3.4 Quantum Chromodynamics

3.4.1 Introduction

Strong-interaction measurements at TESLA will form an important component of the physics programme. The 500-800 GeV collider offers the possibility of testing QCD in the experimentally clean, theoretically tractable e^+e^- environment. In addition, $\gamma\gamma$ interactions will be delivered free by Nature, and a dedicated $\gamma\gamma$ collider is an additional option, allowing detailed measurements of the relatively poorly understood photon structure. The benchmark physics main topics are:

- Precise determination of the strong coupling α_s.
- Measurement of the Q^2 evolution of α_s, searches for new coloured particles and constraints on the GUT scale.
- Measurements of the $t\bar{t}(g)$ system
- Measurement of the total two-photon interactions.
- Measurement of the unpolarised and polarised photon structure.
- Testing of BFKL dynamics.

3.4.2 Precise determination of α_s

3.4.2.1 Event Shape Observables

3.4.2.2 The $t\bar{t}$ System (SHORT, → top section)

3.4.2.3 A High-luminosity Run at the Z^0 Resonance

3.4.2.1 Event Shape Observables

Introduction

Detector systematic errors

Event selection and backgrounds

Hadronisation uncertainties

Theoretical ucnertainties

LINEAR COLLIDER $\alpha_s(M_Z)$ MEASUREMENT

1. Event Shape Observables

- Studied at Snowmass 96 (Burrows *et al.*, SLAC-PUB-7371)
- ECFA/DESY Workshop: O. Biebel, N. America: B. Schumm
- Statistics:

  $\geq$ 50k $q\overline{q}$ events $\Rightarrow$ $\Delta\alpha_s \leq 0.001$

- Detector systematics:

  currently $\Delta\alpha_s \sim 0.002$

  Excellent tracking + calorimetry $\Rightarrow$ $\Delta\alpha_s \sim 0.001$

- Hadronisation uncertainties $\sim 1/Q$

  At $Q = 500$ GeV $\Rightarrow$ $\Delta\alpha_s < 0.001$

- Limiting precision:

  Higher-order pQCD contributions: $\Delta\alpha_s \sim 0.006$

  $\Rightarrow$ NNLO calculation needed

  (in progress)

3.4.2.2 The $t\bar{t}$ System

Introduction

σ_{tt} **near threshold**

σ_{tt} **above threshold**

$t\bar{t}g$ **events**

Currently : not competitive
for α_s determination

=> SHORT discussion only

LINEAR COLLIDER α_s (M_Z) MEASUREMENT

2. Top Quark Observables

- $\sigma_{t\bar{t}}$ near threshold (Peralta)

  new NNLO calculations ⇒

  reduced correlation $\alpha_s \leftrightarrow M_t$ [redacted]

  [redacted] THEORY UNCERTAINTY

  ± 0.012

- $\sigma_{t\bar{t}}$ above threshold (Bernreuther)

  PRELIMINARY study of NLO calculations

  $\sqrt{s} = 400$ GeV: $\Delta\alpha_s = 0.005$

  (theory limiting)

  $\sqrt{s} \geq 500$ GeV: $\Delta\alpha_s = 0.012$

  (exp. syst. limiting)

- $e^+e^- \to t\bar{t}\,g$ (Brandenburg)

  α_s : en passant

  running mass $m_t(Q)$

3.4.2.3 A High-luminosity Run at the Z^0 Resonance

Introduction

$\Gamma_Z^{had}/\Gamma_Z^{lept}$ (see also EW section)

$\Gamma_\tau^{had}/\Gamma_\tau^{lept}$

En passant:

Running b mass

QCD colour factor measurement

Rich programme of "all the rest"

LINEAR COLLIDER $\alpha_s(M_Z)$ MEASUREMENT

2. Lower-energy running offers new possibilities:

- Z^0 **decay widths:** $\Gamma_Z^{had}/\Gamma_Z^{lept}$

  calculated at NNLO

  current precision, 16M Z^0 at LEP: $\Delta\alpha_s = 0.003$

1000M Z^0 $\Rightarrow$ $\Delta\alpha_s =$ [redacted] 0.0016

  BEWARE: event selection (Mönig *et al.*),

  ~~theory uncertainties?~~ NEW: 0.0009

Theoretically safe ground.

- τ **decay widths:** $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$

  calculated at NNLO

  current exp. precision, LEP+CLEO: $\Delta\alpha_s = 0.001$

  theoretical uncertainties $\Rightarrow$ $\Delta\alpha_s =$ [redacted]

  0.002 → 0.006

3.4.2 Q^2 Evolution of α_s

(New coloured particles)

Extrapolation to GUT scale

$\Rightarrow$ Low-energy data points at TESLA would be desirable

$\rightarrow$

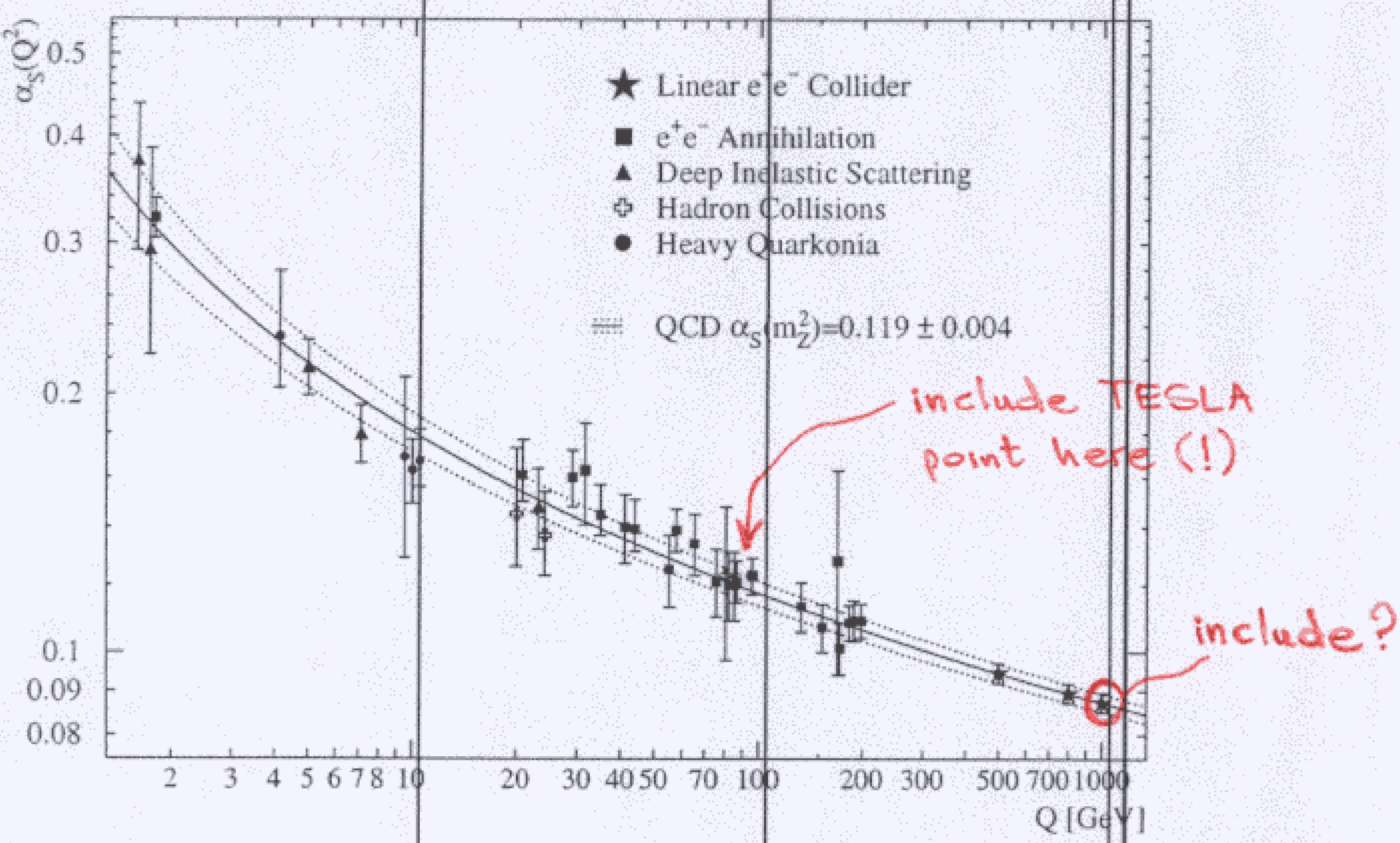


Figure 3.4.1: The evolution of α_s with Q^2 [4]

e^+e^- QCD

3.4.4 OTHER [redacted] TOPICS

- Limits on anomalous strong top-quark couplings

  ⇒ modify gluon energy in $t\bar{t}g$ events × ref to Top

- Measurement of Γ_t using $t\bar{t}g$ events (Orr)

  ⇒ Γ_t affects degree of soft-gluon coherence

- Polarisation-based asymmetries in $q\bar{q}g$ events:

  $\vec{P}_e \cdot \vec{k}_{q1} \times \vec{k}_{q2}$ (CP+ T−)

  $\vec{P}_e \cdot \vec{k}_q \times \vec{k}_{\bar{q}}$ (CP− T−)

  ⇒ Search for anomalous final-state interactions

- Particle multiplicity in heavy- vs. light-quark jets

  ⇒ add long lever-arm to current tests

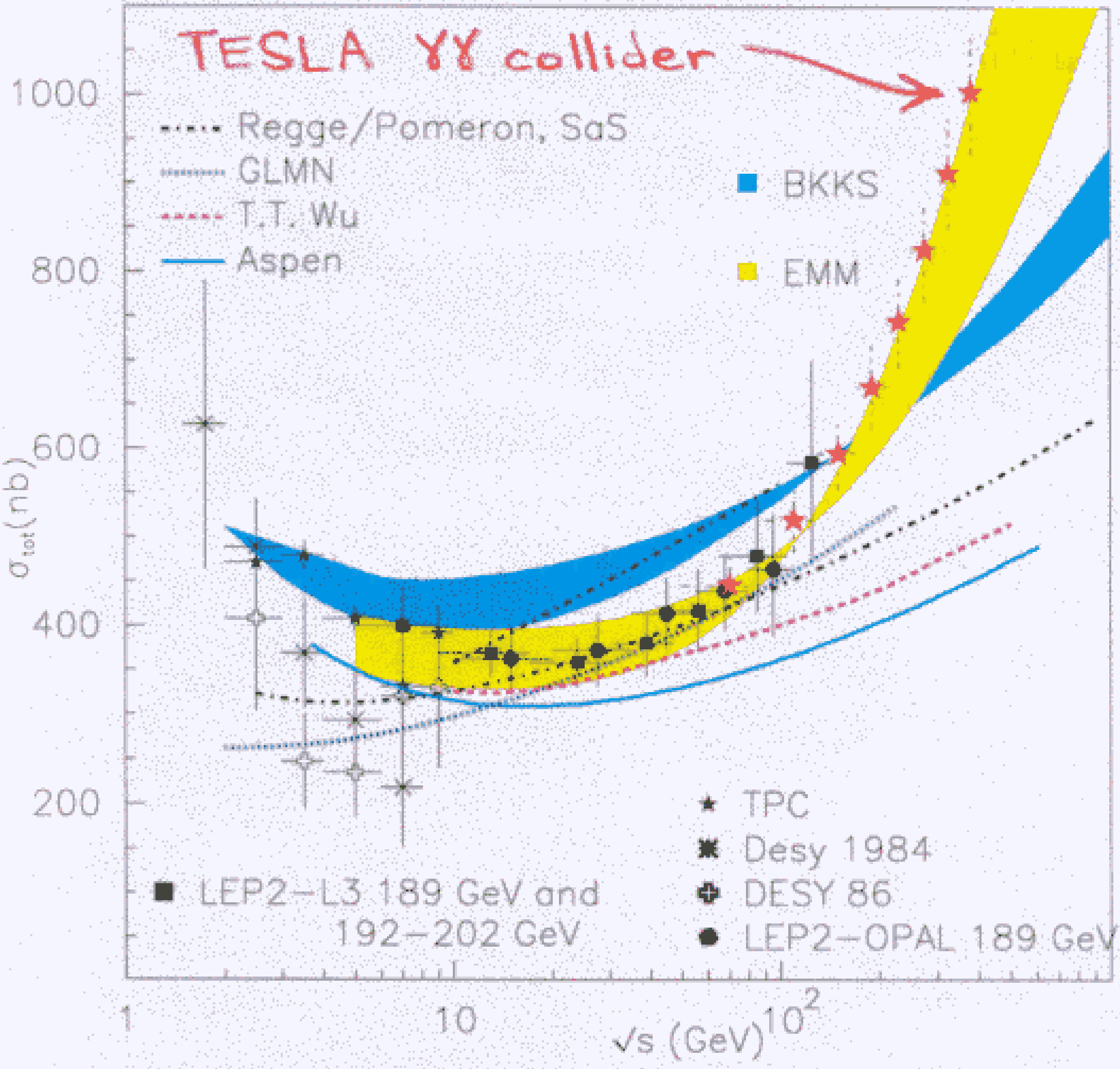
[redacted]

- Colour reconnection and Bose-Einstein correls.

[redacted]

- power corrections

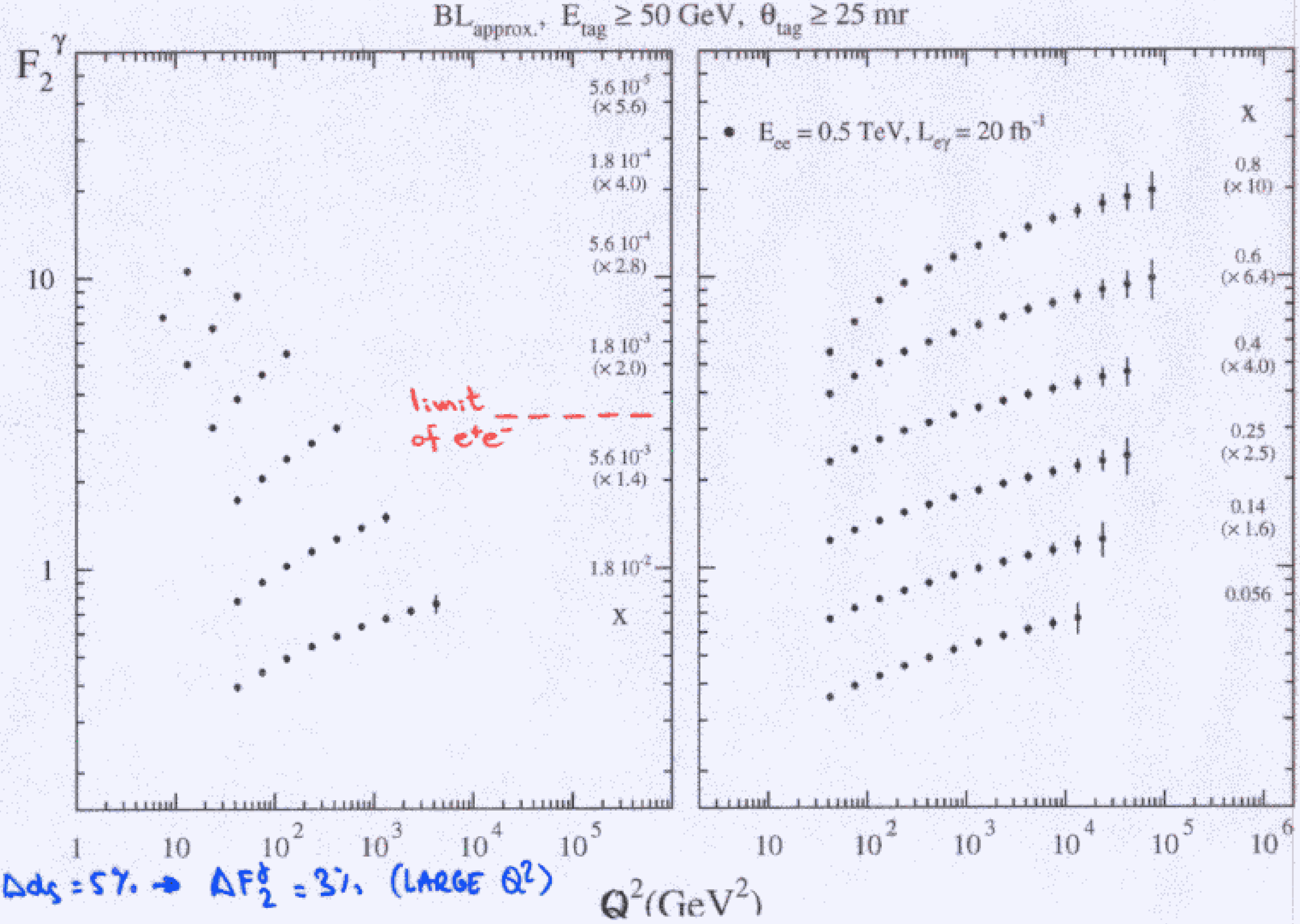
γγ total σ


TESLA γγ collider
Regge/Pomeron, SaS
GLMN
T.T. Wu
Aspen
BKKS
EMM
TPC
Desy 1984
DESY 86
LEP2-OPAL 189 GeV
LEP2-L3 189 GeV and 192-202 GeV
σ_tot(nb)
√s (GeV)
1000
800
600
400
200
1
10
10^2

eγ collider : 20 fb^{-1} (1 year)

STAT + (3%) SYST ERROR

CHARM: 30-40% OF CROSS SECTION



(VOGT)

NOTE: $\Delta d\sigma = 5\% \rightarrow \Delta F_2^{\gamma} = 3\%$ (LARGE Q^2)

POLARIZED STRUCTURE FUNCTION

PROTON: POLARISED DIS $\longrightarrow \Delta q$ (POL. PARTON DISTR.)

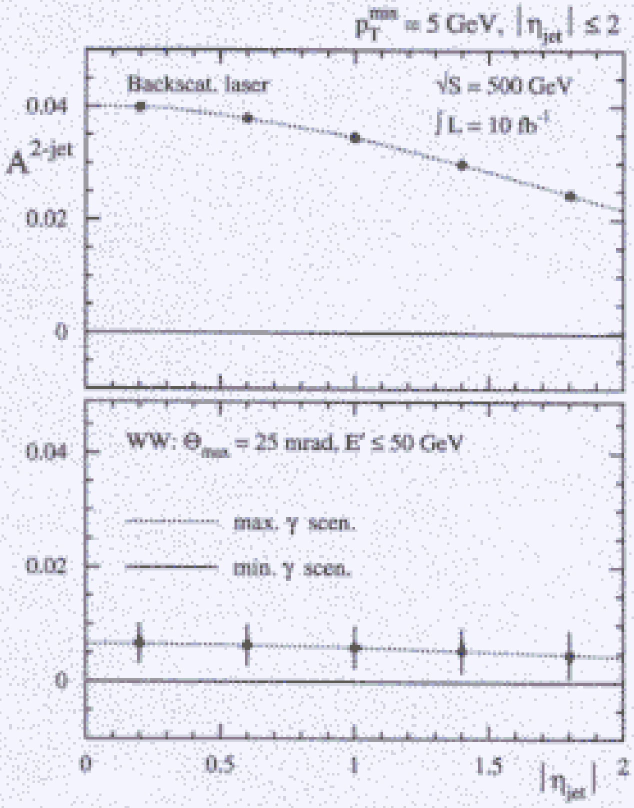
SPIN PUZZLE (EMC): SPIN PROTON $\neq \sum$ SPIN QUARKS

* PHOTON: NO DATA AVAILABLE ON Δq^{γ}

LINEAR COLLIDER $\Rightarrow$ POLARIZED BEAMS

M. Stratmann, W. Vogelsang

- $g_1(\sim F_1) \longrightarrow e^+e^-$, $e\gamma$ ✓
- JETS $\longrightarrow e^+e^-$ ✓ $\gamma\gamma$ ✓



$e\gamma$

e^+e^-

$$\frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}}$$

2 DIFFERENT Δq^{γ}'S

CLEAR SENSITIVITY IN $\gamma\gamma$!!

SUMMARY

Two-photon QCD studies for TESLA

- Photon structure can be measured in $e\gamma$ in the region $6 \cdot 10^{-5} < x < 0.6$, $6 < Q^2 < 10^5$ GeV^2. Lower x and Q^2 range reachable with smaller angle tagging (15 mrad?). F_2^γ in e^+e^- more difficult (smaller region).
- Access to the gluon density in the photon down to $2 - 5 \cdot 10^{-3}$ from di-jet events.
- Unique measurements can be made of polarized parton distributions, Δq^γ from $e\gamma$ scattering and jets.
- Total cross section $\sigma_{tot}^{\gamma\gamma}(W)$ can be measured in $\gamma\gamma$ upto W of 400 GeV. Cross sections should be measured to the 5-10% level.
- Several promising ways to test the large $\ln 1/x$ resummation: total $\gamma^*\gamma^*$ cross section, vector meson production, forward jets, diffractive photon production...

Two-photon QCD will be part of the TESLA physics program tions in the photon. Already with very modest luminosity significant measurements of the polarised parton distributions become accessible at a linear collider. The extraction of the polarised structure function $g_1(x,Q^2) = \Sigma_q e_q^2(\Delta q^\gamma(x,Q^2) + \Delta\bar{q}^\gamma(x,Q^2))$, with Δq the polarised parton densities, can however be best done at a $e\gamma$ collider for similar reasons as outlined above for F_2^γ measurements. Measurements of g_1, particularly at low x, are extremely important for studies of the high energy QCD limit, or BFKL regime [47]. Indeed, the most singular terms of the effects of small x resummation on $g_1(x,Q^2)$ behave like $\alpha_s^n \ln^{2n} 1/x$, compared to $\alpha_s^n \ln^n 1/x$ in the unpolarised case of F_2^γ. Thus large $\ln 1/x$ effects are expected to set in much more rapidly for polarised than for unpolarised structure measurements. Leading order calculations, including kinematic constraints, show that differences in predictions of g_1 with and without these large logarithms can be as large as a factor 3 to 4 for $x = 10^{-4}$ and could thus be easily measured with a few years of data taking at a photon collider.

3.4.5.3 Testing of BFKL Dynamics

Apart from the inclusive polarised structure function measurements, discussed in the previous section, several dedicated measurements exist for detecting and studying the large $\ln 1/x$ logarithm resumation effects in QCD, also called BFKL dynamics. These calculations, done in LO, underwent a revolution in the 1998 and 1999, when it was pointed out that the NLO corrections could be very large [46]. The dust is settling, showing that the corrections to experimental variables are generally not as large as thought at first, and several methods have been developed to get improved estimates[48].

The most promising measurement for observing the effect of the large logarithms is the total $\gamma^*\gamma^*$ cross-section, i.e. two-photon scattering of virtual photons with approximately equal virtualities for the two photons. Recent calculations, taking into account higher order effects, confirm that this remains a gold-plated measurement, which can be calculated essentially entirely perturbatively and has a sufficiently large cross-section. The events are measured by tagging both scattered electrons. At a 500 GeV e^+e^- collider about 3000 events are expected per year (200 fb^{-1}) and a factor of 3 less in the absence of BFKL effects in the data [49]. Tagging electrons down to as low angles as possible (e.g. 25 mrad) is however a crucial requirement for the experiment.

Closely related to the $\gamma^*\gamma^*$ measurement is vector meson production, e.g $\gamma\gamma \to J/\psi J/\psi$ or (at large t) $\gamma\gamma \to \rho\rho$, where the hard scale in the process is given by the J/ψ mass or the momentum transfer t. J/ψ's can be detected via their decay into leptons, and separated from the background through a peak in the invariant mass. Approximately 100 fully reconstructed 4-muon events are expected for 200 fb^{-1} of luminosity for a 500 GeV e^+e^- collider[50]. For this channel it is crucial that the decay muons and/or electrons can be measured to angles below 10 degrees in the experiment.

The gold plated method to look for BFKL effects at HERA is the study of so-called forward jets and particles [51]. These are jets or particles which a p_T similar to the virtuality of the γ^* and very close to the direction of the outgoing proton beam at HERA. A similar process can be studied at a linear collider in $e\gamma$ scattering, with a jet