50 Years of Quantum Chromodynamics. UCLA, September11 – 15, 2023
Luskin Conference Center, Los Angeles, CA

Mikhail Shifman
William I. Fine Theoretical Physics Institute, University of Minnesota

QCD, the theory of hadrons: then and now

September 11

♕ Between 1972 and 1974

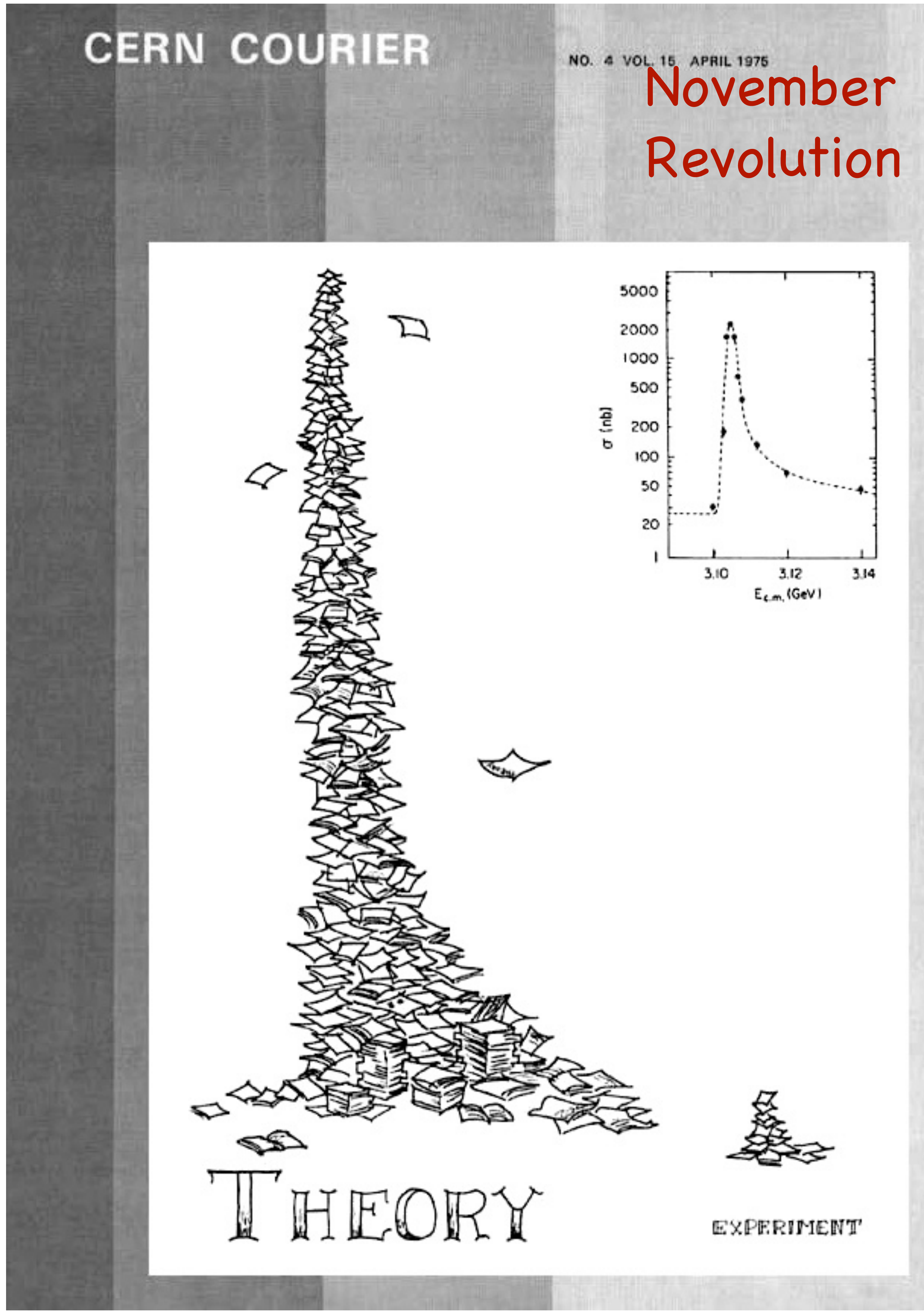
- ♦ XVI International Conference On High Energy Physics, 6 – 13 September 1972, Batavia, IL
- ♦ October 1972 $\rightarrow$ ITEP Grad school

Theoretical talks:

- Dual models (precursor to string theory);
- DIS, Bjorken Scaling, current algebra;
- $e^+e^- \rightarrow$ hadrons;
- Zumino, Bjorken and Ben Lee discussed Weinberg-Salam model;
- Ben Lee was the only person to refer to 't Hooft 1971 papers;
- Gell-Mann summarized: are quarks physical objects or abstract mathematical constructs? $\pi^0 \rightarrow 2\gamma$ factor of 3 missing; if quarks are fermions then theoretically predicted amplitude is factor of 3 lower than the corresponding experimental result; Makes no statement of inevitability of quark color.

Arkady Vainshtein arrived from Novosibirsk, but kept a secret 😀

$\longrightarrow$ Electroweak physics (first paper early 1973)

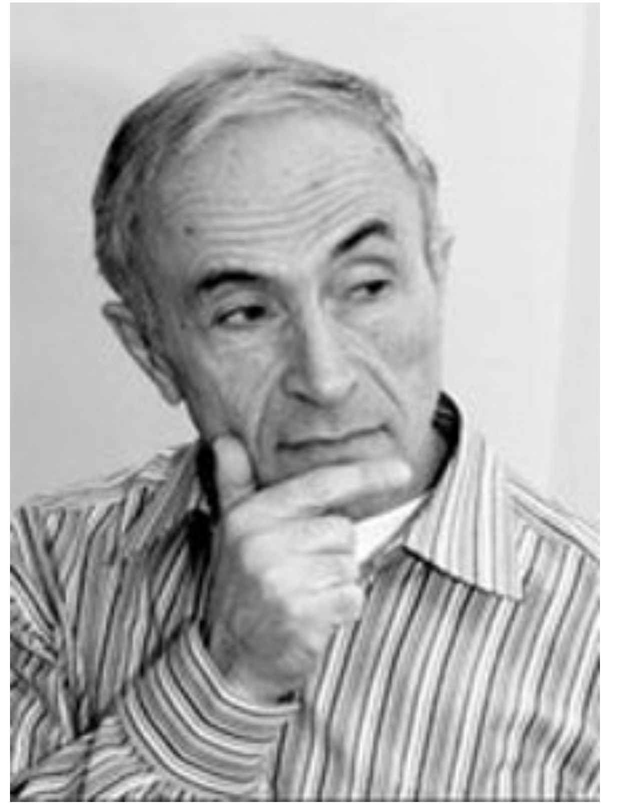


July 1973 Coleman and Gross (PRL): ``no renormalizable field theory that consisted of theories with arbitrary Yukawa, scalar or Abelian gauge interactions could be asymptotically free."

- In ITEP known from the Landau time.

- In Yang-Mills theories in physical ghost-free gauges some graphs have no imaginary parts which gives hope for asymptotic freedom

• I.B. Khriplovich, Green's functions in theories with non-Abelian gauge group, Yad. Fiz. (SJNP) 10, 409 (1969)



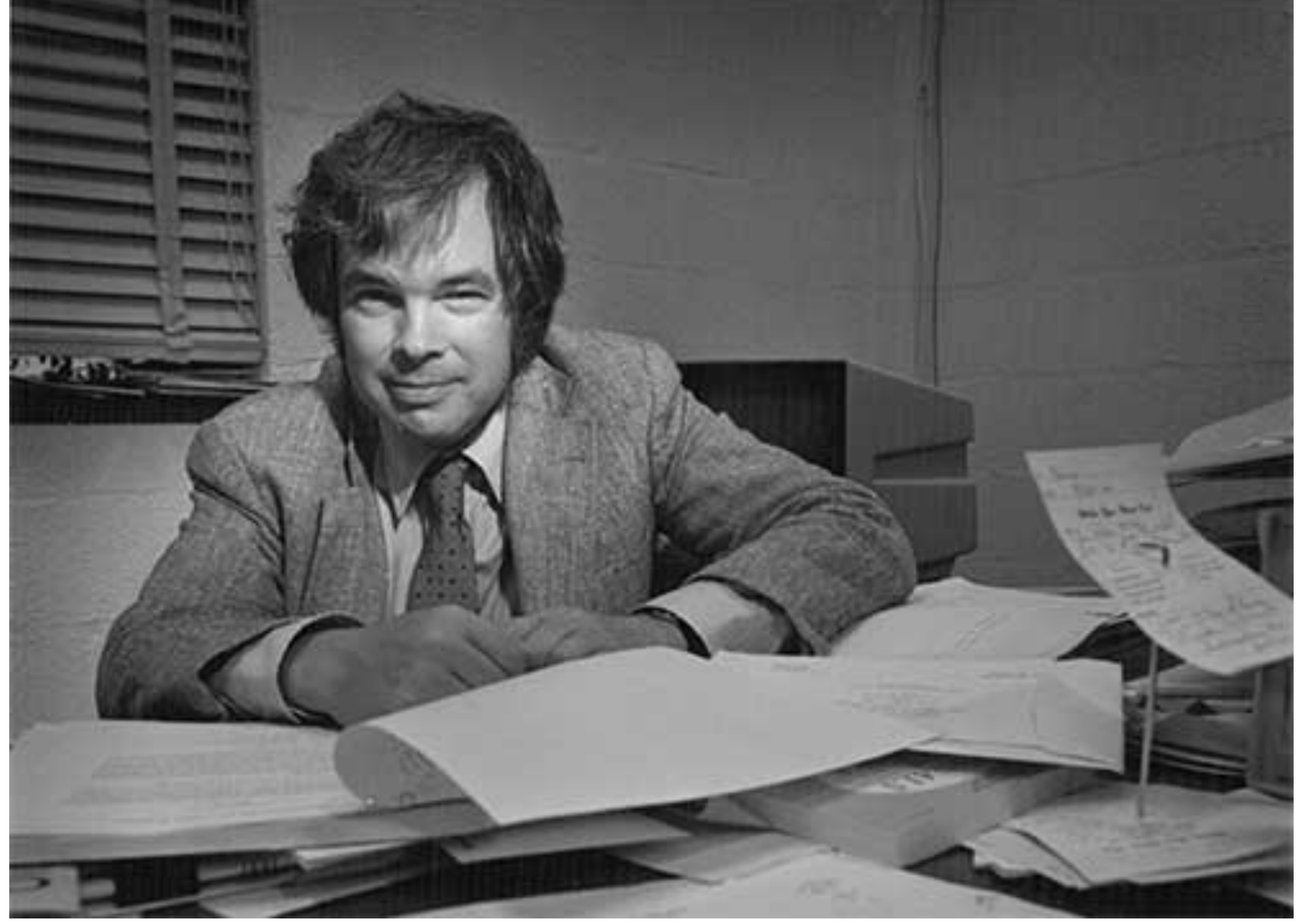
- In ITEP known from the Landau time.

April 1973 Coleman and Wilczek; Politzer (PRL)
Gross: ``We completed the calculation in a spurt of activity. At one point a sign error in one term convinced us that [Yang-Mills] theory was, as expected, non-Asymptotically free. As I sat down to put it together and to write up our results, I caught the error. At almost the same time Politzer finished his calculation and we compared, through Sidney [Coleman], our results. The agreement was satisfying.

The gates were open. A few extra months. Culmination: November 1974 Revolution

J/ψ discovery

K. Wilson, Nonlagrangian models of current algebra, Phys. Rev. 179, 1499-1512 (1969)*



Wilson OPE or Wilsonian RG flow from UV to IR grew from ↑

W's framework of separation of scales in QFT was especially suitable for AF theories

GENERAL; Adjustments needed for QCD!

- In QCD fixed point at $\alpha_s = 0$, hence slow logarithmic approach
- Scale Λ is not unique; heavy quark masses m_Q had to be included
- At least some information about IR was needed!

Early 1970s: OPE formalism in HEP: on theoretical side, exclusively perturbation theory. On practical side, most applications were in DIS in leading-twist approximation

Seemingly the first deliberate decision to build QCD version of Wilson's OPE made in 1974 (penguins): VZ, AV,MS

In 1969 paper Wilson considered the K->pions decay puzzle and suggested a general framework! /// Arkady Vainshtein

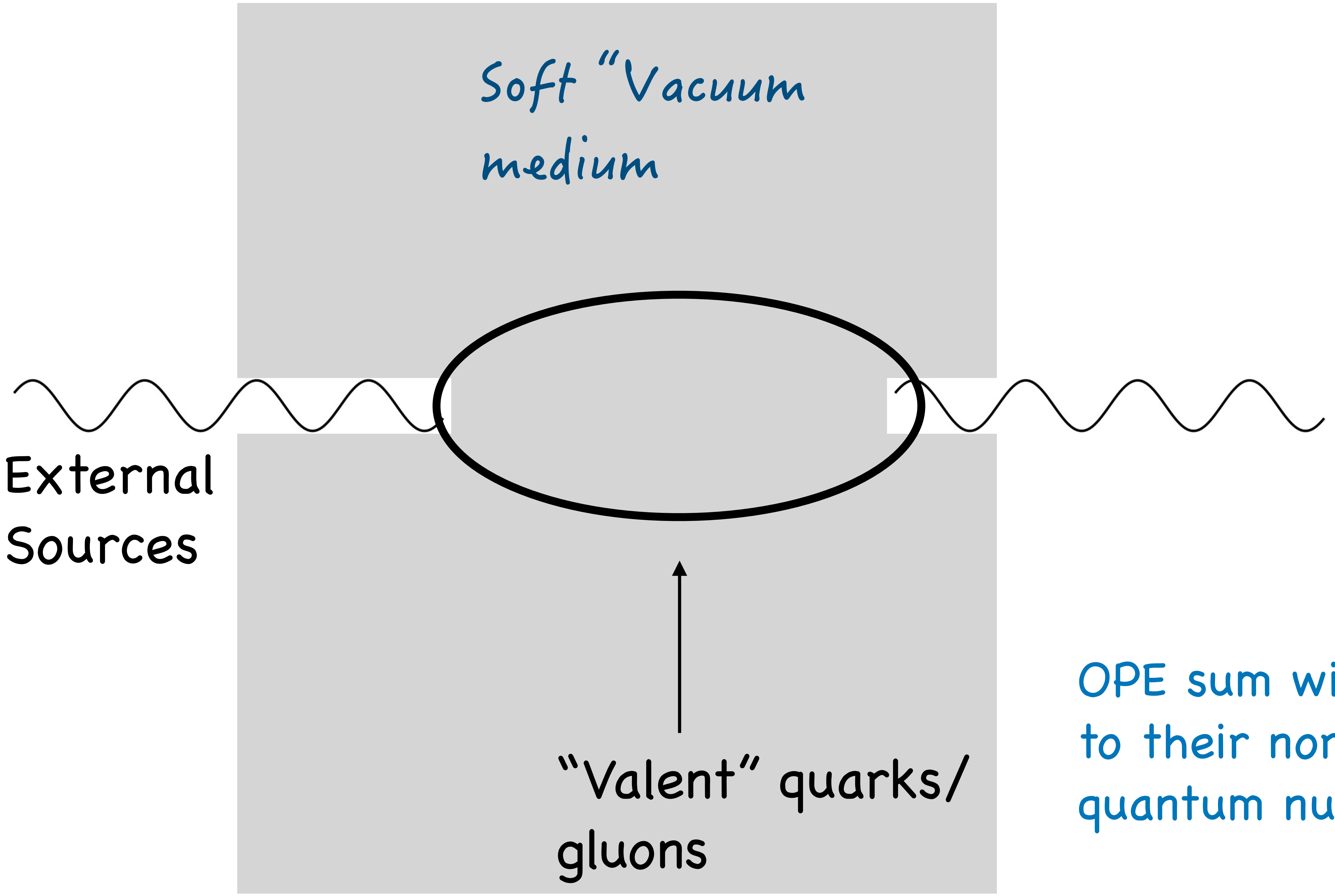
$O_{\text{peng}} = \bar{s}_L \gamma^\mu \mathscr{D}_\nu G^{\mu\nu} d_L \leftrightarrow$ flavor changing . Full class . 6 operators + more if EM is included

VEVs

Table 1 The lowest-dimension operators in OPE. Γ is a generic notation for combinations of the Dirac γ matrices.

Normal dim	3	4	5	6	6
Operator	$O_q = \bar{q}q$	$O_G = G^2_{\mu\nu}$	$O_{qG} = \bar{q}\sigma^{\mu\nu}G_{\mu\nu}q$	$O_{4q} = (\bar{q}\Gamma q)^2$	$O_{3G} = GGG$

Basic Idea



$$= \sum_{\text{dim}_n} C_n(Q,\mu)\langle O_n(\mu)\rangle = \frac{f_0^2}{Q^2+m_0^2} \quad + \sum_{\text{excit}} \cdots$$

OPE sum with a finite number of the lowest-dimension operators ordered according to their normal dimensions (left) . Right: sum over mesons with appropriate quantum numbers. The ground state in the given channel is singled out.

Borelization $\mathscr{B}$

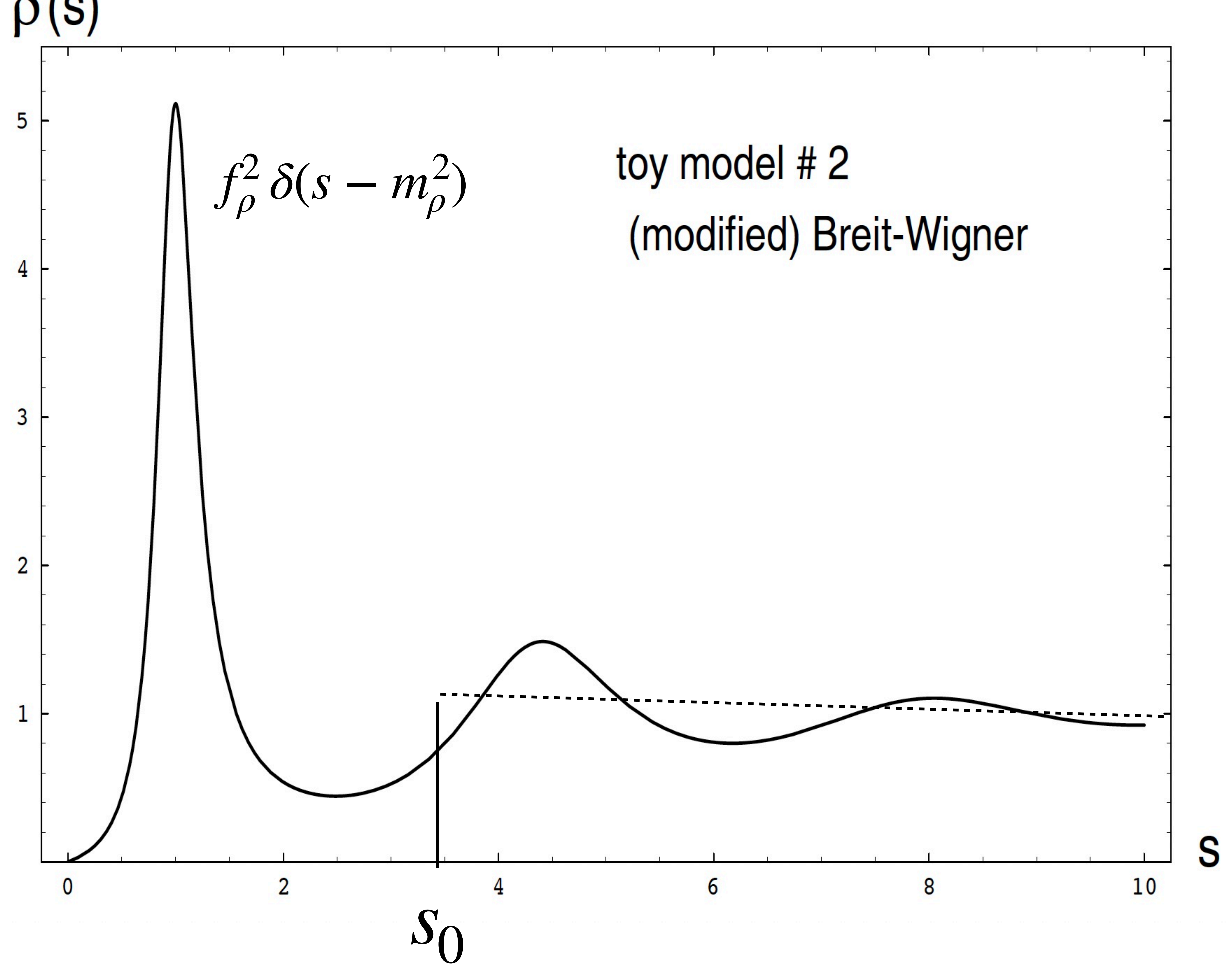
$$\mathscr{B}\frac{f_i^2}{m_i^2+Q^2} = \mathscr{B}\frac{f_i^2}{Q^2}\sum_n (-1)^n\left[\frac{m_i^2}{Q^2}\right]^n \to \frac{f_i^2}{Q^2}\sum_n \frac{(-1)^n}{n!}\left[\frac{m_i^2}{Q^2}\right]^n = \frac{f_i^2}{Q^2}\exp\left(-\frac{m_i^2}{Q^2}\right) \to \frac{f_i^2}{M^2}\exp\left(-\frac{m_i^2}{M^2}\right)$$

$1/Q^2$ expansion

weignt function

Works perfectly for functions with the Källén-Lehmann (dispersion) representation

Alternatively, expansion in the coordinate space $\exp\left(-\frac{m_i^2}{M^2}\right) \to K(m|x|) \sim \exp\left(-m_i x\right)$



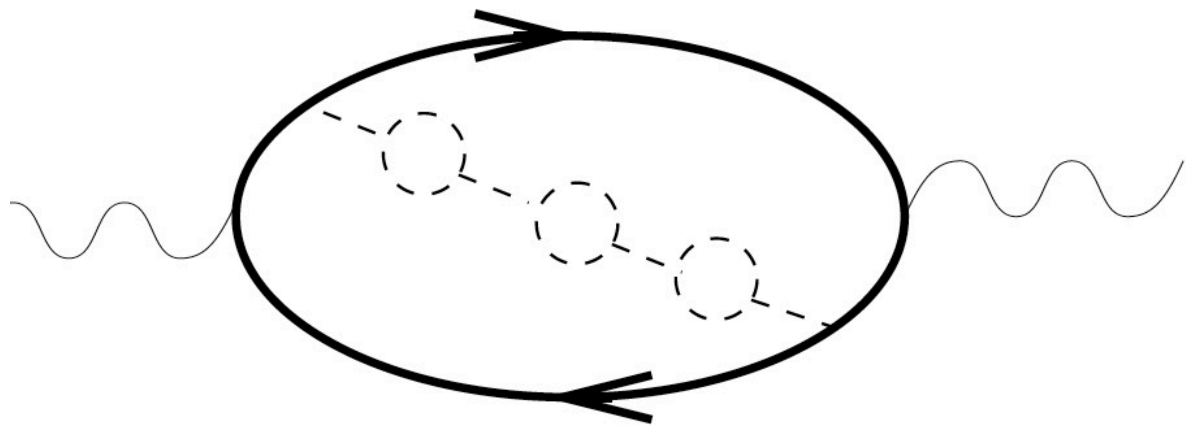
$$\frac{1}{Q^2+m_n^2} \to \frac{1}{Q^2+m_n^2-im_n\Gamma_n} \to \frac{1}{Q^2+m_n^2-im_n^2B/N_c} \to$$

$$\frac{1}{Q^2+m_n^2-\gamma Q^2\ln Q^2} \to \frac{1}{(Q^2)^{1-\gamma}+m_n^2}\,,$$

$$\gamma = \frac{B}{\pi N_c}\,,$$

$$\Gamma_n \sim \frac{1}{N_c}L\Lambda^2, \quad L\sim m_n\Lambda^{-2}$$

- Quark-Hadron Duality (oscillations!)
- Renormalon-G conspiracy (no in SYM)



One of the graphs from the bubble chain set

$n!\alpha_s^n$ at large n

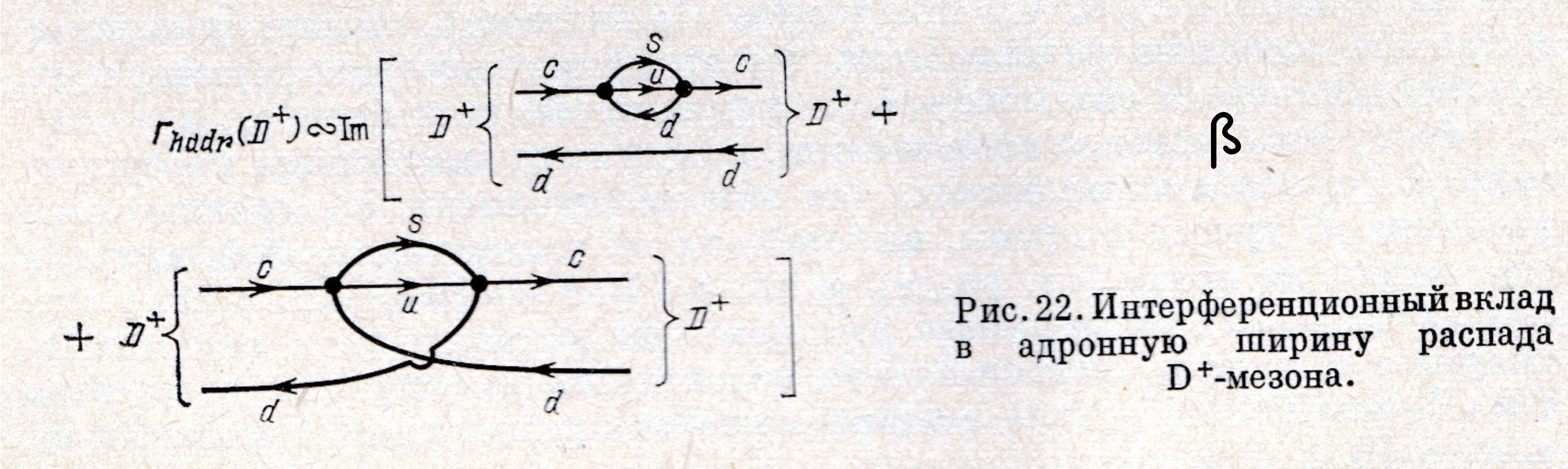
Introduce μ, n! gone $\langle G_{\mu\nu}G^{\mu\nu}\rangle$, defined

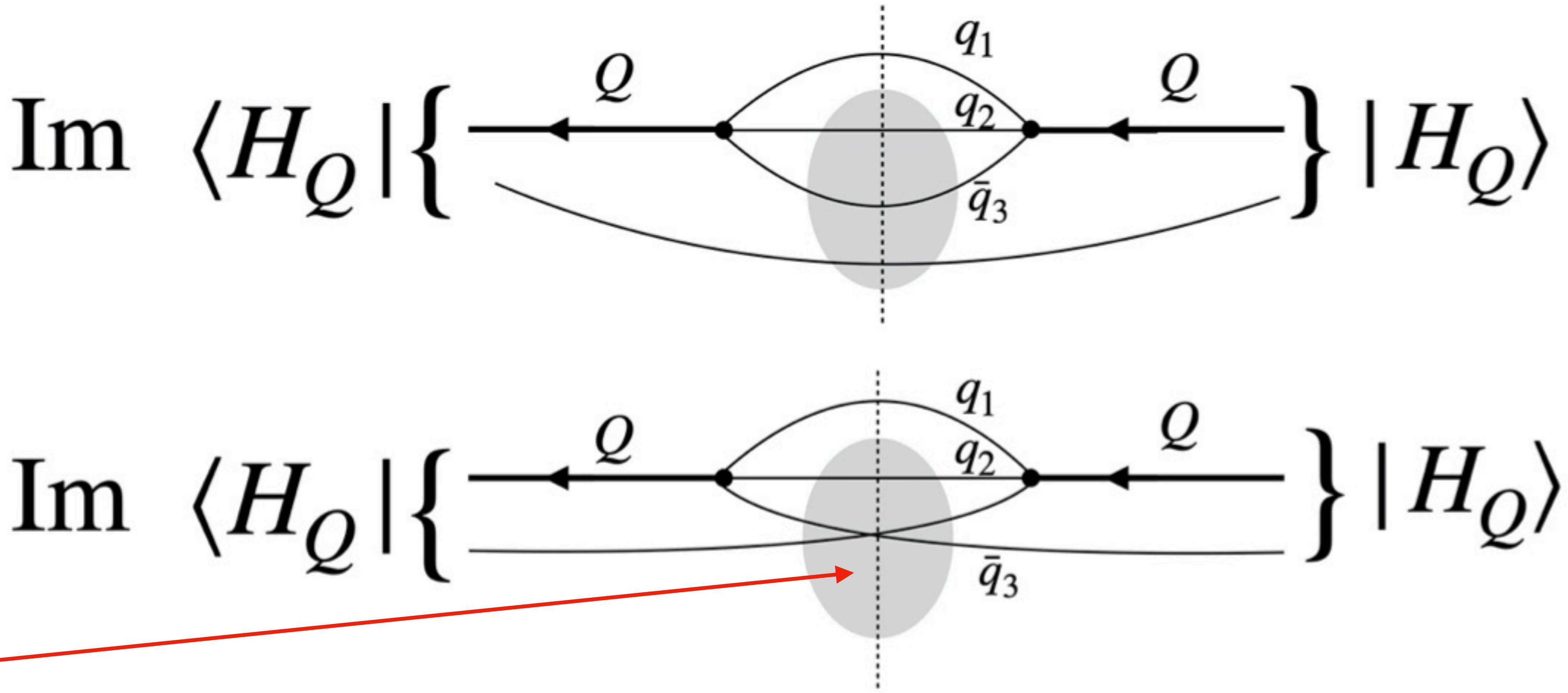
SVZ is approximate. Not a model.
X(2.83) story (Jan. 1977) $\bar{c}c\,(0^-)$ paracharmonium
$\Delta(J/\psi\ldots\eta_c)\approx 270$ MeV.
SVZ → no way. 100 MeV predicted
1979: $\eta_c(2.98\pm 0.01)$ was discovered. X(2.83) wrong!

SVZ spin offs, e.g. light-come sum rules (form-factors and heavy-light decay constants) and HEAVY QUARK EXPANSION (+MV+NU)*

* Until 1990s, when lattice QCD (with chiral/heavy quarks) , started approaching its maturity, the SVZ method was the main tool for analyzing static hadronic properties.

Since mid-1980s: $1/m_Q$ expansion in analysis of $Q\bar{q}$ and Qqq





MB and I figured out how to estimate interference $1/m_Q^2$ effects through the four-fermion operators and designed relevant graphs at ITEP cantine. We actually made an estimate on a napkin, I put it in a review with Khoze, and forgot about this, since at this time I was heavily engaged with SUSY. A few months later, in 1983, Branko Guberina and Neven Bilic from Croatia saw it and detected a wrong sign. They called me (!). ……1985,1986

Soft Cloud instead of vacuum medium

$1/m_Q$ expansion for a H_Q weak inclusive decay rate (see Eq. (8.2)). Depicted are two operators, the leading $\bar{Q}Q$ and a subleading $(\bar{Q}q_3)(\bar{q}_3Q)$. Both are sandwiched between the heavy hadron states $\langle H_Q|$ and $|H_Q\rangle$ and the decay rate is determined by the imaginary part. The grey area depicts the soft quark-gluon cloud. .

$$\Gamma(H_Q \to f) = G_F^2 |V_{\rm CKM}|^2 m_Q^5 \sum_i \tilde{c}_i^{(f)}(\mu) \frac{\langle H_Q|O_i|H_Q\rangle_\mu}{2M_{H_Q}}$$

$$\propto \Big[c_3^{(f)}(\mu) \frac{\langle H_Q|\bar{Q}Q|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

No $1/m_Q$ CGG/BUV th

$$+ c_5^{(f)}(\mu) m_Q^{-2} \frac{\langle H_Q|\bar{Q}\frac{i}{2}\sigma G Q|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

$$+ \sum_i c_{6,i}^{(f)}(\mu) m_Q^{-3} \frac{\langle H_Q|(\bar{Q}\Gamma_i q)(\bar{q}\Gamma_i Q)|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

$$+ \mathcal{O}(1/m_Q^4) + \ldots \Big] .$$

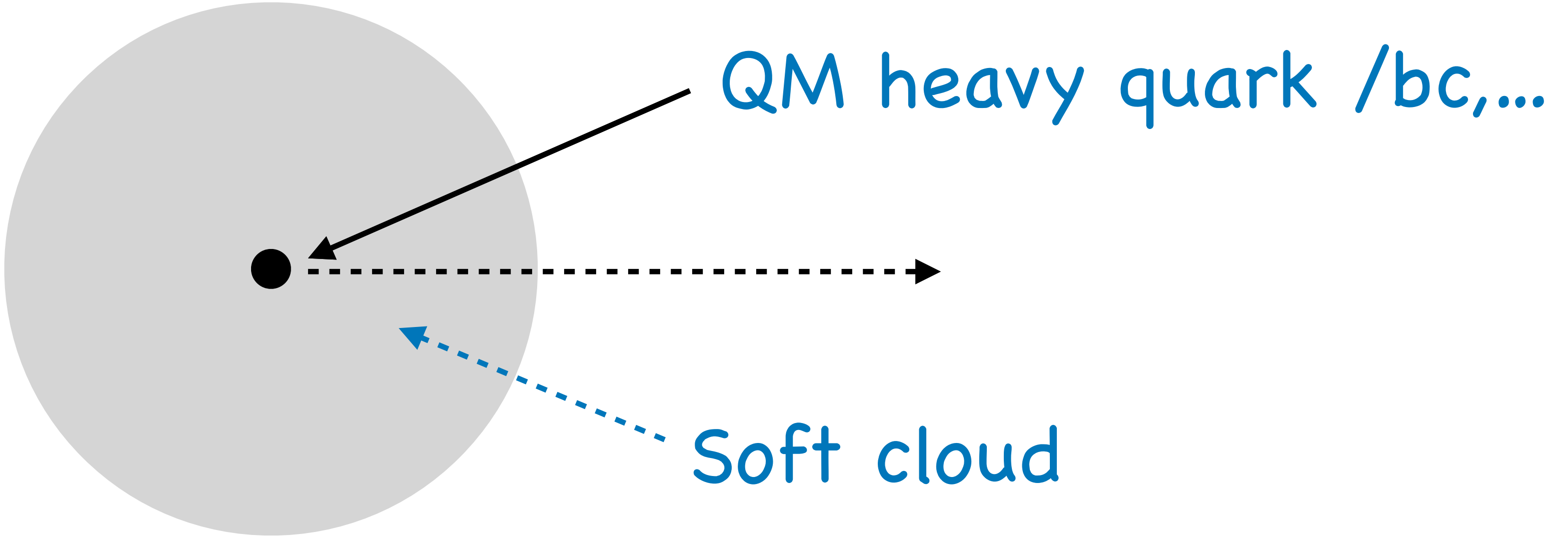
In the mid-1980s predicted $\tau(\Lambda_b)/\tau(B_d) = 0.9 \pm 0.03$

In the late 1990's $\tau(\Lambda_b)/\tau(B_d)_{\rm exp} = 0.77 \pm 0.05$

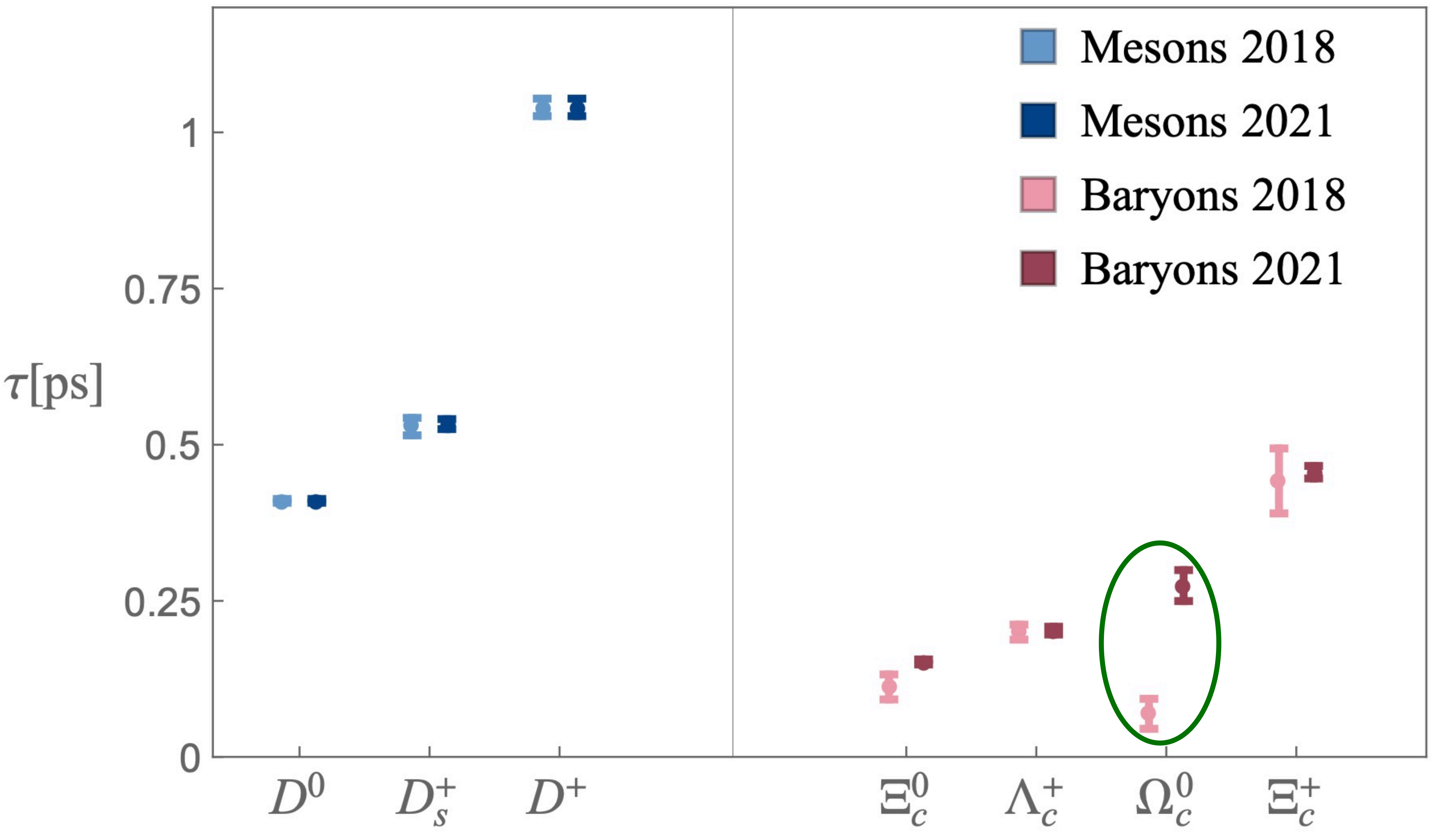
In the late 2010's $\tau(\Lambda_b)/\tau(B_d)_{\rm exp} = 0.93 \pm 0.05$

1990s

Heavy Quark Symmetry ff (e.g. b → c); HQET $F(v_\mu)$, $F(SV) = 1$



☞Vector charge non-renormalization theorem (say, $\bar{u}\gamma^\mu d$) at zero momentum transfer



Changes in experimental lifetime averages for mesons (blue, on the left) and baryons (red, on the
018 (light) and 2021 (dark) owing to the recent LHCb results. Recent Belle II results [24] support
$_c$ lifetime measurement. Note that the error bars indicate 2σ uncertainties in all cases.

$m_c \approx 1.3\,\mathrm{GeV}$; Expansion parameter $\sim \frac{1}{3}$

For b quark expansion parameter $\sim \frac{1}{10}$

$$2018\ \mathrm{PDG}:\ \tau(\Omega_c^0) = 69 \pm 12\,\mathrm{fs}, \quad 2020\ \mathrm{PDG}:\ \tau(\Omega_c^0) = 268 \pm 24 \pm 10\,\mathrm{fs}$$

LHCb

$$\tau(\Xi^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi^+)$$

In 1993 Blok+MS argued that Ω_c^0 is likely to be the most long-living

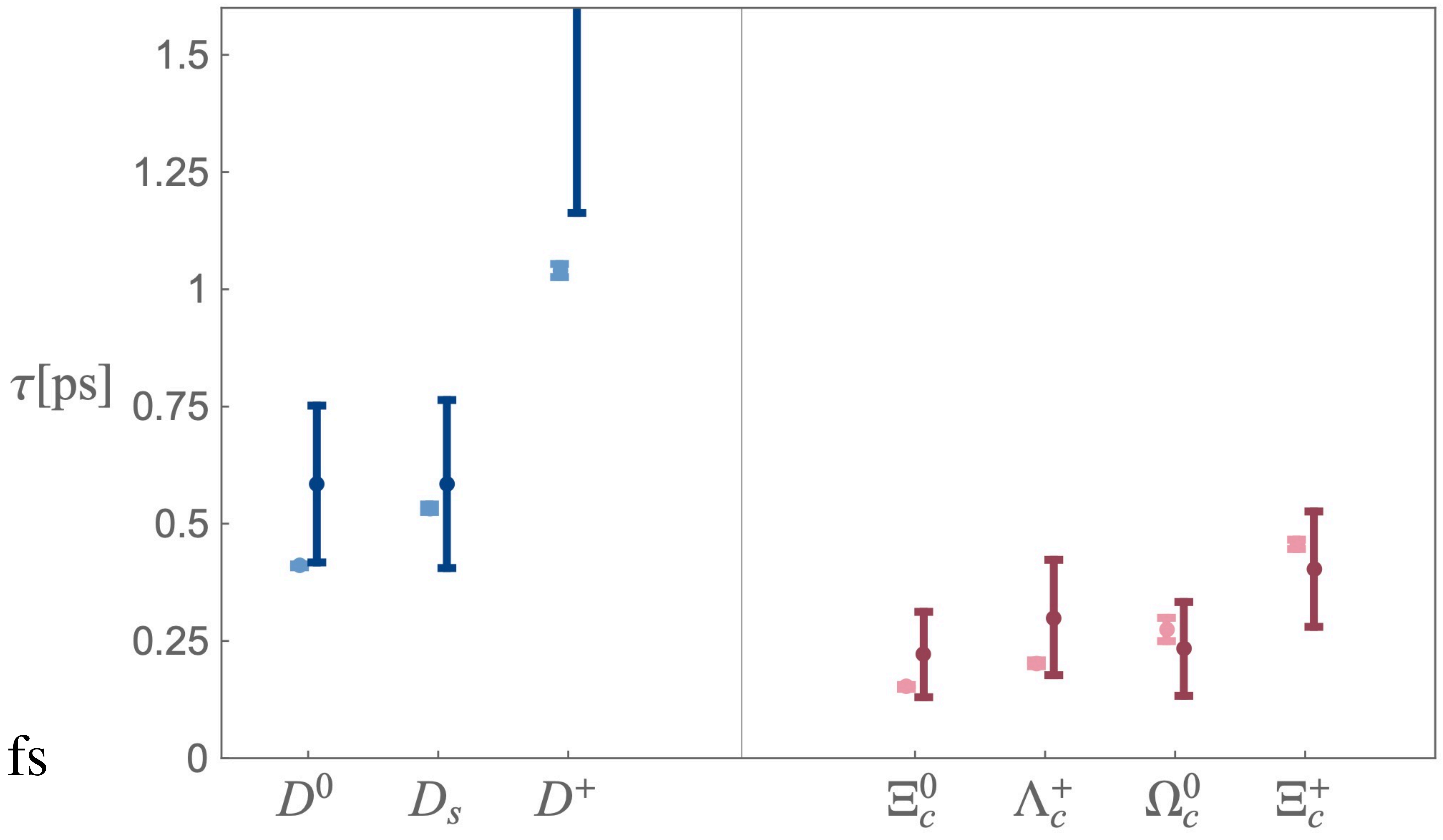


Figure 4: Hierarchy of lifetimes of charmed mesons (left, in blue) and singly charmed baryons (right, in red). Our predictions, in the kinetic scheme, are compared to the latest experimental values (left of each pair of values) [1, 11]. © B. Melic

$\mathcal{L}^0_{\text{heavy}}$, up to terms $1/m_Q^2$,

1990s HQET language

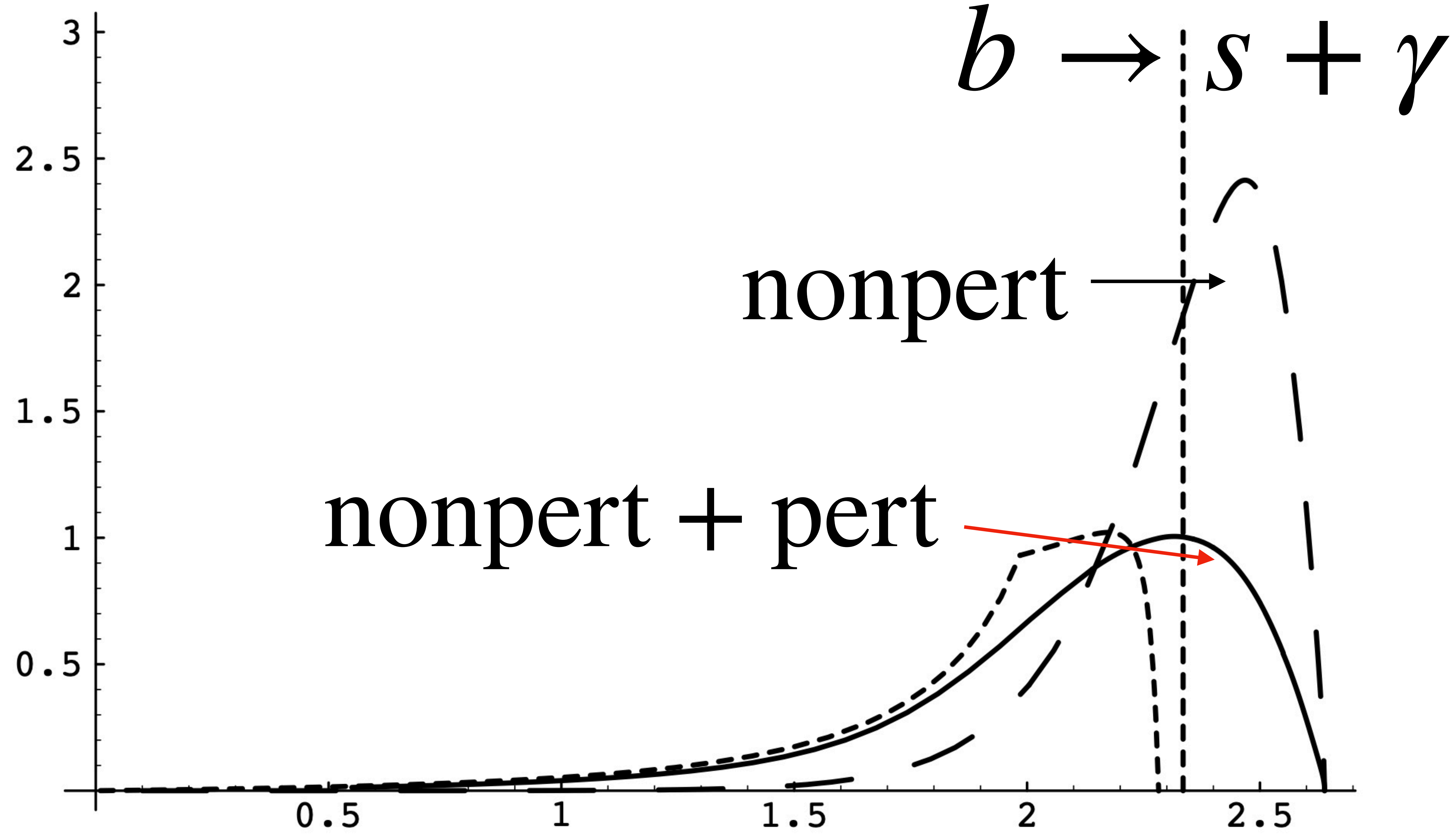
$$= \bar{Q}\frac{1+\gamma_0}{2}\left(1+\frac{(\boldsymbol{\sigma\pi})^2}{8m_Q^2}\right)\left[\pi_0 - \frac{1}{2m_Q}(\boldsymbol{\pi\sigma})^2 - \right.$$

$$\left. - \frac{1}{8m_Q^2}\left(-(\mathbf{DE}) + 2\boldsymbol{\sigma}\cdot\mathbf{E}\times\boldsymbol{\pi}\right)\right]\left(1+\frac{(\boldsymbol{\sigma\pi})^2}{8m_Q^2}\right)\frac{1+\gamma_0}{2}Q$$

$$+\ \mathcal{O}\left(\frac{1}{m_Q^3}\right)$$

NR Dirac in external fields; Add logs reflecting evolution from M_Q to μ:
"Matching logarithms" (SVP)

Spectra and line shapes



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QCD Predictions for Lepton Spectra in Inclusive Heavy Flavor Decays

I. I. Bigi,[1,*] M. Shifman,[2,†] N. G. Uraltsev,[1,3,‡] and A. Vainshtein[2,4,§]

Parallel developments in Yang-Mills at strong coupling

- 1980s : Exact super−instanton in SYM; Exact β functions in $\mathcal{N} = 1$ $SQCD$; Exact calculation of gluino condensate, . . .
  Hints on instanton localization in SQCD

- 1990s : Conformal window and Seiberg duality; Low energy sol′n of $\mathcal{N} = 2$ SYM (1994 *CULMINATION*)
  by Seiberg and Witten, Domain walls (D branes) in SYM, monopole condensation and confining flux tubes confirming
  Nambu−Mandelstam−′t Hooft conjecture of dual Meissner effect, . . .2D – 4D correspondence, . . . Planar equivalence, . . .
  Instanton Localization, . . .
  We live in a New Era of qualitative understanding! And still···

Unlike models whose relevance to nature is "?" QCD will stay with us forever.

Still, I do not expect **FULL** **Analitic** solution to QCD to be found

QCD is extremely rich:

- ☆ Nuclear Physics
- ☆ Regge behavior
- ☆ Soft and hard dynamics overlap
- ☆ QGM: high-T/high μ (neutron stars)
- ☆ Richness of the hadronic world:

☆ chiral; ☆ glueballs & exotics; ☆ exclusive & inclusive phenomena;

☆ interplay between strong forces & weak interactions...

☆ Highly excited states and their decays···

- MS: "Snapshots of hadrons or the story of how the vacuum medium determines the properties of the classical mesons which are produced, live and die in the QCD vacuum," Prog. Theor. Phys. Suppl. 131 (1998) 1-71 • e-Print: hep-ph/9802214

- IB, MS, NU: "Aspects of heavy quark theor,y" Ann. Rev. Nucl. Part. Sci. 47 (1997) 591-661 • e-Print: hep-ph/9703290

- MS: "OPE-based Methods in Nonperturbative QCD", e-Print: 2208.10600, see Franz Gross et al., "50 Years of Quantum Chromodynamics," e-Print: 2212.11107, to appear in EPJC

- MS: "New and Old about Renormalons: in Memoriam Kolya Uraltsev", Int. J. Mod. Phys. A 30 (2015) 10, 1543001 • e-Print: 1310.1966

- MS: "Persistent Challenges of Quantum Chromodynamics. Julius Edgar Lilienfeld Prize Lecture," Int. J. Mod. Phys. A 21 (2006) 5695-5720 • e-Print: hep-th/0606015

- MS: "Supersymmetric Tools in Yang-Mills Theories at Strong Coupling: the Beginning of a Long Journey, Dirac Medal Lecture," Int. J. Mod. Phys. A 33 (2018) 12, 1830009 • e-Print: 1804.01191

Pioneers of heavy quarks physics – OPE-based Methods (ITEP, now non-existent)

M. Voloshin, 1953-2020

(Since late 1970s)

N. Uraltsev, 1957-2013

(Since mid-1980s)