ICHEP - Osaka - 2000

CONSTRAINTS ON $g(x, \mu_f^2)$ AND $\Delta g(x, \mu_f^2)$ FROM LEPTON PAIR PRODUCTION

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July 27, 2000

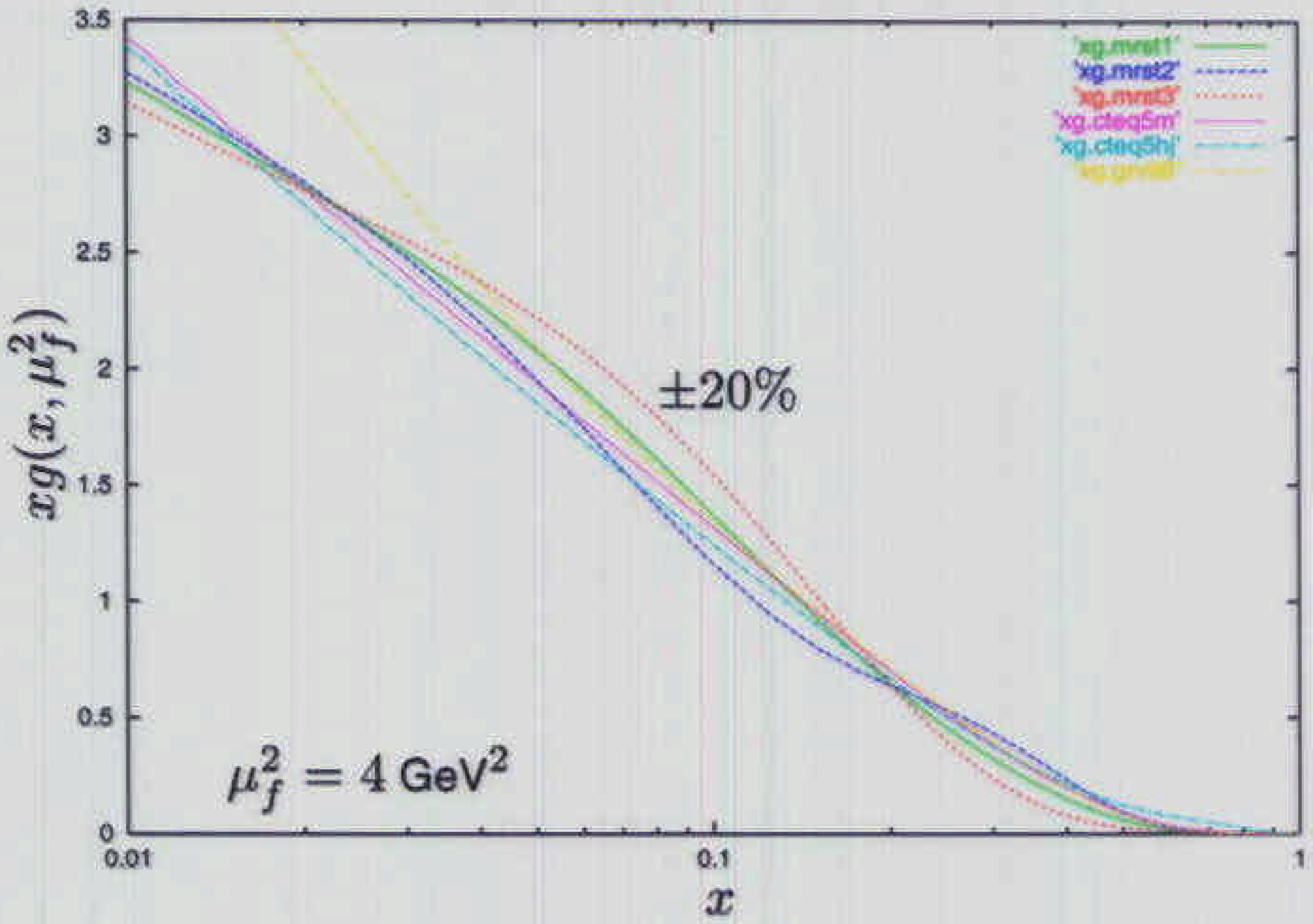
Outline:

- Introduction
- Next-to-Leading Order QCD Formalism
- Differential Cross Sections at Fixed Target and Collider Energies
- Longitudinal Spin Asymmetries at RHIC
- Summary

E.L. Berger, L.E. Gordon, M.Klasen, Phys.Rev. D58, 074012 (1998)
E.L. Berger, M.Klasen, Nucl.Phys.Proc.Suppl. 82, 179 (2000)
E.L. Berger, L.E. Gordon, M.Klasen, Phys.Rev. D62, 014014 (2000)

http://gate.hep.anl.gov/berger/seminars/ICHEPQCD.ps

UNPOLARIZED GLUON DISTRIBUTIONS



- A.Martin, R.Roberts, W.Stirling, R.Thorne, Eur.Phys.J. **C4**, 463 (1998):
  $xg(x,\mu_0^2 = 1.0\mathrm{GeV}^2) = A_g x^{-\lambda_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g x)$
- H.L. Lai *et al.* [CTEQ Collaboration], hep-ph/9903282:
  $xg(x,\mu_0^2 = 1.0\mathrm{GeV}^2) = A_g x^{-\lambda_g}(1-x)^{\eta_g}(1+\gamma_g x^{A_4})$
- M. Glück, E. Reya and A. Vogt, Eur. Phys. J. **C5**, 461 (1998):
  $xg(x,\mu_0^2 = 0.4\mathrm{GeV}^2) = A_g x^{-\lambda_g}(1-x)^{\eta_g}$
- H1/ZEUS:
  $xg(x,\mu_0^2 = 2/7\mathrm{GeV}^2) = A_g x^{-\lambda_g}(1-x)^{\eta_g}(1+\gamma_g x)$
- W. Giele, S. Keller, D. Kosower, Phys. Rev. **D58**, 094023 (1998):
  $xg(x,\mu_0^2 = 9.0\mathrm{GeV}^2) = A_g x^{-\lambda_g}(1-x)^{\eta_g}$

NEW CONSTRAINT: LEPTON PAIR PRODUCTION

- Massive lepton pair production dominated by $q\bar{q} \to \gamma^* X$
  "Drell-Yan process", traditionally $M_{\gamma^*} = Q$ large, Q_T^2 small
  → Extract $\bar{q}(x, \mu_f^2 = Q^2)$ and $\Delta\bar{q}(x, \mu_f^2 = Q^2)$ from data
  Complementary to DIS → Extract $(q + \bar{q})(x, \mu_f^2 = Q^2)$
- Prompt photon production dominated by $qg \to \gamma X$:
  "QCD Compton process", traditionally p_T^2 large, $Q^2 = 0$
  → Extract $g(x, \mu_f^2 = p_T^2)$ and $\Delta g(x, \mu_f^2 = p_T^2)$ from data
- Partonic subprocesses at finite Q_T, p_T are identical:
  - $q\bar{q} \to \gamma^{(*)} g$
  - $qg \to \gamma^{(*)} q$
  - Higher order processes
- Focus on modest mass, large transverse momentum,
  $Q_T > Q/2$
- Lepton pair production dominated by QCD Compton process
  → Extract $g(x, \mu_f^2)$ and $\Delta g(x, \mu_f^2)$ from data
- Relation between lepton pair and virtual photon production

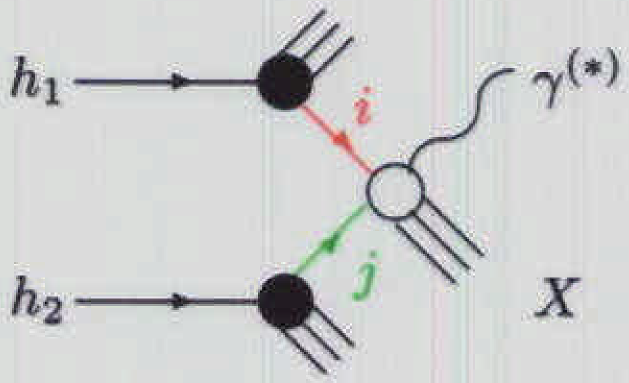
$$\frac{d^3\sigma_{h_1h_2}^{l\bar{l}}}{dQ^2 dQ_T^2 dy} = \left(\frac{\alpha_{em}}{3\pi Q^2}\right) \frac{d^2\sigma_{h_1h_2}^{\gamma^*}}{dQ_T^2 dy}(S, Q, Q_T, y)$$

"Drell-Yan factor" included in results for $h_1h_2 \to \gamma^* X$

LEPTON PAIR PRODUCTION

- Advantages:
  - No non-perturbative fragmentation contribution
    → Phenomenologically cleaner
  - No need to isolate the photon experimentally
    → Reduces systematic uncertainty
    → Removes theoretical infrared uncertainty
  - No need for intrinsic $< k_T >$
- Drawbacks:
  - Cross section lower due to "Drell-Yan factor"
  - Range in $x_g \simeq x_T = \frac{2Q_T}{\sqrt{S}}$ more limited
- Despite more restricted reach, valuable to investigate $g(x,\mu)$ with a process that has reduced experimental and theoretical systematic uncertainties with respect to prompt photon and hadronic jet production
- Suggestions:
  - Look at regions of low $Q \simeq 2$ GeV, Q_T large perturbation theory still valid
  - Use large bins in Q
  - Avoid ρ, J/Ψ, Υ resonances
  - Use otherwise neglected data

NEXT-TO-LEADING ORDER QCD FORMALISM



$Q_T,\, p_T \neq 0$

- Factorization:

$$\frac{d^2\sigma^{\gamma^*}_{h_1 h_2}}{dQ_T^2\,dy} = \sum_{ij} \int dx_1 dx_2 f^i_{h_1}(x_1, \mu_f^2) f^j_{h_2}(x_2, \mu_f^2) \frac{s\,d^2\hat{\sigma}^{\gamma^*}_{ij}}{dt\,du}(s, Q, Q_T, y; \mu_f^2)$$

$$\frac{d^2\Delta\sigma^{\gamma^*}_{h_1 h_2}}{dQ_T^2\,dy} = \sum_{ij} \int dx_1 dx_2 \Delta f^i_{h_1}(x_1, \mu_f^2) \Delta f^j_{h_2}(x_2, \mu_f^2) \frac{s\,d^2\Delta\hat{\sigma}^{\gamma^*}_{ij}}{dt\,du}(s, Q, Q_T, y$$

μ_f = Factorization Scale

- Expansion in α_s:

$$\frac{d^2\hat{\sigma}^{\gamma^*}_{ij}}{dt\,du} = \alpha_s(\mu^2)\frac{d^2\hat{\sigma}^{\gamma^*,(a)}_{ij}}{dt\,du} + \alpha_s^2(\mu^2)\frac{d^2\hat{\sigma}^{\gamma^*,(b)}_{ij}}{dt\,du} + \alpha_s^2(\mu^2)\frac{d^2\hat{\sigma}^{\gamma^*,(c)}_{ij}}{dt\,du} + \mathcal{O}(\alpha_s^3)$$

μ = Renormalization Scale

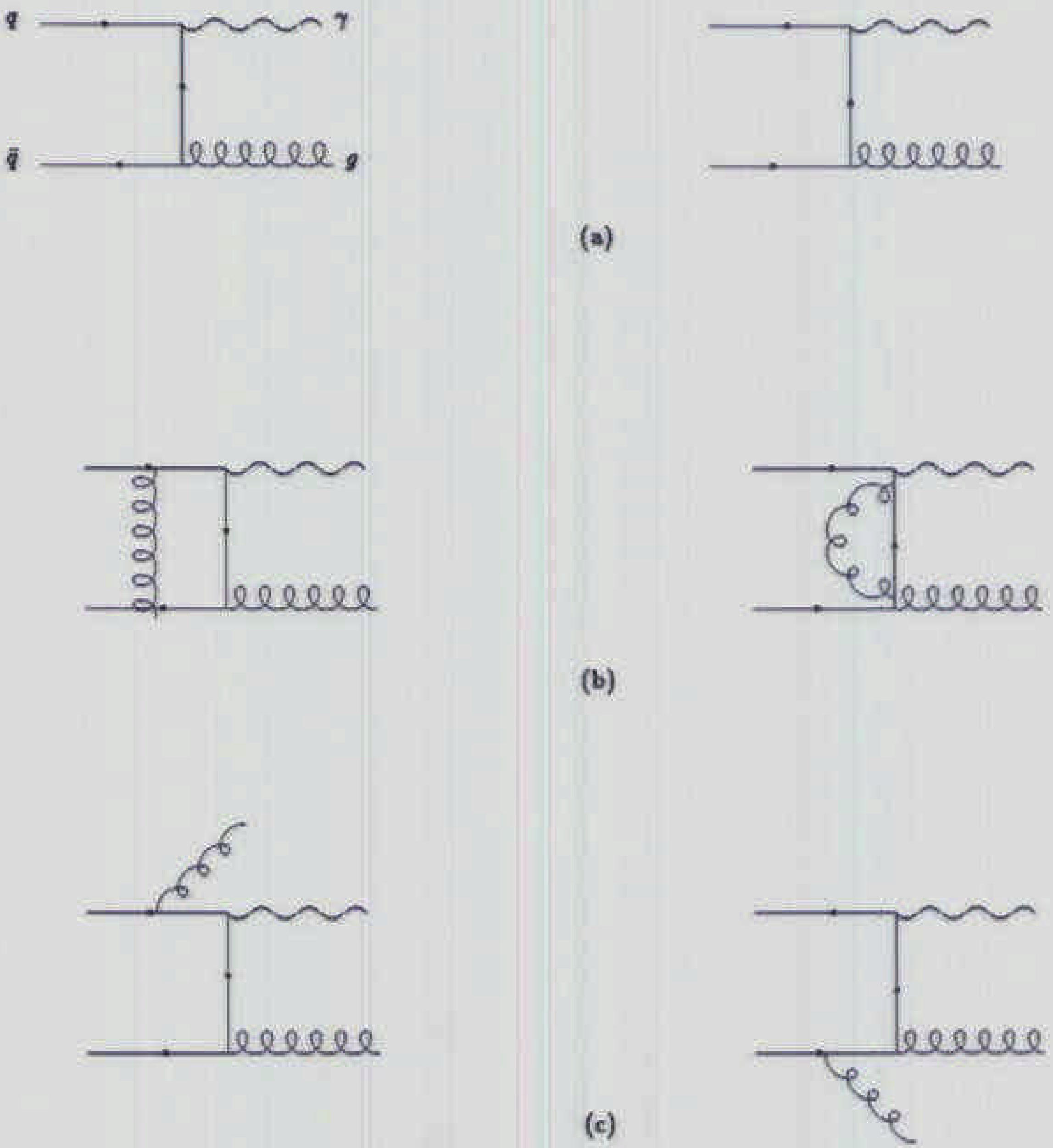
2-loop α_s with 5 flavors

- Choice of Scales:

$$\mu_f = \mu = \sqrt{Q^2 + Q_T^2} \overset{Q^2 \to 0}{\longrightarrow} p_T$$

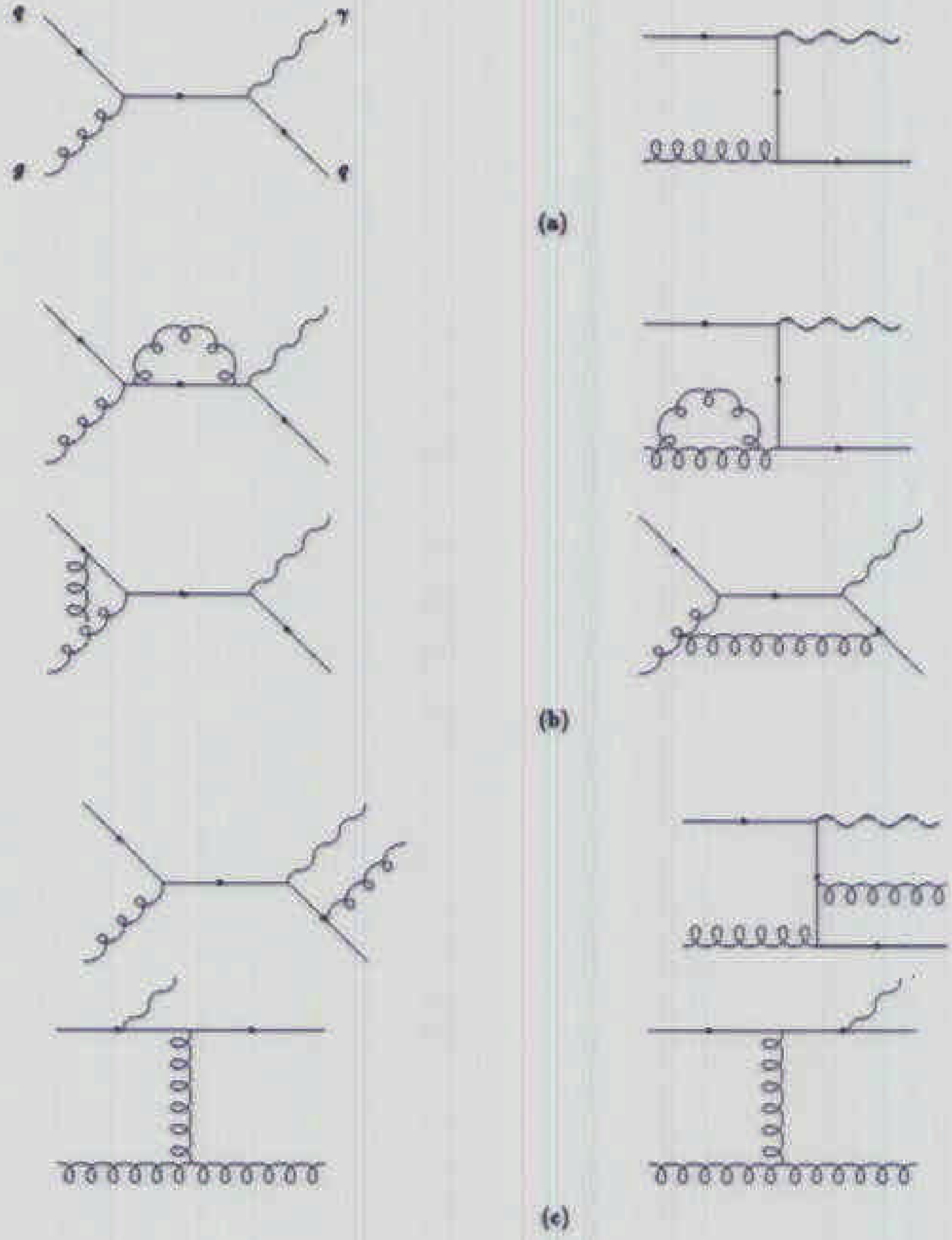
NEXT-TO-LEADING ORDER QCD FORMALISM

- $q\bar{q} \to \gamma^{(*)}X$



NEXT-TO-LEADING ORDER QCD FORMALISM

- $qg \rightarrow \gamma^{(*)} X$



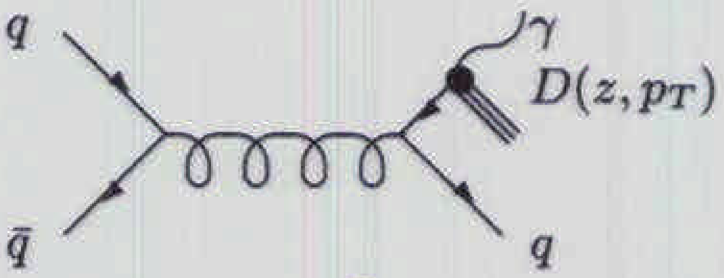
NEXT-TO-LEADING ORDER QCD FORMALISM

- Gluon emission and gluon loop corrections to the LO $\mathcal{O}(\alpha_s)$ $q\bar{q} \to g\gamma^{(*)}$ and $gq \to q\gamma^{(*)}$ subprocesses
- Real $\mathcal{O}(\alpha_s^2)$ subprocesses without $\mathcal{O}(\alpha_s)$ counterparts:
  - $qq \to qq\gamma^{(*)}$
  - $gg \to q\bar{q}\gamma^{(*)}$
  - $q\bar{q} \to q\bar{q}\gamma^{(*)}$
- Complete set is included in our NLO calculations:
  - Lepton pair production
  - Prompt photon production
- Dimensional regularization: Integration in $4 - 2\epsilon$ dimensions
- $\overline{\mathrm{MS}}$ renormalization scheme removes UV singularities
- KLN-cancellation of virtual and real IR singularities
- Polarized lepton pair production: Only LO results available
- Correspondence of lepton pair and prompt photon production for the *"Direct Contribution"*:

$$\frac{d^2\sigma^{\gamma^*}_{h_1 h_2}}{dQ_T^2\,dy}(S, Q, Q_T, y) \overset{Q\to 0}{\longrightarrow} \frac{d^2\sigma^{\gamma}_{h_1 h_2}}{dp_T^2\,dy}(S, p_T, y)$$

NEXT-TO-LEADING ORDER QCD FORMALISM

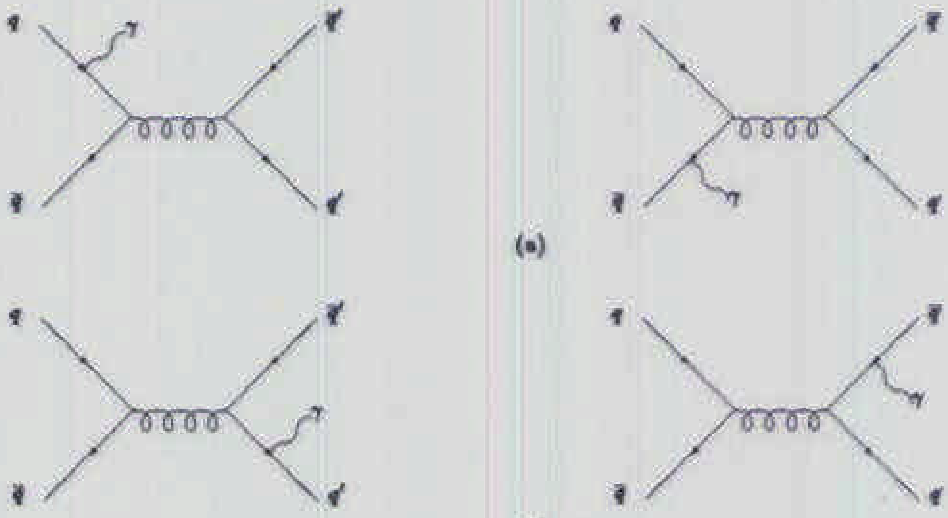
- Important difference: Prompt photon has a long-distance non-perturbative *"Fragmentation Contribution"*



- Hard partonic subprocess is $\mathcal{O}(\alpha_s^2)$
- Asymptotic behavior of the fragmentation function:

$$D(z, p_T) \sim \ln p_T^2 \sim \mathcal{O}(\alpha_s^{-1})$$

- Hadronic cross section is $\mathcal{O}(\alpha_s)$ as the LO direct contribution
- Phenomenologically important at small p_T
- Related to NLO collinear quark-photon singularity:



(a)

(b)

NEXT-TO-LEADING ORDER QCD FORMALISM

- Prompt photon cross section:

$$\frac{1}{\epsilon} 2K_\gamma \frac{-(t^2+u^2)(2s^2+2st+t^2+2su+2tu+u^2)}{s(t+u)^4} = \frac{1}{\epsilon} f(s,t,u)$$

  Dimensional regularization: $1/\epsilon$ pole

- Drell-Yan cross section:

$$\begin{aligned}
&\ln\left[\frac{s+Q^2-s_2+\lambda}{s+Q^2-s_2-\lambda}\right] K_{DY} \\
&\left[\frac{1}{\lambda^5}\left(\frac{3Q^2u^2(u-t)(t+u-2s_2)}{s} + \frac{3(s-Q^2)u^2(u^2-t^2)}{Q^2+s-s_2}\right)\right. \\
&+\frac{1}{\lambda^3}\left(\frac{u(2ss_2-2s_2^2+2s_2t-su+4s_2u-tu-3u^2)}{s}\right. \\
&\qquad\left.+\frac{u^2}{Q^2+s-s_2}\left(-2s-t+\frac{t^2}{s}+3u-\frac{u^2}{s}\right)\right) \\
&\left.+\frac{1}{\lambda}\left(\frac{1}{s}\left(\frac{3s}{4}-\frac{s_2}{2}+u\right)+\frac{1}{Q^2+s-s_2}\left(\frac{3s}{2}+\frac{5u}{2}+\frac{2u^2}{s}\right)\right)\right] \\
&+\ (t \longleftrightarrow u) \\
&= \ln\left[\frac{s+Q^2-s_2+\lambda}{s+Q^2-s_2-\lambda}\right] g(s,t,u,Q^2).
\end{aligned}$$

  with $\lambda = \sqrt{(t+u)^2 - 4Q^2 s_2}$ and $s_2 = s+t+u-Q^2$.
  Mass regularization: No $1/\epsilon$ pole, instead $\ln Q^2$ terms

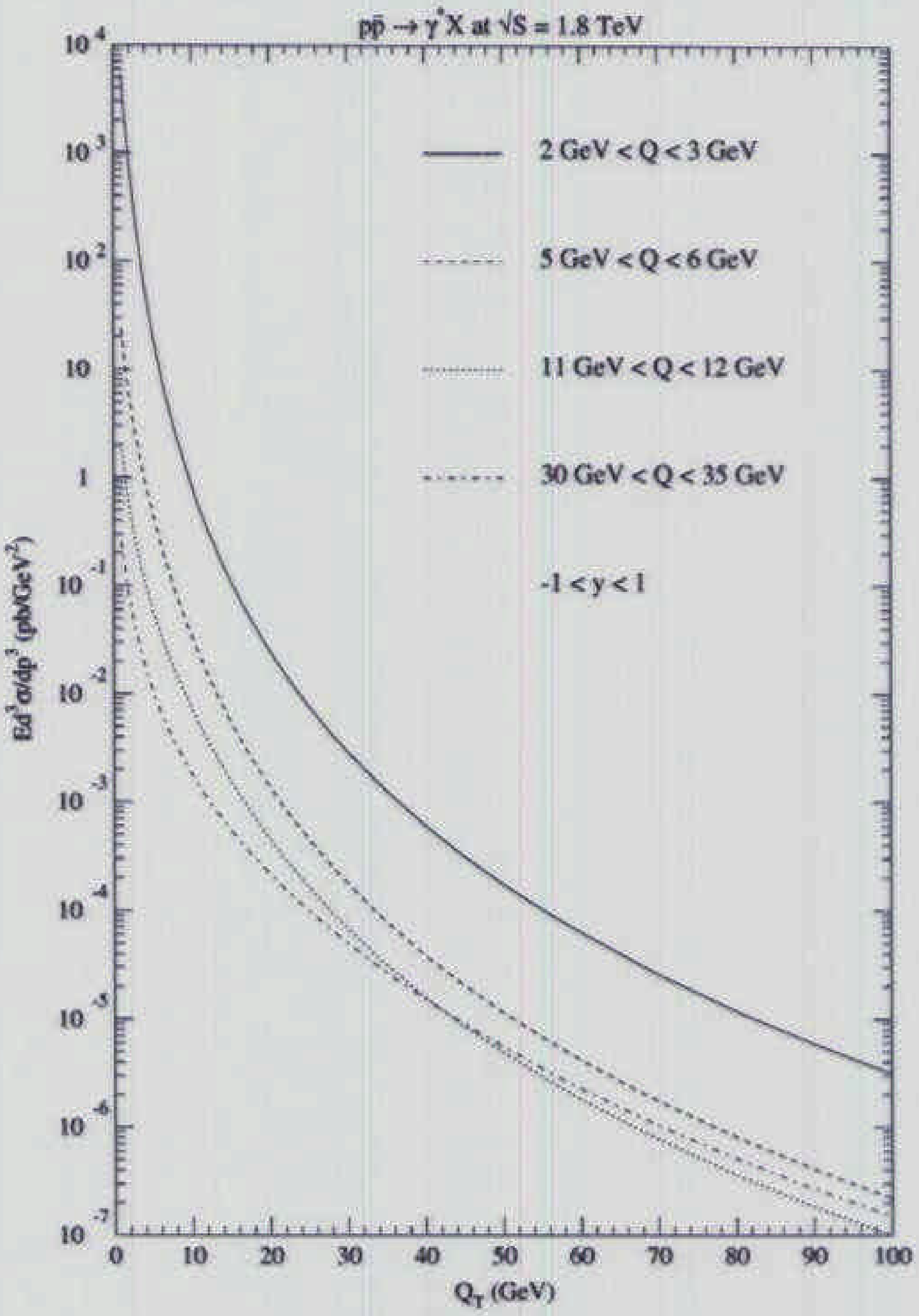
- K_γ, K_{DY} contain color, electric charge, phase space factors

- $g(s,t,u,Q^2) \overset{Q^2\to 0}{\longrightarrow} f(s,t,u)$. It contains
  - Altarelli-Parisi splitting function $P_{q\to\gamma}(z)$
  - Born matrix element $\hat{\sigma}^{q\bar{q}}$

DIFFERENTIAL CROSS SECTIONS AT FIXED TARGET AND COLLIDER ENERGIES

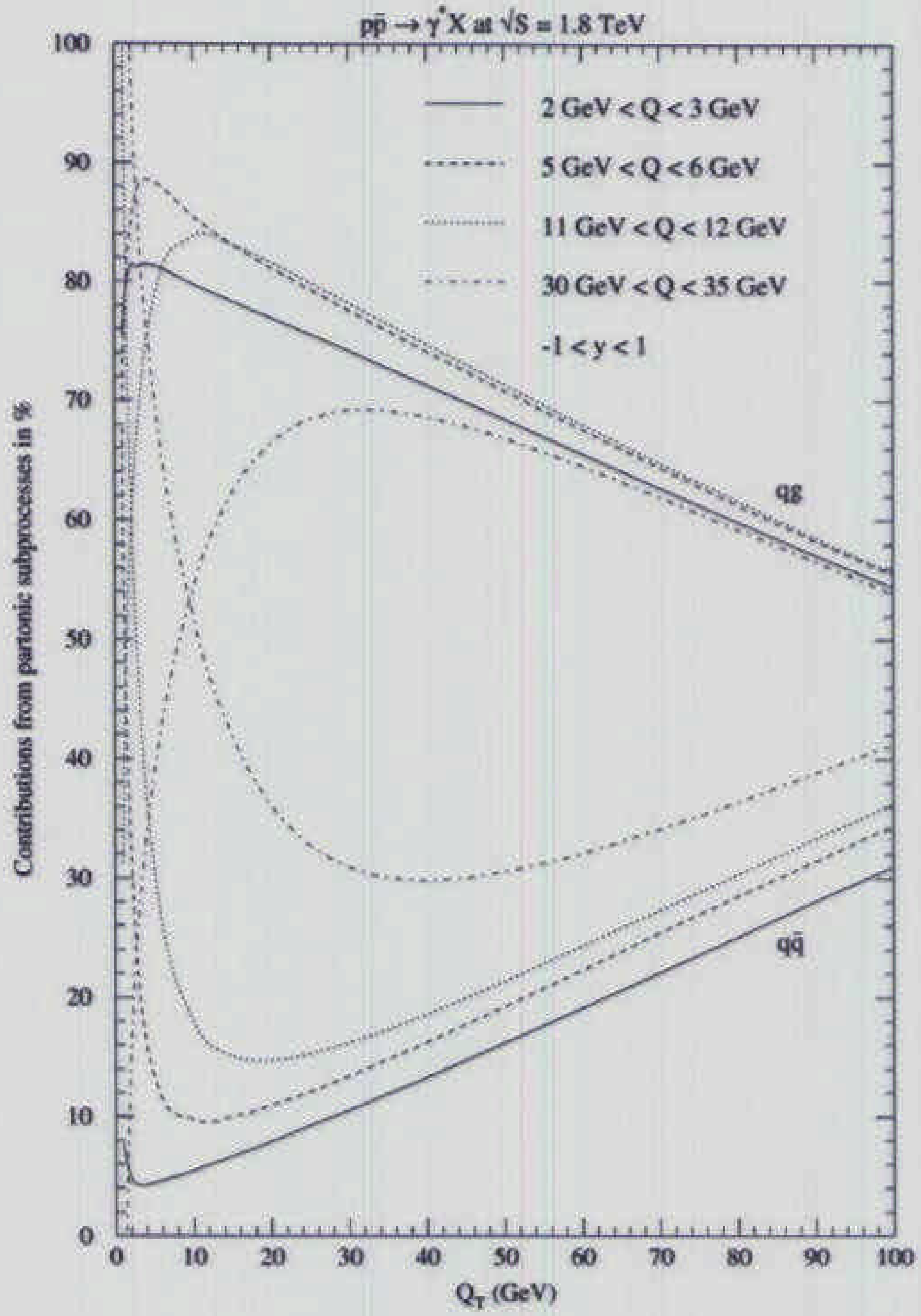
- Collider experiments:
  - $p\bar{p} \to \gamma^{(*)} X$ at $\sqrt{S} = 1.8 - 2.0$ TeV (CDF, D0)
  - $pp \to \gamma^{(*)} X$ at $\sqrt{S} = 50 - 500$ GeV (RHIC)
  - $pp \to \gamma^{(*)} X$ at $\sqrt{S} = 14$ TeV (LHC)
  - $p\bar{p} \to \gamma^{(*)} X$ at $\sqrt{S} = 630$ GeV (UA1)
- Fixed target experiments:
  - $pN \to \gamma^* X$ at $p_{\text{lab}} = 800$ GeV, N=^{2}H (E772)
  - $pN \to \gamma^* X$ at $p_{\text{lab}} = 820$ GeV, N=C,Ti,Al,W (HERA-B)
- Study size of cross sections as a function of Q_T, p_T for
  - Prompt photon production
  - Lepton pair production
- Demonstrate accessibility of lepton pair production
- Show dominance of qg incident channel for $Q_T > Q/2$
- Test sensitivity to parton (gluon) densities:
  - CTEQ (4M, 5M, 5HJ)
  - MRST (central gluon, $g \uparrow, g \downarrow$)
  - GRV 98

CROSS SECTIONS AT COLLIDER ENERGIES



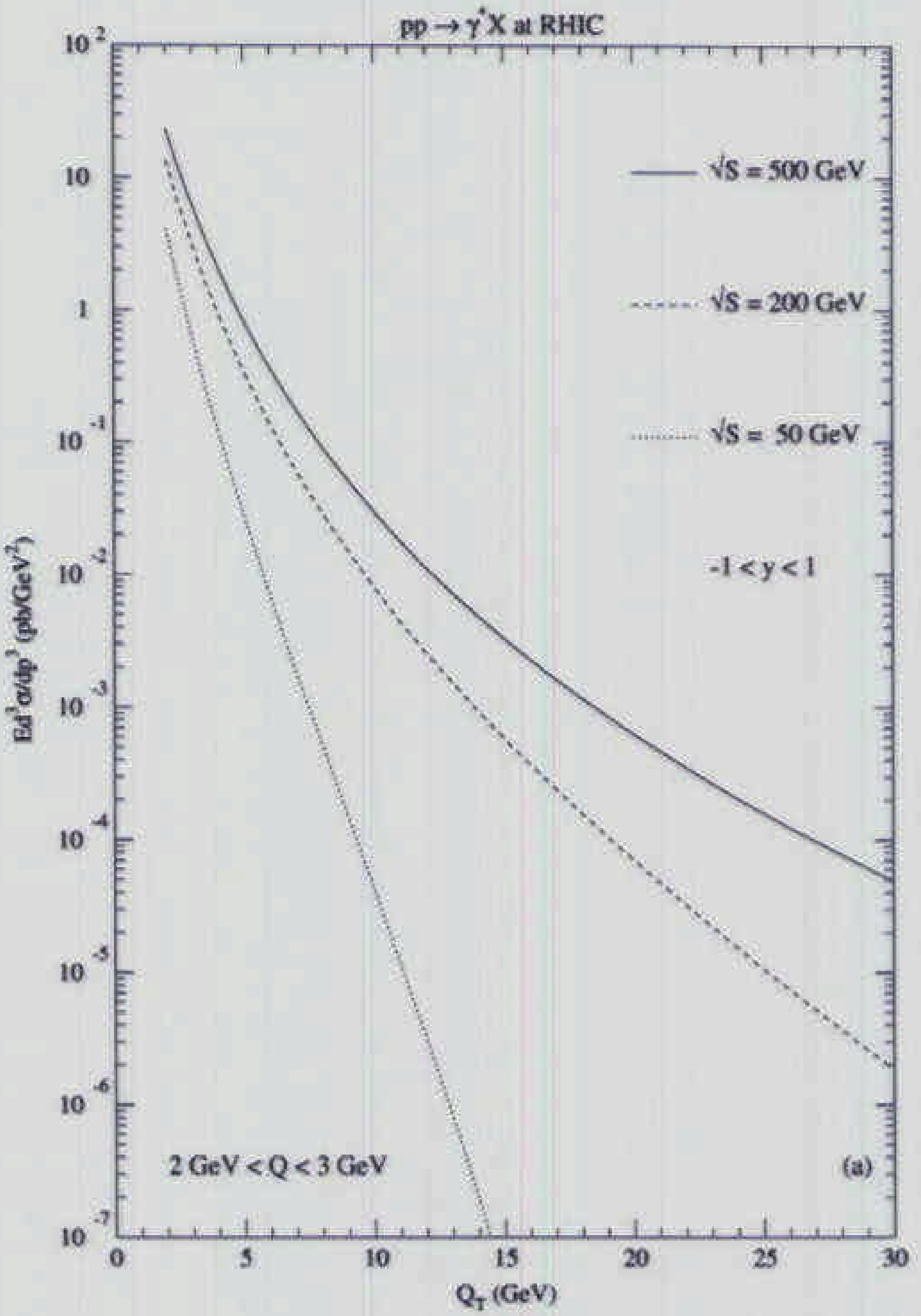
- Lepton pair production at the FNAL Tevatron collider
- "Drell-Yan factor" reduces cross section by factor of 400
- Cross section measurable to $p_T = 30$ GeV, $x_T = 0.03$
- Important to look at regions of low $Q \simeq 2$ GeV, Q_T large

CROSS SECTIONS AT COLLIDER ENERGIES



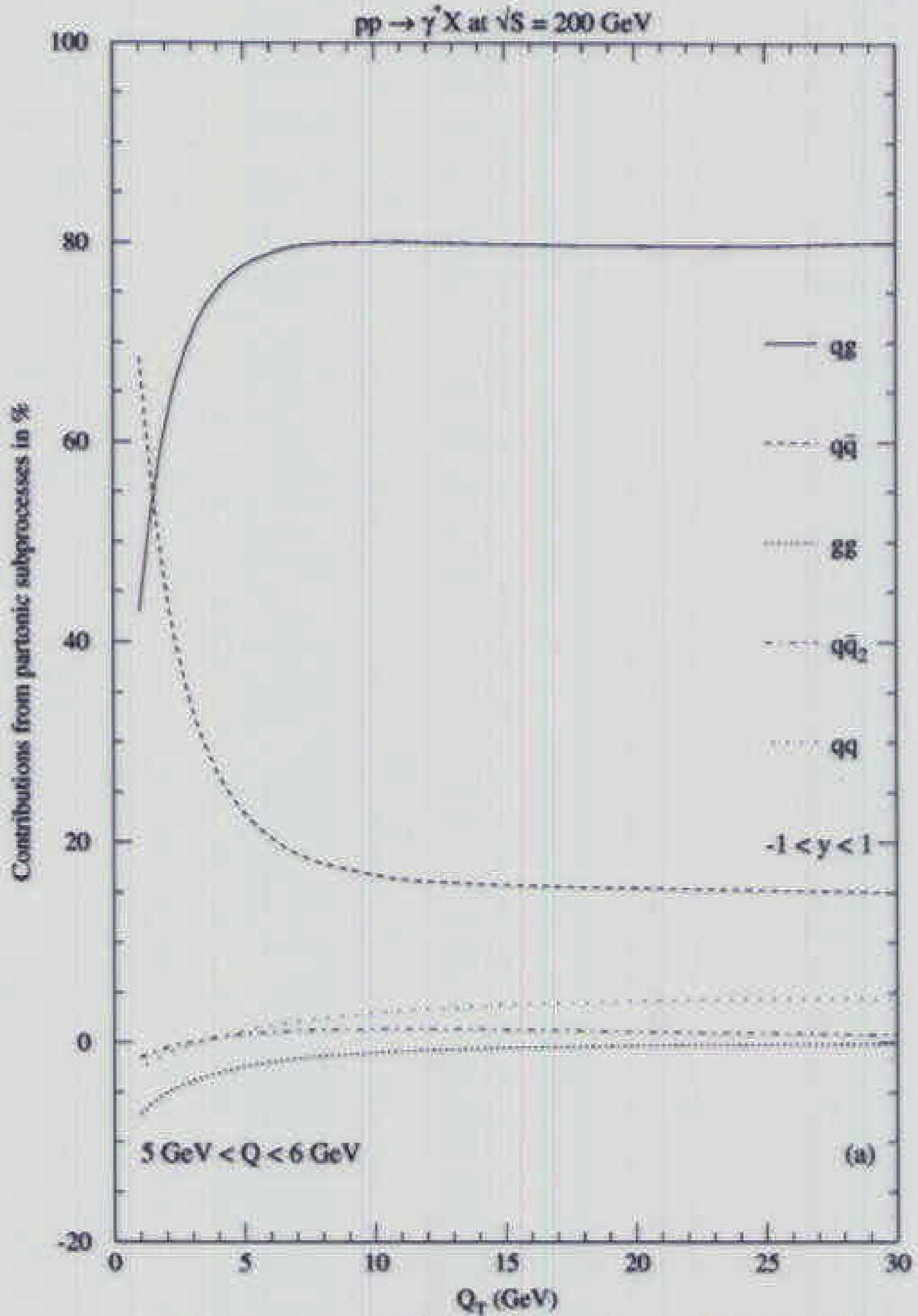
- qg is most the important subprocess for $Q_T > Q/2$
- Dominance of qg diminishes with Q from 80% to 70%
- At large Q_T, valence dominated $\bar{q}$ density raises $q\bar{q}$

CROSS SECTIONS AT COLLIDER ENERGIES



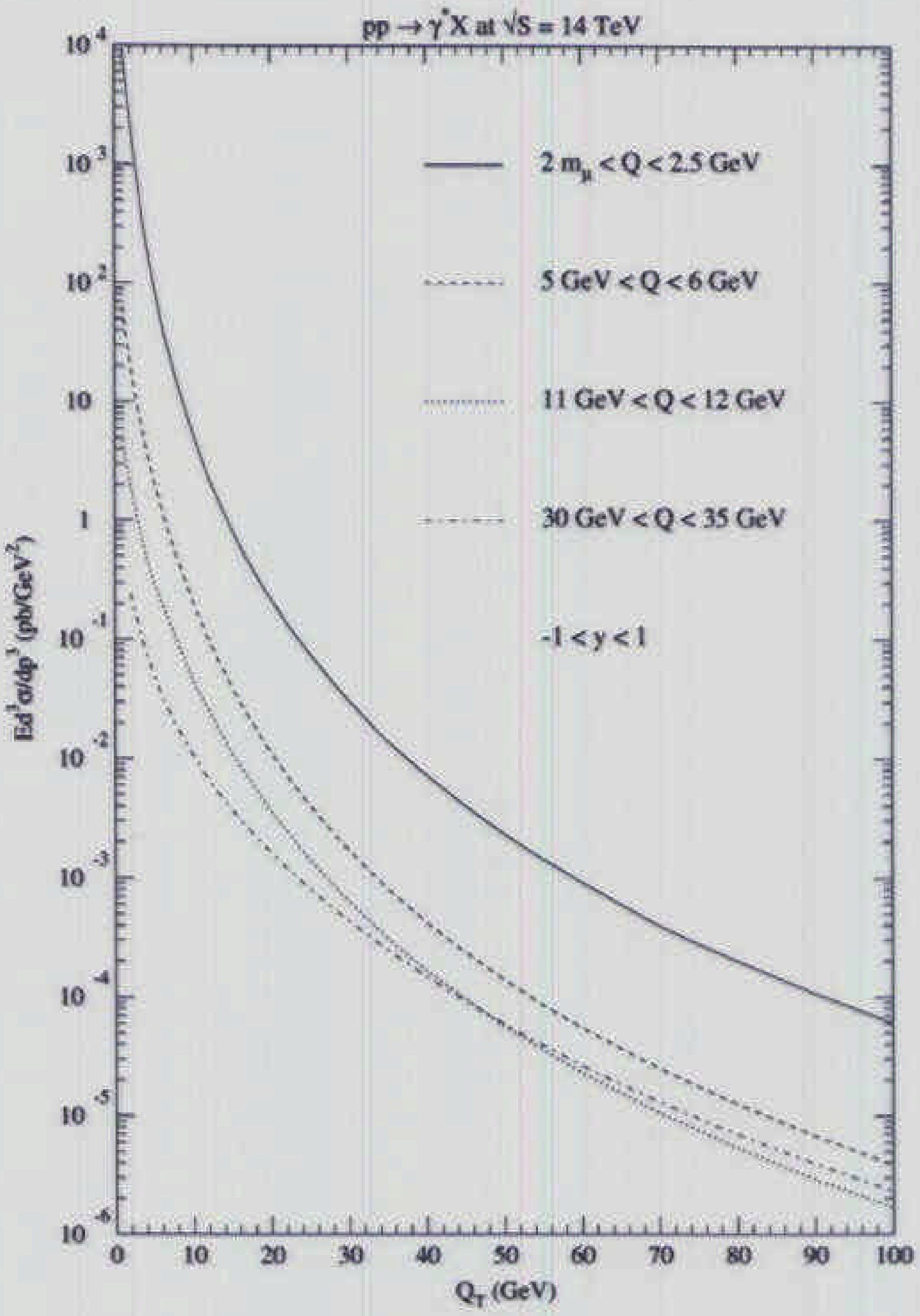
- Lepton pair production at different RHIC energies
- qg dominates at the level of 80% for $Q_T > Q/2$
- Cross section measurable to $p_T = 7.5,\ 14,\ 18.5$ GeV, $x_T = 0.3,\ 0.14,\ 0.075$ at $\sqrt{S} = 50,\ 200,\ 500$ GeV

CROSS SECTIONS AT COLLIDER ENERGIES



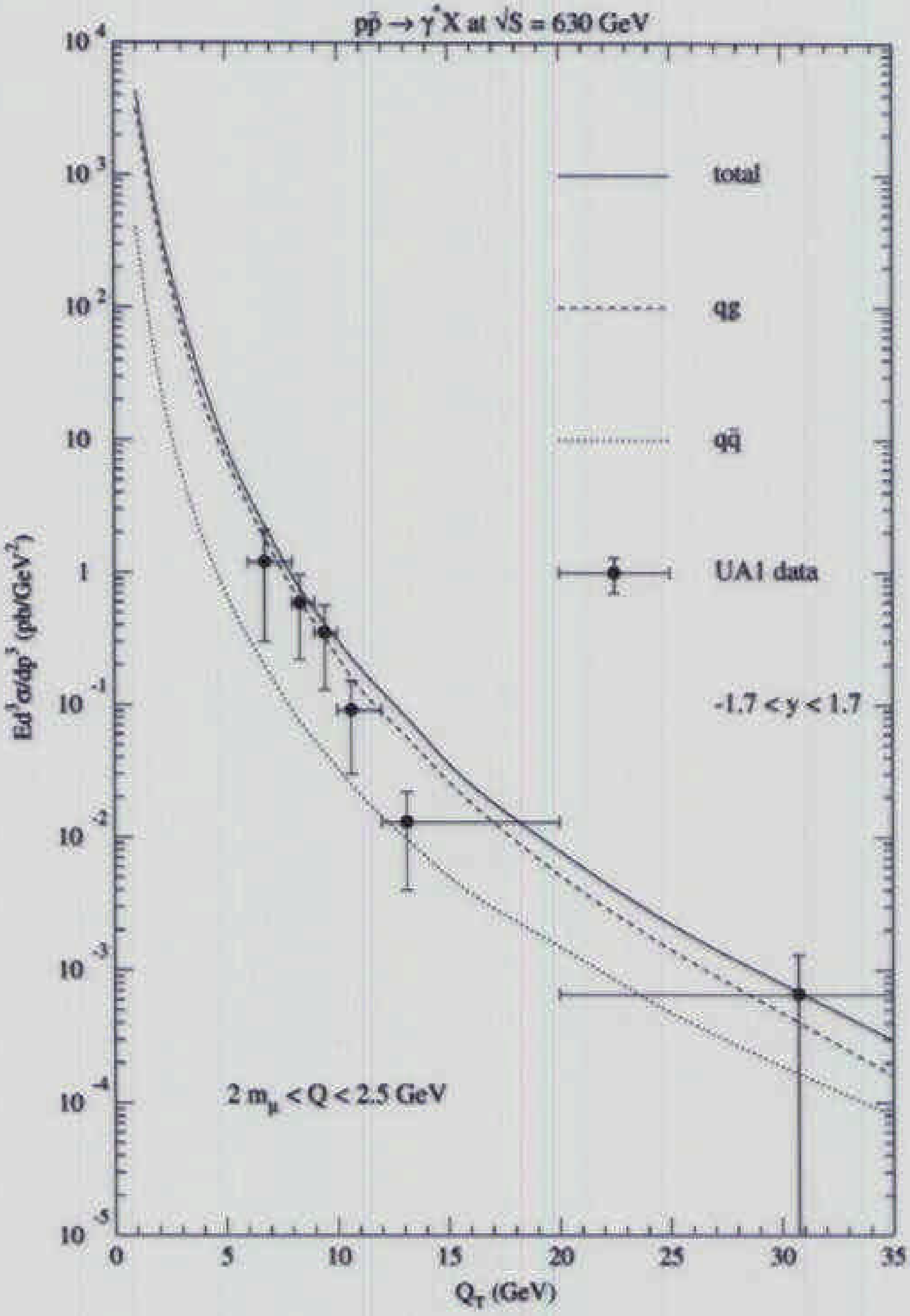
- qg accounts for about 80% of the rate at $Q_T \simeq Q$
- Subprocesses other than $q\bar{q}$ and qg are negligible

CROSS SECTIONS AT COLLIDER ENERGIES



- Lepton pair production at the CERN LHC collider
- qg dominates at the level of 80% for $Q_T > Q/2$
- Cross section is an order of magnitude larger than at Tevatron

CROSS SECTIONS AT COLLIDER ENERGIES



- Lepton pair production at the CERN Sp̄pS collider
- UA1 data prove feasibility of measuring low mass muon pairs
- qg is most the important subprocess

SENSITIVITY TO QUARK DENSITIES?

- qg Compton subprocess is dominant, but will uncertainties in the quark density compromise the possibility to determine the gluon density?
- Recall (Berger and Qiu, Phys.Rev.D40, 778,(1989)): when the Compton subprocess is dominant
- spin-averaged cross section:

$$\frac{Ed^3\sigma^{l\bar{l}}_{h_1h_2}}{dp^3} \approx \int dx_1 dx_2 \left(\frac{F_2(x_1)}{x_1} G(x_2) \frac{Ed^3\hat{\sigma}^{l\bar{l}}_{qg}}{dp^3} + (x_1 \leftrightarrow x_2) \right)$$

- spin-dependent cross section:

$$\frac{Ed^3\Delta\sigma^{l\bar{l}}_{h_1h_2}}{dp^3} \approx \int dx_1 dx_2 \left(2g_1(x_1)\Delta G(x_2) \frac{Ed^3\Delta\hat{\sigma}^{l\bar{l}}_{qg}}{dp^3} + (x_1 \cdot \right.$$

- $F_2(x,\mu_f^2)$ and $g_1(x,\mu_f^2)$ are *measured* in spin-averaged and spin-dependent deep-inelastic lepton-proton scattering.
- Massive lepton-pairs at large enough Q_T will determine the gluon density provided the proton structure functions are measured well in deep-inelastic lepton-proton scattering.

SUMMARY

- Current methods for determining the gluon density (prompt photon, high-p_T jets) valuable but have limitations
- Lepton pair production dominated by qg for $Q_T > Q/2$
- Advantages:
  - No non-perturbative fragmentation contribution
  - No need to isolate the photon experimentally
- Drawbacks: Lower cross section, limited range in x_T
- Suggestions: Regions of low $Q \simeq 2$ GeV, large bins in Q
- Accessibility of $g(x, \mu_f^2)$
  - Tevatron: $p_T = 30$ GeV, $x_T = 0.03$
  - RHIC: $p_T = 7.5,\ 14,\ 18.5$ GeV, $x_T = 0.3,\ 0.14,\ 0.075$ at $\sqrt{S} = 50,\ 200,\ 500$ GeV
  - Fixed Target: $p_T = 10$ GeV, $x_T = 0.52$
- Asymmetries at RHIC: Accessibility of $\Delta g(x, \mu_f^2)$
  - About same size as prompt photon production if $Q_T \geq Q$
  - $A_{LL} = 20\%,\ 7.5\%,\ 3\%$ at $\sqrt{S} = 50,\ 200,\ 500$ GeV
  - Independent of Q as long as Q_T is not too small
  - Depend strongly on parametrization of $\Delta g(x, \mu_f^2)$