Light gluino and PDF global fitting

Jon Pumplin – MSU Journal Club 12/8/04

Work described in

"Light gluino constituents of hadrons and a global analysis of hadron scattering data"

Ed Berger, Pavel Nadolsky, Fred Olness and JP.
(hep-ph/0406143 to be published in Phys. Rev. D.)

Synopsis:

- The Parton Distribution Function analysis tests a great deal of Standard Model physics. It can therefore be used to look for inconsistencies that signal Beyond Standard Model physics.

- We have generalized the CTEQ6 PDF analysis to include a light gluino as an additional parton constituent in the proton.

- By requiring consistency with the Global Fitting data set, we obtain
  - A limit: $M_{\tilde{g}} > 5\,\mathrm{GeV}$.
  - A mild suggestion: $10\,\mathrm{GeV} \lesssim M_{\tilde{g}} \lesssim 20\,\mathrm{GeV}$.

Conventional PDF Global analysis

High energy hadrons interact at short distances via their quark and gluon constituents.

For single hard scattering ("leading twist") processes, the quark and gluon content is fully described by universal Parton Distribution Functions $f_a(Q, x)$ where Q is the characteristic large momentum transfer (1/distance) scale, x is the light cone momentum fraction, and a is the flavor index.

PDFs are essential to interpreting data from hadron accelerators such as Tevatron and LHC. Since they cannot be calculated from first principles, they must be extracted from experiment.

Since the PDFs are Universal (i.e., process independent) a great variety of experiments can be used. The need to perform phenomenology on a diverse set of experiments with poorly-known experimental and theoretical systematic errors is the essential challenge in the PDF industry.

The Global Fitting PDF programme

1. Parametrize the PDFs at a small Q_0 by smooth functions with lots of free parameters, e.g., $A_0\, x^{A_1}\,(1-x)^{A_2}\, e^{A_3 x}(1+A_4 x)^{A_5}$ subject to number- & momentum-sum rule constraints.

2. Calculate $f_a(Q,x)$ at all $Q > Q_0$ from $f_a(Q_0,x)$ by renormalization group (DGLAP evolution).

3. Calculate $\chi^2 = \sum_i [(\mathrm{data}_i - \mathrm{theory}_i)/\mathrm{error}_i]^2$ measure of the quality of fit to the experiments.

4. Vary the parameters to minimize χ^2.

Essential ingredients

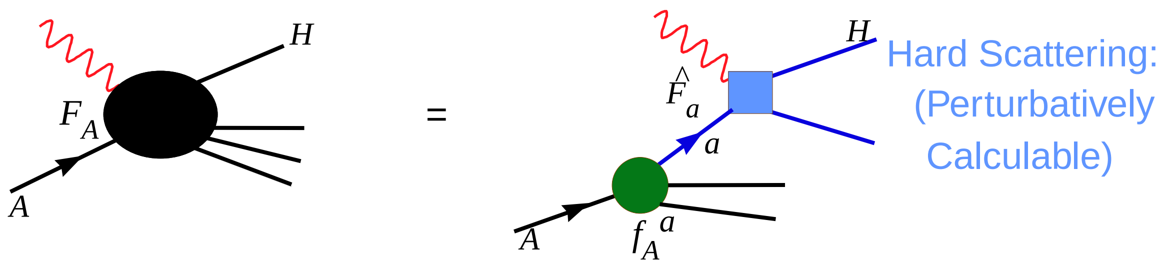
- Factorization Theorems: Short distance (perturbative) and long distance are separable.

- Asymptotic Freedom: $\alpha_s(Q)$ small at large Q allows hard scattering to be calculated at NLO.

- Renormalization Group Evolution in scale: PDFs are characterized by functions of single variable x since DGLAP gives the Q-dependence.

Factorization Theorem

$$F_A^\lambda(x, \frac{m}{Q}, \frac{M}{Q}) = \sum_a f_A^a(x, \frac{m}{\mu}) \otimes \widehat{F}_a^\lambda(x, \frac{Q}{\mu}, \frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$



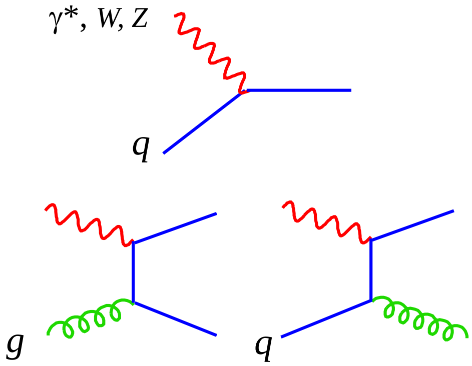
Experimental
Input

Parton Distributions:
Nonperturbative parametrization at Q_0
DGLAP Evolution to Q

Experimental Input

DIS

e N
μ N
ν N
ν̄ N

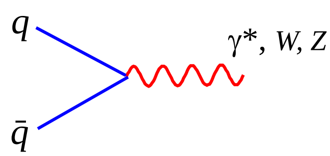


SLAC
BCDMS
NMC, E665
H1, ZEUS

CDHS, CHARM
CCFR
CHORUS

DY

p N
π N
k N
p̄ N

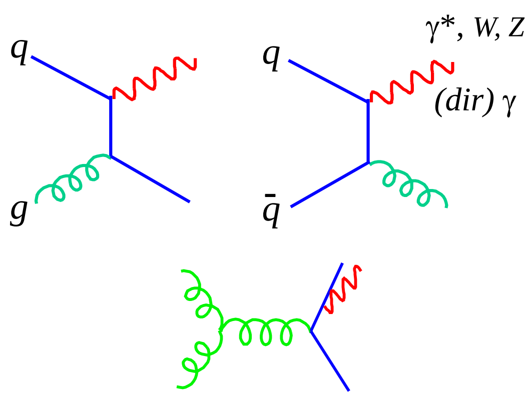


E605, E772
NA51
E866

CDF, D0

Dir.Ph.

p N
π N
k N
p̄ N

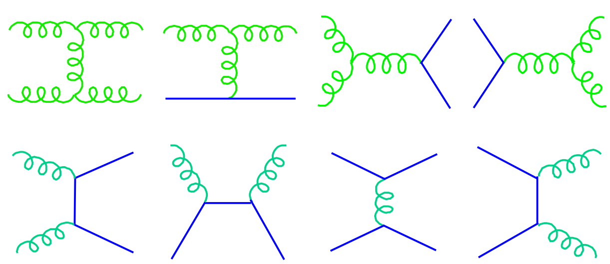


WA70, UA6
E706

CDF, D0

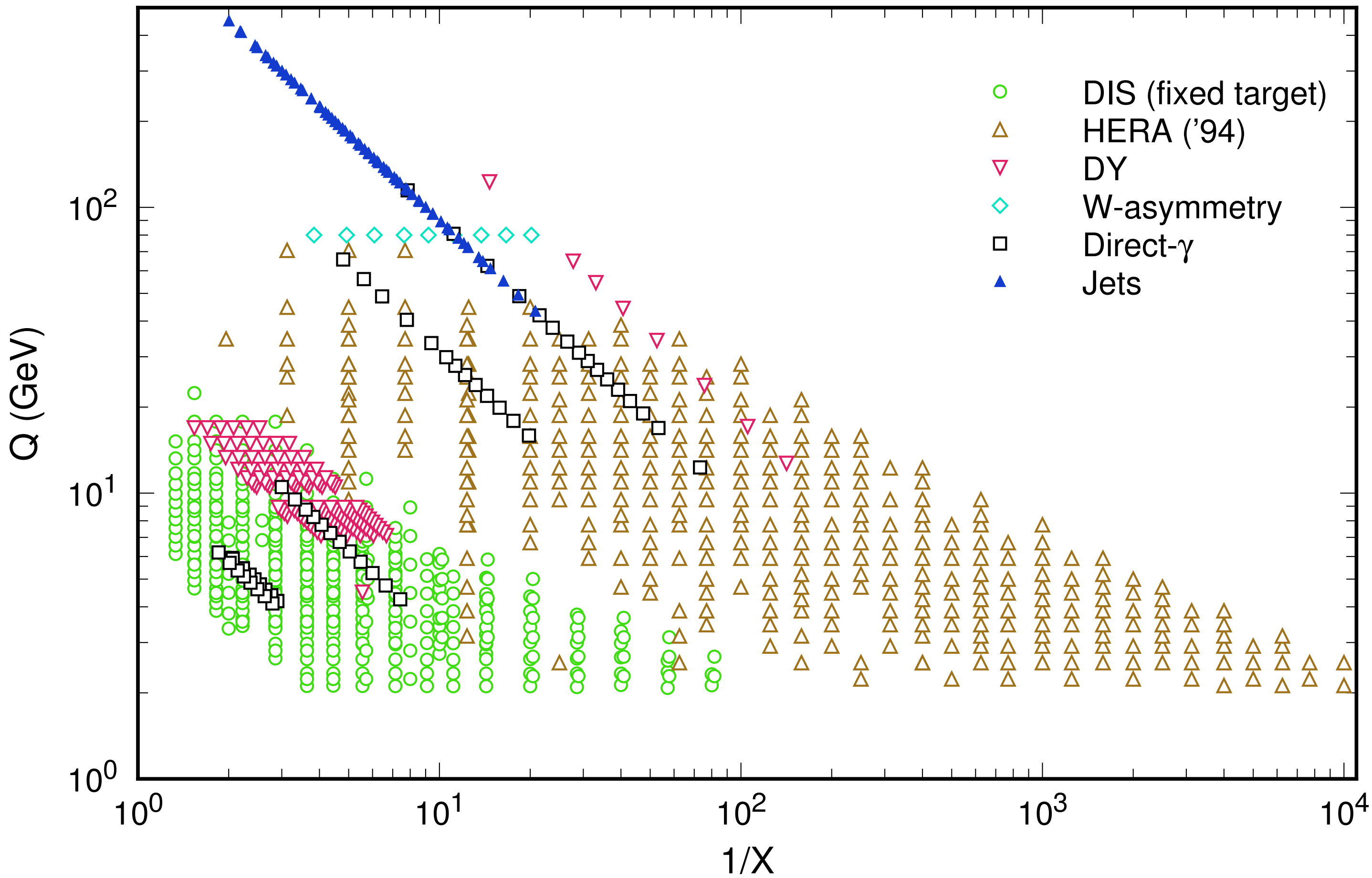
Jet Inc.

p̄ p



CDF, D0

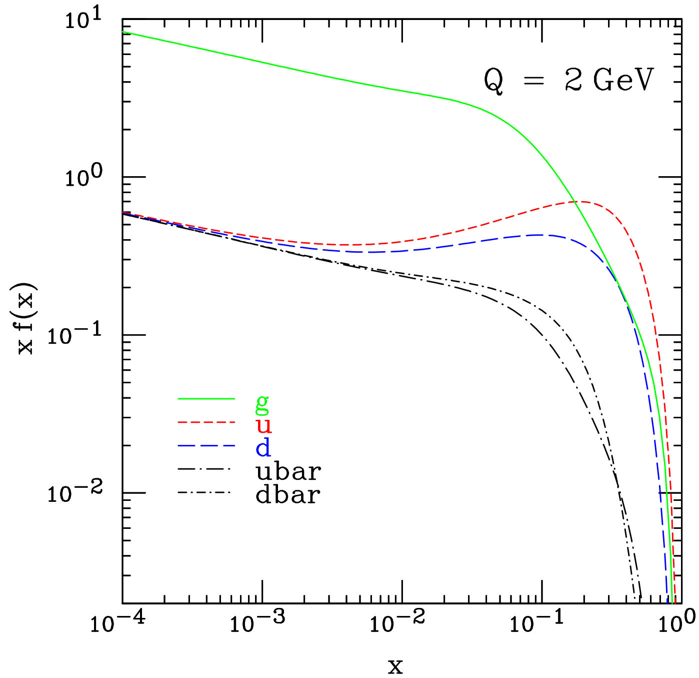
Kinematic region covered by data

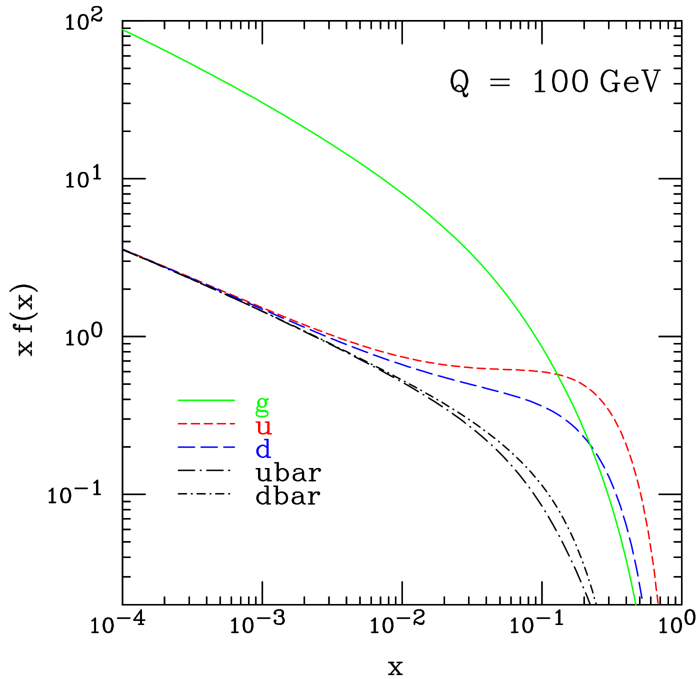


Data with a wide range of scales are tied together by the DGLAP evolution.

Consistency between the different processes can be tested only by applying QCD to tie them together in a global fit.

Typical parton distribution results





- Valence quarks dominate for $x \to 1$
- Gluon dominates for $x \to 0$, especially at large Q

Uncertainty Ranges

Based on many studies of the effect of removing portions of the data set by experiment, or by type of experiment, or by cuts on Q or x etc., we estimate the allowed uncertainty region as the region of parameter space where

$$\chi^2 < \chi^2_{\text{BestFit}} + T^2$$

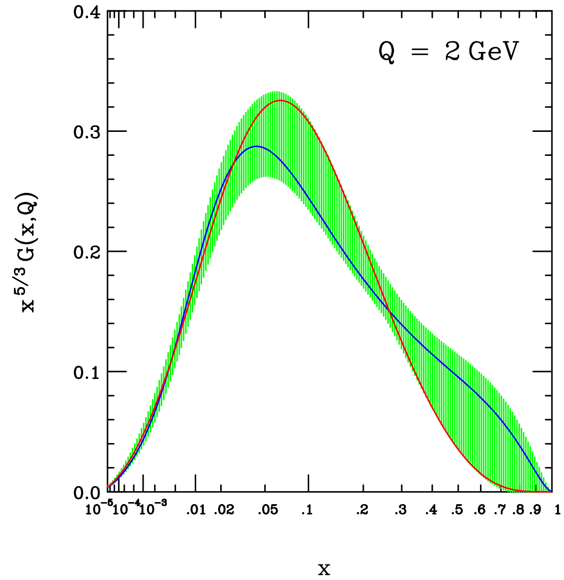
with $T \approx 5$ for an effectively "$1\,\sigma$" error.

This is quite different from the $T \approx 1$ that would be expected if the experimental errors were known and Gaussian, and the theoretical errors were negligible.

The "allowed" fits at 90 % confidence have $\Delta\chi^2 = 100$ above the Best Fit, which has $\chi^2 \approx N_{\text{pts}} \approx 2000$. Their average difference from the data is thus larger than the Best Fit by only $\sqrt{2100/2000}$, i.e., 2.5 %. Fits allowed by $\Delta\chi^2 = 100$ therefore look good when plotted with the data, in typical cases where $\Delta\chi^2$ is spread over many experiments and many points.

(The similarity between $\Delta\chi^2 = 100$ and $\sqrt{2\,N_{\text{pts}}}$ is coincidental.)

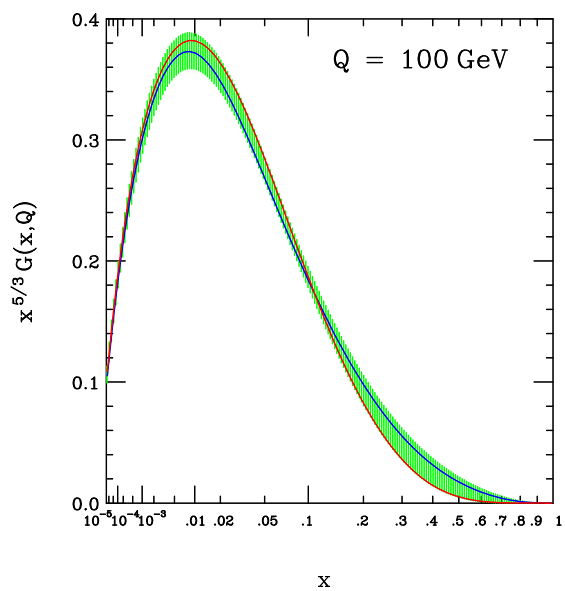
Uncertainty of Gluon distribution



$\Delta\chi^2 = 100$ uncertainty band
Weight 50 for CDF Jets
Weight 50 for DØ Jets

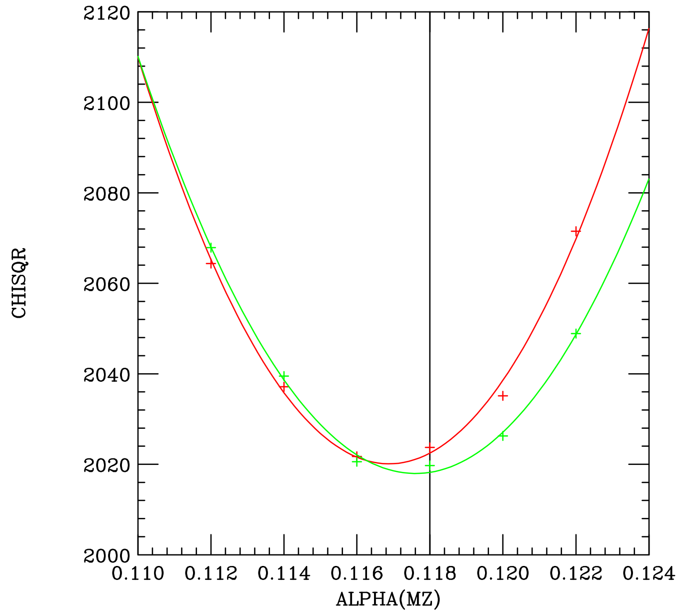
Consistency check: Uncertainty estimated by $\Delta\chi^2 = 100$ is comparable to the difference between nominally similar experiments.

(Area under curve is proportional to momentum fraction carried by gluon – strongly constrained by DIS data. Hence the envelope itself is not an allowed solution.)



Convergent Evolution: Uncertainty is smaller at large Q.

χ^2 for Global Fit vs $\alpha_s(m_Z)$



Red curve (traditional CTEQ) and Green curve (QCDNUM, ~MRST) correspond to different choices for defining $\alpha_s(Q)$ at NLO.

If assume $\Delta\chi^2 = 100$ defines the 2σ limit, we get $\alpha_s(m_Z) = 0.1169 \pm 0.0036$ (0.1176 ± 0.0039)

- Consistent with the LEP Working Group compilation $0.1201 \pm 0.0003 \pm 0.0048$, which shows that the Global Fit is consistent with the standard model.

- We fix $\alpha_s(m_Z) = 0.1180$ in the standard CTEQ6 PDFs. (Particle Data Group currently gives world average 0.1187 ± 0.0020.)

Definitions for $\alpha_s(Q)$ at NLO

Several choices of the definition of $\alpha_s(Q)$ at NLO are in use:

- QCDNUM choice (MRST is close to this):

$$Q\, d\alpha/dQ = c_1\alpha^2 + c_2\alpha^3$$

  where

$$\begin{aligned} c_1 &= -\beta_0/(2\pi) \quad \text{with} \quad \beta_0 = 11 - (2/3)n_f \\ c_2 &= -\beta_1/(8\pi^2) \quad \text{with} \quad \beta_1 = 102 - (38/3)n_f \,. \end{aligned}$$

- CTEQ standard choice:

$$\alpha(Q) = c_3\,[1 - c_4 \ln(L)/L]/L,$$

  where

$$\begin{aligned} L &= \ln[(Q/\Lambda)^2] \\ c_3 &= -2/c_1 \\ c_4 &= -2\,c_2/c_1^2 \,. \end{aligned}$$

(Particle Data Group use the NNLO generalization of the CTEQ choice.)

SUSY Search by PDF analysis

PDF extraction is sensitive to many features of the standard model. Have just shown how it can be used to measure $\alpha_s(m_Z)$.

We can introduce non-SM assumptions and see if they raise or lower χ^2. I have previously done this to measure the valence quark numbers $N_u = 2$ and $N_d = 1$. (Measuring the N in $SU(N)$ of color would be even more fun.)

In the subject at hand, the SM analysis was modified by assuming the existence of a light SUSY gluino, which changes the PDF analysis in three ways:

1. Evolution of $\alpha_s(Q)$ is made slower.

2. DGLAP evolution is modified because of momentum carried by gluinos. (For simplicity, the gluinos are included only in LO, so they don't feed back into the normal partons.)

3. Additional contributions to hard scattering – in particular to inclusive jet production, where $\tilde{g}$ might improve the fit to CDF and D0 data.

SUSY effect on $\alpha_s(Q)$

$$
\begin{aligned}
Q\, d\alpha/dQ &= c_1\alpha^2 + c_2\alpha^3 \\
c_1 &= -\beta_0/(2\pi) \\
c_2 &= -\beta_1/(8\pi^2)
\end{aligned}
$$

where

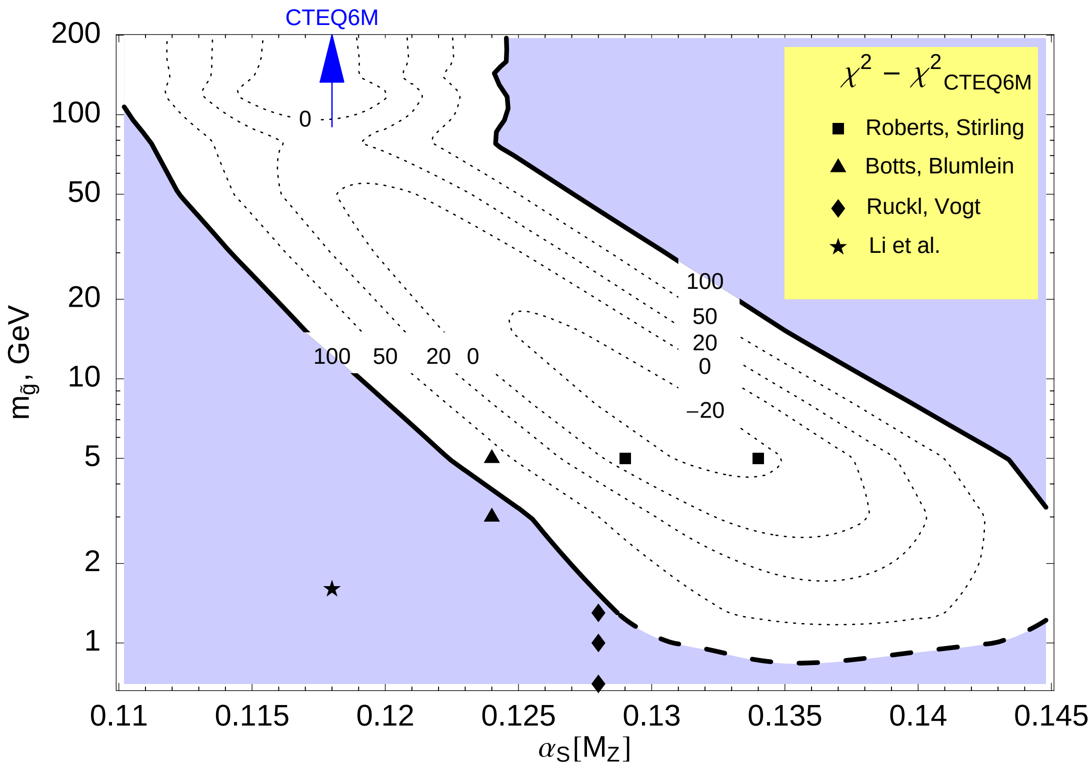
$$
\begin{aligned}
\beta_0 &= 11 - \frac{2}{3}n_f - 2n_{\tilde{g}} - \frac{1}{6}n_{\tilde{f}} \\
\beta_1 &= 102 - \frac{38}{3}n_f - 48n_{\tilde{g}} - \frac{11}{3}n_{\tilde{f}} + \frac{13}{3}n_{\tilde{g}}n_{\tilde{f}}\,.
\end{aligned}
$$

n_f is the number of quark flavors
$n_{\tilde{g}}$ is the number of gluinos
$n_{\tilde{f}}$ is the number of squark flavors.

To leading order, one generation of gluinos $\tilde{g}$ contributes the equivalent of 3 quark flavors, while one squark flavor is equivalent to only one-fourth of a quark flavor. Hence we can neglect any light squark contributions.

We implement the modified coefficients β_0 and β_1 for $n_{\tilde{g}} = 1$ and $n_{\tilde{f}} = 0$ in our numerical calculation to full NLO accuracy.

Results



All of the results are contained in the contour plot of $\chi^2 - \chi^2_{\text{CTEQ6}}$ as a function of $M_{\tilde{g}}$ and $\alpha_s(M_Z)$.

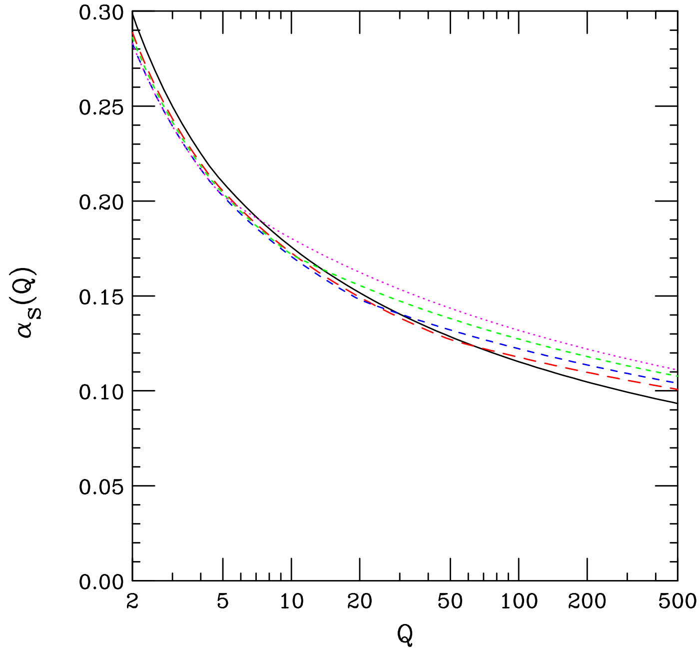
- At $M_{\tilde{g}} > 200\,\text{GeV}$, SUSY effects are negligible so the fits reduce to the previous α_s study.

- The shaded region is excluded: $\Delta\chi^2 > 100$.

- Saddle point at $M_{\tilde{g}} \sim 40 - 100\,\text{GeV}$ has fine structure due to interactions between $M_{\tilde{g}}$ and individual DØ and CDF data points.

- Valley with $5\,\text{GeV} < M_{\tilde{g}} < 20\,\text{GeV}$ has $\Delta\chi^2 \approx -25$ $\Rightarrow$ $\sim 1\,\sigma$ "suggestion" of a light gluino.

$\alpha_s(Q)$ for fits in the Valley of Low χ^2



Choose $\alpha_s(m_Z)$ to minimize χ^2 at each $m_{\tilde{g}}$

Black	$\alpha_s(m_Z) = 0.1169$	$m_{\tilde{g}} = \infty$
Red	$\alpha_s(m_Z) = 0.1188$	$m_{\tilde{g}} = 50\,\text{GeV}$
Blue	$\alpha_s(m_Z) = 0.1234$	$m_{\tilde{g}} = 20\,\text{GeV}$
Green	$\alpha_s(m_Z) = 0.1286$	$m_{\tilde{g}} = 10\,\text{GeV}$
Magenta	$\alpha_s(m_Z) = 0.1333$	$m_{\tilde{g}} = 5\,\text{GeV}$

Not unexpectedly, the $\alpha_s(Q)$ values are about the same for all good fits at small Q, where most of the global data set is located. $Q < 2\,\text{GeV}$ doesn't matter because a $Q > 2\,\text{GeV}$ cut is imposed on the data set.

The increased $\alpha_s(Q)$ at larger Q probably contributes to improved fit to the inclusive jet data.

The high $\alpha_s(M_Z)$ end of the valley may be excluded by LEP measurements, so the suggested $M_{\tilde{g}}$ is probably more like $10 - 20\,\mathrm{GeV}$.

Other "measurements" of $\alpha_s(M_Z)$, such as lattice calculations or the extraction from τ lifetime would need to be corrected for the effect of the gluino on the evolution of α_s.