Inclusive Measurement of $h_c(1^1P_1)$ in $\psi(2S)$ decay

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04 November 2019

BESIII Italy Meeting

Perugia

Outline:

- Analysis summary:
  - Goal and Strategy
  - The Data Sets
  - Event Selection in a nutshell
  - Background Suppression
  - Efficiency and Resolution
- I/O Test
- 2012 Data
- 2009 Data
- 2009+2012 Data
- Angular Distributions
- Systematic Errors
- Conclusions

In the beginning was the Word

Goal

Measure the **$h_c(1^1P_1)$** features with higher precision wrt Phys. Rev. Lett. 104

Measurements of branching ratios
($\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$)
will be performed too

Previous Analysis: 106M of ψ(2S) events
This Analysis: 410M of ψ(2S) events

Strategy

Reconstruction of the h_c mass
from the π^0 recoiling mass,
throughout two decay routes

Inclusive Decay
$\psi(2S) \longrightarrow \pi^0 h_c$

Bigger sample
Background dominated

E1 Tagged Decay
$\psi(2S) \longrightarrow \pi^0 h_c$, $h_c \longrightarrow \gamma \eta_c$

Purer sample
Less statistics

Through data sets all analyses are made

Signal MC

- **How big?** 2 samples of 300k events each
- **What?** MC simulations of the $\psi(2S) \rightarrow \pi^0 h_c$ decay and the $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\, \eta_c$ decay chain

Inclusive MC

- **How big?** 400M events (2012)
- **What?** MC simulation of $\psi(2S)$ resonance with its and its daughters main known decay modes

Data

- **How big?**
  - 2012 → ~ 340M events
  - 2009 → ~ 106M events
- **What?** Taken @ $\psi(2S)$ resonance (on-peak)

Continuum

- **How big?** 44 pb^{-1}
- **What?** Continuum @ 3.650 GeV (off-peak)

Events selection in a nutshell

Charged Tracks

Vertex: R_{xy} < 1 cm & R_z < 10 cm

Polar angle: |cos θ| < 0.93

Momentum: p < 2.0 GeV

Photons

Isolation: Δ(Ω) > 10°

EMC Time Info: 0 ≤ t ≤ 14

E_γ (Barrel) > 25 MeV, |cos θ| < 0.80

E_γ (End Caps) > 50 MeV, 0.86 < |cos θ| < 0.92

Event

At least 2 good charged tracks

$\psi(2S) \to \pi^0 h_c$: At least 2 good photons

$h_c \to \gamma \eta_c$: At least 3 good photons

Recoiling π^0

γ in the Barrel (|cos θ| < 0.8)

E_γ > 40 MeV

120 MeV < $M_{\gamma\gamma}$ < 145 MeV

Inclusive

γ, from signal π_0, must not belong to other π_0

$M_{\gamma\gamma}$ invariant mass constrained to the π_0 nominal one by a 1-C kinematic fit

E1 Tagged

465 MeV < $E_{\gamma\ Tag}$ < 535 MeV

γ_{E1} must not to form a π_0 with any other γ

If more than one π_0 is found in the signal region the π_0 with the best 1-C fit χ^2 is kept

Signal Region
3.500 GeV – 3.550 GeV

Background Suppression

From Inclusive MC:

i. $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$

ii. $\psi(2S) \rightarrow \pi^0 \pi^0 J/\psi$

iii. $\psi(2S) \rightarrow \gamma \chi_c^0$

i. & ii. Studied to define vetoing windows.

iii. Not a problem, because the γ recoiling energy is not in the signal range (465 MeV < $E_{\gamma\ Tag}$ < 535 MeV). However, as a sanity check, the $\psi(2S) \rightarrow \gamma \chi_c^0$ decay (and its subsequent $\chi_c^0 \rightarrow \pi^0 \eta_c$) was studied to search for resonant features. Nothing but a typical combinatorial shape was found.

$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$

$M(J/\psi) \pm 5$ MeV

$\psi(2S) \rightarrow \pi^0 \pi^0 J/\psi$

$M(J/\psi)^{+15\ \mathrm{MeV}}_{-45\ \mathrm{MeV}}$

Efficiency Study

Tagged Channel

Signal MC Sample of 300k events

```
Decay psi(2S)
  1.0000 h_c pi0 HELAMP 0 0 1 0 0 0;
Enddecay

Decay h_c
  1.0000 gamma eta_c AngSam 1.0 1.0;
Enddecay

End
```

Cut	$\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ (%)
$N_{Good\ Ch} \geq 2$	89.09
$N_{Good\ \gamma} \geq 2$	88.07
0.6 GeV $\leq E_{EMC} \leq 3.2$ GeV	87.46
Good π^0	66.92
Tagged selection (with $\pi\pi$ J/ψ veto)	15.61

Final Efficiency

Efficiency Study

Inclusive Channel

Signal MC Sample of 300k events

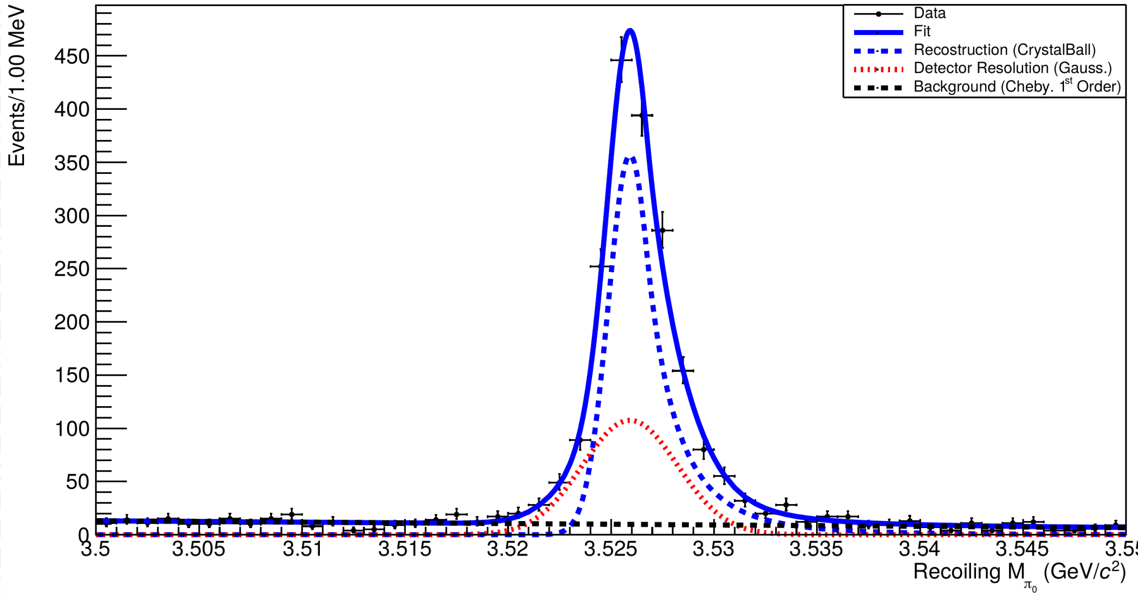
```
Decay psi(2S)
  1.0000 h_c pi0 HELAMP 0 0 1 0 0 0;
Enddecay

End
```

Cut	$\psi(2S) \to \pi^0 h_c$ (%)
$N_{Good\ Ch} \geq 2$	91.24
$N_{Good\ \gamma} \geq 2$	89.95
$0.6\ GeV \leq E_{EMC} \leq 3.2\ GeV$	89.31
Good π^0	70.91
Inclusive selection (with $\pi\pi$ J/ψ veto)	16.80

Final Efficiency

Resolution Study
Tagged Channel

- Signal shape:
  - Sum of Gaussian (Detector Resolution) and Crystalball (Reconstruction) functions, with the tail of the Crystalball on the right due to recoil energy of π^0
- Resolution: **2.7 MeV**
- The reconstruction induced background (here modeled by a 1st order Chebychev function) is absorbed by the background in the inclusive MC/data



Resolution Study

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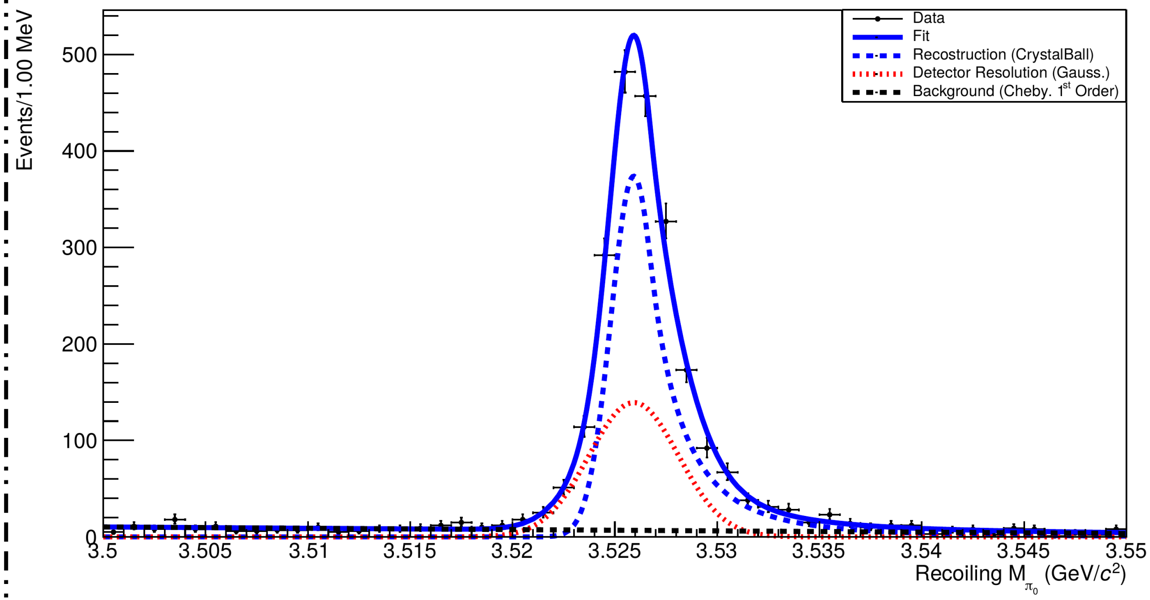


I/O Test
Fit Procedure

Binned (1 bin/MeV) fit of each channel (**Inclusive** and **Tagged**), where:

- In the **Tagged channel**, the h_c mass and width, and the background parameters are allowed to float;
- In the **Inclusive channel**, the h_c mass and width are fixed to the values found in the Tagged channel, and the background parameters are obtained by blinding the signal and fitting the signal region extremities.

I/O data set

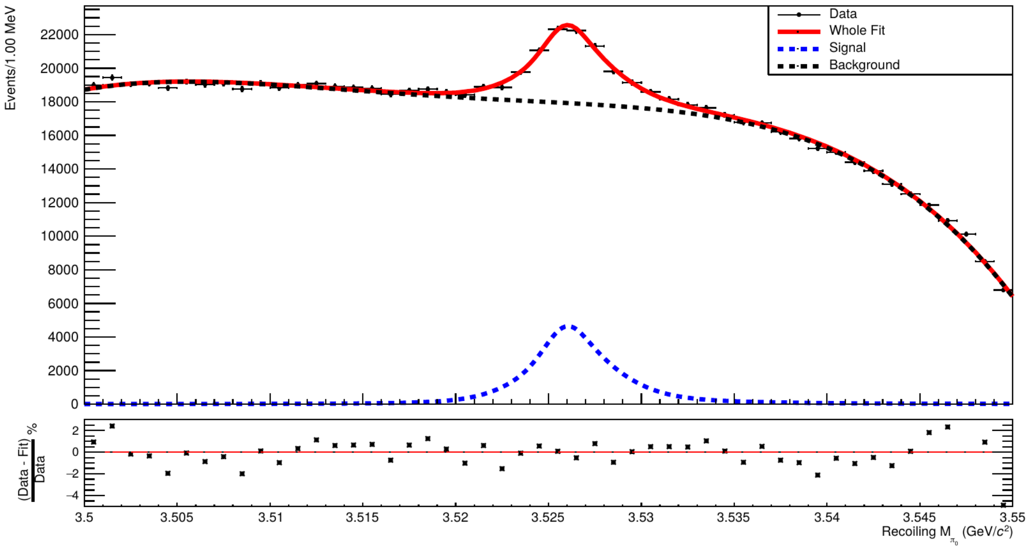
Inclusive MC was cleared from the h_c signal events.

A 340k signal MC data set was merged with the background-only Inclusive MC.

I/O Test
Tagged Channel

Features:

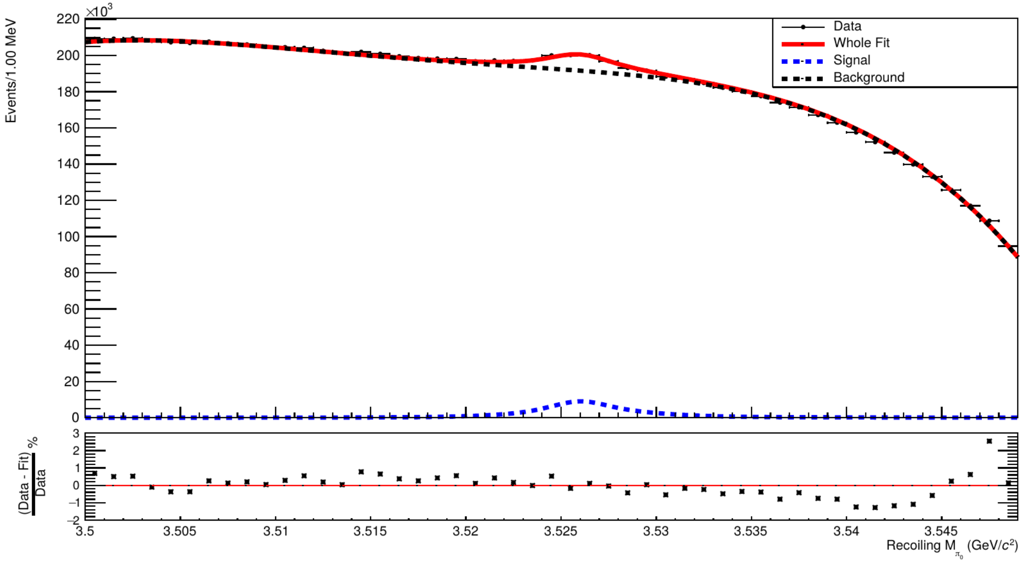
- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are left floating
- Background: 4^{th} order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



I/O Test
Inclusive Channel

Features:

- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are fixed to the values found in the Tag channel
- Background: 4^{th} order Chebychev function with fixed parameters (from the [3.500 GeV - 3.520 GeV] + [3.530 GeV - 3.550 GeV] fit)
- Fitting Region: 3.500 GeV – 3.550 GeV



I/O Test

Results

Feature [Unit of Measurement]	Input	Output	$\sigma(\lvert\Delta(I-O)\rvert)$
M(h_c) [GeV]	3525.93	3526.03 ± 0.06	1.67
Γ(h_c) [MeV]	1.00	1.38 ± 0.26	1.46
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	4.34	$4.26^{+0.25}_{-0.24}$	0.32
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	8.51	8.54 ± 0.26	0.16
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	51	$49.82^{+3.28}_{-3.20}$	0.36

Good I/O

Output features are within 2σ from the input values

Data
Fit Procedure

Binned (1 bin/MeV) fit of each channel (**Inclusive** and **Tagged**), where:

- In the **Tagged channel**, the h_c mass and width, and the background parameters are allowed to float;
- In the **Inclusive channel**, the h_c mass and width are fixed to the values found in the Tagged channel, and the **background parameters are allowed to float**.

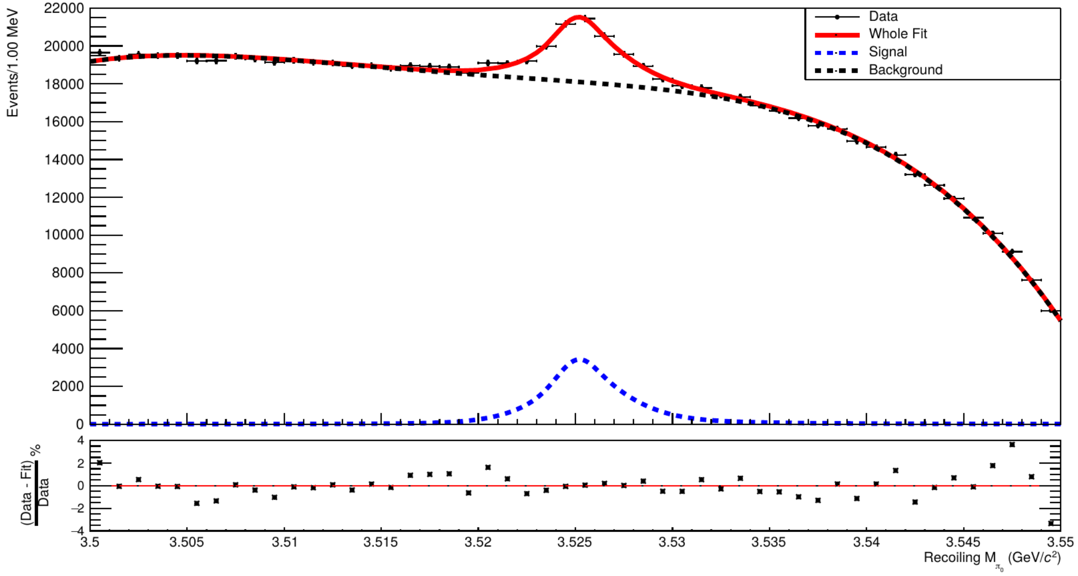
The fit is performed maximizing the profile-likelihood ratio, and makes use of MIGRAD, HESSE (for better error estimation) and MINOS (for single parameter optimization)

2012 Data

Tagged Channel

Features:

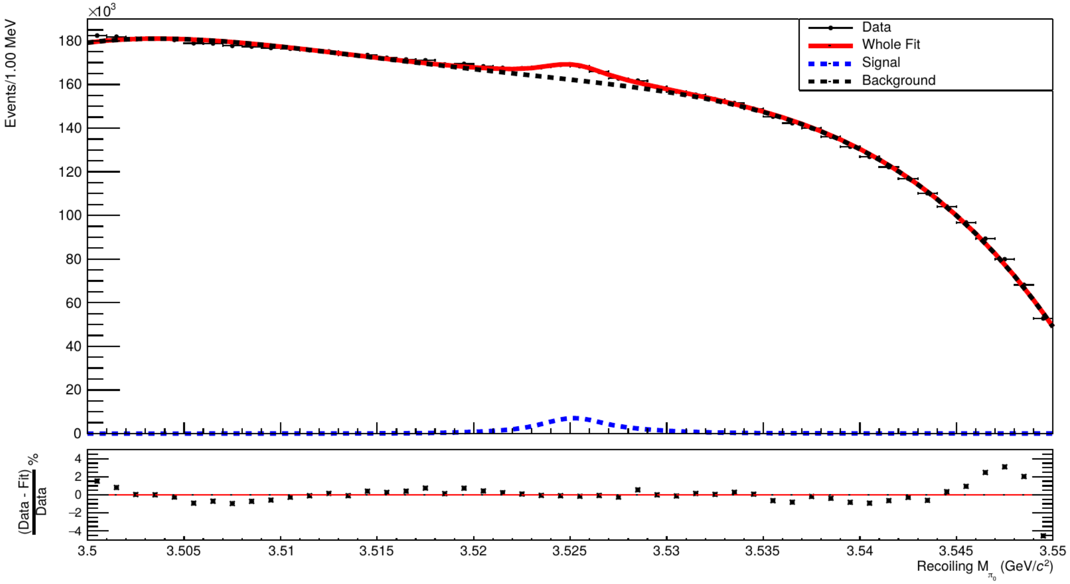
- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are left floating
- Background: 4th order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



2012 Data
Inclusive Channel

Features:

- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are fixed to the values found in the Tag channel
- Background: 4^{th} order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



2012 Data

Results

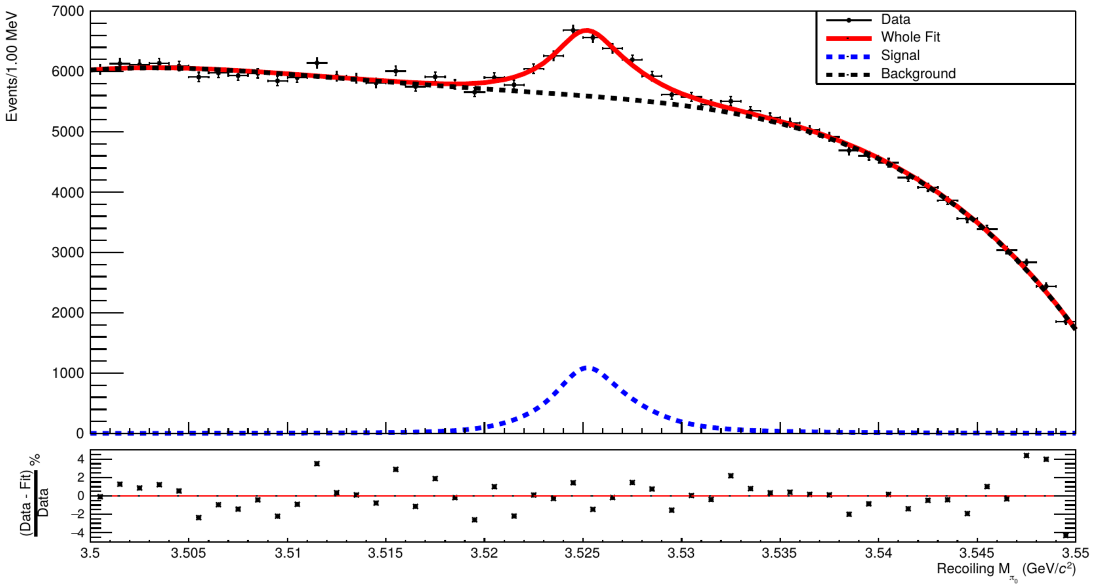
Feature [Unit of Measurement]	Value	PDG
$M(h_c)$ [MeV]	3525.19 ± 0.07	3525.38 ± 0.11
$\Gamma(h_c)$ [MeV]	1.06 ± 0.36	$0.70 \pm 0.28 \pm 0.22$
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	3.42 ± 0.28	4.3 ± 0.4
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	7.41 ± 0.36	8.6 ± 1.3
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	46.18 ± 4.37	51 ± 6

Decay and resonance features are **compatible** with the PDG within **1.5σ**

2009 Data
Tagged Channel

Features:

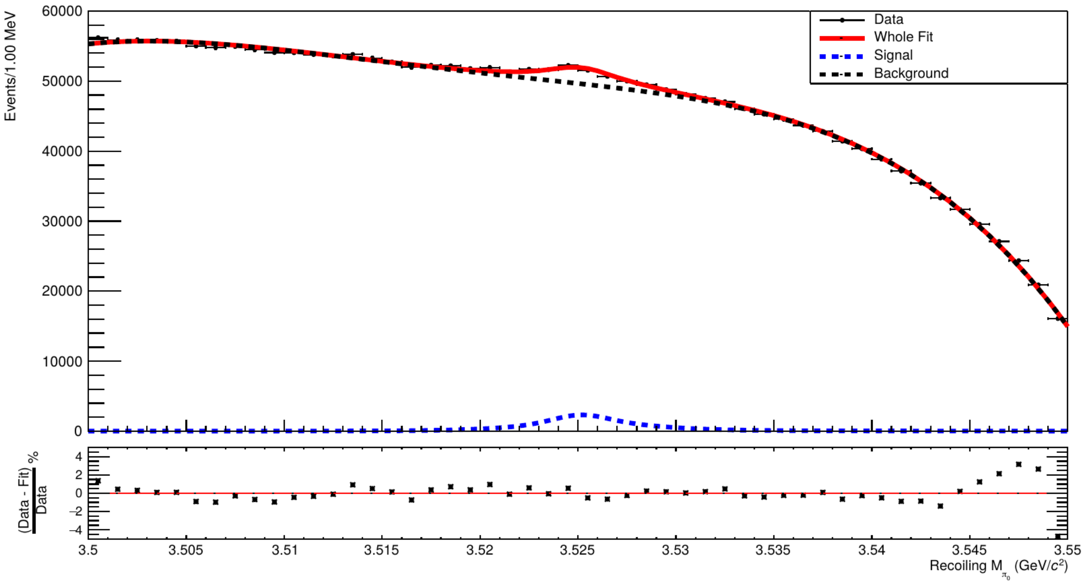
- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are left floating
- Background: 4th order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



2009 Data
Inclusive Channel

Features:

- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are fixed to the values found in the Tag channel
- Background: 4^{th} order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



2009 - 2012 Comparison

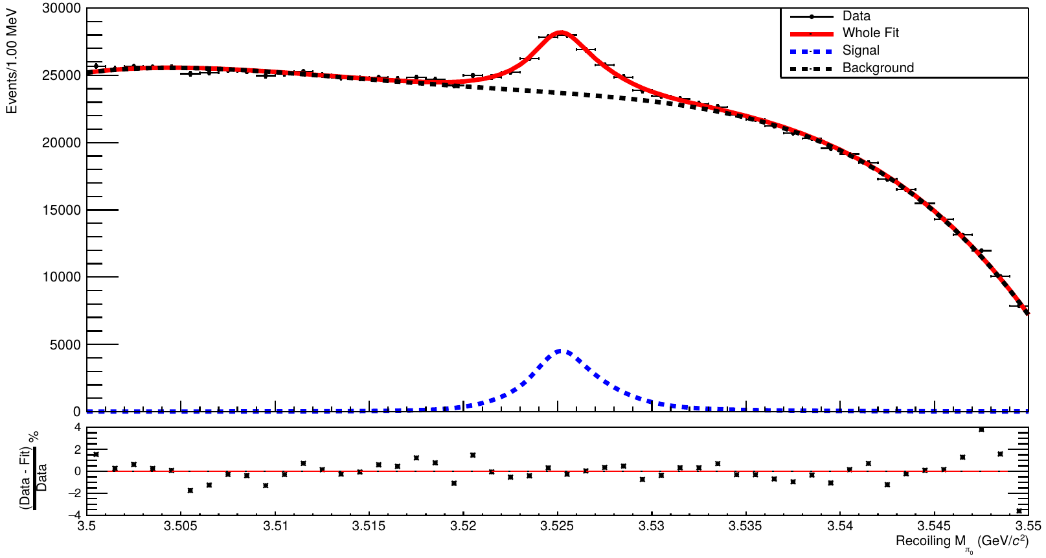
Feature [Unit of Measurement]	2009 Value	2012 Value
$M(h_c)$ [MeV]	$3525.20 \ ^{+\ 0.13}_{-\ 0.12}$	3525.19 ± 0.07
$\Gamma(h_c)$ [MeV]	$1.49 \ ^{+\ 0.61}_{-\ 0.56}$	1.06 ± 0.36
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	$3.87 \ ^{+\ 0.54}_{-\ 0.50}$	3.42 ± 0.28
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	8.49 ± 0.69	7.41 ± 0.36
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	$45.53 \ ^{+\ 7.34}_{-\ 6.98}$	46.18 ± 4.37

Decay and resonance features of the 2 data-sets are **compatible** within **1.5σ**

2009+2012 Data
Tagged Channel

Features:

- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are left floating
- Background: 4th order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV

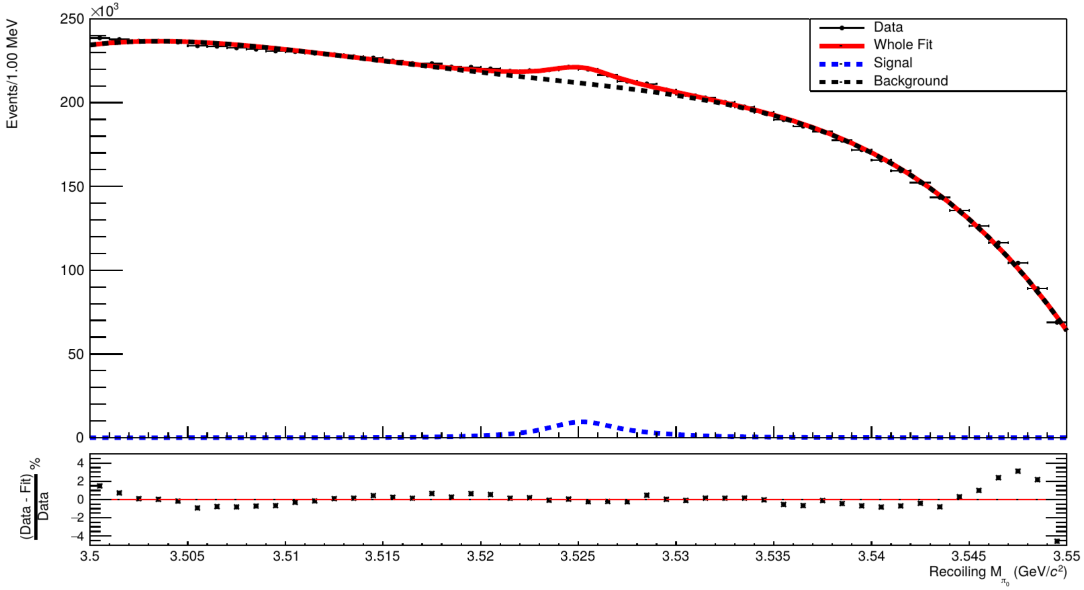


2009+2012 Data

Inclusive Channel

Features:

- Signal: Resolution function convoluted with a Breit-Wigner function describing the h_c state
- h_c features (mass and width) are fixed to the values found in the Tag channel
- Background: 4^{th} order Chebychev function with floating parameters
- Fitting Region: 3.500 GeV – 3.550 GeV



2009+2012 Data

Comparative results

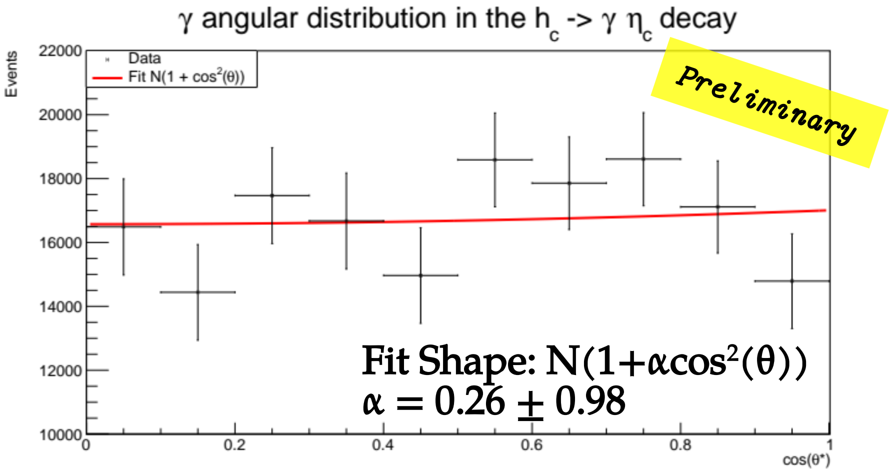
Feature [Unit of Measurement]	2009 Value	2012 Value	2009+2012 Value
$M(h_c)$ [MeV]	$3525.20 {}^{+\,0.13}_{-\,0.12}$	3525.19 ± 0.07	3525.19 ± 0.06
$\Gamma(h_c)$ [MeV]	$1.49 {}^{+\,0.61}_{-\,0.56}$	1.06 ± 0.36	$1.19 {}^{+\,0.31}_{-\,0.33}$
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	$3.87 {}^{+\,0.54}_{-\,0.50}$	3.42 ± 0.28	$3.89 {}^{+\,0.28}_{-\,0.29}$
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	8.49 ± 0.69	7.41 ± 0.36	8.44 ± 0.35
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	$45.53 {}^{+\,7.34}_{-\,6.98}$	46.18 ± 4.37	$46.09 {}^{+\,3.85}_{-\,3.89}$

Decay and resonance features of the data-sets are **compatible** within **1.5σ**.
The table shows as well that the **scaling of the absolute errors** with the increase of ψ(2S) events follows the expected ratio **1:0.56:0.49**.

Angular Distribution of the E1 photon

The angular distribution of the E1 photons is obtained by fitting separately the (corrected in efficiency) number of events in the h_c peak for different cos(θ) ranges, where θ is the angle between the E1 photon and the beam direction in the h_c frame.

Bin	Efficiency [%]	δEfficiency [%]
$0 \leq \lvert\cos(\theta)\rvert < 0.1$	15.52	0.01
$0.1 \leq \lvert\cos(\theta)\rvert < 0.2$	15.58	0.01
$0.2 \leq \lvert\cos(\theta)\rvert < 0.3$	15.68	0.01
$0.3 \leq \lvert\cos(\theta)\rvert < 0.4$	15.75	0.01
$0.4 \leq \lvert\cos(\theta)\rvert < 0.5$	15.82	0.01
$0.5 \leq \lvert\cos(\theta)\rvert < 0.6$	16.32	0.01
$0.6 \leq \lvert\cos(\theta)\rvert < 0.7$	16.58	0.01
$0.7 \leq \lvert\cos(\theta)\rvert < 0.8$	16.63	0.01
$0.8 \leq \lvert\cos(\theta)\rvert < 0.9$	16.74	0.01
$0.9 \leq \lvert\cos(\theta)\rvert < 1.0$	16.33	0.01



Fit Shape: $N(1+\alpha\cos^2(\theta))$

$\alpha = 0.26 \pm 0.98$

Systematic Errors

Bin.

Different binning ratios were tested (ranging from 1 MeV/bin to an unbinned fit).

Fitting region.

The boundaries of the signal region (3.500 - 3.550) were changed of 5 MeV on both sides and of 10 MeV on the lower side.

Background functional shapes. (*ongoing*)

Tag channel:

- 3^{rd} and 5^{th} order Chebychev
- ARGUS (re-wegihted)
- MC Shape re-weighted

Inclusive channel:

- 3^{rd} and 5^{th} order Chebychev
- ARGUS (re-weighted)
- MC Shape re-weighted

TO BE DONE:

Signal MC production. The information from the Angular Distribution will be used to correct the signal MC data sets.

Photon energy calibration.

Mass ranges for veto. Due to the wide plateau in the FoM plot for the background suppression, different (less strict) ranges will be tested.

π^0 **selection.** The 2γ invariant mass will be changed by 10 MeV on both sides, affecting both the tag and inclusive channel.

Conclusions

Fits on data sets are all under control and compatible among them

The statistical errors scale as expected

Angular distribution for the E1 photon is under study, a preliminary fit was performed to determine its shape

Systematic errors are under study

Next Steps

Finalize the angular distribution study

Finish to assess the systematic errors

Upload the updated Memo on Hypernews

Thanks for your attention

BACK UP SLIDES

Charmonium Spectroscopy

$h_c(1^1P_1)$

Mass [MeV]	Width [MeV]	Δ_{hyp} [MeV]	Experiment	
$3525.4 \pm 0.8 \pm 0.4$	-	-	R704	Baglin *et al.*, Phys. Lett. B 171, Issue 1
$3526.28 \pm 0.18 \pm 0.19$	< 1.1	-	E760*	T.A. Armstrong *et al.*, Phys. Rev. Lett. 69, 2337
3527 ± 8	-	-	E705	L. Antoniazzi *et al.*, Phys. Rev. D 50, 4258
$3524.4 \pm 0.6 \pm 0.4$	-	$1.0 \pm 0.6 \pm 0.4$	CLEO-c	J. L. Rosner *et al.*, Phys. Rev. Lett. 95, 102003
$3525.8 \pm 0.2 \pm 0.2$	$0.5 < \Gamma < 1.1$	-	E835*	M. Andreotti *et al.*, Phys. Rev. D 72, 032001
$3525.20 \pm 0.18 \pm 0.12$	-	$0.02 \pm 0.19 \pm 0.13$	CLEO-c*	S. Dobbs *et al.*, Phys. Rev. Lett. 101, 182003
3525.6 ± 0.5	-	-	CLEO-c	G. S. Adams *et al.*, Phys. Rev. D 80, 051106
$3525.40 \pm 0.13 \pm 0.18$	< 1.44	$-0.10 \pm 0.13 \pm 0.18$	BESIII*	M. Ablikim *et al.*, Phys. Rev. Lett. 104, 132002
$3525.31 \pm 0.11 \pm 0.14$	$0.70 \pm 0.28 \pm 0.22$	$-0.01 \pm 0.11 \pm 0.15$	BESIII*	M. Ablikim *et al.*, Phys. Rev. D 86, 092009

Summary of the h_c mass and width measurements.
The * represents the measurements used by the PDG "*for averages, fits, limits, etc.*".

Branching Ratios

Signal

$$\psi(2S) \rightarrow \pi^0 h_c \qquad \mathcal{BR} = (8.6 \pm 1.3) \times 10^{-4}$$
$$h_c \rightarrow \gamma\eta_c \qquad \mathcal{BR} = (51 \pm 6)\ \%$$

Background

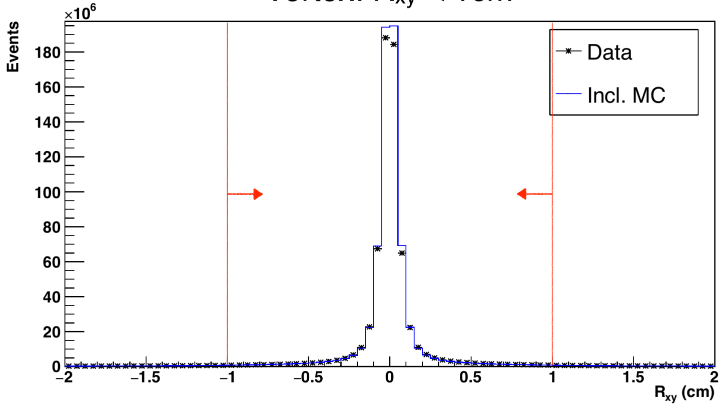
$$\psi(2S) \rightarrow \pi^+\pi^- J/\psi \qquad \mathcal{BR} = (34.49 \pm 0.30)\ \%$$
$$\psi(2S) \rightarrow \pi^0\pi^0 J/\psi \qquad \mathcal{BR} = (18.17 \pm 0.31)\ \%$$
$$\psi(2S) \rightarrow \gamma\chi_{c0} \qquad \mathcal{BR} = (9.99 \pm 0.27)\ \%$$

General Selection Criteria

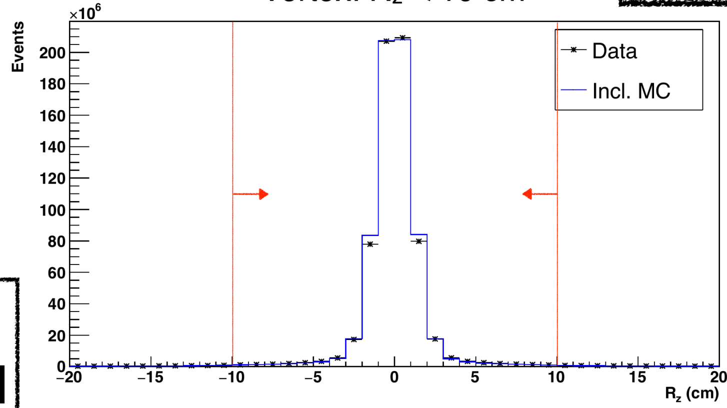
Charged Tracks

* Data
—— Incl. MC

Vertex: $R_{xy} < 1$cm

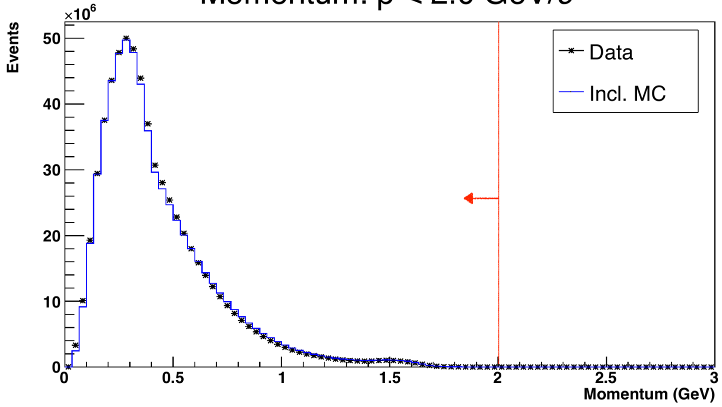


Vertex: $R_z < 10$ cm

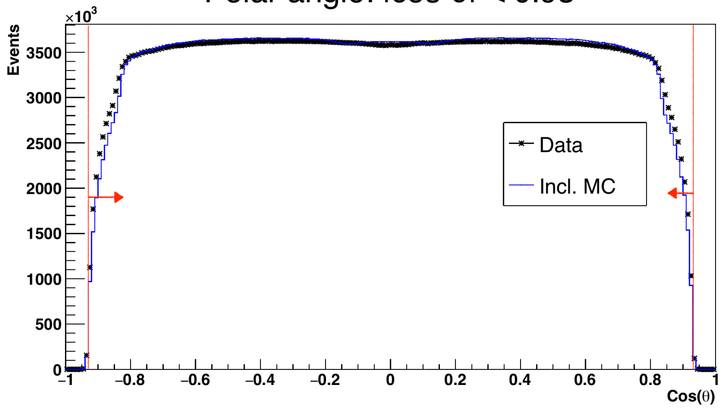


CUTS Applied

Momentum: p < 2.0 GeV/*c*



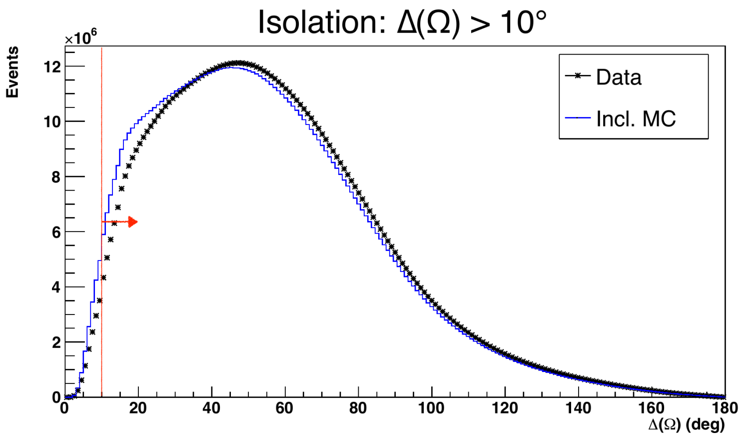
Polar angle: |cos θ| < 0.93



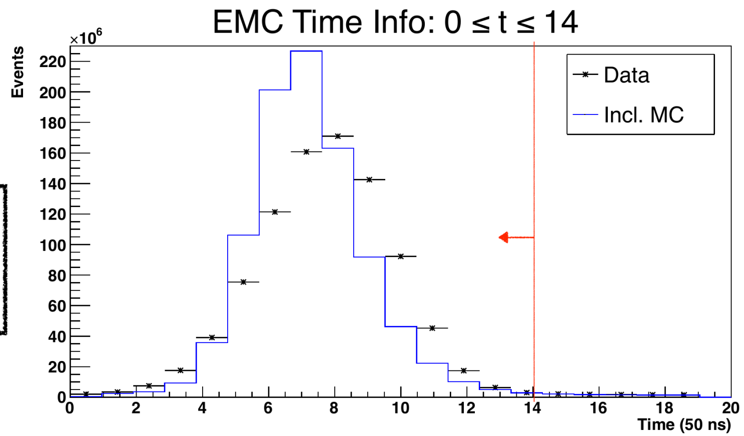
General Selection Criteria

Neutral Candidates

* Data
—— Incl. MC

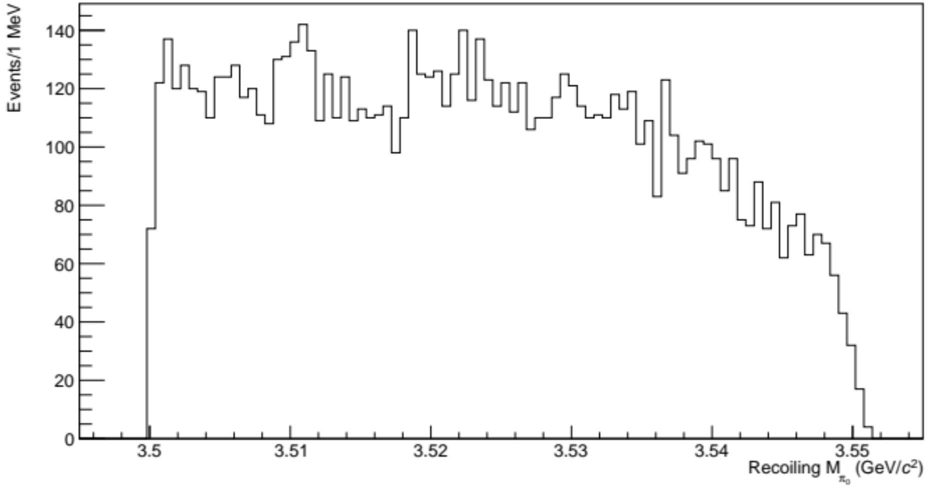


CUTS Applied

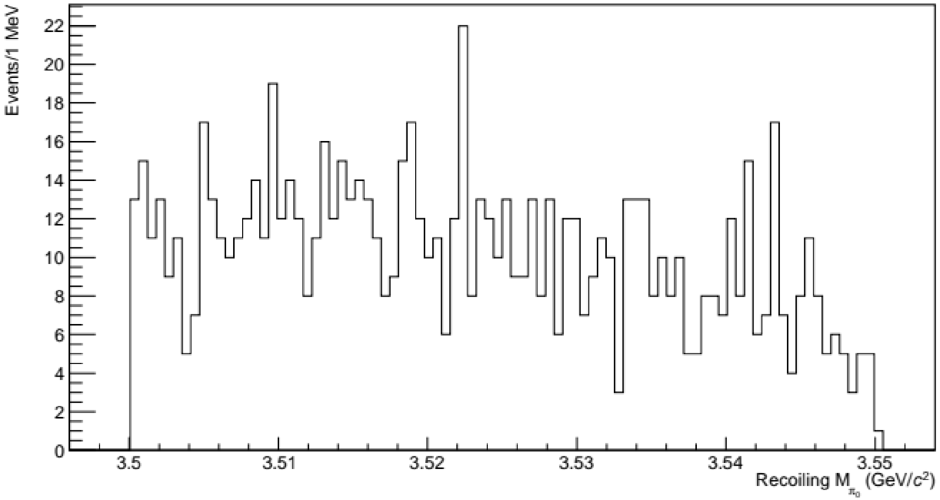


2012 Data
Continuum Sanity Checks

No resonant features



Inclusive channel



Tag channel

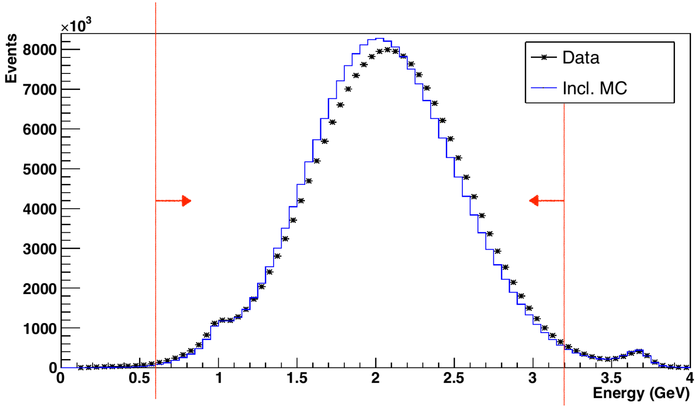
General Selection Criteria

Energy Cuts

* Data
Incl. MC

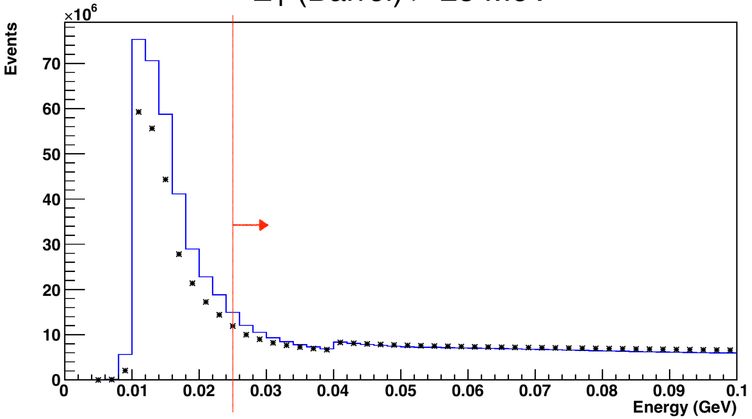
Charged Tracks
&
Neutral Candidates

EMC Energy: 0.6 GeV < E < 3.2 GeV

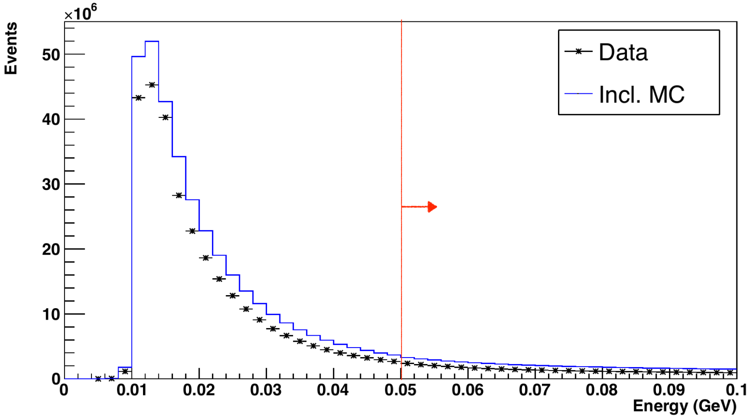


Neutral
Candidates

Eγ (Barrel) > 25 MeV



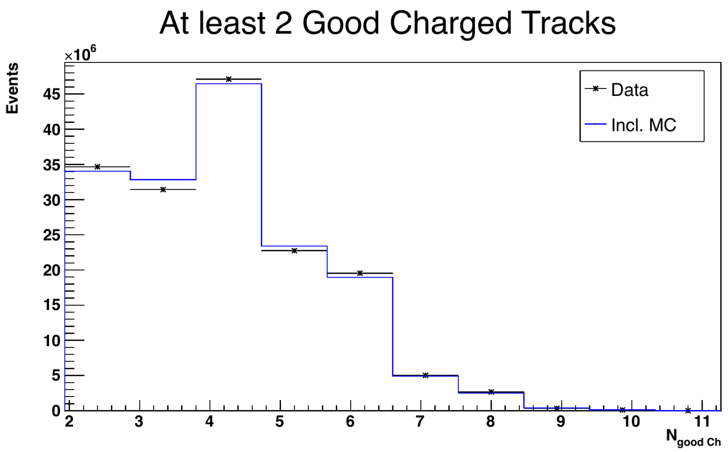
Eγ (End Caps) > 50 MeV

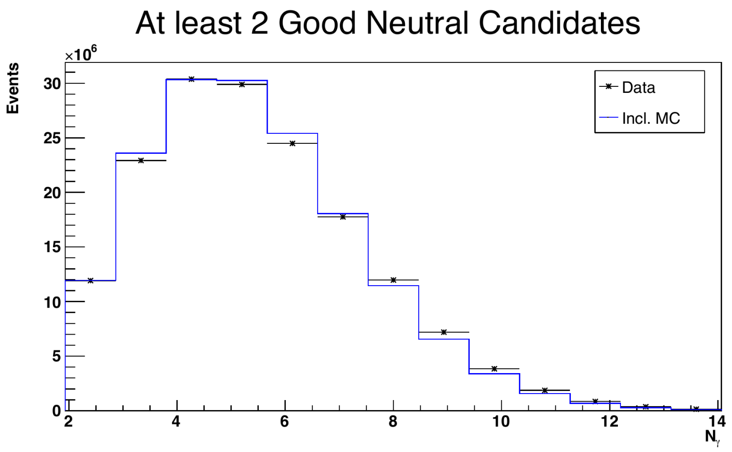


General Selection Criteria

Number of Good Charged Tracks and Good Neutral Candidates

* Data
—— Incl. MC



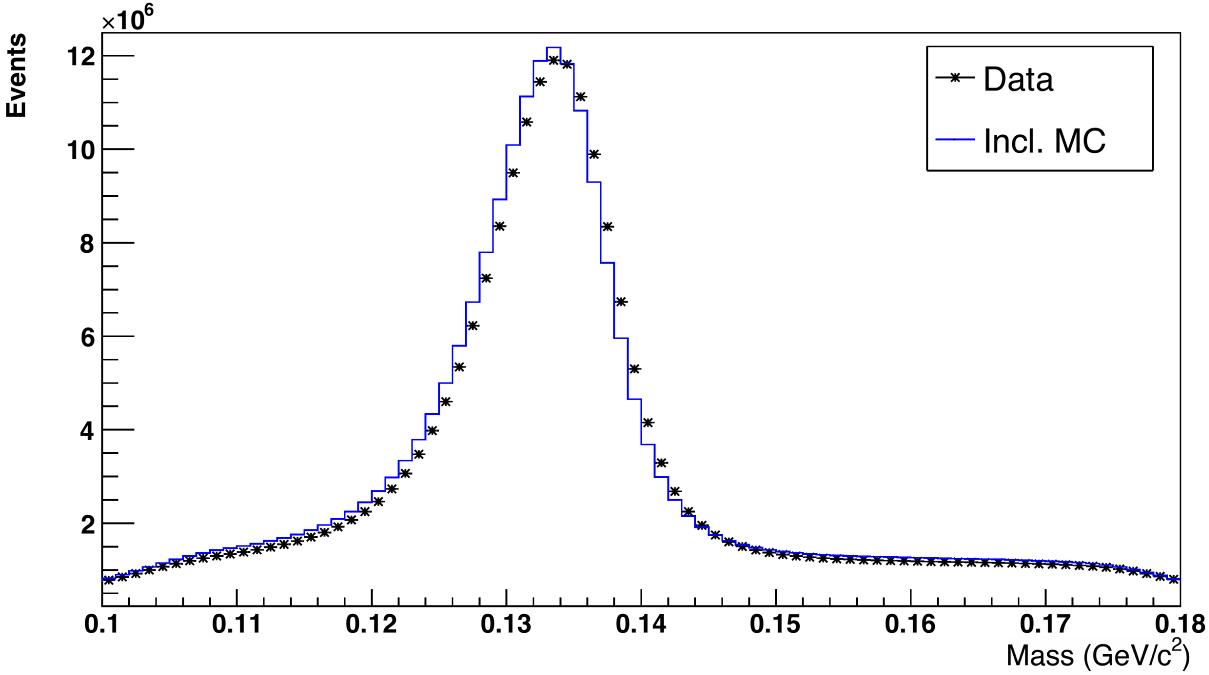


Recoiling π^0 Selection

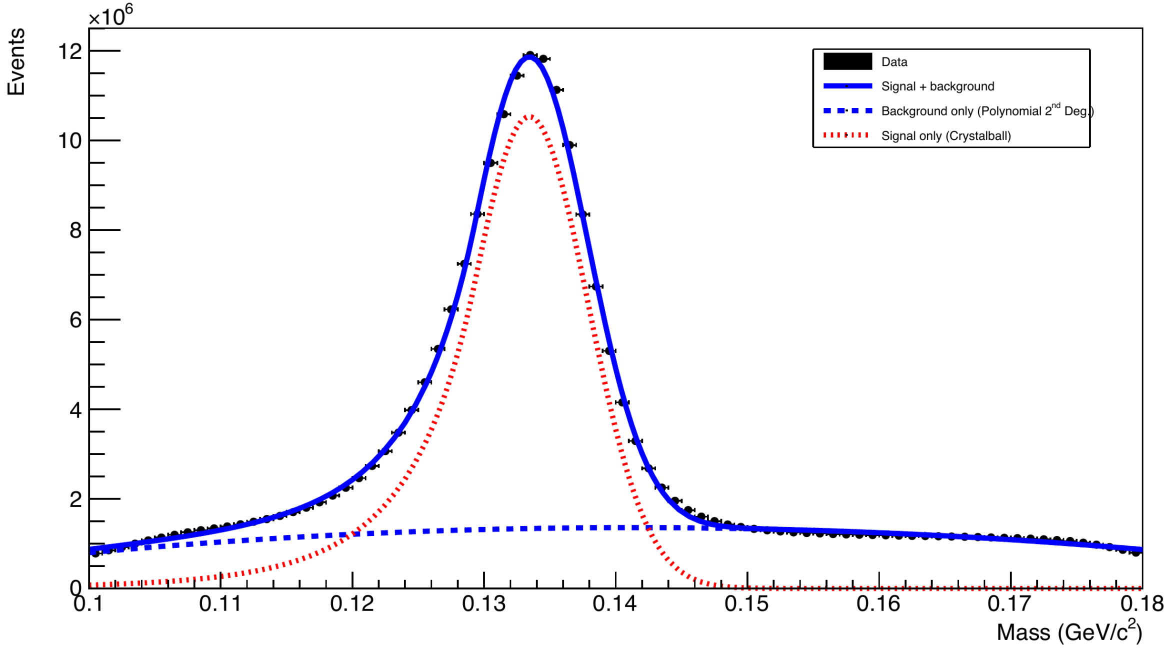
γ in the Barrel (|cos θ| < 0.8)

Eγ > 40 MeV

120 MeV < Mγγ < 145 MeV



Recoiling π^0 Selection

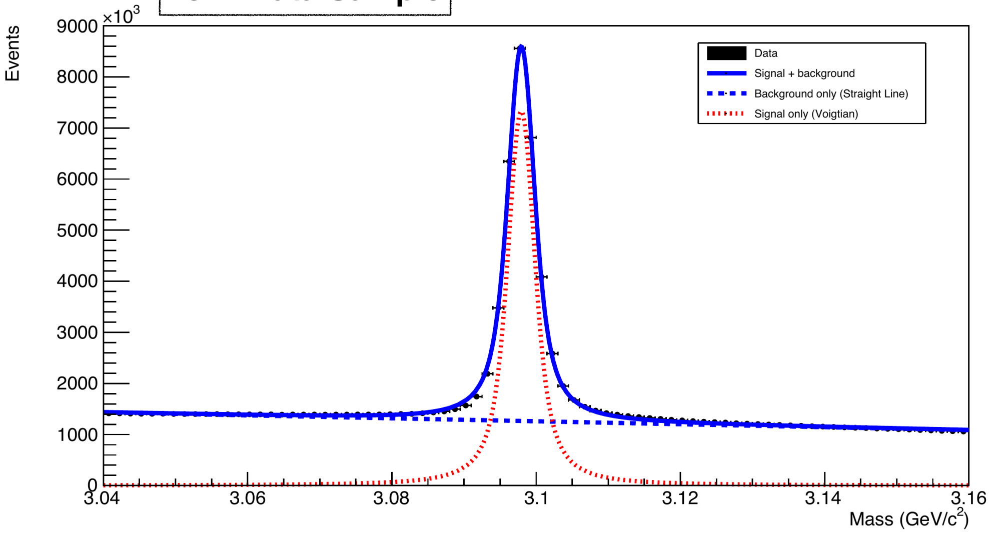


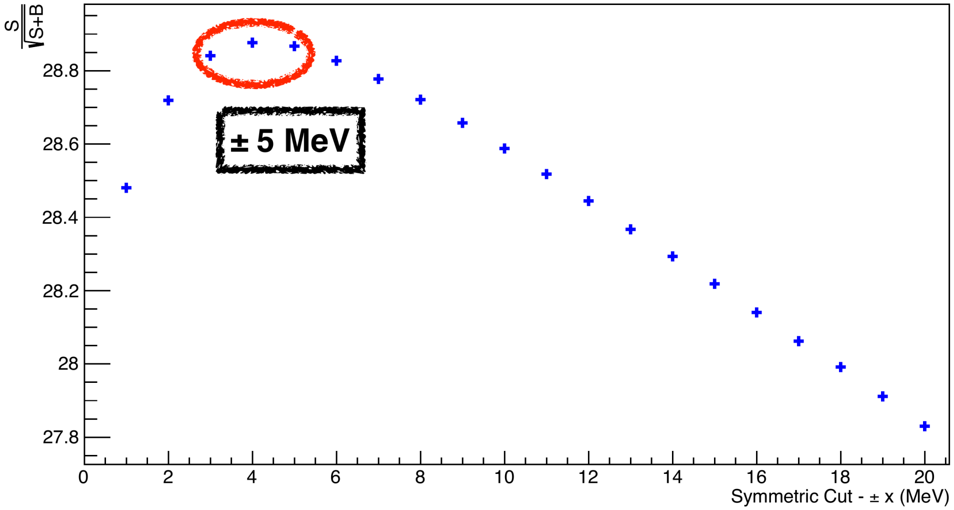
Signal —> Crystal-ball
Background —> 2nd Order Polynomial

Background evaluation & Suppression

$\psi(2S) \to \pi^+ \pi^- J/\psi$

2012 Data Sample



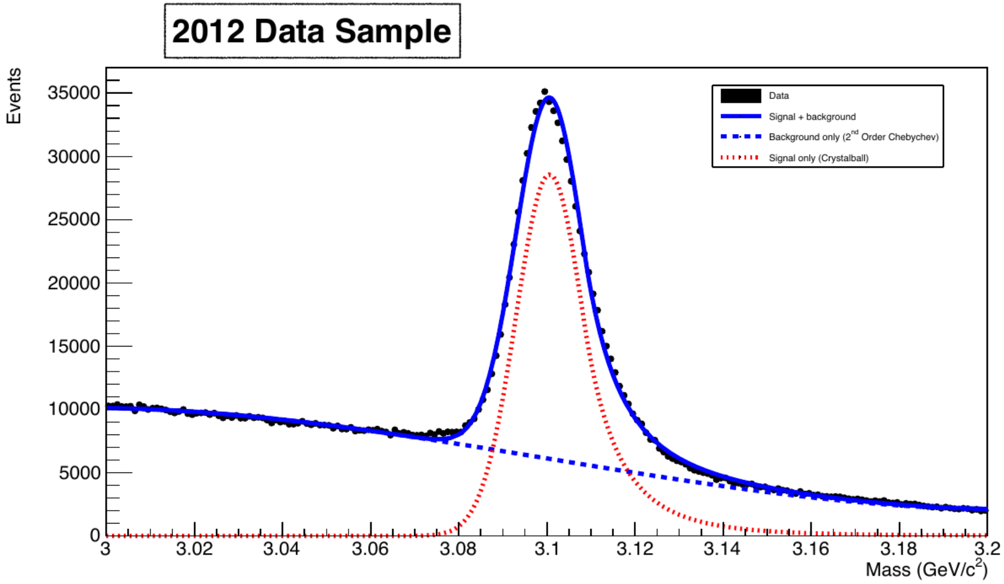


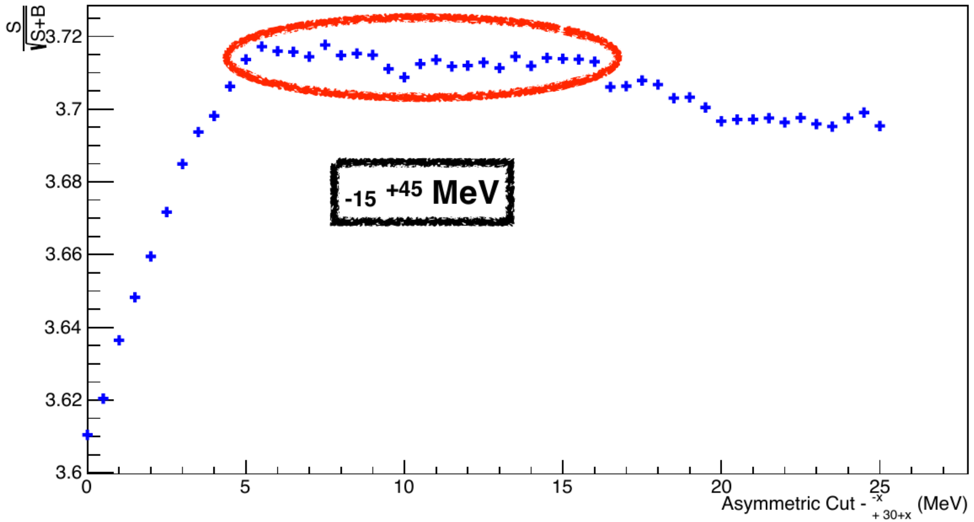
Signal —> Voigtian;
Background —> Straight Line (α < 0).

The x-axis represents the energy regions (around the J/ψ mass) in which the events are rejected

Background evaluation & Suppression

ψ(2S) —> π⁰ π⁰ J/ψ





Signal —> Crystalball;
Background —> 2nd Order Chebichev

The x-axis represents the energy regions (around the J/ψ mass) in which the events are rejected

2010 Analysis

Efficiencies and BR Estimation

1 ϵ_1^{E1} is the event selection efficiency in the inclusive analysis of $\psi(2S) \to \pi^0 h_c$, h_c is forced to decay to $\gamma\eta_c$.

2 ϵ_1^{had} is the event selection efficiency in the inclusive analysis of $\psi(2S) \to \pi^0 h_c$, h_c is forced to decay to other final states (generated by PYTHIA).

3 ϵ_{12} is the event selection efficiency in the E1-photon-tagged analysis of $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$.

$$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) = \frac{N_{E1}}{\epsilon_{E1} \times N(\psi(2S))}$$

$$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) = \frac{N_{tot}}{(\epsilon_{E1}^{Incl} \times \mathcal{B}_2) \times (\epsilon_{had}^{Incl} \times (1-\mathcal{B}_2)) \times N(\psi(2S))}$$

$$\mathcal{B}_2(h_c \to \gamma\eta_c) = \frac{\frac{\epsilon_{had}^{Incl}}{\epsilon_{E1}}}{\frac{N_{tot}}{N_{E1}} + \frac{\epsilon_{had}^{Incl} - \epsilon_{E1}^{Incl}}{\epsilon_{E1}}}$$

2009 Efficiency Study

Tagged Channel

Signal MC Sample of 300k events

```
Decay psi(2S)
  1.0000 h_c pi0 HELAMP 0 0 1 0 0 0;
Enddecay

Decay h_c
  1.0000 gamma eta_c AngSam 1.0 1.0;
Enddecay

End
```

Cut	$\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ (%)
$N_{Good\ Ch} \geq 2$	89.49
$N_{Good\ \gamma} \geq 2$	88.44
$0.6\ GeV \leq E_{EMC} \leq 3.2\ GeV$	87.71
Good π^0	67.03
Tagged selection (with $\pi\pi$ J/ψ veto)	15.57

Final Efficiency

2009 Efficiency Study
Inclusive Channel

Signal MC Sample of 300k events

```
Decay psi(2S)
  1.0000 h_c pi0 HELAMP 0 0 1 0 0 0;
Enddecay

End
```

Cut	$\psi(2S) \to \pi^0 h_c$ (%)
$N_{Good\ Ch} \geq 2$	91.54
$N_{Good\ \gamma} \geq 2$	90.23
0.6 GeV $\leq E_{EMC} \leq 3.2$ GeV	89.55
Good π^0	71.05
Inclusive selection (with $\pi\pi$ J/ψ veto)	16.83

Final Efficiency

Tag Channel Background Fitting Methods Comparison

Sidebands method. Similar as performed in Ref. [8], the sidebands method consists of taking the background shape of the recoiling π^0 mass spectrum in the sidebands of the γ_{E1}. The sidebands were constructed by requesting that no photon had an energy between 400 MeV - 600 MeV (i.e. $E_{\gamma_{E1}} < 400$ MeV & $E_{\gamma_{E1}} > 600$ MeV).

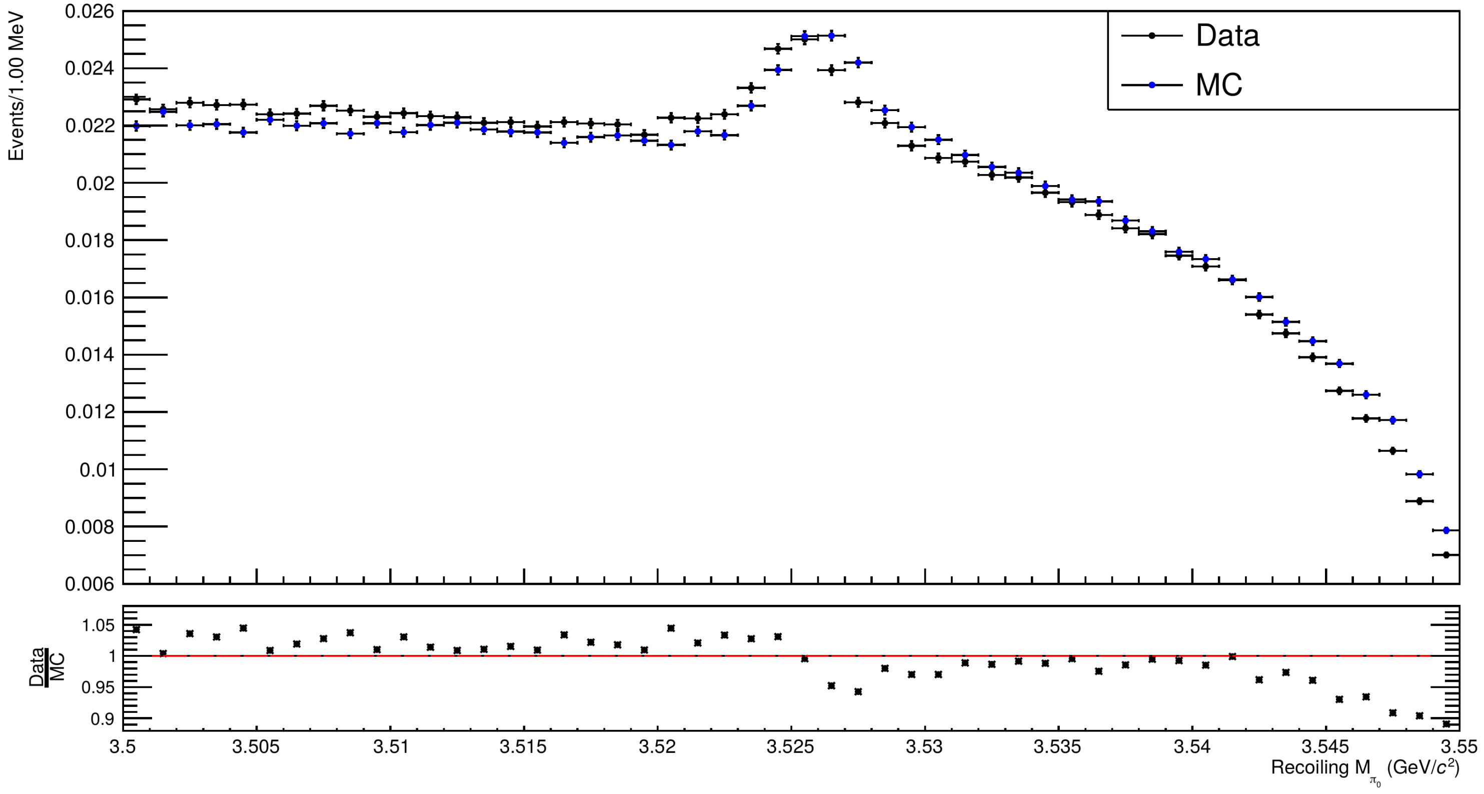
Signal MC shape. This method consists of taking the background shape from the Inclusive MC sample purged by the signal events. The drawback of this method is that cannot be used to fit the data due to the mismodeling as shown in Fig. 28.

Extremities fit. This method consists of taking the signal region and blinding the portion in which the h_c signal is found, in order to fit the lower ([3.500 GeV - 3.520 GeV]) and upper ([3.530 GeV - 3.550 GeV]) extremities with a 4^{th} order Čebyšëv polynomial constraining its parameters.

Fixing the Čebyšëv parameters. This method, similar to the previous one, makes use of a "*control region*" (CR) to constrain the Čebyšëv parameters. The CR would be the same aforementioned sidebands region of the γ_{E1}.

Free-to-float-parameters. This method simply consists of leaving the 4^{th} order Čebyšëv parameters free to float, adding four additional constraints to the whole model.

Tag Channel Background Fitting Methods Comparison



Tag Channel Background Fitting Methods Comparison

Feature [unit of measurement]	Input	Float Čeby. Param.	Extr. Fit
$M(h_c)$ [MeV]	3525.93	3526.03 ± 0.06	3526.07 ± 0.05
$\Gamma(h_c)$ [MeV]	1.00	1.38 ± 0.26	$0.89\ ^{+\,0.20}_{-\,0.21}$
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	4.34	$4.26\ ^{+\,0.25}_{-\,0.24}$	$3.69\ ^{+\,0.13}_{-\,0.14}$

Feature [unit of measurement]	Input	SB Shape	SB Fix Čeby. Param.
$M(h_c)$ [MeV]	3525.93	3526.01 ± 0.05	3526.03 ± 0.06
$\Gamma(h_c)$ [MeV]	1.00	0.65 ± 0.32	0.96 ± 0.19
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ [10^{-4}]	4.34	3.22 ± 0.18	3.80 ± 0.13

Table 10: I/O comparison of different background fitting methods for the Tag channel. In both the table on top the two methods shown are the *free-to-float 4^{th} order Čebyšëv polynomial parameters* method and the *extremities fit* one. In the table below the two methods that make use of the sidebands are presented. One can notice from the comparison of these four methods that leaving the parameters free to float provides a better estimation of the features, despite increasing the absolute errors (which is due to the increase of free parameters.

Inclusive Channel Background Fitting Methods Comparison

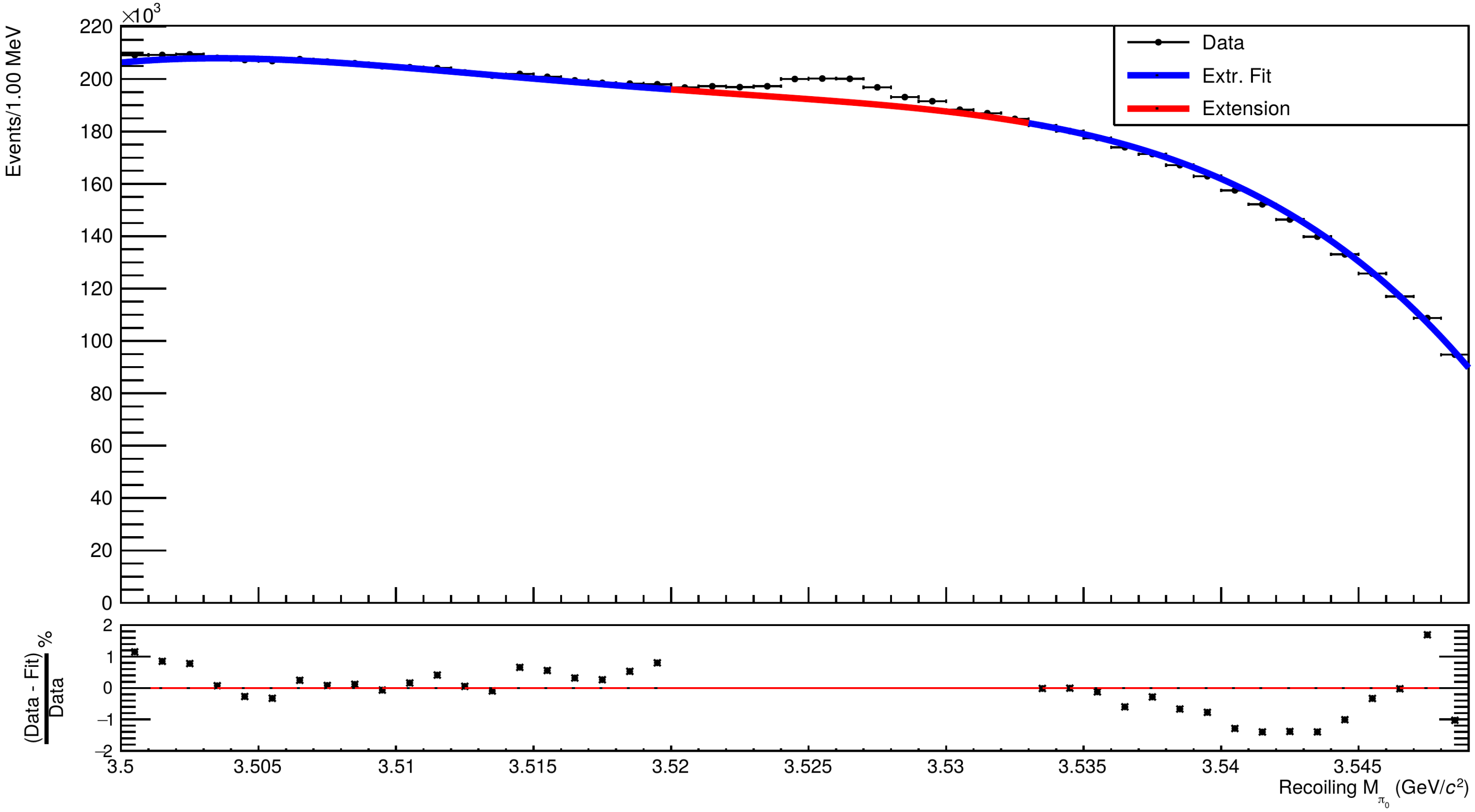
Good π^0 sidebands method. Similarly to the method mentioned for the Tag channel, the method makes use of sidebands region. Here, the sidebands were constructed by rejecting any good π^0 in the signal region[2]. The problem of this method is that this sidebands region does not describe well the signal background (as shown in Fig. 31).

Signal MC shape. This method consists of taking the background shape from the Inclusive MC sample purged by the signal events. The drawback of this method is that cannot be used to fit the data due to the mismodeling as shown in Fig. 31.

Extremities fit. This method (shown in Fig. 29) consists of taking the signal region and blinding the portion in which the h_c signal is found, in order to fit the lower ([3.500 GeV - 3.520 GeV]) and upper ([3.533 GeV - 3.549 GeV]) extremities with a 4^{th} order Čebyšëv polynomial constraining its parameters.
A scan study was performed to select the best configuration for such a fit: different intervals for both the lower and upper extremities were tested. The best configuration was chosen such that the percentile difference between the Data and the Fit of said configuration was below 2%.

Free-to-float-parameters. This method simply consists of leaving the 4^{th} order Čebyšëv parameters free to float, adding four additional constraints to the whole model.

Inclusive Channel Background Fitting Methods Comparison



Tag Channel Background Fitting Methods Comparison

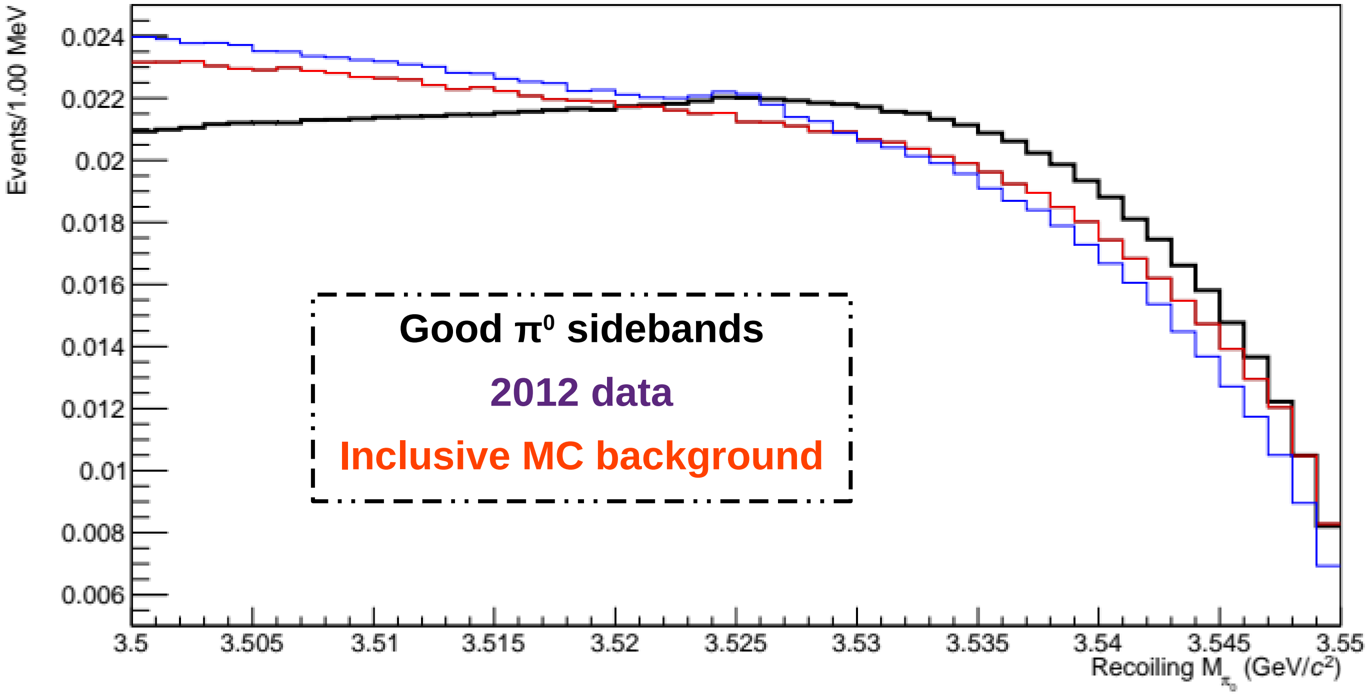
MC

Feature [unit of measurement]	Input	Float Čeby. Param.	Extr. Fit
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	8.50	10.08 ± 0.36	8.47 ± 0.26
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	51	$42.21^{+2.89}_{-2.82}$	$50.24^{+3.32}_{-3.23}$

Data

Feature [unit of measurement]	PDG	Float Čeby. Param.	Extr. Fit
$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c)$ [10^{-4}]	8.6 ± 1.3	7.41 ± 0.36	5.97 ± 0.26
$\mathcal{B}_2(h_c \to \gamma\eta_c)$ [%]	51 ± 6	46.18 ± 4.67	57.37 ± 5.68

2012 Data
Inclusive Channel Background Comparison



Due to these differences between MC and data bkg shapes: the **multi-range fit on data** did **not** provide **acceptable results** (too far from PDG, without any meaningful reason), so...

Angular Distribution of the E1 photon

V. $\bar{p}p \to (\psi, {}^1P_1) \to \gamma\eta_c$

These decays proceed by only one multipole, $M1$ for $\psi \to \gamma\eta_c$ and $E1$ for ${}^1P_1 \to \gamma\eta_c$, so we have

$$a_1 = A_0 = 1 \ . \quad (23)$$

For these states the angular distributions are

$$\frac{32\pi^2}{3}\hat{W}(\theta;\theta',\phi') = (K_1 + K_2\cos^2\theta) \ ,$$

$$K_1 = 1 - \tfrac{1}{2}R \ , \quad (24)$$

$$K_2 = \tfrac{3}{2}R - 1 \ ;$$

$$\hat{W}(\theta) = \hat{W}(\pi/2)(1 + \alpha\cos^2\theta) \ , \quad (25a)$$

$$\alpha = \frac{3R-2}{2-R} \ ;$$

$$\hat{W}(\theta') = \tfrac{1}{2} \ ; \quad (25b)$$

$$\hat{W}(\phi') = \frac{1}{2\pi} \ . \quad (25c)$$

For $\psi \to \gamma\eta_c$, $\psi' \to \gamma\eta_c$, and $\psi' \to \gamma\eta_c'$ transitions, the angular distribution $\hat{W}(\theta)$ depends on R varying from $1+\cos^2\theta$ for $R=1$ to $\sin^2\theta$ for $R=0$.

Because of C-parity conservation the B_1 helicity state does not enter into ${}^1P_1$ production. Since the ${}^1P_1$ state is formed by pure $R=0$, the decay-angular distribution is uniquely $\sin^2\theta$.

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Radiative angular distributions from $c\bar{c}$ states directly produced by $p\bar{p}$ annihilation

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(Received 23 May 1986)

2010 Memo of Inclusive measurement of hc

The angular distribution of the h_c signals is fitted with the function $N(1+\alpha\cos^2\theta^*)$ as shown in Figure 14, leading to $\alpha = 0.92 \pm 0.80$. This is consistent with the $\alpha = 1$ expected for an E1 transition from $h_c(J^{pc} = 1^{+-})$ to $\eta_c(J^{pc} = 1^{-+})$.