Progress Towards a Generator for BFKL Physics

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Outline

1. Intro
2. Exp'tal status
   Improved BFKL MC
3. $\gamma^*\gamma^*$: a closer look
   - asymptotic behavior
   - BFKL at LEP energies?

Collaborator: W.J. Stirling

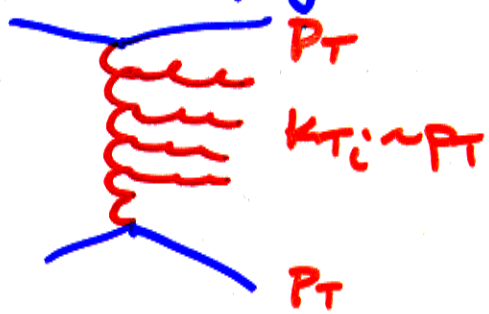
Introduction: BFKL equation

Some processes/kinematic regimes:

multiple soft gluon emissions $\Rightarrow$
expansion in powers of $\alpha_s \ln\left(\frac{\hat{s}}{Q^2}\right)$
large

$\Rightarrow$ fixed order QCD no good.

BFKL* eq'n resums these large logs due to (real + virtual) gluon emissions



- all k_T comparable
- strong ordering in rapidity

Analytic sol'n typically gives

$$\hat{\sigma} \sim (\quad)^{\lambda}$$

some relevant variable

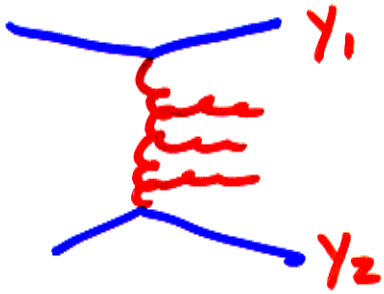
$$\lambda = \frac{4 N_c \alpha_s \ln 2}{\pi}$$

$$\simeq 0.5$$

(a.k.a. $\alpha_P - 1$)

*Balitsky, Fadin, Kuraev, Lipatov

Tevatron / LHC: dijet prod. at large rapidity



$\Delta = y_1 - y_2$

$\Rightarrow \hat{\sigma} \sim e^{\lambda \Delta}$

Mueller
Navelet

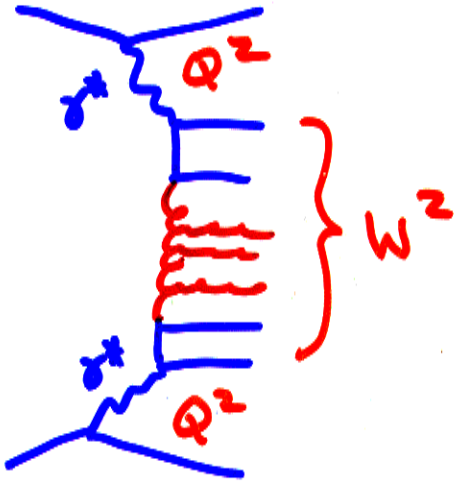
$\Rightarrow$ azimuthal decorrelation

HERA: forward jet production

$\Rightarrow \hat{\sigma} \sim \left(\frac{x_j}{x_{Bj}}\right)^{\lambda}$

(also $F_2 \sim \frac{1}{x^{\lambda}}$)

LEP / LC: $\gamma^* \gamma^*$ scattering



$s \gg Q^2 \gg \Lambda^2_{QCD}$

Brodsky
Hautmann
Soper

$\Rightarrow \sigma_{\gamma^*\gamma^*} \sim \left(\frac{W^2}{Q^2}\right)^{\lambda}$

Experimental status : Ambiguous at best

- Data tend to lie between fixed-order QCD + analytic BFKL
  - e.g. DØ azimuthal decorr. in dijet prod. ← fig.
  - similarly for HERA, LEP

[Exception: $R = \frac{\sigma_{dijet}(1800)}{\sigma_{dijet}(630)}$ at DØ lies above <u>all</u> predictions. (cf. talk by B. Pope)]

Not surprising at all! Why?

- Analytic BFKL sol'ns have
  - sum over arbitrary numbers of gluons
  - leading order kinematics only

  ⇒ no kinematic cost to emit gluons

  ⇒ energy + momentum not conserved!

- Sol'n is BFKL Monte Carlo

  C. Schmidt
  LHO, W.J. Stirling

  ⇒ explicit gluon sum allows kin. constraints ← fig.

BFKL MONTE CARLO

Basic idea: We want to un-resum (de-resum) the emitted gluons ⇒ make gluon sum explicit so we can impose kin. constraints.

How it works: Back to BFKL eq'n. Write**

$$\int_{\text{virtual}} + \int_{\text{real}} = \int_{\text{virtual}} + \underbrace{\int_{\substack{\text{real},\\ k_T^2<\mu^2}}}_{\text{"unresolved"}} + \underbrace{\int_{\substack{\text{real},\\ k_T>\mu^2}}}_{\text{"resolved"}}$$

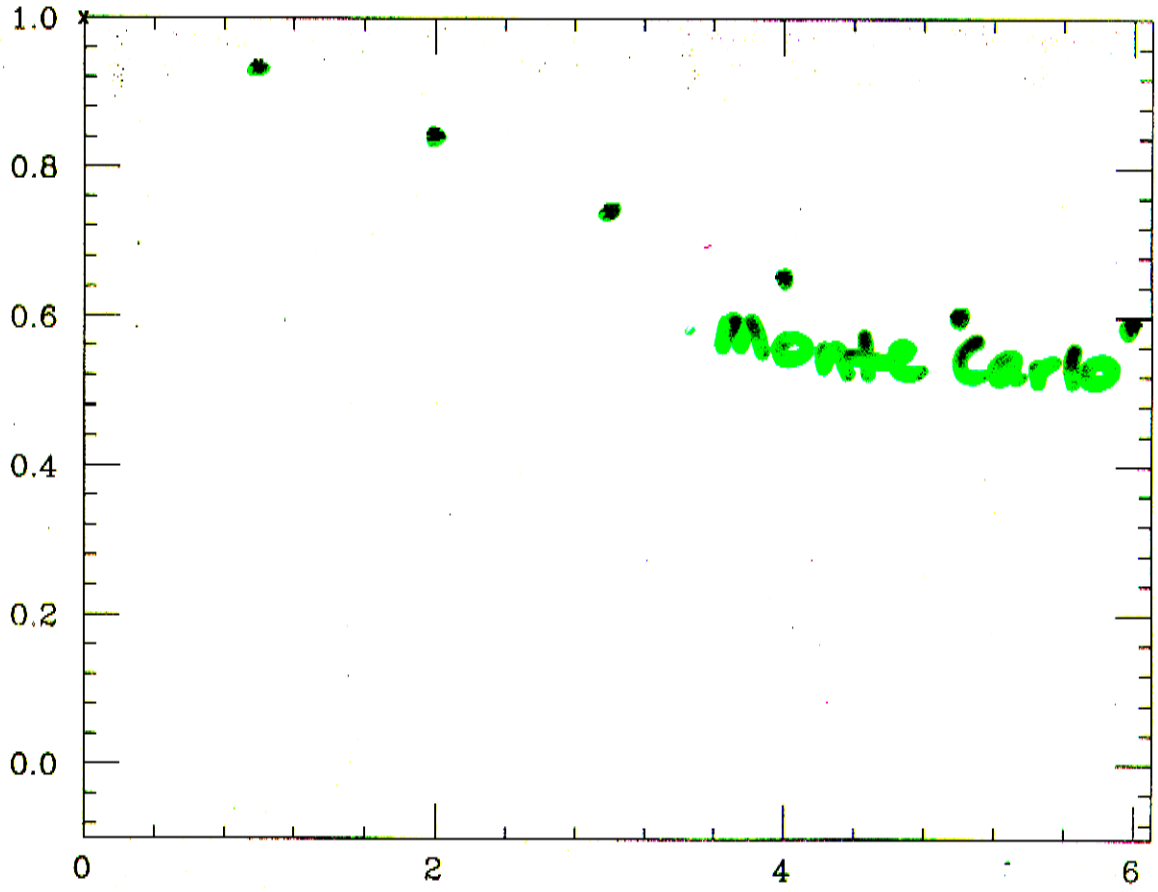
with μ^2 = small cutoff. Virtual + unres. get folded into a form factor. Solve by iteration, back transform, & voila:

⇒ an explicit sum over emitted gluons* suitable for implementation in a MC.

While we're at it, we'll let α_s run.

** à la Kwiecinski, Lewis, + Martin

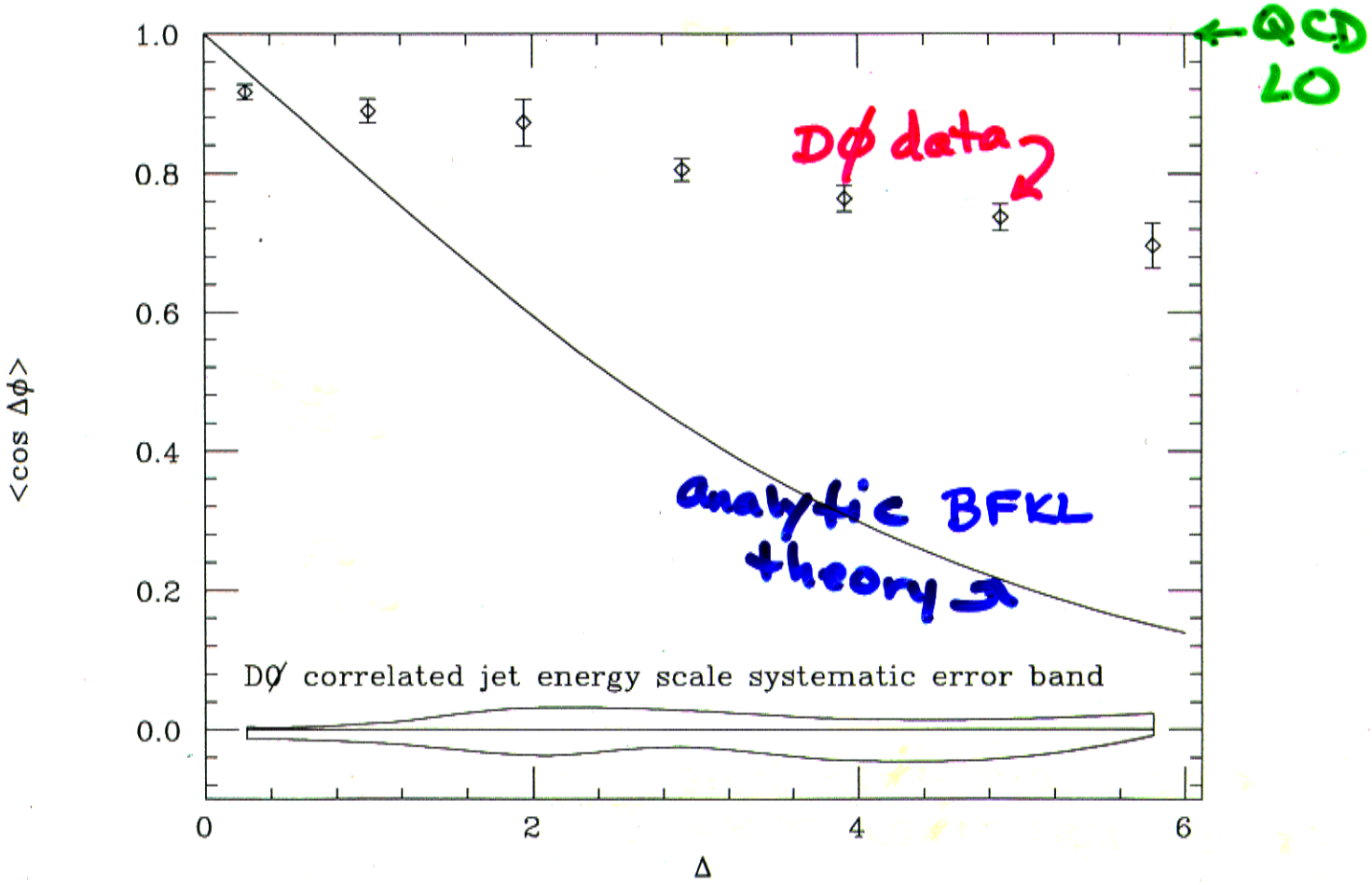
* N.B. This is still leading log. These gluons represent overall energy flow but cannot be identified with individual jets.


1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
Monte Carlo

Azimuthal Decorrelation in Dijet Production at the Tevatron

Figure 5

$p_T > 20$ GeV



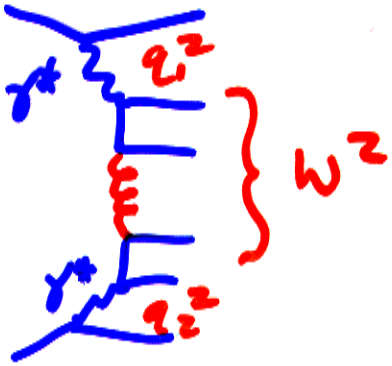
$\langle \cos \Delta\varphi \rangle = 1 \iff$ back-to-back

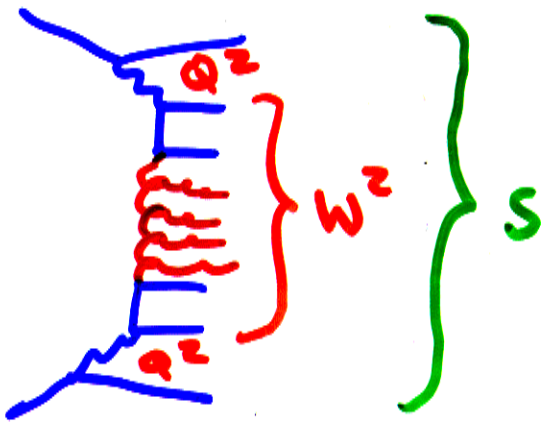
LHO, W.J. Stirling

$\gamma^*\gamma^*$ Scattering: a closer look

Forward e^+e^- scattering: $e^+e^- \to e^+e^- + \text{hadrons}$
("double tagged")

~~qqqq~~ BFKL





Relevant regime: $s \gg Q^2 \gg \Lambda^2_{QCD}$
$q_1^2 \sim q_2^2 = -Q^2$ + W^2 large

For large W^2/Q^2, fixed $\sqrt{s}/W$, consider

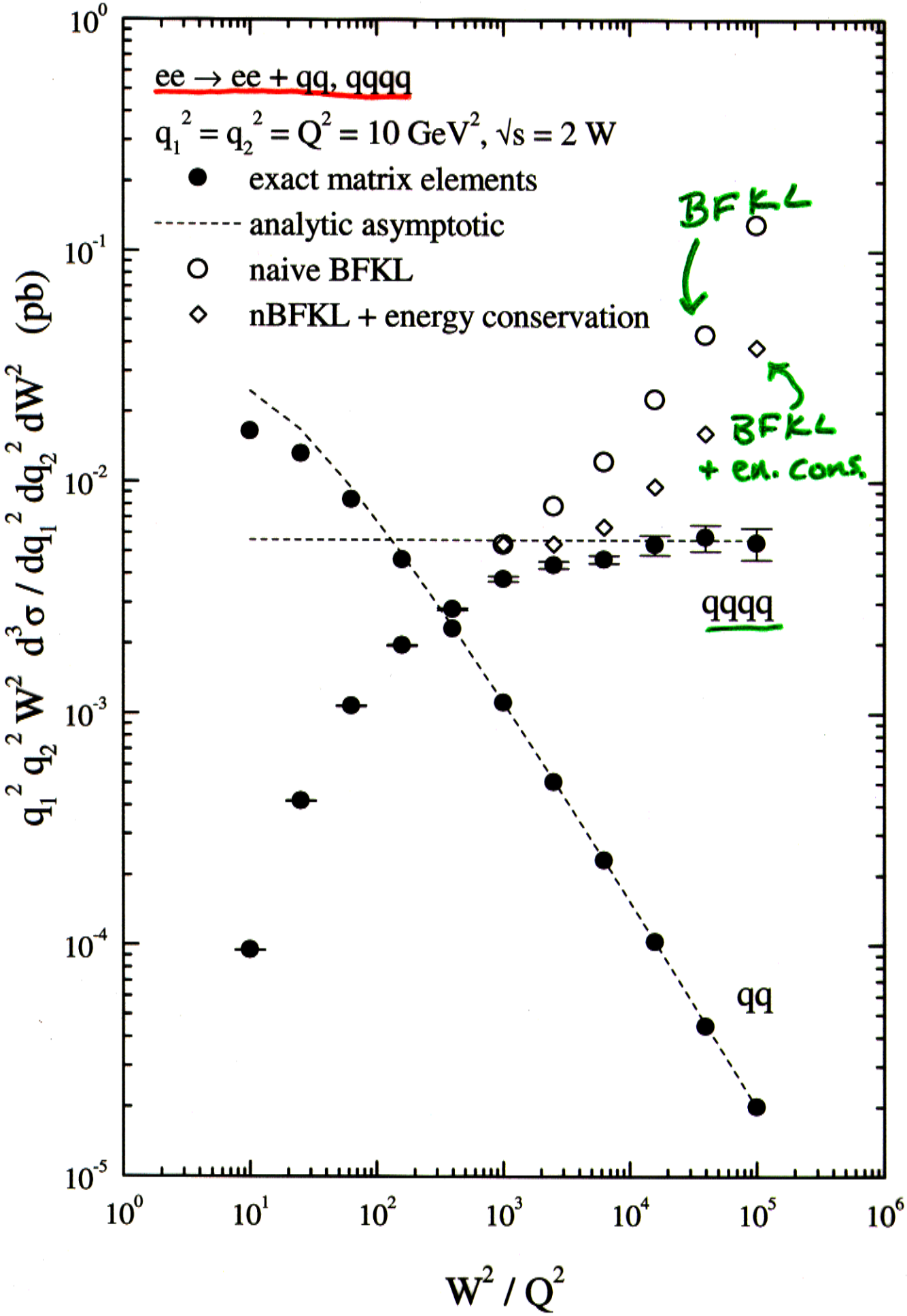
$$q_1^2 q_2^2 W^2 \frac{d^3\sigma}{dq_1^2\, dq_2^2\, dW^2} \text{ vs. } W^2/Q^2$$

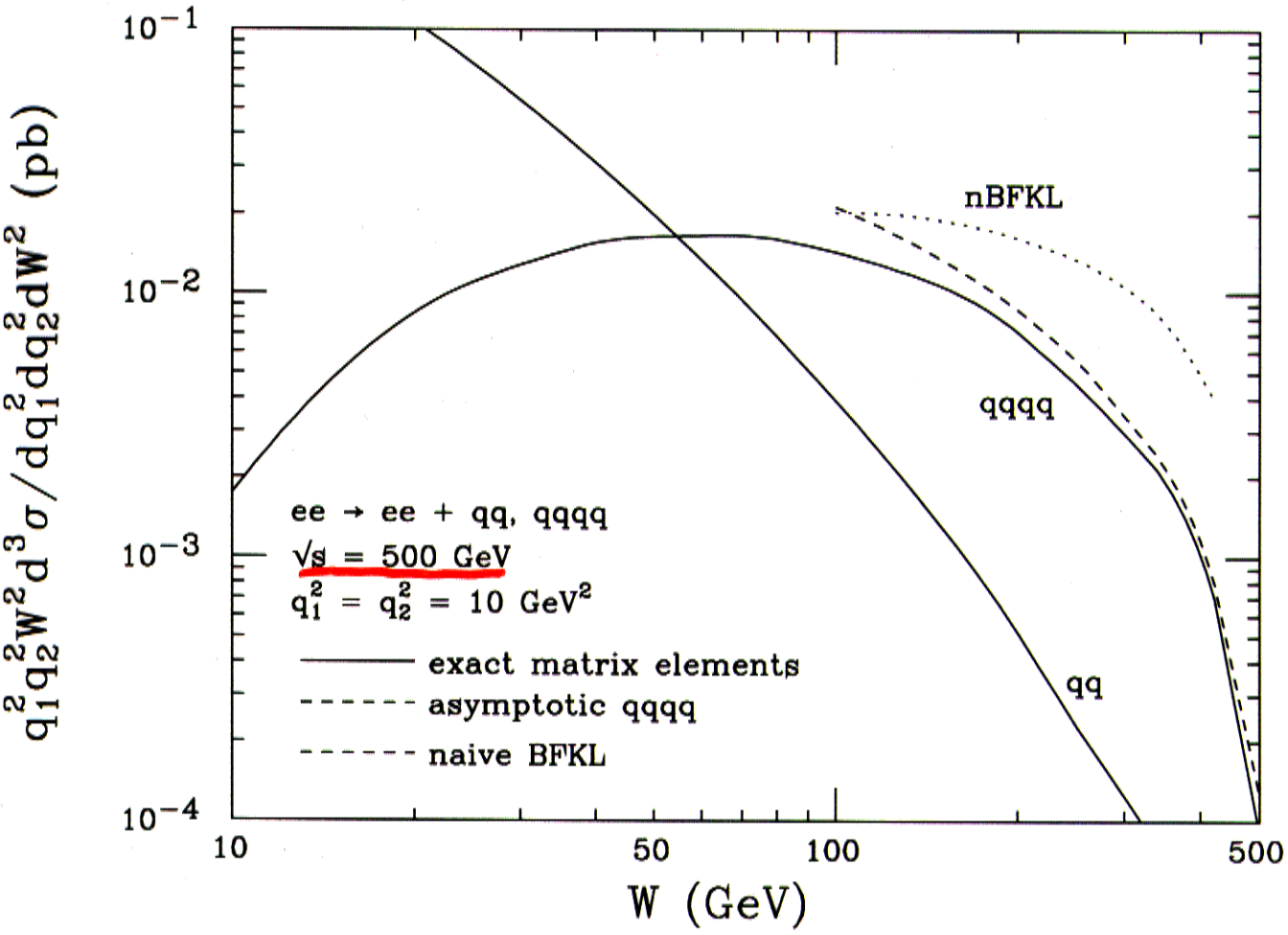
$\Rightarrow$ qqqq $\to$ const

$\Rightarrow$ BFKL rises

$\leftarrow$ fig

<u>N.B.</u> Where in W^2/Q^2 BFKL starts is arbitrary at LO!!


ee → ee + qq, qqqq
$q_1^2 = q_2^2 = Q^2 = 10\ \mathrm{GeV}^2$, $\sqrt{s} = 2$ W
exact matrix elements
analytic asymptotic
naive BFKL
nBFKL + energy conservation
BFKL
BFKL
+ en. cons.
qqqq
qq
$q_1^2 q_2^2 W^2\ d^3\sigma / dq_1^2\, dq_2^2\, dW^2$ (pb)
W^2 / Q^2
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^1
10^2
10^3
10^4
10^5
10^6


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
50
100
500
W (GeV)
$q_1^2 q_2^2 W^2 d^3\sigma / dq_1^2 dq_2^2 dW^2$ (pb)
nBFKL
qqqq
qq
ee → ee + qq, qqqq
√s = 500 GeV
$q_1^2 = q_2^2 = 10$ GeV^2
exact matrix elements
asymptotic qqqq
naive BFKL

BFKL at LEP energies

$\gamma^*\gamma^*$ c.s. from e^+e^- : divide by $\gamma\gamma$ luminosity

⇒ L3 data at 183, 189–202 GeV*

← fig

Q: Is the asymptotic QCD limit for $qqqq$ appropriate here?

A: Compare exact and asymp.

← figs

⇒ No!

⇒ QCD $qqqq$ $\gamma^*\gamma^*$ c.s. rises !!!

... but approaches asymp. fr/ below
There is some normalization uncertainty (α_s, etc).

Q: What about BFKL pred?

A1: Charm mass, γ polarization potential complications. Bartels et al: effects cancel at LEPII

A2: BFKL MC in progress

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* Talk by M. Wadhwa

L3

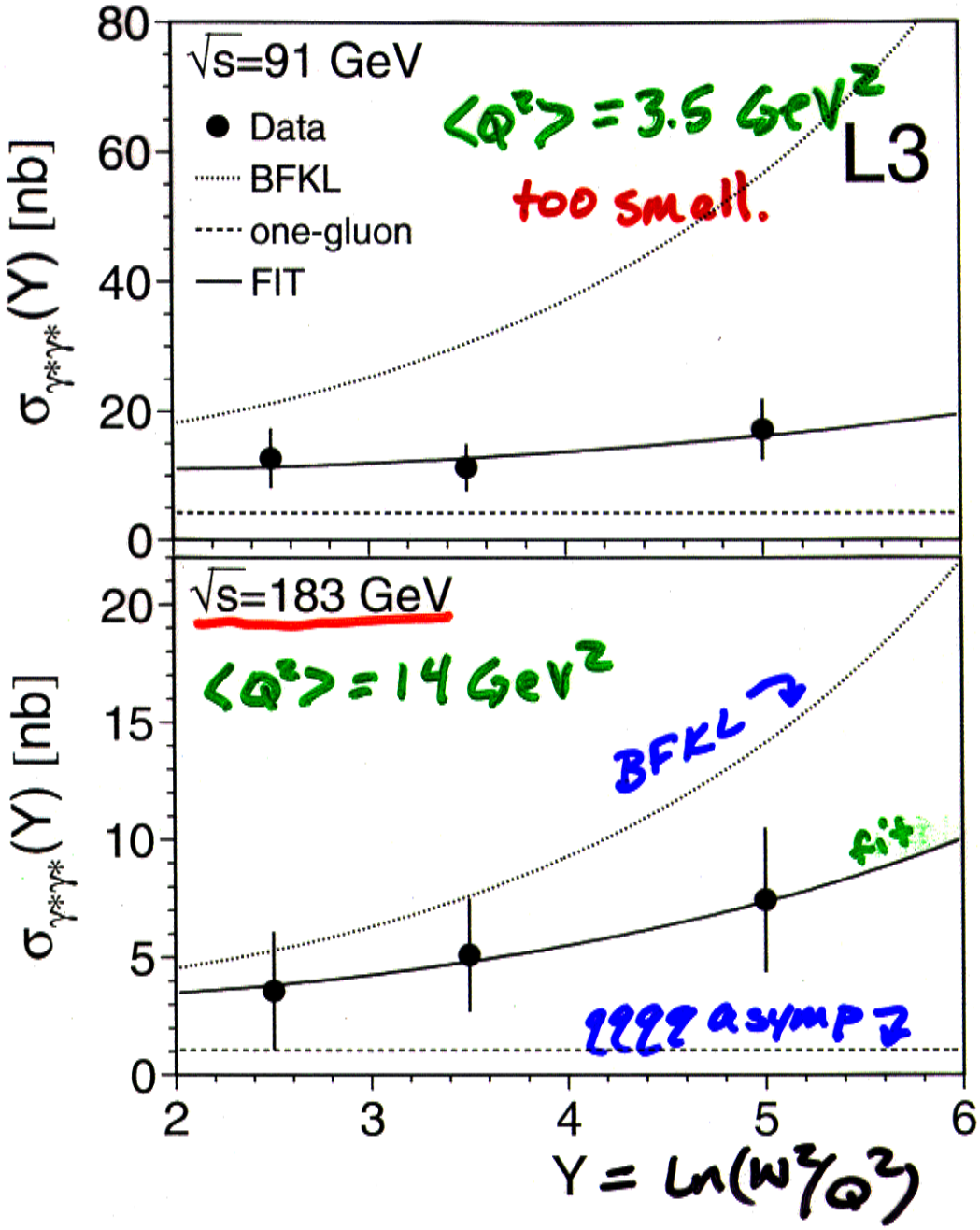
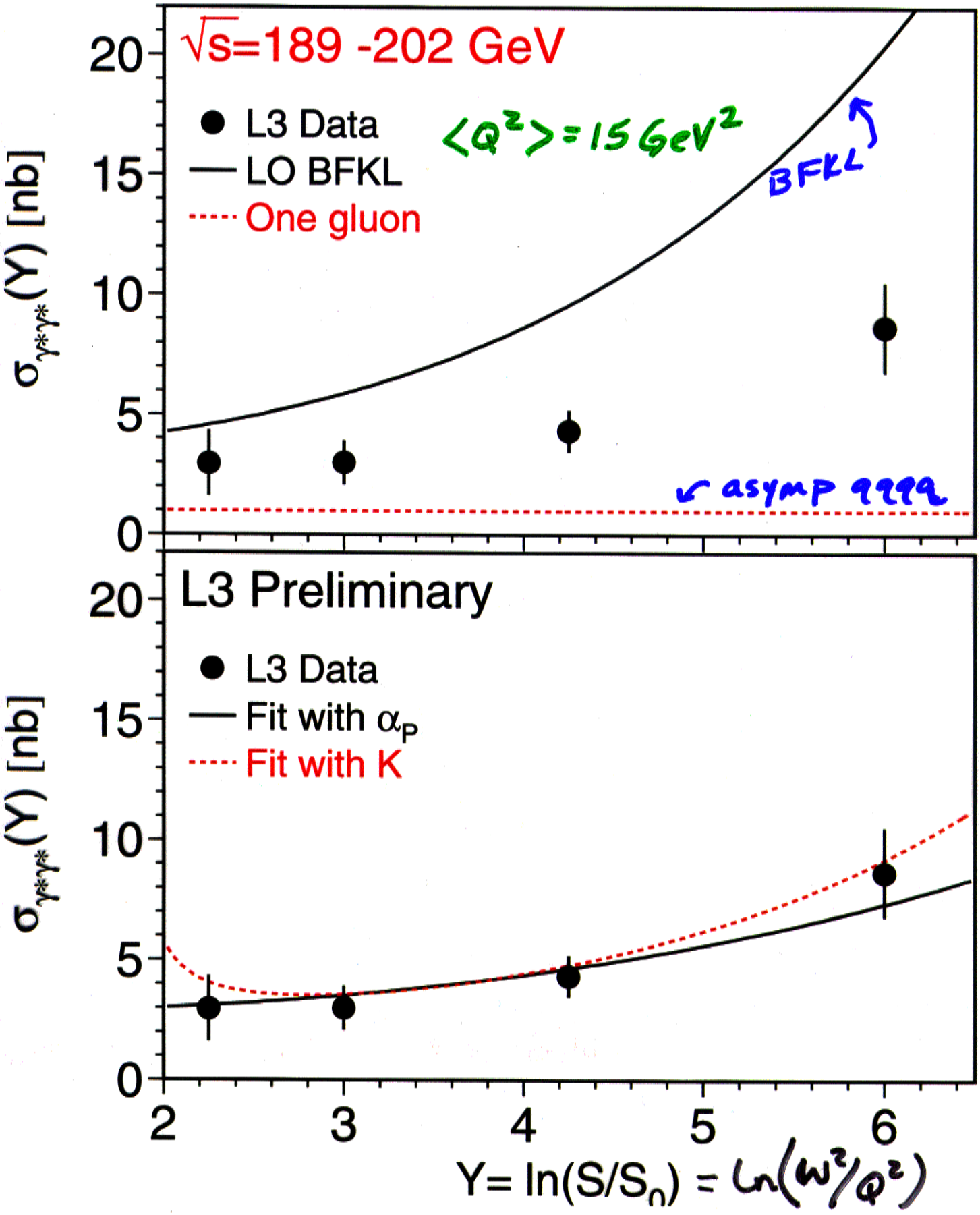
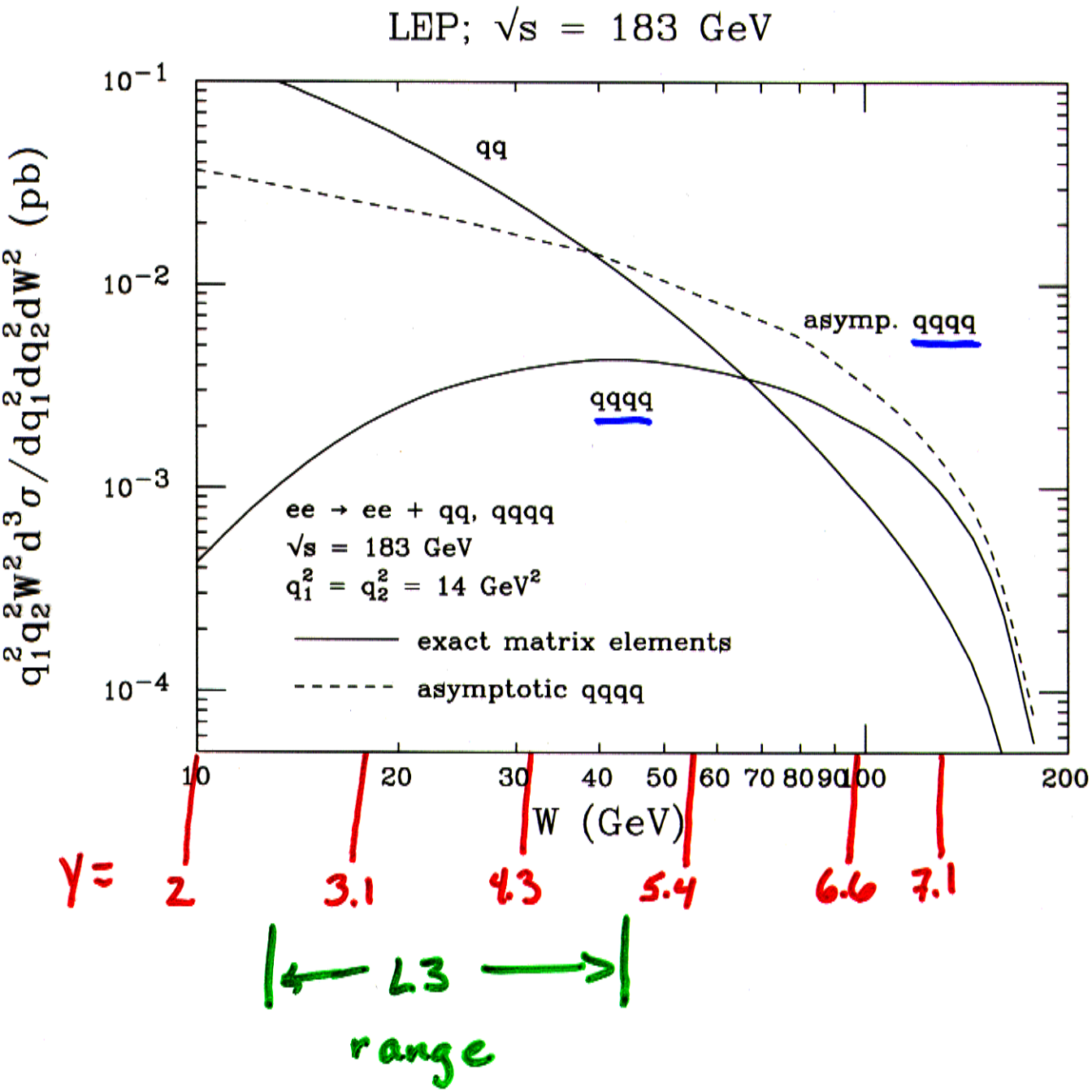
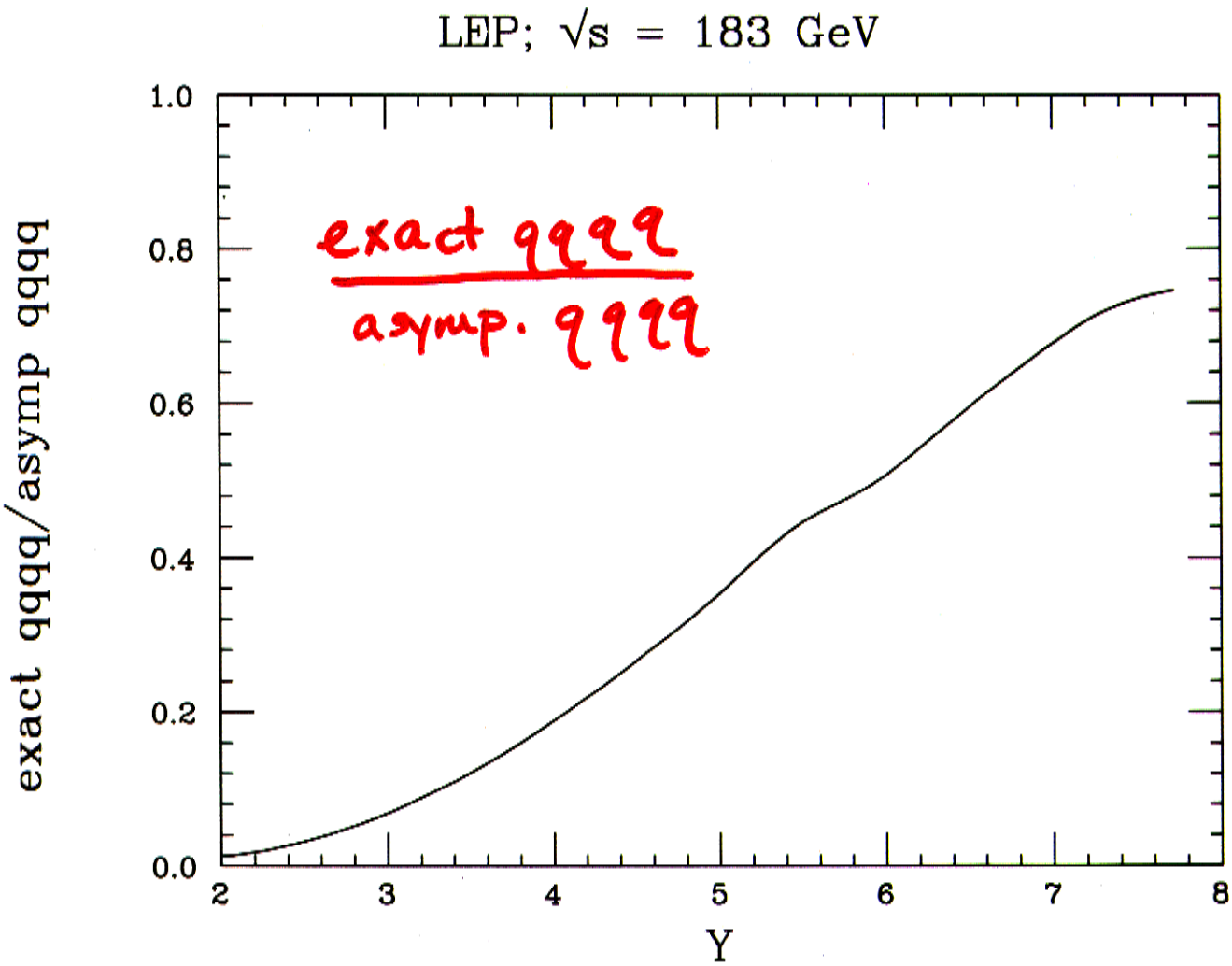


Figure 6: Two-photon cross-sections, $\sigma_{\gamma^*\gamma^*}$, after subtraction of the QPM contribution at $\sqrt{s} \simeq$ 91 GeV ($\langle Q^2 \rangle = 3.5$ GeV^2) and $\sqrt{s} \simeq 183$ GeV ($\langle Q^2 \rangle = 14$ GeV^2). The data are compared to the predictions of the BFKL model and of the one-gluon exchange diagram. The continuous line is a fit to the data with Eq. 1 by leaving α_P as a free parameter.

L3


√s=189 -202 GeV
L3 Data
LO BFKL
One gluon
<Q²> = 15 GeV²
BFKL
asymp 9999
L3 Preliminary
L3 Data
Fit with α_P
Fit with K
σ_γ*γ*(Y) [nb]
Y= ln(S/S_0) = ln(W²/Q²)


LEP; √s = 183 GeV
$q_1^2 q_2^2 W^2 d^3\sigma / dq_1^2 dq_2^2 dW^2$ (pb)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
qq
asymp. qqqq
qqqq
ee → ee + qq, qqqq
√s = 183 GeV
$q_1^2 = q_2^2 = 14$ GeV^2
exact matrix elements
asymptotic qqqq
10
20
30
40
50
60
70
80
90
100
200
W (GeV)
Y = 2
3.1
4.3
5.4
6.6
7.1
L3
range


LEP; √s = 183 GeV
exact qqqq / asymp. qqqq
exact qqqq/asymp qqqq
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
Y

Status of NLL Corrections

Obviously, LO BFKL is not sufficient. We need NLO corrections

- extra real emissions (2 gluons)
- virtual corr's to real emissions (1 gluon)
- virtual 2-loop corrections

⇒ 10 years of heroic efforts by Fadin, Lipatov + many others

Good news: They're done!

Bad news: They're huge! and unstable! and can give negative cross sections!

What's the problem? Collinear limit.

- recall LO BFKL ⇒ strong ordering in rapidity
- NLO corr's give gluons w/ close rapidity.

What are the solutions?

Salam Colferai Ciafaloni } • Resum the resummation (double transverse logs) ← fig

Schmidt • Require min. rapidity sep.

Forshaw Ross Sabio Vera } • Both

• Renorm. scheme {Brodsky, Fadin, Kim, Lipatov, Pivovarov

-Improved BFKL MC in Progress

Conclusions

- BFKL physics is a complicated business.
- Tests being performed in a variety of experiments
  - Tevatron, HERA, LEP
  - future: LHC, LC
- Comparisons are not straightforward!
  - LO BFKL insufficient
  - Subleading corrections (esp. kin. constraints) matter. A lot.

[Worst case scenario: we can't reach sufficiently asymptotic region to see unambiguous effects.]

- Reports of demise of BFKL physics due to instability of NLO corrections are greatly exaggerated.
  - Source of large corr's understood + being brought under control.

Bottom line: Jury is out. Stay tuned!