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

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Outline:

- Analysis summary:
  - Goal and Strategy
  - The Data Sets
  - Event Selection in a nutshell
  - Background Suppression
  - Efficiency and Resolution
- I/O Test
- Conclusions & Plans

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: 450M 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: $|\cos\theta| < 0.93$

Momentum: $p < 2.0$ GeV

Photons

Isolation: $\Delta(\Omega) > 10°$

EMC Time Info: $0 \leq t \leq 14$

E_γ (Barrel) > 25 MeV, $|\cos\theta| < 0.80$

E_γ (End Caps) > 50 MeV, $0.86 < |\cos\theta| < 0.92$

Event

At least 2 good charged tracks

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

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

Recoiling π^0

γ in the Barrel ($|\cos\theta| < 0.8$)

$E_\gamma > 40$ 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

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

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

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
$0.6\ \text{GeV} \leq E_{EMC} \leq 3.2\ \text{GeV}$	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

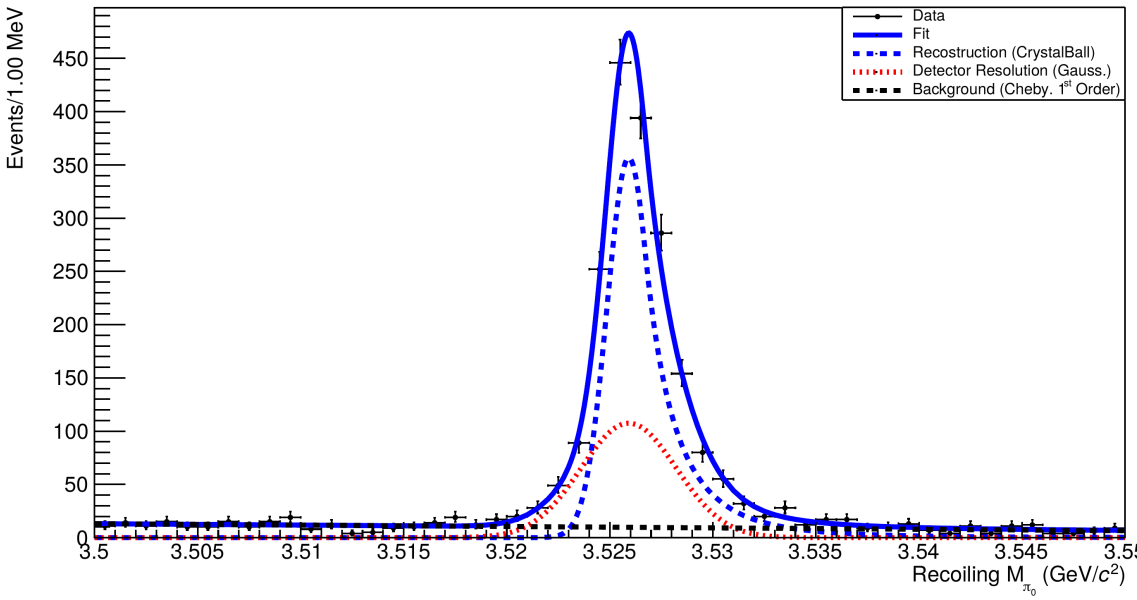
```
Decay psi(2S)
  1.0000 h_c pi0 HELAMP 0 0 1 0 0 0;
Enddecay

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



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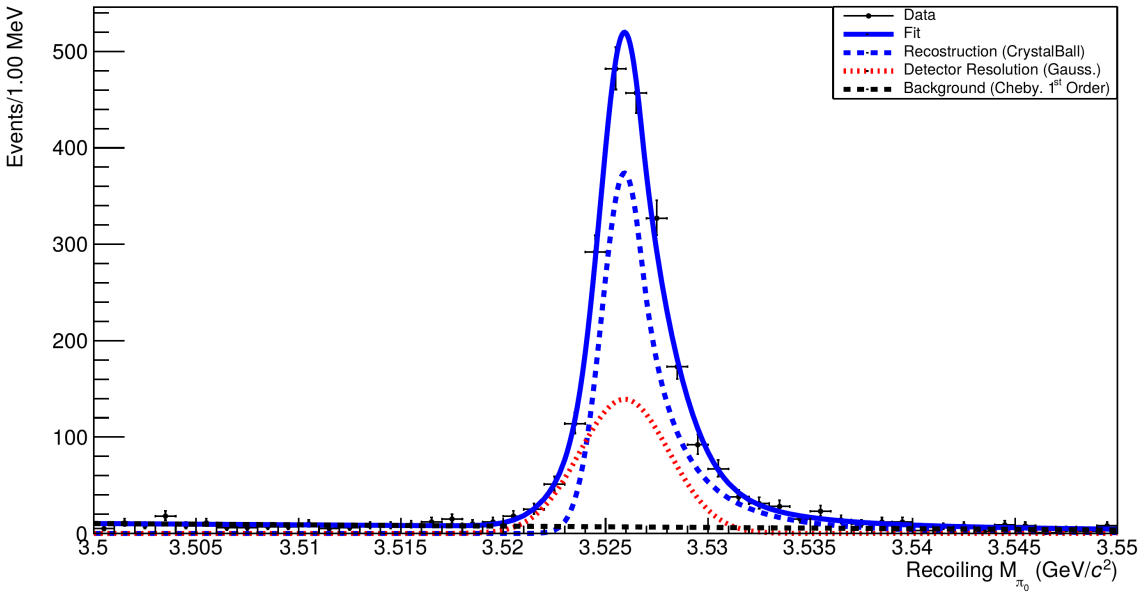


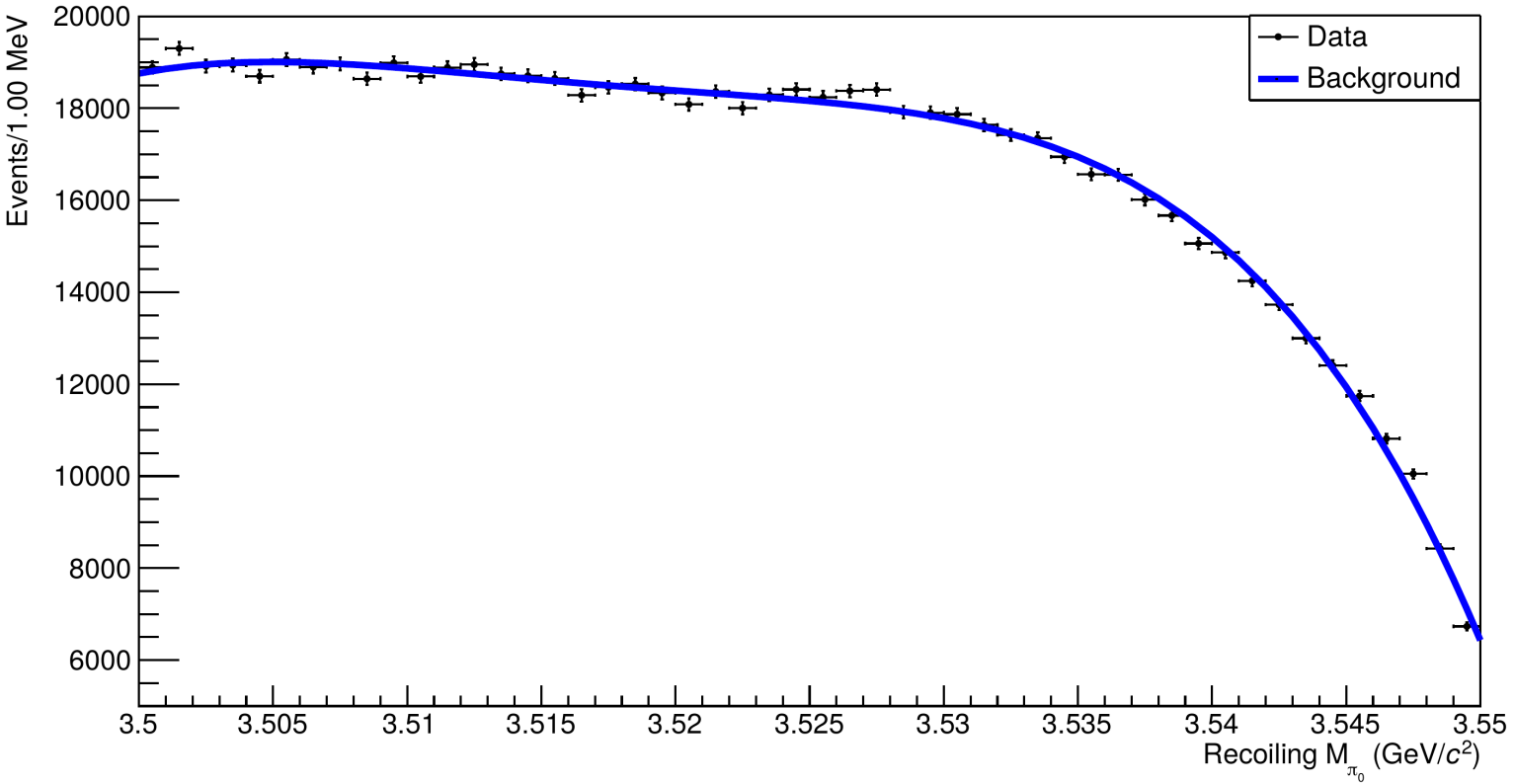
I/O Test
Fit Procedure

Fit each binned (1 bin/MeV) channel (**Inclusive** and **Tagged**) separately, 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, while the background parameters are fixed to the ones found in the background study.

I/O Test

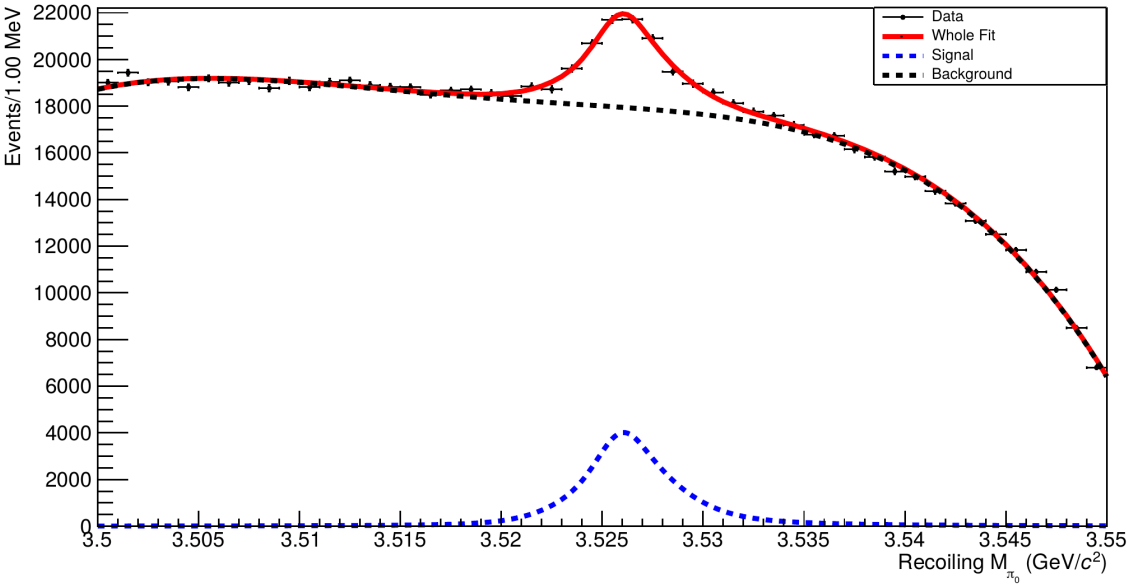
Background Tagged Channel = Inclusive MC + if(!h_c && !η_c)



I/O Test
Tagged Channel

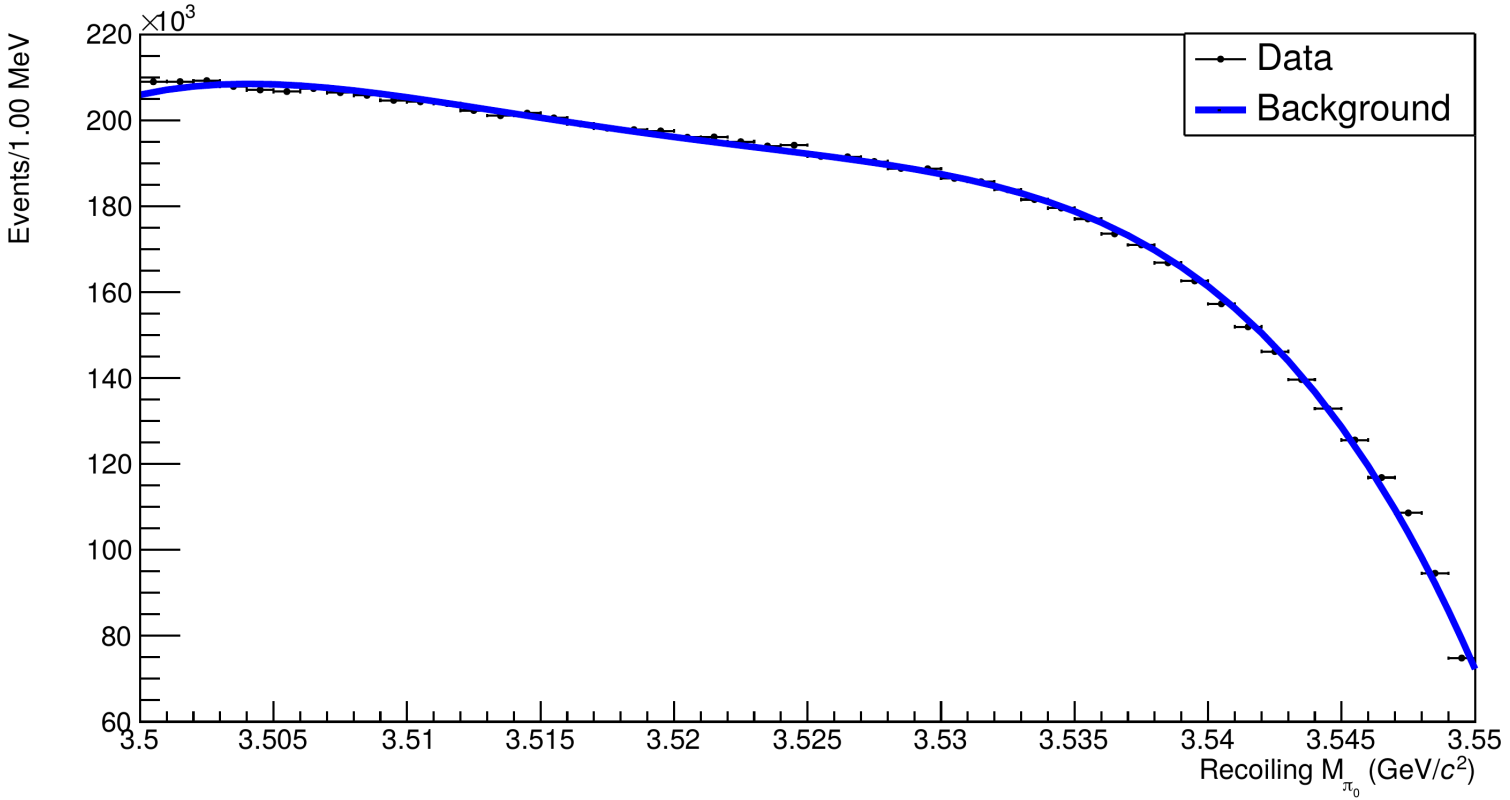
Features:

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



I/O Test

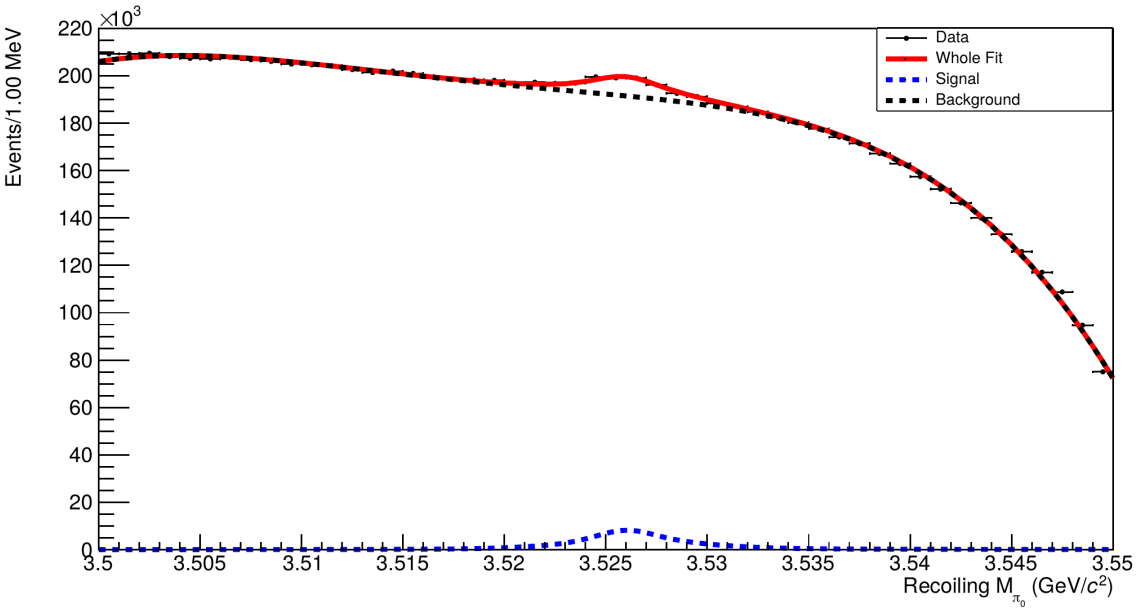
Background Inclusive Channel = Inclusive MC + if(!h_c)



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: 4th order Chebychev function with fixed parameters (from the bkg only MC)
- Fitting Region: 3.500 GeV – 3.550 GeV



I/O Test
Results

Feature [unit of measurement]	Input	Tagged	Inclusive	$\Delta(O-I)[\sigma]$
$\mathrm{M}(\mathrm{h}_c)$ [MeV]	3525.93	3526.04 ± 0.06	—	1.83
$\Gamma(\mathrm{h}_c)$ [MeV]	1.00	1.43 ± 0.30	—	1.43
$\mathcal{B}_1(\psi(2\mathrm{S}) \to \pi^0 \mathrm{h}_c) \times \mathcal{B}_2(\mathrm{h}_c \to \gamma\eta_c)$ $[10^{-4}]$	4.34	$3.72\ ^{+\ 0.25}_{-\ 0.24}$	—	2.50
$\mathcal{B}_1(\psi(2\mathrm{S}) \to \pi^0 \mathrm{h}_c)$ $[10^{-4}]$	8.51	—	7.83 ± 0.26	2.67
$\mathcal{B}_2(\mathrm{h}_c \to \gamma\eta_c)$ [%]	51	—	$47.51\ ^{+\ 3.59}_{-\ 3.48}$	0.99

Conslusions & Plans

Acceptable I/O

(output features < 3σ from the input values)

Memo is up to date

Will proceed to analyze the continuum and the 2012 data, as well as the 2009 Efficiency, I/O and data

Expected to present the full analysis (without the systematic errors) and to upload the Memo in the hypernews in time for the Shanghai parallel Charmonium session

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

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

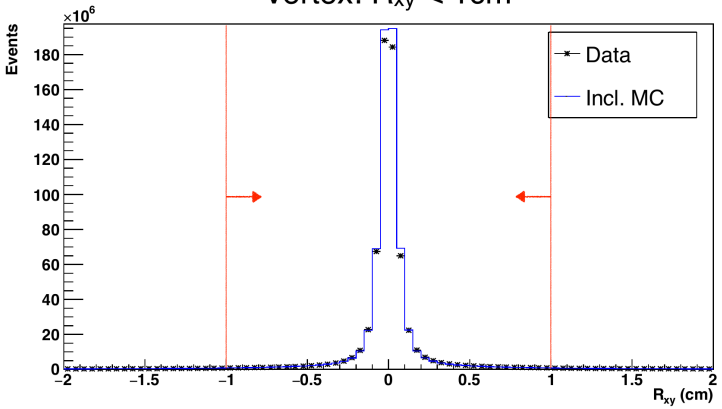
Background

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

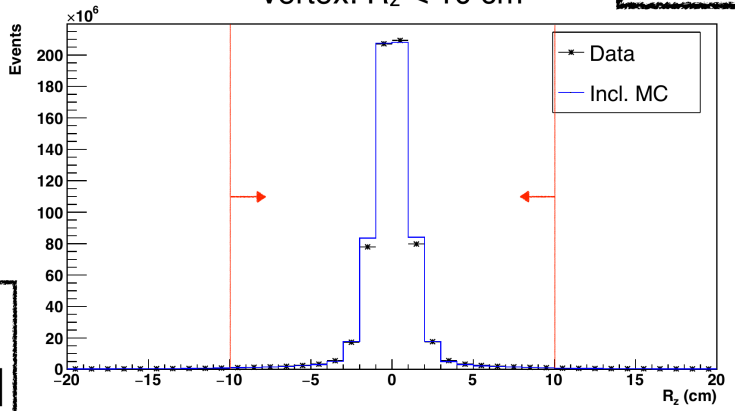
General Selection Criteria

Charged Tracks

Vertex: $R_{xy} < 1$cm

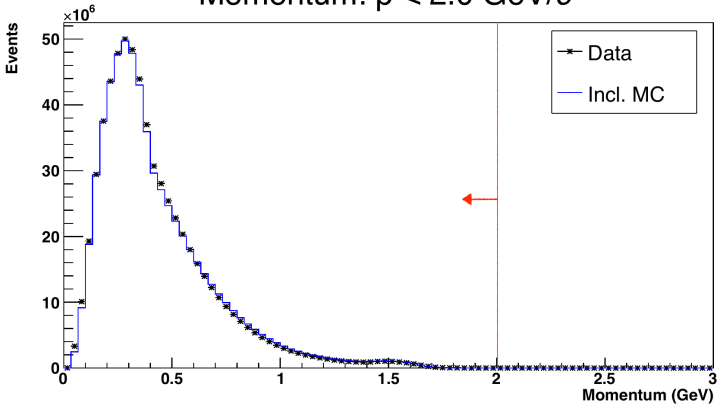


Vertex: $R_z < 10$ cm

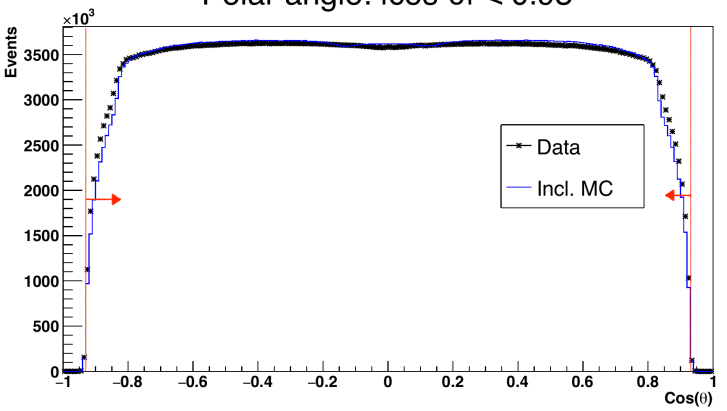


CUTS Applied

Momentum: $p < 2.0$ GeV/c



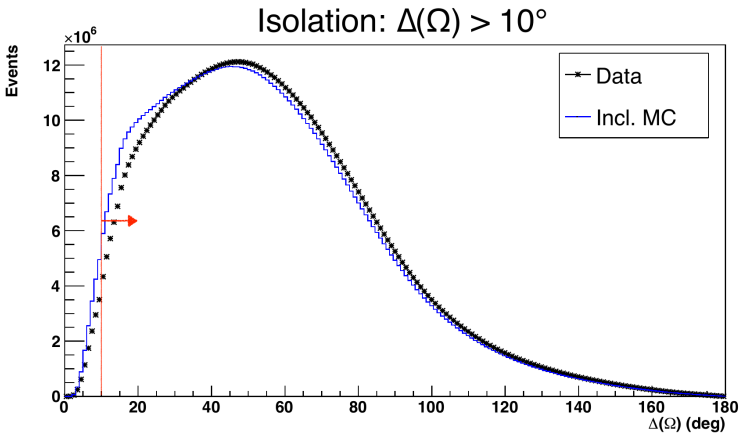
Polar angle: $|\cos\theta| < 0.93$



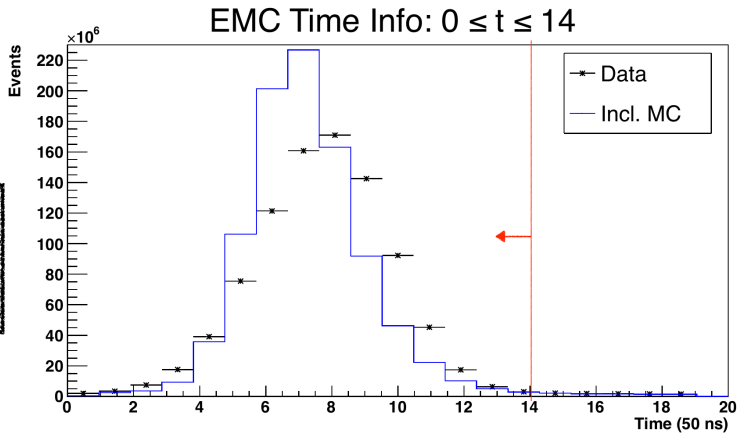
General Selection Criteria

Neutral Candidates

* Data
Incl. MC



CUTS Applied



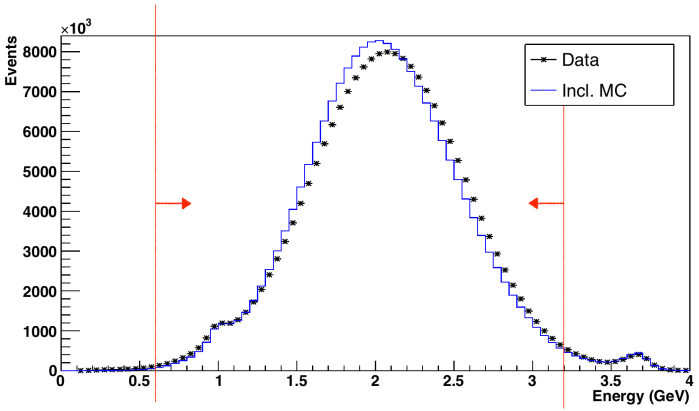
General Selection Criteria

Energy Cuts

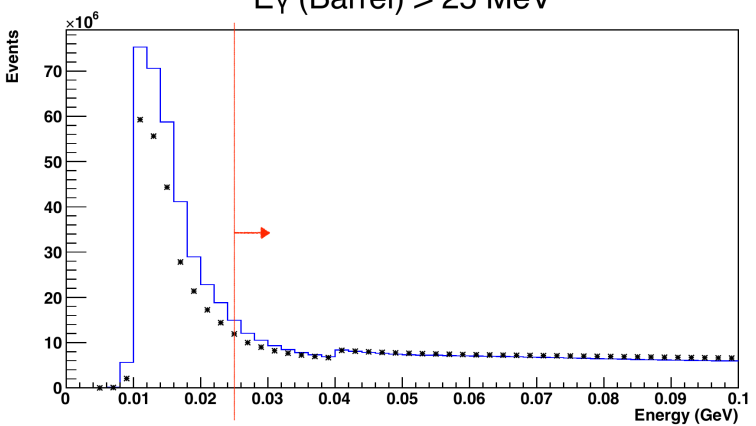
* Data
Incl. MC

Charged Tracks
&
Neutral Candidates

EMC Energy: 0.6 GeV < E < 3.2 GeV

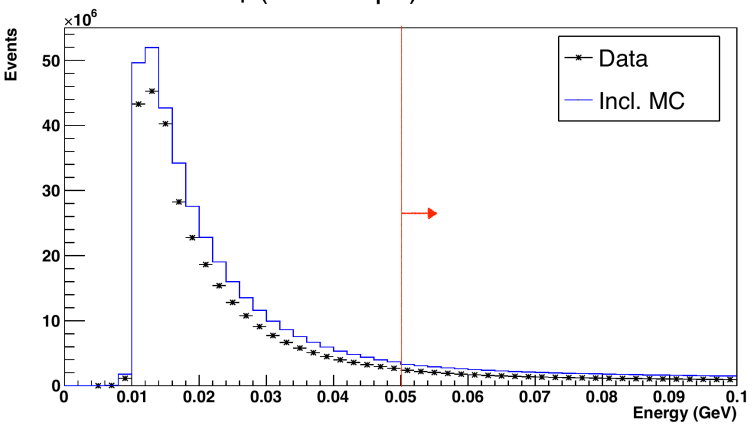


Eγ (Barrel) > 25 MeV



Neutral
Candidates

Eγ (End Caps) > 50 MeV

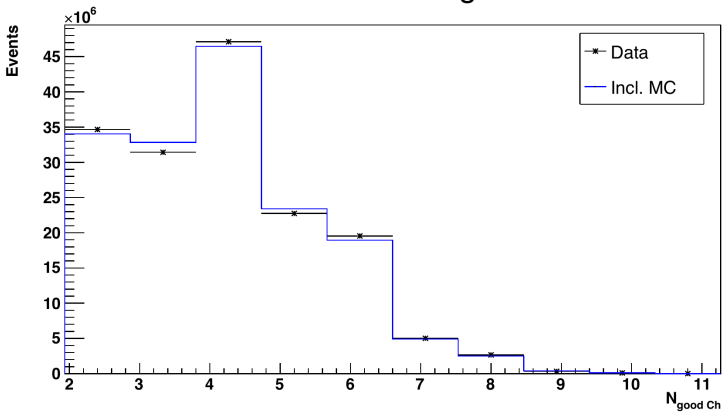


General Selection Criteria

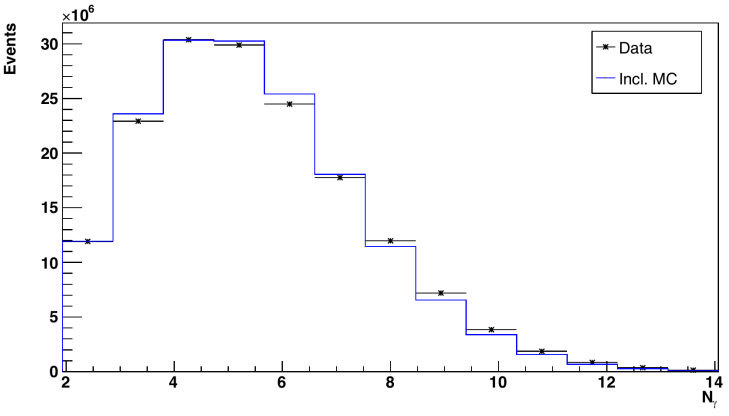
Number of Good Charged Tracks and Good Neutral Candidates

* Data
Incl. MC

At least 2 Good Charged Tracks



At least 2 Good Neutral Candidates



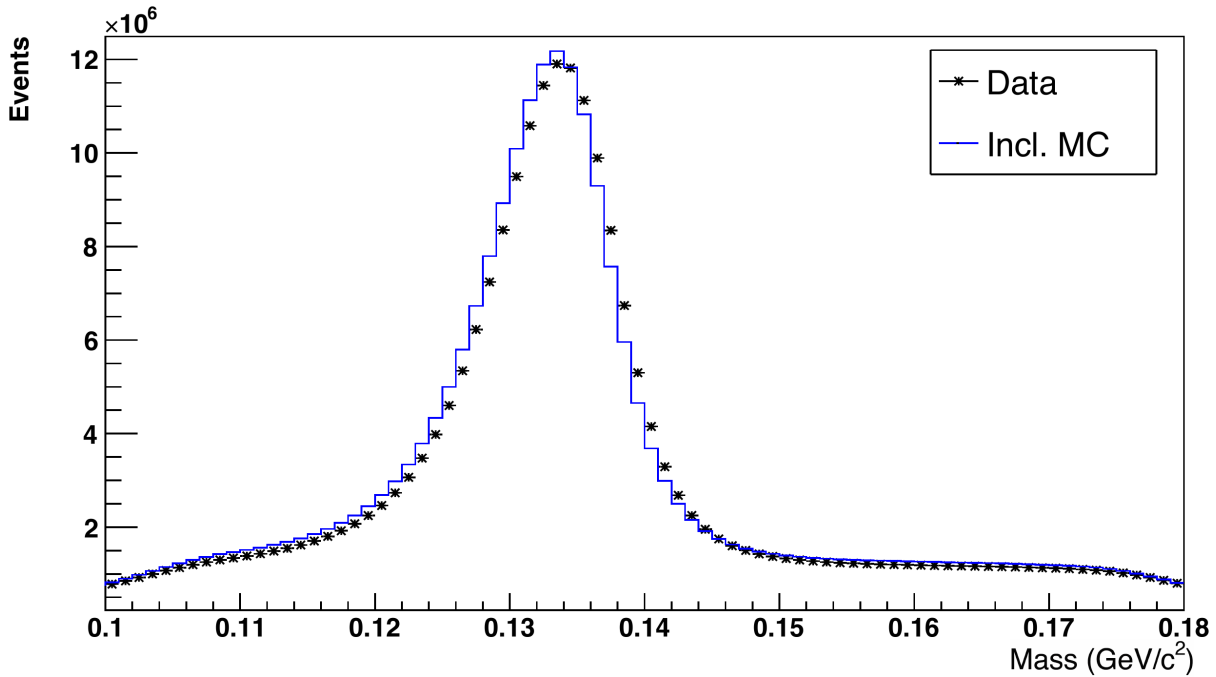
Recoiling π^0 Selection

* Data
— Incl. MC

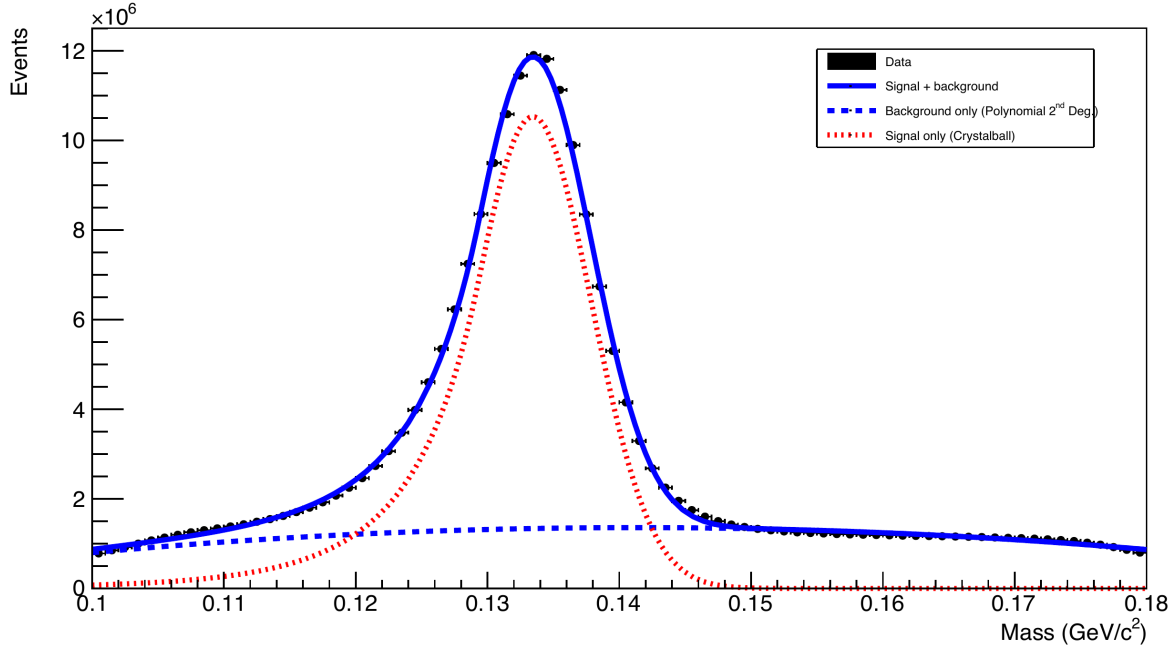
γ in the Barrel (|cos θ| < 0.8)

Eγ > 40 MeV

120 MeV < Mγγ < 145 MeV



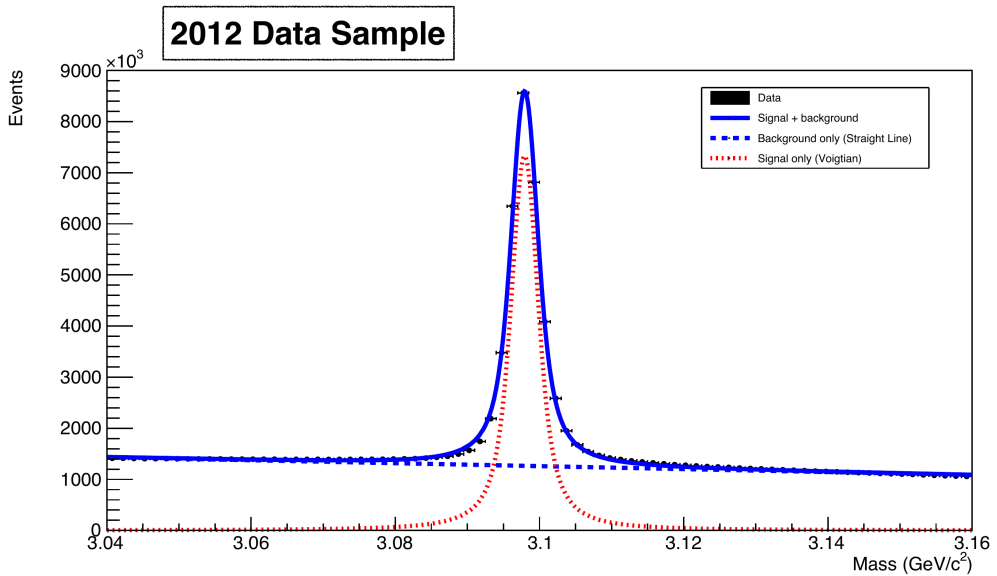
Recoiling π^0 Selection

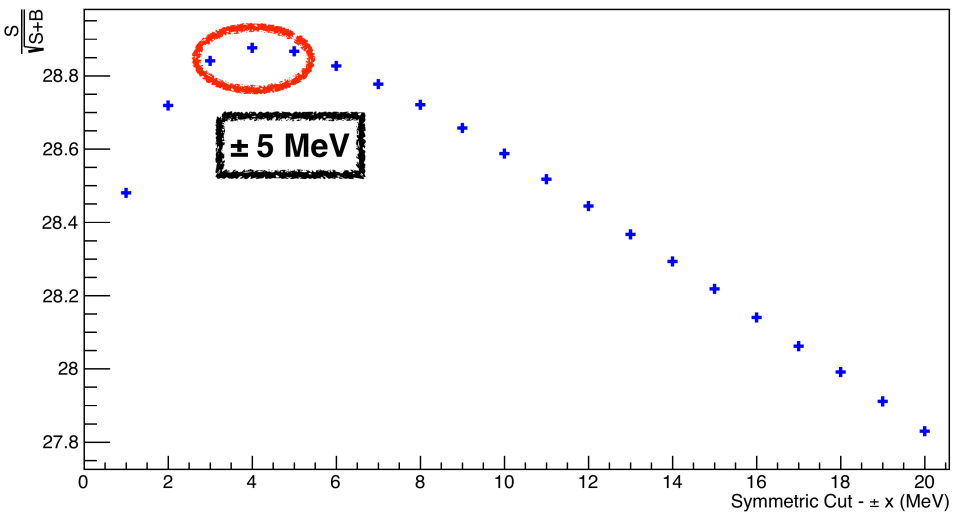


Signal —> Crystal-ball
Background —> 2nd Order Polynomial

Background evaluation & Suppression

ψ(2S) —> π⁺ π⁻ J/ψ



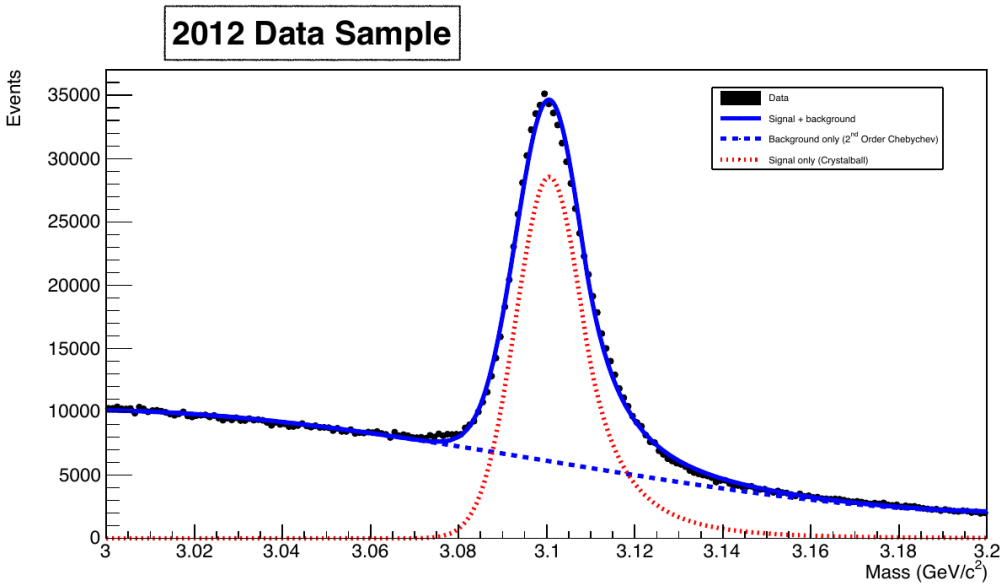


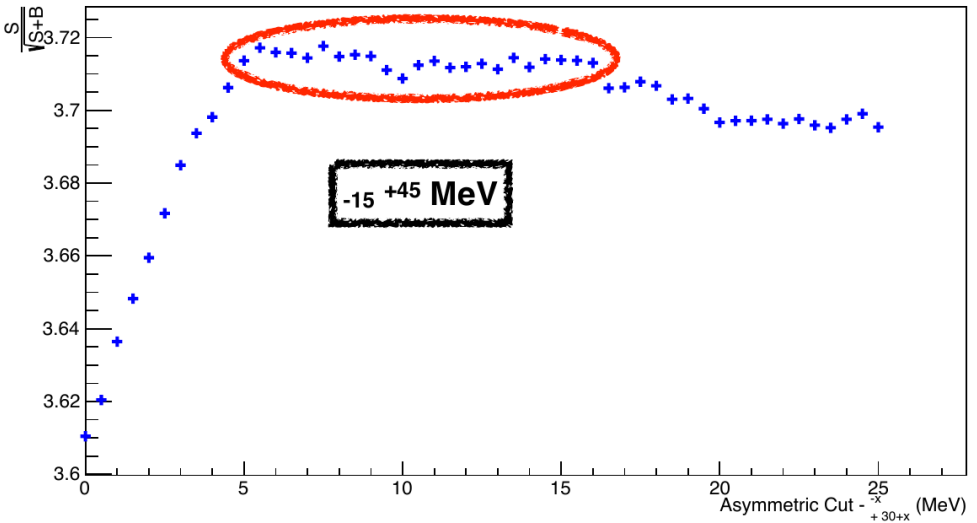
Signal —> Voigtian;
Background —> Straight Line (α < 0).

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

Background evaluation & Suppression

ψ(2S) —> π 0 π 0 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