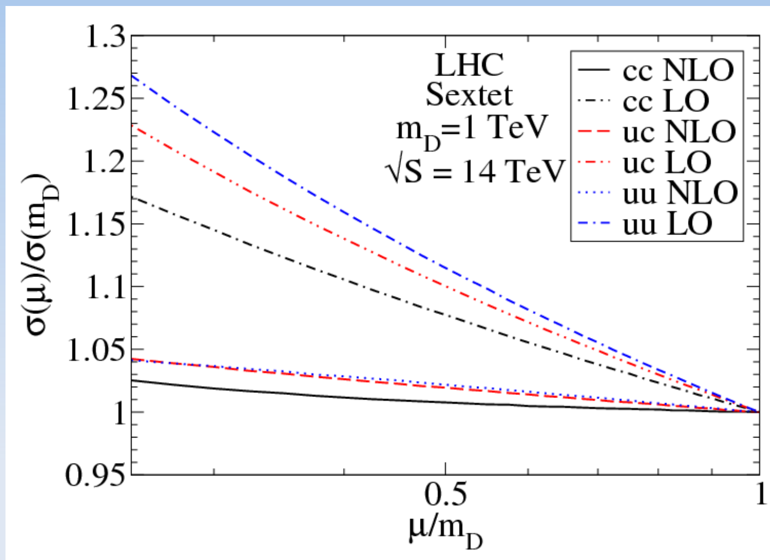
K-factors

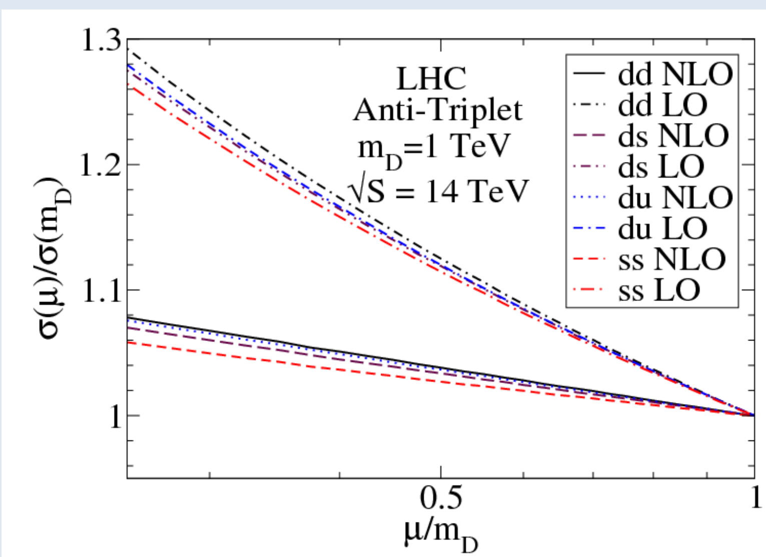




- The K-factor is the ratio of the NLO cross section to leading order cross section

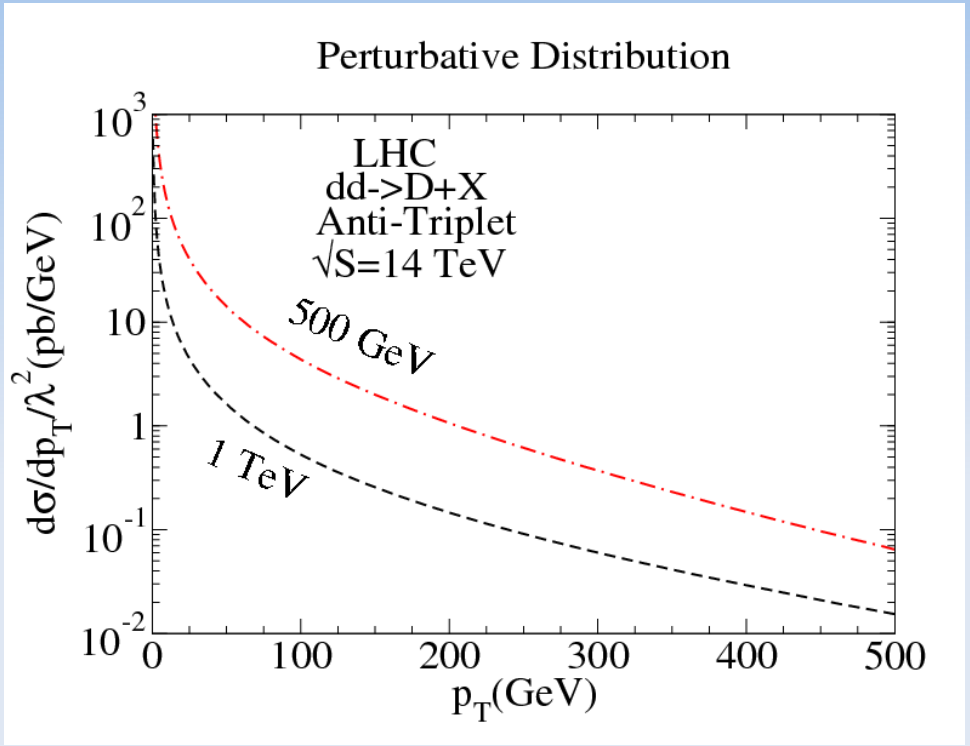
Scale Dependence

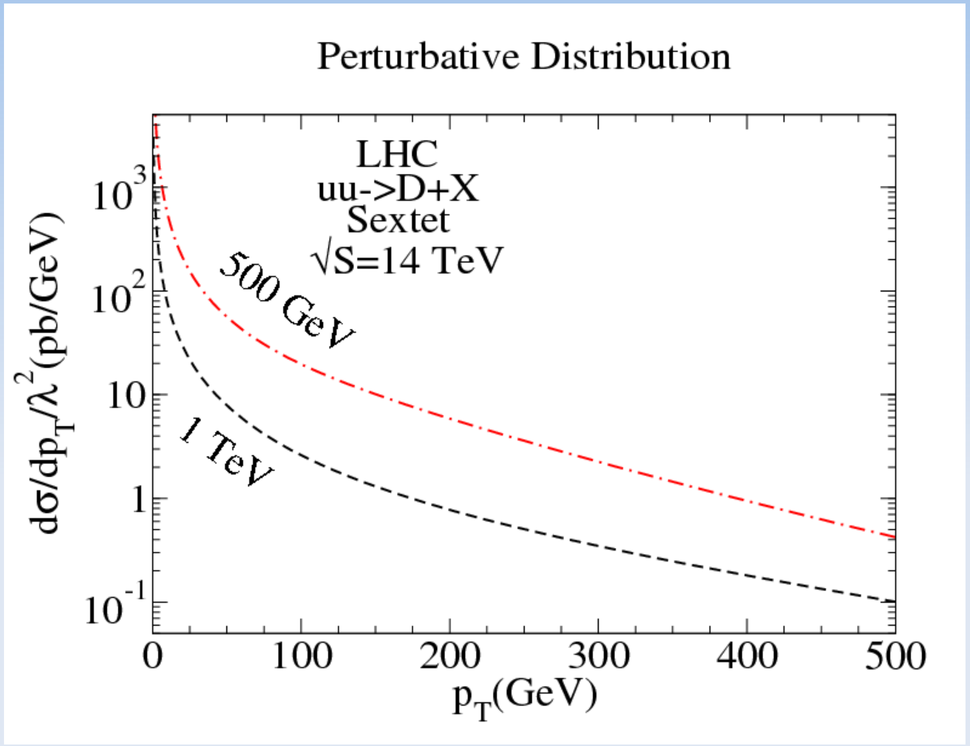




- Factorization and renormalization scales varied for $m_D/4<\mu_F=\mu_R<m_D$
- m_D=1 TeV
- Scale dependence of NLO cross section is less than that of the leading order cross section

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)]:

$$\frac{d^2\sigma^{resum}}{dp_T^2 dy} = \frac{\sigma_0}{S}\int \frac{d^2b}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{p_T}} W(b^*) e^{-S_{np}}$$

- $$W(b) = \exp\left\{ -\int_{b_0^2/b^2}^{m_D^2} \frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\left[\ln\left(\frac{m_D^2}{q^2}\right)A^{(1)} + B^{(1)}\right]\right\} \times \left[f_q(x_1^0)_{q'}(x_2^0) + (x_1^0 \leftrightarrow x_2^0)\right]$$

- $b_0 = 2e^{-\gamma_E}; \qquad b^* = \dfrac{b}{\sqrt{1 + b^2/b_{max}^2}}$

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

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]

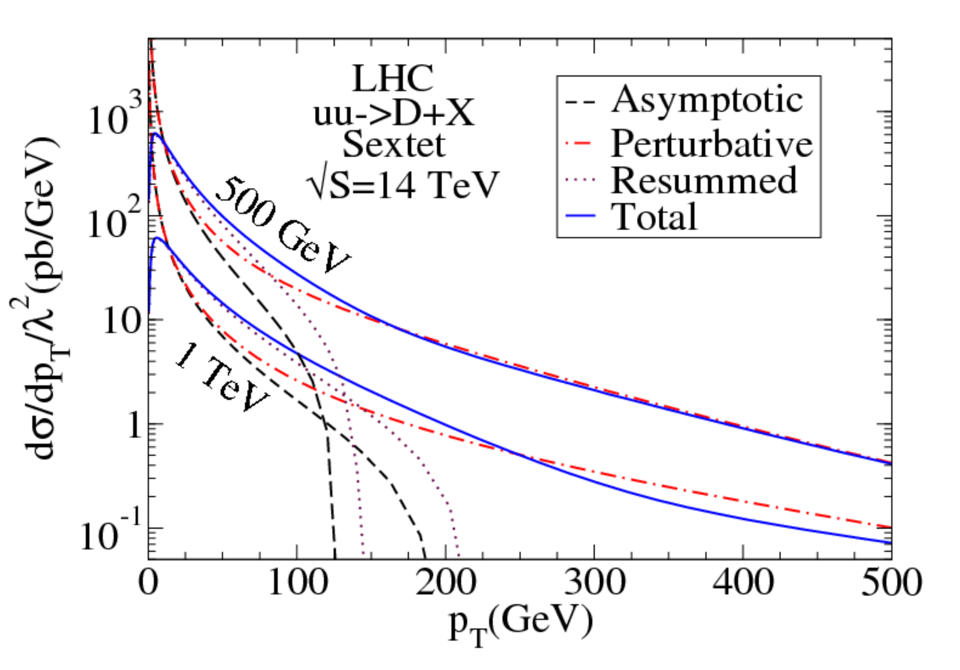
Matching

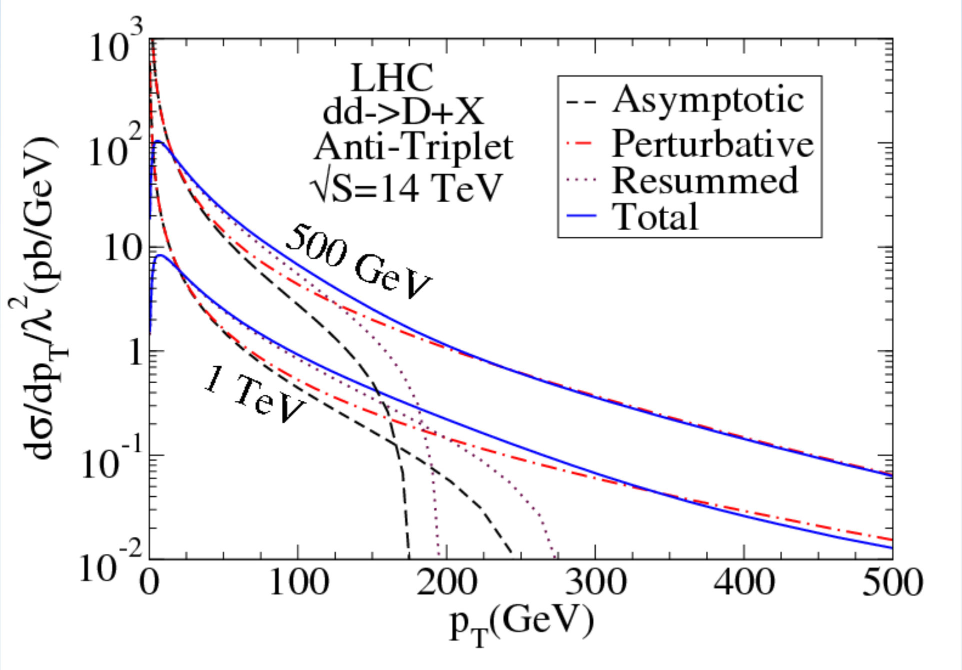
- To match the perturbative and resummed distributions:

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

  - $f(p_T) = \frac{1}{1 + (p_T/p_T^{match})^4}$ 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 ~ 5 GeV

Summary

- Diquarks produced at favorable rates and LHC.
- K-factors for production from initial state valence quarks:
  - 1.3-1.35 for anti-triplet 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~5 GeV

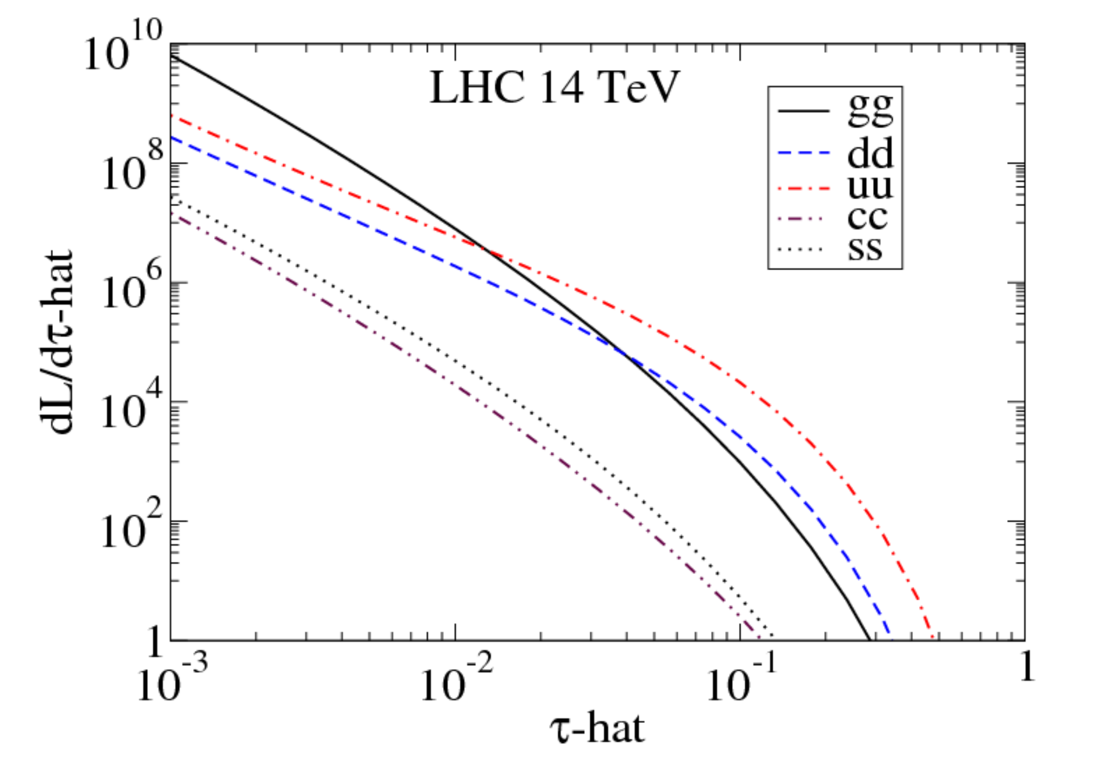
Extra Slides

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



Renormalization

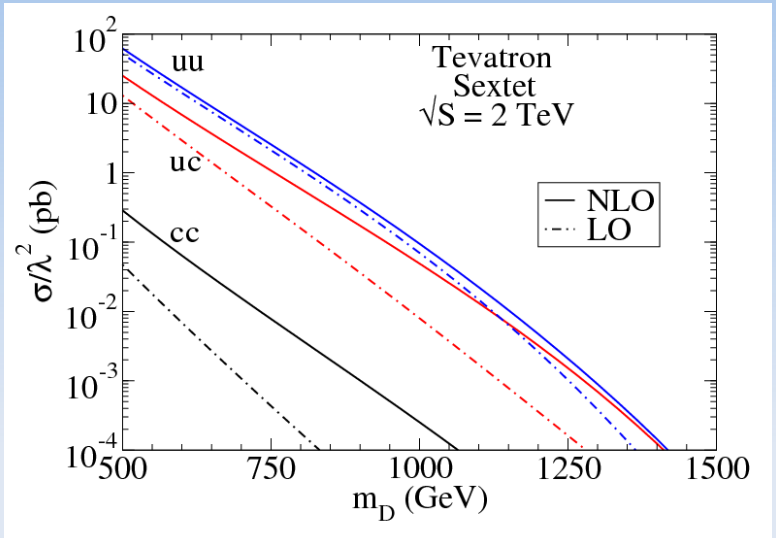
- Renormalization constants in MS-bar scheme:

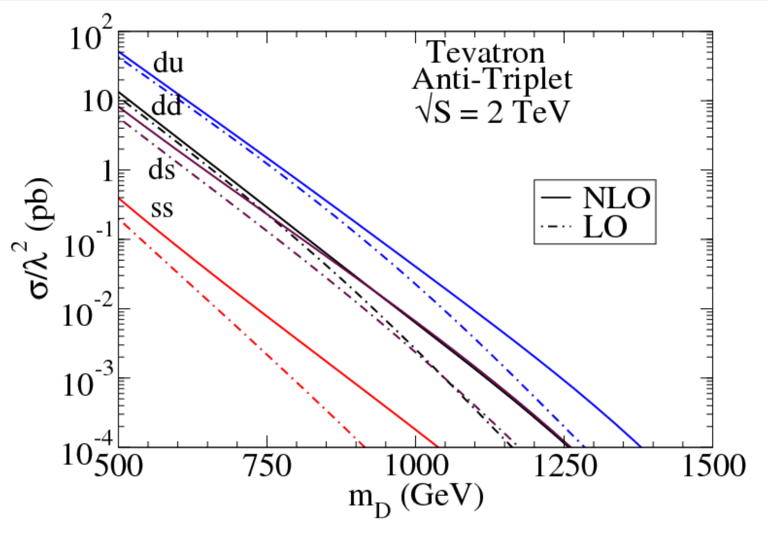
- Quark wave-function: $$Z_2^q = 1 - \frac{\alpha_s C_F}{4\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}$$
- Di-quark wave-function: $$Z_2^D = 1 + \frac{\alpha_s C_D}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}$$
- Vertex: $$Z_\lambda = 1 - \frac{\alpha_s C_F}{4\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\frac{1}{\epsilon}\left(4 - 2\frac{N_C \pm 2}{N_C \pm 1}\right)$$

- The scale dependence of the quark-di-quark coupling is found to be

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

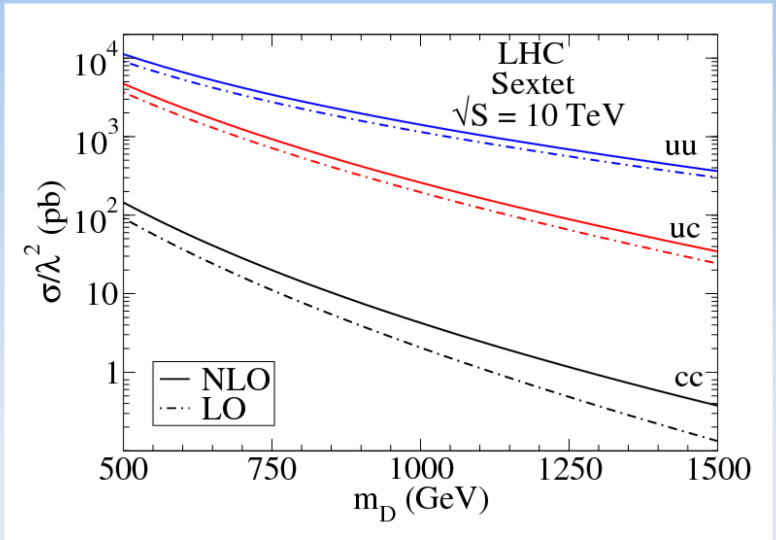
Tevatron Cross Section

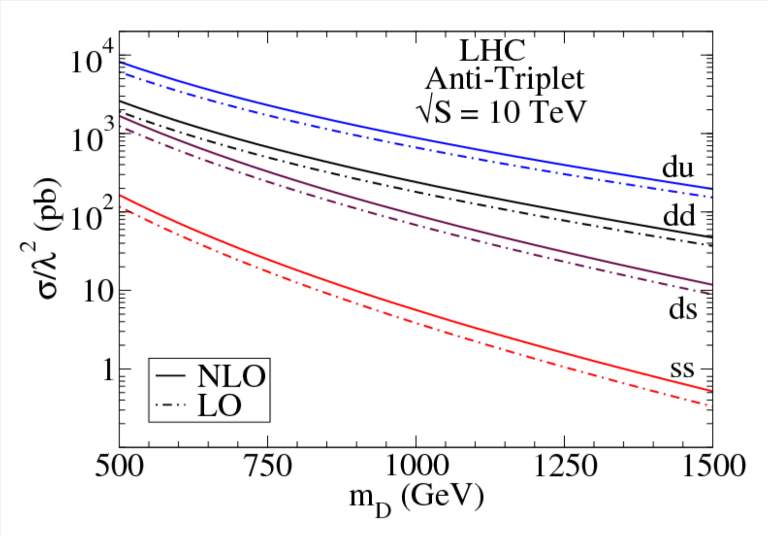




- p-pbar at 2 TeV
- $\mu_F = \mu_R = m_D$
- Scattering involving valence quarks dominates

LHC Cross Section





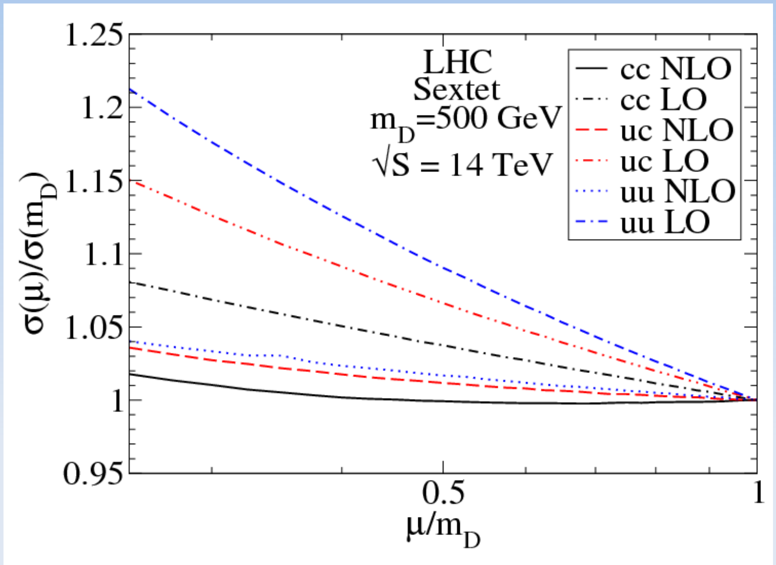
- LHC will initially turn on at a lab frame energy of 10 TeV
- pp at 10 TeV
- $\mu_F = \mu_R = m_D$

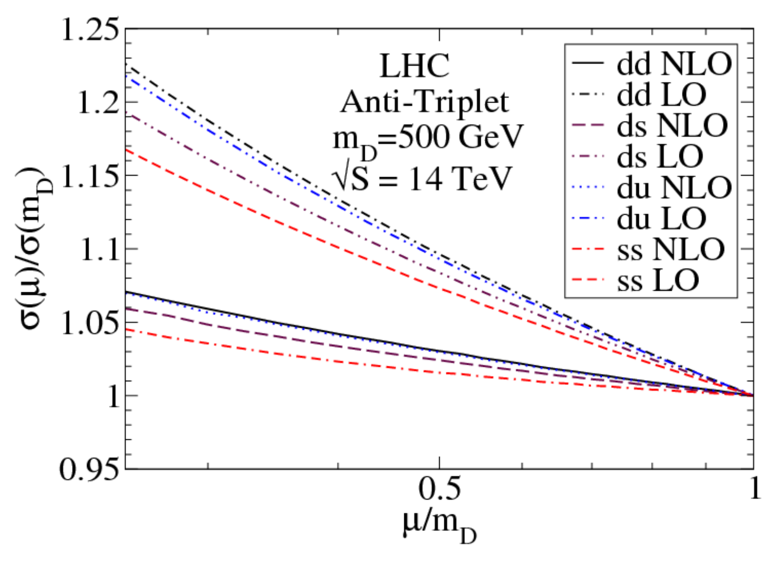
LHC Cross Section

	m_D	σ_{LO}^{CTEQ6L}	$\sigma_{LO}^{CTEQ6.1M}$	$\sigma_{NLO}^{CTEQ6.1M}$	$\sigma_{\Phi+q}^{CTEQ6.1M}$	$\sigma_{\Phi+g}^{CTEQ6.1M}$
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
dd	500 GeV	2.86×10^3 pb	3.14×10^3 pb	3.84×10^3 pb	356 pb	1.11×10^3 pb
	1 TeV	294 pb	317 pb	396 pb	21.1 pb	161 pb

- Jet cross sections for p_T>20 GeV
- Gluon jet cross section dominant, especially for higher masses

Scale Dependence





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- m_D=500 GeV
- Scale dependence of NLO cross section is less than that of the leading order cross section