Measurement of timelike nucleon form factors

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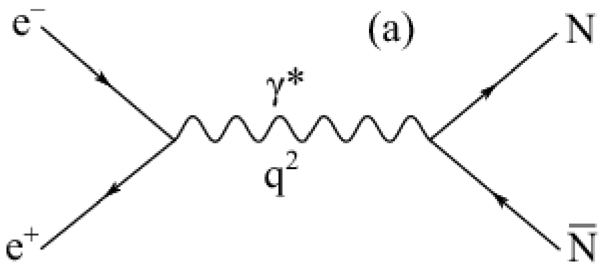
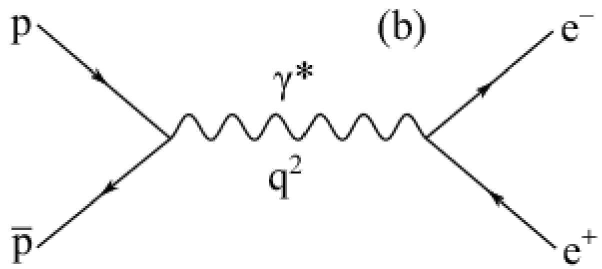
Methods

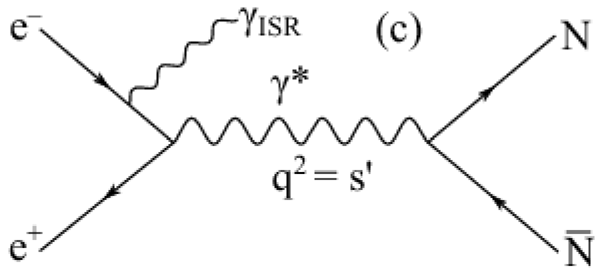
e^+e^- annihilation (scan)



p anti-p annihilation



e^+e^- annihilation (ISR)



$$\frac{d\sigma_{e^+e^-\to N\bar{N}}}{ds'} = \frac{2m}{s} W(s,x)\,\sigma_{e^+e^-\to N\bar{N}}(s')$$

$$x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{s'^2}{s}$$

Experiments

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

Adone 1973
DM1 1979
DM2 1983,1990
FENICE 1994
BESII 2005
CLEO 2005
BABAR 2013
BESIII 2015
CMD-3 2015

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

E760 1993
PS170 1994
E835 1999,2003

$e^+e^- \to n\bar{n}$

FENICE 1998
SND 2014

Current and future experiments

BESIII
CMD-3
SND
Belle II
PANDA

$e^+e^- \to p\bar{p}$ cross section

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

C is the Coulomb factor. ➡ The cross section is nonzero at threshold.

G_E and G_M are the electric and magnetic form factors, $G_E(0)=1$, $G_M(0)=2.79$.

From the measured cross section, a combination of the squared form factors can be extracted. We define the effective form factor:

$$\left|F_p(s)\right| = \sqrt{\frac{\left|G_M(s)\right|^2 + (2m_p^2/s)\left|G_E(s)\right|^2}{1+2m_p^2/s}}$$

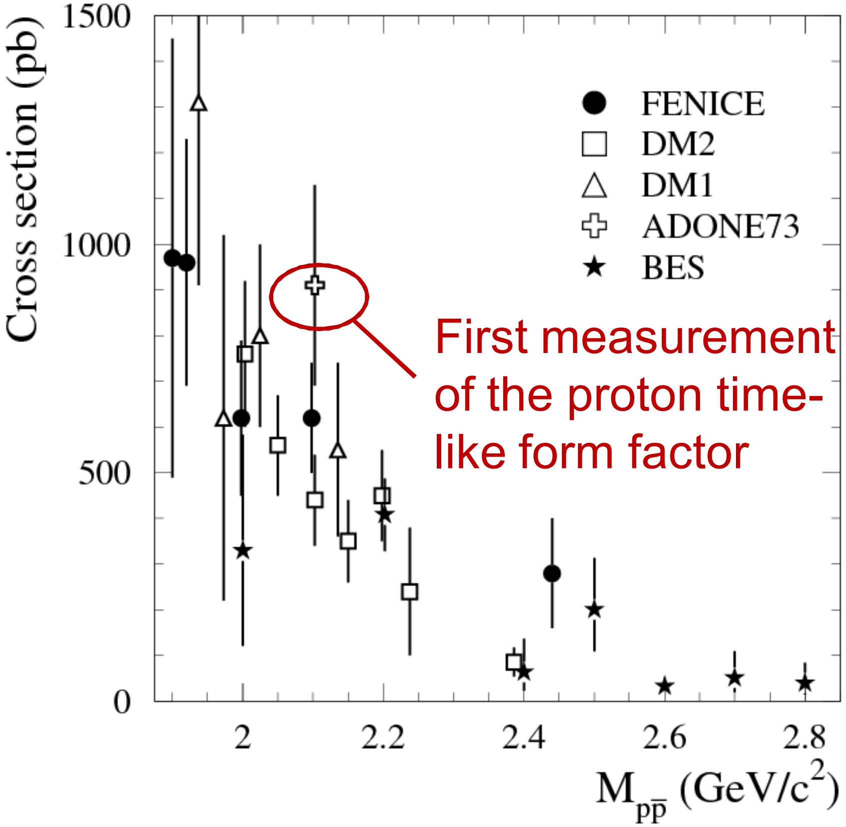
The G_E term decreases with energy increase as $1/E^2$.

The ratio of the form factors $|G_E/G_M|$ can be determined from the analysis of the proton polar-angle distribution.

$$\frac{d\sigma}{d\Omega}(s,\theta) = \frac{\alpha^2\beta C(s)}{4s}\left(\left|G_M(s)\right|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}\left|G_E(s)\right|^2\sin^2\theta\right)$$

At threshold $|G_E(4m_p^2)|=|G_M(4m_p^2)|$.

Old $e^+e^- \to p\bar{p}$ measurements



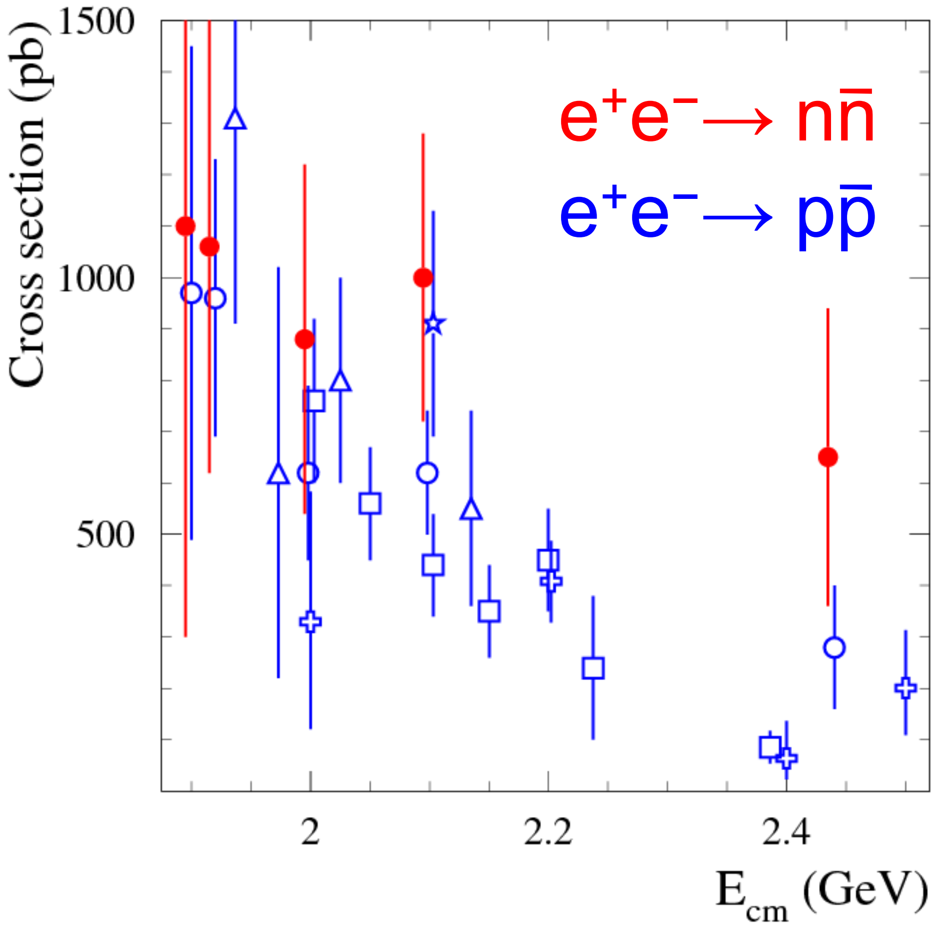
Below 3 GeV: ADONE (1973), DM1(1979), DM2(1983,1990), FENICE(1994), BES(2005).

Statistical accuracy of these measurements is (20-30)%.

Limited statistics do not allow to extract the G_E/G_M ratio from the analysis of the angular distribution.

The detection efficiency was calculated assuming $|G_E|=|G_M|$ ⟹
With modern knowledge on the $|G_E/G_M|$ ratio the model uncertainty is estimated to be 5-7% depending on detector acceptance.

FENICE $e^+e^- \to n\bar{n}$ measurement

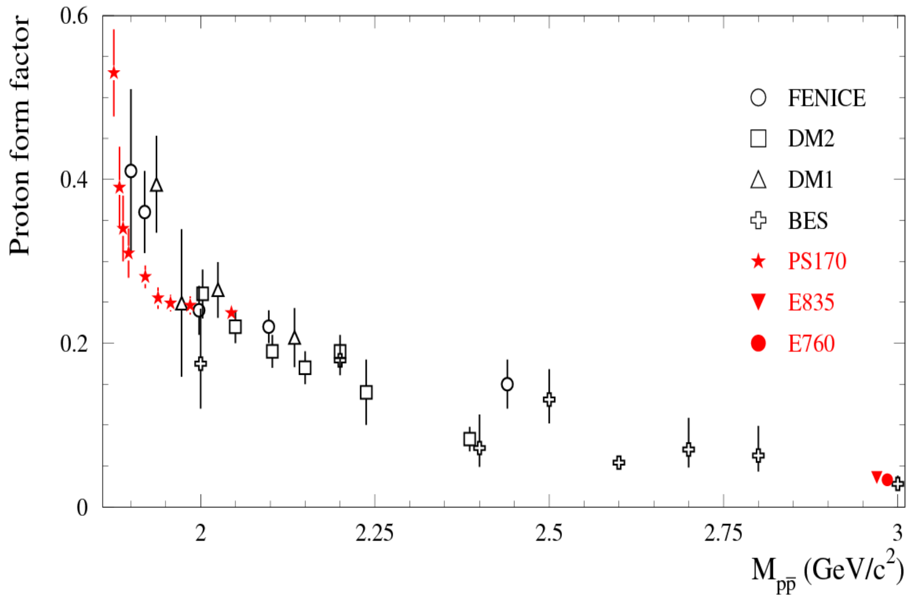


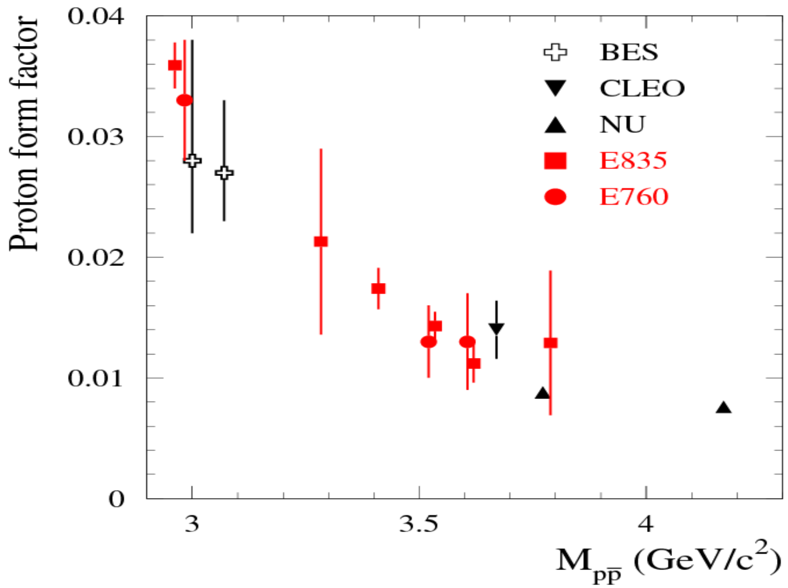
The first and only untill 2014 measurement of $e^+e^- \to n\bar{n}$ was performed by the FENICE collaboration at the ADONE e^+e^- collider in 1998.

The neutron cross section was found to be larger than the proton cross section in contrast with the pQCD asymptotic expectation $\sigma_p / \sigma_n = 4$

The FENICE is a nonmagnetic detector specially designed for measurement the neutron timelike form factor.

Proton-antiproton collisions





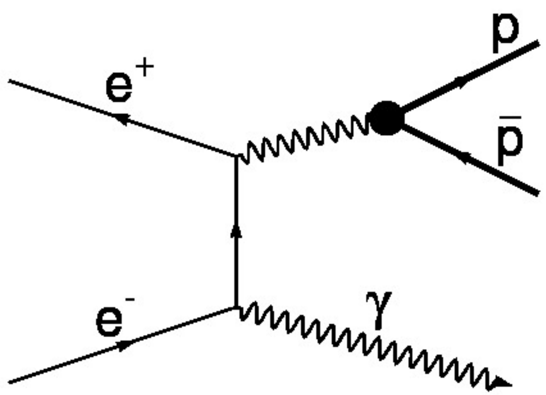
Near threshold data were obtained in PS170 experiment at the antiproton storage ring LEAR (CERN):

✓steep growth of the form factor near threshold,

✓the ratio $|G_E/G_M|$ measured with 30% accuracy in five energy points agrees with unity.

Above 3 GeV measurements were performed at FNAL (E835 and E760). The strong decrease of the form factor was observed which agrees with the dependence $\alpha_s(m)^2/m^4$ predicted by QCD for the asymptotic proton form factor.

ISR method



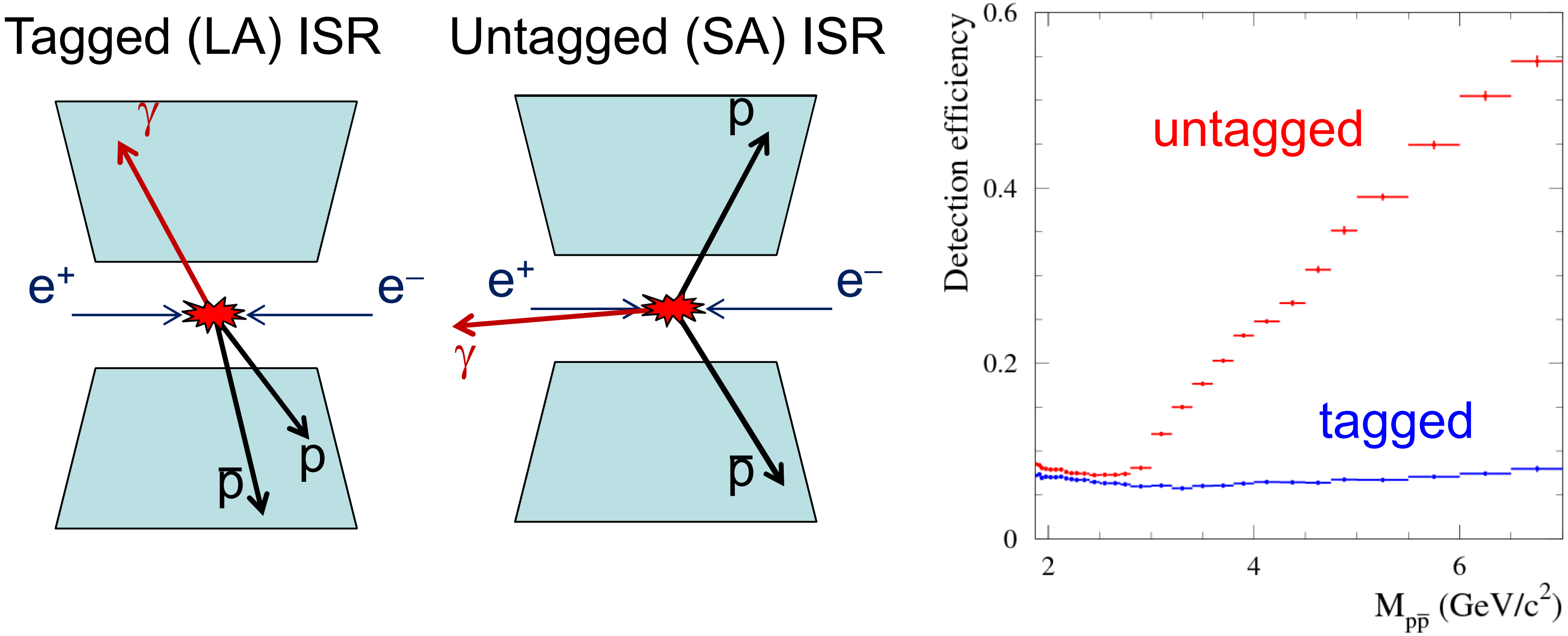
The mass spectrum of the proton-antiproton system in the reaction $e^+e^- \to p\bar{p}\gamma$ is related to the cross section for the nonradiative process $e^+e^- \to p\bar{p}$.

$$\frac{d\sigma_{e^+e^-\to p\bar{p}\gamma}}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\,\sigma_{e^+e^-\to p\bar{p}}(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s}$$

The function $W(s,x,\theta)$ is calculated in QED. It describes angular ($1/\sin^2\theta$ at $\theta >> m_e/\sqrt{s}$) and energy ($1/x$) distributions of the ISR photon.

The ISR method was used for proton form factor measurement at BABAR and will be used at BESIII, Belle II.

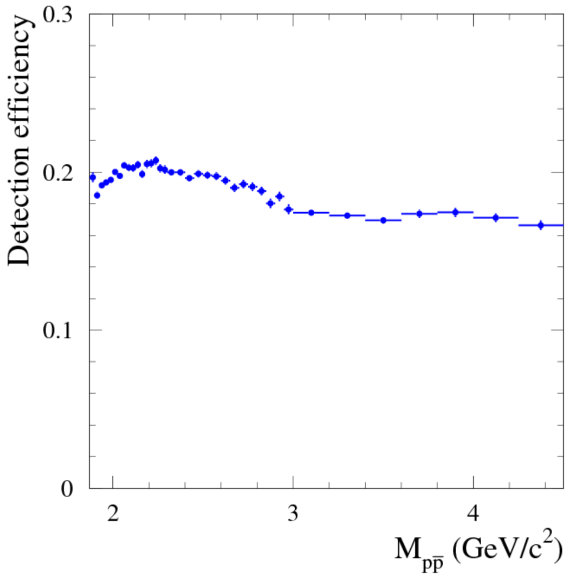
ISR method

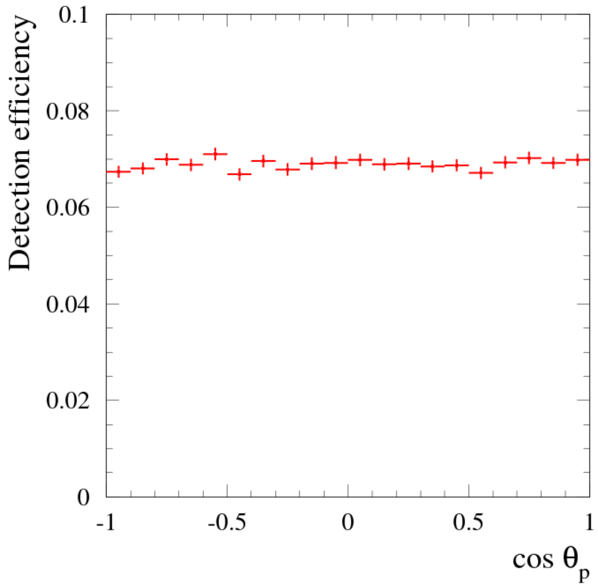


The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 3 GeV can be studied only with detected photon (about 10% of ISR events).

However, above 3 GeV statistics can be significantly increased using small-angle ISR.

Advantages of LA ISR method





✓A wide energy region is studied in a single experiment.

The effective ISR luminosity (pb^{-1}/GeV) increases with mass, partly compensating a decrease of the measured cross section.

✓ A low dependence of the detection efficiency on hadron invariant mass.

Measurement near and above threshold with the same selection criteria.

✓ A low dependence of the detection efficiency on hadron angular distributions (in the hadron rest frame).

For protons this significantly increases sensitivity for measurements of the G_E/G_M ratio.

Disadvantages of the ISR method

- ✓A significantly larger, compared with scan experiments, background, especially for LA ISR

  Background suppression is impossible without special subdetectors providing particle identification (DIRC at BABAR).

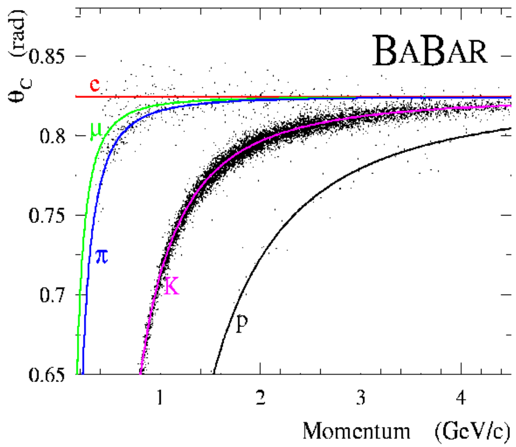
- ✓ Only exclusive measurements are possible.

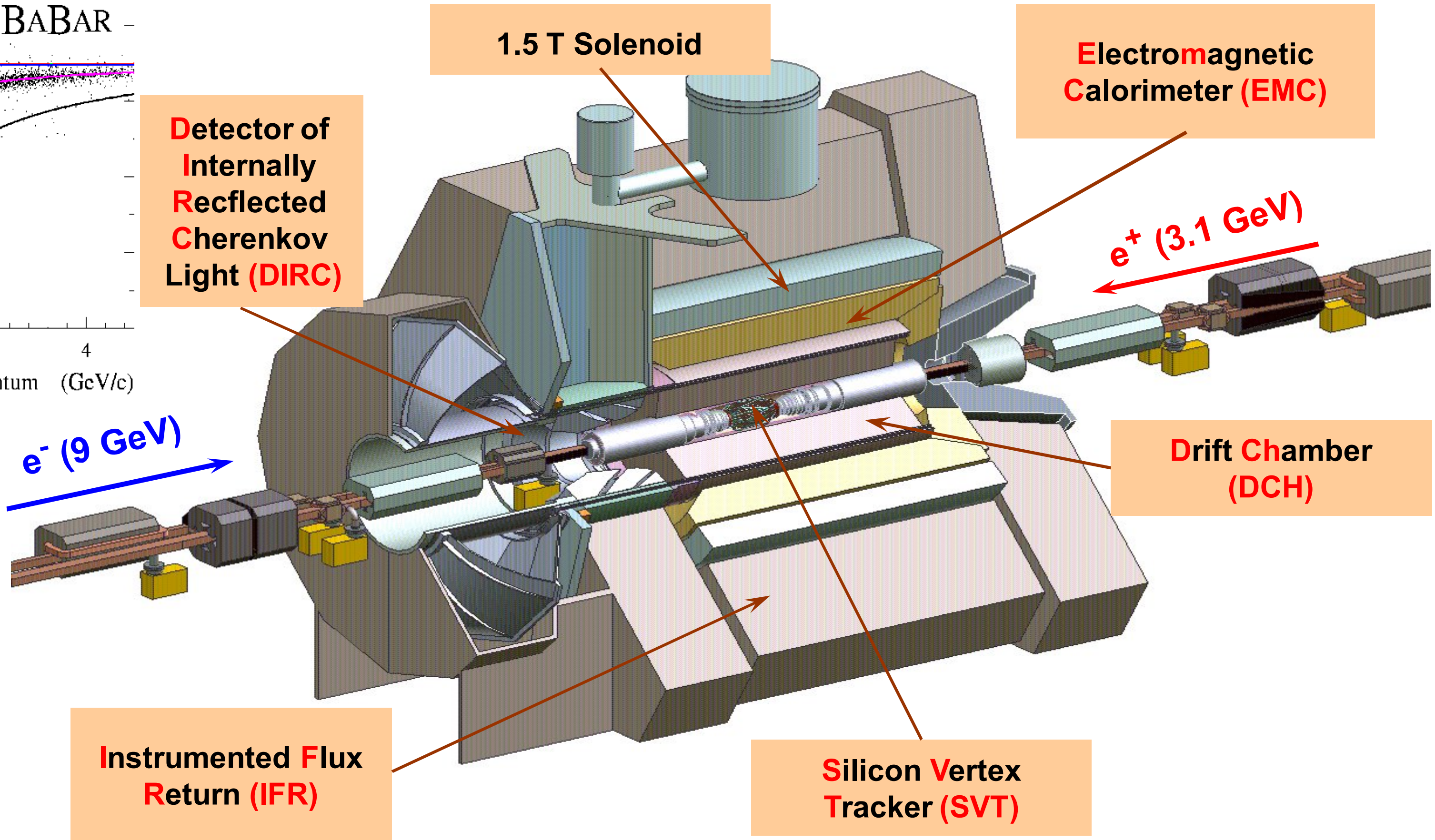
  The process $e^+e^- \to n\bar{n}$ cannot be measured using ISR technique.

- ✓ FSR background

  is negligible in experiments at B-factories but should be taken into account at BESIII.

BABAR detector





The full data sample collected at and near $\Upsilon(4S)$: 469 fb^{-1}.

The LA analysis is published in Phys. Rev. D **87**, 092005 (2013)
The SA analysis is in Phys. Rev. D **87**, 092005 (2013)

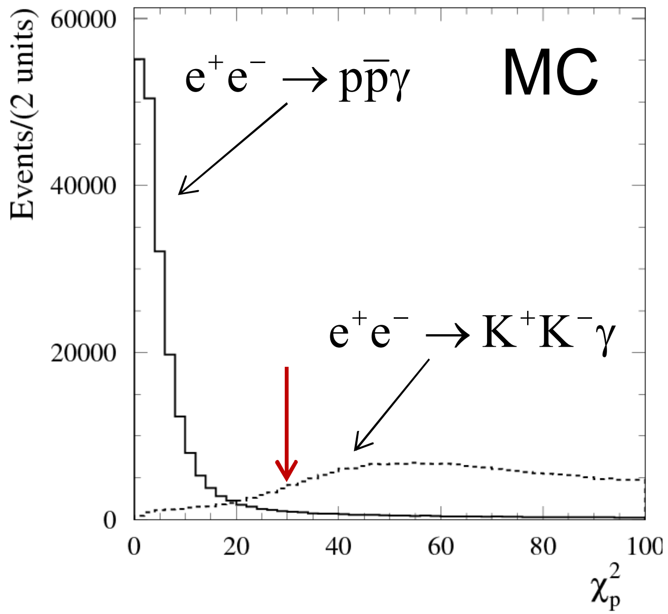
LA event selection

All final particles must be detected and well reconstructed.

✓2 tracks of opposite charges originating from the interaction point and identified as protons (25.8° < θ < 137.5°).

✓A photon candidate with $E_{c.m.}$ > 3 GeV (20.0° < θ < 137.5°).

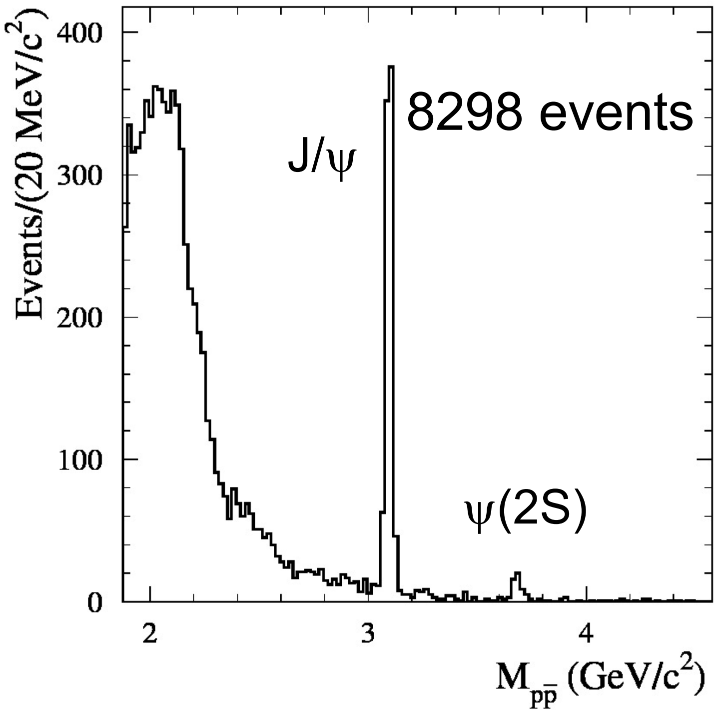
✓A kinematic fit to the $e^+e^- \to h^+h^-\gamma$ hypothesis (h=p,K) is performed with requirements of energy and momentum conservation. $\boxed{\chi^2_p < 30,\ \chi^2_K > 30}$



Backrounds from $e^+e^- \to \pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$, $K^+K^-\gamma$ exceed signal by 2-3 orders of magnitude.

These backgrounds are suppressed by the PID requirement and χ^2 cuts by a factor of 10^6 for pions and muons, and 3×10^5 for kaons.

Background for LA selection



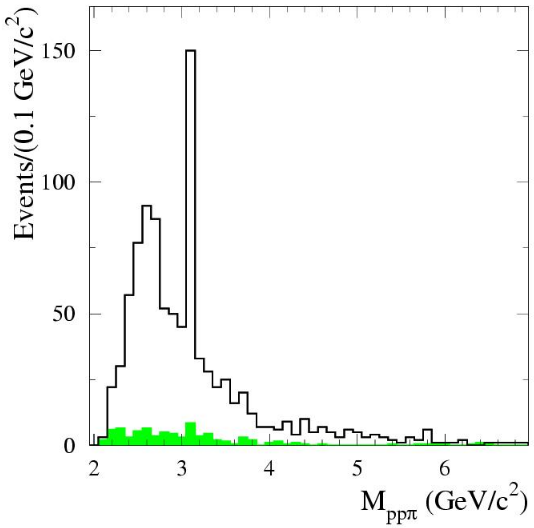
- The main background arises from $e^+e^-\to p\bar{p}\pi^0$ events with an undetected low-energy photon or with merged photons from the π^0 decay.
- This background is estimated from a control sample of $e^+e^-\to p\bar{p}\pi^0$ events.
- Increases from 5% at M_{pp}< 2.5 GeV to 50% at 4 GeV.
- All observed data events above 4.5 GeV are explained by this background.

data	$pp\gamma$	$pp\pi^0$	ISR and e^+e^-
8298	7741 ± 113	448 ± 42	109 ± 30

Background from e^+e^- annihilation processes other than $e^+e^- \to p\bar{p}\pi^0$ and ISR processes such as $e^+e^- \to p\bar{p}\pi_0\gamma$, $p\bar{p}2\pi_0\gamma$ is estimated using difference of the χ^2 distributions for signal and background events and subtracted.

$e^+e^- \to p\bar{p}\pi^0$ background

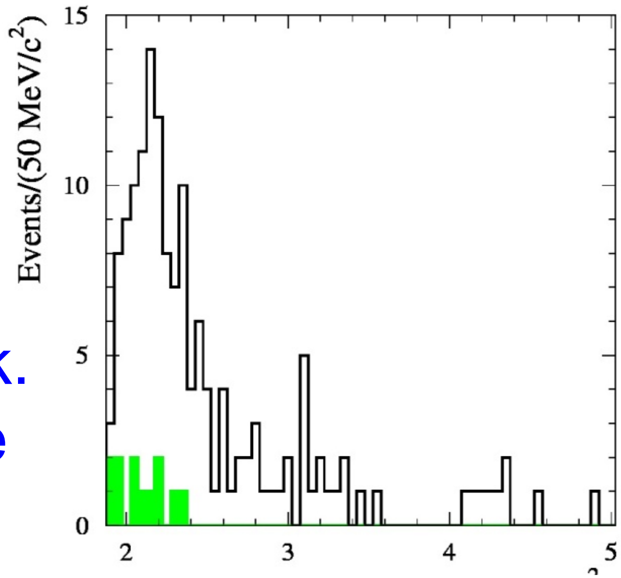
The cross section for $e^+e^- \to p\bar{p}\pi^0$ at c.m. energy of 10.6 GeV is about 5 fb and seems too large.



At low energies this process was studied in our 2005 analysis. Its dominant mechanism was found to be $p\bar{N}(1440)$. So, we expect the QCD scaling $\alpha_s(s)^4/s^5$, similar to $e^+e^- \to p\bar{p}$. The estimated cross section at 10.6 GeV is about 0.02 fb.

π^0 ← → $p\bar{p}$ pair

At high energy the other mechanism works: the $p\bar{p}$ pair has low invariant mass, i.e. the pion and $p\bar{p}$ pair are produced back-to-back. The mass spectrum is reminiscent of the ISR $p\bar{p}$ mass spectrum.

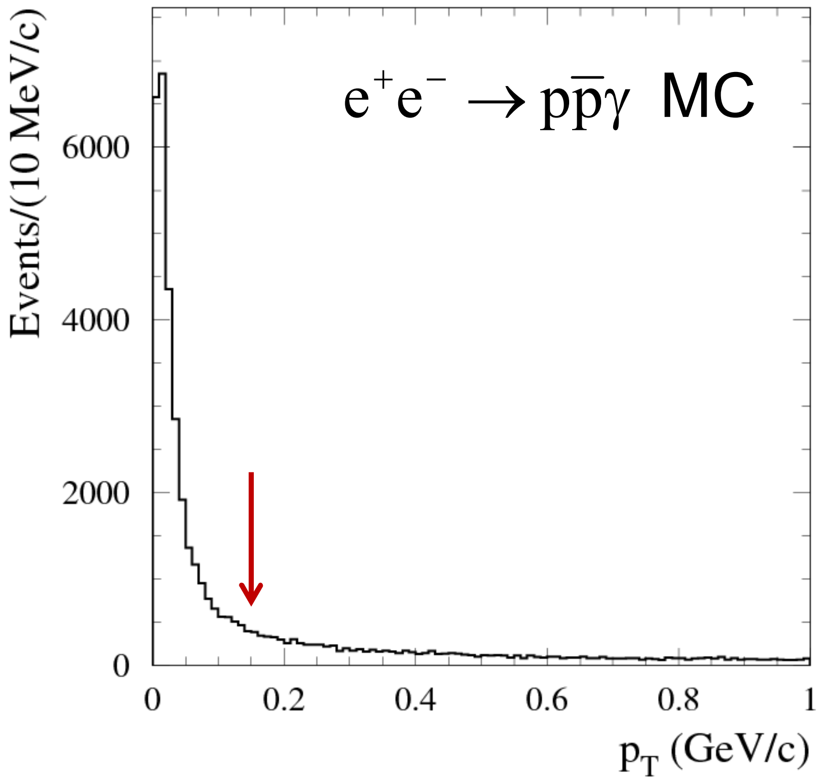


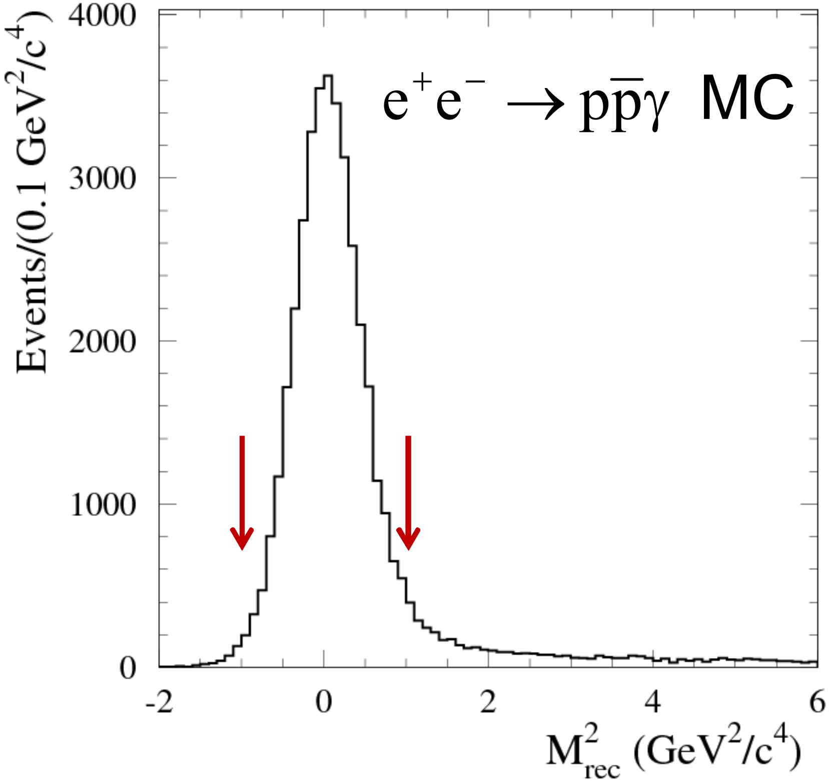
SA event selection

✓2 tracks of opposite charge originating from the interaction point and identified as protons ($25.8^\circ < \theta < 137.5^\circ$).

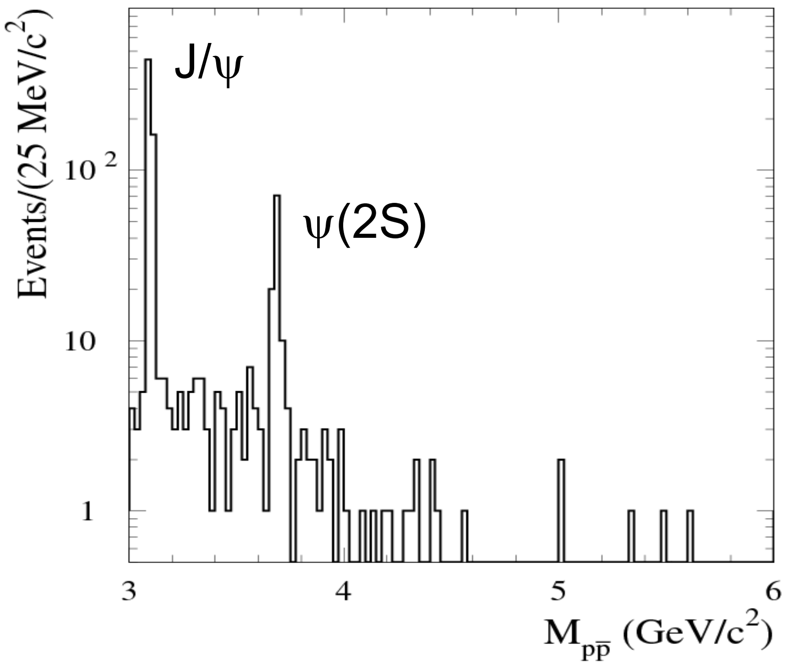
✓ $P_T < 0.15$ GeV/c

✓ $|M^2_{rec}| < 1$ GeV^2/c^4





Background for SA ISR

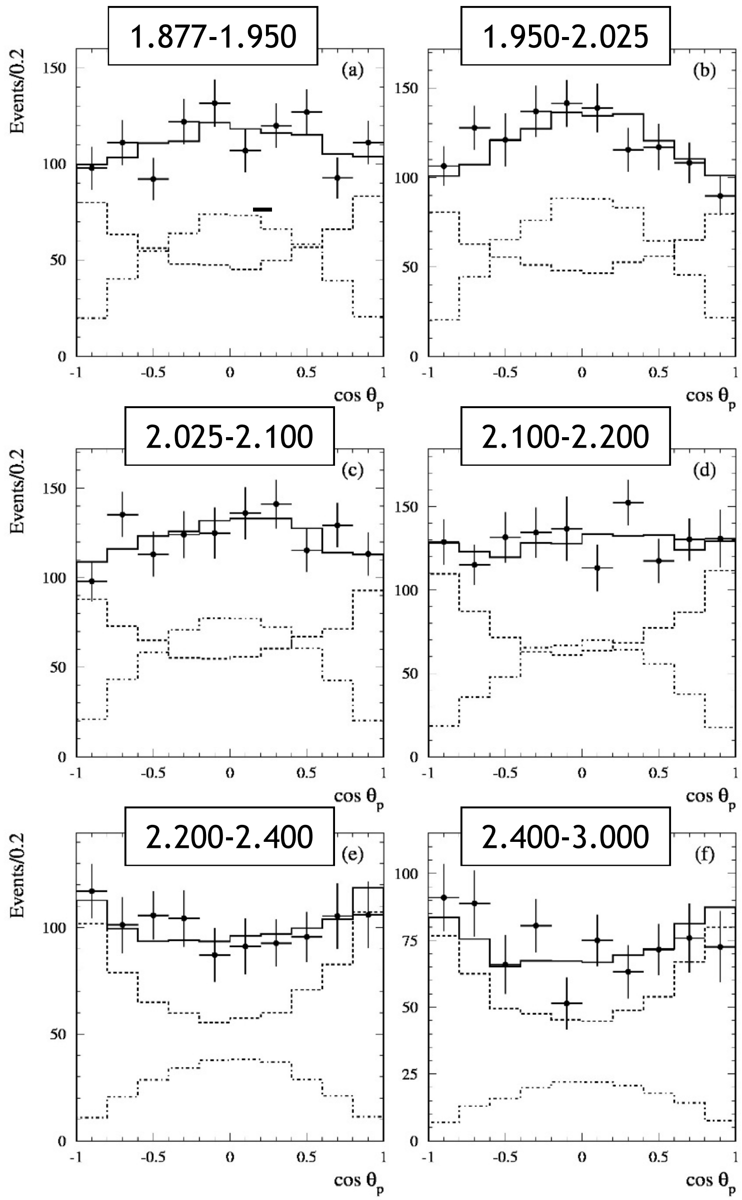


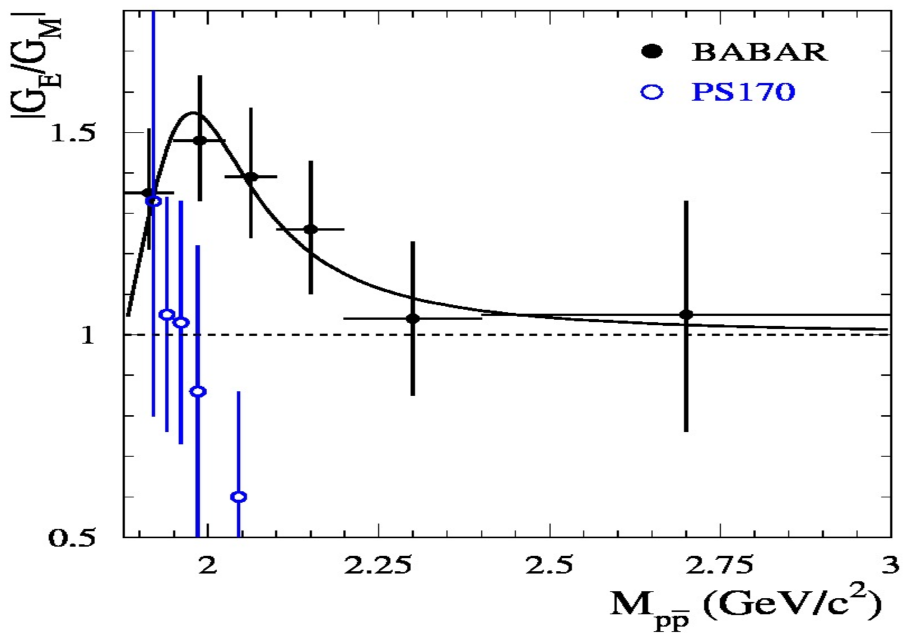
- The total number of selected events is 845.
- The number of nonresonant events is 149.
- No events are observed with mass above 6 GeV/c².

Data	$\mu\mu\gamma$	2-photon	ISR
149	< 1	1.6 ± 09	6.3 ± 3.5

- ➢The dominant background process is $e^+e^- \to p\bar{p}\pi^0\gamma$
- ➢The main background in our large-angle ISR analysis from $e^+e^- \to p\bar{p}\pi^0$ is found to be negligible.

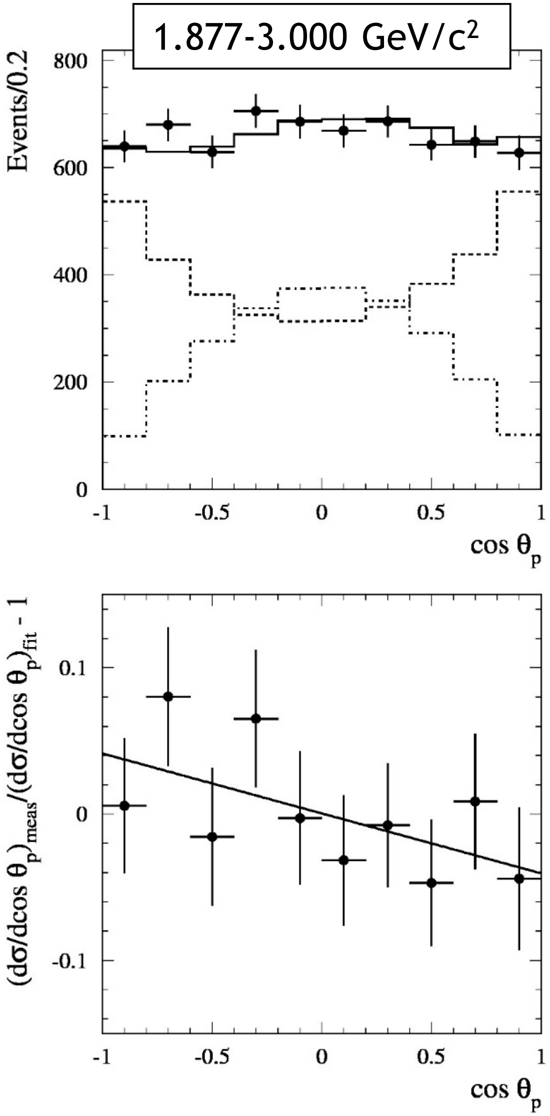
Angular distribution





The distribution over the angle between the proton momentum in the pp̄ rest frame and the momentum of pp̄ system in the e^+e^- c.m. frame is fitted by a sum of histograms, obtained from two simulated event samples, one with G_E=0 and other with G_M=0. These distributions are close to $1+\cos^2\theta_p$ and $\sin^2\theta_p$.

Asymmetry in the angular distribution



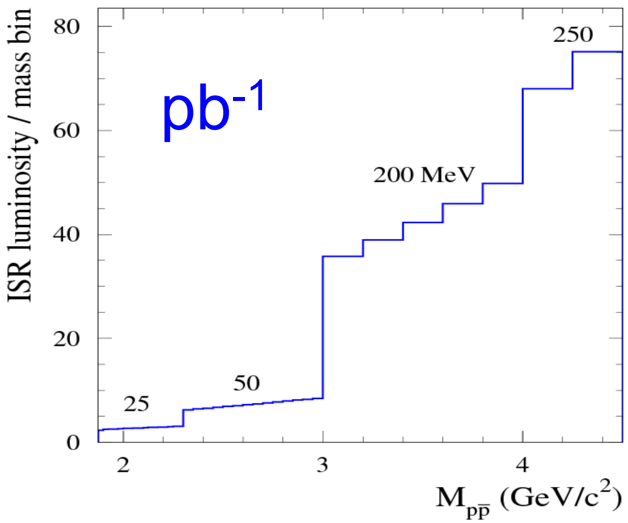
- The asymmetry is absent in lowest order ($\gamma^* \to p\bar{p}$). It arises from higher-order contributions (soft extra ISR and FSR interference, two-photon exchange). Measuring the asymmetry we control the higher-order contributions.
- Our simulation uses a model with one-photon exchange. The asymmetry in the simulated distribution is due to an asymmetry in the detection efficiency.
- We analyze the difference between the measured and fitted distributions.
- The slope is $-0.041 \pm 0.026 \pm 0.005$
- The integral asymmetry

$$A = \frac{\sigma(\cos\theta_p > 0) - \sigma(\cos\theta_p < 0)}{\sigma(\cos\theta_p > 0) + \sigma(\cos\theta_p < 0)} = -0.025 \pm 0.014 \pm 0.003$$

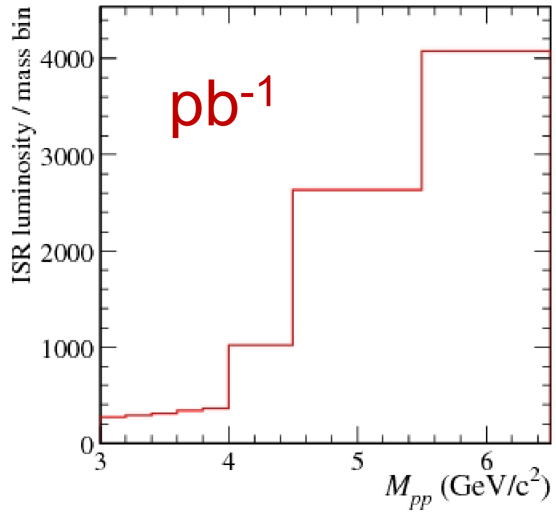
Cross section

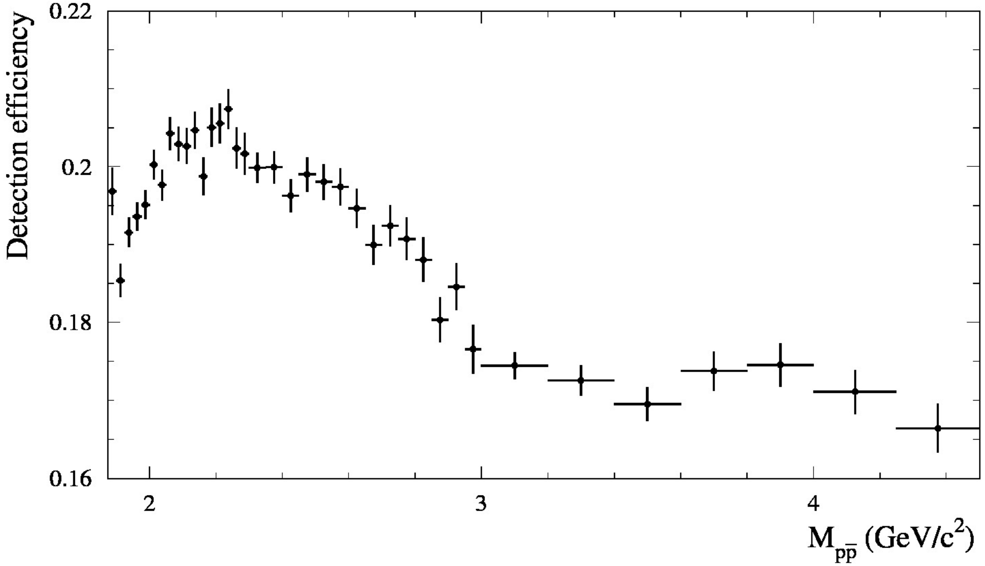
Large-angle ISR ($20^\circ < \theta_\gamma^* < 160^\circ$)

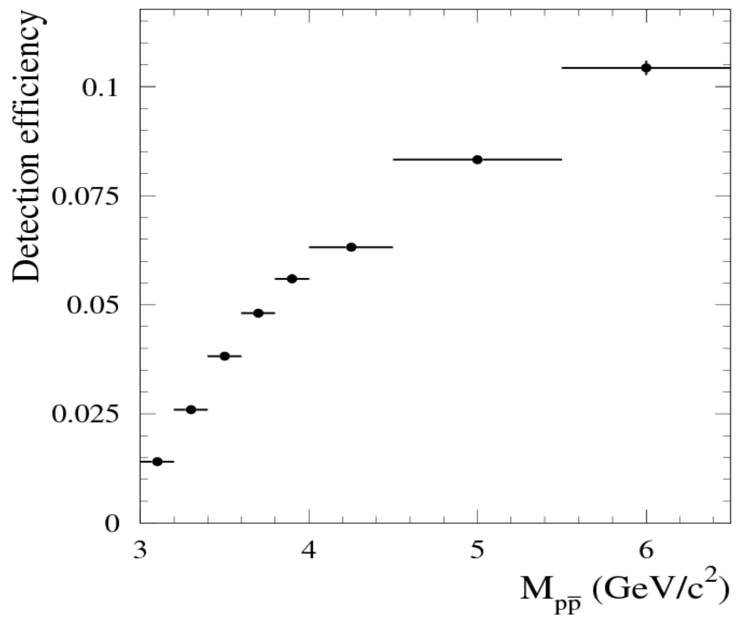
Small-angle ISR



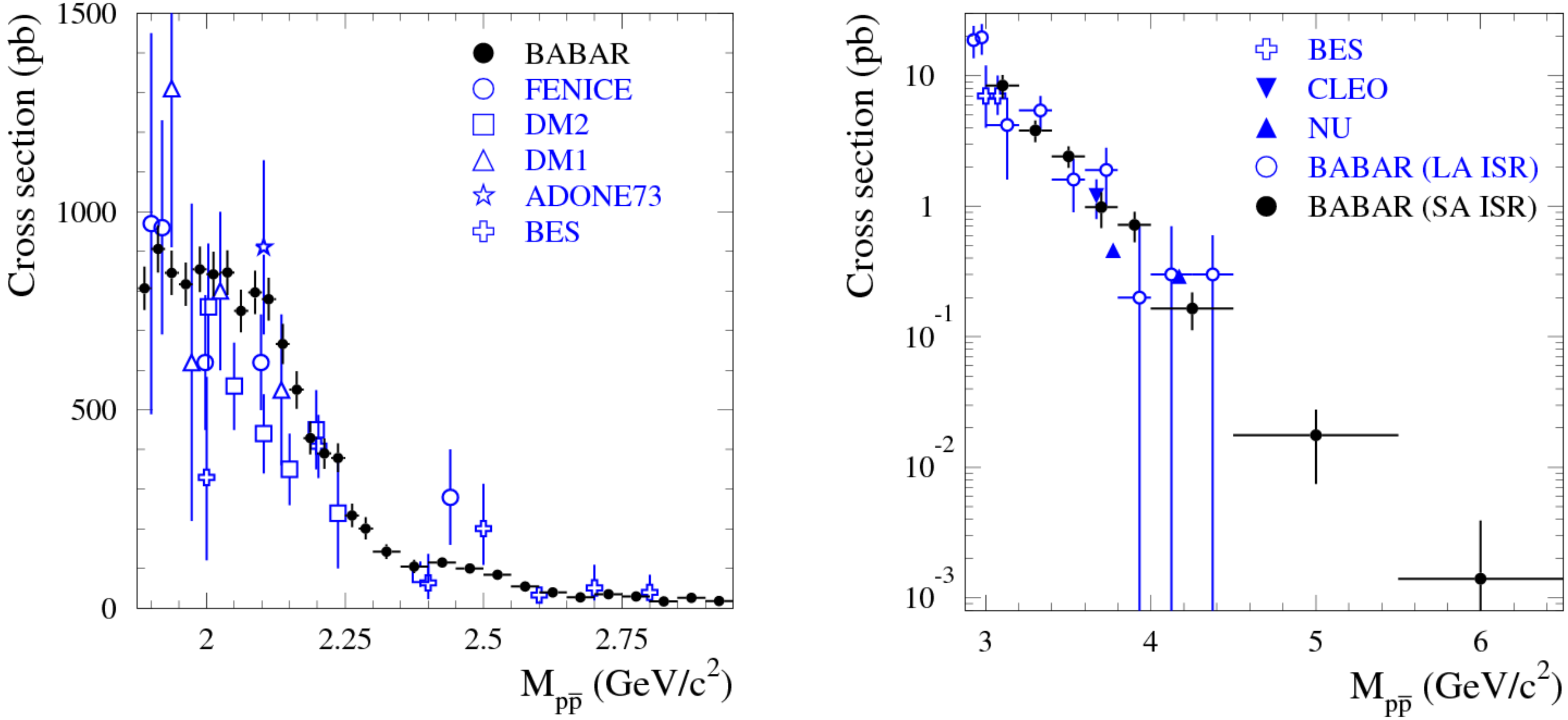
$$\sigma_{ee\to p\bar{p}}(m) = \frac{(dN/dm)_{corr}}{\varepsilon R\ dL/dm},$$







Measured cross section



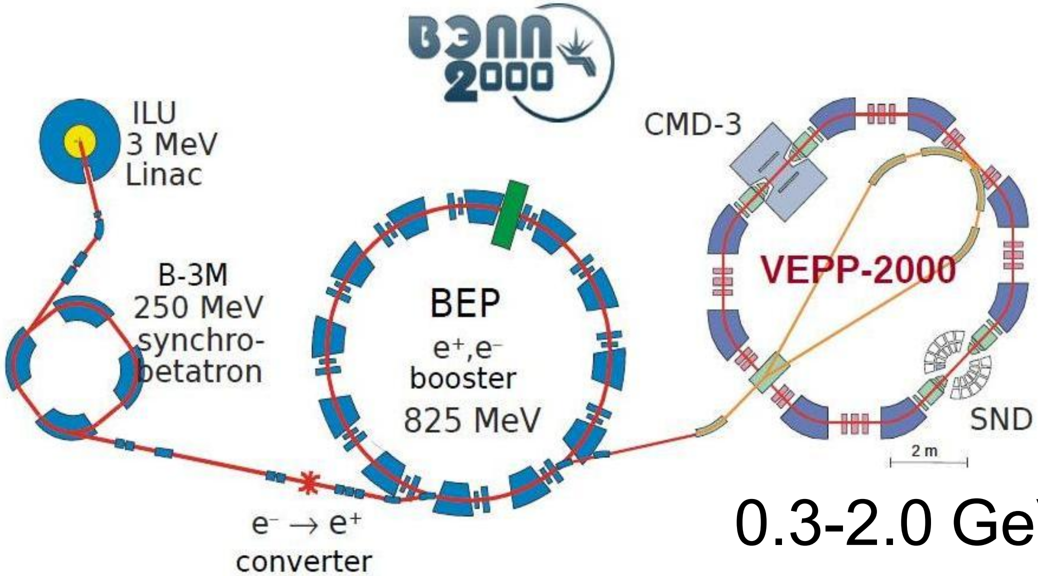
Mass-independent systematic uncertainty is 4-5% for large-angle ISR. For small-angle ISR it decreases from 16% at 3 GeV to 6% at 4.5 GeV.

✓ In the mass region under study the cross section changes by about six orders of magnitude.

✓BABAR data are in reasonable agreement with previous measurements

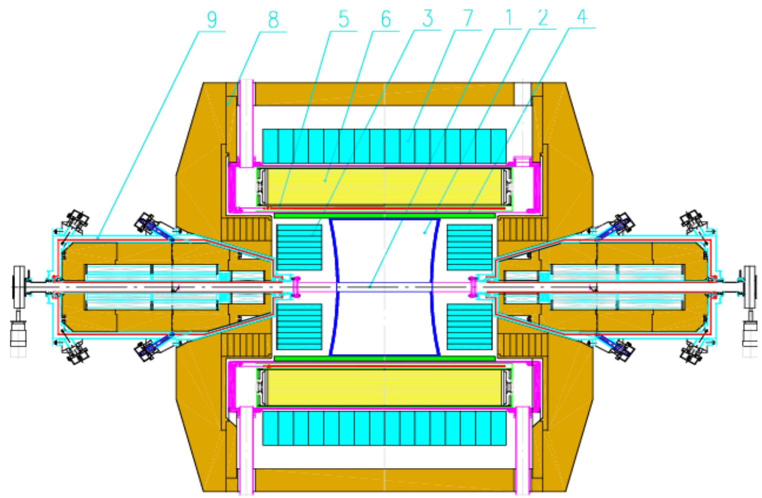
✓ We improve accuracy and extend the mass region of measurements.

Experiments at VEPP-2000

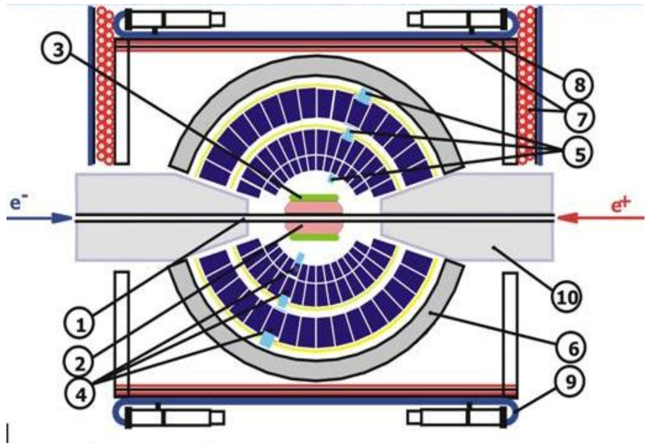


0.3-2.0 GeV

CMD-3



SND



Experiments 2011-2013

C.m. energy 0.3-2.0 GeV

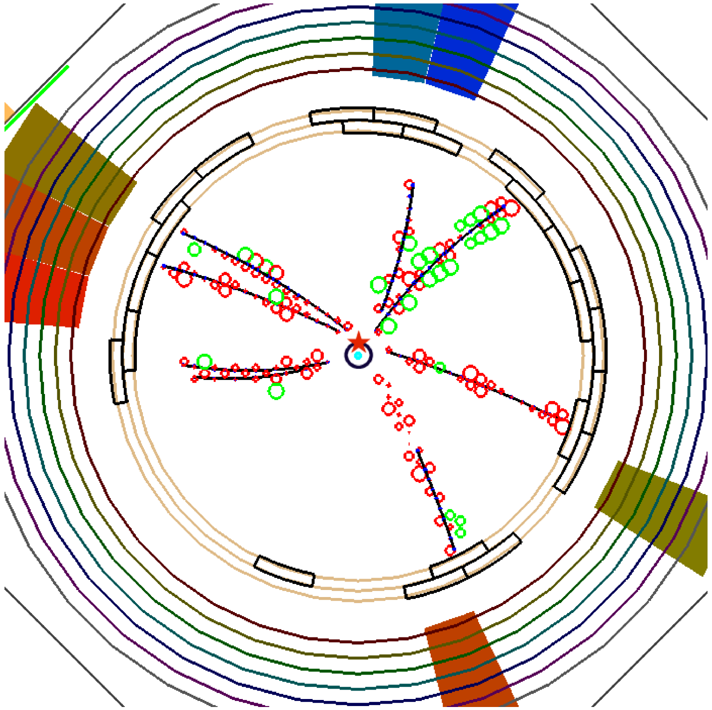
Luminosity 10^{31} cm^{-2} sec^{-1} at E=2 ГэВ

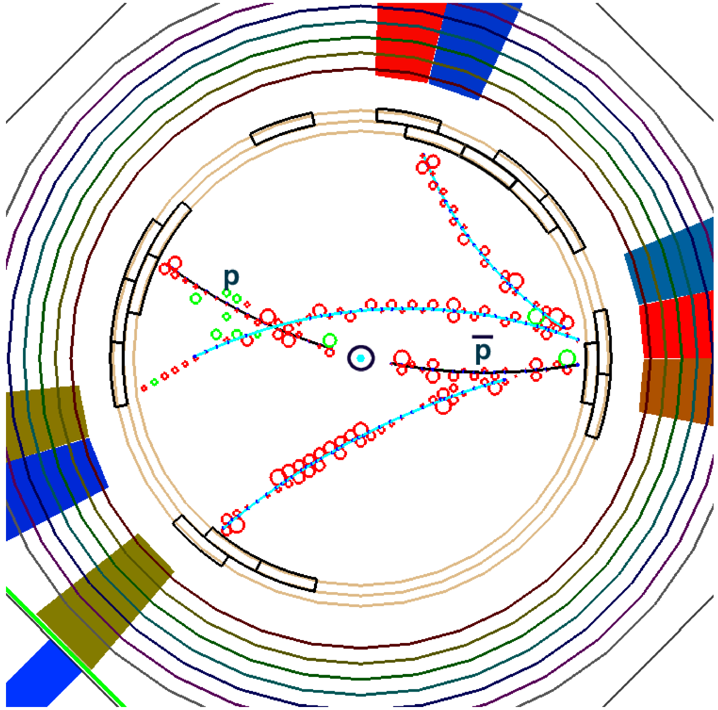
Integrated luminosity ~9 pb at $E>2m_p$

VEPP-2000 is currently upgrated

$e^+e^- \to p\bar{p}$ at VEPP-2000

CMD-3





At E<1.9 GeV the antiproton stops and annihilates in the beam-pipe wall producing secondary particles

At E>1.9 GeV the proton and antiproton produce back-to-back tracks. Several secondary tracks from antiproton annihilation may be detected.

$e^+e^- \to p\bar{p}$ at VEPP-2000

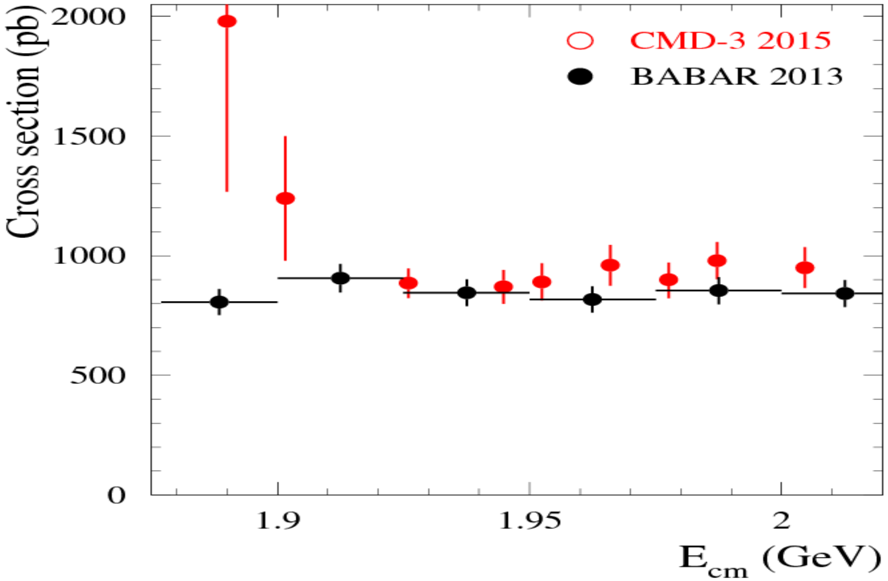
Event selection at E<1.9 GeV

- ✓Four (three at SND) or more tracks with a common vertex located in the beam-pipe wall.
- ✓Energy deposition in the calorimeter higher than 500 MeV (600 MeV at SND)
- ✓Events selected below p anti-p threshold are used to estimate background.

Event selection at E>1.9 GeV

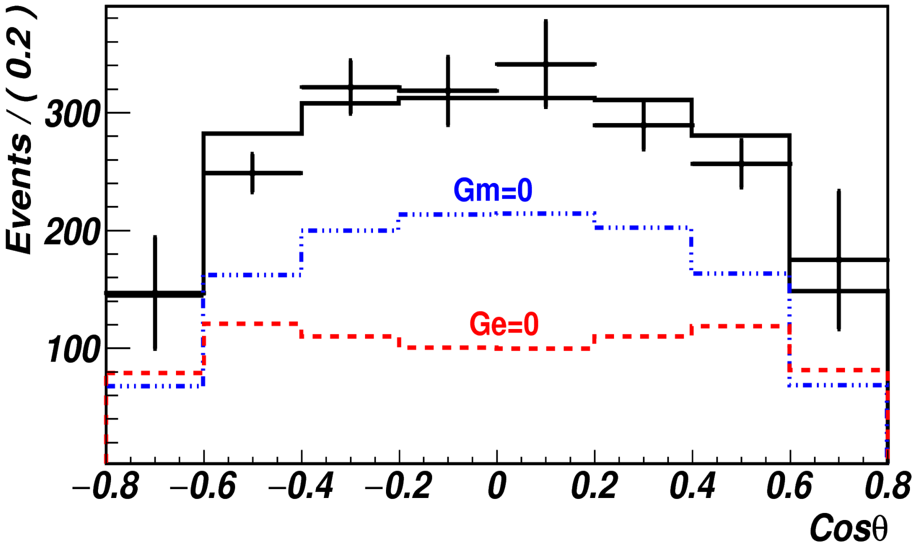
- ✓Two back-to-back tracks originated from the beam-interaction region
- ✓ Large dE/dx in the drift chamber for both tracks
- ✓Energy deposition in the calorimeter higher than 200 MeV (600 MeV at SND)

$e^+e^- \to p\bar{p}$ at CMD-3



arXiv:1507.08013

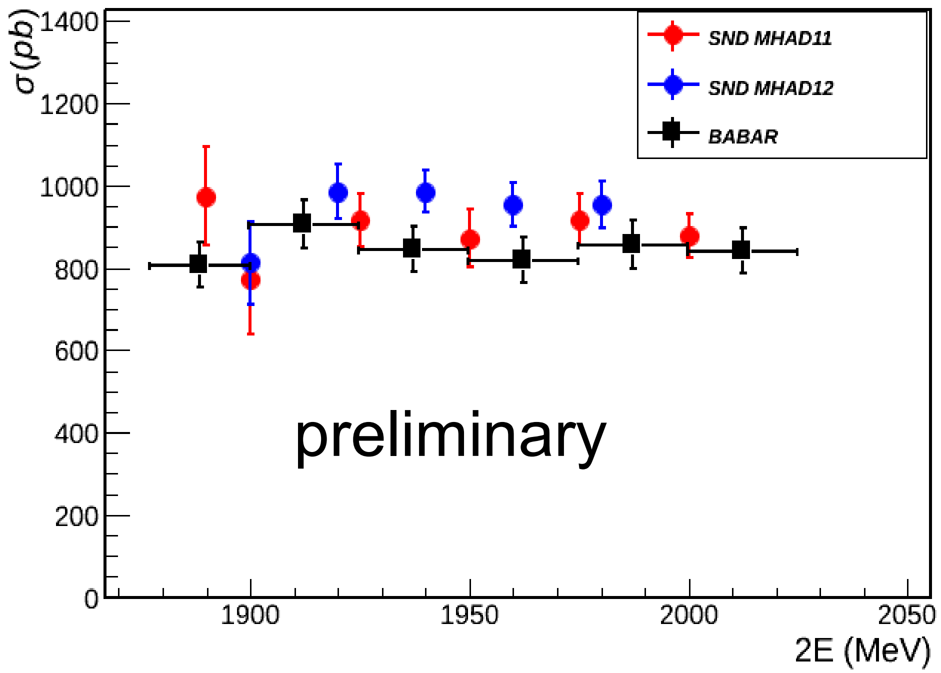
Systematic uncertainty on the cross section is 6% above 1.9 GeV and 30% below.



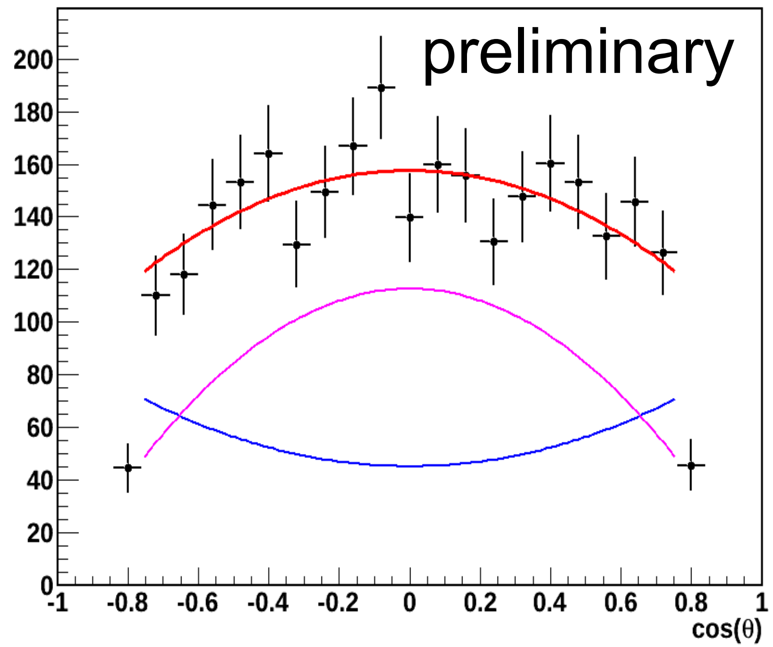
For data events above 1.9 GeV

$|G_E/G_M|=1.49 \pm 0.23 \pm 0.30$

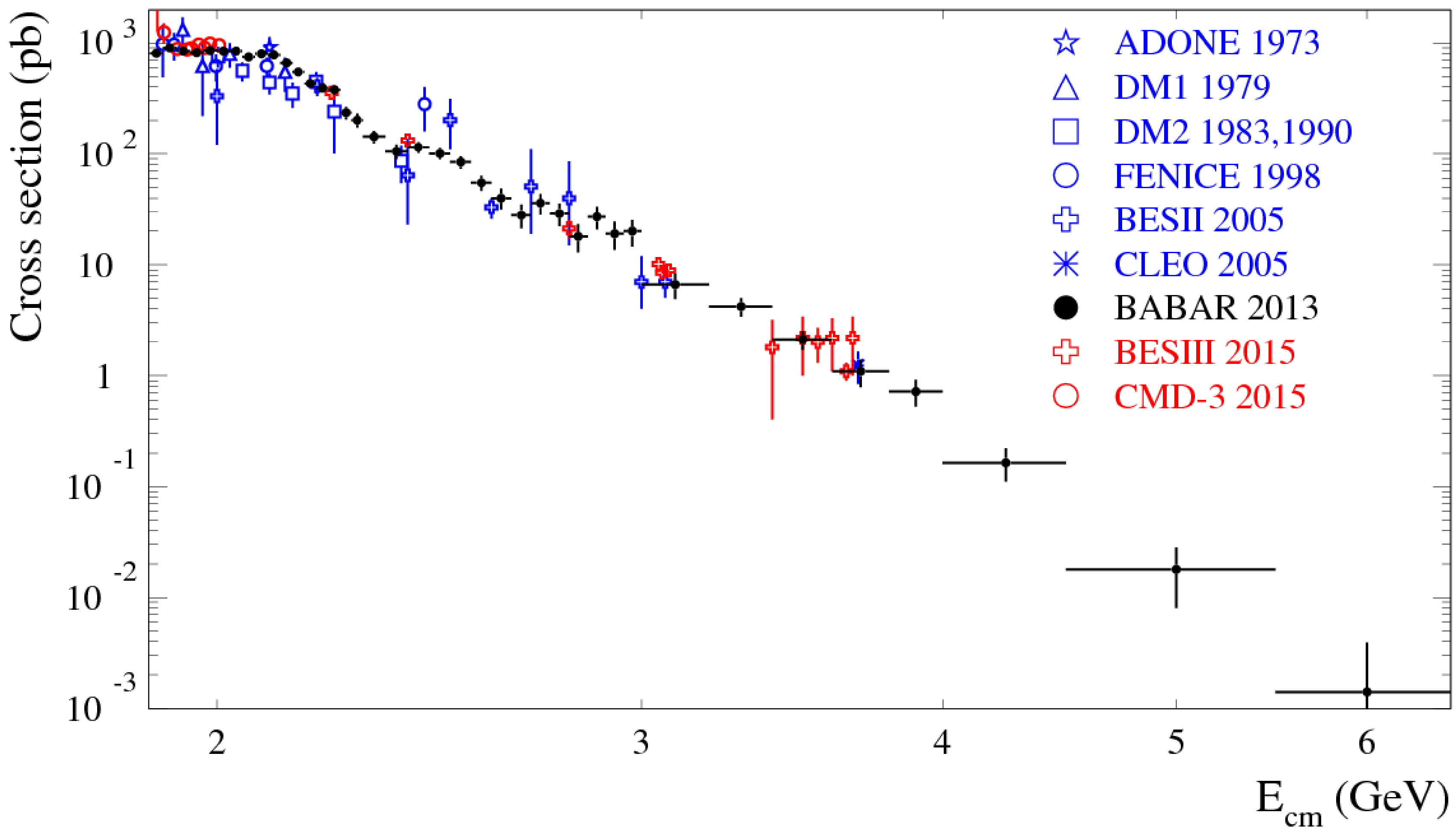
$e^+e^- \to p\bar{p}$ at SND



$|G_E/G_M|=1.64 \pm 0.26$

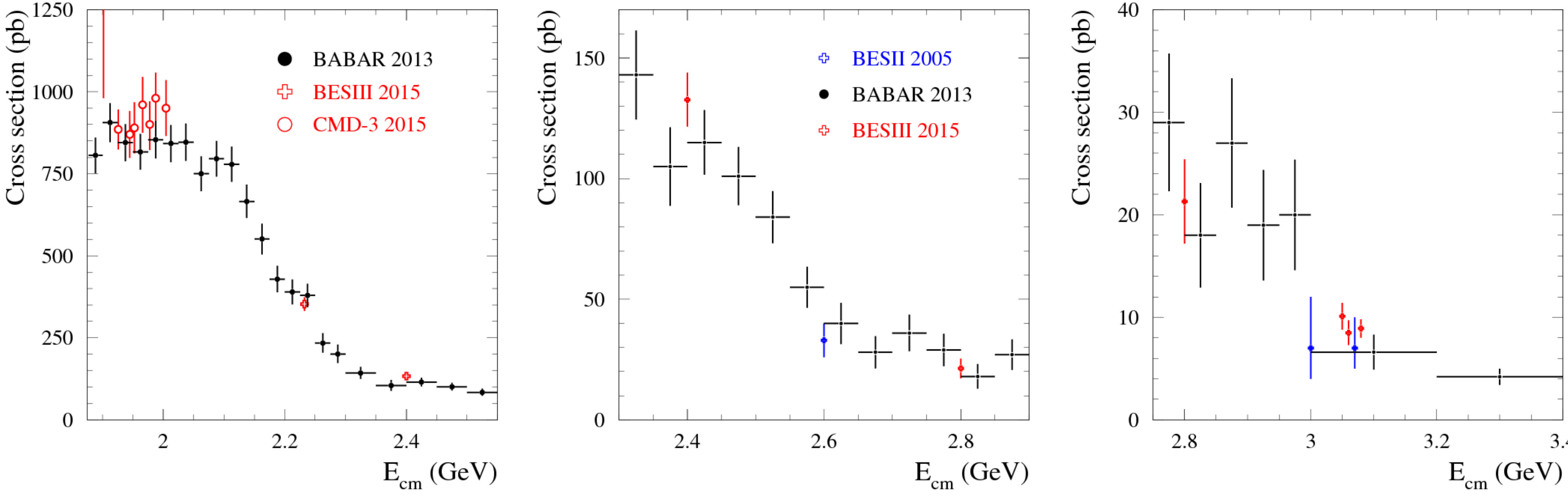


$e^+e^- \to p\bar{p}$ cross section



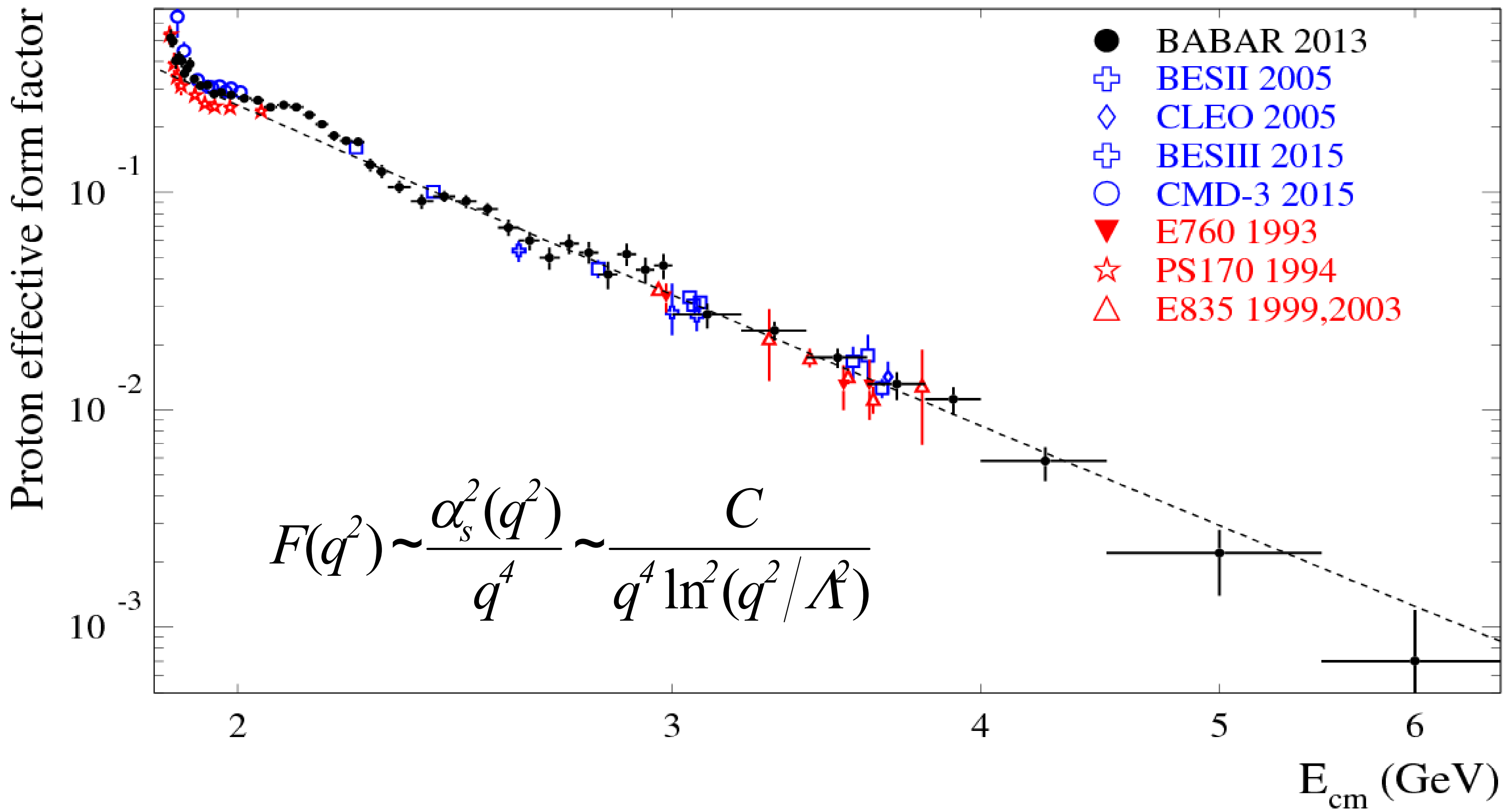
The BESIII data (Phys. Rev. D 91, 112004 (2015)) are in agreement with the BABAR measurements.

$e^+e^- \to p\bar{p}$ cross section



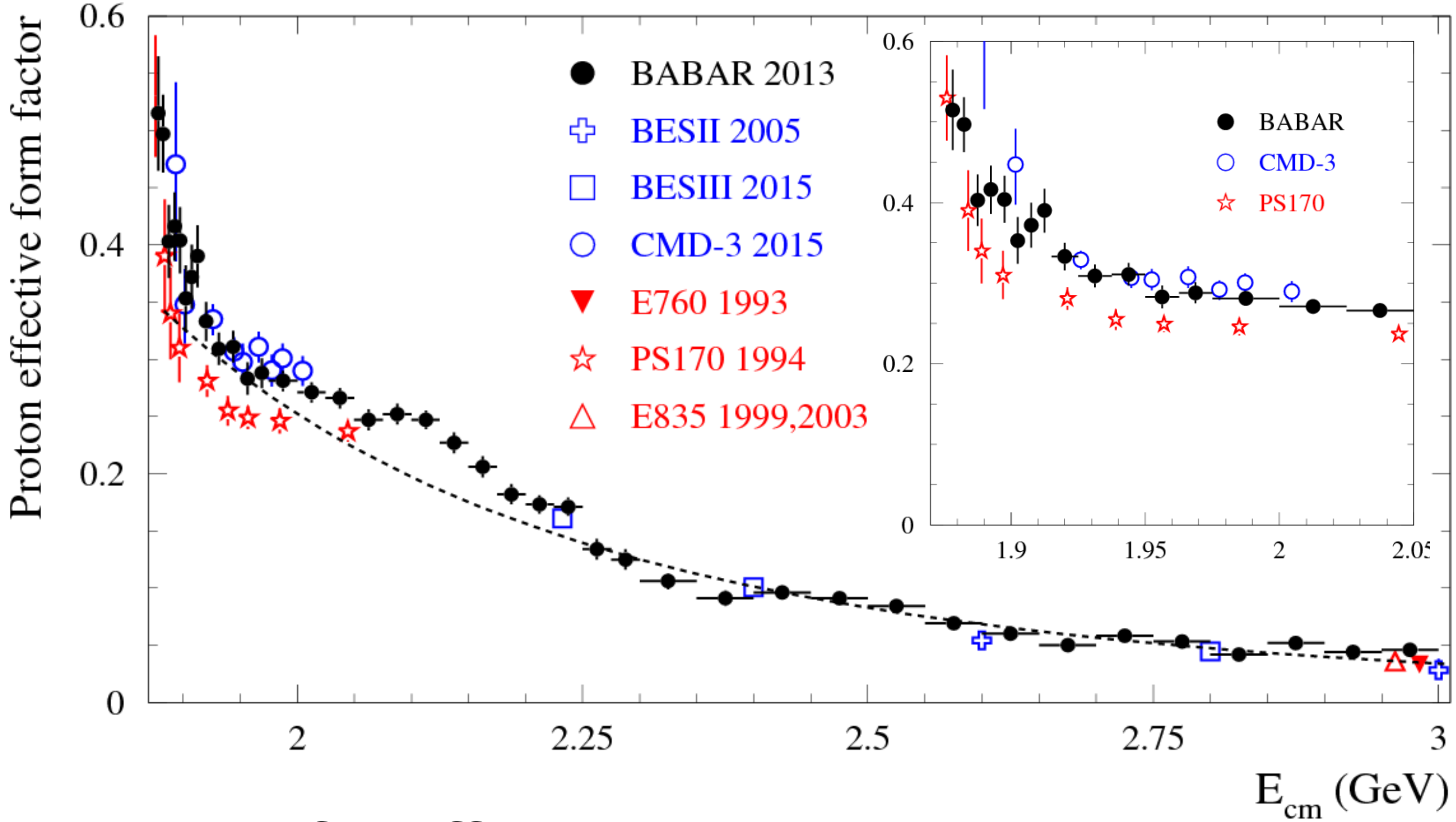
- A complex step-like behavior of the cross section: 2 or even 3 steps at 2.2, 2.55, 3 GeV.
- Explanation: effects of final state interaction, for example, near pΔ and ΔΔ thresholds

Effective proton form factor



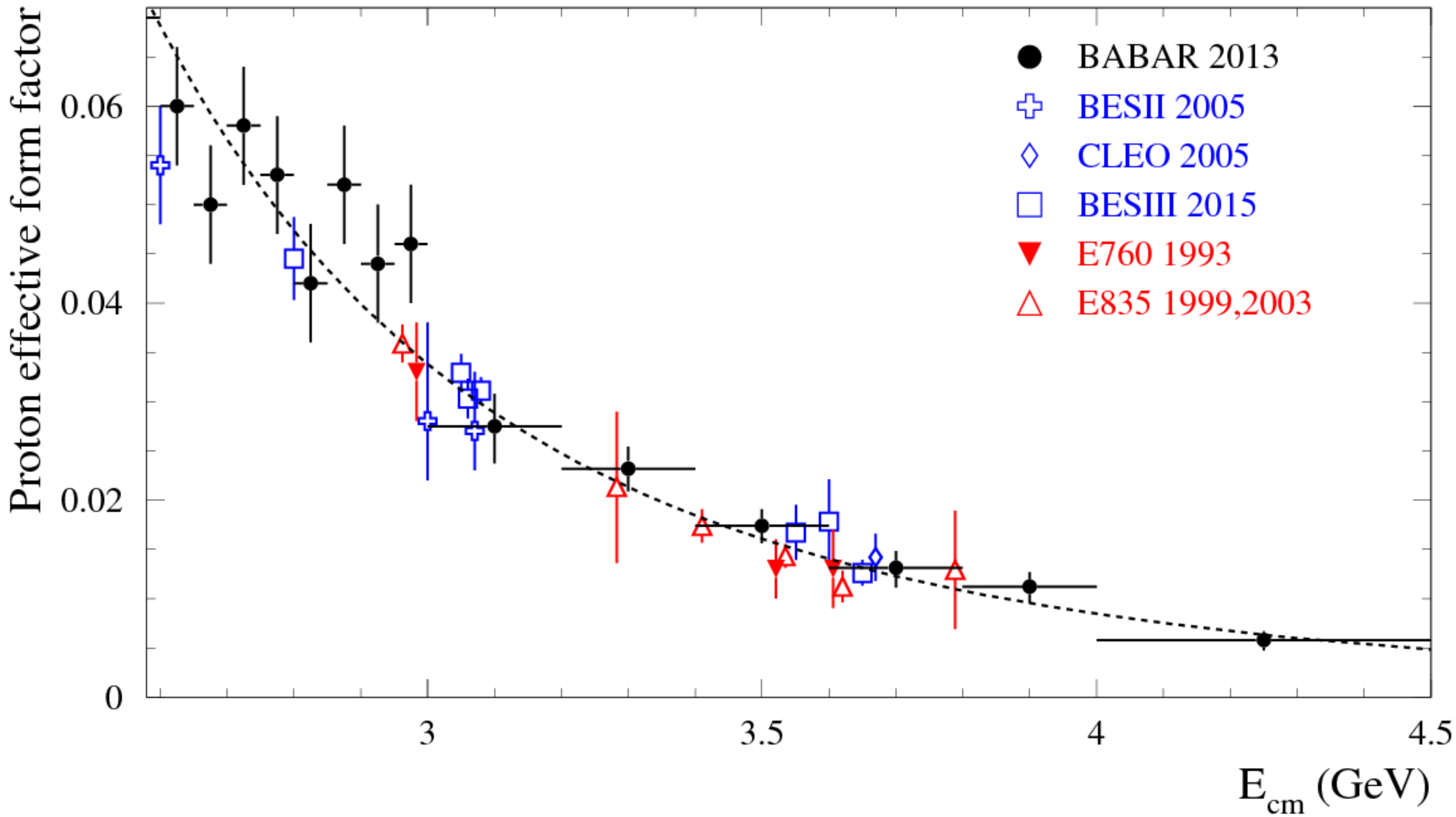
The curve is the result of the QCD-motivated fit to the data points with E_{cm} > 3 GeV.

Effective proton form factor



- A steep falloff near threshold observed in the PS170 experiment at LEAR is confirmed.
- There is a systematic difference between e^+e^- data and PS170 measurements.

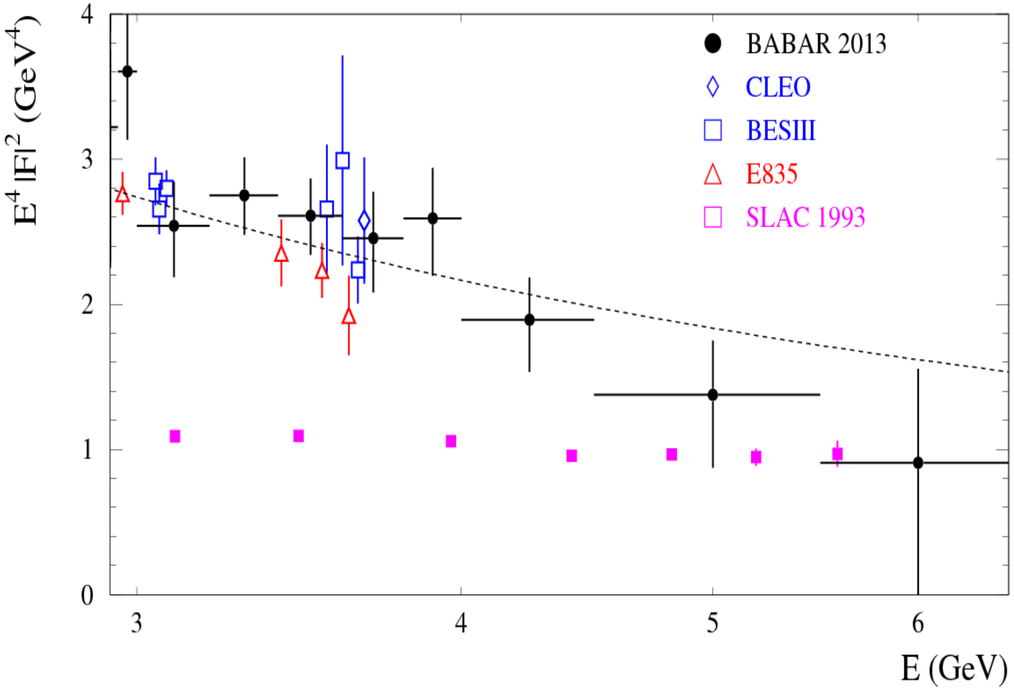
Effective proton form factor



The e^+e^- data and p-anti-p data from Fermilab are in good agreement.

Effective proton form factor

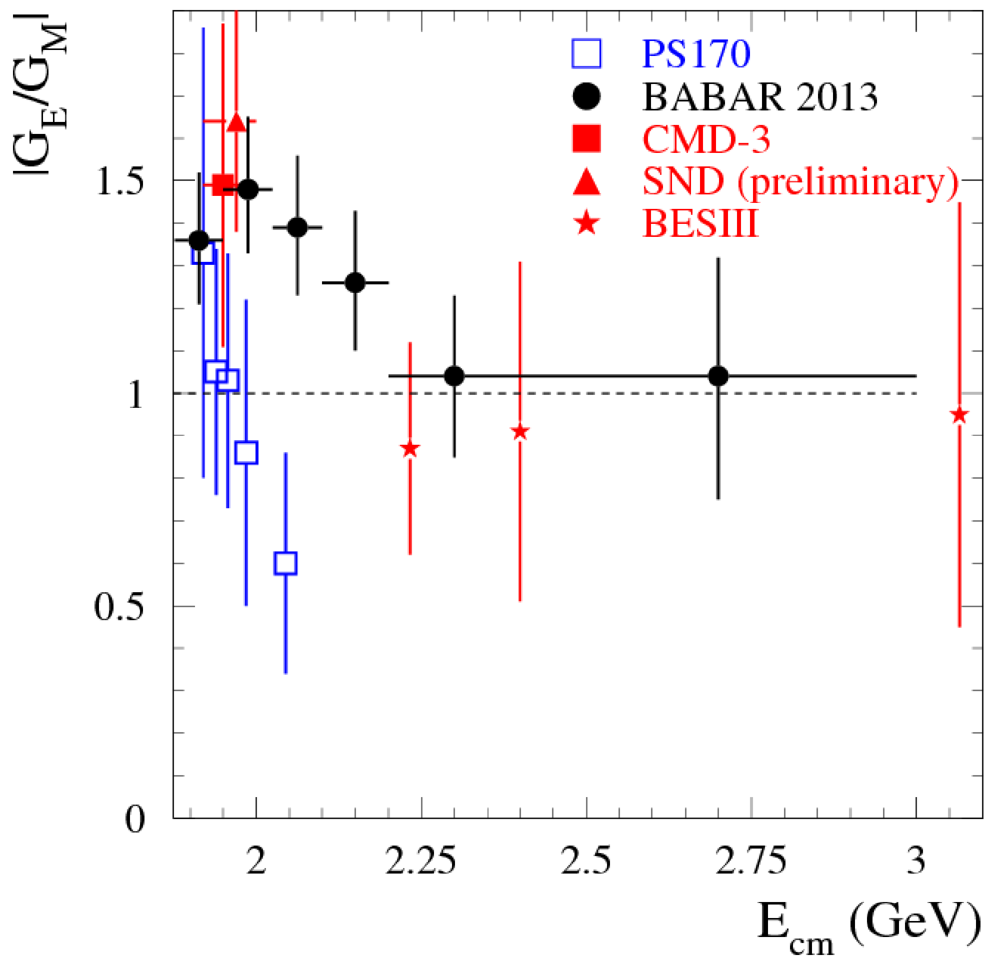
Only the most precise data are shown



- ❑ 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.

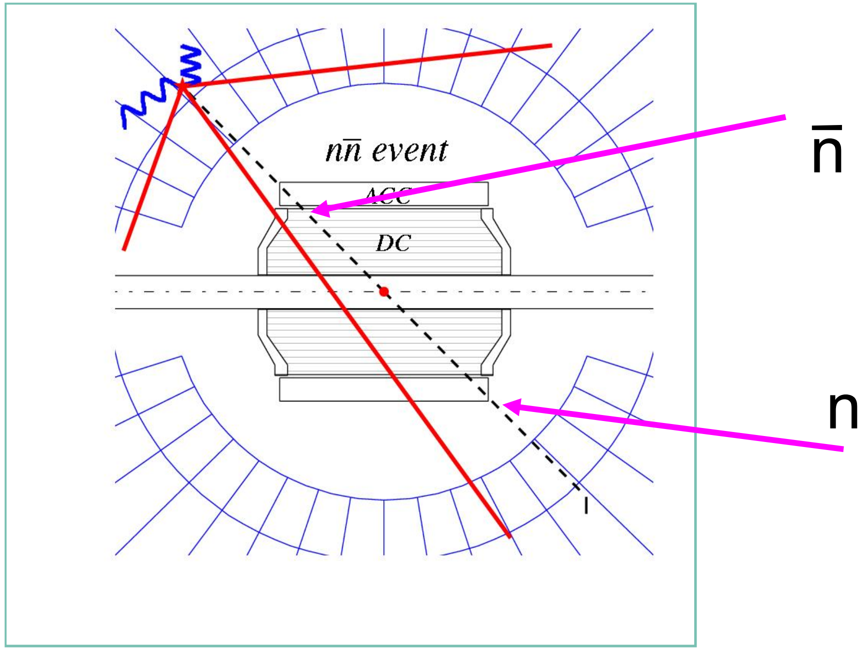
- ❑ In the mass region from 3.0 to 4.5 GeV the time-like form factor is about two-three times larger than the space-like one.
- ❑The BABAR SA ISR measurements give an indication that the difference between the time- and space-like form factors decreases with mass increase.

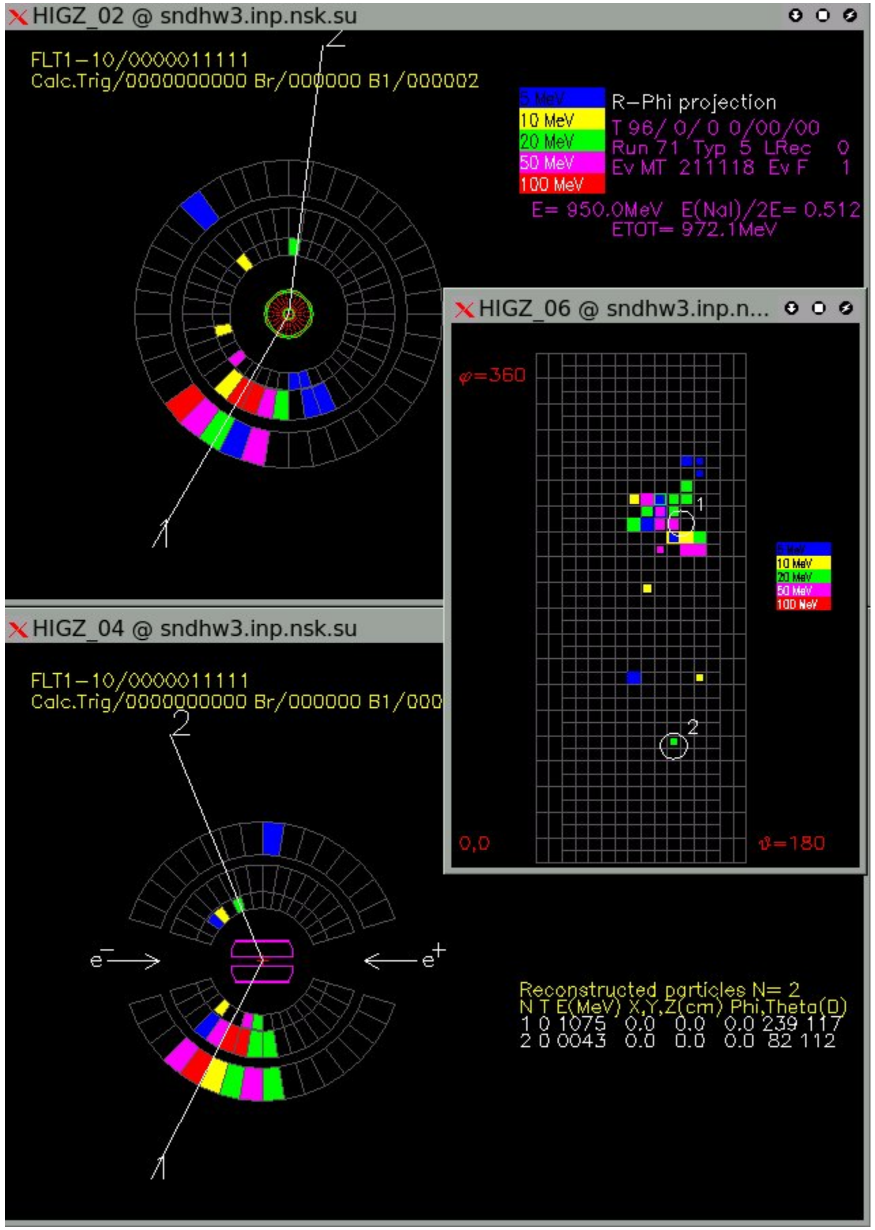
$|G_E/G_M|$ ratio



- ❑ The CMD-3 and SND measurements confirm a large deviation of the $|G_E/G_M|$ ratio from unity below 2.2 GeV observed by BABAR.
- ❑ There are several theoretical works explaining the steep falloff of the form factor near threshold and $G_E/G_M \neq 1$ by nucleons' final state interaction.

$e^+e^- \to n\bar{n}$ at SND





- No signal from neutron
- Annihilation signal from anti-neutron

$e^+e^- \to n\bar{n}$ at SND

Event selection:

- ✓ $0.95 < E_{EMC} < 1.50$ GeV
- ✓ $P_{EMC} > 0.5E_{beam}$
- ✓ $25^o < \theta_{P_{EMC}} < 155^o$
- ✓ No charged tracks originated from IR
- ✓ Special conditions against Bhabha and γγ events
- ✓ Muon-system veto

Selected data sample contains 70% of cosmic events, 27% of signal events, 3% physical background.

$e^+e^- \to n\bar{n}$ at SND

Background subtraction:

- Data were collected during about 1200 independent runs with luminosity ranged from 10^{30} to 10^{31} $cm^{-2}sec^{-1}$. The cosmic background is subtracted using relations

$$N_i = xT_i + \sigma_{vis}(E_i)L_i$$

where x is the cosmic event rate, σ_{vis} is the visible cross section for e^+e^- annihilation, N_i, T_i, L_i are the number of selected events in i-th run, its duration and integrated luminosity. The 1200 equations were solved using the maximum-likelihood method to find x and σ_{vis}.

- The physical background (2γ, 3γ, 4γ, $2\pi^0\gamma$, $K_SK_L\pi^0$, …) is estimated from the numbers of events selected below nn threshold.

The systematic uncertainty on the cross section is 17%.

$e^+e^- \to n\bar{n}$ at SND

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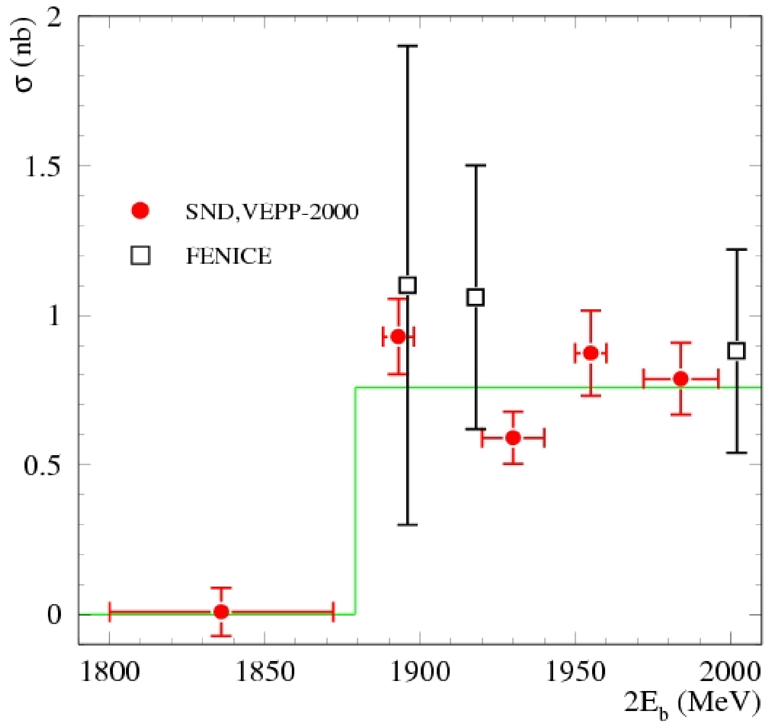
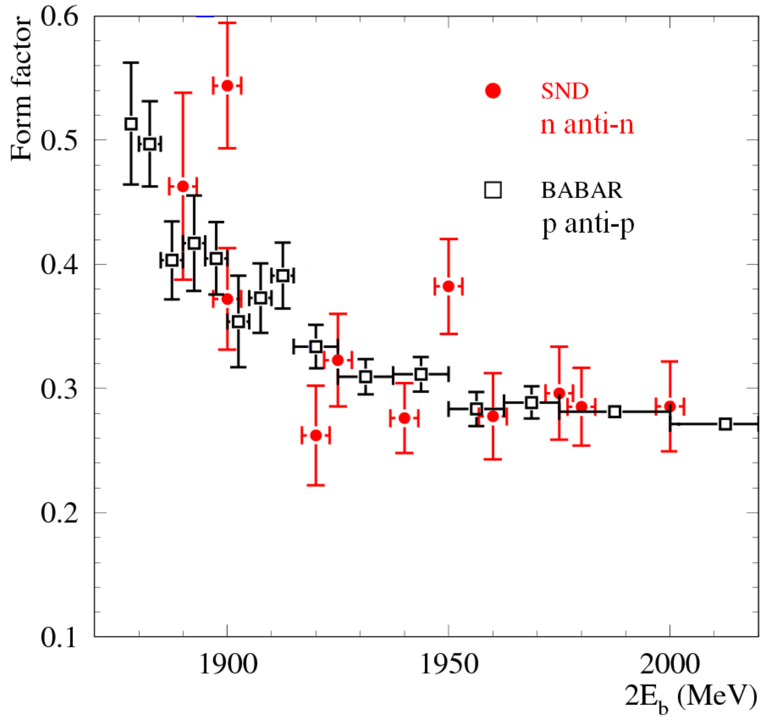
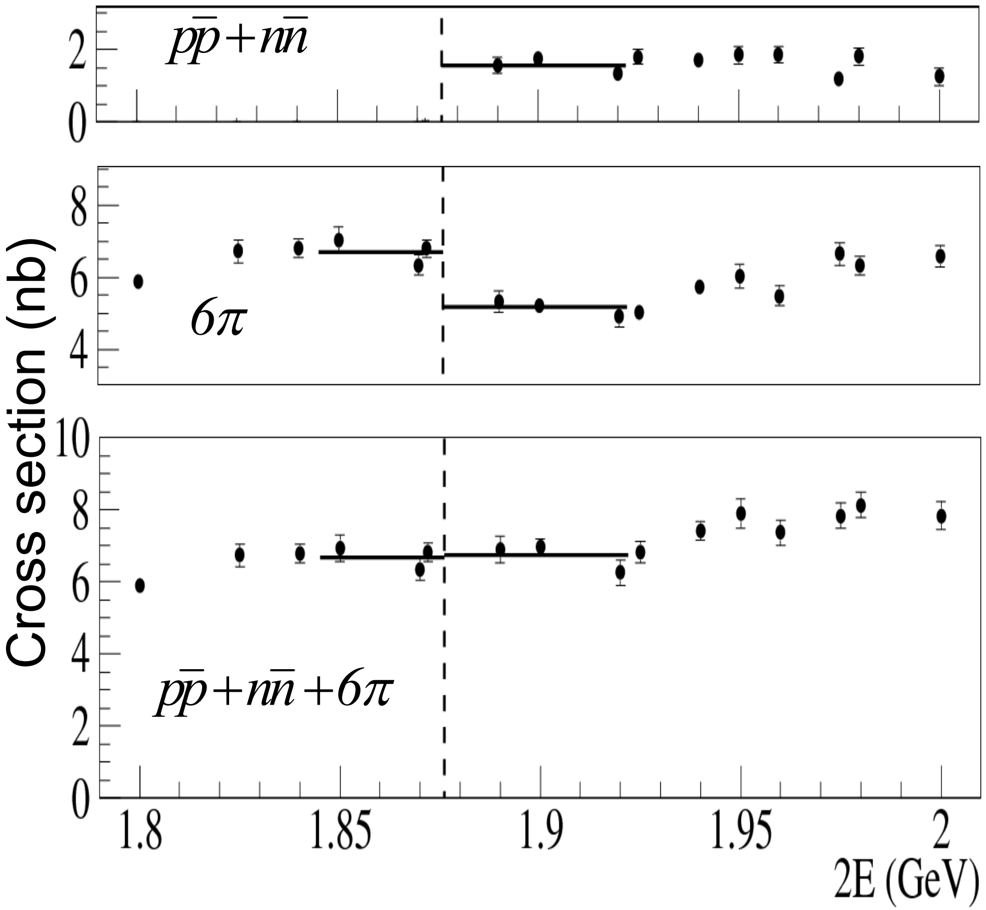




- The $e^+e^- \to$ n anti-n cross section is constant near threshold and coincides within the errors with that for proton anti-proton (pQCD $\sigma_p / \sigma_n = 4$).
- $\sigma_p = \sigma_n \Rightarrow$ Either isoscalar or isovector amplitude dominates in $e^+e^- \to$ N anti-N.

$e^+e^- \to N\bar{N}$ and $e^+e^- \to 6\pi$



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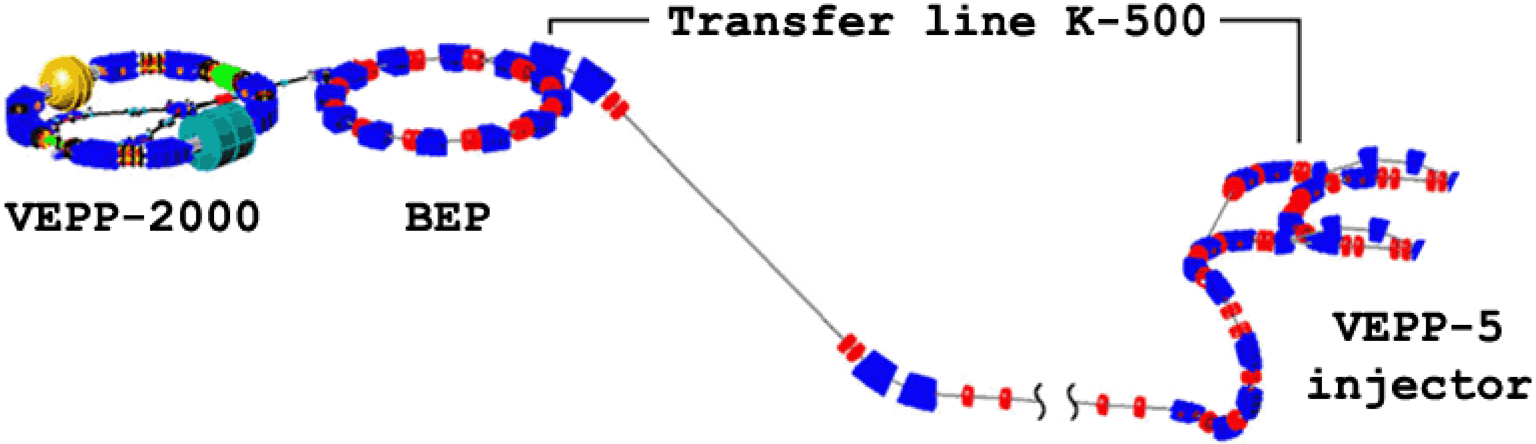
- In the total $e^+e^- \to$ hadrons cross section, the appearance of $e^+e^- \to$ N anti-N is fully compensated by the dip in the cross section for the isovector processes $e^+e^- \to 3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$.
- In other cross sections near N anti-N threshold, any features, comparable in magnitude with that for $e^+e^- \to 6\pi$, are not observed.

Summary

- The $e^+e^- \to p\bar{p}$ cross section and the proton effective form factor have been measured from threshold up to 6.5 GeV. The BABAR data agree with recent SND,CMD, and BESIII measurements.
- The form factor have complex mass dependence. There are a near-threshold steep falloff and a step-like behavior at higher masses.
- The $|G_E/G_M|$ ratio has been measured from threshold up to 3 GeV. A large deviation of this ratio from unity is observed below 2.2 GeV.
- Above 3 GeV the decrease of the form factor agrees with the asymptotic dependence $\alpha_s^2(q^2)/q^4$ predicted by QCD. An indication is observed that the difference between the time- and space-like form factors decreases with energy increase.

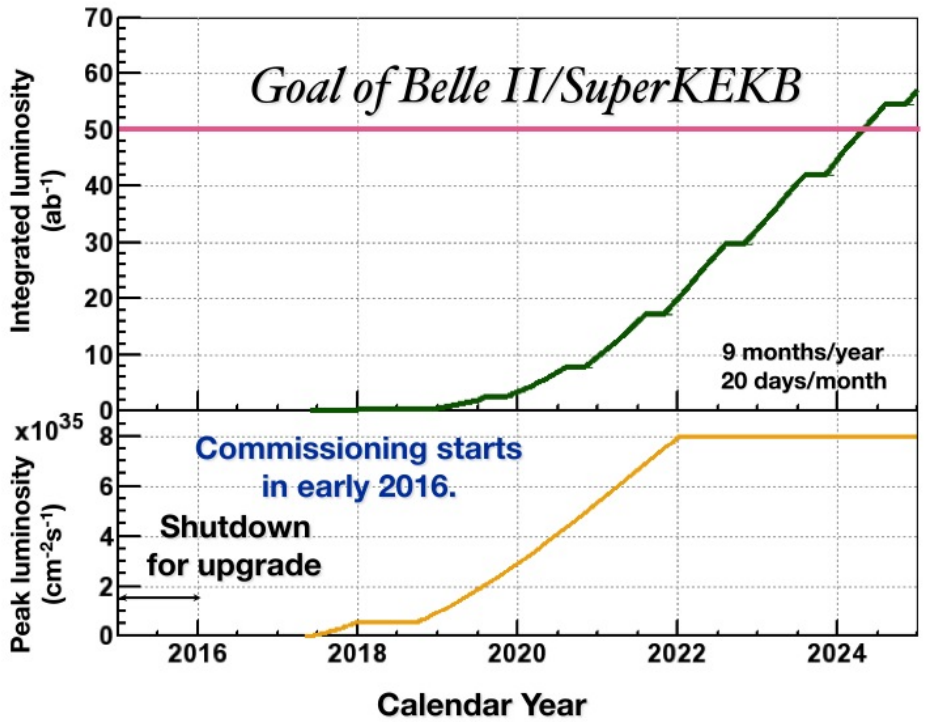
Summary

- The $e^+e^- \to n\bar{n}$ cross section and the neutron effective form factor have been measured from threshold up to 2.0 GeV at SND experiment.
- The $e^+e^- \to$ n anti-n cross section and effective form factor coincide within the errors with those for proton.
- New results on $e^+e^- \to$ p anti-p based on data collected in 2015 in the energy region 2-3 GeV are expected soon from BESIII.
- Experiments with SND and CMD-3 will start at the updated VEPP-2000 in 2016. During ~4 years nucleon production statistics will be increased by a factor of 100.



Summary

- Belle II experiment at SuperKEKB will start in 2017. It will measure the proton form factors using ISR technique. BABAR×100 data are expected to be collected up to 2025.



- PANDA at the HESR antiproton beam at FAIR will measure the proton form factor in the q^2 range from 5 to 25 GeV^2