Some surprises in e^+e^- -> Hadrons
Baryon Timelike Form Factors close to threshold
Non Breit-Wigner Charmonium Lineshape

Annual Meeting of the GRD PH-QCD

December 15th -17th , 2014, Paris

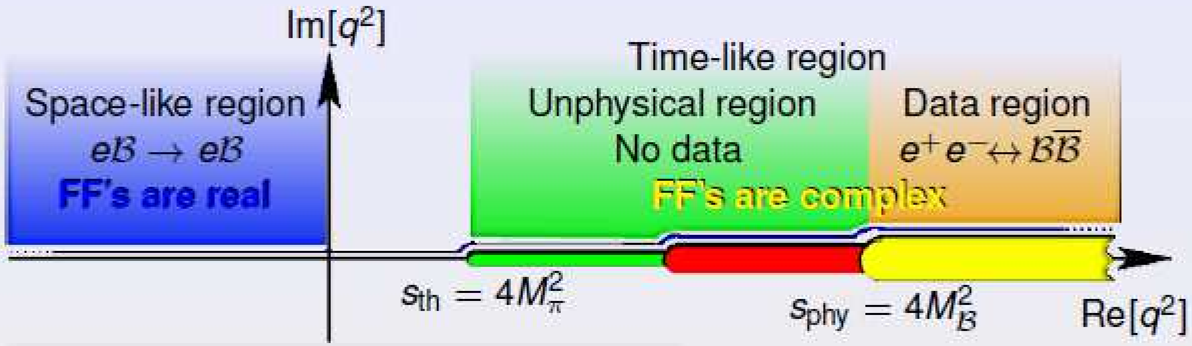
Outline

- Charged Baryon cross section at threshold:
  - Jump at threshold (Coulomb Enhancement)
  - Unexpected $G(4\ M^2_B) \sim 1$ (?)
  - Unexpected flat cross section above threshold (no Sommerfeld Resumm?)
  - Unexpected analyticity violation at threshold (?!)

- Neutral Baryon cross section at threshold:
  - Unexpected jump at threshold (Coulomb at quark level?) ?!

- Charmonium Lineshape:
  - Imaginary Decay Width
  - A charmonium model for non Breit-Wigner lineshape
  - A proposal for PANDA

Cross sections and analyticity



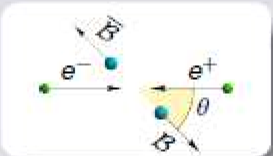
$$\text{Time-like: had. helicity} = \begin{cases} 1 \Rightarrow |G_E| \\ 0 \Rightarrow |G_M| \end{cases}$$

$$G_E(4M_{\mathcal{B}}^2) = G_M(4M_{\mathcal{B}}^2)$$

Elastic scattering

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

$$\tau = \frac{q^2}{4M_{\mathcal{B}}^2}$$



Annihilation

Coulomb correction

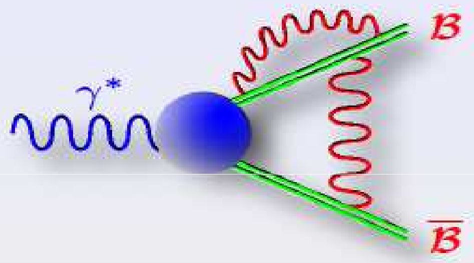
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} \left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta |G_E|^2 \right]$$

$$\beta = \sqrt{1 - \frac{1}{\tau}}$$

The Coulomb Factor

Coulomb effects predominant at threshold

Strong interactions: short range, while Coulomb long range:
Coulomb acts on hadrons and pointlike Coulomb should be applied



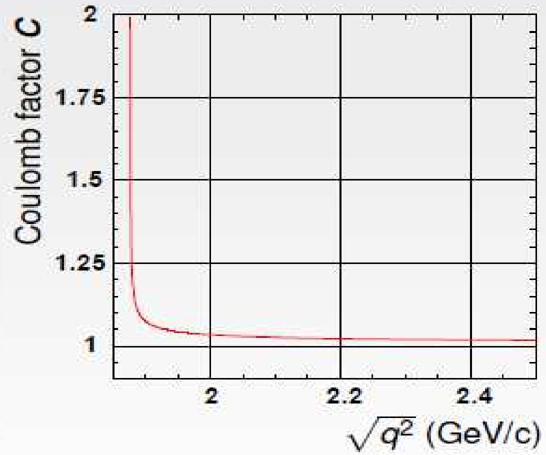
$p\bar{p}$ Coulomb interaction as FSI
[Sommerfeld, Sakharov, Schwinger, Fadin, Khoze]

Distorted wave approximation

$$C = |\Psi_{\mathrm{Coul}}(0)|^2$$

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

No Coulomb factor for boson pairs (P-wave)



Sommerfeld Enhancement and Resummation Factors

Coulomb Factor $\mathcal{C}$ for S-wave only:

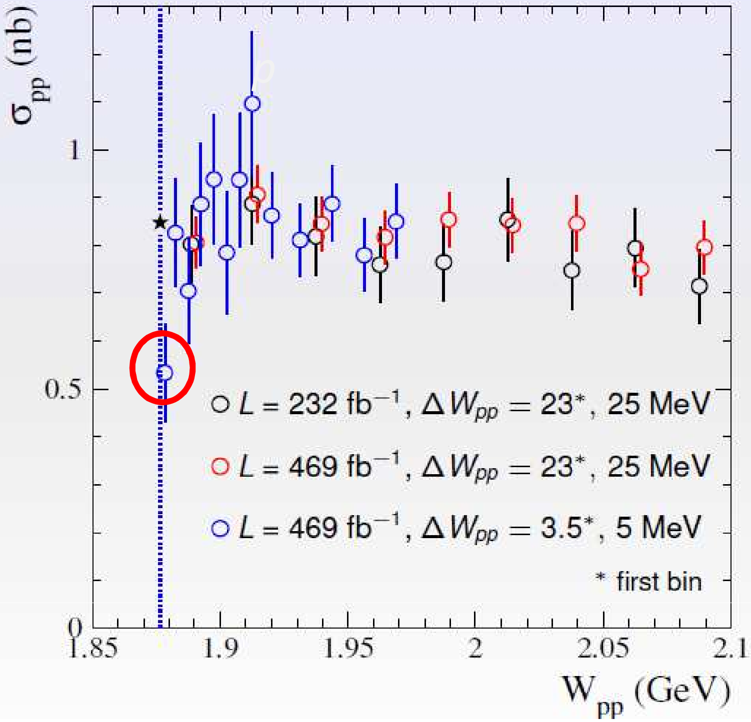
- Partial wave FF: $G_S = \dfrac{2G_M\sqrt{q^2/4M^2} + G_E}{3}$ $\quad G_D = \dfrac{G_M\sqrt{q^2/4M^2} - G_E}{3}$
- Cross section: $\sigma(q^2) = 2\pi\alpha^2\beta\,\dfrac{4M^2}{(q^2)^2}\left[\mathcal{C}\,|G_S(q^2)|^2 + 2|G_D(q^2)|^2\right]$

$$\mathcal{C} = \mathcal{E} \times \mathcal{R}$$

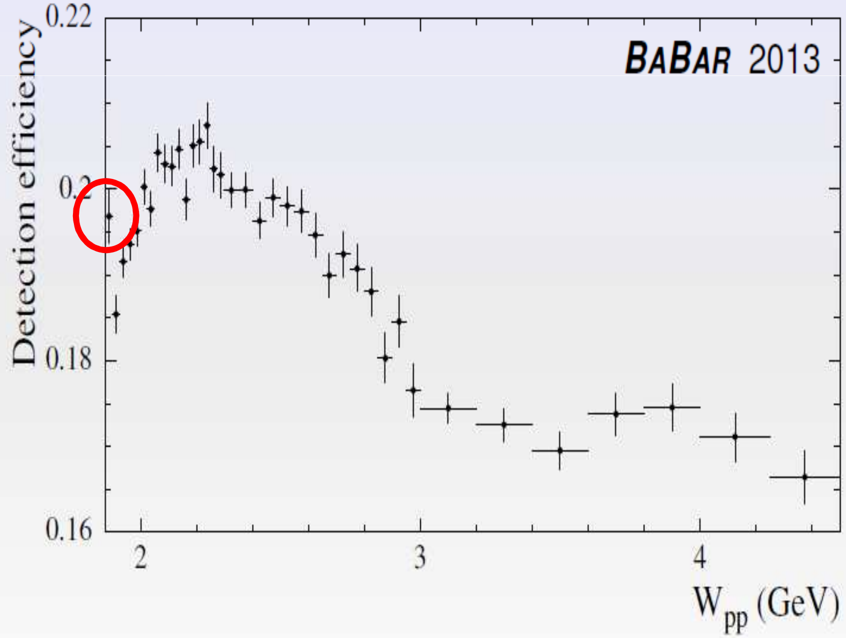
- Enhancement factor: $\mathcal{E} = \pi\alpha/\beta$
- Step at threshold: $\sigma(4M^2) = \dfrac{\pi^2\alpha^3}{2M^2}\dfrac{\cancel{\beta}}{\cancel{\beta}}|G_S(4M^2)|^2 = 0.85\,|G_S(4M^2)|^2$ nb

- Resummation factor: $\mathcal{R} = 1/[1 - \exp(-\pi\alpha/\beta)]$
- Few MeV above threshold: $\mathcal{C} \simeq 1 \;\Rightarrow\; \sigma(q^2) \propto \beta\,|G_S(q^2)|^2$

BABAR 2013: $e^+e^- \to p\bar{p}$: jump at threshold



$e^+e^- \to p\bar{p}$: *efficiency*



ISR : non vanishing ε at threshold

BaBar: indeed jump at threshold

but ε anomalous

as well as the cross section

Λ_c : can check it at threshold

Proton form factor at $q^2 = 4\,M_p^2$

Extrapolating the flat cross section
(neglecting for a while the very first point , waiting for Λ_c)

$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = 0.83 \pm 0.05\ \text{nb}$$

BABAR

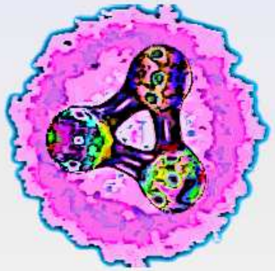
$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\cancel{\beta}}{\cancel{\beta}}|G^p(4M_p^2)|^2 = 0.85\,|G^p(4M_p^2)|^2\ \text{nb}$$

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

$$|G^p(4M_p^2)| = 0.99 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$$

Proton form factor at $q^2 = 4\,M_p^2$

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



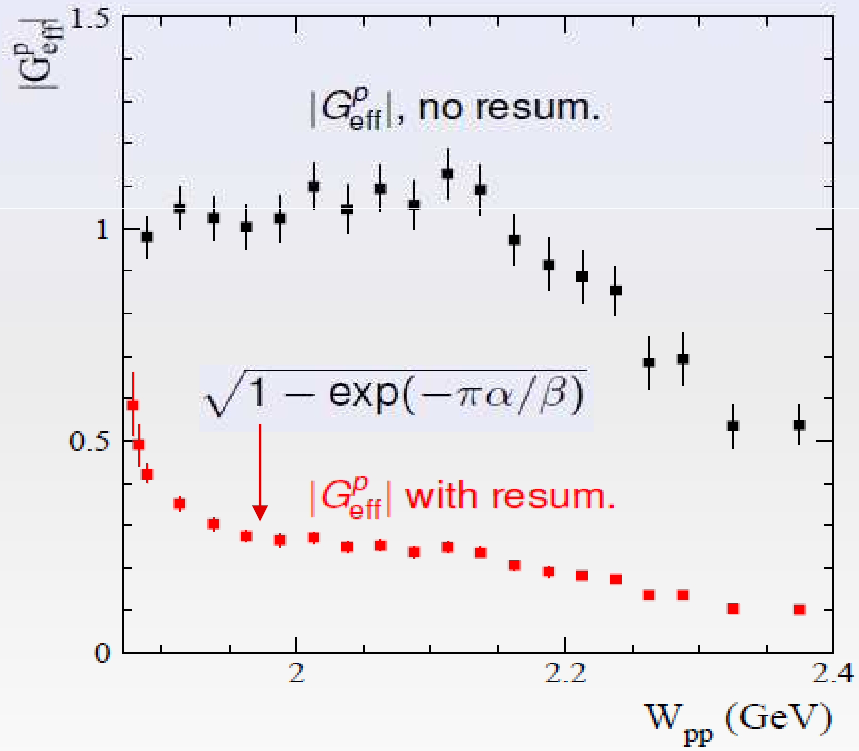
At $q^2 = 4M_p^2$ protons behave as pointlike fermions!

Sommerfeld Resummation Factor Needed?

BABAR: $|G_{eff}^{p}|$ with and without resummation [PRD73, 01200]

Sommerfeld pointlike R implies a rising cross section, while it is flat
Hence G_{eff} sharp decrease is an artefact (just the inverse of R)?
No narrow resonance below threshold ?

An explanation: α_{em} -> α_S (many gluons exchange, not only photons) ?



Neutral Baryon cross sections non zero at threshold unlike the expectation

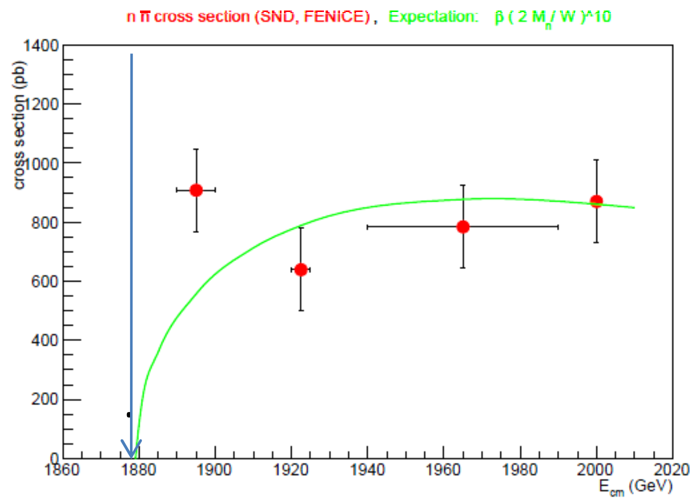
Cross section should vanish at threshold, due to vanishing phase space (cancelled by Coulomb enhancement factor if the baryon is charged).

While it is ~ 450 pb	in the case of $\Lambda\bar{\Lambda}$	(BESIII)
(might be) ~ 850 pb	in the case of $n\bar{n}$	(SND2011-12, FENICE)

$\Lambda\bar{\Lambda}$

Preliminary

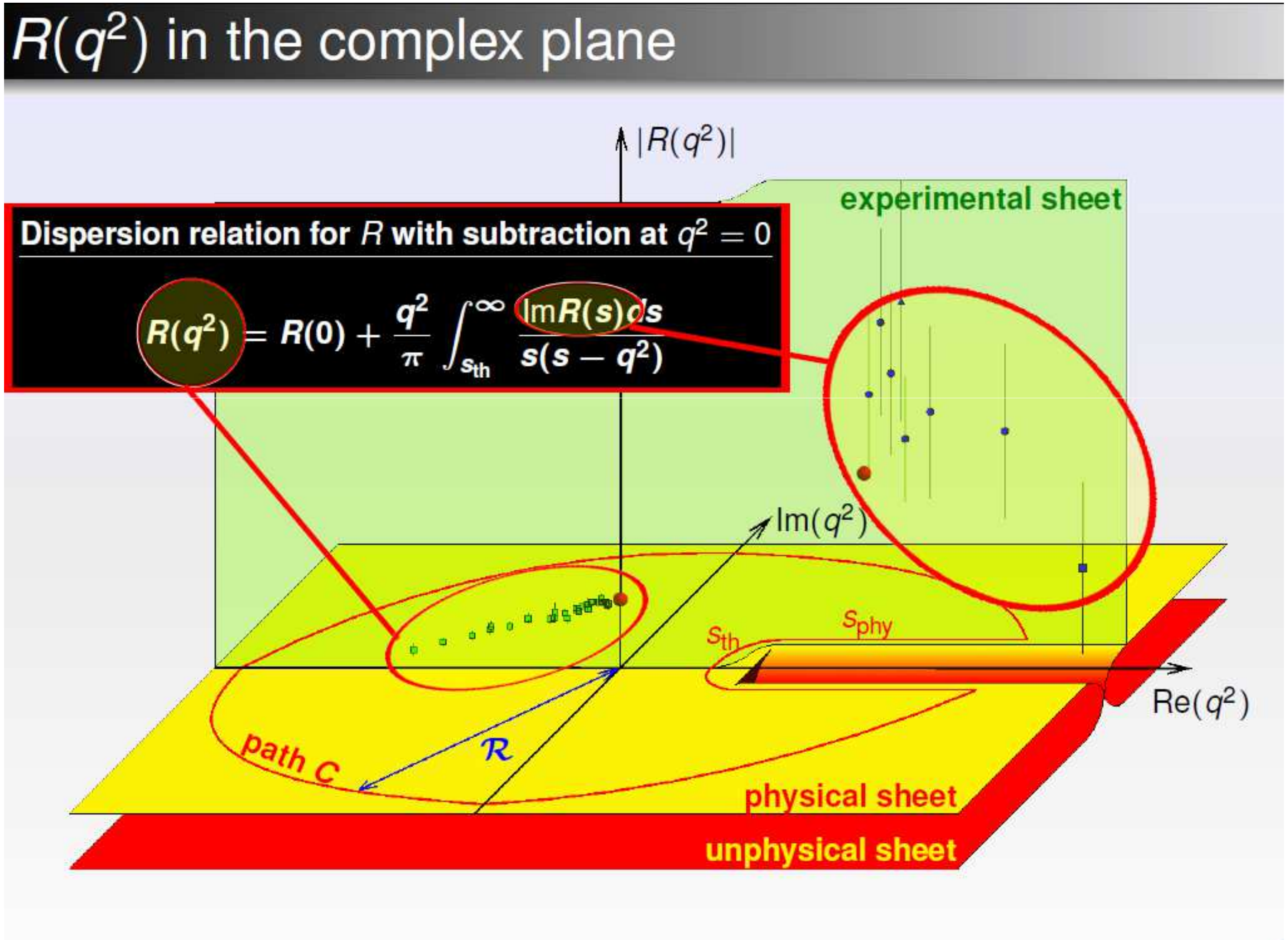
$n\bar{n}$ 2012



Baryons at threshold do not behave as expected

$R(q^2)$= GE (q^2) / GM(q^2) from space to timelike

Uncontested assumption: $R(4\ M^2)$ =1, but !!



Analyticity Violation in $e^+ e^-$ -> $B \bar{B}$?

Istituto Nazionale di Fisica Nucleare

December 16th , 2014, Paris

Why to waste your time

- Always postulated that in e^+e^- -> Baryon Antibaryon at threshold :

  angular distribution is isotropic, due to FF analiticity

- Exactly at threshold in the c.m. difficult in the case of e^+e^- -> $p\bar{p}$

  - PS 170 by means of $p\bar{p}$ -> e^+e^- (atomic uncert.-> normalization)
  - BaBar by means of ISR (limited in statistics)

- SND e^+e^- -> $n\bar{n}$ (in principle closer to threshold than $p\bar{p}$)

- **Heavy baryons weak decay -> feasible at threshold** (BESIII) **!**

  - $\Lambda\bar{\Lambda}$ (BESIII: anomalous at threshold)
  - $\Lambda_c\bar{\Lambda}_c$ (BESIII tested $J^P= 1/2^+$)

BaBar and BESIII present results

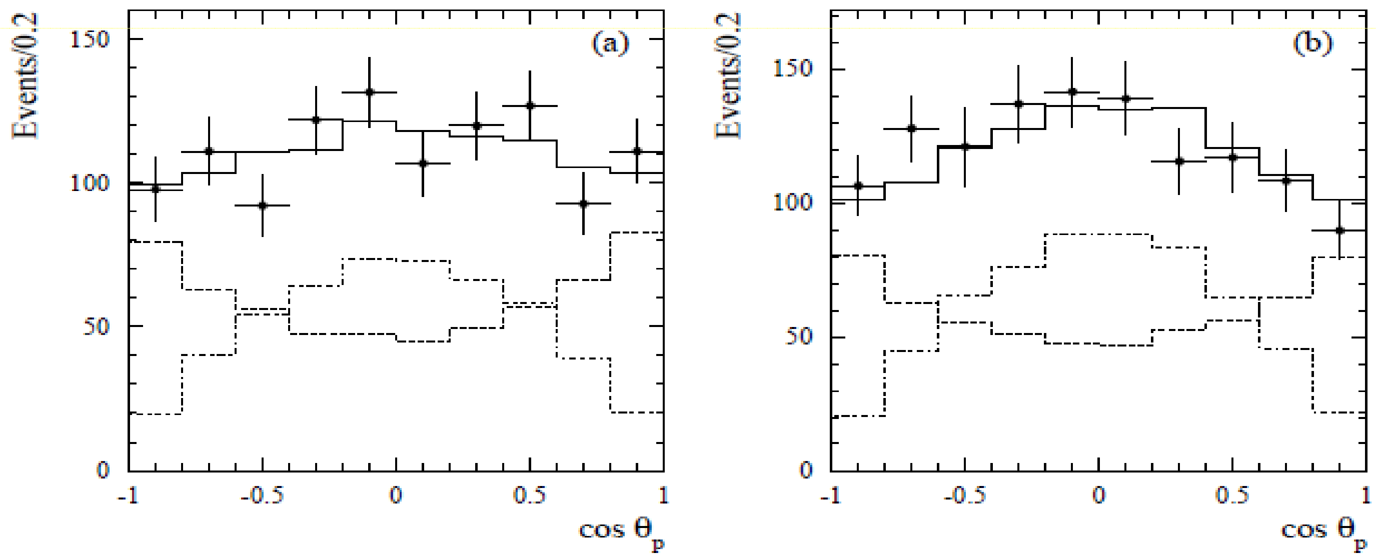
BESIII Λ_c and BaBar $p\bar{p}$ statistics not yet enough,

But, together, a trend is pointed out

(a baryon common feature? Quantitatively not necessarily the same)

BaBar: W= 1877-1950 MeV W=1950-2025 MeV

β = 0.20 β = 0.33



VERY PRELIMINARY

$\pi\alpha$
Coulomb
dominance

Why it *should* be isotropic : $G_E(4M^2_{\Lambda c}) = G_M(4M^2_{\Lambda c})$

- $J_\mu \sim F_D \gamma_\mu + F_P\, i\, \sigma_{\mu\nu} q_\nu /(2M_B)$
- (lowest order QED : $F_D = 1$, $F_P = 0$)
- Time-like: Outgoing Baryon spin antiparallel: G_E
Outgoing Baryon spin parallel: G_M
- $\mathbf{G_E = F_D + F_P / \tau, \quad \tau = (2M_B)^2/ Q^2}$ (time-like $Q^2 > 0$)
$\mathbf{G_M = F_D + F_P}$
- $\mathbf{d\sigma/d\cos\theta = \pi\, \alpha^2/(2\, M_B^2)\, \beta\; C_0\, [\, |G_M|^2\, (1+\cos^2\theta) + \tau\, |G_E|^2 \sin^2\theta\,]}$
- **Standard understanding: at threshold ($\tau = 1$) :**
  - $\mathbf{G_E = G_M = F_D + F_P}$
  - **Isotropy. S wave only**

Why it *could* be anisotropic : $G_E(4M_{\Lambda c}) \neq G_M(4M_{\Lambda c})$

- Assume $G_E(4M_{\Lambda c}) \neq G_M(4M_{\Lambda c})$, always possible to define F_D and F_P

  so that $G_E = F_D + F_P / \tau$, $G_M = F_D + F_P$

- But F_D and F_P no more analytic (continous) through the threshold
  - $F_D = (G_M - G_E)/(\tau - 1)$
  - $F_P = (\tau G_E - G_M)/(\tau - 1)$

❑ **F_D and F_P not analytic** equivalent to $G_E(4M_{\Lambda c}) \neq G_M(4M_{\Lambda c})$,

- **Coulomb interactions not analytic at threshold:**

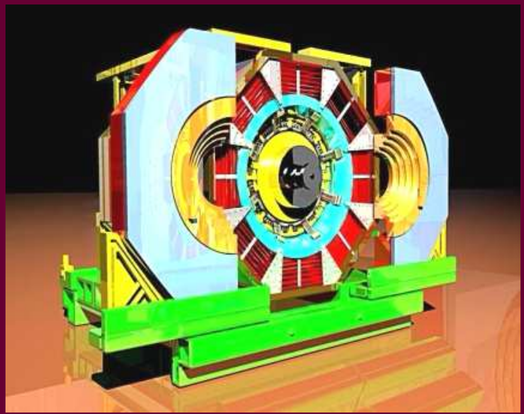
  $|G_S^{Coulomb}|^2 \sim \pi \alpha / \beta$

More data expected soon from BESIII

at neutral and charged baryon threshold

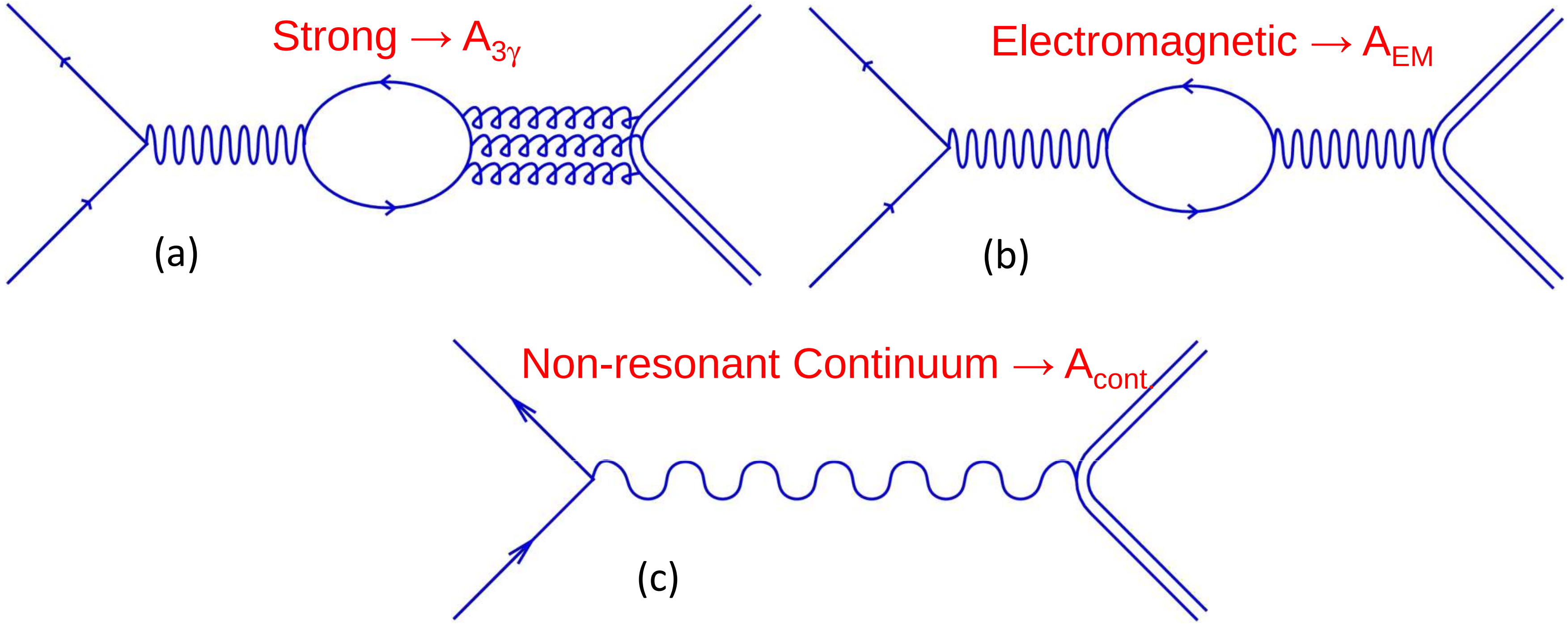
in particular at the $\Lambda_c \bar{\Lambda}_c$ threshold

(jump + almost pointlike FF + flat above + anisotropy ?)



Imaginary Charmonium Decay Widths ?

Vector Quarkonium Decay Mechanisms



(a) $e^+e^- \to J/\psi \to$ *hadrons* via strong mechanism (b) via em mechanism

(c) non-resonant $e^+e^- \to$ *hadrons* via a virtual photon.

pQCD regime: all amplitudes real (apart BW resonance behaviour),

while data are as if there is an additional i in front of the BW

J/Ψ Vector + Pseudoscalar
SU3 and SU3 Breaking Amplitudes

Use reduced amplitudes $B=B_0 / P^{*\,3}$

Process $J/\psi \to$	Amplitude
$\rho^+\pi^-, \rho^0\pi^0, \rho^-\pi^+$	$g+e$
$K^{*+}K^-, K^{*-}K^+$	$g(1-s)+e$
$K^{*0}\bar{K}^0, \bar{K}^{*0}K^0$	$g(1-s)-2e$
$\omega\eta$	$(g+e)X_\eta + \sqrt{2}rg(\sqrt{2}X_\eta + Y_\eta)$
$\omega\eta'$	$(g+e)X_{\eta'} + \sqrt{2}rg(\sqrt{2}X_{\eta'} + Y_{\eta'})$
$\phi\eta$	$(g(1-2s)-2e)Y_\eta + rg(\sqrt{2}X_\eta + Y_\eta)$
$\phi\eta'$	$(g(1-2s)-2e)Y_{\eta'} + rg(\sqrt{2}X_{\eta'} + Y_{\eta'})$
$\rho^0\eta$	$3eX_\eta$
$\rho^0\eta'$	$3eX_{\eta'}$
$\omega\pi^0$	$3e$
$\phi\pi^0$	0

J/Ψ
Vector + Pseudoscalar

Parameter		Fit
SU_3 strong Amplitude	g	7.22 ± 0.38
SU_3 breaking strange	s	0.18 ± 0.04
SU_3 breaking DOZI	r	-0.04 ± 0.02
E.M. Amplitude	e	0.75 ± 0.04
Phase	f	**81.51± 6.75**

J/ψ

Vector + Pseudoscalar Decay

Decay	Amplitude	PDGX10^4	FitX10^4	$\Delta\chi^2$
$\rho^0 \pi^0$	$g\, e^{i\phi} + e$	169.0 ± 15.0	133.00	1.13
$K^{*+} K^-$	$g\,(1\text{-}s)\, e^{i\phi} + e$	51.2 ± 3.0	51.5	0.01
$K^{*0} K^0$	$g\,(1\text{-}s) e^{i\phi} - 2e$	43.9 ± 3.1	48.5	0.48
$\omega\, \eta$	$(g\, X + d) e^{i\phi} + eX$	17.4 ± 2.0	18.5	0.06
$\phi\, \eta$	$(g\,(1\text{-}2s)Y + d) e^{i\phi} - 2eY$	7.5 ± 0.8	3.9	4.02
$\rho\, \eta$	$3eX$	1.9 ± 0.2	2.2	0.30
$\omega\, \pi$	$3e$	4.5 ± 0.5	4.1	0.11
$\omega\, \eta'$	$(g\, X' + d')e^{i\phi} + eX'$	7.0 ± 7.0	11.9	0.10
$\phi\, \eta'$	$(g\,(1\text{-}2s)Y' + d\,`\,)e^{i\phi} - 2eY'$	4.0 ± 0.7	6.1	1.87
$\rho\, \eta$	$3eX'$	1.1 ± 0.2	1.1	0.04

J/ψ

Pseudoscalar + Pseudoscalar Decay

- It is possible to avoid $\pi\pi$ and complications from s quark by means of KK BR's and $|E^{KK}|$ only

- $B^{+-} = |S|^2 + |E^{+-}|^2 + 2\,|S|\,|E^{+-}| \cos\Phi$

  $B^{SL} = |S|^2 + |E^{SL}|^2 - 2\,|S|\,|E^{SL}| \cos\Phi$

- $|E^{+-}|^2 \;=\; B^{\mu\mu}\; \sigma(e^+e^- \to K^+ K^-) / \sigma(e^+e^- \to \mu\,\mu)$

  $|E^{SL}|^2 \;\sim\; 0$, since

  $\sigma\,(e\,e \to K_S\, K_L) << \sigma\,(e\,e \to K^+ K^-)$

  $\sigma\,(e^+ e^- \to K_S\, K_L) \sim 0.6$ pb at J/Ψ

  $B^{+-} \;=\; (2.37 \pm 0.31)\, 10^{-4}$ $\quad B^{SL} = (1.66 \pm 0.26)\, 10^{-4}$

  $|E^{+-}|^2 \;=\; (1.3 \pm 0.6)\, 10^{-4}$ *from BaBar*

  $\Phi \;=\; 83.7^0 \pm 9.0^0$

Experimental evidences for $\Psi(3770)$ imaginary strong decay widths

ψ''(3770):

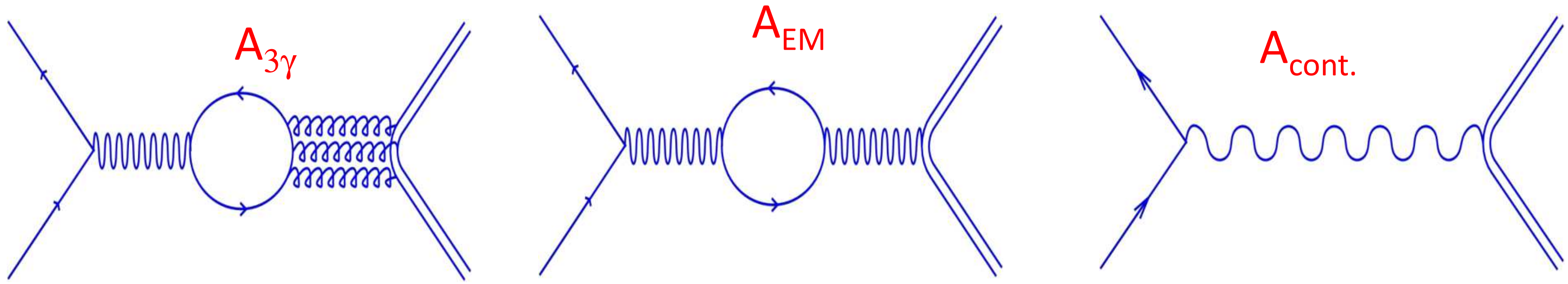
- non DDbar (small) -> throught the interfence with continuum
- For a wide resonance Φ from interference at the peak :

  $\Phi \sim -2|A_{3g}|/\Gamma_{tot}$ sin Φ x continuum

- CLEOc and BESIII: $\Phi \sim$ **- 90°**, since continuum sign

decay	continuum	Ψ''(3770)	sign	
$\rho\ \pi$	13.1±2.8	7.4±1.3	-	CLEOc, PRD 73(2006)012002
$\phi\ \eta$	2.1±1.6	4.5±0.7	+	CLEOc, PRD 73(2006)012002
$p\bar{p}$	0.74±0.08	0.4±0.02	-	BESIII Y.Liang, Nov (2012)

Model independent (BESIII) from interference in q^2 behavior

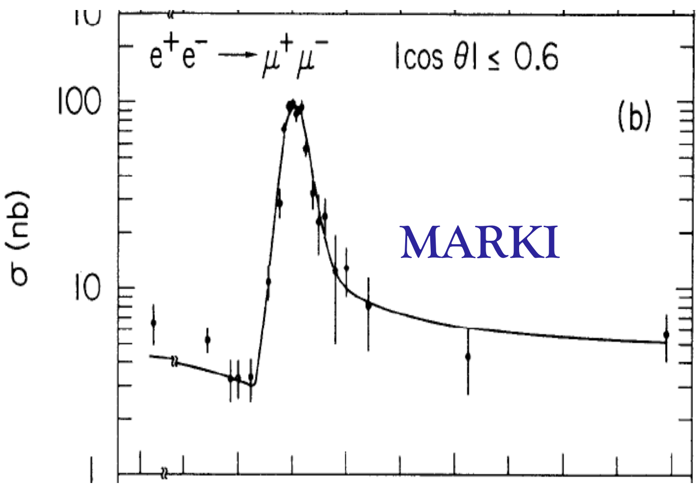


$$s_{born} = |A_{3\gamma} + A_{EM} + A_{cont}|^2 = \left| |A_{3\gamma}| e^{\iota\varphi} + |A_{EM} + e^{\iota\varphi'} A_{cont}| \right|^2$$

Actually $\Phi_{meas} = \Phi - d_{cont}$ and $|\Phi_{meas}|$ only is measured, since it is difficult to get the sign

In the $\mu\mu$ case full interference between A_{EM} and A_{cont} observed , as expected, by MARKI(1975), BESII (1995), KDER(2010) (1/2 γ propagators : $\varphi' = 180^o$)

Results on $\mu\mu$ and hadronic strong /em decay will come soon, from BESIII



Open Issues related to Unitarity

- **No explanation for imaginary strong decay J/ Ψ widths has been put forward until now**

- J/ Ψ description as a Breit Wigner might have some difficulties , dealing with imaginary decay widths

- Optical theorem : Im $T_{el} = W/8\pi \cdot \sigma_{tot}$ implies Im $T_{el} > 0$

- Γ(J/ Ψ -> $p\bar{p}$) imaginary: Im T_{el}($p\bar{p}$ -> J/ Ψ -> $p\bar{p}$) < 0

- $p\bar{p}$ continuum could restore unitarity, even if unrelated to J/ Ψ (?)

- Looking for a different J/ Ψ description

- σ_{el}($p\bar{p}$ -> J/Ψ -> hadrons) : a test of the following model

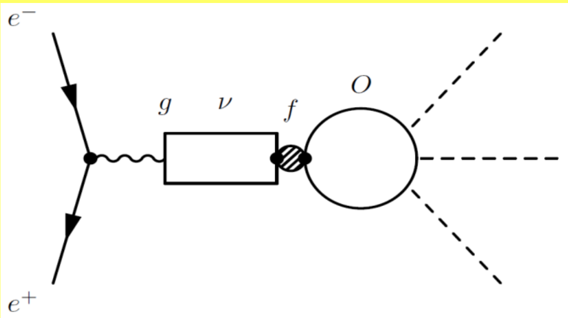
A model to explain imaginary widths

Yochiro Nambu

Quarkonium OZI breaking decay as Freund and Nambu (PRL 34(1975), 1645)

- Quarkonium as a superposition of
  - A narrow V (coupled to the virtual photon, but not directly to hadrons)
  - A wide one (a glueball O) (not coupled to leptons i.e. to a virtual photon, but strongly coupled to hadrons)

***f* is the coupling between V and $\mathcal{O}$**



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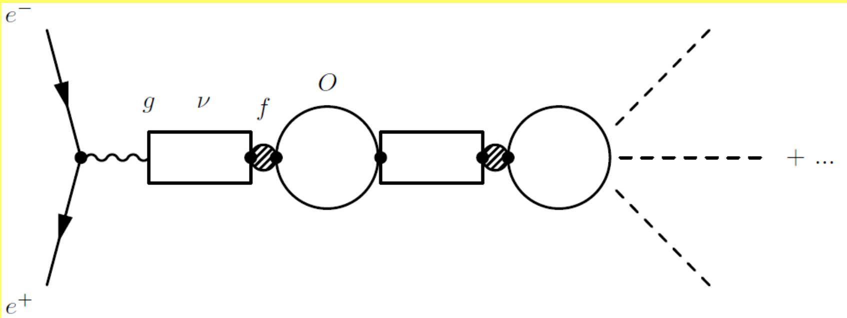


iterated in f

Quarkonium OZI breaking decay as Freund and Nambu (PRL 34(1975), 1645)

- Quarkonium as a superposition of V and O:

$$A_{strong} = G_e V^{-1} f\, O^{-1} G_f + G_e\, V^{-1} f\, O^{-1} f\, V^{-1} f\, O^{-1}\, G_f + \text{iterations}$$

$$= G_e V^{-1} f\, O^{-1} G_f / (1 - V^{-1} O^{-1} f^2) = G_e\, f\, G_f / (V\,O - f^2)$$

- $$A_{em} = G_e\, V^{-1} G_l + G_e V^{-1} f\, O^{-1} f\, V^{-1} G_l + \text{iterations}$$

$$= G_e\, O\, G_f / (V\,O - f^2)$$

- An infinity of radial O recurrences (with exceptions?)

- A similar model mainly used to study Br(ψ') /Br(J/ψ) anomalies
  S. J. Brodsky, G. P. Lepage, S. F. Tuan, PRL 59, 621(1987)
  W.S. Hou, C.Y. Ko, NTUTH-97-11, 1997

Narrow V and wide glueball O superposition

P.J.Franzini, F.J.Gilman, PR D32, 237 (1985)

$$A_{strong} = \frac{\sqrt{\Gamma_{ee}} M_V M_O f \sqrt{\Gamma_O}}{(M_V^2 - W^2 - iM_V\Gamma_V)(M_O^2 - W^2 - iM_O\Gamma_O) - M_V M_O f^2}$$

assuming $\Gamma_O >> \Gamma_{J/\psi}$, $f^{\,2} \sim G_O\,(\Gamma_{J/\psi} - G_V)$

$$A_{strong} \sim \frac{i\sqrt{B_{ee}}\; M_V f\; \sqrt{B_h}}{M^2_{J/\Psi} - W^2 - iM_{J/\Psi}\Gamma_{J/\Psi}} \qquad A_{em} = \frac{\sqrt{B_{ee}}\; M_V \Gamma_{J/\Psi}\; \sqrt{B_{em}}}{M^2_{J/\Psi} - W^2 - iM_{J/\Psi}\Gamma_{J/\Psi}}$$

- **The additional 90° phase is naturally achieved**
- J/ψ shape reproduced if: $|f| \sim 0.012$ GeV , $M_O \sim M_{J/\psi}$, $\Gamma_O \sim 0.5$ GeV
- different only far from the J/ψ (no contradiction with BES, PR 54(1996)1221)
- ψ ''(3770) decay phases agree with Nambu suggestion.
- **ψ ' unclear; ψ ' -> J/ψ ππ (?)**

SND $\Phi \to \pi^+ \pi^- \pi^0$

SND measured $\Phi \to \pi^+\pi^-\pi^0$.

ϕ interferes with ω and ω' tails:

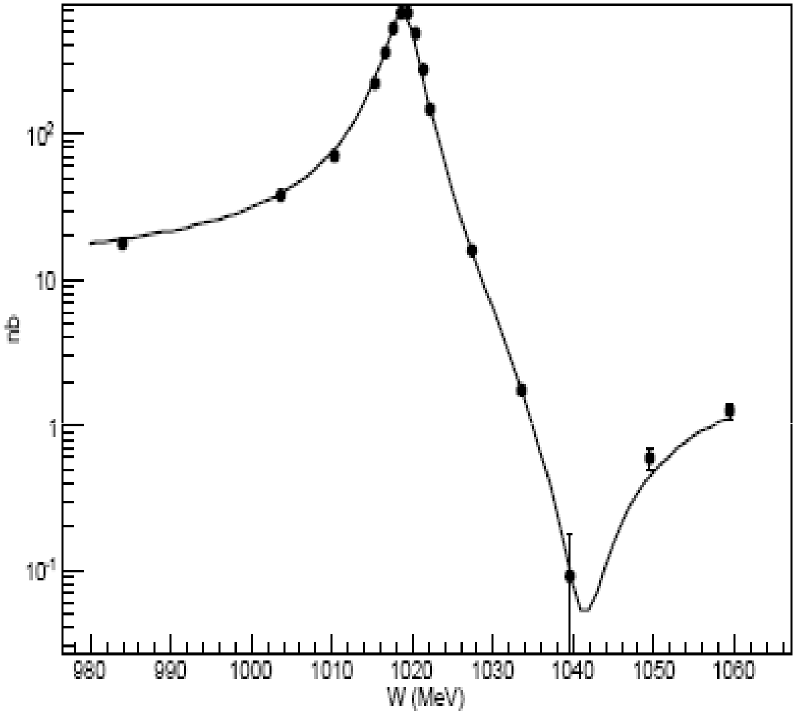
$\varphi \sim 180^0$ (interference dip after the Φ)

Fit SND Φ and continuum data with

f = - 0.016 GeV (like J/Ψ !)

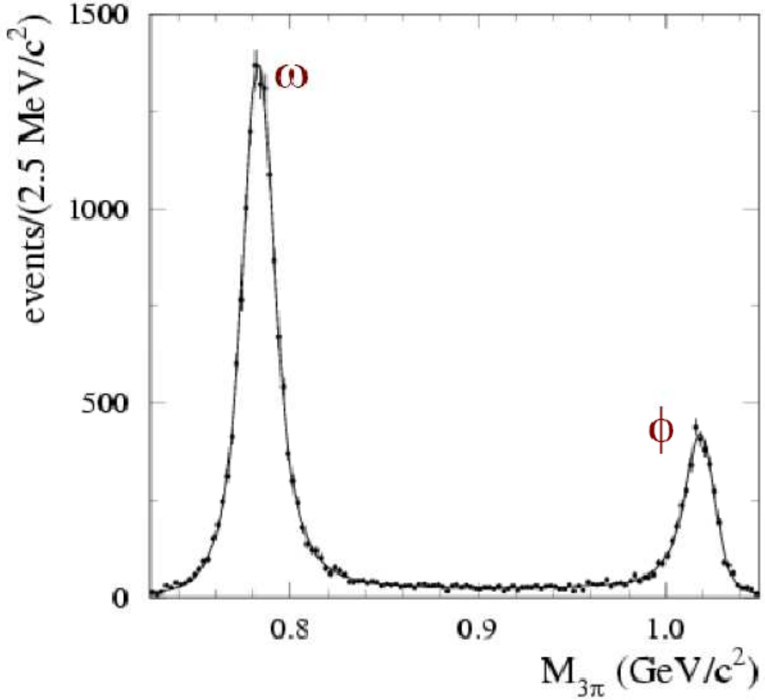
M_O = 1.34 GeV (far from the Φ)

$\Gamma_O \sim$ 0.5 GeV

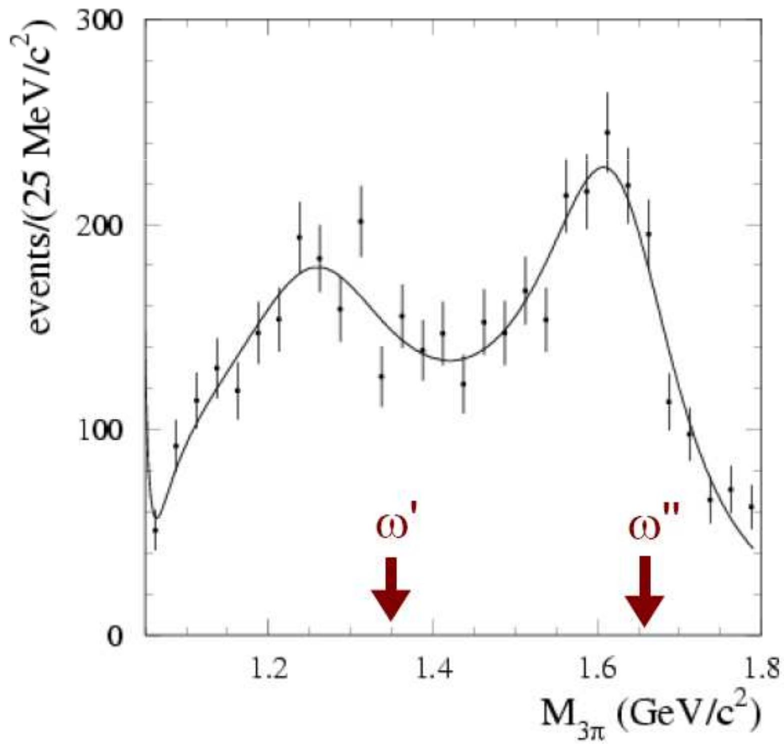


SND data on 3π and present model prediction

BaBar $\pi^+ \pi^- \pi^0$ PR D 70, 072004(2004)



BaBar found indeed an unexpected resonance (ω' , O ?)
at 1.35 GeV , wide 0.45 GeV



Masses and widths

$$M_{\omega'} = (1350 \pm 20 \pm 20)\,\mathrm{MeV}/c^2$$
$$\Gamma_{\omega'} = (450 \pm 70 \pm 70)\,\mathrm{MeV}/c^2$$
$$M_{\omega''} = (1660 \pm 10 \pm 2)\,\mathrm{MeV}/c^2$$
$$\Gamma_{\omega''} = (230 \pm 30 \pm 20)\,\mathrm{MeV}/c^2$$

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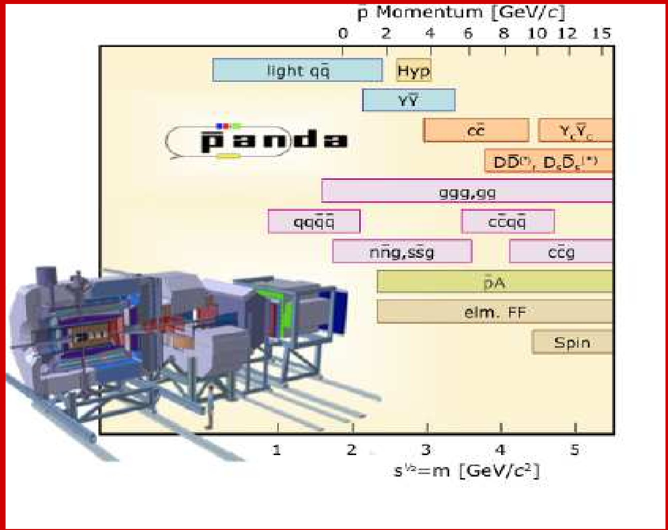
A proposal for PANDA:
a J/Ψ scan



A Proposal for PANDA

- Expected σ ($p\bar{p}$ -> J/Ψ –> hadrons) ~ 1 μb

  while σ ($p\bar{p}$ -> hadrons) ~ 70 mb

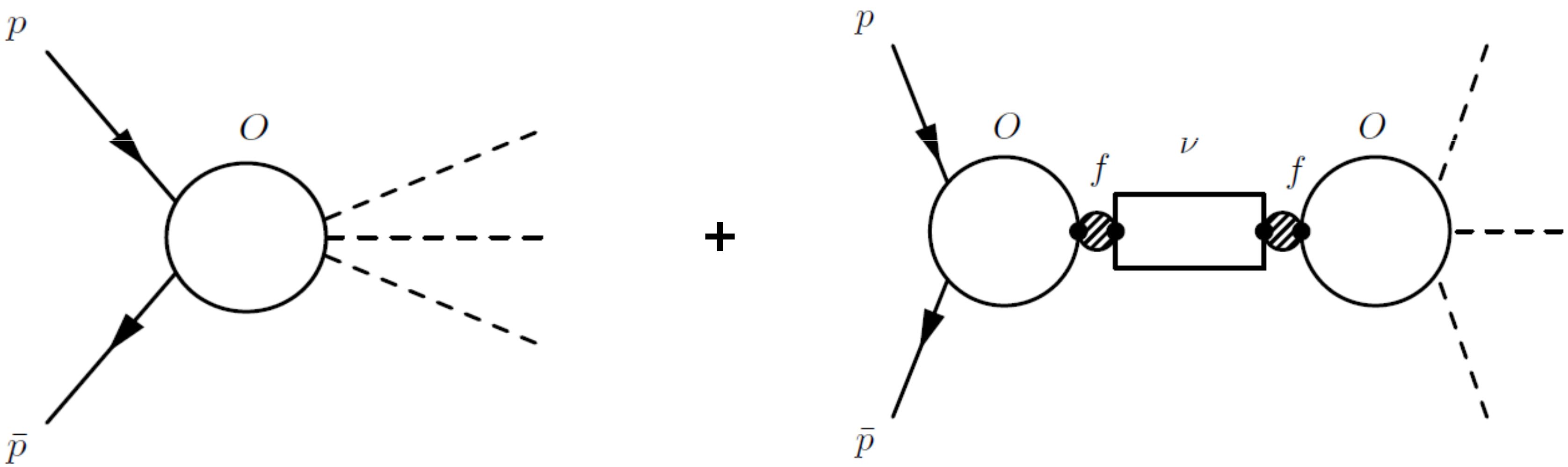
- No J/ Ψ exclusive production evidence in present data

  (too small cross section + $p\bar{p}$ c.m. energy spread)

- Different mechanism in inclusive or exclusive production:
- Inclusive production: direct coupling to gluons or virtual photon
- Exclusive production: hadronic -> apply FN model

A Proposal for PANDA

Contributions to $p\bar{p}$ -> J/Ψ -> hadrons, according to the FN model



A Proposal for PANDA

- According to the FN approach

$$\sigma_{FN} = \frac{B_p \;\; [(M^2_{J/\Psi} - W^2)^2 + (M_{J/\Psi}\Gamma_V)^2)] \;\; B_h}{(M^2_{J/\Psi} - W^2)^2 + (M_{J/\Psi}\Gamma_{J/\Psi})^2}$$

Taking into account that $\Gamma_V << \Gamma_{\vartheta/Y}$

$$\sigma_{FN} = \frac{B_p \, (M^2_{J/\Psi} - W^2)^2 \; B_h}{(M^2_{J/\Psi} - W^2)^2 + (M_{J/\Psi}\Gamma_{J/\Psi})^2}$$

Almost a zero -> a dip in σ_h

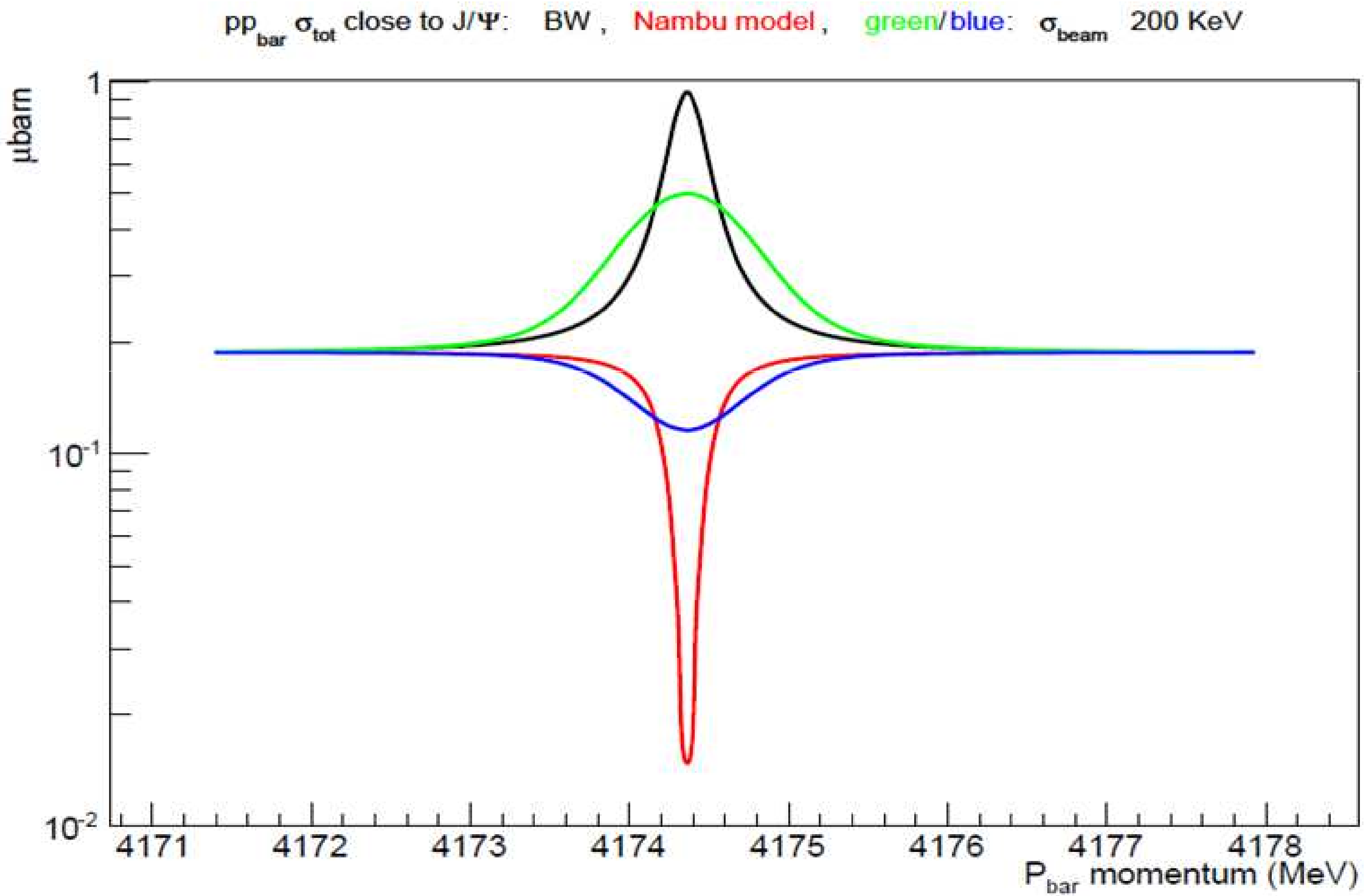
- To be compared to a Breit Wigner

$M^2{}_{J/Y}$

$$\sigma_{BW} = \frac{B_p \;\; \Gamma^2_{J/\Psi} \;\; B_h}{(M^2_{J/\Psi} - W^2)^2 + (M_{J/\Psi}\Gamma_{J/\Psi})^2}$$

A Proposal for PANDA

PANDA good inv. mass resolution: small beam energy spread and no ISR



Conclusions

- **$B\bar{B}$ cross section unexpected features at threshold:**

- Jump followed by a flat behavior
- Pointlike cross section
- Analyticity violation (?)
- Jump also in the case of neutral baryon (?)

- **Charmonium lineshape:**

- Imaginary Decay Widths
- A model for a non Breit-Wigner charmonium lineshape
- A proposal for PANDA

Hope you acknowledge that
Even if it might be not true
it is well conceived
(italian common saying)