

# $DK$ Scattering and $D_{s0}^*(2317)$

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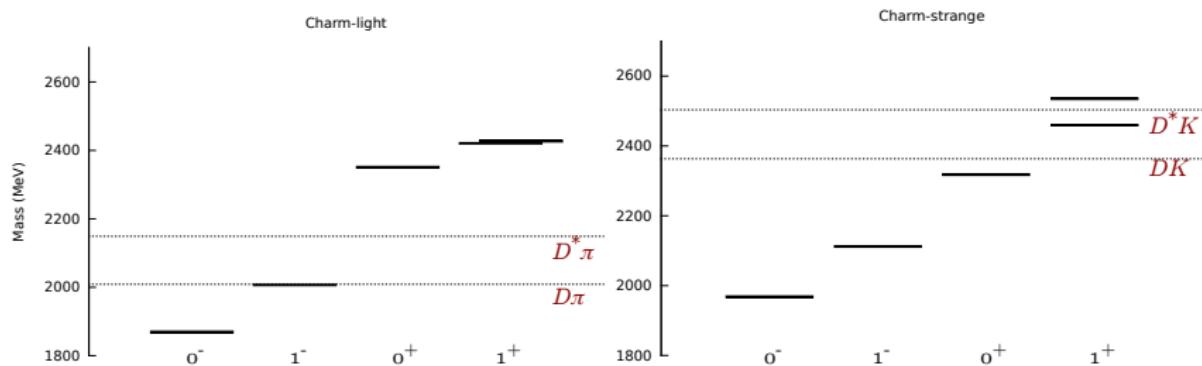


Hadron Spectrum Collaboration



26 May 2018

# Open Charm Mesons ( $c\bar{l}$ and $c\bar{s}$ )



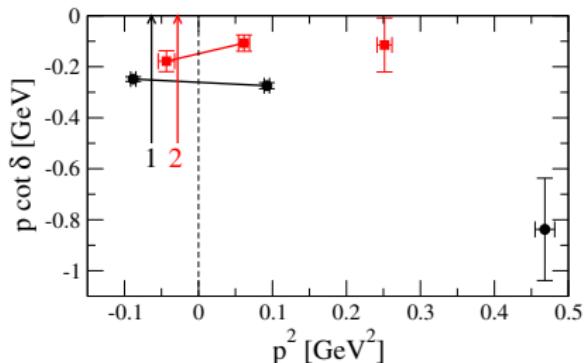
- ▶ Charm-light  $0^+$  and  $1^+$  above  $D^{(*)}\pi$  threshold. In agreement with quark model predictions.
- ▶ Charm-strange  $0^+$  and  $1^+$  below  $D^{(*)}K$  threshold. Exotic?

# $J^P = 0^+$ Mesons

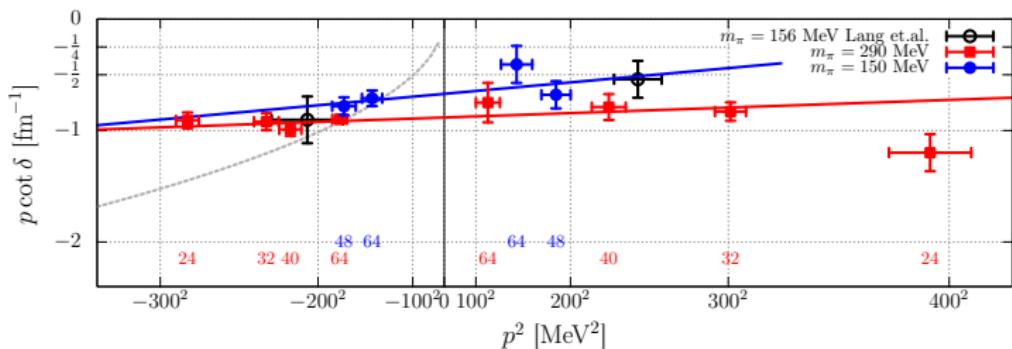
$J^P = 0^+$	Mass (MeV)	Width (MeV)
$D_0^*(2400)$	2318(29)	267(40)
$D_{s0}^*(2317)$	2317.6(6)	< 3.8

- ▶ There is difficulty in assigning  $D_{s0}^*(2317)$  as a conventional quark model state.
- ▶ Molecule? Tetraquark? Threshold effects?
- ▶ Only way to understand this from first principles is to use lattice QCD.
- ▶ Relevant quantities to compute are isospin-0  $DK$  scattering amplitudes.

# Previous lattice QCD studies



2 energy levels [Lang, Leskovec, Mohler, Prelovsek, Woloshyn, Phys. Rev. D 90, 034510 (2014)]



$N_f = 2$  [Bali, Collins, Cox, Schäfer, Phys. Rev. D 96, 074501 (2017)]

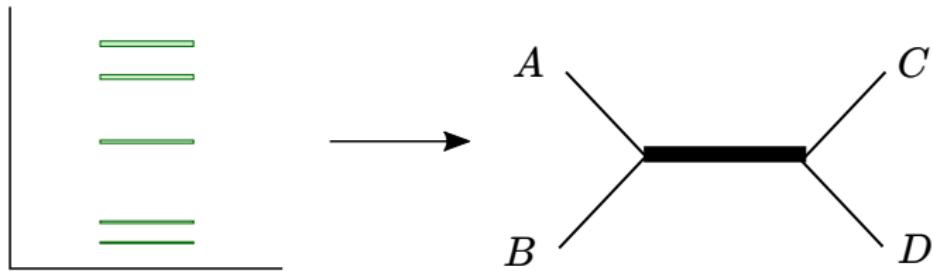
# Objectives and calculation details

- ▶ Determine elastic isospin-0  $DK$  scattering amplitudes from **many energy levels** in multiple irreps using Lüscher method.

Lattice Size	$a_s$ (fm)	$\frac{a_s}{a_t}$	$M_\pi$ (MeV)	$M_K$ (MeV)	$M_\pi L$	$N_{\text{cfgs}}$
$32^3 \times 256$	0.12	3.5	236	500	4.4	484

- ▶ Anisotropic  $\mathbf{N_f} = \mathbf{2 + 1}$  ensemble with Symanzik-improved gauge action and Clover fermion action.

# Scattering in lattice QCD: Lüscher Method



- ▶ Finite-volume spectrum  $E_n \rightarrow$  Scattering amplitudes in infinite-volume  $\mathcal{M}$

$$\det[F^{-1}(E_n, \vec{P}, L) + \mathcal{M}(E_n)] = 0$$

- ▶ Matrices in partial wave space.  $\mathcal{M}$  an infinite-volume quantity and diagonal in partial wave space.
- ▶  $F$  a known function of energy, momentum of frame  $\vec{P}$  and volume  $L$ . Mixes partial waves.

# Obtaining finite-volume spectra from correlation functions

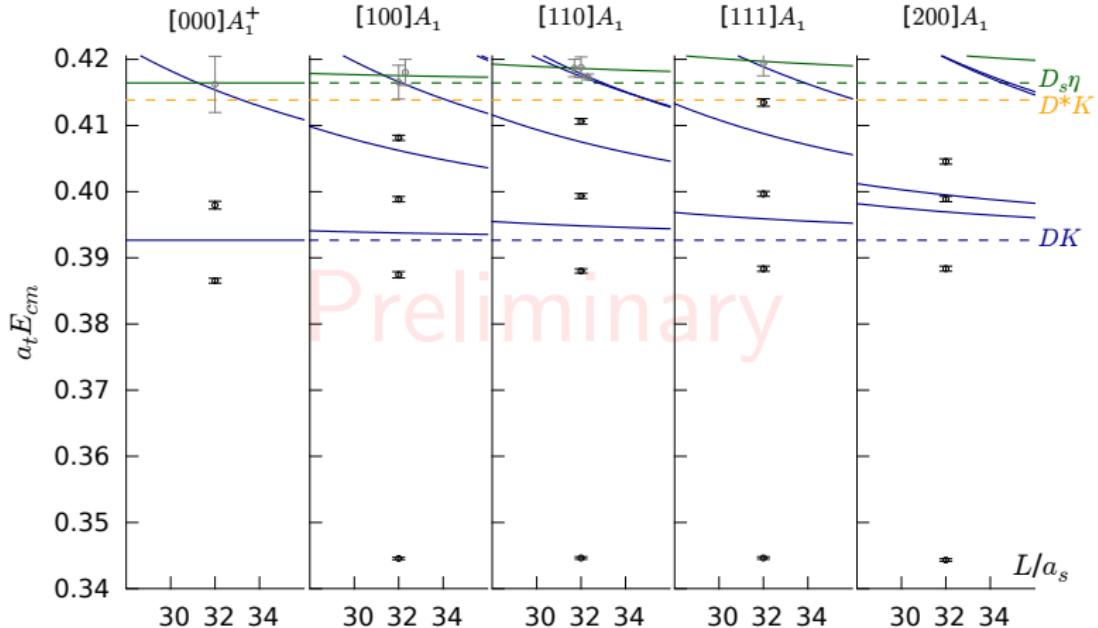
- ▶ Calculate matrices of two-point correlation functions for various momenta and irreps with a large operator basis of
  - ▶  $q\bar{q}$ -like  
 $\bar{q}\Gamma D \dots Dq$
  - ▶ Meson-meson-like
    - $\sum_{\vec{p}_1, \vec{p}_2} C(\vec{p}_1, \vec{p}_2; \vec{P}) D(\vec{p}_1) K(\vec{p}_2)$
    - $\sum_{\vec{p}_1, \vec{p}_2} C(\vec{p}_1, \vec{p}_2; \vec{P}) D_s(\vec{p}_1) \eta(\vec{p}_2)$
    - ...

[HadSpec, Phys.Rev. D82 (2010) 034508]

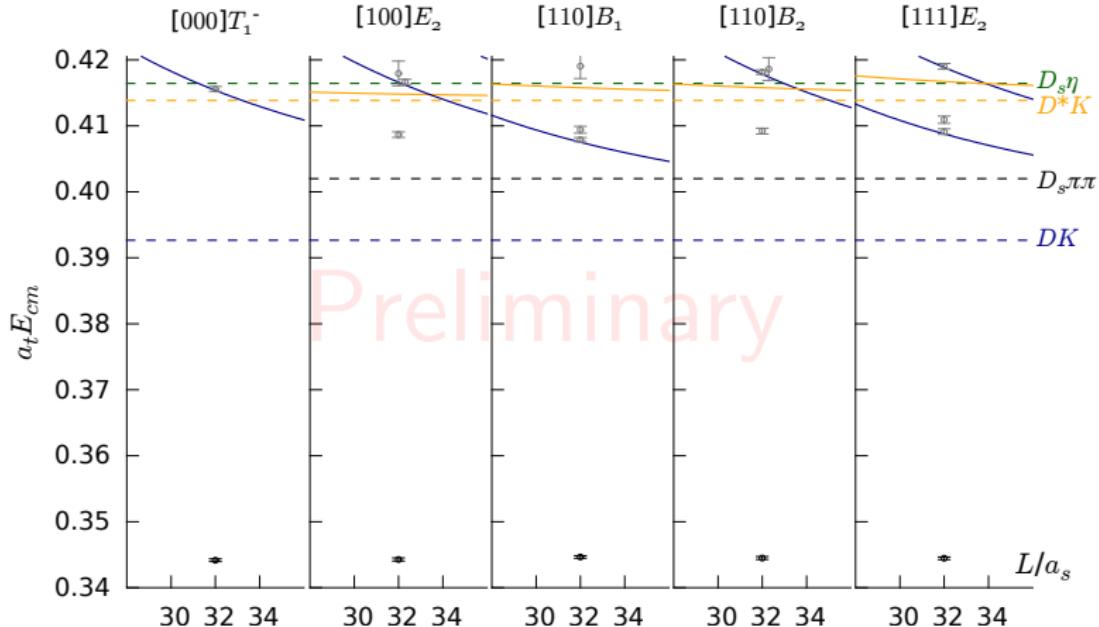
[HadSpec, Phys.Rev. D86 (2012) 034031]

- ▶ **All** Wick contractions evaluated including disconnected contributions using distillation framework.  $N_{\text{vec}} = 256$ .
- ▶ Finite-volume spectrum is extracted from correlation functions using variational method.

# Finite-volume spectrum ( $\ell \geq 0$ )



# Finite-volume spectrum ( $\ell \geq 1$ )



# Obtaining scattering amplitudes

$$\det[F^{-1}(E_n, \vec{P}, L) + \mathcal{M}(E_n)] = 0$$

- ▶ Matrices are infinite in partial wave space.
- ▶ Ignore  $\ell \geq 1$  partial wave contributions:  
 $\cot \delta_0(E_n) + \cot \phi(E_n, \vec{P}, L) = 0$
- ▶ Include  $\ell = 0, 1$  partial waves but quantisation condition becomes underdetermined. Parametrise energy dependence of amplitude whilst preserving unitarity.

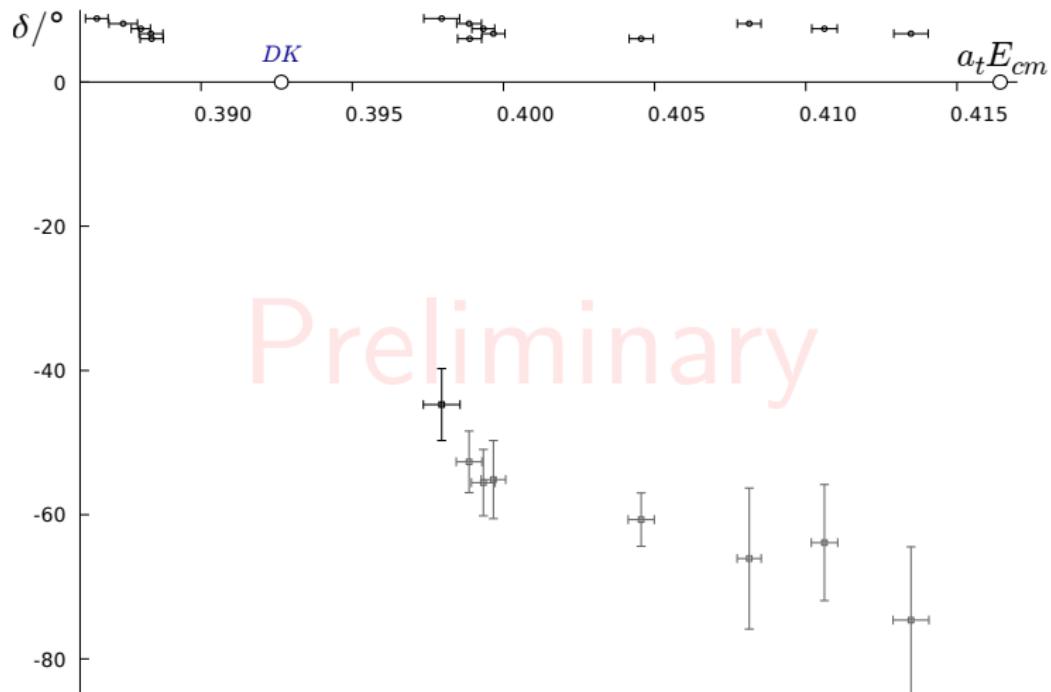
E.g.

$$\mathcal{M}^{-1}(s) = K^{-1}(s) + I(s)$$

$$K(s) = \frac{g^2}{m^2 - s} + c, \quad \text{Im}[I(s)] = -\rho$$

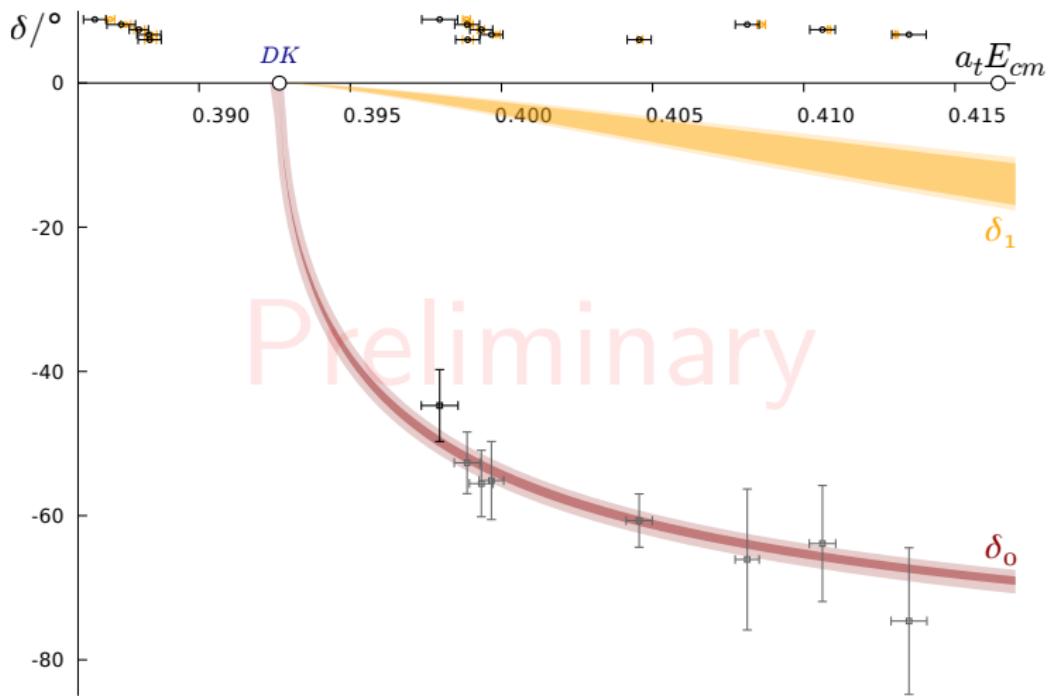
[HadSpec, Phys.Rev. D91 (2015) no.5, 054008]

# Phase shift



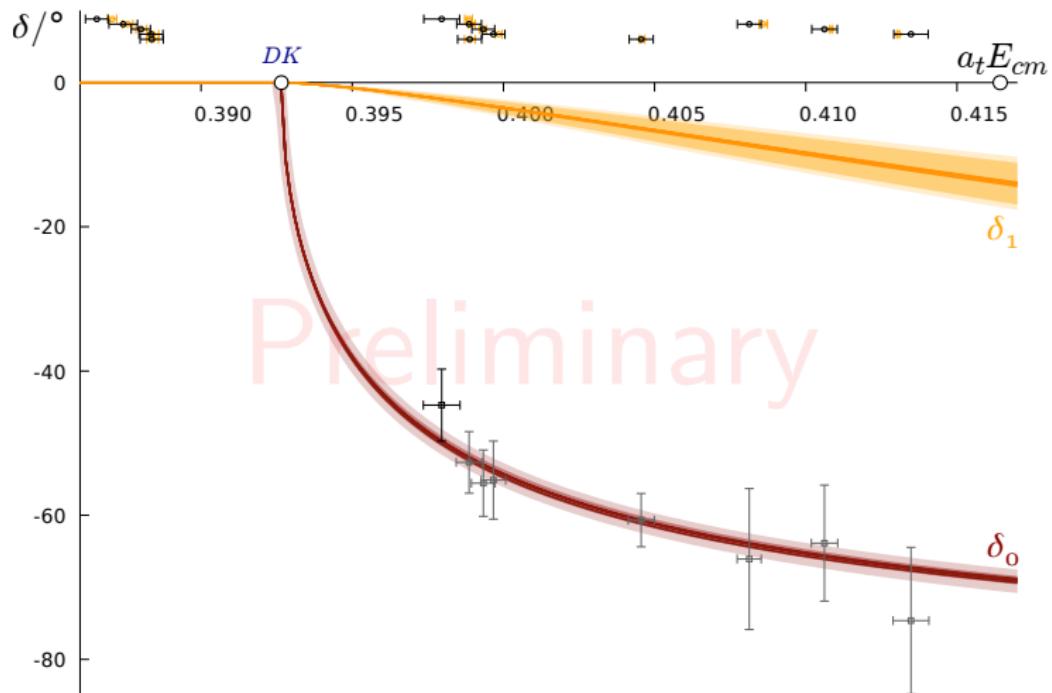
Ignore  $\ell \geq 1$  partial wave contributions and solve  
 $\cot \delta_0(E_n) + \cot \phi(E_n, \vec{P}, L) = 0$ .

# Phase shift



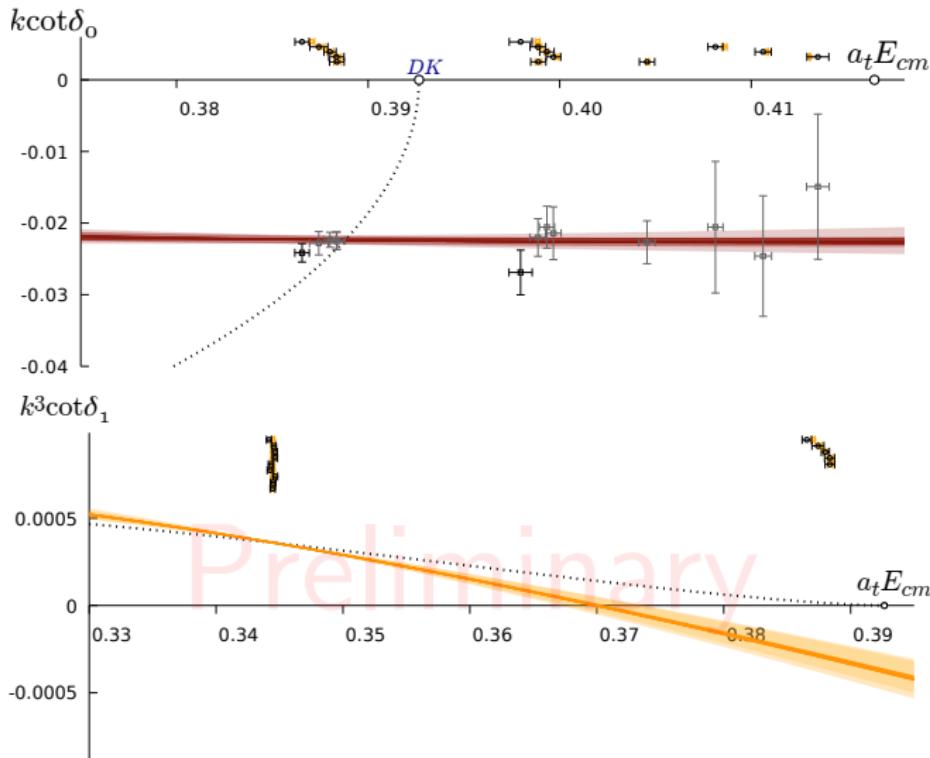
Parametrise  $K_{\ell=0} = \frac{g_0^2}{m_0^2 - s} + \gamma$  and  $K_{\ell=1} = \frac{g_1^2}{m_1^2 - s}$ . Orange points show data reproduced successfully.

# Phase shift



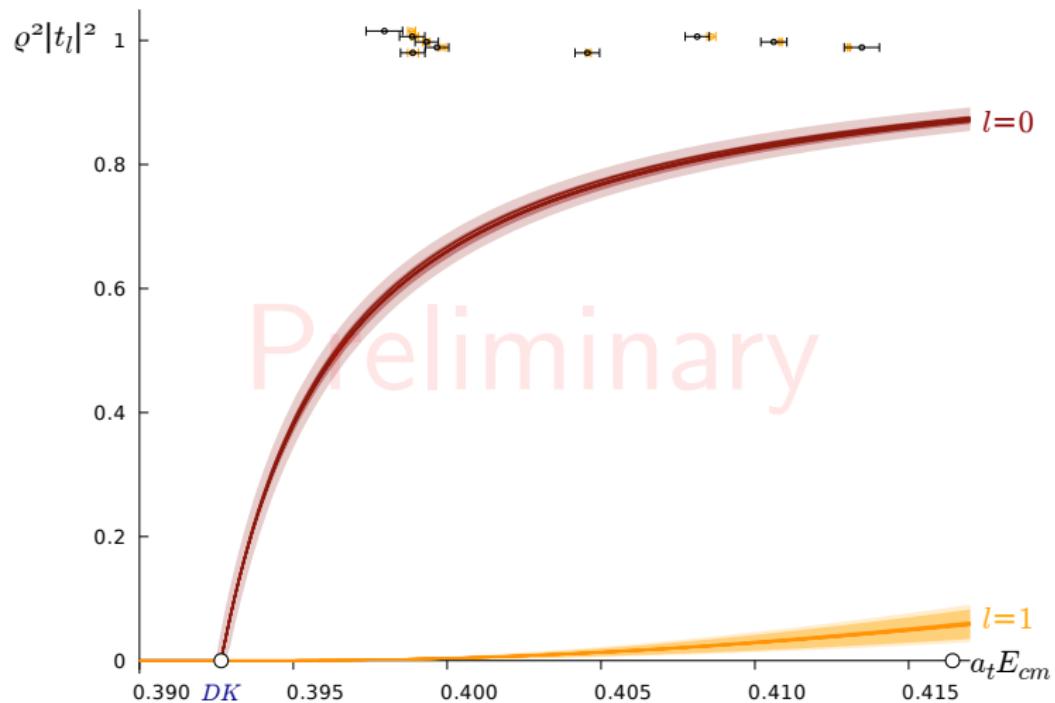
Eight parametrisations showing little variation.

$$k^{2l+1} \cot \delta$$



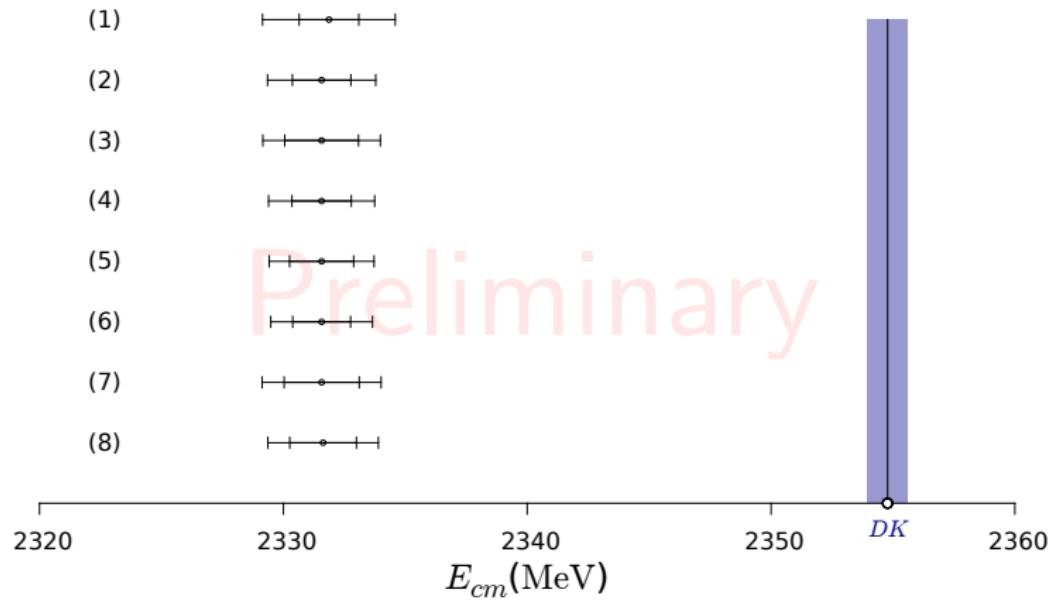
Bound state pole below threshold on physical sheet occurs at  
 $k^{2l+1} \cot \delta_l = ik^{2l+1}$ .

# 'Cross section'



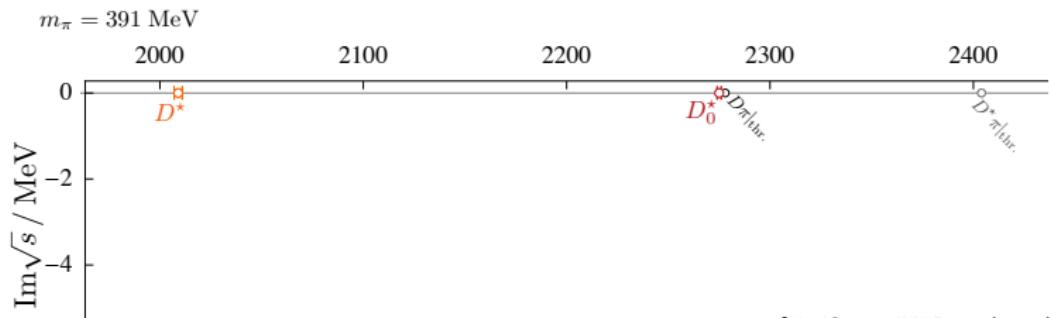
Rapid rise in 'cross section' gives further hint of pole.

# Singularity content of scattering amplitudes



$J^P = 0^+$  bound state pole near threshold on real axis of physical  
21(3) MeV below threshold c.f. experiment  $\approx 40$  MeV. Good  
qualitative agreement with experiment.

# Quark mass dependence



[HadSpec, JHEP 10 (2016) 011]

- ▶ Interesting to compare with previous HadSpec results on  $D\pi$  scattering on  $M_\pi = 391$  MeV ensembles where a  $J^P = 0^+$  pole was found closer to threshold.
- ▶ Similar quark flavours ( $c\bar{q}_1)(q_1\bar{q}_2)$  but different quark masses.
- ▶  $D_{s0}^*(2317)$  more stable than  $D_0^*(2400)$  because of heaviness of strange quark?

## Conclusion and outlook

- ▶ Many energy levels used to map out the  $DK$  scattering amplitude. Bound state pole found that is qualitatively consistent with  $D_{s0}^*(2317)$ .
  
- ▶ Coupled-channel scattering:  $D_s\eta$ .
- ▶  $D^*K$  scattering to study  $D_{s1}(2460)$ .
- ▶ Understanding of pion mass dependence.
- ▶ Radiative transition  $D_{s0}^*(2317) \rightarrow D_s^*\gamma$ .

Thank you!



## Hadron Spectrum Collaboration

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**Tata Institute:** Nilmani Mathur



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# Operators

$[000]A_1^+$	$[100]A_1$	$[110]A_1$	$[111]A_1$	$[200]A_1$
$D_{A_1}^{[000]} K_{A_1}^{[000]}$	$D_{A_2}^{[100]} K_{A_1}^{[000]}$	$D_{A_2}^{[110]} K_{A_1}^{[000]}$	$D_{A_2}^{[111]} K_{A_1}^{[000]}$	$D_{A_2}^{[200]} K_{A_1}^{[000]}$
$D_{A_2}^{[100]} K_{A_2}^{[100]}$	$D_{A_1}^{[000]} K_{A_2}^{[100]}$	$D_{A_2}^{[100]} K_{A_2}^{[100]}$	$D_{A_2}^{[110]} K_{A_2}^{[100]}$	$D_{A_2}^{[100]} K_{A_2}^{[100]}$
$D_{A_2}^{[110]} K_{A_2}^{[110]}$	$D_{A_2}^{[110]} K_{A_2}^{[100]}$	$D_{A_1}^{[000]} K_{A_2}^{[110]}$	$D_{A_2}^{[100]} K_{A_2}^{[110]}$	$D_{A_2}^{[210]} K_{A_2}^{[100]}$
$D_{A_2}^{[111]} K_{A_2}^{[111]}$	$D_{A_2}^{[200]} K_{A_2}^{[100]}$	$D_{A_2}^{[111]} K_{A_2}^{[100]}$	$D_{A_2}^{[000]} K_{A_2}^{[111]}$	$D_{A_2}^{[110]} K_{A_2}^{[110]}$
$D_{sA_1} \eta_{A_1}$	$D_{sA_2} \eta_{A_2}$	$D_{sA_2} \eta_{A_2}$	$D_{sA_2} \eta_{A_2}$	$D_{sA_1} \eta_{A_2}$
$D_{sA_1} \eta_{A_1}$				
$D_{sA_2} \eta_{A_2}$	$D_{sA_2} \eta_{A_1}$	$D_{sA_2} \eta_{A_1}$	$D_{sA_2} \eta_{A_1}$	$D_{sA_2} \eta_{A_2}$
$D_{sA_2} \eta_{A_2}$	$D_{sA_1} \eta_{A_2}$	$D_{sA_1} \eta_{A_2}$	$D_{sA_1} \eta_{A_2}$	$D_{sA_1} \eta_{A_2}$
$D_s^{*[100]} \sigma_{A_1}^{[000]}$	$D_s^{*[100]} \sigma_{A_1}^{[000]}$	$D_s^{*[110]} \sigma_{A_1}^{[000]}$	$D_s^{*[110]} \sigma_{A_1}^{[000]}$	$D_s^{*[200]} \sigma_{A_1}^{[000]}$
		$D_s^{*[110]} \sigma_{A_1}^{[000]}$	$D_s^{*[111]} \sigma_{A_1}^{[000]}$	$D_s^{*[111]} \sigma_{A_1}^{[000]}$
		$D_s^{*[110]} \sigma_{A_1}^{[000]}$	$D_s^{*[111]} \sigma_{A_1}^{[000]}$	$D_s^{*[200]} \sigma_{A_1}^{[000]}$
		$D_s^{*[100]} K_{A_2}^{[100]}$	$D_s^{*[110]} K_{A_2}^{[100]}$	$D_s^{*[100]} K_{A_1}^{[100]}$
		$D_s^{*[100]} K_{A_2}^{[100]}$	$D_s^{*[111]} K_{A_2}^{[100]}$	$D_s^{*[100]} K_{A_1}^{[100]}$
$(\bar{\psi} \Gamma \psi) \times 18$	$(\bar{\psi} \Gamma \psi) \times 32$	$(\bar{\psi} \Gamma \psi) \times 52$	$(\bar{\psi} \Gamma \psi) \times 36$	$(\bar{\psi} \Gamma \psi) \times 32$

## Partial Waves

$\vec{P}$	$\text{LG}(\vec{P})$	$\Lambda(P)$	$I^N$
[000]	$O_h^D$	$A_1^+$ $T_1^-$	$0^1, 4^1$ $1^1, 3^1$
[n00]	$\text{Dic}_4$	$A_1$ $E_2$	$0^1, 1^1, 2^1, 3^1, 4^2$ $1^1, 2^1, 3^2, 4^2$
[nn0]	$\text{Dic}_2$	$A_1$ $B_1$ $B_2$	$0^1, 1^1, 2^2, 3^2, 4^3$ $1^1, 2^1, 3^2, 4^2$ $1^1, 2^1, 3^2, 4^2$
[nnn]	$\text{Dic}_3$	$A_1$ $E_2$	$0^1, 1^1, 2^1, 3^2, 4^2$ $1^1, 2^2, 3^2, 4^3$