Study of the $e^+e^- \to p\bar{p}$ Process at BaBar

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- **Introduction**
- **Analysis**
- **Results:**
  - **J/ψ, ψ(2S) $\to p\bar{p}$**
  - **Electric vs. Magnetic Form Factors**
  - **Form Factors near threshold**
  - **Form Factors at higher E**
- **Summary**

previous result:	PRD 73, 012005 used half our data
this result:	full data sample 469 fb^{-1} improved analysis submitted to PRD
still to come:	untagged analysis

The $e^+e^- \to p\bar{p}$ Cross Section

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

- β = proton velocity
  m_p = mass
  θ = angle wrt the e^- beam
  } in the c.m. frame

- $s=Q^2=E_{CM}^2=m_{p\bar{p}}^2$ is the squared c.m. energy

- $C(s)= \pi\alpha/\beta(1-e^{-\pi\alpha/\beta})$ is the Coulomb term
  → the cross section is nonzero at threshold

- G_E and G_M are electric and magnetic Form Factors
  → measured for spacelike Q^2 in elastic $e^{\pm}p$ scattering
  → at (timelike) threshold, must have $G_M(4m_p^2)=G_E(4m_p^2)$
  → at high s: G_E becomes invisible
  expect $G_M(s) \sim \alpha_s^2(s)/s^2$

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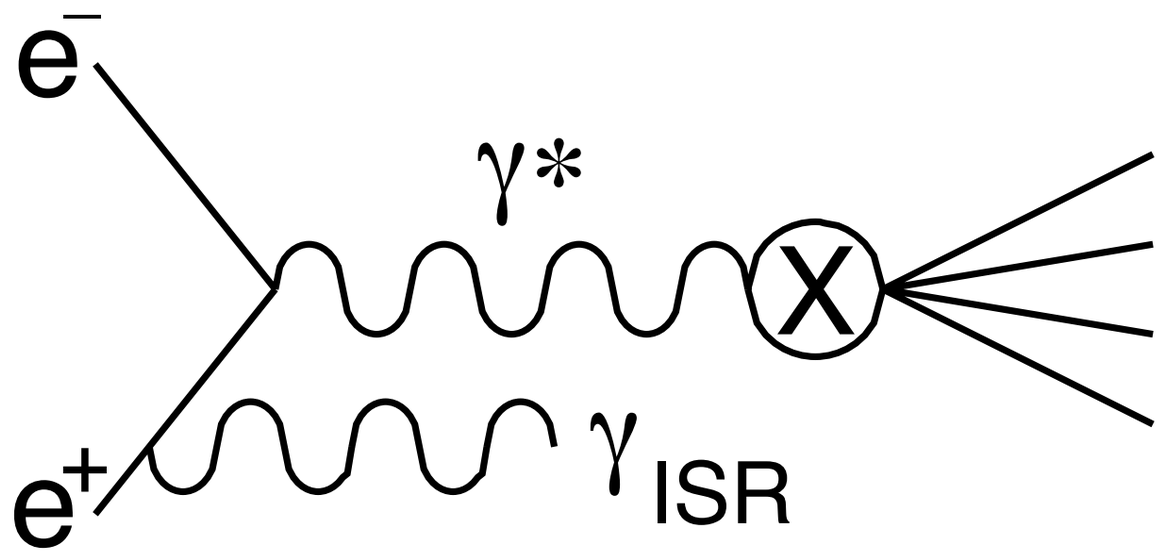
- interesting physics if: structure in $G_M(s)$ or $G_E(s)$
  $G_E \neq G_M$
  any deviation from above expectations

- their behavior near threshold is especially interesting
  → enhancements near threshold have been observed in a variety of baryon-antibaryon mass distributions

- in practice, measure:
  → the ratio $|G_E/G_M|$ ↔ angular distribution
  → the effective FF ↔ total cross section

$$F_p^2 = (|G_M(s)|^2 + r|G_E(s)|^2) / (1+r),\quad r=2m_p^2/s$$

Initial State Radiation in e^+e^- Annihilations

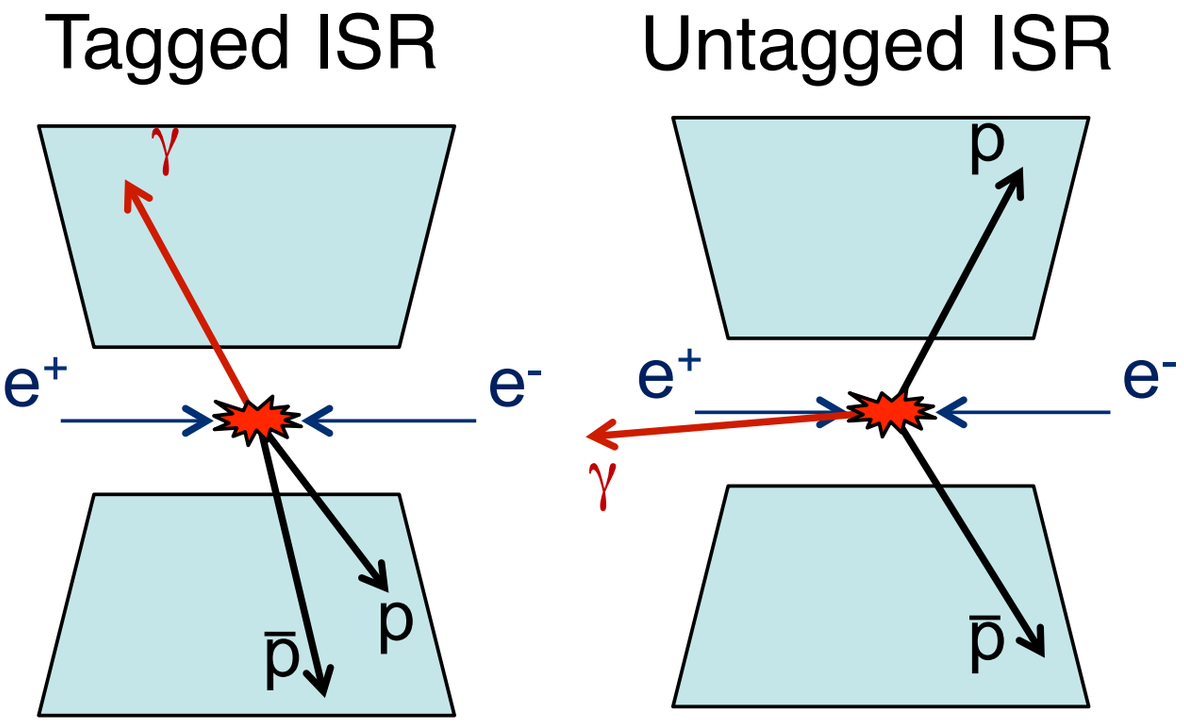


- $e^+e^- \rightarrow \gamma_{ISR} e^+e^- \rightarrow \gamma_{ISR}\gamma^* \rightarrow \gamma_{ISR} X$

- X is any system allowed at the reduced c.m. energy s'
  → here, $X=p\bar{p}$
  → ...or $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-, $p\bar{p}\pi^0$, ...
- the cross section: $d\sigma(s,s',\theta_\gamma)/ds'd\cos\theta_\gamma = W(s,s',\theta_\gamma)\sigma(s')$
- the radiator function W is known to ~1%
- measure $\sigma(e^+e^- \rightarrow X)$ vs. $m = m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$

- ISR gives access to a continuous, wide s′ range in a single experiment
  → very small point-to-point systematic errors

- if the γ_{ISR} is detected (tagged) then the $p\bar{p}$ is also well contained in the detector
  → minimal acceptance issues
  → measure the full angular distribution



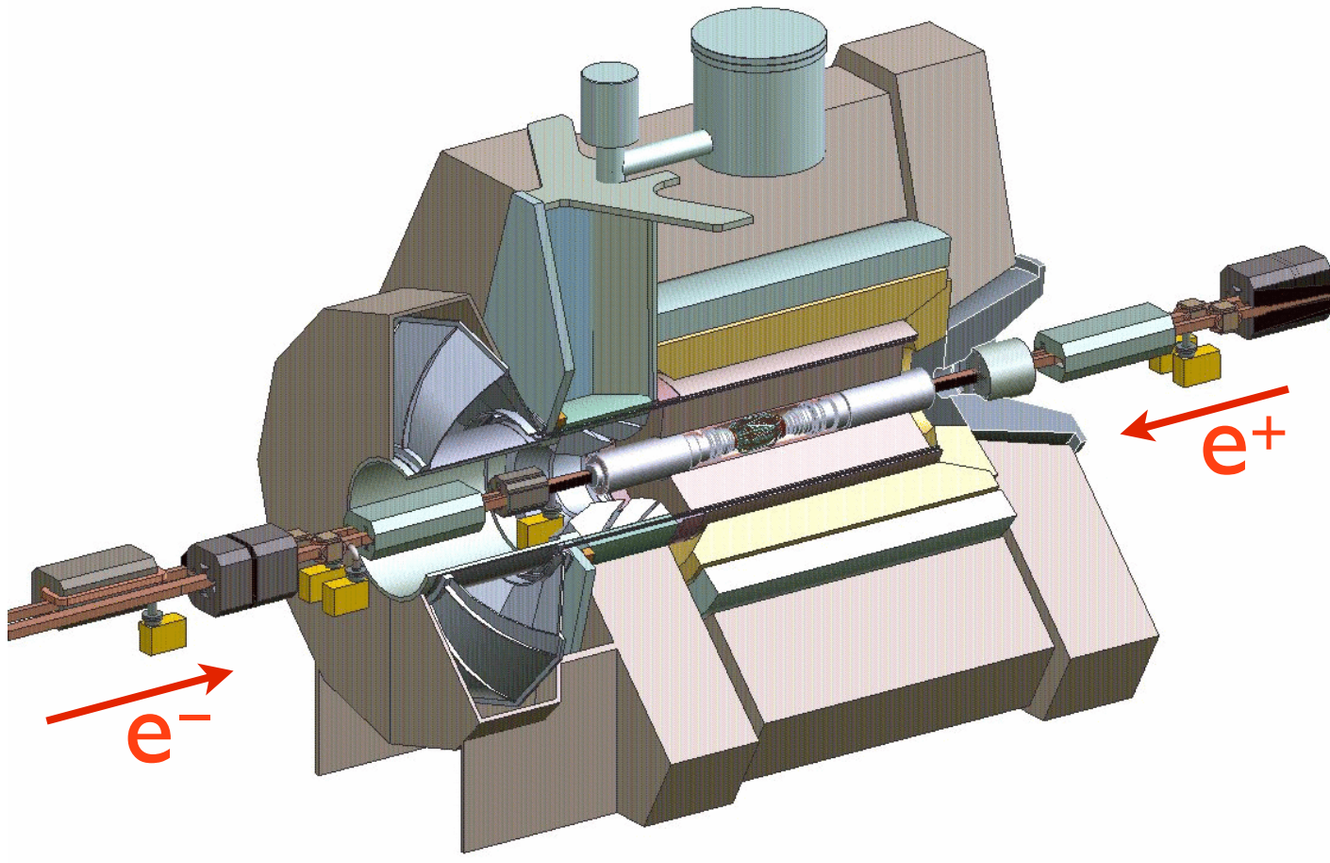
- the $p\bar{p}$ system is boosted
  → good efficiency, resolution all the way down to threshold

- untagged ISR is useful at higher s′
  → we have a measurement in review, expected soon

The BaBar Experiment

- e^+e^- collisions at E_{CM}=10.6 GeV,
  designed for CP violation in B decays

- Different beam energies
  - → E_{e^-} = 9.0 GeV
  - → E_{e^+} = 3.1 GeV
  - → c.m.-lab boost, $\beta\gamma$=0.55



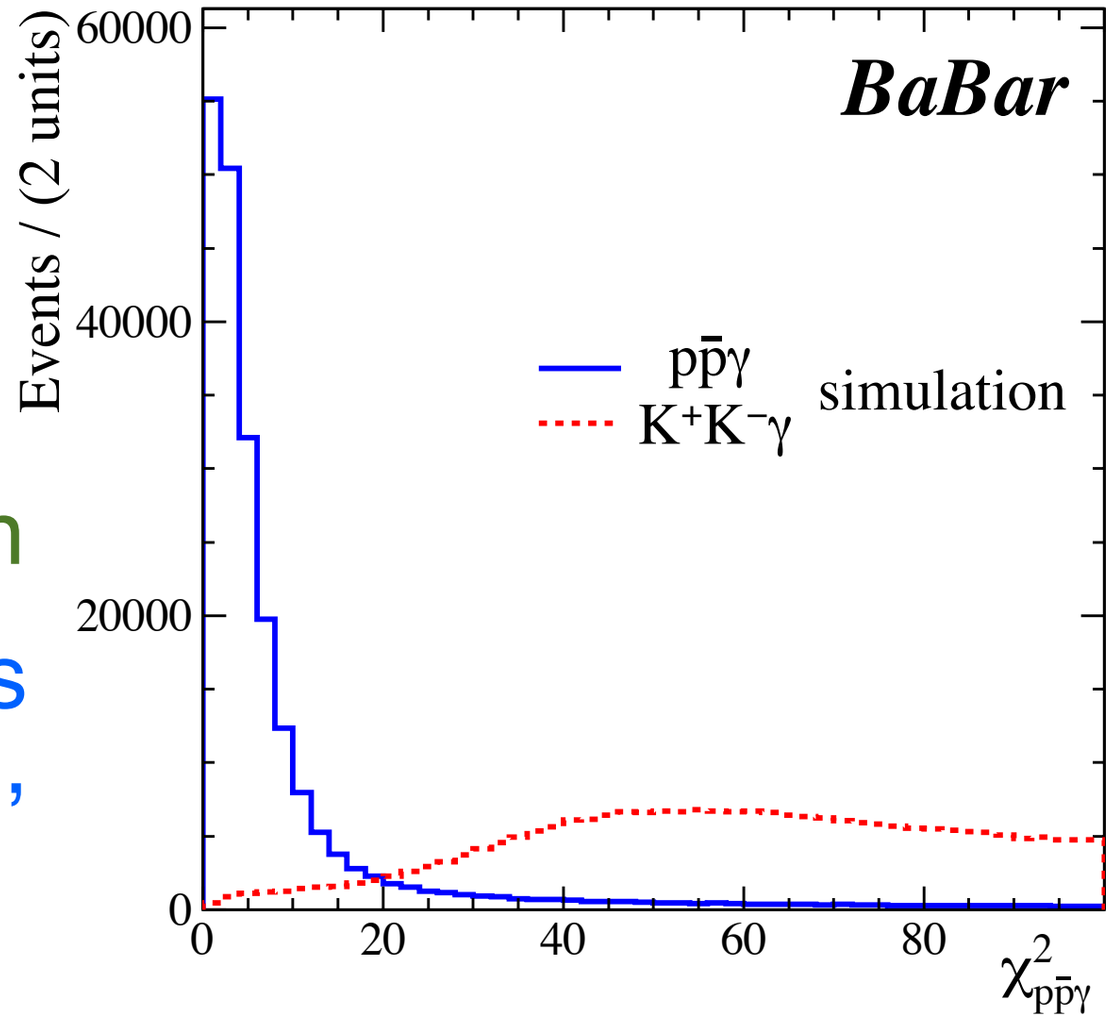
- Asymmetric detector
  - → c.m. frame acceptance
    $-0.9 \sim \cos\theta^* \sim 0.85$
    wrt e^- beam

- with excellent performance
  - → good tracking, mass resolution
  - → good γ, π^0 recon.
  - → full e,μ,π,K,p ID

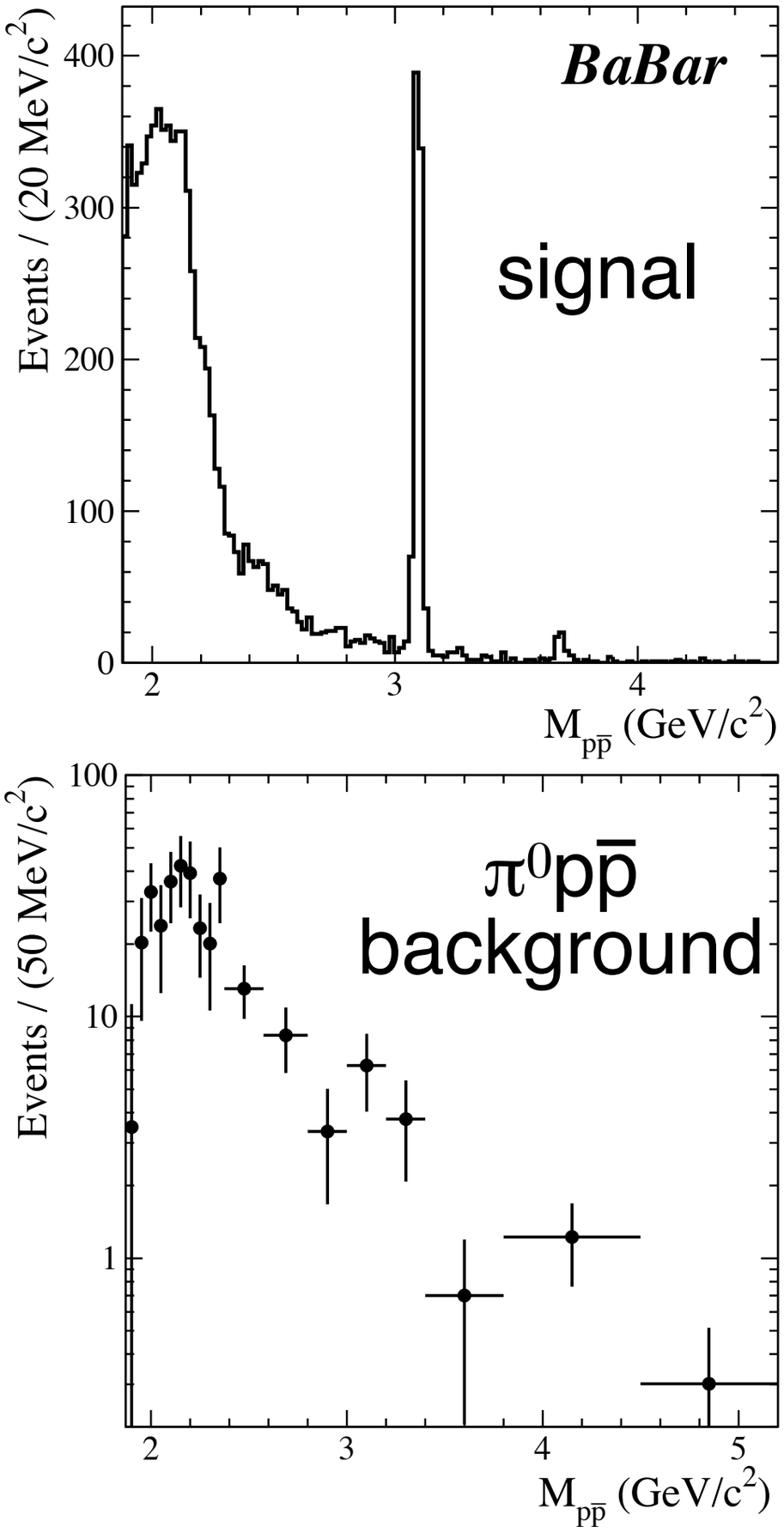
- High luminosity
  - → ~520 fb^{-1} accumulated
  - ↔1.7 billion $e^+e^- \to q\bar{q}$ evts
  - ↔12 million $e^+e^- \to \gamma_{ISR}\rho^0$
  - ↔40 thousand $e^+e^- \to \gamma_{ISR}p\bar{p}$

Event Selection

- 1 hard photon well within the calorimeter, $20°<\theta<137.5°$
  2 tracks from IP, well within the DIRC $25.8°<\theta<137.5°$
  → very efficient within that range
- suppress $\gamma_{ISR}\mu^+\mu^-$, $\gamma_{ISR}\pi^+\pi^-$, $\gamma_{ISR}K^+K^-$: ID tracks as p, $\bar{p}$
  → 70% efficient
  → $>10^4$ suppression
- kinematic fits, $\gamma_{ISR}h^+h^-$ hypes, require $\chi^2_{pp\gamma}<30$, $\chi^2_{KK\gamma}>30$
  → 75% efficient
  → further 30-50x suppression
- cross calibrate using samples w/ e.g. 1 ID'd p/p, $\chi^2_{\pi\pi\gamma}<30$, ..., plus known cross sections
  → background <0.2%
  → small contribution to systematic uncertainty

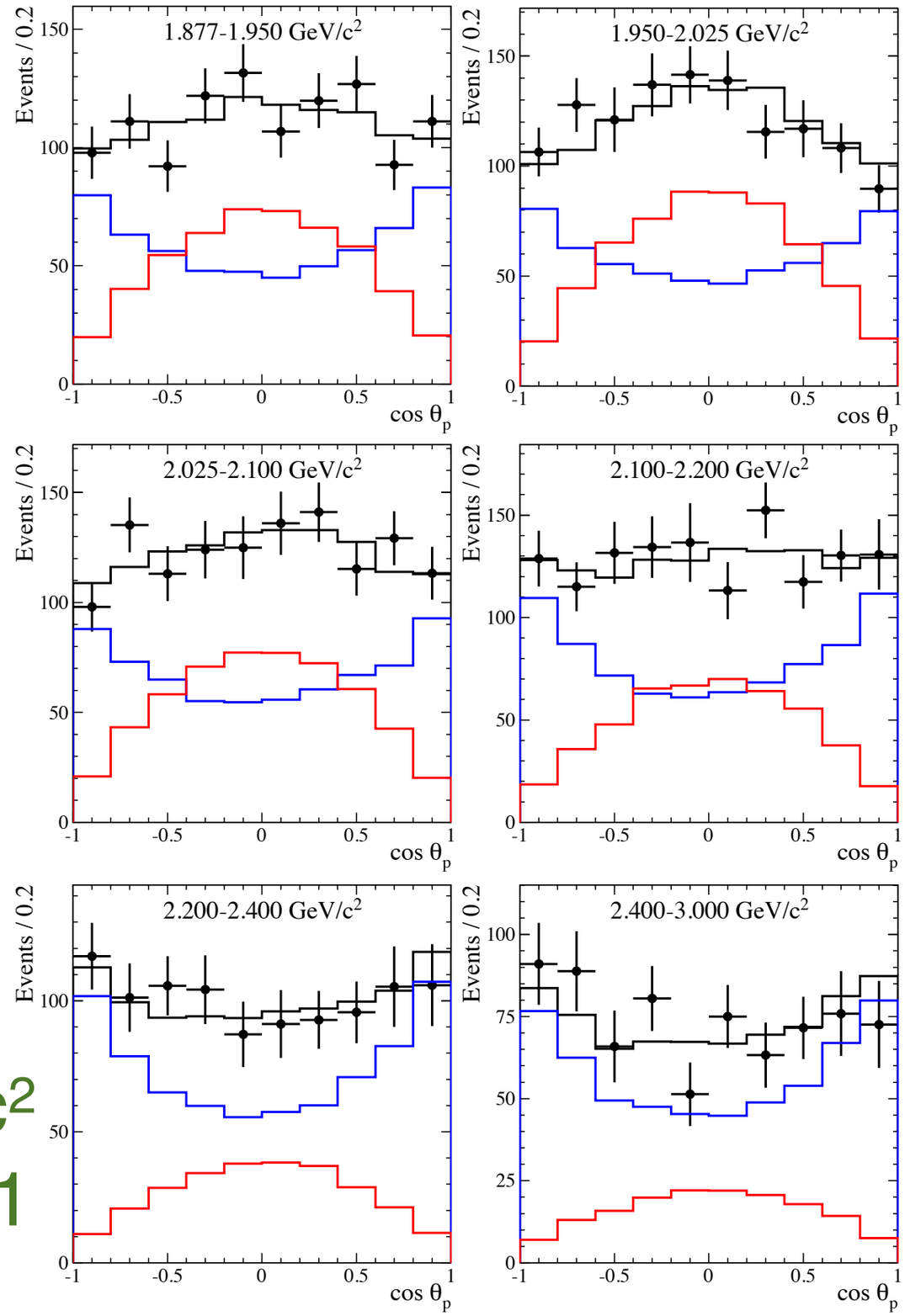


- 8298 selected events
  - → predominantly near threshold, interesting structure?
  - → signals for J/ψ and ψ(2S)
- largest bkg. is $e^+e^- \to q\bar{q} \to \pi^0 p\bar{p}$ where one or merged photons from the hard π^0 mimic a γ_{ISR}
  - → evaluate from π^0 peak in data when γ_{ISR} combined w/ other γ
  - → 5±0.5% at threshold → 50±20% at 4 GeV
  - → limits measurement at high E
- other backgrounds from
  - → $e^+e^- \to q\bar{q} \to p\bar{p}\pi^0\pi^0$, $p\bar{p}\eta$, ...
    $e^+e^- \to \gamma_{ISR}\pi^0 p\bar{p}$, $\gamma_{ISR} p\bar{p}\eta$, ...
  - → evaluate from χ^2 control region
  - → total about 10% of $\pi^0 p\bar{p}$

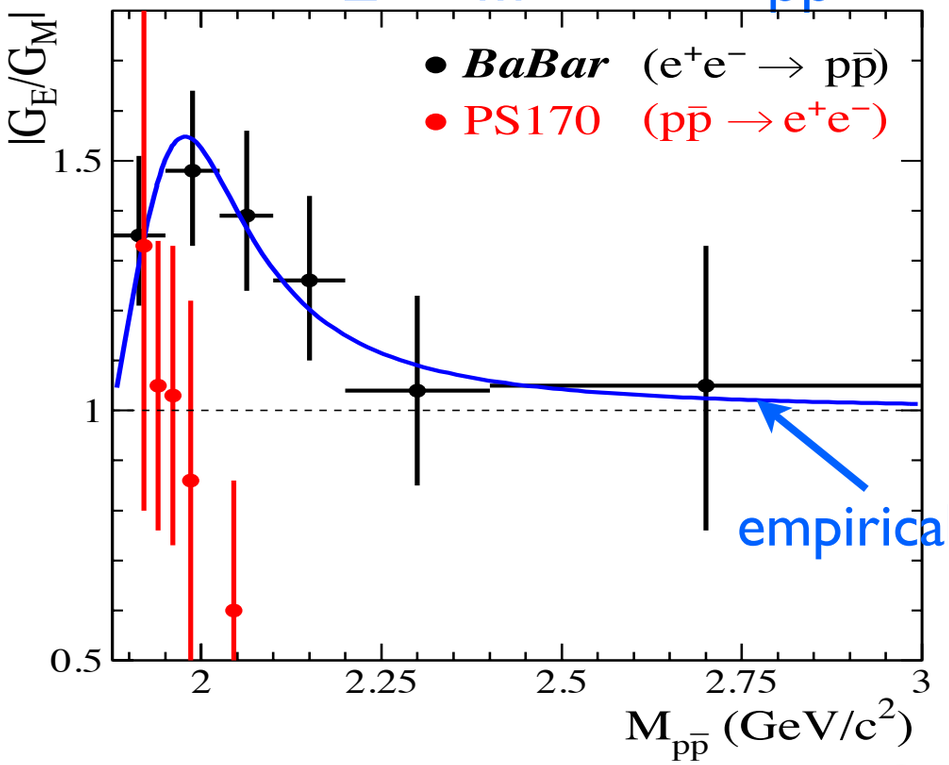


Angular Distributions

- studied at detector level
  → in $m_{p\bar{p}}$ bins, fit with sum of simulated G_E and G_M contributions



- the ratio G_E/G_M vs. $m_{p\bar{p}}$

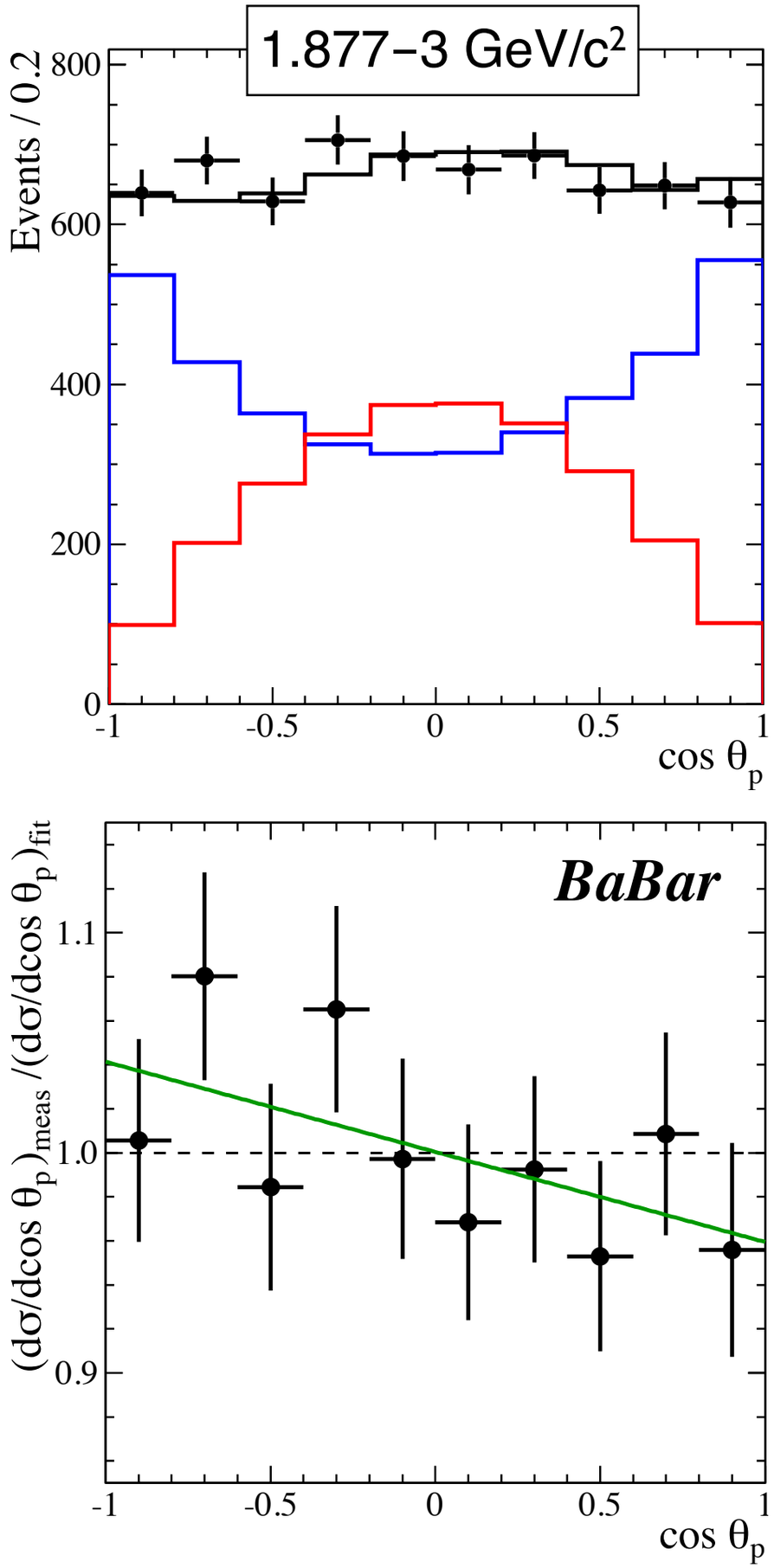


→ >1 for $1.95<m_{p\bar{p}}<2.2$ GeV/c²

→ fit a simple function that →1 at threshold, high $m_{p\bar{p}}$

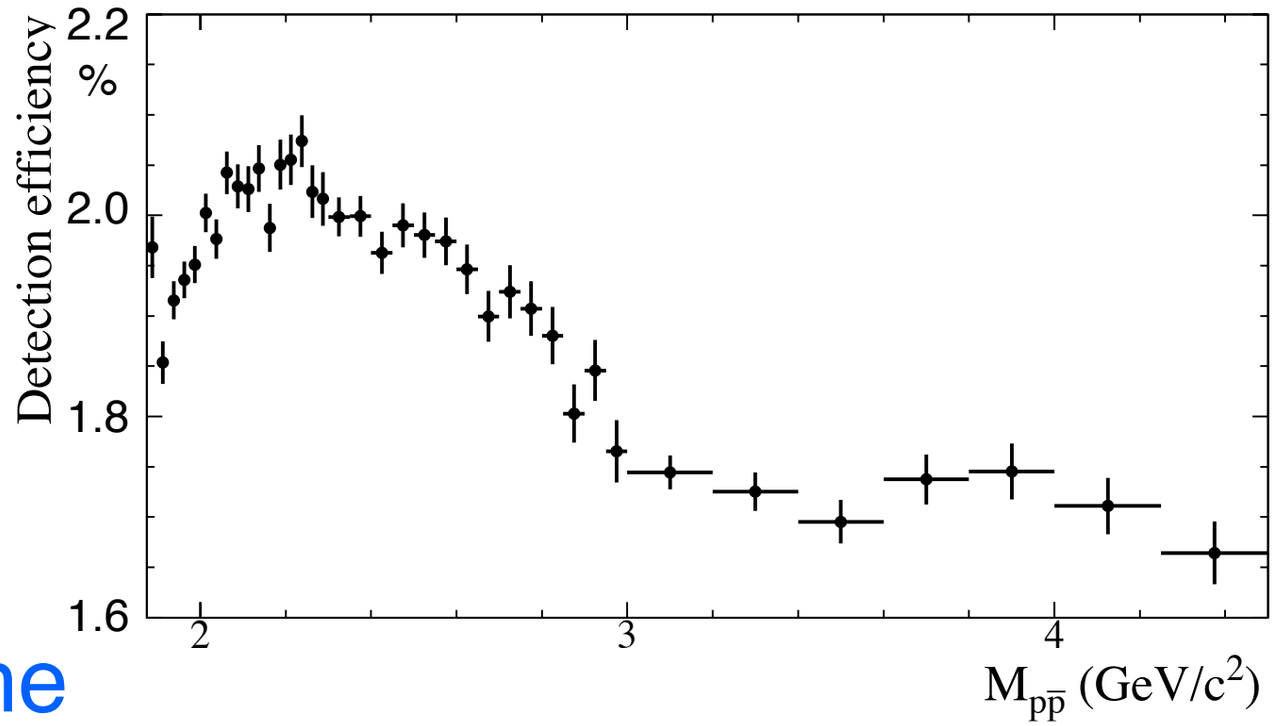
→ inconsistent with results from PS170 at LEAR

- expect a few-% asymmetry in $\cos\theta_p$
  - → from interference with higher-order processes
  - → FSR expected to be small
- compare data with simulation
  - → which contains no such effects...
  - → but is slightly asymmetric due to detection efficiency
- fit a line to the binwise ratio
  - → slope: $-0.41\pm0.26\pm0.05$
  - → integral asymmetry: $-0.025\pm0.014\pm0.003$
  - → limits any systematic effect on this measurement



Detection Efficiency

- the simulated efficiency
  - → is 1.7-2%, with a
  - → slow, smooth dependence on $m_{p\bar{p}}$
  - → insensitive to G_E/G_M



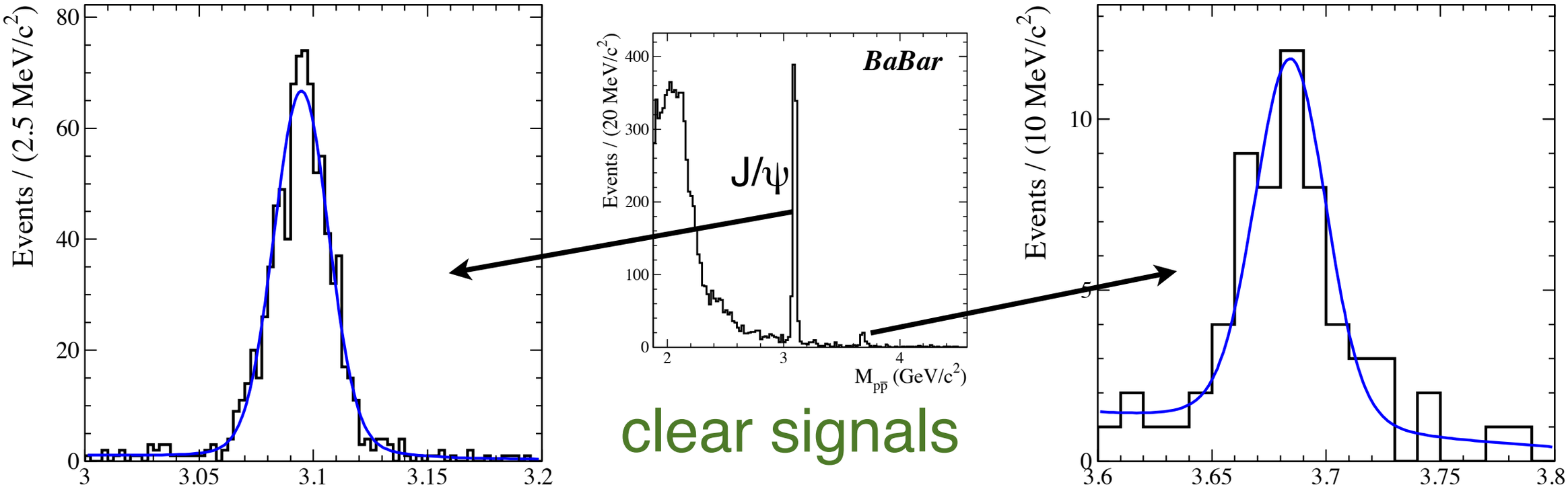
- many effects studied in the data, results used to correct MC, estimate error

→ shape of $\chi^2_{p\bar{p}\gamma}$	−0.9 ↔ −0.5 ± 0.4%
→ track reconstruction	0.0 ± 0.5%
→ track overlap	0.5 ± 0.0 - 1.5%
→ interactions in detector	+0.8 ↔ +1.1 ± 0.4%
→ proton identification	−1.9 ± 2.0%
→ photon inefficiency	−1.9 ↔ −1.7 ± 0.1%
→ trigger and filters	−0.1 ↔ −0.7 ± 0.1 - 0.5%

- overall uncertainty on efficiency: 2.6% near threshold
  → 2.2% for $m_{p\bar{p}} \gtrsim 3$ GeV/c^2

J/ψ and ψ(2S) Decays

- fit peaks in data near 3.1 and 3.7 GeV/c^2



clear signals

821±30 J/ψ events 44±8 ψ(2S)

11.3±0.4±0.3 $\Gamma_{ee}BF(\to p\bar{p})$ 0.67±0.12 ±0.13

- get branching fraction by dividing by PDG Γ_{ee}

2.04 ±0.07 ±0.07 x10^{-3} 2.86±0.51±0.09 x10^{-4}

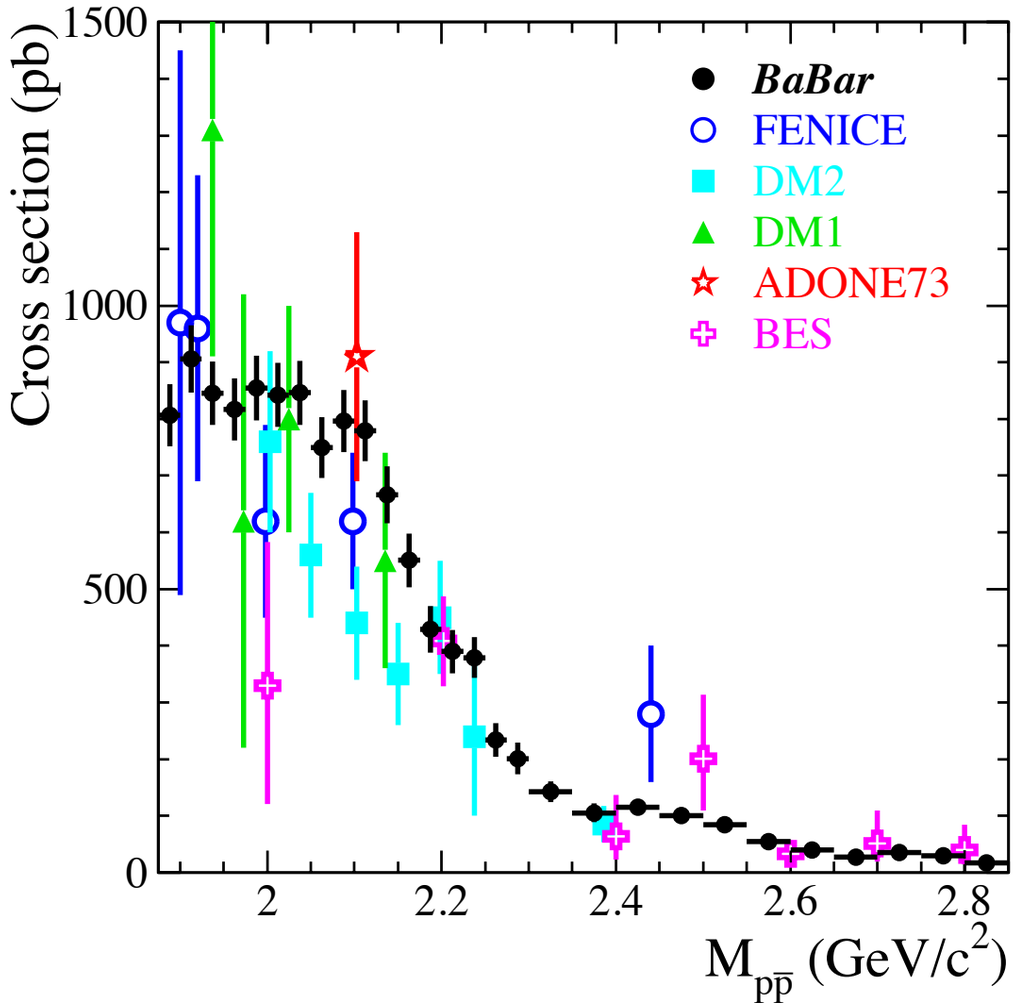
2.17 ±0.07 PDG 2.76±0.12

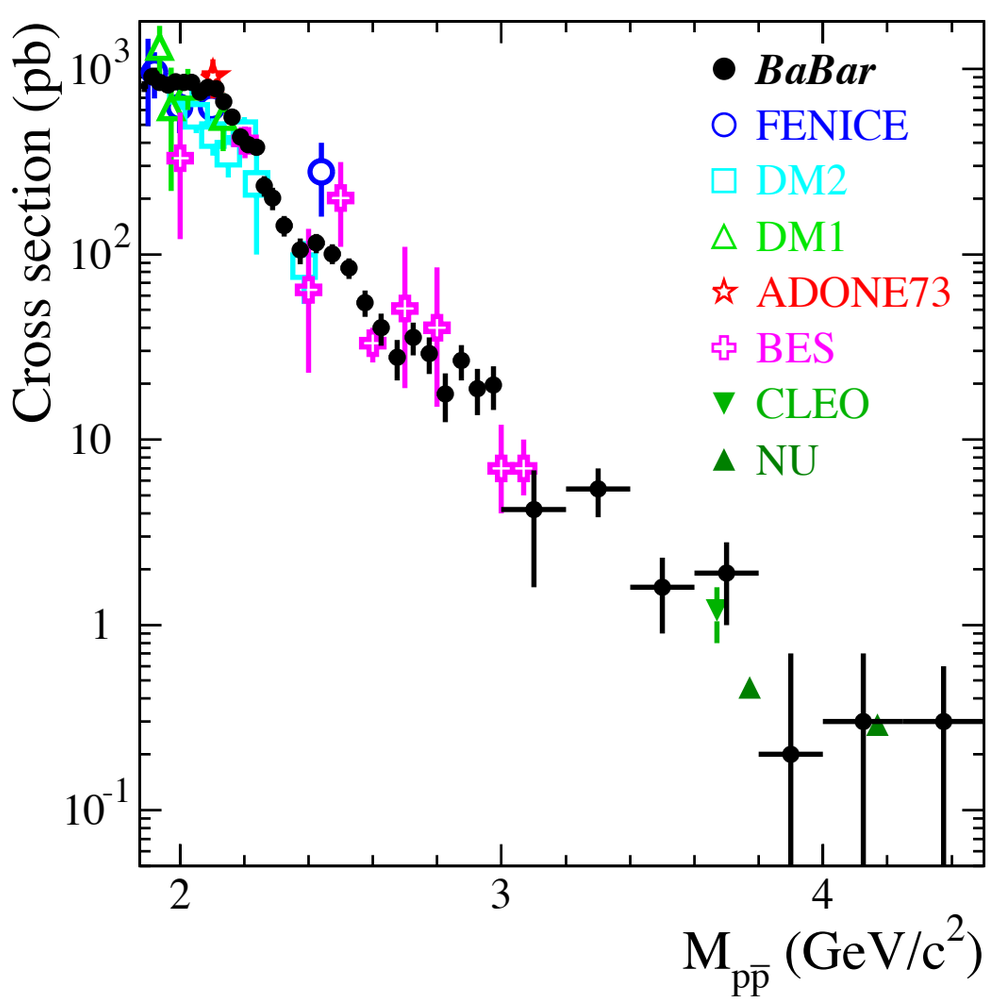
2.112±0.004±0.031 BESIII

- remove charmonium contribution from here on

The $e^+e^- \to p\bar{p}$ Cross Section

- correct data bin by bin for efficiency





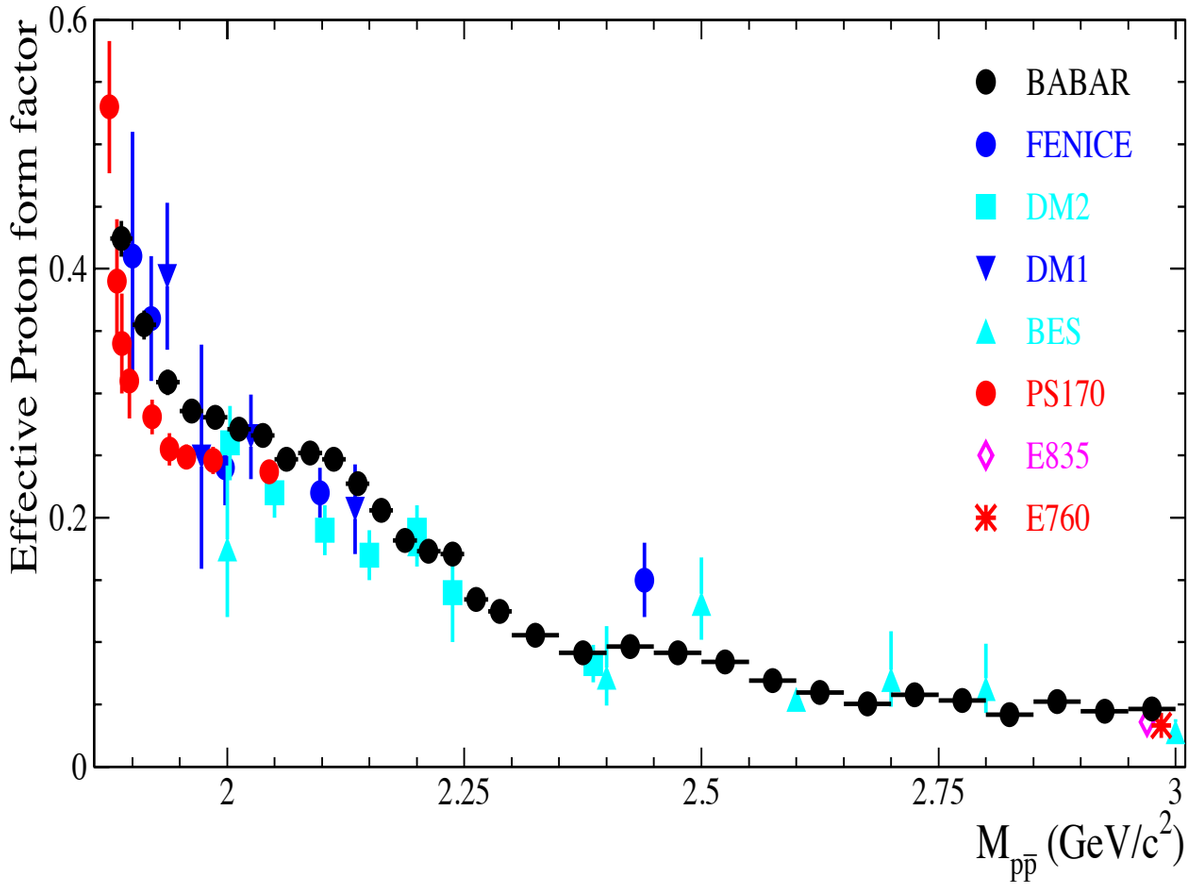
→ consistent with previous results

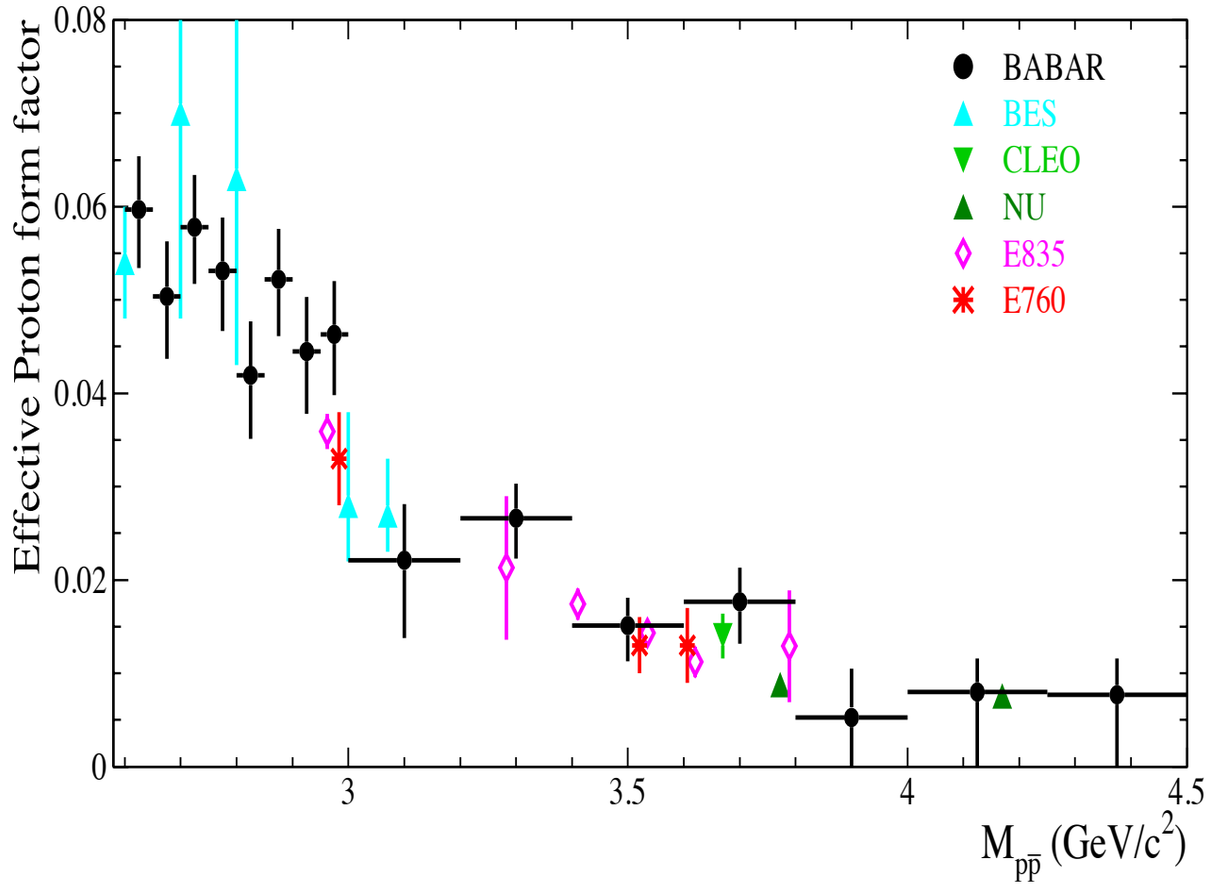
→ better precision at most $m_{p\bar{p}}$, wide & deep coverage

- substantial interesting structure here
  - → flat from threshold to 2.1 GeV/c^2
  - → features at 2.2, 2.5, 3 GeV/c^2

The Effective Proton Form Factor

- convert cross section to (effective) form factor





→ consistent with previous results at high $m_{p\bar{p}}$

→ near threshold, differ by ~3σ from PS170

- similar structure here

→ steep rise toward threshold

→ features at 2.2, 2.5, 3 GeV/c^2

QCD-Motivated Fit

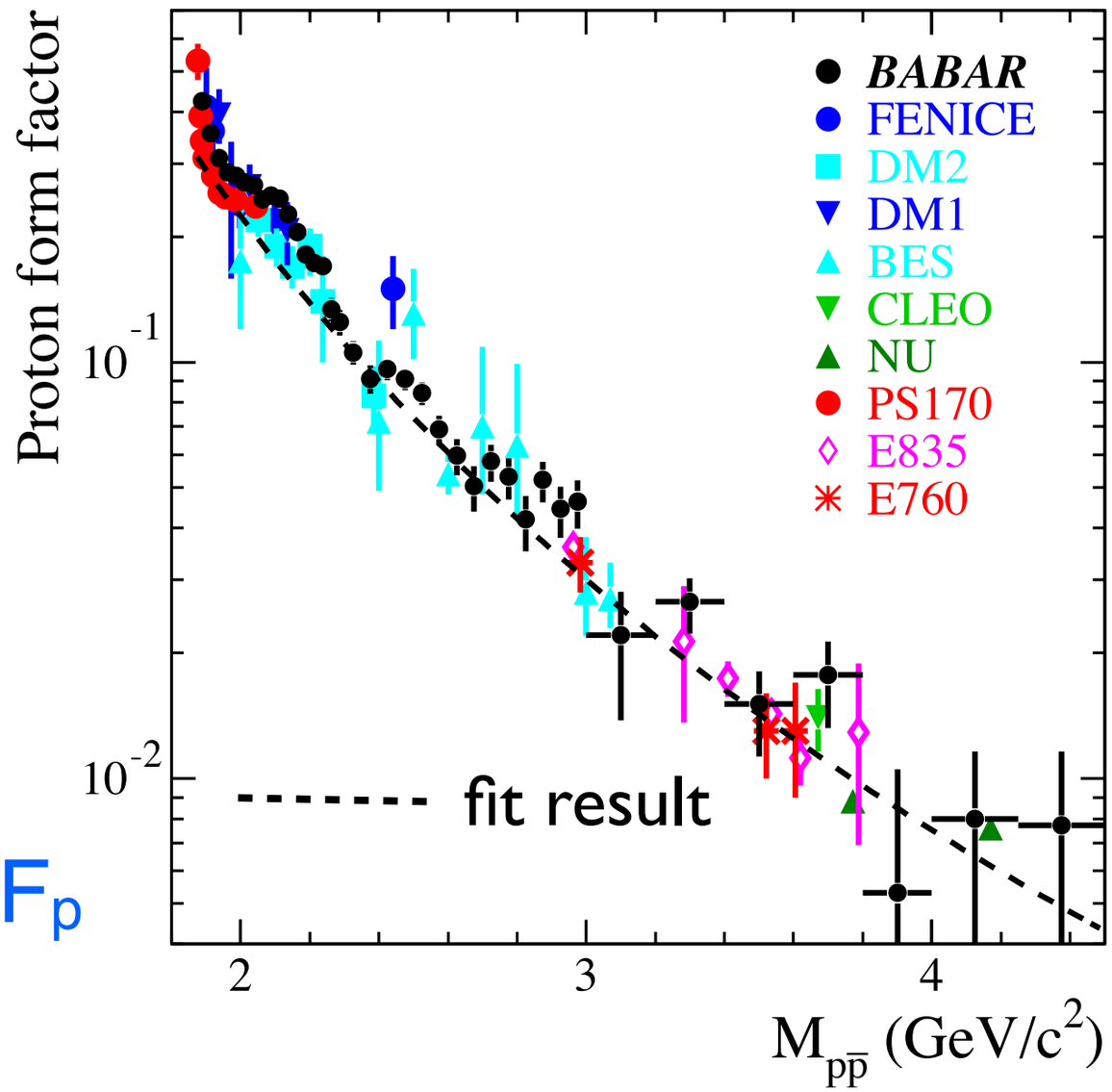
- fit data above 3 GeV/c^2 with the asymptotic form

  $F_p = A\alpha_s(m^2_{p\bar{p}})^2 / m^{2n}_{p\bar{p}}$

  → A, n free in fit

  → good fit quality

  → fitted n value is consistent with the expected value of 2



- at high $m_{p\bar{p}}$, the timelike F_p are about 2x the spacelike F_p

  → do we expect them to be ~equal in this range?

  → ...or converge at higher $m_{p\bar{p}}$?

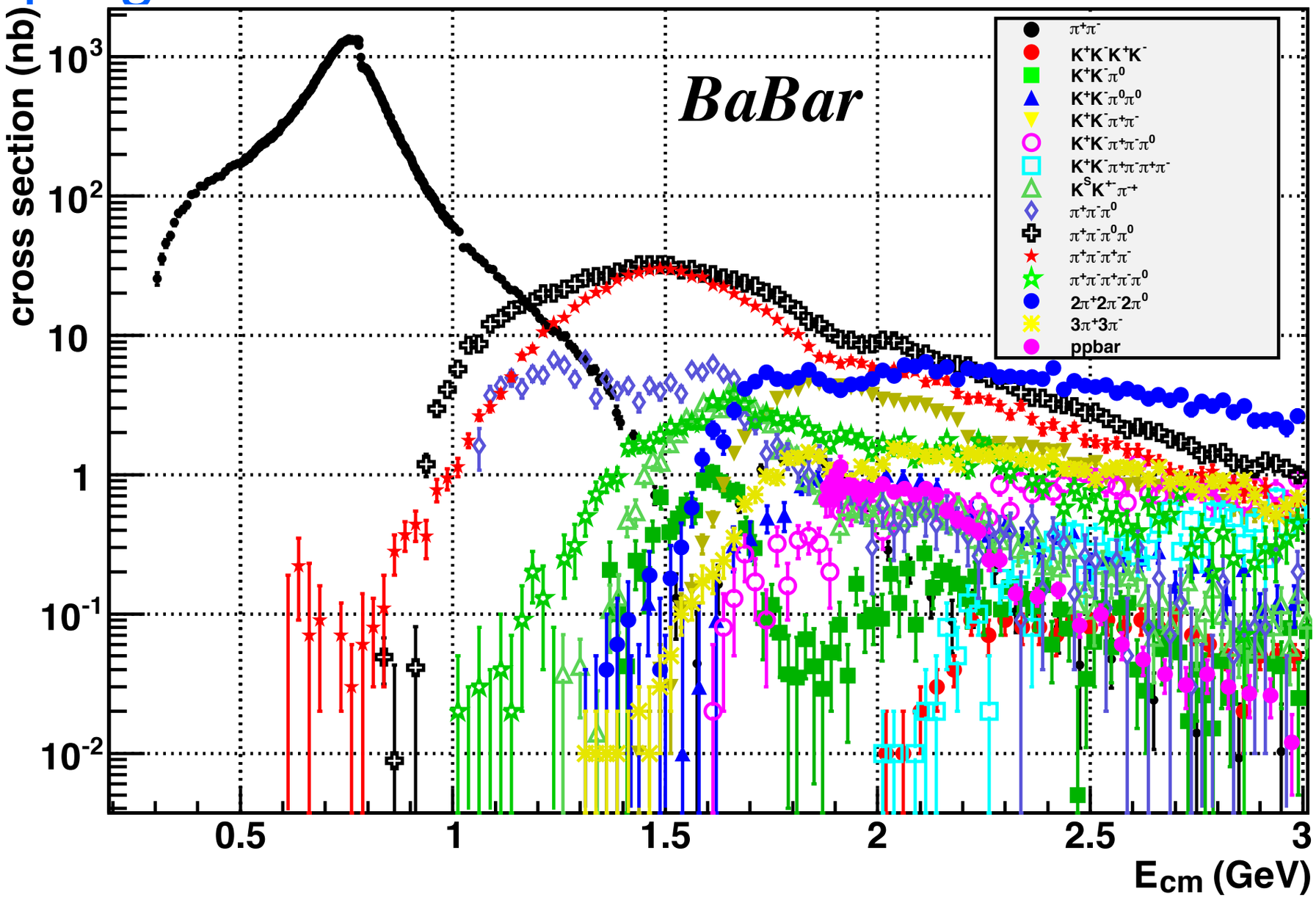
- our untagged measurement will help in the 3-7 GeV/c^2 region

Summary

- We have measured the $e^+e^- \to p\bar{p}$ cross section and the effective proton form factor from threshold to 4.5 GeV
  - → enhancement at threshold remains to be explained
  - → additional structure at several higher masses
  - → asymptotic shape consistent with QCD prediction...
  - → ...but ~2x higher than spacelike measurements
- We have measured the ratio of electric:magnetic form factors from threshold to 3 GeV
  - → ratio is above unity below 2.2 GeV
- We have measured J/ψ, $\psi(2S) \to p\bar{p}$ branching fractions
  - → competitive results, consistent with others
- Still to come
  - → measurement using untagged ISR, 3-7 GeV
  - → measurements for other baryons
    ($\Lambda^0\Lambda^0$, $\Lambda^0\Sigma^0$, $\Sigma^0\Sigma^0$ done with half the data, PRD 76, 092006 (2007))

Backup Slides

- BaBar has a program to measure all individual modes
  - → status in late 2011 (refs. next slide)



→ sub-% precision on $\pi^+\pi^-$; 1-2% per hadron on others

→ need $\underline{K^+K^-}$, K_SK_L, $K_SK_L\pi\pi$, $K_SK^+\pi^-\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$

→ could use improved $\underline{K^+K^-\pi\pi}$, $\pi^+\pi^-\pi^0$, $\underline{4\pi}$, 5π, ...

→ 1-2 GeV region is critical for $g_\mu-2$, $\alpha(M_Z)$ calculations

BaBar cross sections with ISR

$e^+e^- \rightarrow$:

$\pi^+\pi^-$	threshold-3.0 GeV	PRL 103, 231801 (2009) PRD 86, 032013 (2012)
$\pi^+\pi^-\pi^0$	1.05-3.0 GeV	PRD 70, 072004 (2004)
$\pi^+\pi^-\pi^0\pi^0$	threshold-4.5 GeV	Preliminary
$\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 85, 112009 (2012)
$\pi^+\pi^-\pi^+\pi^-\pi^0/\eta$, $K^+K^-\pi^+\pi^-\pi^0/\eta$	threshold-4.5 GeV	PRD 76, 092005 (2007)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ $K^+K^-\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 73, 052003 (2006)
$K^+K^-\pi^0$, $K^+K_S\pi^-$, $K^+K^-\eta$	threshold-2.6 GeV	PRD 77, 092002 (2008)
$K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $K^+K^-K^+K^-$	threshold-4.5 GeV	PRD 86, 012008 (2012)
pp	threshold-4.5 GeV	PRD 73, 012005 (2006) update submitted to PRD
$\Lambda^0\Lambda^0$, $\Lambda^0\Sigma^0$, $\Sigma^0\Sigma^0$	threshold-3.0 GeV	PRD 76, 092006 (2007)
$J/\psi\pi^+\pi^-$	threshold-5.5 GeV	PRL 95, 142001 (2005) PRD 86, 051102 (2012)
$D^{(*)}D^{(*)}$	threshold-6.0 GeV	PRD 79, 092001 (2009)
$\psi(2S)\pi^+\pi^-$	threshold-5.5 GeV	PRL 98, 212001 (2007)