Investigation of h_c Decay Patterns at BESIII

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BESIII Charmonium Group Meeting

Brief Introduction

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

Data Sets

Beam data:	448.1	$\cdot\ 10^6$	ψ´ events
inclusive MC:	506	$\cdot\ 10^6$	events
Signal MC:	1	$\cdot\ 10^6$	events per final state
Boss Version:	664p03		

Final States Analyzed

3-body final states

- $h_c \to K^+K^-\pi^0,\ K_S^0K^\pm\pi^\mp$
- $h_c \to K^+K^-\eta$

4-body final states

- $h_c \to \pi^+\pi^-\pi^0\eta$
- $h_c \to K^+K^-\pi^0\eta$
- $h_c \to \bar{p}p\pi^0\pi^0$

5-body final states

- $h_c \to K^+K^-\pi^+\pi^-\pi^0,\ K_S^0K^\pm\pi^\mp\pi^+\pi^-$
- $h_c \to K^+K^-\pi^+\pi^-\eta$
- $h_c \to 2(K^+K^-)\pi^0$

Branching fractions have been determined

Upper limits have been determined

Questions and Remarks within the Last Talk

1. Using different models in order to parameterize the resolution distribution
   ➡ additional source of systematic uncertainty

2. Generating Signal MC with HELAMP model instead of PHSP model

3. Investigate background from $\phi \to \pi^+\pi^-\pi^0$ in the final state $\mathrm{h_c} \to \mathrm{K_S^0 K^\pm \pi^\mp \pi^+ \pi^-}$

1. Using different models in order to parameterize the resolution distribution

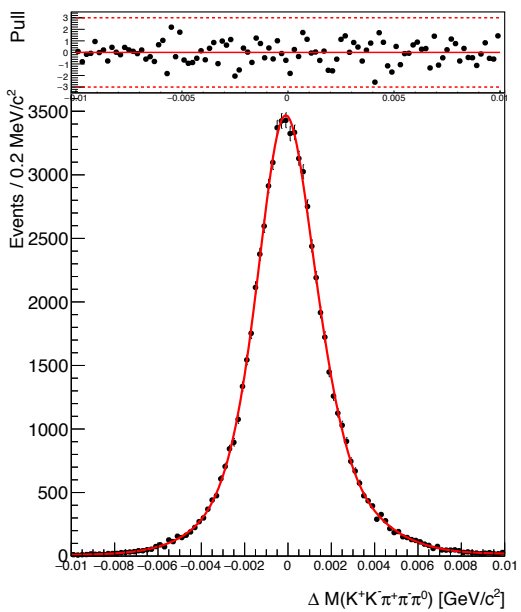
- Consider the final state $h_c \to K^+K^-\pi^+\pi^-\pi^0$

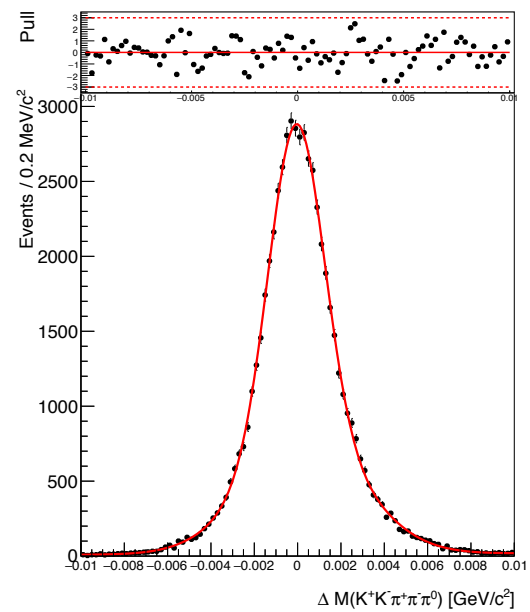
So far Resolution is described by:

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

Another valid parameterization but worse fit stability:

Crystal Ball + 4 Gaussian





➡ results in difference of 2.2% for the determined branching fraction (2-3% for other final states)
➡ taken as additional systematic uncertainty

2. Generating Signal MC with HELAMP model instead of PHSP model

Before

```
#
Decay psi(2S)
1.0000 pi0 h_c PHSP;
Enddecay
```

Now

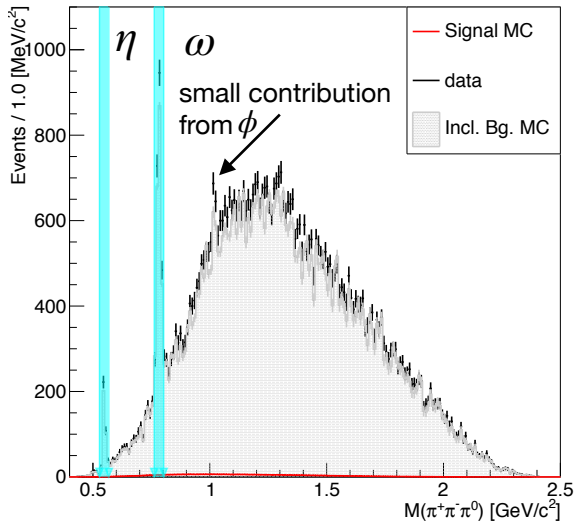
```
#
Decay psi(2S)
1.0000 pi0 h_c HELAMP 0 0 1 0 0 0;
Enddecay
```

➡ difference in efficiency of at most 0.8% for all final states

- HELAMP model will be used from now on

➡ PHSP model will be taken into account within systematic error

3. Investigate background from $\phi \to \pi^+\pi^-\pi^0$ in the final state $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$



- Background is visible in the system of the π^0 from $\psi' \to \pi^0 h_c$
- and charged pions from h_c decay
- Background from ϕ contributes with only ~1% to all background events
- Cut on ϕ affects signal efficiency by 1%!

➡ not sufficient to reduce this background

Summary

- In total 10 final states have been analyzed which have never been measured before - hints for 3 new decay modes of the h_c have been found
- Changes to last talk:

1. Additional systematic uncertainties have been determined for the parametrization of the resolution distribution
2. Different generator model has been used for signal MC (HELAMP instead of PHSP)

- Results change slightly:

final state	$BF(h_c \to X)$
$K^+K^-\pi^+\pi^-\pi^0$	$(3.3 \pm 0.4 \pm 0.4 \pm 0.5) \cdot 10^{-3}$
$K^0_S K^\pm \pi^\mp \pi^+ \pi^-$	$(7.6 \pm 1.7 \pm 1.0 \pm 1.1) \cdot 10^{-3}$
$\pi^+\pi^-\pi^0\eta$	$(7.3 \pm 1.9 \pm 0.8 \pm 1.1) \cdot 10^{-3}$
$2(K^+K^-)\pi^0$	$< 2.0 \cdot 10^{-4}$
$K^+K^-\pi^0$	$< 5.7 \cdot 10^{-4}$
$K^+K^-\eta$	$< 9.2 \cdot 10^{-4}$
$K^+K^-\pi^0\eta$	$< 2.2 \cdot 10^{-3}$
$K^+K^-\pi^+\pi^-\eta$	$< 2.5 \cdot 10^{-3}$
$K^0_S K^\pm \pi^\mp$	$< 6.4 \cdot 10^{-4}$
$p\bar{p}\pi^0\pi^0$	$< 5.7 \cdot 10^{-4}$

- Looking forward to taking further steps!

Thank You!

Backup

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

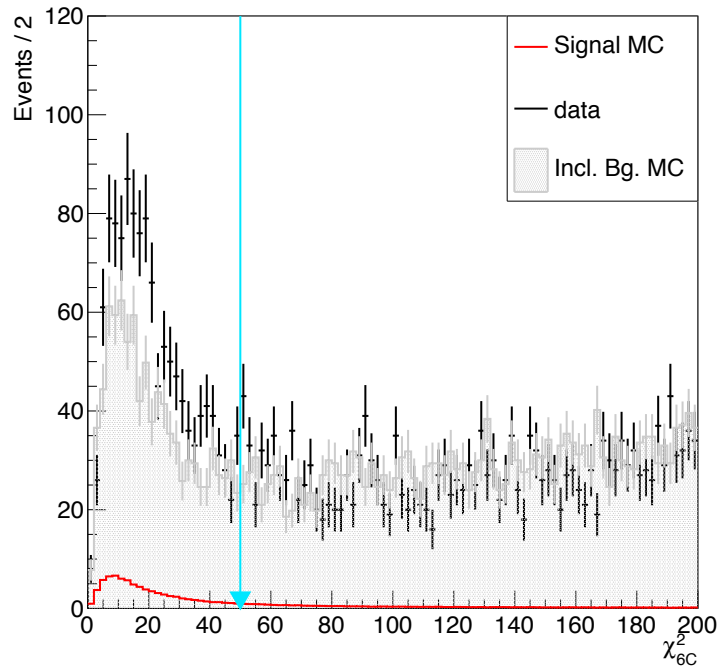
Reconstruction of η candidates

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

mass constrained fit

Analysis of $h_c \to K^+K^-\pi^+\pi^-\pi^0$

- 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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- additional 4C fit under hypothesis $3\gamma K^+K^-\pi^+\pi^-$ to veto background from
  - $\psi' \to \gamma\chi_{cJ}$: $\chi^2_{4C} < \chi^2_{3\gamma}$
- reject background from $\psi' \to \pi^+\pi^- J/\psi,\ \pi^0\pi^0 J/\psi$:
  - $|M(\pi^+\pi^-)_{Rec} - M(J/\psi)| > 25\ \mathrm{MeV/c^2}$
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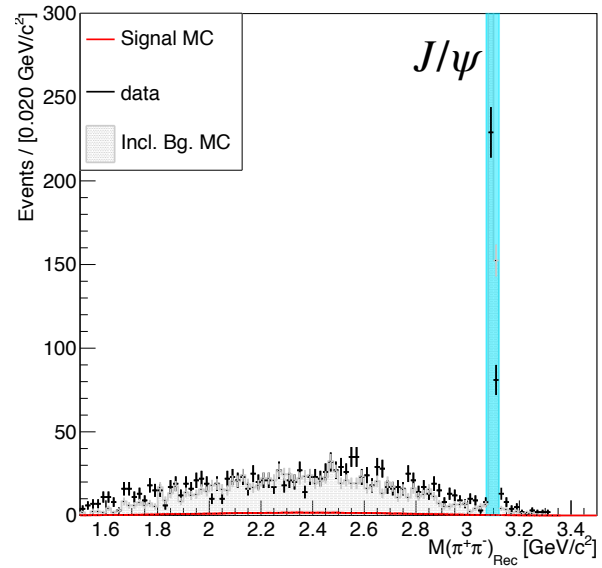

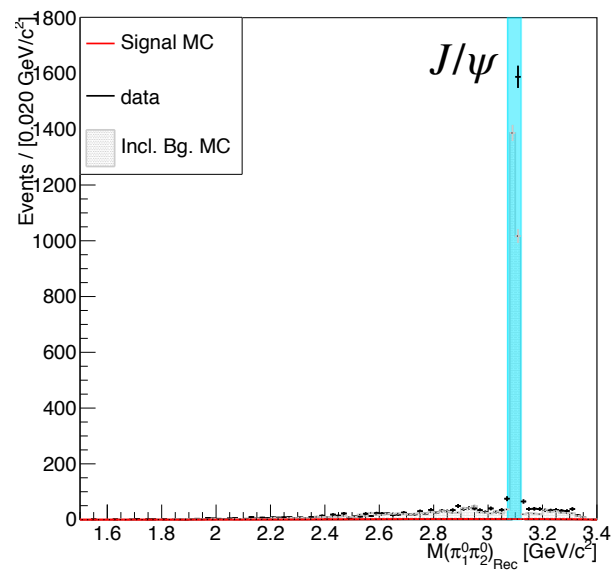

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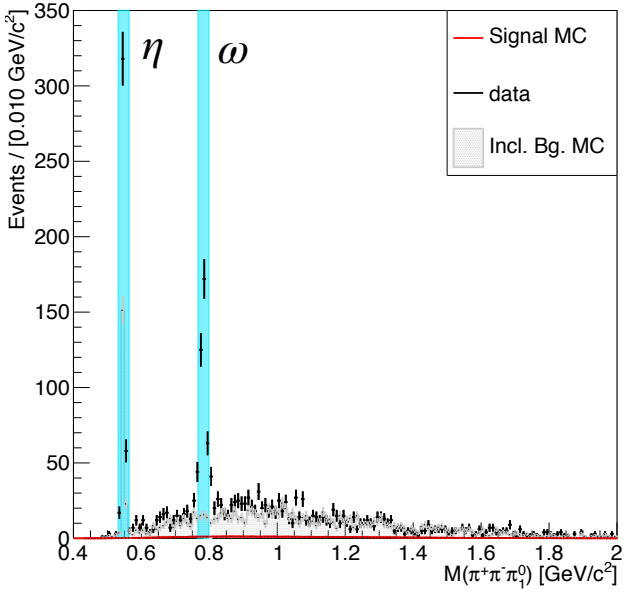
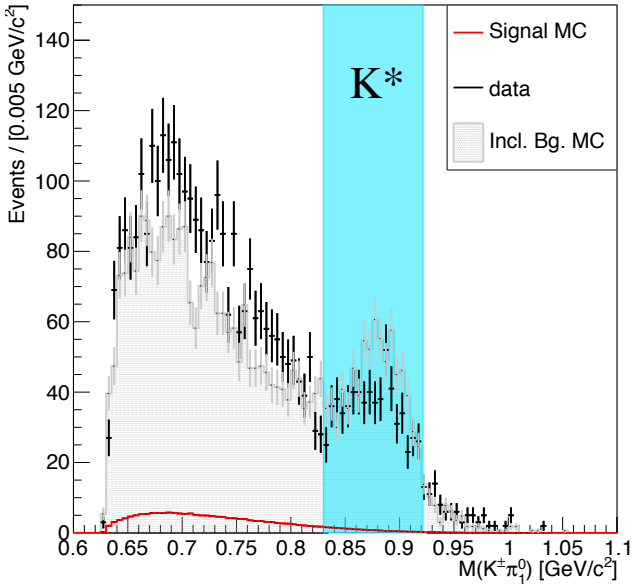
  - $|M(\pi^0\pi^0)_{Rec} - M(J/\psi)| > 25\ \mathrm{MeV/c^2}$
- π^0 from ψ' decay should not from other resonances:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 16\ \mathrm{MeV/c^2}$
  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20\ \mathrm{MeV/c^2}$
  - $0.82\ \mathrm{GeV/c^2} \leq M(K^\pm\pi^0_1) \leq 0.92\ \mathrm{GeV/c^2}$





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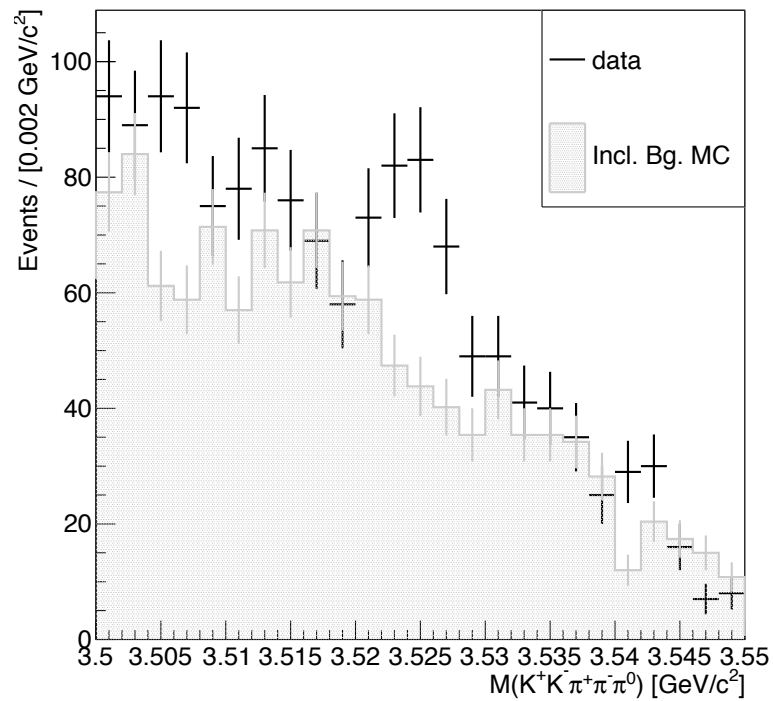


➡ **obtained efficiency 6.5%**

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

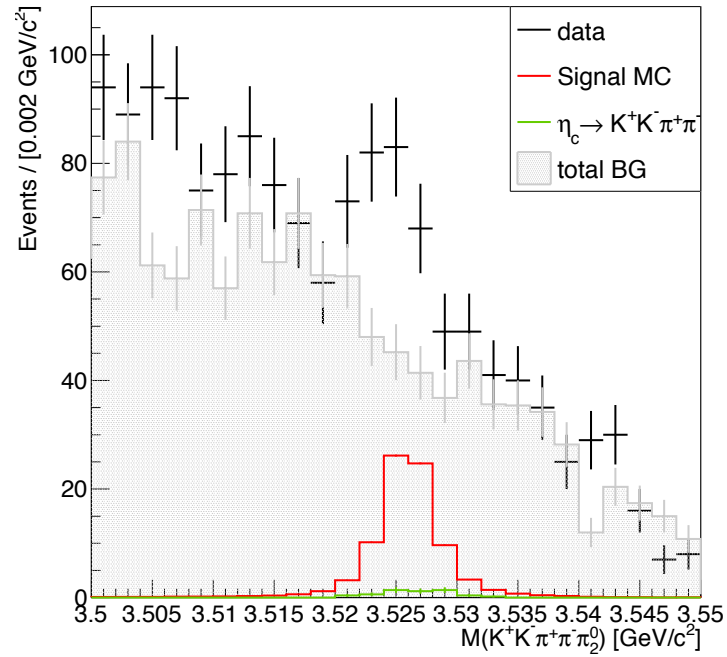
- Study of peaking background caused by radiative decays:
  - $h_c \to \gamma\eta_c, \gamma\chi_{c1}, \gamma\chi_{c0}$

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

➡ remaining peaking background taken into account within fit



- 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

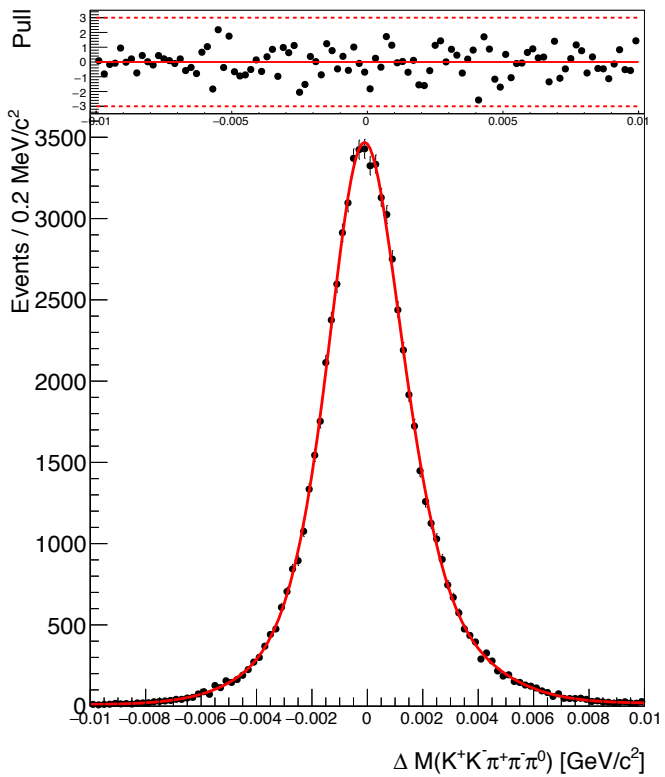
process $h_c \to \gamma X$	intermediate states	N_{rem}	$N_{expected}$
$\eta_c \to K^+K^-\pi^+\pi^-$	$K^{*0}K^{*\pm}\pi^{\mp}$	12	3
$\eta_c \to K^+K^-\pi^+\pi^-$	PSHP	10	2
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\pi^0$	PHSP	2	0
$\eta_c \to K^+K^-\pi^+\pi^-\pi^0\pi^0$	$K^{*+}K^{*-}\pi^0\pi^0$	1	0
$\eta_c \to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

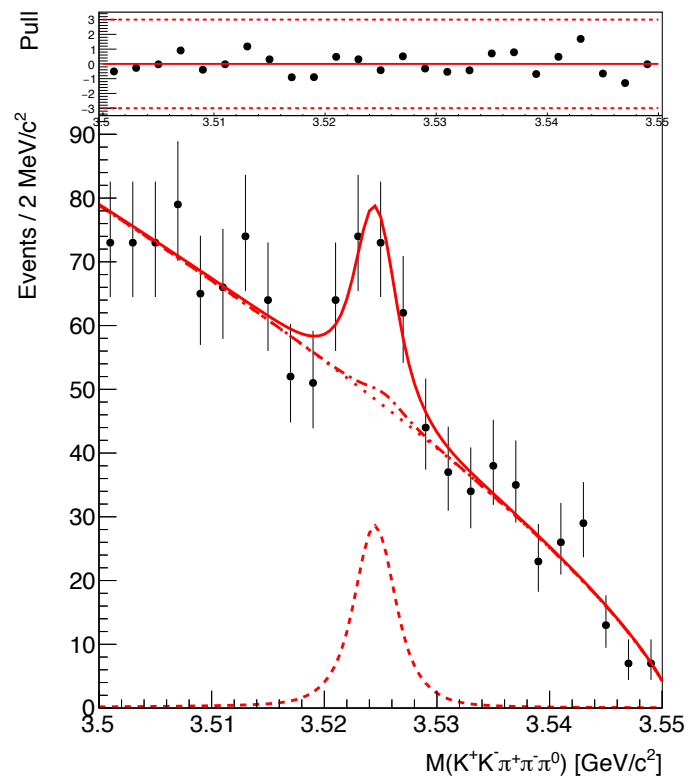
Determination of branching fraction of $h_c \to K^+K^-\pi^+\pi^-\pi^0$

Resolution

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



Breit-Wigner ⊗ Resolution + Argus



Significance calculated to 6.0σ

$M(h_c) = 3524.9 \pm 0.6\ \ \mathrm{MeV/c^2}$

$\Gamma(h_c) = 0.8 \pm 0.5\ \ \mathrm{MeV}$

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

Systematic studies

Selection procedure

- variation of selection criteria

cut	nominal value	range	step size	uncertainty
χ^2_{6C}	50	30-70	1	2.8 %
$\lvert M(\pi^+\pi^-)_{Rec} - M(J/\psi)\rvert \quad [MeV/c^2]$	25	10-40	1	0.5 %
$\lvert M(\pi^0\pi^0)_{Rec} - M(J/\psi)\rvert \quad [MeV/c^2]$	25	10-40	1	1.4 %
$\lvert M(\pi^0 K^\pm) - M(K^{*\pm})\rvert \quad [MeV/c^2]$	30	10-50	1	3.8 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\eta)\rvert \quad [MeV/c^2]$	16	6-26	1	1.3 %
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert \quad [MeV/c^2]$	20	10-30	1	2.5 %

- Kinematic fit using helix correction method: 1.5%

Generator model

- including intermediate resonances to generator model leads efficiency difference of at most **5.1%**

Fit model

- Describing background by Chebychev polynomial instead of Argus function: **1.2%**
- Different parametrization of resolution: **2.2%**
- Fitting range: **0.9%**

Tracking

- 1% per track ➡ 4%

Photon reconstruction

- 1% per photon ➡ 4%

PID

- 1% per track ➡ 4%

π^0 reconstruction

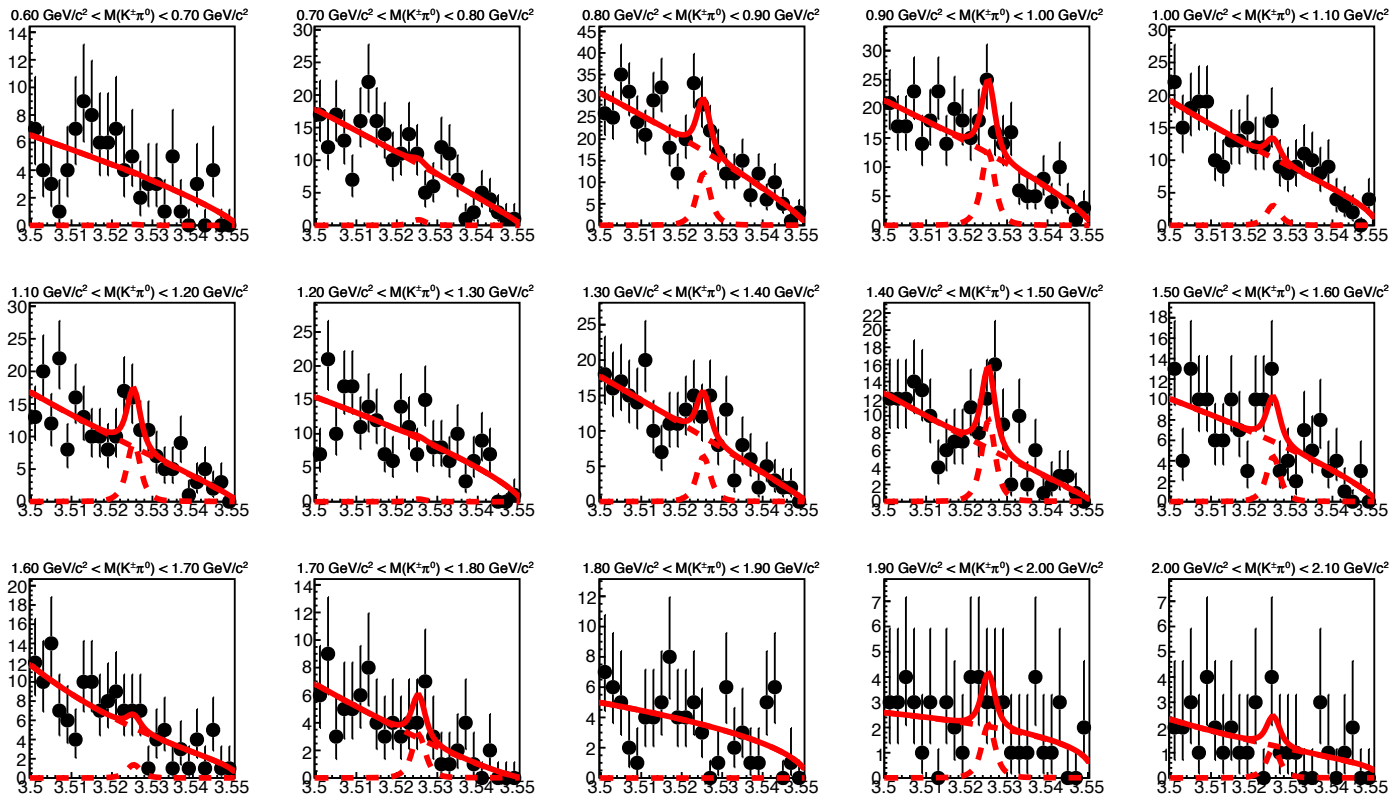
- 1% per π^0 ➡ 2%

total 10.7% + 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



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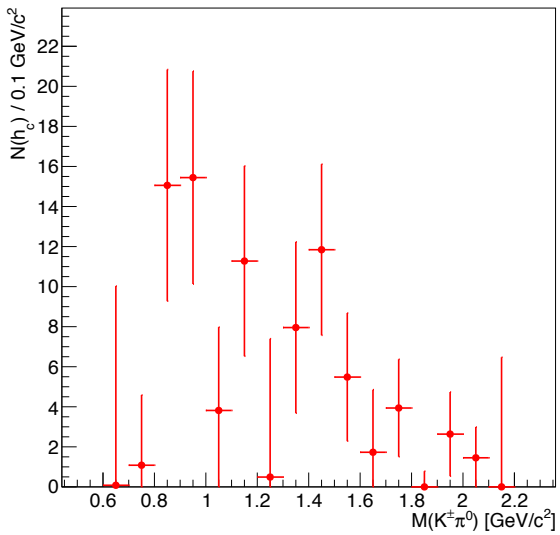
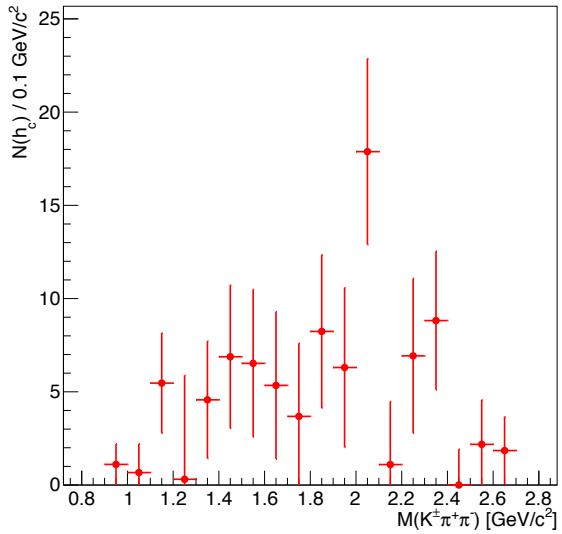
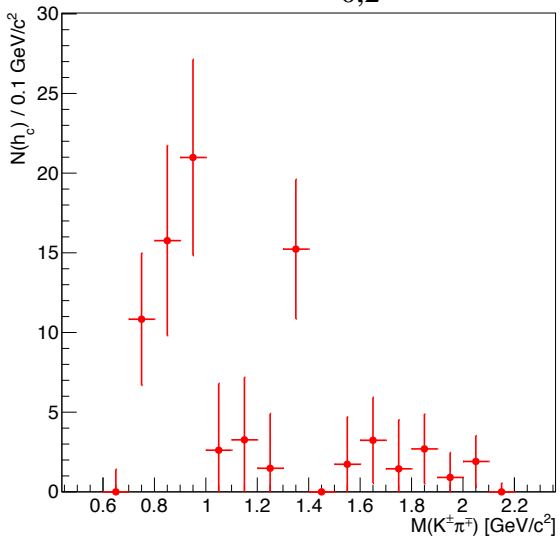
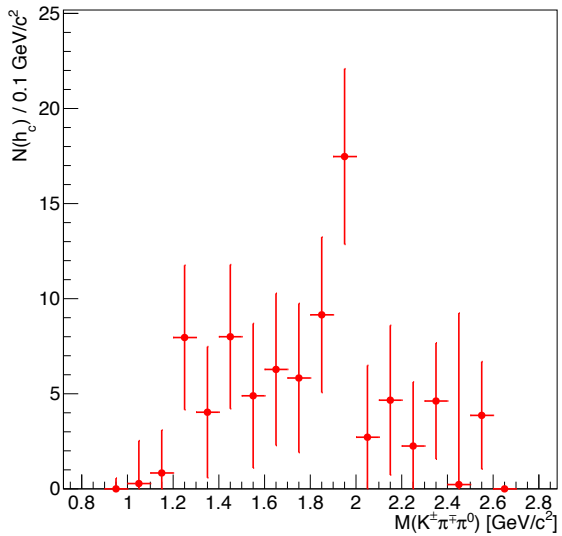


$K^*(892),\ K^*_{0,2}(1430)$



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

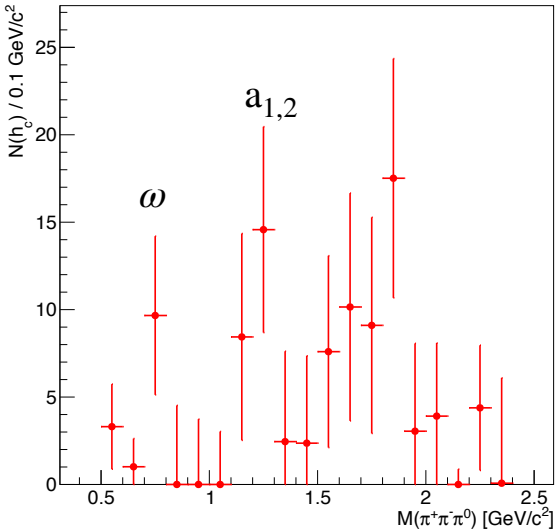


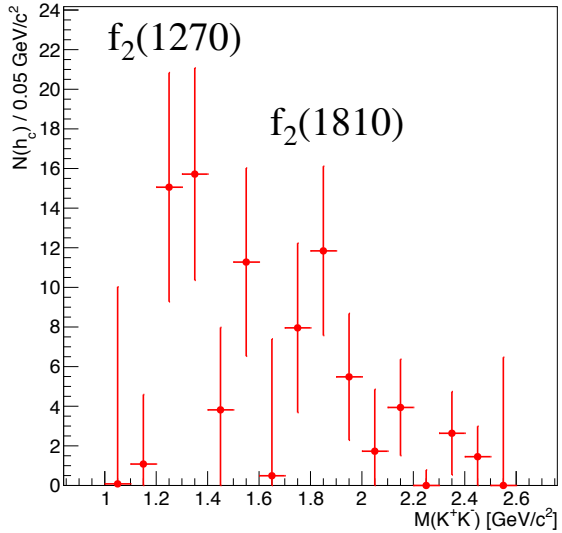


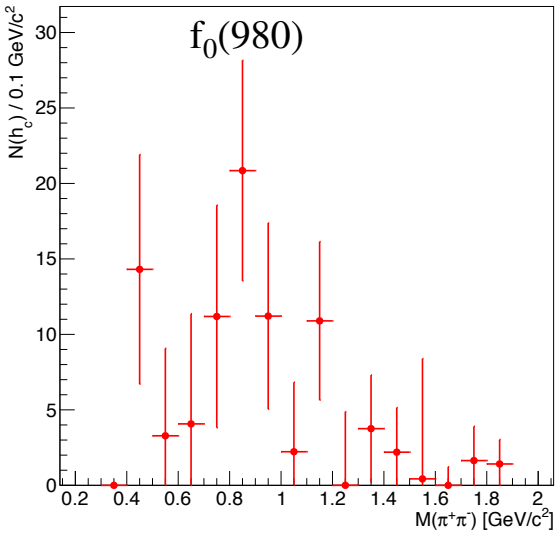
- shown error bars are statistical only
- similar structures in charged and neutral mode
- indication for intermediate reactions like:

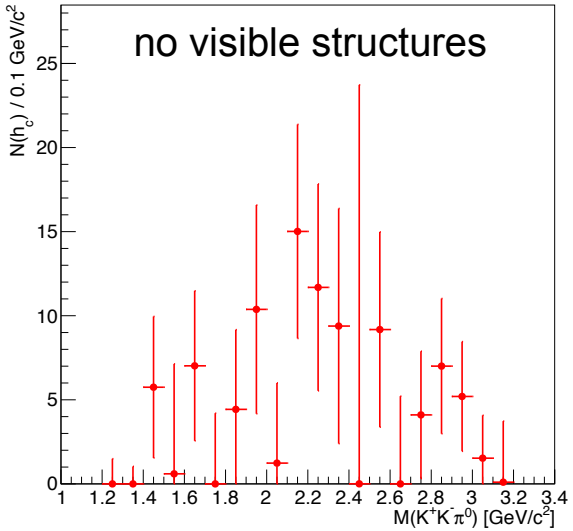
$$h_c \rightarrow \left(K^*(892)/K^*_{0,2}(1430)\right)$$
$$\left(K_2(1820)/K^*_2(1980)\right)$$

Study of intermediate resonances





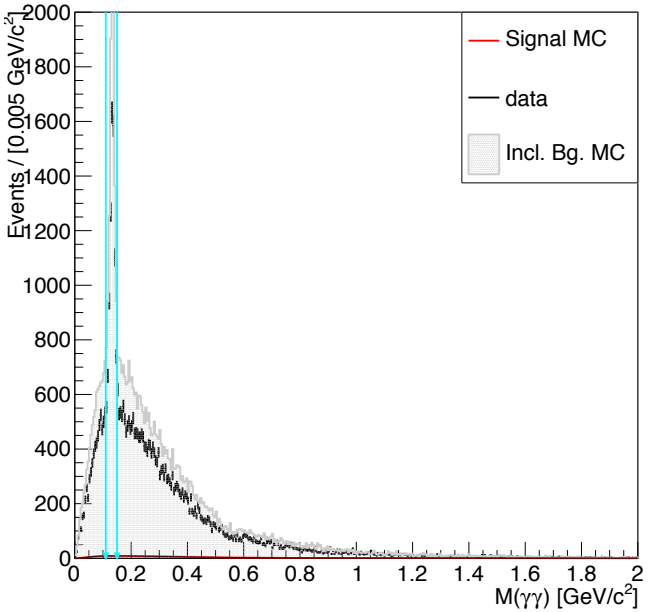




- $h_c \to (\pi^+\pi^-\pi^0)(K^+K^-)$ seems to be more favored than $h_c \to (\pi^+\pi^-)(\pi^0K^+K^-)$
- Correlations between sybsystems have been investigated by generating the supposed intermediate reactions

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

- 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:
  - $|M(\gamma\gamma) - M(\pi^0)| > 15\ \mathrm{MeV/c^2}$



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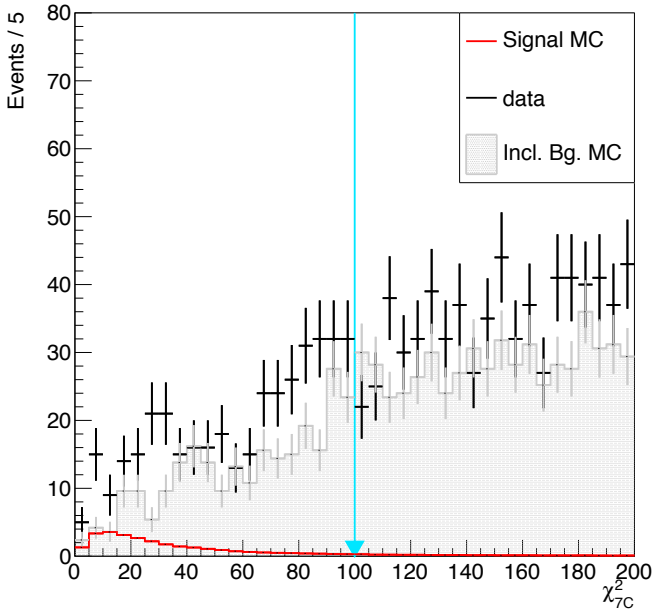

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- π^0 from ψ' decay should not form resonances with other final state particles:
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  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20\ \mathrm{MeV/c^2}$
- reject background from $\psi' \to \pi^0\pi^0 J/\psi,\ \eta J/\psi$:
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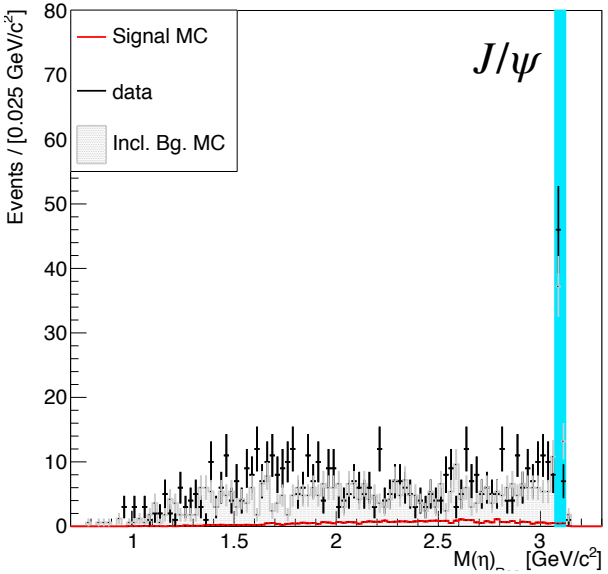
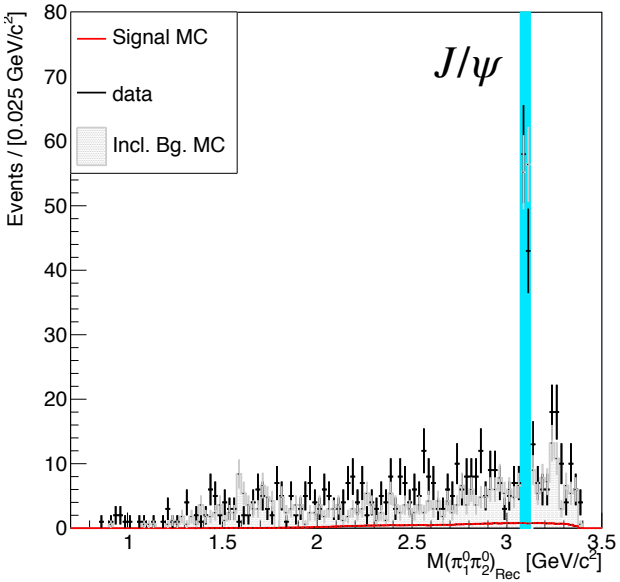
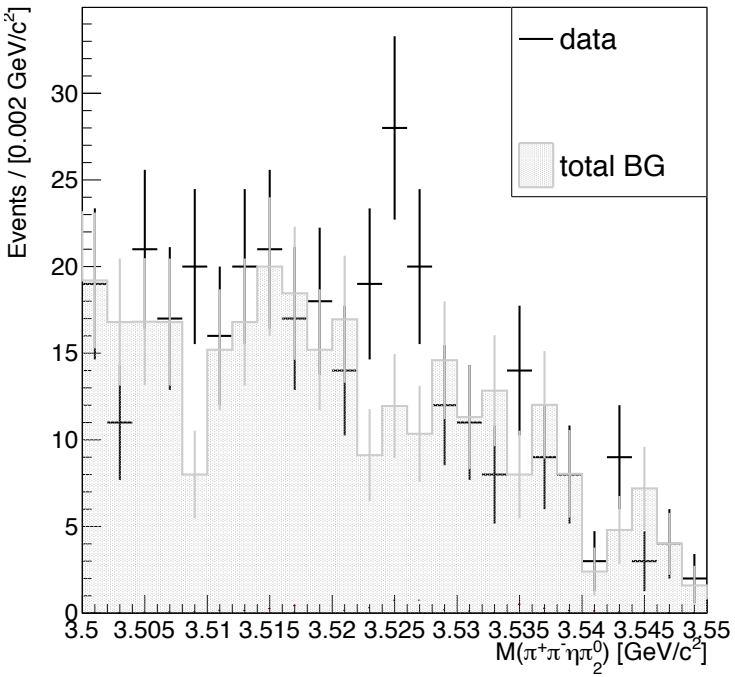
  - $|M(\eta)_{Rec} - M(J/\psi)| > 30\ \mathrm{MeV/c^2}$





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

- 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:
  - $|M(\gamma\gamma) - M(\pi^0)| > 15\ \mathrm{MeV/c^2}$
- Limit goodness of 7C-Fit: $\chi^2_{7C} < 100$
- π^0 from ψ' decay should not form resonances with other final state particles:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 16\ \mathrm{MeV/c^2}$
  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20\ \mathrm{MeV/c^2}$
- reject background from $\psi' \to \pi^0\pi^0 J/\psi,\ \eta J/\psi$:
  - $|M(\pi^0\pi^0)_{Rec} - M(J/\psi)| > 30\ \mathrm{MeV/c^2}$
  - $|M(\eta)_{Rec} - M(J/\psi)| > 30\ \mathrm{MeV/c^2}$



➡ obtained efficiency 3.9 %

Background studies

- Dominating contribution from $e^+e^- \to 4\gamma\pi^+\pi^-\eta$

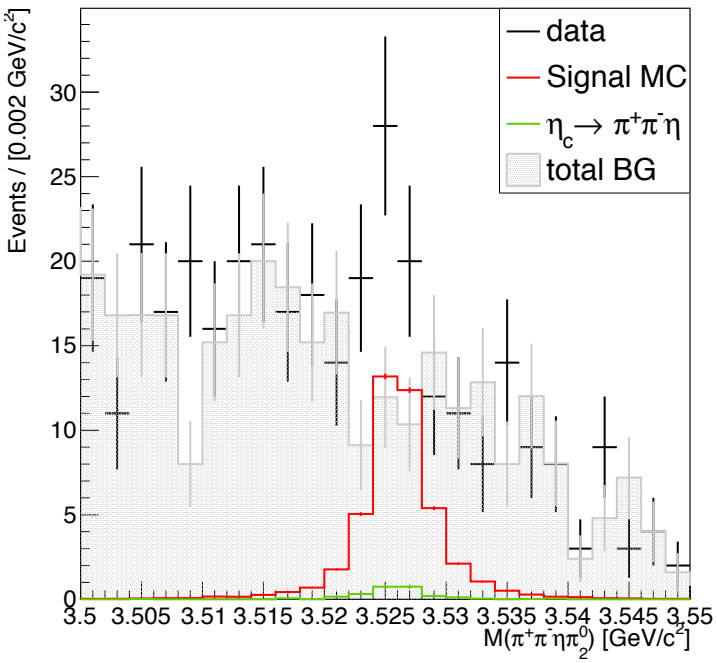
- Study of peaking background caused by radiative decays:
  - $h_c \to \gamma\chi_{c1}, \gamma\chi_{c0}$

  ➡negligible contribution

- $h_c \to \gamma\eta_c$

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

➡ peaking background is taken into account within the fit to determine the effective signal yield

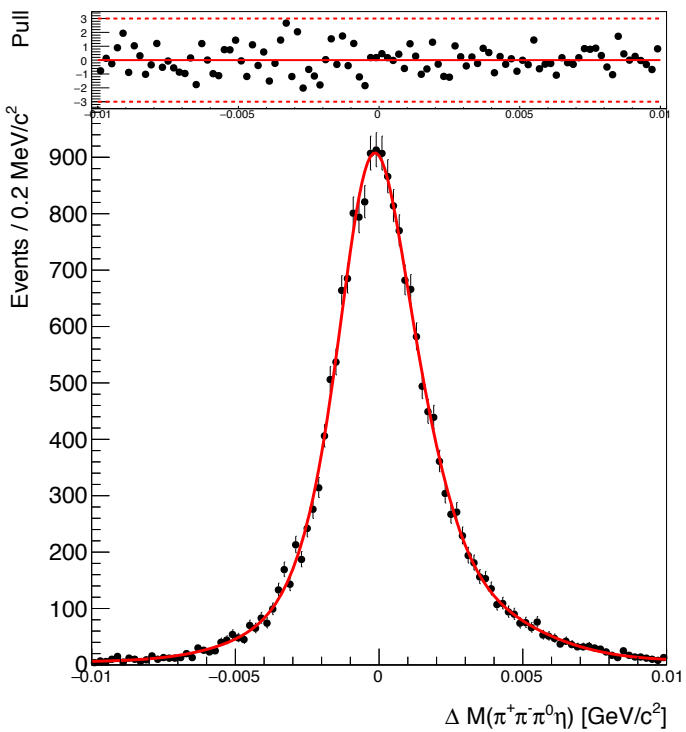


- known decay modes scaled to PDG value
- unknown decay modes generated using LUND Model

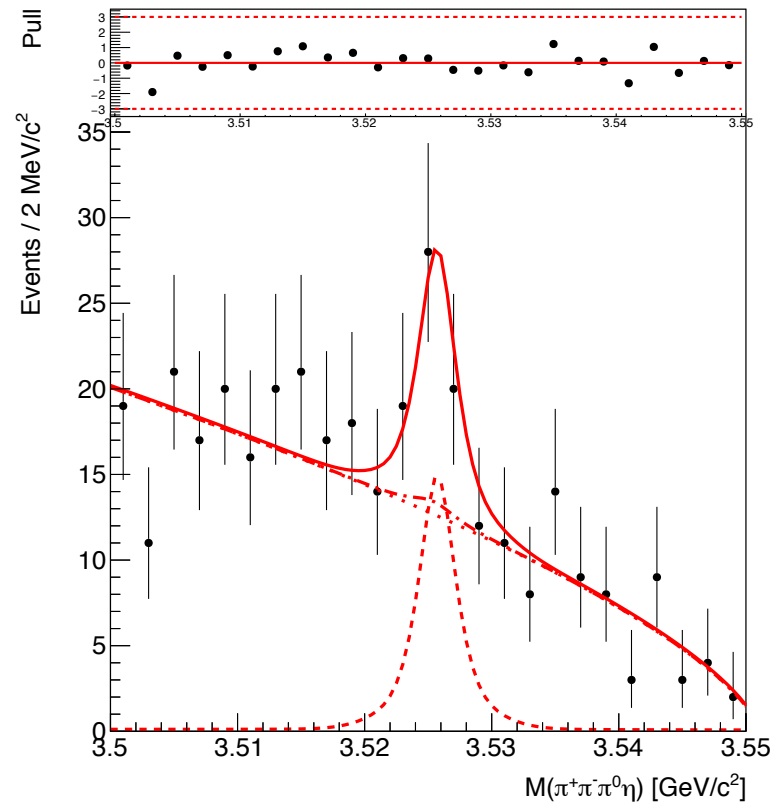
Determination of branching fraction of $h_c \to \pi^+\pi^-\pi^0\eta$

Resolution

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



Breit-Wigner ⊗ Resolution + Argus



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

Significance calculated to 3.8σ

Systematic studies

Selection procedure

- variation of selection criteria

cut	nominal value	range	step size	uncertainty
χ^2_{7C}	100	80-120	1	3.1
$\lvert M(\eta)_{Rec} - M(J/\psi)\rvert$ [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	1.5
$\lvert M(\gamma\gamma) - M(\pi^0)\rvert$ [MeV/c^2]	15	5-25	1	2.8
$\lvert M(\pi^+\pi^-\pi^0) - M(\eta)\rvert$ [MeV/c^2]	16	6-26	1	1.6
$\lvert M(\pi^+\pi^-\pi^0) - M(\omega)\rvert$ [MeV/c^2]	20	10-30	1	2.2

- Kinematic fit using helix correction method: 2.1%

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%

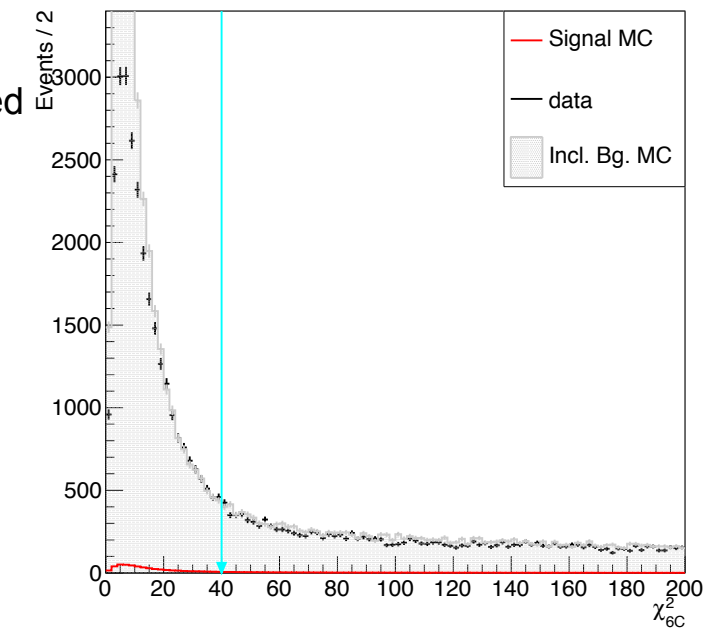
π^0, η reconstruction

- 1% per π^0 or η ➡ 3%

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

Analysis of $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

- $N_\pi = 5$, $N_K = 1$, $N_\gamma \geq 2$
- K_S^0 reconstruction:
  - Limit decay length and error determined by secondary vertex fit: $\lambda / \Delta\lambda < 2$
  - $0.487\ \mathrm{MeV/c^2} \leq M(\pi^+\pi^-) \leq 0.511\ \mathrm{MeV/c^2}$
- Common vertex ensured by converged vertex fit for all charged particles
- Limit goodness of 6C-Fit: $\chi^2_{6C} < 40$



Analysis of $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

- $N_\pi = 5$, $N_K = 1$, $N_\gamma \geq 2$
- K_S^0 reconstruction:
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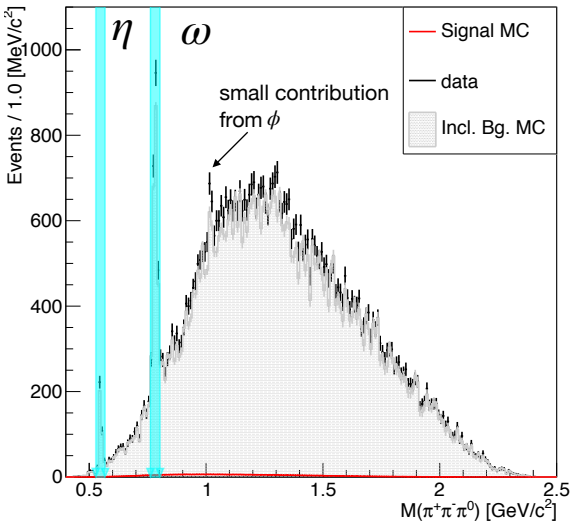
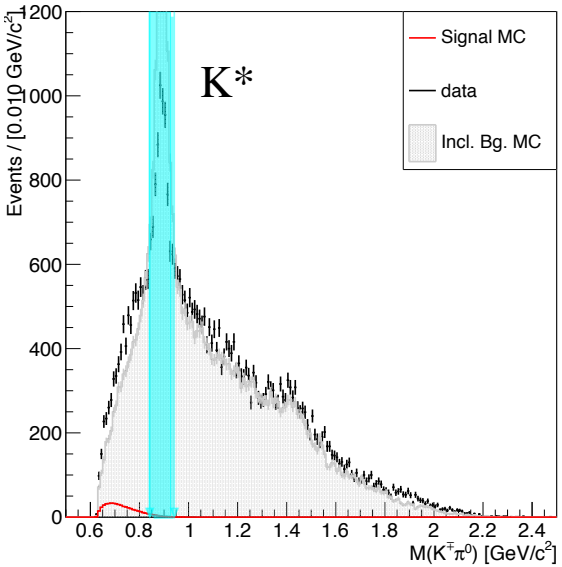
- Common vertex ensured by converged vertex fit for all charged particles
- Limit goodness of 6C-Fit: $\chi^2_{6C} < 40$
- π^0 from ψ' decay should not from other resonances:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 20\ \mathrm{MeV/c^2}$
  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20\ \mathrm{MeV/c^2}$
- No $K\pi$ system should form a K^* meson thus:
  - $|M(K^\pm\pi^0) - M(K^*)| > 50\ \mathrm{MeV/c^2}$
  - $|M(K_S^0\pi^0) - M(K^*)| > 50\ \mathrm{MeV/c^2}$





Analysis of $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

- $N_\pi = 5$, $N_K = 1$, $N_\gamma \geq 2$
- K_S^0 reconstruction:
  - Limit decay length and error determined by secondary vertex fit: $\lambda/\Delta\lambda < 2$
  - $0.487\ \mathrm{MeV/c^2} \leq M(\pi^+\pi^-) \leq 0.511\ \mathrm{MeV/c^2}$
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- π^0 from ψ' decay should not from other resonances:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 20\ \mathrm{MeV/c^2}$
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- No $K\pi$ system should form a K^* meson thus:
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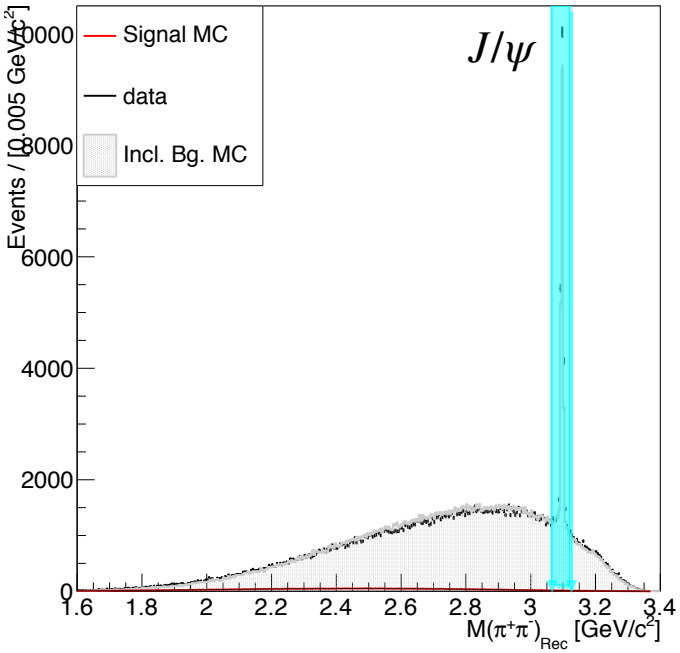
  - $|M(K_S^0\pi^0) - M(K^*)| > 50\ \mathrm{MeV/c^2}$
- No $\pi^+\pi^-$ pair not resulting from the K_S^0 decay should form a K_S^0 :
  - $|M(\pi^+\pi^-) - M(K_S^0)| > 20\ \mathrm{MeV/c^2}$
- Background from $\psi' \to \pi^+\pi^- J/\psi$ is suppressed by:
  - $|M(\pi^+\pi^-)_{Rec} - M(J/\psi)| > 30\ \mathrm{MeV/c^2}$



Analysis of $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

- $N_\pi = 5$, $N_K = 1$, $N_\gamma \geq 2$
- K_S^0 reconstruction:
  - Limit decay length and error determined by secondary vertex fit: $\lambda/\Delta\lambda < 2$
  - $0.487\ \mathrm{MeV/c^2} \leq M(\pi^+\pi^-) \leq 0.511\ \mathrm{MeV/c^2}$
- Common vertex ensured by converged vertex fit for all charged particles
- Limit goodness of 6C-Fit: $\chi^2_{6C} < 40$
- π^0 from ψ' decay should not from other resonances:
  - $|M(\pi^+\pi^-\pi^0) - M(\eta)| > 20\ \mathrm{MeV/c^2}$
  - $|M(\pi^+\pi^-\pi^0) - M(\omega)| > 20\ \mathrm{MeV/c^2}$
- No $K\pi$ system should form a K^* meson thus:
  - $|M(K^\pm\pi^0) - M(K^*)| > 50\ \mathrm{MeV/c^2}$
  - $|M(K_S^0\pi^0) - M(K^*)| > 50\ \mathrm{MeV/c^2}$
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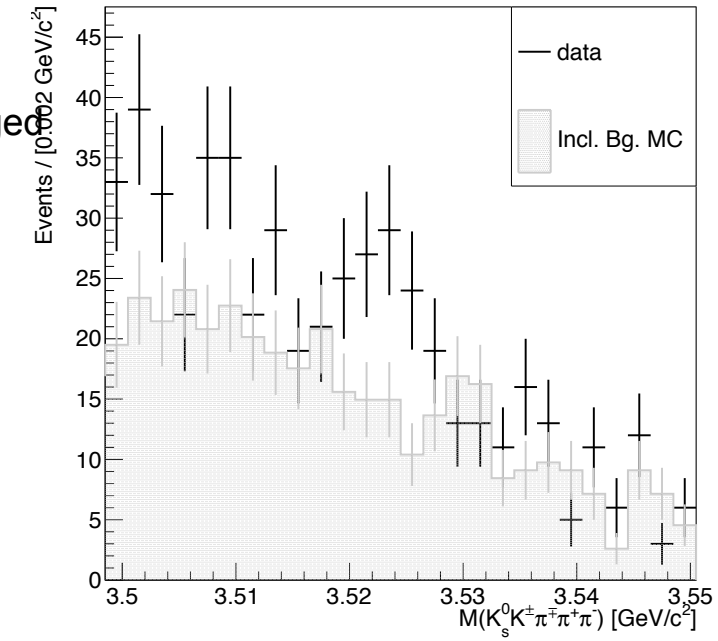


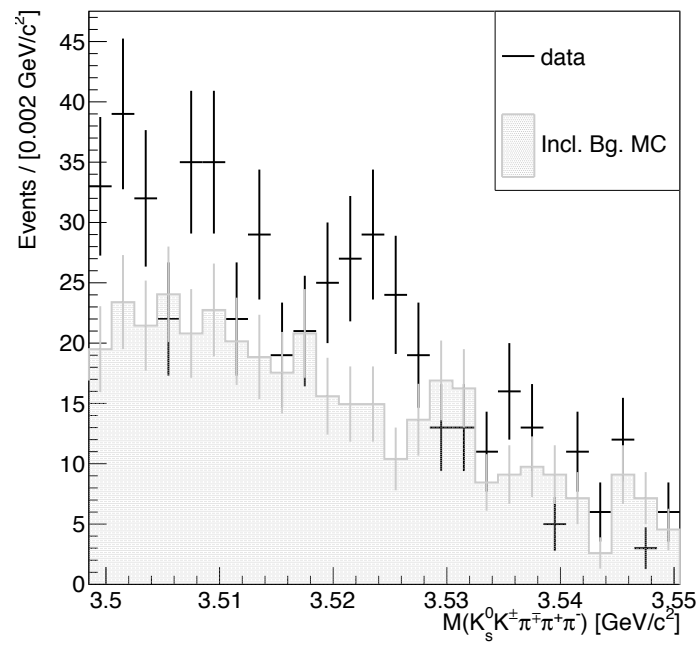
➡ obtained efficiency 6.4%

➡ structure as expected due to $h_c \to K^+K^-\pi^+\pi^-\pi^0$ channel but smaller yield

Background studies

- Here no peaking background can result from $h_c \to \gamma \eta_c$ due to misidentification of a π^0
- Main background contributions are:

process	final state	N_{rem}	$N_{expected}$
$K^{*+}K^{*-}\pi^+\pi^-$	$K^0_S K^\pm \pi^\mp \pi^+ \pi^- \pi^0$	114	35 %
$K^{*0}\overline{K^{*0}}\pi^+\pi^-$	$K^0_S K^\pm \pi^\mp \pi^+ \pi^- \pi^0$	98	30 %
$K^{*0}K^{*\pm}\pi^\mp\pi^0$	$K^0_S K^\pm \pi^\mp \pi^+ \pi^- \pi^0$	92	28 %

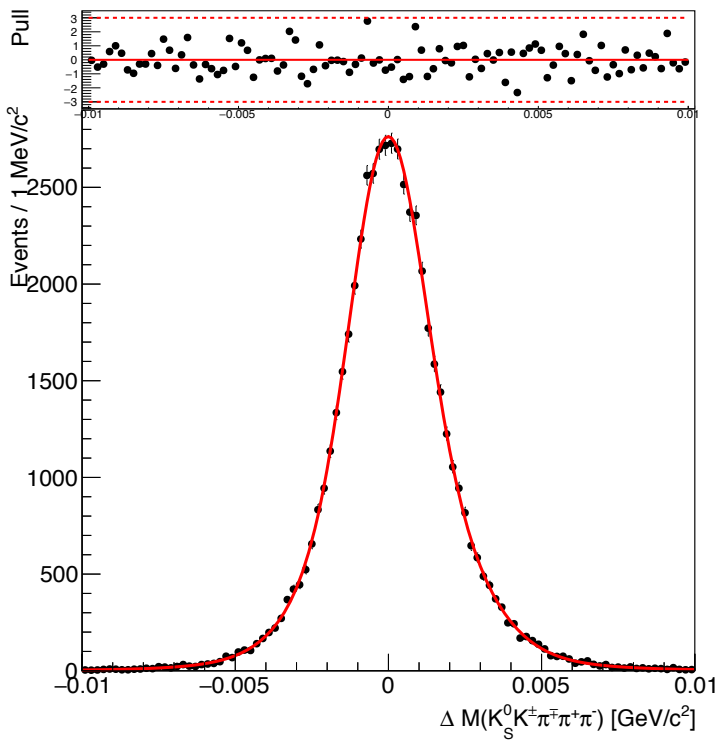


- despite the criterion to reduce K^* resonances, events in which the π^0 meson contributes to a K^*, remain

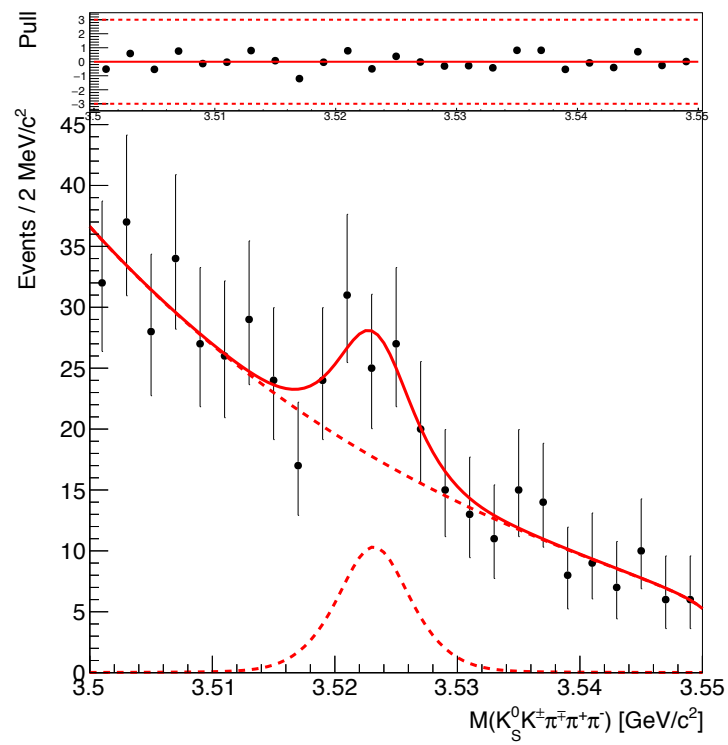
Determination of branching fraction of $h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

Resolution

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



Breit-Wigner ⊗ Resolution + Argus



$$BF(h_c \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-)$$

$$= (7.6 \pm 1.7 \pm 0.9 \pm 1.1) \cdot 10^{-3}$$

Significance calculated to 3.2σ

Overview of Selection Criteria

final state	χ^2_{NC}	J/ψVeto on $M(\pi^0_1\pi^0_2)_{Rec}$	$M(\pi^+\pi^-)_{Rec}$	$M(\eta)_{Rec}$	Veto on η	ω	$K^{*\pm}$	K^0_S	π^0Veto on $M(\gamma\gamma)$
$K^+K^-\pi^+\pi^-\pi^0$	✓	✓	✓		✓	✓	✓		
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	✓		✓		✓	✓	✓	✓	
$\pi^+\pi^-\pi^0\eta$	✓	✓		✓	✓				✓
$2(K^+K^-)\pi^0$	✓	✓					✓		
$K^+K^-\pi^0$	✓	✓					✓		
$K^+K^-\eta$	✓								✓
$K^+K^-\pi^0\eta$	✓	✓		✓					
$K^+K^-\pi^+\pi^-\eta$	✓		✓	✓			✓		✓
$K^0_SK^\pm\pi^\mp$	✓		✓				✓		
					η	Δ^+	Σ^+		
$p\bar{p}\pi^0\pi^0$	✓	✓			✓	✓	✓		✓

- Limit Goodness of kinematic fit to suppress background
- Veto J/ψ in recoil systems
- π^0 from ψ' decay should not from other resonances
- avoid fake π^0

Overview of Selection Criteria

final state	χ^2_{NC}	J/ψ Veto on $M(\pi^0_1\pi^0_2)_{Rec}$	$M(\pi^+\pi^-)_{Rec}$	$M(\eta)_{Rec}$	Veto on η	ω	$K^{*\pm}$	K^0_S	π^0 Veto on $M(\gamma\gamma)$
$K^+K^-\pi^+\pi^-\pi^0$	✓	✓	✓		✓	✓	✓		
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	✓		✓		✓	✓	✓	✓	
$\pi^+\pi^-\pi^0\eta$	✓	✓		✓	✓				✓
$2(K^+K^-)\pi^0$	✓	✓					✓		
$K^+K^-\pi^0$	✓	✓					✓		
$K^+K^-\eta$	✓								✓
$K^+K^-\pi^0\eta$	✓	✓		✓					
$K^+K^-\pi^+\pi^-\eta$	✓		✓	✓			✓		✓
$K^0_SK^\pm\pi^\mp$	✓		✓				✓		
					η	Δ^+	Σ^+		
$p\bar{p}\pi^0\pi^0$	✓	✓			✓	✓	✓		✓

- Limit Goodness of kinematic fit to suppress background
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- avoid fake π^0

Overview of Selection Criteria

final state	χ^2_{NC}	J/ψVeto on $M(\pi^0_1\pi^0_2)_{Rec}$	$M(\pi^+\pi^-)_{Rec}$	$M(\eta)_{Rec}$	Veto on η	ω	$K^{*\pm}$	K^0_S	π^0Veto on $M(\gamma\gamma)$
$K^+K^-\pi^+\pi^-\pi^0$	✓	✓	✓		✓	✓	✓		
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	✓		✓		✓	✓	✓	✓	
$\pi^+\pi^-\pi^0\eta$	✓	✓		✓	✓				✓
$2(K^+K^-)\pi^0$	✓	✓					✓		
$K^+K^-\pi^0$	✓	✓					✓		
$K^+K^-\eta$	✓								✓
$K^+K^-\pi^0\eta$	✓	✓		✓					
$K^+K^-\pi^+\pi^-\eta$	✓		✓	✓			✓		✓
$K^0_SK^\pm\pi^\mp$	✓		✓				✓		
					η	Δ^+	Σ^+		
$p\bar{p}\pi^0\pi^0$	✓	✓			✓	✓	✓		✓

- Limit Goodness of kinematic fit to suppress background
- Veto J/ψ in recoil systems
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- avoid fake π^0

Overview of Selection Criteria

final state	χ^2_{NC}	J/ψVeto on $M(\pi^0_1\pi^0_2)_{Rec}$	$M(\pi^+\pi^-)_{Rec}$	$M(\eta)_{Rec}$	Veto on η	ω	$K^{*\pm}$	K^0_S	π^0Veto on $M(\gamma\gamma)$
$K^+K^-\pi^+\pi^-\pi^0$	✓	✓	✓		✓	✓	✓		
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	✓		✓		✓	✓	✓	✓	
$\pi^+\pi^-\pi^0\eta$	✓	✓		✓	✓				✓
$2(K^+K^-)\pi^0$	✓	✓					✓		
$K^+K^-\pi^0$	✓	✓					✓		
$K^+K^-\eta$	✓								✓
$K^+K^-\pi^0\eta$	✓	✓		✓					
$K^+K^-\pi^+\pi^-\eta$	✓		✓	✓			✓		✓
$K^0_SK^\pm\pi^\mp$	✓		✓				✓		
					η	Δ^+	Σ^+		
$p\bar{p}\pi^0\pi^0$	✓	✓			✓	✓	✓		✓

- Limit Goodness of kinematic fit to suppress background
- Veto J/ψ in recoil systems
- π^0 from ψ' decay should not from other resonances
- avoid fake π^0

Overview of Selection Criteria

final state	χ^2_{NC}	J/ψVeto on $M(\pi^0_1\pi^0_2)_{Rec}$	$M(\pi^+\pi^-)_{Rec}$	$M(\eta)_{Rec}$	Veto on η	ω	$K^{*\pm}$	K^0_S	π^0Veto on $M(\gamma\gamma)$
$K^+K^-\pi^+\pi^-\pi^0$	✓	✓	✓		✓	✓	✓		
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	✓		✓		✓	✓	✓	✓	
$\pi^+\pi^-\pi^0\eta$	✓	✓		✓	✓				✓
$2(K^+K^-)\pi^0$	✓	✓					✓		
$K^+K^-\pi^0$	✓	✓					✓		
$K^+K^-\eta$	✓								✓
$K^+K^-\pi^0\eta$	✓	✓		✓					
$K^+K^-\pi^+\pi^-\eta$	✓		✓	✓			✓		✓
$K^0_SK^\pm\pi^\mp$	✓		✓				✓		
					η	Δ^+	Σ^+		
$p\bar{p}\pi^0\pi^0$	✓	✓			✓	✓	✓		✓

- Limit Goodness of kinematic fit to suppress background
- Veto J/ψ in recoil systems
- π^0 from ψ' decay should not from other resonances
- avoid fake π^0

Determination of Upper Limits

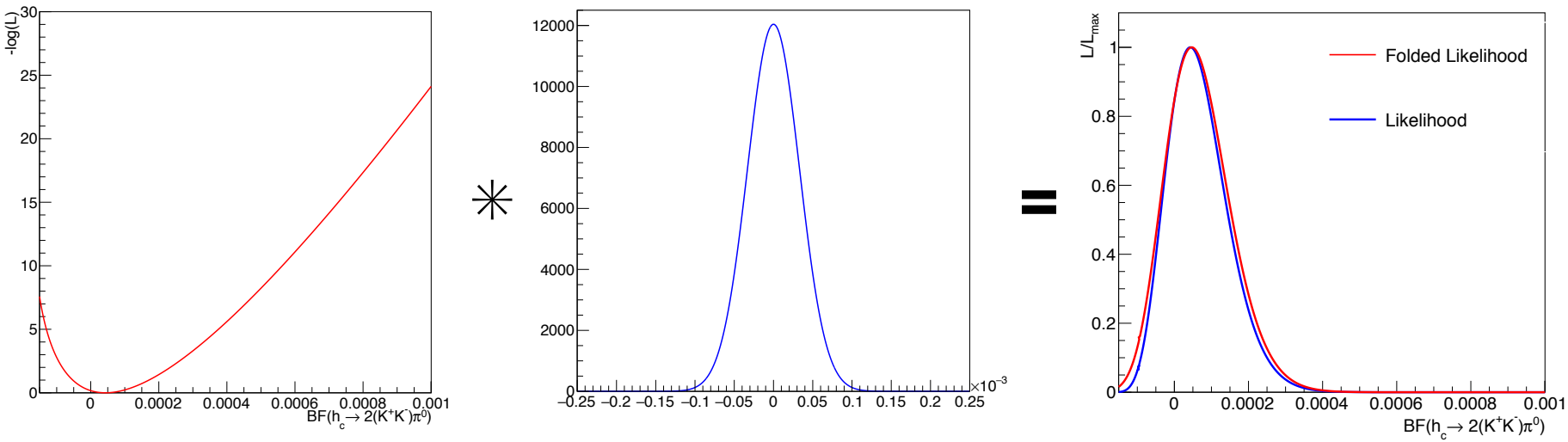
- Using Baysian method:

$$0.9 = \sum\!\!\!\!\!\!\int_{\theta_0 \leq \theta_{up}} \mathrm{d}\theta_0 \, \mathbb{P}(\theta = \theta_0 | x) = \frac{\sum\!\!\!\!\!\!\int_{\theta_0 \leq \theta_{up}} \mathrm{d}\theta_0 \, \mathscr{L}(x|\theta_0) \, \mathbb{P}(\theta = \theta_0)}{\sum\!\!\!\!\!\!\int_{\theta' \in \Theta} \mathrm{d}\theta' \, \mathscr{L}(x|\theta') \, \mathbb{P}(\theta = \theta')}$$

- Taking systematic uncertainties into account by folding the likelihood with a gaussian distribution

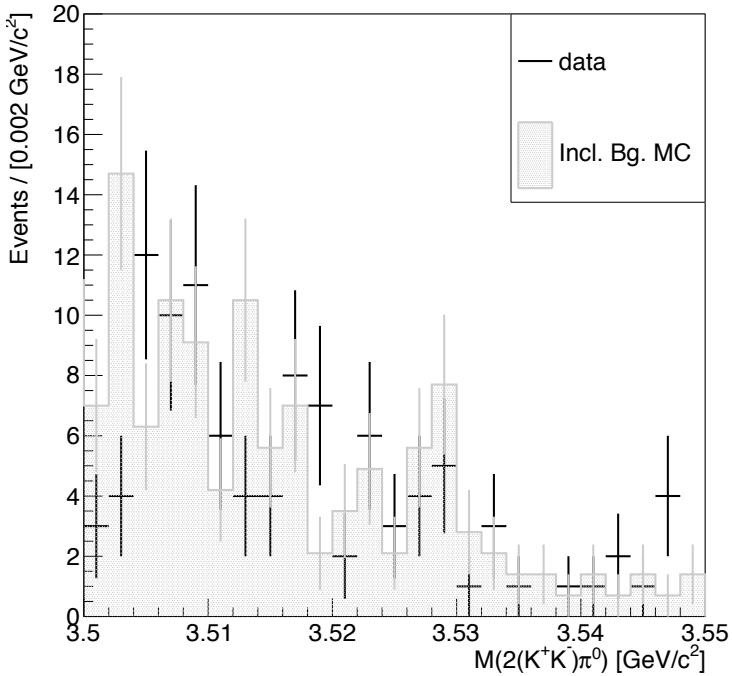
Replace $\mathscr{L}(x|\theta)$ by

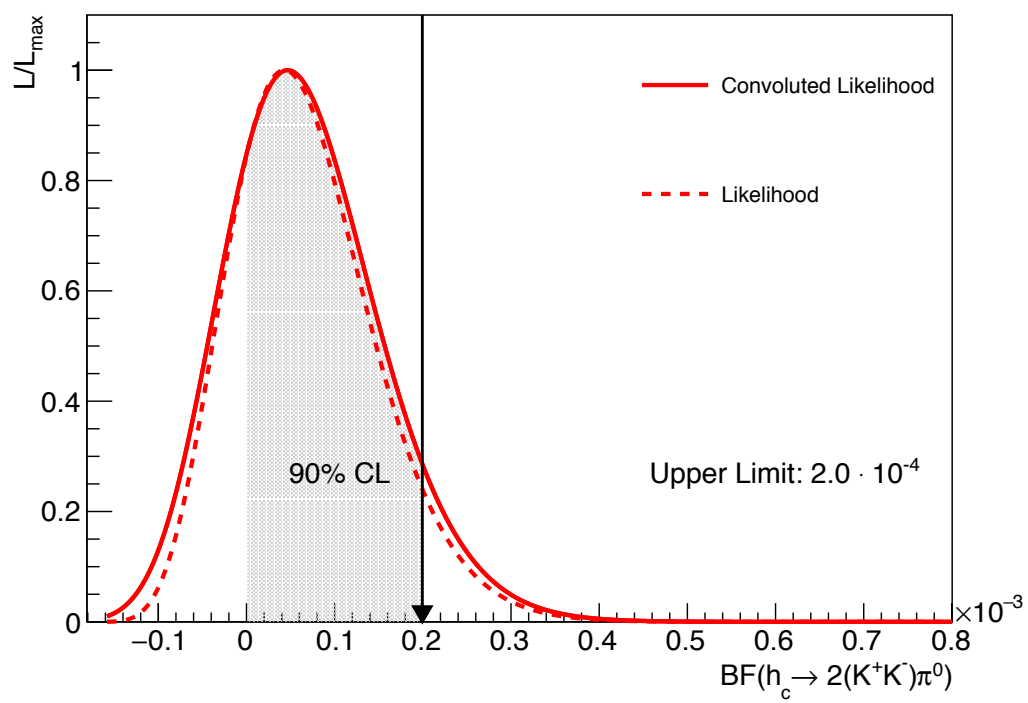
$$\mathscr{L}_{sys}(x|\theta) = \int \mathrm{d}x_i' \, \mathscr{L}(x_1, x_2, ..., x_i', ..., x_k|\theta) \cdot \mathrm{G}(x_i - x_i', \mu_i, \Delta x_i) \, ,$$ x_i fehlerbehaftete Größe mit Fehler Δx_i



At the Example of $h_c \to 2(K^+K^-)\pi^0$

- After applying all selection criteria, no evidence for a signal contribution is visible!



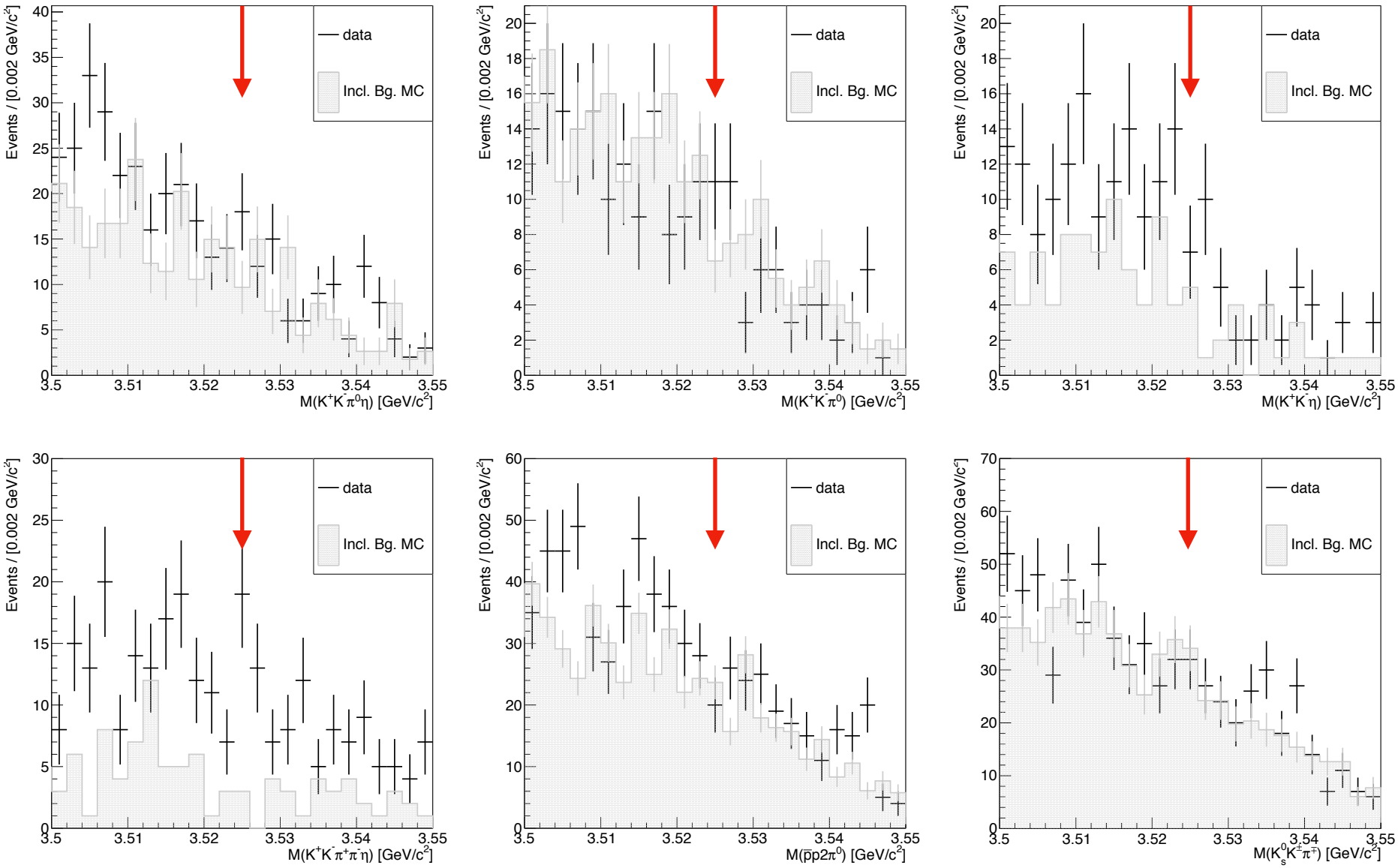


➡ determine an upper limit

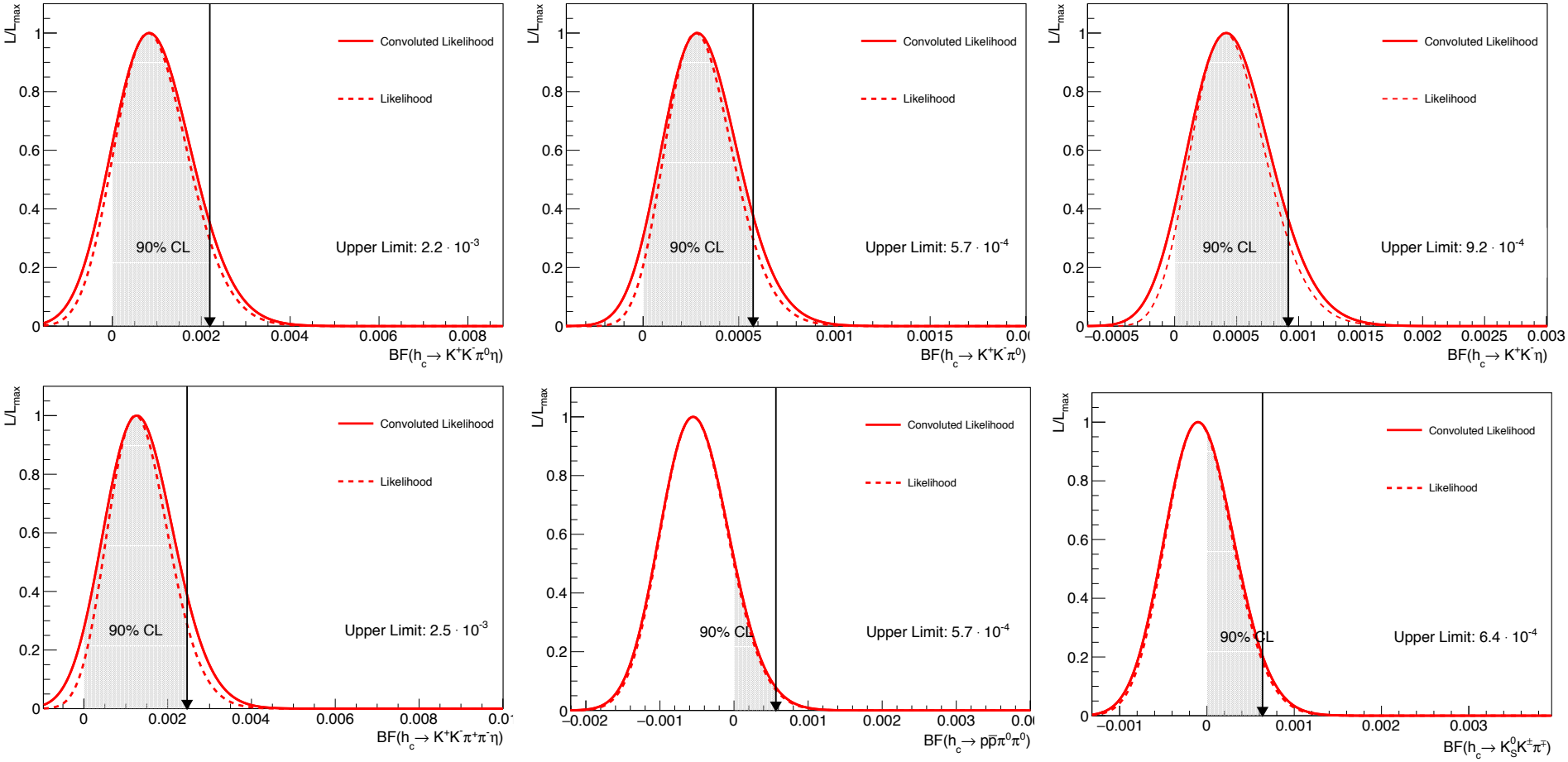
$$BF(h_c \to 2(K^+K^-)\pi^0) < 2.0 \cdot 10^{-4}$$

- systematic uncertainty of 18.5% taken into account

Same Procedure for other Final States



Same Procedure for other Final States



Summary and Outlook

- In total 10 final states have been analyzed which have never been measured before
- It was possible to find hints for 3 new decay modes of the h_c
- Furthermore indications for contributing intermediate resonances have been found for $h_c \to K^+K^-\pi^+\pi^-\pi^0$
- For all other final states upper limits have been determined
- Comprehensive systematic studies have been performed for all final states

final state	$BF(h_c \to X)$
$K^+K^-\pi^+\pi^-\pi^0$	$(3.3 \pm 0.4 \pm 0.3 \pm 0.5) \cdot 10^{-3}$
$K^0_S K^\pm \pi^\mp \pi^+ \pi^-$	$(7.6 \pm 1.7 \pm 0.9 \pm 1.1) \cdot 10^{-3}$
$\pi^+\pi^-\pi^0\eta$	$(7.3 \pm 1.9 \pm 0.8 \pm 1.1) \cdot 10^{-3}$
$2(K^+K^-)\pi^0$	$< 2.0 \cdot 10^{-4}$
$K^+K^-\pi^0$	$< 5.7 \cdot 10^{-4}$
$K^+K^-\eta$	$< 9.2 \cdot 10^{-4}$
$K^+K^-\pi^0\eta$	$< 2.2 \cdot 10^{-3}$
$K^+K^-\pi^+\pi^-\eta$	$< 2.5 \cdot 10^{-3}$
$K^0_S K^\pm \pi^\mp$	$< 6.4 \cdot 10^{-4}$
$p\bar{p}\pi^0\pi^0$	$< 5.7 \cdot 10^{-4}$

- Looking forward to taking further steps!

Thank You!

Overview of Systematic Uncertainties

final state	PID and reconstruction	selection	kinematic fit	efficiency	fit	BF	$\sqrt{\Sigma\Delta_i^2}$
$K^+K^-\pi^+\pi^-\pi^0$	7.2	5.7	1.5	5.1	2.7	15.1	18.7
$\pi^+\pi^-\pi^0\eta$	7.3	5.4	2.1	6.3	2.8	15.1	19
$2(K^+K^-)\pi^0$	7.2	4.7	2.3	5.2	3.7	15.1	18.7
$K^+K^-\pi^0$	5.3	4.2	1.9	4.1	3.8	15.1	17.6
$K^+K^-\eta$	5.3	3.5	1.9	3.7	3.4	15.1	17.2
$K^+K^-\pi^0\eta$	7.3	3.9	2	4.5	4	15.1	18.4
$K^+K^-\pi^+\pi^-\eta$	7.2	5	1.6	3.4	4.7	15.1	18.5
$K_S^0K^\pm\pi^\mp$	6.4	4.4	2.1	4	3.4	15.1	17.9
$K_S^0K^\pm\pi^\mp\pi^+\pi^-$	9	4.5	3.9	5.3	4	15.1	19.7
$p\bar{p}\pi^0\pi^0$	7.3	6.1	2.7	4.9	3.3	15.1	19