Flavor Physics from the past to the future

Guido Altarelli: eredità e prospettive, 10 anni dopo

Roma Tre 2 Dicembre 2025

Guido Martinelli
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UTfit

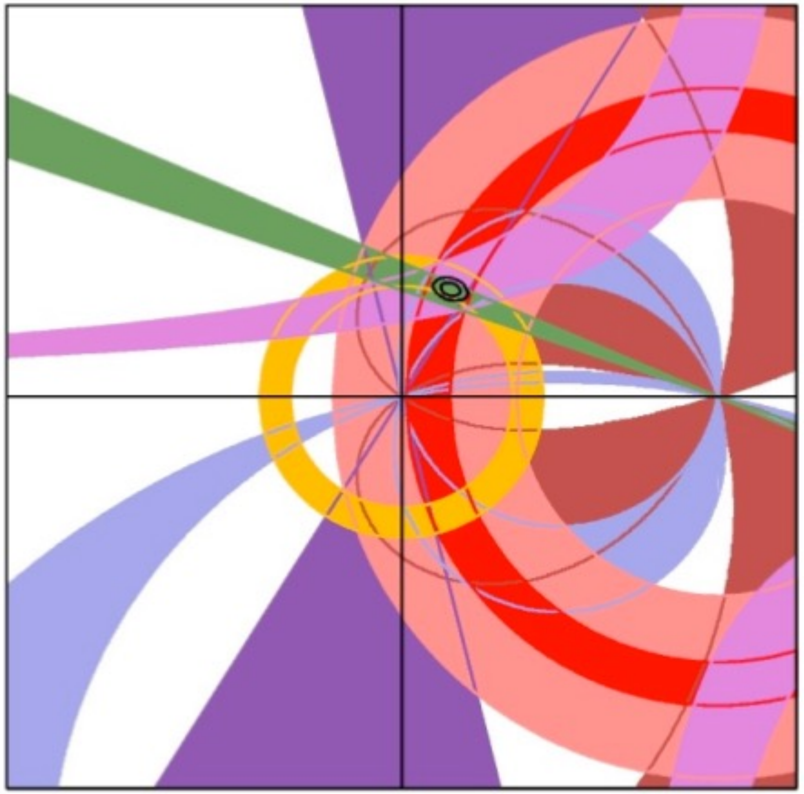
INFN Istituto Nazionale di Fisica Nucleare

Per questi ultimi dieci anni non ho nuovi ricordi di Guido da condividere perciò ho inserito alcuni progressi nella fisica del sapore legati a Guido e ho cercato e incluso altre foto

I apologize if during my talk I will be moved (as it happened already in preparing these slides).

I thank you in advance

PLAN OF THE TALK



- *The beginning of my collaboration and friendship with Guido;*
- *QCD and Weak Interactions: first important steps - see also Maiani talk - ;*
- *The (first) calculation of the NLO corrections to the Effective Weak Hamiltonian;*
- *The game became more complex, new developments;*
- *Final remarks.*

The beginning of my collaboration with Guido

From ``The Early days of QCD" by Guido A. @ the Symposium in Honour of Mario Greco 2011

after Paris and the AP paper,

Back to Rome I met Guido Martinelli, then a post-doc with a contract for doing accelerator physics at Frascati, and I rescued him into particle physics, with a work on the transverse momentum distributions for jets in lepto-production final states [32]. In the same paper we derived an elegant formula for the longitudinal structure function F_L, also an effect of order $\alpha_s(Q^2)$, as a convolution integral over $F_2(x, Q^2)$ and the gluon density $g(x, Q^2)$. I find it surprising that it took 40 years since the start of deep inelastic scattering experiments to get meaningful data on the longitudinal structure function. The present data, recently obtained by the H1 experiment at DESY, are in agreement with this LO QCD prediction but the accuracy of the test is still far from being satisfactory for such a basic quantity.

The first papers together

the 'Elli(s) Collaboration

1. **Transverse Momentum of Jets in Electroproduction from Quantum Chromodynamics**
Guido Altarelli (Rome U. & INFN, Rome), G. Martinelli (Frascati). Jan 1978. 6 pp.
Published in **Phys.Lett. B76 (1978) 89-94**
Print-78-1029 (ROME)
DOI: 10.1016/0370-2693(78)90109-0
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service ; Science Direct
Detailed record - Cited by 323 records 250+

MY FIRST NLO QCD Calculation ($F_2^L(x)$)

2. **Leptoproduction and Drell-Yan Processes Beyond the Leading Approximation in Chromodynamics**
Guido Altarelli (Rome U. & INFN, Rome), R.Keith Ellis (MIT, LNS), G. Martinelli (Frascati). Jun 1978. 25 pp.
Published in **Nucl.Phys. B143 (1978) 521,** Erratum: **Nucl.Phys. B146 (1978) 544**
MIT-CTP-723
DOI: 10.1016/0550-3213(78)90067-6
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 450 records 250+

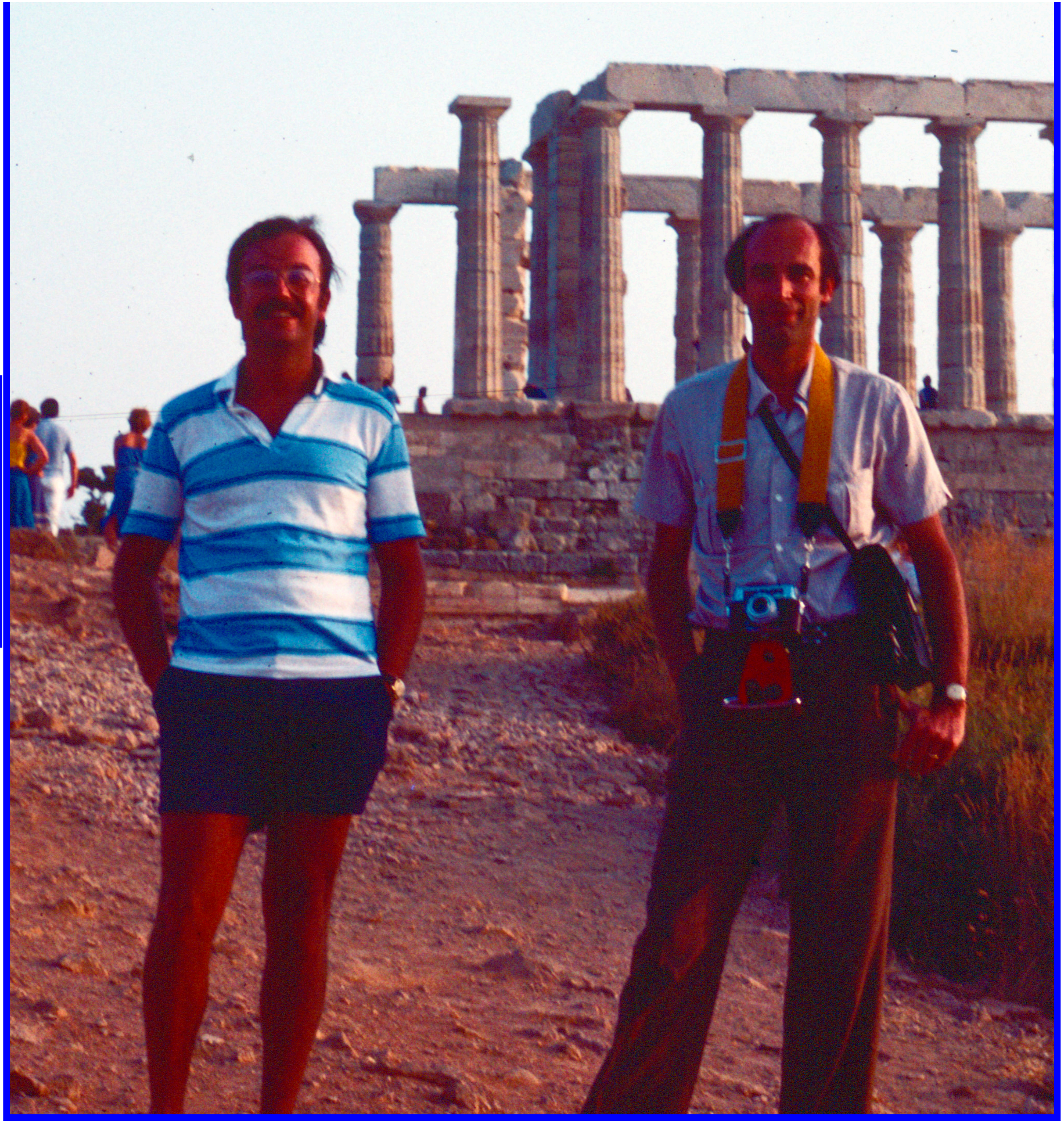
dimensional regularization from Keith Ellis (Marciano)

3. **Large Perturbative Corrections to the Drell-Yan Process in QCD**
Guido Altarelli (Rome U. & INFN, Rome), R.Keith Ellis (MIT, LNS), G. Martinelli (Frascati). Mar 1979. 37 pp.
Published in **Nucl.Phys. B157 (1979) 461-497**
MIT-CTP-776
DOI: 10.1016/0550-3213(79)90116-0
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 846 records 500+

4. **Processes Involving Fragmentation Functions Beyond the Leading Order in QCD**
Guido Altarelli (Rome U. & INFN, Rome), R.Keith Ellis (MIT, LNS), G. Martinelli (Frascati), So-Young Pi (MIT, LNS). Jun 1979. 29 pp.
Published in **Nucl.Phys. B160 (1979) 301-329**
MIT-CTP-793
DOI: 10.1016/0550-3213(79)90062-2
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 251 records 250+

Altarelli, Keithelli and Martinelli Collaboration or Altarellis, Ellis and Martinellis

WE WERE A LITTLE YOUNGER THOUGH !!



A NICE GROUP AT WORK: Manuel Greco, myself, GUIDO, Keith Ellis, Mario Greco
Note Keith tan !

QCD and Weak Interactions: the first important steps

PHYSICS LETTERS 14 October 1974

OCTET ENHANCEMENT OF NON-LEPTONIC WEAK INTERACTIONS IN ASYMPTOTICALLY FREE GAUGE THEORIES

G. ALTARELLI
Istituto di Fisica dell'Università di Roma, Rome, Italy

L. MAIANI
Lab. di Fisica, Istituto Superiore di Sanità, Rome, Italy
and Ist. Naz. di Fisica Nucleare, Sezione Sanità, Rome, Italy

Received 22 June 1974

Octet enhancement of weak non leptonic amplitudes is found to occur in asymptotically free gauge theories of strong interactions, combined with unified weak and e.m. interactions. The order of magnitude of the enhancement factor for different models is discussed.

$$\mathcal{A}^{\Delta S=1}_{FI}\,(2\pi^4)\,\delta^4(p_F-p_I) = \text{tadpoles} + (\text{Higgs scalar exchange}) +$$

$$\int d^4x\, d^4y\, D_{\mu\nu}(x, M_W)\ \langle F\,|T[\,J_\mu(y+x/2)\,J^\dagger_\nu(y-x/2)]\,|\,I\rangle$$

1) Tadpoles cannot give any contribution;

2) Higgs contribution suppressed as m^2/M^2_W

$$\langle F\,|\,\mathcal{H}^{\Delta S=1}\,|\,I\rangle = G_F/\sqrt{2}\,V_{ud}\,V_{us}^*\,\Sigma_i\, C_i(\mu)\,\frac{\langle F\,|\,Q_i(\mu)\,|\,I\rangle}{(M_W)^{d_i-6}}$$

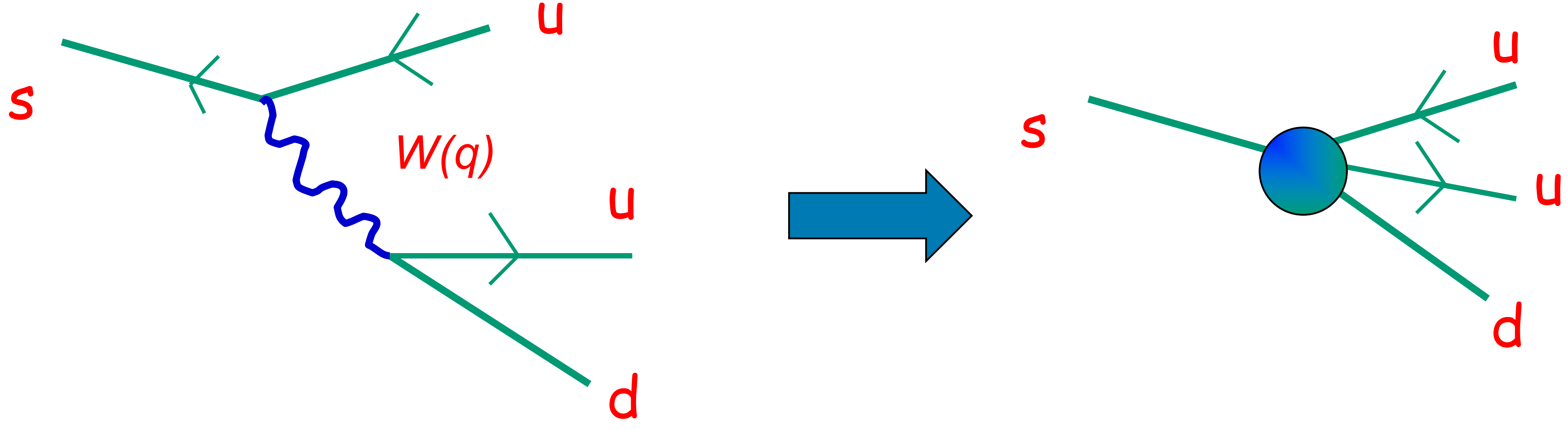
WILSON OPE

$\Delta I = \frac{1}{2}$ Rule for Nonleptonic Decays in Asymptotically Free Field Theories

M. K. Gaillard* and Benjamin W. Lee†
National Accelerator Laboratory, Batavia, Illinois 60510
(Received 10 April 1974)

The effective nonleptonic weak interaction is examined assuming the Weinberg-Salam theory of weak interactions and an exactly-conserved-color gauge symmetry for strong interactions. It is shown that the octet part of the nonleptonic weak interaction is more singular at short distances than the $\underline{27}$ part. The resulting enhancement of the octet term in the effective local weak Lagrangian, together with suggested mechanisms for the suppression of matrix elements of the $\underline{27}$ operator, may be sufficient to account for the observed $|\Delta I| = \frac{1}{2}$ rule.

The Effective Hamiltonian



$$q \sim m_K \ll M_W$$

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left(\bar{s}\gamma_\mu(1-\gamma_5)u\right)\left(\bar{u}\gamma^\mu(1-\gamma_5)d\right)$$

Wilson OPE

$$\mathcal{A}_W \approx \alpha\, M^{-2}_W \sum_k C_k [\ln(M^2_W / m^2)]^{dk} \langle F | Q_k(0) | I \rangle + ..$$

Anomalous dimension of the operator Q_k

``The OPE shows that the amplitude is dominated by the matrix elements of those operators with dk > 0 thus giving rise to a possible mechanism to enhance contributions with definite quantum numbers, e.g. ΔI=1/2 vs ΔI=3/2 as first suggested by Wilson"

$$O_L^1 = \bar\psi\gamma_\mu L^+(1+\gamma_5)\psi\bar\psi\gamma^\mu L^-(1+\gamma_5)\psi$$
$$O_L^2 = \bar\psi\gamma_\mu L^+(1+\gamma_5)t^A\psi\bar\psi\gamma^\mu L^-(1+\gamma_5)t^A\psi \quad (4)$$

$$O_R^1 = \bar\psi\gamma_\mu R^+(1-\gamma_5)\psi\bar\psi\gamma^\mu R^-(1-\gamma_5)\psi$$
$$O_R^2 = \bar\psi\gamma_\mu R^+(1-\gamma_5)t^A\psi\bar\psi\gamma^\mu R^-(1-\gamma_5)t^A\psi \quad (5)$$

Definition of the Operators
Note the perversion: $(1+\gamma_5)$ is left-handed

$$O_{LR}^1 = \bar\psi\gamma_\mu L^+(1+\gamma_5)\psi\bar\psi\gamma^\mu R$$
$$O_{LR}^2 = \bar\psi\gamma_\mu L^+(1+\gamma_5)t^A\psi\bar\psi\gamma$$

$$O_L^\pm = \frac{N\pm 1}{N}O_L^1 \pm \tfrac{1}{2}O_L^2; \quad d_L^\pm = \frac{1}{2b}\left(\frac{3}{8\pi^2}\right)\left(\mp\frac{N\mp 1}{N}\right) \quad (7)$$

same for $O_R^\pm$, $d_R^\pm = d_L^\pm$, and

$$\tilde{O}_{LR}^1 = -\frac{N^2-1}{N}O_{LR}^1 + \tfrac{1}{2}O_{LR}^2;$$
$$\tilde{O}_{LR}^2 = \frac{1}{N}O_{LR}^1 + \tfrac{1}{2}O_{LR}^2;$$
$$d_{LR}^1 = \frac{1}{2b}\left(\frac{3}{8\pi^2}\right)\left(-\frac{1}{N}\right);$$
$$d_{LR}^2 = \frac{1}{2b}\left(\frac{3}{8\pi^2}\right)\left(\frac{N^2-1}{N}\right), \quad (8)$$

First calculation of the LO anomalous dims:
$\Delta I=1/2$ dynamically enhanced
although only qualitatively successful

WEAK INTERACTIONS PHENOMENOLOGY WAS IMPROVING AT A FAST PACE

1. Better and better data on charm production and semileptonic non-leptonic decays
2. The bottom quark was discovered in 1977 and its properties & decays started to be intensively studied
3. The beginning of the Heavy Quark (Effective) Theory

Nuclear Physics B88 (1975) 285–288

ENHANCEMENT OF NON-LEPTONIC DECAYS OF CHARMED PARTICLES

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Laboratori di Fisica, Istituto Superiore di Sanità, Roma, Italy

Received 14 October 1974

The enhancement of non-leptonic rate due to QCD corrections improved agreement of the prediction of the semileptonic branching ratio with data

Calculations of semileptonic branching ratios were done in the ``parton model'' i.e. using the free particle

Search for charm

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A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes, and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar —but not necessarily understood— phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

[7] B.W. Lee, M.K. Gaillard and G. Rosner, Rev. Mod. Phys. 47 (1975) 277;
G. Altarelli, N. Cabibbo and L. Maiani, Nucl. Phys. B88 (1975) 285; Phys. Lett. 57B (1975) 277
S.R. Kingsley, S. Treiman, F. Wilczek and A. Zee, Phys. Rev. D11 (1975) 1914;
J. Ellis, M.K. Gaillard and D. Nanopoulos, Nucl. Phys. B100 (1975) 313

Volume 79B, number 1,2 PHYSICS LETTERS 6 November 1978

THE LIFETIME OF CHARMED PARTICLES

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and

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Received 10 July 1978

We present a computation of the semileptonic decay rate of charmed particles, including the first order gluon corrections and the final quark mass corrections. Taking into account these corrections, the lifetime of charmed particles is estimated to be: $\tau \approx 0.7 \times 10^{-12}$ s.

Nuclear Physics B208 (1982) 365–380

just after I came back from CERN – see Maiani (Franzini suggestion)

LEPTONIC DECAY OF HEAVY FLAVORS:
A theoretical update

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Received 29 June 1982

How Guido remembered that period …

After the Gross-Wilczek and Politzer papers we immediately turned to study the potentiality of QCD for improving the parton model. Myself and Maiani we decided to study the QCD corrections to the effective weak non-leptonic Hamiltonian, written as a Wilson expansion in terms of 4-quark operators of the (V-A)x(V-A) type obtained by integrating away the $W^{\pm}$ exchange [18]. The logarithmically enhanced terms of the QCD corrections are fixed by the anomalous dimensions of these operators, much in the same way as the moments of structure functions get logarithmic corrections as computed by Gross et al [2, 3] from the anomalous dimensions of the leading-twist operators in the light-cone expansion. Our hope was to find that the QCD corrections act in the direction of enhancing the $\Delta T = 1/2$ operators with respect to those with $\Delta T = 3/2$, thus explaining, at least in part, the empirical $\Delta T = 1/2$ rule (where T is the isotopic spin). The explicit calculation turned out to lead to precisely this result, as also obtained in a simultaneous work by M. K. Gaillard and B. W. Lee [19] (actually these authors had pointed out to us the crucial role of charm in this problem). These important papers were the first calculations of the QCD corrections to the coefficients of the Wilson expansion in the product of two weak currents, an approach that, suitably generalised (by considering other weak processes) and improved (for example, by computing the anomalous dimensions beyond the leading order), still represents a basic tool in this field. In the following months we applied the method to charm decays [20], before the discovery of charm, and to weak neutral current processes [21]. To this last paper also contributed Keith Ellis, a scottish PhD student of Cabibbo, who was to stay with us in Rome for a few years, eventually speaking a very good italian and fully understanding the roman way of living. Later, in '81 myself with Curci (who, unfortunately, is no more with us), Martinelli and Petrarca [22] we computed the two-loop anomalous dimensions for the operators of the effective weak non-leptonic Hamiltonian.

The (first) calculation of the NLO corrections to the Effective Weak Hamiltonian

The physical motivations for a NLO calculation

For heavy quark decay (especially for charm) a substantial increase in the non-leptonic width is obtained, which leads to a prediction [7] for the (quark) semileptonic branching ratio B^{SL}, which is considerably smaller than the free field value. For charm, the prediction in the LLA is typically $B^{SL} \simeq 13$–16% as compared with the free field value of ~20%. Until recently, the results for a charm (c) quark

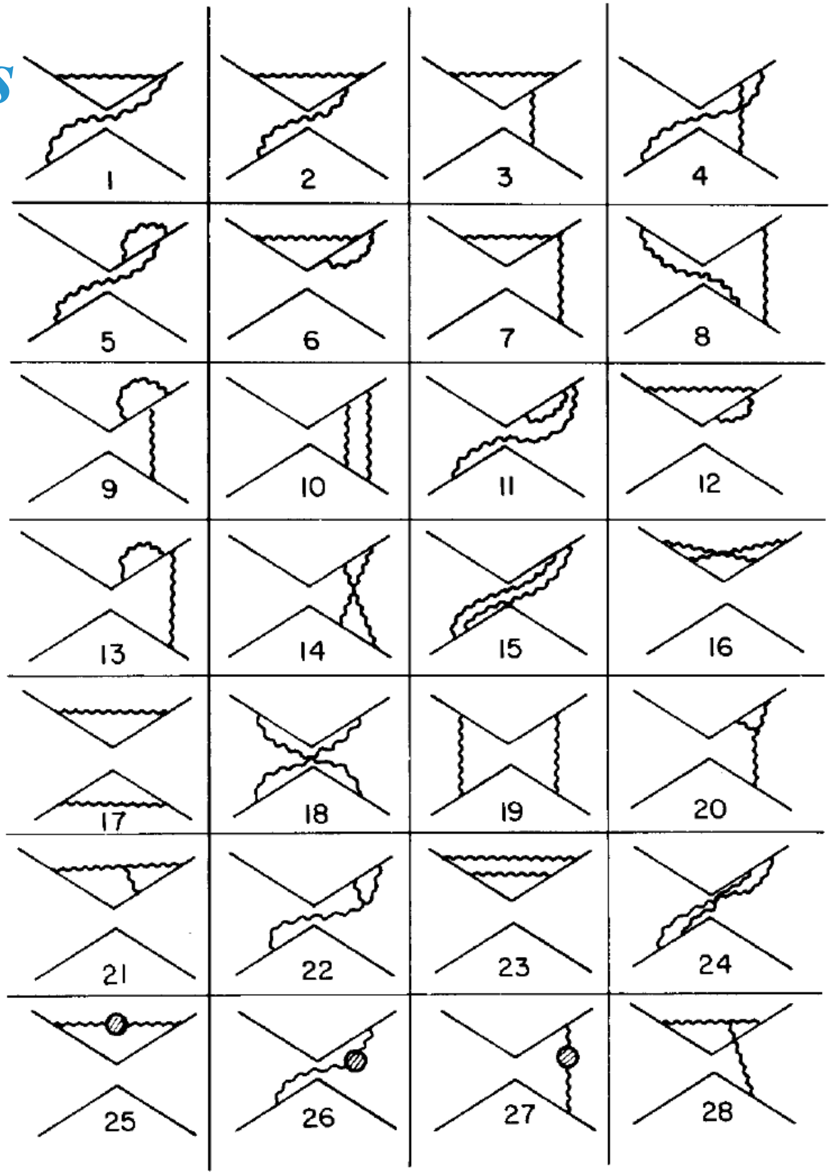
with real gluon emission [9]. However, the c quark decay prediction should remain essentially valid for D^+ (provided the spectator is really inert [10]) because, in D^+, the annihilation process can only occur at the Cabibbo suppressed level. Since a value of B^{SL} for D^+ close to 20% is being currently reported [8] it is important to verify whether or not the LLA is supported by a study of the next to leading corrections.

In order to investigate these matters we computed the first non-leading QCD corrections to the effective weak non-leptonic hamiltonian (a summary of our results has already been published elsewhere [11]). The main ingredients for this calculation

No penguin diagrams necessary for the charm calculation

466 G. Altarelli et al. / Corrections to weak decays

Letters exchanges between the CERN team (G. Curci & GM) And the Rome Team (G. Altarelli and S. Petrarca)



Occasionally some mistake was found

Fig. 2. The 28 independent two-loop diagrams for the anomalous dimension of the four-fermion operators of dimension six. Replicas differing by up–down, left–right reflections of diagrams are not shown. "Penguin" like diagrams are absent in the massless theory. They are irrelevant for transition involving four different flavours as in $c \to s\bar{d}u$.

We were scared of using Naïve Dimensional Regularization (NDR) in the presence of chiral currents (γ_5) and decided to use Dimensional Reduction (we were really naïve!!)

Volume 148B, number 1,2,3 PHYSICS LETTERS 22 November 1984

CONSISTENCY BETWEEN DIFFERENT DIMENSIONAL REGULARIZATIONS IN TWO-LOOP CALCULATIONS FOR SUPERSYMMETRIC GAUGE THEORIES

G. CURCI and G. PAFFUTI
Istituto di Fisica, Università di Pisa, Pisa, Italy
and INFN, Sezione di Pisa, Pisa, Italy

Received 6 August 1984

We show that dimensional regularization and dimensional reduction are consistent up to two-loop in susy gauge theories. No anomalies are found for supersymmetry at two-loop level.

Recently Van Damme and 't Hooft [1] have raised the problem of compatibility between standard dimensional regularization (DR) [2] and the dimensional reduction scheme (SDR) [3] in supersymmetric gauge theories.

A convenient device to perform calculations for the $N = 1, 2, 4$ models at once is offered by the formalism of ref. [4] used for similar computations in ref. [5].

Let us consider the Yang–Mills theory in D dimensions with fermions in the adjoint representation

Climbing NLO and NNLO Summits of Weak Decays
Andrzej J. Buras *arXiv:1102.5650v4*

In 1981 Guido (M.) took part in the pioneering calculation of the two loop anomalous dimensions of the current-current operators. This calculation done in collaboration with Guido Altarelli, Giuseppe Curci and Silvano Petrarca has been unfortunately performed in the dimensional reduction scheme (DRED) that was not familiar to most phenomenologists and its complicated structure discussed in detail by these authors most probably scared many from checking their results. Moreover it was known that the treatment of γ5 in the DRED scheme, similarly to the dimensional regularization scheme with anticommunicating γ5 (known presently as the NDR scheme), may lead to mathematically inconsistent results.

Consequently it was not clear in 1988 whether the result of Altarelli et al. was really correct.

The calculation by Buras & Weiz, in NDR and DRED, of the NLO corrections to KKbar mixing confirmed our results and demonstrated that the calculation could have been done in NDR as well.

Further Motivations & Recent Developments

$\mathcal{A}_{\mathbf{FI}}\ (2\pi^4)\ \delta^4\ (p_F - p_I) =$

$\int d^4x\ d^4y\ D_{\mu\nu}(x, M_W)\ \langle F\ |T[\ J_\mu(y+x/2)\ J^\dagger_\nu(y-x/2)]|\ I\ \rangle$ ⟹

$$\langle F \,|\, \mathcal{H}^{\Delta S=1} \,|\, I \rangle = G_F/\sqrt{2}\ V_{ud}\ V_{us}^{*}\ \ \Sigma_i\, C_i(\mu)\ \frac{\langle F \,|\, Q_i(\mu) \,|\, I \rangle}{(M_W)^{di-6}}$$

di= dimension of the operator $Q_i(\mu)$

$C_i(\mu)$ Wilson coefficient: it depends on M_W/μ and $\alpha_W(\mu)$ @NLO

$Q_i(\mu)$ local operator renormalized at the scale μ FROM LATTICE

Without the next-to-leading corrections it is impossible to fix the renormalization scale and to match consistently the Wilson coefficients to the matrix elements of the (lattice) operators (see also citation from Buras *)

Numerical Estimates of Hadronic Masses in a Pure SU(3) Gauge Theory
H. Hamber & *G. Parisi*
Phys.Rev.Lett. 47 (1981) 1792

- Weak Hamiltonian on the Lattice Cabibbo et al. + Gavela et al. + Bernard & Soni
- Construction and renormalization of the Weak Hamiltonian on the Lattice Bochicchio et. al.
- Renormalization of composite operators GM et al.
- $K\pi\pi$ amplitudes on a finite volume Lellouch & Luscher

Leptonic, Semileptonic, $K\pi\pi$, B and K Mixing, Radiative, …

Andrzej J. Buras Gospel *arXiv:1102.5650v4*

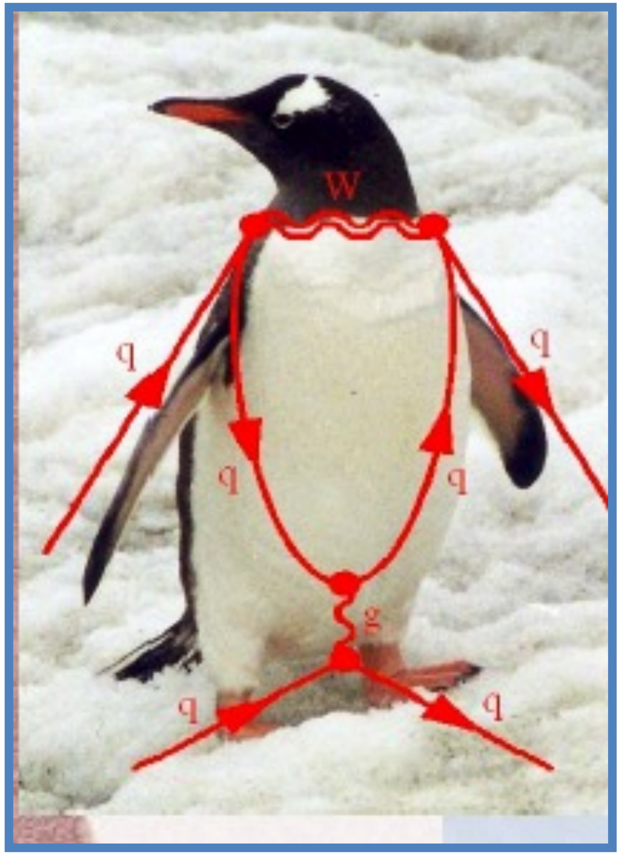
During the last supper of the Ringberg workshop ('88) Guido Martinelli and me realized that it would be important to calculate NLO QCD corrections to the Wilson coefficients of penguin operators relevant for $K \to \pi\pi$ decays

.. NLO QCD corrections to $\Delta S = 1$ and $\Delta B = 1$ non-leptonic decays… $\Delta S = 2$ & $\Delta B = 2$ transitions, rare K and B decays, in particular $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$ and $B_{s,d} \to \mu^+\mu^-$… the inclusive decay $B \to X_s\gamma$, $B \to X_s$ gluon, … $K_L \to \pi^0 \ell^+\ell^-$, $B \to X_s \ell^+\ell^-$…$B \to K^*(\rho)\, \ell^+\ell^-$

several thousands citations

still the road has been opened by Guido Altarelli

The Penguin Era Begins (J. Ellis)



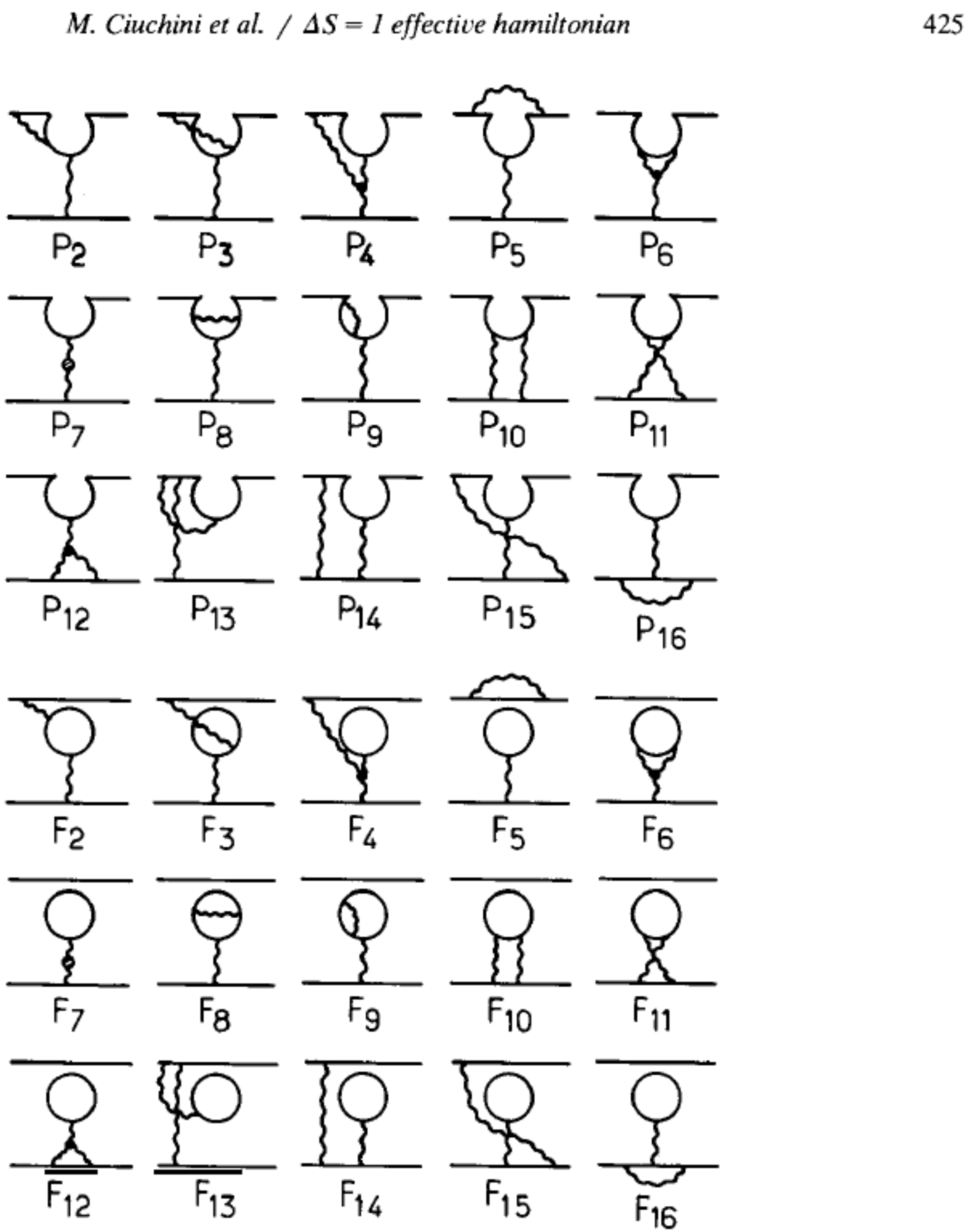


Fig. 11. Penguin diagrams at two loops.

M. Shifman, A.I. Vainshtein, V. I. Zakharov

J. Flynn and L. Randall

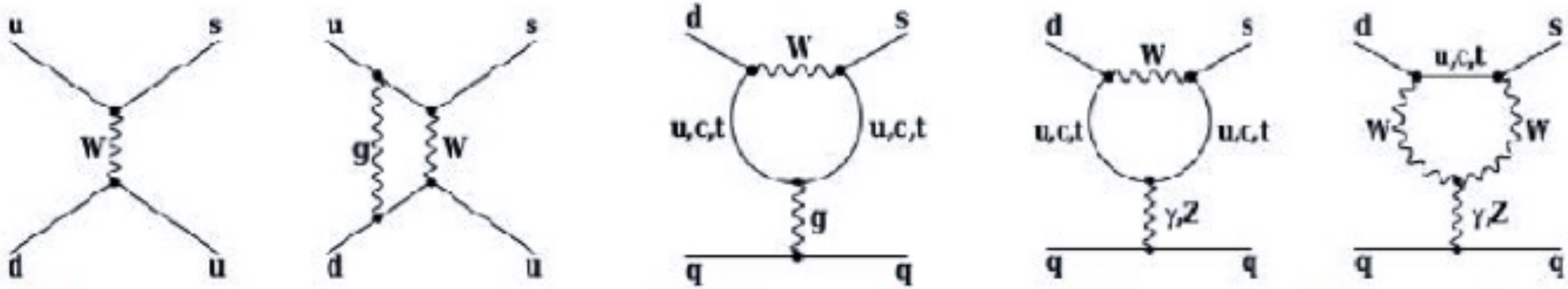
Weak Hamiltonian for $K \to \pi\pi$

Weak Hamiltonian is given by local four-quark operator

Courtesy by Xu Feng

$$\mathcal{H}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[z_i(\mu) + \tau y_i(\mu) \right] Q_i \right\}, \quad \tau = -\frac{V_{td} V_{ts}^*}{V_{ud} V_{us}^*}$$

- $\tau = -\frac{V_{td} V_{ts}^*}{V_{ud} V_{us}^*} = 1.543 + 0.635i$
- $z_i(\mu)$ and $y_i(\mu)$ are perturbative Wilson coefficients
- Q_i are local four-quark operator



Current-current operator
Q_1, Q_2
dominate $\mathrm{Re}[A_0]$, $\mathrm{Re}[A_2]$

QCD penguin
$Q_3 - Q_6$
Q_6 dominate $\mathrm{Im}[A_0]$

Electro-weak penguin
$Q_7 - Q_{10}$
Q_7, Q_8 dominate $\mathrm{Im}[A_2]$

New local four-fermion operators are generated

$Q_1 = (\bar{s}_L{}^A \gamma_\mu u_L{}^B)(\bar{u}_L{}^B \gamma_\mu d_L{}^A)$ Current-Current

$Q_2 = (\bar{s}_L{}^A \gamma_\mu u_L{}^A)(\bar{u}_L{}^B \gamma_\mu d_L{}^B)$

$Q_{3,5} = (\bar{s}_R{}^A \gamma_\mu d_L{}^A) \sum_q (\bar{q}_{L,R}{}^B \gamma_\mu q_{L,R}{}^B)$ Gluon

$Q_{4,6} = (\bar{s}_R{}^A \gamma_\mu d_L{}^B) \sum_q (\bar{q}_{L,R}{}^B \gamma_\mu q_{L,R}{}^A)$ Penguins

$Q_{7,9} = 3/2(\bar{s}_R{}^A \gamma_\mu d_L{}^A) \sum_q e_q (\bar{q}_{R,L}{}^B \gamma_\mu q_{R,L}{}^B)$ Electroweak

$Q_{8,10} = 3/2(\bar{s}_R{}^A \gamma_\mu d_L{}^B) \sum_q e_q (\bar{q}_{R,L}{}^B \gamma_\mu q_{R,L}{}^A)$ Penguins

+ Chromomagnetic end electromagnetic operators

$$\mathcal{A}(K \to \pi\pi) = \sum_i C_W^i(\mu) \langle \pi\pi | O_i(\mu) | K \rangle$$

Final result for ε'

- Combining our new result for Im(A_0) and our 2015 result for Im(A_2), and again using expt. for the real parts, we find

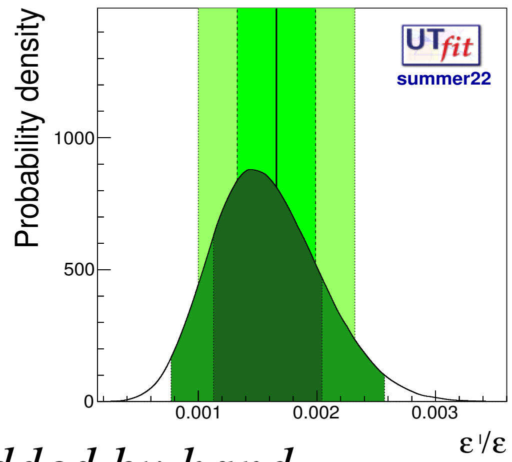
$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= 0.00217(26)(62)(50)$$

stat, sys, IB + EM

Consistent with experimental result:

$$\mathrm{Re}(\epsilon'/\epsilon)_{\mathrm{expt}} = 0.00166(23)$$

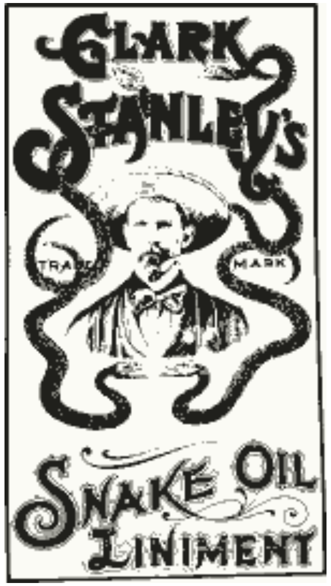


RBC/UKQCD: e'/ e= 16.7 x10^{-4}

Utfit: e'/ e= 15.2(4.7) x10^{-4}

Isospin breaking corretions added by hand

A second group should do this calculation!!



UTfit

www.utfit.org

RELOADED

M.Bona, M. Ciuchini, D. Derkach, R. Di Palma, F. Ferrari, V. Lubicz, G. Martinelli, M. Pierini, L. Silvestrini, S. Simula, A. Stocchi, C. Tarantino, V. Vagnoni, M. Valli, and L.Vittorio

The Unitarity Triangle Analysis

- Flavor-changing processes and CP violation in the SM ruled by 4 parameters in the 3x3 CKM (unitary) matrix

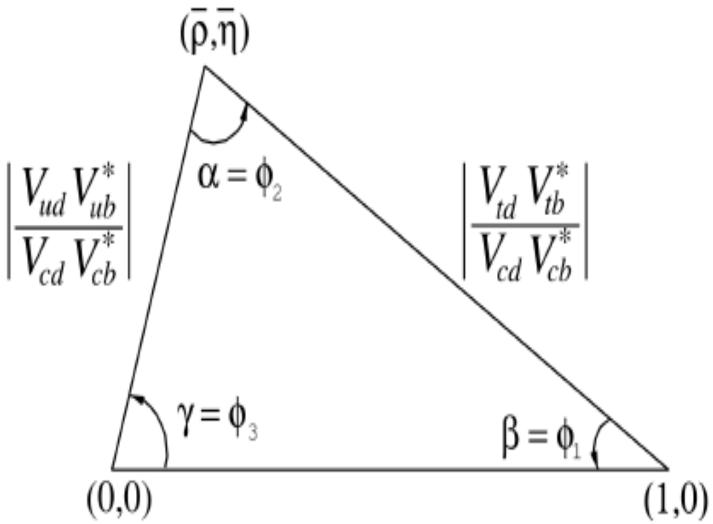
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $A, \lambda, \bar{\rho}$ and $\bar{\eta}$

$$\bar{\rho} = \rho(1-\lambda^2/2+\ldots) \quad \bar{\eta} = \eta(1-\lambda^2/2+\ldots)$$

- Small value sin of Cabibbo angle (λ) makes the CKM matrix close to diagonal

- Unitarity implies relations between elements, that can be represented as a triangle in a plane

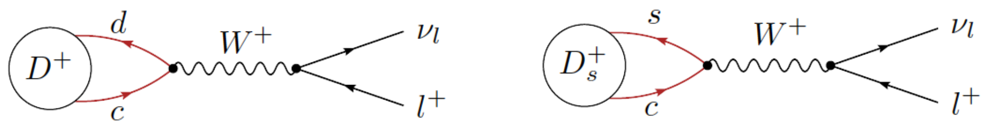


- By determining th
CKM matrix

$\mathrm{Sin}\ \theta_{12} = \lambda$
$\mathrm{Sin}\ \theta_{23} = A\ \lambda^2$
$\mathrm{Sin}\ \theta_{13} = A\ \lambda^3(\rho\text{-}i\ \eta)$

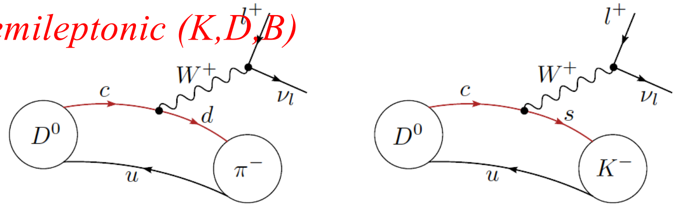
$$\delta_{13} = \gamma = \phi_3$$

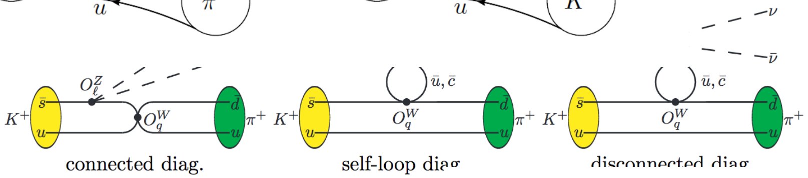
Leptonic (π,K,D,B)

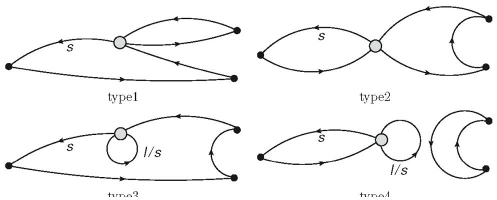


Non-leptonic
but only below the inelastic threshold (may be also 3 body decays) *now changing*

Semileptonic (K,D,B)

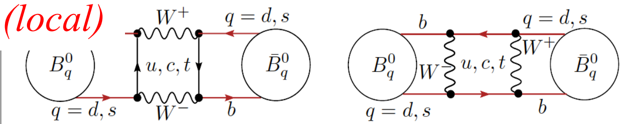






B -> ππ,Kπ, etc. *No-> maybe !*

Neutral meson mixing (local)

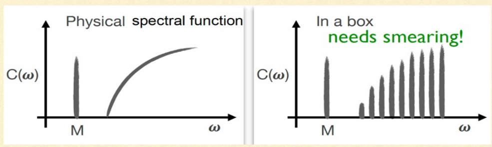


(some) Radiative and Rare *long distance effects*
(also K -> π l⁺l⁻)

INCLUSIVE DECAYS ON THE LATTICE

Inclusive processes impractical to treat directly on the lattice. Vacuum current correlators computed in euclidean space-time are related to $e^+e^- \to$ hadrons or τ decay via analyticity. In our case the correlators have to be computed in the B meson, but analytic continuation more complicated: two cuts, decay occurs only on a portion of the physical cut.

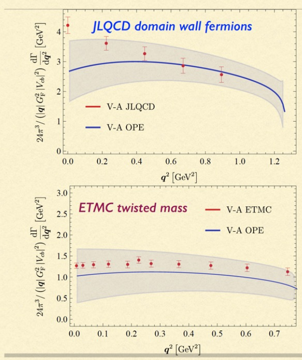
While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing
Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



W. Jay @Snowmass workshop

PG, Hashimoto, Maechler, Panero, Sanfilippo, Simula, Smecca, Tantalo, 2

LATTICE VS OPE



m_b^{kin} (JLQCD)	2.70 ± 0.04
$\overline{m}_c(2\text{ GeV})$ (JLQCD)	1.10 ± 0.02
m_b^{kin} (ETMC)	2.39 ± 0.08
$\overline{m}_c(2\text{ GeV})$ (ETMC)	1.19 ± 0.04
μ_π^2	0.57 ± 0.15
ρ_D^3	0.22 ± 0.06
$\mu_G^2(m_b)$	0.37 ± 0.10
ρ_{LS}^3	-0.13 ± 0.10
$\alpha_s^{(4)}(2\text{ GeV})$	0.301 ± 0.006

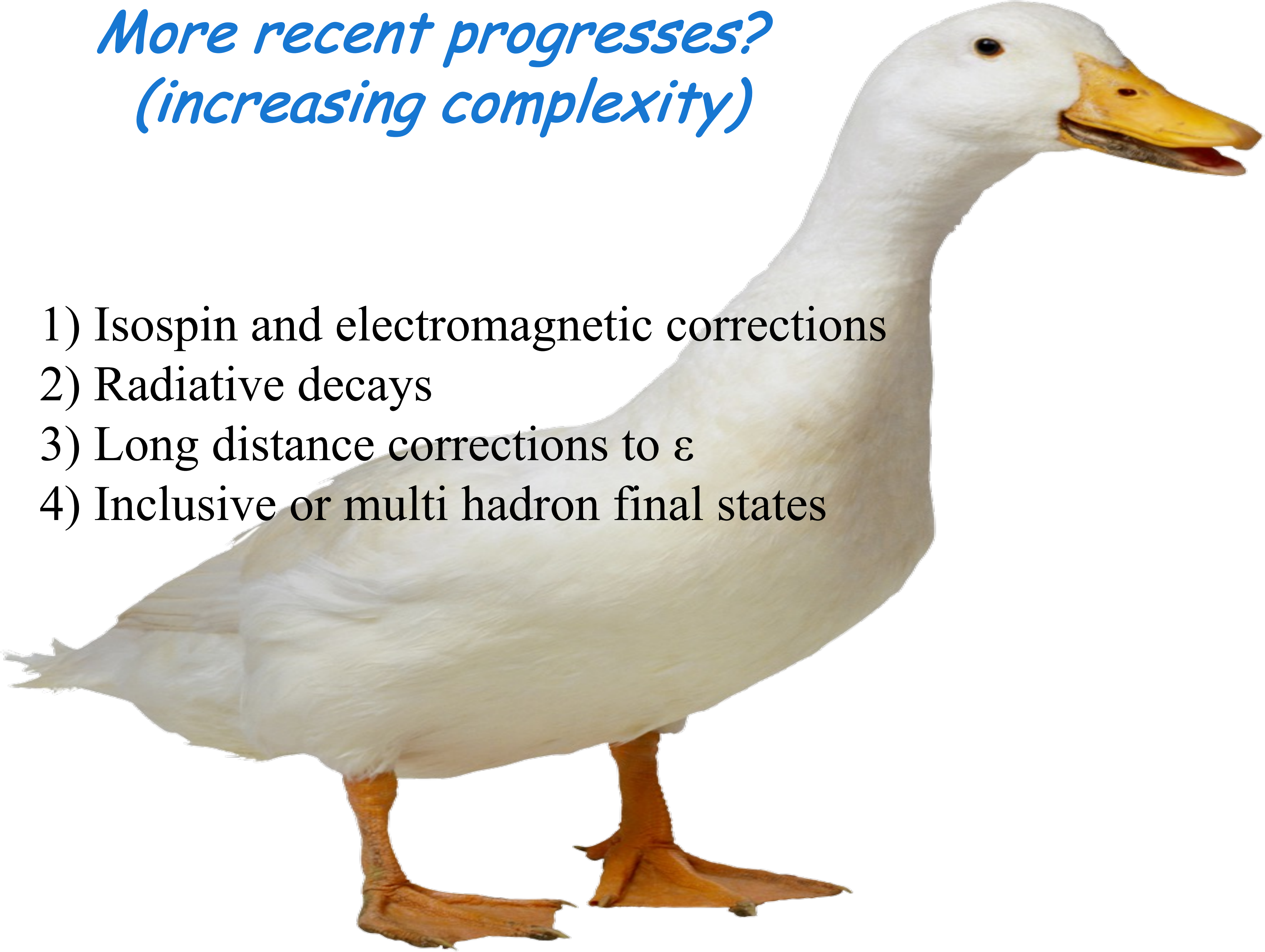
OPE inputs from fits to exp data (physical m_b), HQE of meson masses on lattice
1704.06105, J.Phys.Conf.Ser. 1137 (2019) 1, 012005

We include $O(1/m_b^3)$ and $O(\alpha_s)$ terms
Hard scale $\sqrt{m_c^2 + \mathbf{q}^2} \sim 1 - 1.5\,\text{GeV}$
We do not expect OPE to work at high $|\mathbf{q}|$

Twisted boundary conditions allow for any value of $\vec{q}^2$
Smaller statistical uncertainties

What can be computed and
What cannot be computed

More recent progresses? (increasing complexity)



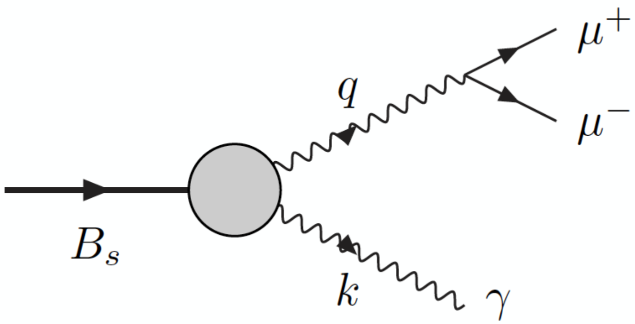
1) Isospin and electromagnetic corrections
2) Radiative decays
3) Long distance corrections to ε
4) Inclusive or multi hadron final states

small q^2 in the future

The $B_s \to \mu^+\mu^-\gamma$ Decay Rate at Large q^2

R.Frezzotti, **G.Gagliardi,** V.Lubicz, G.Martinelli, CTS, F.Sanfilippo, S.Simula, N.Tantalo, arXiv:2402.03262

- I use this interesting FCNC process to illustrate the elements which we are able to compute and to highlight the important theoretical issues which we are still working to resolve.
  - Preview: We can compute the dominant contribution, but are working to solve the problems which will enable an improved precision.



$x_\gamma = \frac{2E_\gamma}{m_{B_s}}$, E_γ is the energy of the real photon in rest frame of the B_s meson.

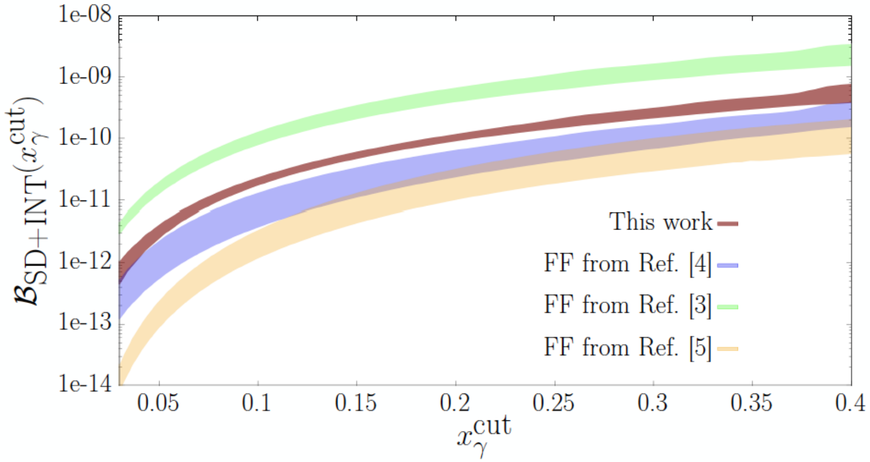
$$q^2 = m_{B_s}^2(1 - x_\gamma), \qquad 0 \le x_\gamma \le 1 - \frac{4m_\mu^2}{m_{B_s}^2}$$

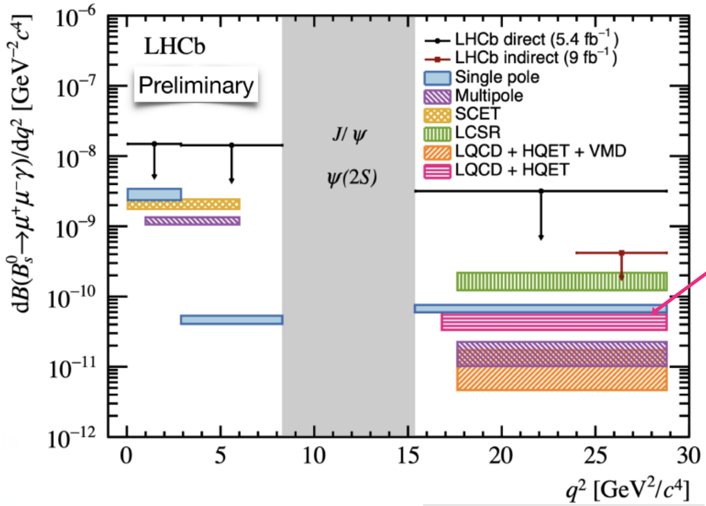
- LHCb: $B(B_s \to \mu^+\mu^-\gamma)|_{\sqrt{q^2}>4.9\,\mathrm{GeV}} < 2.0 \times 10^{-9}$, arXiv:2108.09283/4

Courtesy of C.T. Sachrajda

Comparison

Theoretical progresses:
First lattice calculation by the Rome-Southampton Collaboration G. Gagliardi et al. (2402.03262)





Ref.[3] = T.Janowski, B.Pullin and R.Zwicky, arXiv:2106.13616, LCSR

Ref.[4]= A.Kozachuk, D.Melikhov and N.Nikitin, arXiv:1712.07926, relativistic dispersion relations

Ref.[5]= D.Guadagnoli, C.Normand, S.Simula and L.Vittorio, arXiv:2303.02174, VMD+quark model+lattice at charm

Discrepancy persists since rate dominated by F_V

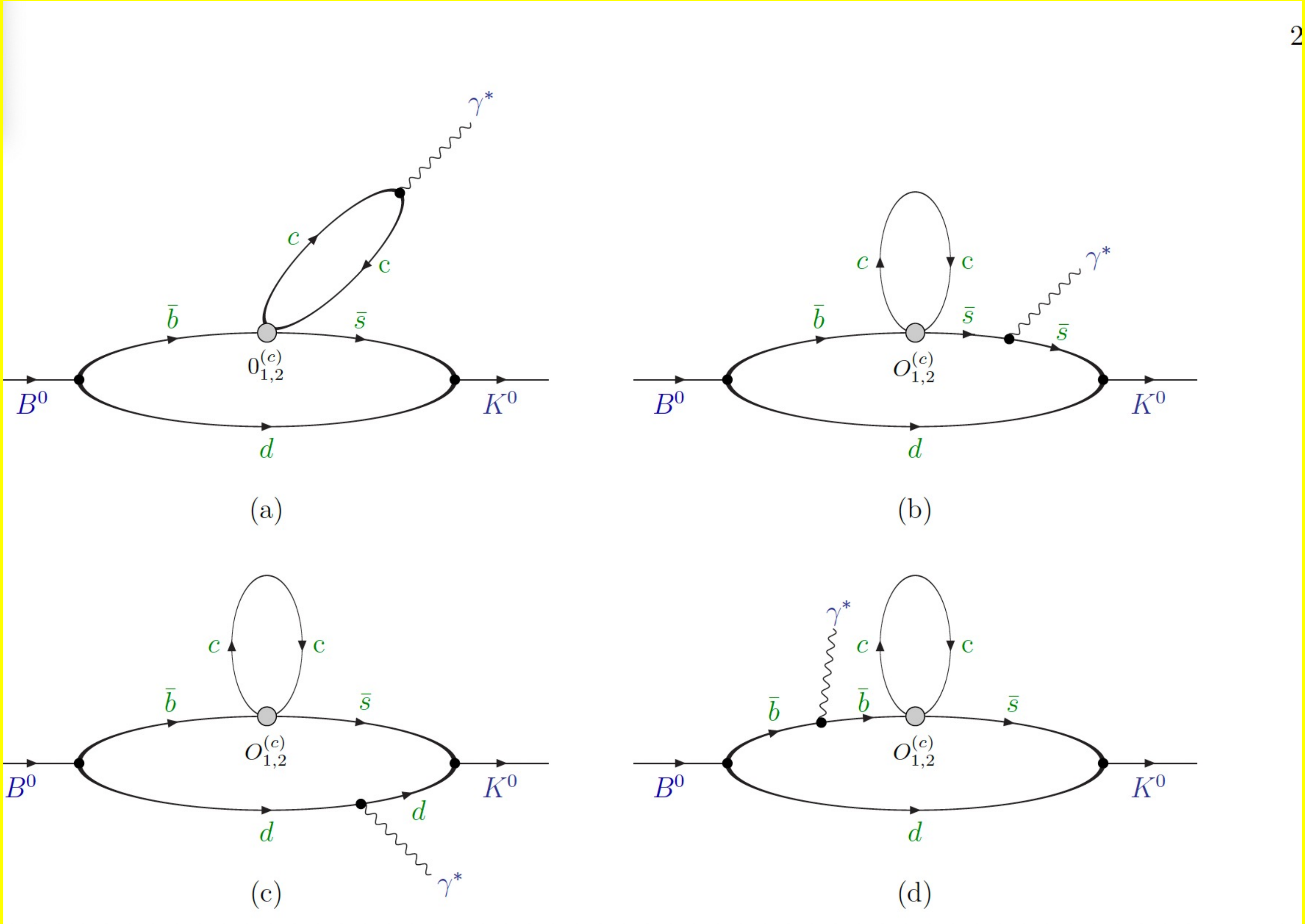
- New LHCb update with direct detection of final state photon.

I.Bachiller, La Thuile 2024
LHCb, 2404.07648

- For $q^2 > 15$ GeV^2 the bound is about an order of magnitude higher than before.

From the May/June 2024 issue of the Cern Courier

Charming Penguins Diagrams
(previously neglected)



Theoretical framework for lattice QCD computations of $B \to K\ell^+\ell^-$ and $\bar{B}_s \to \ell^+\ell^-\gamma$ decays rates, including contributions from "Charming Penguins"

Roberto Frezzotti (Rome U., Tor Vergata and INFN, Rome2), Nazario Tantalo (Rome U., Tor Vergata and INFN, Rome2), Giuseppe Gagliardi (Rome III U. and INFN, Rome3), Vittorio Lubicz (Rome III U. and INFN, Rome3), Guido Martinelli (INFN, Rome and U. Rom La Sapienza (main)) et al. (Aug 5, 2025)

e-Print: 2508.03655 [hep-lat]

The amplitude can be computed

34

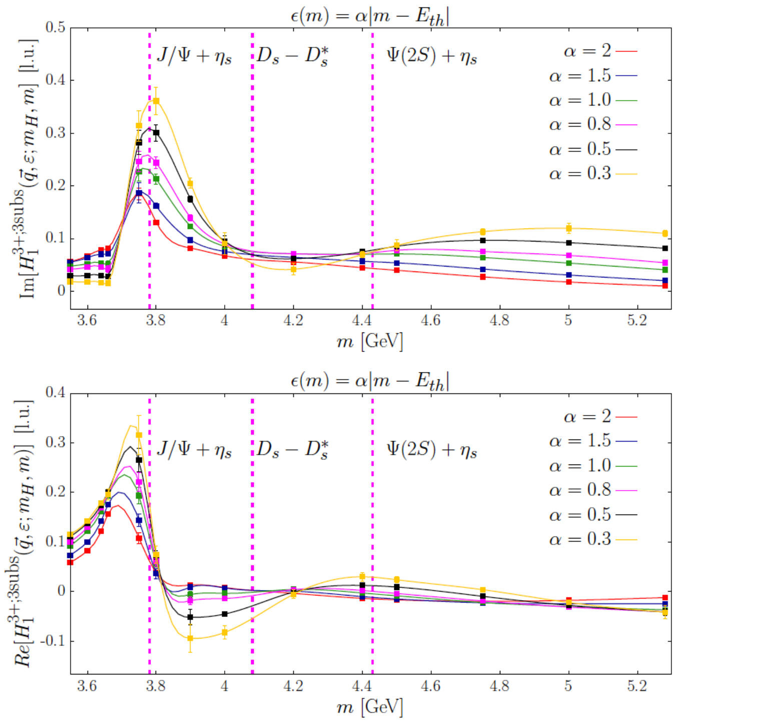


FIG. 12: The real (bottom) and imaginary (top) part of the smeared amplitude $H_1^{3+;3\mathrm{subs}}(\vec{q}, \varepsilon; m_H, m)$, as a function of m, for some of the simulated values of α in Eq. (140). The continuous lines correspond to spline interpolations of the lattice data.

We are working on

$$B \to K^*\mu^+\mu^- \to K\pi\mu^+\mu^-$$

Uppsala, July 1, 1987

Schubert

SUMMARY & PERSPECTIVE

G. ALTARELLI

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$= \begin{pmatrix} c_\theta c_\beta & s_\theta c_\beta & s_\beta e^{-i\delta} \\ -s_\theta c_\gamma - c_\theta s_\beta s_\gamma e^{i\delta} & c_\theta c_\gamma - s_\theta s_\beta s_\gamma e^{i\delta} & c_\beta s_\gamma \\ s_\theta s_\gamma - c_\theta s_\beta c_\gamma e^{i\delta} & -c_\theta s_\gamma - s_\theta s_\beta c_\gamma e^{i\delta} & c_\beta c_\gamma \end{pmatrix}$$

$$V = \begin{pmatrix} .9754 \pm .0004 & .2206 \pm .0018 & .0000 \pm .0076 \\ -.2203 \pm .0019 & .9743 \pm .0005 & .0474 \pm .0066 \\ .0104 \pm .0075 & -.0462 \pm .0067 & .9989 \pm .0003 \end{pmatrix}$$

$$+ i \begin{pmatrix} 0 & 0 & 0 \pm .0076 \\ 0 \pm .0004 & 0 \pm .0001 & 0 \\ 0 \pm .0075 & 0 \pm .0017 & 0 \end{pmatrix}$$

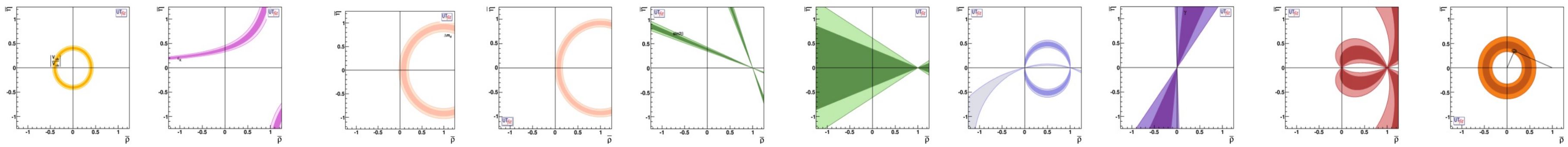
$\theta = (12.74 \pm 0.11)^\circ$ $\beta = (0 \pm 0.43)^\circ$

$\gamma = (2.72 \pm 0.38)^\circ$

$\left|\frac{V_{ub}}{V_{cb}}\right| < 0.20$ 90% CLEO.

CKM December 2022

$$\begin{pmatrix} 0.97431(19) & 0.22517(81) & 0.003715(93)\,e^{-i(65.1(1.3))^o} \\ -0.22503(83)\,e^{+i(0.0351(1))^o} & 0.97345(20)\,e^{-i(0.00187(5))^o} & 0.0420(5) \\ 0.00859(11)\,e^{-i(22.4(7))^o} & -0.04128(46)\,e^{+i(1.05(3))^o} & 0.999111(20) \end{pmatrix}$$

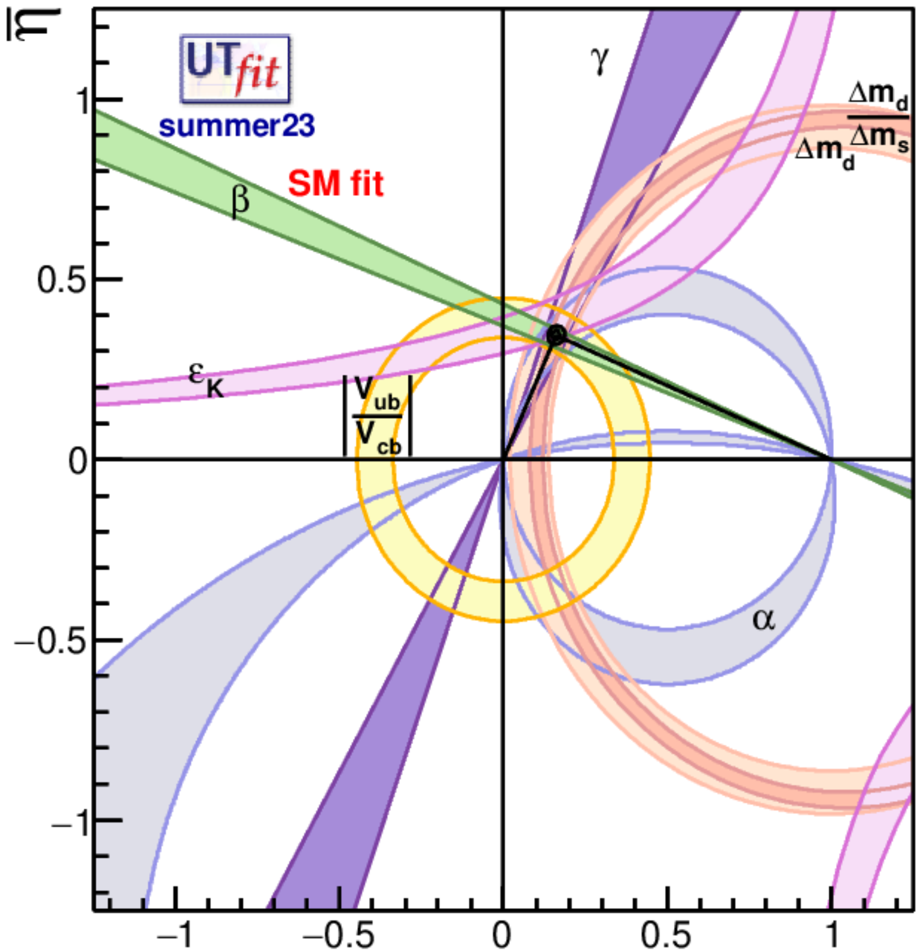


2023 results

$\bar{\rho} = 0.160 \pm 0.009 \quad \bar{\eta} = 0.345 \pm 0.011$

To be updated

In the hadronic sector, the SM CKM pattern represents the principal part of the flavor structure and of CP violation



$\alpha = (92.4 \pm 1.4)^0$

$\sin 2\beta = 0.703 \pm 0.014$

$\beta = (22.46 \pm 0.68)^0$

$\gamma = (65.1 \pm 1.3)^0$

$A = 0.828 \pm 0.011$

$\lambda = 0.22519 \pm 0.00083$

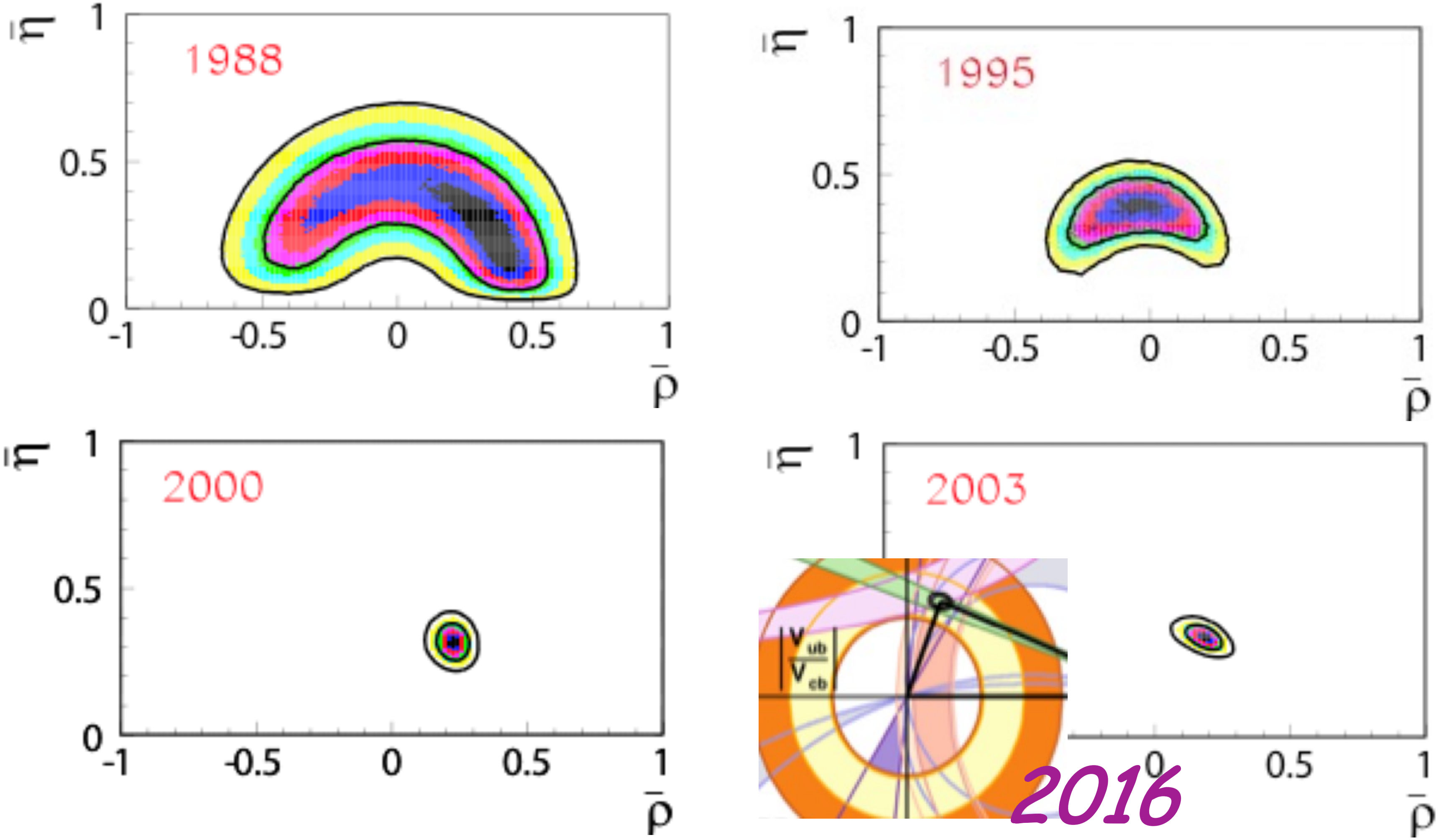
2022

Consistence on an over constrained fit of the CKM parameters

CKM matrix is the dominant source of flavour mixing and CP violation

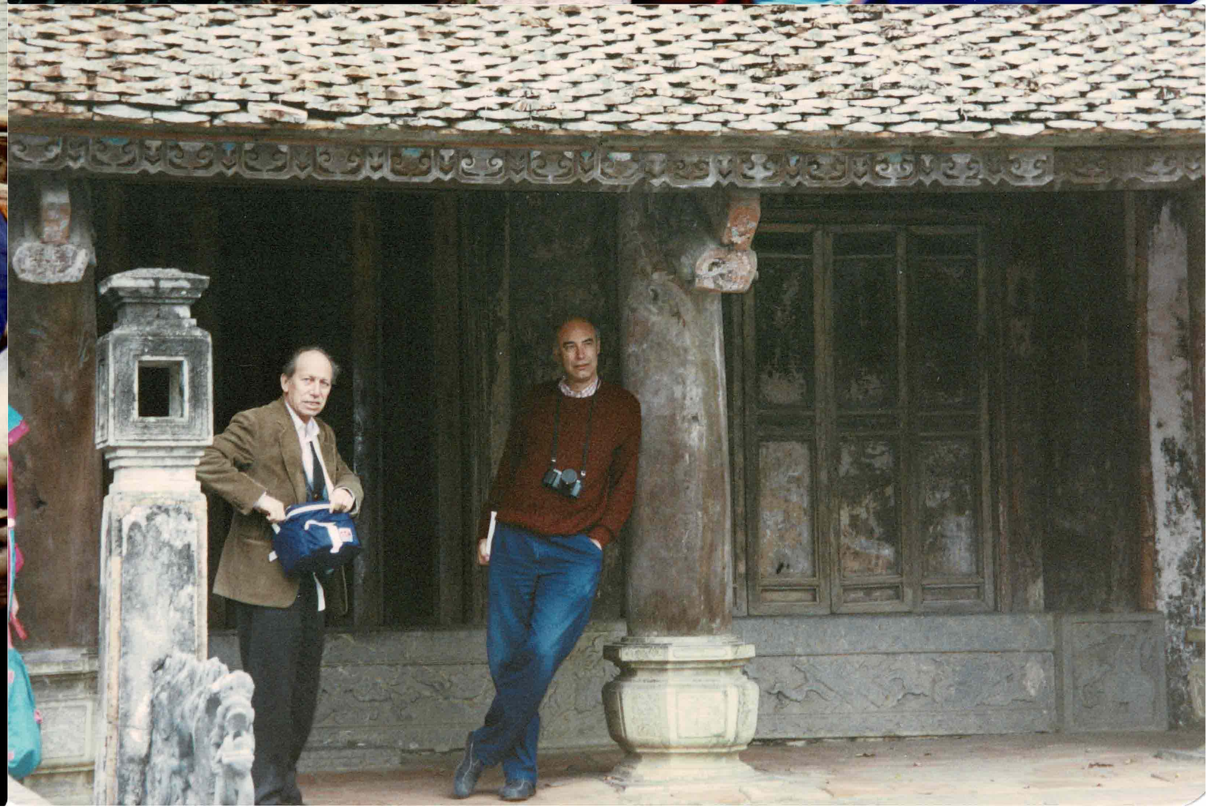
PROGRESS SINCE 1988

Experimental progress so impressive that we can fit the hadronic matrix elements (in the SM)




Caravan

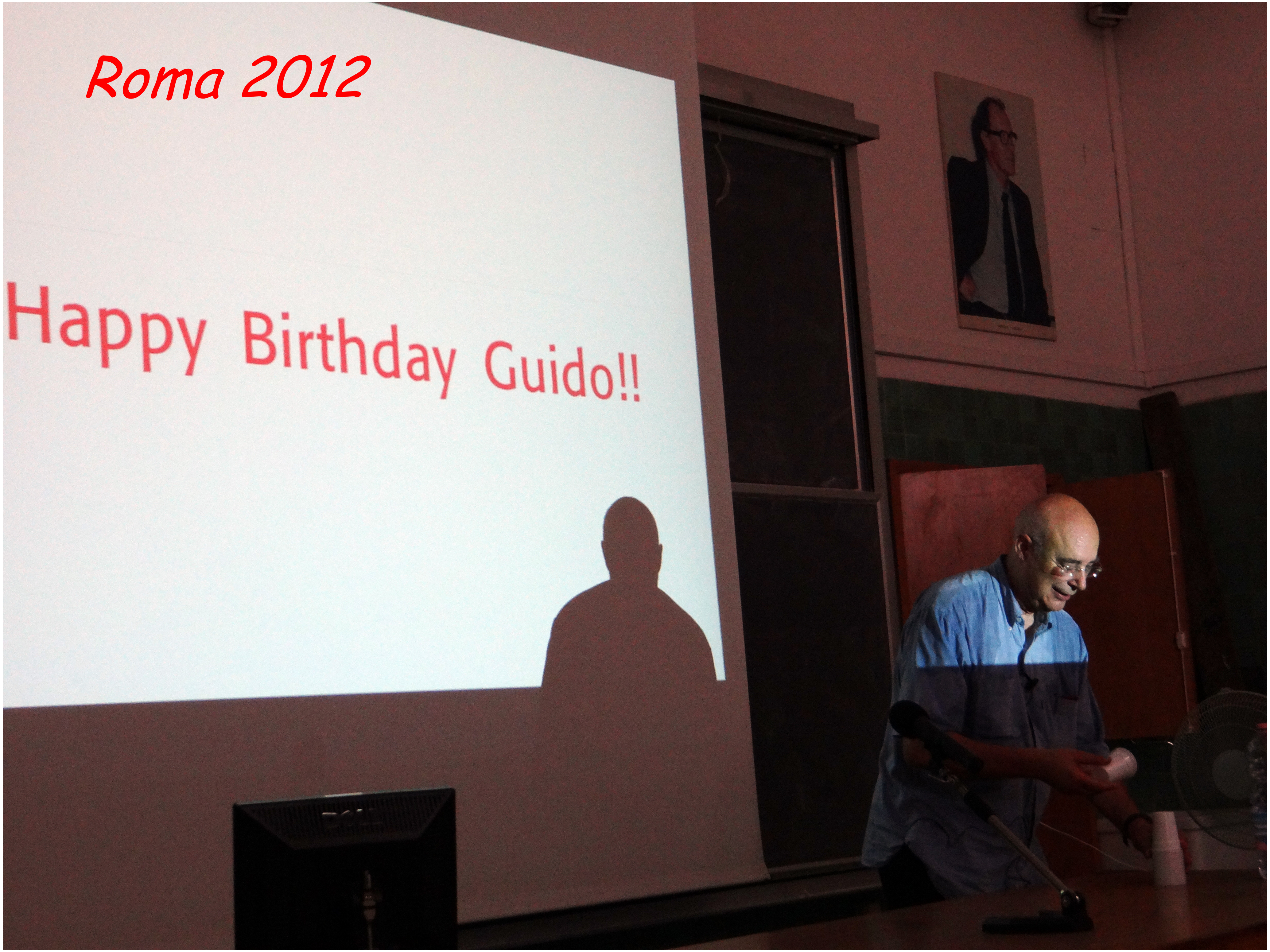




This is my last paper with Guido

1. **Failure of local duality in inclusive nonleptonic heavy flavor decays**
Guido Altarelli (CERN & Rome III U.), G. Martinelli, S. Petrarca, F. Rapuano (Rome U. & INFN, Rome). Mar 1996. 9 pp.
Published in **Phys.Lett. B382 (1996) 409-414**
CERN-TH-96-77, ROME1-1143-96
DOI: 10.1016/0370-2693(96)00637-5
e-Print: **hep-ph/9604202** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
Detailed record - Cited by 62 records 50+

but our friendship continued untouched ….


Roma 2012
Happy Birthday Guido!!

Qui Nhon, Vietnam, 12 August '13

Theoretical Implications of the LHC Results

Guido Altarelli
Roma Tre/CERN


CIENCE ET D'EDUCATION INTERDISCIPLINAIRES
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LỄ KHÁNH THÀNH TRUNG TÂM QUỐC TẾ KHOA HỌC VÀ GIÁO DỤC LIÊN NGÀNH



LHC 7-8 TeV

A great triumph: the 126 GeV Higgs discovery

A particle apparently just as predicted by the SM theory

The main missing block for the experimental validation of the SM is now in place

A negative surprise: no production of new particles, no evidence of new physics

Not at ATLAS&CMS
Not in HF decays (LHCb, ... B-factories)
Not in $\mu \to e\gamma$ (MEG),.... Perhaps a deviation in $(g-2)_\mu$?


Singapore 2014

Chi ha avuto il privilegio di collaborare con Guido o semplicemente di conoscerlo continuerà a ricordarlo con ammirazione e rispetto. Noi, che di Guido siamo stati amici e gli abbiamo voluto bene, non lo abbiamo dimenticato e oggi onorariamo la sua memoria

THANKS FOR YOUR ATTENTION

UTfit

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Istituto Nazionale di Fisica Nucleare