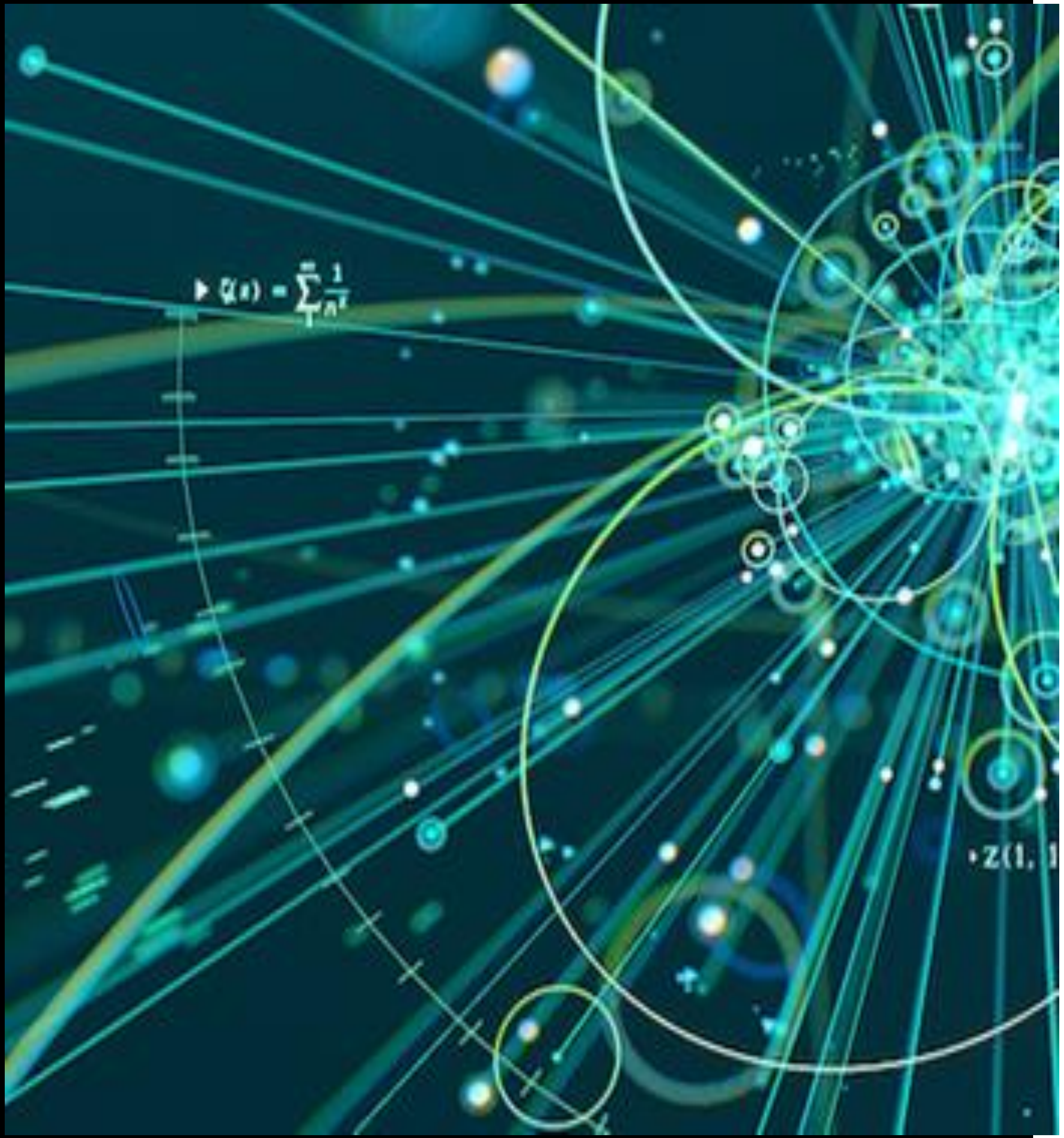

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Measurement of the relative phase between EM and strong amplitudes in $\psi(2S) \to p\bar{p}$

B. Passalacqua, M. Maggiora, M. Destefanis

OUTLINE

01

1. INTRODUCTION

- The BESIII Experiment
- Phase Measurement
- Initial State Radiation

02

2. DATA ANALYSIS

- Event Selection
- Radiative Corrections
- Simultaneous Fit
- Background Studies and Sistematic Uncertanties

03

3. RESULTS

- Cross Section
- Relative Phase

04

4. SUMMARY

BESIII

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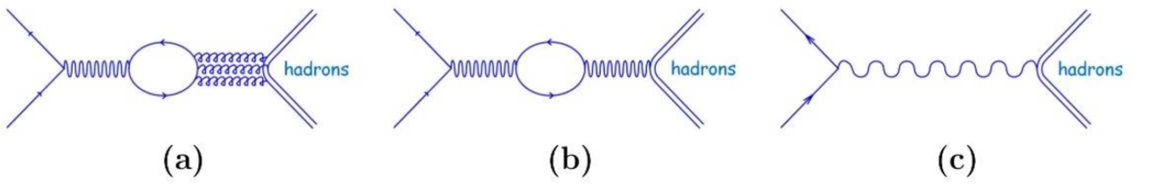
INTRODUCTION

Phase Measurement

The relative phase measurement by means of the interference pattern of the e^+e^- reaction cross section as a function of the center of mass energy (W) near the resonance.

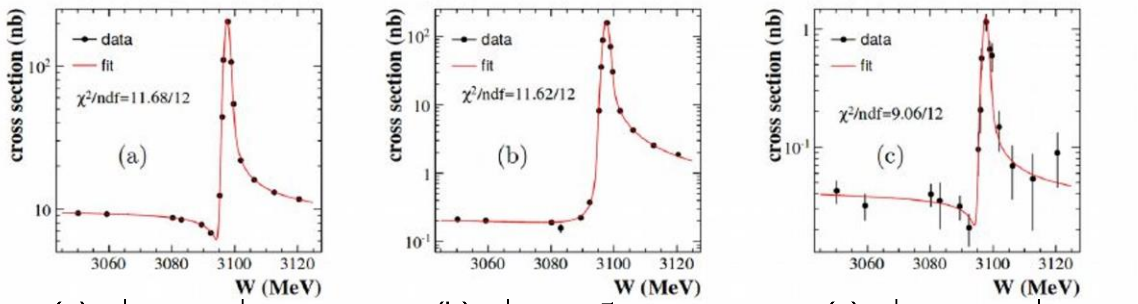
Process $e^+e^- \rightarrow hadrons$ around Charmonia

pQCD regime → all amplitudes are expected to be almost real



(a) A_g strong (b) A_γ electromagnetic (c) $A_{EM} \equiv A_{cont}$ continuum

$$\sigma_0 \cong |A_g(W) + A_\gamma(W)e^{i\Phi_{g,EM}} + A_{cont}(W)e^{i\Phi_{g,EM}}|^2$$



(a) $e^+e^- \rightarrow \mu^+\mu^-$ Pure EM (b) $e^+e^- \rightarrow 5\pi$ EM+Strong (c) $e^+e^- \rightarrow \eta\pi^+\pi^-$ Pure EM

But experiments pointing to another direction for the J//ψ

- e.g. $J/\psi \rightarrow p\bar{p}$ $\Phi = 89° \pm 8°$
- e.g. $J/\psi \rightarrow \rho\pi$ $\Phi = 106° \pm 10°$

A possible explanation:

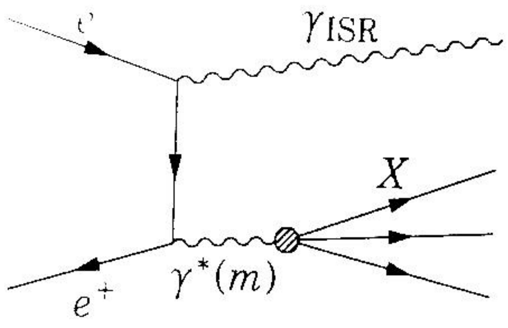
- Quarkonium OZI breaking decay as Freund and Nambu

R. Baldini et al., Phys. Lett. B404, 362 (1997)
R. Baldini et al., Phys. Lett. B444, 111 (1998)
L. Kopke and N. Wermes, Phys. Rep. 174, 67(1989)
J. Jousset et al., Phys. Rev. D41, 1389 (1990).
M. Tanabashi et al. (*Particle Data Group*), Phys. Rev. D. (2019)

Initial State Radiation

In a e^+e^- pair collision one or both leptons can eventually radiate one or more photons:

the radiated energy reduces the effective CM energy of the e^+e^- annihilation.



The probability of radiating an ISR photon is described by the *radiator function* $W(s, x, \theta_\gamma)$

- *x* is the fraction of the beam energy carried away by the ISR photon
- θ_γ is the angle of the photon.
- ISR photon energy ~50-100 MeV
- ISR correction factor 1+$\delta \equiv \int_0^1 \frac{\sigma(x)}{\sigma_0} W(x) dx$, where $x = 1 - \frac{E^2}{E_0^2}$

Cross section:

$$\sigma = \frac{N}{L\varepsilon'(1+\delta)}$$

Check with ad-hoc generator

$p(k)dk = \beta k^{\beta-1}$ probability distribution of the ISR photon

The factor $\beta \cong 0.07$ is parametrized as:

$$\beta = 2\frac{\alpha}{\pi}[\ln\left(\frac{Q^2}{m^2}\right) - 1]$$

Study of the process $e^+e^- \rightarrow p\bar{p}$ via initial state radiation at BESIII – BESIII Collaboration, M. Ablikim et al., Physical Review D, 99:092002, 2019

DATA ANALYSIS

Event Selection

Data collected during the 2018 run around the $\psi(2S)$ resonance (3.4 - 3.8 GeV)

→ $BR(\psi(2S) \to p\bar{p}) = (2.94 \pm 0.08) \times 10^{-4}$

Beam Energies:

Nominal E [MeV]	E [MeV]	$\sigma_E[MeV]$	L $[pb^{-1}]$
3580.0	3581.543	0.060	85.7
3670.0	3670.158	0.063	84.7
3681.0	3680.144	0.061	84.8
3683.0	3682.752	0.115	28.7
3684.0	3684.224	0.119	28.7
3685.5	3685.264	0.105	26.0
3686.6	3686.496	0.120	25.1
3690.0	3691.363	0.075	69.4
3710.0	3709.755	0.074	70.3

Kinematic cuts for the proton tracks:

- $|R_{xy}| < 1\ cm$, $|R_z| < 10\ cm$
- $P \leq 2\ GeV/c$
- $|cos\theta| < 0.8$
- $E_{show}/P < 0.5$ for protons

Cuts for both the proton and the antiproton tracks:

- $178° < \theta_{p\bar{p}} < 180°$, $\theta_{p\bar{p}}$ is the polar angle between the two tracks $p\bar{p}$ in the CM frame
- PID tags selecting proton and antiproton
- $1.4\ GeV/c < P_{p\bar{p}} < 1.7\ GeV/c$

→ **Selections optimization:**
- Barrel region
- Back to back and charged tracks

M. Tanabashi et al. (*Particle Data Group*), Phys. Rev. D (2019)

MonteCarlo Simulations $e^+e^- \rightarrow \psi(2S) \rightarrow p\bar{p}$

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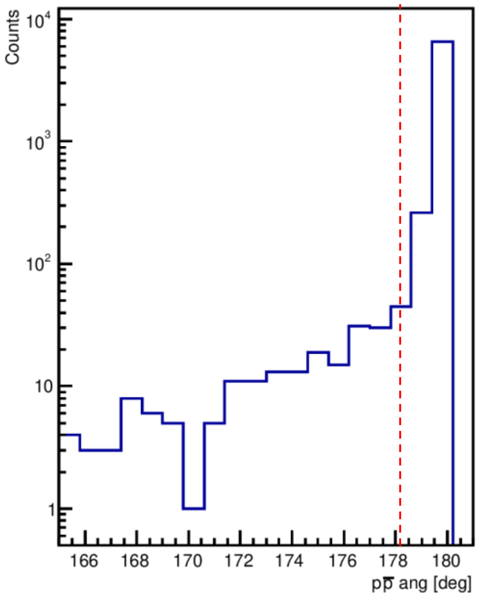
N of generated event: 10000

Generator: BesEvtGen

Transport: Geant4

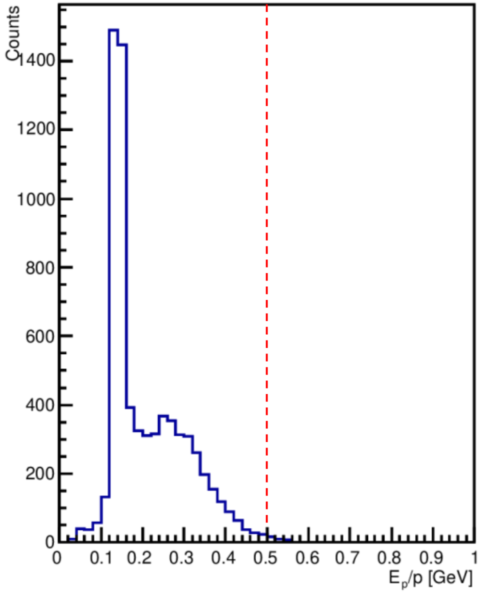
$p\bar{p}$ angle

E = 3.580 GeV



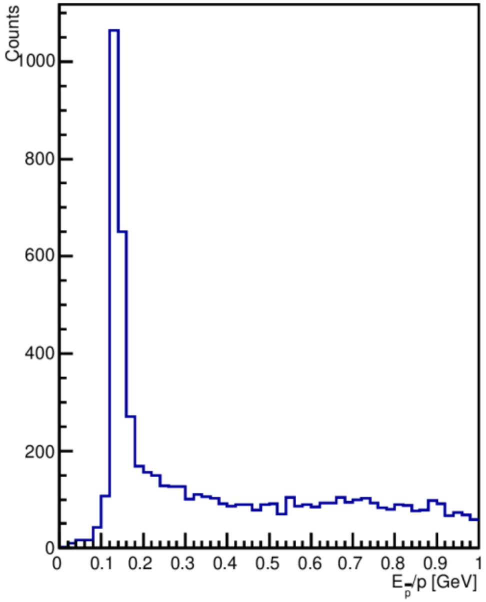
$\frac{E_{show}}{p}$ for proton

E = 3.580 GeV



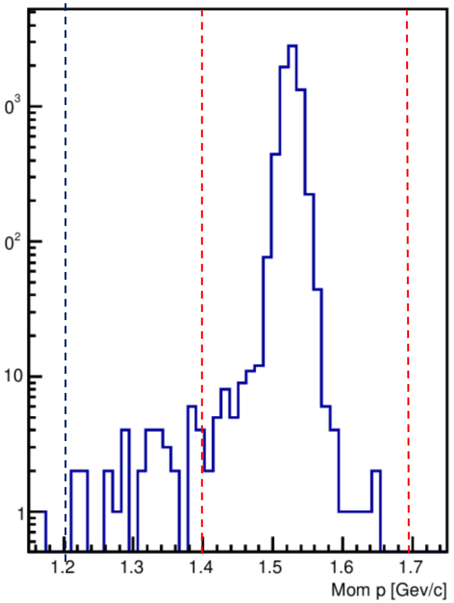
$\frac{E_{show}}{p}$ for antiproton

E = 3.580 GeV



p momentum

E = 3.580 GeV



J2BB1 Model: $\frac{d|M|^2}{dcos\theta} \propto (1 + \alpha cos^2\theta)$ $\alpha = 0.68$

Monte Carlo Generators for Tau-Charm Physics at BESIII, Rong-Gang Ping and Cai Ying Pang, BESIII internal note, BAD522 V6 (2006)

Efficiency

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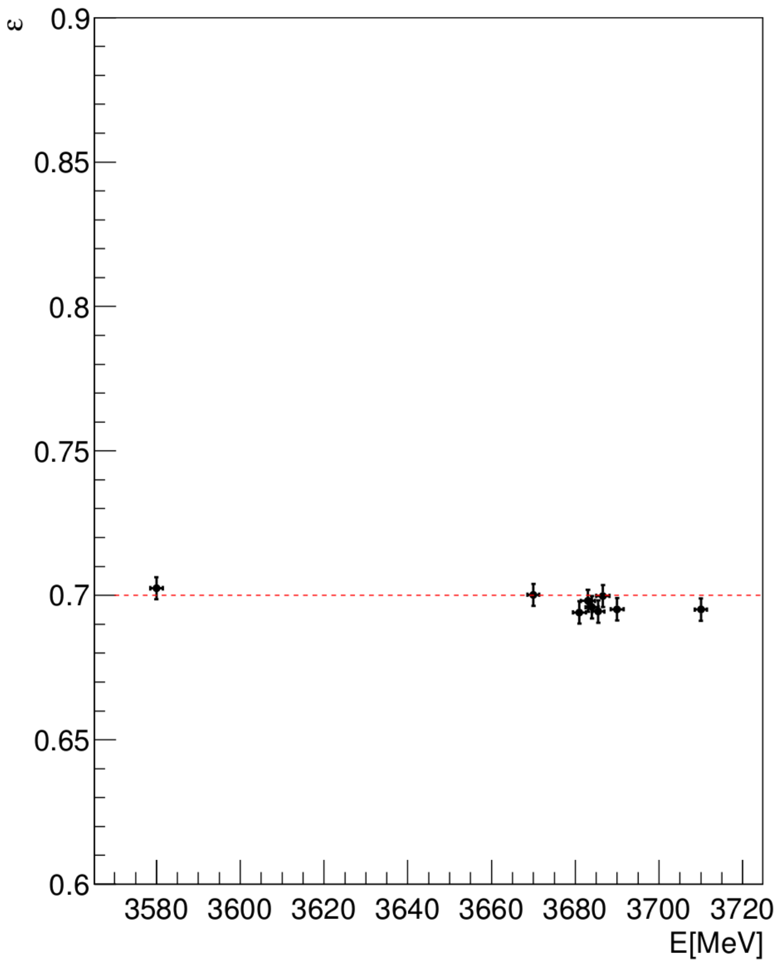
Values of reconstructed events obtained from the Montecarlo simulations

Nominal Energy $[MeV]$	$N_{reconstructed}$	Efficiency	Error Efficiency
3580.0	110	0.7025	0.0038
3670.0	180	0.7002	0.0038
3681.0	257	0.6941	0.0038
3683.0	304	0.6981	0.0038
3684.0	1408	0.6959	0.0038
3685.5	3113	0.6944	0.0038
3686.6	2955	0.6998	0.0038
3690.0	622	0.6952	0.0038
3710.0	300	0.6951	0.0038



The statistical uncertainty is estimated as binomial:

$$\frac{\sigma_\varepsilon}{\varepsilon} = \sqrt{\frac{1-\varepsilon}{N_{gen}}}$$

Event Selection - Real data $e^+e^- \to \psi(2S) \to p\bar{p}$

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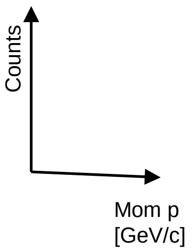
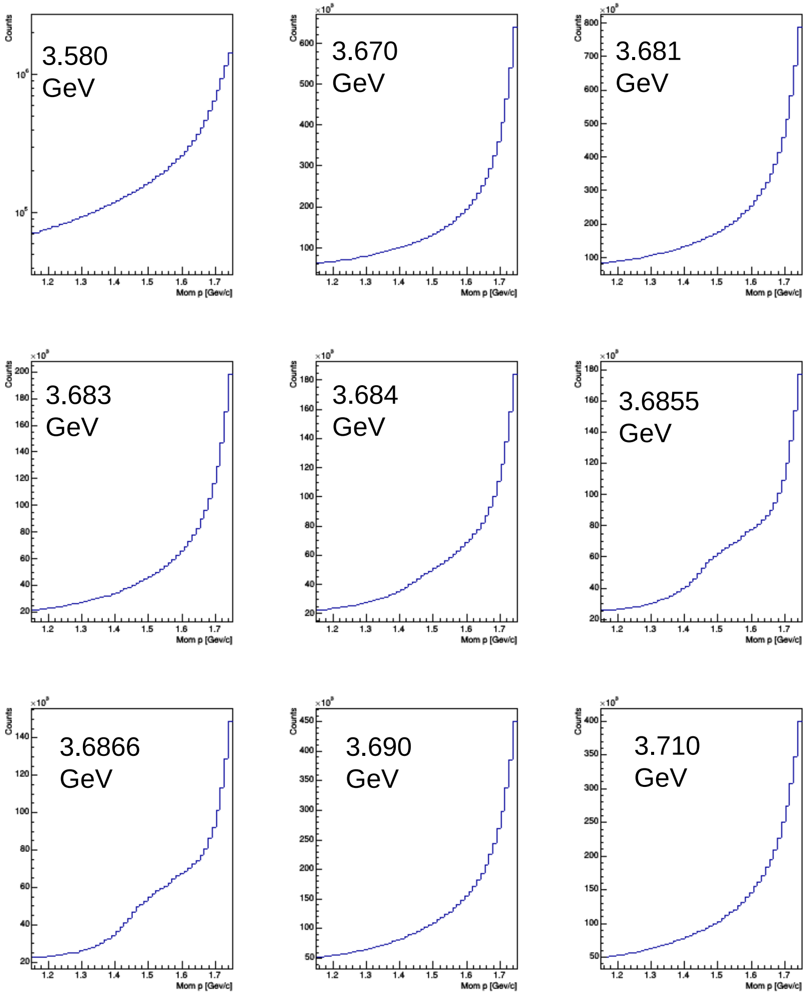


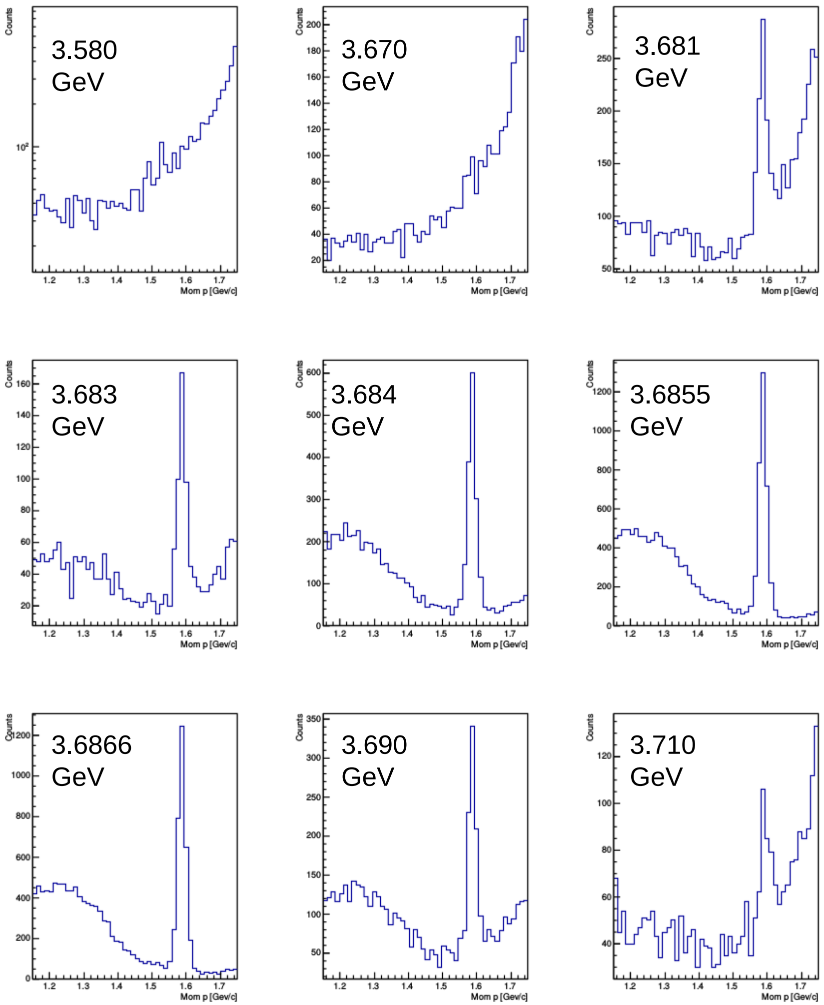
Proton momentum spectra:

no cuts applied



Proton momentum spectra:

the cut on momentum is not applied



Radiative Corrections

In central production process:

$$\beta = 4\,\frac{\alpha}{\pi}[\ln\left(\frac{W_1}{m_e}\right) - 0.5]$$

According to Touscheck,
the correction factor is:

$$C = |1 - E_n^{(1-\beta)} + 0.5E_n^{(2-\beta)}|$$

Where $E_n = k/R$

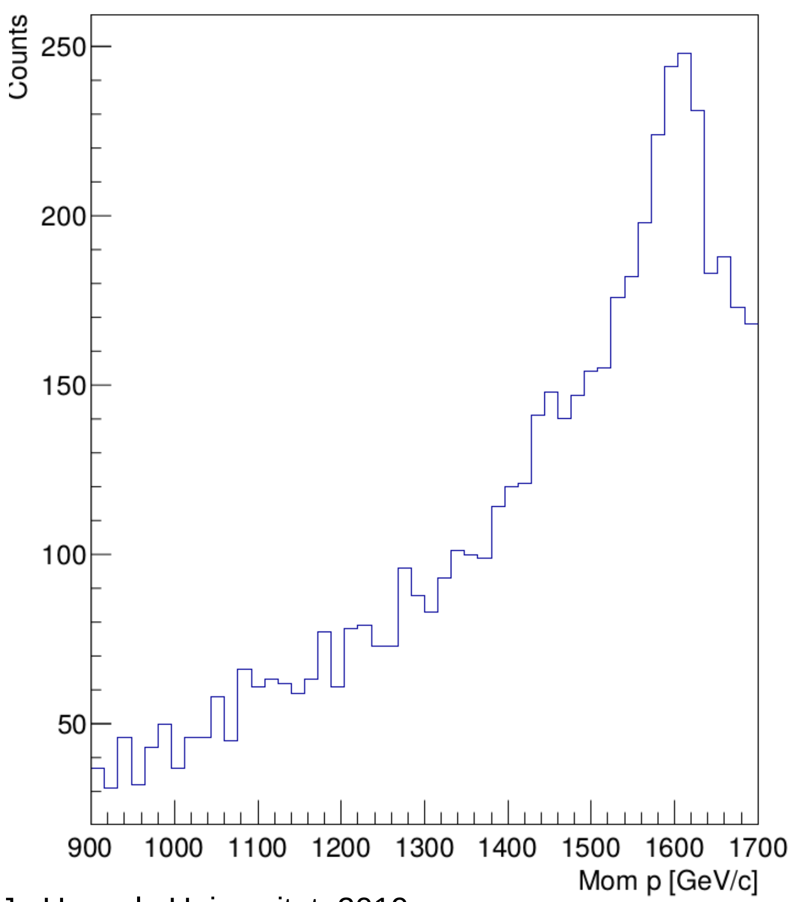
The energy after ISR:

$$W_2 = \sqrt{W_1^2 - 2kW_1}$$

- Simulated angular distribution $\propto 1 + \alpha cos^2\theta$ where $\alpha = 0.68$
- Photon ISR energy $< E_\gamma > \sim 100\ keV$
- Collinearity: usually $\theta_{DIFF} \sim 4°$,

where $\theta_{DIFF} = 180° - \theta_{afterISR}$

Preliminary distribution of proton momentum after ISR, private algorithm for simulation at 3.710 GeV



Number of event generated: 10000

From Strange to Charm: Meson production in electron-positron collisions, PhD Thesis, Petterson J., Uppsala Universitet, 2019.

Simultaneous Fit

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Signal distribution:

Crystal Ball

Background:

Polynomial function

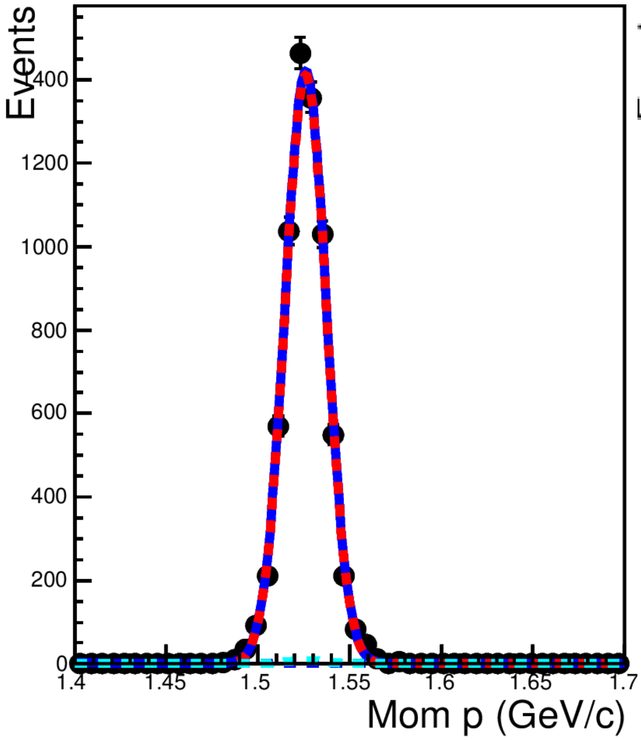
$$N_{ev} = I \cdot N_{sig}$$

$$\sigma = \sqrt{N_{ev}}$$

p momentum

E=3.580 GeV

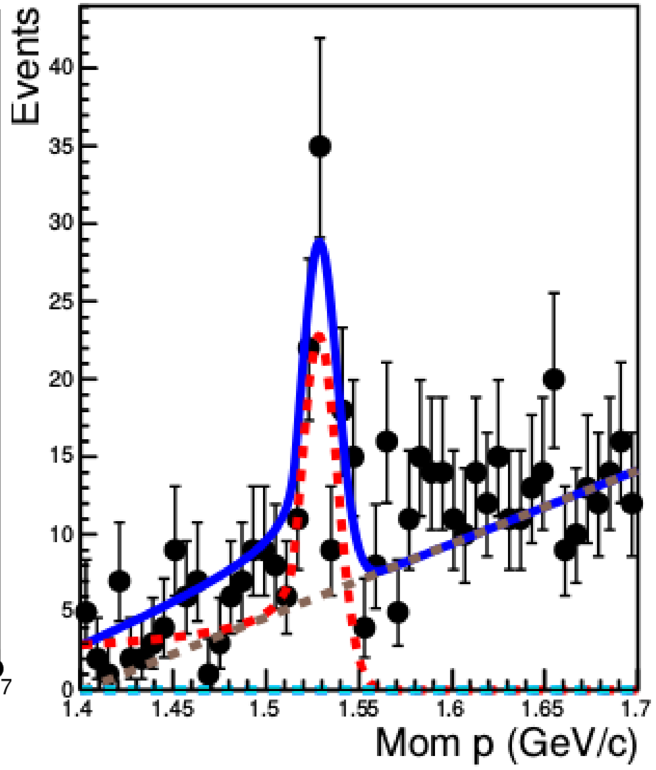
MonteCarlo Simulations



p momentum

E=3.580 GeV

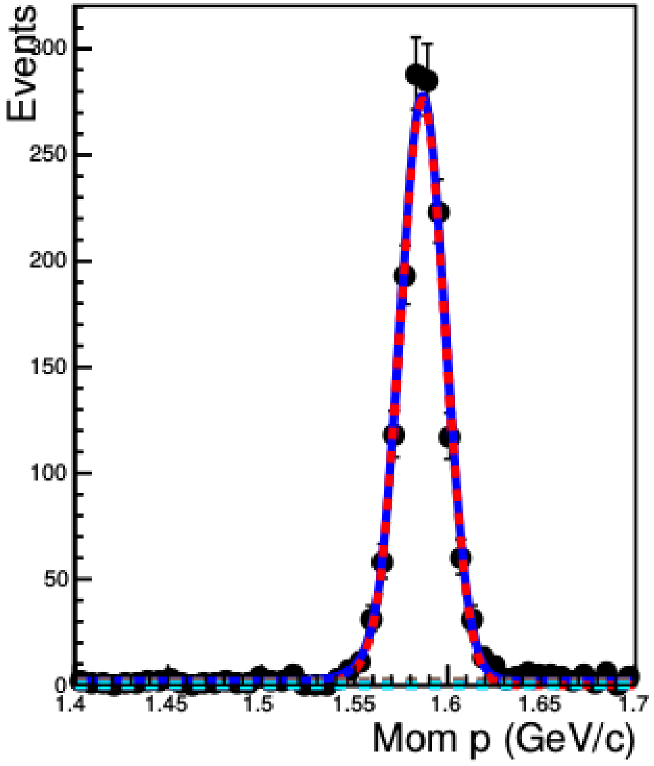
Real dataset



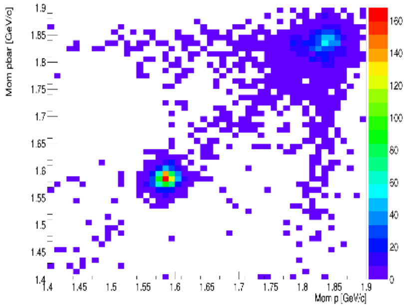
p momentum

E=3.6866 GeV

Real dataset



Background Studies



N of event generated: 10000

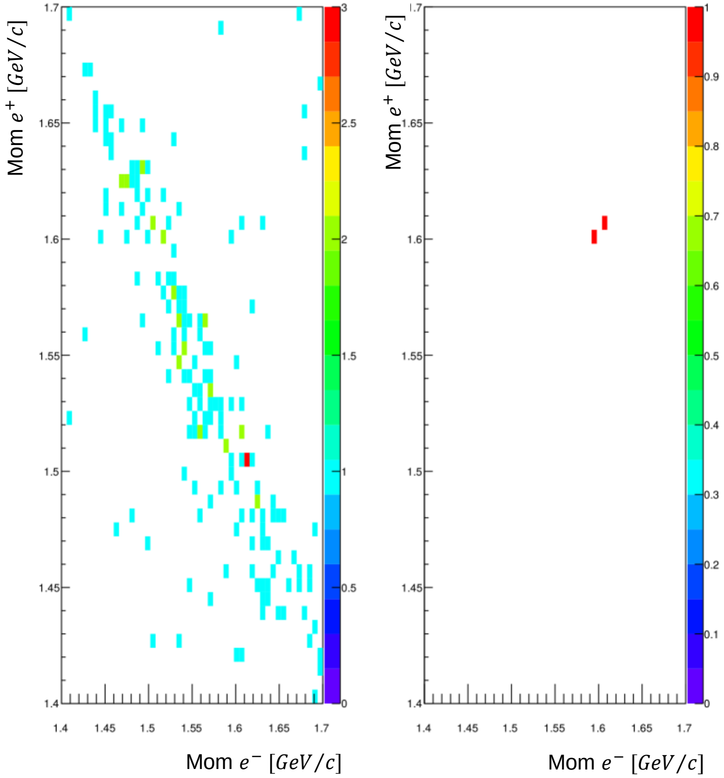
Generator: KKMC

Transport: Geant4

$e^+e^- \rightarrow e^+e^-$

E = 3.684 GeV

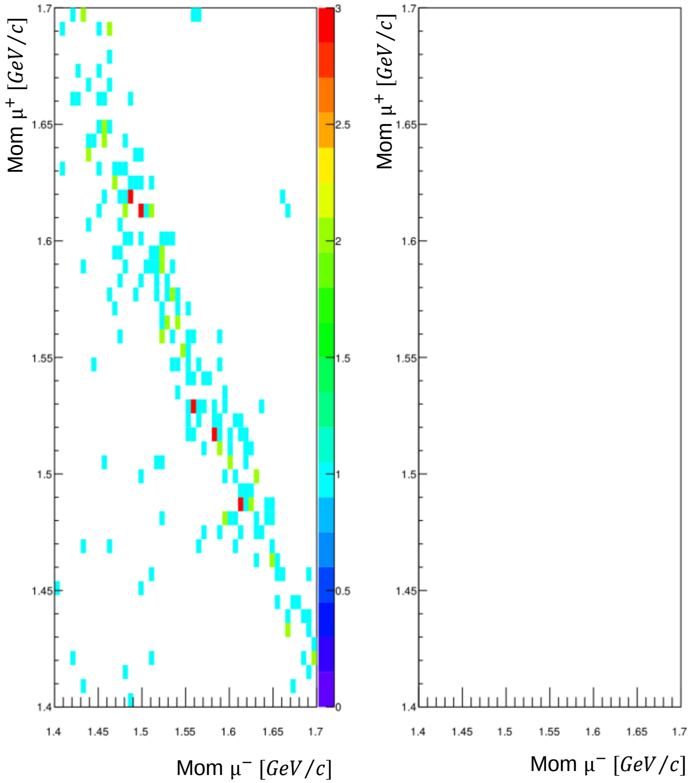
Simulations – PHSP Model



$e^+e^- \rightarrow \mu^+\mu^-$

E = 3.684 GeV,

Simulations – PHSP Model

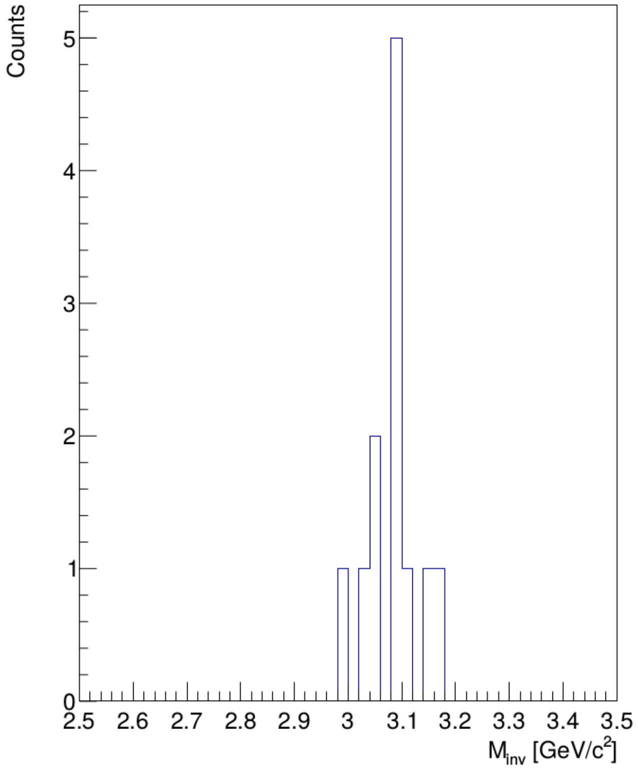


$e^+e^- \rightarrow J/\psi \rightarrow p\bar{p}$

Invariant mass

E = 3.670 GeV

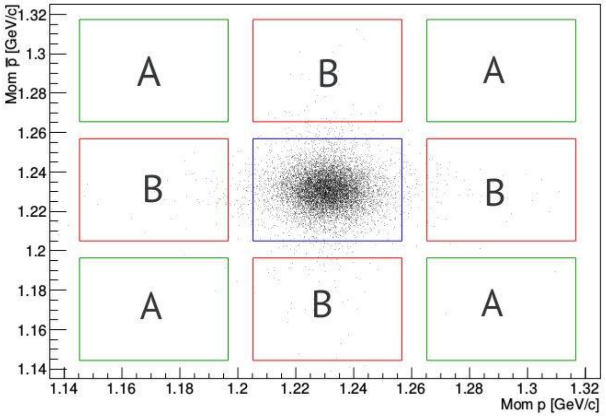
Real dataset



Sistematic Uncertanties

Variations on the selection criteria:

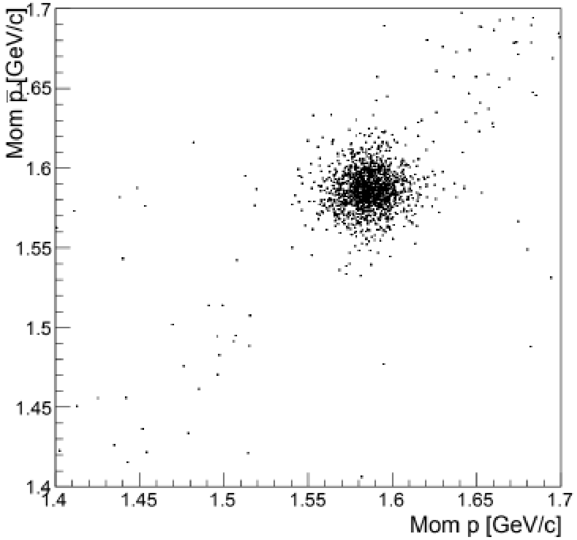
Cut	Value	Variation
E_{show}/p	0.5	$\pm$ 0.05
$\theta_{p\bar{p}}$	$178° < \quad < 180°$	$-0.5°$ and $+1°$
fit	$-3\sigma < \quad < 3\sigma$	$\pm$ 0.5
PID	0.00	+ 0.001



$$N_0 = N - \frac{1}{2}B + \frac{1}{4}A$$

Fit routine:

- Simultaneous fit
- Sideband method



$p\bar{p}$

E = 3.684 GeV

Considering the variables as uncorrelated:

$$\sigma_{syst} = \sqrt{\sum_i \sigma_i^2}$$

Measurement of the phase between Strong and Electromagnetic J/ψ → $p\bar{p}$ Decay amplitudes, Destefanis M., Baldini Ferroli R. et al. BAM-00106, BESIII memo

Sistematic Uncertanties

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Number of events and their error for each number of $p\bar{p}$ pairs variation and total systematic error:

Energy $[MeV]$	N_E	σ_E	N_T	σ_T	N_{PID}	σ_{PID}	N_F	σ_F	σ_{tot}
3580.0	80.03	5.19	6.05	0.94	80.55	8.97	93.51	5.36	9.84
3670.0	62.77	4.57	10.94	2.54	62.77	7.92	122.54	5.23	9.28
3681.0	537.38	13.38	27.02	3.29	537.38	23.18	531.39	13.11	25.11
3683.0	349.42	10.80	12.73	2.38	350.28	18.72	349.87	10.71	20.31
3684.0	1381.20	21.54	5.17	1.66	1396.93	37.38	1405.44	21.23	40.20
3685.5	3076.45	32.09	45.88	4.06	3097.80	55.66	3126.30	31.87	60.09
3686.6	2938.12	31.29	31.07	3.83	2094.12	54.17	3125.32	31.58	58.82
3690.0	736.47	15.68	21.02	2.83	740.49	27.21	752.39	15.43	29.37
3710.0	236.59	8.87	53.67	3.44	236.59	15.38	259.07	8.91	16.97

$E \equiv \frac{E_{show}}{p}$ $\quad$ $T \equiv \theta_{p\bar{p}}$ $\quad$ $F \equiv \text{fit}$

RESULTS

Cross Section

$$\sigma = \frac{N_{p\bar{p}}}{L\ \varepsilon}$$

N number of $p\bar{p}$ pairs

L integrated luminosity

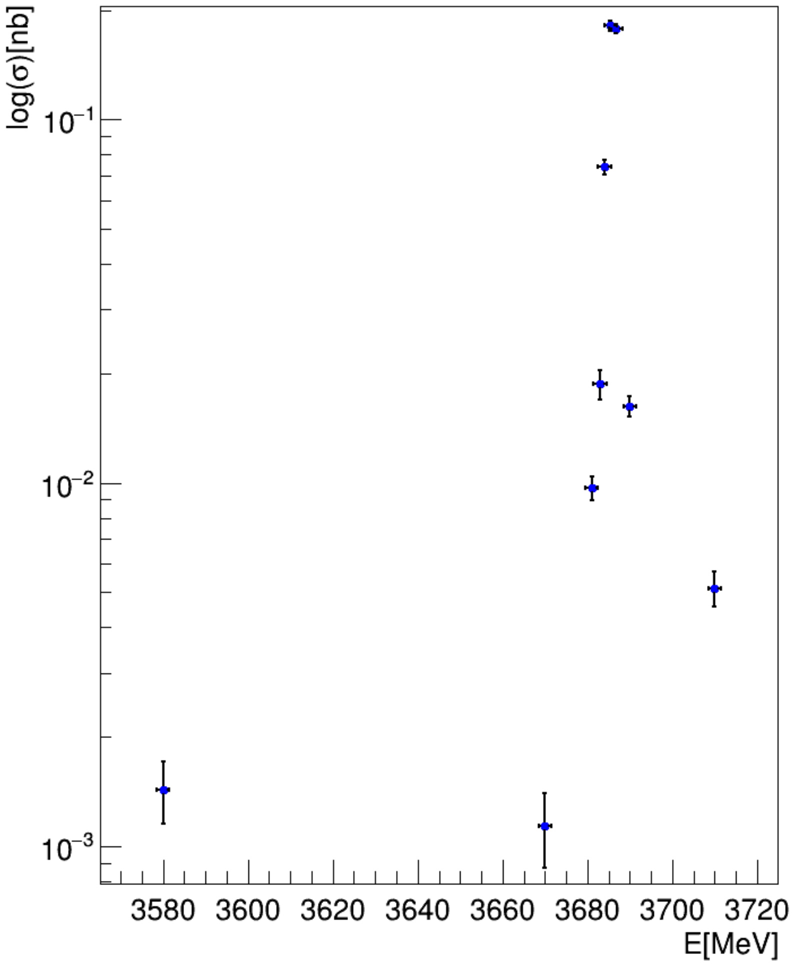
ε efficiency

Cross section for each CM energy with their statistical and systematic error

Nominal Energy $[MeV]$	$\sigma[pb]$	$\sigma_{stat}[pb]$	$\sigma_{syst}[pb]$
3580.0	1.43	0.16	0.23
3670.0	1.14	0.14	0.22
3681.0	9.66	0.42	0.58
3683.0	18.68	1.00	1.40
3684.0	74.01	1.98	2.79
3685.5	181.42	3.26	4.59
3686.6	177.80	3.28	4.66
3690.0	16.23	0.59	0.84
3710.0	5.13	0.33	0.47

Observed cross section for the $p\bar{p}$ final states

Error bars include both statistical and systematic uncertanties



Relative Phase

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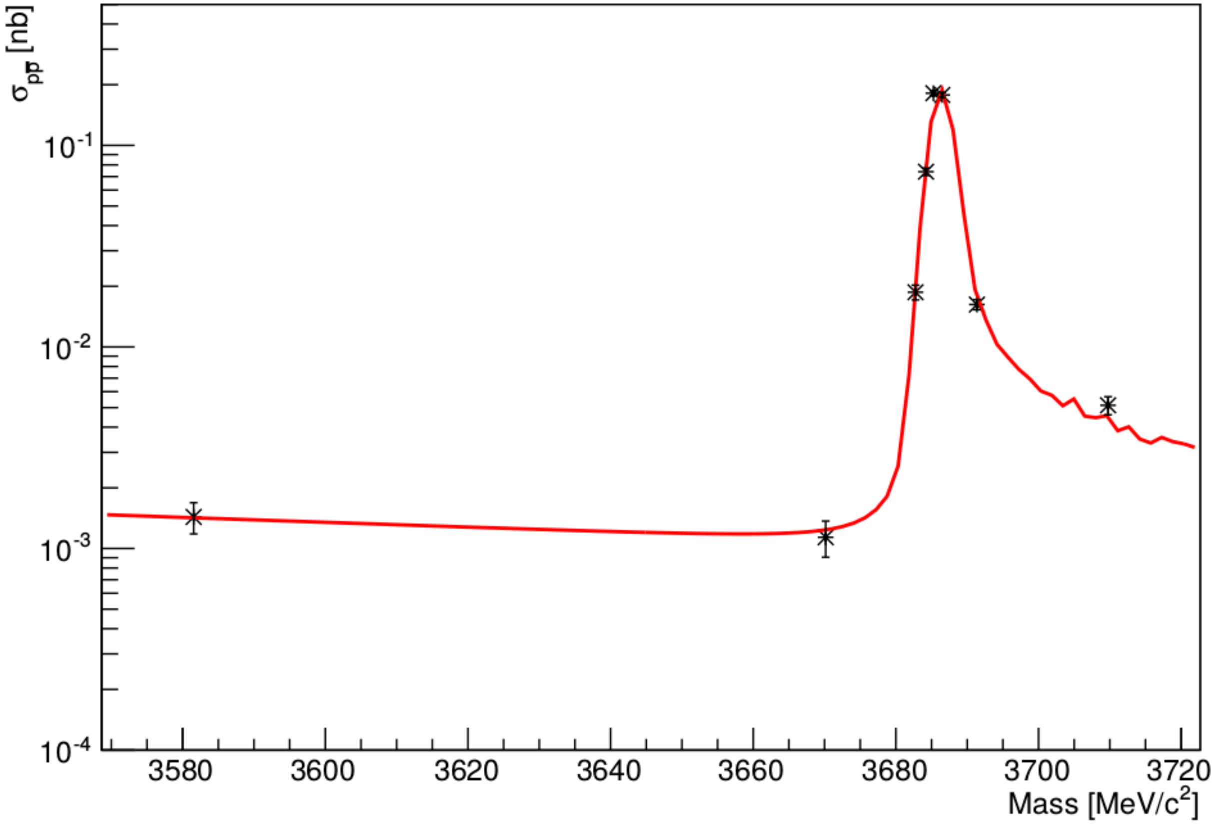
Fit of the $p\bar{p}$ cross section



The cross section can be written as:

$$\sigma[nb] = \left| \sqrt{12\pi B_{in} B_{out} \left[\frac{\hbar c}{W}\right]^2 \cdot 10^7} \frac{C_1 + C_2 e^{i\phi}}{M_\psi - W - i\frac{\Gamma}{2}} + C_3 e^{i\phi} \right|^2$$

Where C_1,C_2 and C_3 are the three parameters which correspond to the A_{3g},A_γ and A_{EM}

- Multiple extraction to simulate ISR effects
- Cross section calculated at each extraction

$$\sigma = \frac{1}{N_{ext}} \sum \sigma_i$$

First generation measurement

Relative Phase: $\phi = (89.05 \pm 14.70)°$

Branching Ratio: $B_{out} = (3.06 \pm 0.07) \times 10^{-4}$

$B_{PDG} = (2.94 \pm 0.08) \times 10^{-4}$

Cross section at the continuum: $\sigma_c = (7.54 \pm 1.12) pb$

M. Tanabashi et al. (*Particle Data Group*), Phys. Rev. D (2019)

Summary

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01 $e^+e^- \to \psi(2S) \to p\bar{p}$ **Event Selection**

02 **Simultaneous fit of momentum spectra**

03 **Background studies and Systematic uncertanties**

04 **Cross section**

05 **Relative Phase:**

$$\phi = (89.05 \pm 14.70)°$$

and Branching Fraction

$$B_{out} = (3.06 \pm 0.07) \times 10^{-4}$$

06 **Next steps:**

- **Energy optimization**
- **New data**

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Thanks!

BACKUP SLIDES

Formalism

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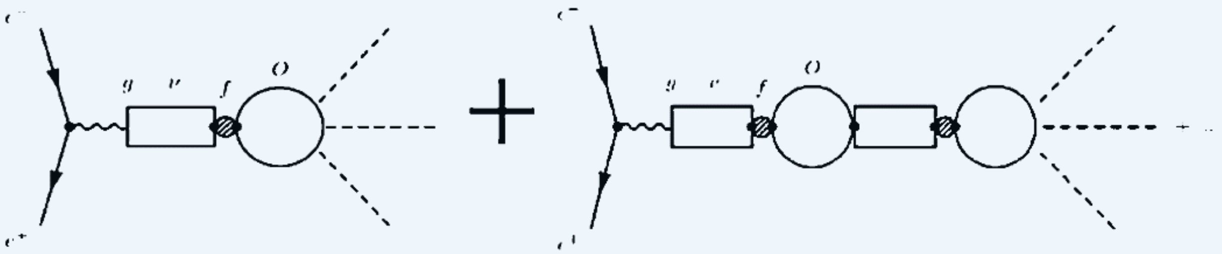
A proposal: Quarkonium OZI breaking decay as Freund and Nambu

Considering quarkonium as a superposition of a narrow resonance ν_O , not directly decay into hadrons, and a wide resonance, a glueball O, not coupled to leptons but strongly coupled to hadrons:



Scheme of the process iterated in f, where f is the coupling between ν and O

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

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

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

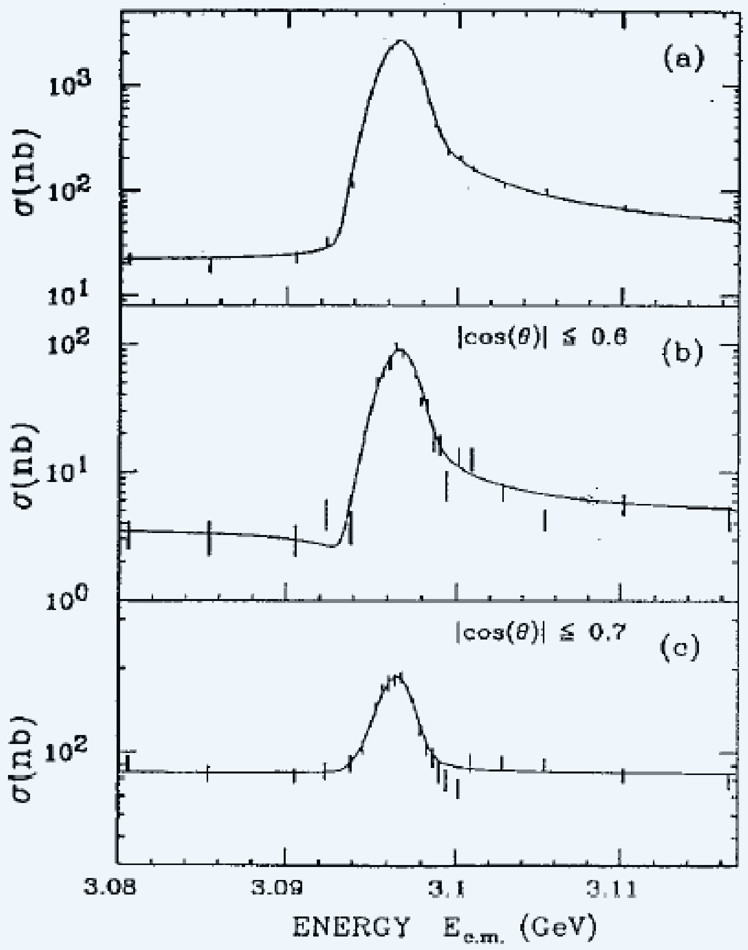
Cross section of J/ψ reproduced with
$|f| \sim 0.012 GeV$
$M_O \sim M_{J/\psi} \cong$ 3.096 GeV
$\Gamma_O \sim 0.5\ GeV$

Dynamics of the Zweig- Izuka Rule and a New Vector Meson below 2 GeV/c^2, Peter G. O. Freund and Yoichiro Nambu Phys. ReV. Lett. 34, 1645

R. Baldini, C. Bini, E. Luppi, Phys. Lett. B404, 362 (1997)

Interference

Was an interference already seen?



$e^+e^- \rightarrow hadrons$

$e^+e^- \rightarrow \mu^+\mu^-$

$e^+e^- \rightarrow e^+e^-$

Yes,
without the strong contribution

J.Z. Bai et al., Phys. Lett. B 355, 374-380 (1995)

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Radiator function

$$W(s,x) = \Delta\beta x^{\beta-1} - \frac{\beta}{2}(2-x) + \frac{\beta^2}{8}\left((2-x)(3\ln(1-x) - 4lnx) - 4\frac{\ln(1-x)}{x} - 6 + x\right)$$

where

$$L = 2ln\frac{\sqrt{s}}{m_e}$$

$$\Delta = 1 + \frac{\alpha}{\pi}\left(\frac{3}{2}L + \frac{1}{3}\pi^2 - 2\right) + (\frac{\alpha}{\pi})^2\delta_2$$

$$\delta_2 = L^2\left(\frac{9}{8} - 2\xi_2\right) - L(\frac{45}{16} - \frac{11}{2}\xi_2 - 3\xi_3) - \frac{6}{5}\xi_2^2 - \frac{9}{2}\xi_3 - 6\xi_2 ln2 + \frac{57}{12}$$

$$\beta = \frac{2\alpha}{\pi}(L-1), \qquad \xi_2 = 1.64493407, \qquad \xi_3 = 1.2020569$$

The angular distribution of the ISR photon is described by:

$$P(\theta_\gamma) = \frac{sin^2\theta_\gamma - \frac{x^2 sin^4\theta_\gamma}{2(x^2-2x+2)}}{(sin^2\theta_\gamma + \frac{m^2}{E^2}cos^2\theta_\gamma)^2} - \frac{\frac{m^2}{E^2}\frac{(1-2x)sin^2\theta_\gamma - x^2cos^4\theta_\gamma}{(x^2-2x+2)}}{(sin^2\theta_\gamma + \frac{m^2}{E^2}cos2\theta_\gamma)}$$

Signal Distribution

Crystal Ball function

$$f(x,\alpha,n,\bar{x},\sigma) = N\begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right) & for\ \frac{x-\bar{x}}{\sigma} \succ -\alpha \\ A\,(B-\frac{x-\bar{x}}{\sigma})^n & for\ \frac{x-\bar{x}}{\sigma} \le -\alpha \end{cases}$$

where

$$A = (\frac{n}{|\alpha|})^n \exp(-\frac{|\alpha|^2}{2})$$

$$B = \frac{n}{|\alpha|} - |\alpha|$$

$$N = \frac{1}{\sigma(C+D)}$$

$$C = \frac{n}{|\alpha|}\frac{1}{n-1}\exp(-\frac{|\alpha|^2}{2})$$

$$D = \sqrt{\frac{\pi}{2}}(1+\mathrm{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right))$$

M. J. Oreglia, *A Study of the Reaction* $\psi' \to \gamma\gamma\psi$, Ph. D. Thesis, SLAC-R-236, 1980

Relative Phase Evaluation

The cross section can be written as:

$$\sigma[nb] = \left| \sqrt{12\pi B_{in} B_{out} \left[\frac{\hbar c}{W}\right]^2 \cdot 10^7} \frac{C_1 + C_2 e^{i\phi}}{M_\psi - W - i\frac{\Gamma}{2}} + C_3 e^{i\phi} \right|^2$$

Where C_1,C_2 and C_3 are the three parameters which correspond to the A_{3g},A_γ and A_{EM}

The Real and the Imaginary part of the cross section AA and BB respectively, can be defined as:

$$AA = \sqrt{C_0} \frac{(C_1 + C_2 cos\phi) - (M_\psi - W) + C_2\, \Gamma/2\, sin\phi}{(M_\psi - W)^2 + (\Gamma/2)^2} + C_3 cos\phi$$

$$\mathrm{BB} = \sqrt{C_0} \frac{(C_1 + C_2 cos\phi)\, \Gamma/2 + C_2 sin\phi}{(M_\psi - W)^2 + (\Gamma/2)^2} + C_3 sin\phi$$

For each extraction the cross section is:

$$\sigma_i = AA^2 + BB^2$$

The final value of the simulated cross section is:

$$\sigma = \frac{1}{N_{est}} \sum \sigma_i$$

Measurement of the phase between Strong and Electromagnetic J/ψ → $p\bar{p}$ Decay amplitudes, Destefanis M., Baldini Ferroli R. et al. BAM-00106, BESIII memo

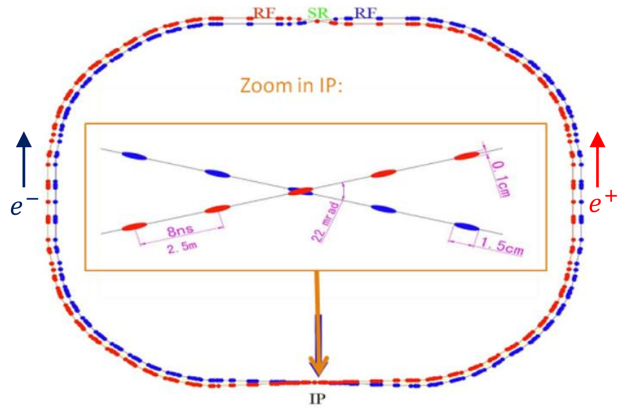
The BESIII Experiment

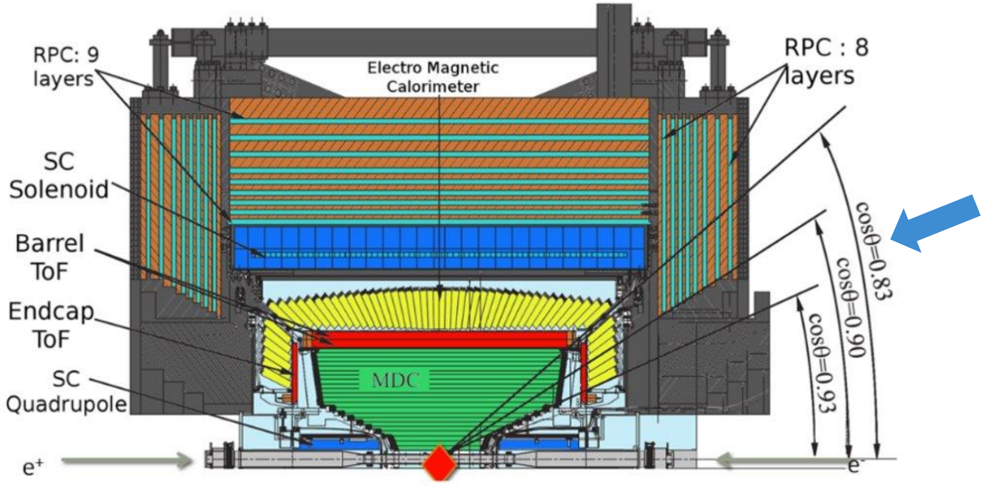
BARBARA PASSALACQUA

Where? Beijing in People's Republic of China (PRC)

BESIII Collaboration now has ~500 members from 72 institution

from 15 countries, including IHEP and INFN





Beijing Electron Positron Collider II (BEPCII)

- Beam energy: 1.0 – 2.3 GeV/c
- Design Luminosity: 10^{33} $cm^{-2}s^{-1}$
- Center of mass energy: ranging 2.0 - 4.6 GeV
- Circumference: 237 m

Physics of BESIII

Charmonium, D, τ, Light Hadron Spectroscopy and search for New Hadronic states

BEijing Spectrometer III (BESIII)

- **Drift chamber** (MDC), momentum resolution for charged particles is 0.5% at 1 GeV
- **Electromagnetic calorimeter** EMC, energy resolution* 2.5% and position resolution* 6 mm
- **Time of Flight system** (TOF), time resolution* 80 ps
- **Solenoid magnet** providing a 1.0 Tesla magnetic field
- **Muon Chamber System** (MUC) made of Resistive Plate Chamber
- **Geometrical acceptance** 93 % of 4 π

*in the barrel

Physics at BESIII , Asner D. M. et al. Int. J. Mod. Phys A24 (2009) S1-794 arXiv: 0809.1869 [hep – ex]