Study of e^+e^- annihilation to a proton-antiproton pair

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

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

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:

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

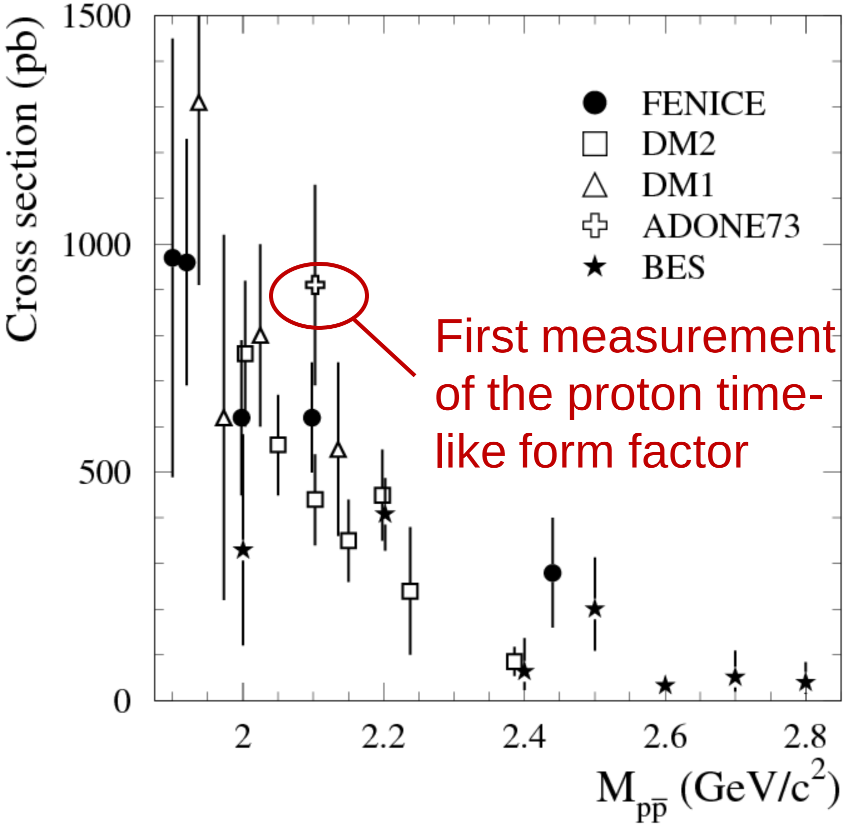
The G_E term decreases with energy increase as $1/E^2$.

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

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

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

Previous e^+e^- experiments



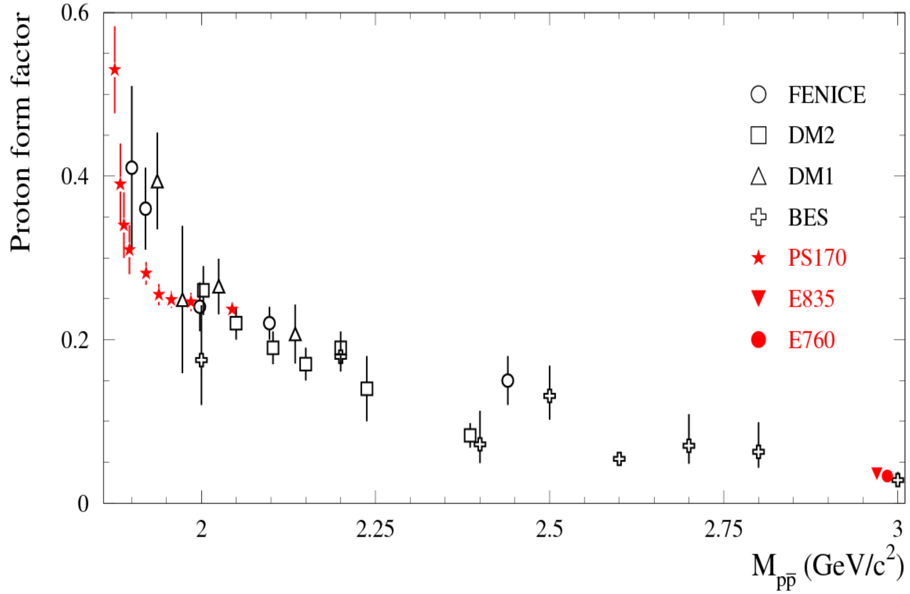
Below 3.2 GeV: ADONE73 (1973), DM1(1979), DM2(1983,1990), FENICE(1994), BES(2005).

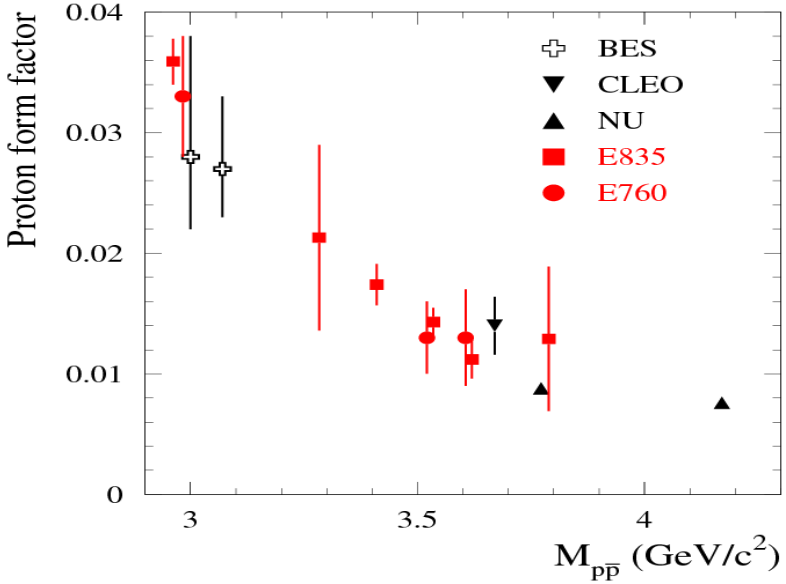
Statistical accuracy of these measurements is (20-30)%.

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.

Proton-antiproton collisions





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

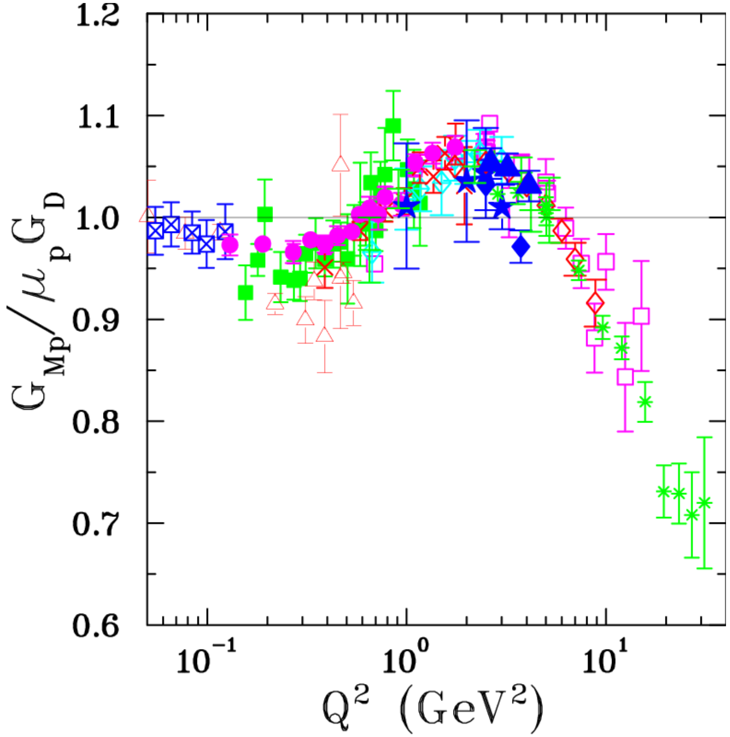
✓steep growth of the form factor near thershold,

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

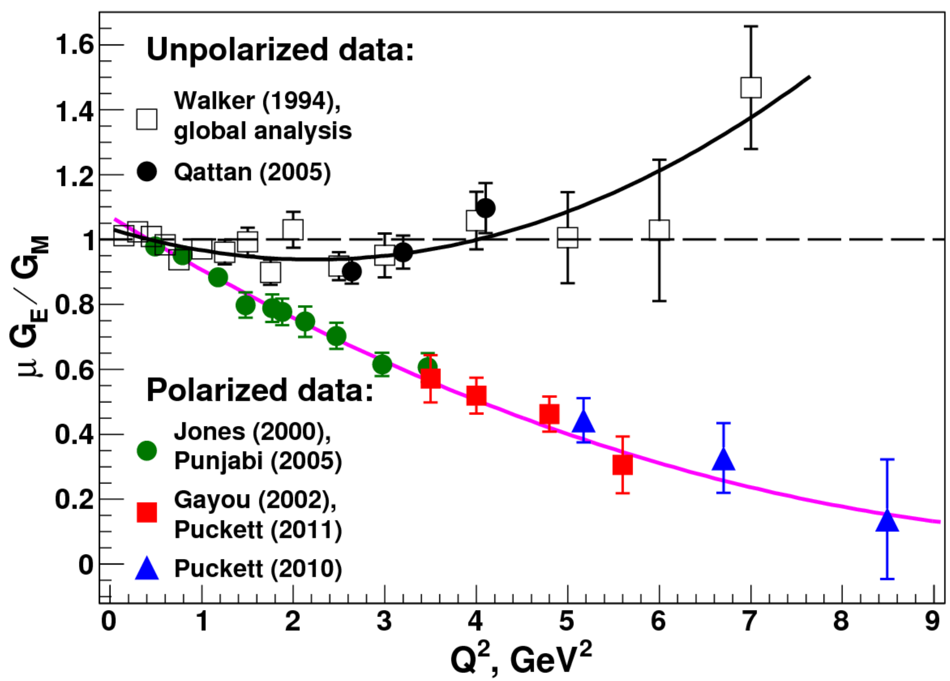
Above 3 GeV measurements were performed at FNAL (E835 and E760). The strong decrease of the form factor was observed which agrees with the dependence $\alpha_s(m)^2/m^4$ predicted by QCD for asymptotic proton form.

Space-like form factors (e-p scattering)

arXiv:hep-ph/0612014



arXiv:1210.1596



$$Q^2 = -q^2$$

$$G_D = \frac{1}{(1 + Q^2(GeV^2)/0.71)^2}$$

Two methods to determine G_E/G_M:

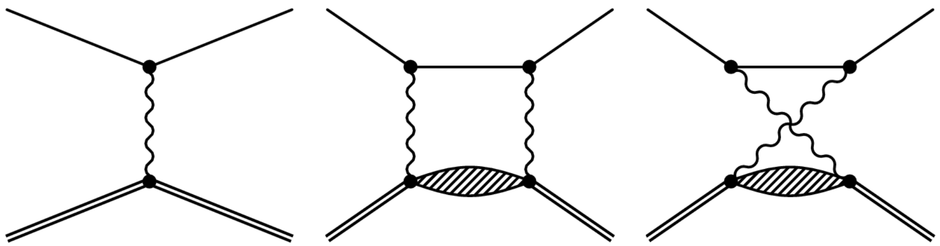
Rosenbluth: from angular distribution

Polarization transfer: polarized electron beam + measurement of the final-proton polarization.

Measurement G_E/G_M ratio

We use the method close to Rothenbluth to measure the ratio of the time-like form factors. Is our measurement correct?

A possible explanation of the Rosenbluth-polarization difference is a contribution of higher-order diagrams, in particular, two-photon exchange.



Space-like:

✓ $G_E/G_M(0)=1/2.79$

✓ No charge symmetry in ep scattering $\Rightarrow$ the interference of one- and two-photon amplitudes contributes to the cross section

Time-like:

✓ $G_E/G_M(2m_p)=1$

✓ Annihilation is charge-symmetric $\Rightarrow$ the interference does not contribute to the total cross section

✓ The interference can be seen as asymmetry in angular distribution

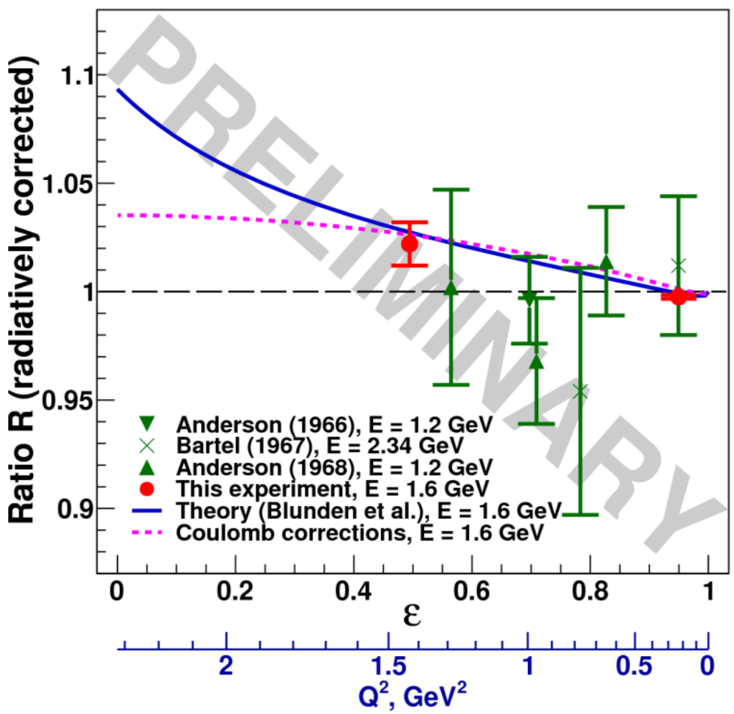
Size of the two-photon contribution

$$\frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4\frac{\mathcal{R}e\left(\mathcal{M}^{\dagger}_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2}$$

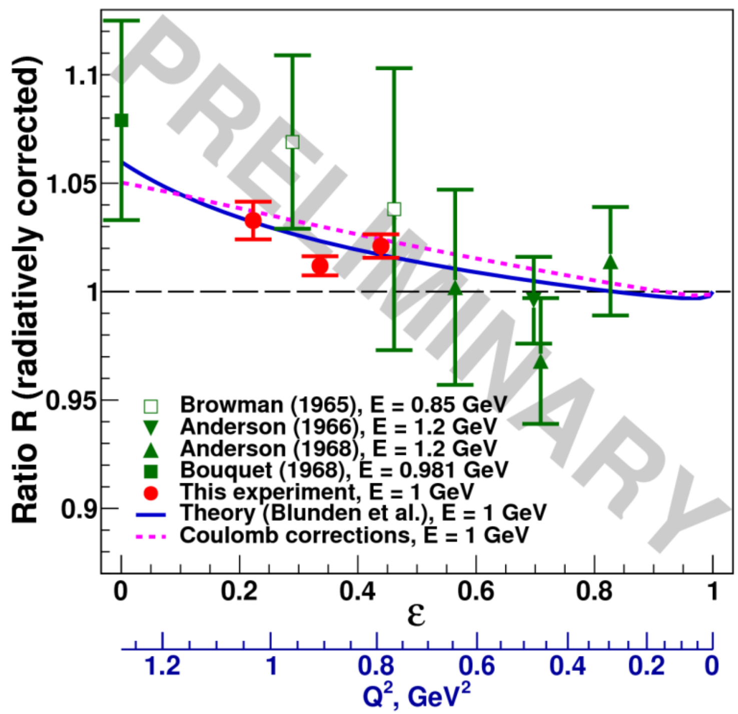
From A.Gramolin talk at the workshop “Scattering and annihilation electromagnetic processes” Trento, February 18-22, 2013.

Preliminary results of the Novosibirsk TPE experiment

Run I (2009):
$E_{\mathrm{beam}} = 1.6$ GeV



Run II (2011–2012):
$E_{\mathrm{beam}} = 1$ GeV

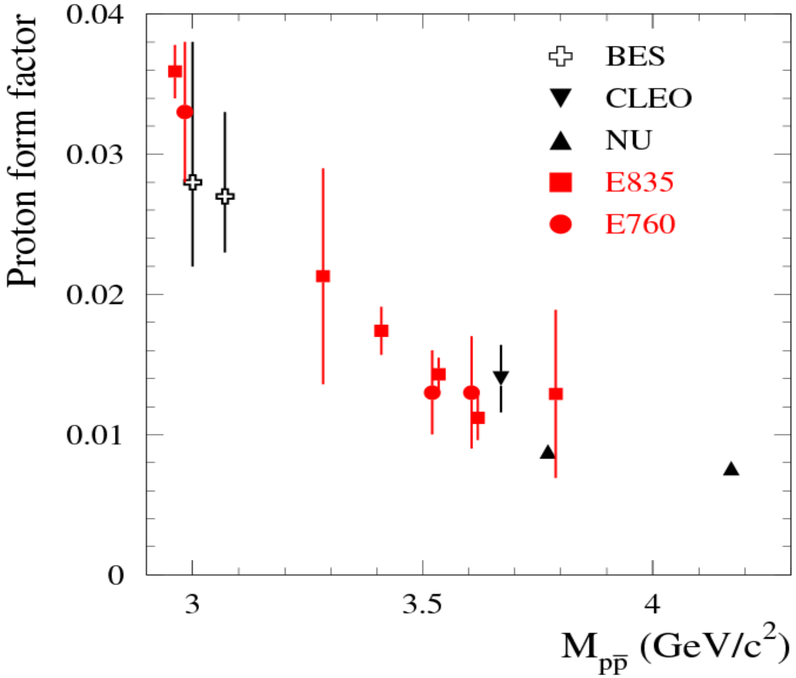


Theory: *J. Arrington and I. Sick*, Phys. Rev. **C70** (2004) 028203
P. G. Blunden, et al., Phys. Rev. **C72** (2005) 034612

Recent and new measurements

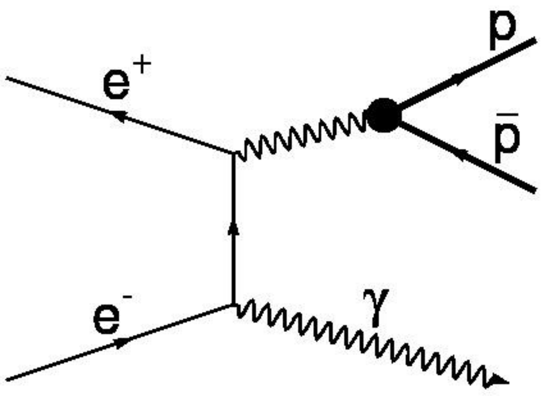
Progress in measurements became possible with developing high luminosity e^+e^- -colliders:

- direct measurements: CESR (CLEO), BEPC-II (BESIII), VEPP-2000 (SND and CMD-3)
- ISR method: PEP-II (BABAR), BEPC-II (BESIII)



The points marked “NU” (Phys. Rev. Lett. 110 (2013) 022002) was obtained on CLEO data (~1 fb), collected at 3.77 and 4.17 GeV. The accuracy of the cross section measurement is about 10%.

ISR method

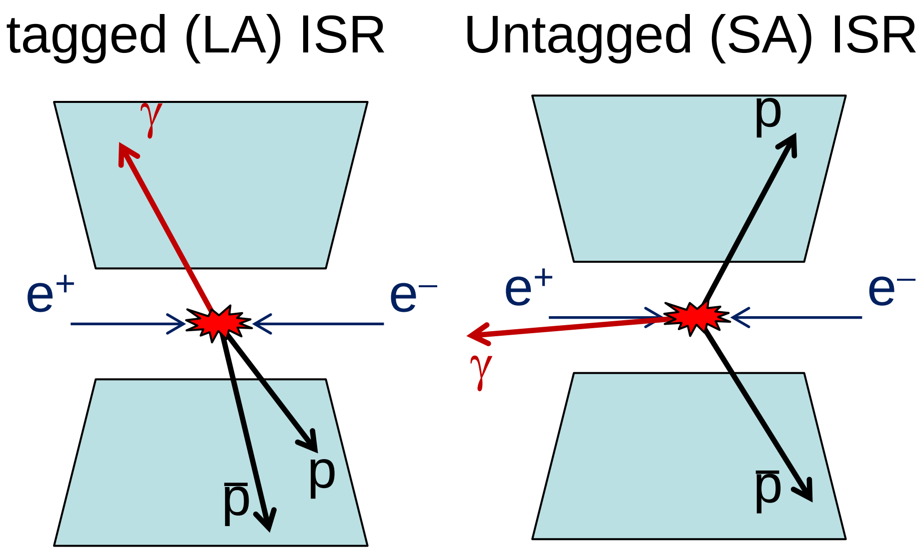


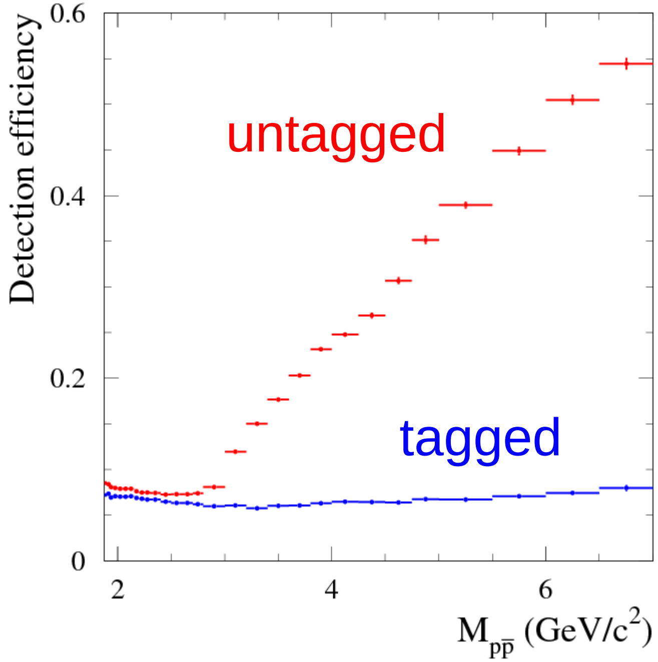
The mass spectrum of the proton-antiproton system in the reaction $e^+e^- \to p\bar{p}\gamma$ is related to the cross section for the nonradiative process $e^+e^- \to p\bar{p}$.

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

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.

ISR method

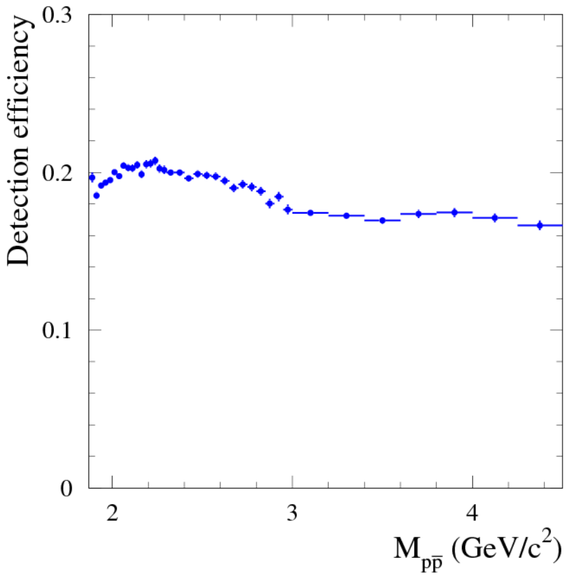


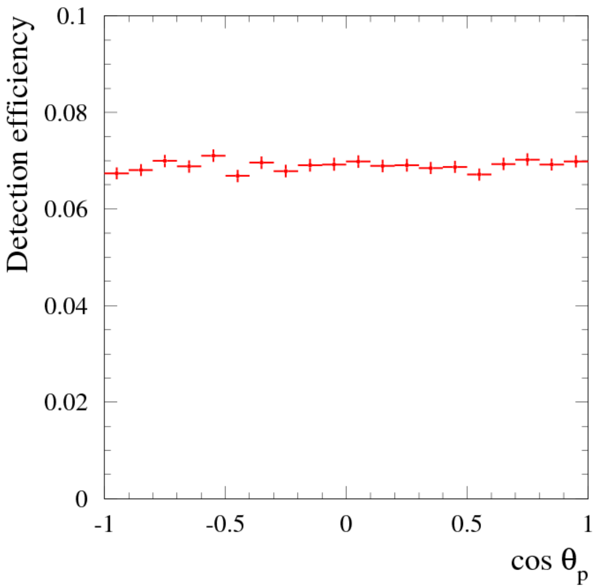


The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 3 GeV can be studied only with detected photon (about 10% of ISR events).

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.

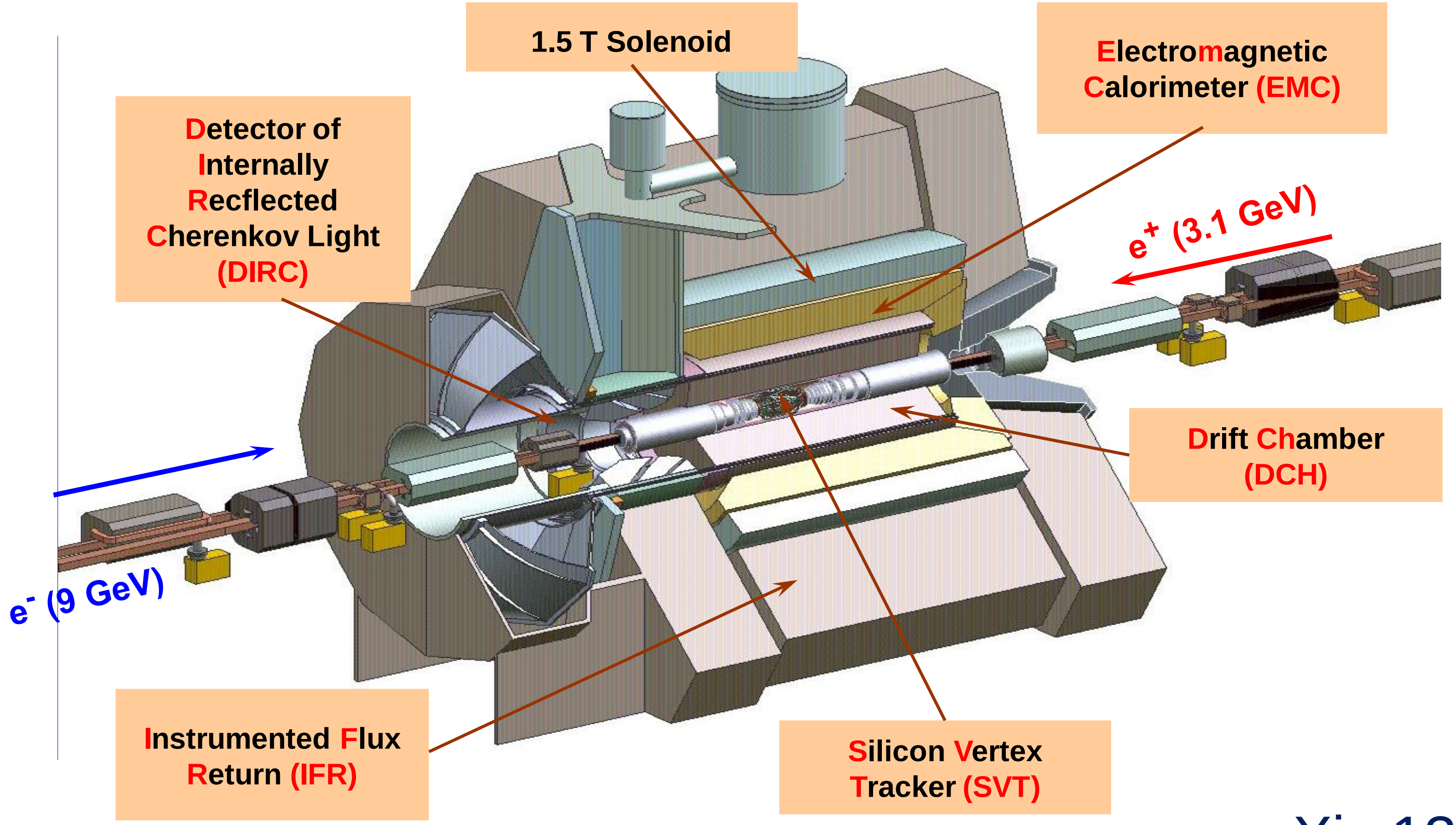
✓ A low dependence of the detection efficiency on hadron invariant mass.

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.

BABAR detector



arXiv:1302.0055

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

The previous analysis (Phys. Rev. D **73**, (2005) 012005) was based on a half of the data: 231 fb^{-1}.

Event selection

All final particles must be detected and well reconstructed.

✓2 tracks with opposite charge, which are required to originate from the interaction region and be identified as protons. They must be in the DIRC polar angle range: $25.8° < \theta < 137.5°$.

✓A photon candidate with $E_{c.m.} > 3$ GeV in the well understood calorimeter region: $20° < \theta < 137.5°$.

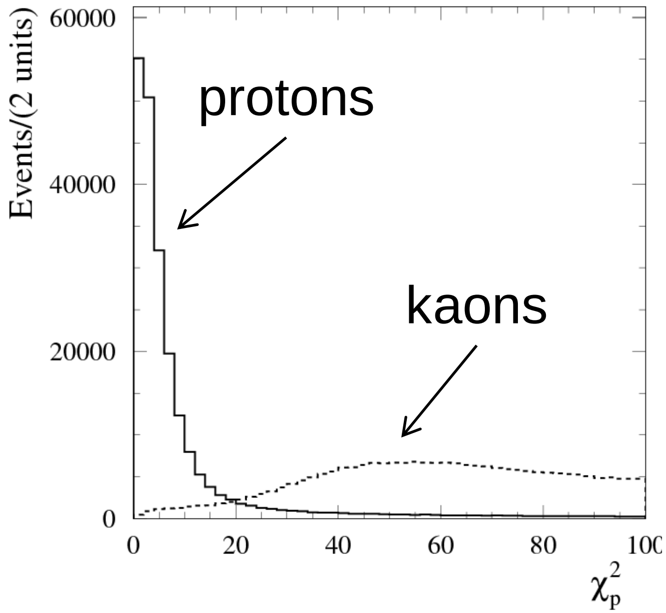
A significant fraction of data events contain beam-generated backgrounds photons and charged tracks. Any number of extra photons and charged tracks are allowed in an event.

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

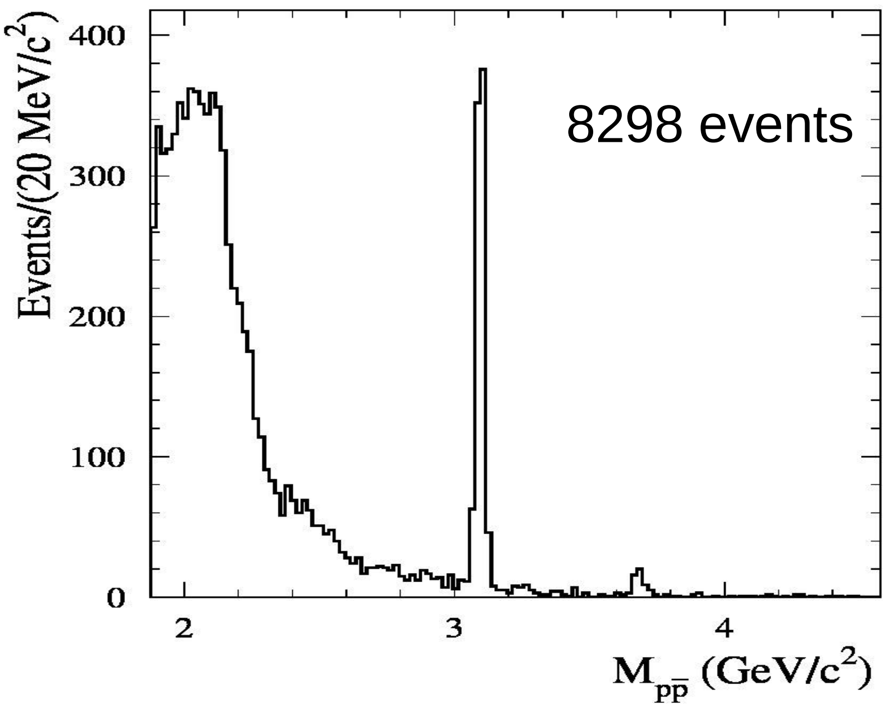
These backgrounds are suppressed by the PID requirement by a factor of 3×10^4 for pions and muons, and 10^4 for kaons with a loss of about 30% of the signal events.

Event selection

Further background suppression is based on kinematic fitting. A kinematic fit to the $e^+e^- \to h^+h^-\gamma$ hypothesis (h=p,K) is performed with requirements of energy and momentum conservation.

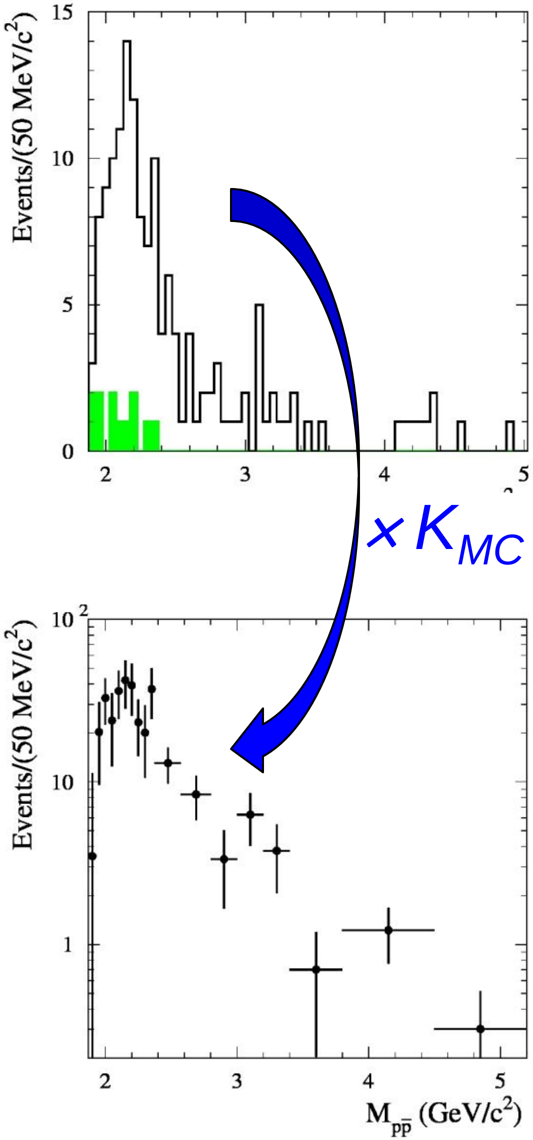


$$\chi^2_p < 30, \ \chi^2_K > 30$$



The χ^2 requirements provide additional background suppression by a factor of 50 for pions and muons, and 30 for kaons, with a loss of 25% of signal events.

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



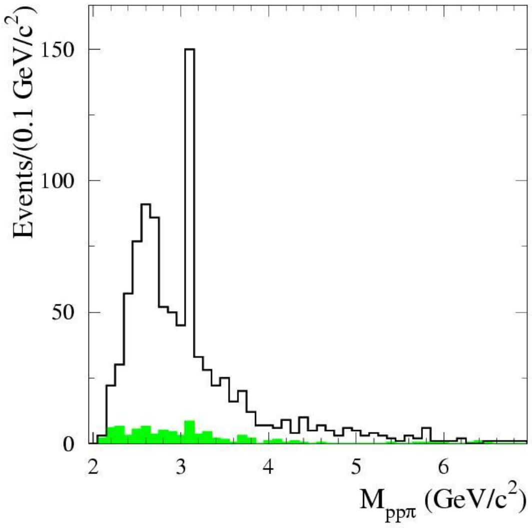
The main background arises from $e^+e^-\to p\bar{p}\pi^0$ with an undetected low-energy photon or with merged photons from the π^0 decay. These events have χ^2 distribution peaked at low χ^2 values and cannot be separated from signal events.

The $e^+e^-\to p\bar{p}\pi^0$ events are selected in data using χ^2 of the kinematic fit to the $e^+e^-\to p\bar{p}\gamma\gamma$ hypothesis and requirement on the two-photon invariant mass. The mass spectrum of $p\bar{p}\pi^0$ events passing the $p\bar{p}\gamma$ selection is determined as $K_{MC} \times (dN/dM)_{data}$. The scale factor K_{MC} found from simulation is about 3.

M_{pp}	<2.5	2.5-3.0	3.0-4.5	>4.5
N_{data}	6695	592	105	9
$N_{pp\pi}$	321 ± 37	66 ± 15	43 ± 11	6 ± 3

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

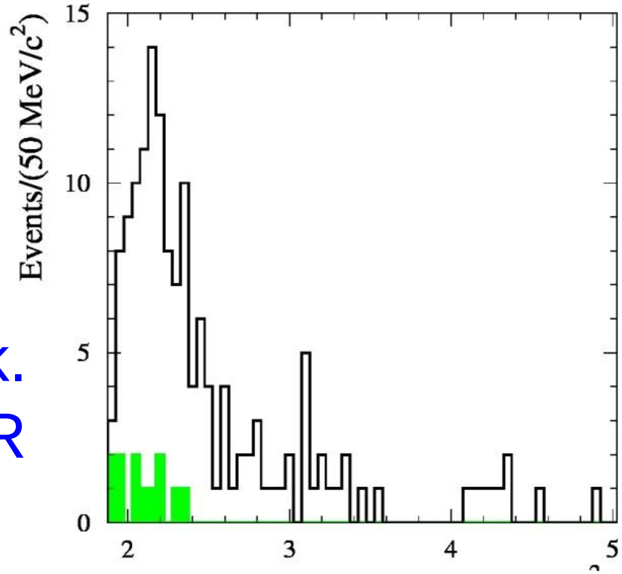
The cross section for $e^+e^- \to p\bar{p}\pi^0$ at c.m. energy of 10.6 GeV is about 5 fb and seems too large.



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.

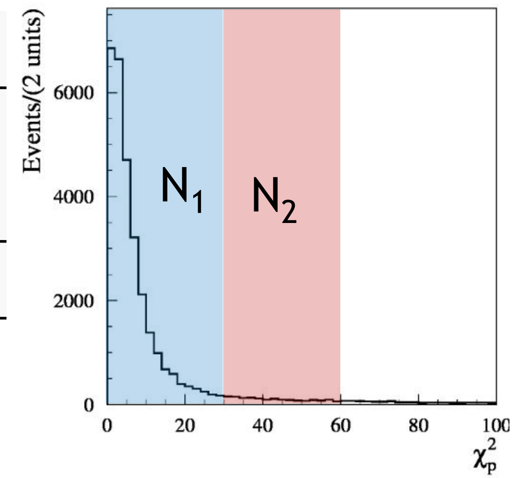
π^0 ← → $p\bar{p}$ pair

At high energy mechanism is different: the pp 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 ISR pp mass spectrum.



Background subtraction

	$p\bar{p}\pi^0$	ISR and e^+e^-	$\bar{p}p\gamma$	data
N_1	448 ± 42	95 ± 8	7741 ± 113	8298
N_2	79 ± 7	150 ± 10	337 ± 16	560
$\beta=N_2/N_1$	0.18 ± 0.04	1.6 ± 0.3	0.044 ± 0.002	



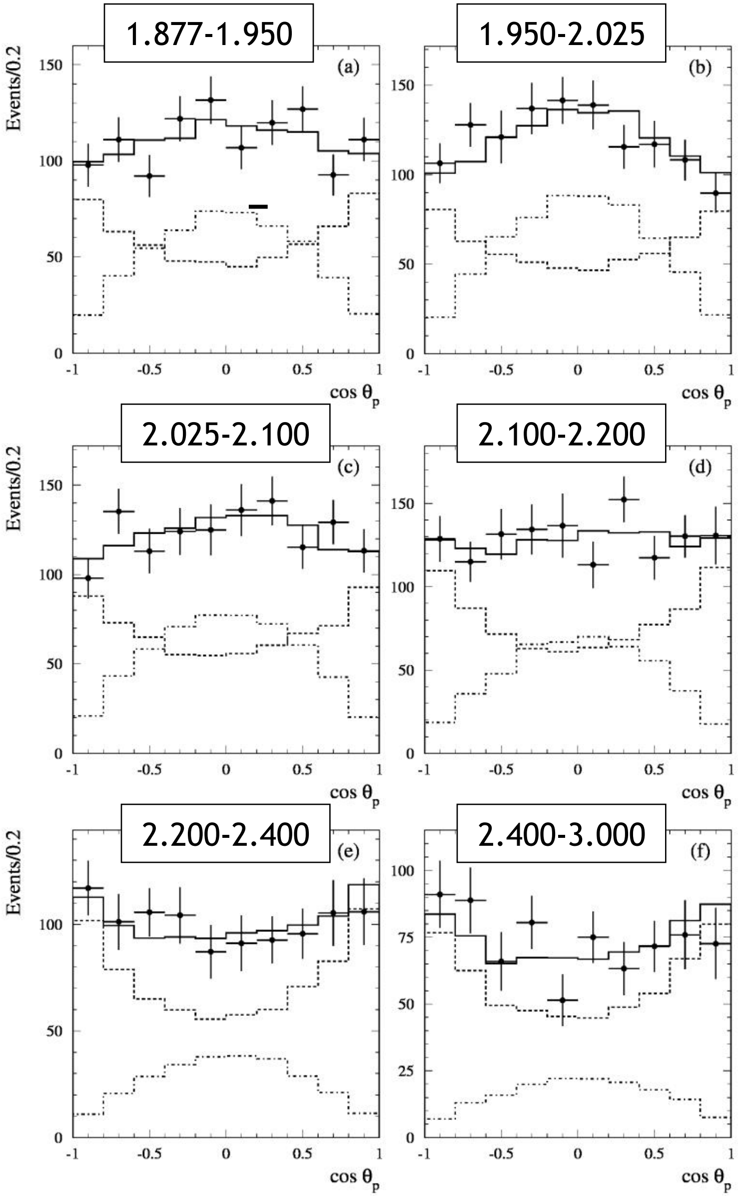
"ISR and e^+e^-" column shows JETSET prediction for backgrounds from processes other than $e^+e^- \to p\bar{p}\pi^0$:
$e^+e^- \to p\bar{p}\eta$, $p\bar{p}2\pi^0$, $p\bar{p}\pi_0\gamma$, $p\bar{p}2\pi_0\gamma$ …

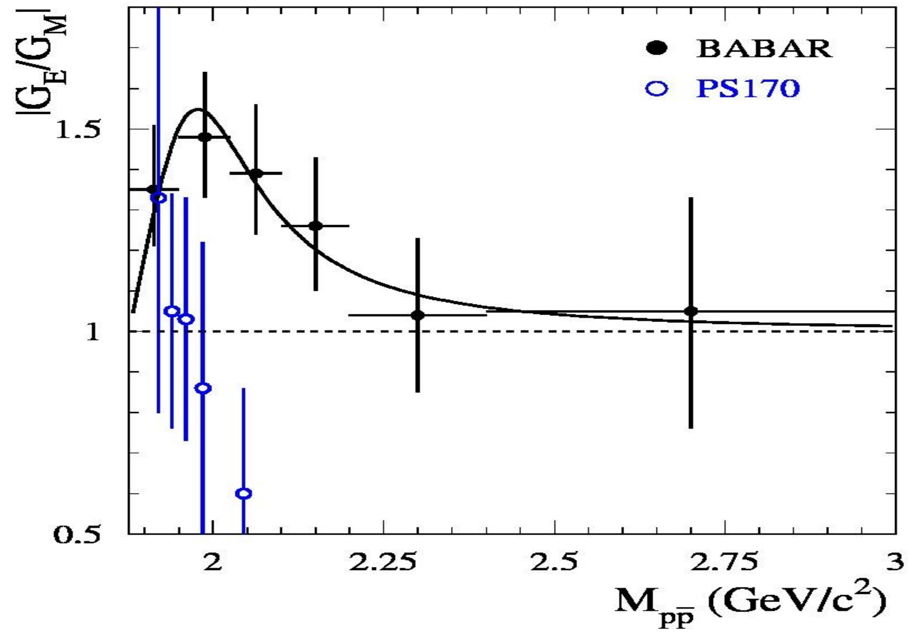
To subtract "ISR and e^+e^-" background, we use the method based on difference of the χ^2 distributions for signal and background events:

$$N_{sig} = \frac{N_1' - N_2'/\beta_{bkg}}{1 - \beta_{p\bar{p}\gamma}/\beta_{bkg}}, \quad N_{bkg} = N_1' - N_{sig}.$$

The "ISR and e^+e^-" background is about 1% (110 ± 30).

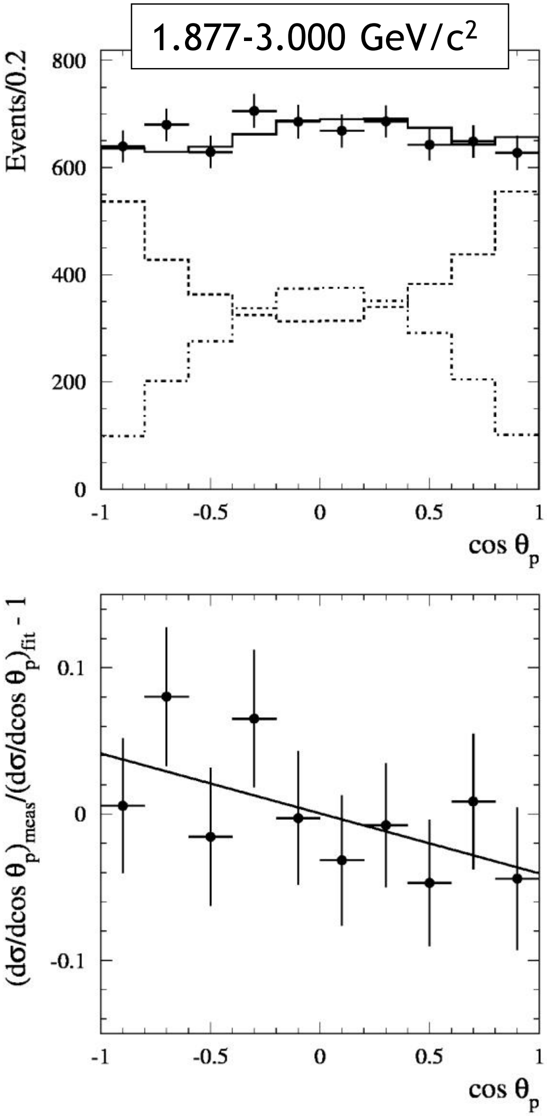
Angular distribution





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

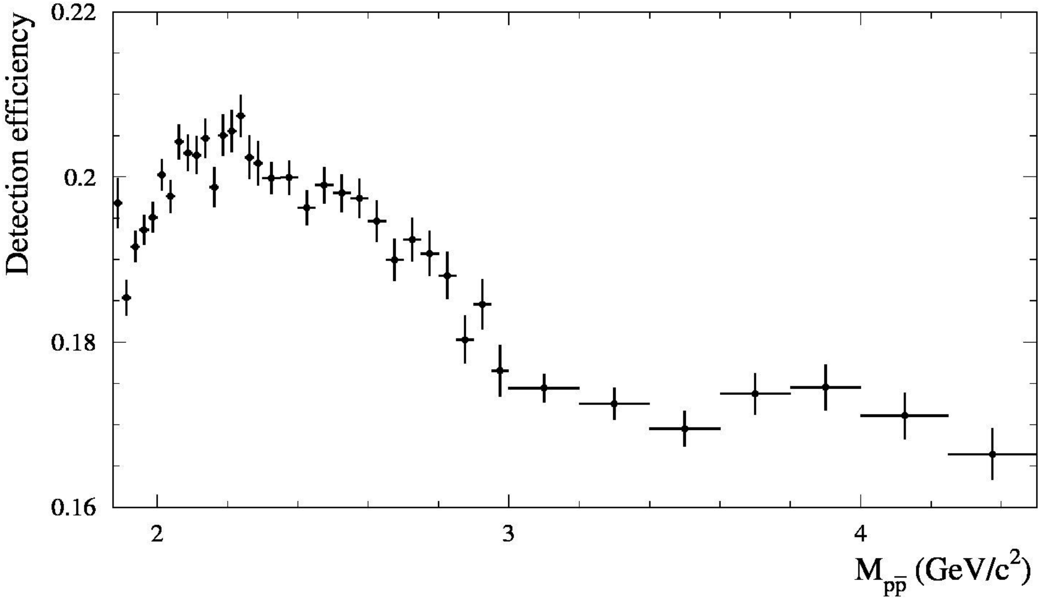


- The asymmetry is absent in lowest order ($\gamma^* \to p\bar{p}$). It arises from higher-order contributions (soft extra ISR and FSR interference, two-photon exchange). Measuring the asymmetry we control the higher-order contributions.
- Our simulation uses a model with one-photon exchange. The asymmetry 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±0.026±0.005
- The integral asymmetry

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

Detection efficiency

The detection efficiency is determined using MC simulation with 20° < θ_γ^* < 160°. The model dependence due to uncertainty in the $|G_E/G_M|$ ratio is about 1% for M_{pp}<3 GeV/c^2, and 4% for higher masses, where we use $|G_E|=|G_M|$ assumption.



This MC efficiency must be corrected to account for data-MC difference in detector response:

$$\varepsilon = \varepsilon_{MC} \prod_i (1+\delta_i)$$

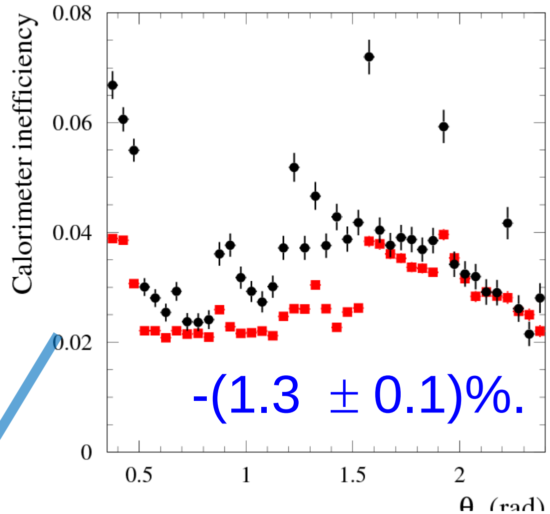
Efficiency corrections (%)

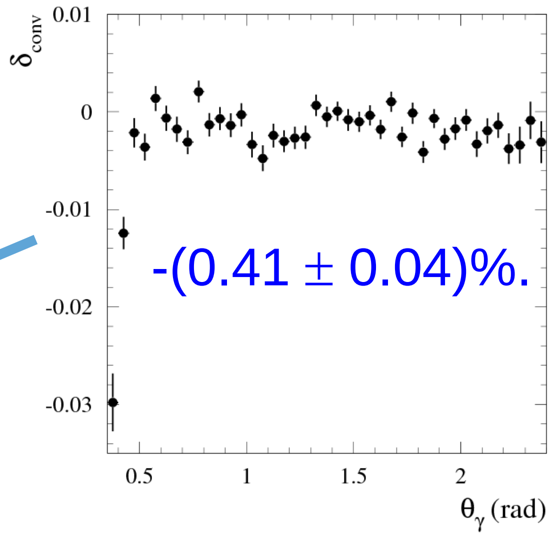
Effect	1.9 GeV/c^2	3.0 GeV/c^2	4.5 GeV/c^2
χ^2 cuts	-0.5 ± 0.4	-0.9 ± 0.4	-1.5 ± 0.4
Track reconstruction	0.0 ± 0.5	0.0 ± 0.5	0.0 ± 0.5
Track overlap	0.0 ± 1.5	–	–
Nuclear interaction	0.8 ± 0.4	1.1 ± 0.4	1.0 ± 0.4
PID	-1.9 ± 2.0	-1.9 ± 2.0	-1.9 ± 2.0
Photon inefficiency	-1.9 ± 0.1	-1.7 ± 0.1	-1.7 ± 0.1
Trigger and filters	-0.7 ± 0.6	-0.1 ± 0.5	-0.1 ± 0.5
Total	-4.2 ± 2.6	-3.5 ± 2.2	-4.2 ± 2.2

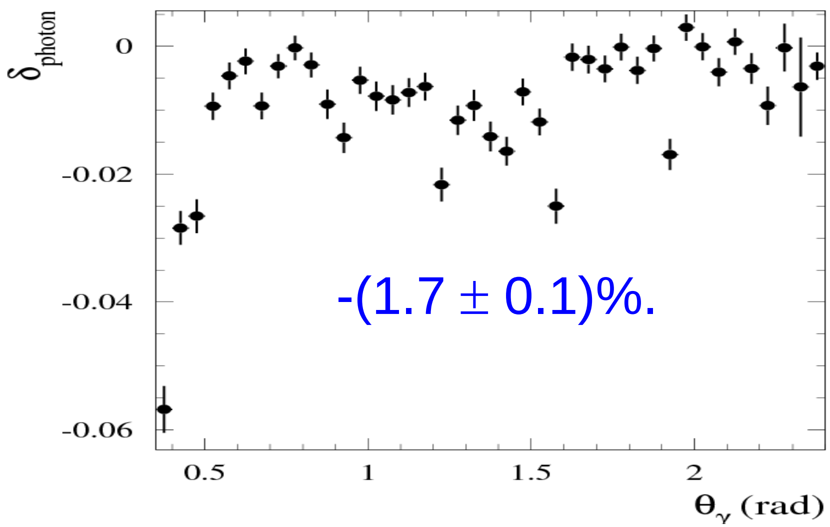
Photon detection efficiency

- **Calorimeter inefficiency** is studied using $e^+e^- \to \mu^+\mu^-\gamma$ events selected with the requirement of two identified muons with zero recoil mass and without any conditions on photon parameters.

- **Photon conversion** is studied using $e^+e^- \to \mu^+\mu^-\gamma$ events with four tracks (two muons and two close electrons).

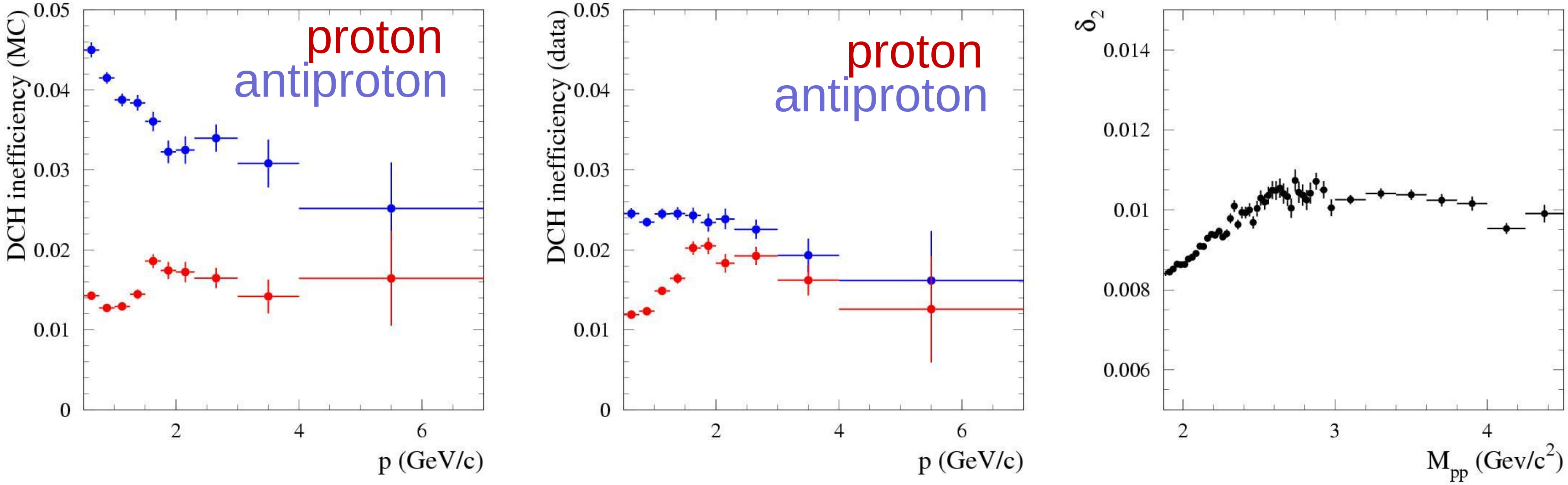






Nuclear interaction

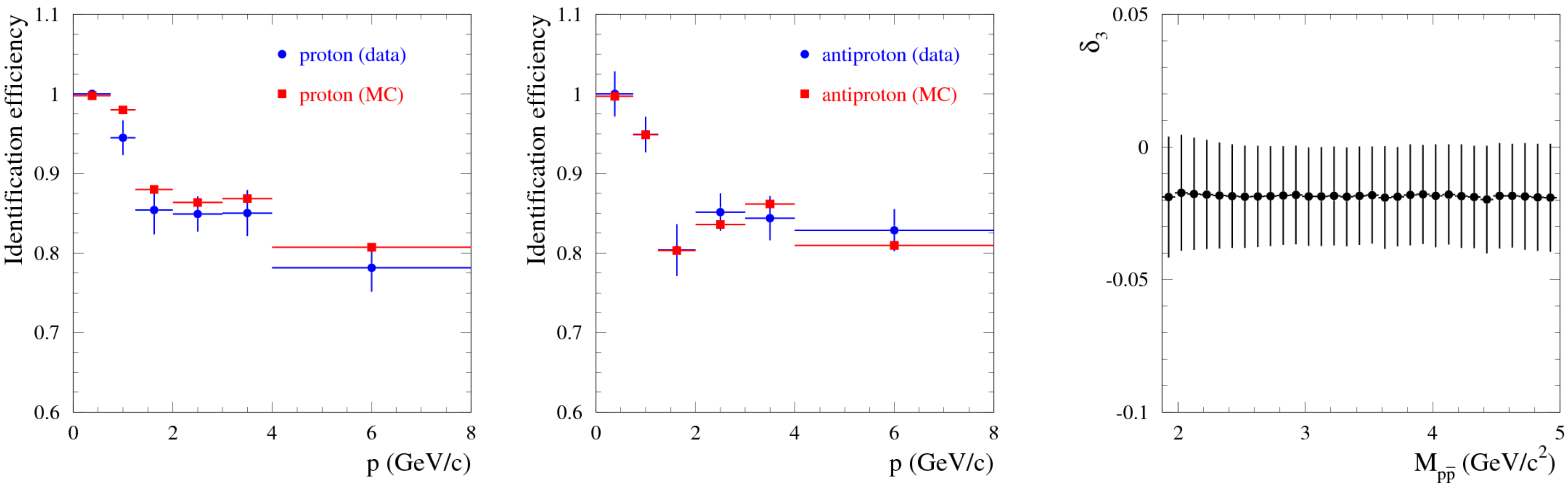
MC data



In MC simulation the nuclear interaction leads to about 6% event loss. To check correctness of the simulation we compare track losses in SVT in data and MC using protons and antiprotons from $\Lambda\to p\pi$ decay.

Data and MC are in a good agreement for protons. For antiprotons the simulation overestimates the annihilation cross section by a factor of 2.6 1.0. This leads to $(1.0 \pm 0.4)\%$ efficiency correction.

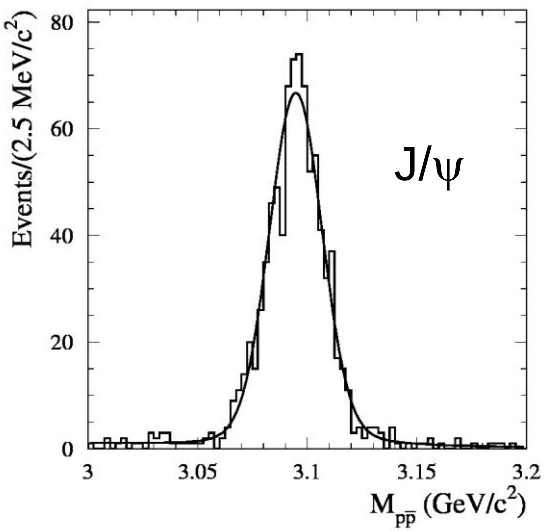
PID efficiency

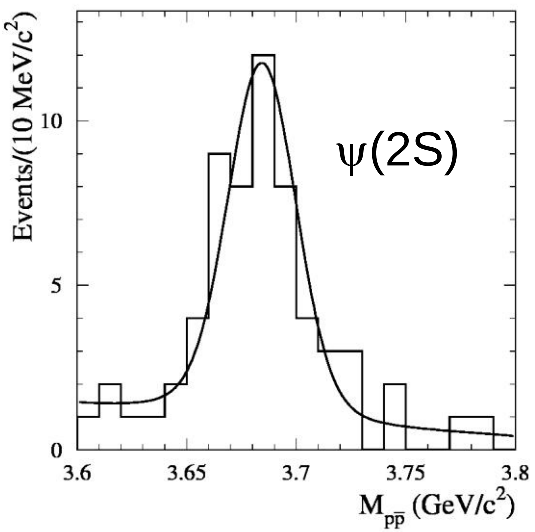


Data-MC difference in proton ID is studied with the use of $J/\psi\gamma \rightarrow p\bar{p}\gamma$ events selected with one and two identified protons.

The correction is found to be about (1.9 ± 2.0)%.

J/ψ and ψ(2S) decays





$$\frac{d\sigma}{d\cos\theta_\gamma^*} = \frac{12\pi^2\Gamma(V\to e^+e^-)B(V\to f)}{m_V\, s} W(s, x_0, \theta_\gamma^*)$$

$$x_0 = 1 - \frac{m_V^{\ 2}}{s}$$

$$\sigma(20^\circ < \theta_\gamma < 160^\circ) = \frac{N}{\varepsilon R L},$$

	N	ε,%	R	$\Gamma_{ee}B_{pp}$, eV
J/ψ	821 ± 30	17.4 ± 0.1	1.007	11.3 ± 0.4 ± 0.3
ψ(2S)	44 ± 8	17.2 ± 0.1	1.011	0.67 ± 0.12 ± 0.02

PDG

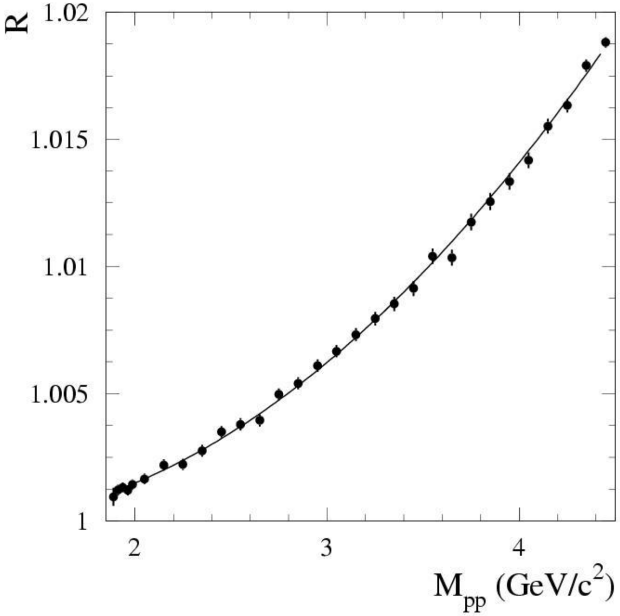
$$B(J/\psi \to p\bar{p}) = (2.04 \pm 0.07 \pm 0.07)\times 10^{-3}$$ 2.17 ± 0.07

$$B(\psi(2S) \to p\bar{p}) = (2.86 \pm 0.51 \pm 0.09)\times 10^{-4}$$ 2.76 ± 0.12

BESIII: $B(J/\psi \to p\bar{p}) = (2.112 \pm 0.004 \pm 0.031)\times 10^{-3}$

Cross section

Radiative correction

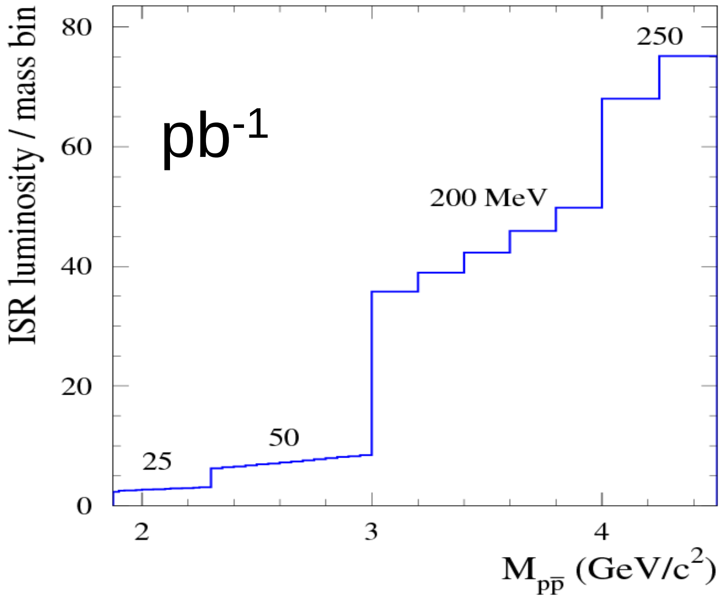


$$\sigma_{ee\to p\bar{p}}(m) = \frac{(dN/dm)_{corr}}{\varepsilon R\, dL/dm},$$

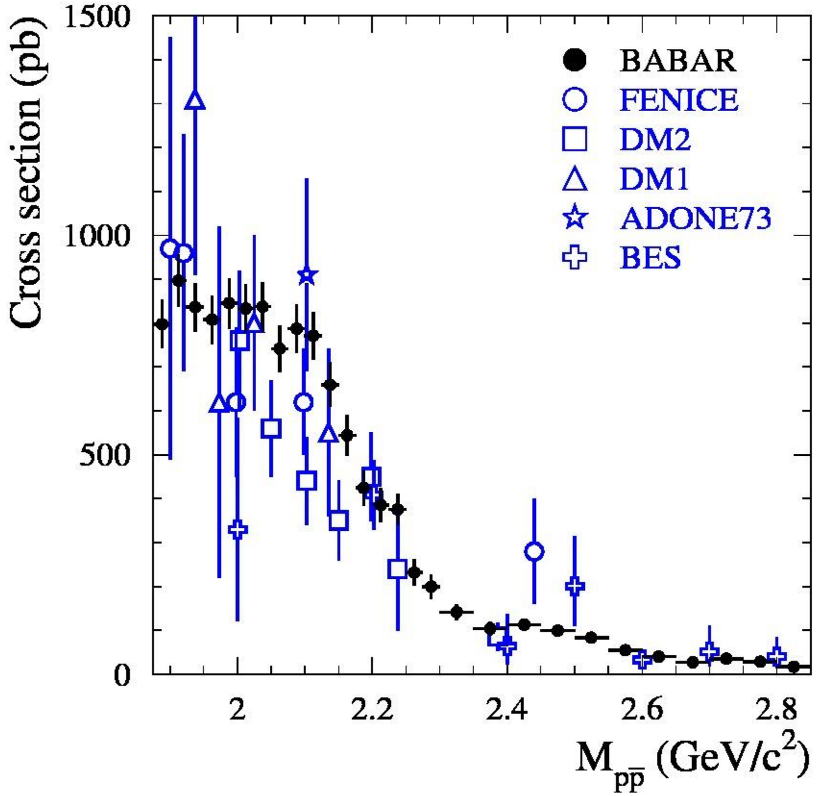
With chosen width of the mass bin the resolution correction insignificantly changes the shape of mass spectrum but leads to about 20% increase in the errors and their correlation.

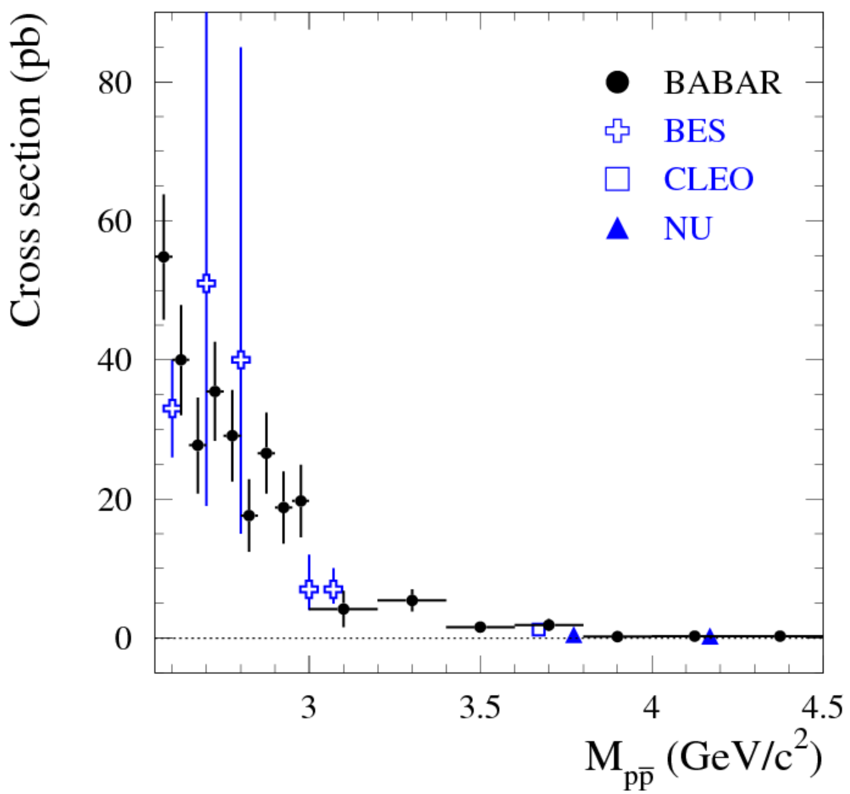
$$\frac{dL}{dm} = \frac{\alpha}{\pi x}\left[\left(2-2x+x^2\right)\log\frac{1+C}{1-C} - x^2 C\right]\frac{2m}{s}L,$$

$$x = 1-\frac{m^2}{s}, \quad C=\cos\theta_0,\ \theta_0 = 20^\circ.$$



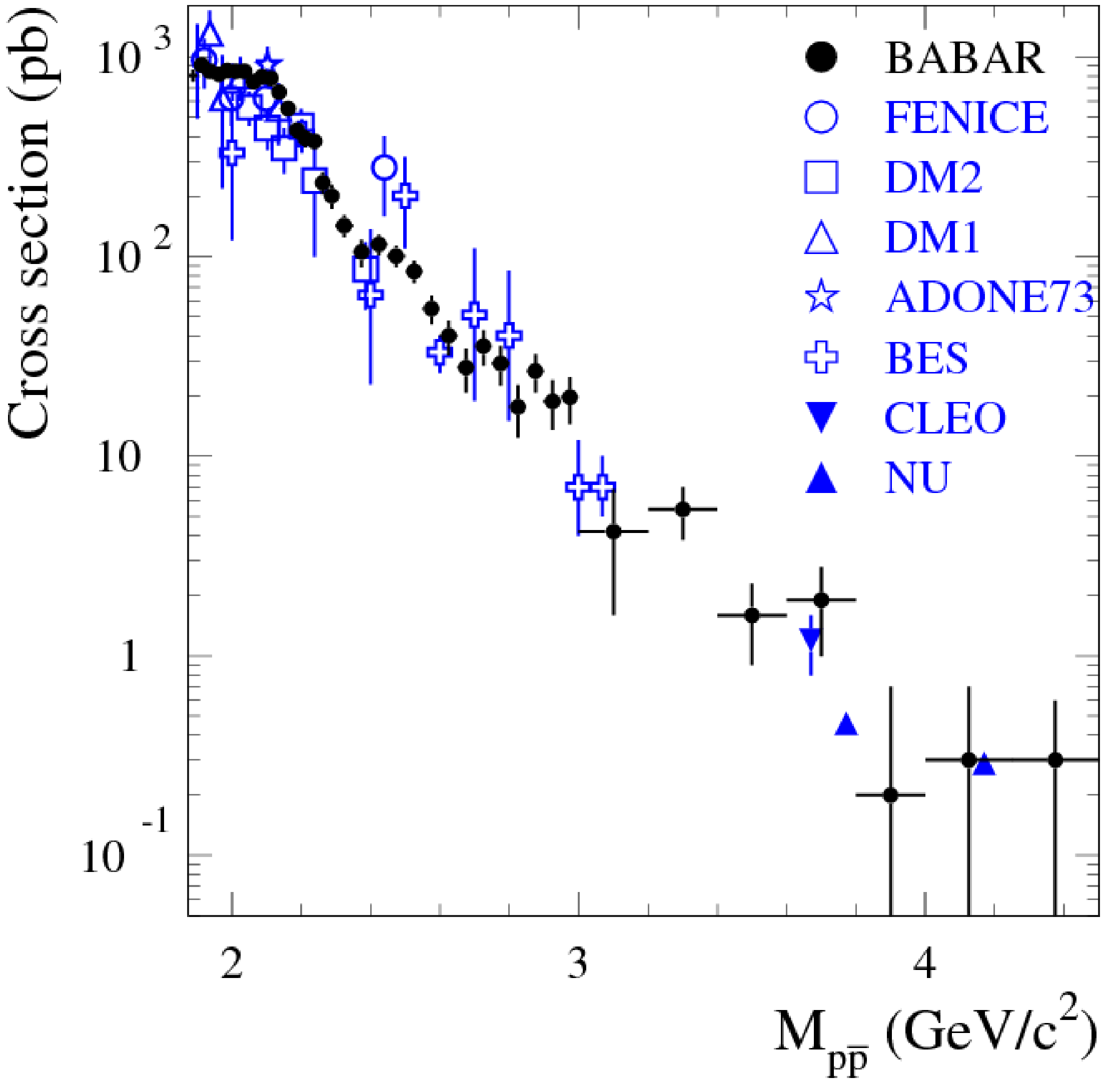
Measured cross section





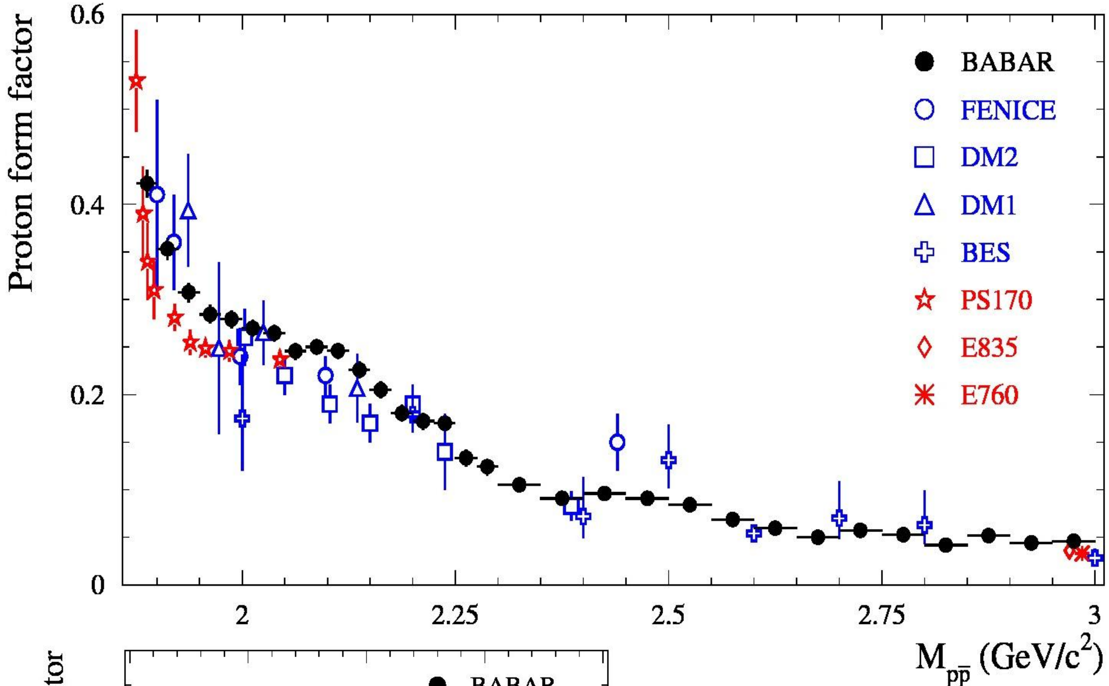
- Agreement with the 2005 results.
- Improvement in accuracy by a factor of about 1.5.
- Step-like mass dependence near 2.2, 2.55, 3.0 GeV.

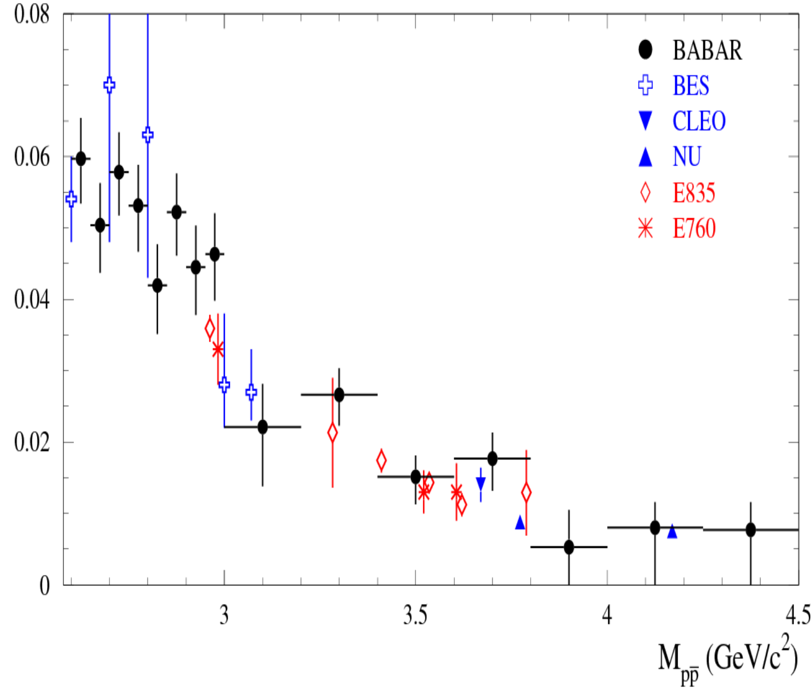
Measured cross section

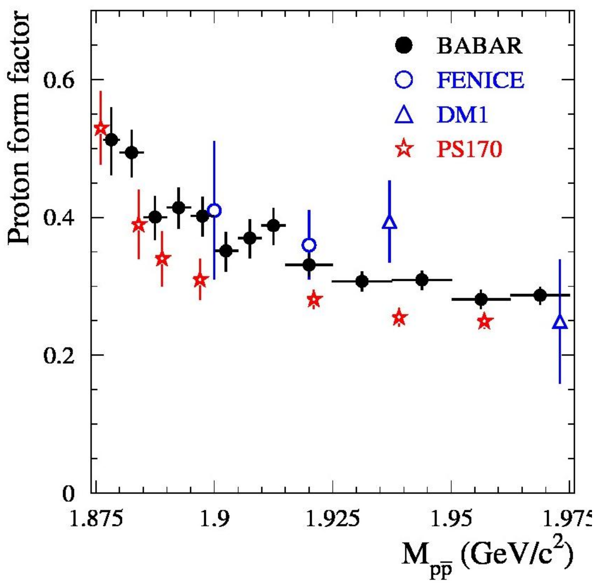


- In the mass region under study the cross section changes by about 4 orders of magnitude.
- Reasonable agreement with previous e^+e^- measurements

Effective proton form factor



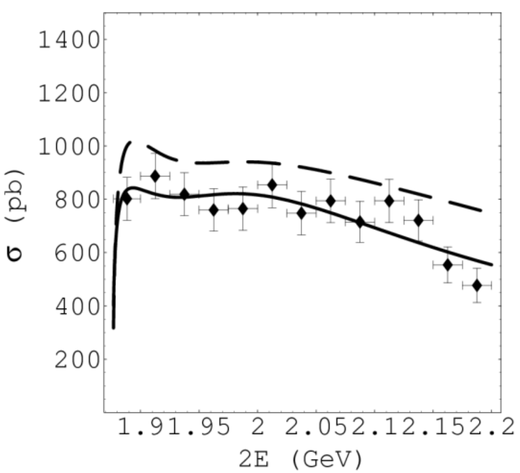


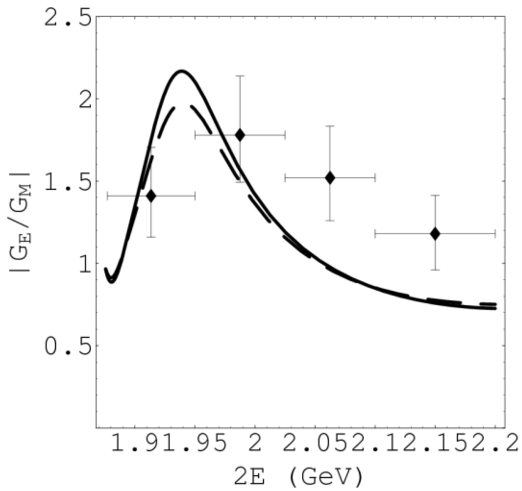


- A steep falloff and GE/GM $\neq$ 1 near threshold are explained by nucleons' final state interaction.
- A complex step-like behavior far of threshold (2 or even 3 steps at 2.2, 2.55, 3 GeV/c^2) is not described by existing models.

Near threshold enhancement

V.F.Dmitriev and A.I.Milstein
arXiv: nucl-th/1302.0053

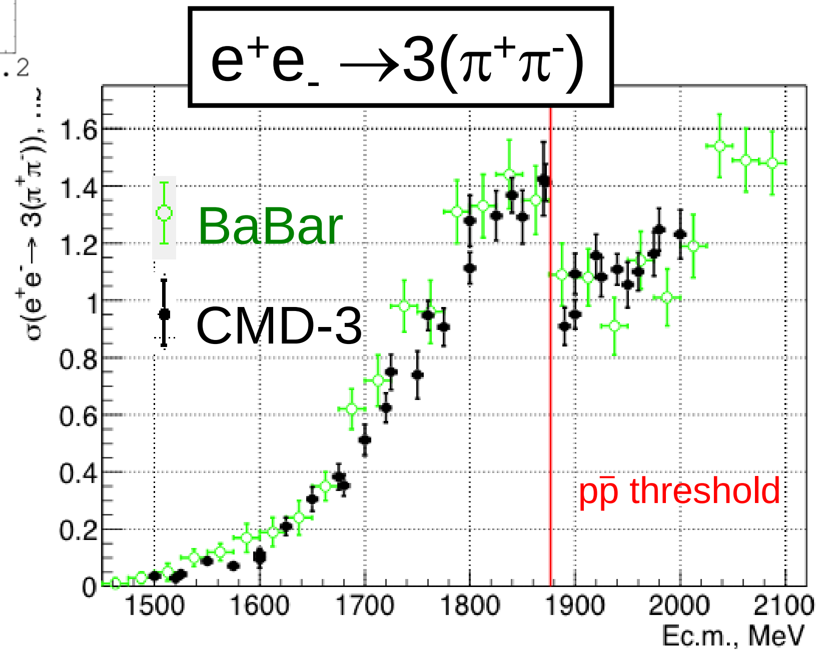




The Paris nucleon-antinucleon potential with an absorptive part is used.

The question: Can such a model describe the dip observed in $e^+e_- \to 6\pi$?

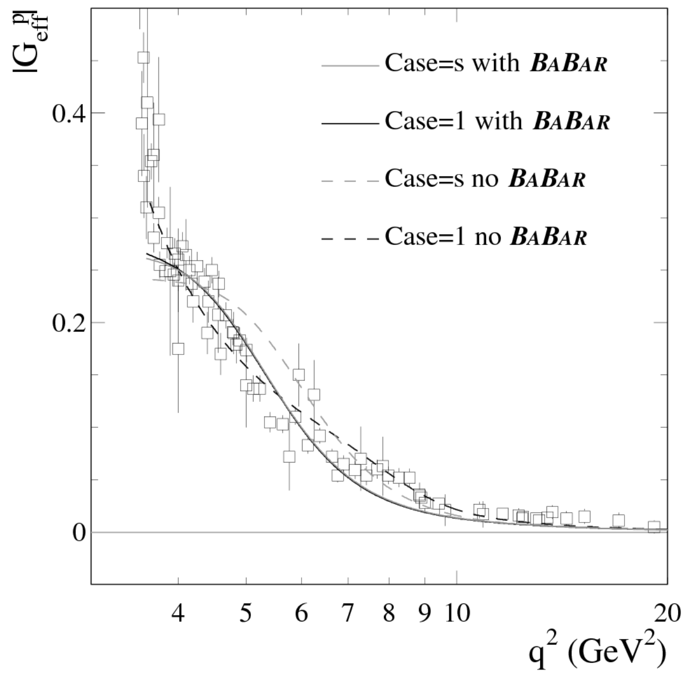
arXiv:1302.0053

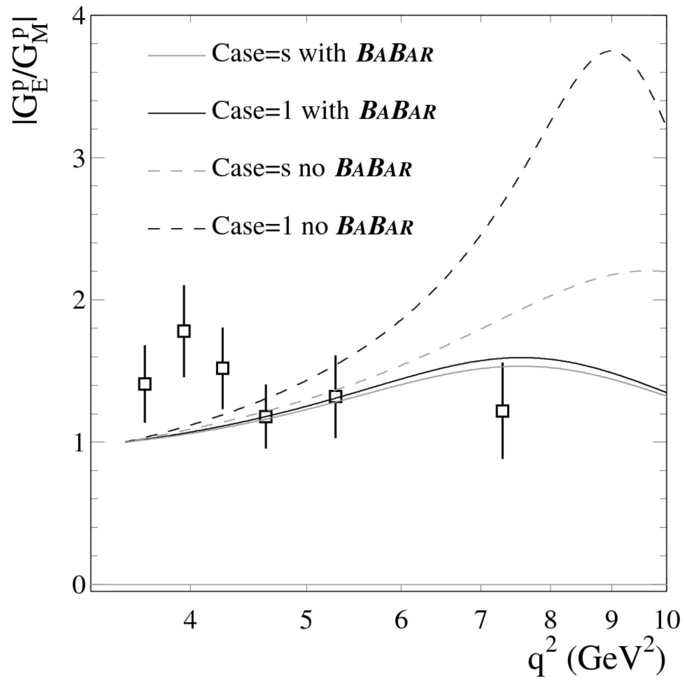


Similar to Coulomb interaction, nuclear interaction of proton and antiproton may modify the cross section and the $|G_E/G_M|$ ratio near threshold.

Example of the form-factor model

Existing form-factor models (based on VMD) describe reasonably well the space-like form factors, but are not capable of reproducing the complex mass dependence of the time-like form factor.



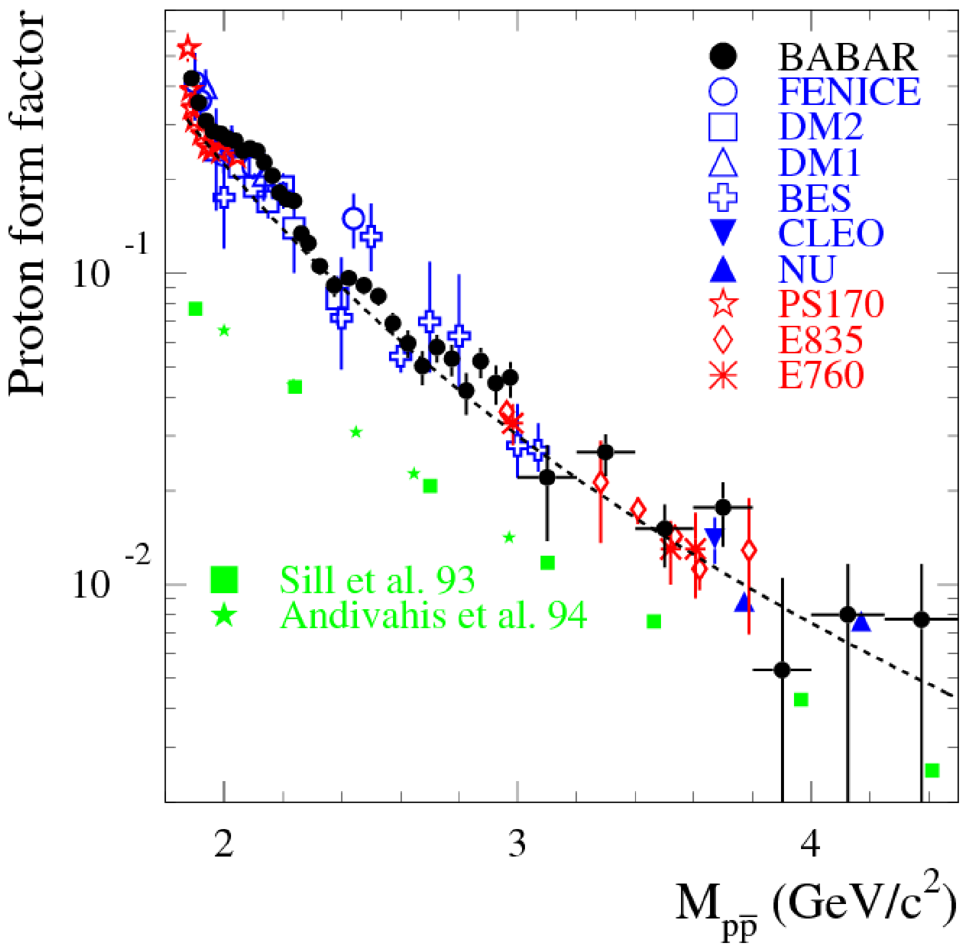


E.L.Lomon and S.Pacetti, Phys. Rev. D 85, 113004 (2012)

There is a hypothesis that the steps in the cross section arise because of opening new channels: $\Lambda\bar{\Lambda}$, $p\bar{\Delta}$ (J.L.Rosner, Phys.Rev. D74, 076006 (2006)),… But there is no even qualitative explanation of a possible mechanism.

Λ's or Δ's eat away the proton cross section?

QCD-motivated fit



QCD prediction for the asymptotic proton form factor:

$$F_{p\bar{p}} \propto \alpha_s^2(m^2)/m^4$$

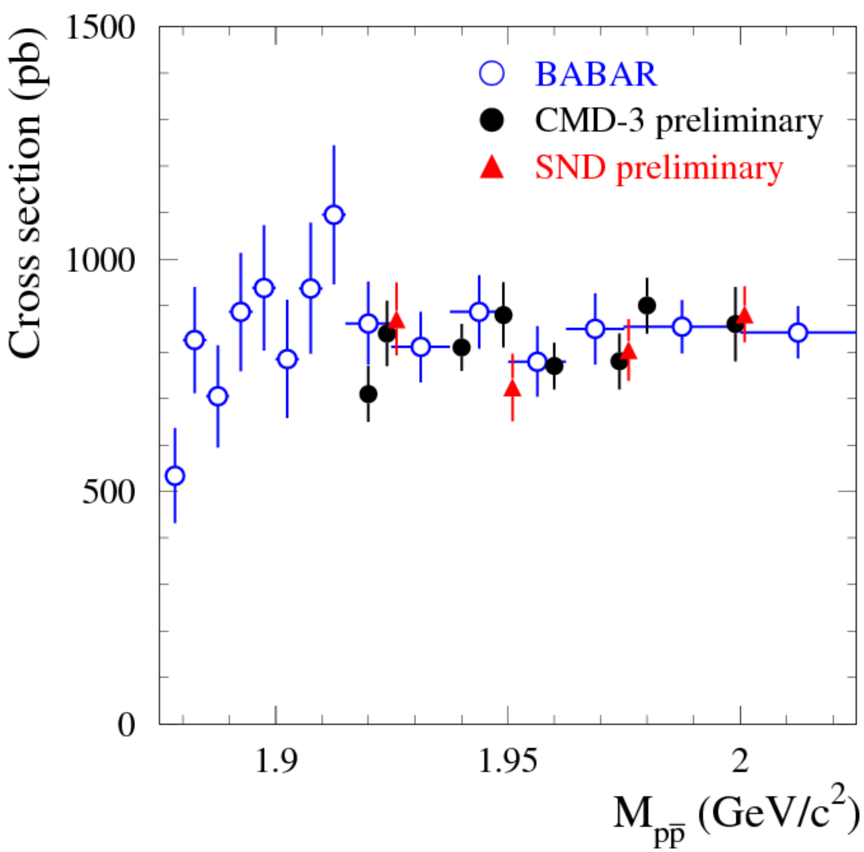
- All the data above 3 GeV except the two “NU” points are described well by this function.
- Adding the “NU” points change the fit χ^2/ν from 9/16 to 41/18.
- The NU result indicates that the form factor near 4 GeV decreases slowly than predicted by QCD.

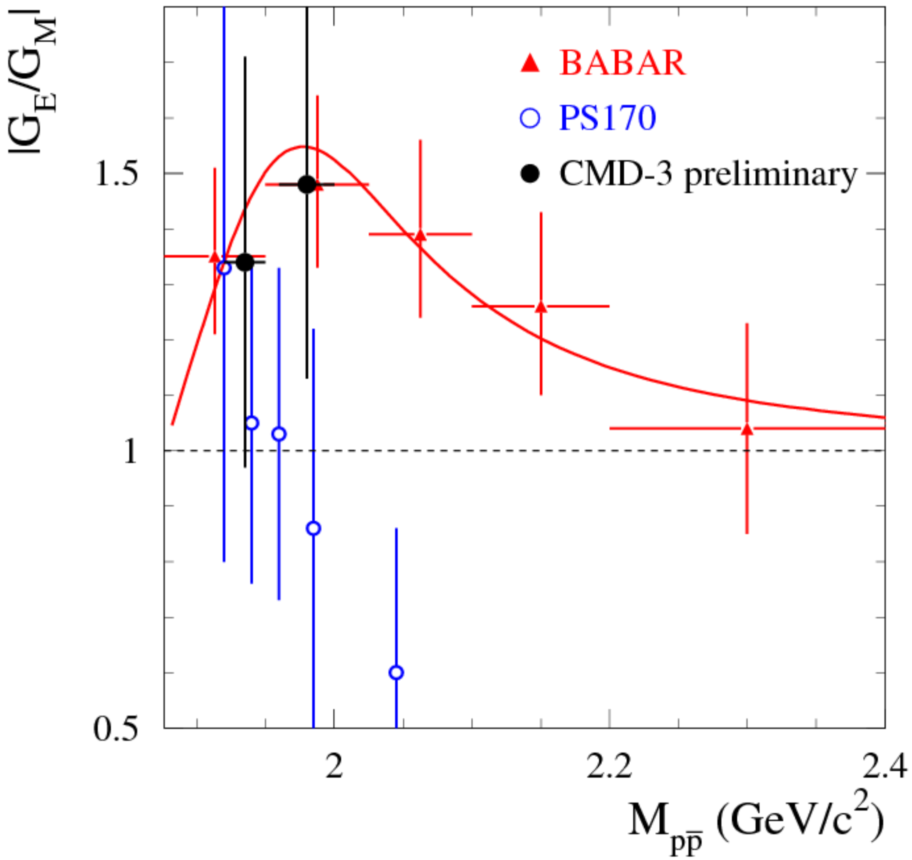
- In the mass region from 3 to 4.5 GeV the time-like form factor is about two times larger the the space-like one.
- The asymptotic values of the space- and time-like form factors are expected to be the same.

Summary on the BABAR measurement

- The $e^+e^- \to p\bar{p}$ cross section and the proton effective form factor have been measured from threshold up to 4.5 GeV using the full BABAR data sample.
- 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 to 3 GeV/c^2. A large deviation of this ratio from unity is observed below 2.2 GeV/c^2.
- Asymmetry in the proton angular distribution have been measured.
- The branching fractions for J/ψ and $\psi(2S)$ decays to $p\bar{p}$ have been measured.
- We plan to measure the cross section in the mass range 3-7 GeV using the same data, but small angle ISR.

VEPP-2000 results





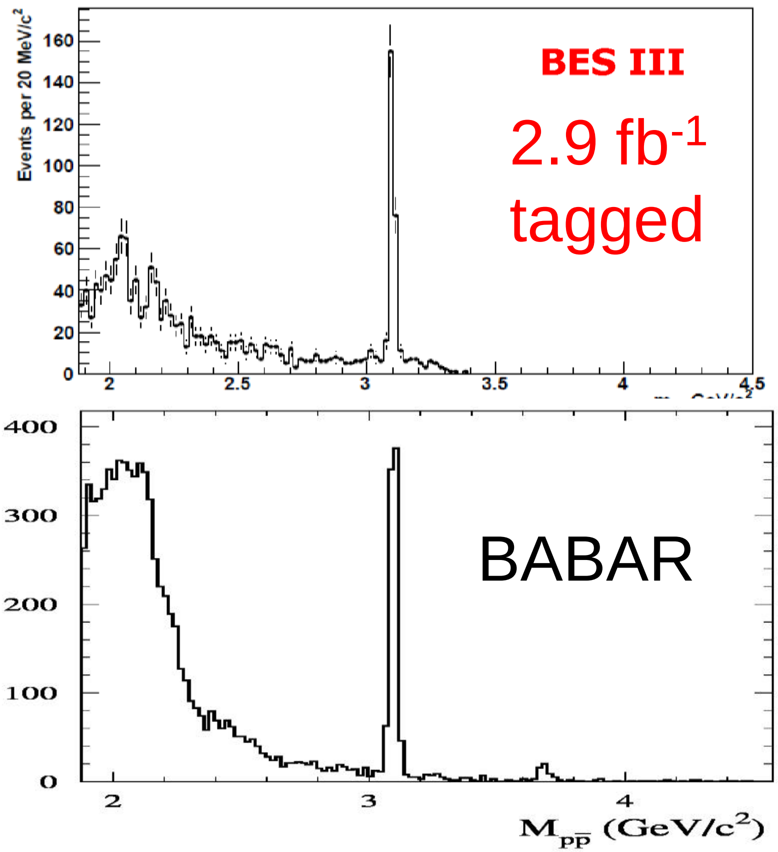
The polar angle range used by CMD-3 is $|\cos\theta| < 0.7$.

A significant (~100) increase of data is expected after VEPP-2000 upgrade, in 2014 - ...

BES-III plans

ISR, tagged and untagged: 10 fb^{-1} at 3.77 GeV

From Cristina Morales talk at "Mainz-Orsay joint meeting on EM physics at PANDA", Orsay, January 2012



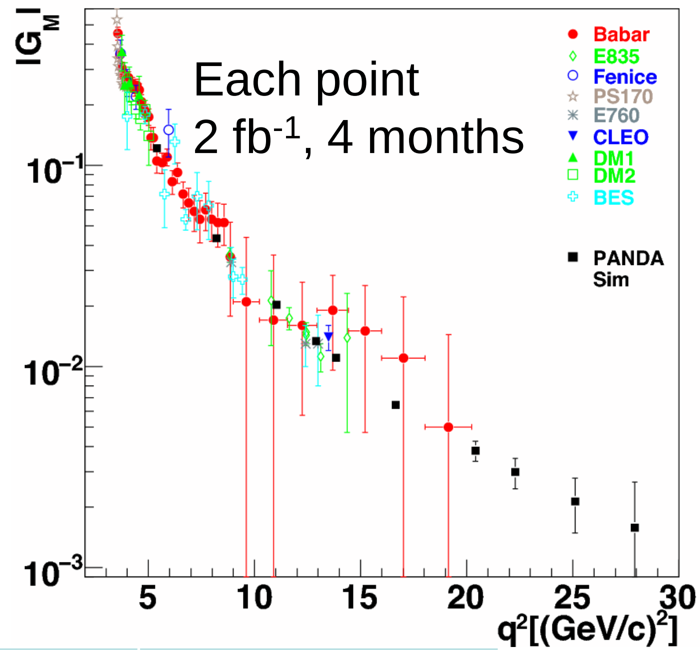
Direct scan (2014?)

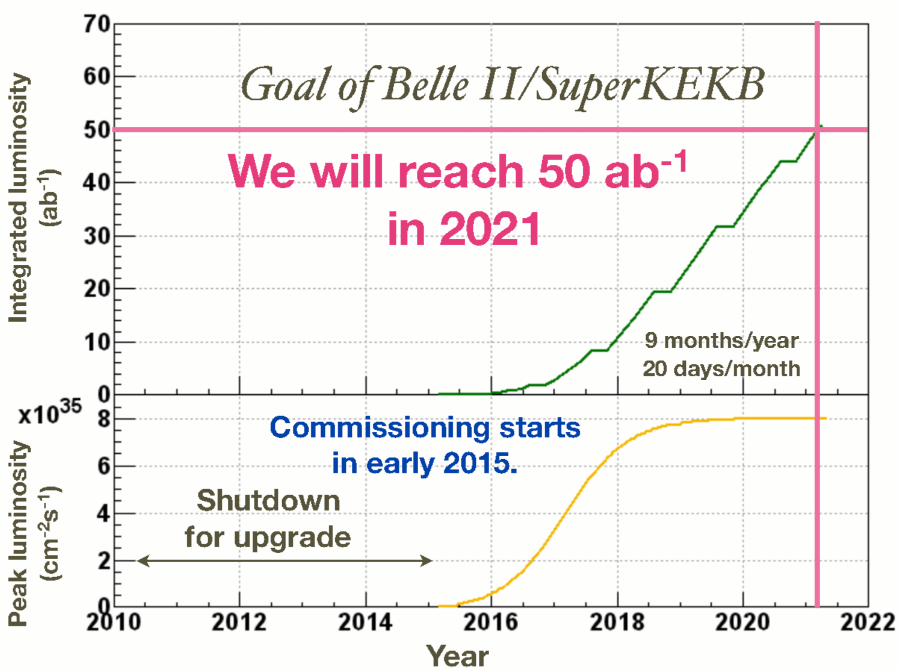
E	L	N_{BES} (50%)	N_{BABAR} / 100 MeV
2.0	7.1	3000	1600
2.1	10.2	4000	1600
2.2	13.5	2800	1000
2.3	20.9	1800	430
2.4	25.1	1400	270
2.5	29.4	1300	240
2.6	37.9	890	130
2.7	48.0	770	90
2.8	60.3	700	70
2.9	69.9	800	70

Due to the restricted polar angle range ($|\cos\theta|<0.8$, a significant improvement in $|G_E/G_M|$ accuracy is not expected.

PANDA and SuperKEKB

- PANDA at the HESR antiproton beam at FAIR (2018):
  - $p\bar{p} \to e^+e^-$ при q^2 от 5 до 25 ГэВ^2
- Belle II at SuperKEKB
  - BABAR×100 data are expected





E	N_{PANDA} (50%)	SuperKEKB N/(bin GeV)
2.32	100000	43000/0.1
2.70	14000	9000/0.1
2.87	6400	7000/0.1
3.31	1000	3600/0.2
3.60	320	1300/0.2