Highlights and Challenges of Hadron Physics

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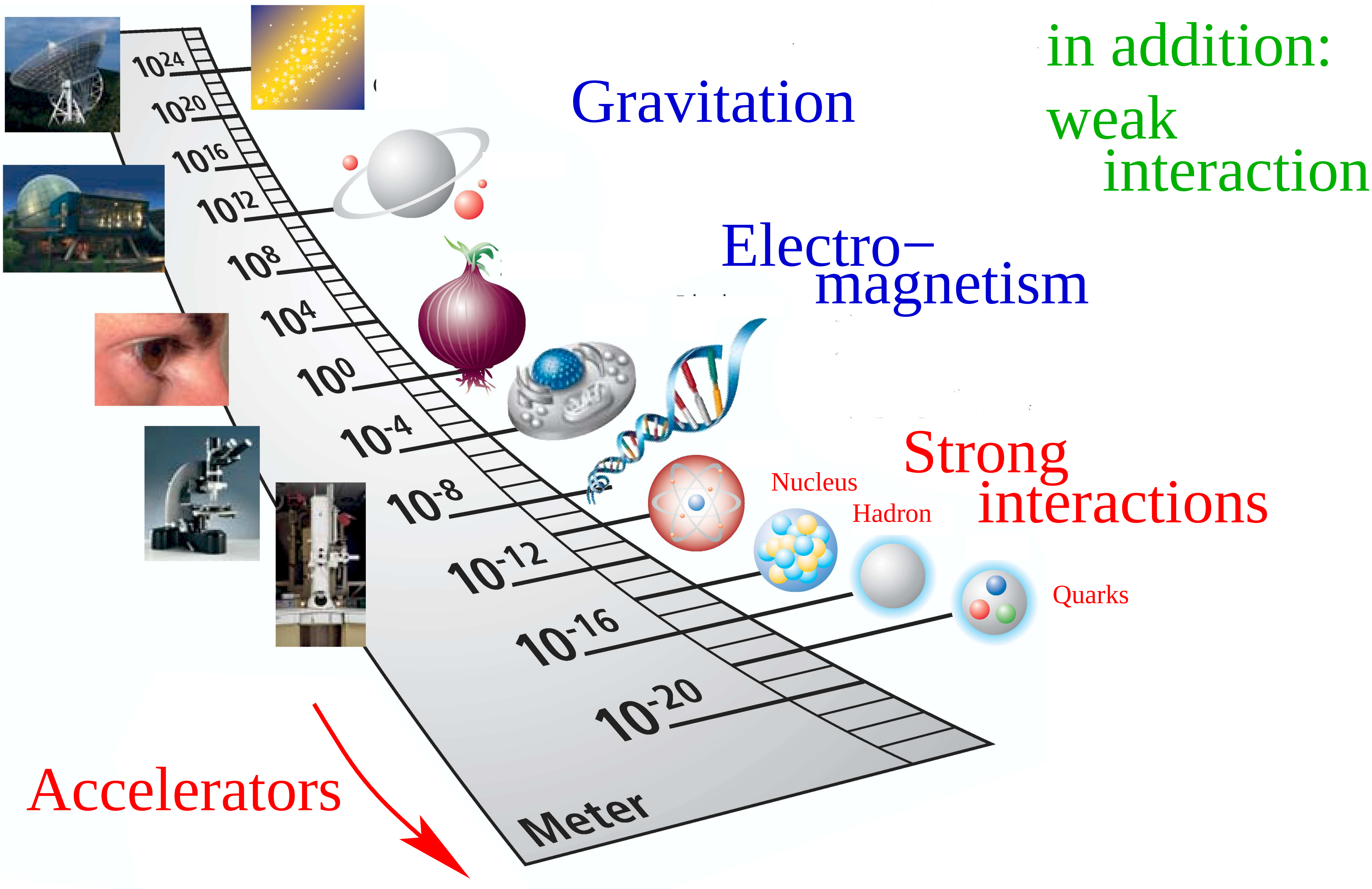
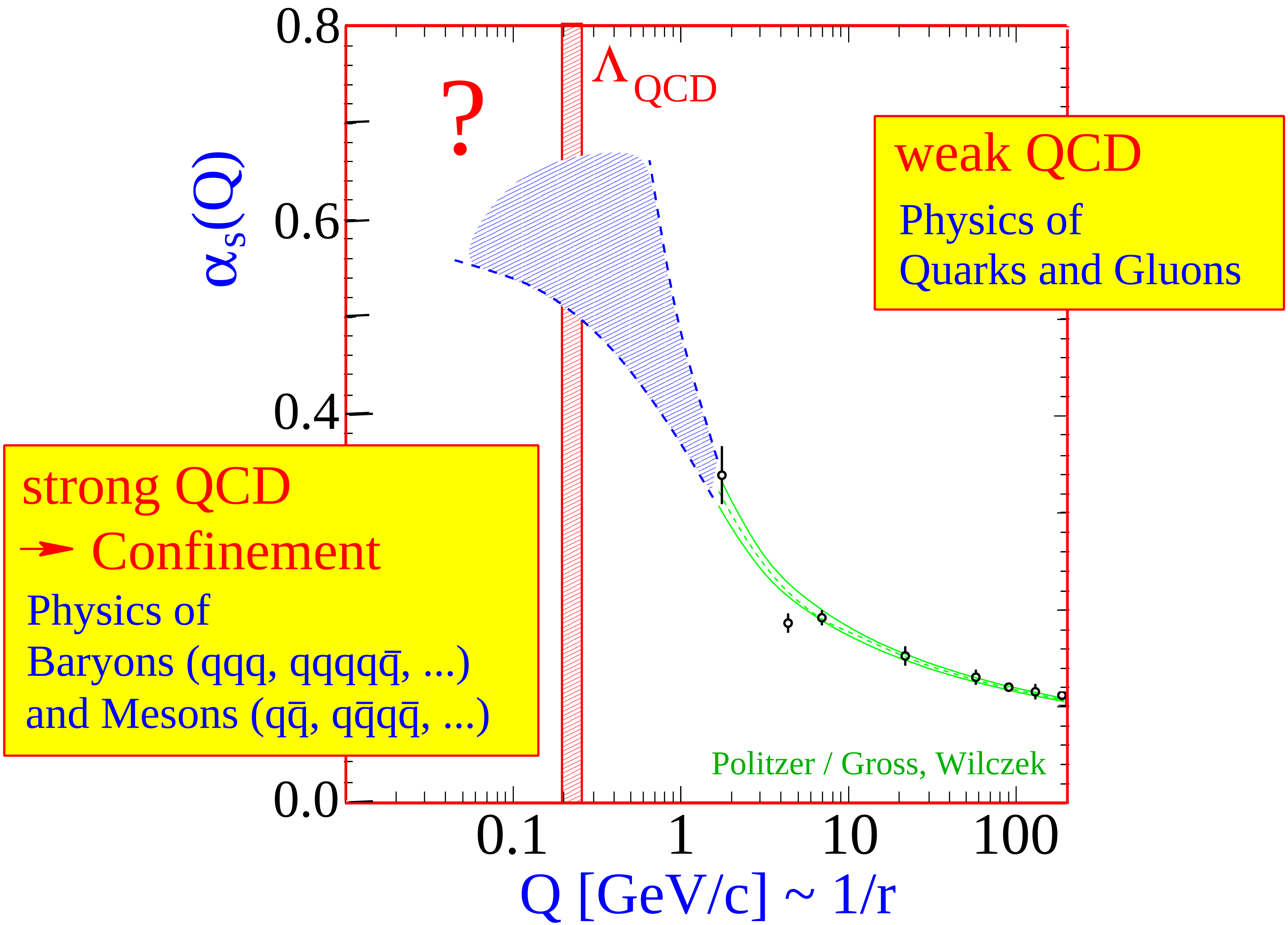
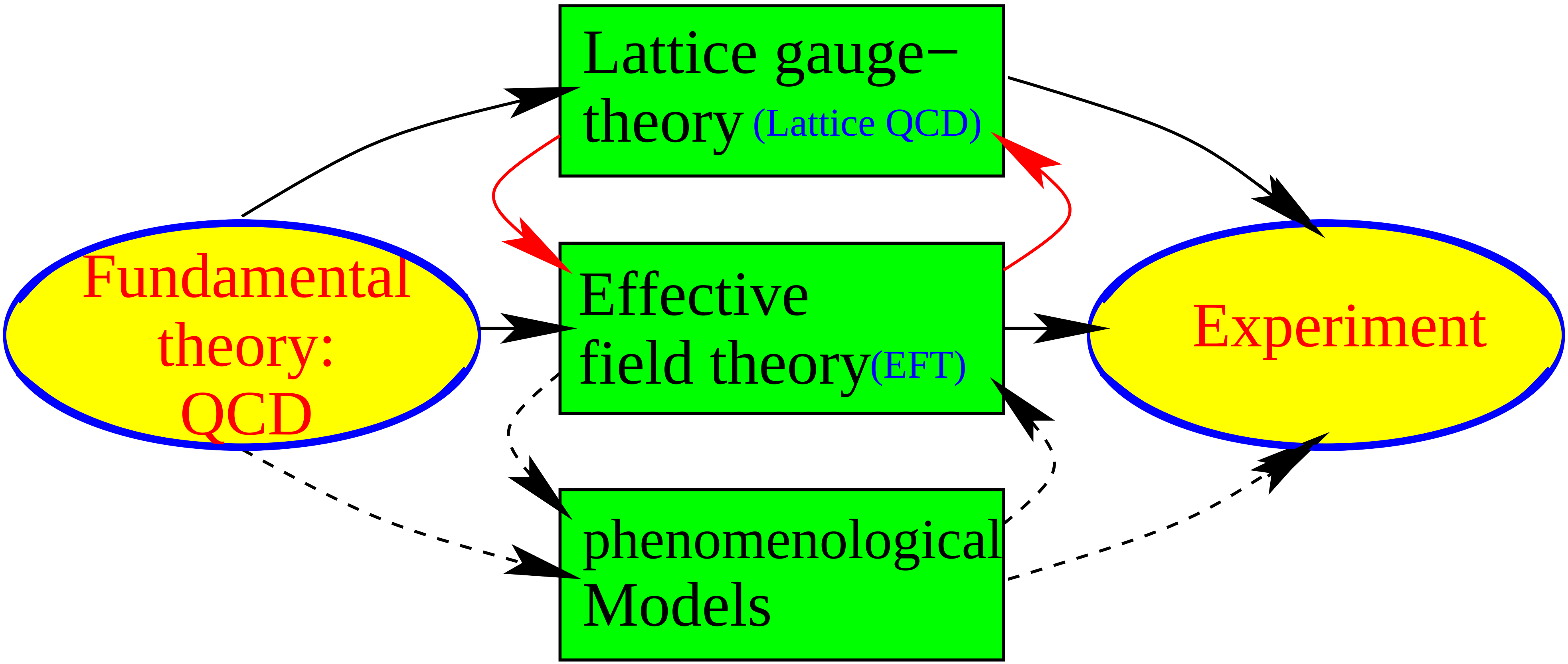
The fundamental interactions



The faces of QCD



Strategies to treat strong QCD



→ Lattice Gauge Theory: direct solution
but requires long computing times → few Observables

→ EFT: most general structure compatible with QCD
but with increasing accuracy more free parameters

Limiting cases of QCD

Weinberg/ Gasser, Leutwyler/ Isgur, Wise

$$\mathcal{L}_{\rm QCD} = \sum_f \bar{q}_f \left\{ i\partial\!\!\!/ - m_f + g A\!\!\!/^a t^a \right\} q_f - \frac{1}{4} G^a_{\lambda\rho} G^{\lambda\rho\, a} + \ldots$$

Limit of massless Quarks

$$\mathcal{L}_{\rm QCD} = \bar{q}_L \left\{ i\partial\!\!\!/ + g A\!\!\!/^a t^a \right\} q_L + \bar{q}_R \left\{ i\partial\!\!\!/ + g A\!\!\!/^a t^a \right\} q_R + \mathcal{O}(m_f/\Lambda_{\rm QCD})$$

L and R Quarks decouple + spontaneous symmetry breaking

$\rightarrow$ Chiral Perturbation Theory (ChPT)

Limit of infinitely Heavy Quarks

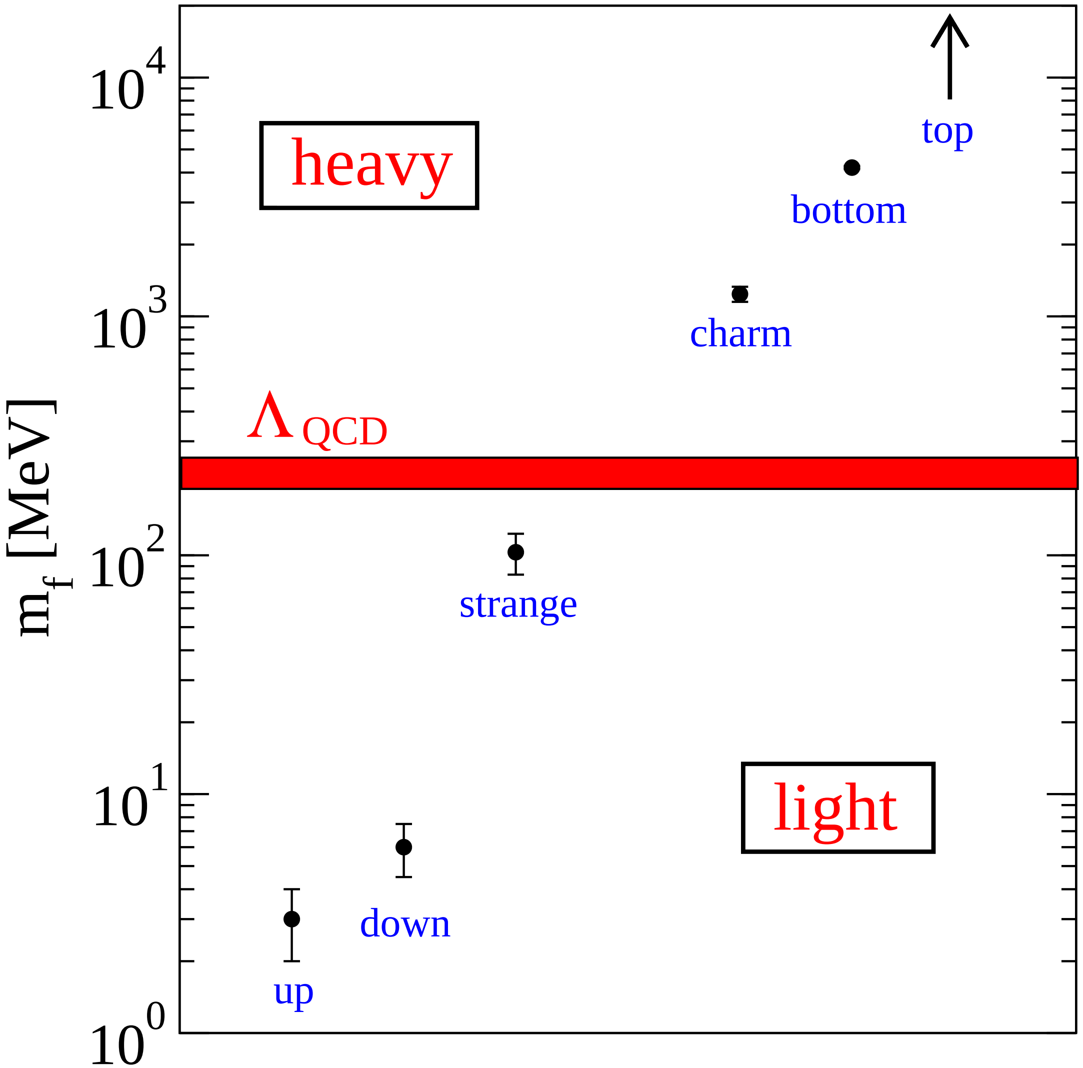
$$\mathcal{L}_{\rm QCD} = \bar{q}_f \left\{ i v \cdot \partial + g v \cdot A^a t^a \right\} q_f + \mathcal{O}(\Lambda_{\rm QCD}/m_f)$$

Independent of Heavy Quark Spin and Flavour

$\rightarrow$ Heavy Quark Effective Field Theory (HQEFT)

Quark Masses

Quark Masses (in $\overline{\mathrm{MS}}$ at μ=2 GeV)



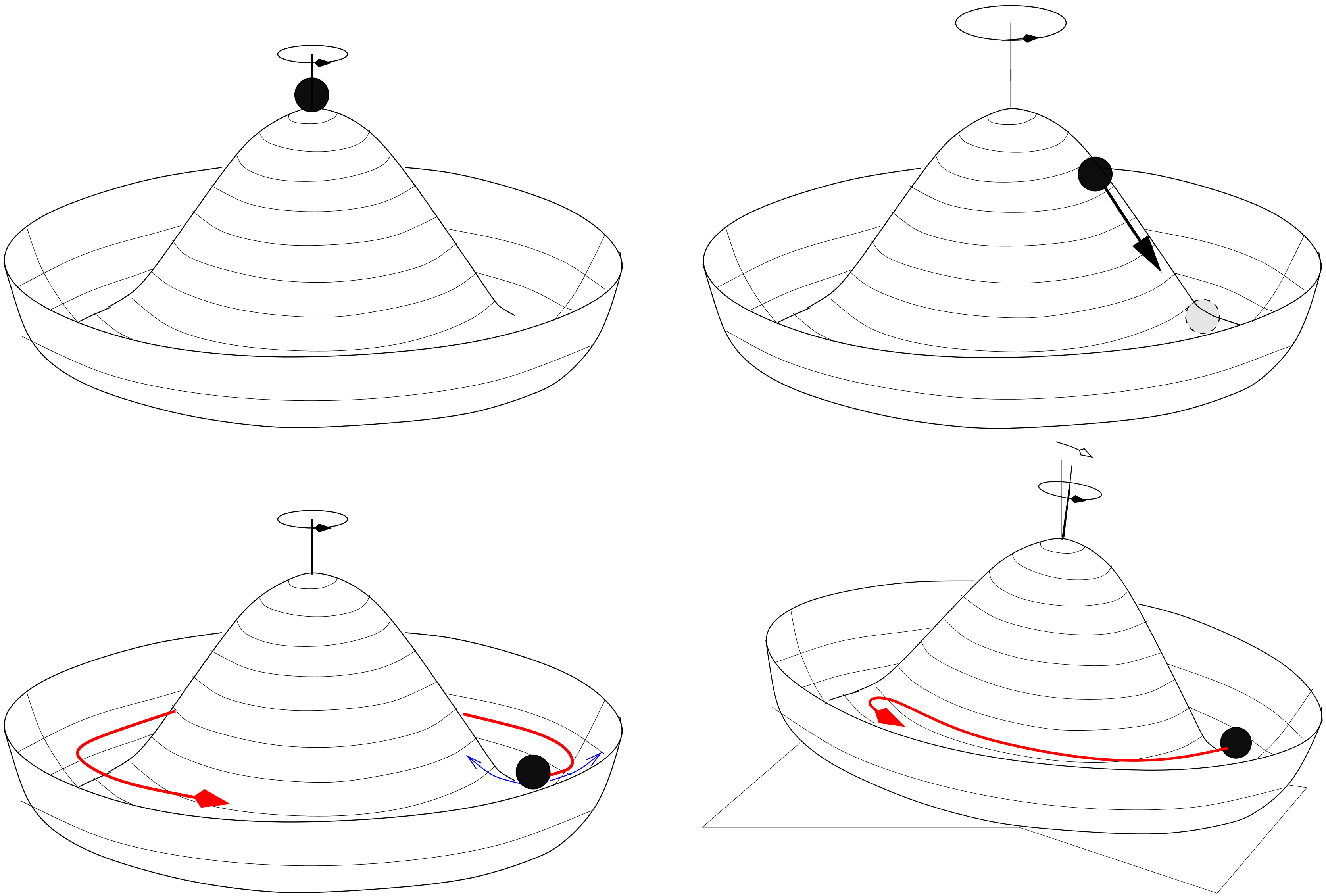
Particle Data Group (2008)

Expect very different phenomena for light (u,d,s) and heavy (c,b) quarks

- What are the spectra?
- What structures are there?

Study systematically particle properties, decays, and interactions!

Spontaneous Symmetry Breaking



$m_q = 0$: massless Goldstone bosons; $m_q \neq 0$: light physical pion

Example: CSB

Charge Symmetry $\equiv$ physics invariant under up $\leftrightarrow$ down

In Standard Model Charge Symmetry Breaking (CSB) via

$\rightarrow$ different quark masses:

$$-m_u \bar{u}u - m_d \bar{d}d \quad \Longrightarrow \quad \frac{\delta m_N^{\rm str}}{2} N^\dagger \left(\tau_3 - \frac{1}{2F_\pi^2}\, \boldsymbol{\tau} \cdot \boldsymbol{\pi} \pi_3 \right) N$$

$\rightarrow$ different quark charges:

$$+q_u \bar{u} \not{A} u + q_d \bar{d} \not{A} d \Longrightarrow \frac{\delta m_N^{\rm em}}{2} N^\dagger \left(\tau_3 - \frac{1}{2F_\pi^2} \left(\tau_3 \boldsymbol{\pi}^2 - \boldsymbol{\tau} \cdot \boldsymbol{\pi} \pi_3 \right) \right) N$$

with $\delta m_N^{\rm str} + \delta m_N^{\rm em} = M_p - M_n = 1.3$ MeV

CSB Nullexperiments

There are two recent measurements:

$\rightarrow$ Forward–backward asymmetry in $pn \rightarrow d\pi^0$ (A_{fb})
to see this assume recall $T_d = 0$ and $T_\pi = 1$
thus: initial state is $T = 1 \Longrightarrow$ should behave as pp
forward and backward not defined
F–b asymmetry due to $T = 0$ admixture in initial state

$\rightarrow$ $\sigma_{tot}(dd \rightarrow \alpha\pi^0)$
to see this recall $T_d = T_\alpha = 0$

Experimentally:

$A_{fb}(pn \rightarrow d\pi^0) = 0.17 \pm 0.08(\text{st.}) \pm 0.06(\text{sys.})\ \%$ (TRIUMF, 2003)

$$\sigma_{tot}(dd \rightarrow \alpha\pi^0) = \begin{cases} 13 \pm 2 \text{ pb} & \text{at } T_{lab} = 228.5 \text{ MeV} \\ 15 \pm 3 \text{ pb} & \text{at } T_{lab} = 231.8 \text{ MeV} \end{cases}$$ (IUCF, 2003)

Theoretical aspects

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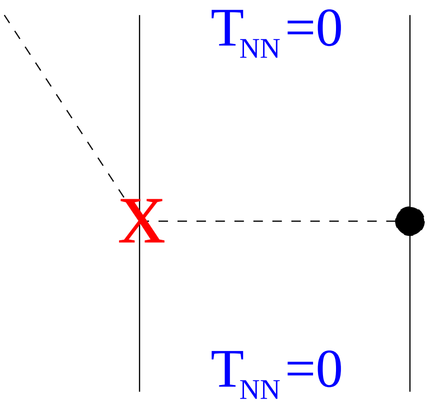
Relevant transition:

A. Filin et al. (2010); for dd reaction: CSB collaboration



$$A_{\rm fb}^{\rm LO} = (11.5 \pm 3.5) \times 10^{-4} \; \frac{\delta m_N^{\rm str}}{\rm MeV}$$

$$\Longrightarrow \delta m_N^{\rm str} = (1.5 \pm 0.8\;({\rm exp.}) \pm 0.5\;({\rm th.}))\;\;{\rm MeV}\;,$$

from lattice

Beane et al. (2008)

$$\Longrightarrow \delta m_N^{\rm str} = 2.26 \pm 0.57 \pm 0.42 \pm 0.10 \text{ MeV}$$

consistent with $\delta m_N^{\rm em} = -0.7 \pm 0.3$ MeV!!

Gasser, Leutwyler (1982)

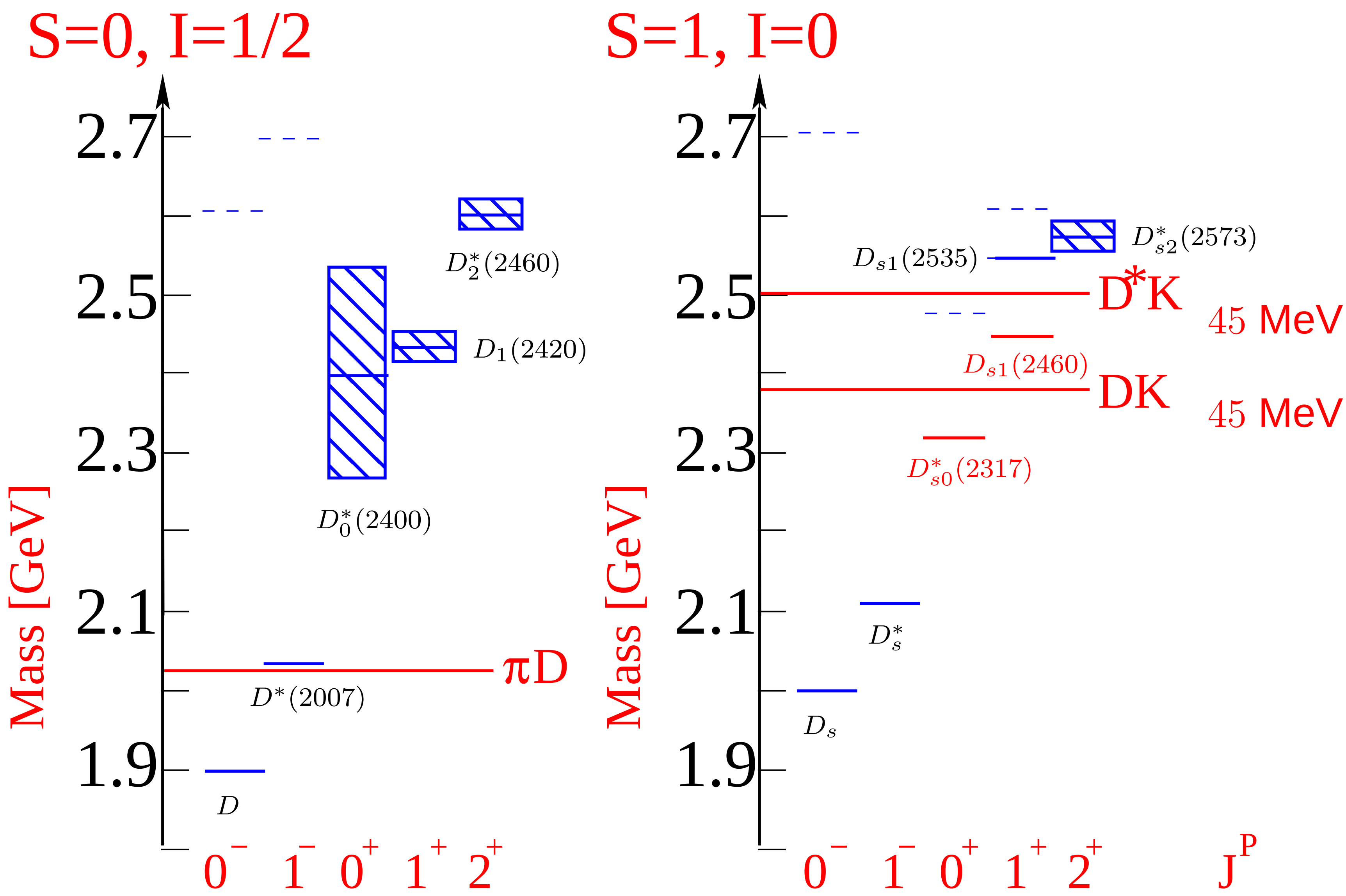
$\rightarrow$ gives leading order effect to CSB pion production

$\rightarrow$ (potentially) sizable loop/higher order corrections; to be done

$\rightarrow$ $dd \rightarrow \alpha\pi^0$ has complicated few–body physics

- $\triangleright$ data for $dd \rightarrow {}^3$He$N\pi \Longrightarrow$ constrains dd dynamics
- $\triangleright$ higher energy data for $dd \rightarrow \alpha\pi^0 \Longrightarrow$ important test

Spectrum with open Charm



Quark Modell: Di Pierro, Eichten (2001)

Heavy light Systems

→ Effective field theorie ChPT and HQEFT control interactions

- ▷ Systematic improvements + uncertainty estimates
- ▷ consistent inclusion of isospin breaking
- ▷ quark mass dependence

→ unitarization
generation of resonances and bound states

Kaiser, Weise/ Oller, Oset, Pelaez/ Lutz, Kolomeitsev, Soyeur/
Guo, C.H., Krewald, Meißner (2008)/ Guo, C.H., Meißner (2009)

Here: $\pi/K/\eta$–D/D_s Streuung
$\longrightarrow D^*_{s0}(2317)$ as bound state mass fitted

- $D_{s1}(2460)$ + other other things predicted;
- uncertainty estimates through higher order Operators

$D_{s0}^*(2317)/D_{s1}(2460) \to \pi^0 D_s^{(*)}$

Isospin breaking in QCD and EFT through quark mass and charge differences

The same effective operators lead to

→ mass differences, e.g.

- $$m_{D^+} - m_{D^0} = \Delta m^{\text{strong}} + \Delta m^{\text{e.m.}} = ((2.5 \pm 0.2) + (2.3 \pm 0.6)) \text{ MeV}$$
- $\pi^0 - \eta$ mixing $\longrightarrow$ parameters fixed

→ Isospin breaking scattering amplitude

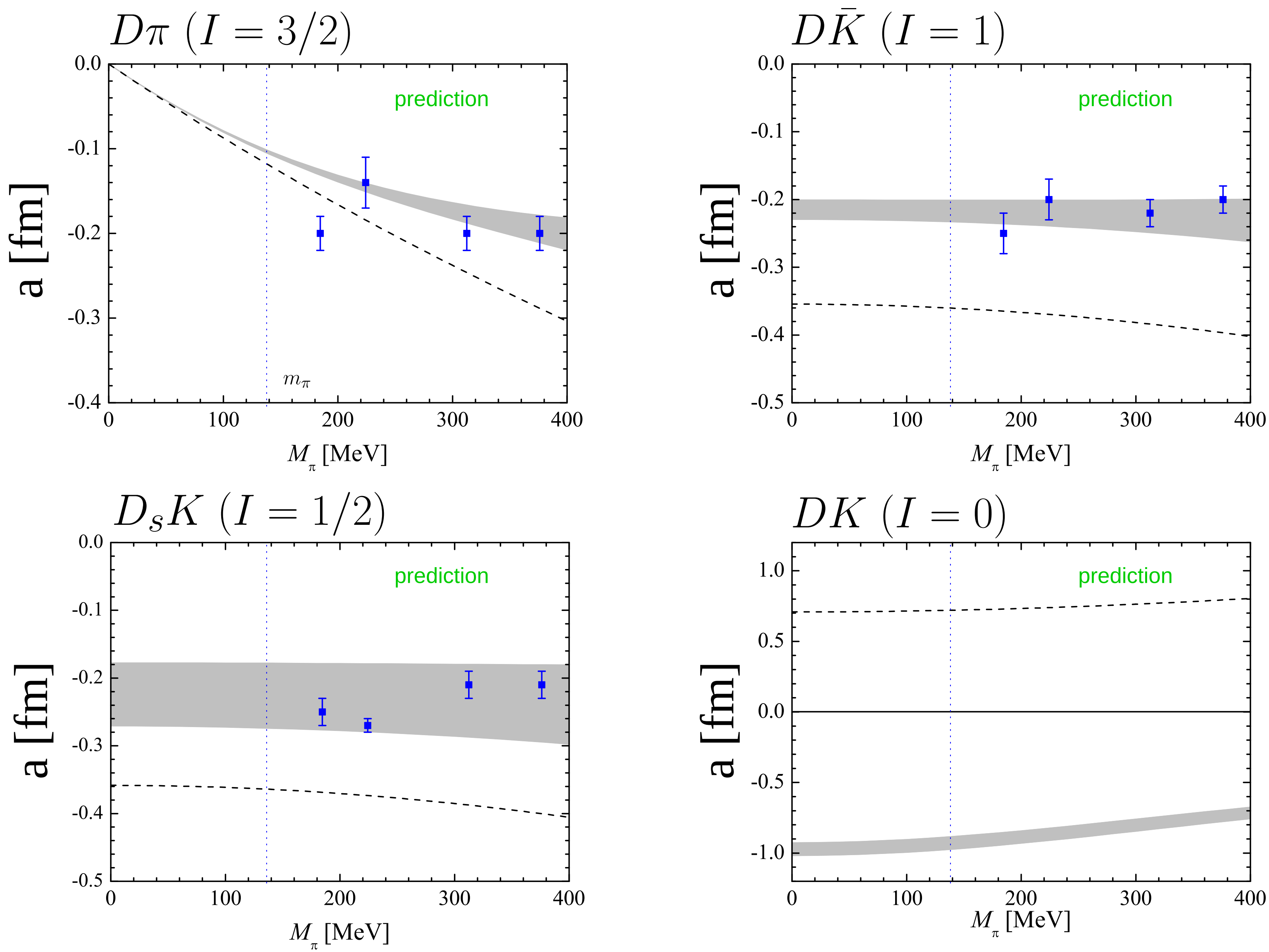
- e.g. $KD \to \pi^0 D_s$ predicted; with this

$$\Gamma(D_{s0}^*(2317) \to D_s\pi^0) = (133 \pm 110)\text{keV}$$
$$\Gamma(D_{s1}(2460) \to D_s\pi^0) = (126 \pm 110)\text{keV}$$

Lutz, Soyeur (2007); complete to NLO+uncertainty estimate: Guo et al. (2008)

much smaller in quark model → direct measurement necessary

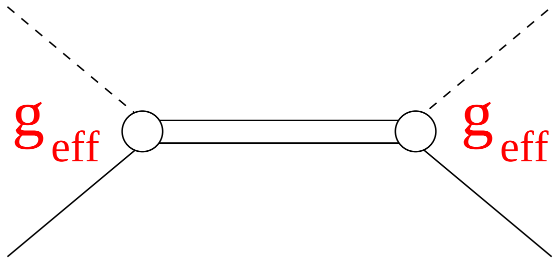
Chiral extrapolation



Lattice: Liu, Lin, Orginos (2008); UChPT: Guo et al. (2009)

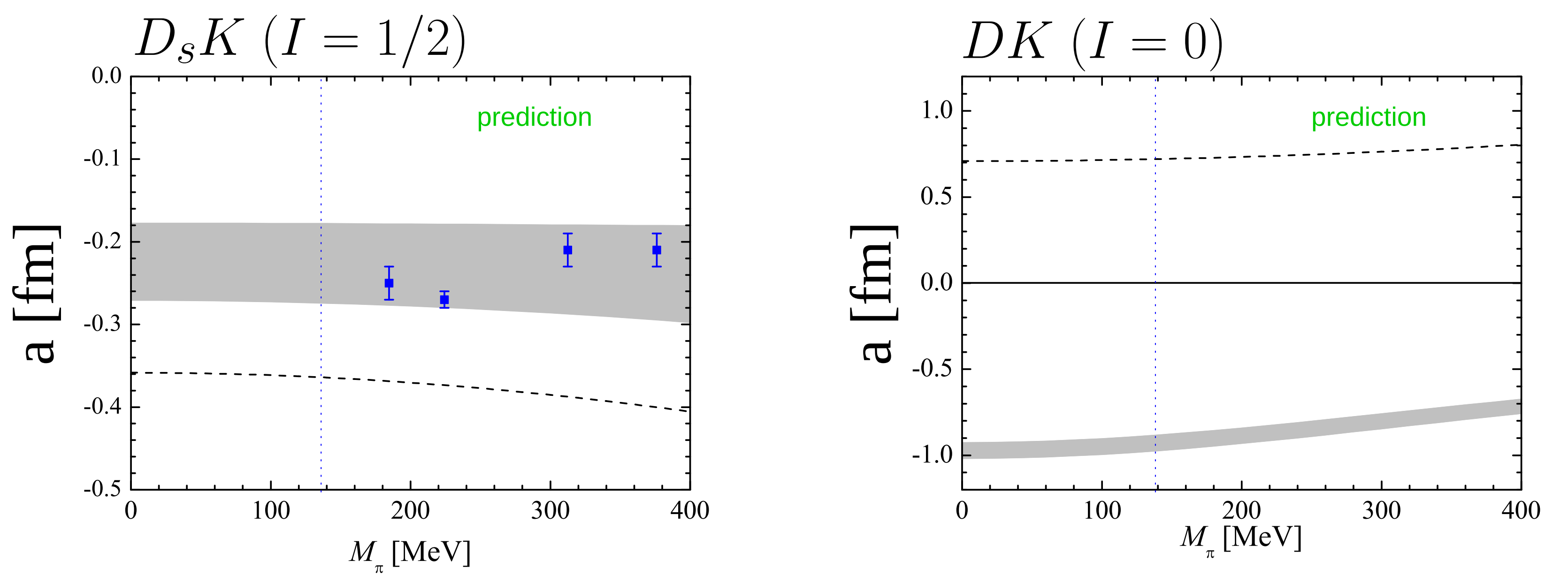
Chiral extrapolation

$D_S(2317)$: $a =$ $\mathbf{g}_{\text{eff}}$



$\mathbf{g}_{\text{eff}} + \mathcal{O}(1/\beta) \simeq \left(\frac{2\lambda^2}{1+\lambda^2}\right) \frac{-1}{\sqrt{2 m_K \epsilon}}$

$a = 1\ \text{fm}$ for molecule $(\lambda^2 = 1)$; smaller otherwise



Lattice: Liu, Lin, Orginos (2008); UChPT: Guo et al. (2009)

Thus ...

→ Effective field theories hadron physics can be studied

- ▷ to high precision
- ▷ with controlled uncertainties

→ Combination of EFT and resummation schemes very promising

→ Symbiosis of lattice gauge theory and EFT on the horizon

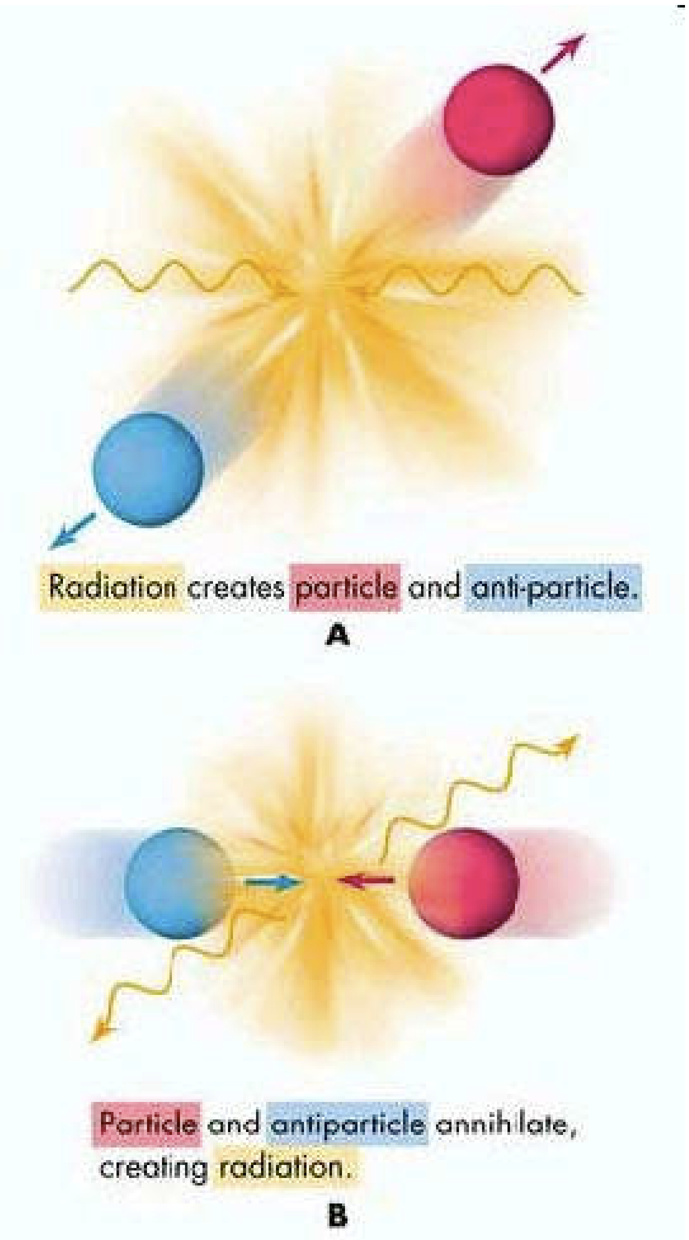
⟶ we are on a good way to understand QCD

Standard Model tested in many aspects

⟶ it (nearly) always works

But: WE KNOW IT IS NOT COMPLETE!

Matter Excess



In the early universe:

matter:antimatter as

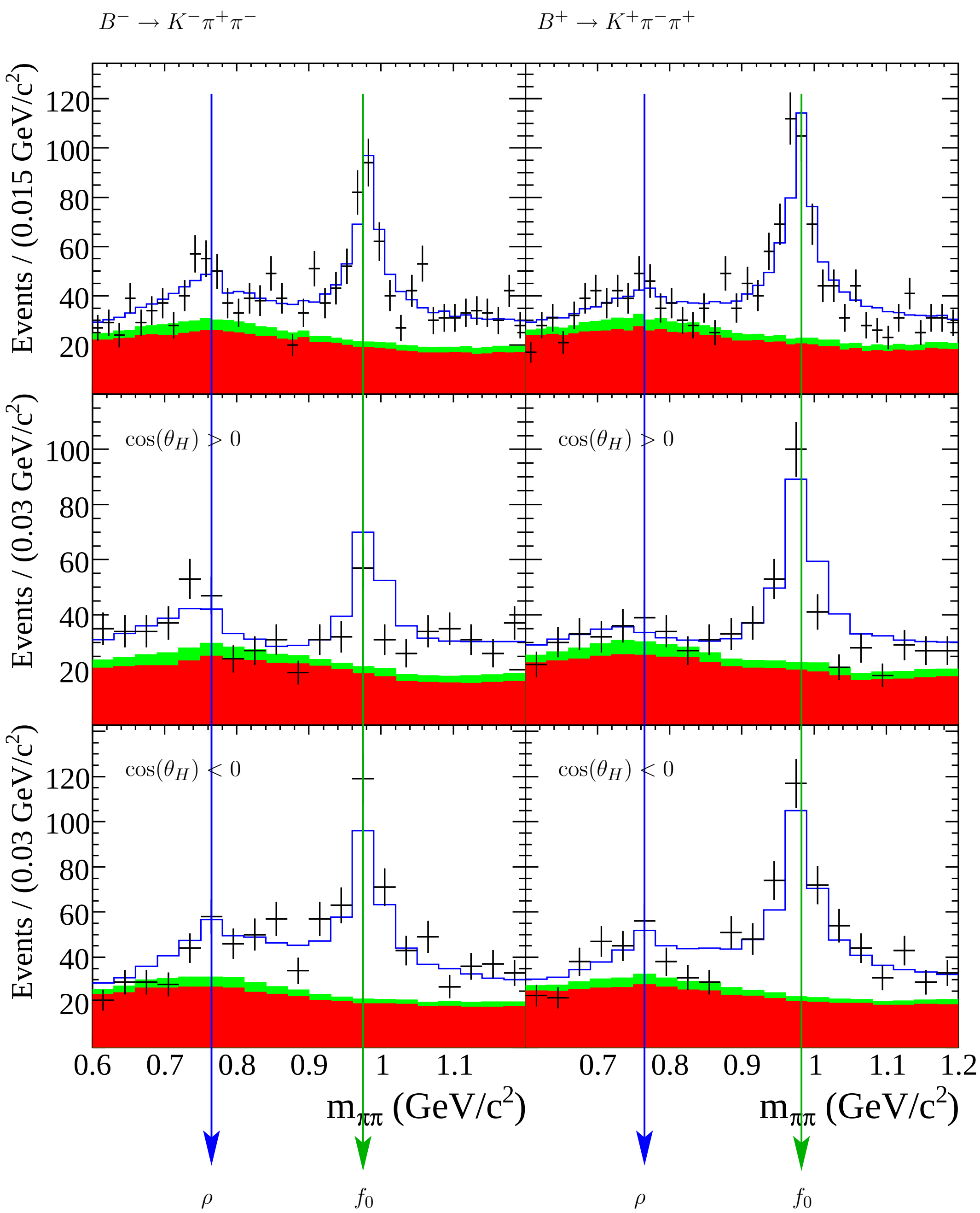
1 000 000 001:1 000 000 000

Problem: The Standard Model falls short by several orders of magnitude!

⟶ What is missing?

Look for the needle in the haystack

Sensitive Observables



Here: $B^\pm \to K^\pm\pi^\mp\pi^\pm$

BABAR (2008); Belle (2006)

$\rightarrow$ 3.7σ in ρK

$\rightarrow$ 3.5σ in $f_2(1270)K$

$\rightarrow$ 1.8σ in $f_0(980)K$

Consistent with SM

Important next steps:

$\rightarrow$ Improve analysis and thus sensitivity $\Longrightarrow$ Les NABIS

$\rightarrow$ Study D decays $\longrightarrow$ SM prediction tiny

Summary

Various experiments (will be) looking for systems with charm

- BABAR (USA – data taking finished)
- Belle (Japan) (in operation) + Belle II (planned)
- BES-III (China) (in operation)
- LHCb (at LHC, CERN; just started)
- PANDA (FAIR, Germany; after 2014)

together with the expected developments of theoretical tools

There are exciting times to come!

THANKS FOR YOUR ATTENTION