QCD/Two-Photon Physics - Summary Report

Physics Topics	*Detector Requirements*
α_s	*improved tracking, calorimetry*
$\gamma\gamma$ *Scattering*	*double anti-tag EM calorimetry* *Laser Backscattering system*
$\gamma^*\gamma$ *Scattering*	*single tag EM calorimetry* *Laser Backscattering system*
$\gamma^*\gamma^*$ *Scattering*	*double tag EM calorimetry*

Why is QCD and 2-Photon Physics important at a Linear Collider?

- *Best measurement of fundamental QCD parameter -α_s*
  - *variety of precise methods (event shapes, jets, decay widths)*
  - *tests running at scales > M_z*
  - *takes α_s to a precision level of ~1% as NNLO theory becomes available (~5 years)*
  - *Competition? - HERA dijets, LHC?*
- *Two-Photon Physics*
  - *measurement of $\gamma\gamma$ Total Cross Section*
  - *direct measurement of Photon structure functions*
  - *tests of QCD Dynamics*
  - *Competition? - none*
- *Background to everything else! - must be understood*

α_s

P. Burrows

Precise Determination of α_s

Event Shapes

statistical errors - 50k qq events --> $\Delta\alpha_s < 0.001$

detector systematics --> $\Delta\alpha_s \sim 0.001$

hadronization uncertainties (~1/Q) --> $\Delta\alpha_s < 0.001$

needs a_s^3 calculation for 1% measurement - within 5 years (currently $\Delta\alpha_s \sim 0.006$)

Top Quarks

σ_{tt} --> $\Delta\alpha_s \sim$ +-10% (theoretical near threshold, exp.syst.above)

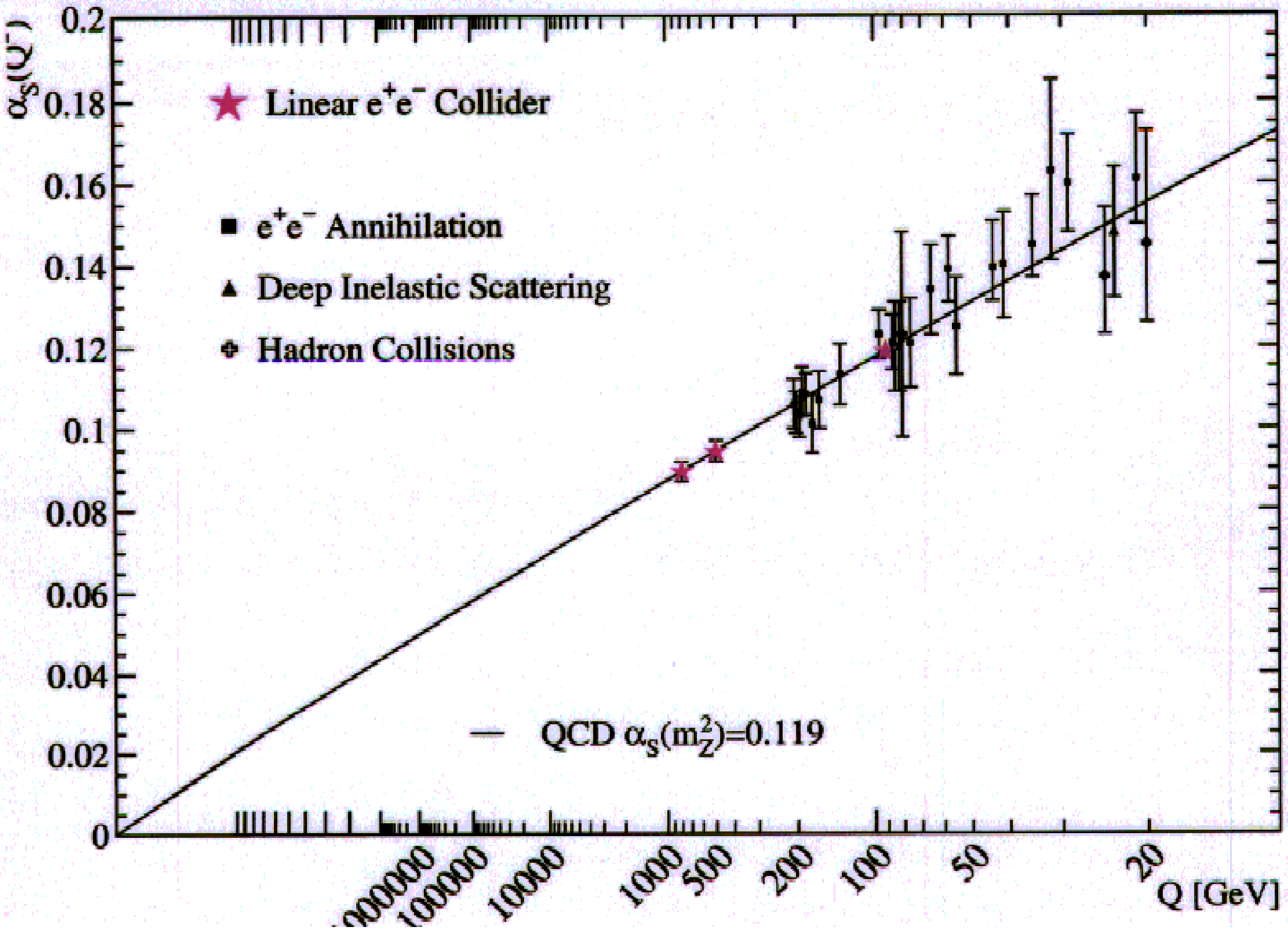
$R_t = \sigma_{tt}/\sigma_{\mu\mu}$ --> $\Delta\alpha_s \sim$ +-6%

Giga-Z running

$\Gamma_z^{had}/\Gamma_z^{lept}$ --> $\Delta\alpha_s = 0.0009$

$\Gamma_\tau^{had}/\Gamma_\tau^{lept}$ --> $\Delta\alpha_s = 0.001 - 0.006$ (theoretical)

Q2 Evolution of α_s----->



αs(Q²)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Linear e+e− Collider
e+e− Annihilation
Deep Inelastic Scattering
Hadron Collisions
QCD αs(m_Z^2)=0.119
1000000
100000
10000
1000
500
200
100
50
20
Q [GeV]

α_s

B. Schumm

- *QCD event selection cuts ----->*
  - *Replace hemisphere mass cut with precision vertexing and electron beam polarization*
    - *no more than 3 tracks miss IP by more than 3σ*
    - *require Pe > 80% for clean qq sample*
    - *jet rate correction greatly reduced ----->*

- *Detector systematics*
  - *boost loss : calorimeter coverage* $|\cos\theta| < 0.99$, $R_3/R_3^{true} = 0.982$
  - *under control to ~ 1% level*

European Working Group

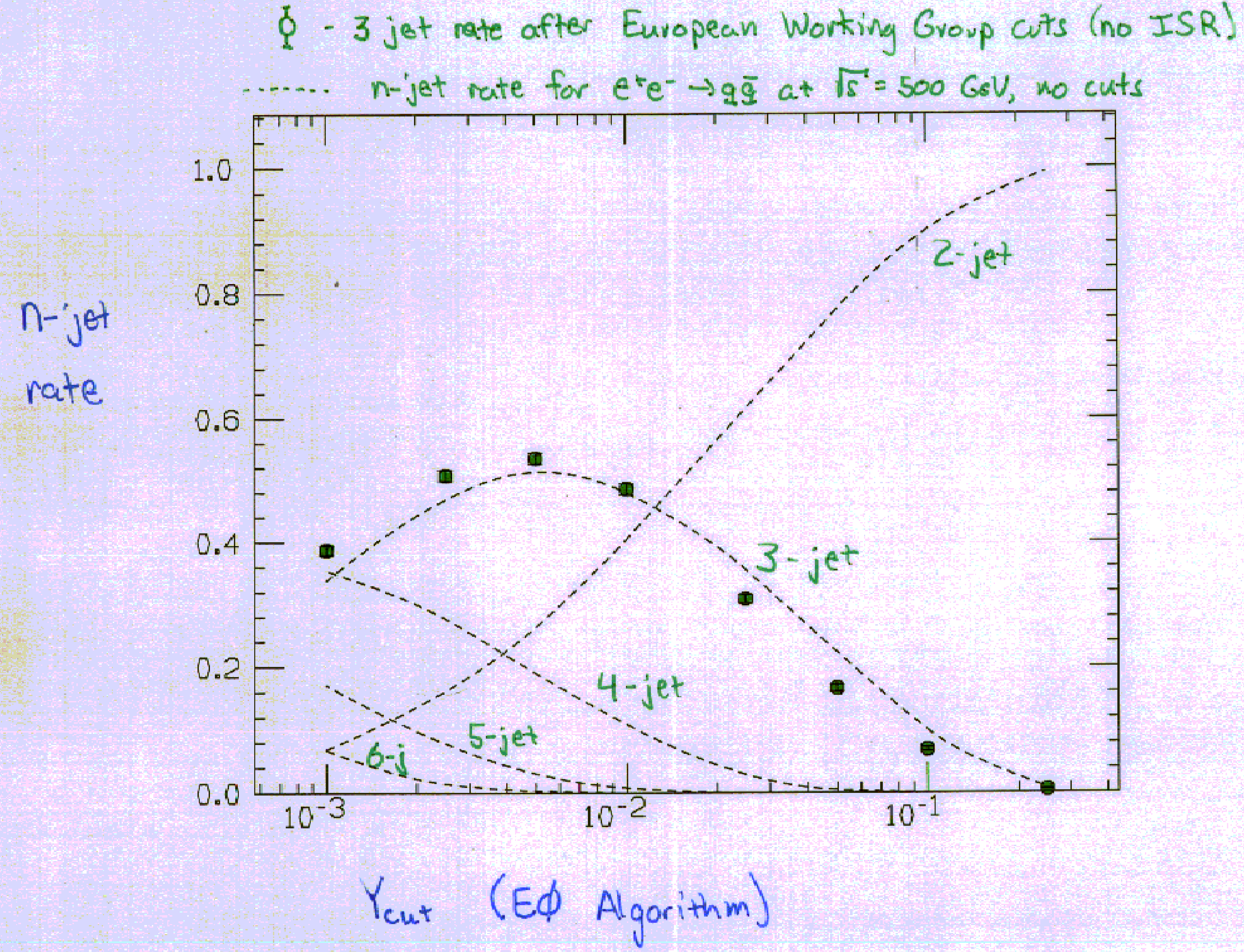
$q\bar{q}$ Selection Cuts (pre-Snowmass)

Cut	Value	Vetoes
particle multiplicity	$N_{part} \geq 8$	2-γ events beam-gas events leptonic final states
Polar angle of thrust axis	$\lvert\cos\theta_T\rvert < 0.8$	W^+W^- events highly radiative events losses around beampipe
visible hadronic energy and longitudinal momentum balance	$\frac{E_{vis}}{E_{cm}} > 0.5$ $\frac{\lvert\sum \vec{p}_z\rvert}{E_{vis}} < 0.4$	2-γ events highly radiative events poorly measured events
hemisphere masses	$M_1, M_2 > 3$ GeV	τ pair events
hemisphere multiplicities	$N^{1,2}_{charged} \geq 4$	lept. decays of boson pairs
hemisphere masses *	$\left[\frac{M_1}{E_{vis}}.\mathrm{or}.\frac{M_2}{E_{vis}}\right] < 0.13$	$t\bar{t}$ and boson pair events

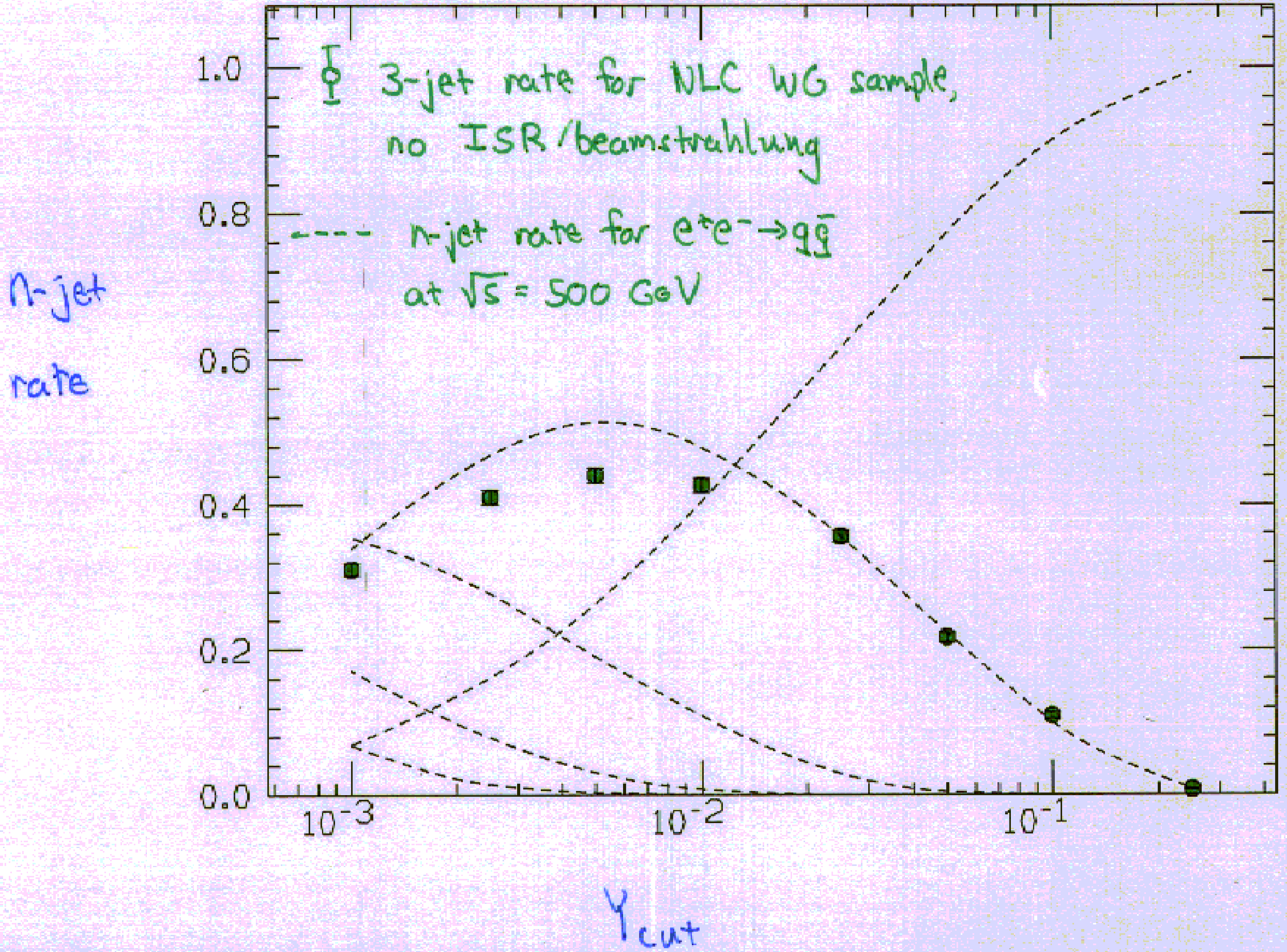
But introduces substantial bias (especially *)

to 3-jet rates

⇒20-25% correction to α_s!



- 3 jet rate after European Working Group cuts (no ISR)
n-jet rate for $e^+e^- \to q\bar{q}$ at $\sqrt{s} = 500$ GeV, no cuts
n-jet rate
1.0
0.8
0.6
0.4
0.2
0.0
2-jet
3-jet
4-jet
5-jet
6-j
10^{-3}
10^{-2}
10^{-1}
Y_{cut} (EΦ Algorithm)


3-jet rate for NLC WG sample, no ISR/beamstrahlung
n-jet rate for $e^+e^- \to q\bar{q}$ at $\sqrt{s} = 500$ GeV
n-jet rate
1.0
0.8
0.6
0.4
0.2
0.0
10^{-3}
10^{-2}
10^{-1}
Y_{cut}

Tools for 2-Photon Physics studies

T. Sjostrand

F. Hautmann

- *2-photon processes in PYTHIA*
  - *consistent picture of all processes*
  - *process composition for virtual photon scattering ----->*
- *NLO + parton shower MCs*
  - *Issues*
    - *LO --> NLO Monte Carlos ----->*
    - *subtraction methods work for IR safe quantities, but not for IR unsafe Monte Carlos*
    - *new method localizes calculations to small regions (soft, collinear, UV) with subtraction of divergences from larger regions*

Photon 'high-$p_\perp$' processes

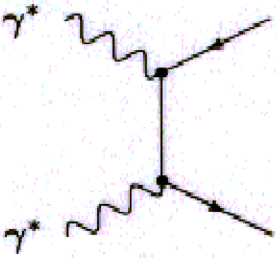
Three main 'high-$p_\perp$' jet process classes:

1. direct×direct

$\gamma^*_T\gamma^*_T \to q\overline{q}$

$\gamma^*_T\gamma^*_L \to q\overline{q}$

$\gamma^*_L\gamma^*_L \to q\overline{q}$



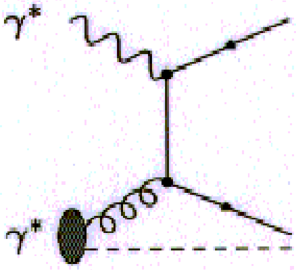
2. direct×resolved , resolved = VMD or anomalous

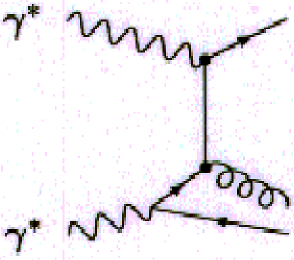
$\gamma^*_T g \to q\overline{q}$

$\gamma^*_L g \to q\overline{q}$

$\gamma^*_T q \to qg$

$\gamma^*_L q \to qg$





etc.

3. resolved×resolved

$qq' \to qq'$

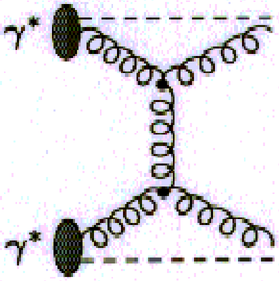
$q\overline{q} \to q'\overline{q}'$

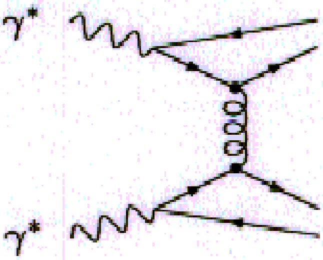
$q\overline{q} \to gg$

$qg \to qg$

$gg \to gg$

$gg \to q\overline{q}$



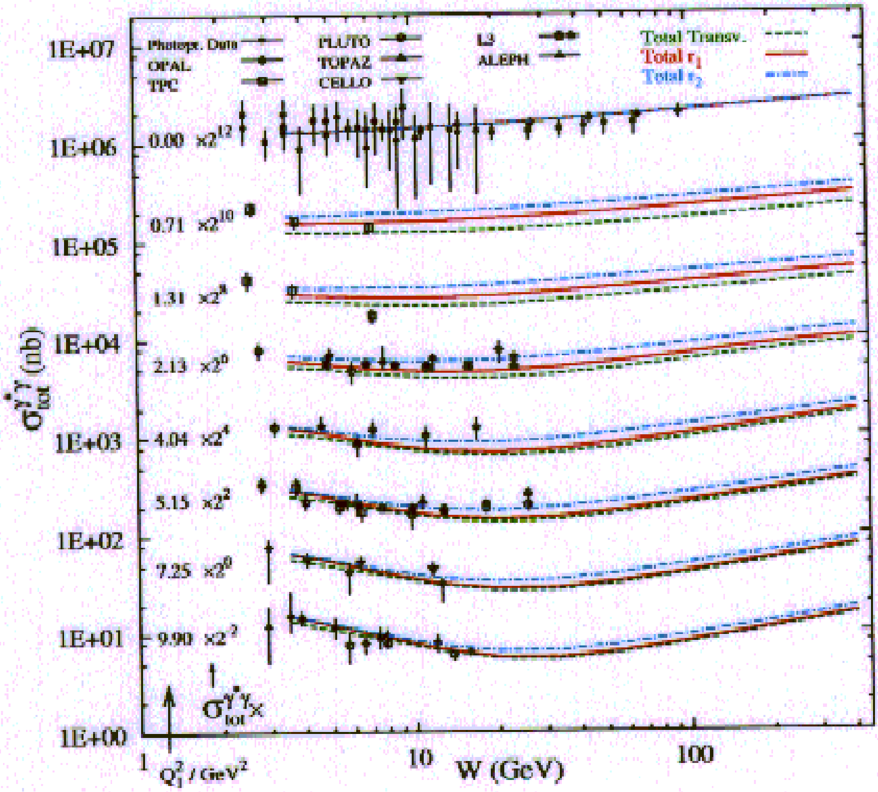


etc.

$$d\sigma(\gamma^*\gamma^* \to X) = \left(\int d\hat{x}_1\, f_i^{\gamma^*}(\hat{x}_1, \mu^2, Q_1^2)\right)$$

$$\times \left(\int d\hat{x}_2\, f_j^{\gamma^*}(\hat{x}_2, \mu^2, Q_2^2)\right) \int d\hat{t}\, \frac{d\hat{\sigma}}{d\hat{t}}(\hat{s} = \hat{x}_1\hat{x}_2 W^2)$$

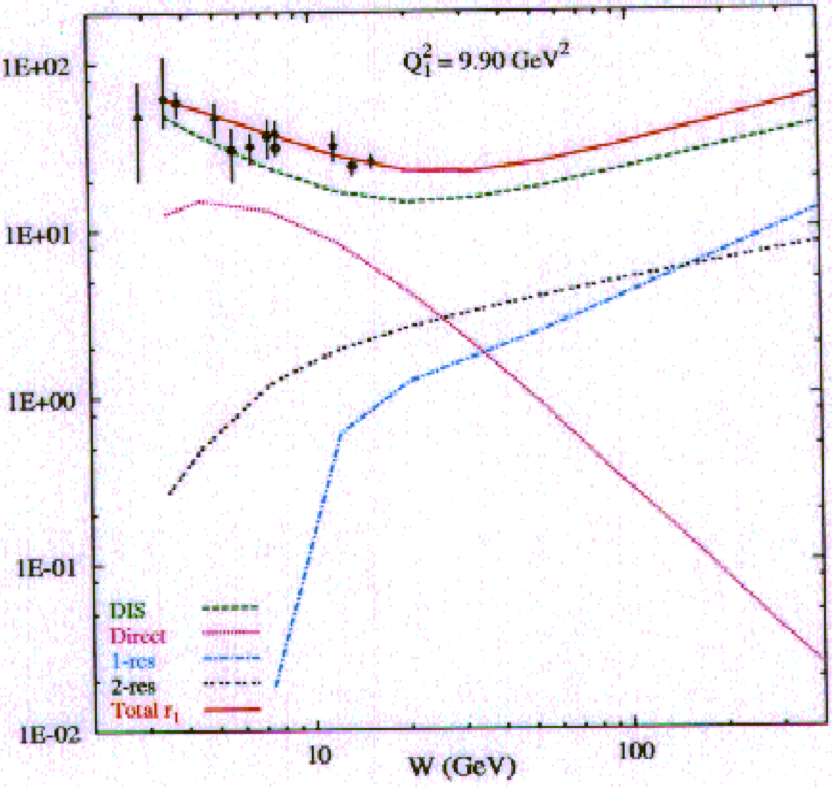
Energy dependence



$f_i^{\gamma_L^*} / f_i^{\gamma_T^*}$:

$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

$$r_2 = \frac{2Q^2}{m^2+Q^2}$$



Cross section in a parton shower MC event generator:

$$\sigma[W] = \underset{\text{final states } X}{\sum} \underset{\substack{\uparrow \\ \text{weight} \\ \text{function}}}{W(X)} \; \underset{\substack{\uparrow \\ \text{parton} \\ \text{shower}}}{PS} \otimes \underset{\substack{\uparrow \\ \text{hard} \\ \text{scattering}}}{H}$$

- Standard MC: H is taken to the LO
- NLO-improved MC:

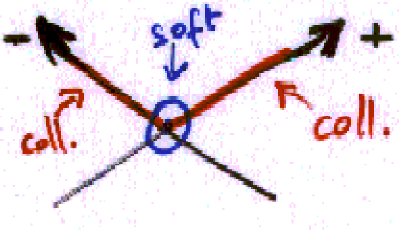
$$PS \otimes \Big[\underbrace{H^{(LO)}}_{\text{LO events}} + \alpha_s \underbrace{\Big(H^{(NLO)} - PS_I(1) \otimes H^{(LO)} - PS_F(1) \otimes H^{(LO)}\Big)}_{\text{NLO correction events}}\Big]$$

Example (simple): $\gamma^* g \to q\bar{q}$ in DIS

Collins, hep-ph/00010

- $PS_I(1)$ term only
- no soft gluons

General NLO processes:



overlapping soft and collinea regi

QUESTION: COLLINEAR REGIONS ACCURATELY TAKEN INTO ACCOUN BY SUBTRACTION TERMS. SOFT REGION?

TWO-PHOTON QCD STUDIES

TOPIC	ee	$e\gamma$ $\gamma\gamma$
Photon Structure		
• F_2^γ (low-x and α_s)	(✓)	✓
• F_2^γ (high-Q^2: CC/NC)	(✓)	✓
• $xg(x)$ (jets)	✓	✓
• $xg(x)$ (charm)	(✓)	✓
Polarized Photon Structure		
• Δf^γ (g_1)	(↯)	✓
• Δf^γ (jets)	✓	✓
Photon Interactions		
• $\sigma_{tot}(W_{\gamma\gamma})$	↯	✓
Large $\ln(1/x)$ (AKA BFKL)		
• $\gamma^*\gamma^*$	✓	–
• $\gamma\gamma \rightarrow$ J/ψ J/ψ	(✓)	✓
• Forward Jets	✓	✓
• $ee \rightarrow ee\gamma X$	✓	✓

✓ OK!

(✓) MAYBE OK

↯ KO

$\gamma\gamma$ Scattering - Total Cross Section/Photon Structure

R. Godbole

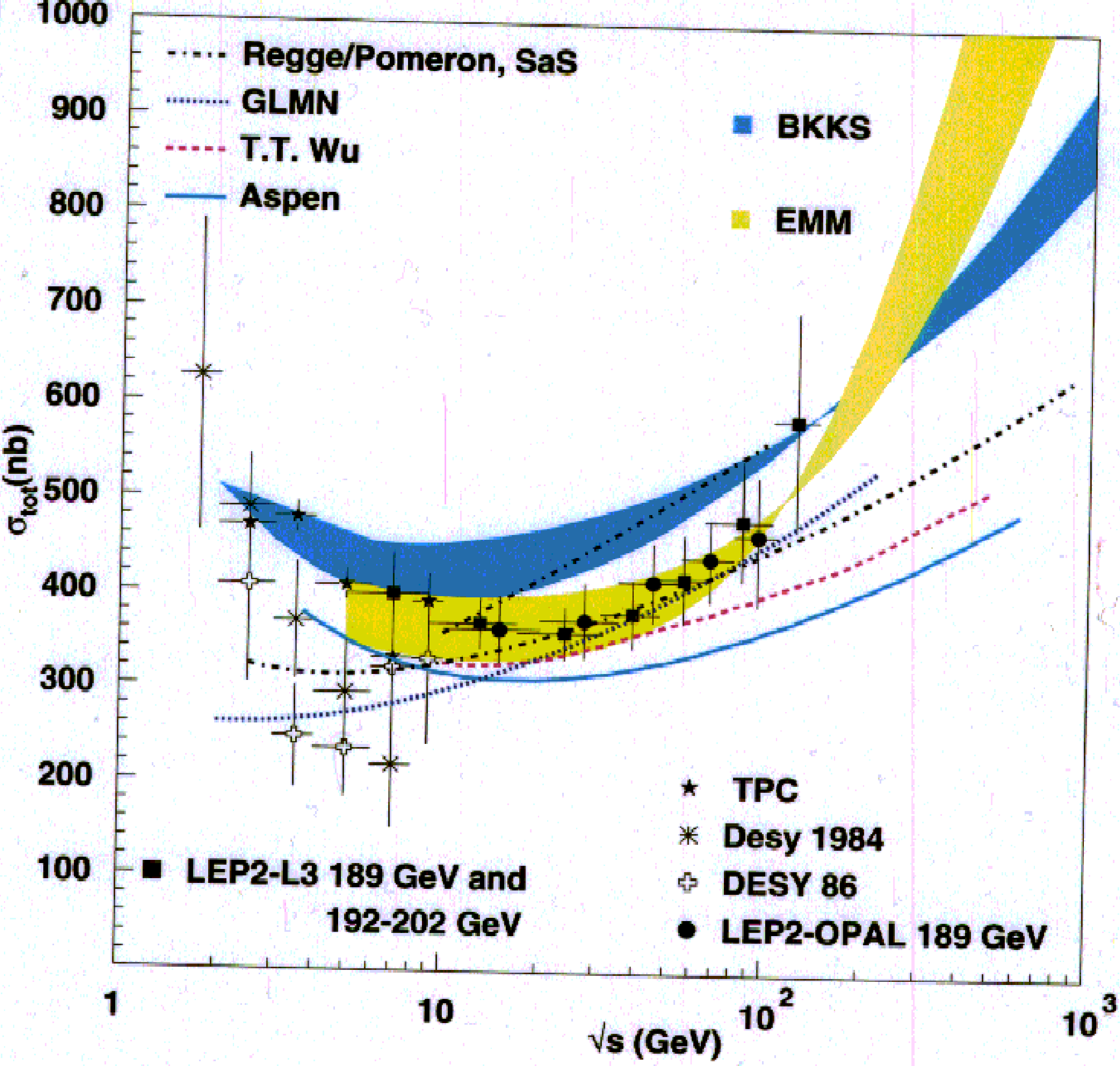
A. DeRoeck

- Total cross section measurement
  - Model comparisons to $\gamma\gamma$, γp, pp data
    - QCD-based (F_2^γ, minijet)
    - "Photon is like a proton" (Regge/Pomeron)
  - Precision required at LC to distinguish models ----->

- Photon q/g structure from dijets (low x_γ)
  - e+e- mode --> 70%g/30%q
  - Laser $\gamma\gamma$ mode--> 90%g/10%q (almost pure g)

⑪

G. Pancheri, R.M.G.



Precision for discrimination betwen models

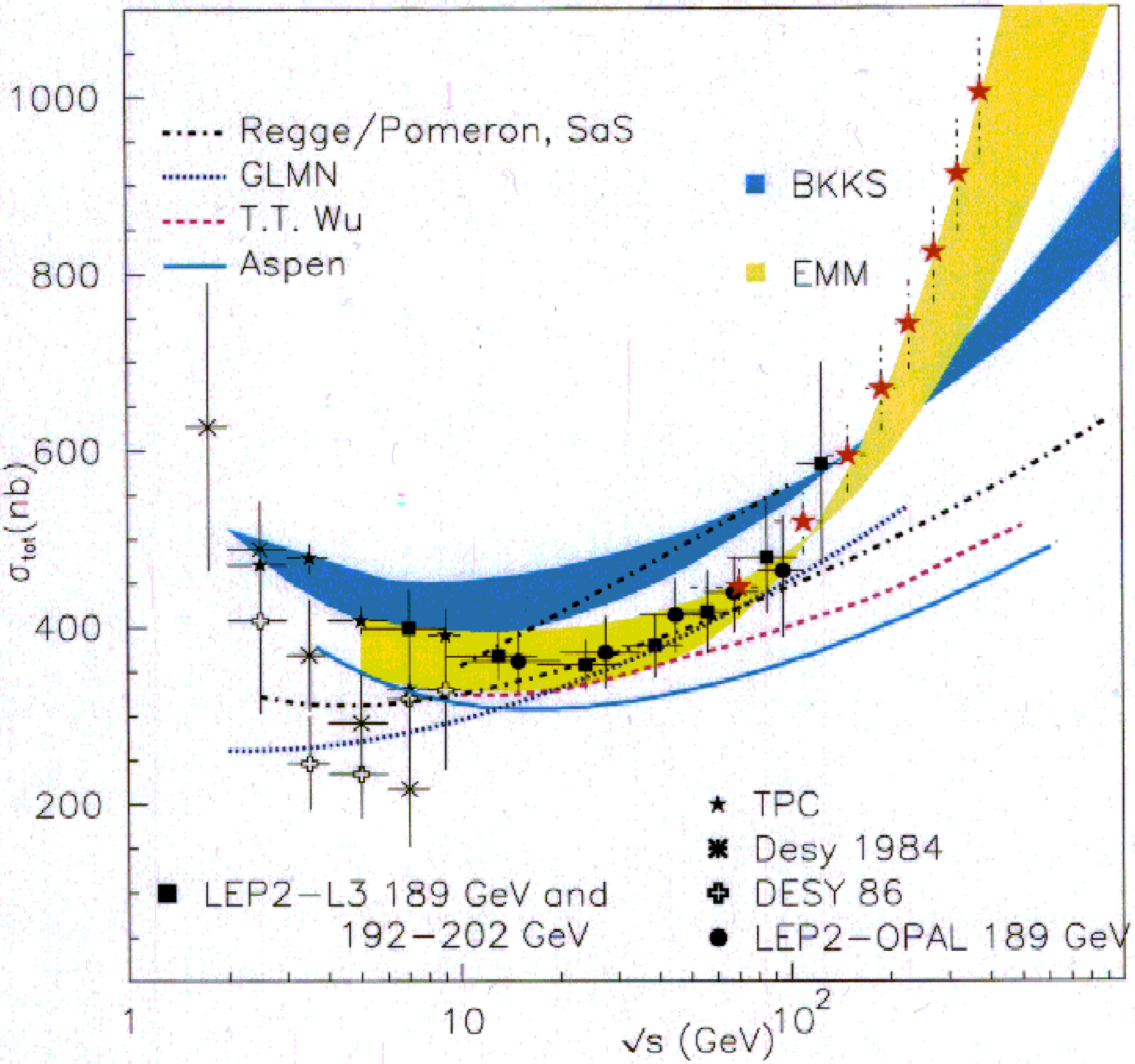
Table 1: Total $\gamma\gamma$ cross-sections and required precision for models based on factorization

$\sqrt{s_{\gamma\gamma}}(GeV)$	Aspen	T.T. Wu	DL	1σ
20	309 nb	330 nb	379 nb	7%
50	330 nb	368 nb	430 nb	11%
100	362 nb	401 nb	477 nb	10%
200	404 nb	441 nb	531 nb	9%
500	474 nb	515 nb	612 nb	8%
700	503 nb	543 nb	645 nb	8%

Table 2: As in Table 1 for Eikonal Minijet Models

$\sqrt{s_{\gamma\gamma}}(GeV)$	BN GRV p_{tmin} 2 GeV	IPT GRS p_{tmin} 1.5 GeV	IPT GRV p_{tmin} 2 GeV	1σ
20	329 nb	312 nb	308 nb	0.3%
50	367 nb	357 nb	360 nb	1%
100	454 nb	435 nb	463 nb	4%
200	547 nb	581 nb	672 nb	8%
500	730 nb	928 nb	1171 nb	18%
700	873 nb	1105 nb	1420 nb	27%

G. Pancheri, R.M.G., A. de Roeck.



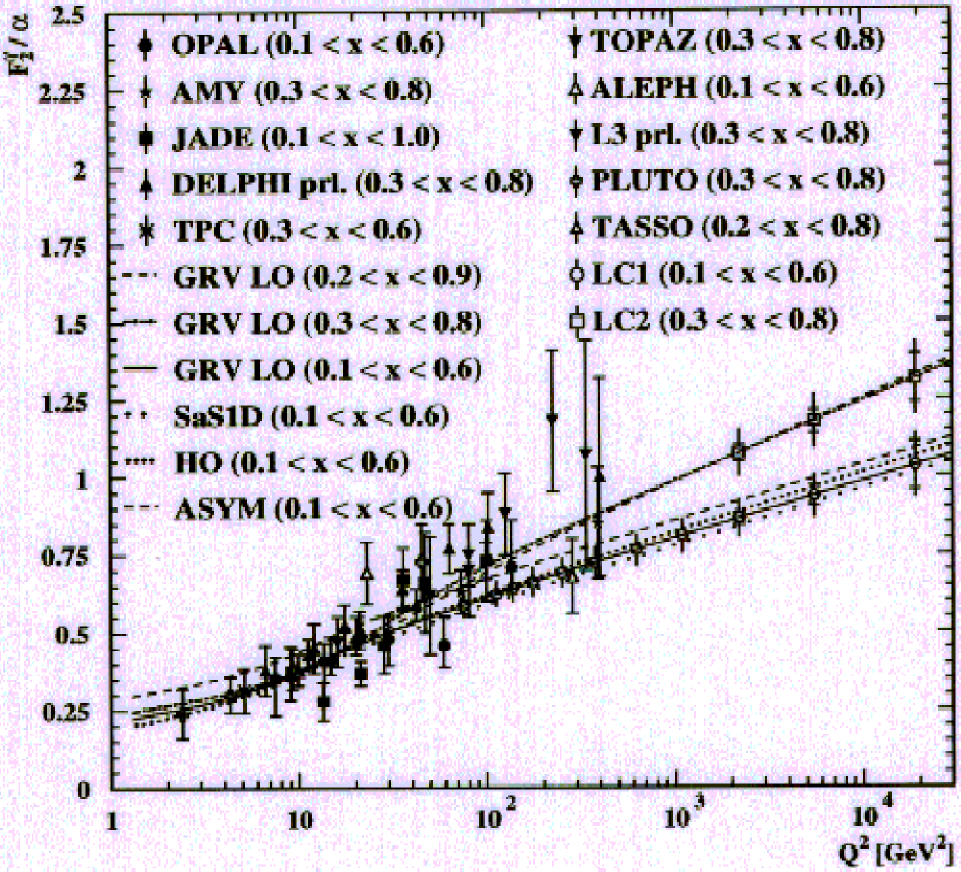
$\gamma^*\gamma$ *Scattering - eγ DIS*

A. DeRoeck

- *F_2^γ - direct measurement in DIS process*
  - *Measurement of F_2^γ at high Q^2 - Q^2 evolution ----->*
  - *Measurement of F_2^γ at low x (LEP ~10^{-3} --> LC ~few 10^{-5})*
    - *x reconstruction (Wvis) for single tag e+e-)*
    - *enhancement of low x region with Laser ----->*
- *Polarised Structure Function*
  - *for photon - no data available for Δq^γ*
  - *g_1, Δq may be large at low x --> Laser photons*
  - *ln 1/x (BFKL) terms in unpolarised scattering enter as $\ln^2$ 1/x for polarised --> enhanced effect at low x*

F_2^γ STRUCTURE FUNCTION

- e^+e^- MODE: HIGH Q^2, HIGH-x

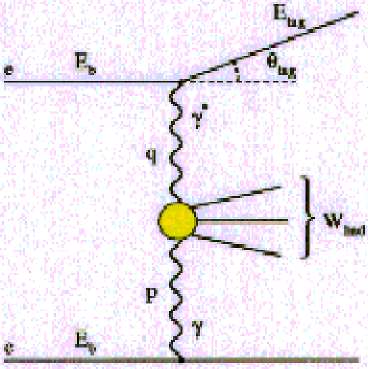


- LC1 ($\theta_{tag} > 40$ MRAD); LC2 ($\theta_{tag} > 175$ MRAD)
- SYST. ERROR ~ 7% (~ 1/2 ERROR FROM LEP)
- $\Delta\alpha_s = 5\% \rightarrow \Delta F_2^\gamma = 3\%$ (LARGE Q^2)
- HIGH Q^2: CHARGED/NEUTRAL CURRENTS → UP/DOWN QUARK CONTENT
- LOW-x: CHARM 30-40% OF CROSS SECTION

F_2^γ STRUCTURE FUNCTION

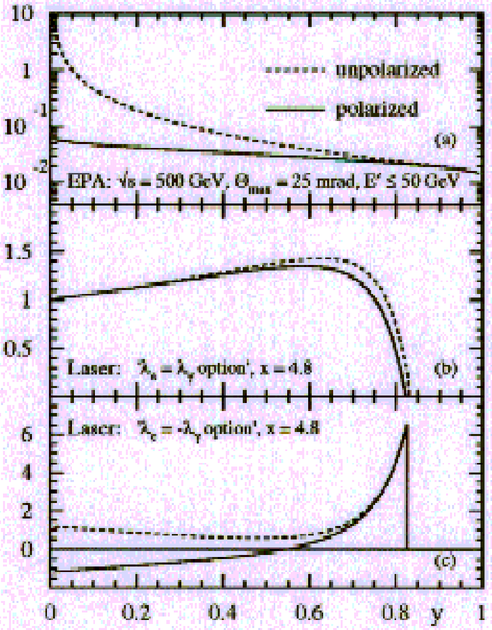
VOGT, MILLER, NISIUS, ZERWAS, SPIESBERGER, GEHRMAN-DE RIDDER, ADR...

$$\frac{d\sigma_{e\gamma\to eX}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)F_2^\gamma$$



- ELECTRON TAGGING: $\Theta > 25$ MRAD, $E_e > 50$GEV
(SMALLER Θ? FORWARD ELECTRON TAGGING $Q^2 \sim 0$?)

PHOTON SPECTRA USED:



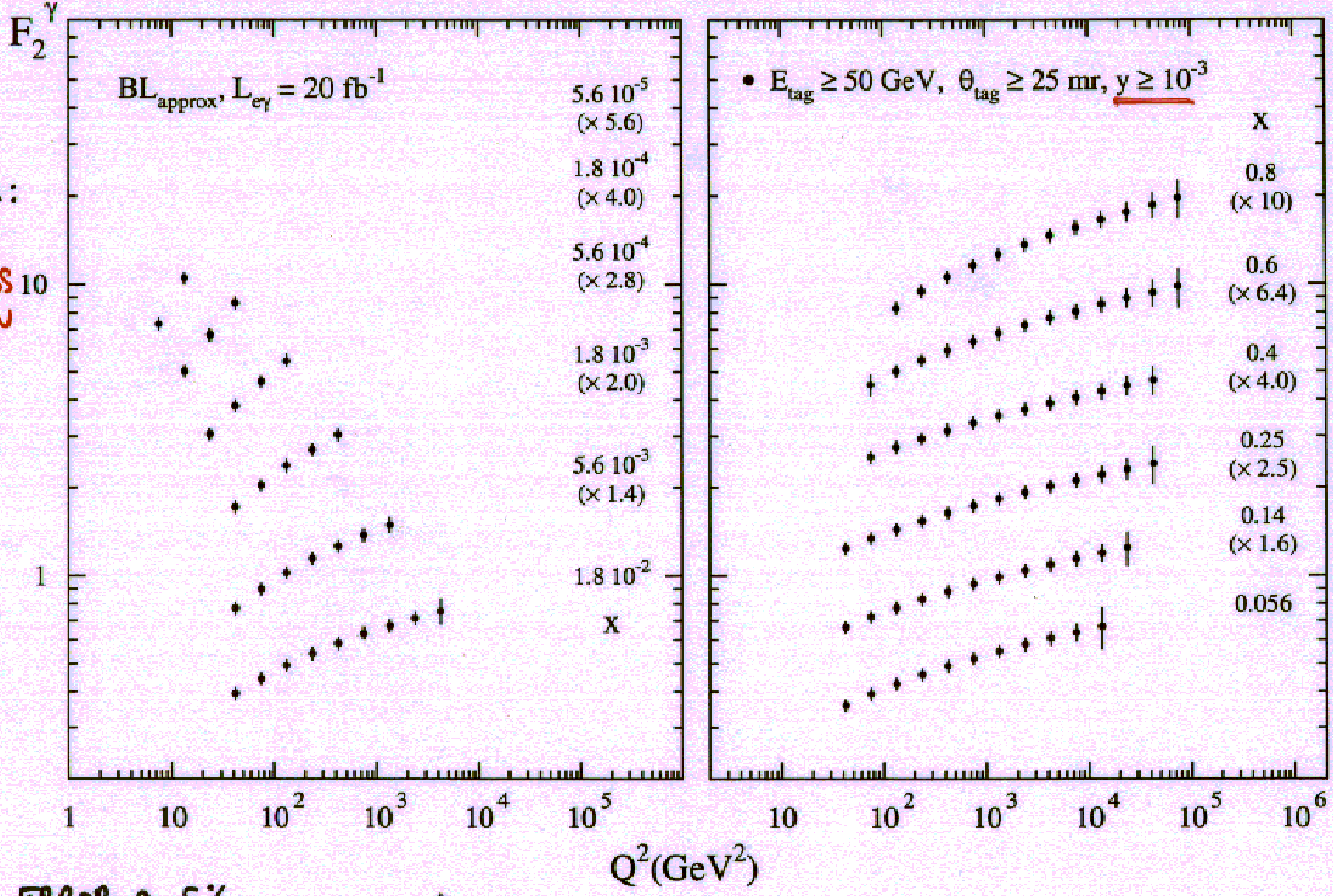
e^+e^-

$\gamma\gamma$, $e\gamma$

- e^+e^- MODE: DIFFICULT, ONLY $Q^2 > 20 - 50$ GEV^2, $x \gtrsim 10^{-3}$
- $e\gamma$ MODE: LOW-x ACCESSABLE!

A. VOGT, ADR

u:
%,
oss
on



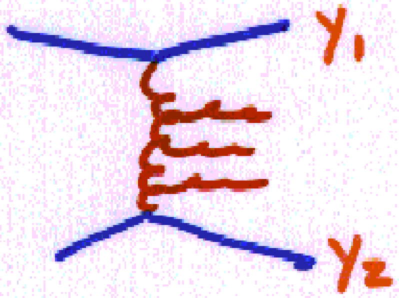
T ERROR ~ 5%
+STAT ERROR

$\gamma^*\gamma^*$ *Scattering - QCD Dynamics (BFKL)*

L. Orr C. Royon
A. DeRoeck. C-F. Qiao

- *Cleanest test of mechanism of QCD dynamics --->*
- *Measurement for "free" with beam pipe EM tagging calorimeters*
  - *Signal/background vs experiment ----->*
- *Towards complete NLO BFKL calculation/Monte Carlo*
  - *LO BFKL problems*
    - *non-conservation of E, p*
    - *huge NLO corrections*
    - *constant background? ----->*
  - *Partial NLO calculation - comparison to LEP,DO data ----->*
  - *Calculation of photon-pomeron coupling - PIF (photon impact factor - needed for NLO*
- *Other methods (J/Psi, Forward jets, ee->eeγX)*

Tevatron / LHC: dijet prod. at large rapidity



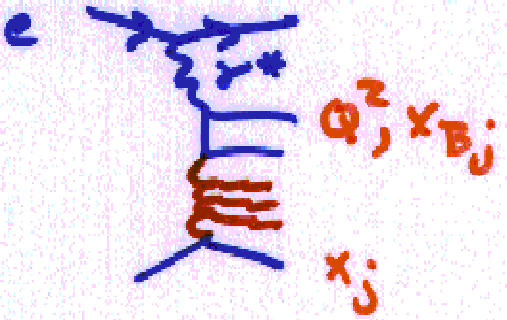
$\Delta = Y_1 - Y_2$

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

$\Rightarrow$ azimuthal decorrelation

Mueller
Navelet

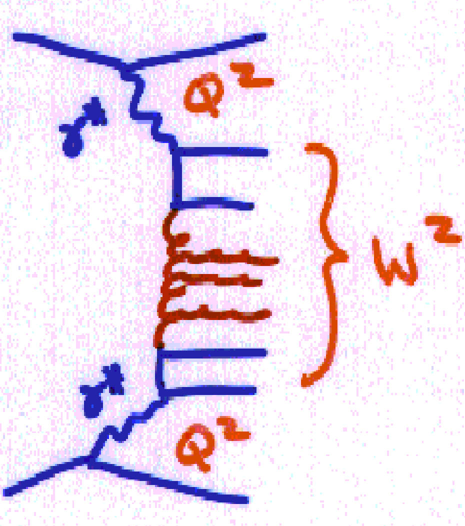
HERA: forward jet production



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

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

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



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

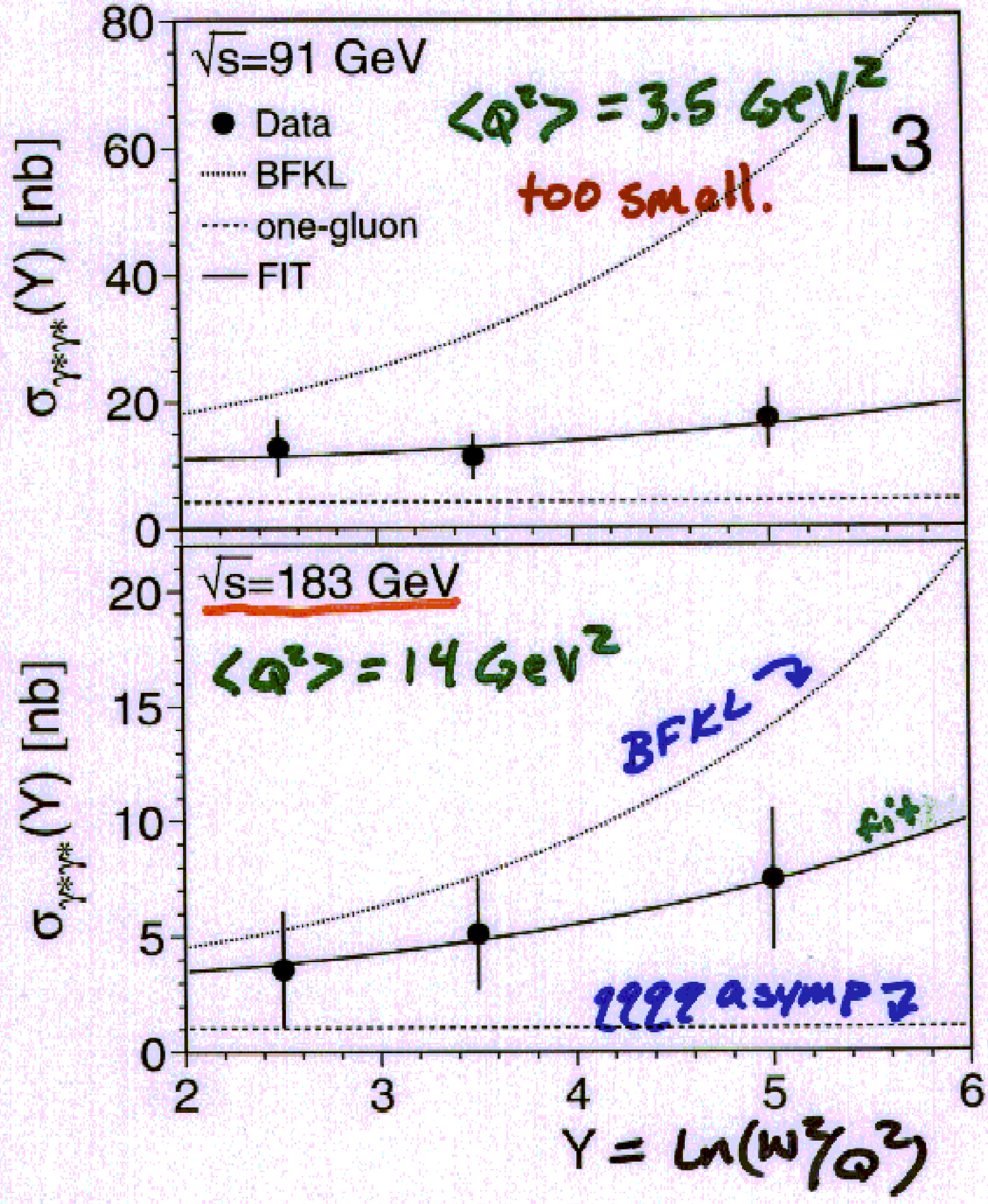
$\Rightarrow \sigma_{\gamma^*\gamma^*} \sim \left(\frac{W^2}{Q^2}\right)^{\lambda}$

Brodsky
Hautman
Soper

Y-dependence of cross-section (CLIC)

- Possibility to cut on Y to enhance BFKL cross-section with respect to 2-gluon one
- 3 TeV center-of-mass energy $Y > 9$ (resp. 8): σ_{BFKL}= 1.9 10^{-6} pb, ratio= 6.2 (σ_{BFKL}= 7.8 10^{-6} pb, ratio= 4.8)
- 5 TeV center-of-mass energy $Y > 9$ (resp. 8): σ_{BFKL}= 9.3 10^{-7} pb, ratio= 5.7 (σ_{BFKL}= 2.8 10^{-6} pb, ratio= 4.5)
- $Y > 9$, and $\theta > 25$ mrad,
  σ_{BFKL} (3 TeV) =3.3 10^{-5} pb, ratio= 7.5
  σ_{BFKL} (5 TeV) =1.1 10^{-5} pb, ratio= 6.2

L3



$\langle Q^2\rangle = 3.5$ GeV^2

too small.

$\langle Q^2\rangle = 14$ GeV^2

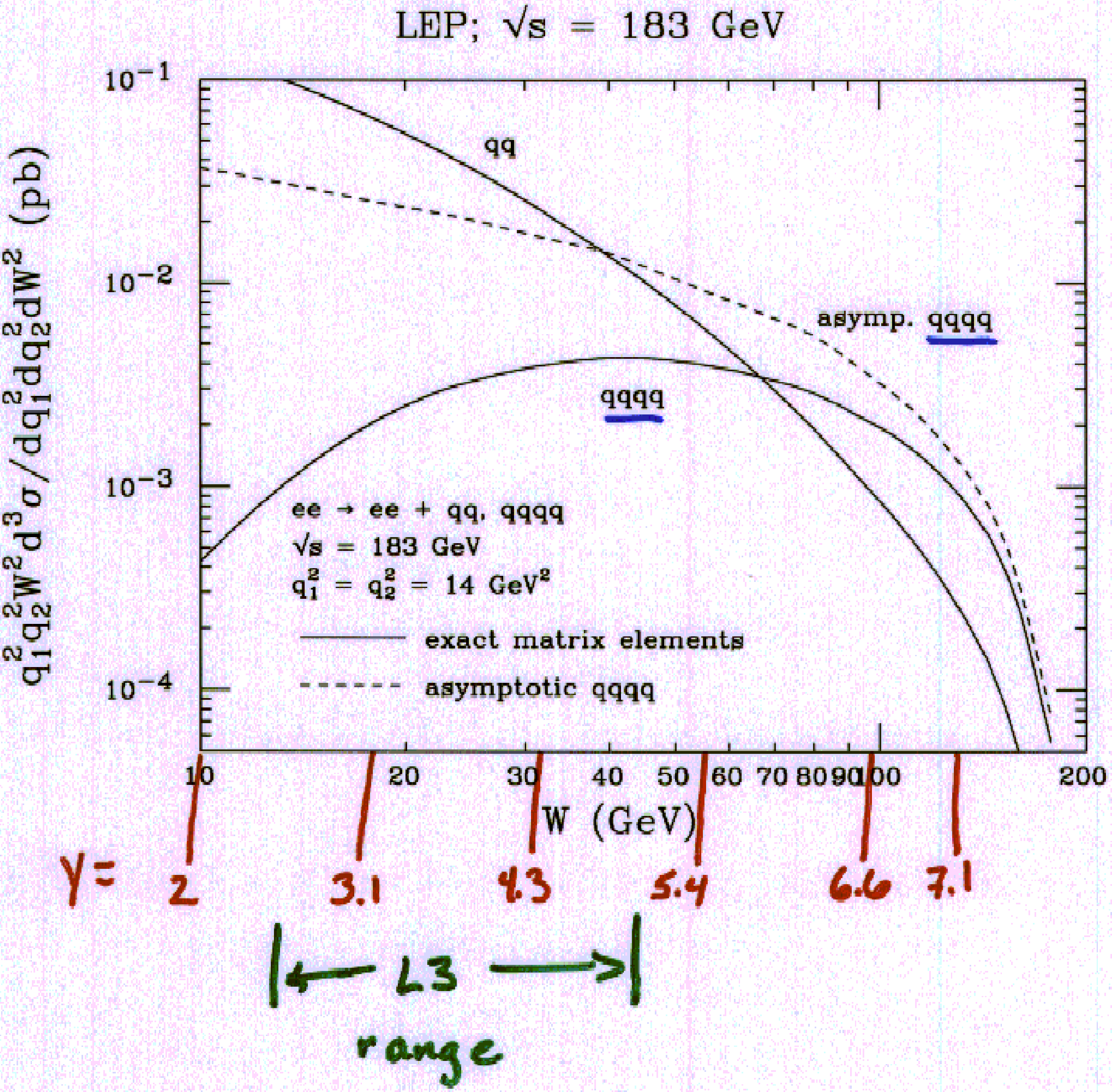
BFKL

fit

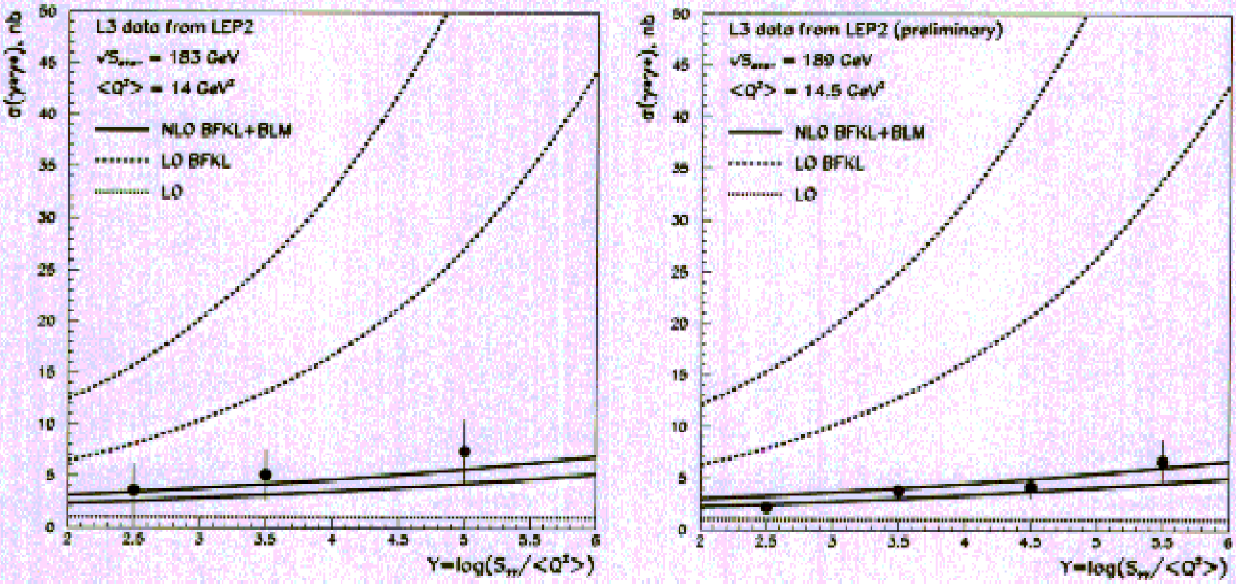
2222 asymp

$Y = \ln(W^2/Q^2)$

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 $\alpha_{I\!P}$ as a free parameter.


LEP; √s = 183 GeV
$q_1^2q_2^2W^2d^3\sigma/dq_1^2dq_2^2dW^2$ (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

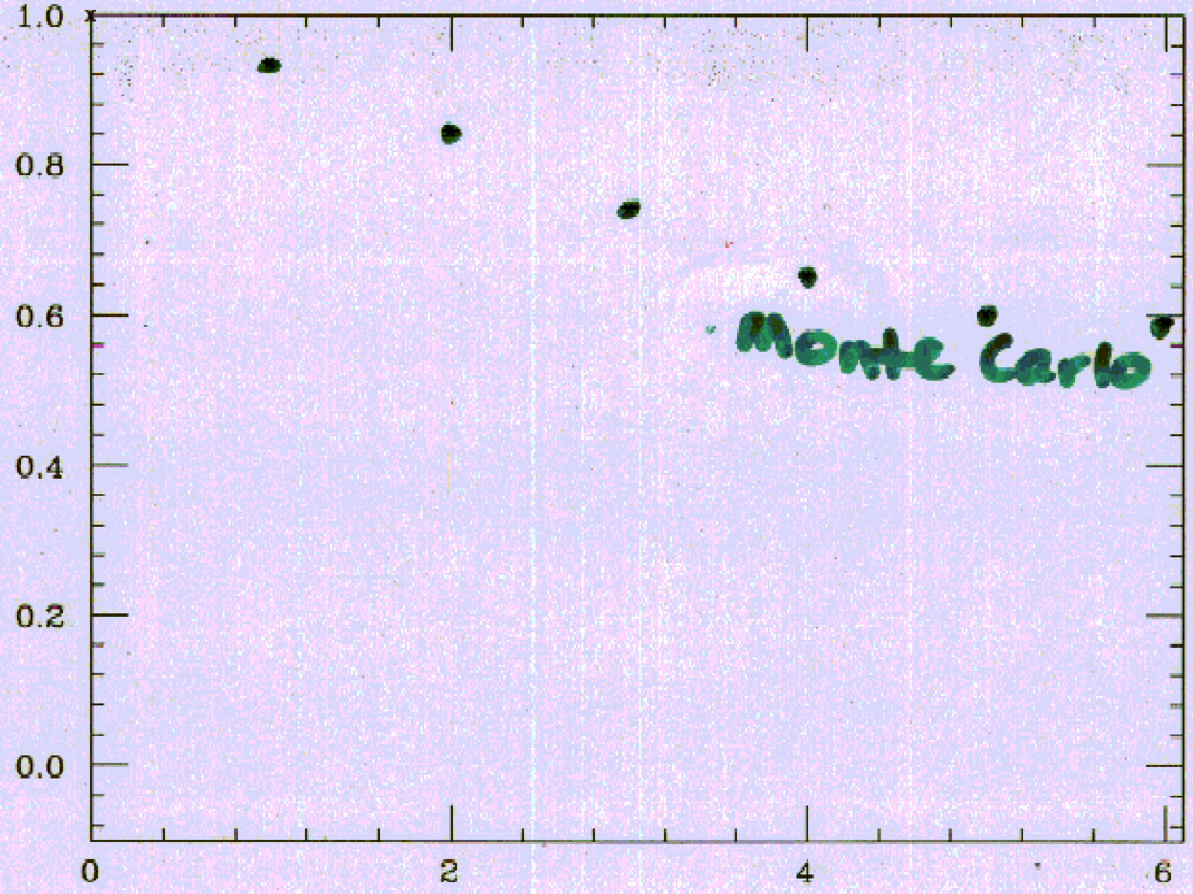
Improvement by NLO calculation?



(Kim, Lipatov, Pivovarov, `hep-ph/9911242`)

- leading BFKL too large, strong α_S- and mass-dependence
- NLO BFKL improves the situation considerably (but strong renormalisation scheme dependence)
- Overall normalisation still open

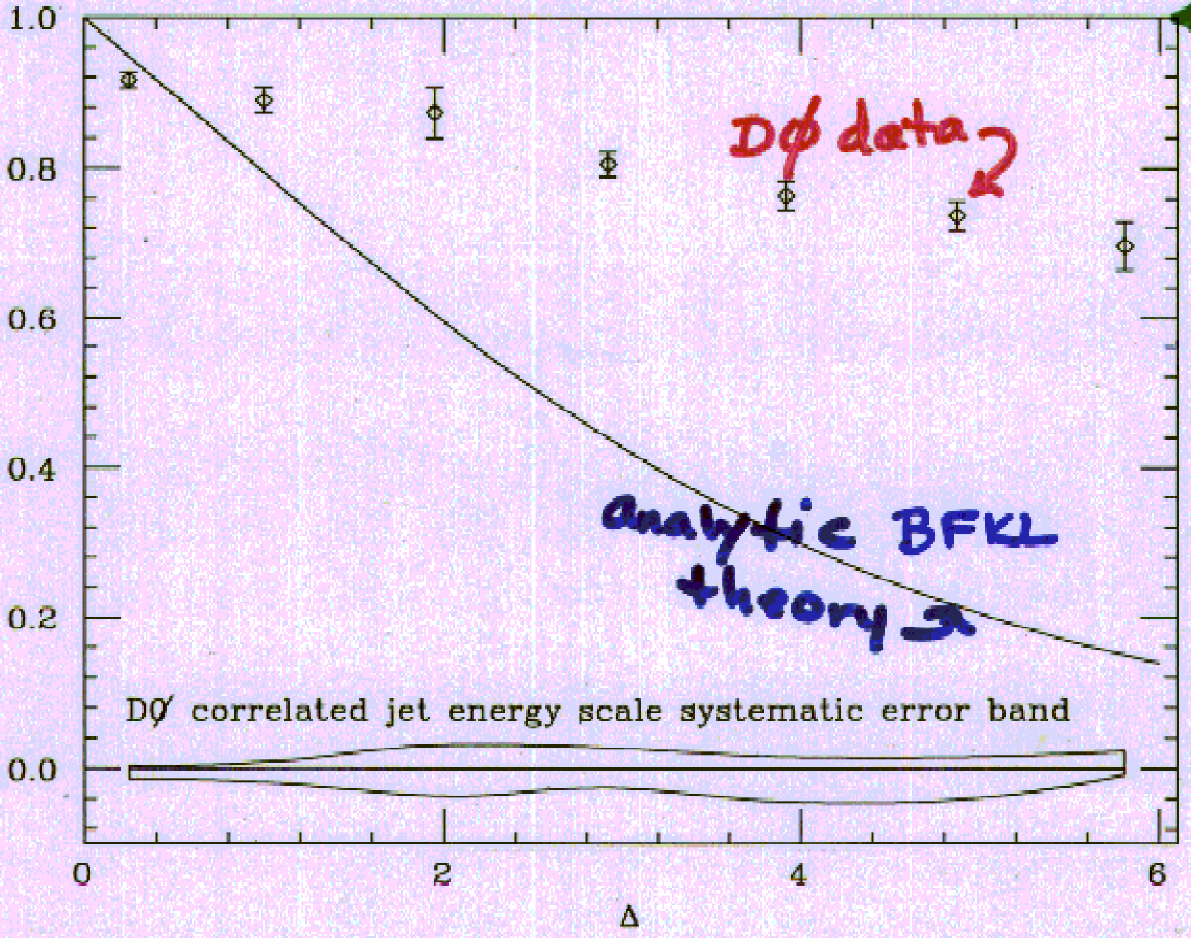
⟶ Calculation of the NLO impact factors for virtual photons is highly desirable.


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

Azimuthal Decorrelation in Dijet Productio at the Tevatron

Figure 5

$P_T > 20$ GeV



← QCD LO

DØ data

analytic BFKL theory

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

LHO,
W.J. Stirling

Summary

- *Precise determination of α_s at high energy scales can be made in a clean and well-understood theoretical environment*

- *Two-Photon Physics in the e+e- mode (Bremstrahlung photons)*
  - *High Q^2 F_2^γ (quarks)*
  - *Dijets in DIS, $\gamma\gamma$ (gluon component)*

    $\gamma^*\gamma^*$ Scattering - BFKL (better theoretical understanding and experimental conditions)

- *Two-Photon Physics in the $e\gamma$, $\gamma\gamma$ (Laser backscattering) modes*
  - *Low x $F_{2\gamma}$ - full use of higher W*
  - *High energy $\gamma\gamma$ scattering - understanding of total cross section*