Observation of new resonances decaying to Dπ and D*π

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Workshop: Decay B → D** and related issues
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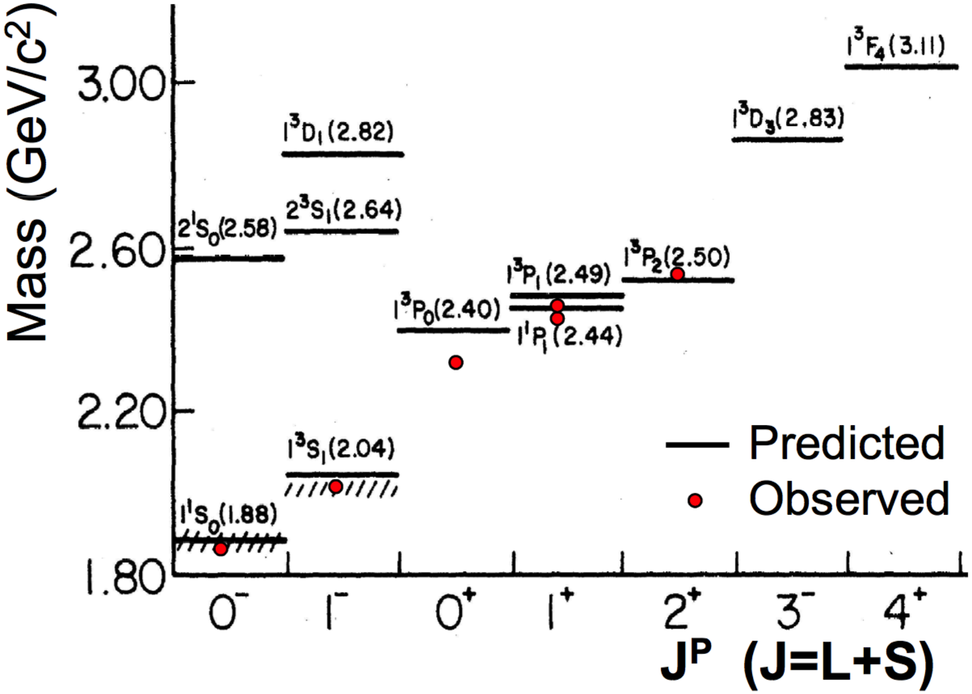
The spectrum of charmed mesons

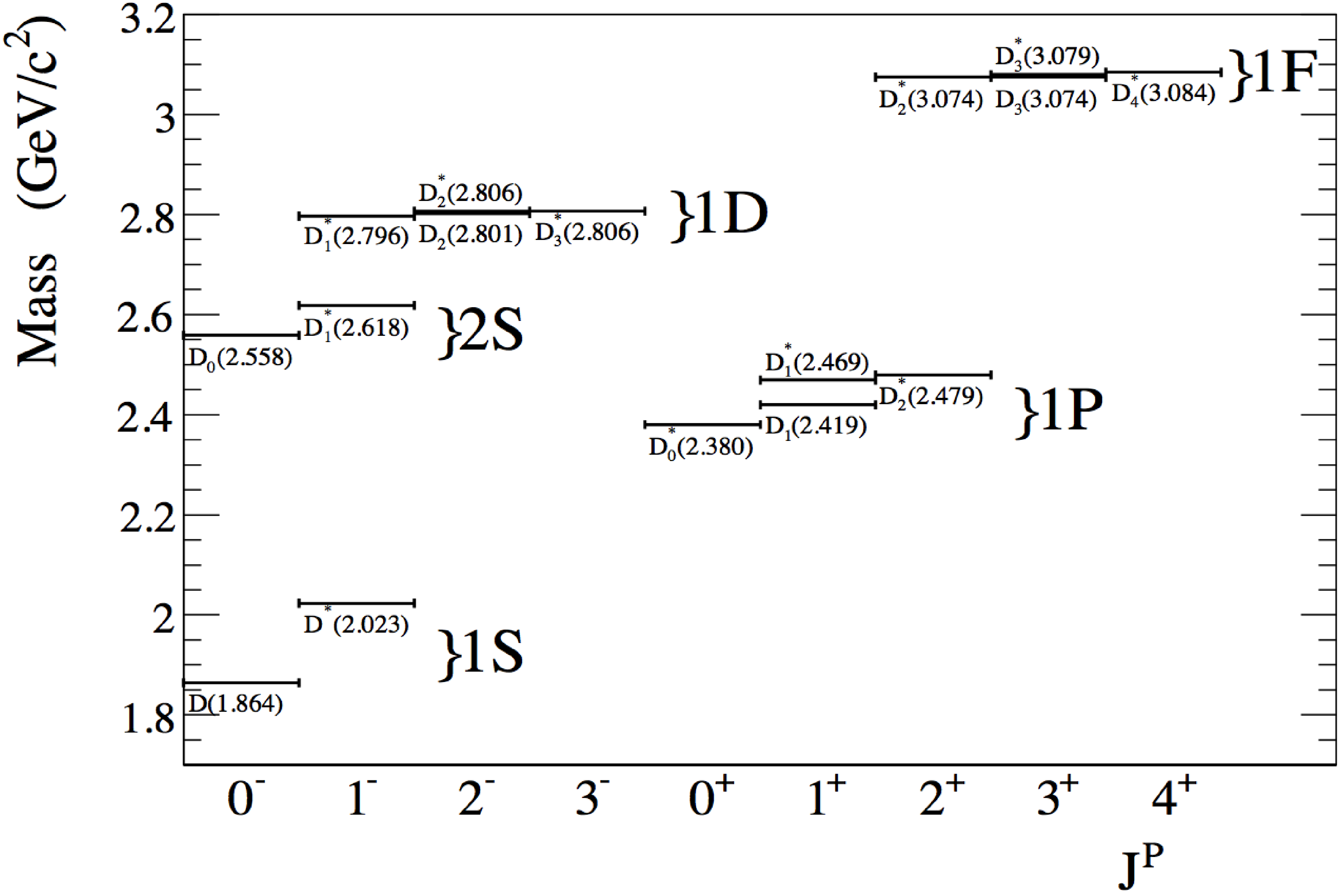
- The spectroscopy of D mesons is still poorly known.
- The bound states of a *c* quark and a *u* or *d* quark were predicted using QCD potential models in 1985.
- Only the ground states D and D* and the narrow L=1 states are well known.
- Observations of higher states have been hindered by poor statistics and their relatively large widths.



[Plot: S. Godfrey and N. Isgur PRD 32, 189 (1985)]

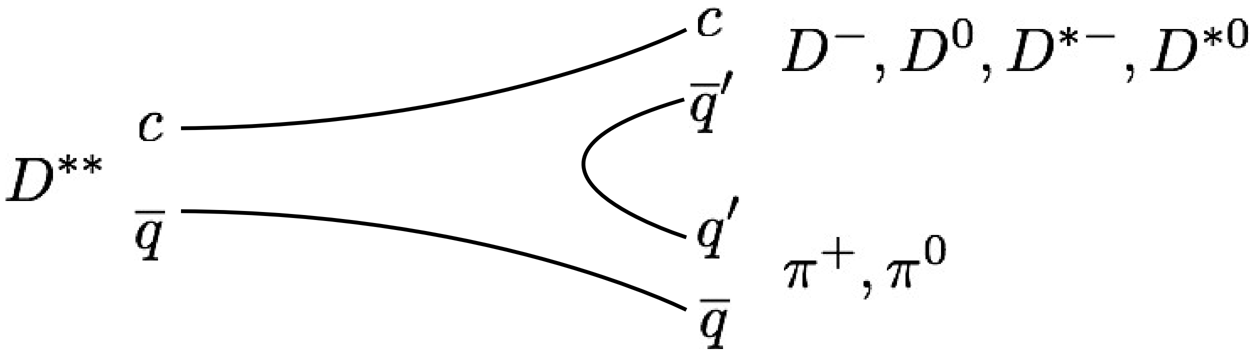
Results in this presentation:
Phys.Rev., D82:111101, 2010.

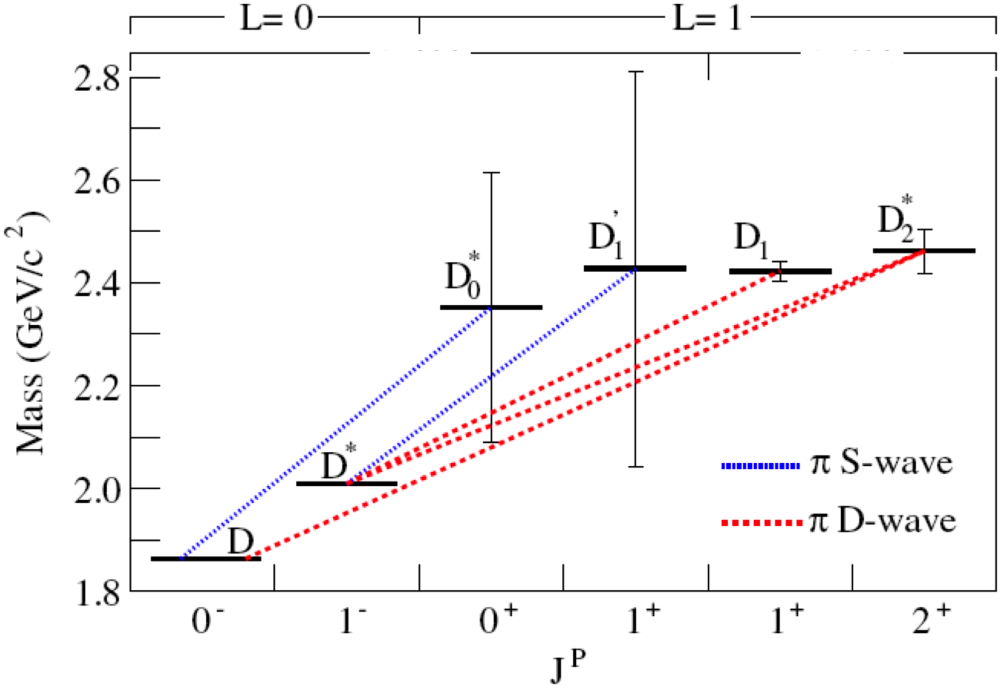
The spectrum of charmed mesons



Decay properties of the excited states

Excited states decay primarily through single pion emission to Dπ or D*π.





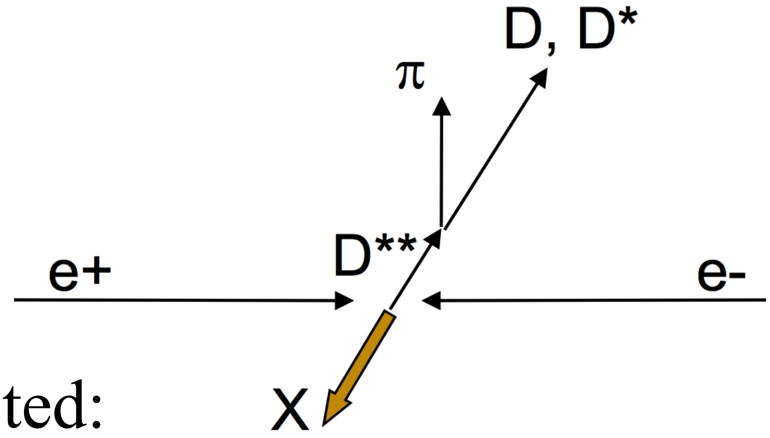
- Four states are known with L=1.
- Two decay through a D-wave and are “narrow” (~40 MeV): D_2*(2460) and D_1(2420).
- Two decay through a S-wave and have very large widths (~300 MeV): D_0*(2400) and D_1(2430)'.
- $J^P = 1^+$ states can interfere.

Analysis overview

- Perform an inclusive reconstruction of Dπ and D*π produced from $c\bar{c}$ events:

$$e^+e^- \to c\bar{c} \to D^{**}X \to D^{(*)}\pi X$$

any additional system



- The following 4 channels are reconstructed:

$$D^{**0} \to D^+\pi^-$$
$$\llcorner K^-\pi^+\pi^+$$

$$D^{**+} \to D^0\pi^+$$
$$\llcorner K^-\pi^+$$

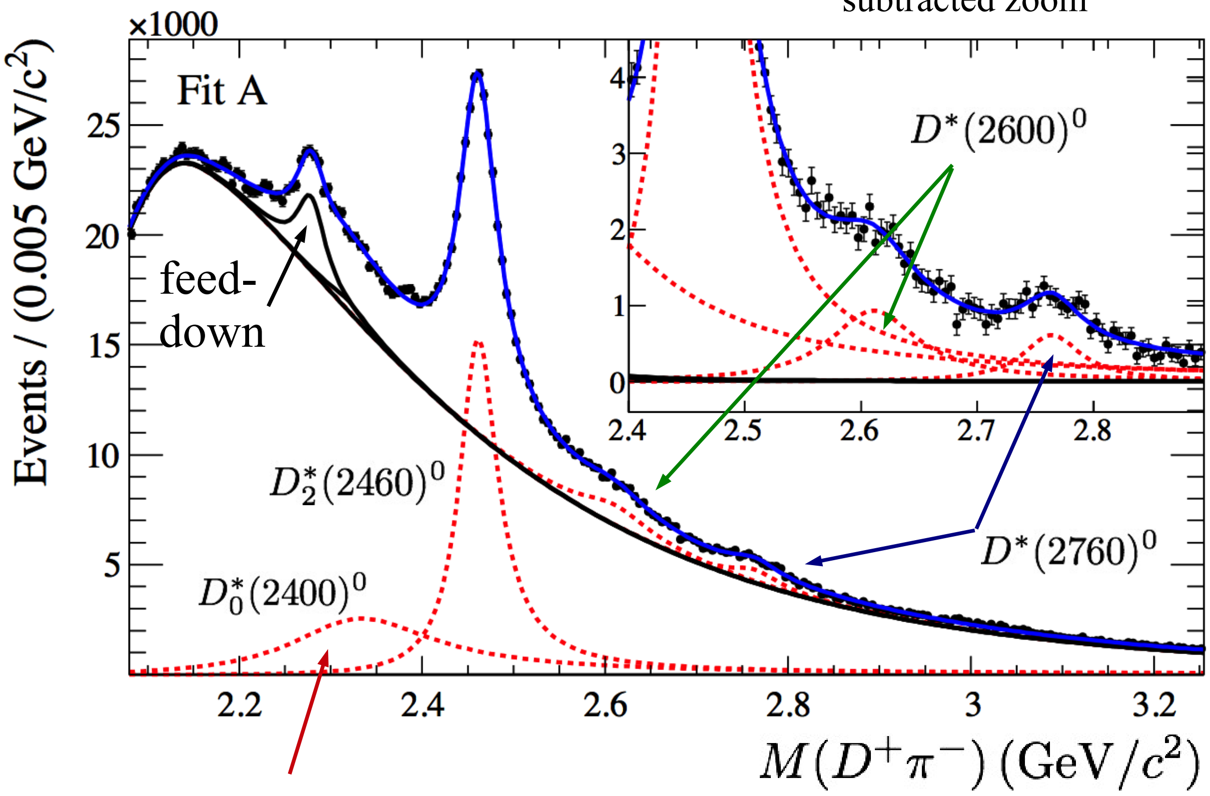
$$D^{**0} \to D^{*+}\pi^-$$
$$\llcorner D^0\pi^+$$
$$\llcorner K^-\pi^+ \text{ or } K^-\pi^+\pi^-\pi^+$$

- The data set consists of 454 fb^{-1} (~590 Million $e^+e^- \to c\bar{c}$ events)

$D^+\pi^-$ mass spectrum

- The known signals are modeled using Breit-Wigner functions corrected with angular momentum form factors and phase-space factors.
- Simple Breit-Wigners for the new signals.
- Shape corrections due to resolution and varying efficiency are applied.
- Two additional signals at 2600 and 2760 MeV/c^2!

background subtracted zoom



floated within 2σ of known values

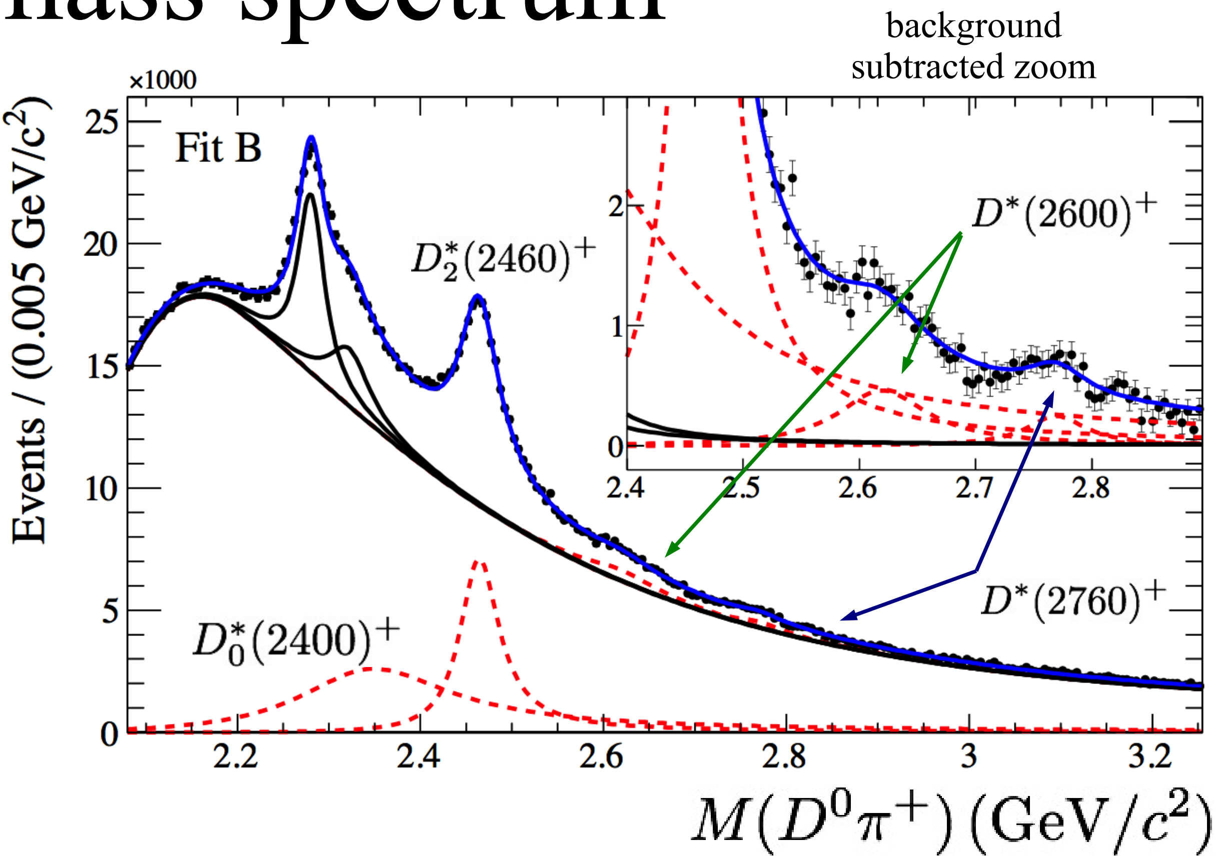
$\chi^2/\mathrm{NDF} = 140/112$

new

Resonance	Yield ($\times 10^3$)	M (MeV/c^2)	Γ (MeV)
$D_2^*(2460)^0$	$242.8 \pm 1.8 \pm 3.4$	$2462.2 \pm 0.1 \pm 0.8$	$50.5 \pm 0.6 \pm 0.7$
$D^*(2600)^0$	$26.0 \pm 1.4 \pm 6.6$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$
$D^*(2760)^0$	$11.3 \pm 0.8 \pm 1.0$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$

$D^0\pi^+$ mass spectrum

- We observe similar additional signals.
- In this channel the feed-down backgrounds are stronger and the statistics of this channel are smaller so the widths of all signals are fixed to the widths measured in $D^+\pi^-$.
- Mass values are slightly higher than in $D^+\pi^-$ consistent with being the isospin partners.



χ^2/NDF = 278/224

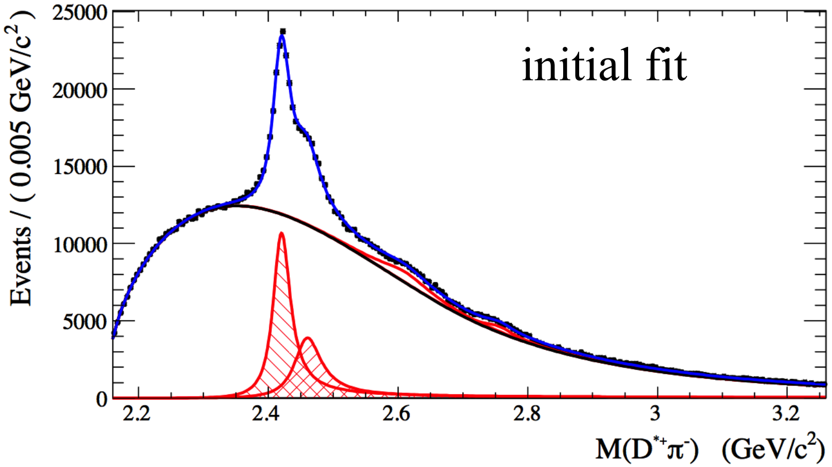
new

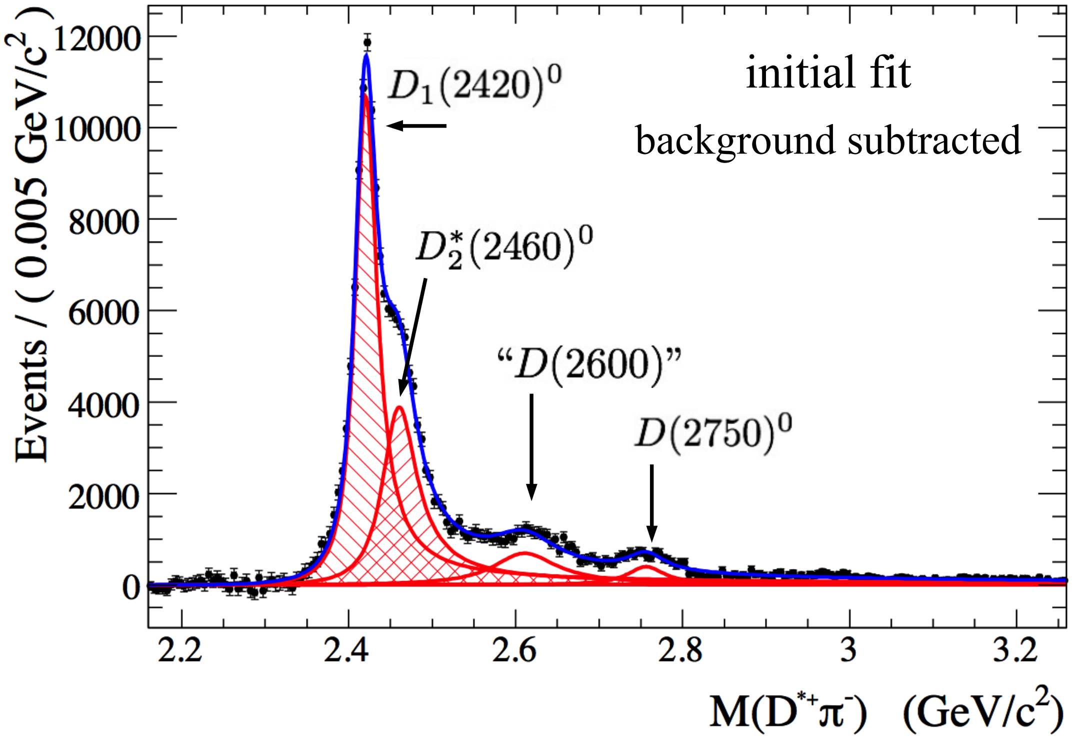
Resonance	Yield ($\times 10^3$)	M (MeV/c^2)	Γ (MeV)
$D_2^*(2460)^+$	$110.8 \pm 1.3 \pm 7.5$	$2465.4 \pm 0.2 \pm 1.1$	50.5 (fixed)
$D^*(2600)^+$	$13.0 \pm 1.3 \pm 4.5$	$2621.3 \pm 3.7 \pm 4.2$	93 (fixed)
$D^*(2760)^+$	$5.7 \pm 0.7 \pm 1.5$	$2769.7 \pm 3.8 \pm 1.5$	60.9 (fixed)

Analysis of D*π

Initial fit to $D^{*+}\pi^-$

- The fit uses the same background model as in the $D^+\pi^-$ fit.
- The parameters of the $D_2^*(2460)^0$ are fixed from the $D^+\pi^-$ fit.
- Two new signals, "D(2600)" and $D(2750)^0$, are included in this initial fit.



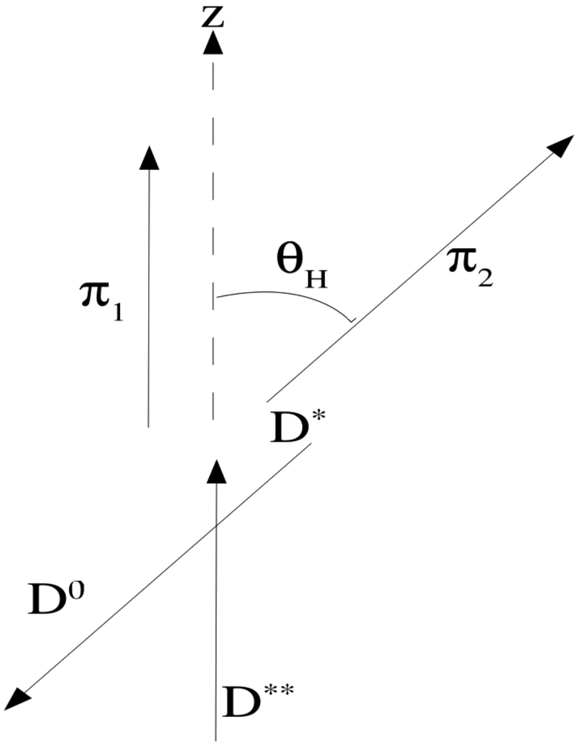


Definition of the helicity variable

- In addition to analyzing the mass spectra we extract the angular distributions in the helicity angle $\cos\theta_H$.
- In the D^{*+} rest frame the D^{*+} spin state cannot have a z-component. Thus different values of the parent's J^P are distinguished by the intensity of the signal as a function of $\cos\theta_H$.

Helicity distributions of the predicted states. The A coefficients are due to mixing and need to be determined from experiment.

Label $D_J^{2S+1}(nL)$	PDG Name	J^P	$D\pi$ Partial Waves	$D^*\pi$ Partial Waves	$D^*\pi$ Helicity Distribution
$D_1^1(1P)$	$D_1(2420)$	1^+	-	S,D	$\propto 1 + A cos^2(\theta)$
$D_0^3(1P)$	$D_0^*(2400)$	0^+	S	-	-
$D_1^3(1P)$	$D_1'(2430)$	1^+	-	S,D	$\propto 1 + A cos^2(\theta)$
$D_2^3(1P)$	$D_2^*(2460)$	2^+	D	D	$\propto sin^2(\theta)$
$D_2^1(1D)$		2^-	-	P,F	$\propto 1 + A cos^2(\theta)$
$D_1^3(1D)$		1^-	P	P	$\propto sin^2(\theta)$
$D_2^3(1D)$		2^-	-	P,F	$\propto 1 + A cos^2(\theta)$
$D_3^3(1D)$		3^-	F	F	$\propto sin^2(\theta)$
$D_0^1(2S)$		0^-	-	P	$\propto cos^2(\theta)$
$D_1^3(2S)$		1^-	P	P	$\propto sin^2(\theta)$

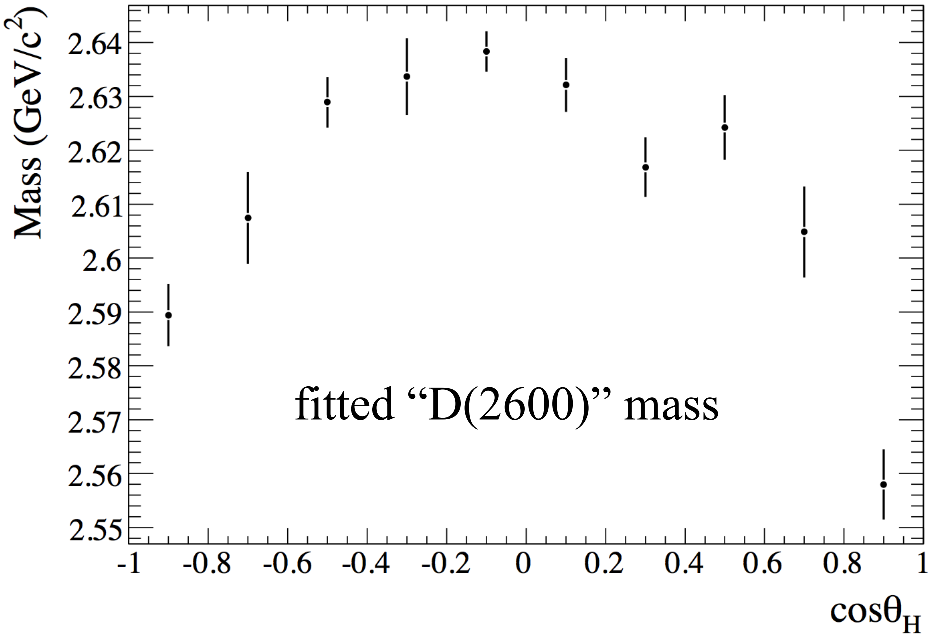


$$D^{**} \to D^* \pi_1$$

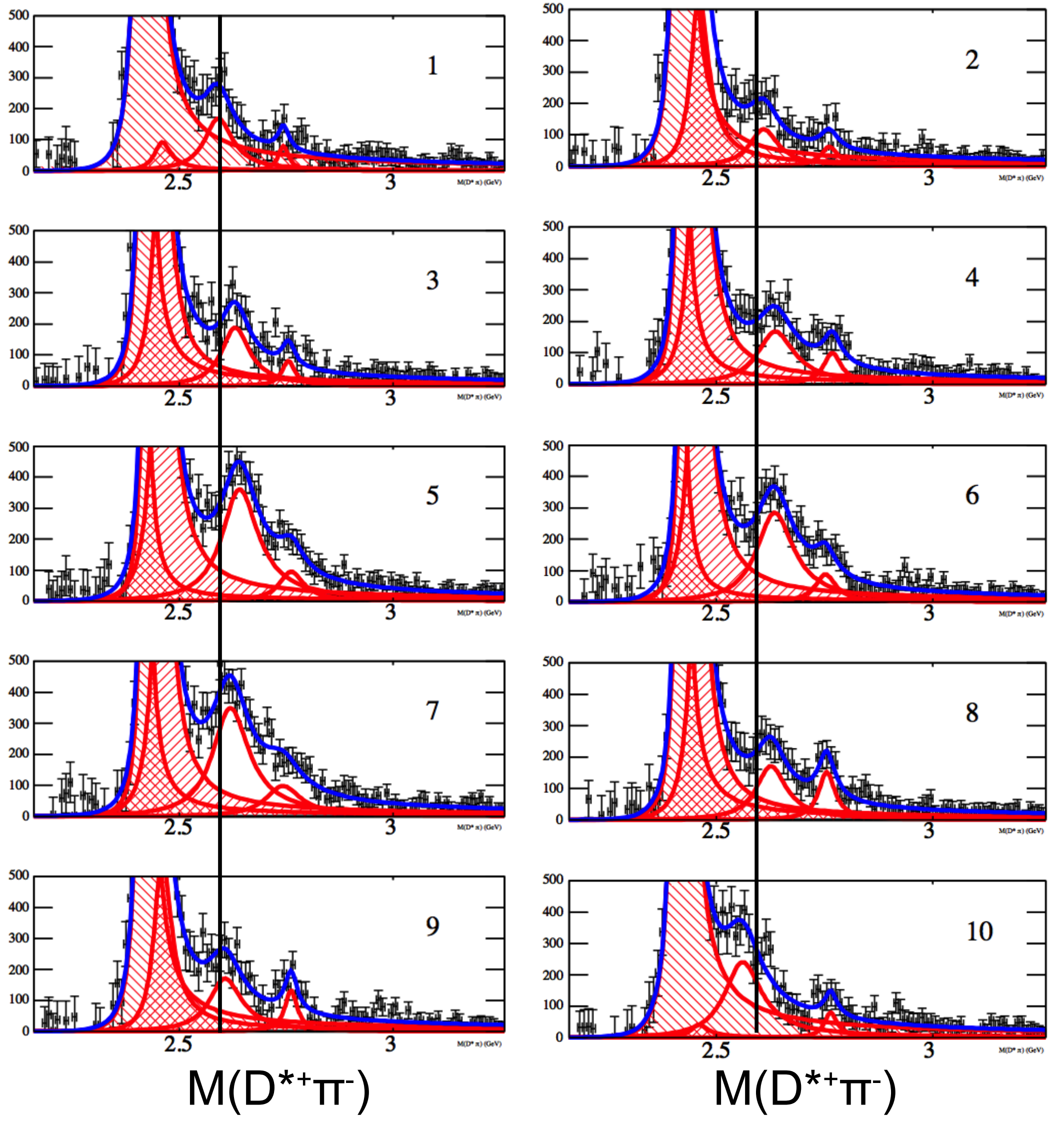
$$D^* \to D^0 \pi_2$$

Problem with initial fit model

- The “D(2600)” peak shifts as a function of the helicity angle.
- The other signals are stable.
- This implies that this peak might be composed of two signals!



Data divided by helicity angle. “D(2600)” peak seems to shift.



Problem with initial fit model

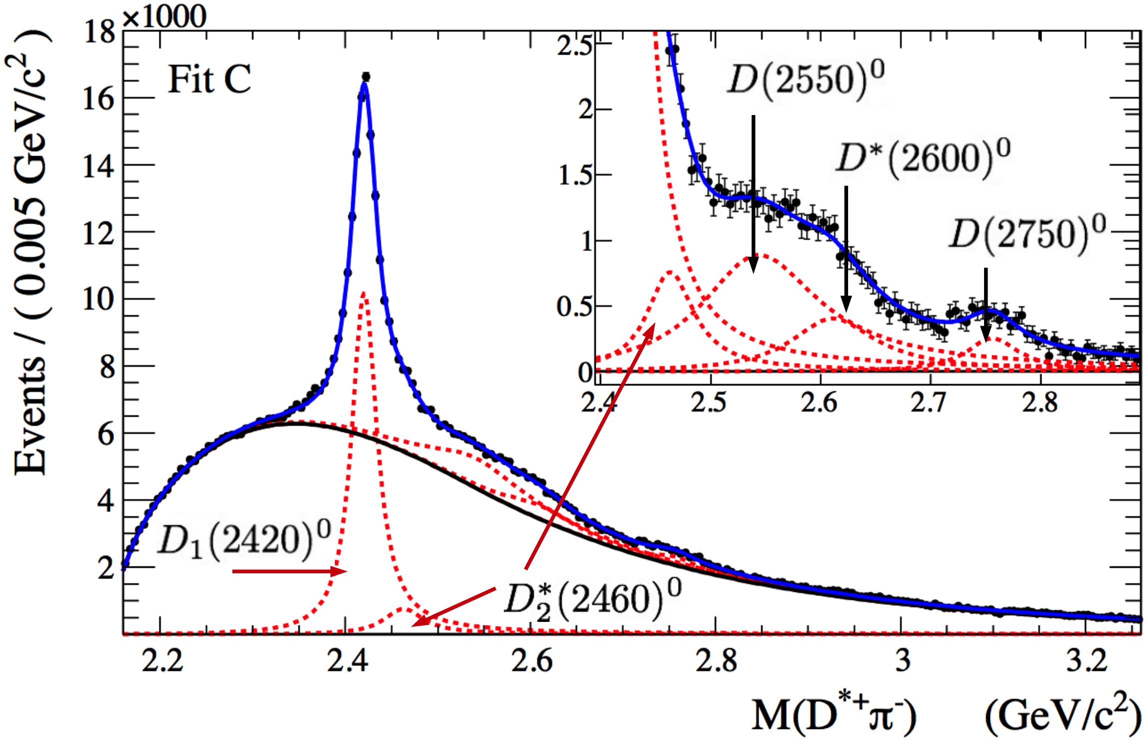
Strategy to fix the initial model:

labels correspond to the mass plots

1. Assume $D^*(2600)^0$ is same as observed in $D^+\pi^-$ and fix its parameters.
2. Introduce another signal: $D(2550)^0$
3. Apply a restrictive helicity cut, $|\cos\theta_H|>0.75$, to enhance the $D(2550)^0$ contribution and determine its parameters ("Fit C").
4. Perform a complementary fit by requiring $|\cos\theta_H|<0.5$, with the $D^*(2600)^0$ parameters left free and those of $D(2550)^0$ fixed ("Fit D").
5. Perform full fit with new model, without cutting on $\cos\theta_H$ ("Fit E").

Extraction of $D(2550)^0$ signal

- A cut $|\cos\theta_H|>0.75$ is applied.
- We include one more signal around 2.55 GeV/c^2 into the fit.
- The parameters of $D_2^*(2460)^0$ and $D^*(2600)^0$ are fixed to the ones from $D^+\pi^-$.

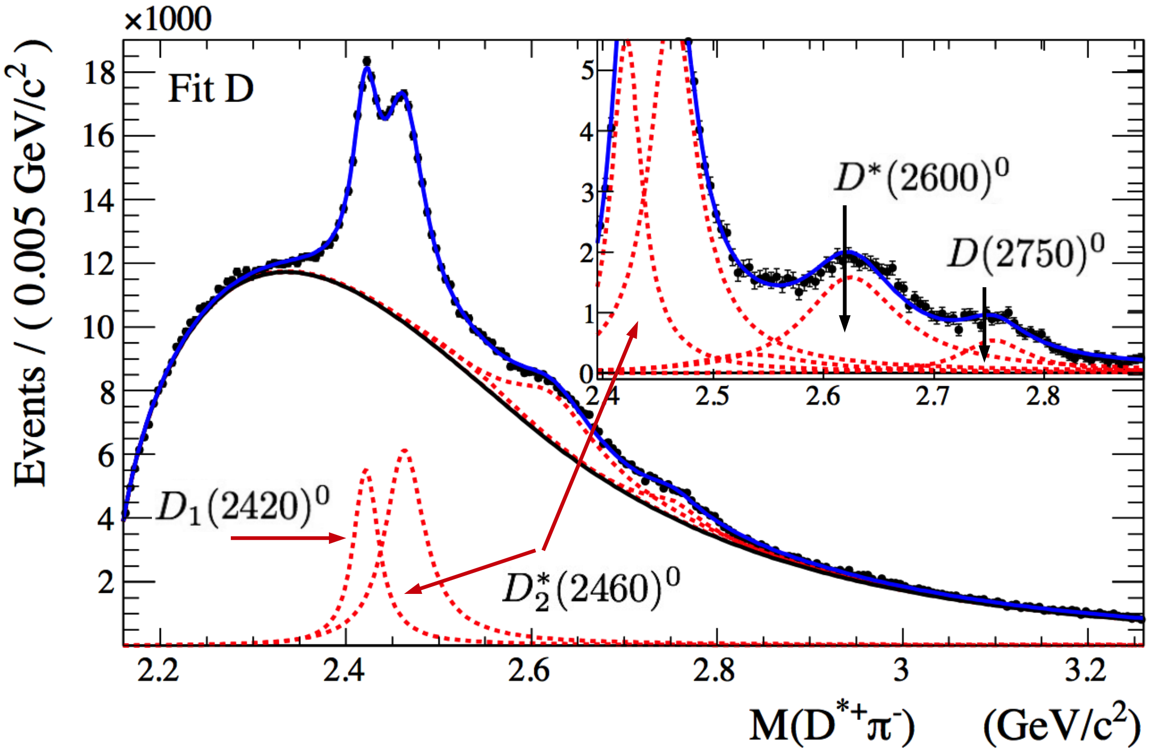


$|\cos\theta_H| > 0.75$ χ^2/NDF = 214/205

Resonance	Yield ($\times 10^3$)	M (MeV/c^2)	Γ (MeV)
$D_1(2420)^0$	$102.8 \pm 1.3 \pm 2.3$	$2420.1 \pm 0.1 \pm 0.8$	$31.4 \pm 0.5 \pm 1.3$
$D(2550)^0$	$34.3 \pm 6.7 \pm 9.2$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$

Complementary fit for D*(2600)^0

- Now an opposite cut is applied: $|\cos\theta_H|<0.5$.
- The D*(2600)^0 significance is 7.3σ.

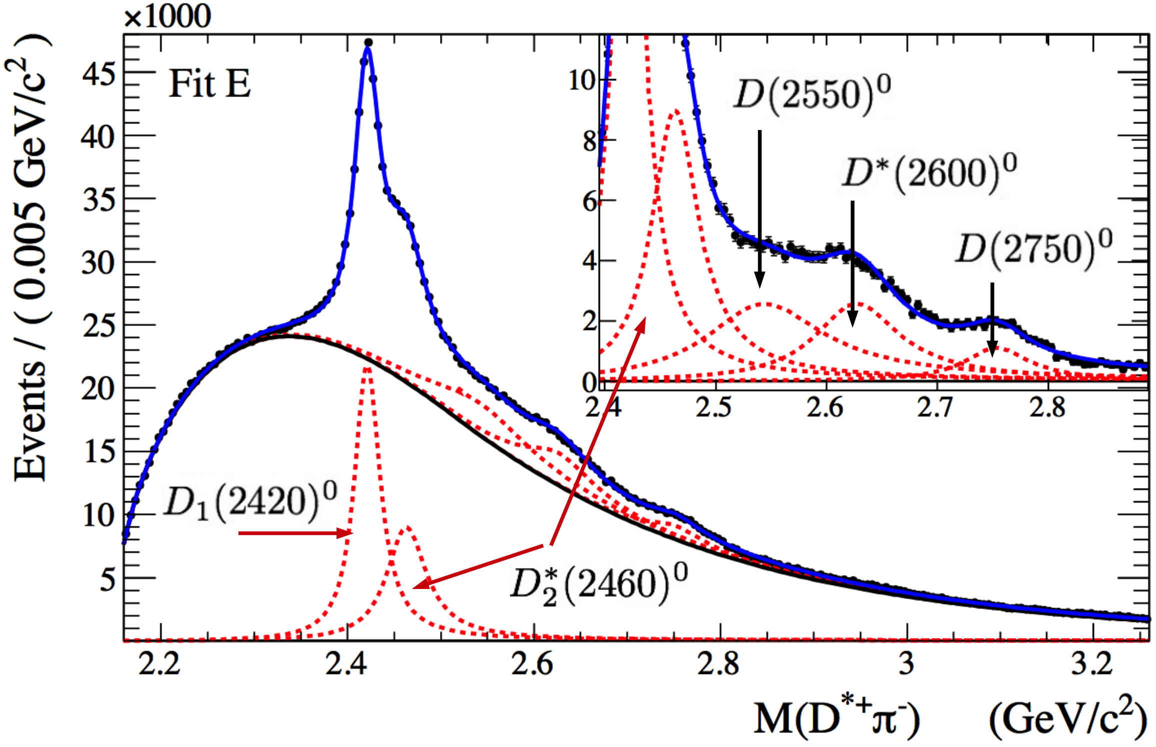


$|\cos\theta_H| < 0.5$ χ^2/NDF = 210/209

Resonance	Yield ($\times10^3$)	M (MeV/c^2)	Γ (MeV)
$D^*(2600)^0$	$50.2 \pm 3.0 \pm 6.7$	2608.7 (fixed)	93 (fixed)

Final fit to $D^{*+}\pi^-$

- The parameters of the $D_1(2420)^0$ and $D(2550)^0$ are fixed to the ones found in the fit with the helicity cut.
- The parameters of $D_2^*(2460)^0$ and $D^*(2600)^0$ are constrained to the ones from $D^+\pi^-$.
- We obtain final parameters for the $D(2750)^0$ from this fit.

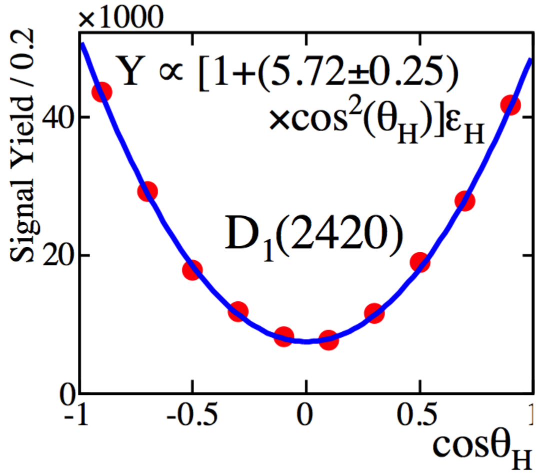


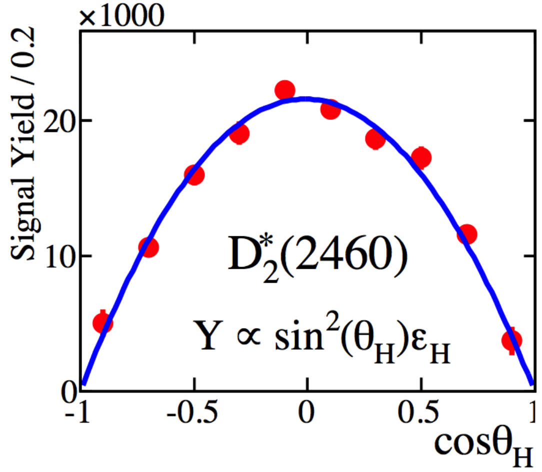
$|\cos\theta_H| < 1$ $\chi^2/\mathrm{NDF} = 244/207$

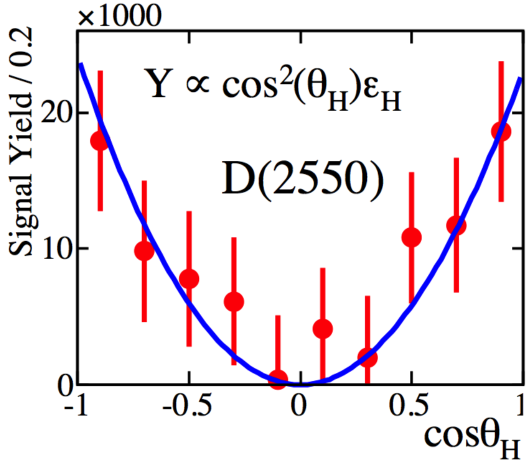
	Resonance	Yield ($\times 10^3$)	M (MeV/c^2)	Γ (MeV)
	$D_1(2420)^0$	$214.6 \pm 1.2 \pm 6.4$	2420.1 (fixed)	31.4 (fixed)
	$D(2550)^0$	$98.4 \pm 8.2 \pm 38$	2539.4 (fixed)	130 (fixed)
new	$D^*(2600)^0$	$71.4 \pm 1.7 \pm 7.3$	2608.7 (fixed)	93 (fixed)
	$D(2750)^0$	$23.5 \pm 2.1 \pm 5.2$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$

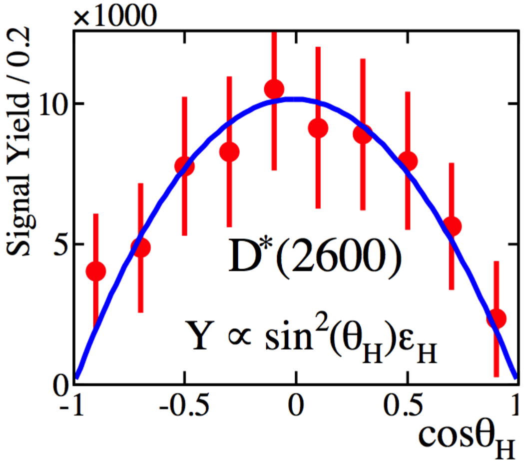
Helicity distributions

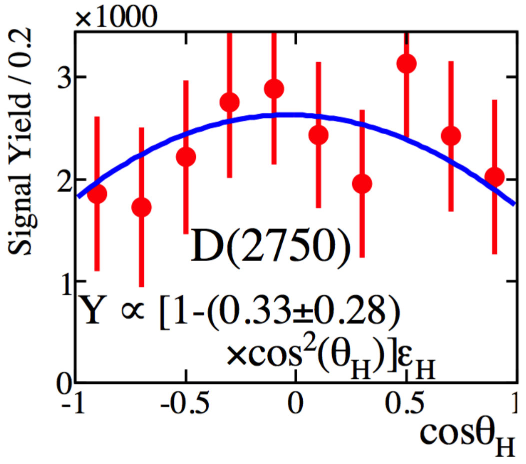
- The helicity distribution for the known resonances $D_1(2420)^0$ and $D_2{}^*(2460)^0$ are as expected.
- For $D(2550)^0$, a $\cos^2(\theta_H)$ distribution is obtained, consistent with the radial excitation of the D^0.
- For $D^*(2600)^0$, a $\sin^2(\theta_H)$ is obtained, consistent with the radial excitation of the D^{*0}.
- For the signal $D(2750)^0$, the distribution is not easily interpreted. It could be a composite peak; the L=2 states could be fitting candidates.





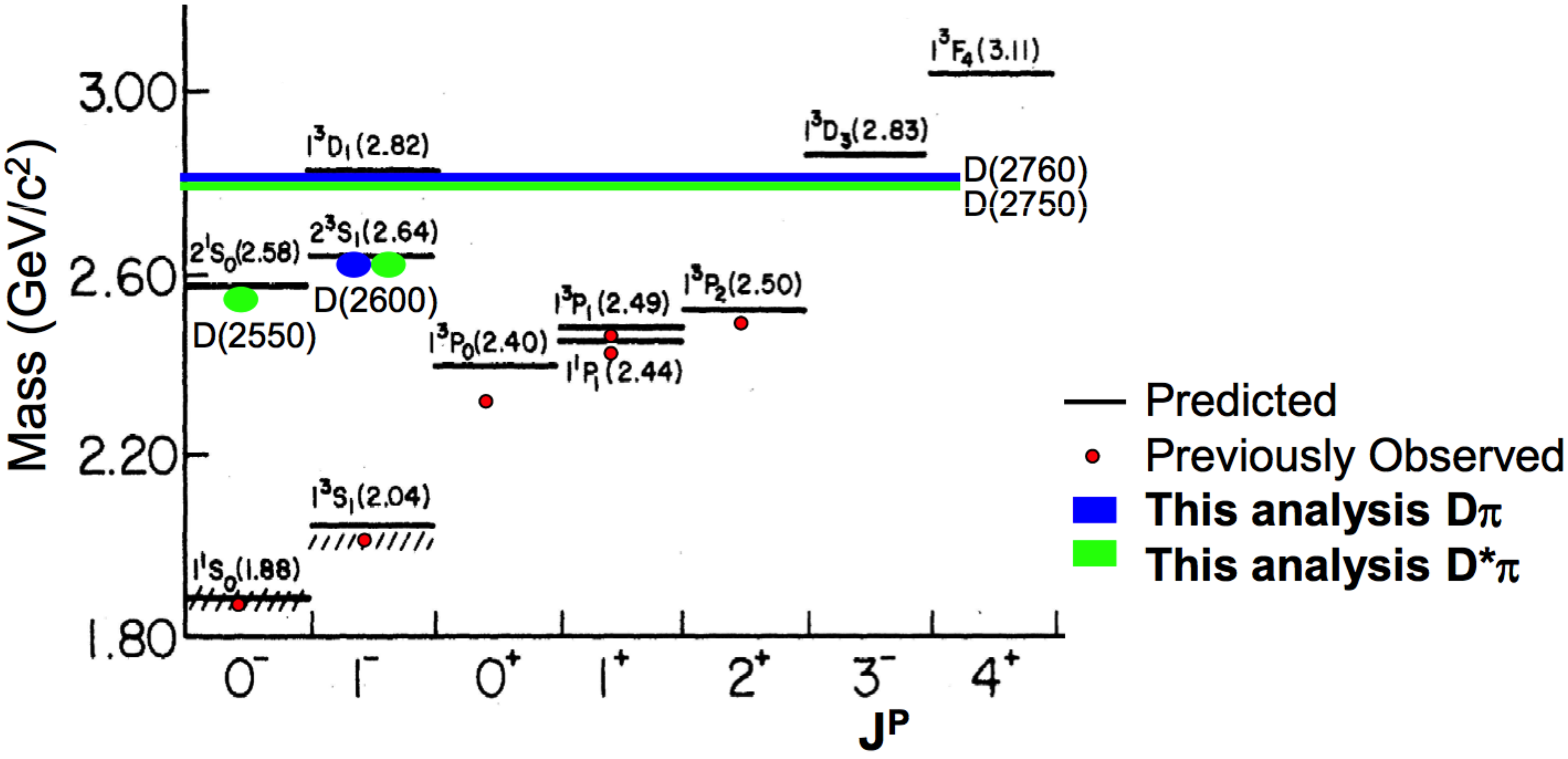






Overview of results

The signals observed in this analysis are shown in the plot and are qualitatively consistent with the predictions.



[Underlying plot: S. Godfrey and N. Isgur PRD 32, 189 (1985)]

Conclusions

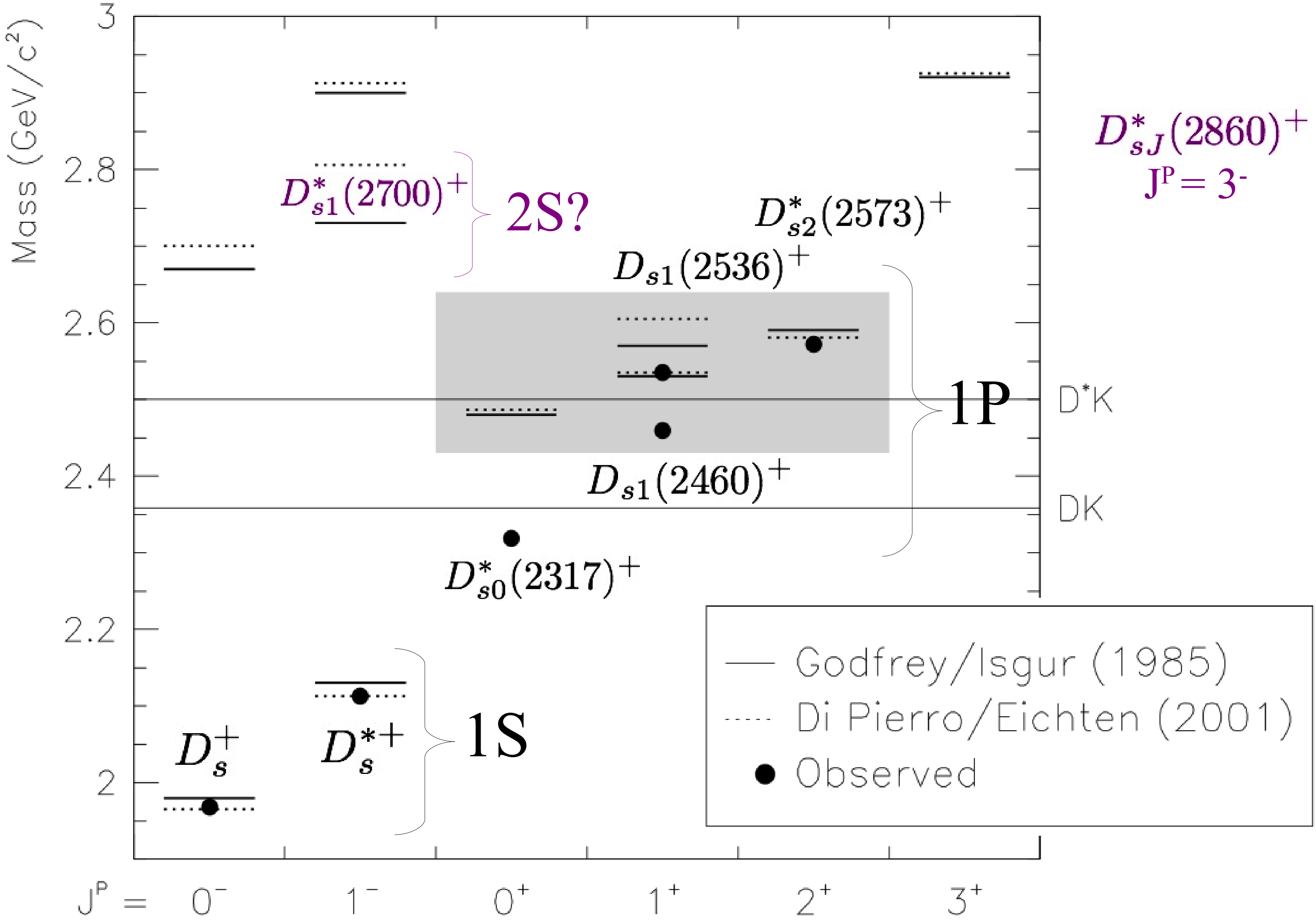
- We have analyzed the inclusive final states $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ in search for unobserved excited D mesons.
- In **$D^+\pi^-$** we find **two new signal**s with masses at about 2610 MeV/c^2 and 2760 MeV/c^2. The isospin partner signals are confirmed in $D^0\pi^+$.
- In **$D^{*+}\pi^-$** we find **three new signals** at about 2530 MeV/c^2, 2610 MeV/c^2 and 2750 MeV/c^2. We assume the signal at 2610 MeV/c^2 is the same as in $D^+\pi^-$.
- The helicity distributions indicate that the signal at 2530 MeV/c^2 may be identified as the **radial excitation** of the D^0. Similarly, the signal at 2610 MeV/c^2 may be identified as the radial excitation of the D^{*0}. Finally, the helicity distribution of the signal at 2750 MeV/c^2 indicates this signal may be composite, the L=2 excitations could be fitting candidates.
- The mass values are similar to the predicted states.

Thanks to Jose Benitez, these slides are largely based on his.

D_{sJ} spectroscopy

D_{sJ} spectroscopy

$D^*_{sJ}(3040)^+$



D_{sJ} spectroscopy

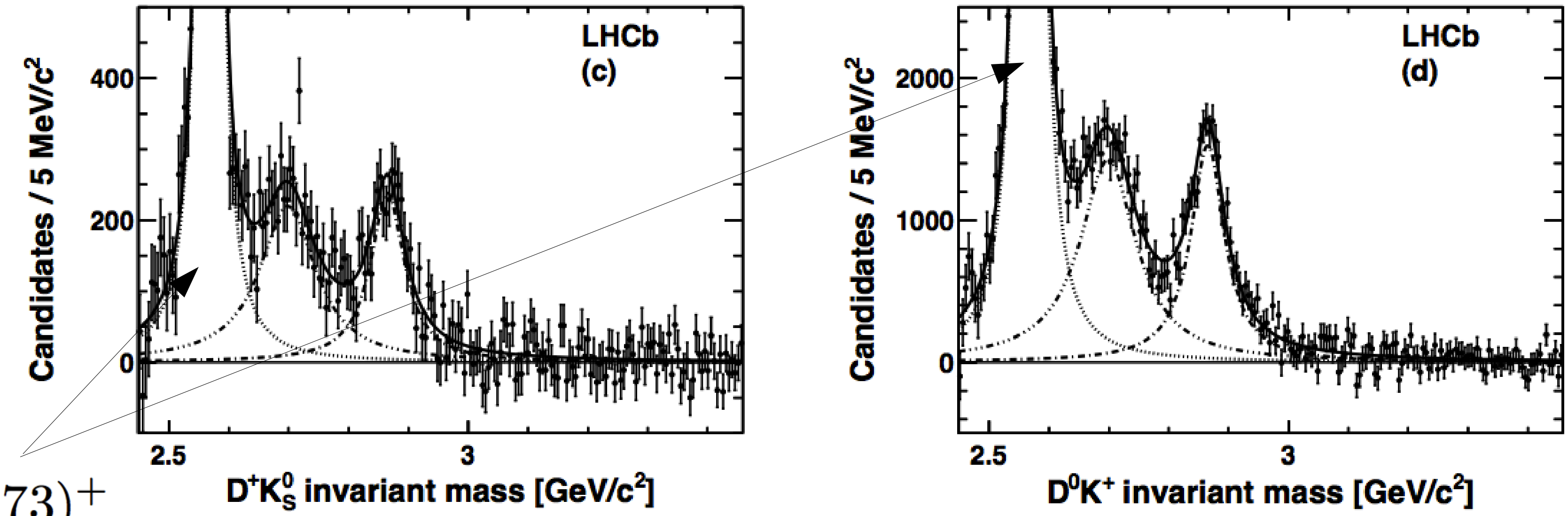
There is a recent measurement by LHCb: **JHEP 1210 (2012) 151**

$$D^+_{sJ} \rightarrow D^+ K^0_S$$

$$D^+ \rightarrow K^- \pi^+ \pi^+$$

$$D^+_{sJ} \rightarrow D^0 K^+$$

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



$D^*_{s2}(2573)^+$

$$\begin{aligned}
m(D^*_{s1}(2700)^+) &= 2709.2 \pm 1.9(\text{stat}) \pm \ \ 4.5(\text{syst})\ \ \text{MeV}/c^2,\\
\Gamma(D^*_{s1}(2700)^+) &= \ \ 115.8 \pm 7.3(\text{stat}) \pm 12.1(\text{syst})\ \ \text{MeV}/c^2,\\
m(D^*_{sJ}(2860)^+) &= 2866.1 \pm 1.0(\text{stat}) \pm \ \ 6.3(\text{syst})\ \ \text{MeV}/c^2,\\
\Gamma(D^*_{sJ}(2860)^+) &= \ \ \ \ 69.9 \pm 3.2(\text{stat}) \pm \ \ 6.6(\text{syst})\ \ \text{MeV}/c^2.
\end{aligned}$$

Consistent with previous measurements!

backup

fit results

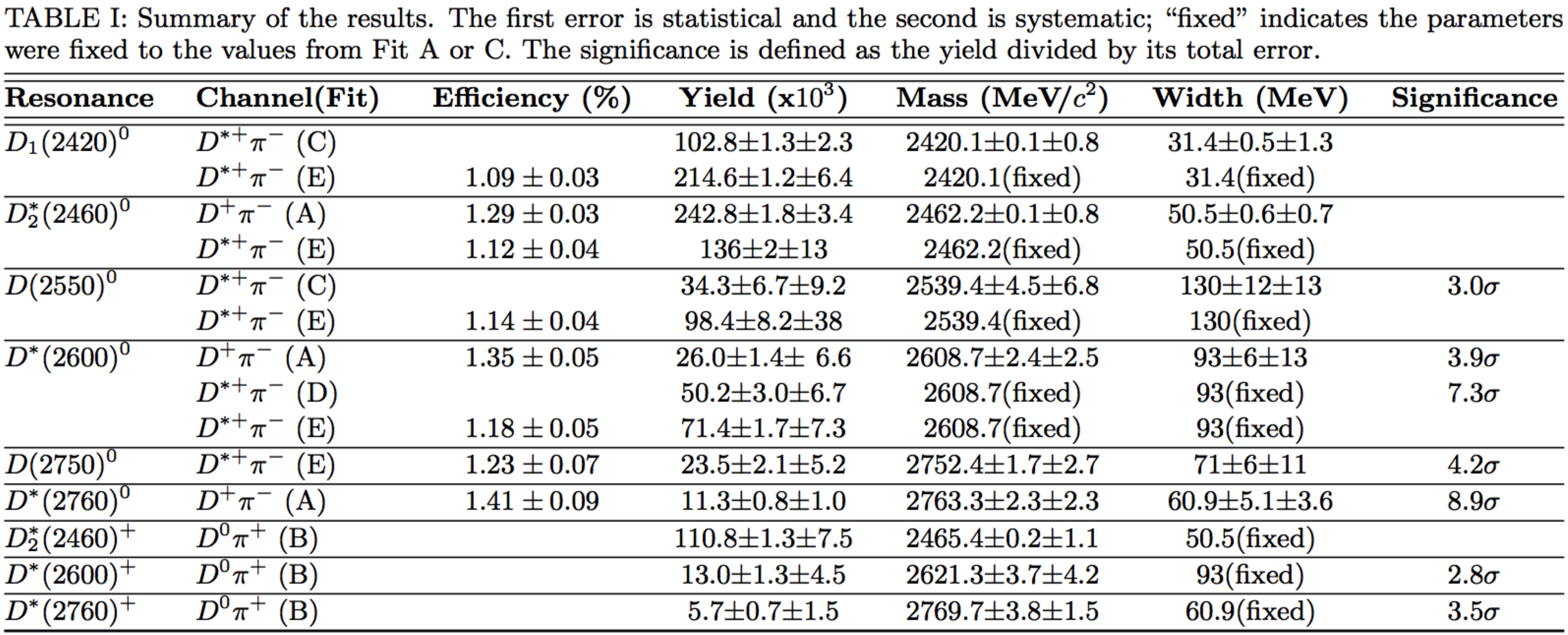


TABLE I: Summary of the results. The first error is statistical and the second is systematic; "fixed" indicates the parameters were fixed to the values from Fit A or C. The significance is defined as the yield divided by its total error.

Resonance	**Channel(Fit)**	**Efficiency (%)**	**Yield (x10^3)**	**Mass (MeV/c^2)**	**Width (MeV)**	**Significance**
$D_1(2420)^0$	$D^{*+}\pi^-$ (C)		102.8±1.3±2.3	2420.1±0.1±0.8	31.4±0.5±1.3	
	$D^{*+}\pi^-$ (E)	1.09 ± 0.03	214.6±1.2±6.4	2420.1(fixed)	31.4(fixed)	
$D_2^*(2460)^0$	$D^+\pi^-$ (A)	1.29 ± 0.03	242.8±1.8±3.4	2462.2±0.1±0.8	50.5±0.6±0.7	
	$D^{*+}\pi^-$ (E)	1.12 ± 0.04	136±2±13	2462.2(fixed)	50.5(fixed)	
$D(2550)^0$	$D^{*+}\pi^-$ (C)		34.3±6.7±9.2	2539.4±4.5±6.8	130±12±13	3.0σ
	$D^{*+}\pi^-$ (E)	1.14 ± 0.04	98.4±8.2±38	2539.4(fixed)	130(fixed)	
$D^*(2600)^0$	$D^+\pi^-$ (A)	1.35 ± 0.05	26.0±1.4± 6.6	2608.7±2.4±2.5	93±6±13	3.9σ
	$D^{*+}\pi^-$ (D)		50.2±3.0±6.7	2608.7(fixed)	93(fixed)	7.3σ
	$D^{*+}\pi^-$ (E)	1.18 ± 0.05	71.4±1.7±7.3	2608.7(fixed)	93(fixed)	
$D(2750)^0$	$D^{*+}\pi^-$ (E)	1.23 ± 0.07	23.5±2.1±5.2	2752.4±1.7±2.7	71±6±11	4.2σ
$D^*(2760)^0$	$D^+\pi^-$ (A)	1.41 ± 0.09	11.3±0.8±1.0	2763.3±2.3±2.3	60.9±5.1±3.6	8.9σ
$D_2^*(2460)^+$	$D^0\pi^+$ (B)		110.8±1.3±7.5	2465.4±0.2±1.1	50.5(fixed)	
$D^*(2600)^+$	$D^0\pi^+$ (B)		13.0±1.3±4.5	2621.3±3.7±4.2	93(fixed)	2.8σ
$D^*(2760)^+$	$D^0\pi^+$ (B)		5.7±0.7±1.5	2769.7±3.8±1.5	60.9(fixed)	3.5σ

ratios of branching ratios

$$\frac{B(D_2^*(2460)^0 \to D^+\pi^-)}{B(D_2^*(2460)^0 \to D^{*+}\pi^-)} = 1.47 \pm 0.03 \pm 0.16,$$

$$\frac{B(D^*(2600)^0 \to D^+\pi^-)}{B(D^*(2600)^0 \to D^{*+}\pi^-)} = 0.32 \pm 0.02 \pm 0.09,$$

$$\frac{B(D^*(2760)^0 \to D^+\pi^-)}{B(D(2750)^0 \to D^{*+}\pi^-)} = 0.42 \pm 0.05 \pm 0.11.$$