Amplitude analysis of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays using CLEO-c data

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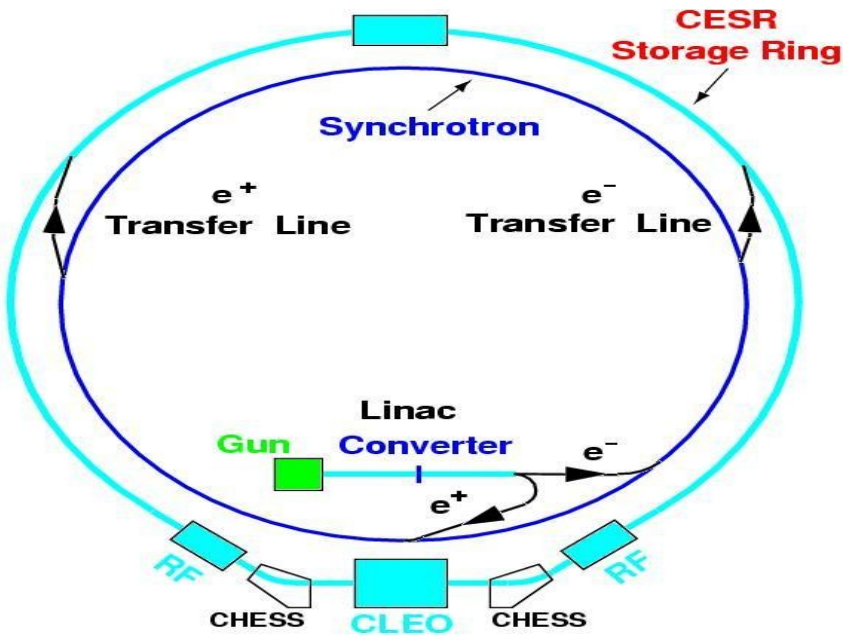
Amplitude analysis of $D \to \pi^+\pi^-\pi^+\pi^-$

- Provides insights into strong phase difference between D and $\overline{D}$ decays
  $\to$ Input for measurement of CKM angle γ in $B^- \to D\,K^-$
- Understanding of hadron dynamics
- Search for direct CP-violation

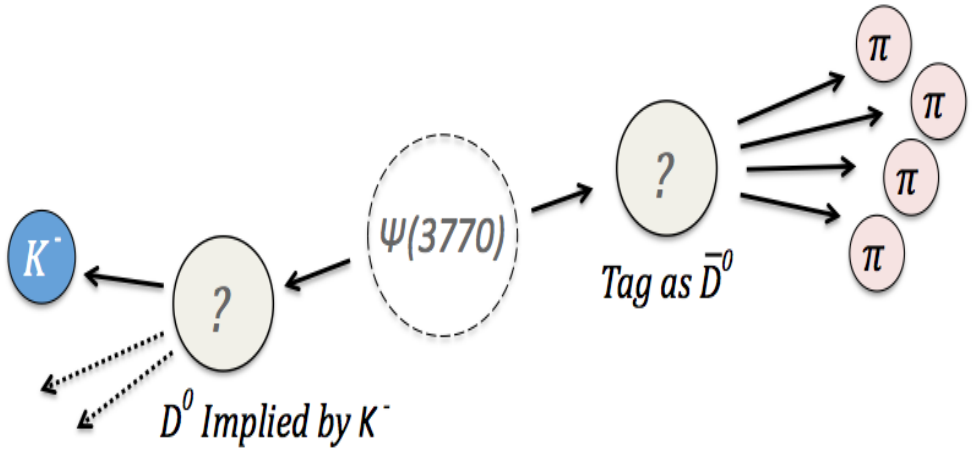
Introduction to CLEO-c



CLEO-c

- 4π detector at the Cornell Electron Storage Ring (CESR)
- Symmetric $e^+ e^-$ collider
- Operated at $\psi(3770)$ resonance
- $L_{int} = 818$ 1/pb collected

Why CLEO-c ?

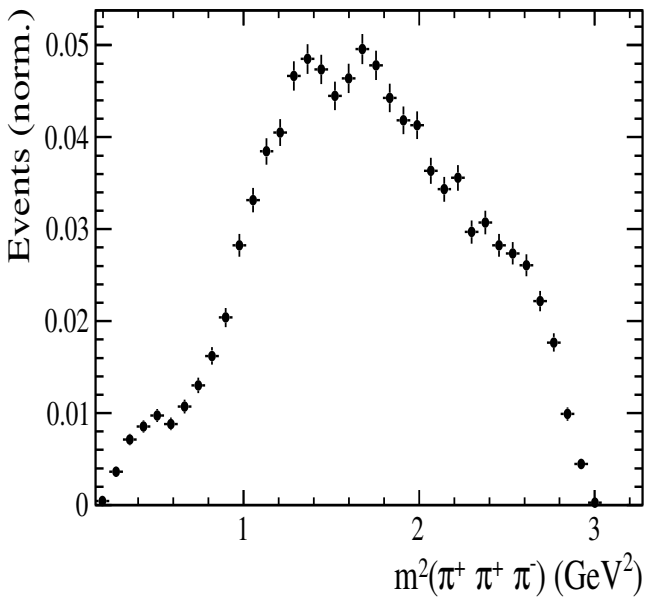


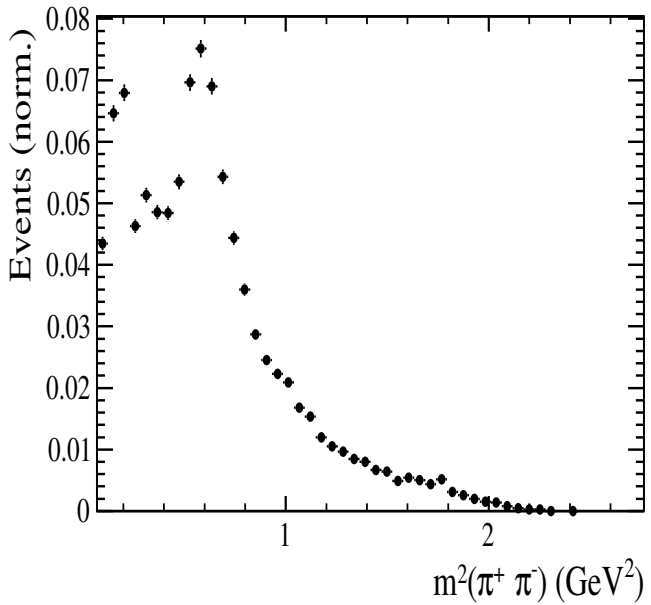
$e^+ e^- \to \psi(3770) \to D_a D_b$

- **Flavour tag:**
  $D_b \to K^- \pi^+ \Rightarrow D_a = \overline{D^0}$
- **CP tag:**
  $D_b \to K^- K^+ (CP+) \Rightarrow D_a =$ CP-
  $\mathcal{A}_{CP\pm} \approx (\mathcal{A}_{D^0} \pm \mathcal{A}_{\overline{D^0}})$
  $\Rightarrow |\mathcal{A}_{CP\pm}|^2 \approx |\mathcal{A}_{D^0}|^2 + |\mathcal{A}_{\overline{D^0}}|^2 \pm 2|\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D^0}}| \cos(\delta_D)$

Look at CLEO-c data

$\approx 8k$ $D \to 4\pi$ flavour tagged candidates

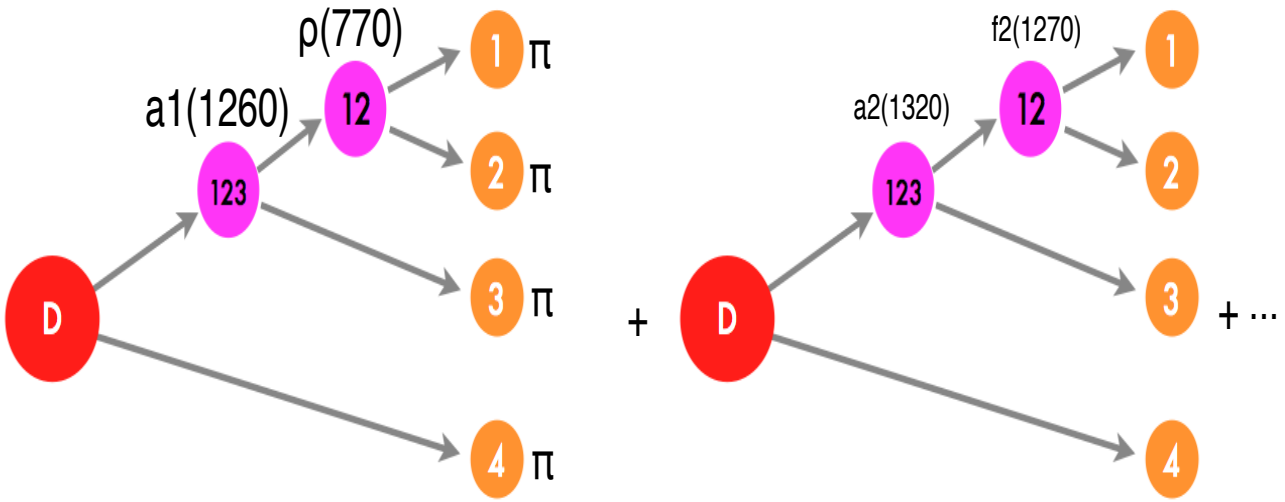




Resonances ?

- $a_1(1260) \to \pi\,\pi\,\pi$
- $\rho(770) \to \pi\,\pi$

Amplitude analysis



Isobar formalism

- Amplitude $\mathcal{A}_i \approx \mathcal{B}W_{a1}(m^2_{123}) \cdot \mathcal{B}W_{\rho}(m^2_{12}) \cdot S_f$
- $PDF \approx |\sum_i a_i \mathcal{A}_i|^2$
- Complex coefficients a_i

Decay channels

Plenty of possible decay channels ! How to select them ?

- cascade decays
  $D \to \pi^- \left[a_1(1270)^+[S,D] \to \rho(770)\,\pi^+\right]$
  $D \to \pi^- \left[a_1(1270)^+ \to \sigma\,\pi^+\right]$
- quasi-two-body
  $D \to \sigma\,\sigma$
  $D[S,P,D] \to \rho(770)\,\rho(770)$
- single resonance
  $D \to \sigma\,(\pi\pi)_S$
  $D \to \rho(770)\,(\pi\pi)_S$
- non-resonant
  $D \to (\pi\pi)_S\,(\pi\pi)_S$
  $D[P] \to (\pi\pi)_V\,(\pi\pi)_S$

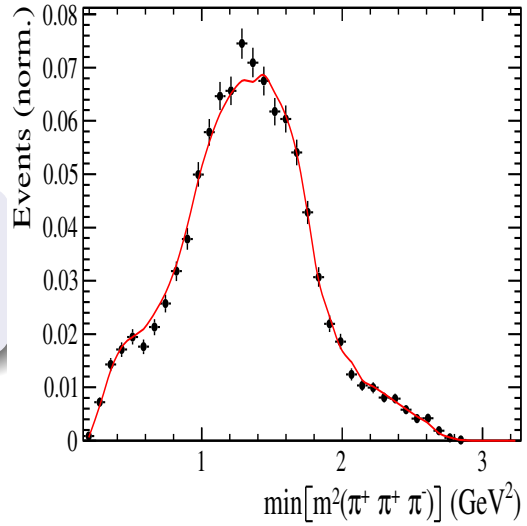
LASSO

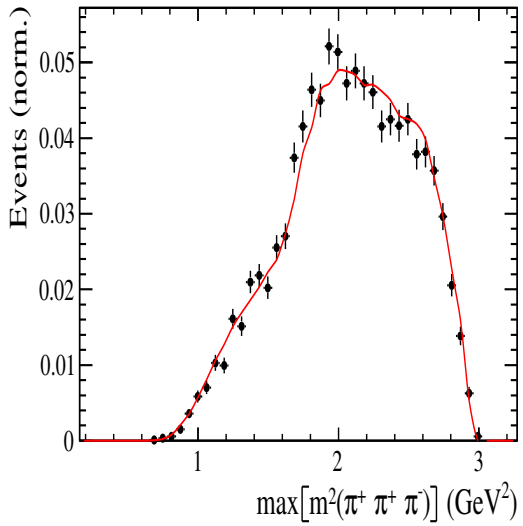
- **LASSO:** Data-driven method for model selection (M. Williams, JINST 10 (2015) no.09, P09002)
- Include "all" amplitudes, but penalize complexity in the likelihood:

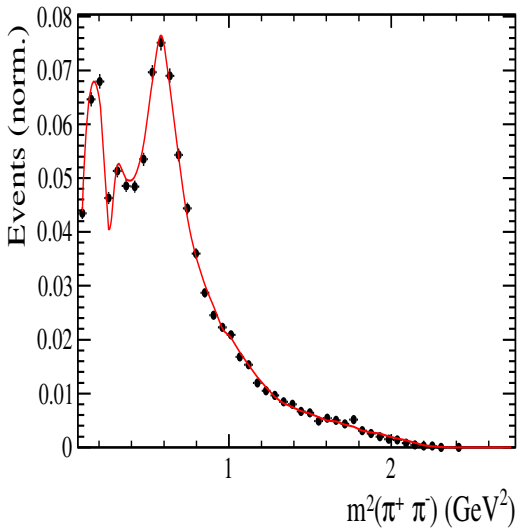
$$-2\cdot\log(L) \rightarrow -2\cdot\log(L) + \lambda \cdot \sum_i |a_i|$$

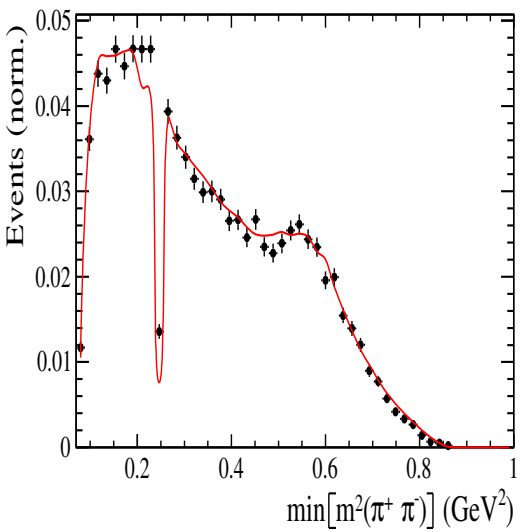
Amplitude fit

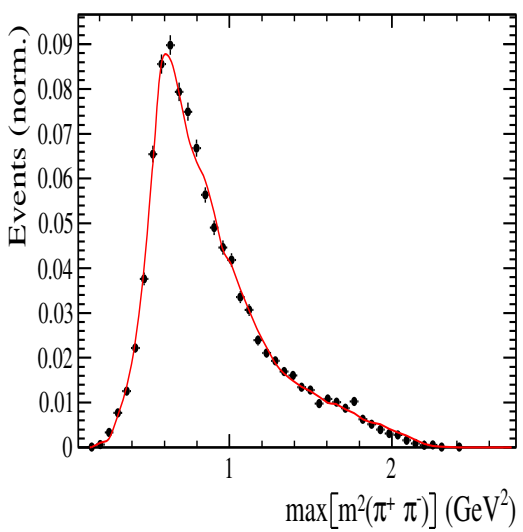
18 amplitudes selected
$\chi^2/\nu = 1.33$











Decay mode	**Fit fraction F_i[%]**
$D^0 \to \pi^- \left[a_1(1260)^+ \to \pi^+ \rho(770)\right]$	36.7 ± 2.4
$D^0 \to \pi^- \left[a_1(1260)^+ \to \pi^+ \sigma\right]$	10.9 ± 1.5
$D^0 \to \pi^+ a_1(1260)^-$	5.3 ± 0.5
$D^0 \to \pi^- \left[\pi(1300)^+ \to \pi^+ \sigma\right]$	4.2 ± 1.0
$D^0 \to \pi^- \left[\pi(1300)^+ \to \pi^+ (\pi\pi)_P\right]$	6.1 ± 0.7
$D^0 \to \pi^- \pi(1300)^-$	3.3 ± 0.6
$D^0 \to \pi^- \left[a_1(1640)^+[D] \to \pi^+ \rho(770)\right]$	3.6 ± 0.6
$D^0 \to \pi^- \left[a_1(1640)^+ \to \pi^+ \sigma\right]$	1.2 ± 0.5
$D^0 \to \pi^- \left[\pi_2(1670)^+ \to \pi^+ f_2(1270)\right]$	1.5 ± 0.3
$D^0 \to \pi^- \left[\pi_2(1670)^+ \to \pi^+ \sigma\right]$	3.3 ± 0.6
$D^0 \to \sigma f_0(1370)$	18.4 ± 1.4
$D^0 \to \sigma \rho(770)$	4.4 ± 1.0
$D^0 \to \rho(770) \rho(770)$	0.9 ± 0.3
$D^0[P] \to \rho(770) \rho(770)$	7.1 ± 0.5
$D^0[D] \to \rho(770) \rho(770)$	15.5 ± 1.2
$D^0 \to f_2(1270) f_2(1270)$	1.1 ± 0.3
Sum	123.7 ± 6.8

Preliminary results

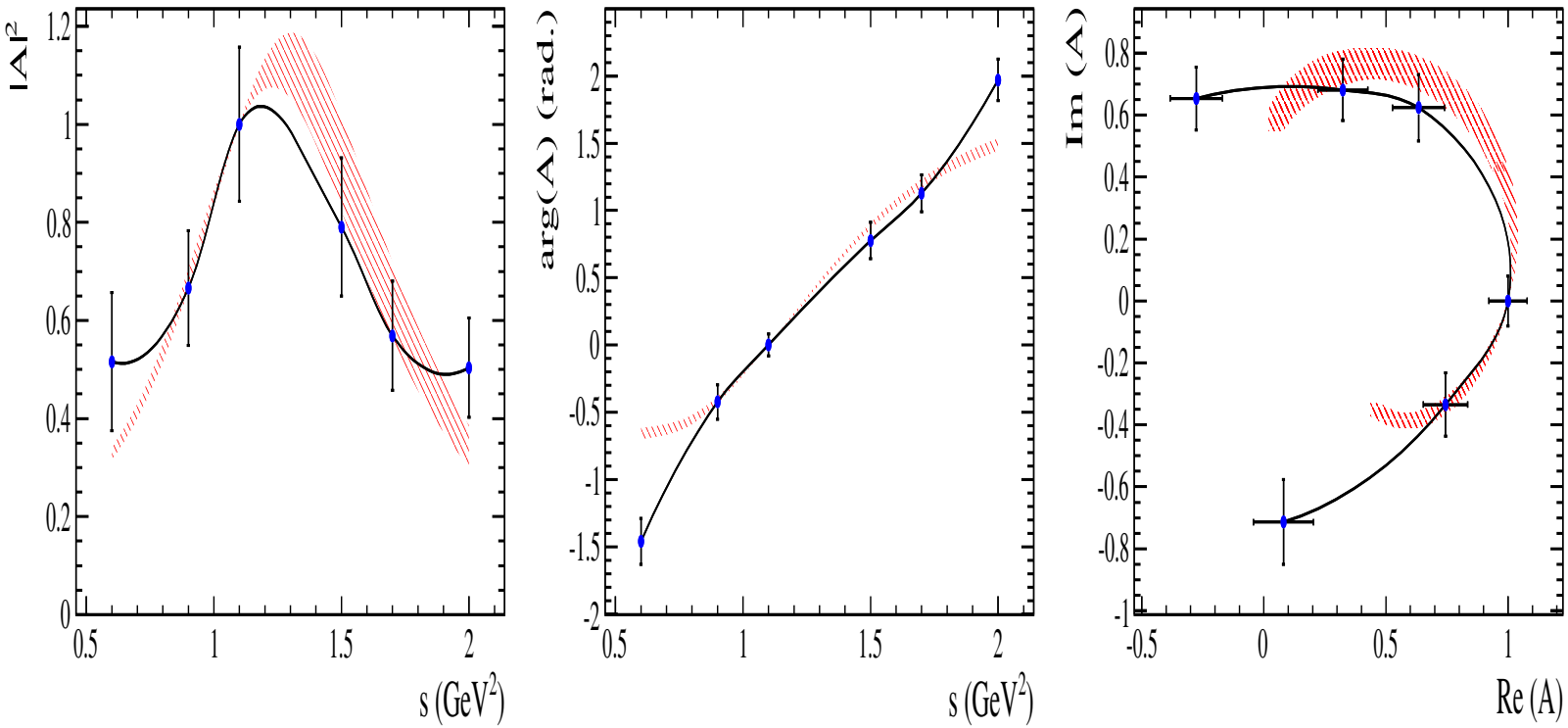
Results

Resonance		Our result	PDG
$a_1(1260)$	$m[\mathrm{MeV}]$	1231 ± 8	1230 ± 40
	$\Gamma[\mathrm{MeV}]$	459 ± 18	$250 - 600$
$\pi(1300)$	$m[\mathrm{MeV}]$	1180 ± 12	1185 ± 18
	$\Gamma[\mathrm{MeV}]$	297 ± 20	$200 - 600$
$a_1(1640)$	$m[\mathrm{MeV}]$	1644 ± 16	1647 ± 22
	$\Gamma[\mathrm{MeV}]$	222 ± 56	254 ± 27

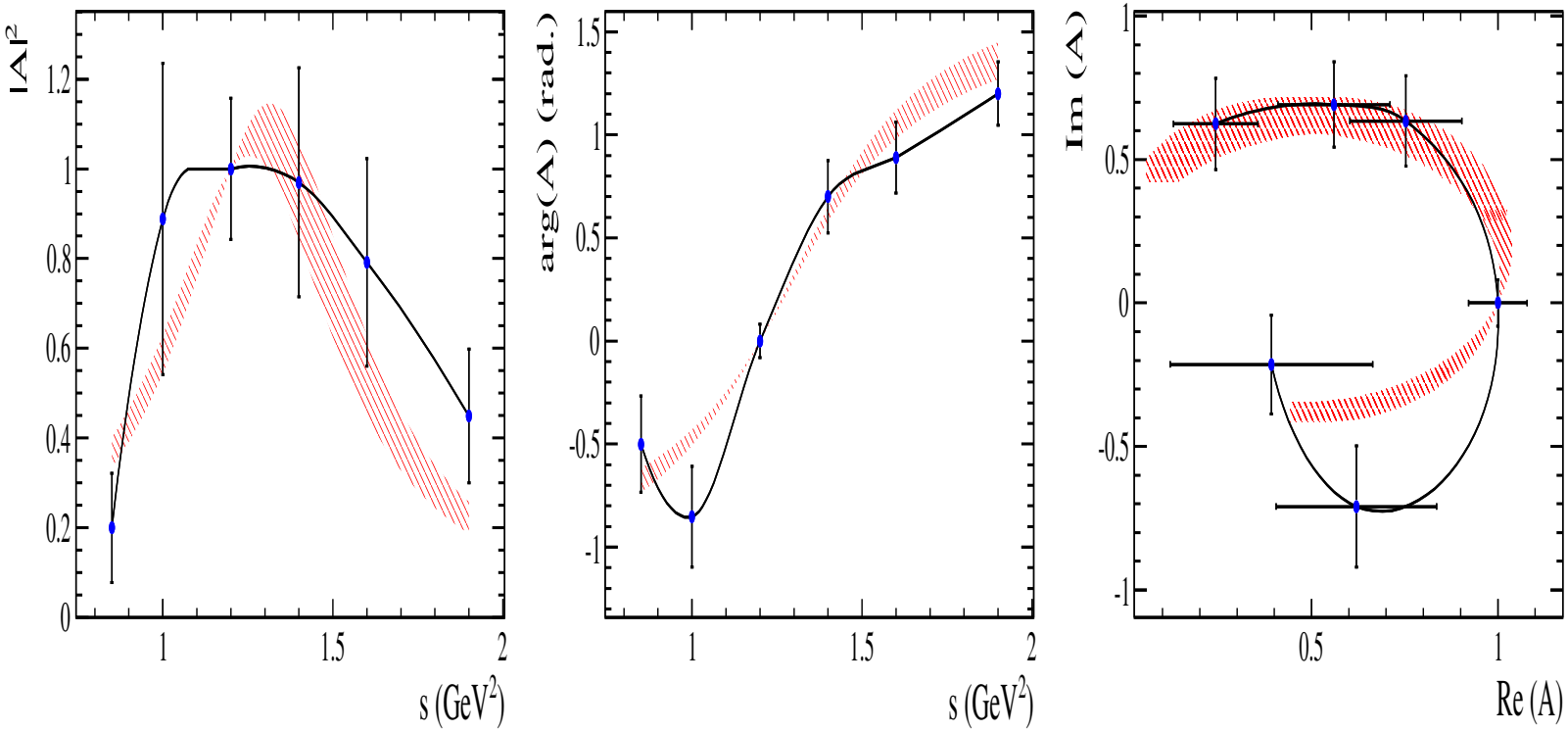
Preliminary results

Model-independent cross-check: $a_1(1260)$

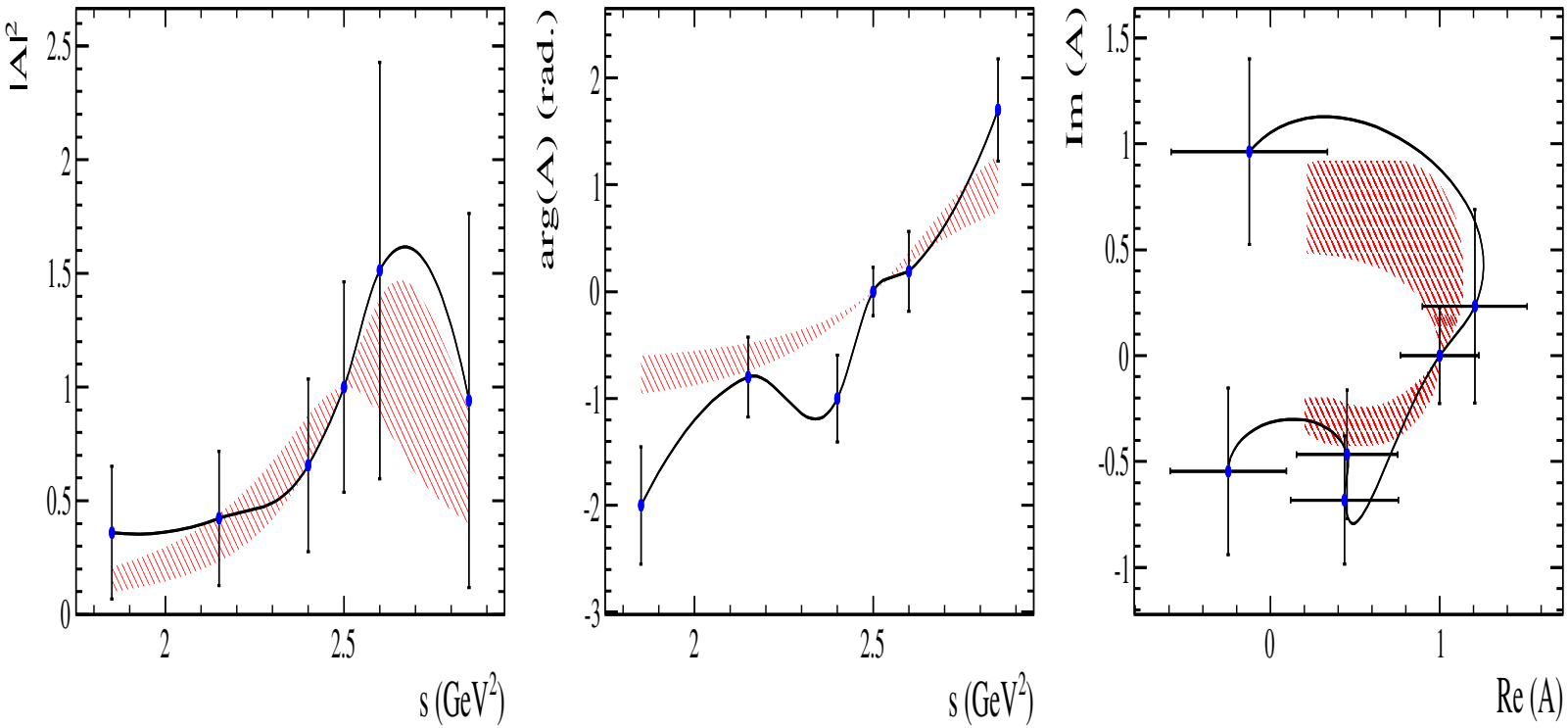
- Replace BW by cubic spline
- 6 independent complex knots placed in $m^2(\pi\pi\pi)$
- Compare with BW expectation



Model-independent cross-check: $\pi(1300)$



Model-independent cross-check: $a_1(1640)$



CP even fraction

$$F_+^{4\pi} = \frac{N_{CP+}}{N_{CP+}+N_{CP-}} = \frac{1}{2}\left(1 + \frac{1}{N}\int |A_D|\,|A_{\overline{D}}|\,cos(\delta_D)\,\mathrm{d}\phi_4\right)$$

- $F_+^{4\pi}$(flavour-tagged, model-dependent) $= (73.5 \pm 0.9)\%$
  (**Preliminary result**)
- $F_+^{4\pi}$(CP-tagged, model-independent) $= (73.7 \pm 2.8)\%$
  (Malde et al., PLB 747 (2015) 9)

Search for direct *CP*-violation

$$A_i^{CP} = \frac{F_i - \overline{F}_i}{F_i + \overline{F}_i}$$

Decay mode	A_i^{CP} [%]
$D^0 \to \pi^- a_1(1260)^+$	5.0 ± 3.2
$D^0 \to \pi^+ a_1(1260)^-$	6.8 ± 13.2
$D^0 \to \pi^- \pi(1300)^+$	-7.4 ± 8.0
$D^0 \to \pi^+ \pi(1300)^-$	-9.6 ± 16.5
$D^0 \to \pi^- a_1(1640)^+$	7.8 ± 12.5
$D^0 \to \pi^- \pi_2(1670)^+$	6.7 ± 14.0
$D^0 \to \sigma f_0(1370)$	-8.7 ± 4.5
$D^0 \to \sigma \rho(770)$	26.3 ± 15.2
$D^0 \to \rho(770) \rho(770)$	-46.7 ± 34.0
$D^0[P] \to \rho(770) \rho(770)$	-9.1 ± 7.9
$D^0[D] \to \rho(770) \rho(770)$	-7.9 ± 8.3
$D^0 \to f_2(1270) f_2(1270)$	-28.7 ± 20.7
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	-5.5 ± 3.3

No evidence for *CP*-violation (**Preliminary results**)

Conclusion

Summary

- First flavour tagged amplitude analysis of $D \to \pi^+\pi^-\pi^+\pi^-$ [preliminary results]
- Verified resonant phase motion of observed $a_1(1260)$, $\pi(1300)$ and $a_1(1640)$ states
- *CP*-even fraction consistent with model-independent measurement
- No evidence for *CP*-violation

Follow-up analyses

- Model-independent measurement of δ_D in multiple phase-space bins for $D \to \pi^+\pi^-\pi^+\pi^-$ [in preparation]
- Will allow measurement of γ in $B^- \to DK^-$, $D \to \pi^+\pi^-\pi^+\pi^-$ (like for $K_S\pi\pi$)

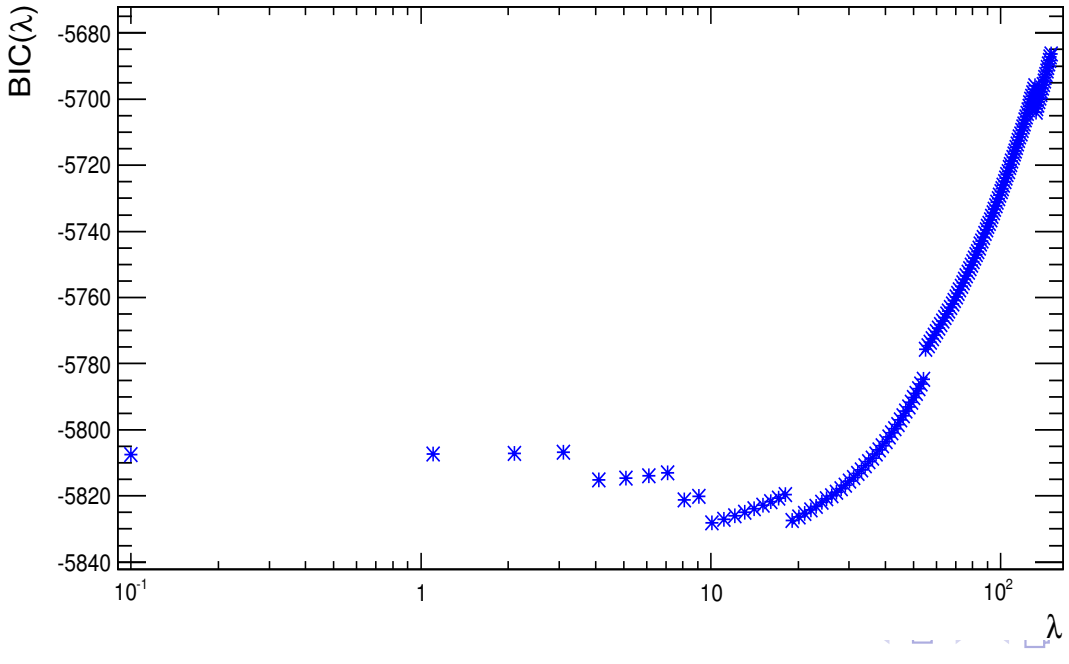
Acknowledgement

We thank the former CLEO collaboration for the privilege to use their precious data !

Backup: LASSO

How to choose λ ?

- $\mathrm{BIC}(\lambda) = -2 \cdot \log(L) + r \cdot \log(N_{events})$
  r = amplitudes with fit fraction $>$ threshold (0.5 %)
- Balances **gain in fit quality vs. complexity**
- Optimal value $\lambda \approx 20$

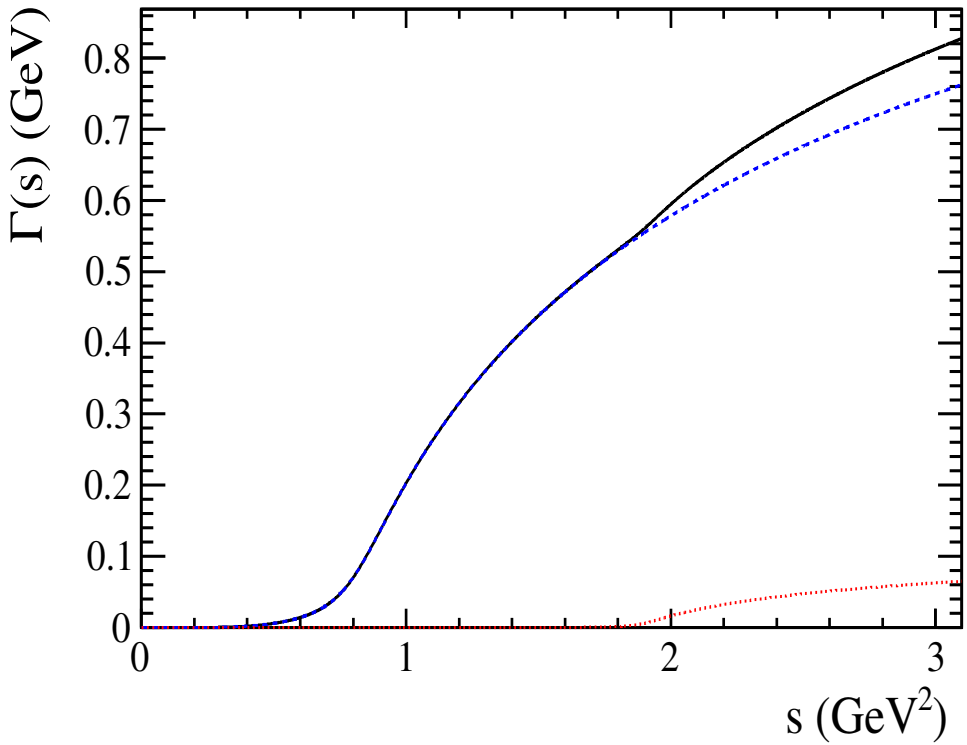


Decay mode	**LASSO**	**No $\pi(1300)$**	**No $a_1(1640)$**
$D^0 \to \pi^- \left[a_1(1260)^+ \to \pi^+ \rho(770)\right]$	36.7 ± 2.4	44.4 ± 3.3	46.2 ± 2.7
$D^0 \to \pi^- \left[a_1(1260)^+[D] \to \pi^+ \rho(770)\right]$	-	-	4.4 ± 0.5
$D^0 \to \pi^- \left[a_1(1260)^+ \to \pi^+ \sigma\right]$	10.9 ± 1.5	5.1 ± 0.7	8.3 ± 1.0
$D^0 \to \pi^+ a_1(1260)^-$	5.3 ± 0.5	3.0 ± 0.5	2.3 ± 0.4
$D^0 \to \pi^- \left[\pi(1300)^+ \to \pi^+ (\pi^+ \pi^-)_P\right]$	6.1 ± 0.7	-	7.0 ± 1.2
$D^0 \to \pi^- \left[\pi(1300)^+ \to \pi^+ \sigma\right]$	4.2 ± 1.0	-	10.0 ± 2.0
$D^0 \to \pi^+ \pi(1300)^-$	3.9 ± 0.6	-	9.2 ± 1.3
$D^0 \to \pi^- \left[a_1(1640)^+[D] \to \pi^+ \rho(770)\right]$	3.6 ± 0.6	4.3 ± 1.2	-
$D^0 \to \pi^- \left[a_1(1640)^+ \to \pi^+ \sigma\right]$	1.2 ± 0.5	-	-
$D^0 \to \pi^- \left[a_1(1640)^+ \to \pi^+ f_2(1270)\right]$	-	2.4 ± 0.6	-
$D^0 \to \pi^- \left[\pi_2(1670)^+ \to \pi^+ f_2(1270)\right]$	1.5 ± 0.3	8.1 ± 1.9	0.4 ± 0.1
$D^0 \to \pi^- \left[\pi_2(1670)^+ \to \pi^+ \sigma\right]$	3.3 ± 0.6	3.9 ± 0.6	0.5 ± 0.2
$D^0 \to \pi^+ \pi_2(1670)^-$	-	-	1.6 ± 0.6
$D^0 \to \sigma f_0(1370)$	18.4 ± 1.4	4.4 ± 0.5	-
$D^0 \to f_0(1370) f_0(1370)$	-	-	12.7 ± 1.4
$D^0 \to \sigma \rho(770)$	4.4 ± 1.0	7.5 ± 0.9	-
$D^0 \to f_0(1370) \rho(770)$	-	-	4.7 ± 0.9
$D^0 \to \rho(770) \rho(770)$	0.9 ± 0.3	3.4 ± 0.8	-
$D^0[P] \to \rho(770) \rho(770)$	7.1 ± 0.5	8.1 ± 0.6	7.1 ± 0.7
$D^0[D] \to \rho(770) \rho(770)$	15.5 ± 1.2	7.0 ± 1.0	17.5 ± 1.6
$D^0 \to f_2(1270) \sigma$	-	4.2 ± 1.2	2.07 ± 0.6
$D^0 \to f_2(1270) f_0(980)$	-	3.0 ± 0.7	0.6 ± 0.3
$D^0 \to f_2(1270) (\pi \pi)_P$	-	4.3 ± 0.9	-
$D^0 \to f_2(1270) f_2(1270)$	1.1 ± 0.3	9.6 ± 1.9	-
$D^0[D] \to (\pi^+ \pi^-)_P (\pi^+ \pi^-)_P$	-	7.8 ± 1.0	-

Backup: Running width

- $\Gamma_{a1}(s) = \Gamma_{\pi\pi\pi}(s) + \Gamma_{KK^*}(s)$
- $\Gamma_{\pi\pi\pi}(s) = \frac{1}{s}\int |A(s_{12}, s_{23})|^2 ds_{12} ds_{23}$

97 % : $a_1(1260) \to \pi\pi\pi$
3 % : $a_1(1260) \to K^*(892)K$



Backup: Systematics

Error sources

- $f_{bkg} = 18.5 \pm 0.8\%$
- background shape
- mistag prob. $\omega = 4.5 \pm 0.5\%$
- efficiency
- fitter bias
- resonance parameters
- form factors

$$\sigma_{sys} \approx 1 \text{ to } 3\,\sigma_{stat}$$