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Baryon em Form Factors from Initial State Radiation processes

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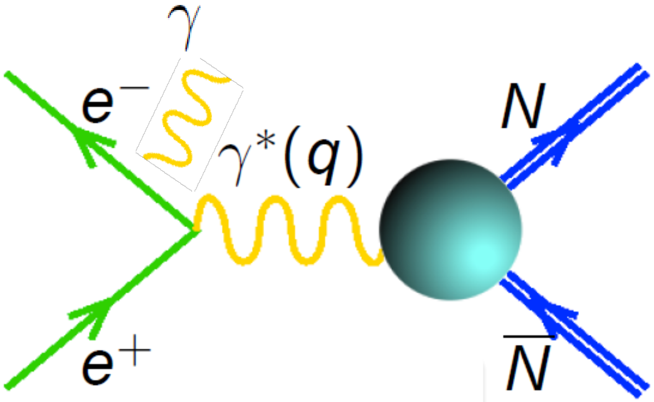
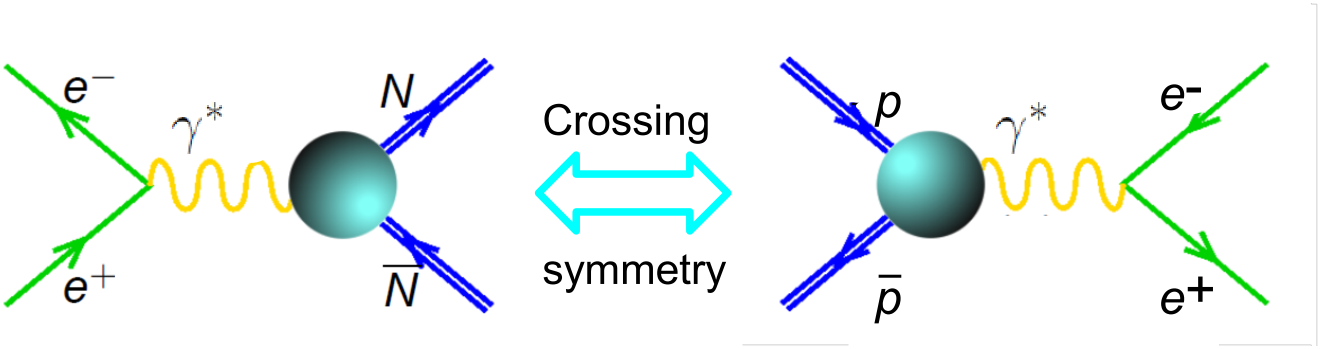
Outline

- Motivation
- Introduction
- Initial State Radiation
- Existing experiments
- Measurements vs expectations
- Conclusions



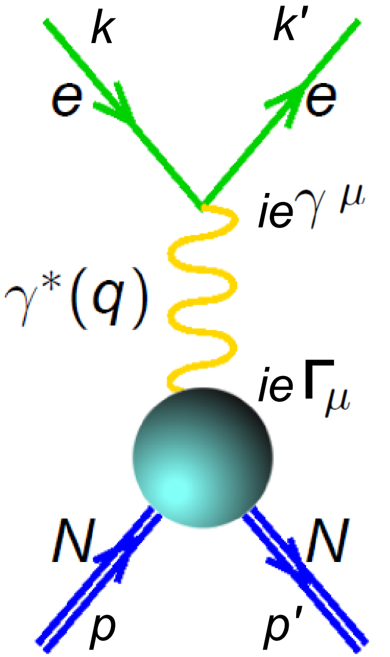
Motivation



- Our working group (HIM, Prof. Maas) interested in **E**lectro**M**agnetic **P**rocesses
- **Main aim**: measurement of **proton em form factors** in the time-like region **with PANDA**
- For this purpose we:
  - do **simulation studies on feasibility of $p\bar{p} \rightarrow e^+e^-, \mu^+\mu^-$** in PANDA (M. Mora, D. Khaneft, I. Zimmermann)
  - develop/implement **MC generators** on signal and background channels (M. Zambrana)
  - simulate/test **shielding of B** at PANDA and **polarization of target** (B. Feher)
  - design,develop and test **prototypes for readout of backwards em calorimeter** (D. Rodrigez, J. Navarro, R. Silva, C. Haberkorn, etc.)
  - **analyze BES-III data on baryon em FFs** (C.M., P. Larin)

Electromagnetic Form Factors

- Account for the non point-like structure of hadrons
- Are **fundamental hadron structure observables**:
  - **At low Q^2**: **charge distribution** and **magnetization**
  - **At higher Q^2**: **dynamics, quark distribution**



N = spin ½ baryon

Vector current, **two form factors** (F_1 and F_2)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$

Dirac	**Pauli**
$F_1^p(q^2=0)=1$	$F_2^p(q^2)=1$
$F_1^n(q^2=0)=0$	$F_2^n(q^2)=1$

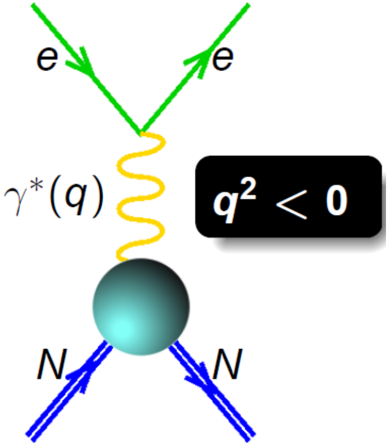
Sachs

$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

Electromagnetic Form Factors

Space-like

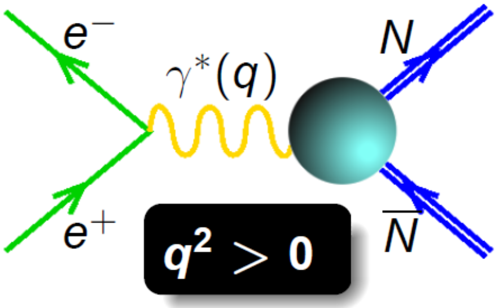
$eN \longrightarrow eN$



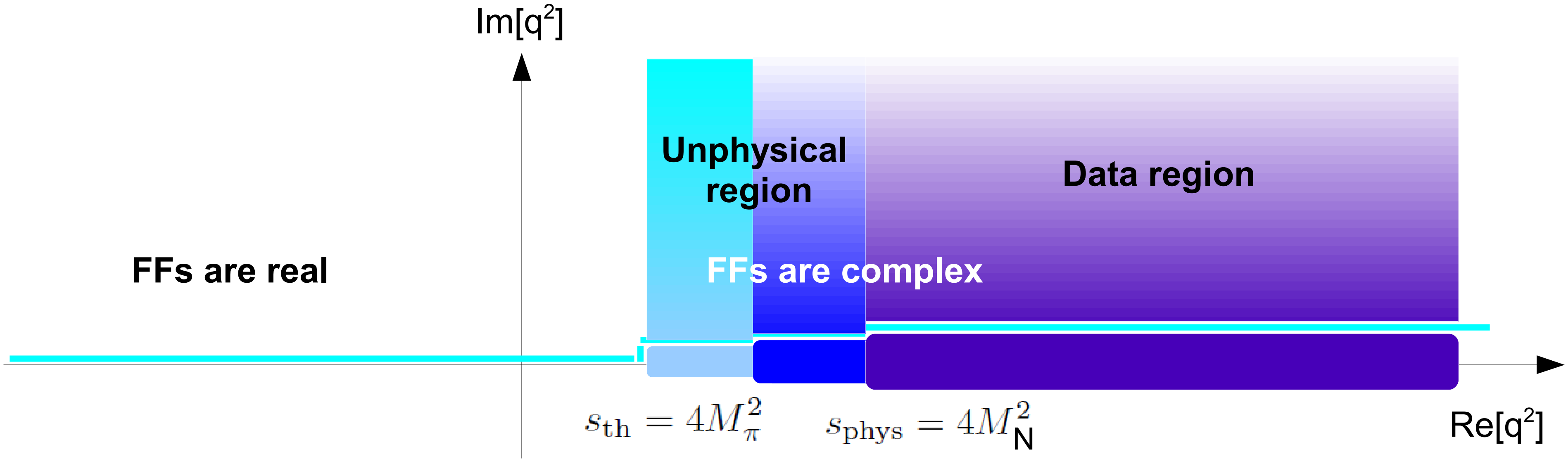
$q^2 < 0$

Time-like

$e^+e^- \leftrightarrow N\overline{N}$



$q^2 > 0$



Unphysical region

Data region

FFs are real

FFs are complex

$$G_E(4M_N^2) = G_M(4M_N^2)$$

Electromagnetic Form Factors

- **Dispersion relations connect space and time-like regions**
- **Perturbative QCD constrains the asymptotic behaviour**

[Matveev,Muradyan,Tevkheldize,Farrar, Brodsky-Lepage,...]

$$F_i(q^2) \rightarrow (-q^2)^{-(i+1)} \left[\ln \left(\frac{-q^2}{\Lambda^2_{\mathrm{QCD}}} \right) \right]^{-2.173_5}$$

$$|G_{E,M}(-\infty)| = |G_{E,M}(+\infty)|$$

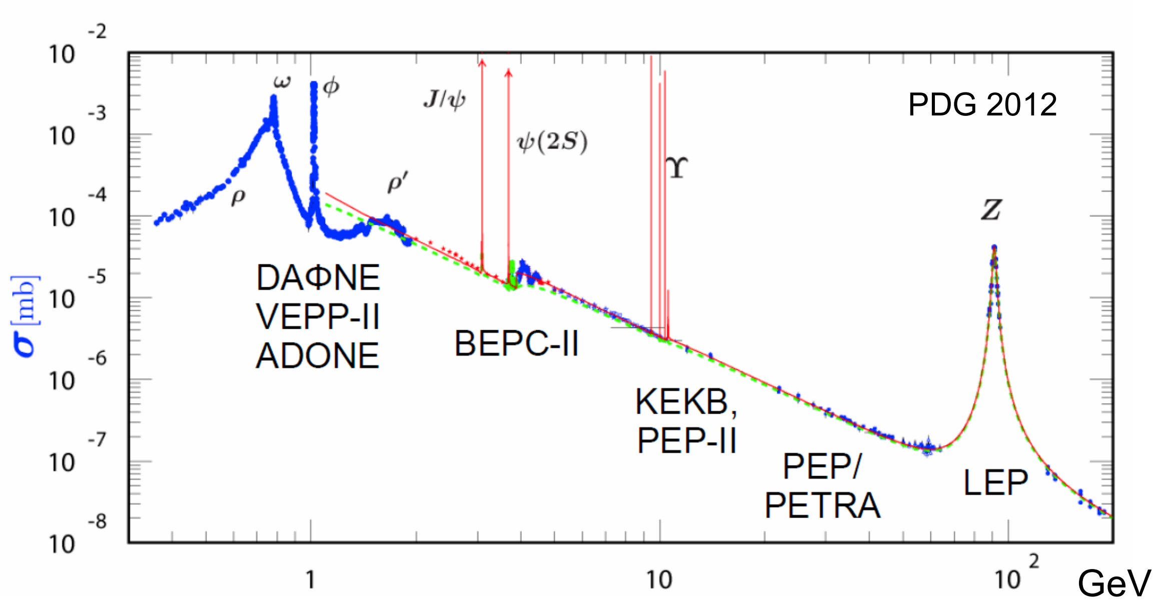
(analiticty)

Why time-like (TL) form factors (FFs)?

- **To test theory relations beween space-like and time-like processes**
- **Precise knowledge of FFs needed** by many experiments and phenomenological models
- **To test pQCD** expanding the Q^2 kinematical domain up to soft-hard transition region (10 – 15 $(\mathrm{GeV}/c)^2$)

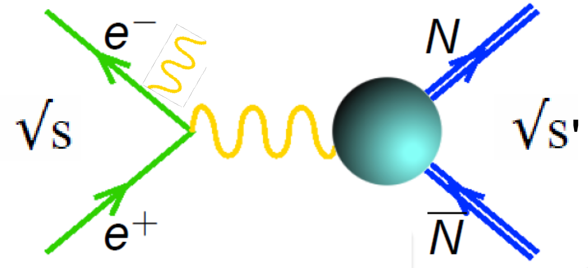
Initial State Radiation

Modern **e+ e- particle factories** designed for (almost) **fixed cm energy**:



energy scan needed
to measure $G_E(q^2)$, $G_M(q^2)$

Alternative: study **Initial State Radiation** channels with hard photon radiated from e^+e^--beams



Continous coverage from $N\overline{N}$ production threshold to $\sqrt{s}$ in one single experiment!!

$$x \equiv 1 - m^2/s = 2E_\gamma/\sqrt{s}$$

$$m^2_{p\bar{p}} = s(1 - x)$$

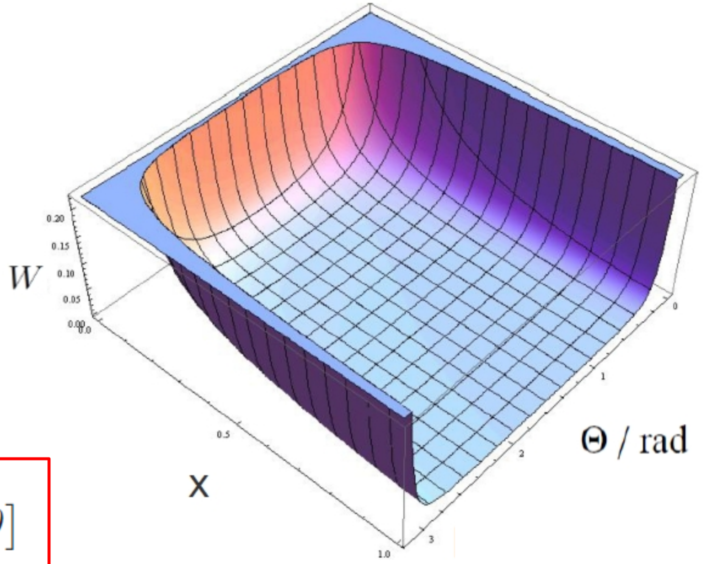
Radiator Function

There is a price to pay: loss of cross section

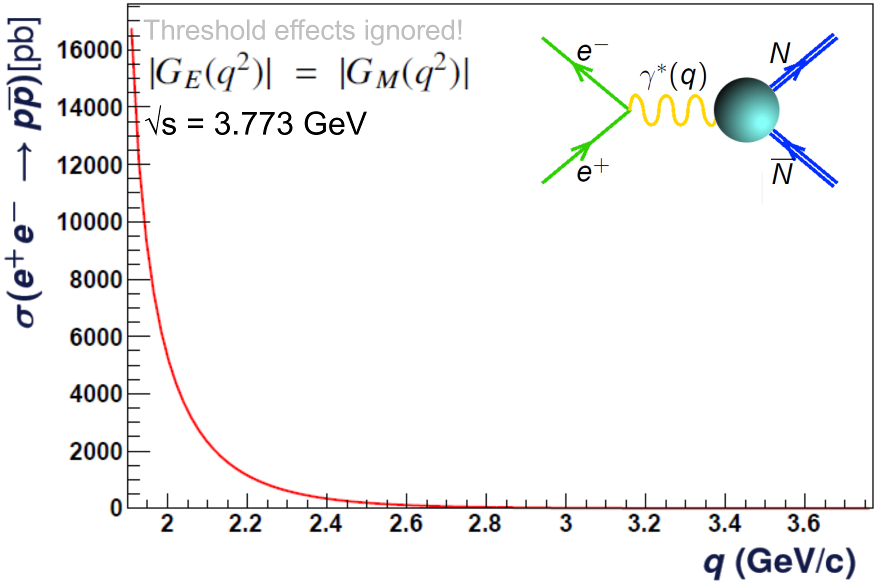
$$\frac{d^2\sigma(e^+e^-\to\gamma X_{\rm had})}{dx\,d\theta_\gamma} = W(x,\theta_\gamma)\,\sigma_{e^+e^-\to X_{\rm had}}(s)$$

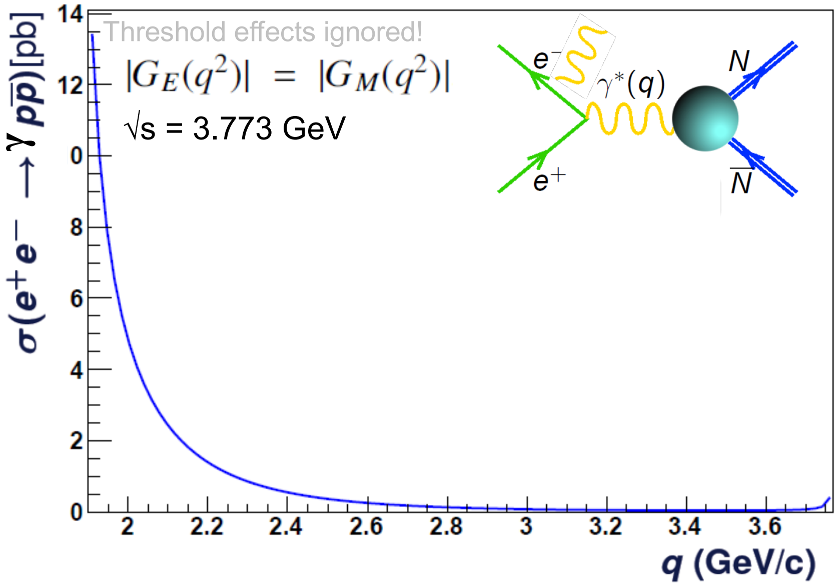
$$W(\overset{\rm LO}{s}, x, \theta^*_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta^*_\gamma} - \frac{x^2}{2}\right)$$

$$\boxed{\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha_e^2 C}{8M^2\tau\sqrt{\tau(\tau-1)}}\left[\tau\boxed{|G_M|^2}(1+\cos^2\theta)+\boxed{|G_E|^2}\sin^2\theta\right]}$$



C: Coulomb interaction correction at threshold

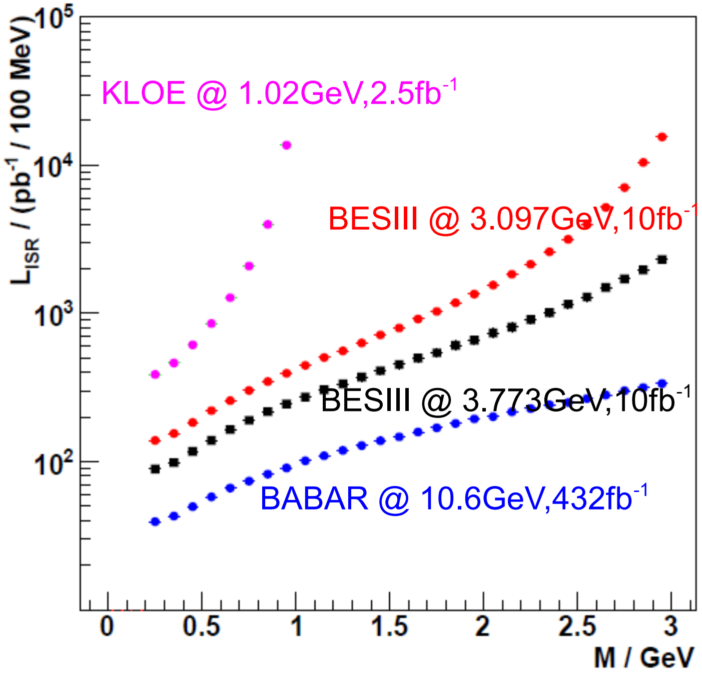




ISR pros and cons

Advantages

- Low σ_{ISR} **compensated by high luminosity** of b,c factories!!
- Same observables as dedicated experiments at low energies and within higher ranges
- Comes for free, no need for a dedicated experiment
- All q at the same time: **better control of point to point sytematics**
- High luminosity also at threshold
- **Acceptance at threshold ≠ 0**
- Detection efficiency almost independent of q^2 and angular distribution



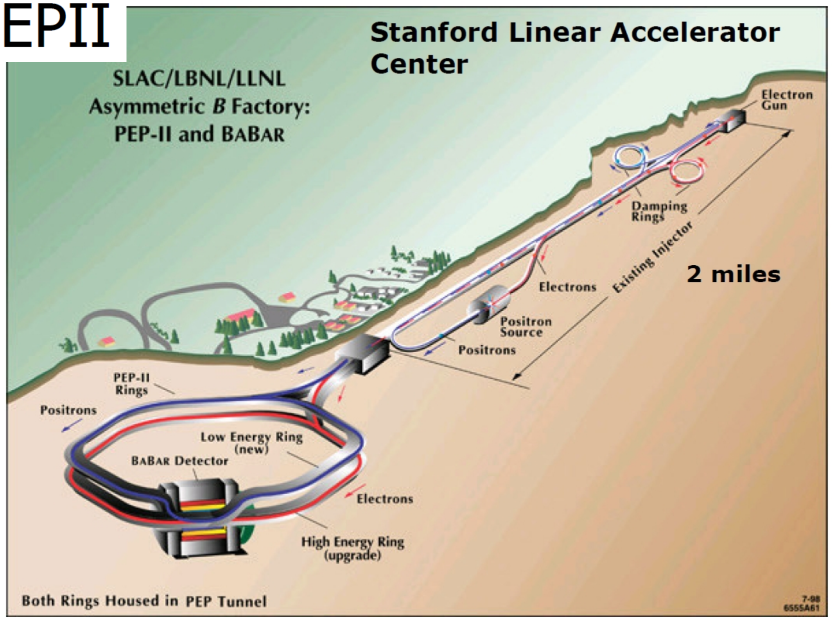
[Ch. Zimmermann, Diplomarbeit. Mainz 2011]

Drawbacks

- Luminosity proportional to bin width
- More backgrounds

PEPII / BEPCII

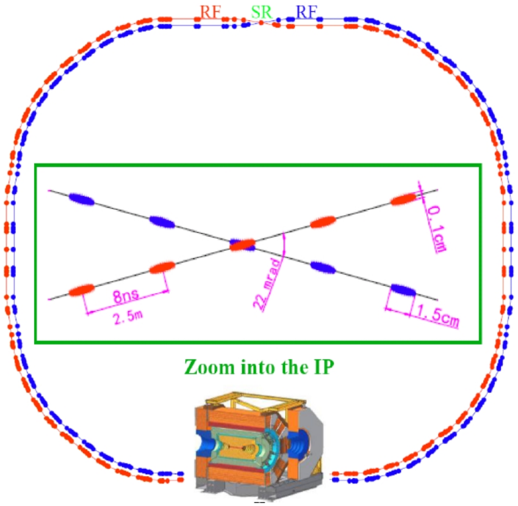
PEPII



	Design
E [GeV] e^- / e^+	9.0 / 3.1
I [mA] e^- / e^+	610 / 2140
L [cm^{-2} s^{-1}]	3 x 10^{33}
L_{int} [pb^{-1}/day]	135

- Asymmetric energy collider: $\beta\gamma = 0.56$
  (for time dependent CP studies)
- Luminosity collected (1999-2008): 530 fb^{-1}
- Luminosity used for ISR publications: 232 fb^{-1} at $\sqrt{s}$ = 10.57 GeV

BEPCII

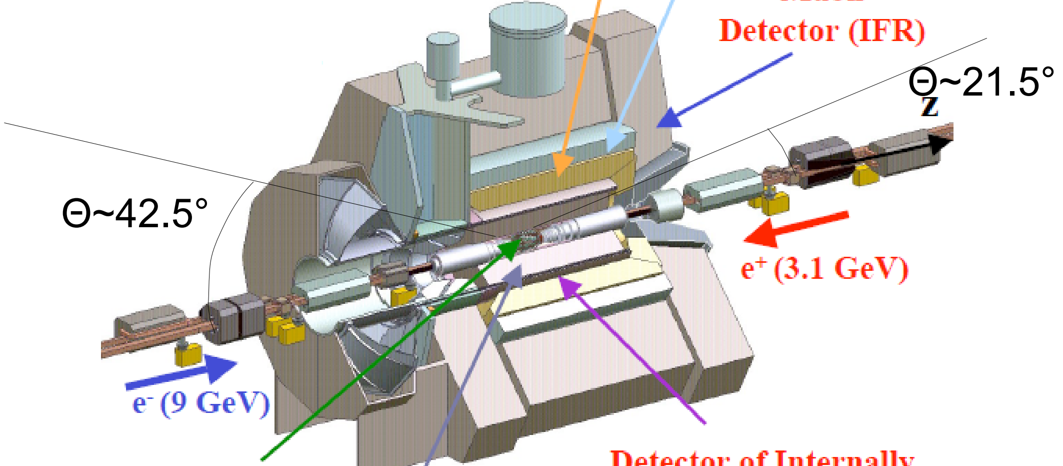


Beam energy: 1.0 – 2.3 GeV
Peak Luminosity:
Design: 1×10^{33} $cm^{-2}s^{-1}$

- Luminosity collected at ψ''(3770) = 2.9 fb^{-1}
- Luminosity aimed at ψ''(3770) = 10 fb^{-1}
- Data at other energies can also be used
- Data from newly started R-Scan 2-3GeV

BABAR / BESIII

BaBar Collaboration Home Page



Electromagnetic Calorimeter (EMC)

Measurement of electron and photon energies

$\sigma(E)/E=1.33\%E^{-1/4}\oplus2.1\%$

Solenoid 1.5T

Muon Detector (IFR)

e^+ (3.1 GeV)

e^- (9 GeV)

Si vertex tracker

Vertex, trajectory and dE/dx

Efficiency 97%

Drift Chamber (DCH)

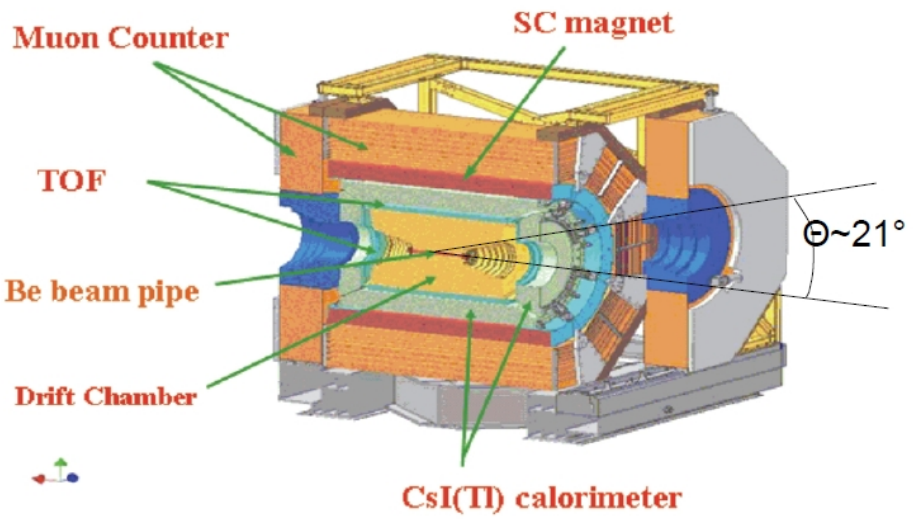
Momentum measurement for charged particles + dE/dx

$\sigma(p_T)/P_T=0.13\%P_T+0.45\%$

Detector of Internally Reflected Cherenkov Light (DIRC)

Typical resolutions: **$\sigma(J/\psi)$ = 12 MeV, $\sigma(\pi^0)$ = 6.5 MeV**

BES-III



Muon Counter

SC magnet

TOF

Be beam pipe

Drift Chamber

CsI(Tl) calorimeter

MDC: main drift chamber (He 60% + propane 40%):

σ(p)/p < 0.5% for 1GeV tracks, σ(xy) = 130 μm

σ(dE/dx)/(dE/dx) < 6%

TOF: time of flight (two layers plastic scintillator):

σ(t) < 90 ps

EMC: Cs I(Tl), barrel+2 end caps:

σ(E)/E < 2.5 %, σ(x) < 6mm for 1 GeV e-

MUC: time of flight (RPC): σ(xy) < 2 cm

Typical resolutions: **$\sigma(J/\psi)$ = 9 MeV , $\sigma(\pi^0)$ = 5 MeV**

ISR @ BABAR / BESIII

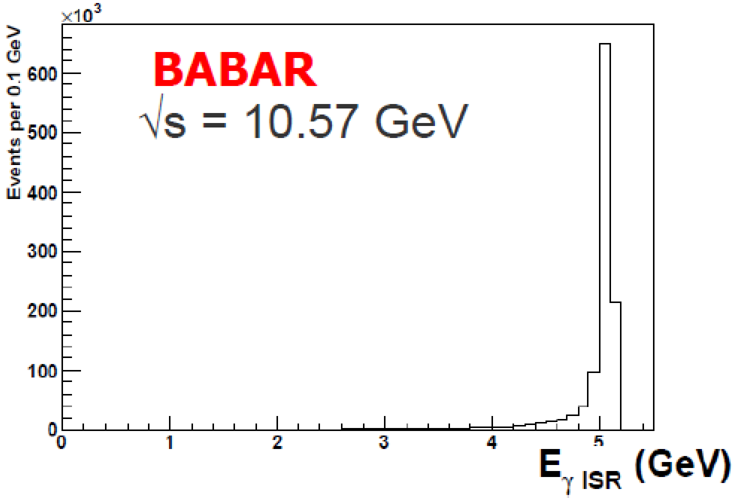
Geometrical acceptance:

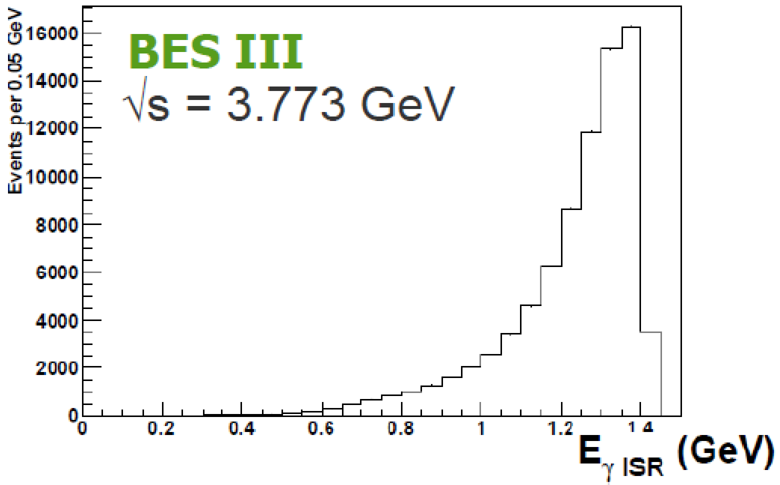
$M_{hadr} << \sqrt{s} \rightarrow$ need high luminosities

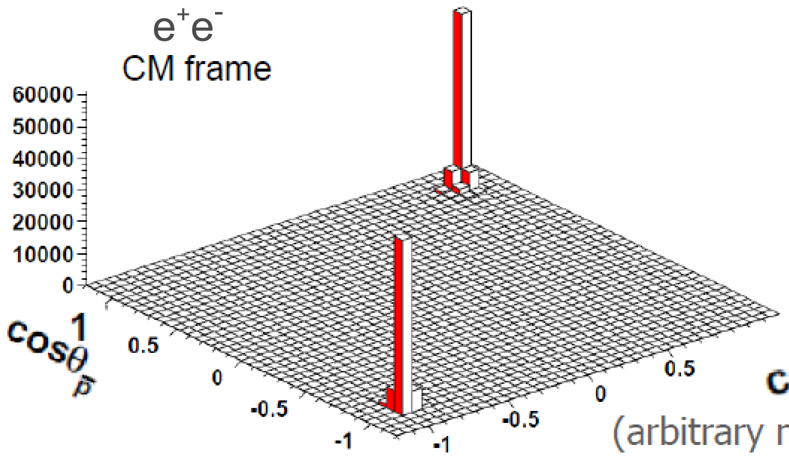
Photon tagging unavoidable

$M_{hadr} <$ but close to $\sqrt{s}$

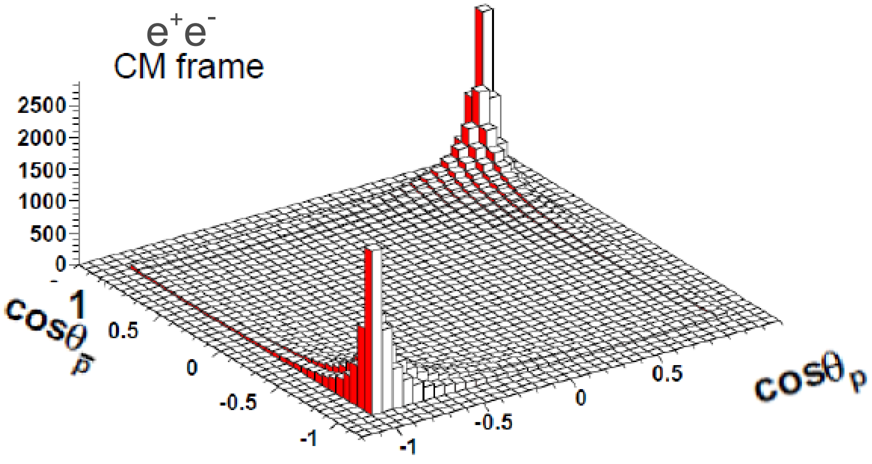
untagged measurement possible







(arbitrary normalization)

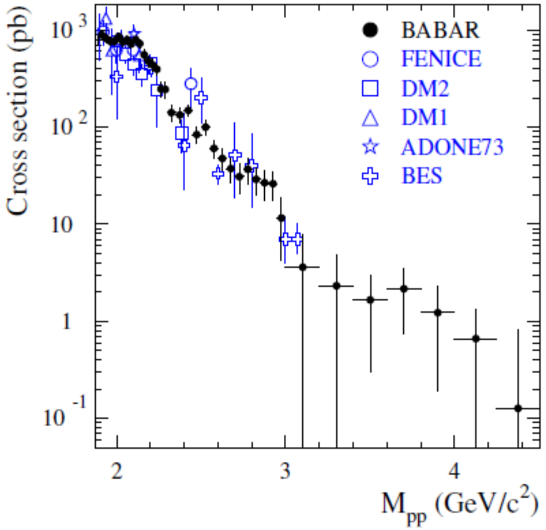


$e^{+}e \rightarrow N\ \bar{N}\ \gamma_{ISR}$

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

Publication based on 232 fb^{-1}. 4025 selected ISR signal events with 6% $e^+e^- \to p\bar{p}\pi^0$

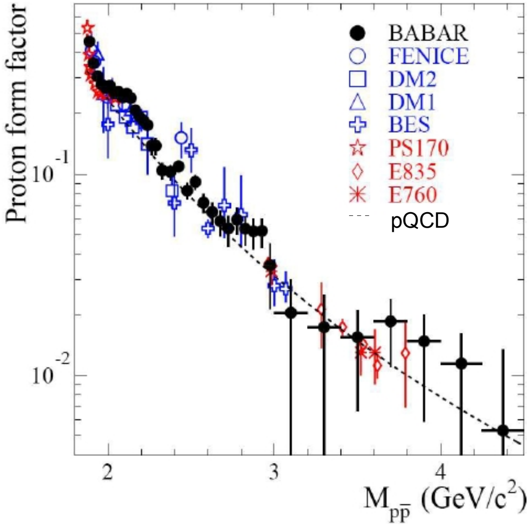


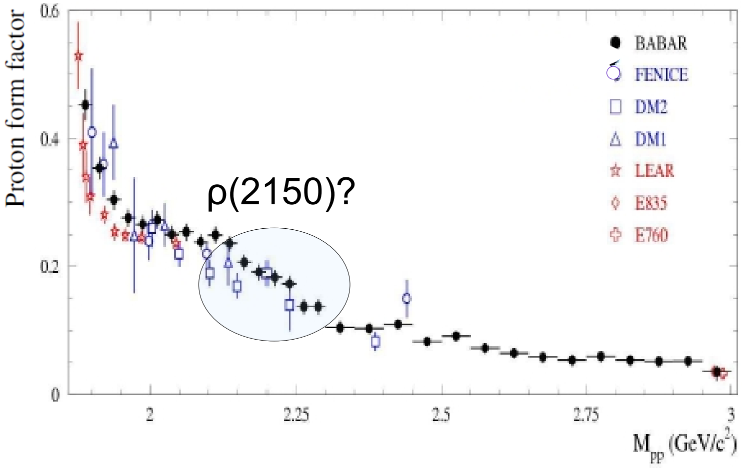
$$\sigma(m_{p\bar{p}}) = \frac{dN/dm_{p\bar{p}}}{\varepsilon R\, dL/dm_{p\bar{p}}} = \frac{4\pi\alpha^2\beta C}{3\,q^2}\left[\underbrace{\left|G_M(q^2)\right|^2 + \frac{1}{2\tau}\left|G_E(q^2)\right|^2}_{\text{Effective proton FF}}\right]$$

- peak at threshold
- plateau from 1.8 to 2.1 GeV/c^2
- decrease with drops at 2.25 (ρ(2150)?) and 3 GeV/c^2 (baryon thresholds? S-wave states open up quickly?)

- **Separation between $G_E(q^2)$ and $G_M(q^2)$ not possible !!**

- **Effective form factor extracted from cross section measurement**



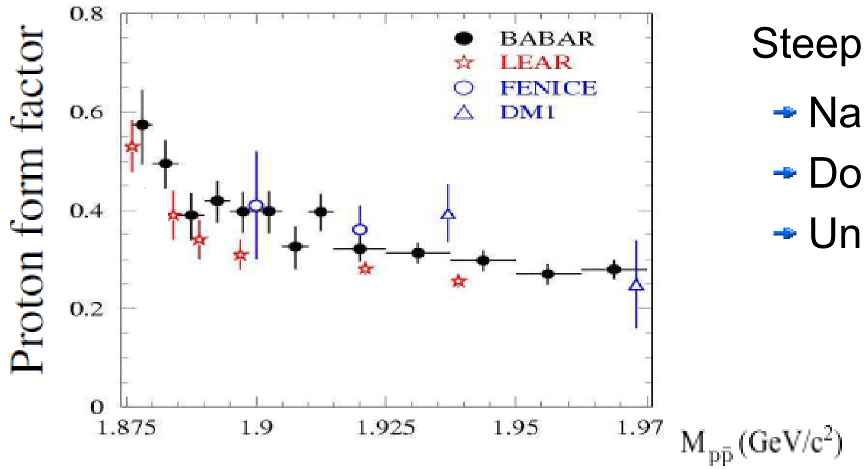


pQCD holds well for all $m_{p\bar{p}}$ but at high $m_{p\bar{p}}$ **is a factor 2 greater than in space like region !!**

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

What happens at threshold?

[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

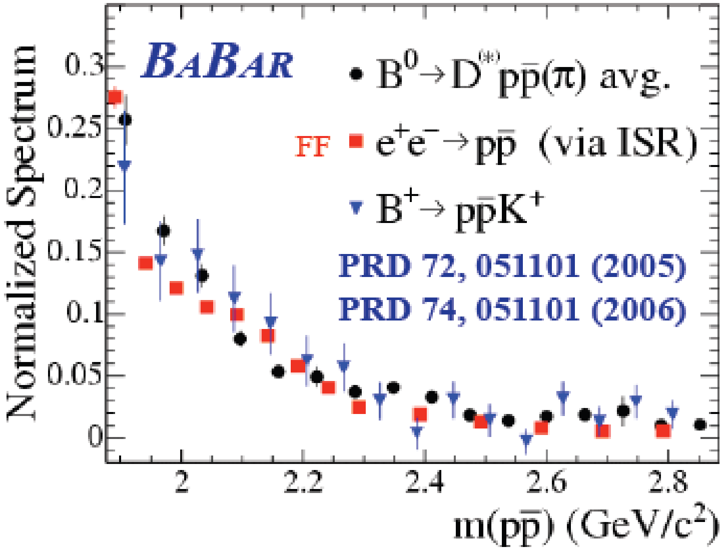


Steep rise at threshold seen by both PS170 and BaBar

- Narrow **resonance** below threshold? → Baryonium
- Dominance of pion exchange in **Final State Interaction**?
- Underestimation of **Coulomb factor**?

Is the rise at threshold related to other processes?

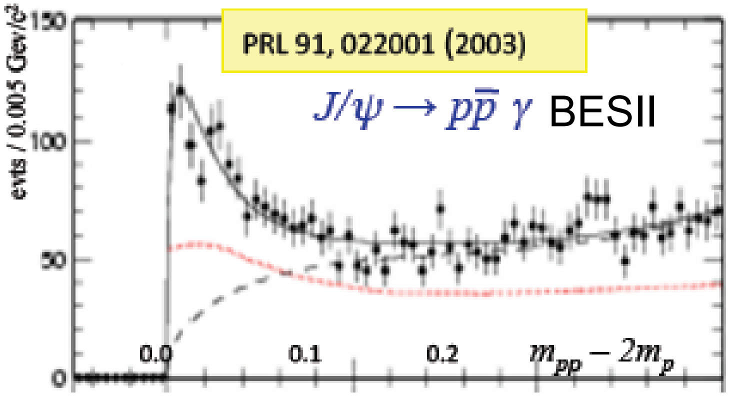
- **Similar behavior observed in $m_{p\bar{p}}$ in processes with different dynamics**:



BELLE

PRL 88, 181803 (2002)
PRL 89, 151802 (2002)

BESIII confirms behavior in radiative ψ'



$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

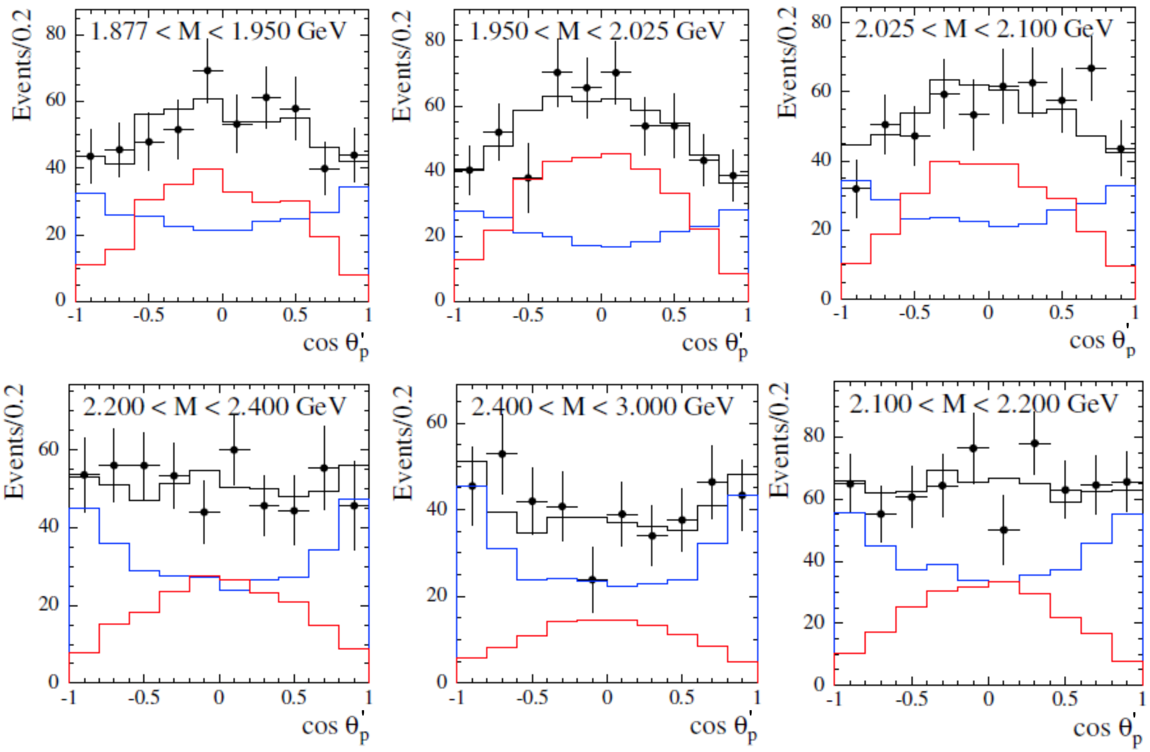
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

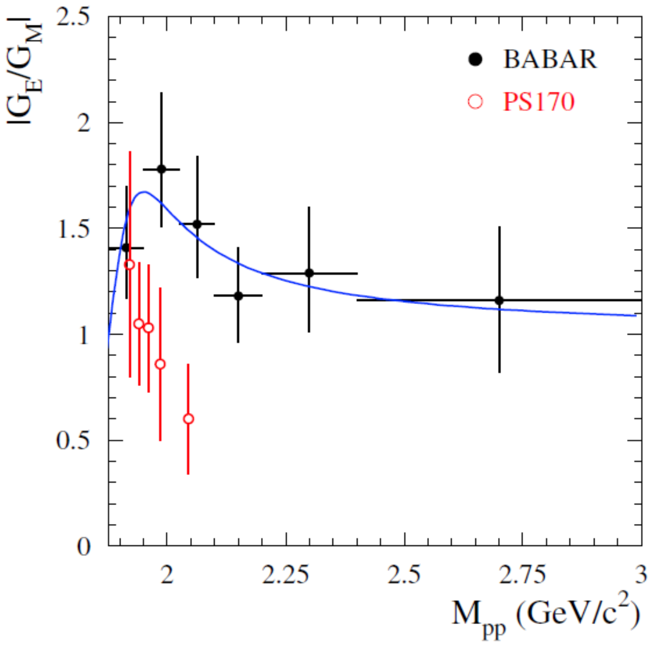
- **Ratio $|G_E(q^2)/G_M(q^2)|$ extracted from analysis of proton helicity angle in the $p\bar{p}$ rest frame**

$$\frac{dN}{d\cos\theta'} = A\left(\boxed{H_M(\cos\theta_p', m_{pp})} + \left|\frac{G_E}{G_M}\right| \boxed{H_E(\cos\theta_p', m_{pp})}\right)$$

Not analytic.Extracted from MC ISR generator
Phokhara with $G_E = 0$ and $G_M = 0$

[H.Czyz,J.H.Kühn,E.Nowak,G.Rodrigo,Eur.Phys.J C35,527 (2004)]





- Maximum at 2 GeV/c^2
- $G_E > G_M$ for all $M_{p\bar{p}}$ (≠ space-like)

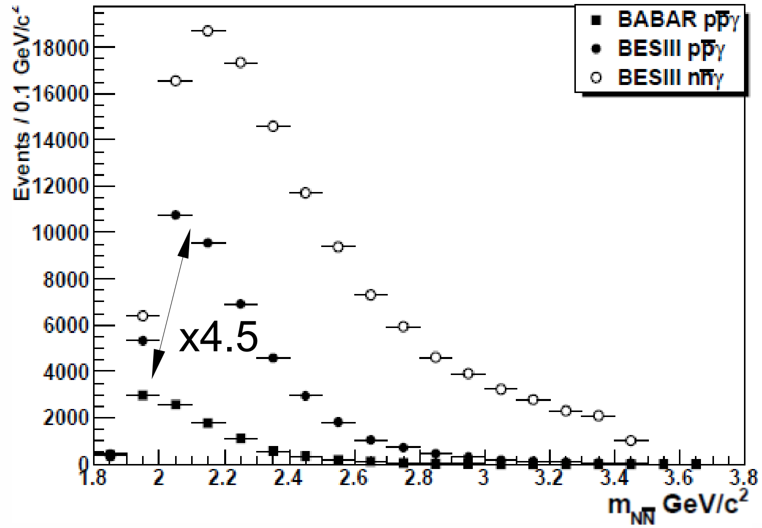
  Inconsistent with PS170

  Agreement at threshold
- Consistent with $|G_E/G_M|$ =1 at large M_{pp}

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

What could BES-III do for this channel? **Which resolution in $|G_E/G_M|$ can BESIII achieve?**

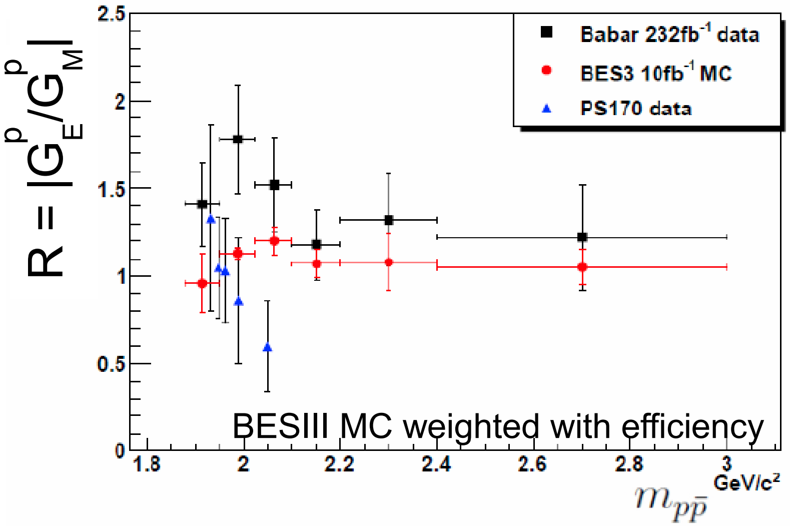
	BES-III	BABAR
$\sqrt{s}$(GeV))	3.77	10.57
$\sigma_{ISR,NLO}$(nb)	8.12×10^{-3}	0.7×10^{-3}
$L(\mathrm{fb}^{-1})$	10	232
$N_{gen} = L \times \sigma$	81261	176856
measurement	"untagged + tagged"	"tagged"
geometry cuts (degrees)	$21.6 < \theta_{p,\bar{p}} < 158.7$	$25.8 < \theta^{lab}_{p,\bar{p}} < 137.7$
	$0 < \theta_{\gamma ISR} < 180$	$21.5 < \theta^{lab}_{\gamma ISR} < 137.5$
$N_{expected}$	45623 (34070 + 11553)	10183



- Expected #data simulated with R=1 MC signal and weighted with selection efficiencies (30% for untagged analysis, 6% for tagged analysis)
- Fit simulated data with:

$$F((cos\hat{\theta}, m)) = F_0 \cdot \boxed{\frac{\sigma_0}{\sigma_1}} \cdot \underbrace{|G_M|^2 \cdot H_M(cos\hat{\theta}, m)}_{\text{Normalized true MC with GE = 0}} + F_1 \cdot \underbrace{|G_E|^2 \cdot H_E(cos\hat{\theta}, m)}_{\text{Normalized true MC with GM = 0}}$$

$$\boxed{R = \frac{|G_E|}{|G_M|} = \sqrt{\frac{F_1}{F_0}}}$$

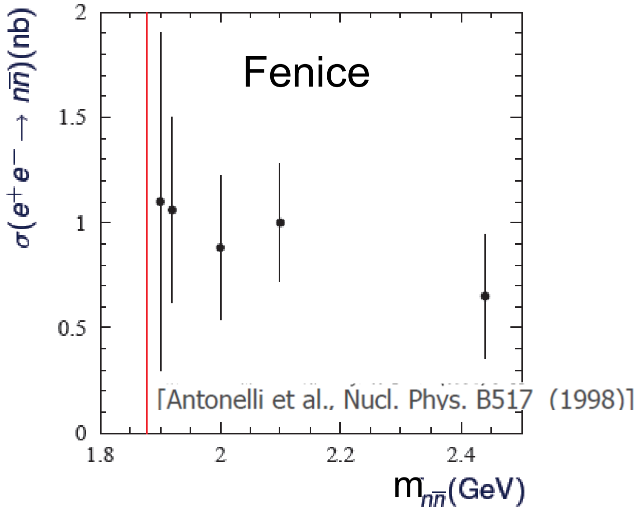


$e^+e^- \to n\,\bar{n}\,\gamma_{ISR}$

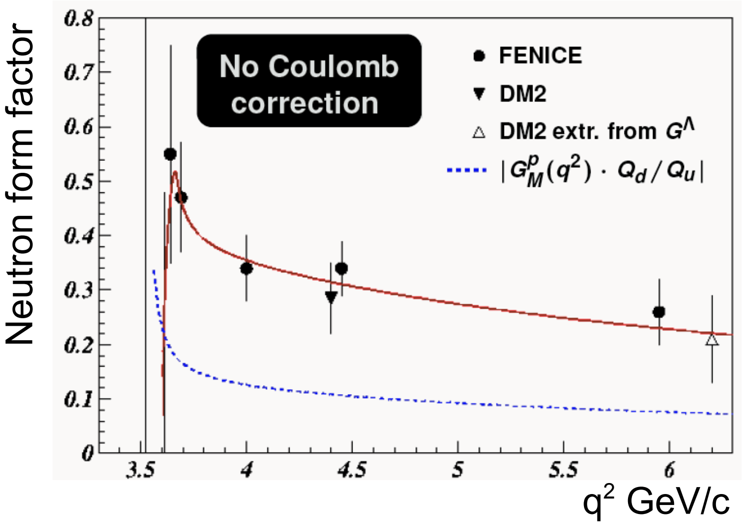
Only one measurement from Fenice with 74 signal events (0.4 pb^{-1}) from $e^+e^- \to n\bar{n}$

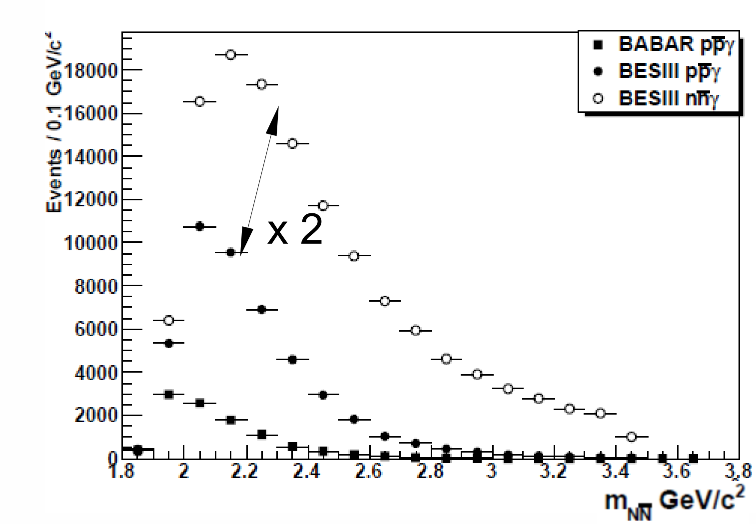
BESIII expects according to Fenice x2 more statistics than for the proton channel

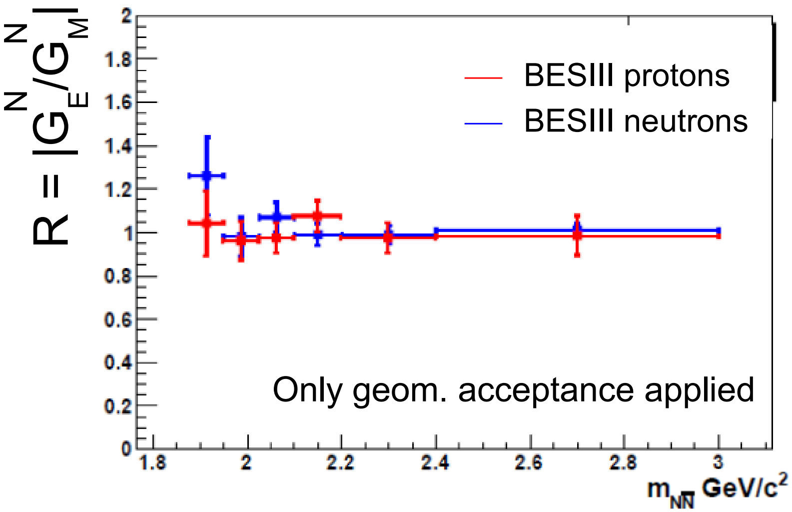
- **30% Efficiency in the $\bar{n}$ identification** in J/ψ → $n\bar{n}$ publication by BESIII



[Antonelli et al., Nucl. Phys. B517 (1998)]





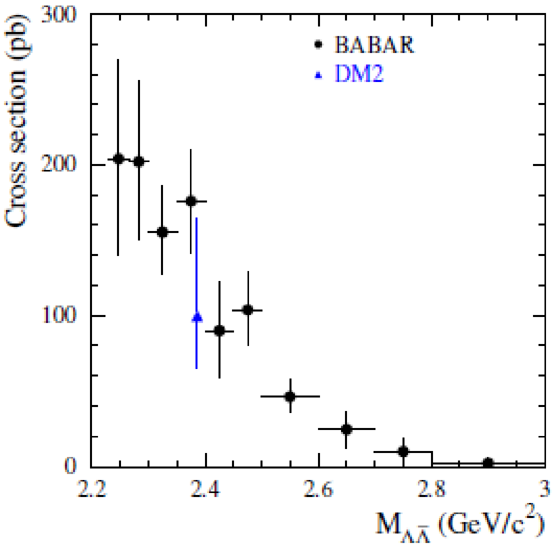


$e^+e \to \Lambda\,\bar{\Lambda}\,\gamma_{ISR}\ ,\ \Lambda\,\bar{\Sigma}\,\gamma_{ISR}\ ,\ \Sigma\,\bar{\Sigma}\,\gamma_{ISR}$

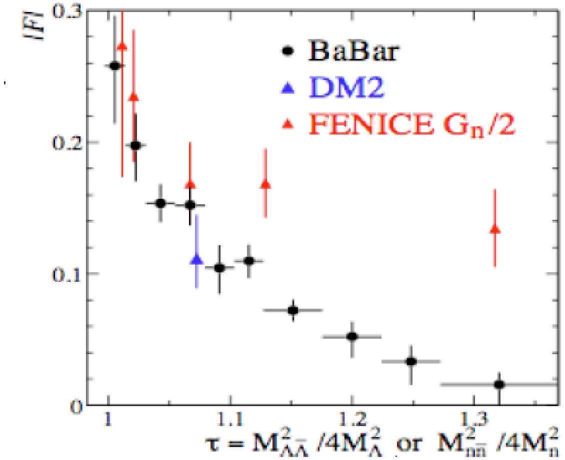
$e^{+}e^{-}\to \Lambda\bar{\Lambda}\gamma_{ISR}$

[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

About 350 $\Lambda\bar{\Lambda}\gamma_{ISR}$ events with $\Lambda\to p\pi^-$ and $\bar{\Lambda}\to\bar{p}\pi^+$ selected by BaBar



- Only one measurement before by DM2
- **Cross section roughly flat at threshold** and **possibly not vanishing** even thogh no Coulomb correction for neutral baryons production
- However, large error bars do not exclude $\sigma_{threshold} = 0$

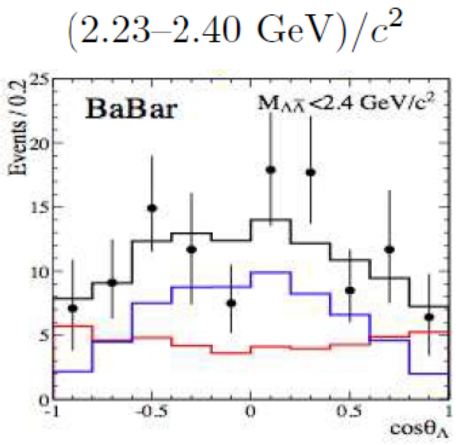


- **Rise of FFs close to threshold** observed also in this case
- Fit with $f = K/q^n$ gives n= 9.2 ±0.3
  - pQCD asymptotic prediction (q^4) reached at 3GeV first
- F_Λ in agreement with DM2 and with F_n by Fenice

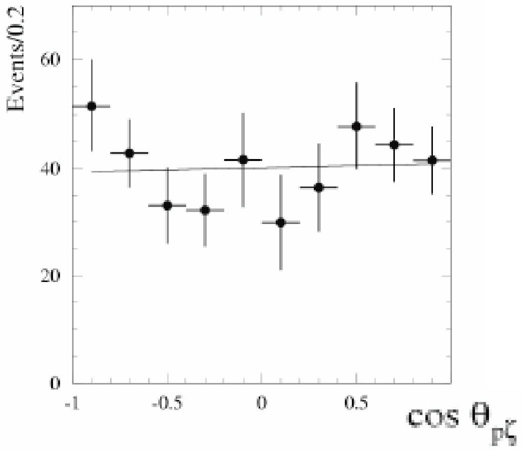
$e^+e^- \rightarrow \Lambda\bar{\Lambda}\gamma_{ISR}$

[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

- **Ratio of form factors** extracted from the analysis of the angular distribution of the lambda helicity angle



$|G_E^\Lambda/G_M^\Lambda| < 1.73^{+0.99}_{-0.57}$ $|G_E^\Lambda/G_M^\Lambda| < 0.71^{+0.66}_{-0.71}$



  - Compatible with $|G_E^\Lambda/G_M^\Lambda| = 1$, but with large uncertainties

- **Polarization** tested by fitting slope of angle between lambda polarization axis and proton momentum in Λ rest frame

$$\frac{dN}{d\cos\theta_{p\zeta}} = A(1 + \alpha_\Lambda \zeta_f \cos\theta_{p\zeta})$$

$$\Longrightarrow \; -0.22 < \zeta_f < 0.28 \quad \text{(90\% CL)}$$

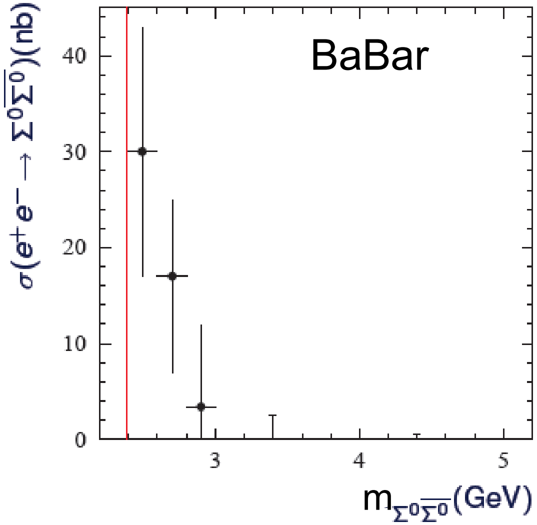
Under $|G_E^\Lambda| = |G_M^\Lambda|$ assumption, tests a **non-zero relative phase** between G_E^Λ and G_M^Λ: $-0.76 < \sin\phi < 0.98$

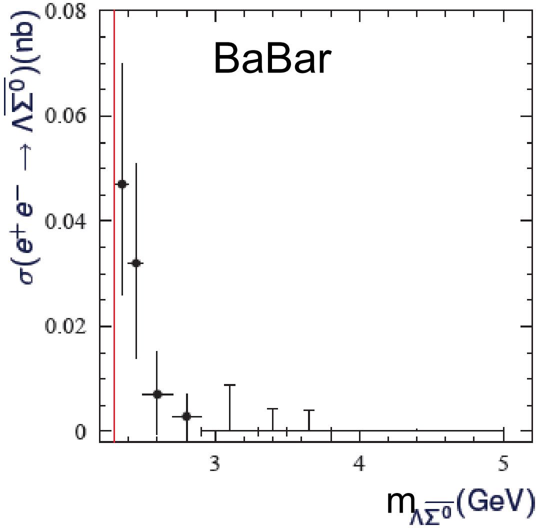
$e^+e^- \rightarrow \Lambda\bar{\Sigma}\gamma_{ISR}$, $\Sigma\bar{\Sigma}\gamma_{ISR}$

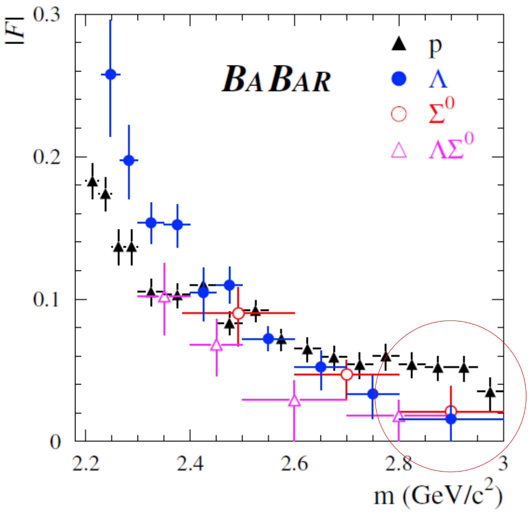
[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

BaBar performed first measurement ever for these channels

Reconstruct Σ baryon in decay channels $\Sigma \rightarrow \Lambda\gamma$ and $\Lambda \rightarrow p\pi$: few tens of signal events







- $\sigma(e^+e^- \rightarrow \Sigma^0\bar{\Sigma}^0)$ is different from zero at threshold, being 0.030 ± 0.013 nb
- $\sigma(e^+e^- \rightarrow \Lambda\bar{\Sigma}^0)$ is different from zero at threshold, being 0.047 ± 0.022 nb

QCD predictions:

$$F_\Lambda/F_p = 0.24$$
$$F_\Sigma/F_\Lambda = -1.18$$
$$F_{\Sigma\Lambda}/F_\Lambda = -2.34$$

- Effective |F| shows same rising behavior
- Data seem to agree with theory only for F_Σ/F_Λ (by accident?)
- F_Λ/F_p decrease with energy, similar to prediction close to 3 GeV

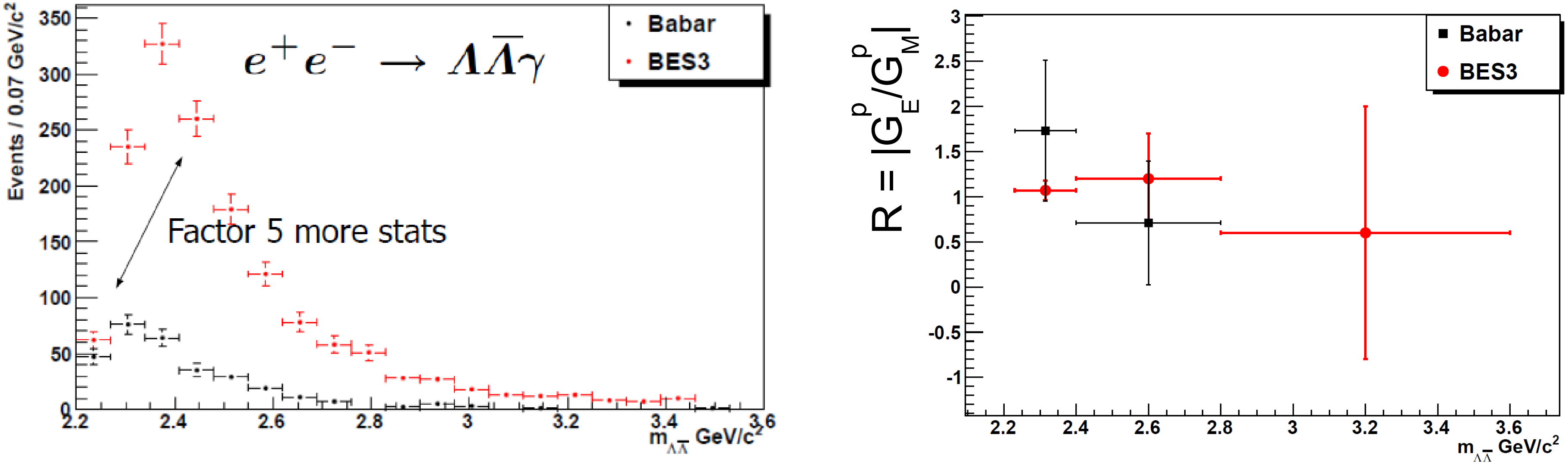
[Chernyak et al. Z. Phys. C 42, 569 (1989)]

$e^+e^- \to \Lambda\,\bar{\Lambda}\,\gamma_{ISR}$, $\Lambda\,\bar{\Sigma}\,\gamma_{ISR}$, $\Sigma\,\bar{\Sigma}\,\gamma_{ISR}$

What could BES-III do for this channel?

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]

- BES-III expects about 5 times more stats in e+e- → $\Lambda\bar{\Lambda}\gamma$ than BaBar



- The resolution of $|G_E^\Lambda/G_M^\Lambda|$ in the first two bins could be improved by a factor 4 and 2 correspondingly and also the measurement of the phase difference

- Assuming statisics in $e^+e \to \Lambda\,\bar{\Sigma}\,\gamma_{ISR}$, $\Sigma\,\bar{\Sigma}\,\gamma_{ISR}$ also increase by a factor 5, BESIII could provide a similar improvement in |F| resolution than for the case of Λ

Conclusions

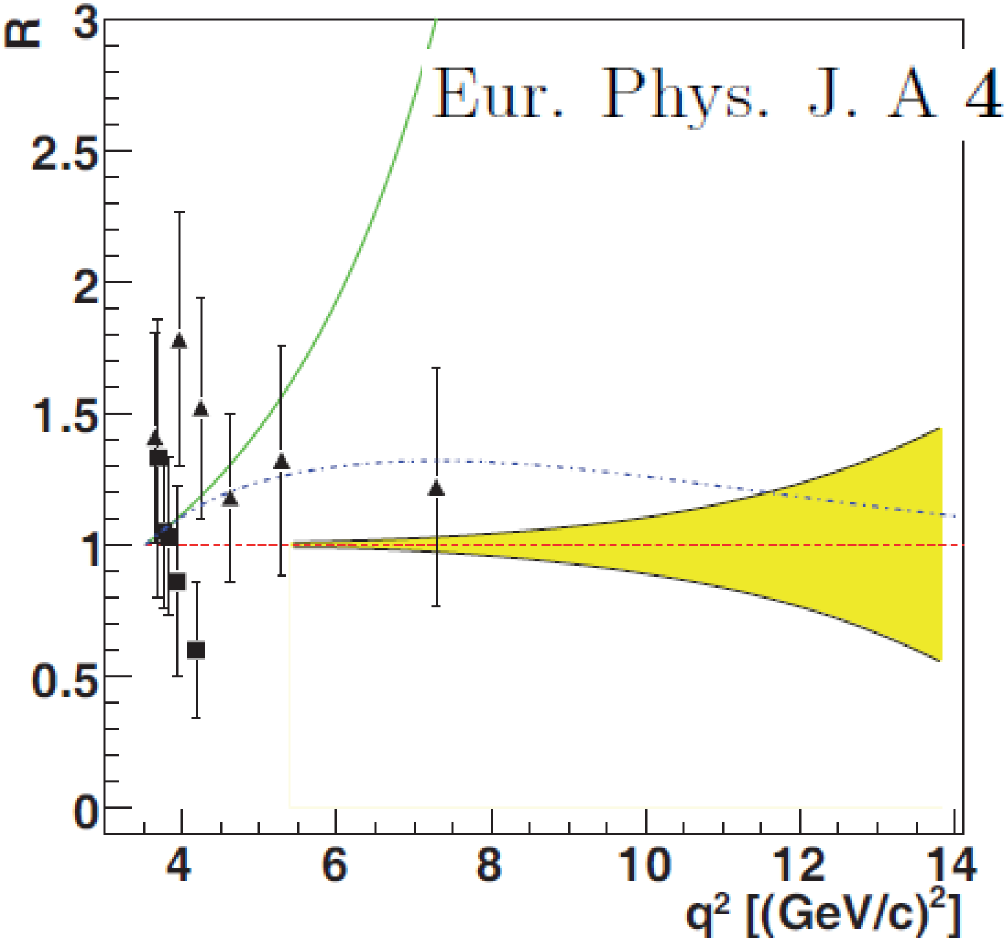
- BaBar and BESIII show the power of ISR method for measuring baryon FFs
- Precise results from BaBar obtained via ISR but several effects remain to be understood
- BESIII will (try to) bring some light on these issues with higher statistics using ISR and a dedicated energy scan near baryon thresholds
- No dedicated experiments planned. Nucleon structure can be studied in several operating or planned facilities (VEPP-2000, BELLE, super B-factories...)
- Feasibility studies on the measurement of proton FFs in $p\bar{p} \rightarrow e^+e^-$ in PANDA predict a factor 10 improvement in the current resolution of ratio of em FFs and $\sigma(p\bar{p} \rightarrow e^+e^-)$ will be measured up to $q^2 = 28\ (\mathrm{GeV}/c)^2$ + great statistics at theshold!!

Eur. Phys. J. A **44**, 373–384 (2010)

Acknowledgements

Thank you for your attention
Thanks to the organizers and
Many thanks to F. Maas, F. Anulli, R. Baldini, S. Pacetti...

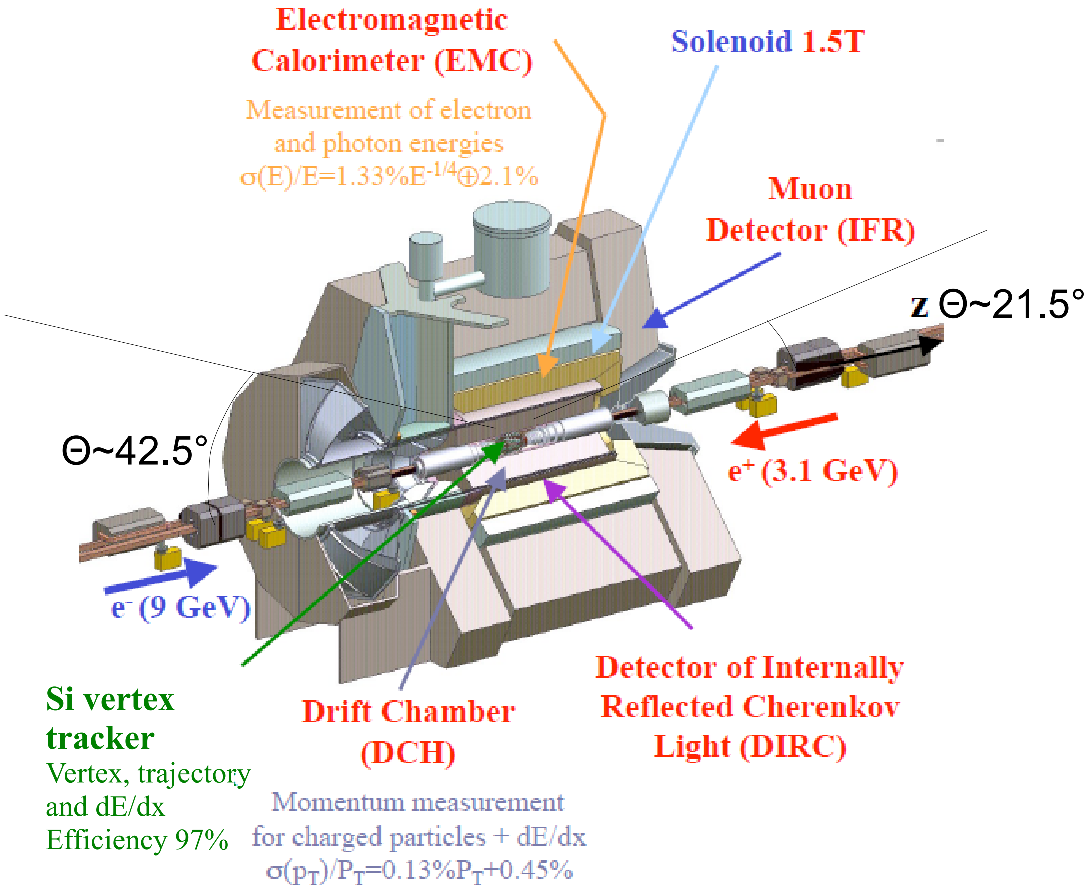
R @ PANDA



Eur. Phys. J. A **44**, 373–384 (2010)

Fig. 7. (Color online) Expected statistical precision on the determination of the ratio $\mathcal{R}$, (yellow band) for $\mathcal{R} = 1$, as a function of q^2, compared with the existing data from refs. [24] (triangles) and [23] (squares). Curves are theoretical predictions (see text).

BABAR / BESIII



Electromagnetic Calorimeter (EMC)

Measurement of electron and photon energies

$\sigma(E)/E=1.33\%E^{-1/4}\oplus 2.1\%$

Solenoid 1.5T

Muon Detector (IFR)

z Θ~21.5°

Θ~42.5°

e^+ (3.1 GeV)

e^- (9 GeV)

Si vertex tracker

Vertex, trajectory and dE/dx

Efficiency 97%

Drift Chamber (DCH)

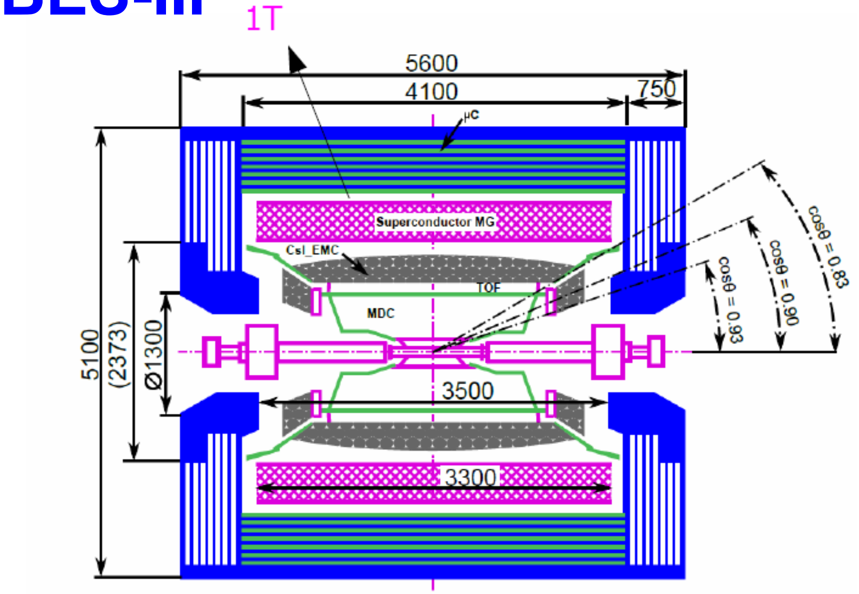
Momentum measurement for charged particles + dE/dx

$\sigma(p_T)/P_T=0.13\%P_T+0.45\%$

Detector of Internally Reflected Cherenkov Light (DIRC)

Typical resolutions: **σ(J/ψ) = 12 MeV, $\sigma(\pi^0)$ = 6.5 MeV**

BES-III



MDC: main drift chamber (He 60% + propane 40%):

σ(p)/p < 0.5% for 1GeV tracks, σ(xy) = 130 μm

σ(dE/dx)/(dE/dx) < 6%

TOF: time of flight (two layers plastic scintillator):

σ(t) < 90 ps

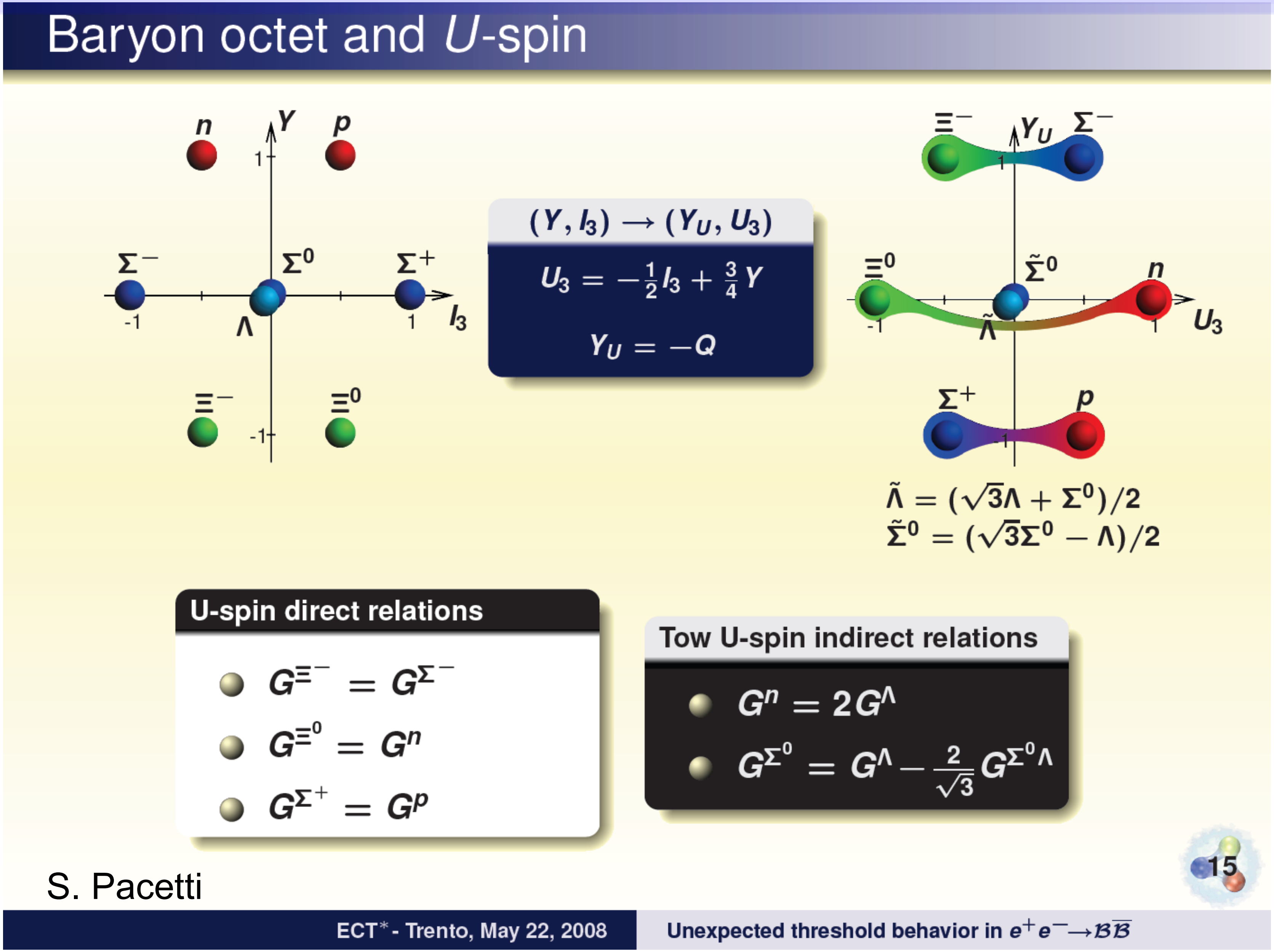
EMC: Cs I(Tl), barrel+2 end caps:

σ(E)/E < 2.5 %, σ(x) < 6mm for 1 GeV e-

MUC: time of flight (RPC): σ(xy) < 2 cm

Typical resolutions: **σ(J/ψ) = 9 MeV , $\sigma(\pi^0)$ = 5 MeV**

Baryon octet and U-spin



Baryon octet and U-spin

$$(Y, I_3) \longrightarrow (Y_U, U_3)$$

$$U_3 = -\tfrac{1}{2} I_3 + \tfrac{3}{4} Y$$

$$Y_U = -Q$$

$$\tilde{\Lambda} = (\sqrt{3}\Lambda + \Sigma^0)/2$$
$$\tilde{\Sigma}^0 = (\sqrt{3}\Sigma^0 - \Lambda)/2$$

U-spin direct relations

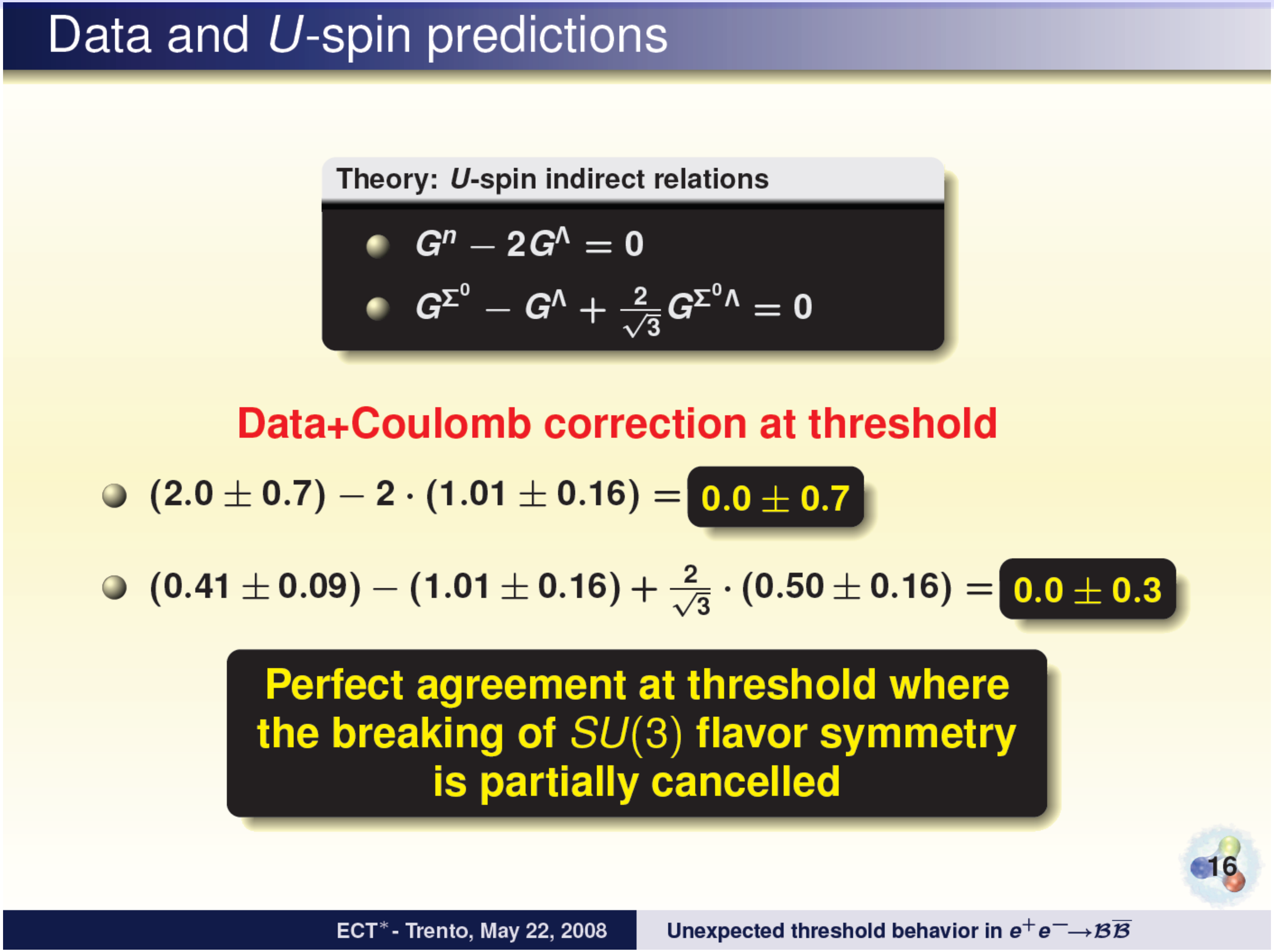
- $G^{\Xi^-} = G^{\Sigma^-}$
- $G^{\Xi^0} = G^n$
- $G^{\Sigma^+} = G^p$

Tow U-spin indirect relations

- $G^n = 2G^\Lambda$
- $G^{\Sigma^0} = G^\Lambda - \frac{2}{\sqrt{3}} G^{\Sigma^0\Lambda}$

S. Pacetti

Baryon octet and U-spin



Data and *U*-spin predictions

Theory: *U*-spin indirect relations

- $G^n - 2G^\Lambda = 0$
- $G^{\Sigma^0} - G^\Lambda + \frac{2}{\sqrt{3}} G^{\Sigma^0\Lambda} = 0$

Data+Coulomb correction at threshold

- $(2.0 \pm 0.7) - 2 \cdot (1.01 \pm 0.16) = \boxed{0.0 \pm 0.7}$
- $(0.41 \pm 0.09) - (1.01 \pm 0.16) + \frac{2}{\sqrt{3}} \cdot (0.50 \pm 0.16) = \boxed{0.0 \pm 0.3}$

Perfect agreement at threshold where the breaking of $SU(3)$ flavor symmetry is partially cancelled

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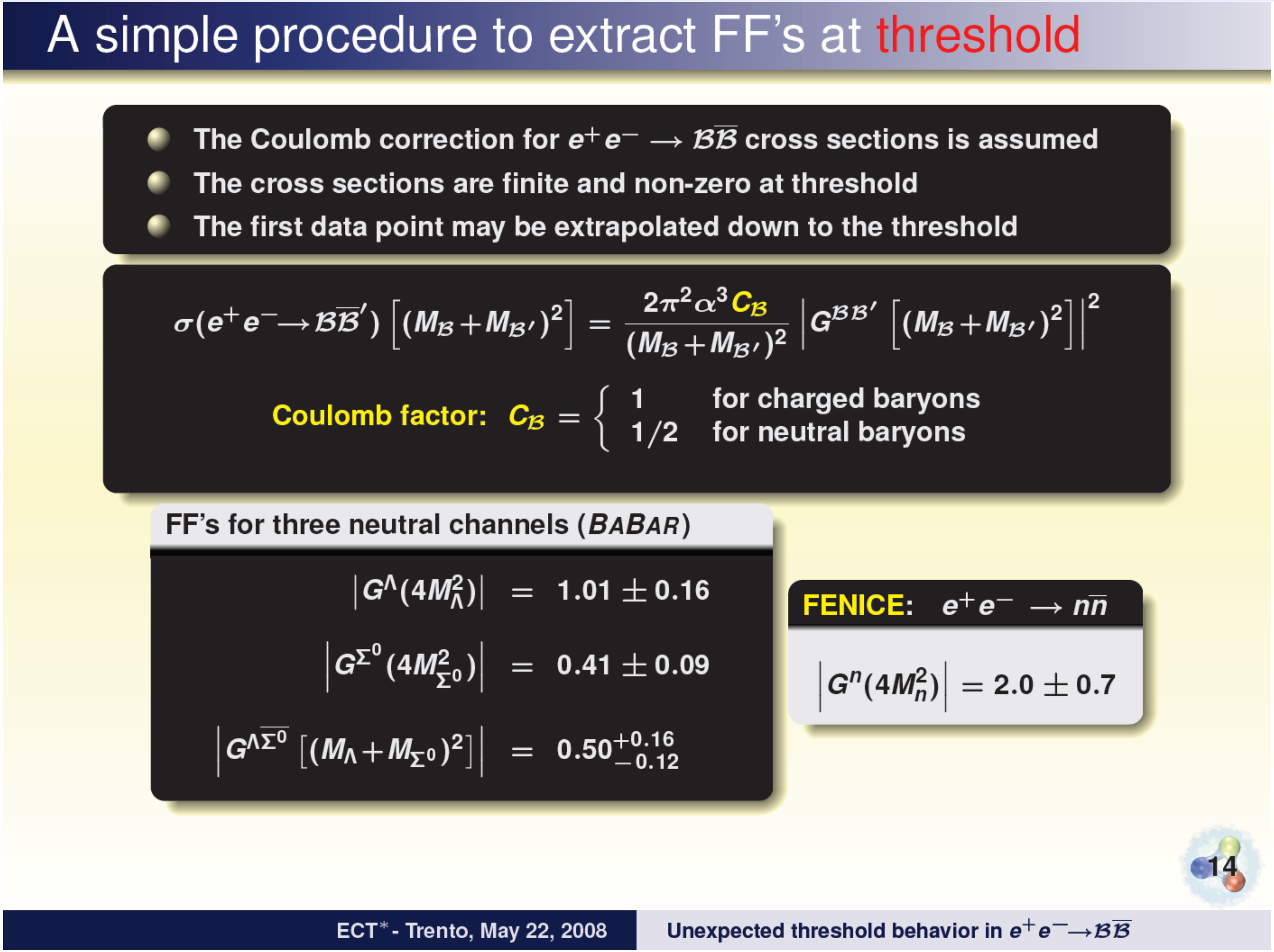
ECT* - Trento, May 22, 2008

Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

Baryon octet and FFs at threshold



A simple procedure to extract FF’s at threshold

- The Coulomb correction for $e^+e^- \longrightarrow \mathcal{B}\overline{\mathcal{B}}$ cross sections is assumed
- The cross sections are finite and non-zero at threshold
- The first data point may be extrapolated down to the threshold

$$\sigma(e^+e^- \!\longrightarrow\! \mathcal{B}\overline{\mathcal{B}}')\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right] = \frac{2\pi^2\alpha^3 C_{\mathcal{B}}}{(M_{\mathcal{B}}+M_{\mathcal{B}'})^2}\left|G^{\mathcal{B}\mathcal{B}'}\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right]\right|^2$$

Coulomb factor: $C_{\mathcal{B}} = \begin{cases} 1 & \text{for charged baryons} \\ 1/2 & \text{for neutral baryons} \end{cases}$

FF’s for three neutral channels (BABAR)

$$\left|G^{\Lambda}(4M_{\Lambda}^2)\right| = 1.01 \pm 0.16$$

$$\left|G^{\Sigma^0}(4M_{\Sigma^0}^2)\right| = 0.41 \pm 0.09$$

$$\left|G^{\Lambda\overline{\Sigma^0}}\left[(M_{\Lambda}+M_{\Sigma^0})^2\right]\right| = 0.50^{+0.16}_{-0.12}$$

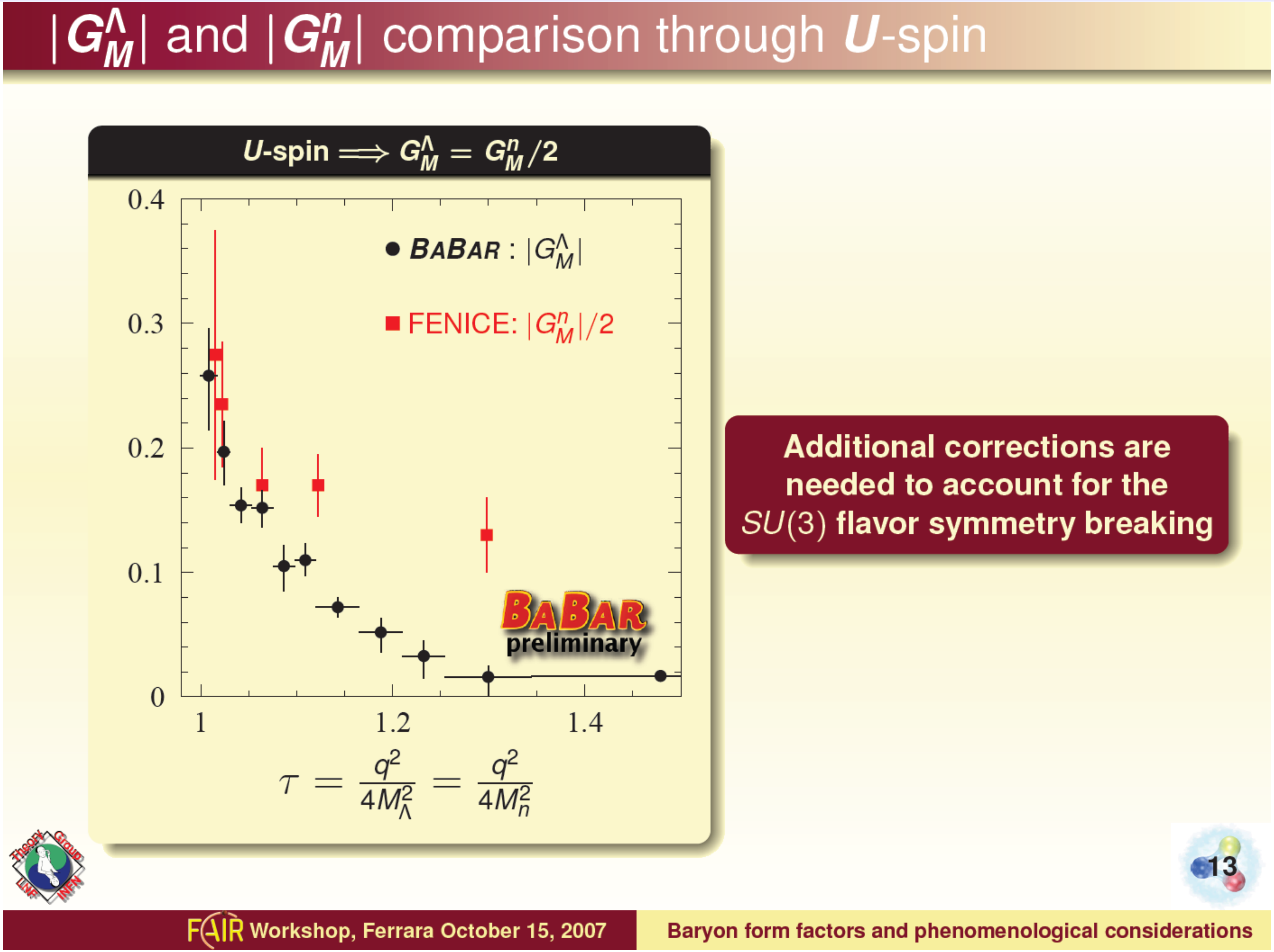
FENICE: $e^+e^- \longrightarrow n\overline{n}$

$$\left|G^{n}(4M_{n}^2)\right| = 2.0 \pm 0.7$$

14

ECT* - Trento, May 22, 2008 Unexpected threshold behavior in $e^+e^- \!\longrightarrow\! \mathcal{B}\overline{\mathcal{B}}$

Baryon octet and FFs at threshold



$|G_M^\Lambda|$ and $|G_M^n|$ comparison through *U*-spin

U-spin $\Longrightarrow G_M^\Lambda = G_M^n/2$

$$\tau = \frac{q^2}{4M_\Lambda^2} = \frac{q^2}{4M_n^2}$$

Additional corrections are needed to account for the $SU(3)$ flavor symmetry breaking

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FAIR Workshop, Ferrara October 15, 2007

Baryon form factors and phenomenological considerations

Extraction of FFs

Two approaches:

- From cross section

1) **Select $e^+e^- \rightarrow X_{had}\,\gamma_{ISR}$** events and **measure $\sigma(e^+e^- \rightarrow X_{had})$**:

\# signal in mass bin
(after acceptance and resousion)

center value of $p\bar{p}$ mass bin

$$\sigma(m_{had}) = \frac{dN/dm_{had}}{\varepsilon R\, dL/dm_{had}} = \frac{4\pi\alpha^2\beta C}{3\,q^2}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right]$$

efficiency of reconstruction
and radiative corrections in mass bin

ISR differential luminosity
From: 1) L_{int} * W(x)
2) $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$

$|F(q^2)|^2$

2) **Extract** effective form factor **$F(q^2)$**

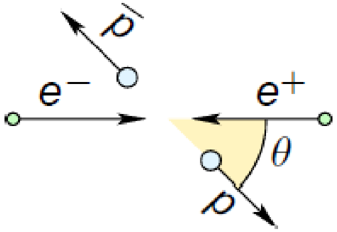
3) **Assume $\mu\cdot|G_E| = |G_M|$** and identify **$F = G_M(q^2)$**

- Used in e+e- colliders at low energies and if low stats available
- **Separation between $G_E(q^2)$ and $G_M(q^2)$ not possible !!**

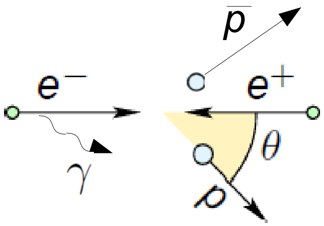
Extraction of FFs

- From angular analysis: $|G_E/G_M|$

1) **Analyze** distribution of **proton helicity angle** in $p\bar{p}$ rest frame



$$\boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}(\cos\theta)} = \frac{\pi\alpha_e^2 C}{8M^2\tau\sqrt{\tau(\tau-1)}}\left[\tau|G_M|^2(1+\cos^2\theta)\ +|G_E|^2\sin^2\theta\right]}$$



$$\frac{dN}{d\cos\theta'_p} = A\left(H_M(\cos\theta'_p, m_{pp}) + \left|\frac{G_E}{G_M}\right| H_E(\cos\theta'_p, m_{pp})\right)$$

No analytic form: extracted from MC

2) Angular distribution analized **in bins of $q^2 = m^2_{pp}$ and fitted** with previous equation with two free parameters: **A and $|G_E/G_M|$**

- **Separation between $G_E(q^2)$ and $G_M(q^2)$ without any assumption possible** if high stats and precise luminosity measurement

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

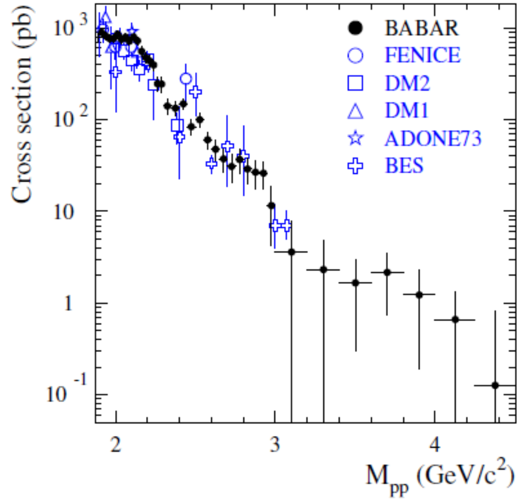
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

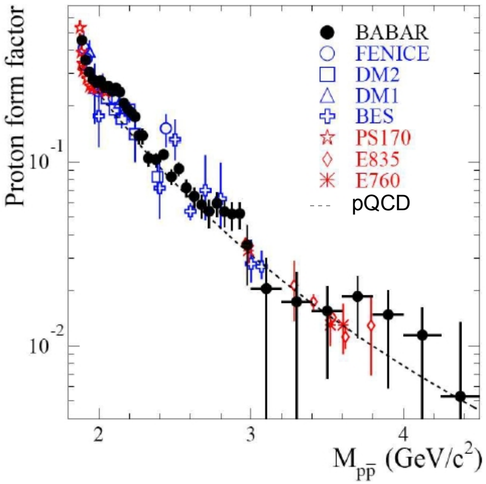
Publication based on 232 fb-1

4025 selected signal events with 6% $e^+e^- \to pp\pi^0$

- **Effective form factor extracted from cross section measurement**

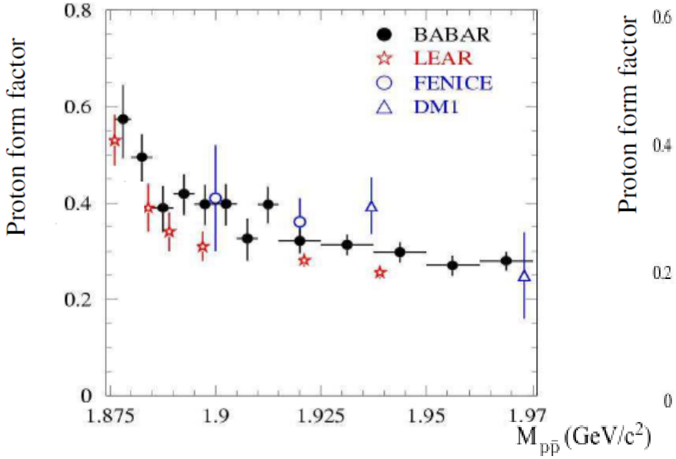
$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}|F|^2$$

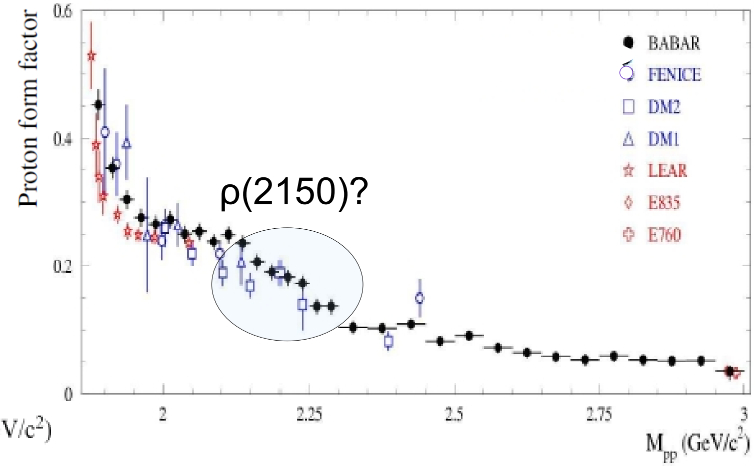




High statistics unveils:

- peak at threshold
- plateau from 1.8 to 2.1 GeV/c^2
- decrease with drops at 2.25 (ρ(2150)?) and 3 GeV/c^2 (baryon thresholds? S-wave states open up quickly?)





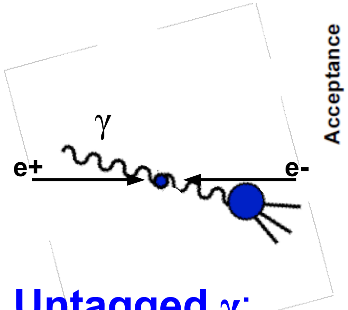
pQCD holds well for all m_{pp} but at high m_{pp} **is a factor 2 greater than in space like region !!**

ISR @ BABAR / BESIII

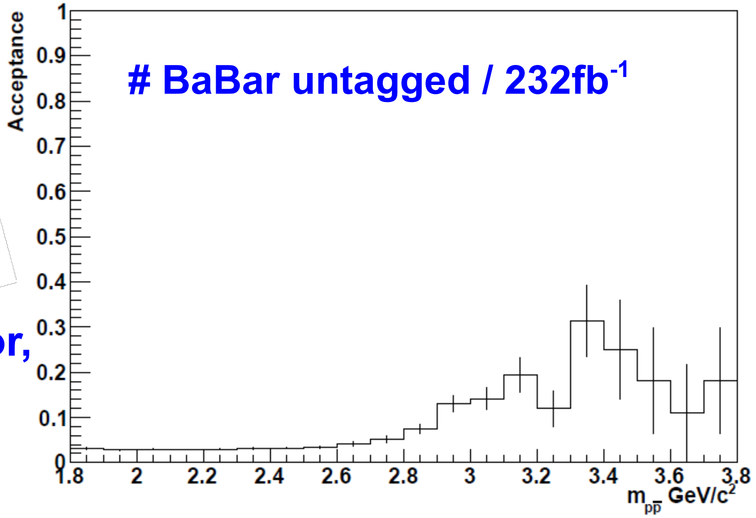
Geometrical acceptance:

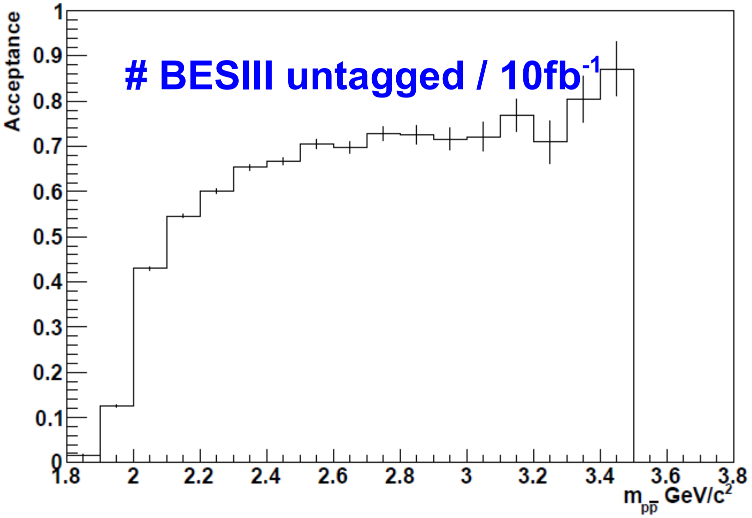
$M_{hadr} << \sqrt{s} \rightarrow$ need high luminosities
Photon tagging unavoidable

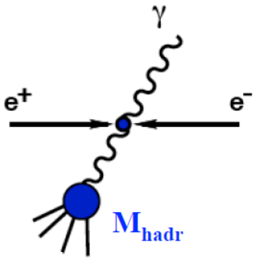
$M_{hadr} <$ but close to $\sqrt{s}$
untagged measurement possible



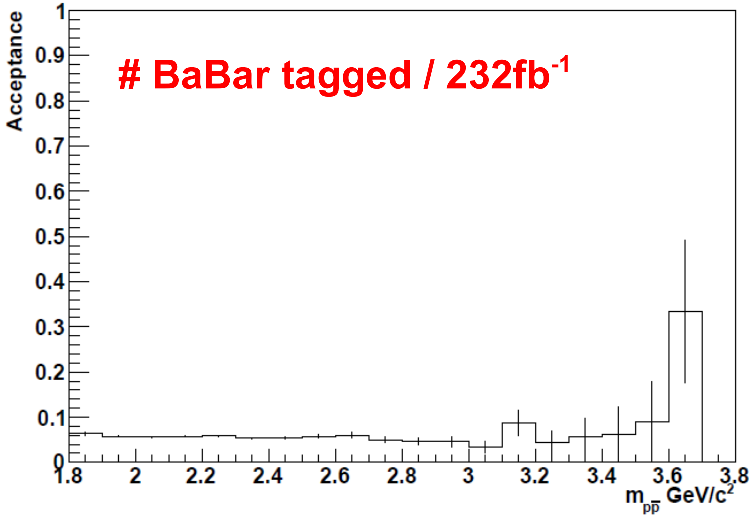
Untagged γ:
γ not in detector, hadrons in detector

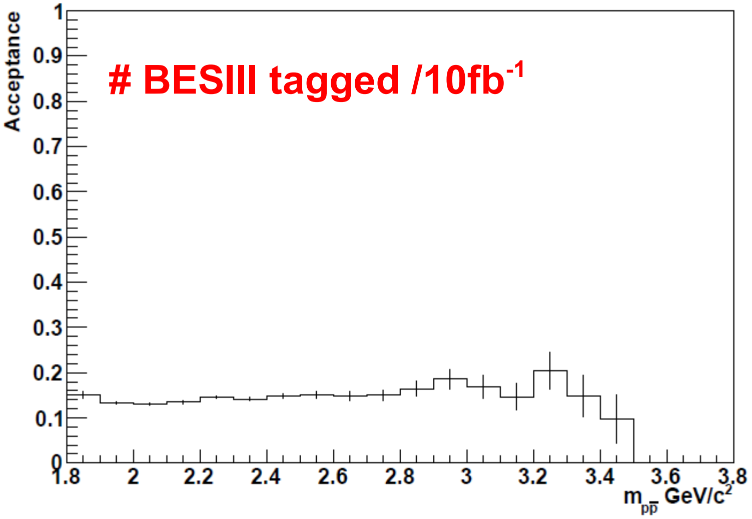




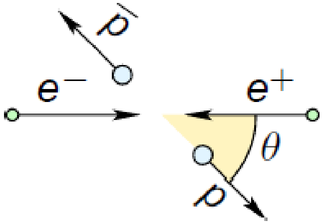


Tagged γ:
γ and hadrons in detector





Time-like em Form Factors

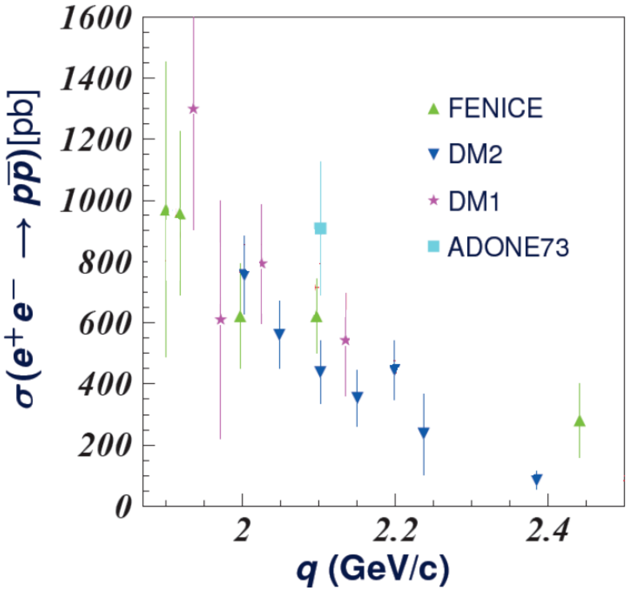


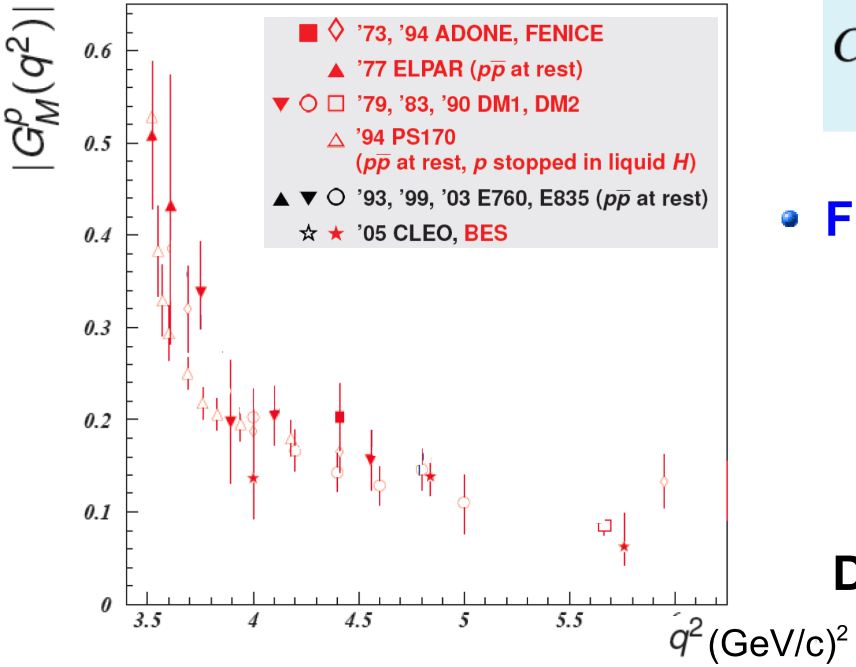
- Only **measurements of cross sections** available

$$\sigma(e^+e^- \longrightarrow p\bar{p}) = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{2M_p^2}{q^2}|G_E|^2\right]$$

C: Coulomb interaction correction at threshold

$$C = \frac{y}{1-e^{-y}}; \quad y = \frac{\pi\alpha M}{\beta q}$$





- **Form factors** extracted under **assumption**:

$\mu_p \cdot |G_E| = |G_M| = |G^p|$

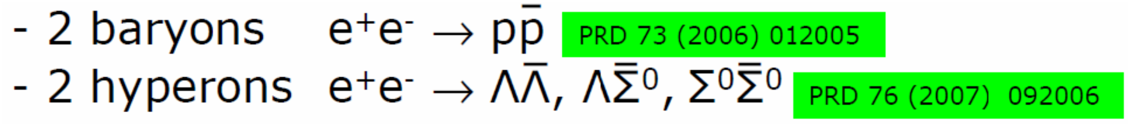
$$|G^p|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{16\pi\alpha^2 C}{3}\frac{\sqrt{1-1/\tau}}{4q^2}(1+1/2\tau)}$$

Due to low statistics: no true separation of G_E and G_M

BABAR / BESIII Data

Status:

BaBar publications on ISR in baryons:



- 2 baryons $e^+e^- \rightarrow p\bar{p}$ PRD 73 (2006) 012005
- 2 hyperons $e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$ PRD 76 (2007) 092006

based on 232 fb^{-1}. Analysis of remaining statistics (x2) ongoing.

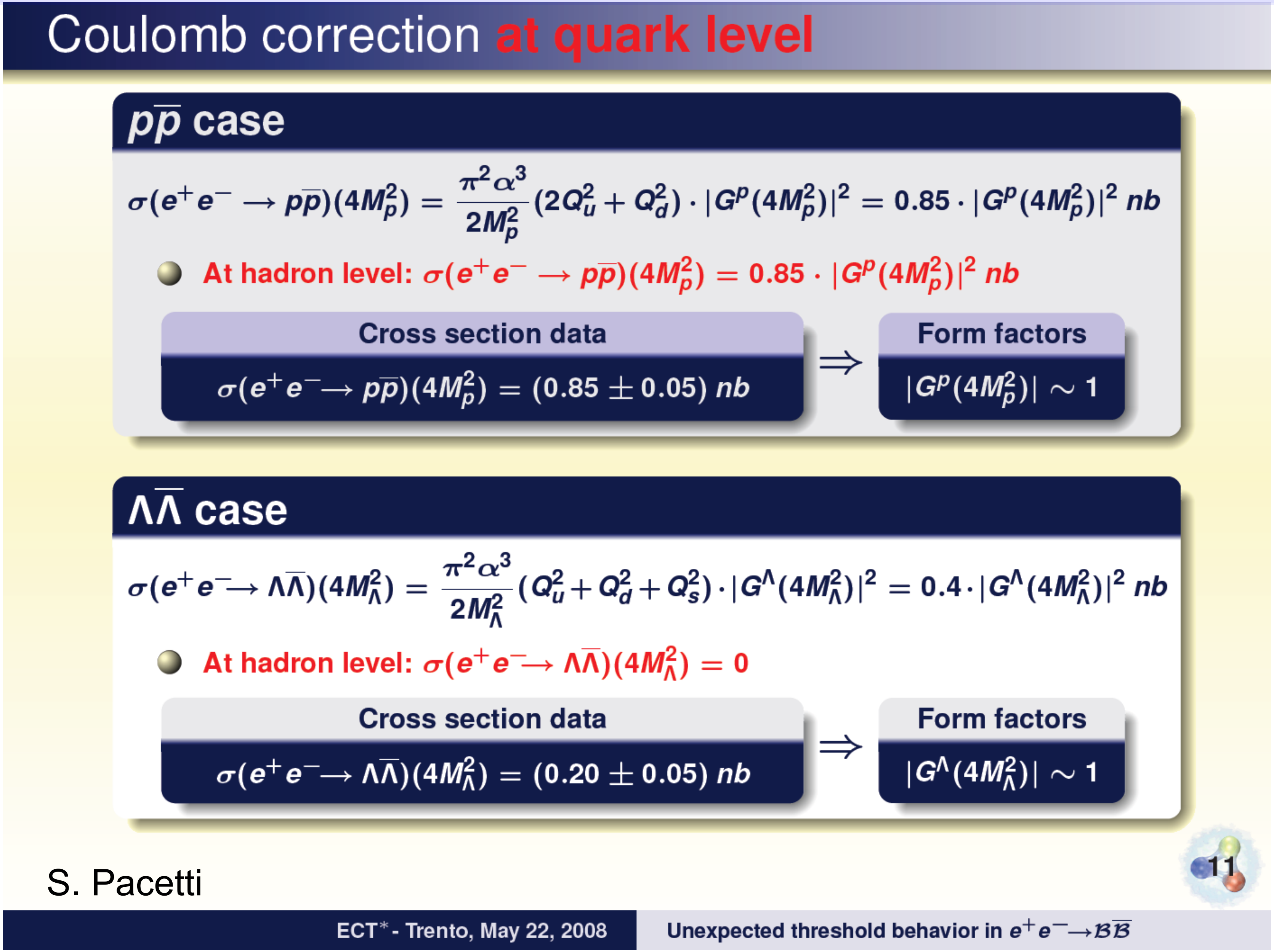
BESIII available data which could be used for Baryon FFs analysis:

- 1225M J/Ψ
- 106M + 8pb^{-1} Ψ(3686)
- 2.9 fb^{-1} Ψ(3770)
- 0.5 fb^{-1} Ψ(4040)
- R-scan 2–3GeV in 100 MeV bins with 10^5 hadrons/bin planned

- For this presentation BaBar's published 232 fb^{-1} at Y(4S) will be shown and compared with BESIII simulations for 10fb^{-1} at Ψ''
- Generator used for all ISR channels: PHOKHARA 7.0

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]
[H.Czyz,J.H.Kühn,E.Nowak,G.Rodrigo,Eur.Phys.J C35,527 (2004)]

Coulomb correction for quarks



Coulomb correction at quark level

$p\bar{p}$ case

$$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}(2Q_u^2+Q_d^2)\cdot|G^p(4M_p^2)|^2 = 0.85\cdot|G^p(4M_p^2)|^2\ nb$$

- At hadron level: $\sigma(e^+e^- \to p\bar{p})(4M_p^2) = 0.85\cdot|G^p(4M_p^2)|^2\ nb$

Cross section data

$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = (0.85 \pm 0.05)\ nb$

$\Rightarrow$

Form factors

$|G^p(4M_p^2)| \sim 1$

$\Lambda\bar{\Lambda}$ case

$$\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = \frac{\pi^2\alpha^3}{2M_\Lambda^2}(Q_u^2+Q_d^2+Q_s^2)\cdot|G^\Lambda(4M_\Lambda^2)|^2 = 0.4\cdot|G^\Lambda(4M_\Lambda^2)|^2\ nb$$

- At hadron level: $\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = 0$

Cross section data

$\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = (0.20 \pm 0.05)\ nb$

$\Rightarrow$

Form factors

$|G^\Lambda(4M_\Lambda^2)| \sim 1$

S. Pacetti

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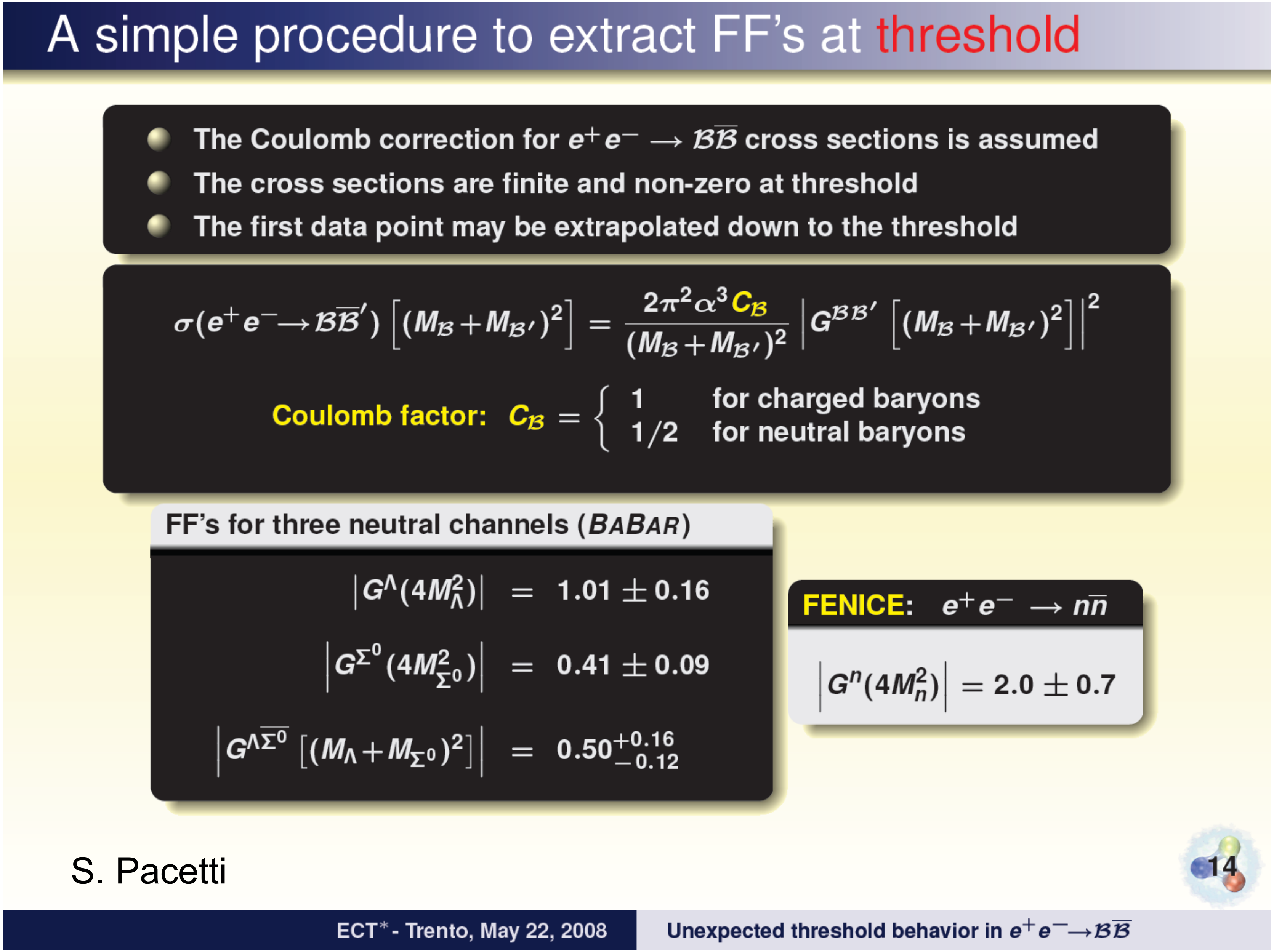
ECT* - Trento, May 22, 2008

Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

FFs at threshold



A simple procedure to extract FF's at threshold

- The Coulomb correction for $e^+e^- \longrightarrow \mathcal{B}\overline{\mathcal{B}}$ cross sections is assumed
- The cross sections are finite and non-zero at threshold
- The first data point may be extrapolated down to the threshold

$$\sigma(e^+e^-\longrightarrow\mathcal{B}\overline{\mathcal{B}}')\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right] = \frac{2\pi^2\alpha^3 C_{\mathcal{B}}}{(M_{\mathcal{B}}+M_{\mathcal{B}'})^2}\left|G^{\mathcal{B}\mathcal{B}'}\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right]\right|^2$$

Coulomb factor: $C_{\mathcal{B}} = \begin{cases} 1 & \text{for charged baryons} \\ 1/2 & \text{for neutral baryons} \end{cases}$

FF's for three neutral channels (BABAR)

$$\left|G^{\Lambda}(4M_{\Lambda}^2)\right| = 1.01 \pm 0.16$$

$$\left|G^{\Sigma^0}(4M_{\Sigma^0}^2)\right| = 0.41 \pm 0.09$$

$$\left|G^{\Lambda\overline{\Sigma^0}}\left[(M_{\Lambda}+M_{\Sigma^0})^2\right]\right| = 0.50^{+0.16}_{-0.12}$$

FENICE: $e^+e^- \longrightarrow n\overline{n}$

$$\left|G^{n}(4M_{n}^2)\right| = 2.0 \pm 0.7$$

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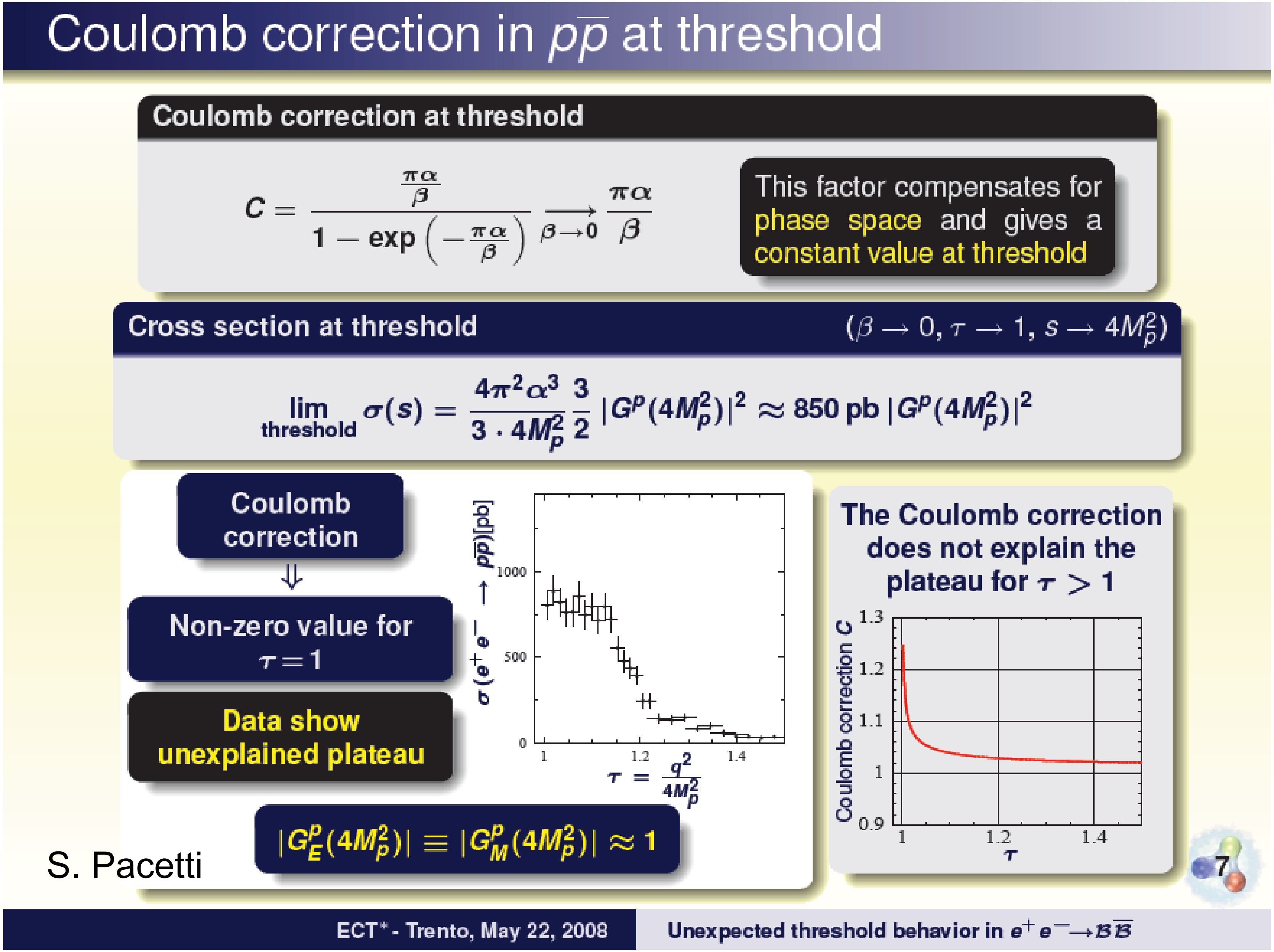
ECT* - Trento, May 22, 2008 Unexpected threshold behavior in $e^+e^-\longrightarrow\mathcal{B}\overline{\mathcal{B}}$

Coulomb correction



Coulomb correction in $p\bar{p}$ at threshold

Coulomb correction at threshold

$$C = \frac{\frac{\pi\alpha}{\beta}}{1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta}$$

This factor compensates for phase space and gives a constant value at threshold

Cross section at threshold $(\beta \to 0, \tau \to 1, s \to 4M_p^2)$

$$\lim_{\text{threshold}} \sigma(s) = \frac{4\pi^2\alpha^3}{3\cdot 4M_p^2}\frac{3}{2}|G^p(4M_p^2)|^2 \approx 850\text{ pb}\,|G^p(4M_p^2)|^2$$

Coulomb correction

$\Downarrow$

Non-zero value for $\tau = 1$

Data show unexplained plateau

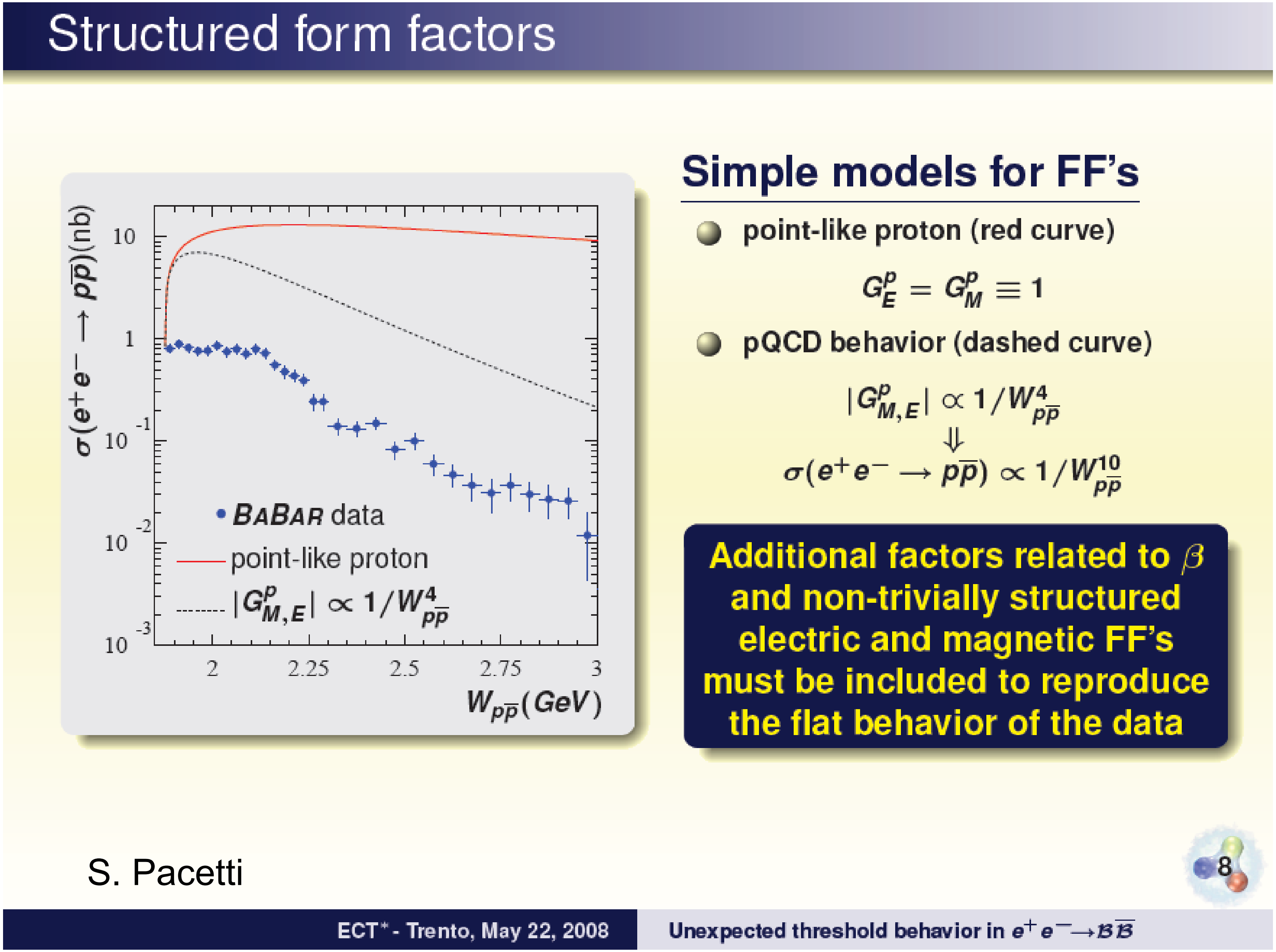
$$|G_E^p(4M_p^2)| \equiv |G_M^p(4M_p^2)| \approx 1$$

The Coulomb correction does not explain the plateau for $\tau > 1$

S. Pacetti

ECT* - Trento, May 22, 2008 Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

Simple FFs models



Structured form factors

Simple models for FF's

- point-like proton (red curve)

$$G^p_E = G^p_M \equiv 1$$

- pQCD behavior (dashed curve)

$$|G^p_{M,E}| \propto 1/W^4_{p\bar{p}}$$
$$\Downarrow$$
$$\sigma(e^+e^- \to p\bar{p}) \propto 1/W^{10}_{p\bar{p}}$$

Additional factors related to β and non-trivially structured electric and magnetic FF's must be included to reproduce the flat behavior of the data

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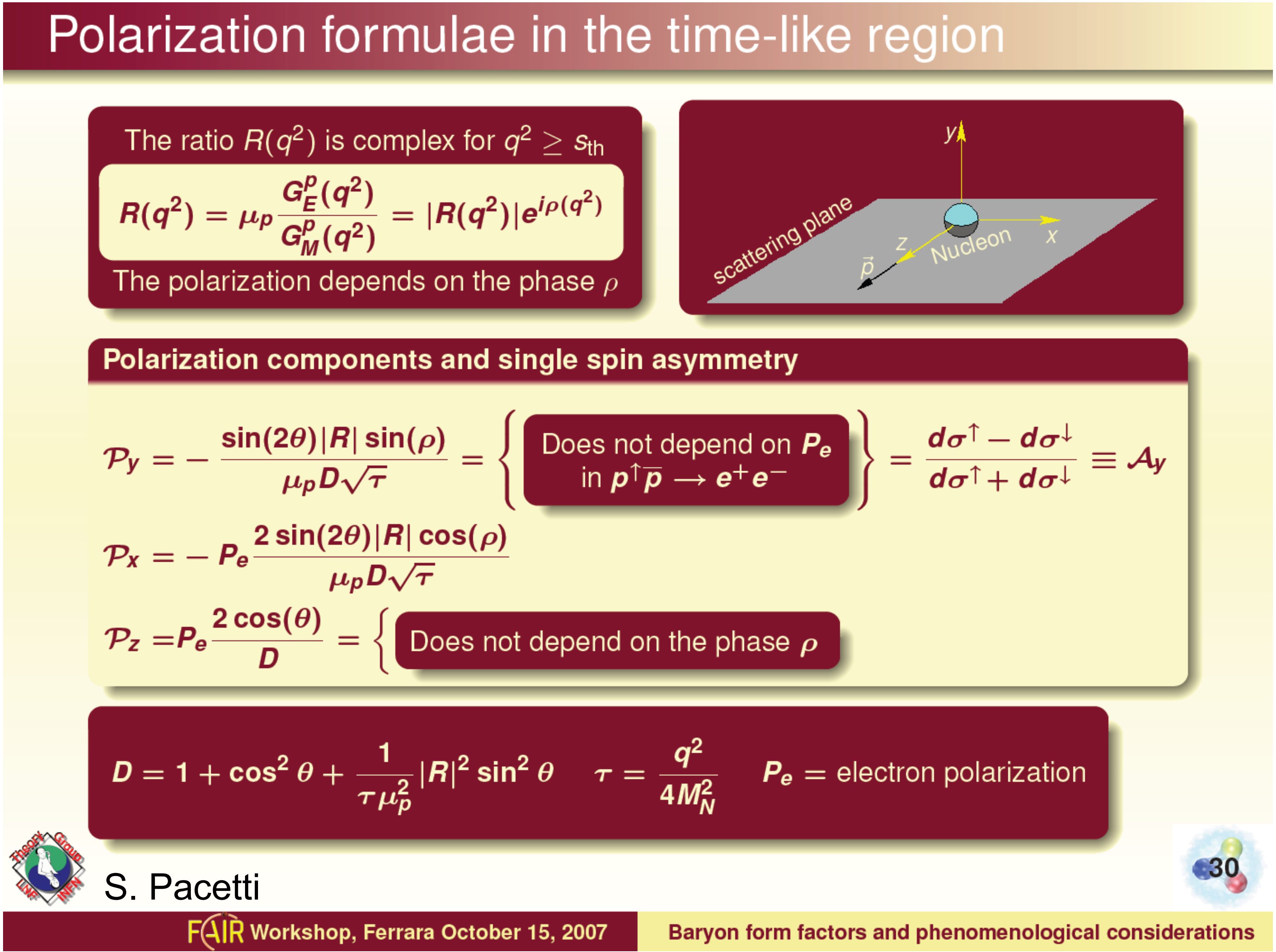
Polarization in TL region



Polarization formulae in the time-like region

The ratio $R(q^2)$ is complex for $q^2 \geq s_{\text{th}}$

$$R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)} = |R(q^2)|e^{i\rho(q^2)}$$

The polarization depends on the phase ρ

Polarization components and single spin asymmetry

$$\mathcal{P}_y = -\frac{\sin(2\theta)|R|\sin(\rho)}{\mu_p D\sqrt{\tau}} = \left\{ \boxed{\text{Does not depend on } P_e \text{ in } p^{\uparrow}\overline{p} \longrightarrow e^+e^-} \right\} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \equiv \mathcal{A}_y$$

$$\mathcal{P}_x = -P_e \frac{2\sin(2\theta)|R|\cos(\rho)}{\mu_p D\sqrt{\tau}}$$

$$\mathcal{P}_z = P_e \frac{2\cos(\theta)}{D} = \left\{ \boxed{\text{Does not depend on the phase } \rho} \right.$$

$$D = 1 + \cos^2\theta + \frac{1}{\tau\mu_p^2}|R|^2\sin^2\theta \qquad \tau = \frac{q^2}{4M_N^2} \qquad P_e = \text{electron polarization}$$

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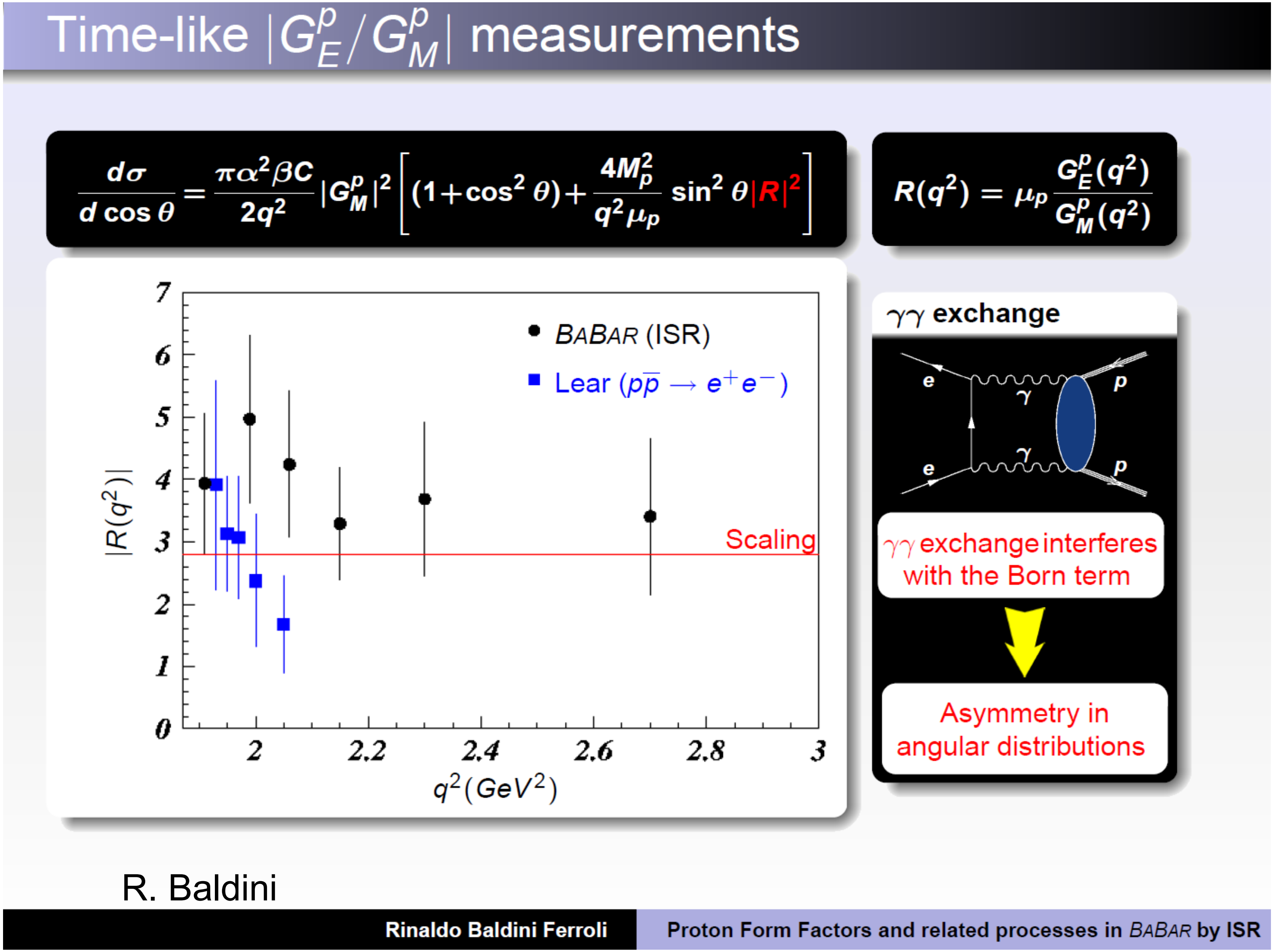
FAIR Workshop, Ferrara October 15, 2007

Baryon form factors and phenomenological considerations

TL region measurements



Time-like $|G_E^p/G_M^p|$ measurements

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M^p|^2\left[(1+\cos^2\theta)+\frac{4M_p^2}{q^2\mu_p}\sin^2\theta|R|^2\right]$$

$$R(q^2) = \mu_p\frac{G_E^p(q^2)}{G_M^p(q^2)}$$

$\gamma\gamma$ exchange

$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions

R. Baldini

Rinaldo Baldini Ferroli | **Proton Form Factors and related processes in *BABAR* by ISR**

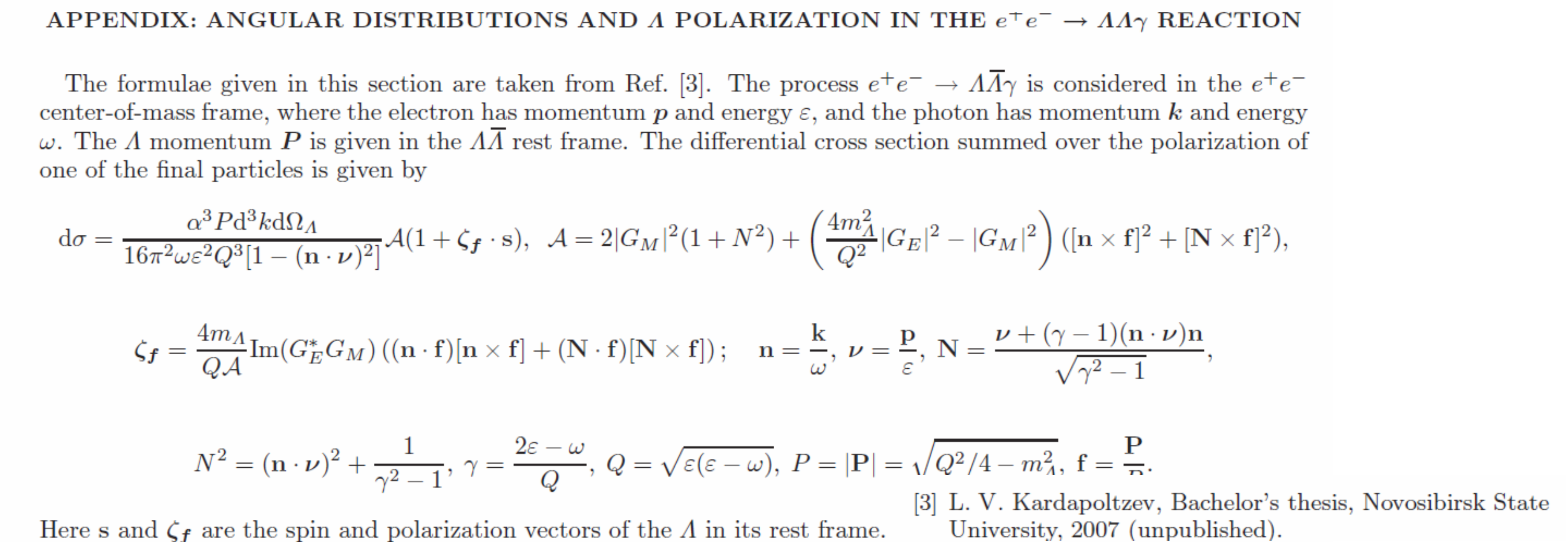
$e^+e^- \to \Lambda\,\bar{\Lambda}\,\gamma_{ISR}$

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]

$$R_\Lambda = 1 - \alpha_\Lambda\ \bar{S}_\Lambda \cdot \bar{n}_{\pi^-}$$

$$\begin{aligned} d\sigma\left(e^+e^- \to \bar\Lambda(\to \pi^+\bar p)\Lambda(\to \pi^- p)\right) = \\ d\sigma\left(e^+e^- \to \bar\Lambda\Lambda\right)\left(S_{\Lambda,\bar\Lambda} \to \mp\alpha_\Lambda n_{\pi\mp}\right) \\ \times\ d\bar\Phi_2(q_1; p_{\pi^+}, p_{\bar p})d\bar\Phi_2(q_2; p_{\pi^-}, p_p) \\ \times\ \mathrm{Br}(\bar\Lambda \to \pi^+\bar p)\mathrm{Br}(\Lambda \to \pi^- p)\ , \end{aligned}$$

$$\begin{aligned} L^{ij}H_{ij} \simeq\ & \tfrac{(4\pi\alpha)^3}{4Q^2y_1y_2}\left(1+\cos^2\theta_\gamma\right)\Big\{|G_M|^2\left(1+\cos^2\theta_{\bar\Lambda}\right) + \tfrac{1}{\tau}|G_E|^2\sin^2\theta_{\bar\Lambda} - \alpha_\Lambda\tfrac{Im(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar\Lambda})\left(n^y_{\pi^-} - n^y_{\pi^+}\right) \\ & +\alpha^2_\Lambda\tfrac{Re(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar\Lambda})\left(n^z_{\pi^-}n^x_{\pi^+} + n^z_{\pi^+}n^x_{\pi^-}\right) - \alpha^2_\Lambda\left(\tfrac{1}{\tau}|G_E|^2 + |G_M|^2\right)\sin^2\theta_{\bar\Lambda}\ \ n^x_{\pi^+}n^x_{\pi^-} \\ & -\alpha^2_\Lambda\left(\tfrac{1}{\tau}|G_E|^2 - |G_M|^2\right)\sin^2\theta_{\bar\Lambda}\ \ n^y_{\pi^+}n^y_{\pi^-} + \alpha^2_\Lambda\left(\tfrac{1}{\tau}|G_E|^2\sin^2\theta_{\bar\Lambda} - |G_M|^2\left(1+\cos^2\theta_{\bar\Lambda}\right)\right)\ \ n^z_{\pi^+}n^z_{\pi^-}\Big\} \end{aligned}$$



APPENDIX: ANGULAR DISTRIBUTIONS AND Λ POLARIZATION IN THE $e^+e^- \to \Lambda\Lambda\gamma$ REACTION

The formulae given in this section are taken from Ref. [3]. The process $e^+e^- \to \Lambda\bar\Lambda\gamma$ is considered in the e^+e^- center-of-mass frame, where the electron has momentum $\boldsymbol{p}$ and energy ε, and the photon has momentum $\boldsymbol{k}$ and energy ω. The Λ momentum $\boldsymbol{P}$ is given in the $\Lambda\bar\Lambda$ rest frame. The differential cross section summed over the polarization of one of the final particles is given by

$$\mathrm{d}\sigma = \frac{\alpha^3 P \mathrm{d}^3k \mathrm{d}\Omega_\Lambda}{16\pi^2\omega\varepsilon^2Q^3[1-(\mathbf{n}\cdot\boldsymbol{\nu})^2]}\mathcal{A}(1+\boldsymbol{\zeta_f}\cdot\mathrm{s}),\ \ \mathcal{A} = 2|G_M|^2(1+N^2) + \left(\frac{4m^2_\Lambda}{Q^2}|G_E|^2 - |G_M|^2\right)([\mathbf{n}\times\mathbf{f}]^2 + [\mathbf{N}\times\mathbf{f}]^2),$$

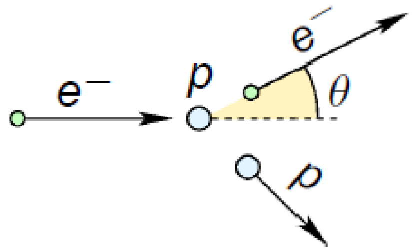
$$\boldsymbol{\zeta_f} = \frac{4m_\Lambda}{Q\mathcal{A}}\mathrm{Im}(G_E^*G_M)\left((\mathbf{n}\cdot\mathbf{f})[\mathbf{n}\times\mathbf{f}] + (\mathbf{N}\cdot\mathbf{f})[\mathbf{N}\times\mathbf{f}]\right);\quad \mathbf{n} = \frac{\mathbf{k}}{\omega},\ \boldsymbol{\nu} = \frac{\mathbf{p}}{\varepsilon},\ \mathbf{N} = \frac{\boldsymbol{\nu} + (\gamma-1)(\mathbf{n}\cdot\boldsymbol{\nu})\mathbf{n}}{\sqrt{\gamma^2-1}},$$

$$N^2 = (\mathbf{n}\cdot\boldsymbol{\nu})^2 + \frac{1}{\gamma^2-1},\ \gamma = \frac{2\varepsilon-\omega}{Q},\ Q = \sqrt{\varepsilon(\varepsilon-\omega)},\ P = |\mathbf{P}| = \sqrt{Q^2/4 - m^2_\Lambda},\ \mathbf{f} = \frac{\mathbf{P}}{\ }.$$

Here s and $\boldsymbol{\zeta_f}$ are the spin and polarization vectors of the Λ in its rest frame.

[3] L. V. Kardapoltzev, Bachelor's thesis, Novosibirsk State University, 2007 (unpublished).

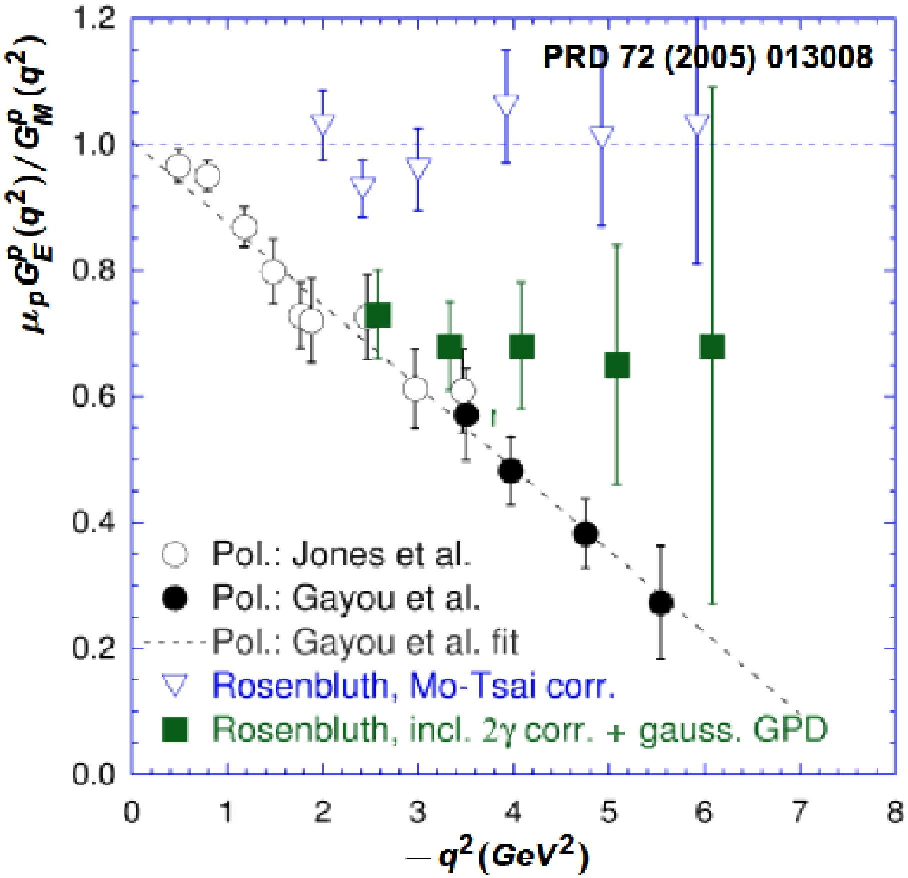
Space-like em Form Factors



Rosenbluth

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta}{2}}{4E_e^3 \sin^4\frac{\theta}{2}}\left[G_E^2 + \tau\left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)G_M^2\right]\frac{1}{1+\tau}$$

$$\sigma_R = d\sigma/d\Omega\,[\varepsilon(1+\tau)/\sigma_{Mott}] = \boxed{\tau G_M^2 + \varepsilon G_E^2}$$



Scaling:

$$G_E^p \simeq G_M^p/\mu_p$$

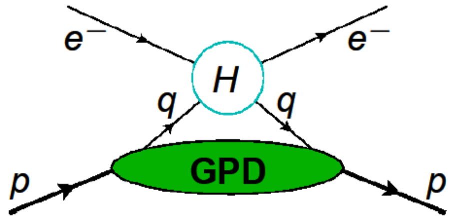
$$\tau = \frac{q^2}{4M_N^2}$$

Polarization method:

$$\frac{G_E^p(q^2)}{G_M^p(q^2)} = -\sqrt{\frac{-2\epsilon}{\tau(1+\epsilon)}\frac{\mathcal{P}_\parallel}{\mathcal{P}_\perp}}$$

$$\frac{1}{\epsilon} = 1 + 2(1-\tau)\tan^2\left(\frac{\theta}{2}\right)$$

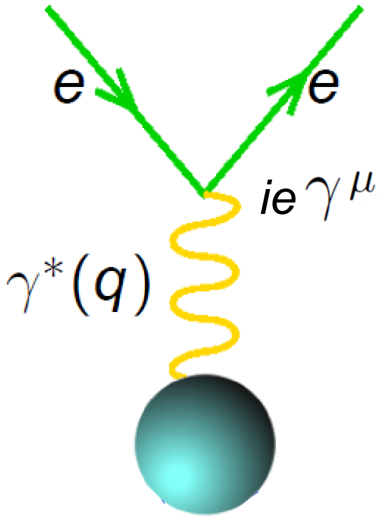
GPD + 2γ



Electromagnetic Form Factors

Suppose we want to determine the **charge distribution** of an object

→ **Elastic scattering**



$$j^{fi}_\mu = -e\bar{u}_f\gamma_\mu u_i\, e^{iq\cdot x} = -\frac{e}{2m}\bar{u}^f(\underbrace{(p_f+p_i)_\mu}_{\text{charge}}\underbrace{-i\sigma_{\mu\nu}q^\nu}_{\text{magnetic moment}})u^i\, e^{iq\cdot x}$$

$$T^{fi} = -i\int j_\mu{}^{fi}A^\mu d^4x$$

$$\boldsymbol{\mu} = -\frac{e}{2m}\boldsymbol{\sigma}$$

Static, spinless object:

$$\frac{d\sigma}{d\Omega} = \frac{(Z\alpha)^2E^2}{4p^4\sin^4\frac{\theta}{2}}(1 - v^2\sin^2\frac{\theta}{2}) \cdot |\mathrm{F}(\mathbf{q})|^{\mathbf{2}}$$

$$F(\mathbf{q}) = \int \rho(\mathrm{x})\mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{x}}\mathrm{d}^3\mathrm{x}$$

$|p_f| = |p_i| = |p|$

θ: scattering angle

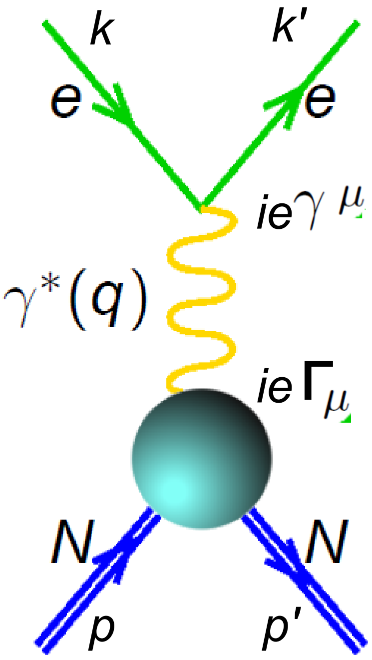
and measure **angular distribution** of scattered electron

Electromagnetic Form Factors

Elastic scattering on nucleon: non static, spin 1/2 object

Spin ½ : two FFs (Pauli, Dirac)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$



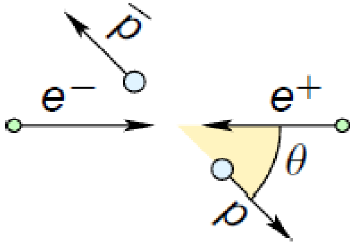
Rosenbluth formula

$$\left[\frac{d\sigma}{d\Omega}\right]_{lab} = \frac{(\alpha)^2}{4E^2\sin^4\frac{\theta}{2}}\frac{E'}{E}\left[(F_1^2 - \frac{\kappa^2q^2}{4M^2}F_2^2)\cos^2\frac{\theta}{2}\right] - \frac{q^2}{2M^2}(F_1+\kappa F_2)^2\sin^2\frac{\theta}{2}$$

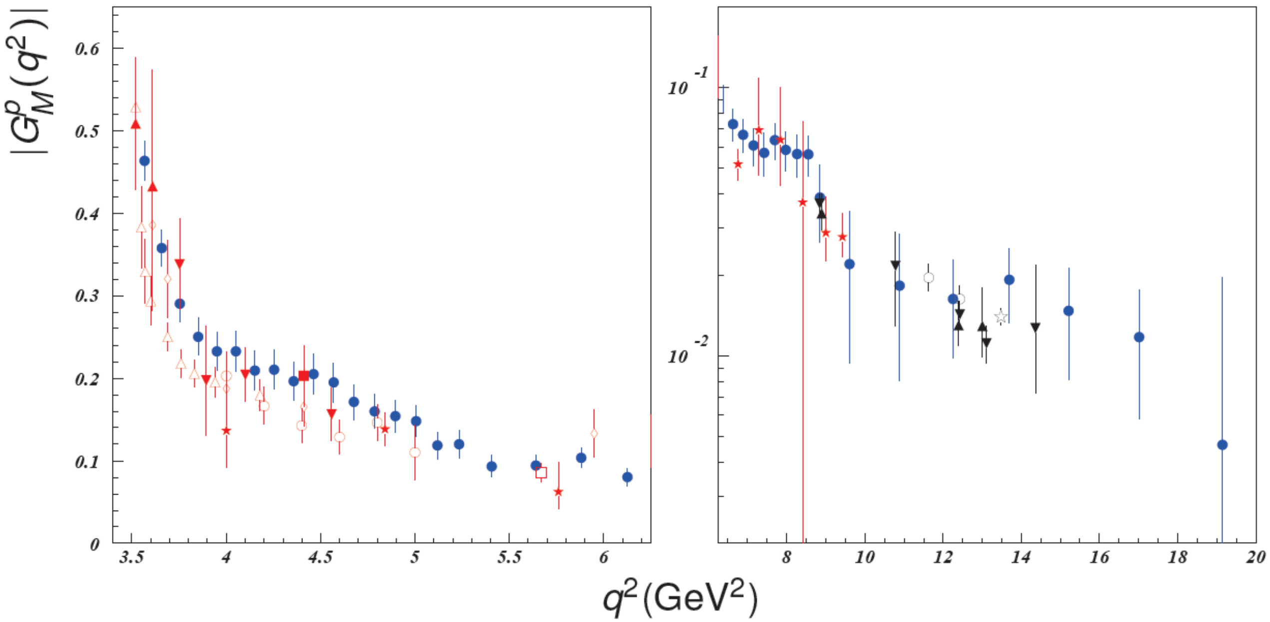
$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

$$\left[\frac{d\sigma}{d\Omega}\right]_{lab} = \frac{\alpha^2 E'_e\cos^2\frac{\theta}{2}}{4E_e^3\sin^4\frac{\theta}{2}}\left[G_E^2 + \tau\left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)G_M^2\right]\frac{1}{1+\tau}$$

Time-like em Form Factors



- Only **measurements of cross sections** available
- **Form factors** (if) extracted under **assumption**: $G_M^p = \mu_p G_E^p$
- Due to low statistics: **no true separation of G_E and G_M**



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\sqrt{1-1/\tau}}{4q^2}\, C\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta\,|G_E|^2\right]$$

Coulomb correction: $C \approx \frac{y}{1-e^{-y}}$ $\qquad y = \frac{\pi\alpha}{\beta}$

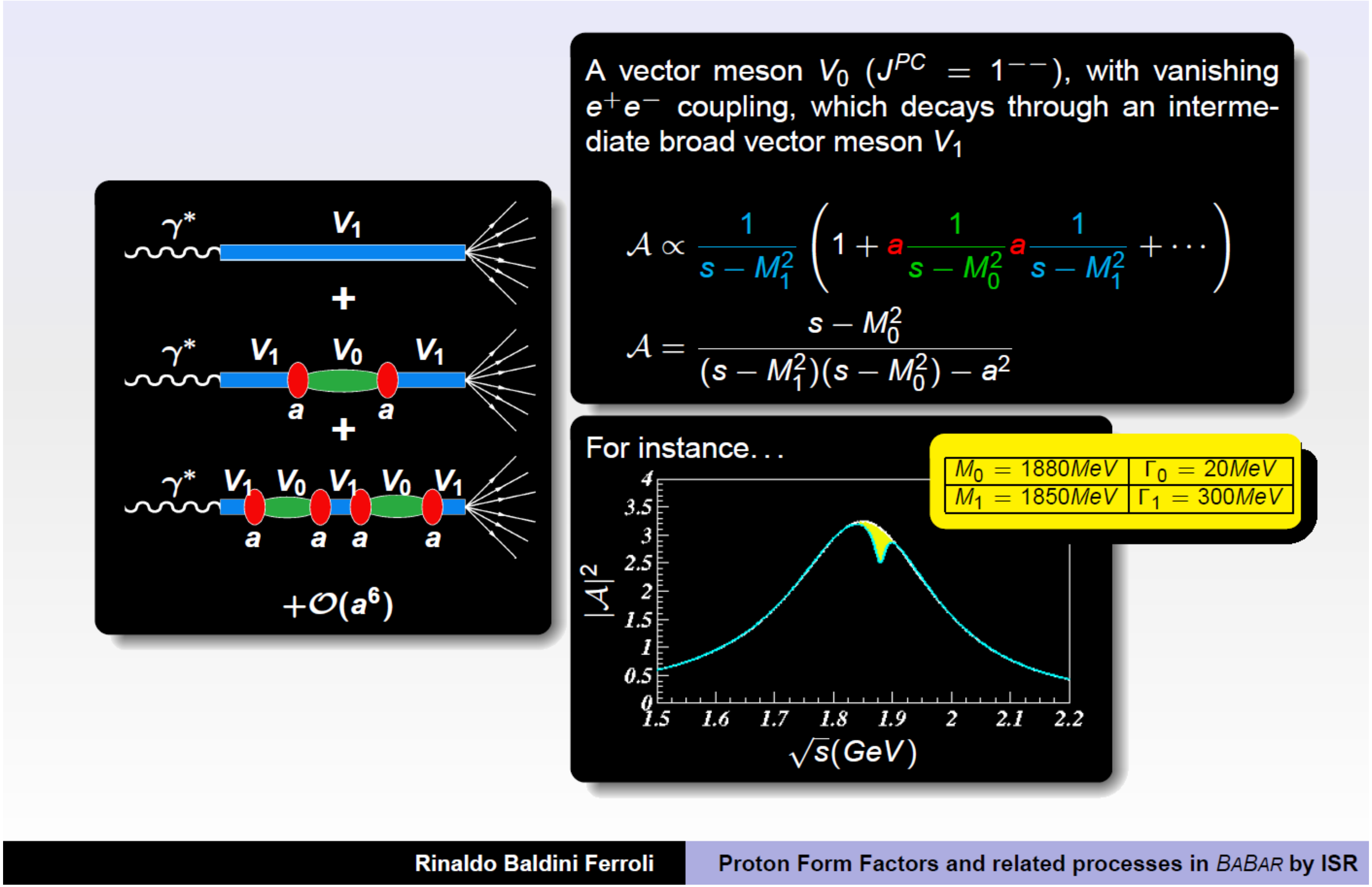
All these data have been obtained assuming $|G_M^p| = |G_E^p| \equiv |G^p|$

$$|G^p|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{16\pi\alpha^2 C}{3}\,\frac{\sqrt{1-1/\tau}}{4q^2}\,(1+1/2\tau)}$$

'Baryonium'

[P.J. Franzini and F.J. Gilman, 1985]

Baryonium: dip in ppbar processes



A vector meson V_0 ($J^{PC} = 1^{--}$), with vanishing e^+e^- coupling, which decays through an intermediate broad vector meson V_1

$$\mathcal{A} \propto \frac{1}{s - M_1^2}\left(1 + a\frac{1}{s - M_0^2}\,a\frac{1}{s - M_1^2} + \cdots\right)$$

$$\mathcal{A} = \frac{s - M_0^2}{(s - M_1^2)(s - M_0^2) - a^2}$$

For instance...

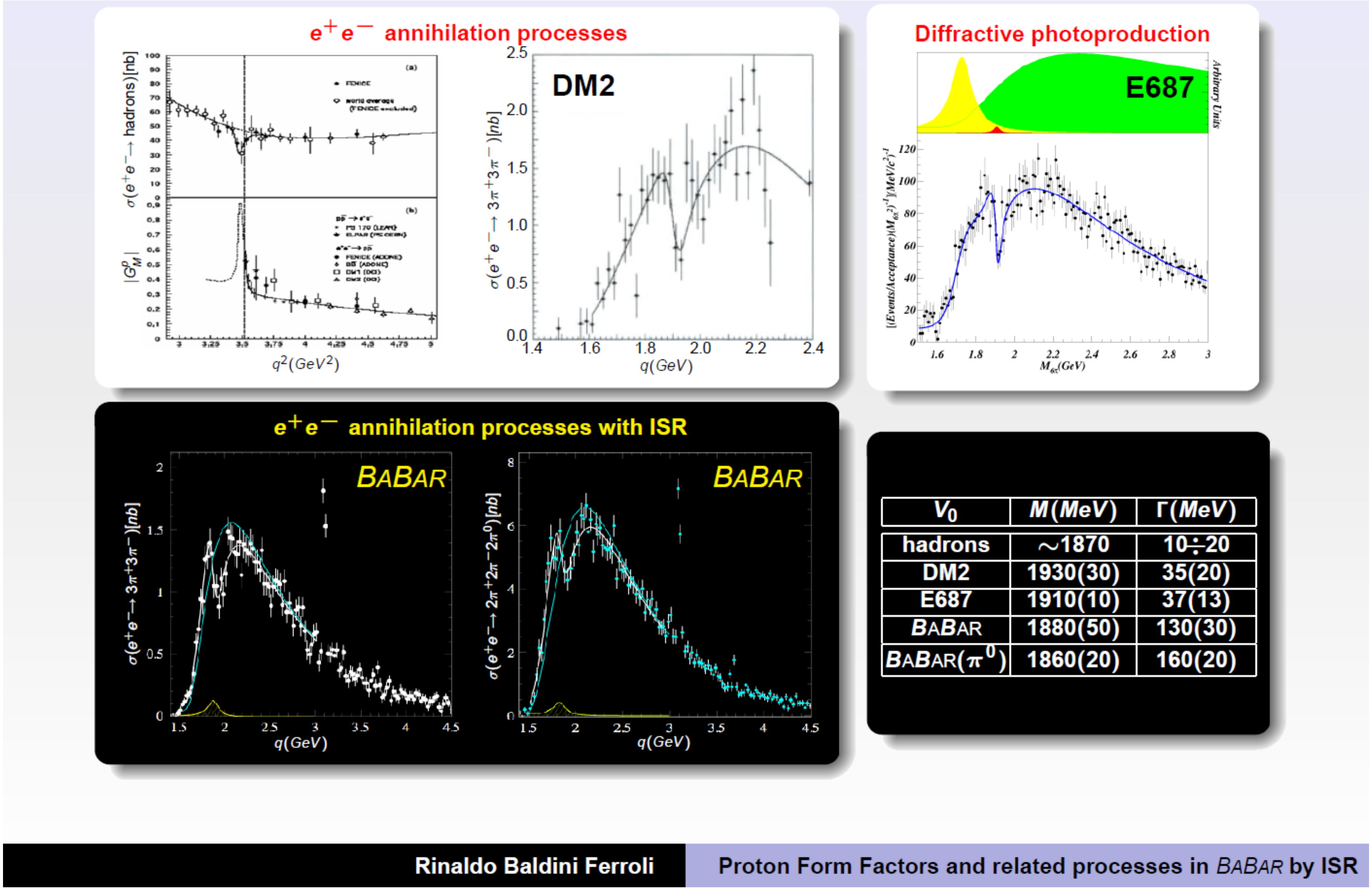
$M_0 = 1880 MeV$	$\Gamma_0 = 20 MeV$
$M_1 = 1850 MeV$	$\Gamma_1 = 300 MeV$

Rinaldo Baldini Ferroli **Proton Form Factors and related processes in *BABAR* by ISR**

'Baryonium'

Dips in multi-hadronic processes

[P.J. Franzini and F.J. Gilman, 1985]



e^+e^- annihilation processes

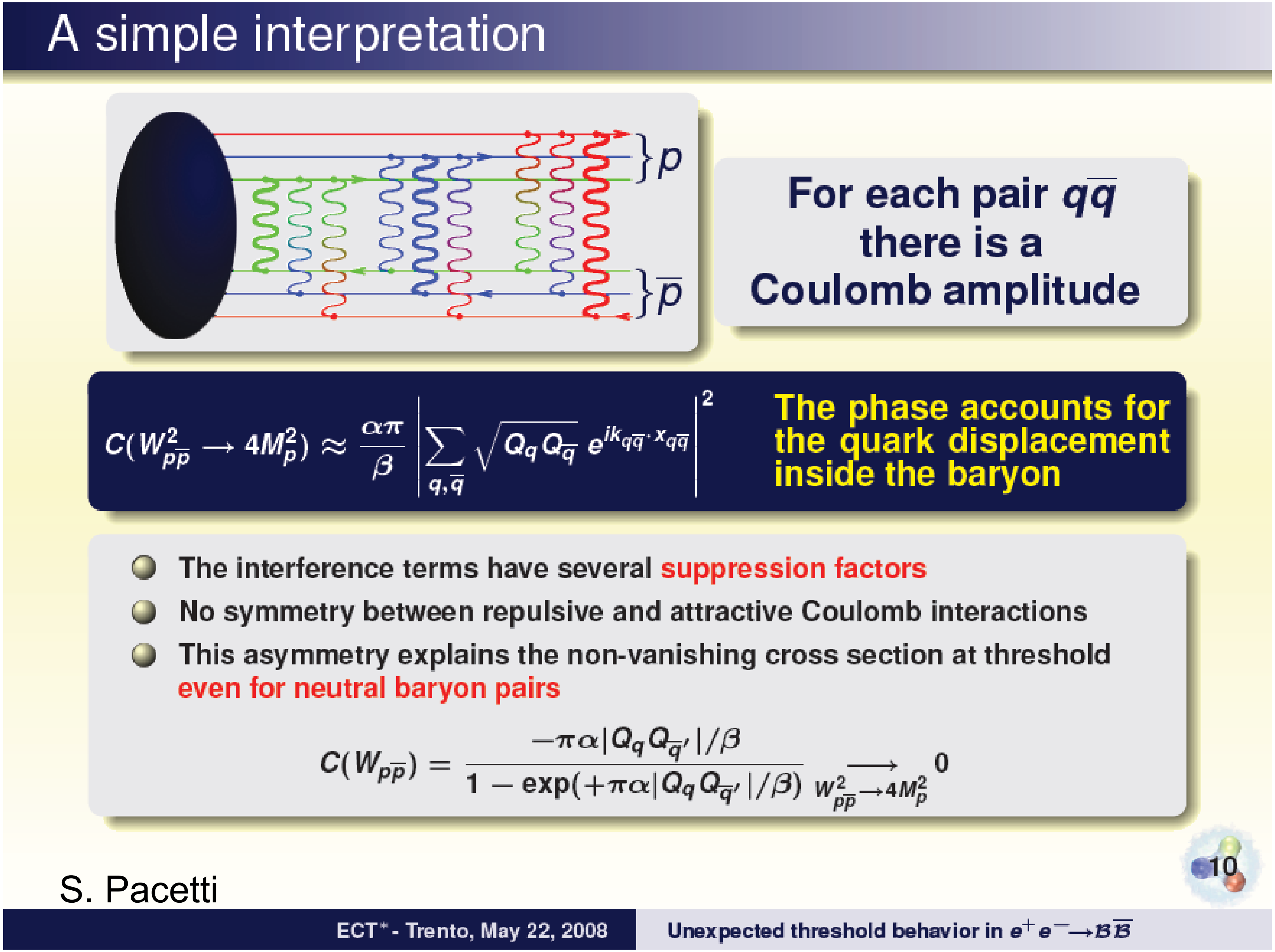
Diffractive photoproduction

e^+e^- annihilation processes with ISR

V_0	$M(MeV)$	$\Gamma(MeV)$
hadrons	∼1870	10÷20
DM2	1930(30)	35(20)
E687	1910(10)	37(13)
BABAR	1880(50)	130(30)
BABAR(π^0)	1860(20)	160(20)

Rinaldo Baldini Ferroli Proton Form Factors and related processes in *BABAR* by ISR

Coulomb term



A simple interpretation

For each pair $q\bar{q}$ there is a Coulomb amplitude

$$C(W^2_{p\bar{p}} \to 4M_p^2) \approx \frac{\alpha\pi}{\beta}\left|\sum_{q,\bar{q}}\sqrt{Q_q Q_{\bar{q}}}\; e^{ik_{q\bar{q}}\cdot x_{q\bar{q}}}\right|^2$$

The phase accounts for the quark displacement inside the baryon

- The interference terms have several suppression factors
- No symmetry between repulsive and attractive Coulomb interactions
- This asymmetry explains the non-vanishing cross section at threshold even for neutral baryon pairs

$$C(W_{p\bar{p}}) = \frac{-\pi\alpha|Q_q Q_{\bar{q}'}|/\beta}{1-\exp(+\pi\alpha|Q_q Q_{\bar{q}'}|/\beta)} \xrightarrow[W^2_{p\bar{p}}\to 4M_p^2]{} 0$$

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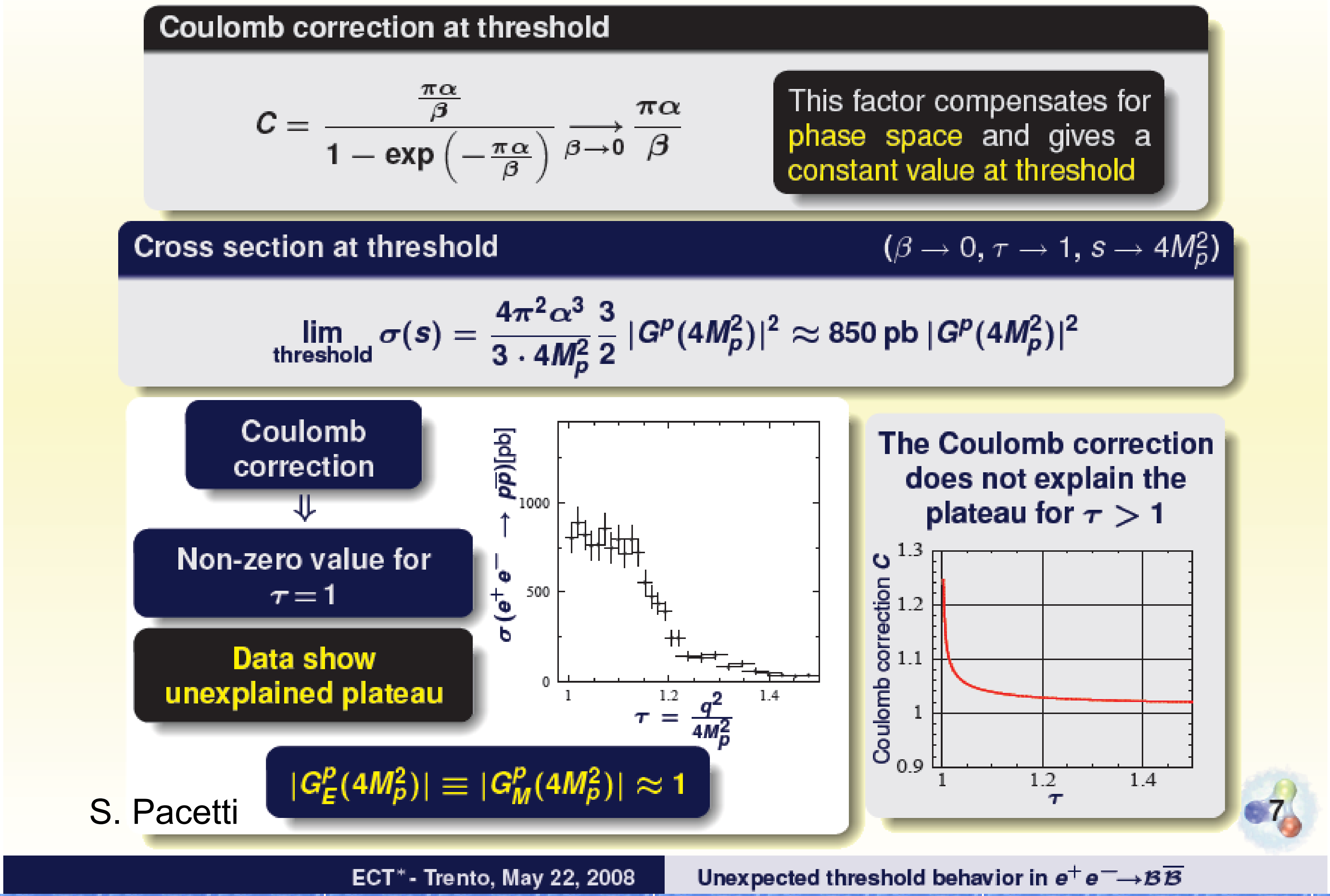
Unexpected threshold behavior in $e^+e^-\to\mathcal{B}\overline{\mathcal{B}}$

Coulomb term



Coulomb correction at threshold

$$C = \frac{\frac{\pi\alpha}{\beta}}{1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta}$$

This factor compensates for phase space and gives a constant value at threshold

Cross section at threshold ($\beta \to 0, \tau \to 1, s \to 4M_p^2$)

$$\lim_{\text{threshold}} \sigma(s) = \frac{4\pi^2\alpha^3}{3\cdot 4M_p^2}\,\frac{3}{2}\,|G^p(4M_p^2)|^2 \approx 850\,\text{pb}\,|G^p(4M_p^2)|^2$$

Coulomb correction

⇓

Non-zero value for $\tau = 1$

Data show unexplained plateau

$$|G_E^p(4M_p^2)| \equiv |G_M^p(4M_p^2)| \approx 1$$

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The Coulomb correction does not explain the plateau for $\tau > 1$

7

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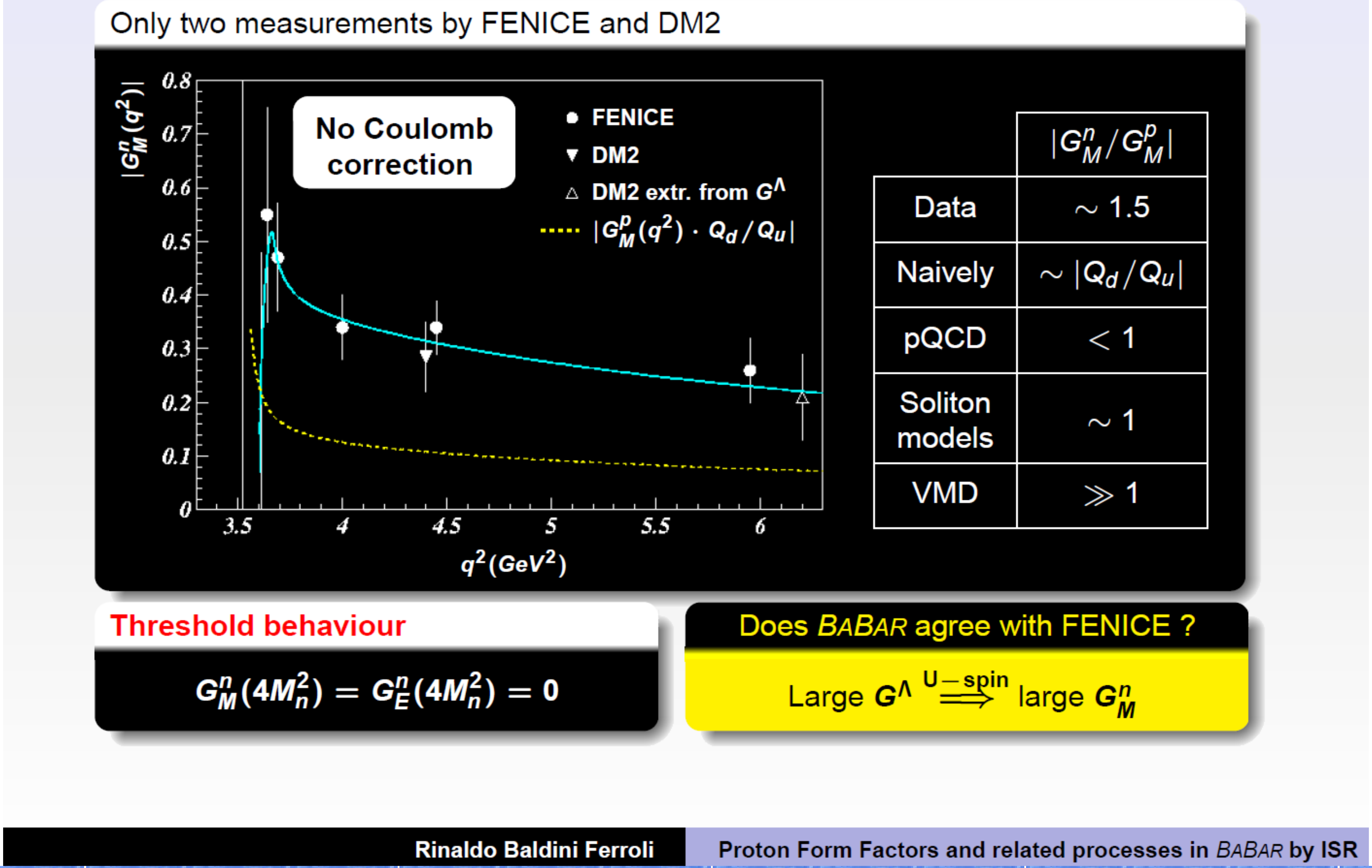
Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

Time-like G_M^n measurements



Only two measurements by FENICE and DM2

	$\lvert G_M^n/G_M^p \rvert$
Data	~ 1.5
Naively	$\sim \lvert Q_d/Q_u \rvert$
pQCD	< 1
Soliton models	~ 1
VMD	$\gg 1$

Threshold behaviour

$$G_M^n(4M_n^2) = G_E^n(4M_n^2) = 0$$

Does *BaBar* agree with FENICE ?

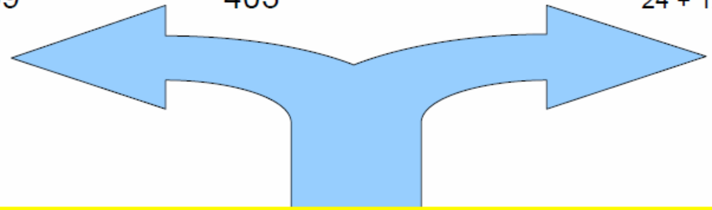
$$\text{Large } G^\Lambda \xrightarrow{\text{U-spin}} \text{large } G_M^n$$

Rinaldo Baldini Ferroli **Proton Form Factors and related processes in *BaBar* by ISR**

$e^+e^- \rightarrow p\,\bar{p}$

R-scan 2-3 GeV

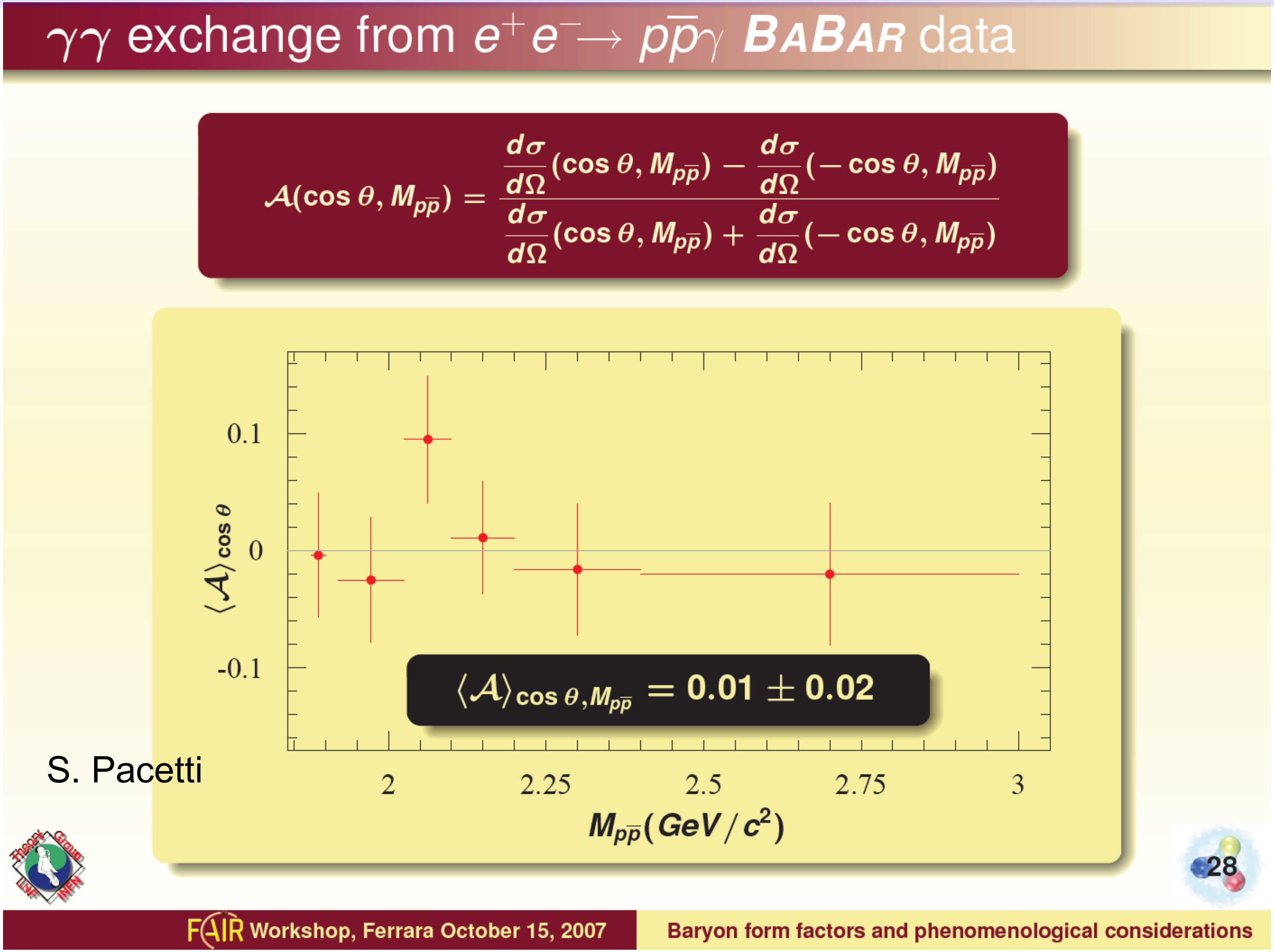
E_{cm}	$N_{had,observed}(10^5)$	L(1/pb)	N_{ppbar} * 50%Eff	$N_{ppbarISR}$(10fb^{-1}produced)	6% Eff_{tagg} +30%Eff_{untagg}
2.0	1.0	7.1	2288	21417 (1.95 < E'_{cm} <= 2.05 GeV)	1285 + 6425 = 7710
2.1	1.5	10.2	2413	16842	1011 + 5053 = 6063
2.2	2.0	13.5	2147	11474	688 + 3442 = 4131
2.3	3.0	20.9	2170	7450	447 + 2235 = 2682
2.4	3.5	25.1	1685	4573	274 + 1372 = 1646
2.5	4.0	29.4	1275	2763	166 + 829 = 995
2.6	5.0	37.9	1066	1631	98 + 489 = 587
2.7	6.0	48.0	881	1025	62 + 308 = 369
2.8	7.0	60.3	728	612	37 + 184 = 220
2.9	8.0	69.9	559	403	24 + 121 = 145



MORE STATISTICS, MUCH FASTER
→ **WE NEED THIS R-SCAN!!**

- Input values provided by Guangshun HUANG
- Observed **ppbar** events after eff of 50%
- **Produced** ISR tagged and untagged at psi(3770) for 10 fb-1
- **Reconstructed** after 6%Eff for tagged events and 30% for untagged events

Gamma gamma exchange



$\gamma\gamma$ exchange from $e^+e^- \to p\bar{p}\gamma$ BaBar data

$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$

$$\langle\mathcal{A}\rangle_{\cos\theta, M_{p\bar{p}}} = 0.01 \pm 0.02$$

S. Pacetti