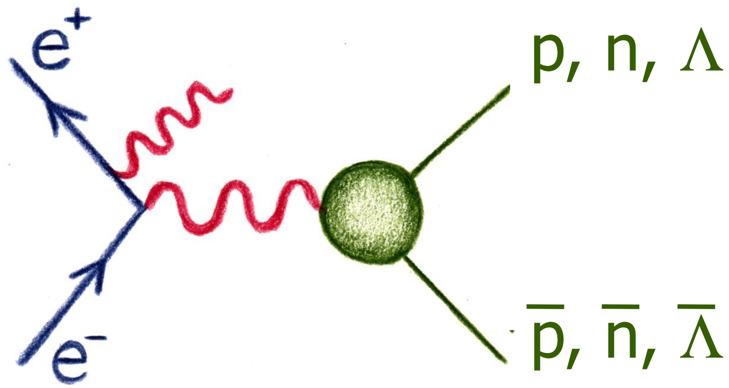


Hadronic Form Factors Measurements in BESIII

Simulations:

ISR Physics: the proton Case
BES III vs BABAR: expectations

First look at the data:

BES-III experiment
Tagged psi(3770) data analysis

Cristina Morales – Helmholtz Institute Mainz

Orsay, January 2011

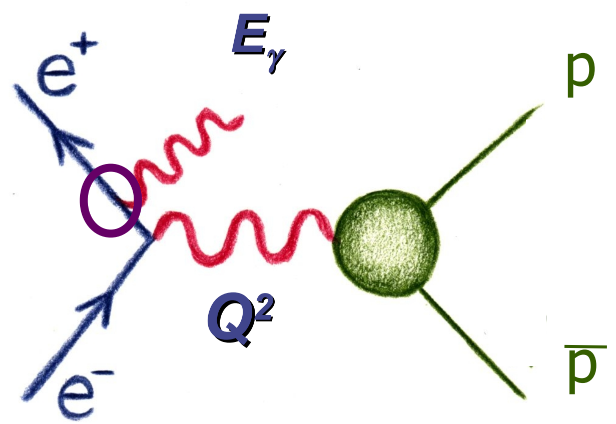
Part I : Simulations

The proton case

[S.Binner,J.H.Kühn,K.Melnikov,Phys.Lett.B.459,279(1999)]

A way to get the hadronic cross section $\sigma(e^+e^- \to p\bar{p})$ vs Q^2 at a fixed energy collider:

the Radiative Return (ISR)



$$E_\gamma = \frac{s - Q^2}{2\sqrt{s}}$$

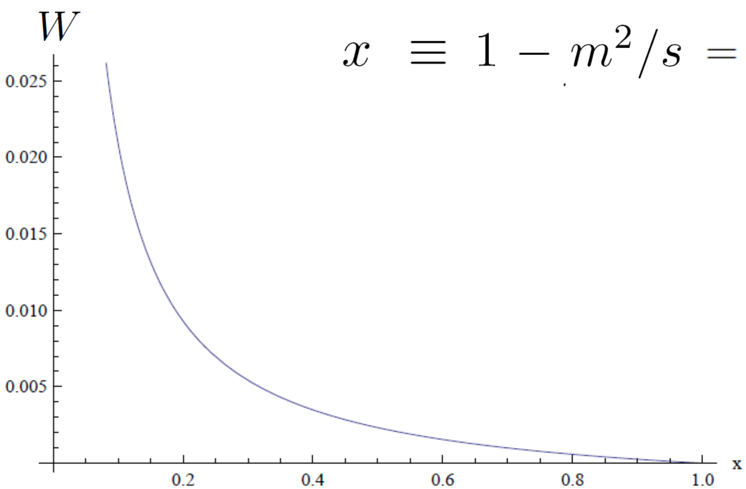
$$\sigma_{e^+e^-\to f+n\gamma}(s) = \frac{2\sqrt{s'}}{s} W \sigma_{e^+e^-\to f}(s')$$

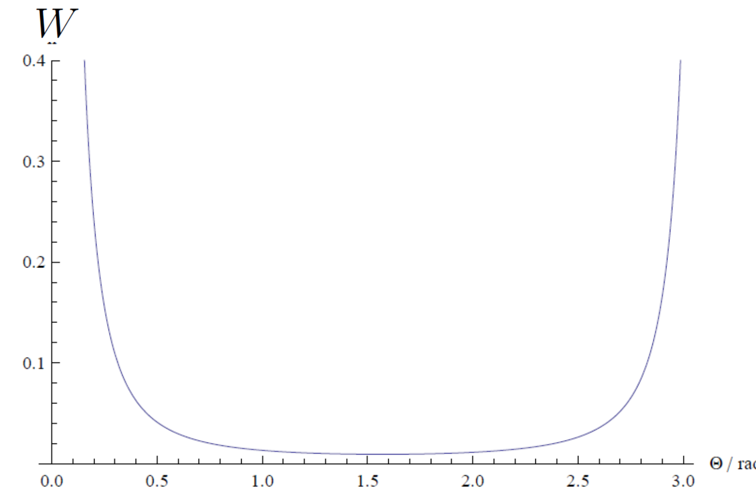
Timelike nucleon FF can be separated though angular analysis

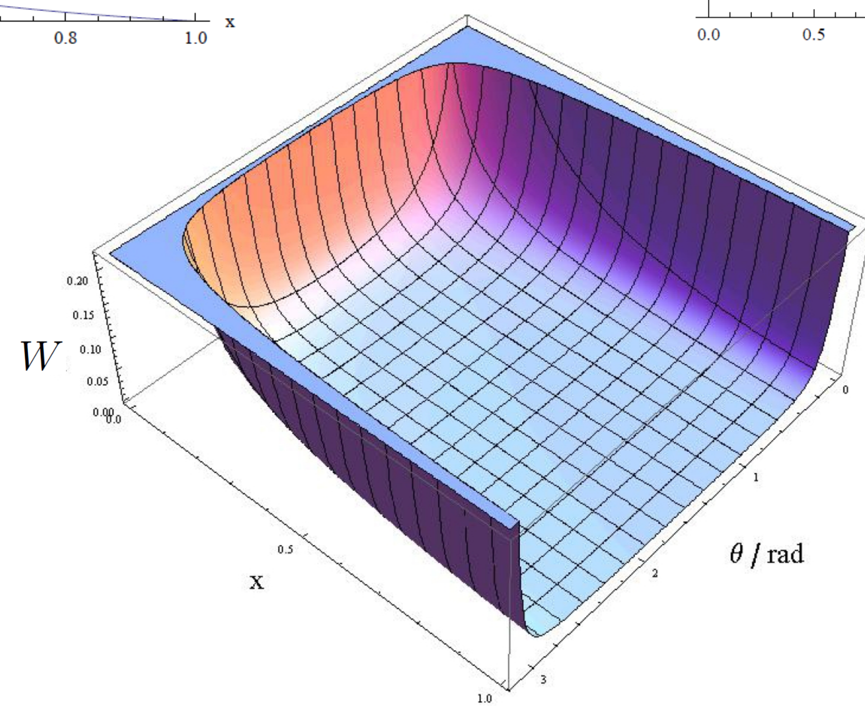
Radiator function

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

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





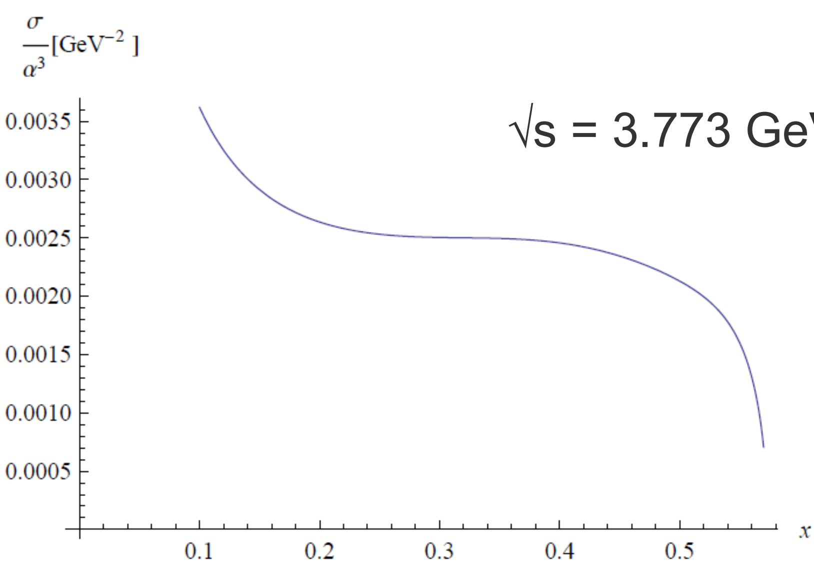


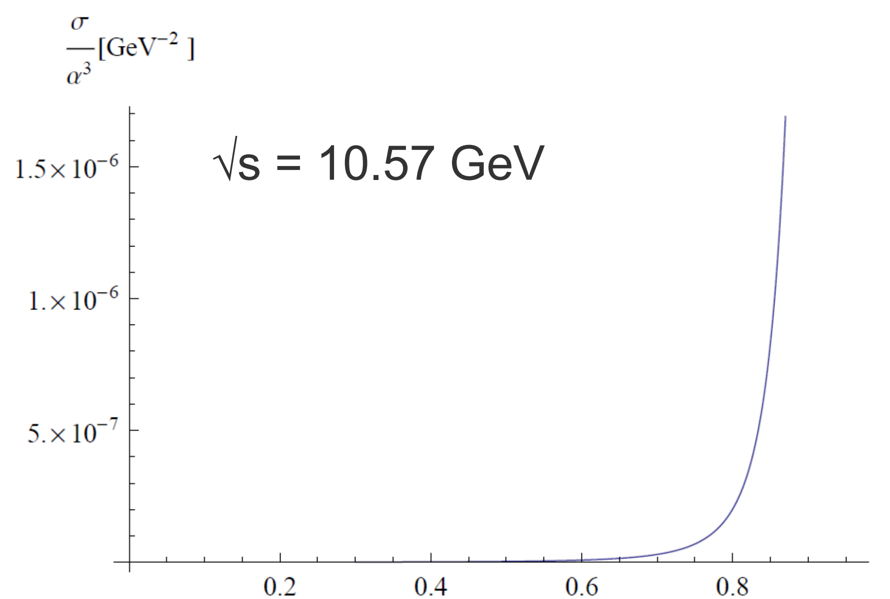
√s = 3.773 GeV

Plots by Christoph Zimmermann

ISR Cross Sections. Expected Statistics

[E. A. Kuraev, V. V. Bytev, E. Tomasi-Gustafsson, arXiv:1103.4470v1(2011)]





	BESIII	BABAR
$\sqrt{s}$(GeV))	3.77	10.57
$\sigma_{ISR,NLO}$(nb)	8.12×10^{-3}	0.7×10^{-3}
$L(\text{fb}^{-1})$	10	232
$N_{gen} = L \times \sigma$	81261	176856

→ ~ x 10^{-1} factor vs BABAR

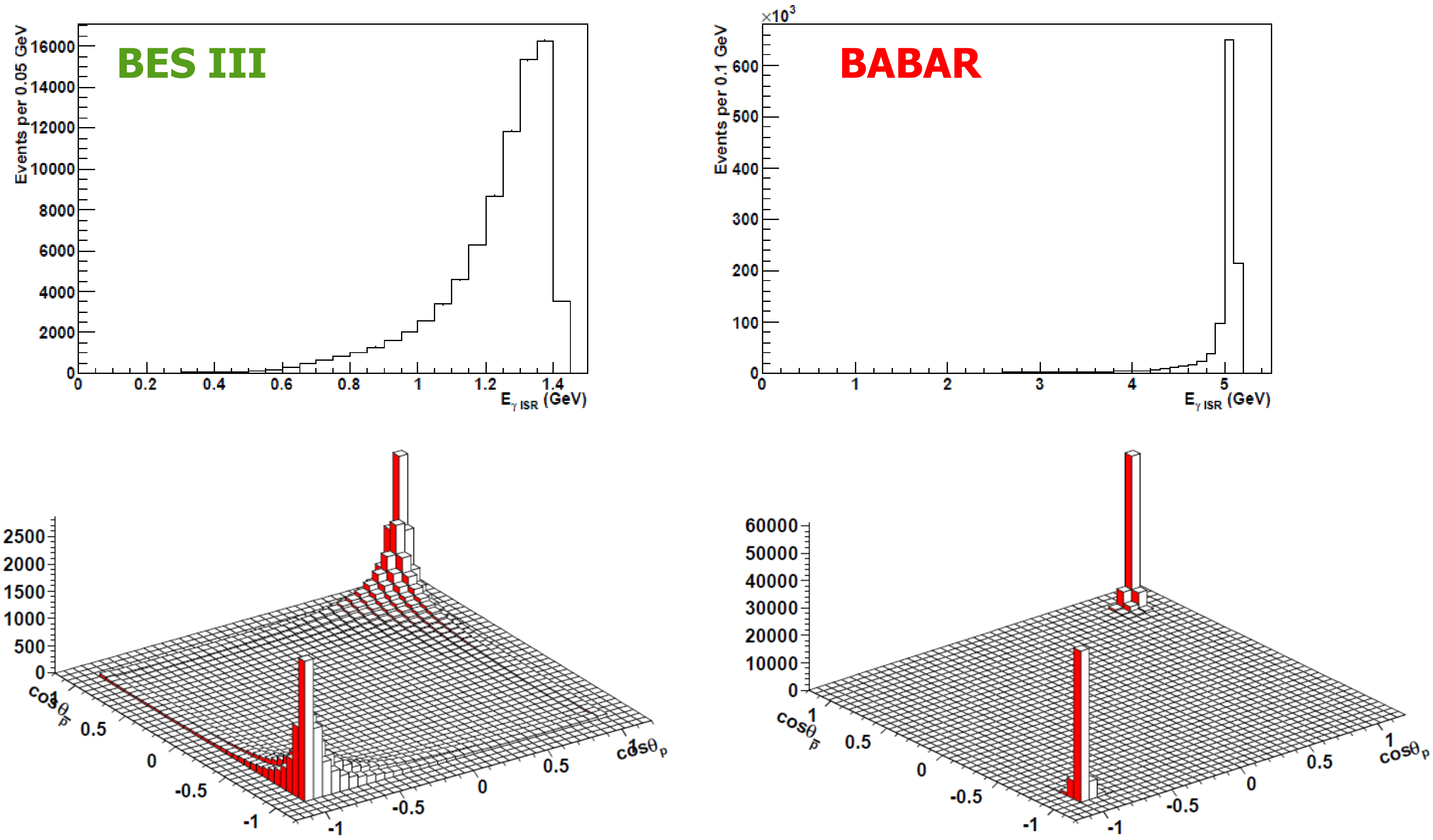
→ ~ x 20 factor vs BABAR

BABAR(*) = ~2 x BES III

Expected Statistics

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

- **BABAR: only tagged events possible** due to **high energy of photon** leading to **back to back signatures** wrt ppbar sytem !!

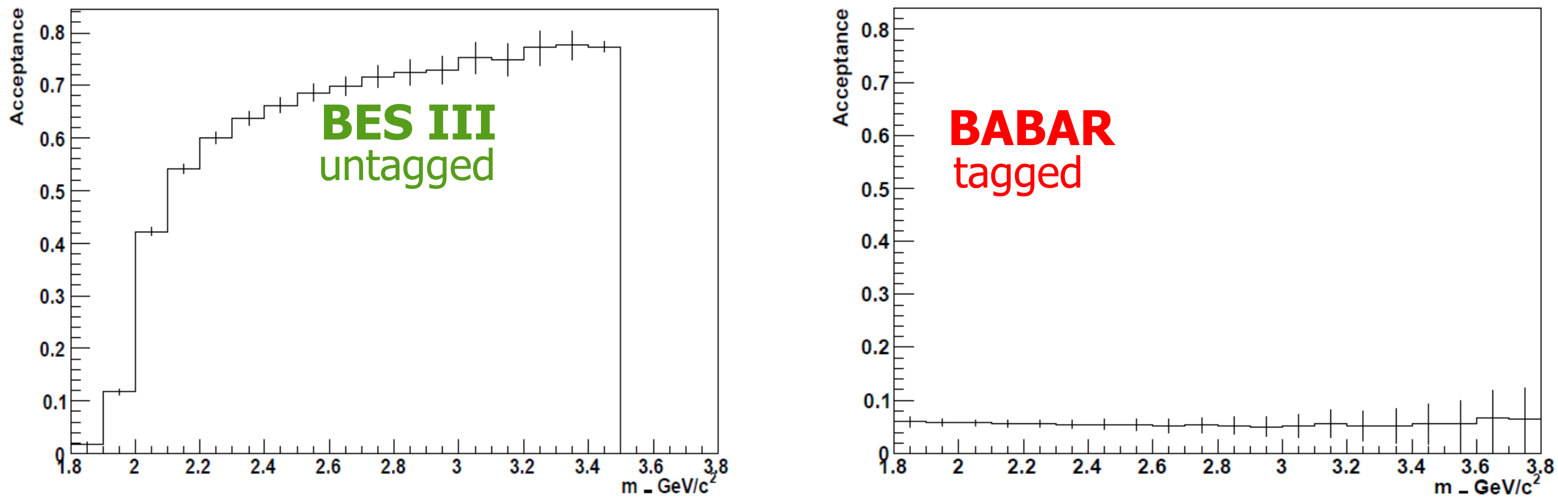


MC used: PHOKHARA ver.7.0 (*NLO+ISR, no FSR included*)

Expected Statistics

$Acc_{untagged} = \frac{\#\text{evts with } \mathbf{p,pbar}\ \mathbf{in}\ \text{detector}, \gamma\ \mathbf{out}}{\#\ \text{evts in } L_{BABAR,BES}\ \text{for } \sqrt{s}_{BABAR,BES}}$

$Acc_{tagged} = \frac{\#\text{evts with } \mathbf{p,pbar,\gamma}\ \mathbf{in}\ \text{detector}}{\#\ \text{evts in } L_{BABAR,BES}\ \text{for } \sqrt{s}_{BABAR,BES}}$



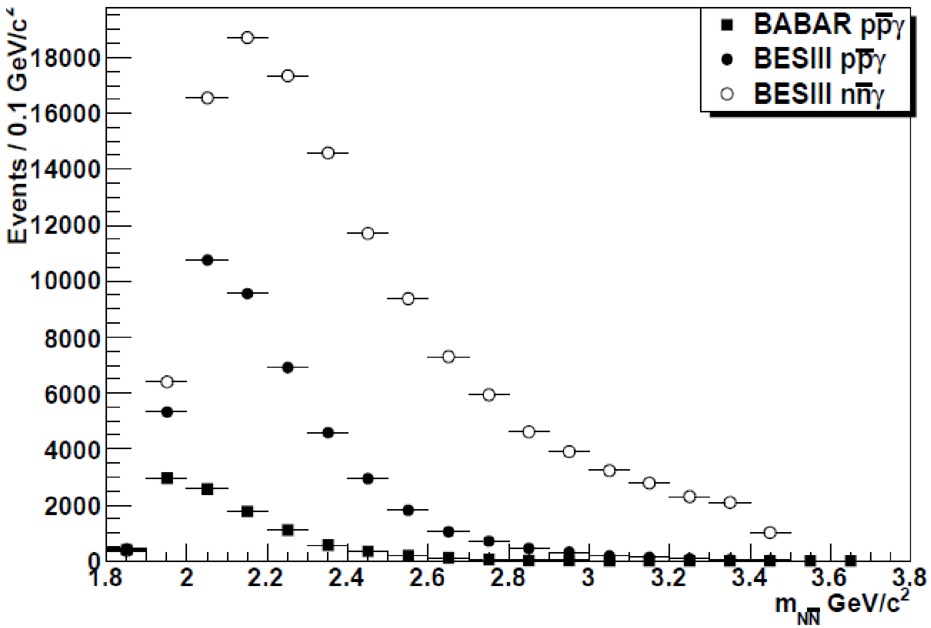
	BESIII	BABAR
$\sqrt{s}$(GeV))	3.77	10.57
$\sigma_{ISR,NLO}$(nb)	8.12×10^{-3}	0.7×10^{-3}
$L(\text{fb}^{-1})$	10	232
$N_{gen} = L \times \sigma$	81261	176856
measurement	"untagged + tagged"	"tagged"
geometry cuts (degrees)	$21.56 < \theta_{p,\bar{p}} < 158.43$	$25.8 < \theta_{p,\bar{p}} < 137.7$
	$0 < \theta_{\gamma ISR} < 180$	$21.5 < \theta_{\gamma ISR} < 137.5$
$N_{expected}$	46462 (33994 + 11375)	10183

BESIII = ~4.5 x BABAR(*)

MC used: PHOKHARA ver.7.0 (*NLO+ISR, no FSR included*)

Expected Statistics

- BABAR: only tagged measurement possible
- BES III can do both tagged and untagged

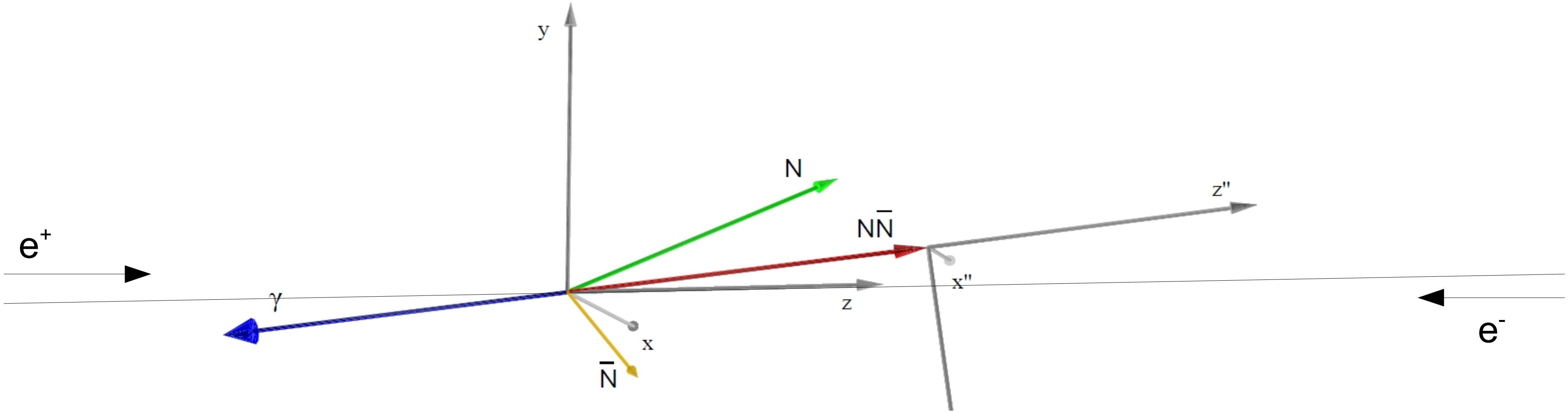


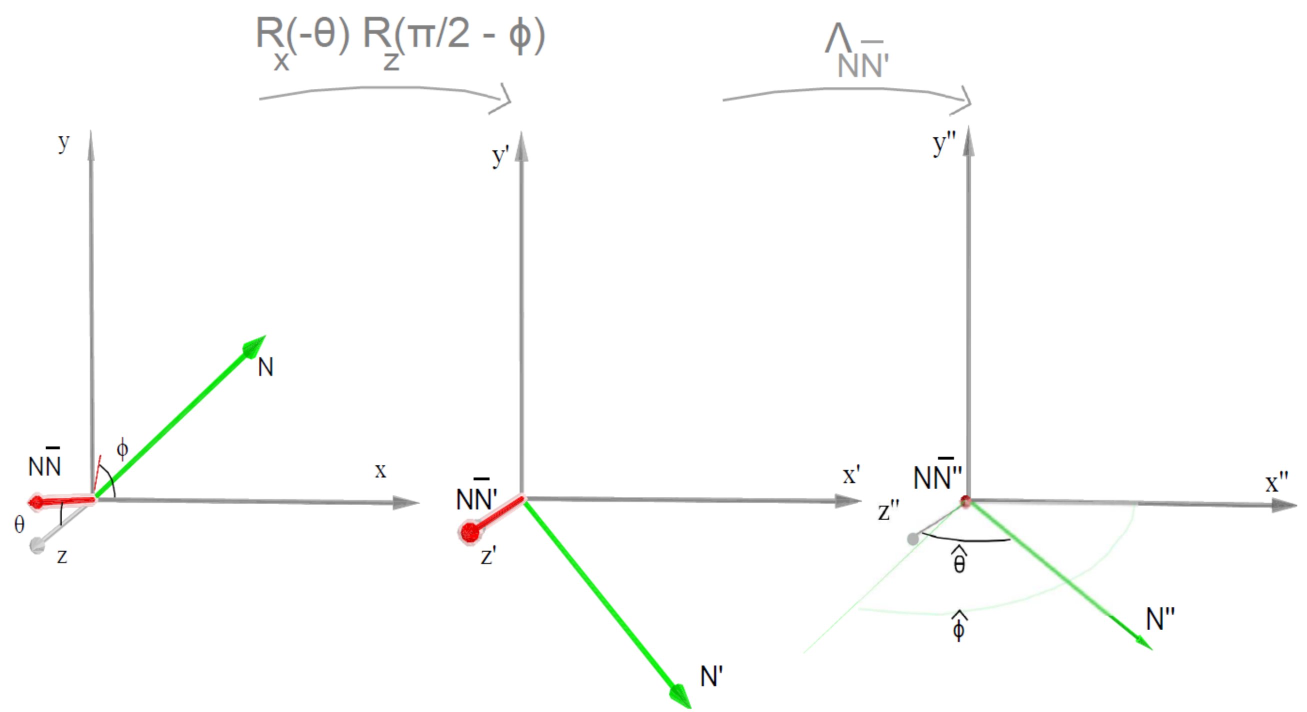
BESIII: estimates for $10fb^{-1}$, $\sqrt{s}$ = 3.77 GeV

BABAR: estimates for $232fb^{-1}$, $\sqrt{s}$ = 10.57 GeV

NOTE that the shapes around threshold might not correspond with what we expect to measure, it is an artifact of the model in the MC and the form factors implemented ---> **This is what we want to measure**

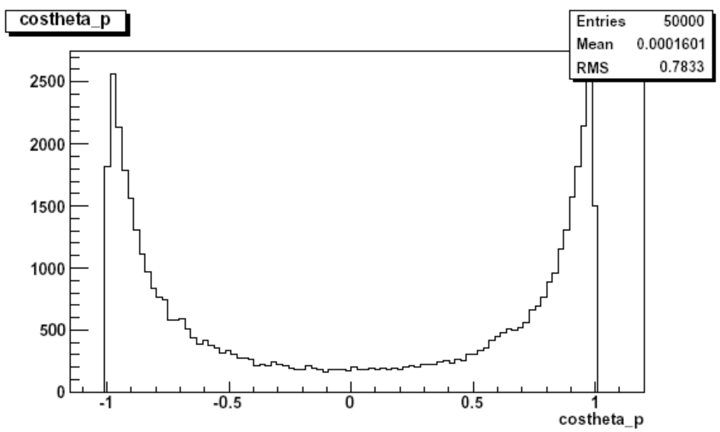
Angular Distribution - Resolution in FF Measurement

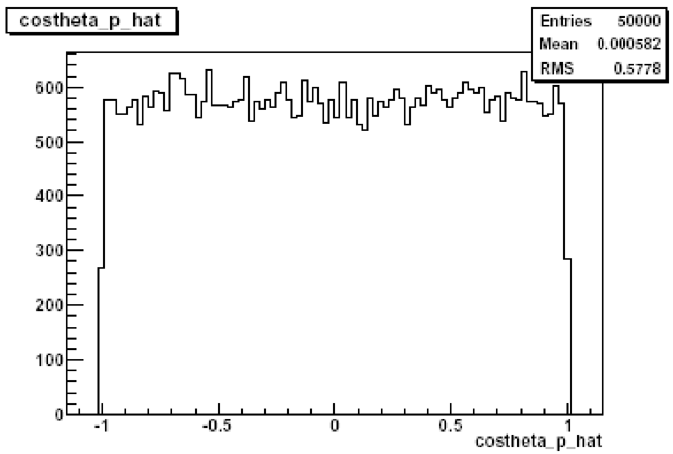




Angular Distribution- Resolution in FF Measurement

$$\frac{\mathrm{d}N}{\mathrm{d}cos\hat{\theta}} = A(H_M(cos\hat{\theta}, m) + |\frac{G_E}{G_M}|^2 H_E(cos\hat{\theta}, m))$$





How to evaluate BESIII statistical resolution in FF measurement?

1) **Signal 'data' sample**: generate $\mathbf{N_{expected}}$ MC events with a **given R = |GE/GM|** which fulfill the geometrical requirements and follow the cross section of the process

2) Since **theta hat allows a separation of the GE- and GM-terms**:

Use two MC samples with GE=0 and GM=0 and high statistics to account for the two terms

3) Find out the **relative amount of the two terms in the MC 'data'** sample in bins of $q^2 = m_{pp}^2$.

Angular Distribution- Fit

Funtion to fit:

$$F((cos\hat{\theta}, m)) = F_0 \frac{\sigma_0}{\sigma_1} G_M \cdot H_M(cos\hat{\theta}, m) + F_1 \, G_E \cdot H_E(cos\hat{\theta}, m)$$

Signal MC with GE = GM = F1 + F2

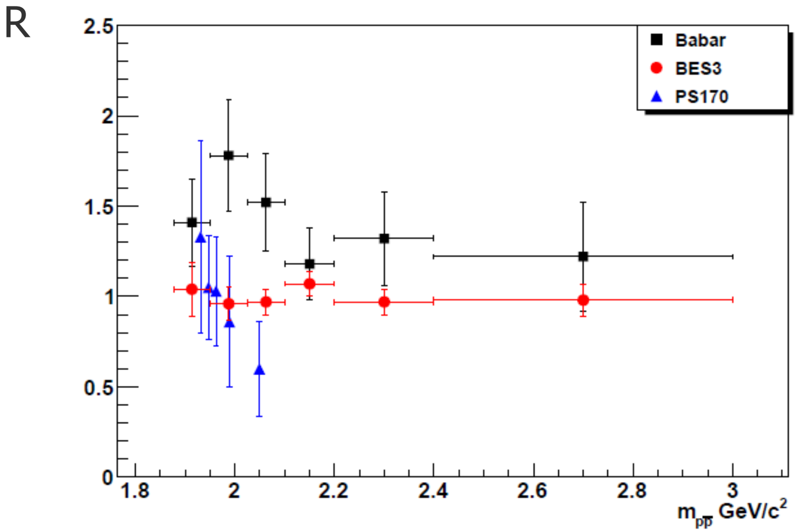
Normalized MC with GE = 0 & GM = F1 + F2

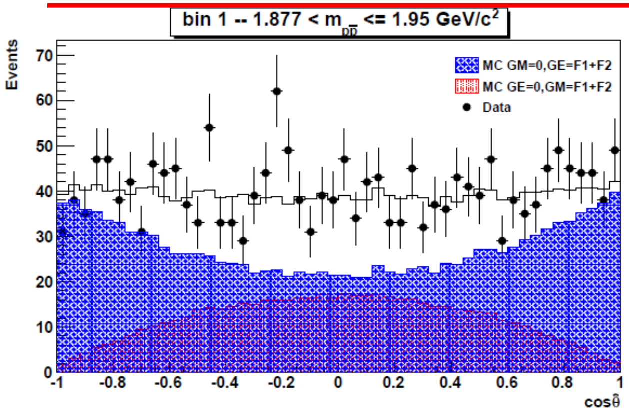
Normalized MC with GM = 0 & GE = F1 + F2

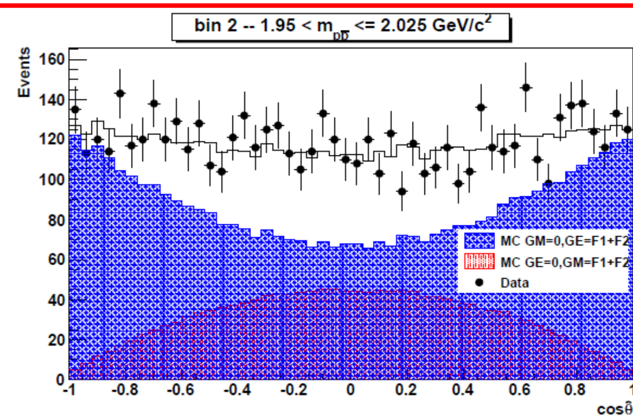
Chi2 minimization: 2 parameters free F0 and F1

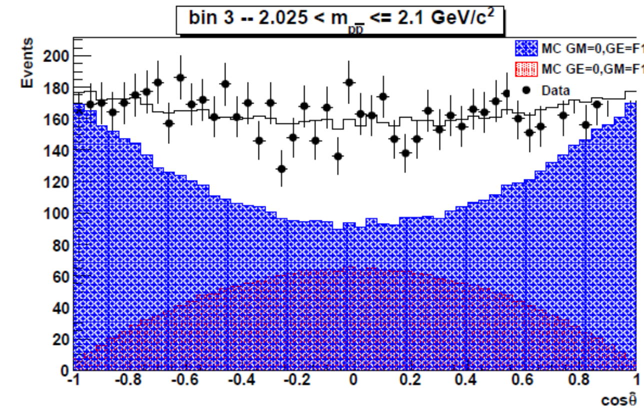
$$R = \sqrt{\frac{F_1}{F_0}} \qquad \frac{\delta R}{R} = \sqrt{(\frac{\delta F_1}{F_1})^2 + (\frac{\delta F_0}{F_0})^2}$$

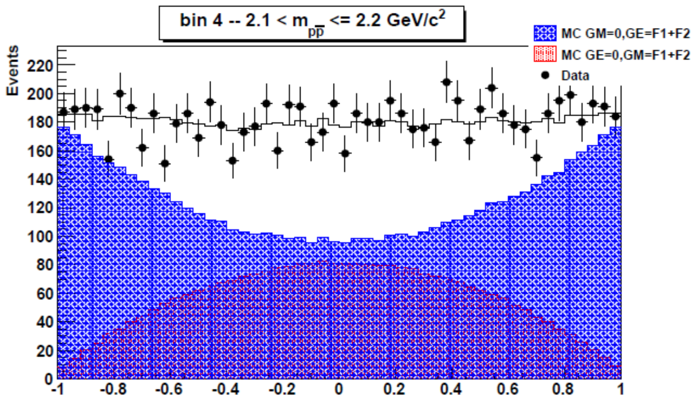
	F_0	F_1	χ^2	R
$1.877 < m_{p\bar{p}} \leq 1.950$	539 ± 31	585 ± 75	51.6	1.04 ± 0.15
$1.950 < m_{p\bar{p}} \leq 2.025$	1705 ± 56	1561 ± 132	55.07	0.96 ± 0.09
$2.025 < m_{p\bar{p}} \leq 2.1$	2341 ± 65	2221 ± 153	42.4	0.97 ± 0.07
$2.1 < m_{p\bar{p}} \leq 2.2$	2439 ± 67	2807 ± 161	50.1	1.07 ± 0.07
$2.2 < m_{p\bar{p}} \leq 2.4$	2937 ± 73	2739 ± 173	37.4	0.97 ± 0.07
$2.4 < m_{p\bar{p}} \leq 3.0$	1608 ± 54	1559 ± 129	42.8	0.98 ± 0.09

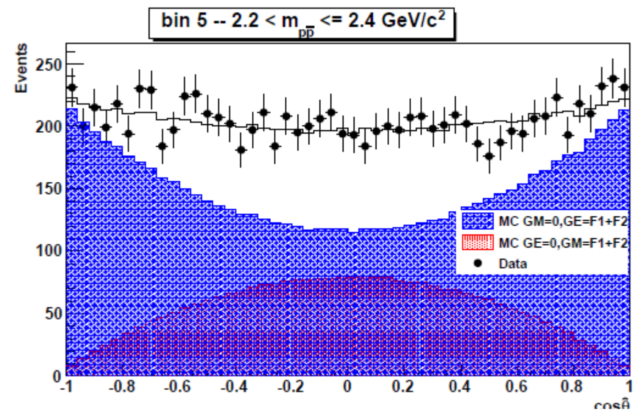


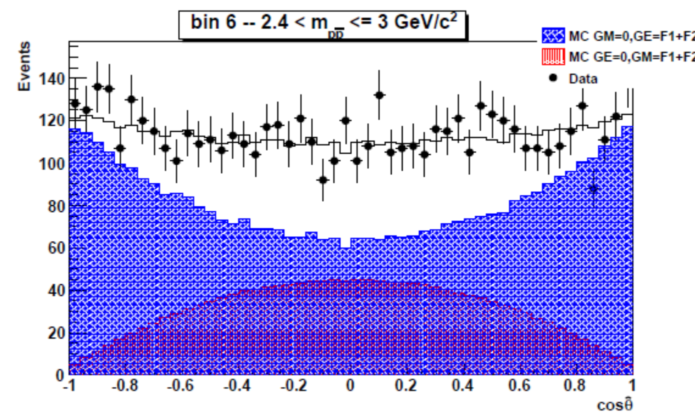

bin 1 -- 1.877 < m_pp̄ <= 1.95 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ̂

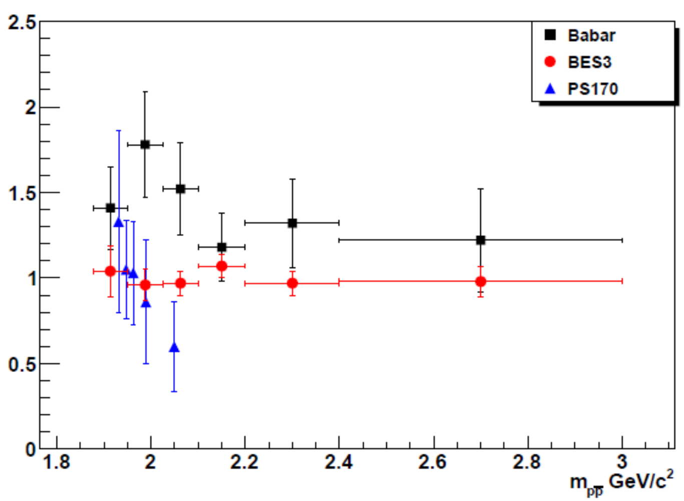

bin 2 -- 1.95 < m_pp̄ <= 2.025 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ̂

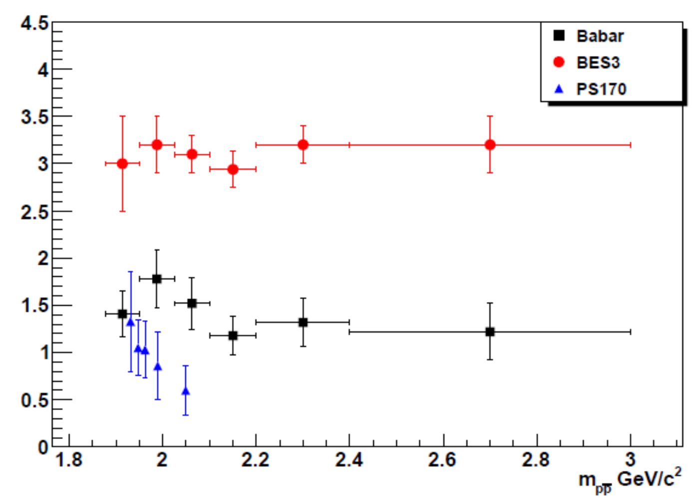

bin 3 -- 2.025 < m_pp̄ <= 2.1 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ̂


bin 4 -- 2.1 < m_pp̄ <= 2.2 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events

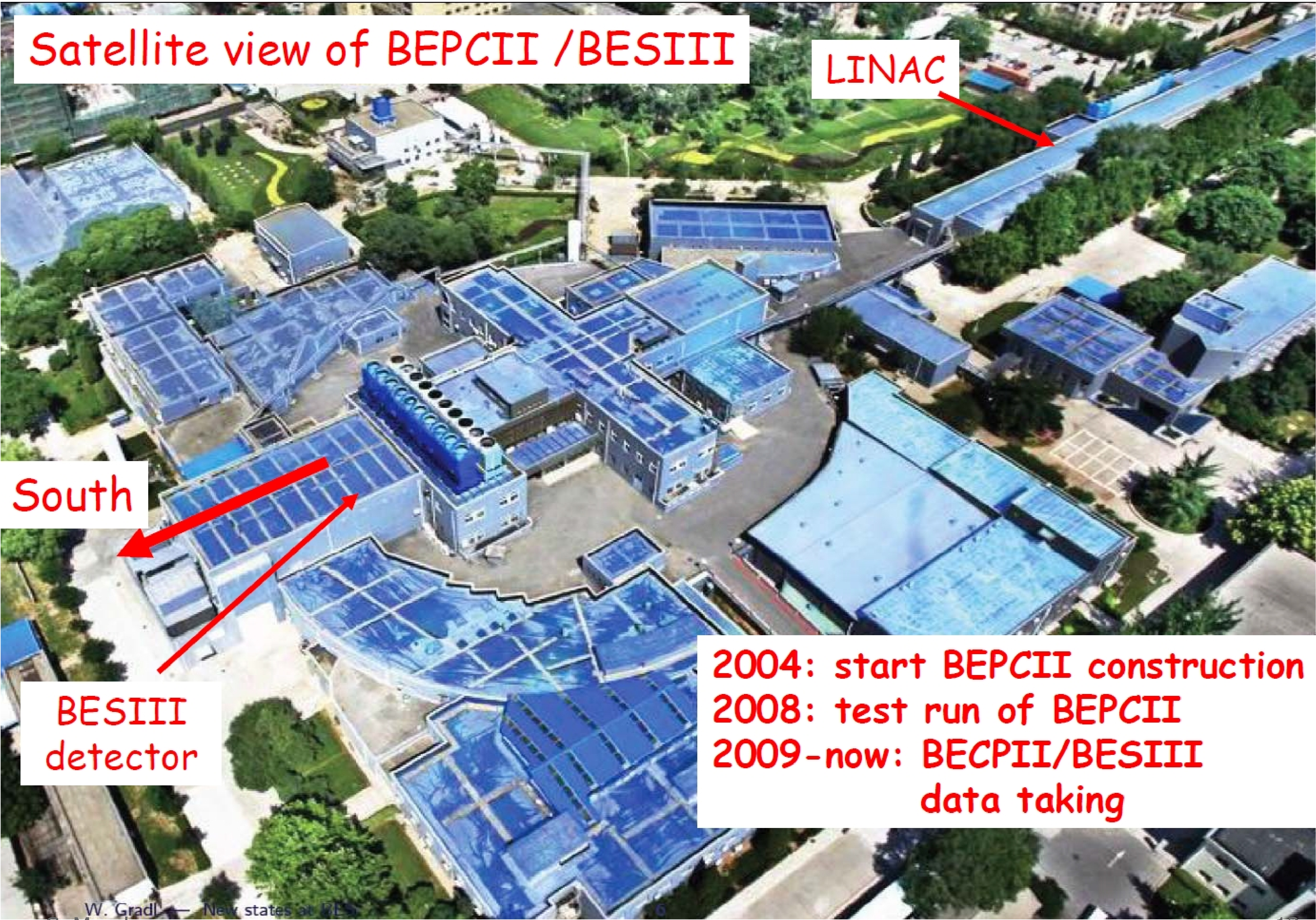

bin 5 -- 2.2 < m_pp̄ <= 2.4 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events


bin 6 -- 2.4 < m_pp̄ <= 3 GeV/c²
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ̂

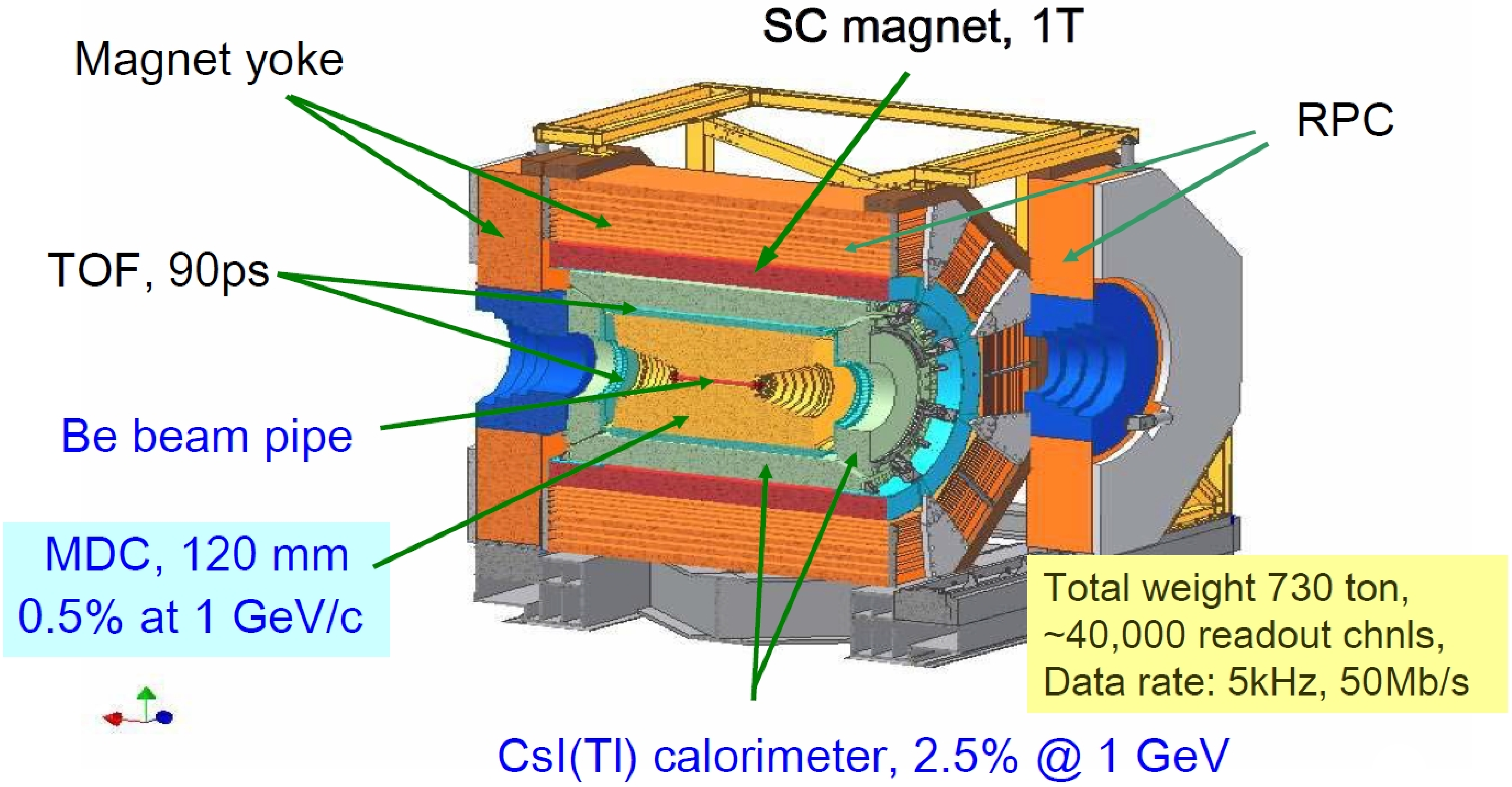

Babar
BES3
PS170
m_pp̄ GeV/c²


Babar
BES3
PS170
m_pp̄ GeV/c²

Part II : First look at the data


Satellite view of BEPCII /BESIII
LINAC
South
BESIII detector
2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BECPII/BESIII data taking

BES III Detector



Selection of $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$

[Ch. Zimmermann, Diplomarbeit, Mainz (2011)]

I run over **2.9fb-1** data available at √s = 3.773 GeV (psi(3770)).

I only selected **tagged** events.

	Cut variable	Cut value
Track	QA	valid MDCKal track
	POA_{xy}	1.0 cm
	POA_z	4.0 cm
	DLL(p,μ)	≥ 0
	DLL(p,e)	≥ 0
	Θ_{tr}	$\in \{0.4, \pi - 0.4\}$ rad
Neutral	Θ_γ	$\in \{0.4, \pi - 0.4\}$ rad
	E_γ	≥ 0.4 GeV
Event	# tracks from IP	2
	# proton tracks	2
	total charge	0
	# high energy neutrals	≥ 1
	Θ_{misMom}	$\in \{-0.15, 0.15\}$ rad
	$\lvert\vec{p}_{misMom}\rvert - \lvert\vec{p}_{HE\gamma}\rvert$	$\in \{-150, 200\}$ MeV
	m_{π^0}	$\notin \{115, 155\}$ MeV
	m_{trk}	$\in \{920, 970\}$ MeV
	m^2_{exc}	$\in \{-0.003, 0.003\}$ GeV^2

Tracks:
- fully reconstructed in drift chamber
- if possible with matching EMC cluster
- close enough to collision point
- compatible with proton ID
- avoid limits of subdetectors

Photons:
- high energy (ISR photon)
- avoid limits of EMC

Event:
- two tracks from interaction point
- two protons of opposite charge
- more than 1 photon allowed but:
  - momentum conserved
  - not belonging to a pi0
- mass of tracks
- kinematic fit

Selection of $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$

[Ch. Zimmermann, Diplomarbeit, Mainz (2011)]

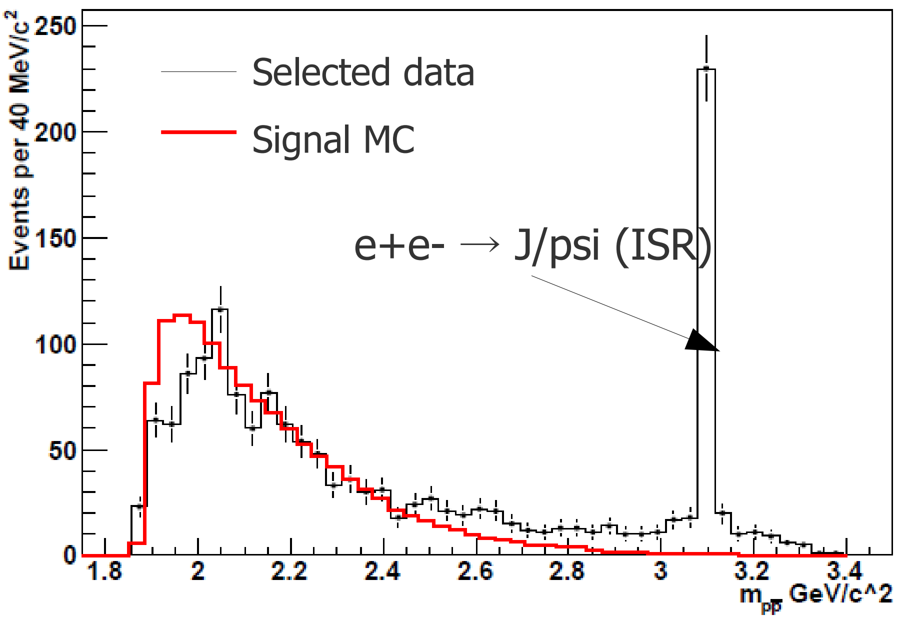
Cut variable	Signal	$q\bar{q}$	$D\bar{D}$	e^+e^-	$\mu^+\mu^-$
QA	0.00	$6.24 \cdot 10^{-5}$	$9.49 \cdot 10^{-6}$	$1.81 \cdot 10^{-5}$	0.00
POA_{xy}, POA_z	0.324	0.217	0.204	0.197	0.0481
DLL(p,μ), DLL(p,e)	0.0230	0.761	0.782	0.981	0.927
Θ_{tr}	0.0223	0.00188	0.0574	0.211	0.0141
Θ_γ	0.101	0.0751	0.074	0.196	0.156
E_γ	0.962	0.929	0.945	0.983	0.976
# tracks from IP	0.00312	0.684	0.808	1.00	0.0161
# proton tracks	0.584	0.991	1.00	n/a	0.988
total charge	0.00277	0.0757	0.148	n/a	0.000173
# high energy neutrals	0.677	0.608	0.505	n/a	0.978
Θ_{misMom}, $\lvert\vec{p}_{misMom}\rvert - \lvert\vec{p}_{HE\gamma}\rvert$	0.378	0.908	0.985	n/a	1.00
m_{π^0}	0.109	0.775	0.50	n/a	n/a
m_{trk}	0.160	0.749	1.00	n/a	n/a
m^2_{exc}	0.0986	0.30	n/a	n/a	n/a
Total efficiency ε	$5.60 \cdot 10^{-2}$	$1.22 \cdot 10^{-5}$	$0.0 \cdot 10^{-7}$	$0.0 \cdot 10^{-6}$	$0.0 \cdot 10^{-6}$
$\Delta\varepsilon$	$^{+0.17}_{-0.16} \cdot 10^{-2}$	$^{+0.45}_{-0.20} \cdot 10^{-5}$	$^{+4.8}_{-0.0} \cdot 10^{-7}$	$^{+3.7}_{-0.0} \cdot 10^{-6}$	$^{+1.2}_{-0.0} \cdot 10^{-6}$

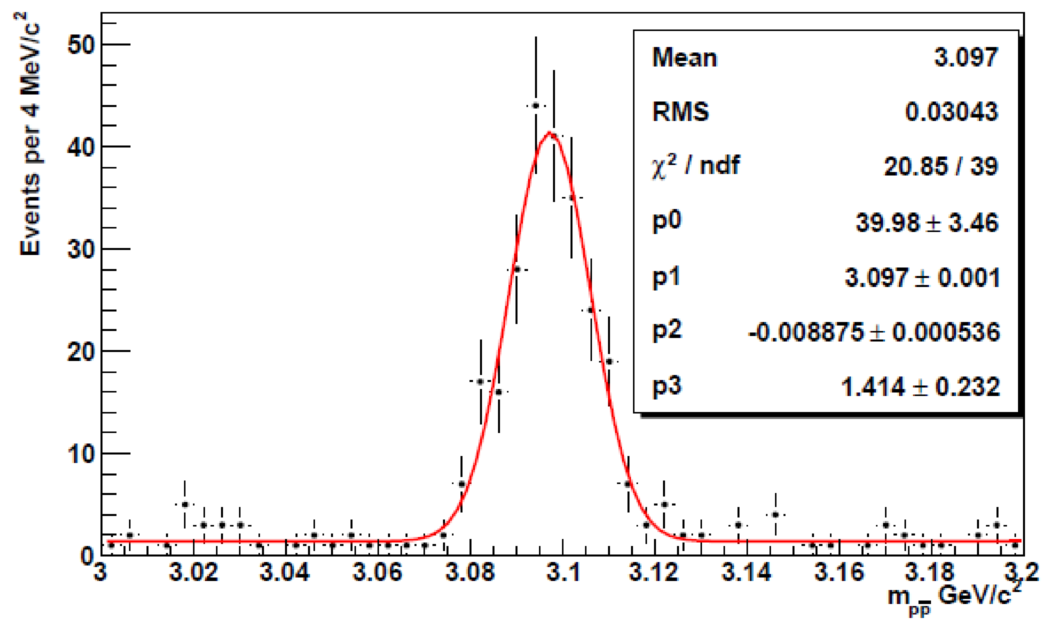
Cuts not yet optimized [to be done].

Other background channels might need some extra attention [to be done]

The features of the qq MC need to be understood, apparently it also includes ISR evts!!!!

Selection of $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$





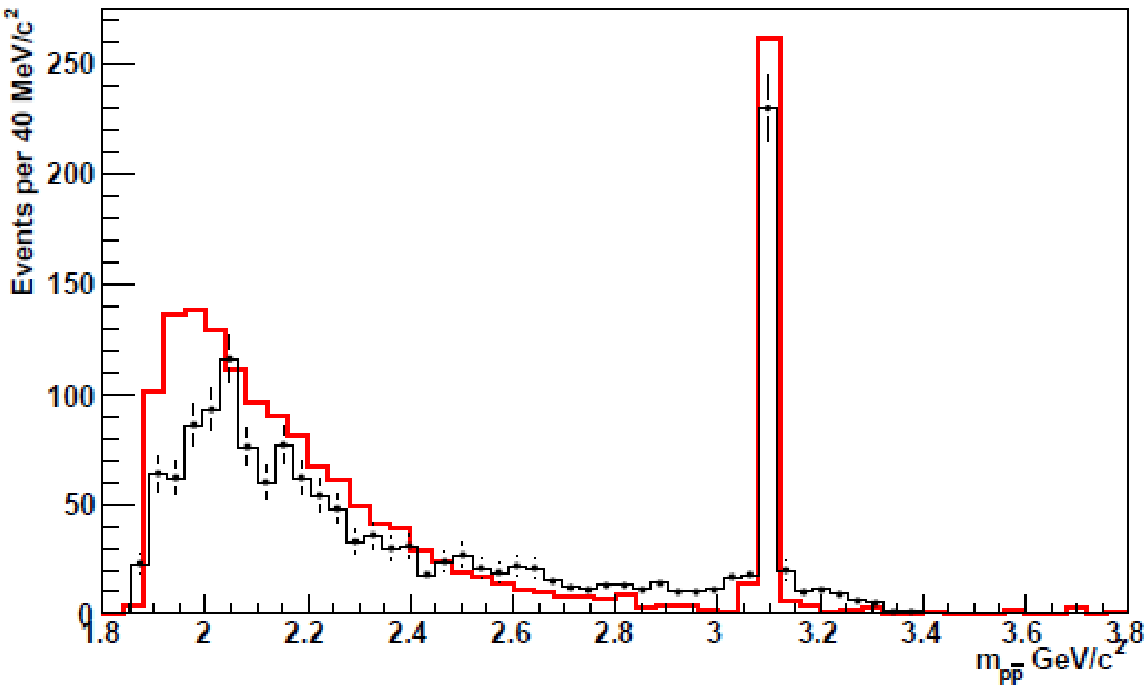
What happens if we add the gaussian shape of the J/psi resonance normalized to the expected e+e- → J/psi (γ) ISR?

Strategy: Let us assume the same efficiency for the J/psi → ppbar channel and add it to the MC signal. For 2.9 fb-1 we expect e+e- → J/psi (ISR) … [to be done, I can't find cross section]

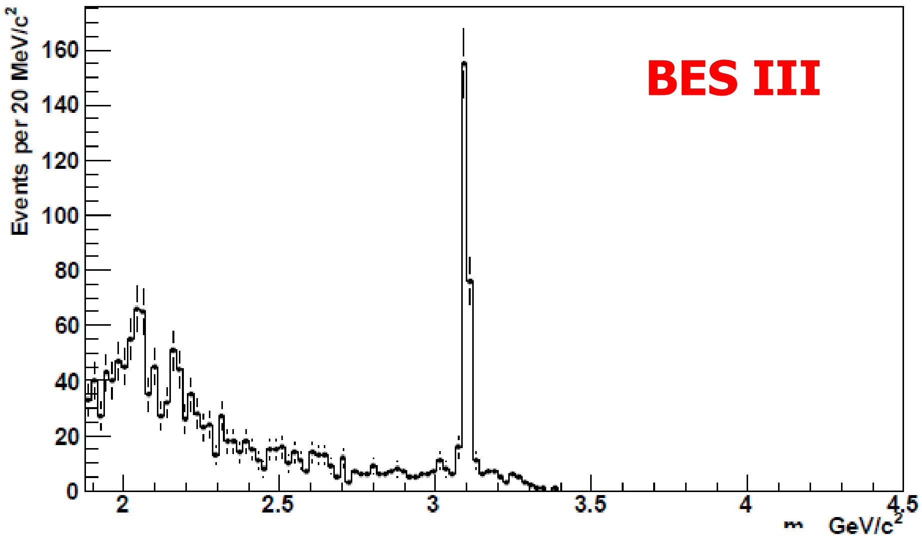
Selection of $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$

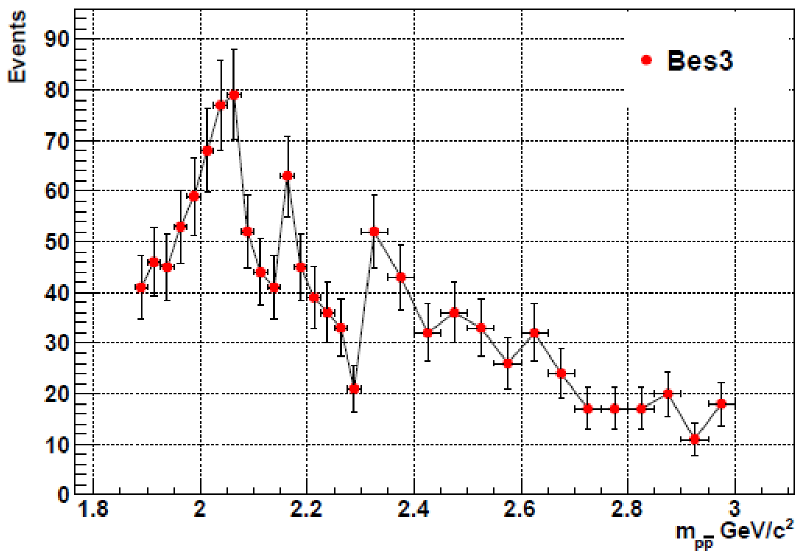
Alternative: assume the J/psi peak we see is in best agreement with what the predicions say.

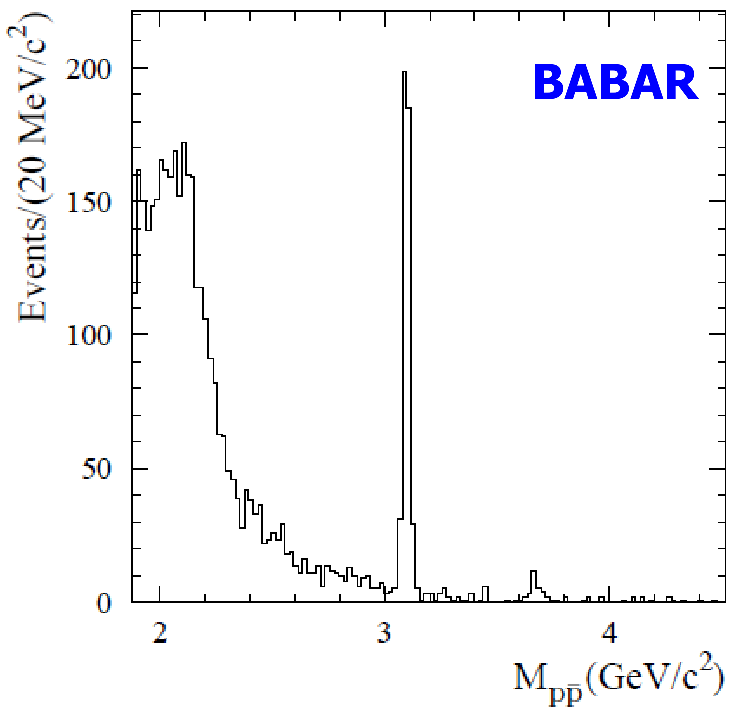
Would the sum of MC signal and the peak that we see explain the spectrum?

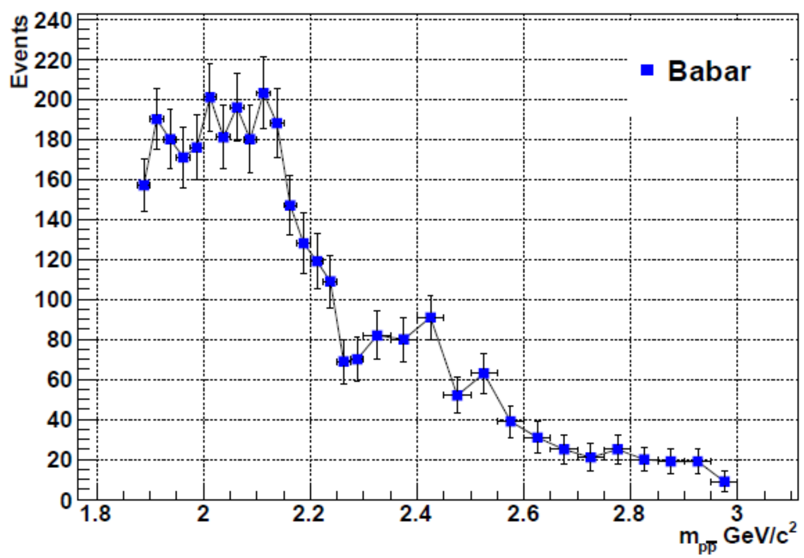


No, it wouldn't. I would be overestimating the e+e- $\to$ J/psi (γ) ISR and some other background is still missing ----> More background studies are necessary.


BES III
Events per 20 MeV/c²
GeV/c²


Events
Bes3
m_{pp̄} GeV/c²


BABAR
Events/(20 MeV/c²)
M_{pp̄}(GeV/c²)


Events
Babar
m_{pp̄} GeV/c²

Conclusions and Outlook

- First results promising. Even at early stage of analysis and without cuts optimization signal is clearly distinguisable from background.
- BESIII will collect 10fb-1 at s = 3.773 GeV. In addition, a future R-scan could make possible a direct measurement of hadron form factors.
- So far only tagged analysis performed. Adding untagged events will at least triplicate the statistics.

TO DO:

- Optimization of the cuts.
- Better understanding and subtraction of background.
- Untagged analysis.
- My fits are ready to go!! $\rightarrow$ First results on |GE/GM| to be expected soon!!
- We want to start also with the challenging nnbar channel.

Backup

Phokhara Generator $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$

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

$$G_M^N = F_1^N + F_2^N \,, \qquad G_E^N = F_1^N + \tau F_2^N$$

Form factors decomposed in isoscalar and isovectorial parts

$$F_{1,2}^p = F_{1,2}^s + F_{1,2}^v \,, \qquad F_{1,2}^n = F_{1,2}^s - F_{1,2}^v$$

Parametrization used F. Iachello, A.D. Jackson, A. Lande, Phys. Lett. B **43**, 191

with analytical continuation to TL region as in

- F. Iachello, nucl-th/0312074; talk at Workshop on e^+e^- in the 1–2 GeV range: Physics and Accelerator Prospects, Alghero, Sardinia (Italy), 10–13 September, 2003
- S.J. Brodsky, C.E. Carlson, J.R. Hiller, D.S. Hwang, hep-ph/0310277

$$F_1^s = \frac{g(Q^2)}{2}\left[(1-\beta_\omega-\beta_\phi) - \beta_\omega \cdot T_\omega - \beta_\phi \cdot T_\phi\right],$$

$$F_2^s = \frac{g(Q^2)}{2}\left[(0.120+\alpha_\phi)\cdot T_\omega - \alpha_\phi \cdot T_\phi\right],$$

$$F_1^v = \frac{g(Q^2)}{2}\left[(1-\beta_\rho) - \beta_\rho \cdot T_\rho\right],$$

$$F_2^v = \frac{g(Q^2)}{2}\left[-3.706 \cdot T_\rho\right],$$

$$T_\rho = \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{Q^2 - m_\rho^2 + (Q^2 - 4m_\pi^2)\Gamma_\rho \alpha(Q^2)/m_\pi},$$

$$\alpha(Q^2) = (1-x^2)^{1/2}\left\{\frac{2}{\pi}\log\left(\frac{1+\sqrt{1-x^2}}{x}\right) - \mathrm{i}\right\}$$

and

$$T_{\omega,\phi} = \frac{m_{\omega,\phi}^2}{Q^2 - m_{\omega,\phi}^2},$$

$$g(Q^2) = \frac{1}{(1-\gamma e^{\mathrm{i}\theta} Q^2)^2},$$

$$x = \frac{2m_\pi}{\sqrt{Q^2}}.$$

The values of the parameters (dimensionful quantities in units of GeV) are $\beta_\rho = 0.672$, $\beta_\omega = 1.102$, $\beta_\phi = 0.112$, $m_\phi = 1.019$, $m_\rho = 0.765$, $m_\omega = 0.784$, $\alpha_\phi = -0.052$, $\Gamma_\rho = 0.112$, $\gamma = 0.25$. The angle θ in (19) is set to $\theta = \pi/4$

Phokhara Generator $e^+(p_1) + e^-(p_2) \to \bar{N}(q_1) + N(q_2) + \gamma(k)$

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

$$\mathrm{d}\sigma = \frac{1}{2s} L_{\mu\nu} H^{\mu\nu} \mathrm{d}\Phi_2(p_1 + p_2; Q, k) \mathrm{d}\Phi_2(Q; q_1, q_2) \frac{\mathrm{d}Q^2}{2\pi}$$

$$L_{\mu\nu} H^{\mu\nu} = \tag{10}$$

$$\frac{(4\pi\alpha)^3}{Q^2} \left\{ \left(\left|G_M^N\right|^2 - \frac{1}{\tau} \left|G_E^N\right|^2 \right) \frac{4Q^2}{(s - Q^2)} \left(\frac{1}{y_1} + \frac{1}{y_2} \right) \right.$$

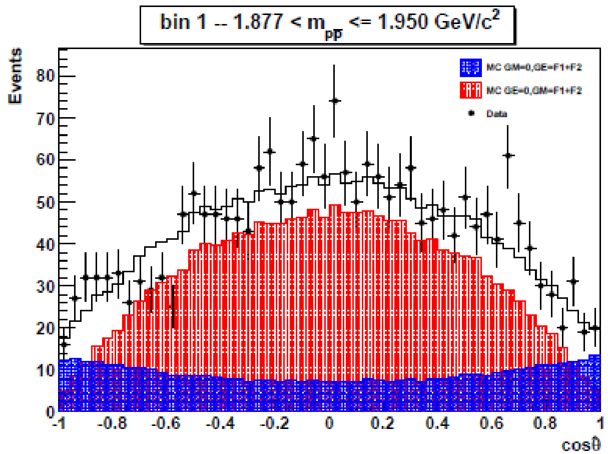
$$\times \left((\beta\gamma \cos\hat{\theta})^2 + (\gamma \cos\theta_\gamma \cos\hat{\theta} - \sin\theta_\gamma \sin\hat{\theta} \sin\hat{\varphi})^2 \right)$$

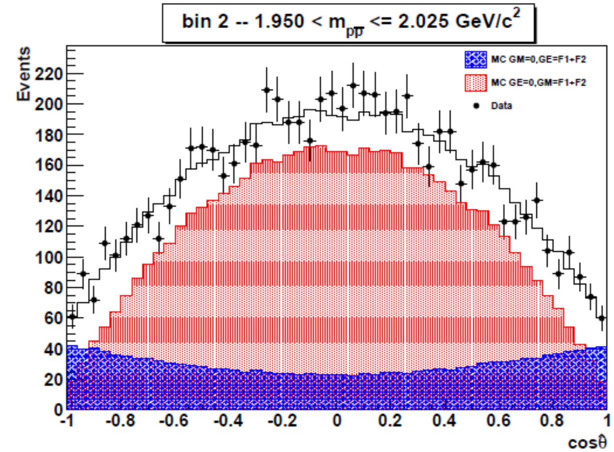
$$\left. + 2 \left(\left|G_M^N\right|^2 + \frac{1}{\tau} \left|G_E^N\right|^2 \right) \left[\left(\frac{1}{y_1} + \frac{1}{y_2} \right) \frac{(s^2 + Q^4)}{s(s - Q^2)} - 2 \right] \right\}$$

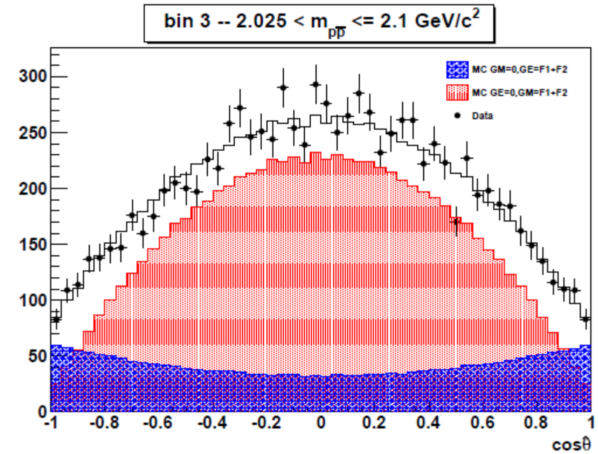
where $\gamma = (s + Q^2)/2\sqrt{sQ^2}$ and $\beta = (s - Q^2)/(s + Q^2)$, $y_{1,2} = \frac{s-Q^2}{2s}(1 \mp \cos\theta_\gamma)$

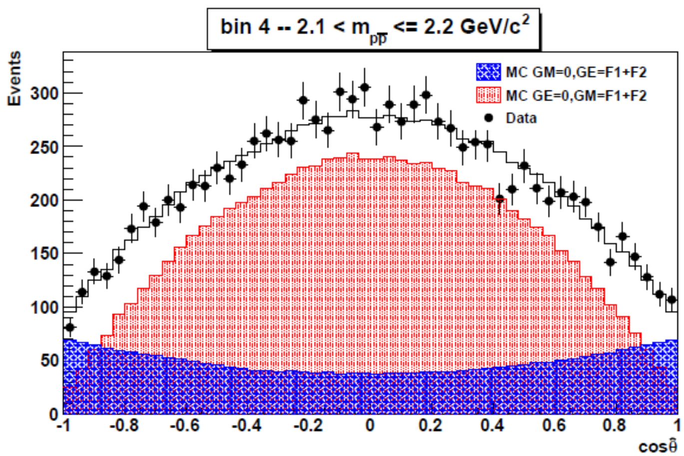
In the limit $Q^2 \ll s$, this can be approximated by

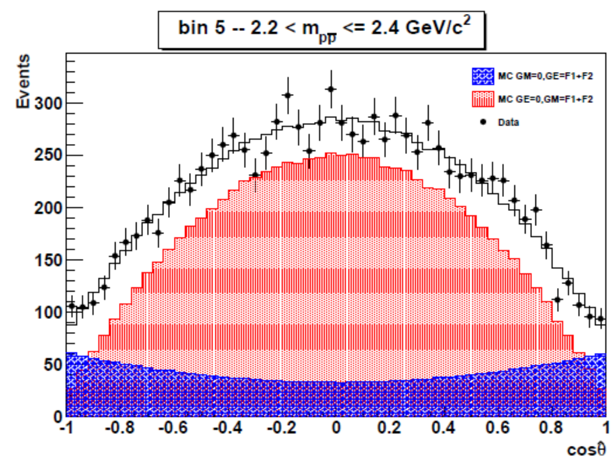
$$L_{\mu\nu} H^{\mu\nu} = \frac{(4\pi\alpha)^3}{Q^2} \frac{(1 + \cos^2\theta_\gamma)}{(1 - \cos^2\theta_\gamma)} \times 4 \left(\left|G_M^N\right|^2 (1 + \cos^2\hat{\theta}) + \frac{1}{\tau} \left|G_E^N\right|^2 \sin^2\hat{\theta} \right).$$

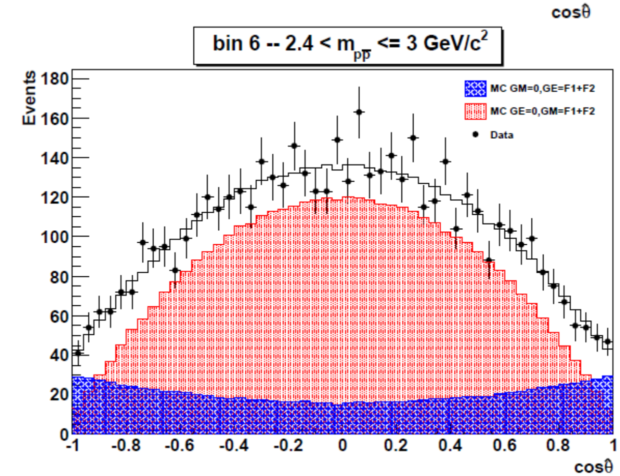

bin 1 -- 1.877 < m$_{p\bar{p}}$ <= 1.950 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ

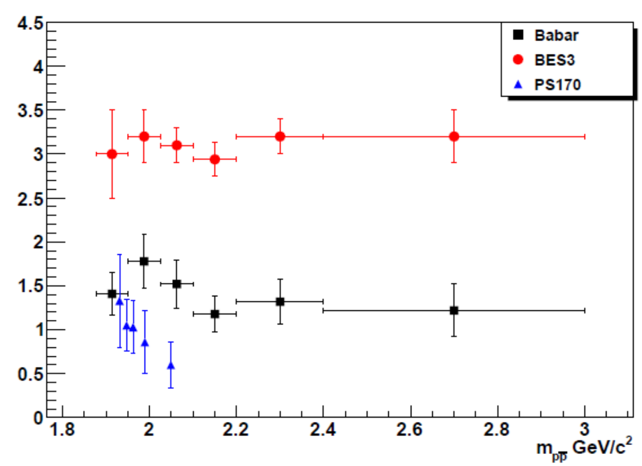

bin 2 -- 1.950 < m$_{p\bar{p}}$ <= 2.025 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ


bin 3 -- 2.025 < m$_{p\bar{p}}$ <= 2.1 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
cosθ


bin 4 -- 2.1 < m$_{p\bar{p}}$ <= 2.2 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ


bin 5 -- 2.2 < m$_{p\bar{p}}$ <= 2.4 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ


bin 6 -- 2.4 < m$_{p\bar{p}}$ <= 3 GeV/c^2
MC GM=0,GE=F1+F2
MC GE=0,GM=F1+F2
Data
Events
cosθ


Babar
BES3
PS170
m$_{p\bar{p}}$ GeV/c^2

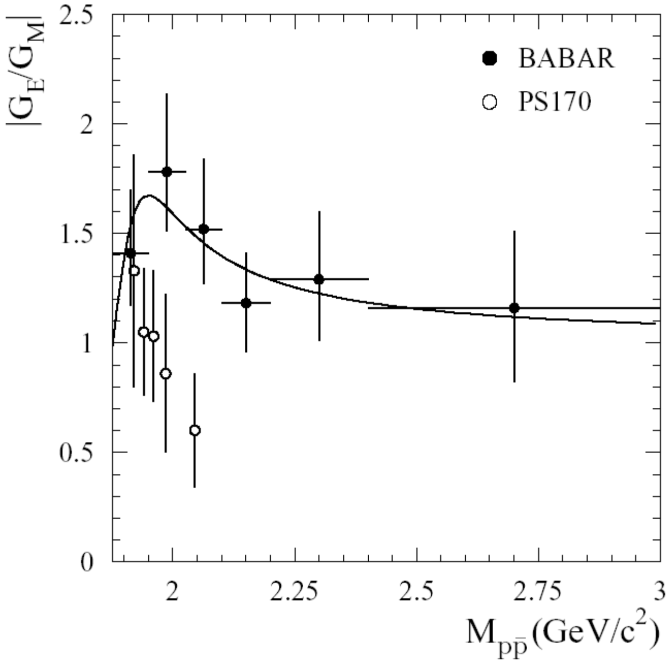
Proton TL FFs measurements

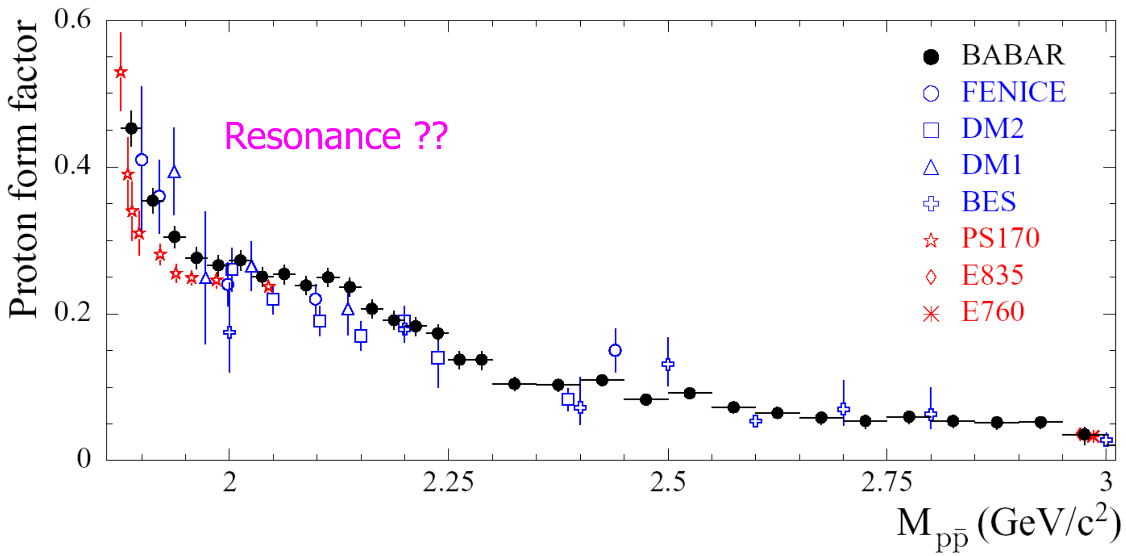
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

- Previous measurements of R = $|G_E|/|G_M|$ by BABAR and PS170@ LEAR with 'large' stat. uncertainties

$$|F_p(m)| = \sqrt{\sigma_{p\bar{p}}(m)/\sigma_n(m)}$$

$$\sigma_n(m) = \frac{4\pi\alpha^2\beta C}{3m^2}\left[1^2 + \frac{2m_p^2}{m^2}\right]$$



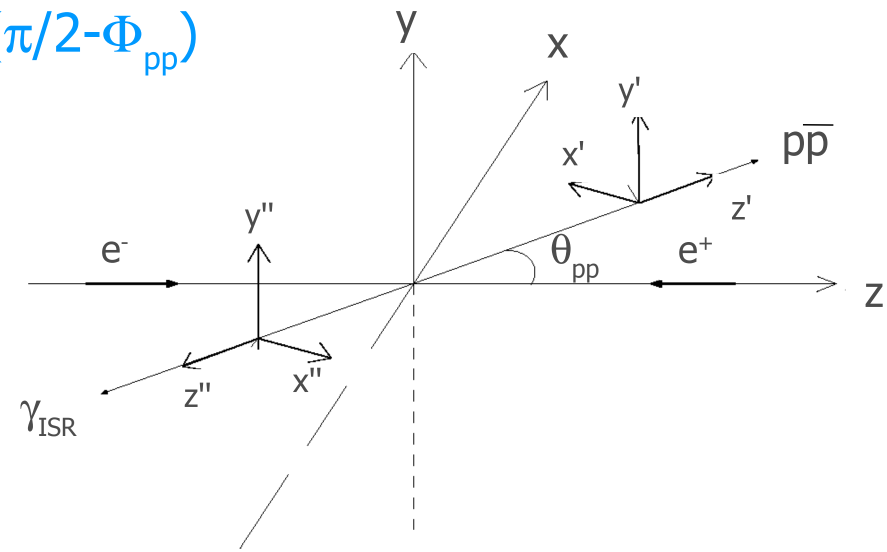


The proton case

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

- **Timelike nucleon FF can be separated over momentum transfer range: angular analysis**
- Possible frame: O' = $\Lambda_{CM} R_X(\theta_{pp}) R_Z(\pi/2-\Phi_{pp})$

[See talk by H. Czyz]



$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_p'} =$$

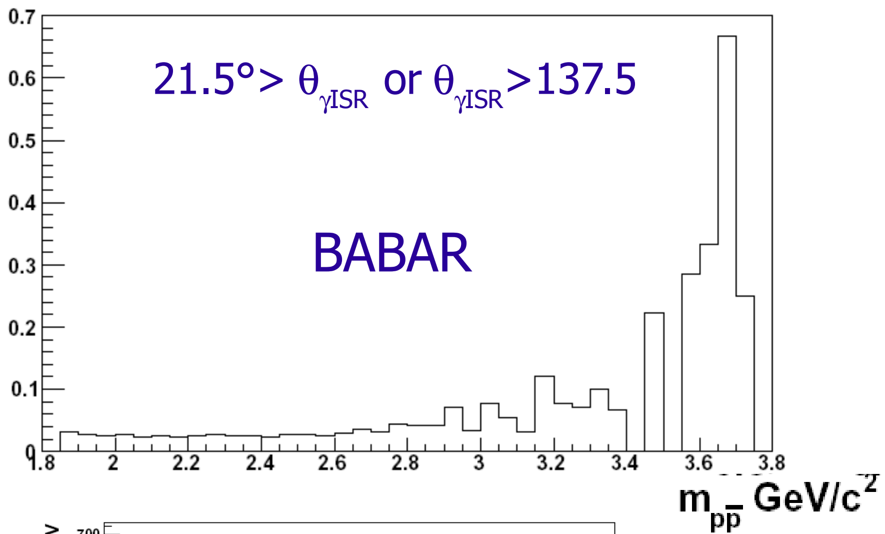
$$A\left(H_M(\cos\theta_p', M_{p\bar{p}}) + \left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta_p', M_{p\bar{p}})\right)$$

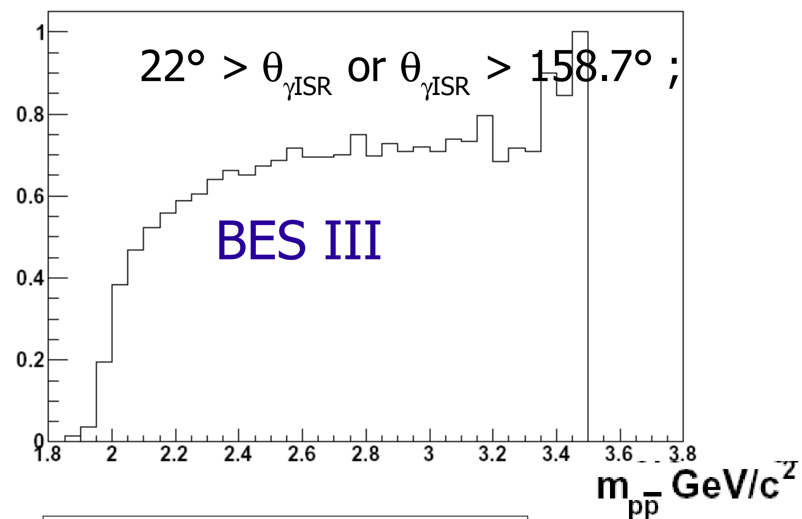
$\rightarrow$ study angular distribution of proton in O' frame

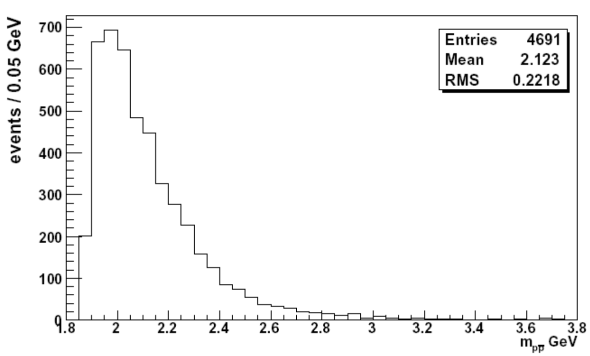
Proton TL FFs @ BESIII

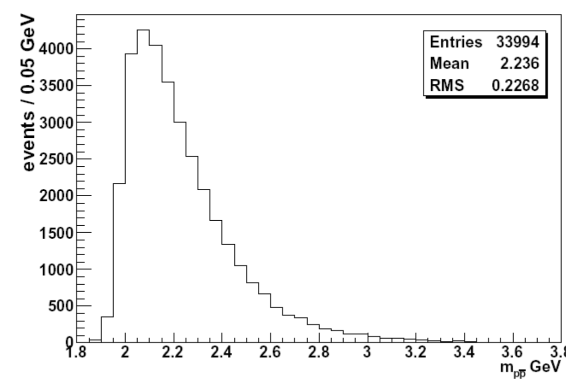
- **Untagged** Acceptance:

$$\text{Acc} = \frac{\#\text{evts with } \mathbf{p,pbar}\ \mathbf{in} \text{ detector}, \gamma\ \mathbf{out}}{\#\text{ evts in } L_{BABAR,BES} \text{ for } \sqrt{s}_{BABAR,BES}}$$

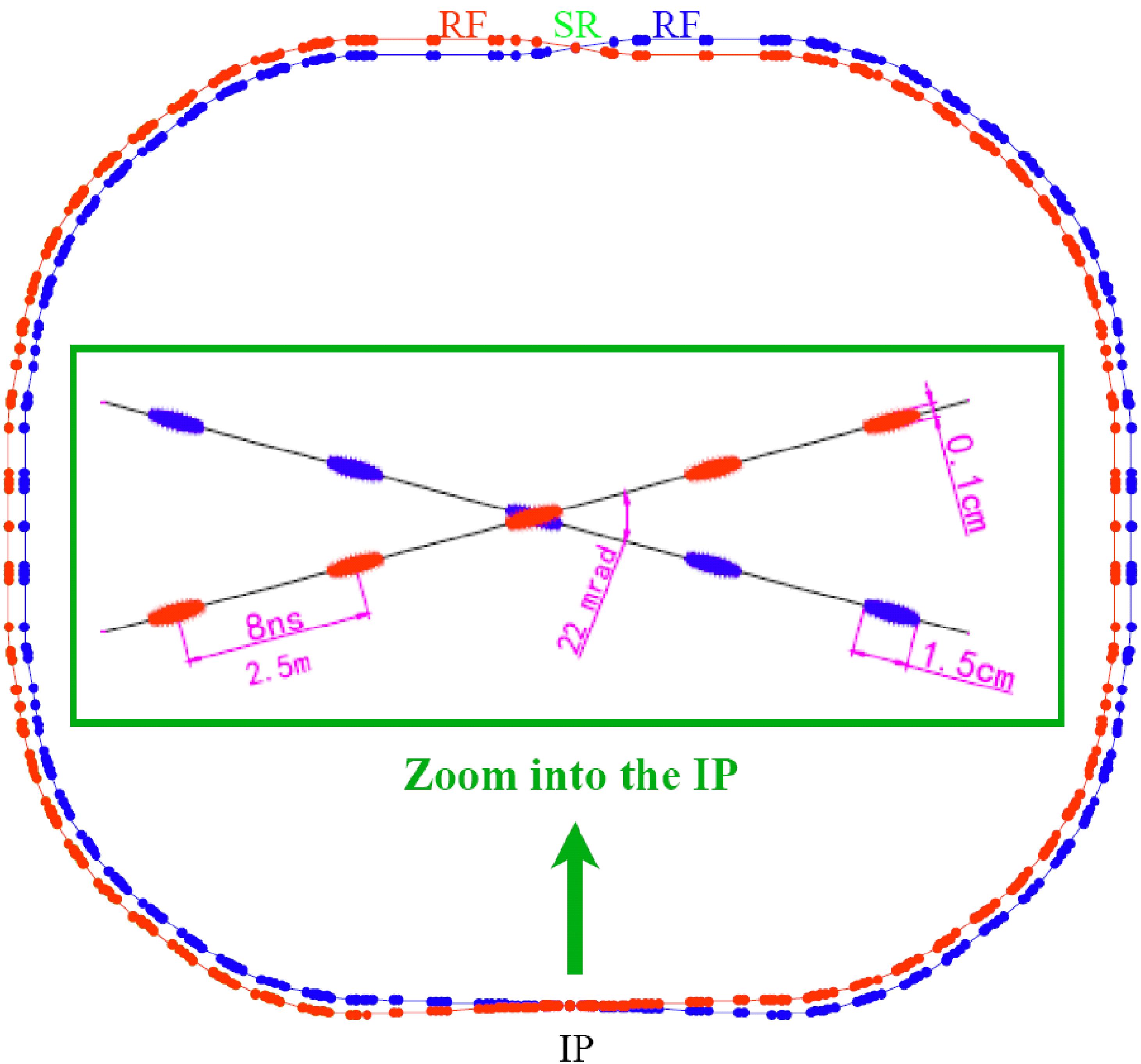








Storage Ring



Beam energy:
1.0-2.3 GeV

Design Luminosity:
1×10^{33} $cm^{-2}s^{-1}$

Optimum energy:
1.89 GeV

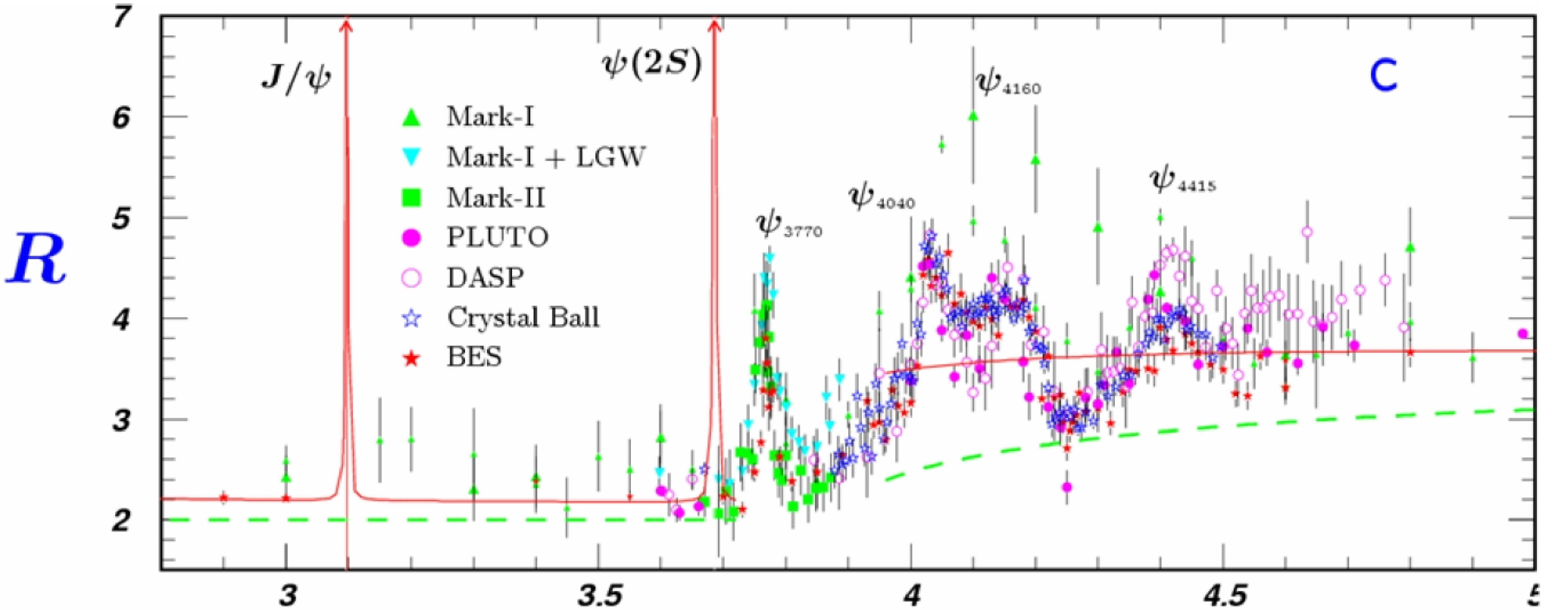
Energy spread:
5.16×10^{-4}

No. of bunches:
93

Bunch length:
1.5 cm

Total current:
0.91 A

Circumference:
237m

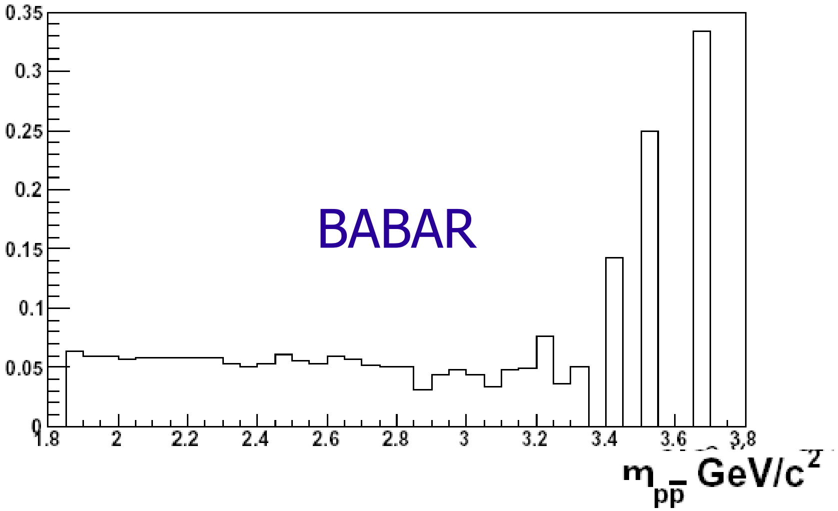


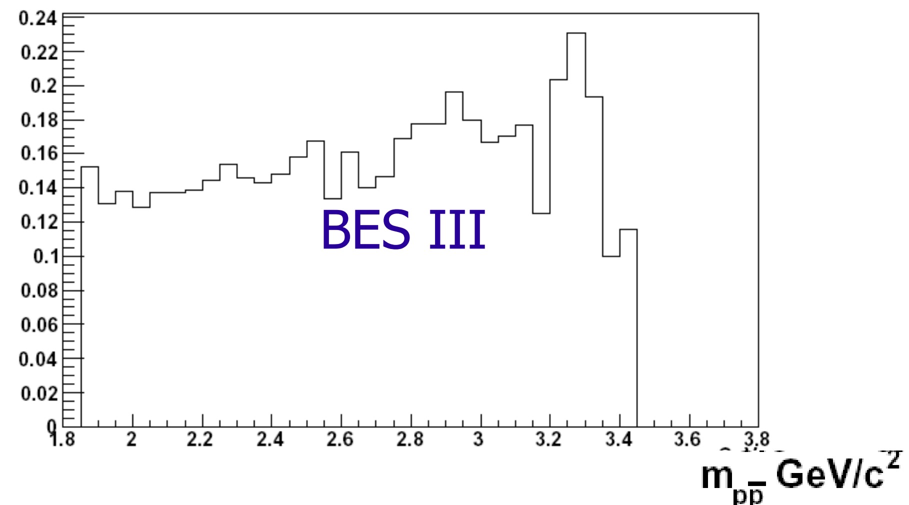
R
7
6
5
4
3
2
3
3.5
4
4.5
5
J/ψ
ψ(2S)
C
ψ4160
ψ4040
ψ3770
ψ4415
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES

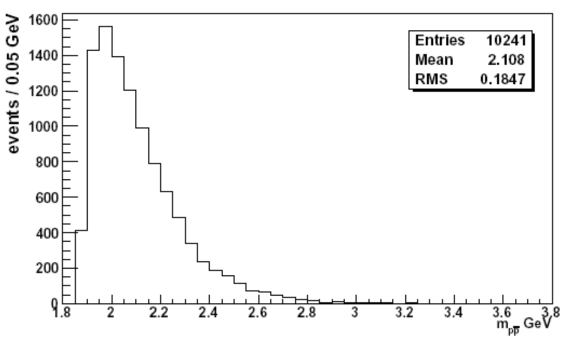
Proton TL FFs @ BESIII

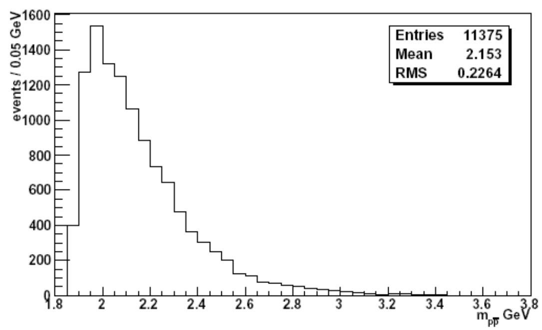
- **Tagged** Acceptance:

$$Acc = \frac{\#\text{evts with } \mathbf{p,pbar,\gamma} \text{ in detector}}{\#\text{ evts in } L_{BABAR,BES} \text{ for } \sqrt{s}_{BABAR,BES}}$$



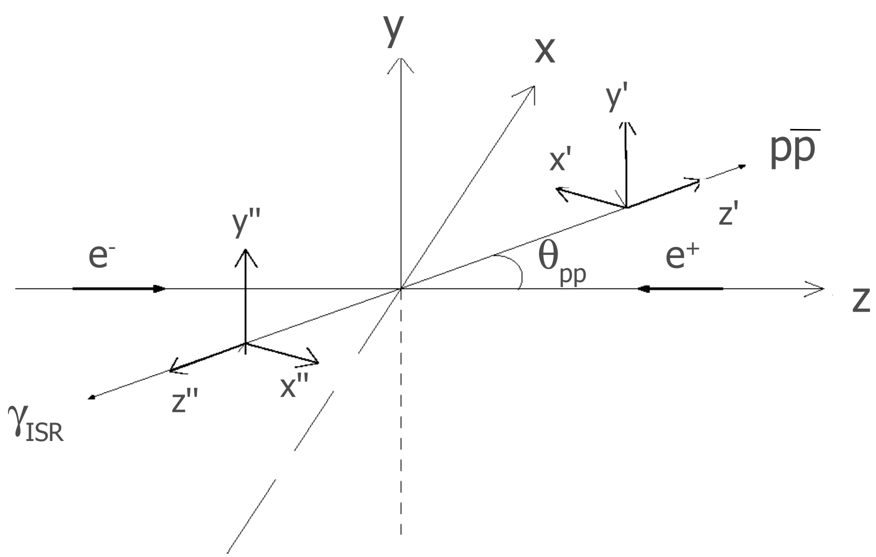






The proton case

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



- Possible frame:

$O' = \Lambda_{CM} R_X(-\theta_{pp}) R_Z(\pi/2-\Phi_{pp})$

Recipe:

1. Define the **z' direction as the direction of movement of hadronic system**.

2. Apply transformation above to proton and photon. This will bring them to the hadronic rest frame.

3. Theta_hat is the angle between proton and z'.