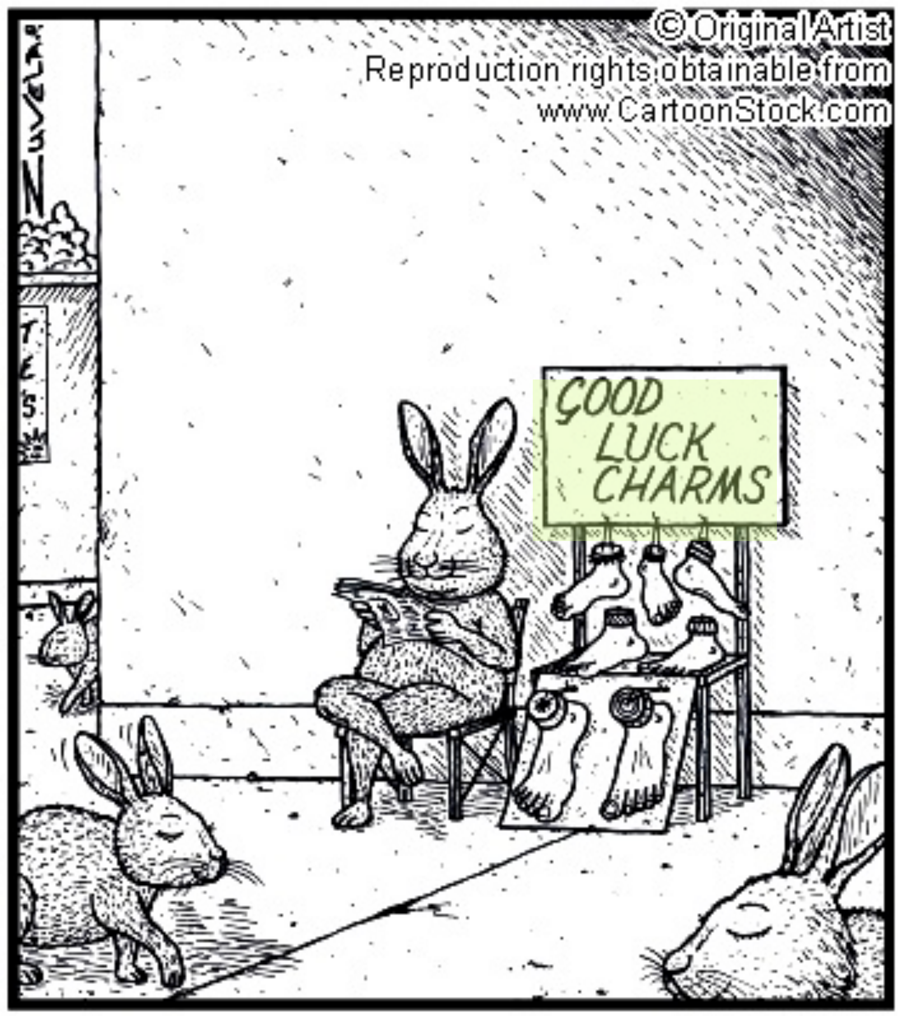
Charm Physics in a unified nonperturbative approach



Bruno El-Bennich

LFTC, Universidade Cruzeiro do Sul, São Paulo

Institute for Theoretical Physics, State University of São Paulo

Charming motivation ...

- Important hadronic effects stem from non-perturbative QCD contributions to strong ***and*** weak decay amplitudes, whether in beauty and charm decays.

- Charm decays are particularly afflicted by hadronic uncertainties since corrections to the decay amplitudes of order Λ_{QCD}/m_c are ***not*** under control.

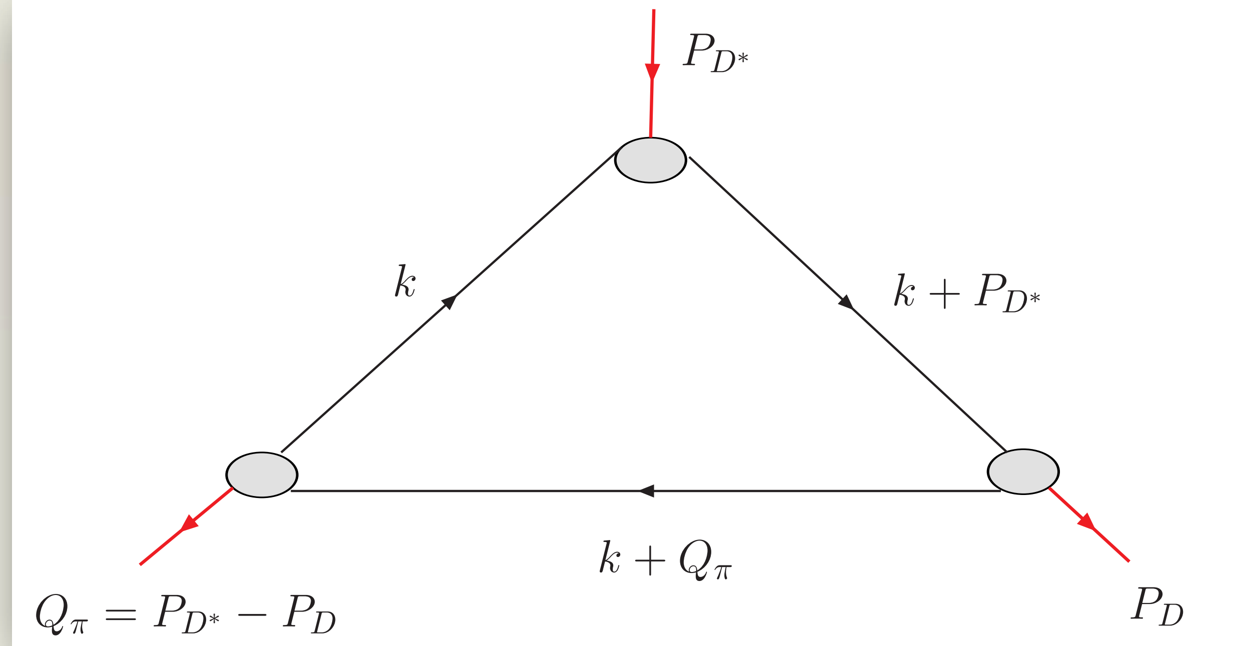
- Charm physics actively studied by LHC*b*, BaBar, Belle, BES, CLEO, FOCUS, RHIC ...

- PANDA at GSI will contribute to further development of *charm* physics.

- Charmonium production rate at RHIC is sensitive to existence and properties of the intermediate “quark-gluon plasma” *as well as* to final-state interactions (J/ψ decays).

A few examples of hadronic charmed decays

Strong decay $D^* \to D\pi$



Coupling yields D^* width

$$A(D^* \to D\pi) = \epsilon_\mu^{\lambda_{D^*}}(p_{D^*}) M^\mu(p_D^2, p_{D^*}^2) := \epsilon_\mu^{\lambda_{D^*}}(p_{D^*}) p_D^\mu \, g_{D^* D\pi}$$

$$M^\mu(p_D^2, p_{D^*}^2) = N_c \, \mathrm{tr} \int^\Lambda \frac{d^4k}{(2\pi)^4} \bar{\Gamma}_D(k; -P_D) S_c(k + P_{D^*}) i\Gamma_{D^*}^\mu(k; P_{D^*}) S_u(k) \bar{\Gamma}_\pi(k; -Q_\pi) S_u(k + Q_\pi)$$

The coupling $g_{H^*H\pi}$ can be calculated even if decay is kinematically forbidden: B^*: $m_{B^*} - m_B \approx 46$ MeV

Unphysical decay $B^* \to B\pi$ to extract effective heavy quark coupling

Heavy Quark Effective Theory

- Dynamics is constrained by heavy quark symmetry.
- Blind to the heavy quark flavor and spin.
- Heavy pseudoscalar and vector mesons are mass degenerate.
- Can be improved upon — take into account light degrees of freedom, chiral symmetry breaking $\Rightarrow$ HMChPT.

$$\mathcal{L}_{\rm heavy} = -{\rm tr}_a {\rm Tr}[\bar{H}_a iv\cdot D_{ba} H_b] + \hat{g}\, {\rm tr}_a {\rm Tr}[\bar{H}_a H_b \gamma_\mu \mathbf{A}^\mu_{ba}\gamma_5]$$

$$D^\mu_{ba} H_b = \partial_\mu H_a - H_b \frac{1}{2}[\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger]_{ba} \ ;$$

$$\mathbf{A}^{ab}_\mu = \frac{i}{2}\left[\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger\right]_{ab} ;$$

$$H_a(v) = \frac{1+\not{v}}{2}\left[P^{*a}_\mu(v)\gamma_\mu - P^a(v)\gamma_5\right] ;$$

$$\xi = \exp(i\Phi/f^0_\pi) \ ;$$

Φ is matrix of $N_f^2 - 1$ pseudo-Goldstone boson.

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Rept. **281**, 145 (1997)

Generalization to higher spin structures

- $D^* \to D\pi$ can be generalized to three-point functions for vector mesons with off-shell momenta.
- Couplings $D\rho D$, $D^*\rho D$, $D^*\rho D^*$ needed in final-state interactions with intermediate $D - D^*$ states.

✻ $D^*\rho D$ coupling : $\mathcal{M} \equiv \varepsilon^{\rho}_{\alpha}\varepsilon^{D^*}_{\beta} M^{\alpha\beta}(p^{D^*}, p^{\rho}) = \epsilon^{\alpha\beta\mu\nu}\varepsilon_{\alpha}(p^{D^*})\varepsilon_{\beta}(p^{\rho})\; p^{D^*}_{\mu} q^{\rho}_{\nu}\, \frac{g_{D^*\rho D}}{m_{D^*}}$

✻ $D^*\rho D^*$ coupling :

$$M^{\mu\nu\rho}(p_1,p_2) = G_1\, g^{\mu\nu} p_2^{\rho} + G_2\, g^{\mu\rho} p_2^{\nu} + G_3\, g^{\nu\rho} p_2^{\mu} + G_4\, g^{\mu\nu} p_1^{\rho} + G_5\, g^{\mu\rho} p_1^{\nu} + G_6\, g^{\nu\rho} p_1^{\mu} + G_7\, p_2^{\mu} p_2^{\nu} p_2^{\rho}$$
$$+ G_8\, p_1^{\mu} p_2^{\nu} p_2^{\rho} + G_9\, p_2^{\mu} p_1^{\nu} p_2^{\rho} + G_{10}\, p_2^{\mu} p_2^{\nu} p_1^{\rho} + G_{11}\, p_1^{\mu} p_1^{\nu} p_2^{\rho} + G_{12}\, p_1^{\mu} p_2^{\nu} p_1^{\rho} + G_{13}\, p_2^{\mu} p_1^{\nu} p_1^{\rho} + G_{14}\, p_1^{\mu} p_1^{\nu} p_1^{\rho}$$

with
$$\mathcal{M} \equiv \epsilon^{\nu}_{\rho^0}(q)\epsilon^{\mu}_{D^*}(p_1)\epsilon^{\rho}_{D^*}(p_2) M^{\mu\nu\rho}(p_1^2, p_2^2, q^2) =$$
$$= \epsilon^{\nu}_{\rho^0}(q)\epsilon^{\mu}_{D^*}(p_1)\epsilon^{\rho}_{D^*}(p_2)\, N_c \,\mathrm{tr} \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \bar{\Gamma}^{\rho}_{D^*}(k;-p_2) S_c(k+p_1) \Gamma^{\mu}_{D^*}(k;p_1) S_u(k) \bar{\Gamma}^{\nu}_{\rho^0}(k;-q) S_u(k+q)$$

$\Gamma^{\mu}_{D^*}$: D^*-meson Bethe-Salpeter amplitude

$\Gamma^{\nu}_{\rho^0}$: ρ^0-meson Bethe-Salpeter amplitude

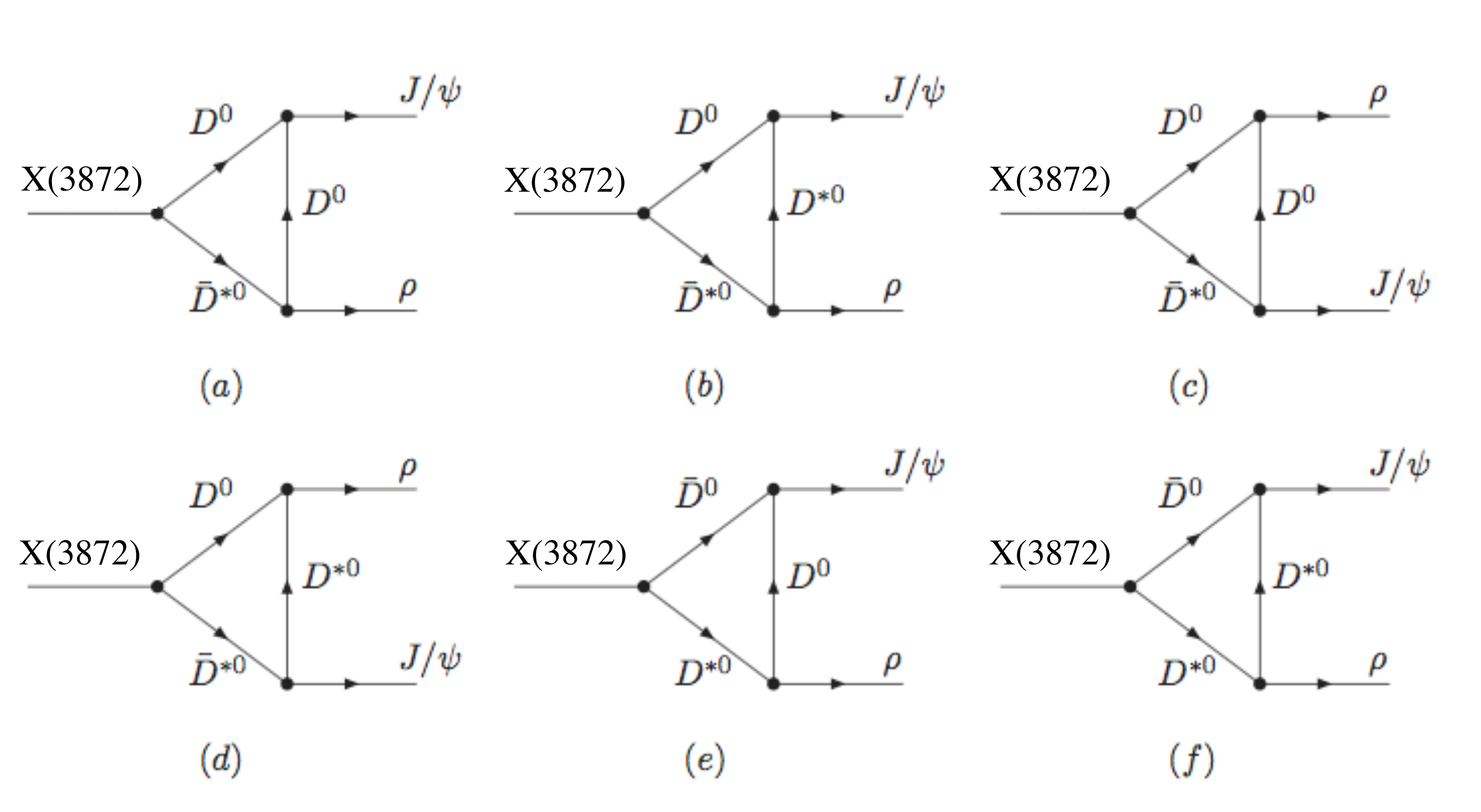
ϵ^{μ}_{i} : Polarization vector

Why higher spin structures?

Example: decay of recently the discovered resonance $X(3872)$ ($J^{PC} = 1^{?+}$)

Main decay modes are $X(3872) \to D^0 D^{0*} (\bar{D}^0 \pi^0), J/\psi \pi^+ \pi^-, J/\psi \gamma, J/\psi \pi^+ \pi^- \pi^+ ...$

➪ **clear isospin violation**



Exotic nuclear bound states: J/ψ mass shift in nuclear matter

- J/Ψ mass decrease in nuclear matter estimated to 4 – 7 MeV with QCD sum rules.
- An interesting challenge are properties of D and $D^{(*)}$ mesons in medium:

  Possible formation of $D(\bar{D})$ meson-nuclear bound states.

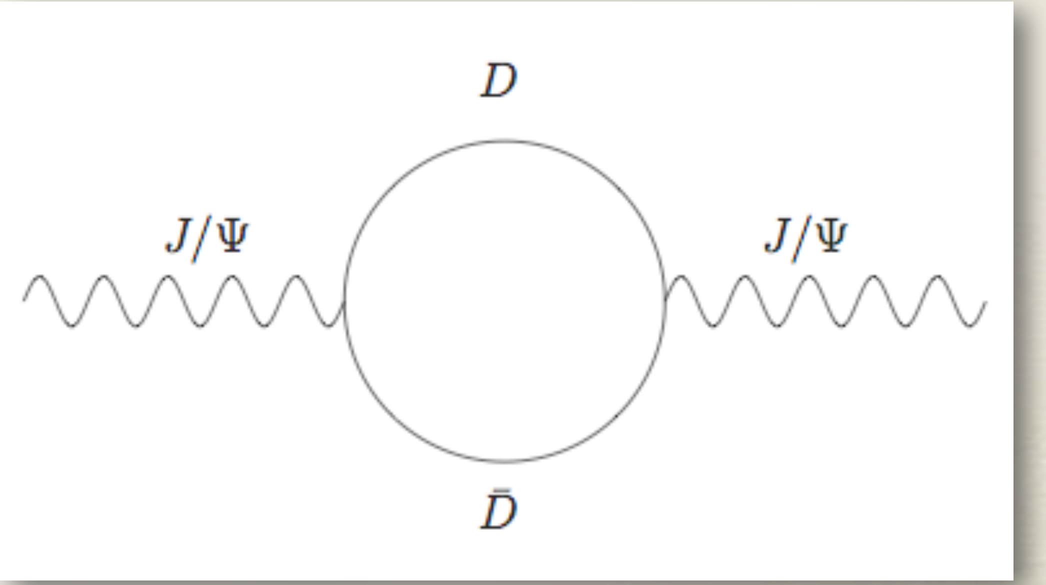
  Enhanced dissociation of J/Ψ in nuclear matter (heavy nuclei).

  Enhancement of $D(\bar{D})$ production in antiproton-nucleus collisions.

G. Krein, A.W. Thomas & K. Tsushima (2010)

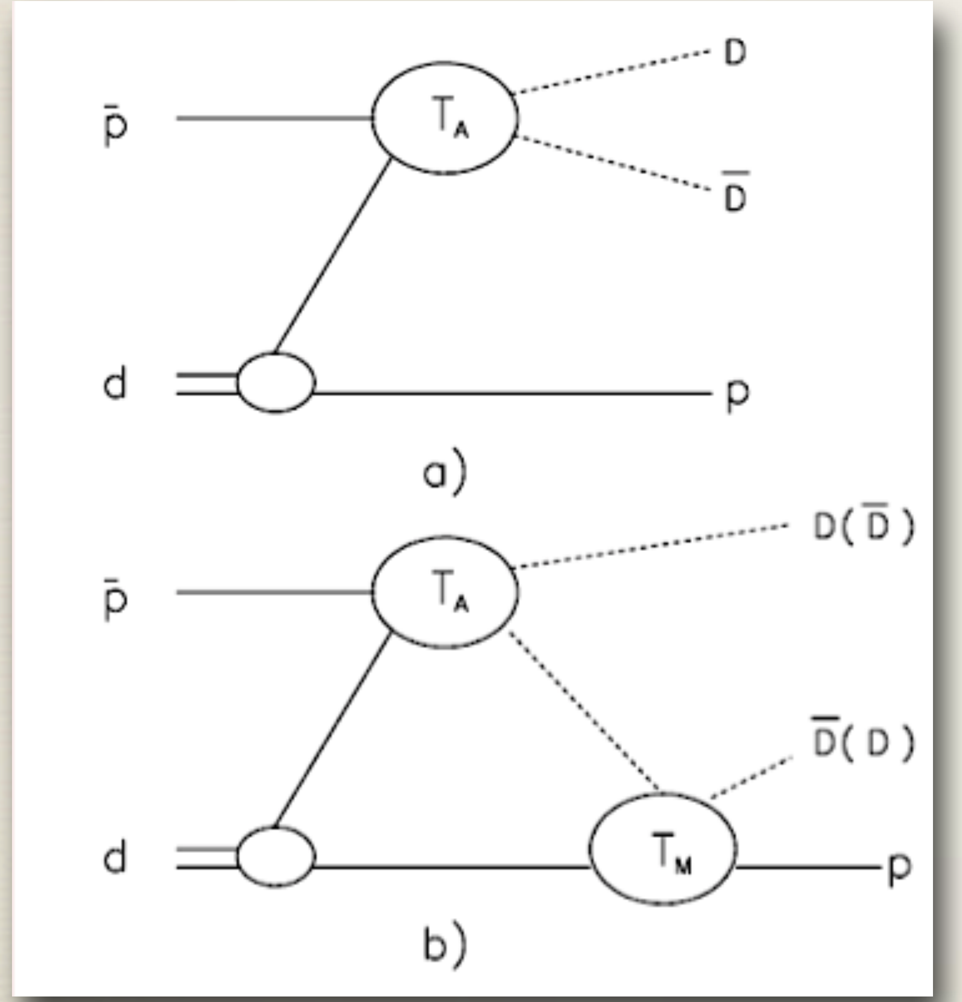
$$
\begin{aligned}
\mathcal{L}_{\psi DD} &= i g_{\psi DD}\, \psi^{\mu}[\bar{D}(\partial_{\mu} D) - (\partial_{\mu}\bar{D})D], \\
\mathcal{L}_{\psi DD^*} &= \frac{g_{\psi DD^*}}{m_{\psi}}\, \varepsilon_{\alpha\beta\mu\nu}(\partial^{\alpha}\psi^{\beta})\left[(\partial_{\mu}\bar{D}^{*\nu})D + \bar{D}(\partial_{\mu}D^{*\nu})\right], \\
\mathcal{L}_{\psi D^*D^*} &= i g_{\psi D^* D^*}\, \{[\psi^{\mu}[(\partial_{\mu}\bar{D}^{*\nu})D^*_{\nu} - \bar{D}^{*\nu}(\partial_{\mu}D^*_{\nu})] \\
&+ [(\partial_{\mu}\psi^{\nu})\bar{D}^*_{\nu} - \psi^{\nu}(\partial_{\mu}\bar{D}^*_{\nu})]\, D^{*\mu} + \bar{D}^{*\mu}\,[\psi^{\nu}(\partial_{\mu}D^*_{\nu}) - (\partial_{\mu}\psi^{\nu})D^*_{\nu}]\}
\end{aligned}
$$

K. Saito, K. Tsushima and A. W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

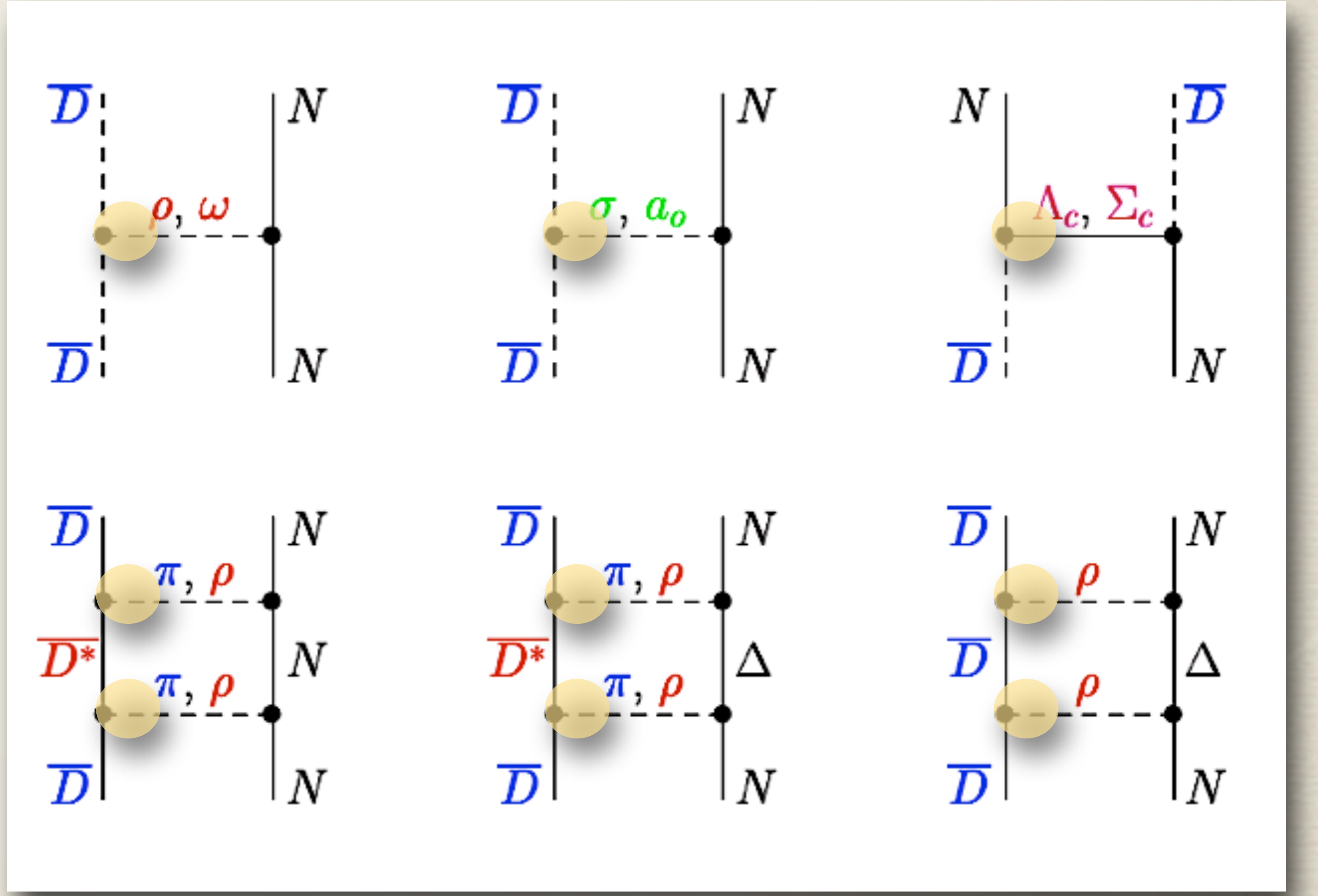


D-meson interaction with nucleons

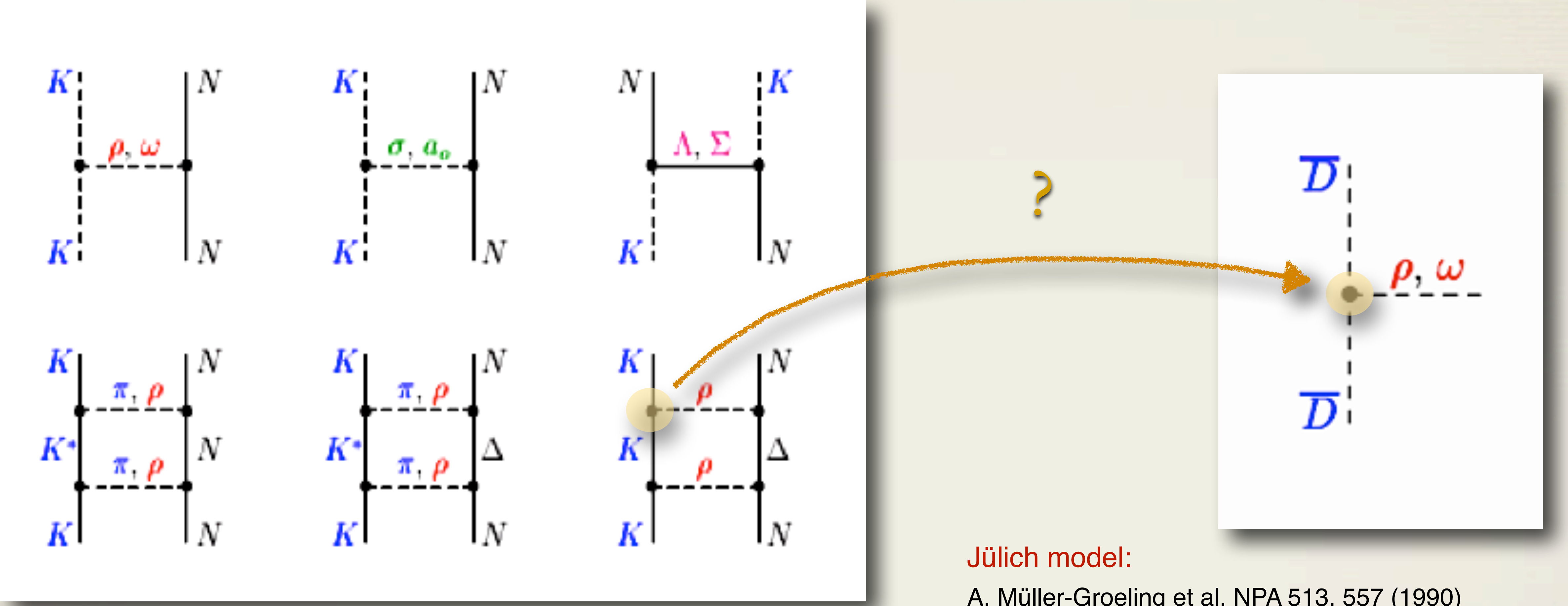
Antiproton annihilation on the deuteron (PANDA @ FAIR)



Meson exchange — effective Lagrangians



SU(4) symmetry used ....



Jülich model:

A. Müller-Groeling et al. NPA 513, 557 (1990)

M. Hoffmann et al. NPA 593, 341 (1995)

D. Hadjimichef, J. Haidenbauer and G. Krein, PRC 66, 055214 (2002)

$$SU(4)\text{ symmetry: } g_{D\rho D} = g_{D\omega D} = g_{KK\rho} = \frac{1}{2} g_{\pi\pi\rho}$$

$PS \to S$ decays and rescattering

Important in Dalitz plot analyses of non-leptonic three-body D and B decays

$$D_{(s)} \to f_0(980)$$
$$D_{(s)} \to K_0^*(1430)$$
$$B_{(s)} \to f_0(980)$$
$$B_{(s)} \to K_0^*(1430)$$

$\longrightarrow$

$$D_{(s)} \to (\pi\pi)_S \, (\bar{K}K)_S$$
$$D_{(s)} \to (K\pi)_S$$
$$B_{(s)} \to (\pi\pi)_S \, (\bar{K}K)_S$$
$$B_{(s)} \to (K\pi)_S$$

- So far there are no BSAs for scalar mesons
- More modeling and assumptions involved
- Scalar mesons tend to be broad (background)

B.E. , O. Leitner, J.-P. Dedonder and B. Loiseau (2009)

Dyson-Schwinger and Bethe-Salpeter framework

Dyson-Schwinger equations

- Well suited to Relativistic Quantum Field Theory
- Non-perturbative continuum approach to QCD
- Hadrons as composites of Quarks *and* Gluons
- Qualitative and quantitative importance for:

  Dynamical Chiral Symmetry Breaking

  Generation of fermion mass from *nothing*

  Quark & Gluon Confinement

- Method yields Schwinger functions (Euclidean Green's Functions) ≡ Propagators
- Confinement can be related to the analytic properties of QCD's Schwinger functions

Caveat

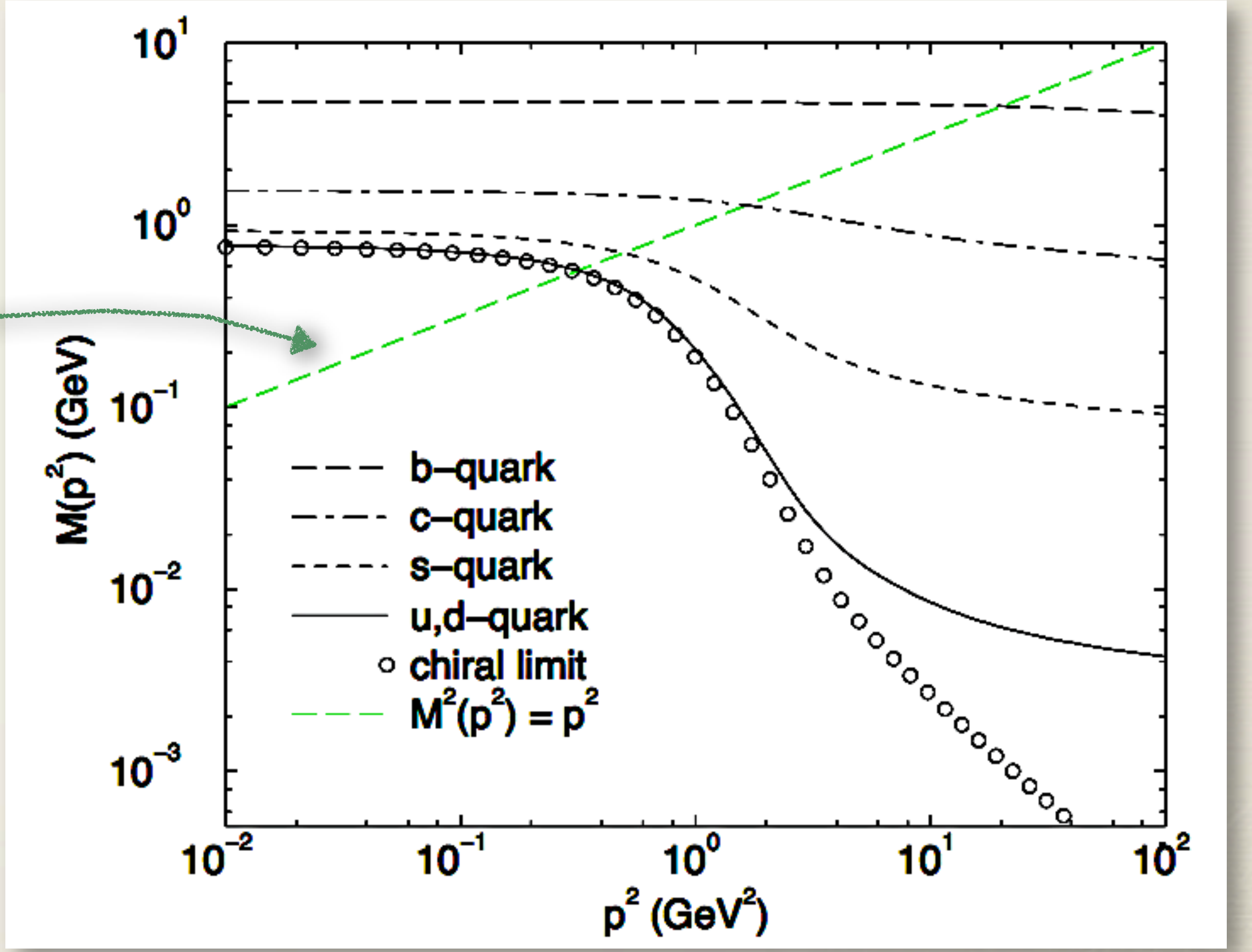
- No assumption of heavy-quark symmetry is made.
- In particular, pseudoscalar and vector meson masses are not degenerate.
- Weak decay constants are not degenerate.
- Although impulse approximation and truncations are employed, $\Lambda_{\rm QCD}/m_c$ contributions are systematically included.

DSE mass functions

The large current-quark mass of the b quark almost entirely suppresses momentum-dependent dressing, so that $M_b(p^2)$ is nearly constant on a substantial domain. This is true to a lesser extent for the c quark.

$$(\hat{M}^E)^2 = \{s | s + M^2(s) = 0\}$$

Euclidean mass definition



Euclidean mass, sigma term

Define a single quantitative measure, namely the renormalization-point invariant ratio $\zeta_f := \frac{\sigma_f}{M_f^E}$

with the constituent-quark **σ** term: $\sigma_f := m_f(\zeta) \frac{\partial M_f^E}{\partial m_f(\zeta)}$ $\quad \sigma_f \xrightarrow{\hat{m}\to 0} 0$

The solutions of $(\hat{M}^E)^2 = \{s|s + M^2(s) = 0\}$ in GeV:

f	chiral	u,d	s	c	b
M_f^E	0.42	0.42	0.56	1.57	4.68

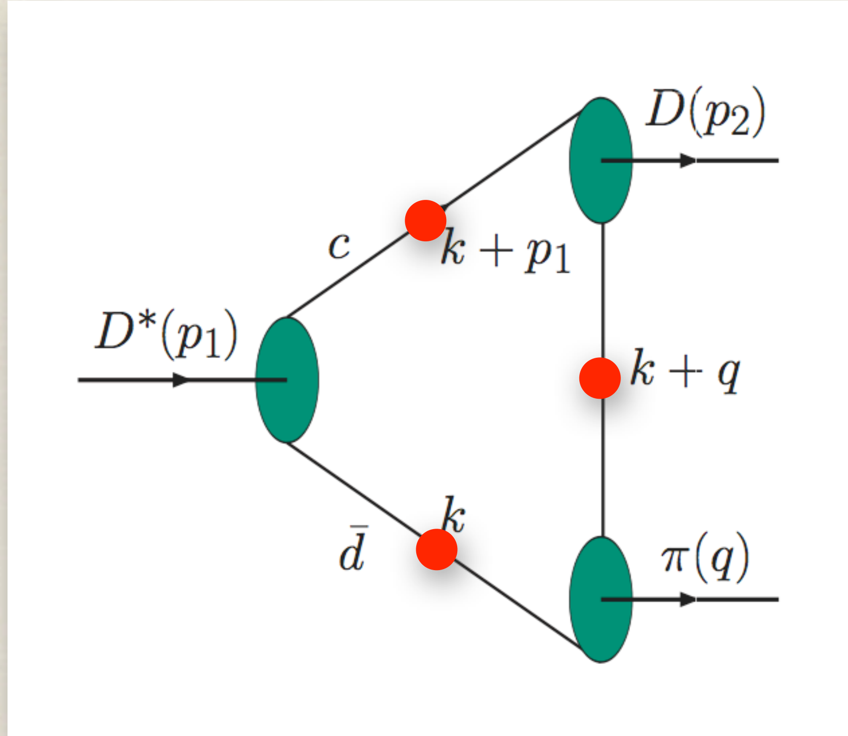
The ratio ζ_f thus quantifies the effect of explicit chiral symmetry breaking on the dressed-quark mass function compared with the sum of the effects of explicit and dynamical chiral symmetry breaking.

→

f	u,d	s	c	b
ζ_f	0.02	0.23	0.65	0.8

Reasonable approximation : $S_{Q=c,b} \approx \frac{1}{i\gamma \cdot p + \hat{M}_Q}$

Strong decays: $D^* \to D\pi$



	CLEO	DSE	QCDSR	Lattice
$g_{D^*D\pi}$	$17.9 \pm 0.3 \pm 1.9$	16.5 ± 2	14.0 ± 1.5	20 ± 2

B. E., M.A. Ivanov and C.D. Roberts (2012)

Coupling yields D^* width

$$A(D^* \to D\pi) = \epsilon_\mu^{\lambda_{D^*}}(p_{D^*}) M^\mu(p_D^2, p_{D^*}^2) := \epsilon_\mu^{\lambda_{D^*}}(p_{D^*}) p_D^\mu \, g_{D^*D\pi}$$

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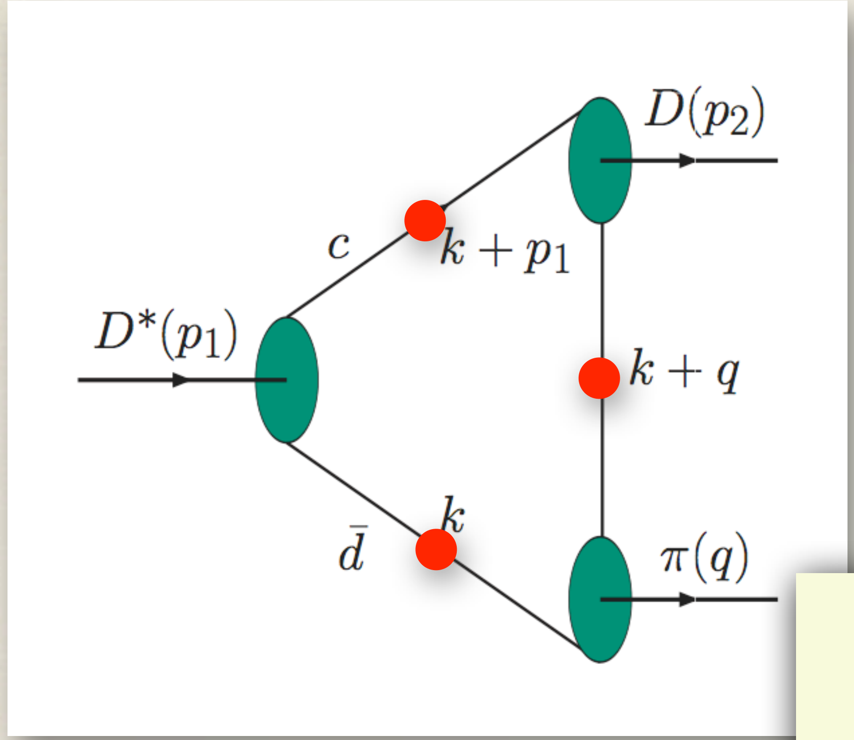
Strong decays: $D^* \to D\pi$



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B. E., M.A. Ivanov and C.D. Roberts (2012)

Similarly: $D_s^* \to DK$

$$g_{D_s^* DK} = 20^{+2.5}_{-1.7}$$

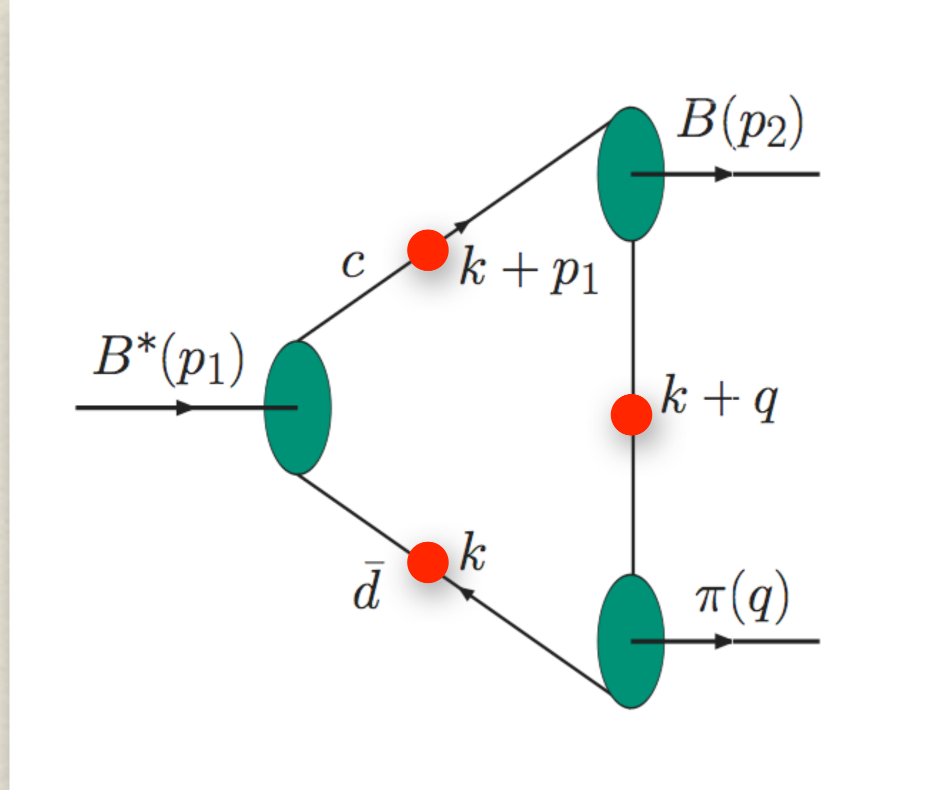
B. E., M.A. Ivanov and C.D. Roberts (2012)

dth

$$A(D^* \to D\pi) = \epsilon_\mu^{\lambda_{D^*}}(p_{D^*})M$$

$$M^\mu(p_D^2, p_{D^*}^2) = N_c \,\mathrm{tr} \int^\Lambda \frac{d^4}{(2\pi} \quad Q_\pi)$$

Strong decays: $B^* \rightarrow B\pi$ (analogy)



This amplitude can be used for $m_\pi^2 \rightarrow 0$ to extract $\hat{g}$ at leading order in HMChPT:

$$\hat{g} = \frac{g_{B^*B\pi}}{2\sqrt{m_B m_{B^*}}} f_\pi$$

	DSE model	Lattice in static limit $(n_f = 2)$
$\hat{g}$	0.37 ± 0.04	$0.44 \pm 0.03^{+0.07}_{-0.0}$

DSE: B. E., M.A. Ivanov and C.D. Roberts (2011)

LQCD: D. Bećirević, B. Blossier, E. Chang and B. Haas (2009)

$$\mathcal{L}_{\text{heavy}} = -\text{tr}_a \text{Tr}[\bar{H}_a i v \cdot D_{ba} H_b] + \hat{g}\, \text{tr}_a \text{Tr}[\bar{H}_a H_b \gamma_\mu \mathbf{A}^\mu_{ba} \gamma_5]$$

The value obtained from D^* decay is: $\hat{g}_c = 0.56^{+0.07}_{-0.03}$ $\longrightarrow$ Λ_{QCD}/m_c corrections important!

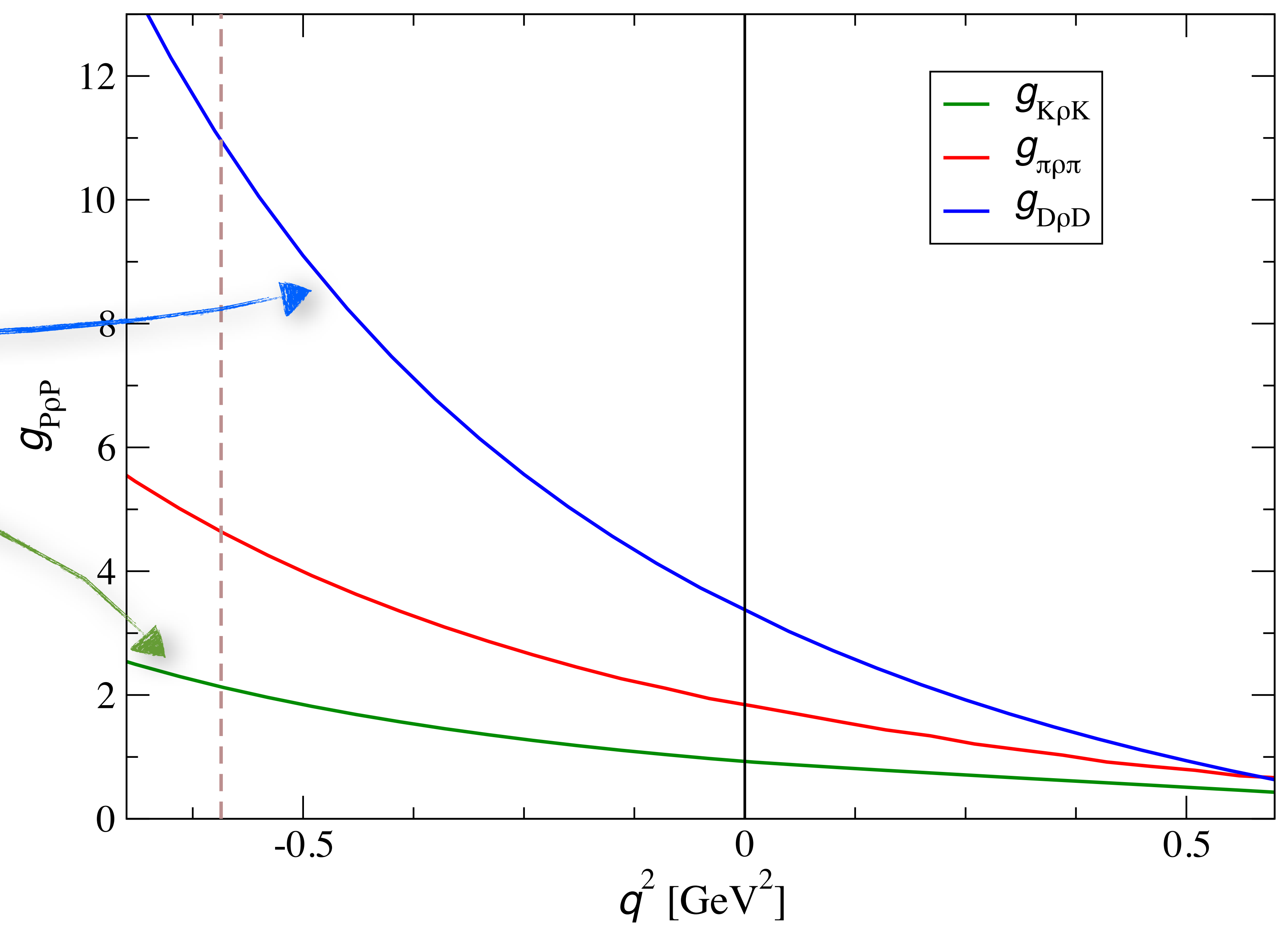
Flavour SU(3), SU(4), sensible symmetries?

Define $\zeta_\rho := \frac{g_{D\rho D}(q^2)}{g_{K\rho K}(q^2)}$

Ratio measures the effect of SU(4) breaking ≈ 300%

SU(3) breaking ≈ 20–30%

$$g_{D\rho D} \neq g_{K\rho K} \neq \frac{1}{2} g_{\pi\rho\pi}$$



B. E., G. Krein, L. Chang, C.D. Roberts and D. Wilson (2012)

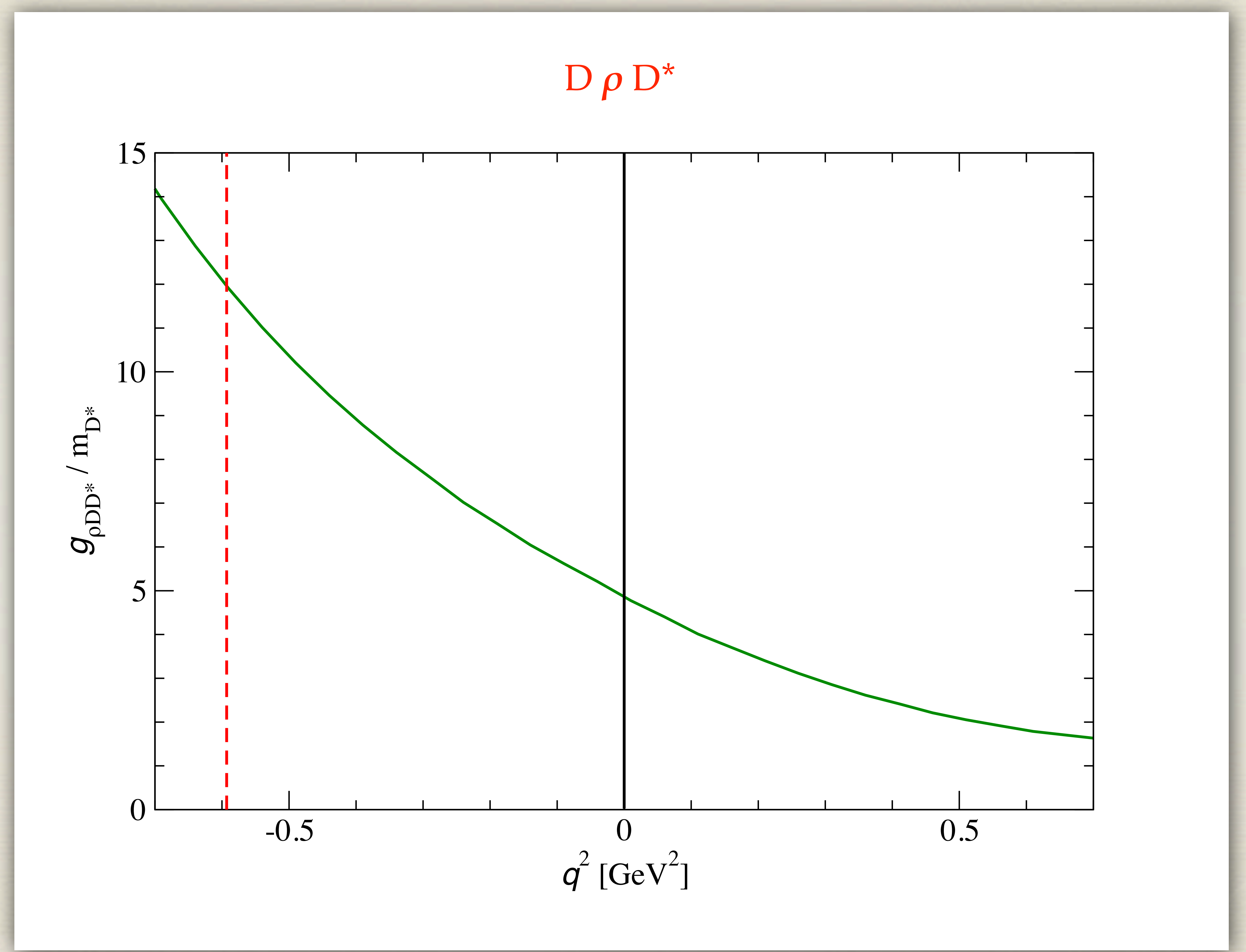
Consequences?

The integrated $D\rho D$ interaction is enhanced by about 40% compared with an $SU(4)$ prediction for the coupling/form factor.

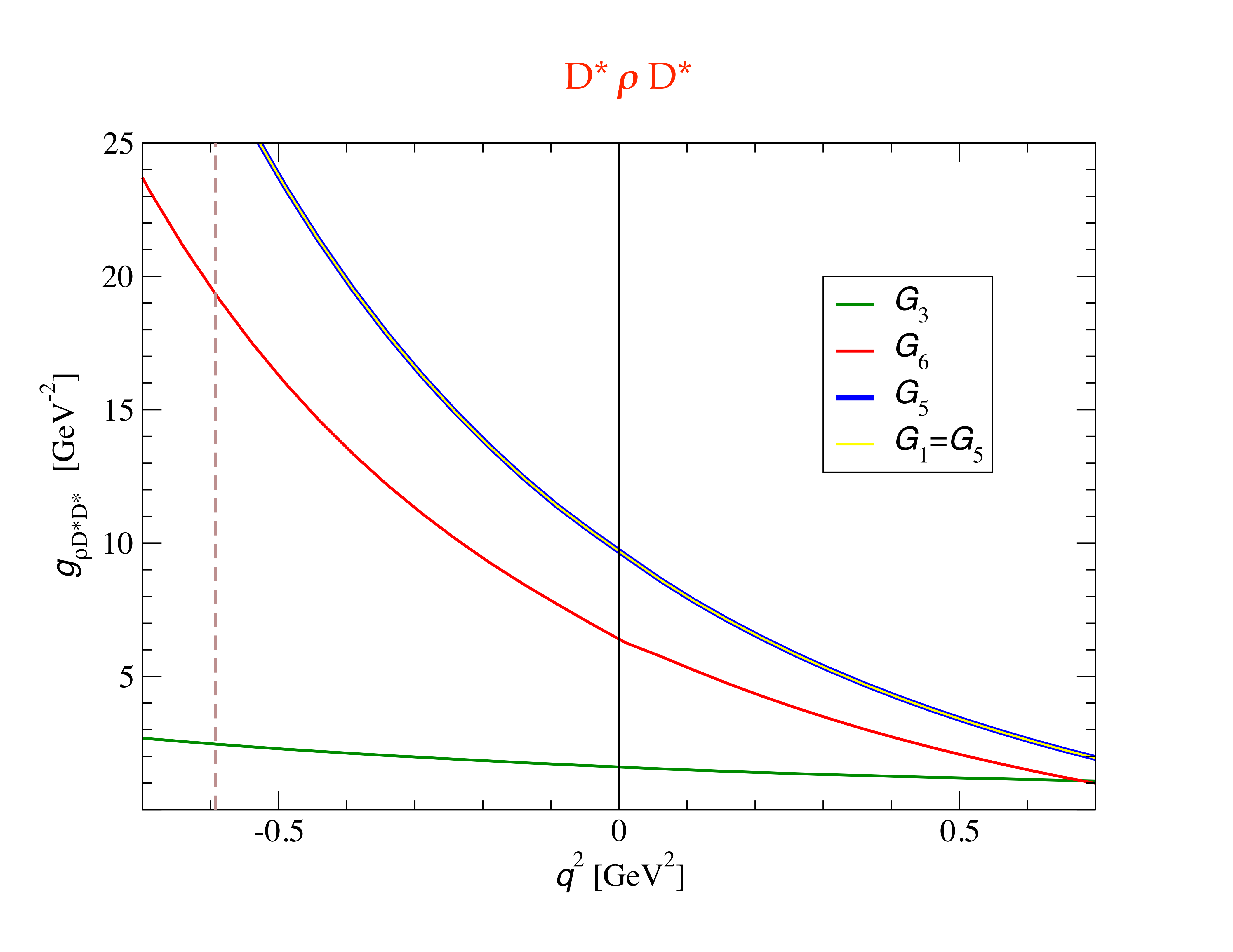
→ Large value value for the interaction strength entails an enhanced cross section in DN scattering ($I = 1$ cross section inflated by a factor 4–5).

Possible novel charmed resonances or bound states in nuclei?

Higher-spin couplings



Higher-spin couplings



Epilogue

- Form factors are the single important source of uncertainties and much work is left to pin down theoretical uncertainties to a few percent in charm physics.
- One aspect learned over and over again is: heavy-quark symmetry is not applicable in charmed mesons and $\Lambda_{\rm QCD}/m_c$ corrections are not negligible.
- Other (flavor) symmetries often invoked to simplify calculations are not justified.
- DSE/BSA treatments of heavy mesons must go beyond the rainbow-ladder approximation.