RUHR-UNIVERSITÄT BOCHUM

RUB

Investigation of h_c decay patterns at BES III

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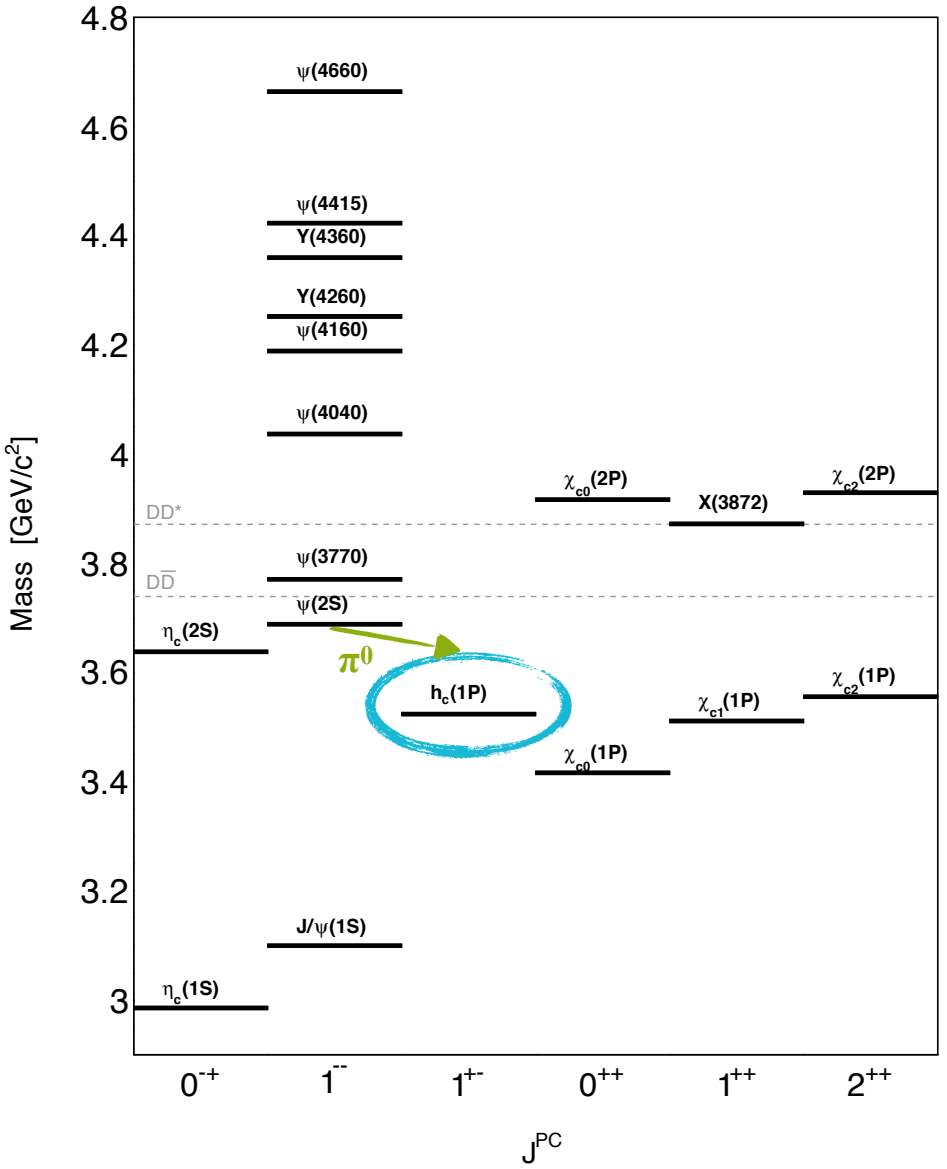
BES III Charmonium group meeting

Introduction

- h_c singlet P-wave charmonium state
- experimentally observed 1992 in $\bar{p}p$ reactions [Phys. Rev. Lett. 69, 2337]
- not directly accessible in $e^+ e^-$ annihilation
- decay pattern still not well known

Process	$\mathcal{BF}(h_c \to X)$
$\gamma\eta_c$	51 ± 6 %
$\gamma\eta$	$(4.7 \pm 2.1) \cdot 10^{-4}$
$\gamma\eta'$	$(1.5 \pm 0.4) \cdot 10^{-3}$
$\pi^+\pi^-\pi^0$	$< 2.2 \cdot 10^{-3}$
$2(\pi^+\pi^-)\pi^0$	$2.2^{+0.8}_{-0.7}$ %
$3(\pi^+\pi^-)\pi^0$	< 2.9 %
$p\bar{p}$	$< 1.5 \cdot 10^{-4}$ %



Final states presented here

How to choose possible final states?

negative G-parity of h_c
$\rightarrow$ odd number of pions

$2(\pi^+\pi^-)\pi^0$ only known final state besides $\gamma\eta_c$
$\rightarrow$ replace $\pi^+\pi^-$ by η or K^+K^-

$h_c \rightarrow K^+K^-\pi^+\pi^-\pi^0$

$h_c \rightarrow \pi^+\pi^-\pi^0\,\eta$

and many more coming soon…

Data sets

- Using production via $\psi' \rightarrow \pi^0 \, h_c$
- Production using XYZ data via $X \rightarrow \pi^+\pi^- h_c$ not suitable due to smaller reconstruction efficiency and lower production rate

- **Beam data:** 448.1 · 10^6 ψ´ events
- **inclusive MC:** 506 · 10^6 events
- **Signal MC:** 1 · 10^6 events
- **Boss Version:** 664p03

General selection criteria

Good charged track criteria

Poca: $R_{xy} < 1$ cm , $R_z < 10$ cm

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

PID criteria

using dE/dx information from MDC and TOF information

p-Value: $P(X) > 10^{-3}$,

$P(X) > P(Y)$, $X \neq Y$

Good photon criteria

Separation from tracks: $\Delta\Omega > 10°$

EMC time info: $t < 700$ ns

Barrel: $E_\gamma > 25$ MeV,

$|\cos\theta| < 0.8$

Endcaps: $E_\gamma > 50$ MeV,

$0.86 < |\cos\theta| < 0.92$

Reconstruction of π^0 candidates

$|M(\gamma\gamma) - M(\pi^0)| < 30$ MeV/c^2

mass constrained fit

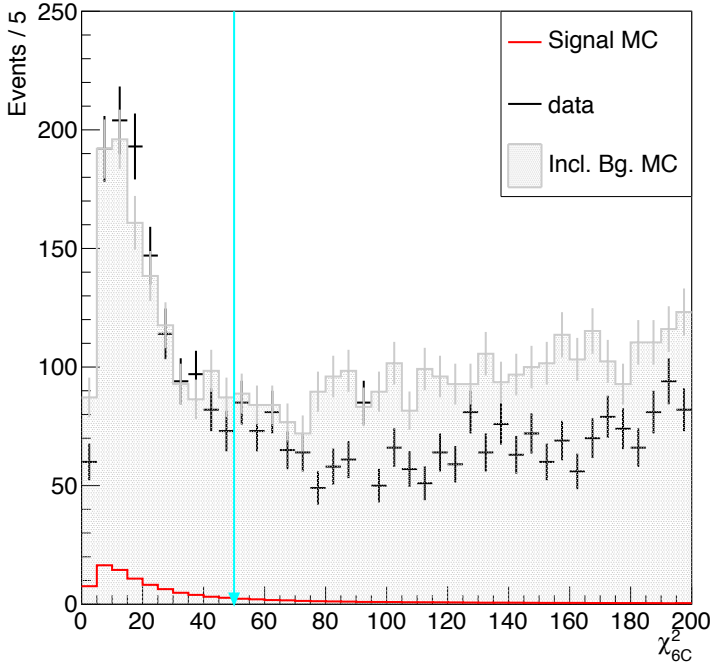
Reconstruction of η candidates

$|M(\gamma\gamma) - M(\eta)| < 30$ MeV/c^2

mass constrained fit

Search for $h_c \to \pi^+\pi^- K^+ K^- \pi^0$

- Common vertex ensured by converged vertex fit
- $N_\pi = 2,\ N_K = 2,\ N_\gamma \geq 4$
- Limit goodness of 6C Fit: $\chi^2_{6C} < 50$



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- 4C fit to hypothesis $3\gamma\ \pi^+\pi^- K^+ K^-$ to veto background from
  - $\psi' \to \gamma\chi_{cJ}:\ \ \chi^2_{4C} < \chi^2_{3\gamma}$
- reject background from $\psi' \to \pi^+\pi^- J/\psi,\ \ \pi^0\pi^0 J/\psi$:
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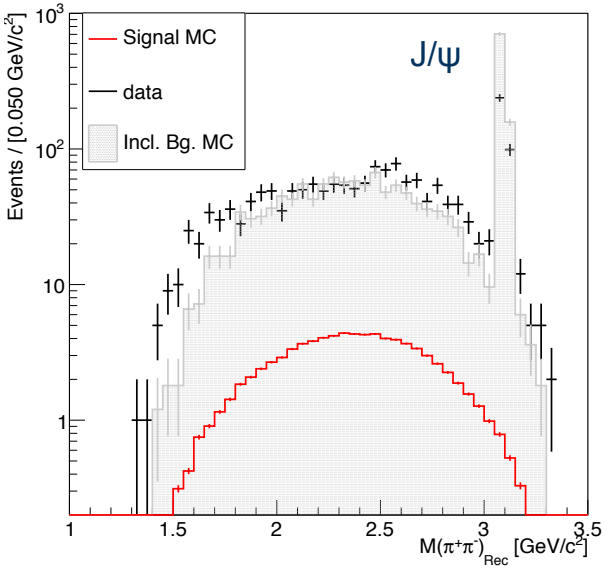

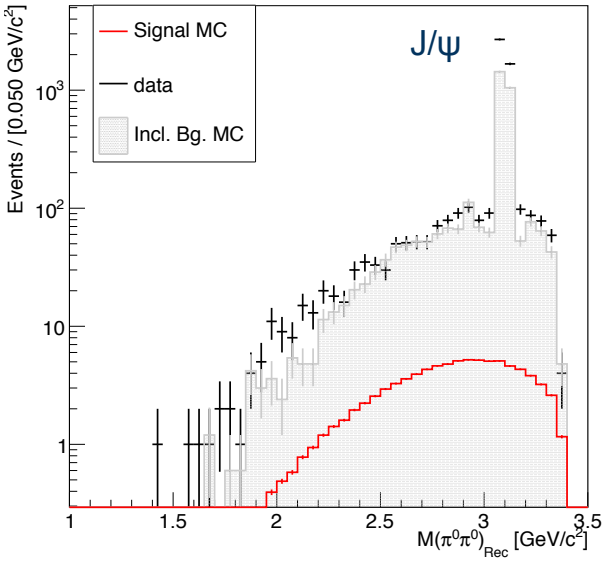

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  - $|M(\pi^0\pi^0)_{Rec} - M(J/\psi)| > 25$ MeV/c^2
- π^0 from ψ' decay should not from other resonances:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 16$ MeV/c^2
  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20$ MeV/c^2
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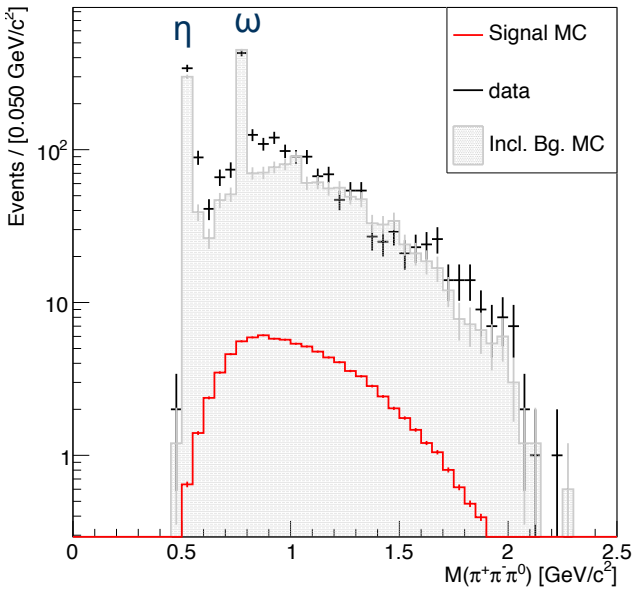

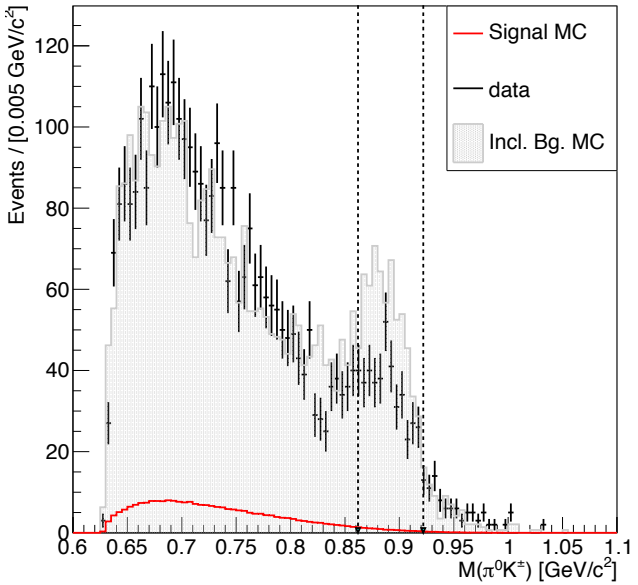

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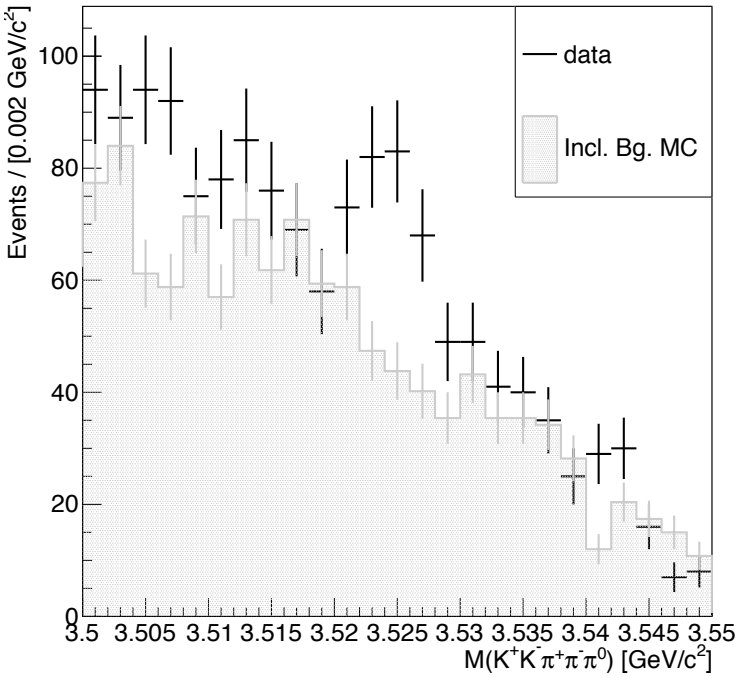
➡ obtained efficiency 7.3%

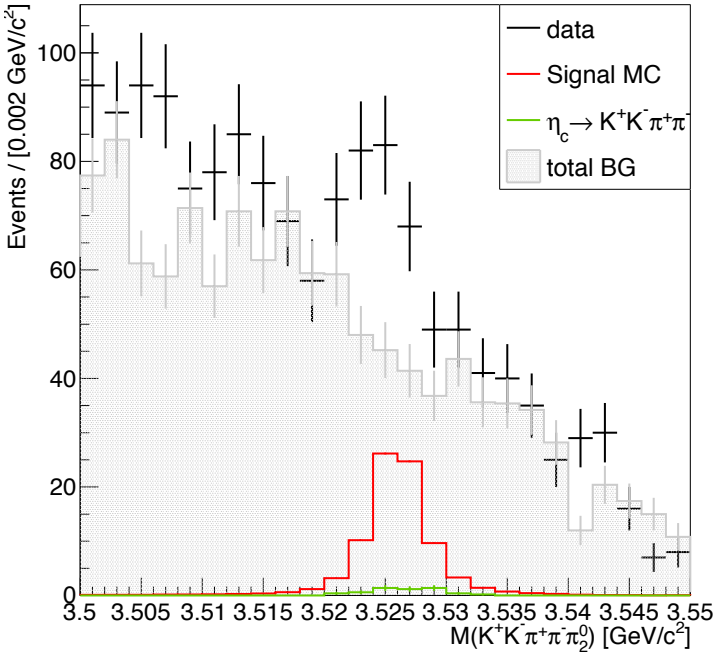


➡ possible structure at h_c mass

Background studies

- Non-resonant contribution dominates (99%)

Process	N_{rem}
$K^{*0}K^{*\pm}\pi^{\mp}\pi^{0}$	437
$K^{*\pm}K^{*\mp}\pi^{+}\pi^{-}$	230
$K^{*0}K^{*\pm}\rho^{\mp}$	185
$K^{*+}K^{*-}\rho^{0}$	25



- Study of peaking background caused by radiative decays:
  - $h_c \to \gamma\eta_c,\ \gamma\chi_{c1},\ \gamma\chi_{c0}$

✖ Problem: decay modes mostly unknown, explicit search limited by statistics and dominated by background

➡ But theoretical predictions exist, used to estimate:

- $BF(h_c \to \gamma\chi_{c1}) \sim 3.4 \cdot 10^{-7}$ (suppressed by PHSP)
- $BF(h_c \to \gamma\chi_{c0}) \sim 8.6 \cdot 10^{-4}$ [Phys. Rev. D 89 11 (2014)]

➡ remaining peaking background subtracted from determined signal yield

- known decay modes scaled to PDG value
- unknown decay modes generated using LUND Model
- additional sets similar to final state have been generated (see next slide)

Background studies

List of explicitly generated final states

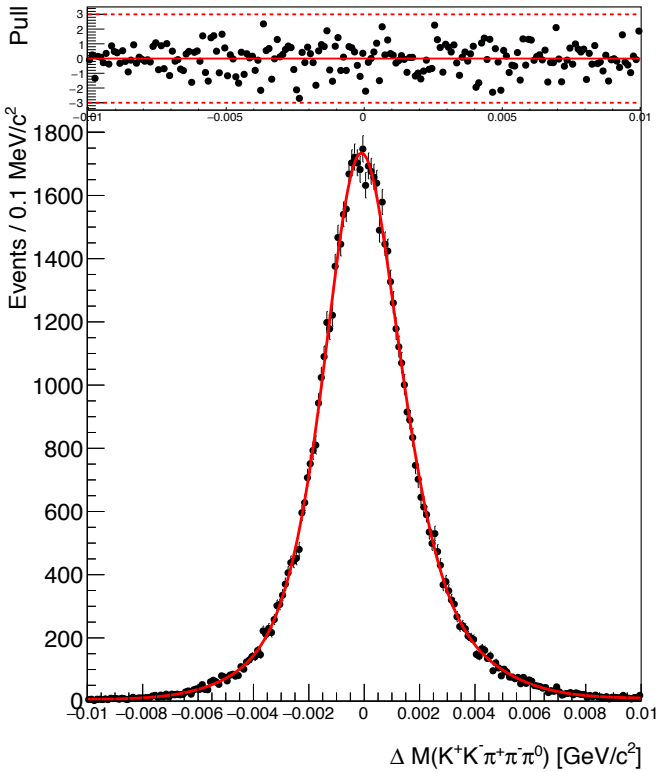
Process $h_c \to \gamma X$	intermediate states	N_{rem}	$N_{expected}$
$\eta_c \to K^+K^-\pi^+\pi^-$	$K^{*0}K^{\pm}\pi^{\mp}$	12	3
$\eta_c \to K^+K^-\pi^+\pi^-$	PHSP	10	2
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\pi^0$	PHSP	2	0
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\pi^0$	$K^{*+}K^{*+}\pi^0\pi^0$	1	0
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\eta$	PHSP	0	0
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\eta$	$K^{*+}K^{*+}\pi^0\eta$	0	0
$\eta_c \to K^+K^-\pi^+\pi^-\eta\eta$	PHSP	0	0
χ_{c0}	PHSP	5	0
χ_{c1}	PHSP	0	0

No background process identified,
which could describe the complete observed structure

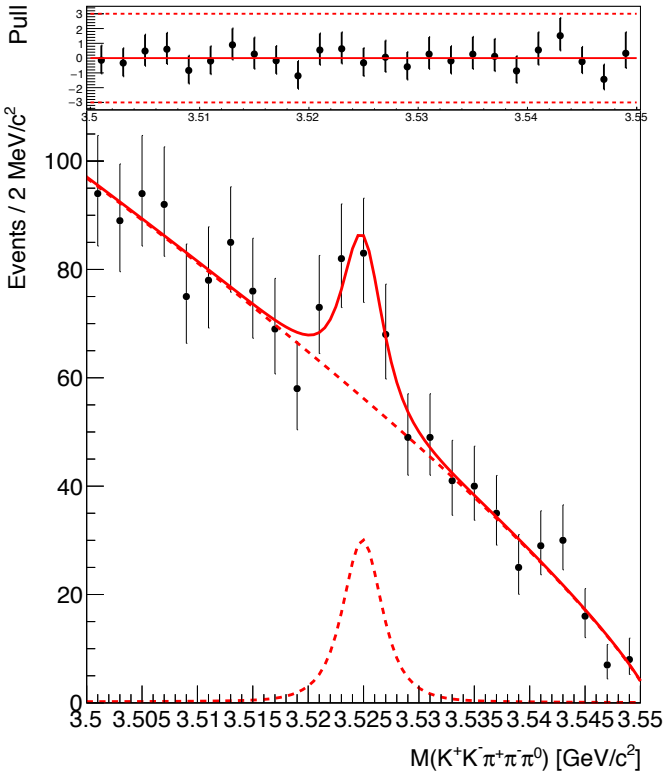
Determination of branching fraction of $h_c \to \pi^+\pi^- K^+ K^- \pi^0$

Resolution

$$= \begin{cases} e^{\frac{\sigma_L^2}{2}+\sigma_L\left(\frac{m-\mu}{\sigma}\right)^2}, & \frac{m-\mu}{\sigma} \le -\sigma_L \\ e^{-\frac{1}{2}\left(\frac{m-\mu}{\sigma}\right)^2}, & -\sigma_L < \frac{m-\mu}{\sigma} \le \sigma_H \\ e^{\frac{\sigma_H^2}{2}-\sigma_H\left(\frac{m-\mu}{\sigma}\right)^2}, & \sigma_H < \frac{m-\mu}{\sigma} \end{cases} + 3\,Gaussian$$



Breit-Wigner ⊗ Resolution + Argus



$M(h_c) = 3525.0 \pm 0.7\,MeV/c^2$

$\Gamma(h_c) = 0.9 \pm 0.6\,MeV$

$BF(h_c \to K^+K^-\pi^+\pi^-\pi^0)$
$= (3.0 \pm 0.4 \pm 0.4 \pm 0.6) \cdot 10^{-3}$

Systematic studies

Selection procedure

- variation of selection criteria

cut	nominal value	range	step size	uncertainty
χ^2_{6C}	50	30-70	1	2.8 %
$\lvert M(\pi^+\pi^-)_{Rec} - M(J/\psi)\rvert \ [MeV/c^2]$	25	10-40	1	0.5 %
$\lvert M(\pi^0\pi^0)_{Rec} - M(J/\psi)\rvert \ [MeV/c^2]$	25	10-40	1	1.4 %
$\lvert M(\pi^0 K^\pm) - M(K^{*\pm})\rvert \ [MeV/c^2]$	30	10-50	1	4.4 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\eta)\rvert \ [MeV/c^2]$	16	6-26	1	1.3 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert \ [MeV/c^2]$	20	10-30	1	2.5 %

Generator model

- including intermediate resonances to generator model leads efficiency difference of at most **7.6%**

Fit model

- Describing background by Chebychev polynomial instead of Argus function: **1.2%**
- Fitting range: **0.9%**

Tracking

- 1% per track ➡ **4%**

Photon reconstruction

- 1% per photon ➡ **4%**

PID

- 1% per track ➡ **4%**

π^0 reconstruction

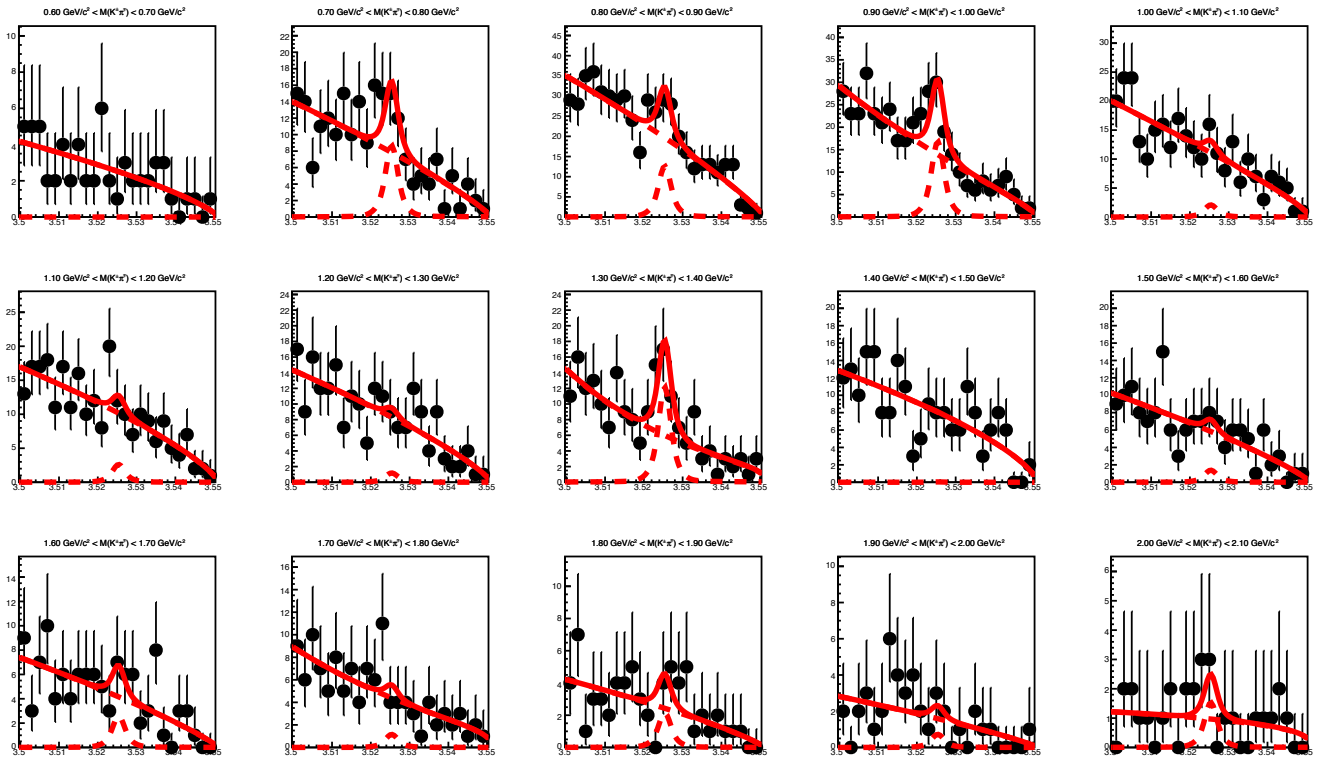
- 1% per π^0 ➡ **2%**

total 12.2% + 15.1% caused by involved branching fractions!

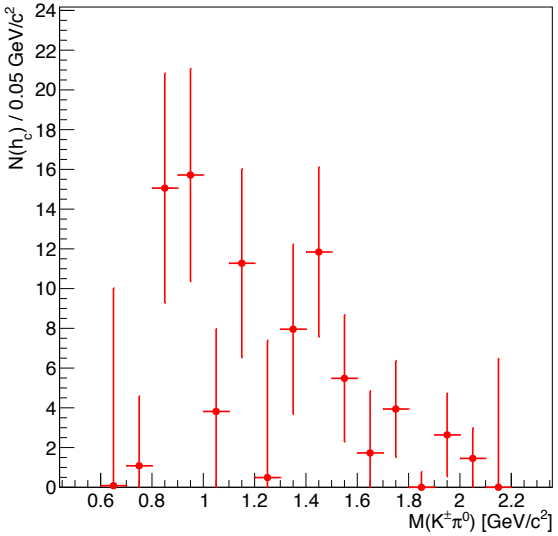
Study of intermediate resonances

- **Problem:** Background dominated process, sideband subtraction not suitable
- **Idea:** Extracting signal yield in slices of subsystems
- same fitting procedure used as before in subregions

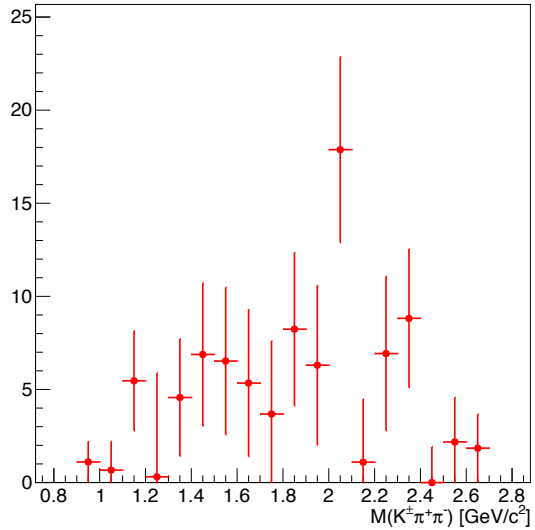
For example fit in slices of Kπ mass



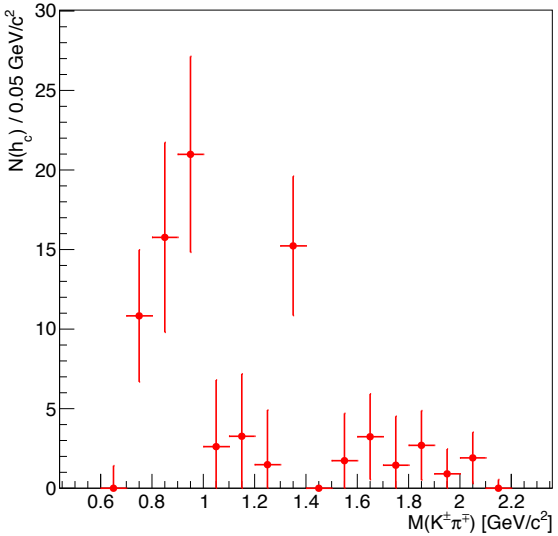
Study of intermediate resonances

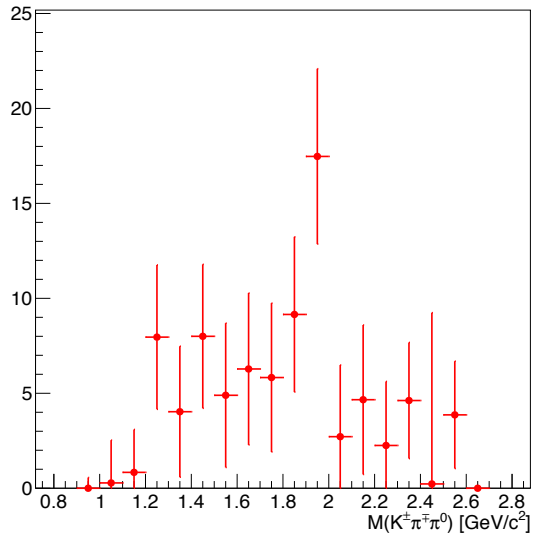


$K^*(892)$, $K^*_{0,2}(1430)$



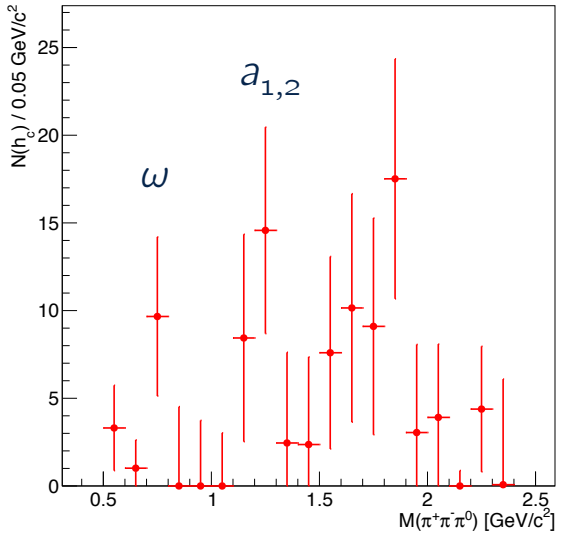
$K_2(1820)$, $K^*_2(1980)$

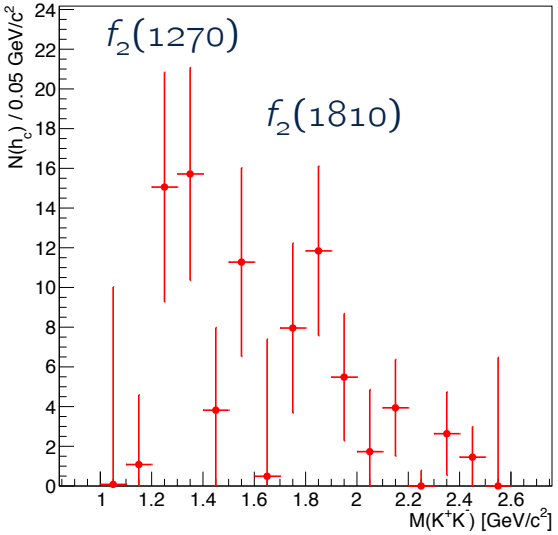


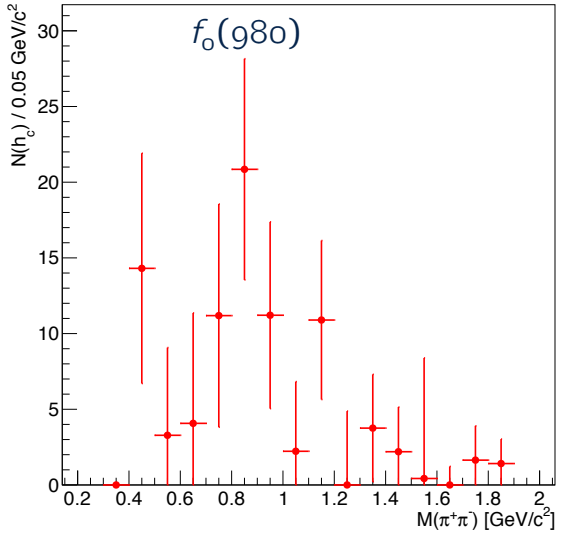


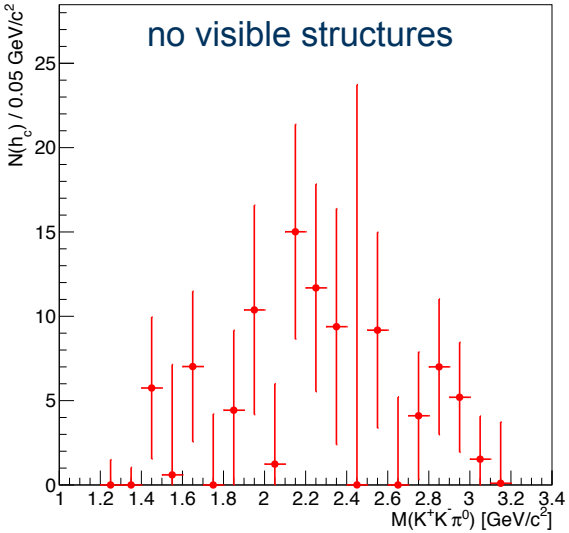
- shown error bars are statistical only
- similar structures in charged and neutral mode
- indication for intermediate reactions:
  - $h_c \to K^*(892)\, K_2^{(*)}$
  - $h_c \to K^*_{0,2}(1430)\, K_2^{(*)}$

Study of intermediate resonances





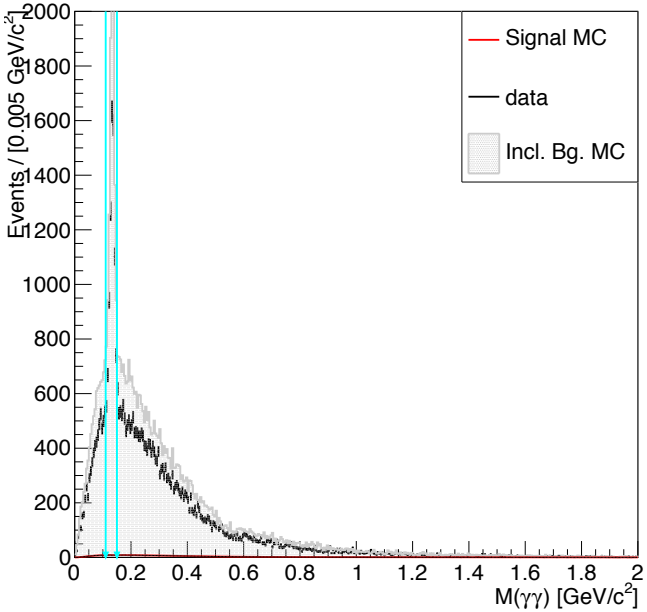




- $h_c \to (\pi^+\pi^-\pi^0)(K^+K^-)$ seems to be more favored than $h_c \to (\pi^+\pi^-)(\pi^0 K^+K^-)$
- Correlations between sybsystems need to be investigated

Analysis of $\psi' \to \pi^0 h_c$, $h_c \to \pi^+\pi^-\pi^0\eta$

- Common vertex ensured by converged vertex fit
- $N_\pi = 2,\ N_\gamma \geq 6$
- no pair of photons from different particles should form a π^0 :
  - $|M(\gamma\gamma) - M(\pi^0)| > 15$ MeV/c^2



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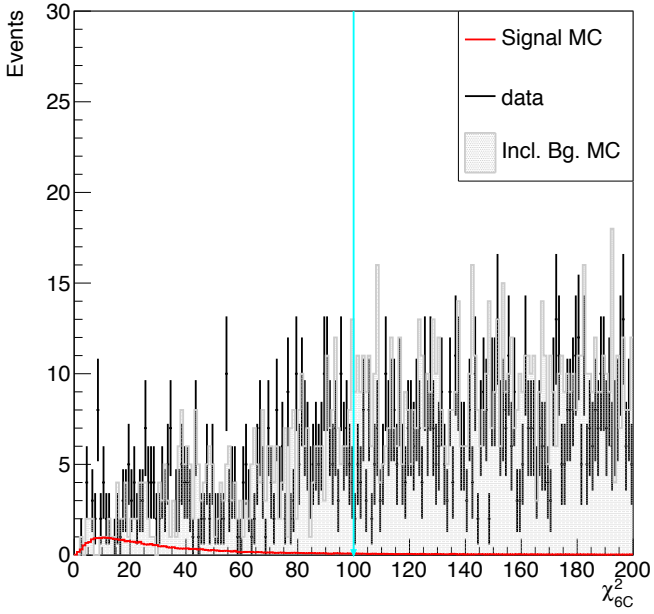

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- reject background from $\psi' \to \pi^0\pi^0 J/\psi,\ \eta J/\psi$:
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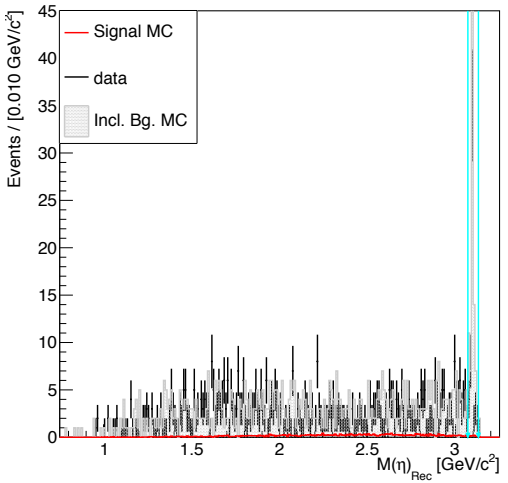

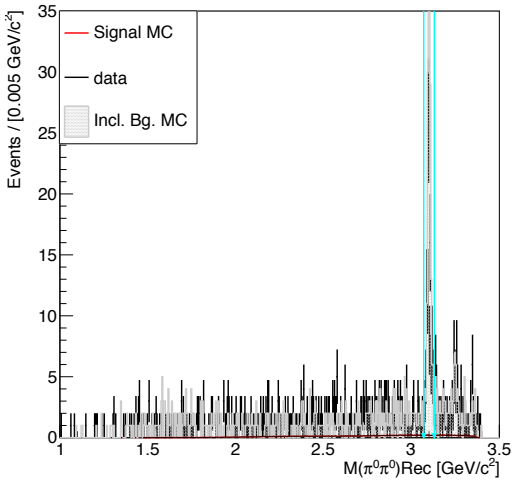

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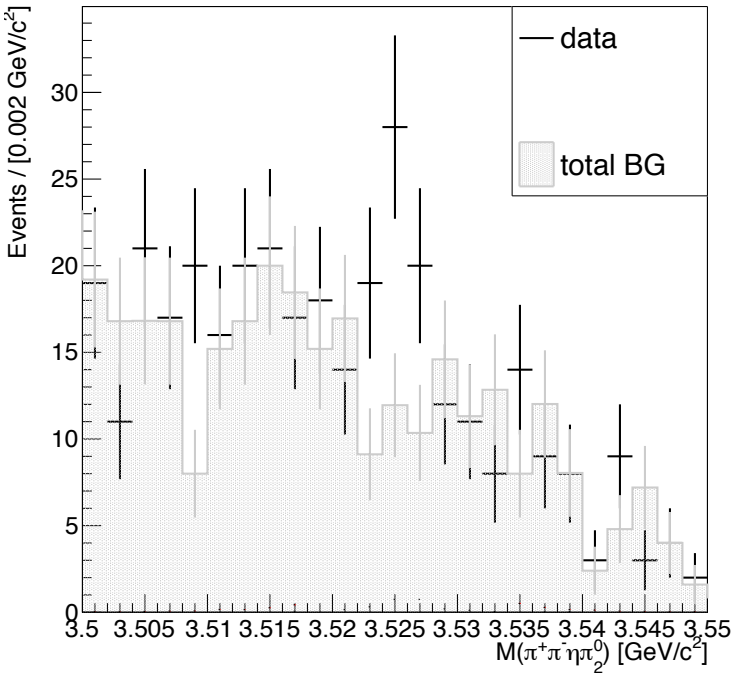
➡ obtained efficiency 3.9 %



➡ possible structure at h_c mass

Background studies

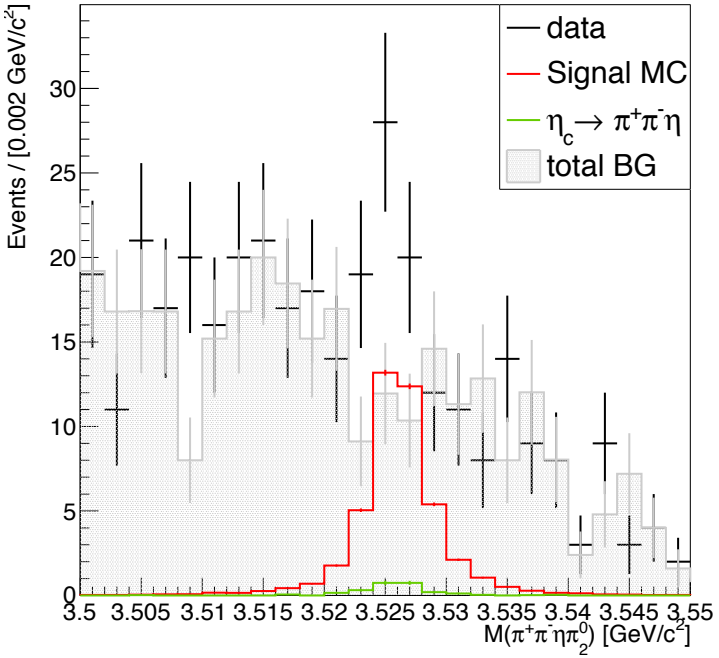
- Dominating contribution from $e^+e^- \to \gamma\pi^+\pi^-\eta$

- Study of peaking background caused by radiative decays:
  - $h_c \to \gamma\chi_{c0}, \gamma\chi_{c1}$
  - ➡ negligible contribution

  - $h_c \to \gamma\eta_c$

Process	N_{rem}	$N_{expected}$
$\eta_c \to \pi^+\pi^-\eta$	16	3
$\eta_c \to \pi^+\pi^-\pi^0\pi^0$	7	1

  - ➡ subtracted from determined signal yield

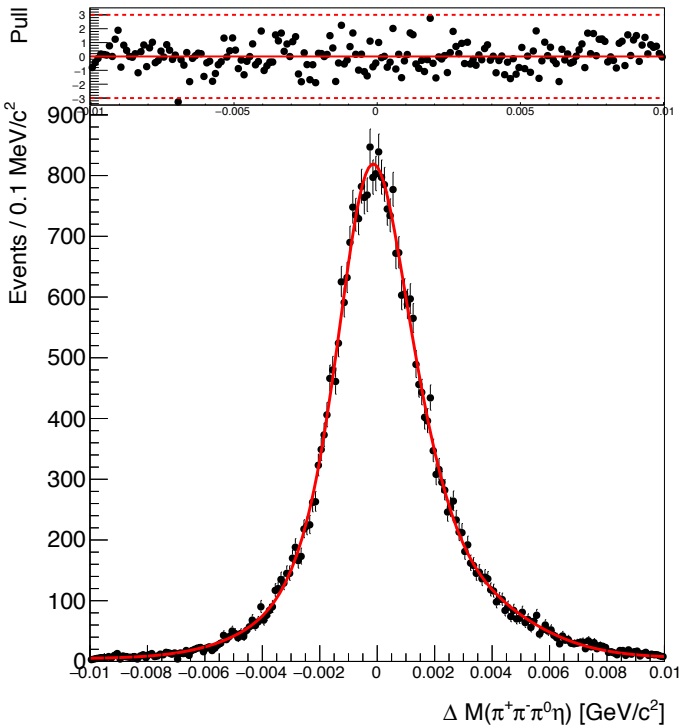


- known decay modes scaled to PDG value
- unknown decay modes generated using LUND Model

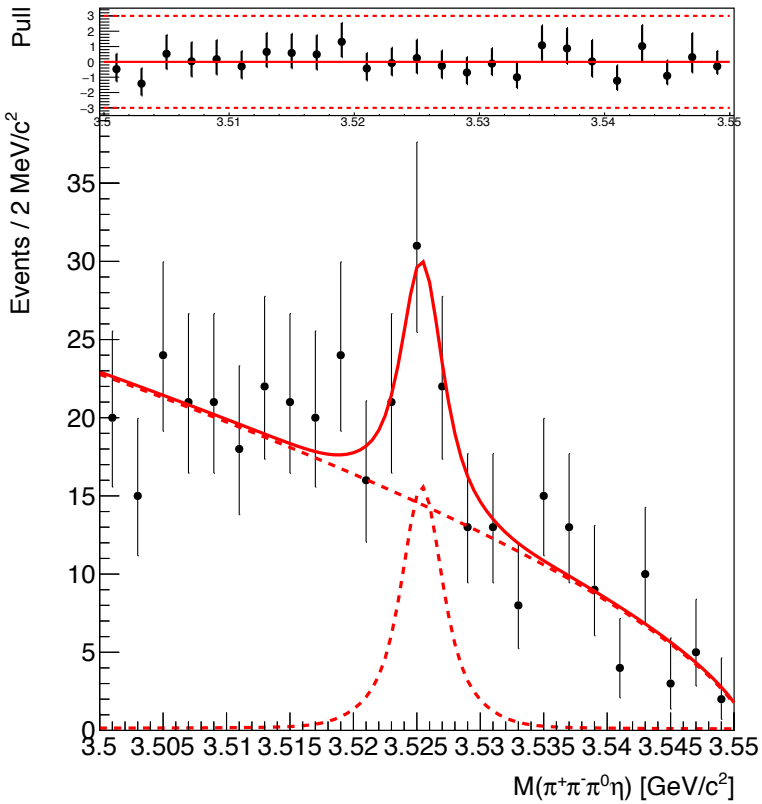
Determination of branching fraction of $h_c \to \pi^+\pi^-\pi^0\eta$

Resolution

$$= \begin{cases} e^{\frac{\sigma_L^2}{2}+\sigma_L\left(\frac{m-\mu}{\sigma}\right)^2}, & \frac{m-\mu}{\sigma} \leq -\sigma_L \\ e^{-\frac{1}{2}\left(\frac{m-\mu}{\sigma}\right)^2}, & -\sigma_L < \frac{m-\mu}{\sigma} \leq \sigma_H \\ e^{\frac{\sigma_H^2}{2}-\sigma_H\left(\frac{m-\mu}{\sigma}\right)^2}, & \sigma_H < \frac{m-\mu}{\sigma} \end{cases} \quad + 3\,Gaussian$$



Breit-Wigner ⊗ Resolution + Argus



$$BF(h_c \to \pi^+\pi^-\pi^0\eta)$$

$$= (9.9 \pm 1.6 \pm 1.2 \pm 1.5) \cdot 10^{-3}$$

Systematic studies

Selection procedure

- variation of selection criteria

cut	nominal value	range	step size	uncertainty
χ^2_{7C}	100	80-120	1	3.2 %
$\lvert M(\eta)_{Rec} - M(J/\psi)\rvert \ [MeV/c^2]$	30	15-45	1	1.3 %
$\lvert M(\pi^0\pi^0)_{Rec} - M(J/\psi)\rvert \ [MeV/c^2]$	30	20-40	1	1.6 %
$\lvert M(\gamma\gamma) - M(\pi^0)\rvert \ [MeV/c^2]$	15	5-25	1	3.3 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\eta)\rvert \ [MeV/c^2]$	16	6-26	1	1.5 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert \ [MeV/c^2]$	20	10-30	1	3.3 %

Generator model

- including intermediate resonances to generator model leads efficiency difference of at most **6.3%**

Fit model

- Describing background by Chebychev polynomial instead of Argus function: **2.1%**
- Fitting range: **1.1%**

Tracking

- 1% per track ➡ **2%**

Photon reconstruction

- 1% per photon ➡ **6%**

PID

- 1% per track ➡ **2%**

π^0 reconstruction

- 1% per π^0 ➡ **2%**

total 11.5% + 15.1% caused by involved branching fractions!

Summary and outlook

So far:

- 11 final states have been analyzed
- Hints for 2 new decay modes of the h_c!
- Branching fractions have bean measured

$$BF(h_c \to K^+K^-\pi^+\pi^-\pi^0) = (3.0 \pm 0.4 \pm 0.4 \pm 0.6) \cdot 10^{-3}$$

$$BF(h_c \to \pi^+\pi^-\pi^0\eta) = (9.9 \pm 1.6 \pm 1.2 \pm 1.5) \cdot 10^{-3}$$

- systematic studies started

Future goals:

- Further systematic studies and background studies
- Optimization of fitting and selection procedure
- Improved strategy for peaking background
- Determination of upper limits for other final states