Relative Phase Measurement in the $p\bar{p}$ Final State

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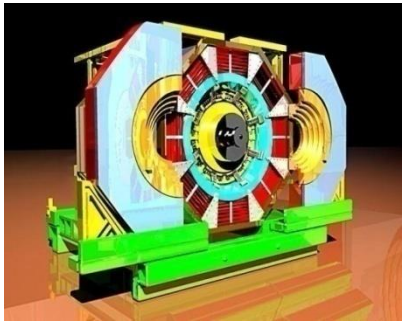


BESIII – Italia

Frascati, Italia

April 7, 2022

J/ψ Strong and Electromagnetic Decay Amplitudes

Resonant contributions

$\Gamma_{J/\psi} \sim 93\text{KeV} \rightarrow$ pQCD

Perturbative regime:

all amplitudes almost real [1]

$A_{3g} \in \Re$

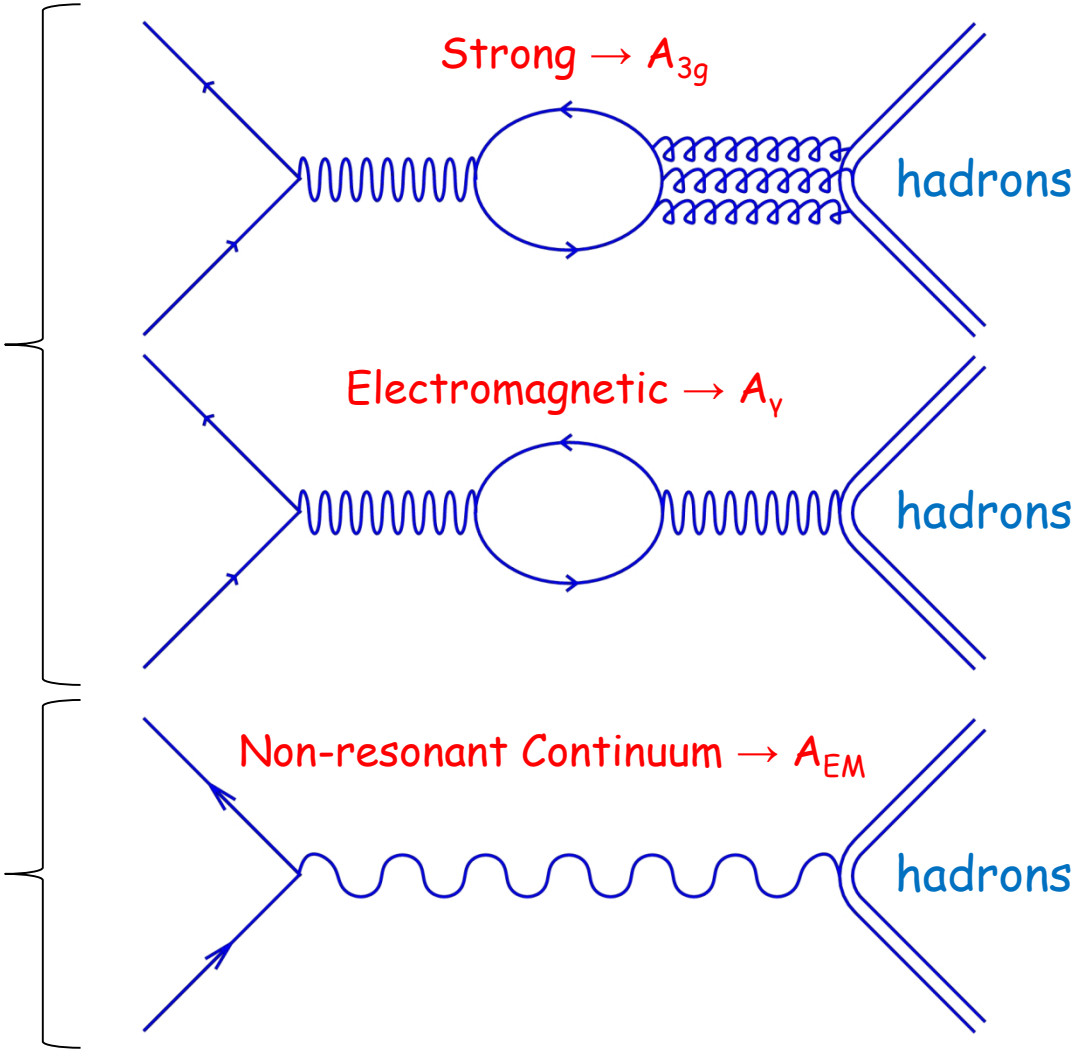
Non-resonant continuum

No more structures

Almost asymptotic regime

$A_{EM} \in \Re$

$A_\gamma \sim -A_{EM}$



[1] S.J. Brodsky, G.P. Lepage, S.F. Tuan, Phys. Rev. Lett. 59, 621 (1987).

J/ψ Strong and Electromagnetic Decay Amplitudes

- If both real, continuum and resonant amplitudes must interfere ($\Phi_p \sim 0°/180°$)
- On the contrary $\Phi_p \sim 90° \rightarrow$ No interference

$J/\psi \rightarrow N\bar{N}$ $(\frac{1}{2}^+\frac{1}{2}^-)$ $\Phi_p = 89° \pm 15°$ [1]; $89° \pm 9°$[2]

$J/\psi \rightarrow$ VP (1^-0^-) $\Phi_p = 106° \pm 10°$ [3]

$J/\psi \rightarrow$ PP (0^-0^-) $\Phi_p = 89.6° \pm 9.9°$ [4]

$J/\psi \rightarrow$ VV (1^-1^-) $\Phi_p = 138° \pm 37°$ [4]

- Results are model dependent
- Model independent test:

energy scan below and at resonance

[1] R. Baldini, C. Bini, E. Luppi, Phys. Lett. B404, 362 (1997); R. Baldini et al., Phys. Lett. B444, 111 (1998)
[2] M. Ablikim et al., Phys. Rev. D 86, 032014 (2012).
[3] L. Kopke and N. Wermes, Phys. Rep. 174, 67 (1989); J. Jousset et al., Phys. Rev. D41,1389 (1990).
[4] M. Suzuki et al., Phys. Rev. D60, 051501 (1999).

J/ψ Strong and Electromagnetic Decay Amplitudes

$J/\psi \to N\bar{N}$

Favoured channel — 3g match $3q\bar{q}$ pairs

Without EM contribution p = n, due to isospin

EM contribution amplitudes should have opposite sign, like magnetic moments

$BR_{n\bar{n}}$ expected ~ ½ $BR_{p\bar{p}}$

$$R = \frac{Br(J/\psi \to n\bar{n})}{Br(J/\psi \to p\bar{p})} = \left|\frac{A_{3g} + A_\gamma^n}{A_{3g} + A_\gamma^p}\right|^2$$

$A_{3g}, A_\gamma \in \Re$ R<<1

$A_{3g} \perp A_\gamma$ R ≈1

But the BR are almost equal according to BESIII[1]:

$BR(J/\psi \to p\bar{p}) = (2.112 \pm 0.004 \pm 0.027)\cdot 10^{-3}$

$BR(J/\psi \to n\bar{n}) = (2.07 \pm 0.01 \pm 0.14)\cdot 10^{-3}$

- Suggests 90° phase

[1] M. Ablikim et al., "*Study of J/ψ → ppbar and J/ψ → nnbar*", Phys. Rev. D86 032014 (2012).

J/ψ Phase – Real Data

E_{cm} (MeV)	$\mathcal{L}$ (pb^{-1})
3050.0	14.919±0.029
3060.0	15.060±0.029
3083.0	4.769±0.017
3085.6	17.507±0.032
3090.0	15.558±0.030
3093.0	14.910±0.030
3094.3	2.143±0.011
3095.2	1.816±0.010

2012

E_{cm} (MeV)	$\mathcal{L}$ (pb^{-1})
3095.8	2.135±0.011
3096.9	2.069±0.011
3098.2	2.203±0.012
3099.0	0.756±0.007
3101.5	1.612±0.010
3105.5	2.106±0.011
3112.0	1.720±0.009
3120.0	1.264±0.009

2015

3000.0	15.849±0.010
3020.0	17.315±0.011
3080.0	126.21±0.029

B.X. Zhang, Luminosity measurement for J/psi phase and lineshape study.

Online Beam Energy Measurement

E_{cm} [MeV]	E_{meas} [MeV]
3050.0	3049.65±0.03
3060.0	3058.70±0.03
3083.0	3082.50±0.04
3085.6	3079.63±0.02
3090.0	3088.86±0.02
3093.0	3091.76±0.02
3094.3	3094.70±0.08
3095.2	3095.43±0.08

E shift included

E_{cm} [MeV]	E_{meas} [MeV]
3095.8	3095.83±0.08
3096.9	3097.22±0.08
3098.2	3098.34±0.08
3099.0	3099.04±0.09
3101.5	3101.36±0.11
3105.5	3105.58±0.09
3112.0	3112.05±0.09
3120.0	3119.88±0.12

No BEMS

3000.0	3000.0±0.2	3080.0	3080.0±0.2
3020.0	3020.0±0.2		

ppbar Events Reconstruction

BOSS versions 6.6.4.p01 and 6.6.5.p01

2 good charged tracks:

- |Rxy| < 1 cm, |Rz| < 10 cm;
- back-to-back tracks: 178° < θ < 180°;
- p < 2 GeV/c;
- |cos| < 0.8

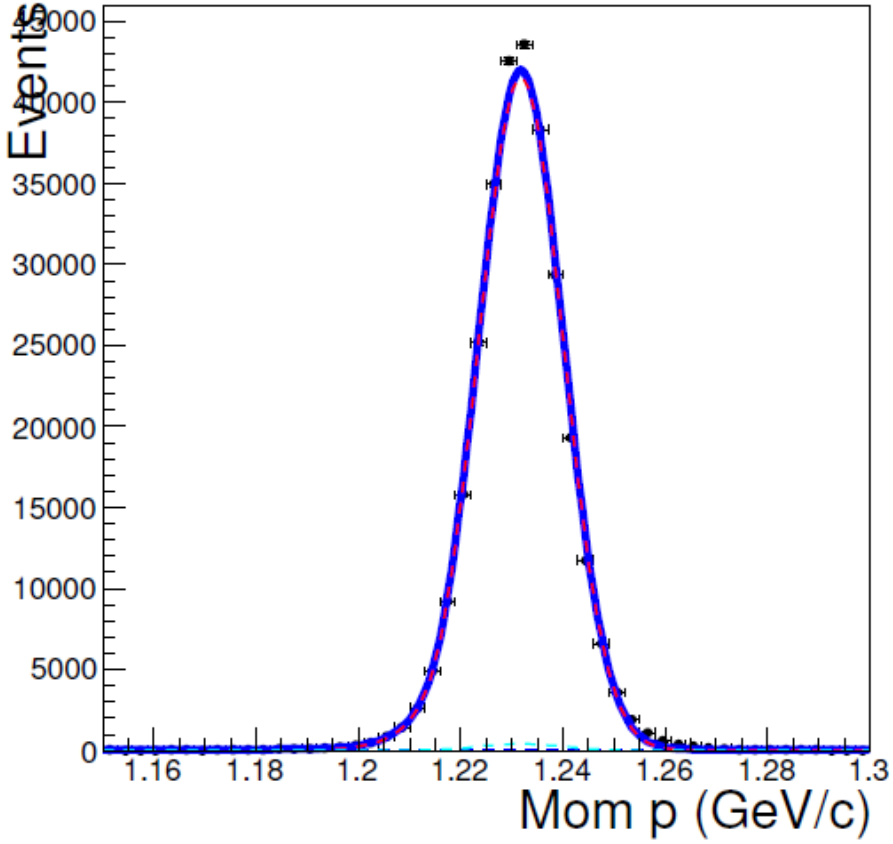
  Analysis in Barrel;
- E shower/ p < 0.5 for protons;
- PID dE/dx + TOF and P(p/pbar) > 0.001
- Events via p-pbar momentum fit and sidebands

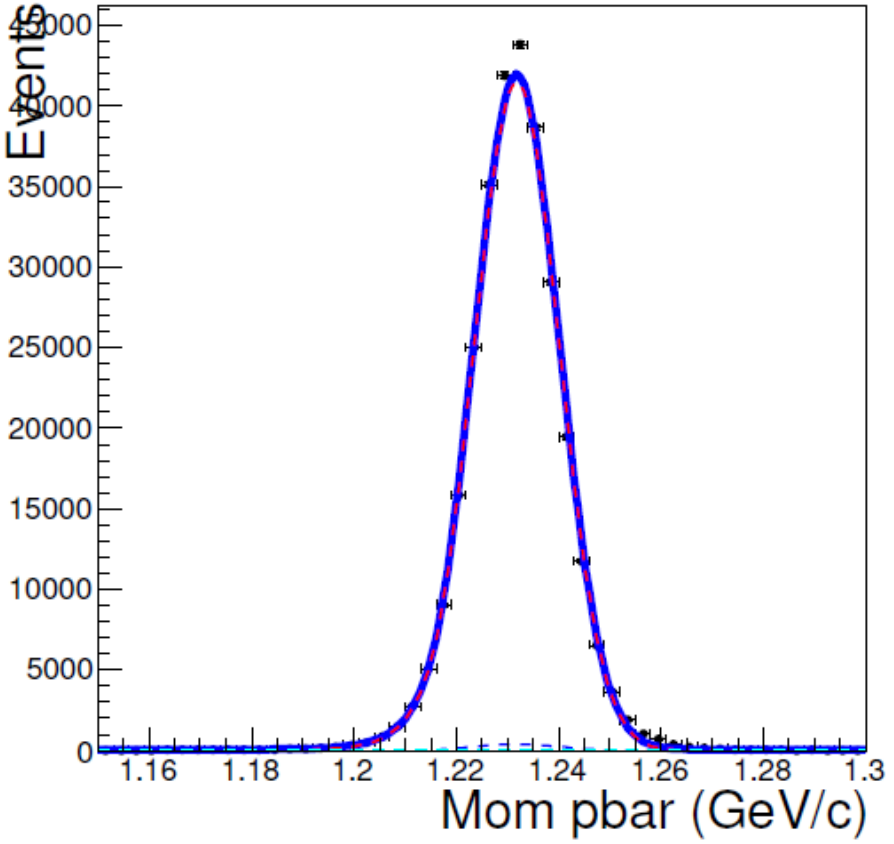
M. Ablikim et al., Phys. Rev. D 86, 032014 (2012).

Number of ppbar Events

3096.9 GeV

- 2-dimensional fit of p and pbar momenta
- Separate the different contributions





ppbar Rates Fit

R = Nev/(Int_Lum)

E_{cm} [MeV]	Rate [pb]
3050.0	4.99±0.58
3060.0	4.32±0.54
3083.0	4.23±0.94
3085.6	4.62±0.51
3090.0	6.91±0.67
3093.0	11.74±0.89
3094.3	224.52±10.30
3095.2	1106.2±25.42

E_{cm} [MeV]	Rate [pb]
3095.8	2645.2±37.75
3096.9	4707.1±53.86
3098.2	2151.6±33.05
3099.0	919.48±35.90
3101.5	225.77±11.92
3105.5	126.05±7.76
3112.0	68.04±6.30
3120.0	55.24±6.62

Systematics not included

3000.0	5.01±0.56	3080.0	4.53±0.19
3020.0	4.77±0.53		

ppbar Rates Sidebands

Nev = S -1/2B + 1/4A

Ecm [MeV]	Rate [pb]
3050.0	4.83±0.57
3060.0	4.33±0.54
3083.0	4.04±0.92
3085.6	4.80±0.52
3090.0	7.21±0.68
3093.0	11.77±0.89
3094.3	224.10±10.29
3095.2	1097.60±25.32

R = Nev/(Int_Lum)

Ecm [MeV]	Rate [pb]
3095.8	2637.94±37.69
3096.9	4695.75±53.79
3098.2	2150.48±33.04
3099.0	918.32±35.87
3101.5	225.03±11.90
3105.5	126.31±7.77
3112.0	69.04±6.35
3120.0	55.18±6.62

Systematics not included

3000.0	4.92±0.56	3080.0	4.44±0.19
3020.0	4.91±0.53		

Background

Upper limits

e^+e^-

$\mu^+\mu^-$

$\gamma\gamma$

$\pi^+\pi^-$

K^+K^-

ppbar π^0

ppbar γ

$\Lambda\Lambda$bar

10^5 events

Energy [MeV]	$\pi^+\pi^-$	K^+K^-	$p\bar{p}\pi^0$	$p\bar{p}\gamma$	$\Lambda\bar{\Lambda}$
3000.0	$4\cdot10^{-3}$	$1.2\cdot10^{-2}$	$4.7\cdot10^{-3}$	$1.2\cdot10^{-3}$	$4.5\cdot10^{-4}$
3020.0	$4\cdot10^{-3}$	$1.4\cdot10^{-2}$	$4.8\cdot10^{-3}$	$1.4\cdot10^{-3}$	$1.9\cdot10^{-4}$
3050.0	$4\cdot10^{-3}$	$1.2\cdot10^{-2}$	$3.7\cdot10^{-3}$	$0.5\cdot10^{-3}$	$1.5\cdot10^{-4}$
3060.0	$4\cdot10^{-3}$	$1.2\cdot10^{-2}$	$3.7\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.5\cdot10^{-4}$
3085.6	$4\cdot10^{-3}$	$1.4\cdot10^{-2}$	$4.0\cdot10^{-3}$	$1.6\cdot10^{-3}$	$3.8\cdot10^{-4}$
3080.0	$3\cdot10^{-2}$	$9.4\cdot10^{-2}$	$2.7\cdot10^{-2}$	$7.5\cdot10^{-3}$	$2.6\cdot10^{-3}$
3083.0	$1\cdot10^{-3}$	$4\cdot10^{-3}$	$1.1\cdot10^{-3}$	$0.2\cdot10^{-3}$	$1.0\cdot10^{-4}$
3090.0	$4\cdot10^{-3}$	$1.2\cdot10^{-2}$	$3.4\cdot10^{-3}$	$1.1\cdot10^{-3}$	$3.3\cdot10^{-4}$
3093.0	$4\cdot10^{-3}$	$1.2\cdot10^{-2}$	$3.3\cdot10^{-3}$	$0.8\cdot10^{-3}$	$3.1\cdot10^{-4}$
3094.3	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$4.8\cdot10^{-4}$	$1.4\cdot10^{-4}$	$0.5\cdot10^{-4}$
3095.2	$6\cdot10^{-3}$	$7\cdot10^{-3}$	$4.4\cdot10^{-4}$	$1.4\cdot10^{-4}$	$0.6\cdot10^{-4}$
3095.8	$1\cdot10^{-2}$	$1.3\cdot10^{-2}$	$5.6\cdot10^{-4}$	$1.6\cdot10^{-4}$	$1.0\cdot10^{-4}$
3096.9	$2\cdot10^{-2}$	$2.3\cdot10^{-2}$	$6.1\cdot10^{-4}$	$1.8\cdot10^{-4}$	$0.6\cdot10^{-4}$
3098.2	$8\cdot10^{-3}$	$9\cdot10^{-3}$	$5.3\cdot10^{-4}$	$2.3\cdot10^{-4}$	$0.3\cdot10^{-4}$
3099.0	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$1.7\cdot10^{-4}$	$0.9\cdot10^{-4}$	$0.2\cdot10^{-4}$
3101.5	$4\cdot10^{-4}$	$1\cdot10^{-3}$	$3.4\cdot10^{-4}$	$2.2\cdot10^{-4}$	$0.3\cdot10^{-4}$
3105.5	$2\cdot10^{-4}$	$2\cdot10^{-3}$	$4.4\cdot10^{-4}$	$1.8\cdot10^{-4}$	$0.4\cdot10^{-4}$
3112.0	$9\cdot10^{-5}$	$1\cdot10^{-3}$	$3.5\cdot10^{-4}$	$1.2\cdot10^{-4}$	$0.1\cdot10^{-4}$
3120.0	$5\cdot10^{-5}$	$1\cdot10^{-3}$	$2.5\cdot10^{-4}$	$0.6\cdot10^{-4}$	$0.2\cdot10^{-4}$

Fitting Routine

- Unfolding beam energy spread not possible -> consider event rates only, all corrections into predictions
- ISR generation and BOSS too slow for fitting
- Goal: separate ISR, BOSS, event selection and fitting routine
- Take into account:
  - energy error for each event
  - beam energy spread
  - ISR

  } in the generator
- Now considered in generation and simulation
- Lists produced:
  - n. of events before and after the experimental cuts
  - generated and passed events for each energy value

Fitting Routine (Babayaga)

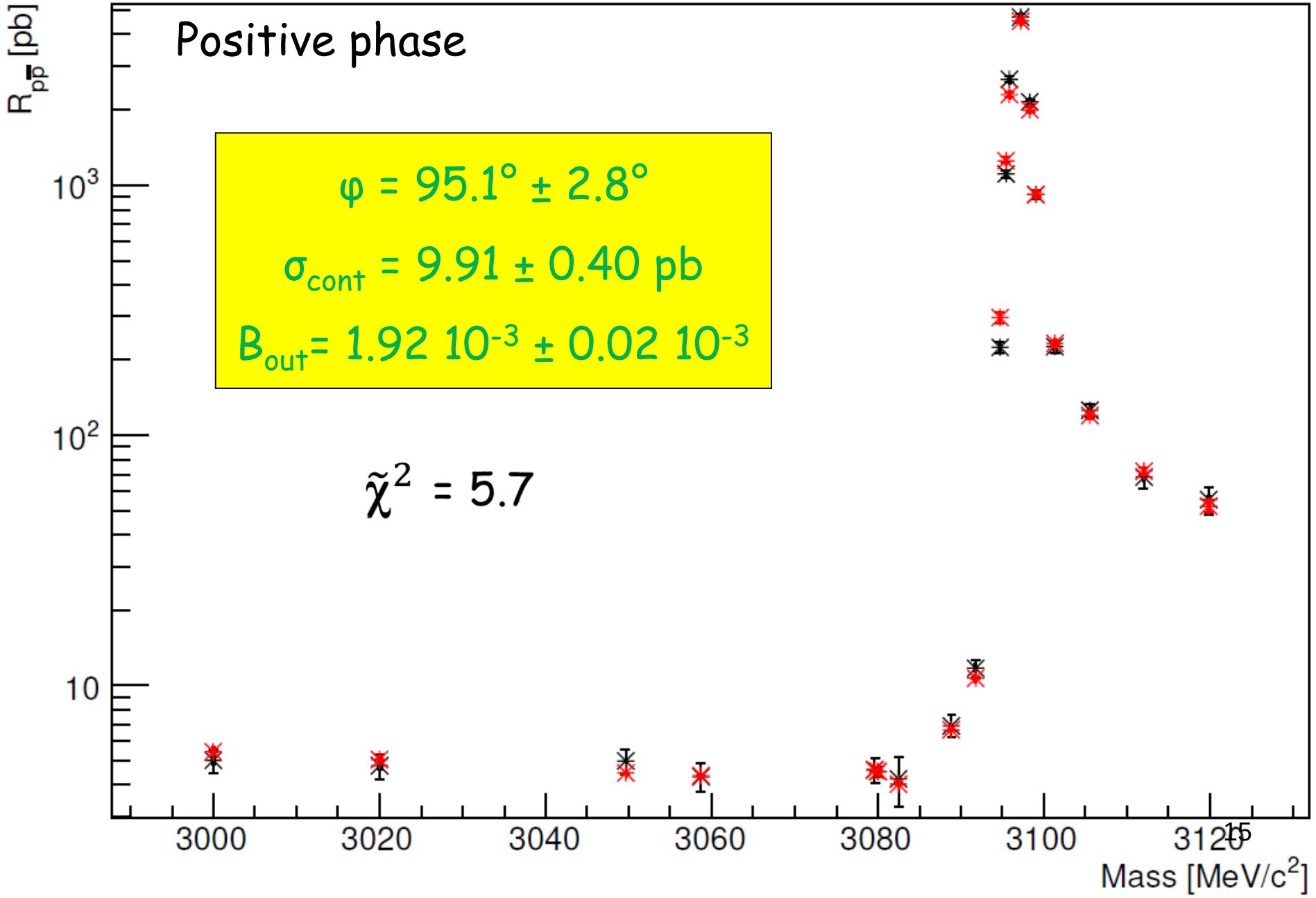
- Babayaga new output by Carlo Calame
  version produced explicitly for the phase measurement
- Full phase space generation
- No dependence on minimum energy
- No need to return to simulations
- The Rate of each event has to be reweighted
- Reweight each event after normalization to n. of events
- Efficiency inserted in the prediction
- Fit of the Rate

Fitting Routine

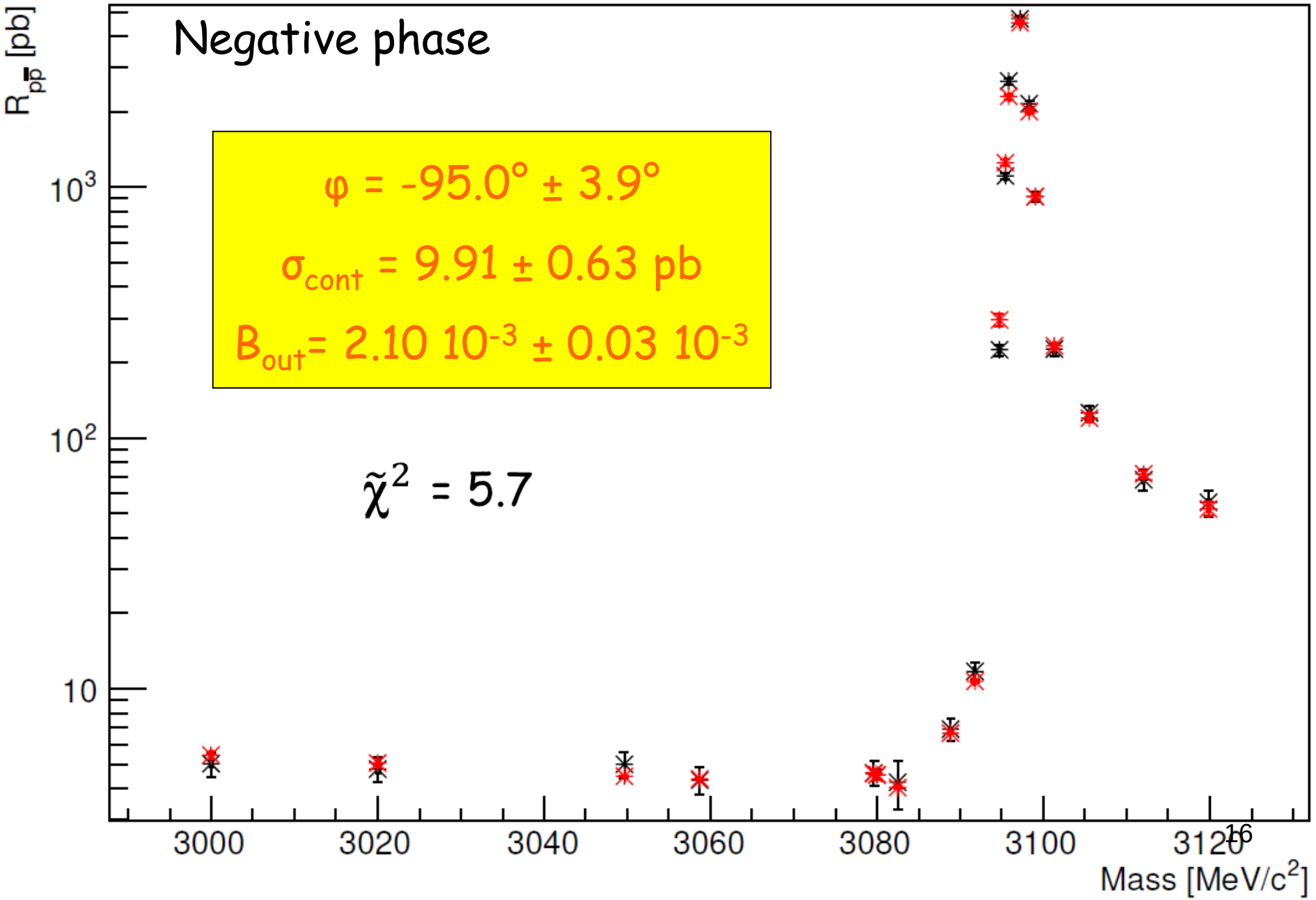
- Cross section calculation for each energy value
  - $A_S e^{i\varphi} + A_{EM} - A_C$
- Weighted mean of the events (contains efficiency)
- Fit parameters: φ, BR, σ_{cont} at 3 GeV (varying like W^{-10})
- Minimization of χ^2 by MonteCarlo
- Errors on parameters:
  - Re-estraction of the experimental values

    (as done in the measurement preparation)
- More reliable with a larger number of iterations
- Use MINUIT routines

Fit Results


Positive phase
φ = 95.1° ± 2.8°
σcont = 9.91 ± 0.40 pb
Bout= 1.92 10-3 ± 0.02 10-3
χ̃2 = 5.7
Rpp̄ [pb]
10³
10²
10
3000
3020
3040
3060
3080
3100
3120
Mass [MeV/c²]

Fit Results


Negative phase
φ = -95.0° ± 3.9°
σcont = 9.91 ± 0.63 pb
Bout= 2.10 10-3 ± 0.03 10-3
χ̃2 = 5.7
RpbarP [pb]
10³
10²
10
3000
3020
3040
3060
3080
3100
3120
Mass [MeV/c²]

Systematic Uncertainties (Rates)

- E shower/ p < 0.5 for protons;
- p-pbar opening angle
- PID
- Tracking (1%)
- Luminosity (~1%)
- Integral limits

Cut	Value	Variation
E_{show}/p	0.5 c	$\pm$ 0.05 c (about 2σ)
$\vartheta_{p\bar{p}}$	$178° <$ $< 180°$	$\pm$ 0.5° (about 2σ)
fit	$-3\sigma <$ $< 3\sigma$	$\pm$ 0.1σ
PID	0.001	$\pm$ 0.0005

Systematic Uncertainties (Rates)

Nominal Energy [MeV]	E_{show}/p	$\vartheta_{p\bar{p}}$	fit	PID	Track	Lum.	σ_{syst} [pb]
3050.0	0.33	0.29	0.33	0.41	0.10	0.05	0.70
3060.0	0.29	0.31	0.31	0.38	0.09	0.04	0.65
3083.0	0.54	0.53	0.54	0.67	0.08	0.05	1.15
3085.6	0.30	0.30	0.30	0.36	0.09	0.05	0.64
3090.0	0.38	0.38	0.38	0.47	0.14	0.07	0.83
3093.0	0.51	0.51	0.51	0.63	0.23	0.12	1.12
3094.3	5.93	5.94	5.94	7.28	4.49	2.41	13.59
3095.2	14.65	14.68	14.66	17.98	22.12	11.57	39.89
3095.8	21.75	21.79	21.77	26.69	52.90	28.50	75.79
3096.9	31.04	31.10	31.06	38.09	94.14	54.60	127.24
3098.2	19.06	19.08	19.06	23.37	43.03	22.46	63.19
3099.0	20.68	20.73	20.70	25.38	18.39	9.73	48.62
3101.5	6.85	6.88	6.87	8.43	4.52	2.52	15.47
3105.5	4.48	4.48	4.48	5.49	2.52	1.32	9.92
3112.0	3.62	3.64	3.64	4.46	1.36	0.75	7.86
3120.0	3.82	3.80	3.82	4.68	1.10	0.57	8.19
3000.0	0.32	0.33	0.32	0.40	0.10	0.03	0.70
3020.0	0.30	0.31	0.30	0.37	0.10	0.03	0.65
3080.0	0.11	0.11	0.11	0.13	0.09	0.03	0.25

Systematic Uncertainties (Phase)

- E shower/ p < 0.5 for protons;
- p-pbar opening angle
- PID
- Tracking (1%)
- Luminosity (~1%)
- Integral limits
- Reconstruction efficiency (1% variation)

Systematic Uncertainties (Phase)

Positive phase

$\varphi = 95.1° \pm 2.8° \pm 4.6°$

$\sigma_{cont} = 9.91 \pm 0.40 \pm 0.78$ pb

$B_{out} = (1.92 \pm 0.02 \pm 0.04)\ 10^{-3}$

Parameters Cuts [MeV]	φ [°]	BR $[10^{-3}]$	σ_{3GeV} [pb]
E_{show}/p	2.0	0.018	0.35
$\vartheta_{p\bar{p}}$	1.2	0.015	0.24
fit	1.3	0.015	0.35
PID	3.0	0.024	0.48
efficiency	1.7	0.016	0.27
Total	4.6	0.040	0.78

Negative phase

$\varphi = -95.0° \pm 3.9° \pm 4.6°$

$\sigma_{cont} = 9.91 \pm 0.63 \pm 0.83$ pb

$B_{out} = (2.10 \pm 0.03 \pm 0.04)\ 10^{-3}$

Parameters Cuts [MeV]	φ [°]	BR $[10^{-3}]$	σ_{3GeV} [pb]
E_{show}/p	1.7	0.010	0.31
$\vartheta_{p\bar{p}}$	0.8	0.018	0.25
fit	2.3	0.017	0.39
PID	2.8	0.025	0.48
efficiency	2.3	0.017	0.38
Total	4.6	0.040	0.83

PDG: $B_{out} = (2.121 \pm 0.029)\ 10^{-3}$

Summary

- Study of the ppbar final state around J/ψ
- Fitting routine based on Babayaga (fast)
- Systematic errors calculation
- Full check of the procedure
- Updated memo version already uploaded (BAM-00106)