Status of Factorization in $B \to D^{(*)} M$ Decays

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INT/SLAC workshop, May 2005

QCD Expansion Parameters for B decays

1)	Isospin	$\frac{m_{u,d}}{\Lambda} \simeq 0.02$
2)	Heavy b-quark	$\frac{\Lambda}{m_b} \simeq 0.1, \quad \alpha_s(m_b) \simeq 0.2$
3)	Energetic Hadron	$\frac{\Lambda}{E_M} \simeq 0.2$ } SCET
4)	Jet Scale expansion	$\alpha_s(\sqrt{E\Lambda}) \simeq 0.3$ } SCET
5)	Heavy c-quark	$\frac{\Lambda}{m_c} \simeq 0.3$
6)	SU(3)	$\frac{m_s}{\Lambda} \simeq 0.3$

Terms in the series expansion are unique

nonperturbative parameters

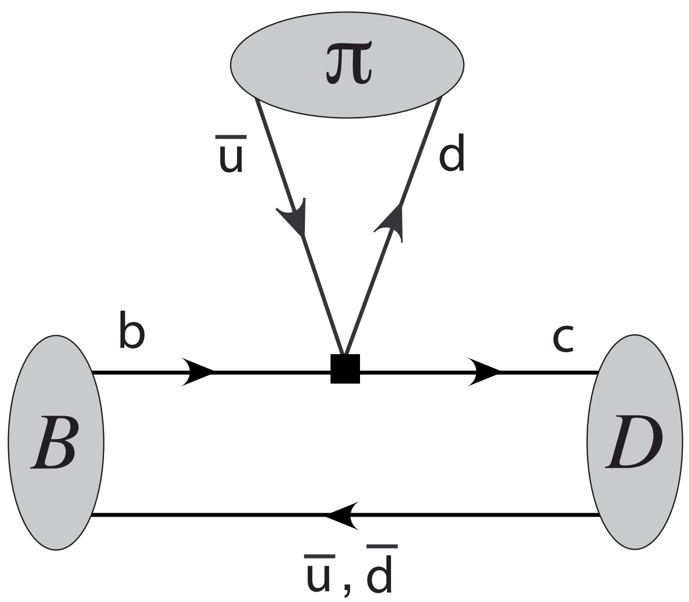
$$\text{Obs} = \sum_i f_i^{(0)} + \epsilon \sum_i f_i^{(1)} + \epsilon^2 \sum_i f_i^{(2)} + \ldots$$

More expansions (more uncertainty) ⟷ More universality (less parameters)

Test the expansions

“$B \to D\pi$ ” Decays

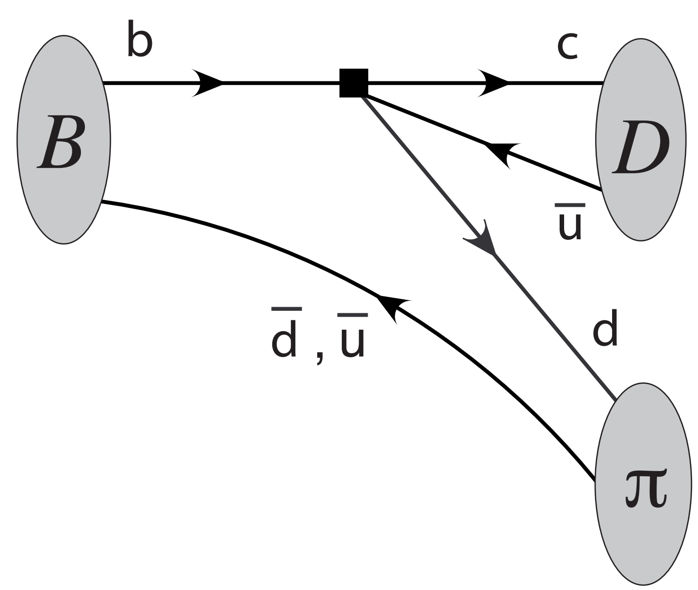
"Tree"



$\bar{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$

$\mathcal{O}(1)$

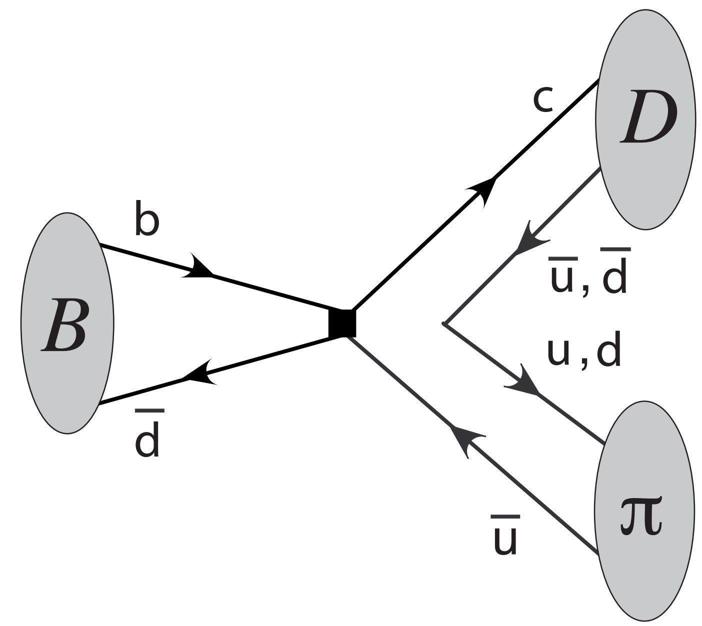
"Color suppressed"



$B^- \to D^0\pi^-$
$\bar{B}^0 \to D^0\pi^0$

$\mathcal{O}\left(\frac{\Lambda}{E}\right)$

"Exchange"



$\bar{B}^0 \to D^+\pi^-$
$\bar{B}^0 \to D^0\pi^0$

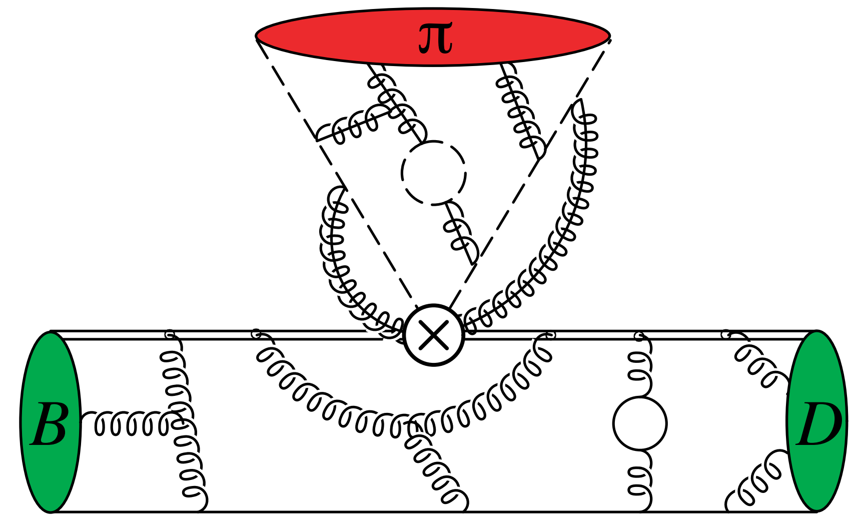
$\mathcal{O}\left(\frac{\Lambda}{E}\right)$

Naive Factorization - too small & disagrees with SCET/QCD(!)

$$A(\bar{B}^0 \to D^0\pi^0) \sim a_2 \langle \pi^0 | (\bar{d}b) | \bar{B}^0 \rangle \langle D^0 | (\bar{c}u) | 0 \rangle$$

Factorization

- $\bar{B}^0 \to D^+\pi^- \;\;,\;\; B^- \to D^0\pi^-$



$$\langle D\pi|(\bar{c}b)(\bar{u}d)|B\rangle = N\,\xi(v\cdot v')\int_0^1 dx\, T(x,\mu)\,\phi_\pi(x,\mu)$$

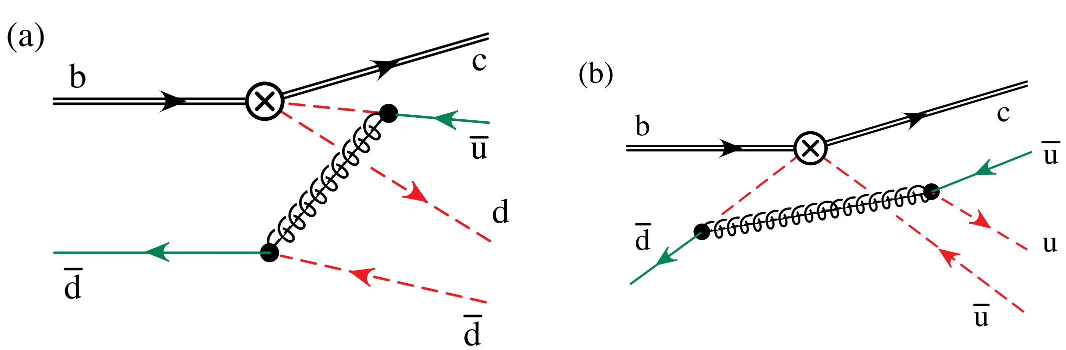
Calculate T

- $\bar{B}^0 \to D^{(*)0}\pi^0$ (power suppressed)

Mantry, Pirjol, I.S.

$$A_{00}^{D^{(*)}\pi} = N_0^{(*)}\int dx\,dz\,dk_1^+\,dk_2^+\,T^{(i)}(z)\,J^{(i)}(z,x,k_1^+,k_2^+)\,S^{(i)}(k_1^+,k_2^+)\,\phi_\pi(x) + A_{\rm long}^{D^{(*)}\pi}$$

$$Q^2 \gg E_\pi\Lambda \gg \Lambda^2$$



color supp. ~ exchange

Data (Cleo, Belle, Babar)

Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)	Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)
$\bar{B}^0 \to D^+\pi^-$	2.76 ± 0.25	5.99 ± 0.27	$\bar{B}^0 \to D^{*+}\pi^-$	2.76 ± 0.21	6.06 ± 0.23
$B^- \to D^0\pi^-$	4.98 ± 0.29	7.72 ± 0.22	$B^- \to D^{*0}\pi^-$	4.6 ± 0.4	7.50 ± 0.33
$\bar{B}^0 \to D^0\pi^0$	0.25 ± 0.02	1.81 ± 0.08	$\bar{B}^0 \to D^{*0}\pi^0$	0.28 ± 0.05	1.95 ± 0.18
$\bar{B}^0 \to D^+\rho^-$	7.7 ± 1.3	10.2 ± 0.9	$\bar{B}^0 \to D^{*+}\rho^-$	6.8 ± 0.9	9.10 ± 0.61
$B^- \to D^0\rho^-$	13.4 ± 1.8	12.9 ± 0.9	$B^- \to D^{*0}\rho^-$	9.8 ± 1.7	10.5 ± 0.92
$\bar{B}^0 \to D^0\rho^0$	0.29 ± 0.11	1.97 ± 0.37	$\bar{B}^0 \to D^{*0}\rho^0$	< 0.51	< 2.78

- size of $\mathrm{Br}(D^+M^-)$ agrees with factorization
- $\mathrm{Br}(D^0M^0)$ small as expected (power suppressed)
- color allowed Br are same for D and D^*
- $\dfrac{|A(B^- \to D^0\rho^-)|}{|A(B^- \to D^0\pi^-)|} = 1.67 \pm 0.12 \simeq \dfrac{f_\rho}{f_\pi}$, $\dfrac{|V_{ud}||A(B^- \to D^0K^-)|}{|V_{us}||A(B^- \to D^0\pi^-)|} = 1.20 \pm 0.10 \simeq \dfrac{f_K}{f_\pi}$

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- but significant power corrections for Br(D^0M^-)/Br(D^+M^-)

$$\frac{|A_{0-}|}{|A_{+-}|} = \begin{cases} 0.77 \pm 0.05 & \text{for} \quad D\pi \\ 0.81 \pm 0.05 & \text{for} \quad D^*\pi \end{cases}$$

20-30% level

- significant strong phases $\delta \sim 30^\circ$

1) Test Λ/E expansion (no expansion for jet, J)

$$\langle D^{(*)0}|O_s^{(0,8)}|\bar{B}^0\rangle \to S^{(0,8)}(k_1^+,k_2^+)$$

complex (universal nonperturbative phases)

same for D and D^*

Predict

equal strong phases $\delta^D = \delta^{D^*}$

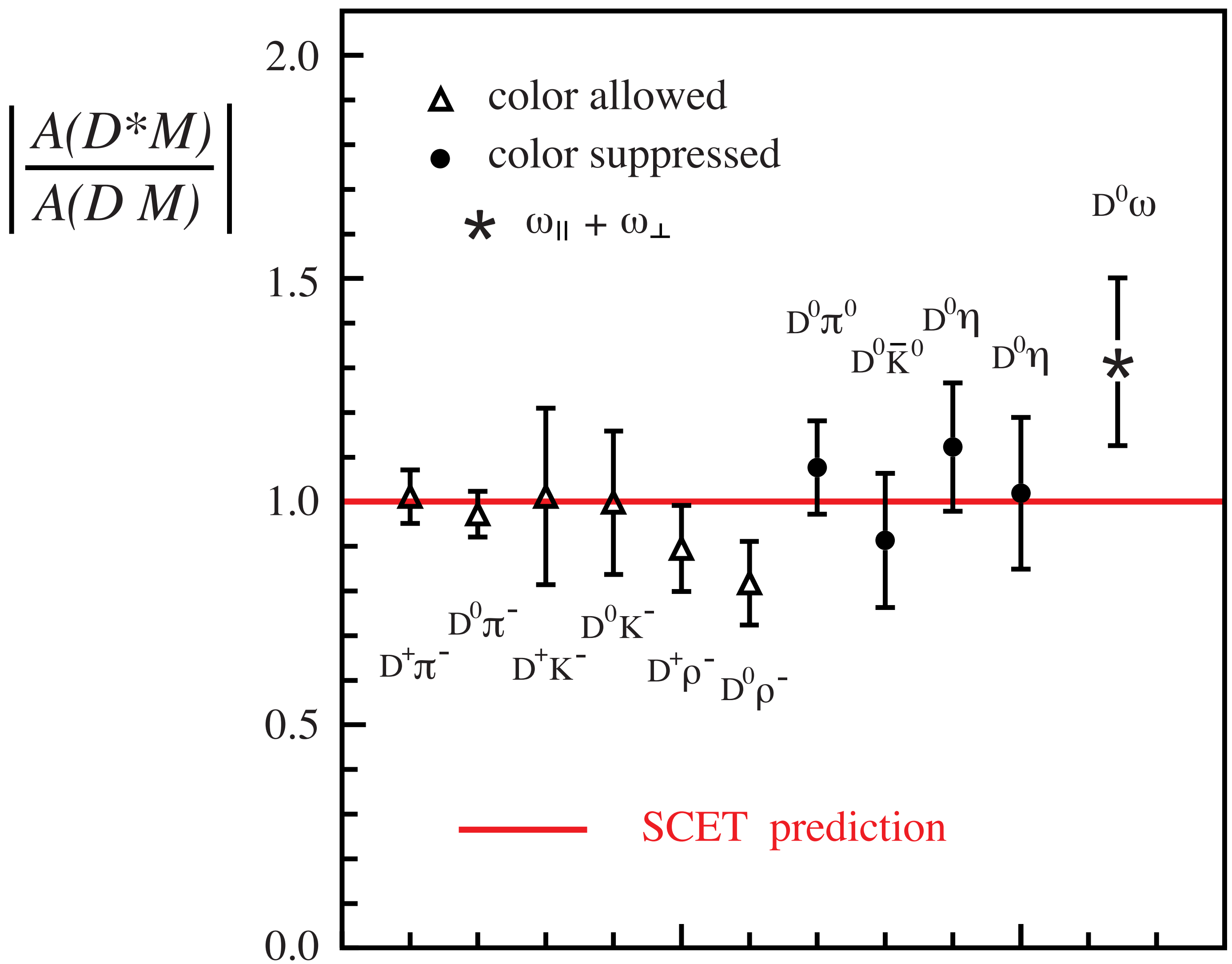
equal amplitudes $A_{00}^D = A_{00}^{D*}$ for color suppressed decays

corrections to this are $\alpha_s(m_b)$, Λ/Q

with HQET $\langle D^{(*)0}\pi|(\bar{c}\,b)(\bar{d}\,u)|\bar{B}^0\rangle$ gives $\frac{p_\pi^\mu}{m_c} \longrightarrow \frac{E_\pi}{m_c} = 1.5$

not a convergent expansion

Expt Average (Cleo, Belle, Babar):



strong phases

$$\delta(D\pi) = 27.3 \pm 3.9^\circ$$

$$\delta(D^*\pi) = 33.0 \pm 4.6^\circ$$

Extension to isosinglets:

Blechman, Mantry, I.S.

Not yet tested:

- $Br(D^*\rho^0_{\parallel}) \gg Br(D^*\rho^0_{\perp})$, $Br(D^{*0}K^{*0}_{\parallel}) \sim Br(D^{*0}K^{*0}_{\perp})$
- equal ratios $D^{(*)}K^*,\ D_s^{(*)}K,\ D_s^{(*)}K^*$; phases for $D^{(*)}\rho,\ D^{(*)}K$

Not yet tested:

Belle:

$$\frac{Br(B^- \to D_2^{*0}\pi^-)}{Br(B^- \to D_1^0\pi^-)} = 0.77 \pm 0.15$$

Babar:

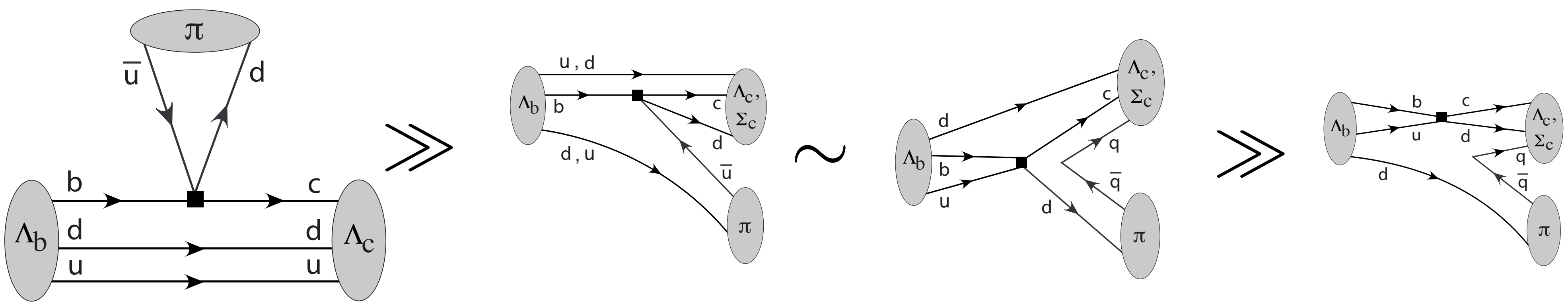
$$\frac{Br(B^- \to D_2^{*0}\pi^-)}{Br(B^- \to D_1^0\pi^-)} = 0.80 \pm 0.17$$

- **Excited D's** Mantry

$$\frac{Br(B \to D_2^*\pi)}{Br(B \to D_1\pi)} = 1 \qquad \phi_{D_2^*\pi} = \phi_{D_1\pi}$$

- **Baryons** Leibovich, Ligeti, I.S., Wise

topologies:



$$\frac{Br(\Lambda_b \to \Sigma_c^*\pi)}{Br(\Lambda_b \to \Sigma_c\pi)} = 2\,, \quad \frac{Br(\Lambda_b \to \Sigma_c^*\rho)}{Br(\Lambda_b \to \Sigma_c\rho)} = 2 \qquad \frac{Br(\Lambda_b \to \Xi_c^*K)}{Br(\Lambda_b \to \Xi_c'K)} = 2\,, \quad \frac{Br(\Lambda_b \to \Xi_c^*K_\parallel^*)}{Br(\Lambda_b \to \Xi_c'K_\parallel^*)} = 2$$

$$\frac{\Gamma(\Lambda_b \to \Lambda_c\pi^-)}{\Gamma(\bar{B}^0 \to D^+\pi^-)} = \frac{8m_{\Lambda_b}^3(1-r_\Lambda^2)^3\,r_D}{m_B^3(1-r_D^2)^3(1+r_D)^2}\left(\frac{\zeta(w_{\max}^\Lambda)}{\xi(w_{\max}^D)}\right)^2$$

↑ 1.6 ↑ need semileptonic

2) Test $\alpha_s(E\Lambda)$ expansion (expansion for J)

Relate π and ρ

Better data would pin down the ratio of these hadronic parameters

- Recall data gives

$$|r^{D\pi}| = \frac{|A(\bar{B}^0 \to D^+\pi^-)|}{|A(B^- \to D^0\pi^-)|} = 0.77 \pm 0.05\,, \qquad |r^{D\rho}| = 0.80 \pm 0.09$$

SCET predicts weak dependence on M if $\langle x^{-1}\rangle_\pi \simeq \langle x^{-1}\rangle_\rho$

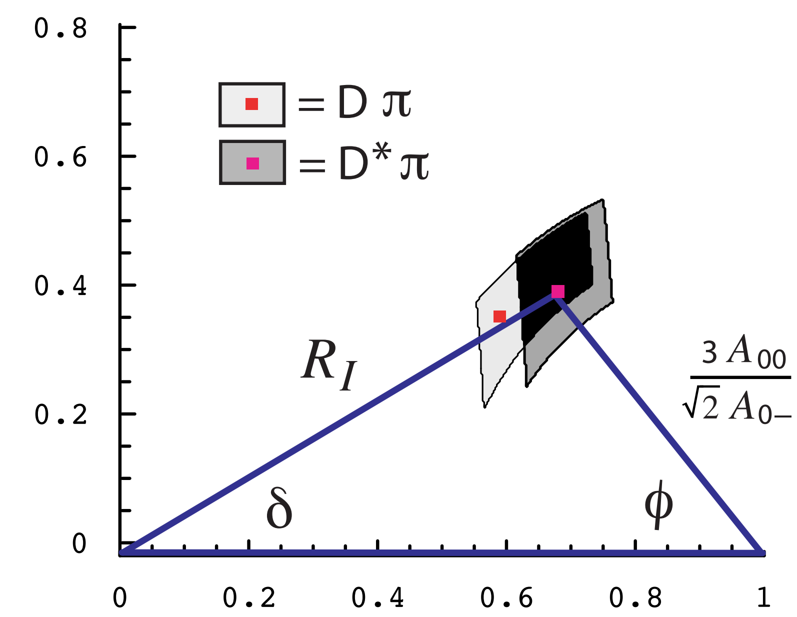
$$r^{DM} = 1 - \underbrace{\frac{16\pi\alpha_s m_D}{9(m_B+m_D)}\,\frac{\langle x^{-1}\rangle_M}{\xi(w_{max})}}_{\sim 2.5}\,\frac{s_{\rm eff}}{E_M}$$

no $f_\rho = 1.6\, f_\pi$

- natural parameters fit data, $s_{\rm eff} \simeq (430\,{\rm MeV})e^{i\,44^\circ}$

2) Test $\alpha_s(E\Lambda)$ expansion (expansion for J)

Relate π and ρ



- predict that $\phi^{D\rho} = \phi^{D\pi}$, not yet tested

if $\langle x^{-1} \rangle_\pi \simeq \langle x^{-1} \rangle_\rho$ then this implies $\delta^{D\pi} \simeq \delta^{D\rho}$

Relate η and η'

FKS mixing angle

- $$\frac{Br(\bar{B} \to D^{(*)}\eta')}{Br(\bar{B} \to D^{(*)}\eta)} = \tan^2(\theta) = 0.67 \quad +\mathcal{O}(\alpha_s(\sqrt{E\Lambda}))$$

$$\text{data} = 0.61 \pm 0.12(D), \quad 0.51 \pm 0.18(D^*)$$

Test SU(3) ?

$$R_{\mathrm{SU(3)}} = \frac{Br(\bar{B}^0 \to D_s^+ K^-)}{Br(\bar{B} \to D^0 \pi^0)} + \left|\frac{V_{ud}}{V_{us}}\right|^2 \frac{Br(\bar{B}^0 \to D^0 \bar{K}^0)}{Br(\bar{B} \to D^0 \pi^0)} - \frac{3Br(\bar{B}^0 \to D^0 \eta_8)}{Br(\bar{B} \to D^0 \pi^0)} = 1$$

$$R^*_{\mathrm{SU(3)}} = \frac{Br(\bar{B}^0 \to D_s^{*+} K^-)}{Br(\bar{B} \to D^{*0} \pi^0)} + \left|\frac{V_{ud}}{V_{us}}\right|^2 \frac{Br(\bar{B}^0 \to D^{*0} \bar{K}^0)}{Br(\bar{B} \to D^{*0} \pi^0)} - \frac{3Br(\bar{B}^0 \to D^{*0} \eta_8)}{Br(\bar{B} \to D^{*0} \pi^0)} = 1$$

$$R_{\mathrm{SU(3)}} = 1.0 \pm 0.6$$

$$R^*_{\mathrm{SU(3)}} = -0.22 \pm 0.97$$