Measurement of the proton and kaon time-like electromagnetic form factors at high energy with the BABAR detector

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I. Introduction

The proton and kaon time-like electromagnetic form factors are extracted from measurements of the cross sections for the reactions $e^+e^- \to K^+K^-$

$$\sigma_{K^+K^-}(s) = \frac{\pi\alpha^2\beta^3 C(s)}{3s}|F_K|^2,$$

and $e^+e^- \to p\bar{p}$

$$\sigma_{p\bar{p}}(s) = \frac{4\pi\alpha^2\beta C(s)}{3s}\left(|G_M(s)|^2 + \frac{2m_p^2}{s}|G_E(s)|^2\right),$$

where s is the e^+e^- center-of-mass energy squared, and C is the correction for the Coulomb final state interaction. At high energies the second term in the $p\bar{p}$ cross section is suppressed and the cross section is proportional to the magnetic form factor squared.

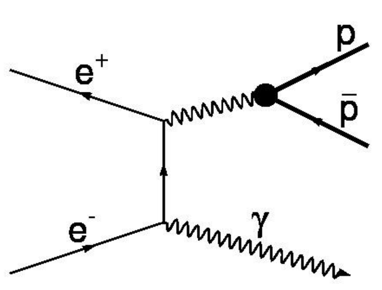
The asymptotic behavior of the form factors is predicted in the frame of perturbative QCD

$$F_K = \frac{8\pi\alpha_s f_K}{s}, \quad G_M \sim \frac{\alpha_s^2}{s^2}.$$

Previously, the proton and kaon form factors were measured up to 4-5 GeV. It was observed that they decrease in agreement with the pQCD predictions. However, the value of the kaon form factors at 4 GeV exceeds the predictions by about 4 times. For proton the ratio of the time- and space-like form factors at 4 GeV is about 2 instead of unity expected at high energy.

Our goal is to perform measurement at larger energies to answer the question: Does the difference between the prediction and data decrease with energy increase.

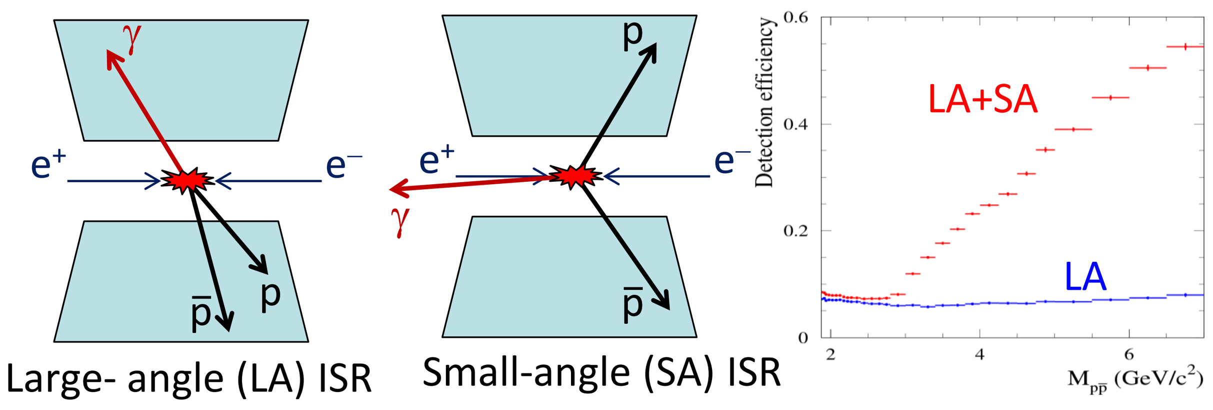
II. ISR method



The mass spectrum of the produced hadron system in the reaction $e^+e^- \to X+\gamma$ is related to the cross section for the nonradiative process $e^+e^- \to X$.

$$\frac{d\sigma_{e^+e^-\to X+\gamma}}{dm\, d\cos\theta} = \frac{2m}{s}W(s,x,\theta)\sigma_{e^+e^-\to X}(m), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$

The function $W(s,x,\theta)$ is calculated in QED with a high accuracy (better than 0.5%). In lowest order it describes angular ($1/\sin^2\theta$ at $\theta \gg m_e/\sqrt{s}$) and energy ($1/x$) distributions of the ISR photon.



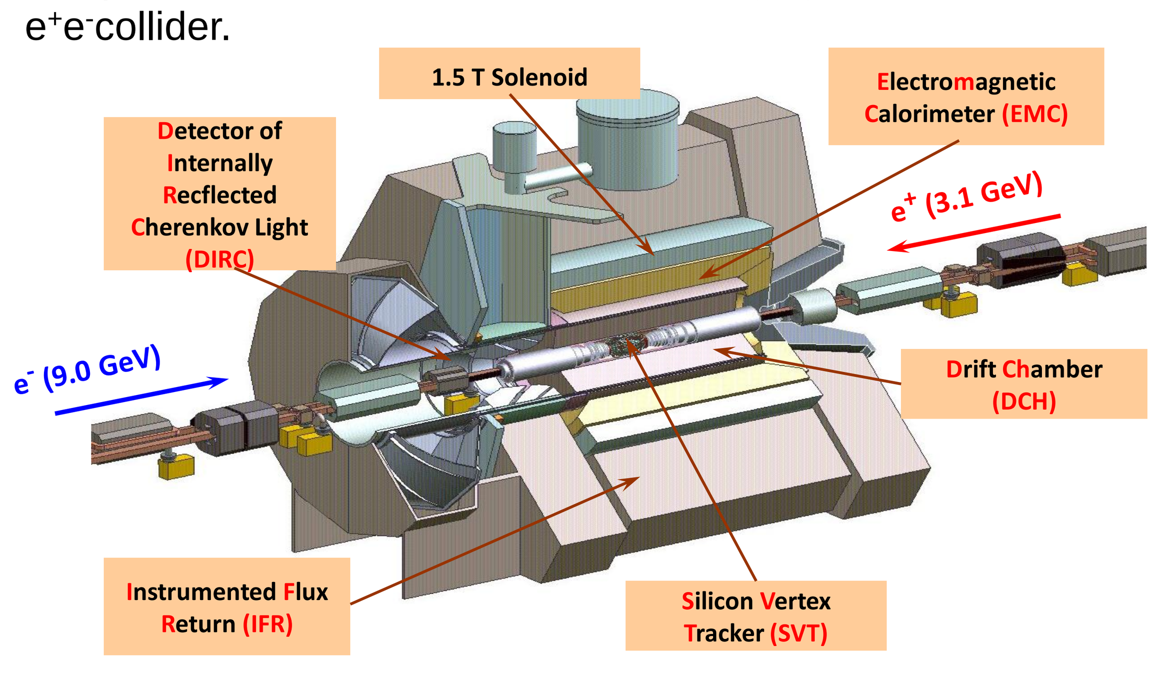
The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the low mass region can be studied only with detected photon (about 10% of ISR events).

Our previous measurements were performed with LA ISR.

Above 3 GeV statistics can be significantly increased by using SA ISR.

III. Experiment

The presented analyses are based on the full **BABAR** data sample, 469 fb^{-1}, collected at and near Υ(4S) at the SLAC PEP-II e^+e^- collider.



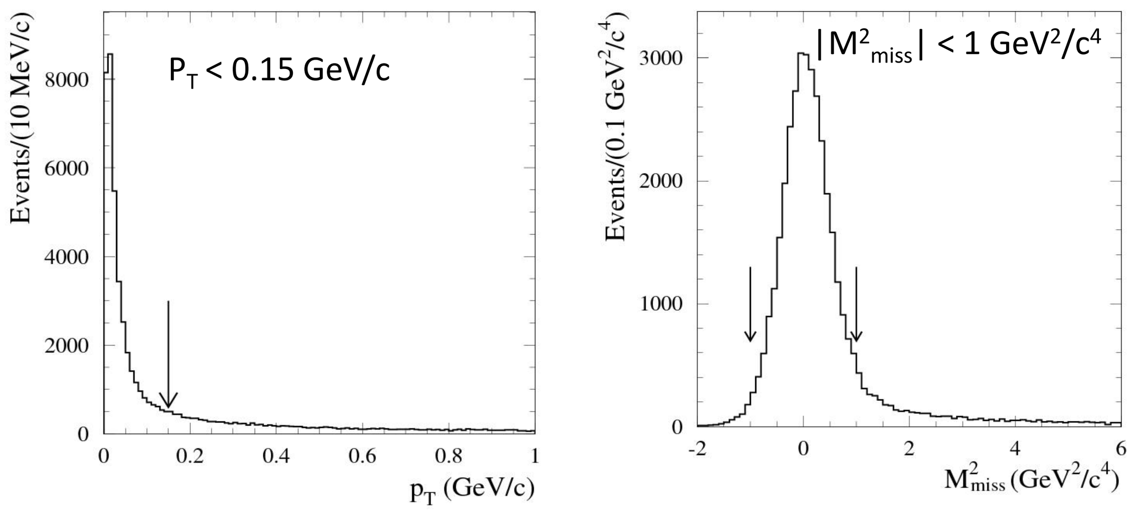
The signal ISR events are simulated with the Phokhara event generator (H. Czyz et al, Eur.Phys.J, C **39**, 411 (2005)), which takes into account next-to-leading order radiative corrections.

The previous BABAR results obtained using LA ISR method:
Phys. Rev. D **87** (2013) , 092005 for $e^+e^- \to$ p anti-p,
Phys. Rev. D **88** (2013), 032013 for $e^+e^- \to K^+K^-$

Here we present the SA ISR results for $e^+e^- \to$ p anti-p (Phys. Rev. D 88 (2013), 072009) and a preliminary SA ISR results for $e^+e^- \to K^+K^-$.

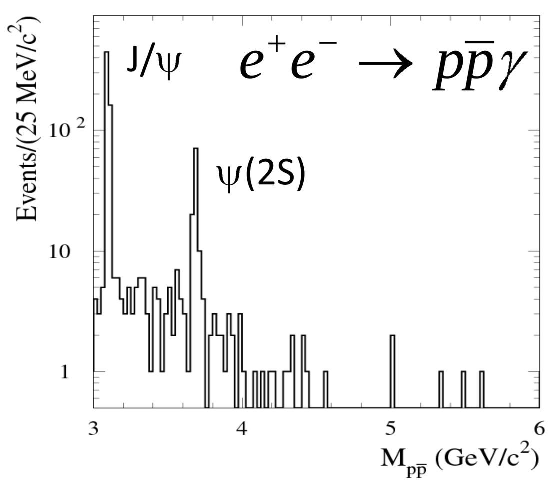
IV. Event selection

We select events with two tracks of opposite charge originating from the interaction region, having the polar angle in the range (25.8°-137.5°) and identified as protons or kaons Further selection are based on two parameters:
- the transverse momentum (p_T) of the proton or kaon pair,
- the missing mass (M_{miss}) recoiling against the proton or kaon



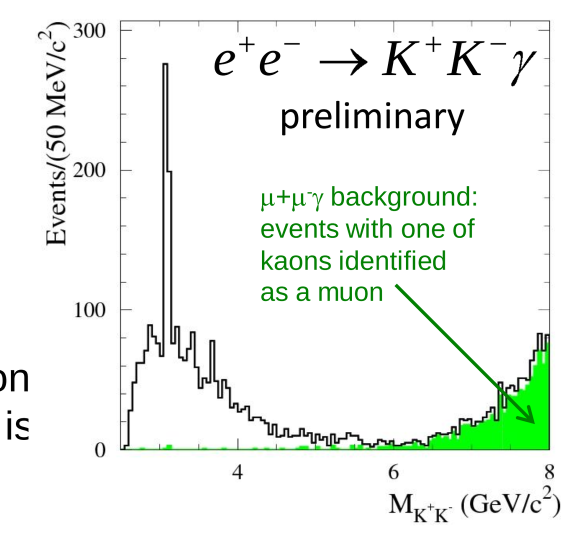
Events, in which the ISR photon is emitted along the positron beam direction, have an average kaon (proton) momentum about 5 GeV/c. We reject such events to decrease background with misidentified particles.

Mass spectra for selected events



- The J/ψ and $\psi(2S)$ peaks are seen.
- The total number of selected events is 845. The number of nonresonant events is 149.
- No events are observed with mass above 6 GeV/c².

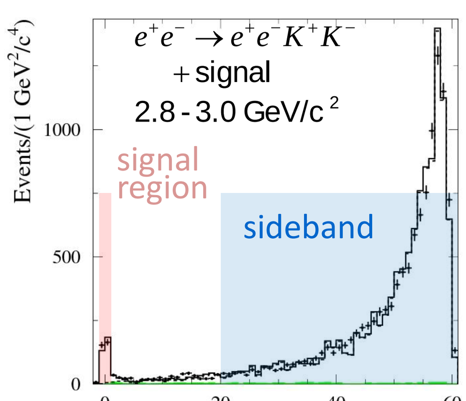
- The peaks from J/ψ, $\psi(2S)$ and χ_{c0} are seen. The χ_{c0}'s are produced in $\psi(2S)$ decays.
- The growth in the number of events above 6 GeV/c² is due to $\mu\mu\gamma$ background.
- To suppress the muon background we apply the condition that none of the kaon candidates is identified as a muon.



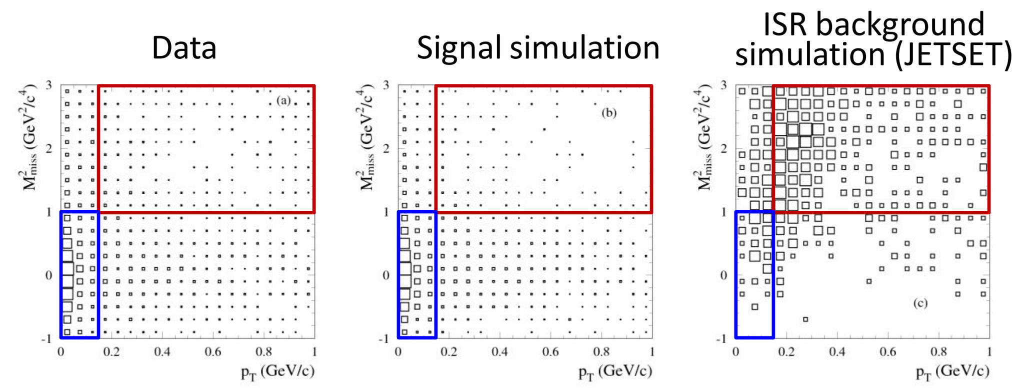
V. Background

- **Two-photon processes: $e^+e^- \to e^+e^-K^+K^-(p\bar{p})$.**

Two-photon background is estimated using M^2_{miss} sideband. It is found to do not exceed 3% of $K^+K^-\gamma$ signal events, and even lower for $p\bar{p}\gamma$.



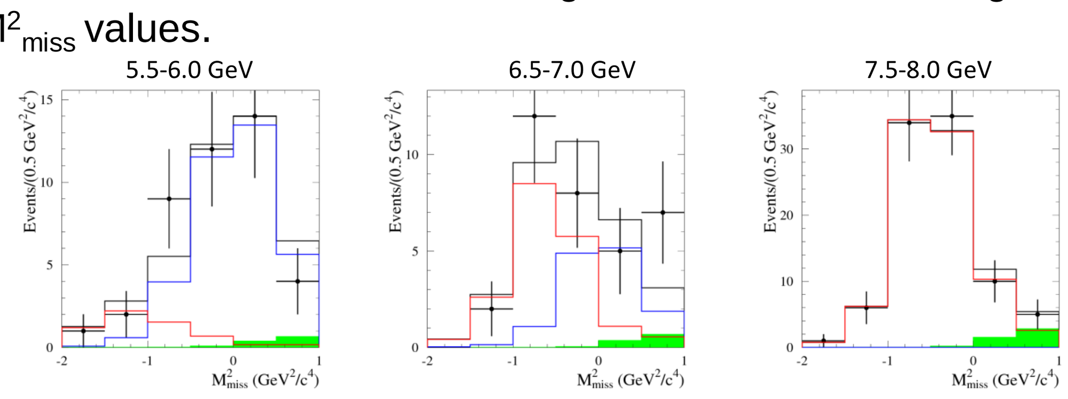
- **ISR processes, e.g., $e^+e^- \to K^+K^-(p\bar{p})\pi^0\gamma$.**



The rectangular sideband in the M^2_{miss} vs p_T plane is used to estimate the ISR background. It is found to do not exceed 5% of $pp\gamma$ signal events, and lower for $K^+K^-\gamma$.

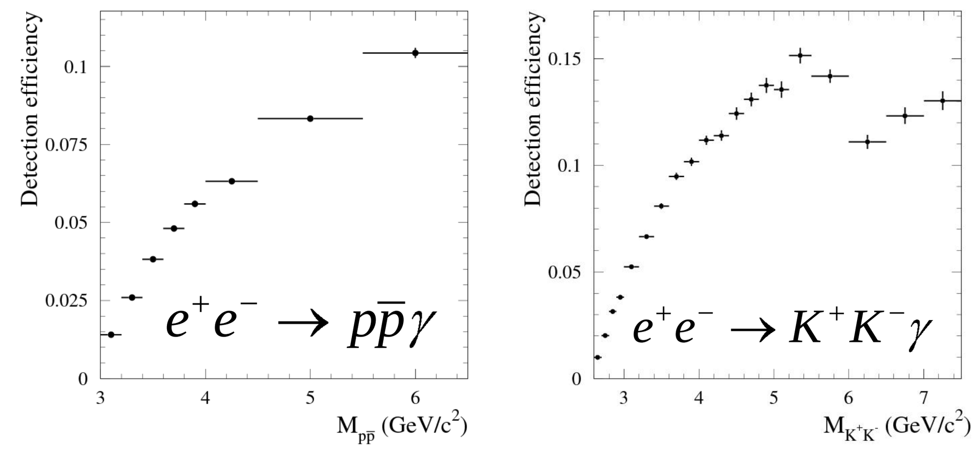
- **ISR process with misidentified particles, e.g., $e^+e^- \to \mu^+\mu^-\gamma$.**

This background sources is found to be negligible for $pp\gamma$ events, and for $K^+K^-\gamma$ with the K^+K^- mass below 5 GeV/c². For higher K^+K^- masses signal and background are separated using the difference in the M^2_{miss} distributions. The signal is peaked at zero, while the background is shifted to negative M^2_{miss} values.



The M^2_{miss} distributions for selected $K^+K^-\gamma$ candidates (points with error bars). The solid histogram is the fit results. The blue, red, and green histograms shows the contribution of signal, muon background, and ISR+two-photon background, respectively. Non-zero signal is seen for M_{K+K-} < 7.5 GeV/c².

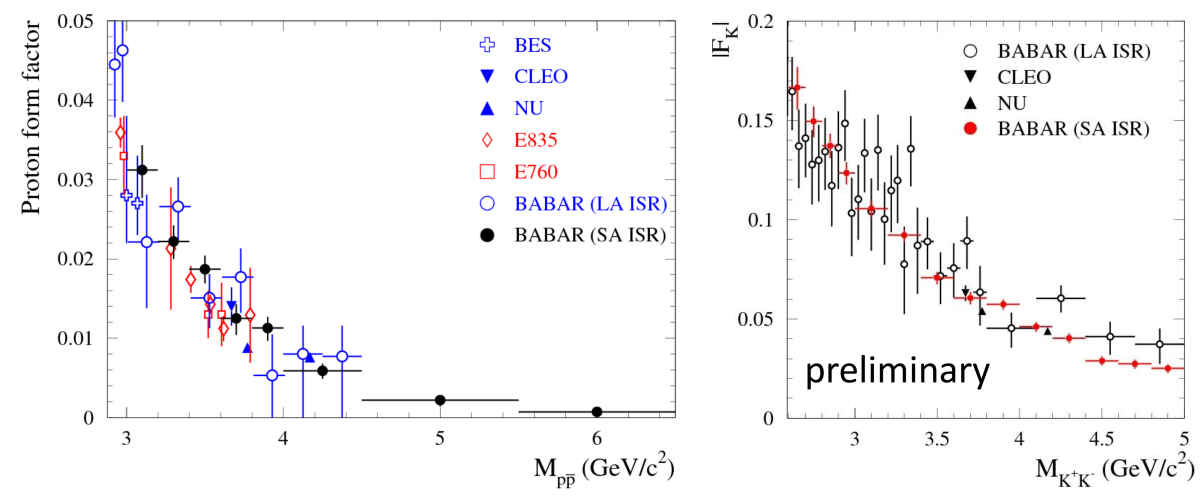
VI. Detection efficiency



The systematic uncertainty in the detection efficiency is estimated to be about 3%. For $p\bar{p}\gamma$ there is a model uncertainty due to unknown $|G_E/G_M|$ ratio. This uncertainty decreases from 15% at 3 GeV to 5% at 4.5 GeV.

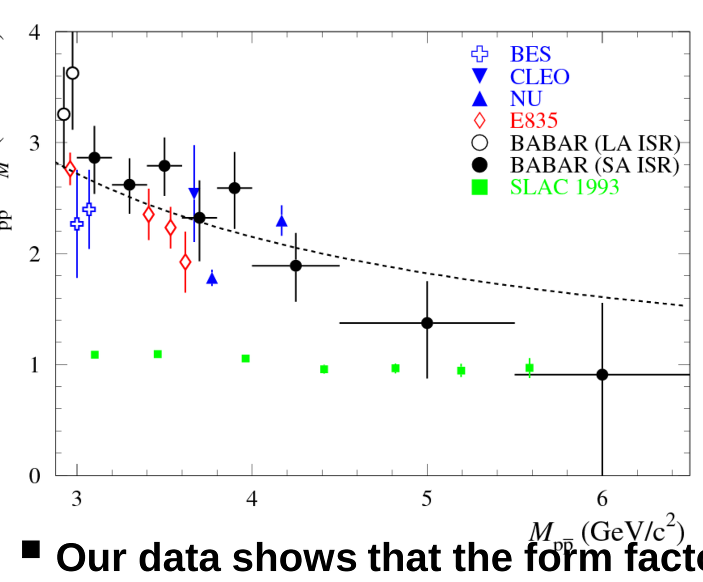
VII. Results

Comparison with previous measurements.



Our results are in reasonable agreement with previous data, except points marked NU (K.K.Seth, Phys.Rev.Lett.110, 022002 (2013)). These points are obtained using CLEO data collected in the maxima of the $\psi(3770)$ and $\psi(4150)$ resonances and may be shifted due to interference of resonant and nonresonant amplitudes..

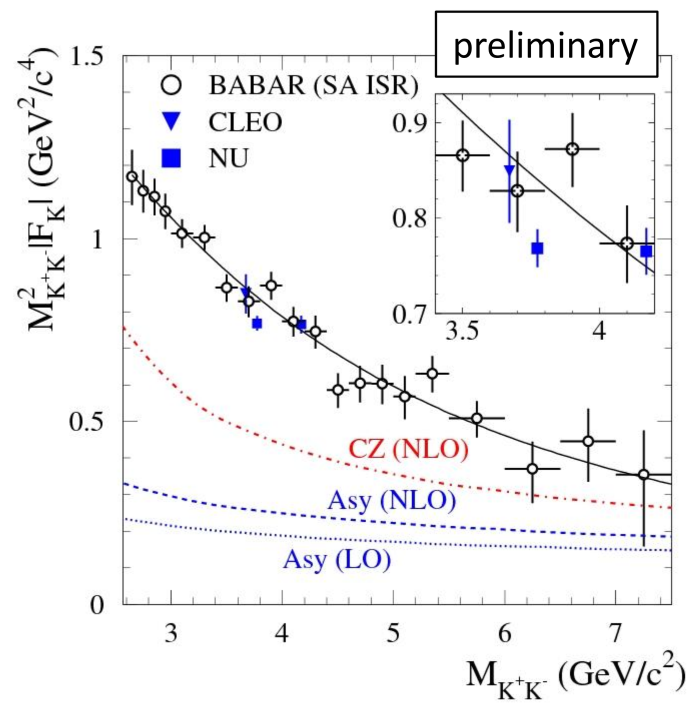
The scaled proton magnetic form factor.



The proton scaled magnetic form factor.
- The dashed curve is the result of the fit to all form-factor data above 3 GeV/c² (except the NU points) with the function $\alpha_s(m^2)/m^4$, which describes the asymptotic mass dependence of the form factor predicted by pQCD.

- **Our data shows that the form factor decreases in agreement with the asymptotic QCD prediction or even faster above 4.5 GeV.**
- The points "SLAC 1993" represent data on the space-like magnetic form factor measured in ep scattering as a function of $\sqrt{-q^2}$. The asymptotic values of the space- and time-like form factors are expected to be the same.
- In the mass region from 3.0 to 4.5 GeV the time-like form factor is about two-three times larger than the space-like one.
- **The BABAR SA ISR measurements give an indication that the difference between the time- and space-like form factors decreases with mass increase.**

The scaled charged kaon form factor.



- ❑ The mass dependence is approximated by a smooth function.
- ❑ The NU point obtained in the maximum of $\psi(3770)$ lies below the curve by 3.5 σ. The deviation may be result of interference resonant and nonresonant amplitudes.
- ❑ The dotted blue curve is the asymptotic pQCD prediction for the form factor.
- ❑ The dashed blue and dash-dotted red curves represent the results of next-to-leading pQCD calculation for the asymptotic (Asy) and Chernyak-Zhitnitsky (CZ) distribution amplitudes (B.Melic, B.Nizic and K.Passek, Phys.Rev.D **60**, 074004 (1999)).
- ❑ **Our data clearly indicate that the form factor decreases faster than α_s/M^2 approaching the pQCD predictions.**

The J/ψ and ψ(2S) decays.

	BABAR$\times 10^4$	PDG$\times 10^4$
$B(J/\psi \to p\bar{p})$	$23.3 \pm 0.8 \pm 0.9$	21.20 ± 0.29
$B(\psi(2S) \to p\bar{p})$	$3.14 \pm 0.28 \pm 0.18$	2.75 ± 0.12
$B(J/\psi \to K^+K^-)$	$3.36 \pm 0.20 \pm 0.12$	2.70 ± 0.17
$B(\psi(2S) \to K^+K^-)$	$0.73 \pm 0.15 \pm 0.02$	0.71 ± 0.05

The BABAR results are in reasonable agreement with the PDG values..