Bounds on the mass of a light gluino from a global PDF analysis of hadron scattering data

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PDF=parton distribution function

If light gluinos (or other new colored particles) exist, can a CTEQ-type parton distribution analysis of hadron scattering data (DIS, Drell-Yan process, jet production at large E_T,...) constrain their masses?

Once admitted, light SUSY particles (i.e., $m < 100$ GeV)

✷ change the evolution of the strong coupling strength $\alpha_s(\mu)$

✓ Question: can the changes accommodate measurements at both $\mu = m_\tau$ and $\mu = m_Z$?

✷ as constituents of hadrons, provide additional partonic degrees of freedom and share in the hadron's momentum along with the SM constituents $\rightarrow$ gluino PDF $\tilde{g}(x, Q^2)$

✓ $\tilde{g}(x, Q^2)$ is generated perturbatively from splitting e.g. $g \rightarrow \tilde{g}\tilde{g}$ for $Q > m_{\tilde{g}}$

✓ how large can $\tilde{g}(x, Q^2)$ be?

✷ contribute to hard-scattering processes as incident partons and/or produced particles. Gluinos materialize as hadron jets and may increase the rate for jet production at large transverse energy E_T

Current study

New! A series of fits to the CTEQ6 set of data for various $m_{\tilde{g}}$ and $\alpha_s(M_Z)$

All standard model contributions are evaluated in QCD at NLO

$\tilde{g}$ contributions to the PDF evolution and jet production evaluated at Born level (sufficient because $\tilde{g}(x) \ll q(x),\ g(x)$)

New! Tevatron jet data $p\bar{p} \to$ jet $+\ X$ at large E_T are included

New! Quantitative bounds on $m_{\tilde{g}}$ from the PDF error analysis

New! Conclusions on the allowed values of $m_{\tilde{g}}$ depend strongly on what is assumed for $\alpha_s(M_Z)$, the value at which the evolution of $\alpha_s(\mu)$ is pinned (but we must and do fit data at all μ)

What is known about $\alpha_s(M_Z)$?

✷ Combined analysis of all Z-pole data within the context of the SM *(Combined LEP and SLD collaborations, hep-ex/0312023)*

$\alpha_s(M_Z) = 0.1187 \pm 0.0027$

✷ SM world-average *(Bethke, hep-ex/0211012)*

$\alpha_s(M_Z) = 0.1183 \pm 0.0027$

obtained from a variety of determinations at different scales μ

✷ SUSY-QCD contributions can affect the extraction of $\alpha_s(\mu)$. A recent estimate finds *(Luo and Rosner PL B569, 194 (2003))*

$\alpha_s(M_Z) = 0.118 - 0.126 \pm 0.005$

Variation in the central value arises from uncertainty in the size of SUSY-QCD corrections to the Z width from, e.g., $Z \to b\bar{\tilde{b}}\tilde{g}/\bar{b}\tilde{b}\tilde{g}$

✷ In our PDF analysis, we perform a series of fits to the hadron scattering data in which $\alpha_s(M_Z)$ is varied over the range

$0.110 \leq \alpha_s(M_Z) \leq 0.150$

We then impose the direct Z-pole 2σ bounds on $\alpha_s(M_Z)$ to establish bounds on $m_{\tilde{g}}$

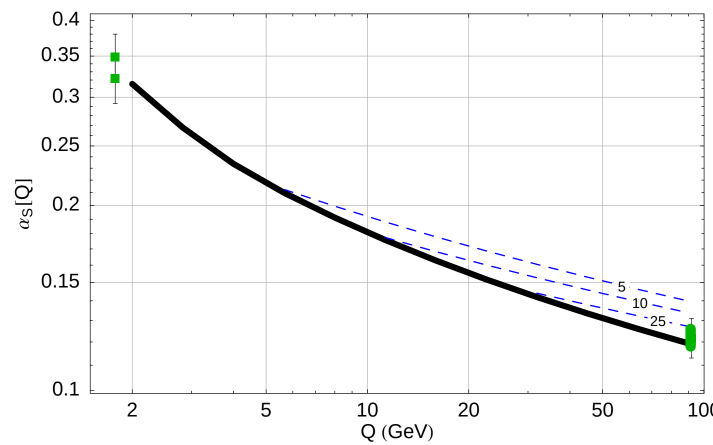
The major effect of $\tilde{g}$: slower evolution of $\alpha_s(\mu)$ from scale $\mu \sim m_{\tilde{g}}$ to large μ (implemented to NLO in our analysis)

$$\mu \frac{\partial}{\partial \mu} \alpha_S(\mu) = -\left[\beta_0 \frac{\alpha_S^2}{2\pi} + \beta_1 \frac{\alpha_S^3}{2^3 \pi^2} + \ldots\right]$$

where

$$\beta_0 = 11 - \frac{2}{3} n_f - 2 n_{\tilde{g}} - \frac{1}{6} n_{\tilde{f}}$$

n_f, $n_{\tilde{g}}$, $n_{\tilde{f}}$ are the numbers of active quarks, gluinos, and squarks



1 generation of gluinos contributes as 3 quark flavors

1 squark flavor contributes as 1/4 quark flavor (can be neglected)

Slower evolution of α_s affects parton densities. The effects can be balanced partially by a larger $\alpha_s(M_Z)$ within experimental uncertainties

Parton distribution function analysis

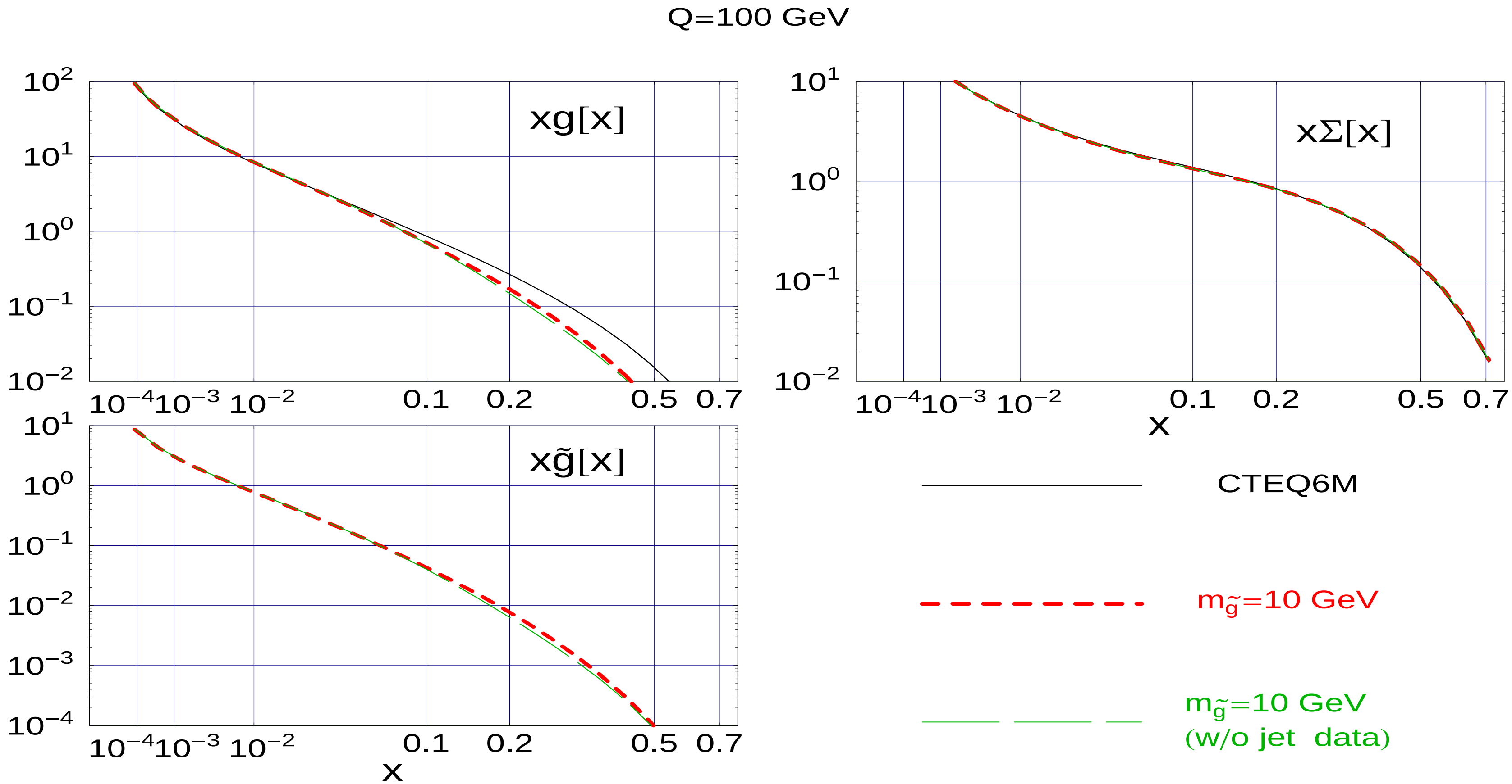
- Distributions $p(x, Q^2)$ are parametrized at starting reference scale Q_0 and evolved to all $Q > Q_0$ with the DGLAP evolution equations
  - ✓ Cross sections are calculated based on the parton distributions
  - ✓ Agreement with experiment is measured by χ^2
  - ✓ PDF shape parameters at $Q = Q_0$ are varied to minimize χ^2
  - ✓ We set $Q_0 = m_{\tilde{g}}$ or $Q_0 = m_c$, whichever is smaller
- Coupled DGLAP equations in the presence of a light gluino:

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} \Sigma(x,\mu^2) \\ g(x,\mu^2) \\ \tilde{g}(x,\mu^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \times$$

$$\times \int_x^1 \frac{dy}{y} \begin{pmatrix} P_{\Sigma\Sigma}\left(x/y\right) & P_{\Sigma g}\left(x/y\right) & P_{\Sigma\tilde{g}}\left(x/y\right) \\ P_{g\Sigma}\left(x/y\right) & P_{gg}\left(x/y\right) & P_{g\tilde{g}}\left(x/y\right) \\ P_{\tilde{g}\Sigma}\left(x/y\right) & P_{\tilde{g}g}\left(x/y\right) & P_{\tilde{g}\tilde{g}}\left(x/y\right) \end{pmatrix}$$

$$\times \begin{pmatrix} \Sigma(y,\mu^2) \\ g(y,\mu^2) \\ \tilde{g}(y,\mu^2) \end{pmatrix}$$

Example of the gluon, singlet, and gluino distributions ($xg(x)$, $x\Sigma(x)$, and $x\tilde{g}(x)$) for $\alpha_s(M_Z) = 0.118$ and $m_{\tilde{g}} = 10$ GeV, at $Q = 100$ GeV



✓ Gluino density is very small $\tilde{g}(x) \ll g(x), \Sigma(x)$

✓ Gluinos remove momentum from the gluon density at $x \gtrsim 0.05$

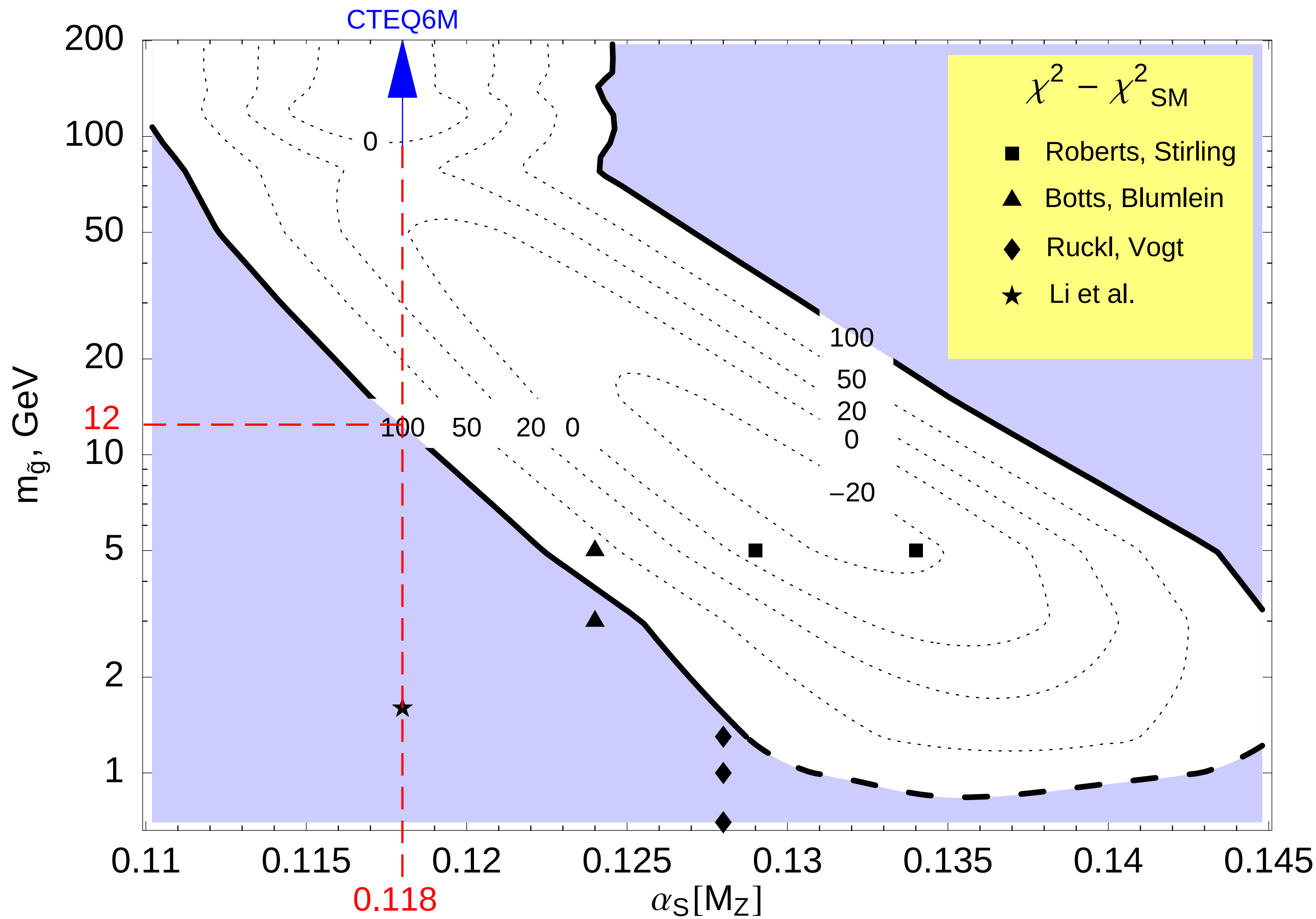
✓ High-E_T hadron jet data are crucial for constraining $m_{\tilde{g}}$

Once SUSY particles are admitted as degrees of freedom, we must consider their impact on all hard scattering processes

- Hadron jet production in $\bar{p} + p \to \text{jet} + X$:
  - ✓ We include $\mathcal{O}(\alpha_s^2)$ subprocesses with gluinos produced in the final state and either one or no gluinos in the initial state:
  - ✓ $q + \bar{q} \to \tilde{g} + \tilde{g}$ and $g + g \to \tilde{g} + \tilde{g}$
  - ✓ $g + \tilde{g} \to g + \tilde{g}$ and $q + \tilde{g} \to q + \tilde{g}$
  - ✓ These are added to the $\mathcal{O}(\alpha_s^2)$ SM contributions to the jet rate, and they offset partially the loss of rate from the smaller gluon PDF

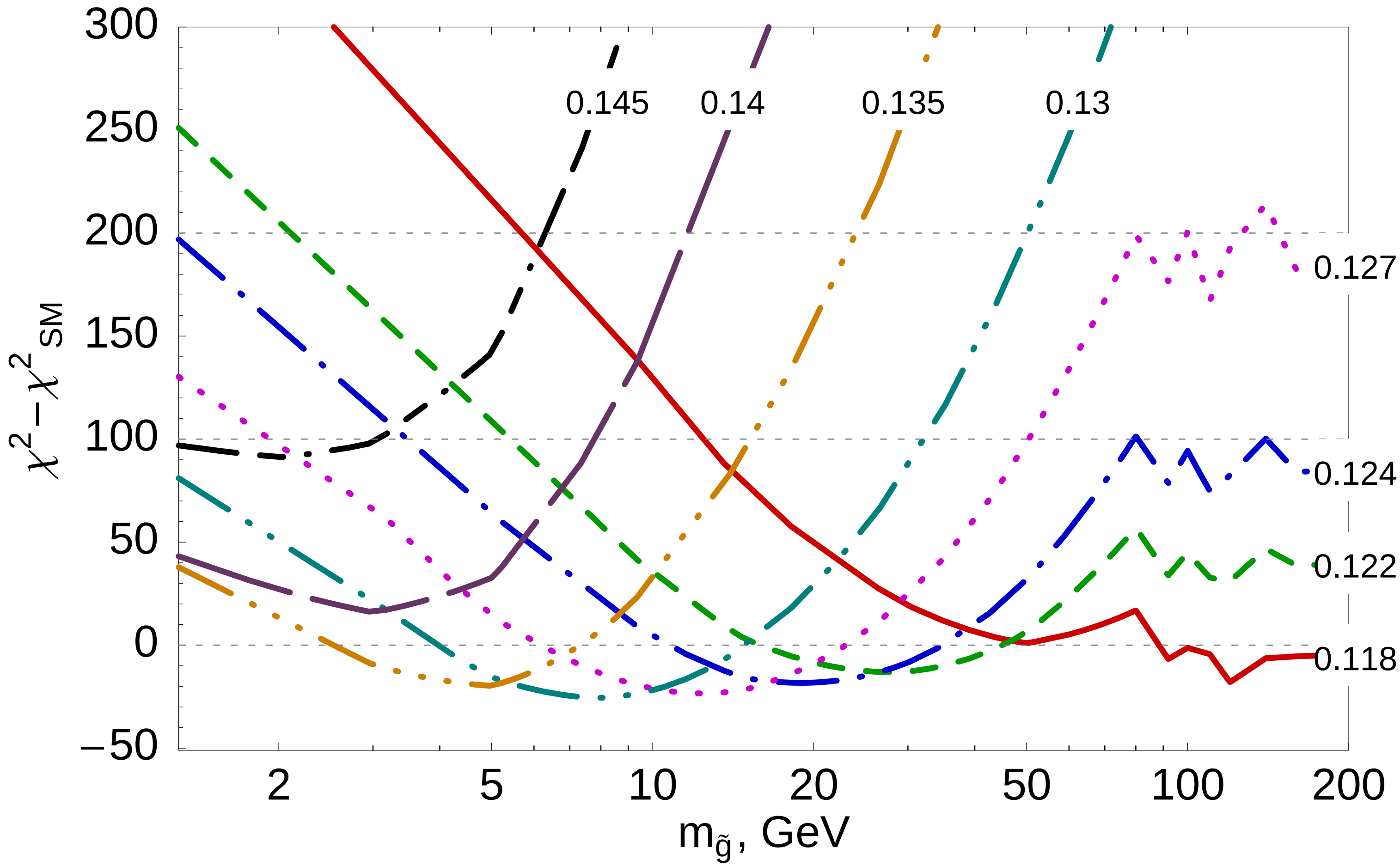
- In deep-inelastic scattering and in massive-lepton-pair production, the SM processes contribute at $\mathcal{O}(\alpha_s^0)$, but the SUSY processes come in at $\mathcal{O}(\alpha_s^1)$
  - ✓ We can neglect $\mathcal{O}(\alpha_s^1)$ SUSY subprocesses such as $\gamma + g \to \tilde{q} + \tilde{g}$ and $\mathcal{O}(\alpha_s^2)$ SUSY subprocesses $\gamma + q \to q + \tilde{g} + \tilde{g}$

Contour plot of $\Delta\chi^2 = \chi^2\left[\alpha_s(M_Z), m_{\tilde{g}}\right] - \chi^2_{\mathrm{CTEQ6M}}$



- ✓ Acceptable fit tolerance criterion: $\Delta\chi^2 < 100$
- ✓ $m_{\tilde{g}} > 12$ GeV at $\alpha_s(M_Z) = 0.118$

Dependence of $\Delta\chi^2$ on $m_{\tilde{g}}$ and $\alpha_s(M_Z)$



Values of $\alpha_s(M_Z)$ are marked on the curves

✓ $m_{\tilde{g}} > 12$ GeV at $\alpha_s(M_Z) = 0.118$

✓ $m_{\tilde{g}} > 5$ GeV at $\alpha_s(M_Z) = 0.122$

Comparison with bounds from analyses of LEP data

- Our global analysis:
  - ✓ $m_{\tilde{g}} > 12$ GeV for $\alpha_s(M_Z) = 0.118$
  - ✓ theoretically clean one-scale inclusive observables only
  - ✓ no assumptions about the stability of the superpartners
- Z boson width measurement *(P. Janot, 2003)*
  - ✓ $m_{\tilde{g}} > 6.3$ GeV at $\alpha_s(M_Z) = 0.118$
- Search for stable hadronizing gluinos
  - ✓ $m_{\tilde{g}} > 18$ GeV *(DELPHI, 2003)*; $m_{\tilde{g}} > 26.9$ GeV *(ALEPH, 2003)*
  - ✓ Does not apply if superpartners decay through R-parity violating channels *(Berger, Sullivan, 2003; Clavelli, Stremnitzer; 2003)*
- $m_{\tilde{g}} > 30 - 40$ GeV from the analysis of jet shape variables *(DELPHI, 2002)*
  - ✓ Multi-scale observables
  - ✓ Theoretical errors too optimistic?

Conclusions

- ✓ Model-independent bounds on color-octet fermions (gluinos)
- ✓ Features of our analysis
  - ◇ Fit the complete CTEQ6 set of inclusive hadron scattering data (1811 points) – high precision, broad x, Q^2 range
  - ◇ SUSY contributions to Tevatron jet production cross sections
  - ◇ CTEQ error analysis
- ✓ Gluino mass limits (smaller $m_{\tilde{g}}$ is allowed for larger $\alpha_s(M_Z)$)
  - ◇ $m_{\tilde{g}} >$12 GeV for $\alpha_s(M_Z) = 0.118$
  - ◇ Open possibility for $m_{\tilde{g}} = 10 - 20$ GeV if $\alpha_s(M_Z) > 0.119$
  - ◇ For $\alpha_s(M_Z) > 0.124$, $m_{\tilde{g}}$ is also bounded from above
  - ◇ The PDF analysis of current hadron scattering data is not sensitive to $m_{\tilde{g}} > 100$ GeV
- ✓ Complementary to bounds on $m_{\tilde{g}}$ from LEP data
- ✓ Potential for the PDF analysis to constrain new physics

Earlier PDF fits (Roberts, Stirling; Blümlein, Botts; Rückl, Vogt; 1993-1994) find gluinos with mass of 5 GeV or less are allowed by data available then

Li, Nadolsky, Yuan, Zhou (1998) conclude that gluinos with mass $m_{\tilde{g}} < 1.6$ GeV are disfavored by a fit to a subset of the CTEQ4 data (for $\alpha_s(M_Z) = 0.118$)

In these earlier analyses, only deep-inelastic lepton scattering (DIS) and vector boson production data are used (no data from hadron jet production at high-E_T, and no NLO contributions from gluino subprocesses to the cross sections)

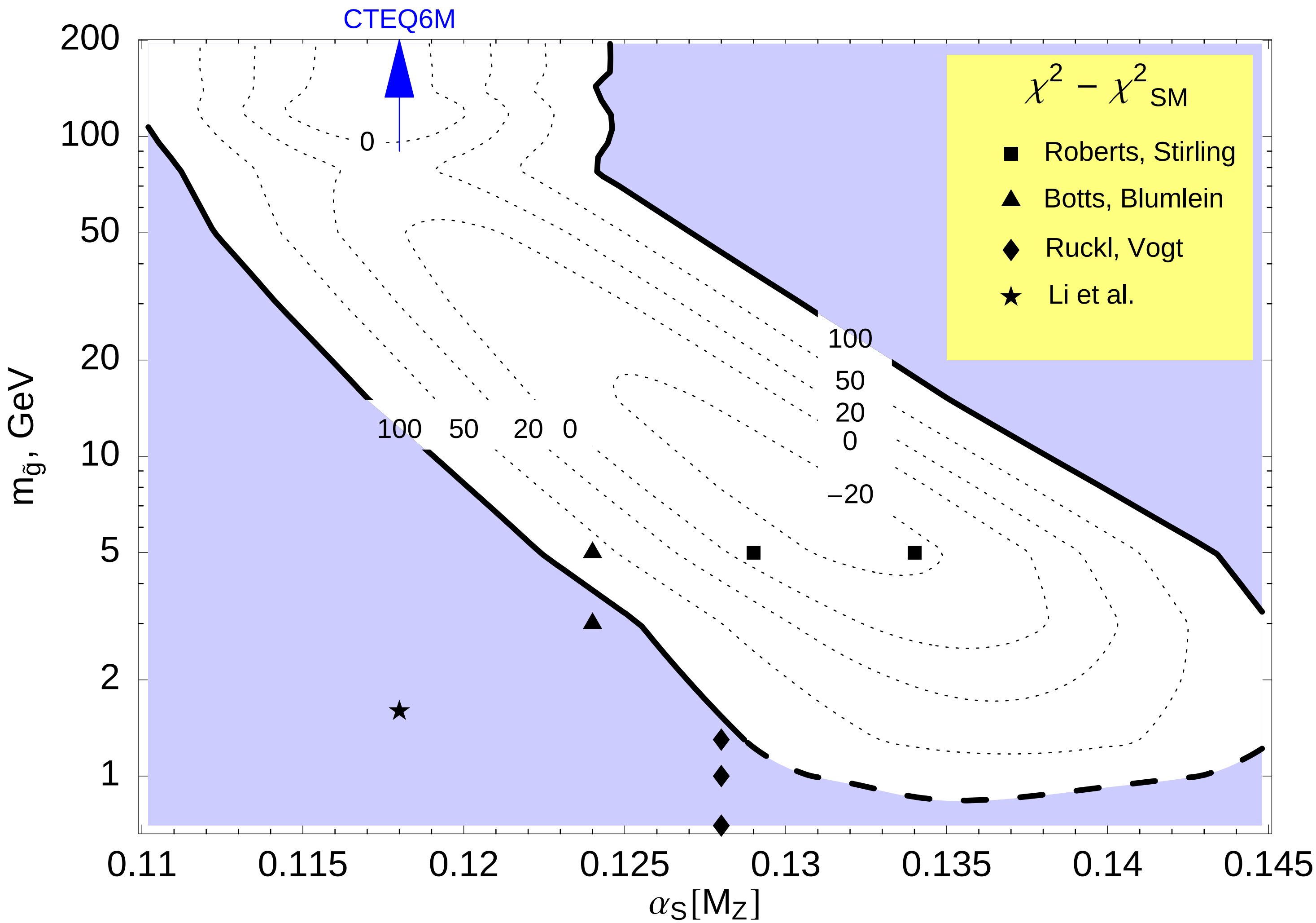
Our results show that the older fits for $m_{\tilde{g}} < 5$ GeV are excluded

Focus in this work on the possibility of gluinos with mass $m_{\tilde{g}}$ less than the "weak scale" $m_{\tilde{g}} < 100$ GeV. The PDF analysis of current hadron scattering data is not sensitive to $m_{\tilde{g}} > 100$ GeV

Assumptions in our work: $m_{\tilde{g}} \geq 0.7$ GeV; possible light bottom-squark contributions to the observables we consider are small and are not included

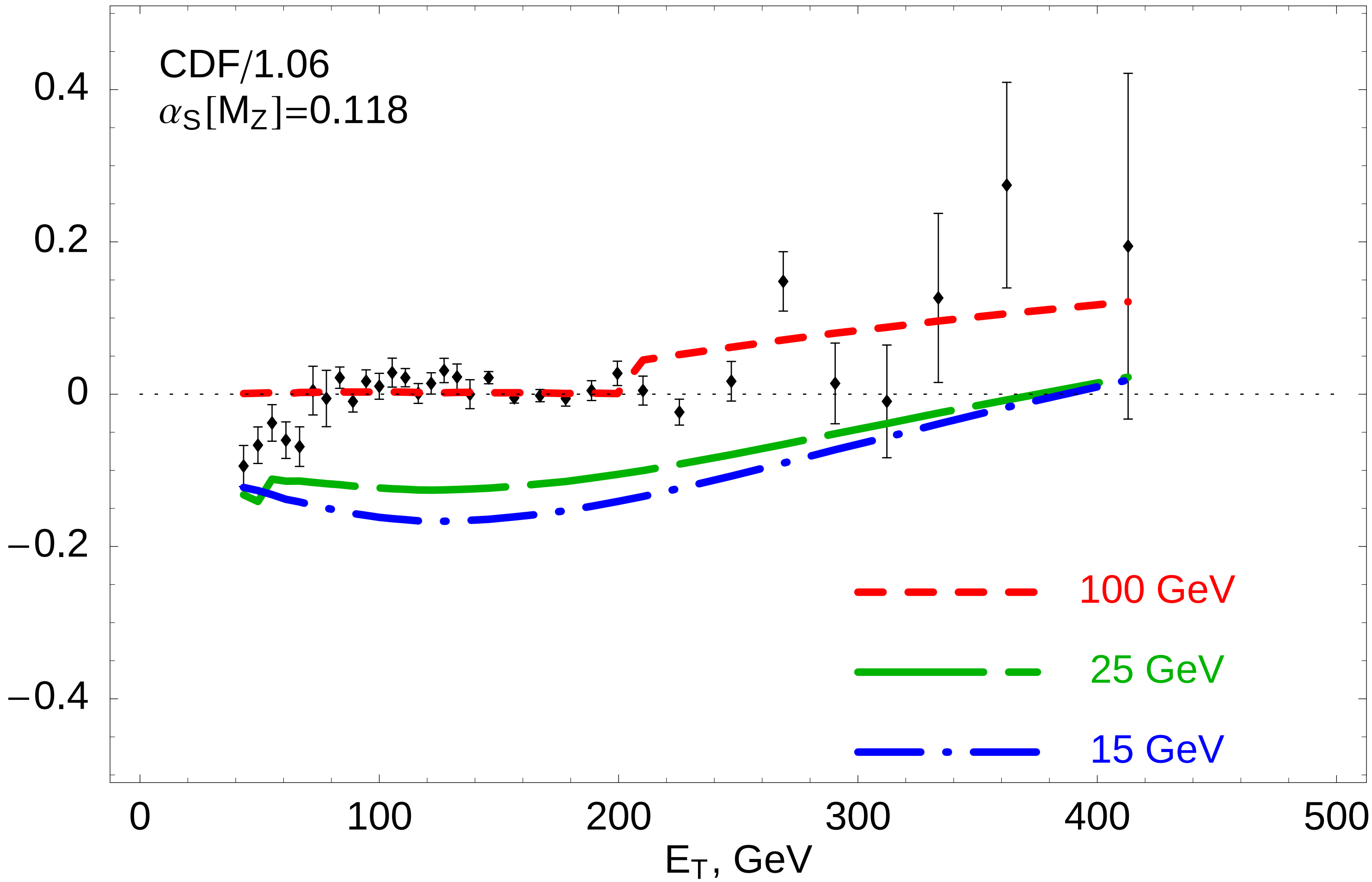
In earlier PDF analyses of light gluinos, only deep-inelastic lepton scattering (DIS) and vector boson production data are used. No data from hadron jet production at high-E_T, and no NLO contributions from gluino subprocesses to the cross sections

Contour plot for $\Delta\chi^2 = \chi^2\left[\alpha_s(M_Z), m_{\tilde{g}}\right] - \chi^2_{\text{CTEQ6M}}$



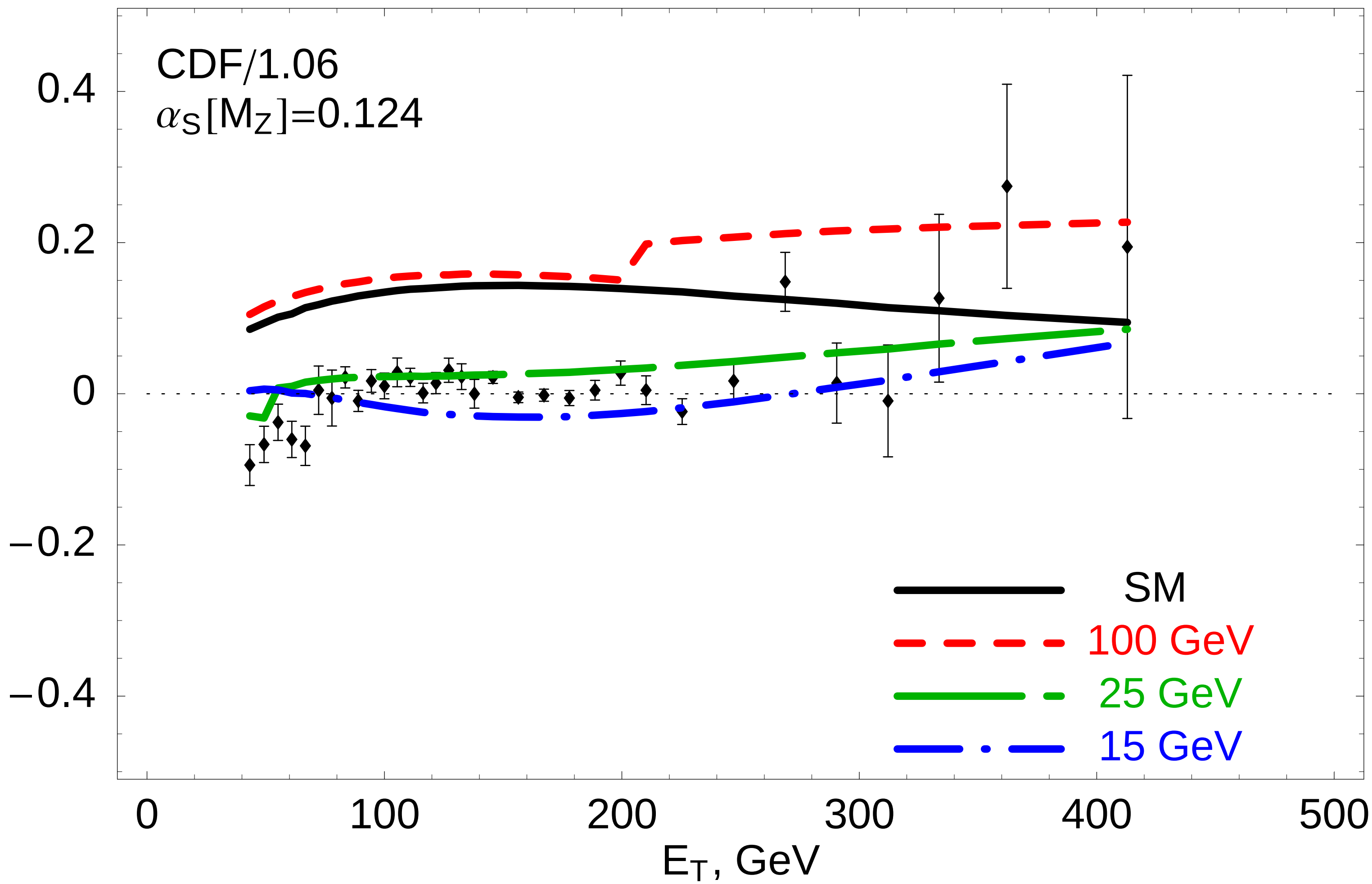
CTEQ6 tolerance criterion: fits with $\Delta\chi^2 > 100$ are excluded (shaded)

(Data-CTEQ6M)/CTEQ6M and (SUSY-CTEQ6M)/CTEQ6M for the CDF inclusive jet cross section and $\alpha_s(M_Z) = 0.118$



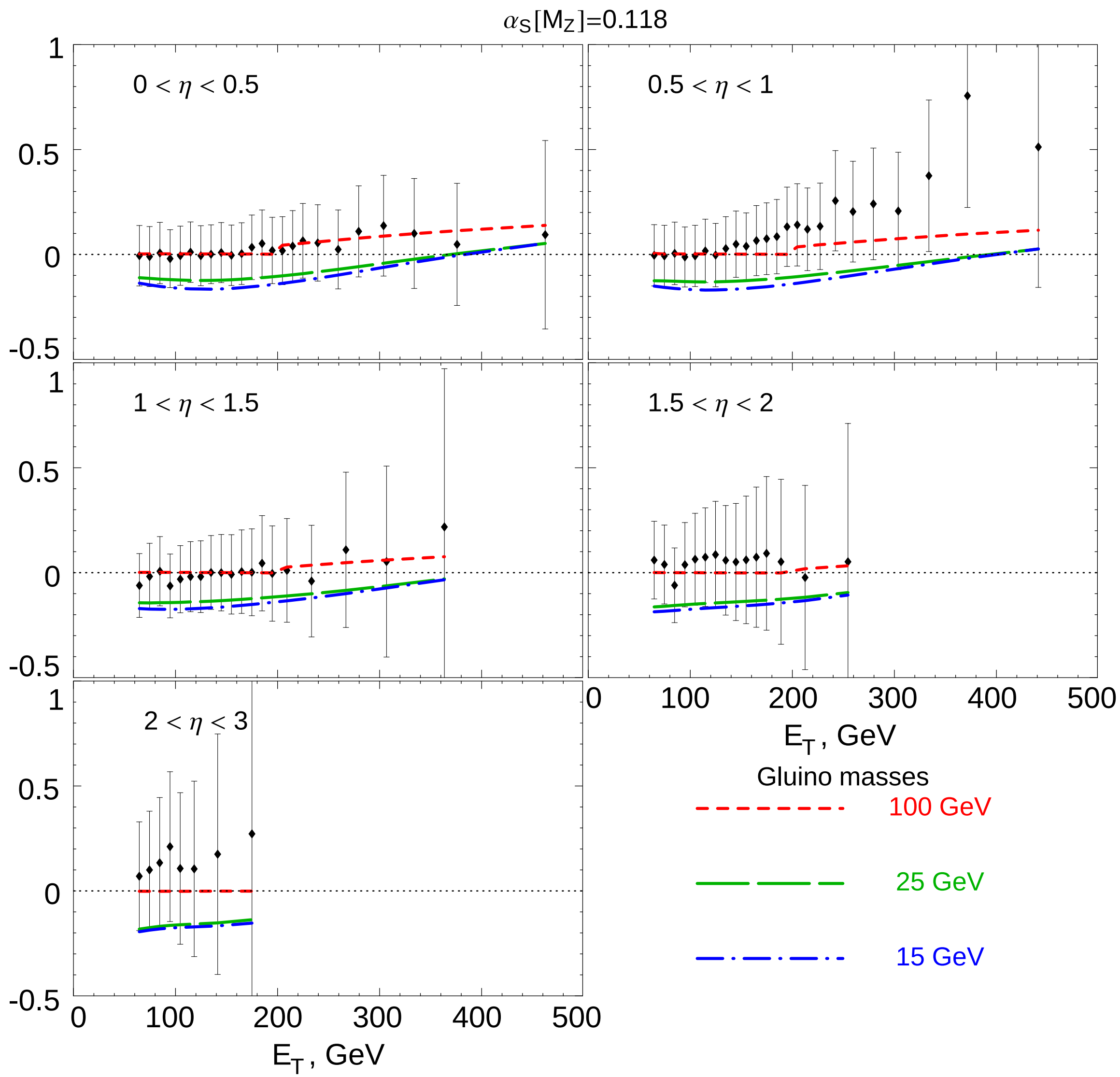
$m_{\tilde{g}} \sim 100$ GeV improves description of high-E_T jet data slightly

(Data-CTEQ6M)/CTEQ6M and (SUSY-CTEQ6M)/CTEQ6M for the CDF jet data and $\alpha_s(M_Z) = 0.124$ (2 σ above world average)

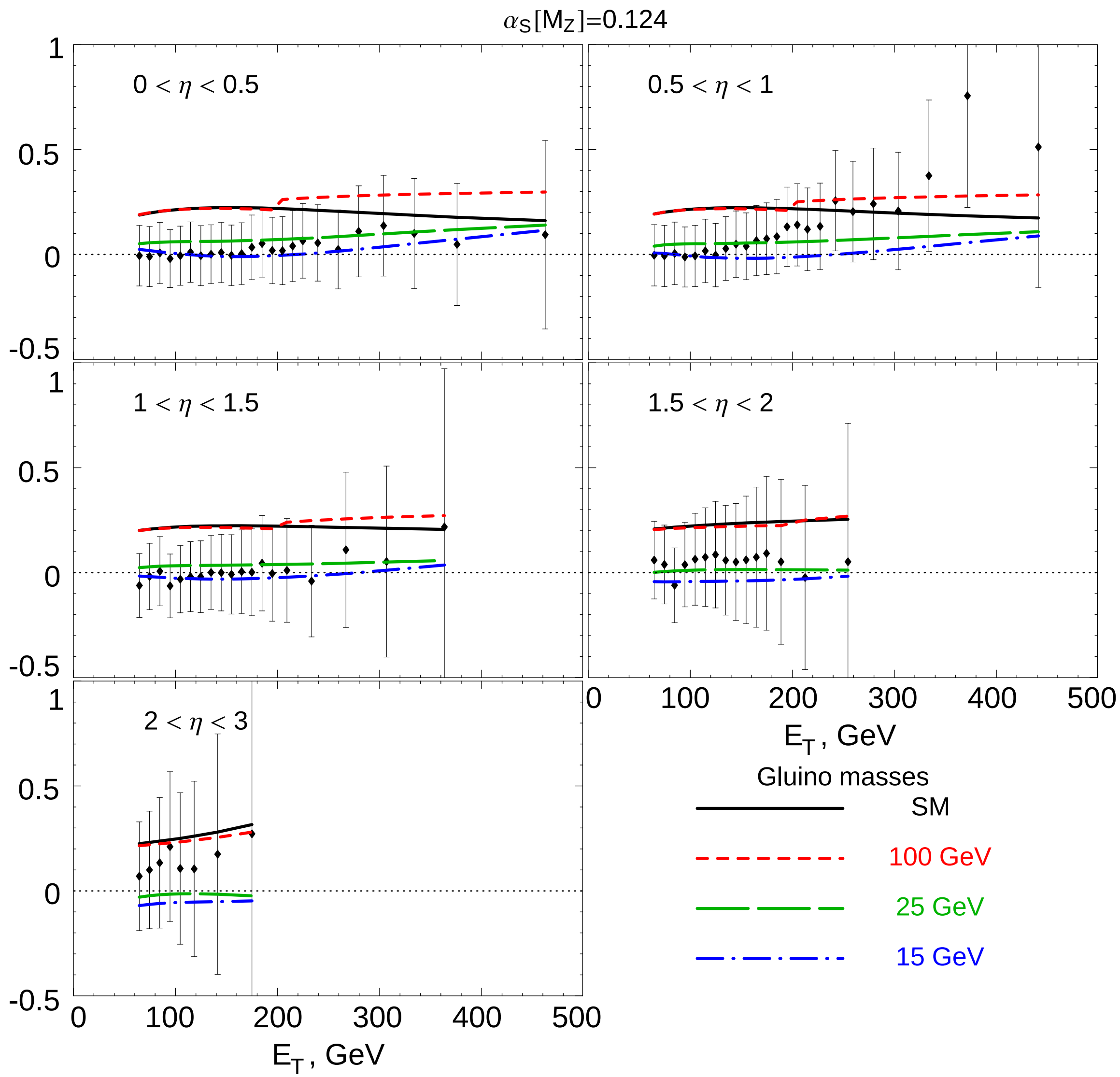


$m_{\tilde{g}} \sim$ 15 – 25 GeV provides a good description of high-E_T data if $\alpha_s(m_Z) \simeq 0.124$

(Data-CTEQ6M)/CTEQ6M and (SUSY-CTEQ6M)/CTEQ6M for the DØ jet data and $\alpha_s(M_Z) = 0.118$



(Data-CTEQ6M)/CTEQ6M and (SUSY-CTEQ6M)/CTEQ6M for the DØ jet data and $\alpha_s(M_Z) = 0.124$



Partial history of light gluino (LG) models ($m_{\tilde{g}} < 100$ GeV)

✓ Proposed in mid-70's (Fayet, Farrar)

✓ Discussed in the early 1990's as a means to explain apparent slower running of $\alpha_s(\mu)$ from scales μ of a few GeV to M_Z

✓ May appear in some SUSY models as the lightest superpartner (LSP)

✓ May appear in some gauge-mediated SUSY-breaking models

✓ $m_{\tilde{g}} \lesssim 6$ GeV ruled out by LEP data (?; see below)

✓ Berger, Harris, Kaplan, Sullivan, Tait, Wagner (2000):

gluino ($m_{\tilde{g}} = 12 - 16$ GeV)
+ bottom squark ($m_{\tilde{b}} = 2 - 5.5$ GeV)
= enhanced b-quark production at the Tevatron collider;
enhanced $B - \bar{B}$ time-averaged mixing

✓ Recent activity to rule out small $m_{\tilde{g}}$ by LEP groups (see below)

Fractions of the proton's momentum carried by parton types at $Q = 100$ GeV in the SM, and for a gluino with mass $m_{\tilde{g}} = 15$ GeV and $\alpha_s(M_Z) = 0.122$

Parton type	SM	$m_{\tilde{g}} = 15$ GeV, $\alpha_s(M_Z) = 0.122$
$u + \bar{u}$	25.2	25.4
$d + \bar{d}$	15.4	15.5
$s + \bar{s}$	5.3	5.1
$c + \bar{c}$	3.9	3.6
$b + \bar{b}$	2.5	2.3
Σ	52.3	51.9
g	47.5	44.7
$\tilde{g}$	0	3.2
Total:	100	100