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QCD now and Then: From the Early Days to Present and Future

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Between 1972 and 1974

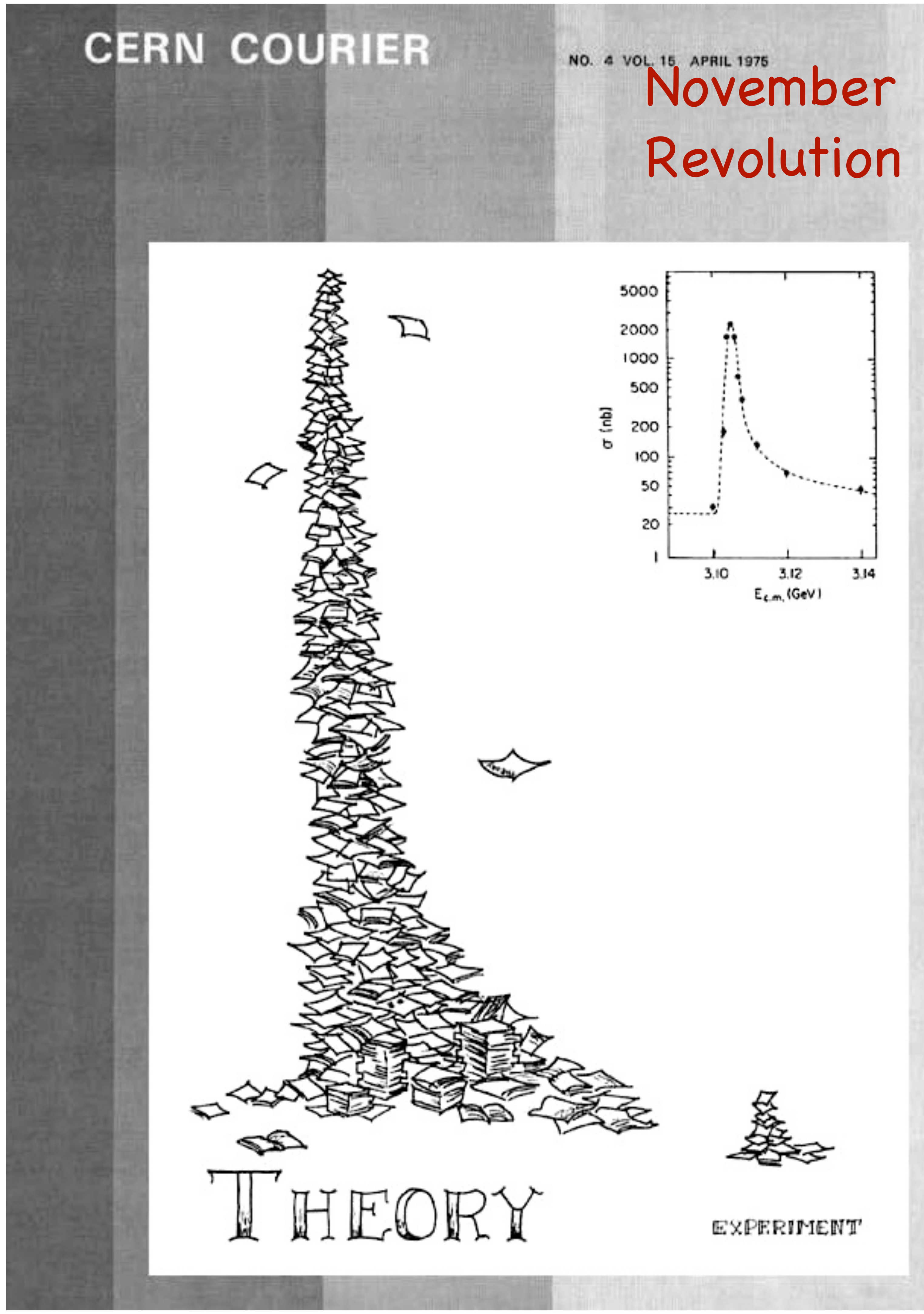
- XVI International Conference On High Energy Physics, 6 – 13 September 1972, Batavia, IL
- October 1972 → ITEP Grad school

Theoretical talks:

- Dual models (precursor to string theory);
- DIS, Bjorken Scaling, current algebra;
- $e^+e^- \to$ 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? $\pi^0 \to 2\gamma$ 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 😀

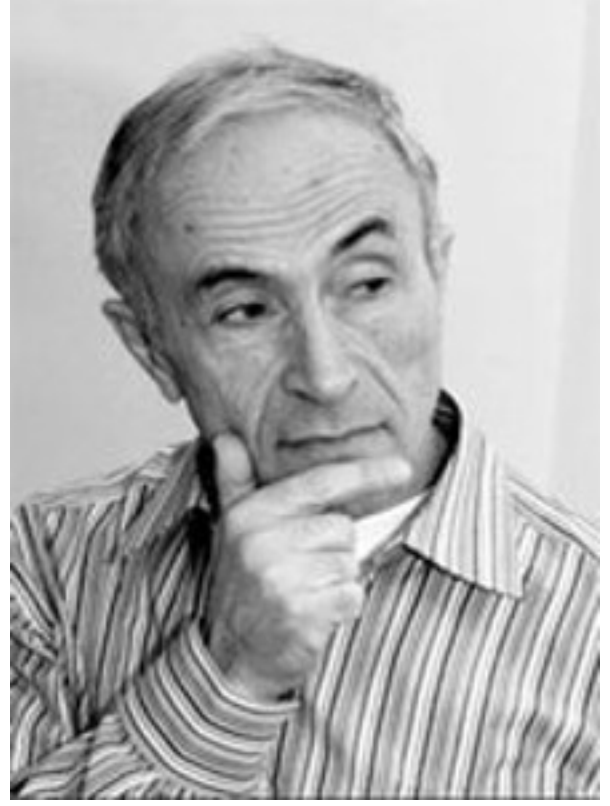
⟶ Electroweak physics (first paper early 1973)



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.

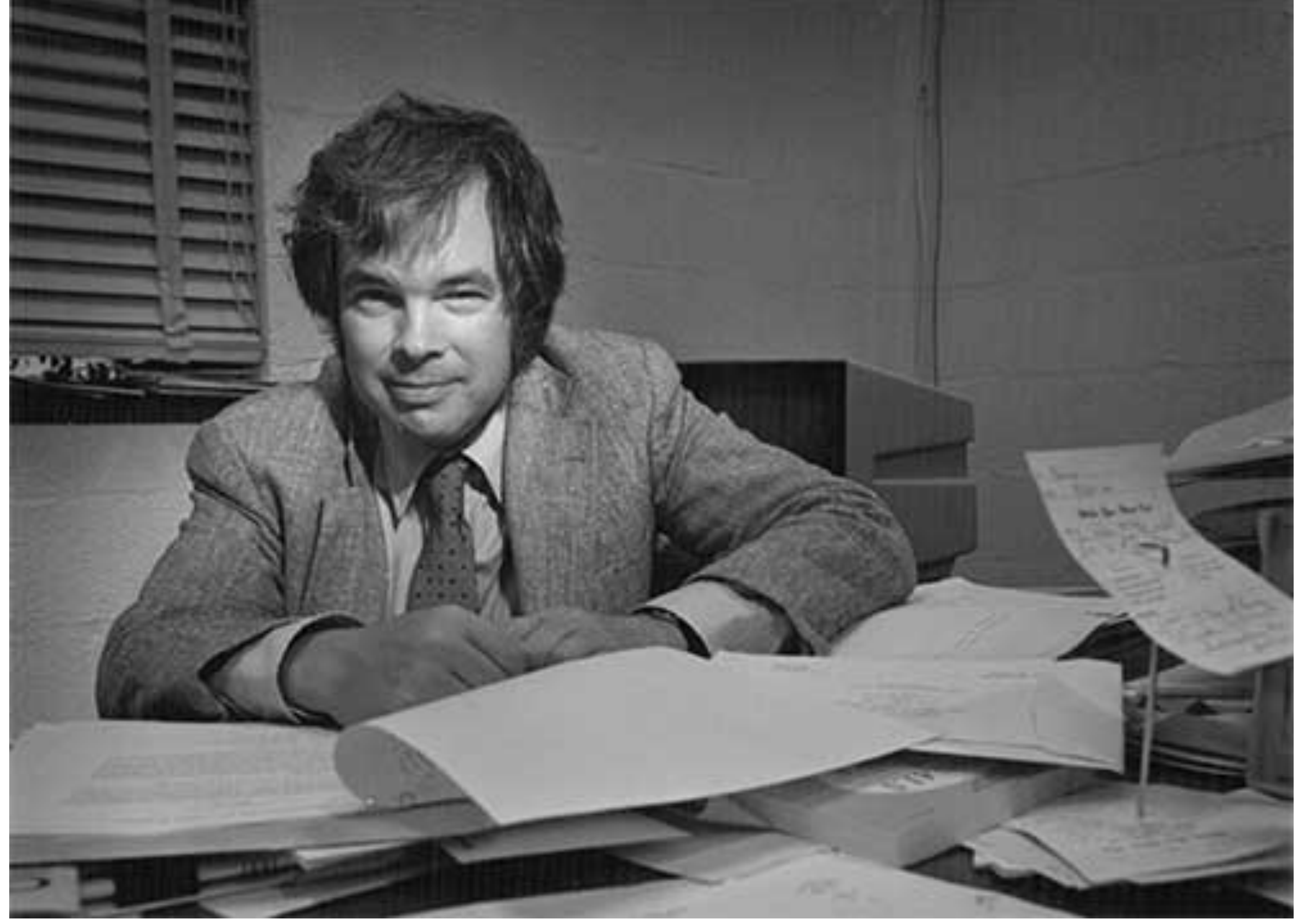
April 1973 Coleman and Wilczek; Politzer (PRL)

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

At small $|x|$: $$O_i(x)\, O_j(0) \to \Sigma_k \left[C_{ijk}(\mu)_{|x|>\mu^{-1}} \times \, (O_k)_{|x|<\mu^{-1}} \right]$$ GWF

1974-76 Breakthroughs

't Hooft:

't Hooft limit : $g^2 N$ fixed at $N \to \infty$

Topological classification of graphs, planar geometry in the leading order, hint to string theory.

Qualitatively describes all regularities of almost all hadronic phenomena in our world.

First non-perturbative contributions identified: MONOPOLES

A. Polyakov:

First non-perturbative contributions identified: MONOPOLES

INSTANTONS, Insanton liquid models of QCD vacuum

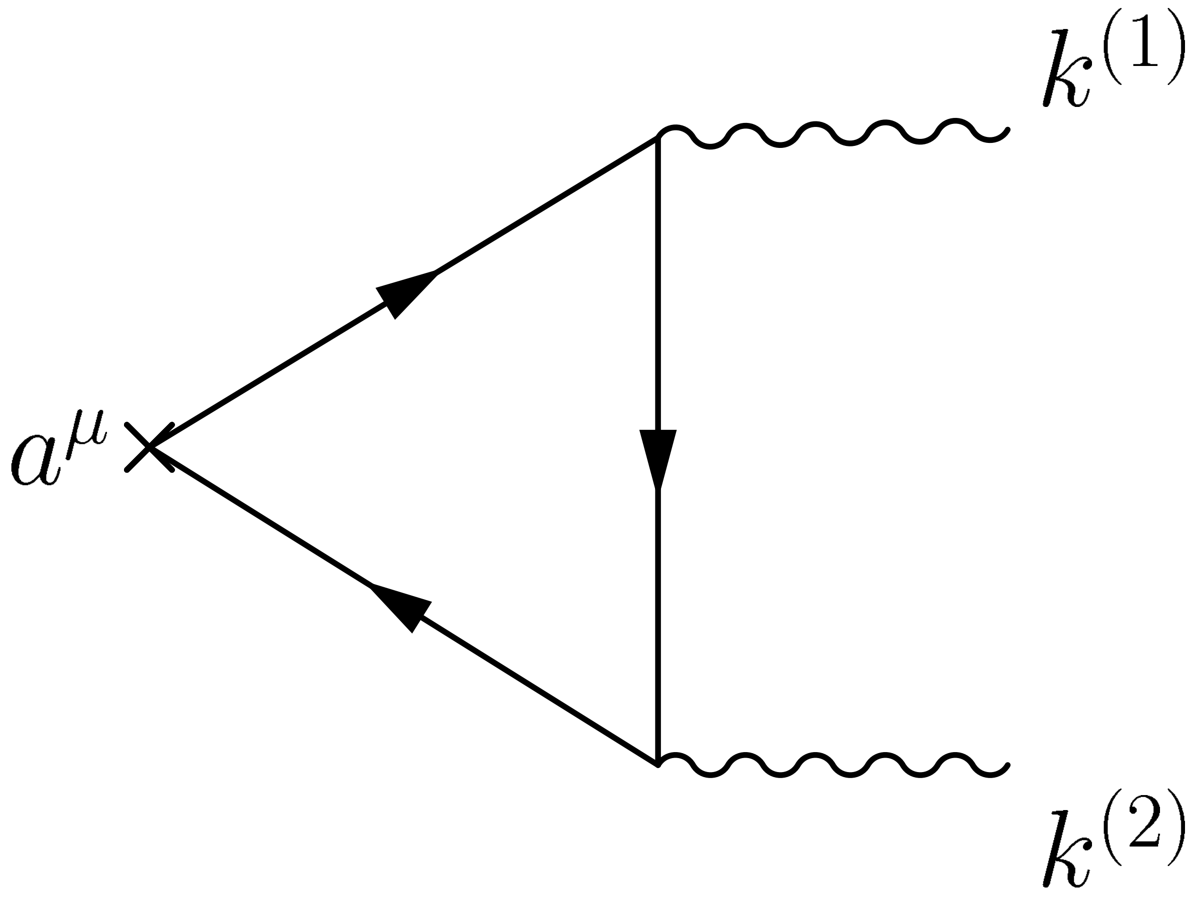
't Hooft

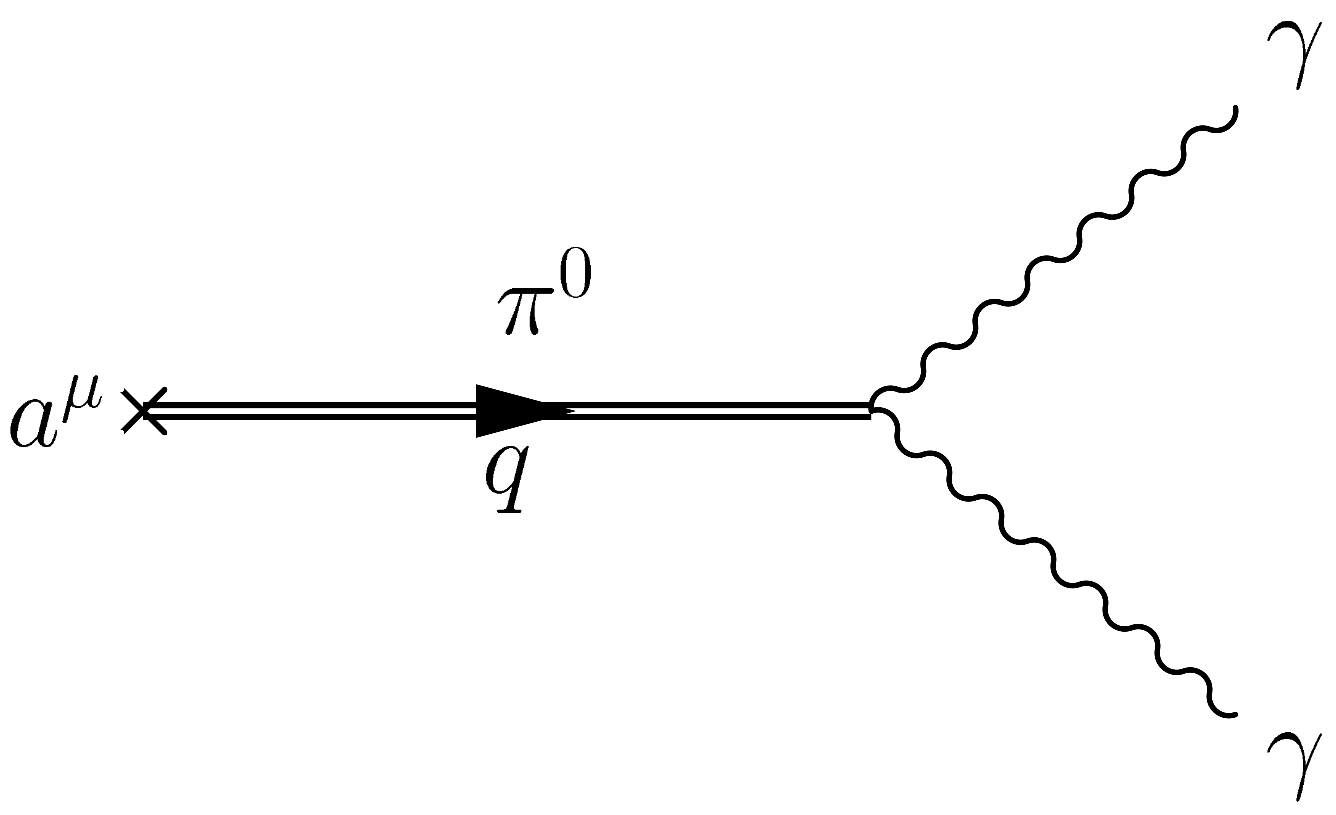
Solution of the long standing η' problem from

INSTANTONS

't Hooft anomaly matchig at $N \to \infty$

Nambu-Mandelsatm-'t Hooft conjecture of the dual Meissner effect as a mechanism of QCD confinement

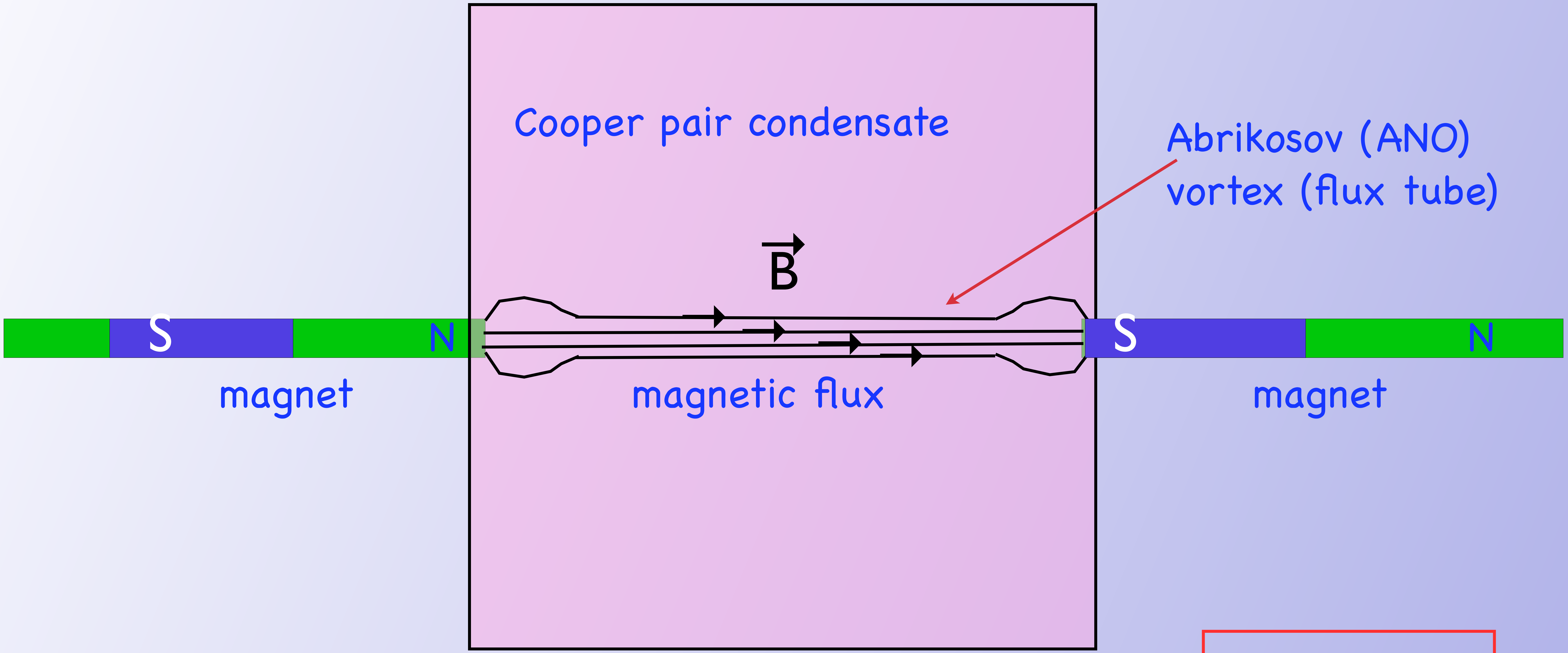




't Hooft anomaly matchig at $N \to \infty$

Nambu-Mandelsatm-'t Hooft conjecture & 1994 Seiberg-Witten **triumph**

☞ The Meissner effect! 1930s

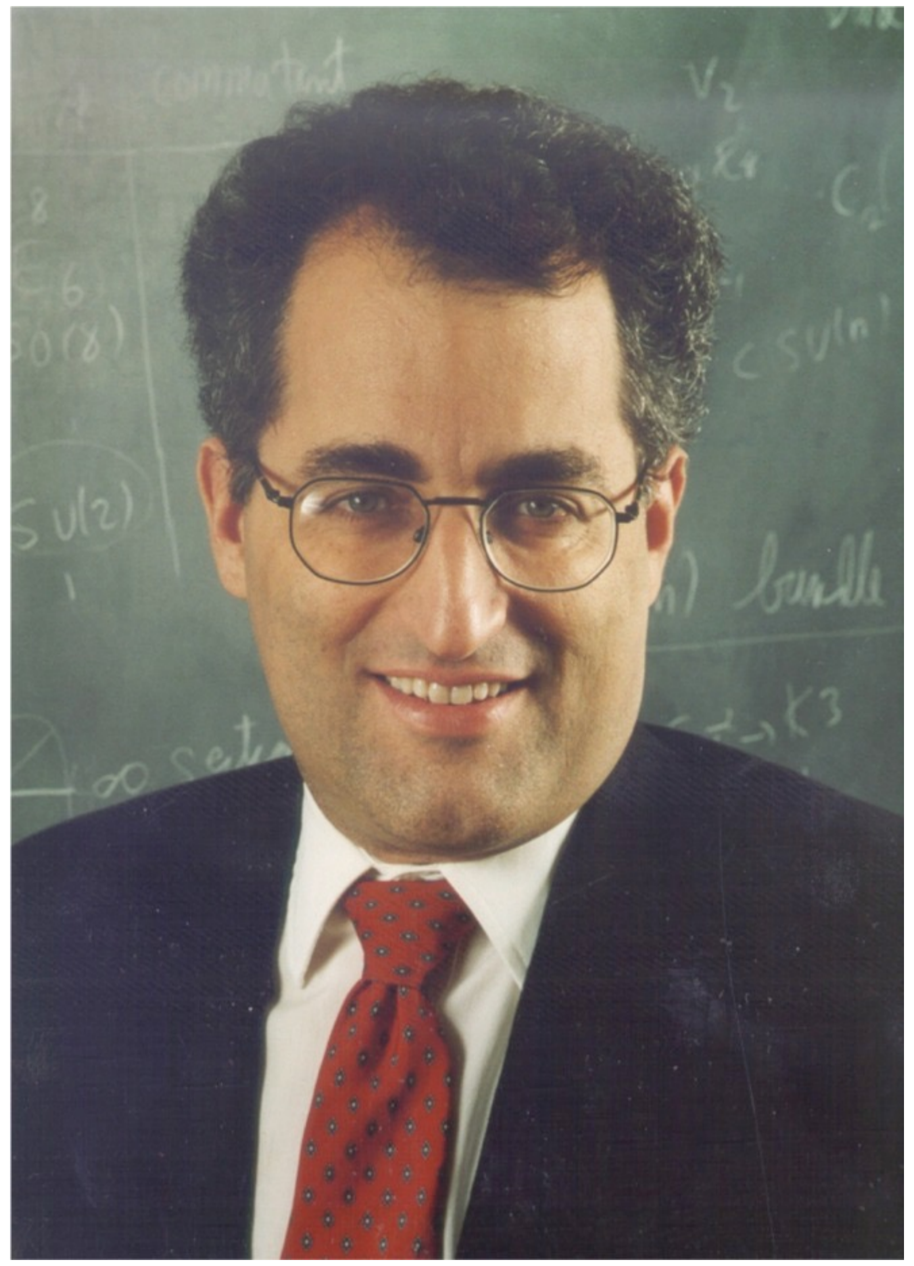


Superconductor of the 2nd kind

Abelian ☚

Crescendo. Seiberg-Witten Culmination (1994)

☺ First demonstration of the dual Meissner effect ☺



$\mathcal{N} = 2$ SYM, 8 supercharges

- **gluons+complex scalar superpartner**
- **two gluinos**
- **Georgi-Glashow model built in**

Any point on the complex plane of $\mathrm{Tr}\varphi^2$ can serve as vacuum

SU(2) $\to$ U(1), Higgsing in the same way as in Georgi-Glashow $\longrightarrow$ monopoles exist; at $|\mathrm{Tr}\varphi^2| \gg \Lambda^2$ seen/calculable quasi classically

Monopoles become light if $|\varphi^3| \lesssim \Lambda$ ➔ At two points, massless!

Multiple FURTHER developments in SUSY QCD 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 and later : 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···

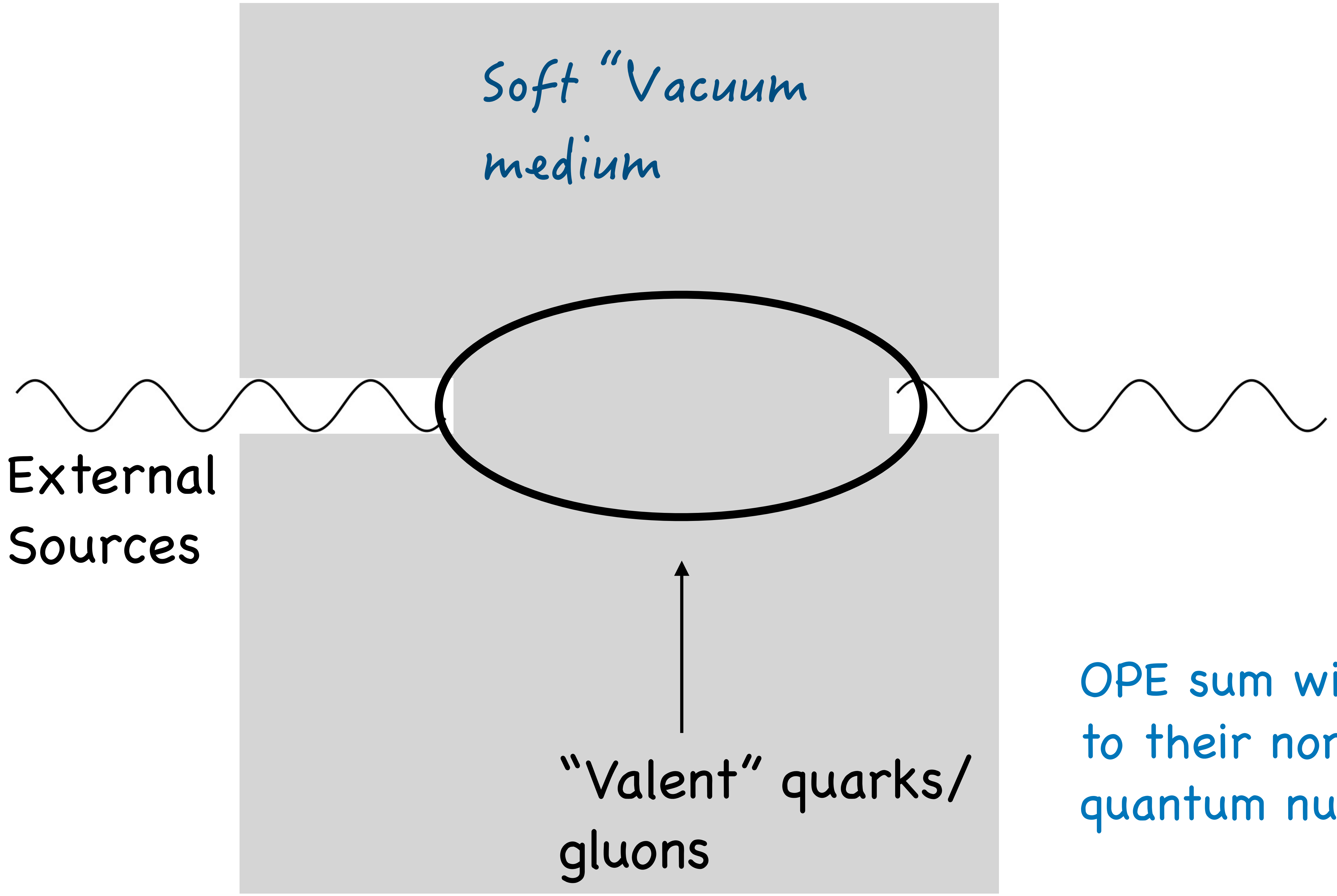
$O_{\text{peng}} = \bar{s}_L \gamma^\mu \mathscr{D}_\nu G^{\mu\nu} d_L \leftrightarrow$ flavor changing. Full class. 6 operators + more if EM is included

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



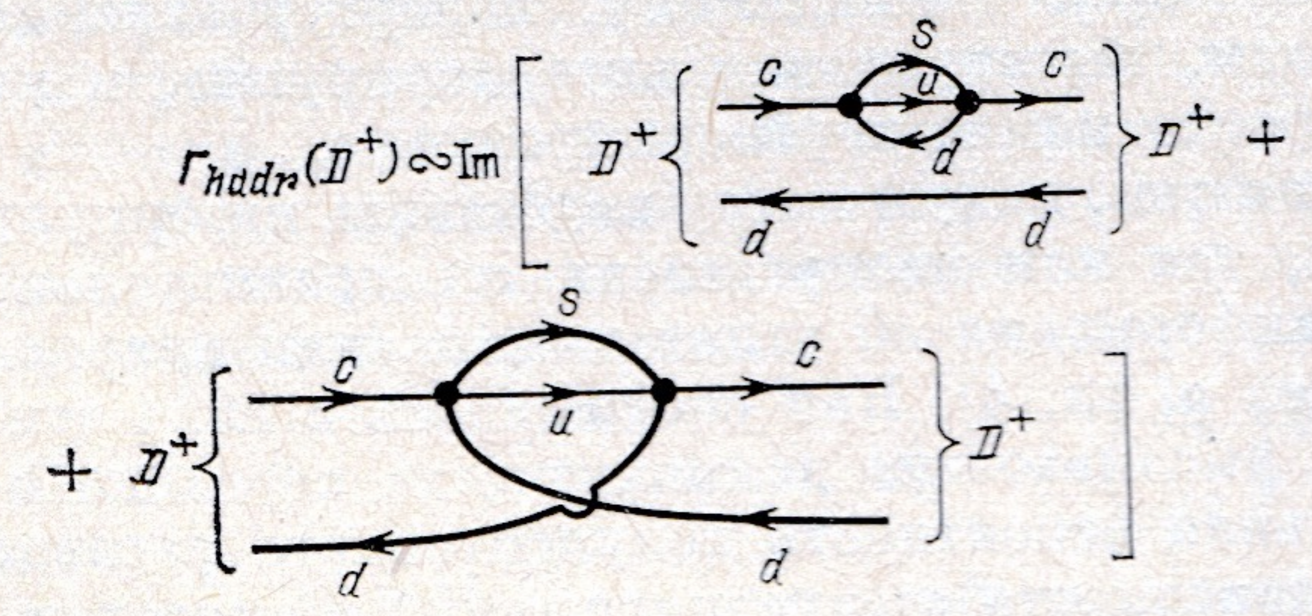
$$= \sum_{\text{dim}_n} C_n(Q,\mu)\langle O_n(\mu)\rangle = \frac{f_0^2}{Q^2 + m_0^2} + \sum_{\text{excit}} \ldots$$

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.

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

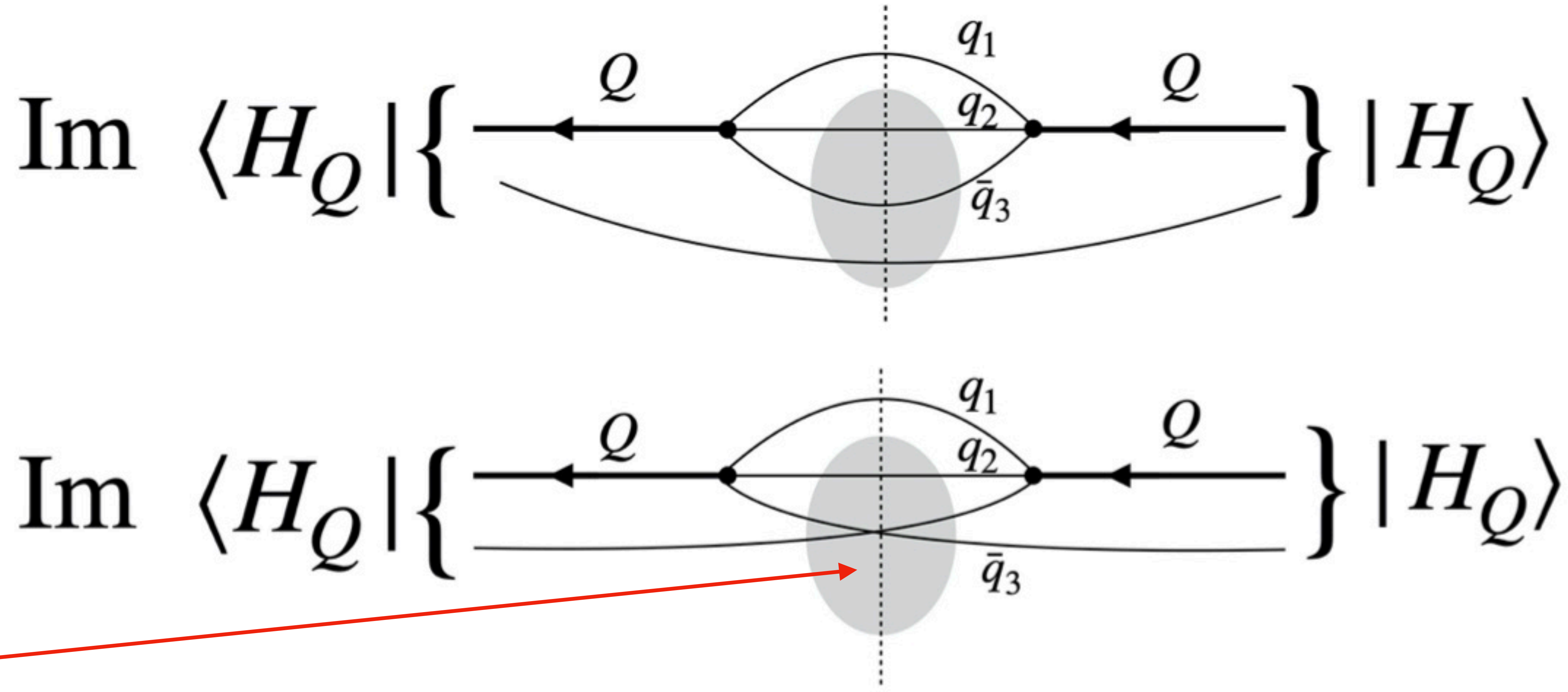
* Until 1990s, when lattice QCD (with chiral/heavy quarks) , started approaching its maturity, the SVZ method was the main tool for analyzing static hadronic properties.

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



β

Рис. 22. Интерференционный вклад в адронную ширину распада D^+-мезона.



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. .

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

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

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

No $1/m_Q$ CGG/BUV th

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

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

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

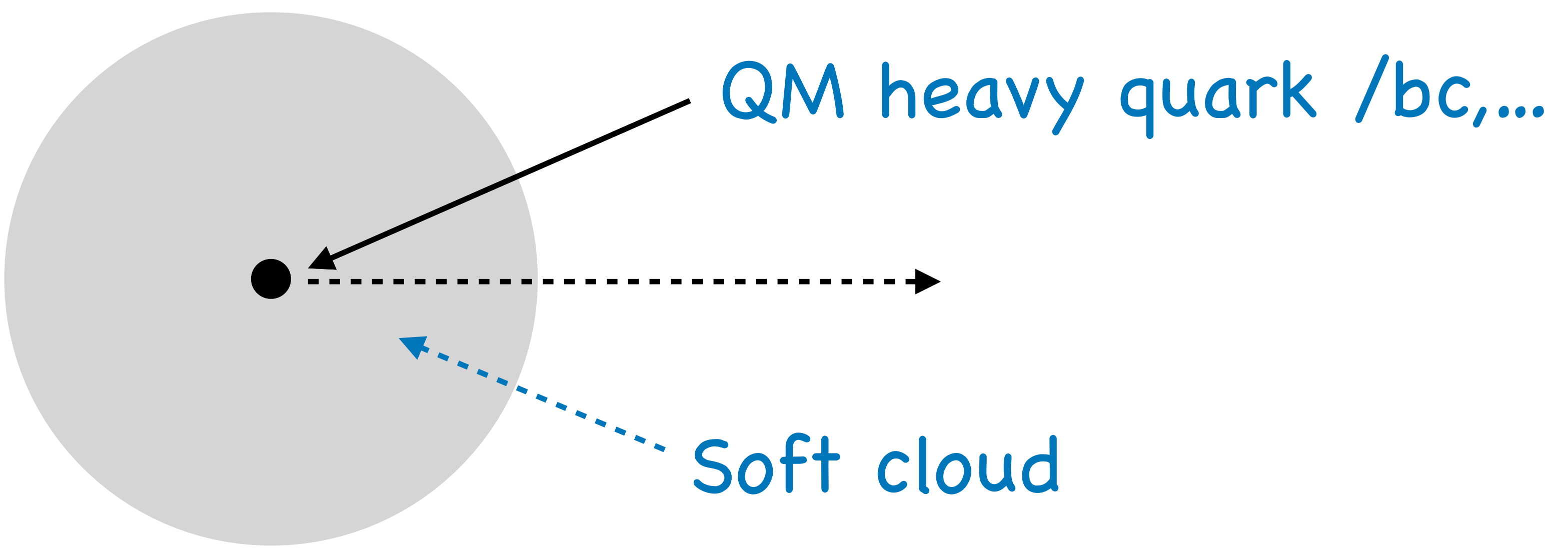
In the mid-1980s predicted $\tau(\Lambda_b)/\tau(B_d) = 0.9 \pm 0.03$

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

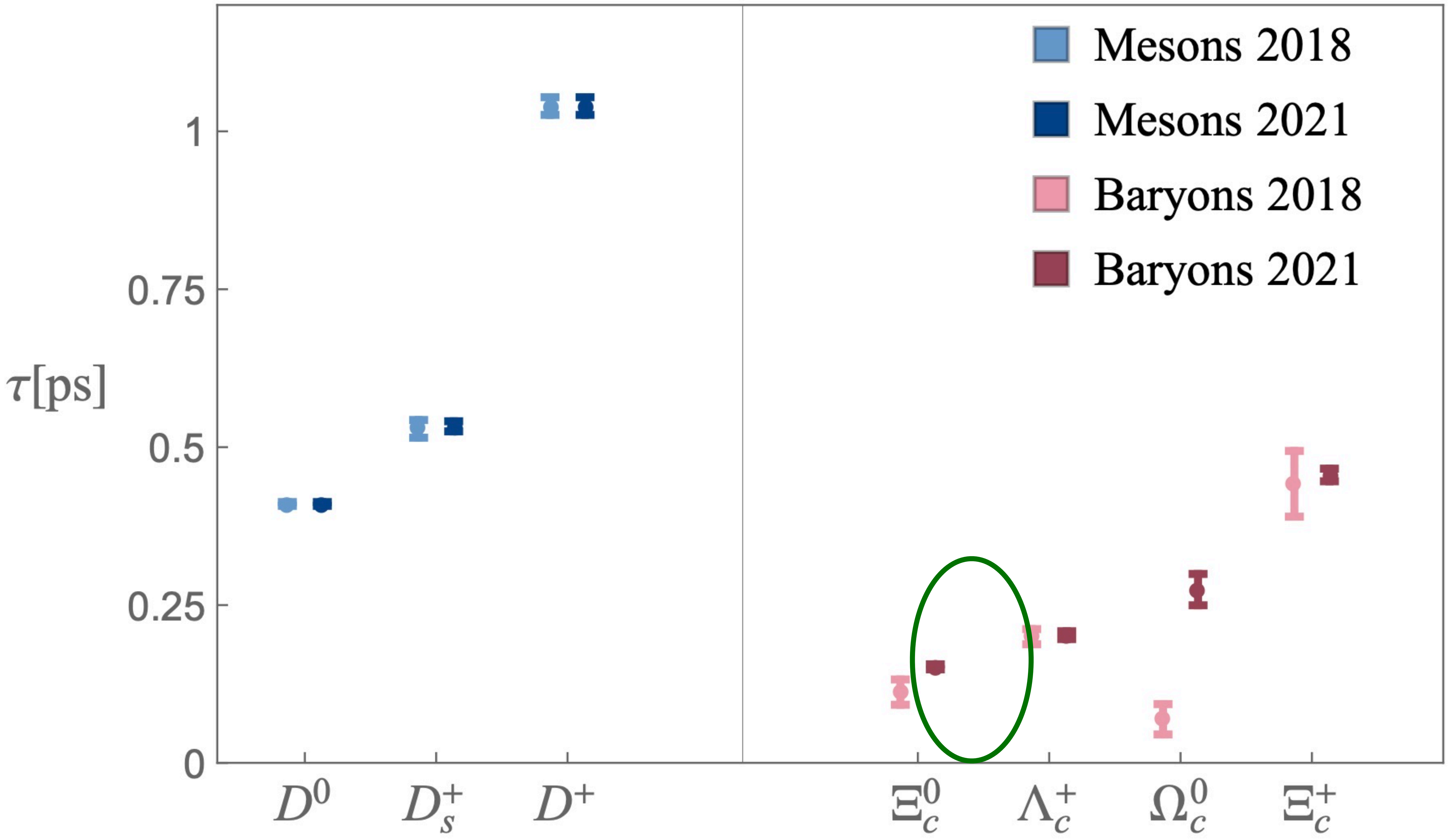
In the late 2010's $\tau(\Lambda_b)/\tau(B_d)_{\rm exp} = 0.93 \pm 0.05$

1990s

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



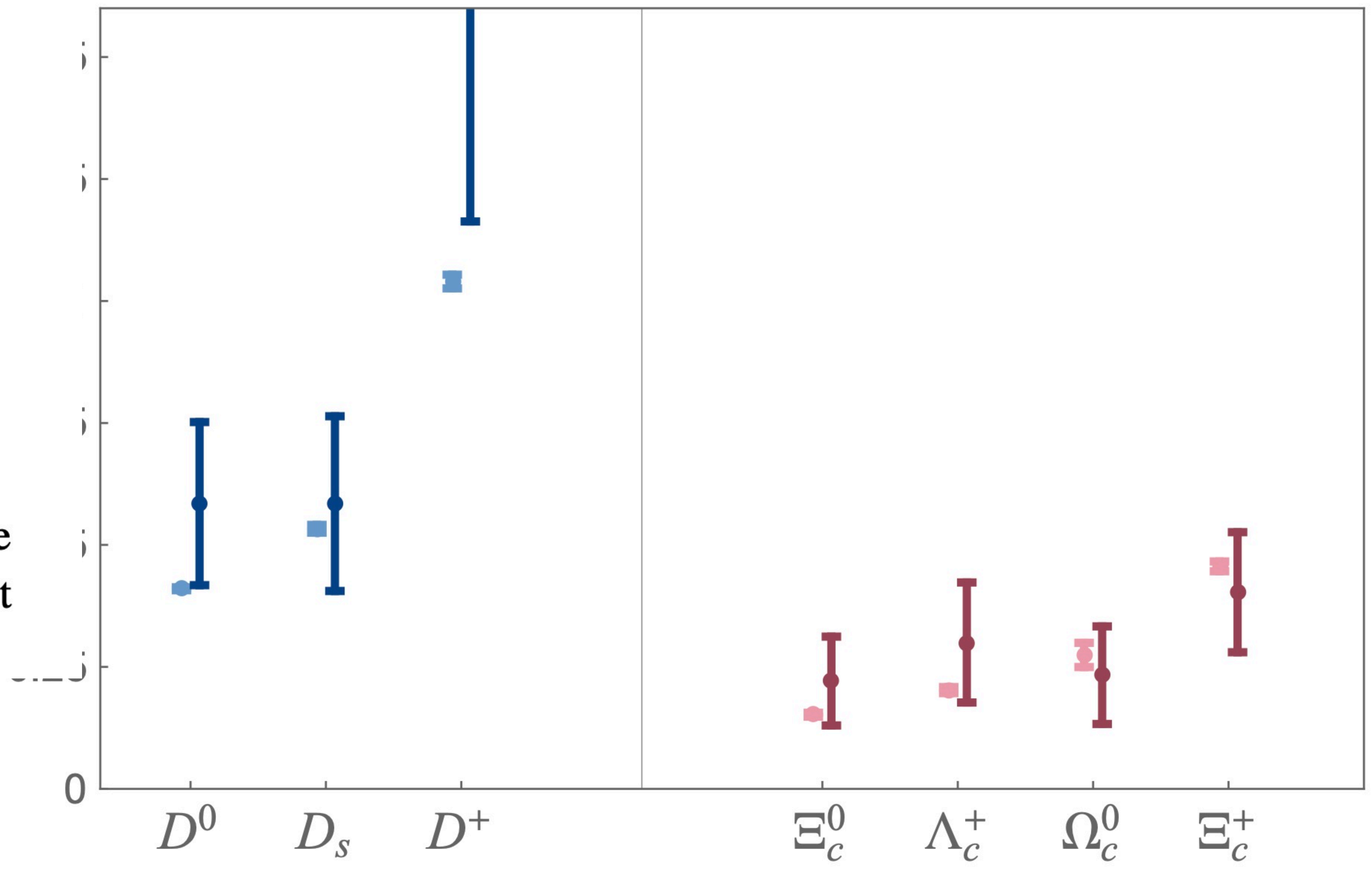
☞Vector charge non-renormalization theorem (say, $\bar{u}\gamma^\mu d$) at zero momentum transfer



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

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

Figure 1: Changes in experimental lifetime averages for mesons (blue, on the left) and baryons (red, on the right) in 2018 (light) and 2021 (dark) owing to the recent LHCb results. Recent Belle II results [24] support the new Ω_c lifetime measurement. Note that the error bars indicate 2σ uncertainties in all cases.



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

LHCb

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

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].

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

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 ☆

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

☆ interplay between strong forces & weak interactions...

☆ Highly excited states and their decays···