Fisica Teorica del Sapore all'INFN tra passato, presente e futuro

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INFN - Bari

November 4th 2022

Flavour Physics

What is flavour Physics?

- 3 fermion generations
- replicae of each other
- feel the forces in the same way (same quantum numbers)
- different masses and mixings

The Yukawa sector of the Standard Model

- Generation of the masses through the Higgs mechanism
- Yukawa matrices diagonalized
- Mixing of down-type quarks: CKM matrix
- Flavour violation only in charged current interactions

Properties and consequences

- CKM unitary and complex→3 angles and 1 phase→ CP violation
- Hierarchical structure of its elements
- Flavour changing Neutral Currents suppressed

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How did we learn all that?

Flavour Physics

- Past

The fascinating history of a path that led to the **Standard Model**
full of successes but with many unanswered questions

The italian contribution

- has shaped the field
- has written the particle physics textbooks
- has dictated how it must be learnt

- Present

The attempt to answer the questions + hints of deviations from SM
(*anomalies, tensions*)
→ intense search for extensions of the SM (**BSM**)
new particles, new interactions

- Future

Perspectives

INFN physicists are major players

Flavour Physics: direct vs indirect searches complementarity

direct searches at colliders

- New particles directly produced on-shell
- Identified through their decay modes

Exp: push the collider energy as much as possible

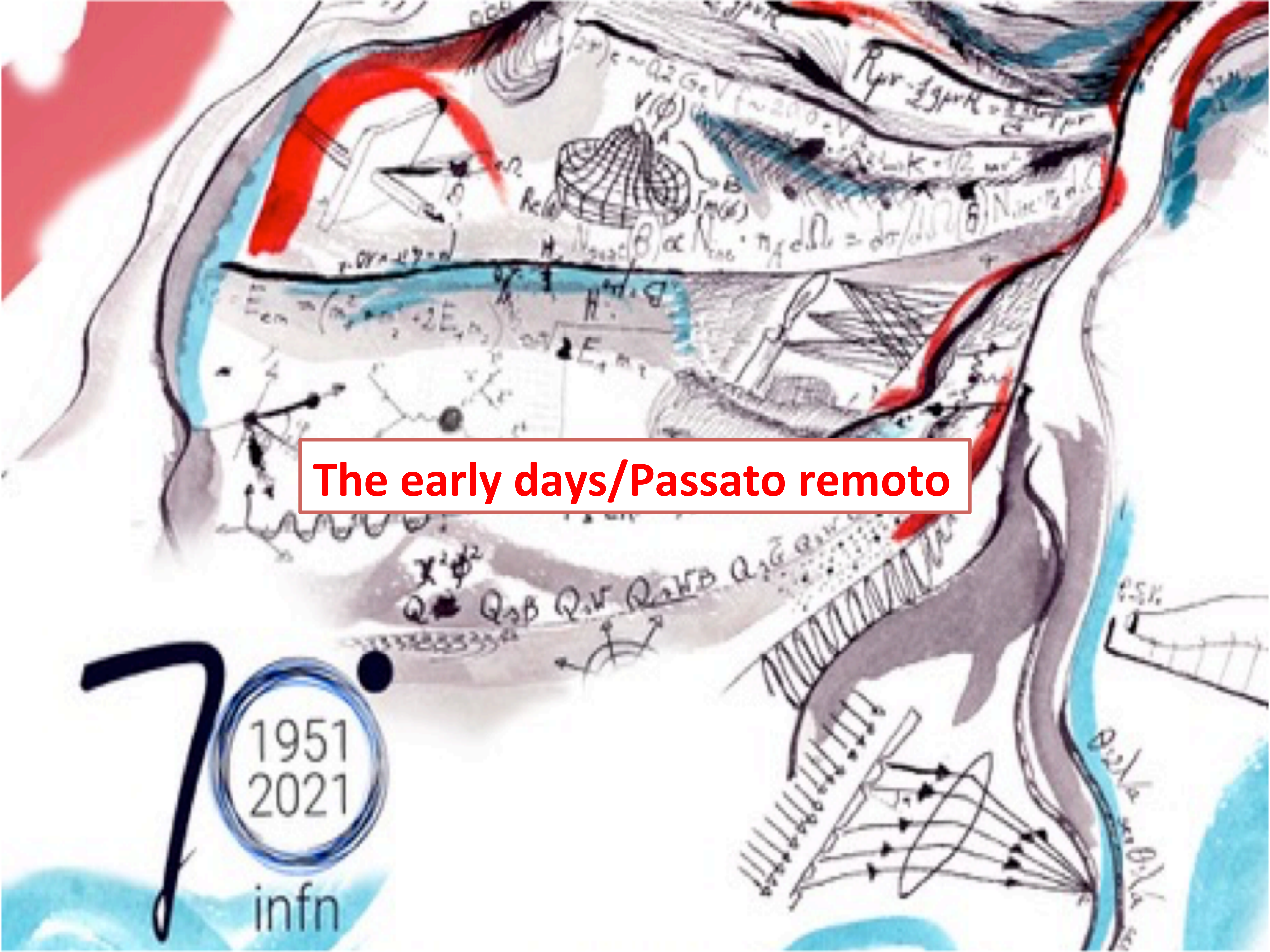
searches through quantum effects

- New particles contribute as virtual states
- Deviations from SM predictions can emerge
- Might be sensitive to large mass scales (e.g. new massive mediators)

Exp: Push the intensity as much as possible

- the appearance of anomalies requires a suitable BSM interpretation
- Quark flavour physics: QCD enters the game.
  Role of the non perturbative sector of QCD and related uncertainties

Th: Push the precision as much as possible



The early days/Passato remoto

Passato remoto

The giants in our history

Passato remoto

- 1944-1945

Conversi Pancini Piccioni:

experiments looking for the *mesotrone* in cosmic rays supposed to be the Yukawa particle, mediator of nuclear interactions

Fermi Teller Weisskopft: the identification is wrong

→The muon was discovered

$$\boxed{\mu \neq e}$$

Passato remoto

- 1944-1945

Conversi Pancini Piccioni:

- The early days of weak interactions

Fermi:

β decay of the neutron: neutrino predicted (Pauli)

Fermi: $n \rightarrow p\, e\, \underline{\nu}$ governed by G_β

μ decay $\rightarrow$ analogous description with coupling G_μ

$$\boxed{\mu \neq e}$$

$$\boxed{G_\mu \simeq G_\beta}$$

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Passato remoto

- 1944-1945

Conversi Pancini Piccioni:

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Fermi:

- 1947-1948

Pontecorvo Puppi:

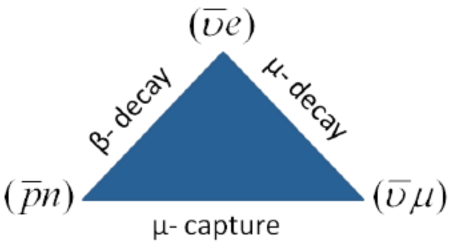
the underlying interaction is the same

→ universality of weak interactions

1958 Feynman and Gell-Mann postulate universality similar to the em interaction

$$\boxed{\mu \neq e}$$

$$\boxed{G_\mu \simeq G_\beta}$$



Puppi Triangle

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a different strenght:

the first flavour anomaly!

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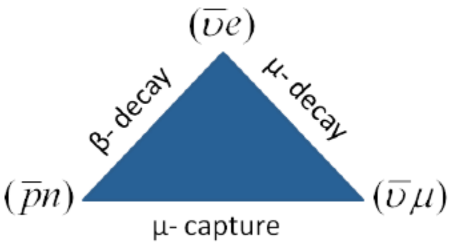
$$\boxed{G_\mu \simeq G_\beta}$$



Puppi Triangle

$$G_\beta \simeq G_\mu$$

$$G_\Lambda \neq G_\mu$$

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Passato remoto

- 1963 Cabibbo angle (only u,d,s quarks known at that time)

suppression of $s \to u$ vs $d \to u$ quark transitions
Cabibbo: in weak interactions *s* and *d* quarks take part «mixed»

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo

Our main hypothesis is that the weak current J_μ (vector + axial) of strongly interacting particles transforms as a member of an octet of SU_3, and is coupled to the leptons with universal strength G. It follows that

$\Delta S=0$ $\Delta S=1$

$$J_\mu = \cos\theta\,(j_\mu^{(o)} + g_\mu^{(o)}) + \sin\theta\,(j_\mu^{(1)} + g_\mu^{(1)})$$

where $j_\mu^{(o)}$ and $j_\mu^{(1)}$ are the two $\Delta Q = 1$ members of an octet of vector currents (with $\Delta S = 0$ and $\Delta S = 1$ respectively) $j_\mu^{(o)}$ and $j_\mu^{(1)}$ the corresponding members of an octet of axial currents.

If θ is small
$\Delta S=1$ are suppressed by $\sin\theta$

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The angle θ can be determined from a comparison of the $K \to \mu\nu$ and $\pi \to \mu\nu$ rates, or from a comparison of $K^+ \to \pi^0 e^+ \nu$ and $\pi^+ \to \pi^0 e^+ \nu$. It is a success of the scheme that the two independent determinations (the first from an axial, the second from a vector transition) coincide within the experimental errors; we get $\theta = 0.26$.

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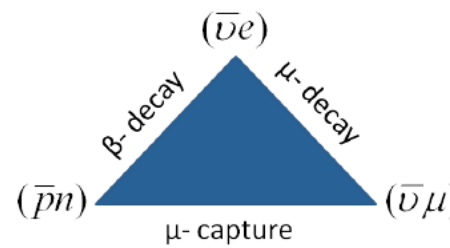
- Solution to the anomaly

- $G_\mu = G_F$ in μ decay
- $G_\beta = G_F$ *cos* θ in neutron decay (slight remodulation)
- $G_\Lambda = G_F$ *sin* θ in hyperon decay (large reduction)

$$\mu \neq e$$

$$G_\mu \simeq G_\beta$$



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- Resulting theory for β decays

Lagrangian density with

- universal coupling G_F
- product of a lepton current and a hadronic current

V-A
Salam, Landau, Lee,Yang

V-A
Feynman, Gell-Mann
Marshak, Sudarshan   Theis

$$\boxed{\mu \neq e}$$

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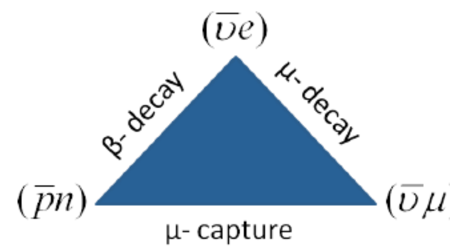

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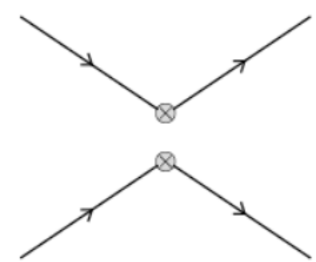

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- V-A theory experimentally confirmed

- Charged current in the SM keeps the same structure

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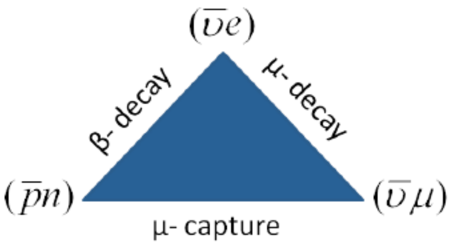

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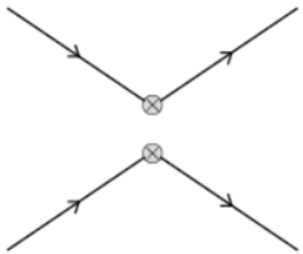

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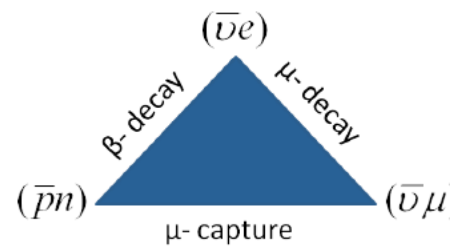

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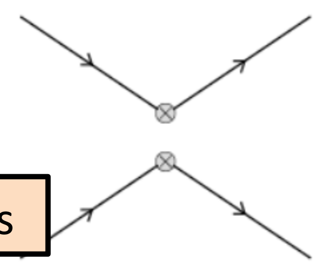

- TODAY: we look for a SM extension possibly containing other structures

Passato remoto

- 1970 GIM mechanism

Glashow Iliopoulos Maiani:

FCNC – flavour changing neutral currents suppressed

- suppression as the result of a cancellation
- another quark (charm) predicted
- quarks in doublets

$$\mathcal{B}(K^+ \to \mu^+ \nu_\mu) = (63.56 \pm 0.11)\%$$

$$\mathcal{B}(K_L \to \mu^+ \mu^-) = (6.84 \pm 0.11) \times 10^{-9}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

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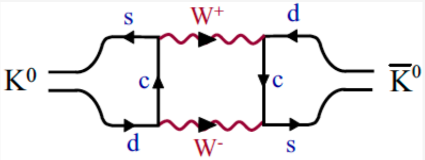
- 1974

M.K. Gaillard and B.W. Lee



studies of **rare** K decays and K^0-$\underline{K}^0$ mixing predict m_c

$$\boxed{m_c \simeq 1.5 \ \ \mathrm{GeV}}$$

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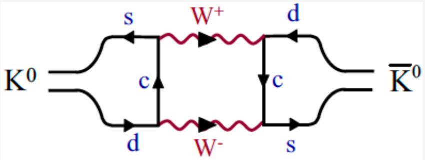

- 1974 prediction verified

J/ψ discovery

November revolution

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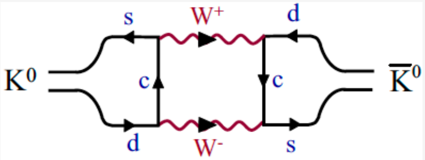

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lesson:

- Importance of rare processes
- Low energy processes can give information about new particles before their actual discovery

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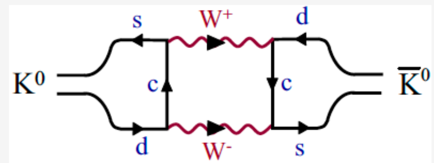

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Pontecorvo:

hypothesis of two neutrinos

Experiment: Fidecaro (CERN) stringent limits on muon decay without neutrino emission

1960 Conversi 1960 (Rubbia in the Collab.) strengthens the bound

$$\nu_\mu \neq \nu_e$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

Passato remoto

- 1952

Bruno Touschek

first ideator of a collider with e^+ e^- circulating in the same ring (AdA)

Passato remoto

- 1952

Bruno Touschek

- 1969

Adone starts data taking with 1.5 GeV energy per beam

Raoul Gatto and Nicola Cabibbo write *La Bibbia*

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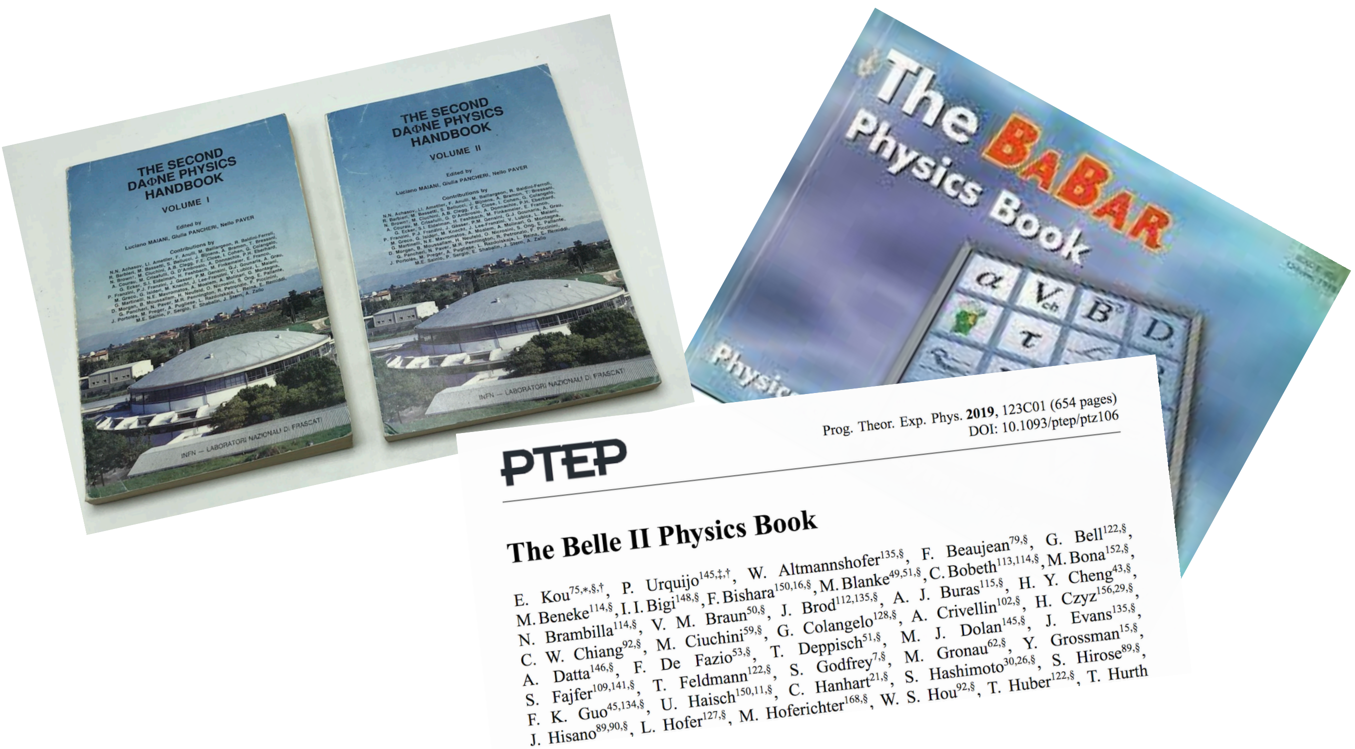

Passato remoto

- 1952

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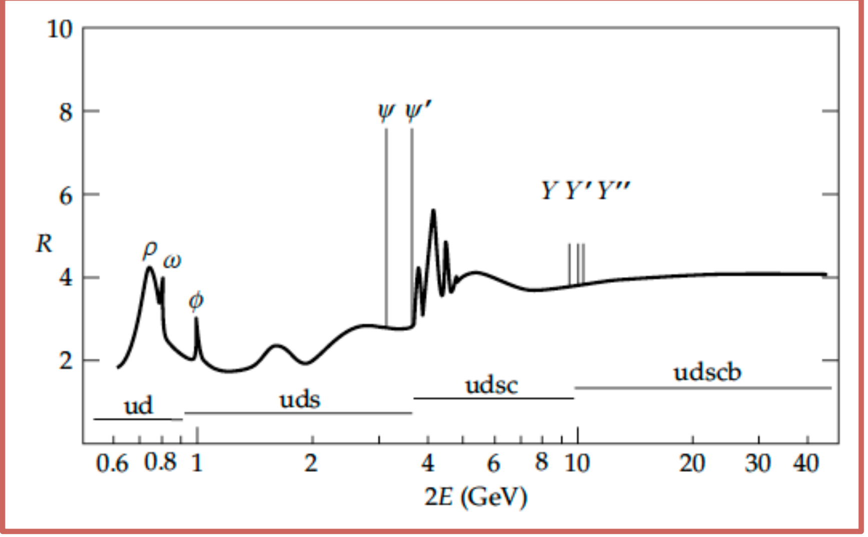
- 1969

Adone starts data taking with 1.5 GeV energy per beam

- Adone finds unexpected

$$R^{th} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq \frac{2}{3} \qquad R^{exp} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq 2$$

- ➢ colour quantum number
- ➢ towards the 3 generation picture: increasing √s → evidence of b quark some years later



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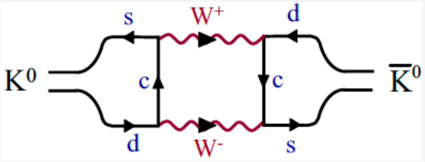

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In SM the suppression of FCNC is due to

- unitarity of CKM generalizing Cabibbo ansatz and GIM
- universality of W, Z couplings to the 3 families

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Near past/Passato prossimo

Passato prossimo

Glashow Weinberg Salam model
A number of parameters not predicted
Fermion masses and mixings, gauge couplings, Higgs potential parameters

Quark mixing matrix
V_{CKM}

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Lepton mixing matrix
V_{PMNS}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

basic questions:

- why 3 generations
- hierarchy among the fermion masses
- structure of the mixing matrices
- values of the parameters

Passato prossimo/presente

Determining CKM elements
goes together with the question: is the SM description of CP violation adequate?

Wolfenstein parametrization

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

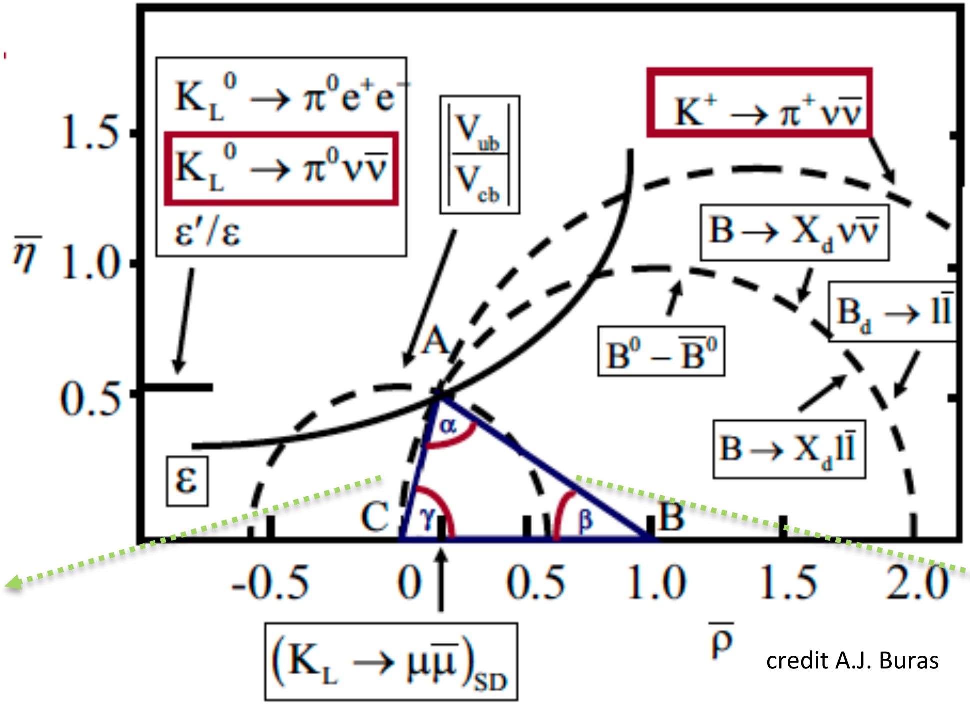
- 4 parameters A, λ, ρ, η
- hierarchical structure: expansion in λ approx *sin* θ_c
- 1 complex phase η the only source of CPV in SM
- sensitivity to the complex phase → third family
- unitarity leads to several relations → unitarity triangles

Passato prossimo/presente

Determining CKM elements
Consistency of all the results: unitarity triangle

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$$



credit A.J. Buras

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

$$V_{td} = |V_{td}|e^{-i\beta}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Passato prossimo/presente

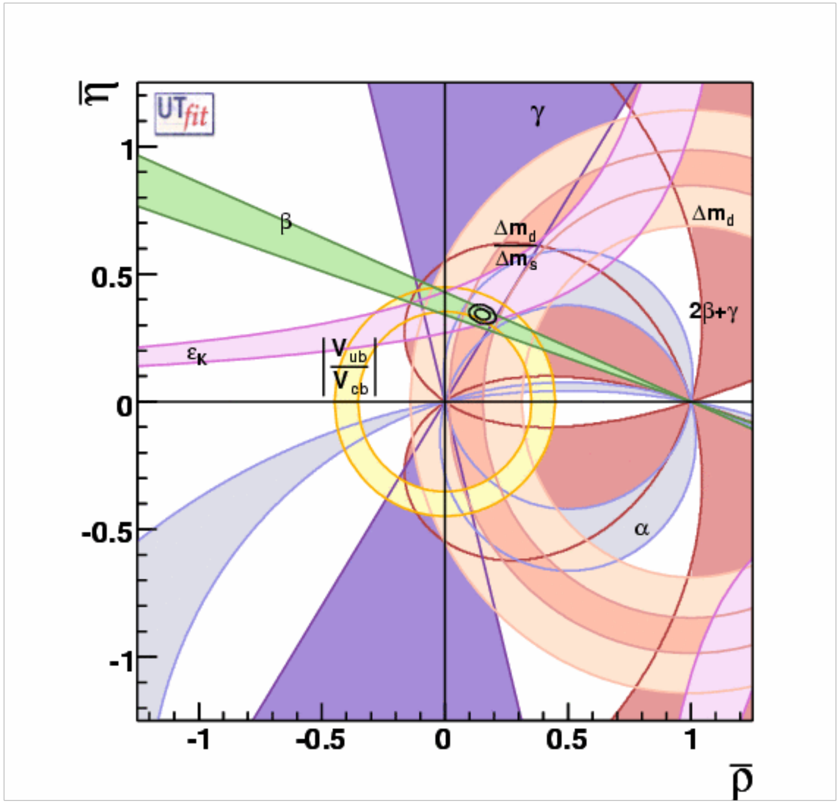
Determining CKM elements
Consistency of all the results: unitarity triangle

Combine all available measurements of **CP violation** and **rare decays** in the flavour sector into a **global Unitarity Triangle fit**

Check the validity of the **CKM mechanism** in the Standard Model and determine accurately the **parameters of the CKM matrix**

Look for **indirect effects of New Physics** and put stringent bounds on relevant **New Physics parameters**

Compare the values of **hadronic parameters** obtained from the Unitarity Triangle fits with theoretical predictions from **Lattice QCD**



UTfit: joint effort of TH & EXP
an Italian project

Passato prossimo/presente

Challenge: processes involve hadrons – QCD enters the game

- OPE +RGE
  - separate SD from LD
  - effective Hamiltonian (like Fermi):
  - resum large logs in the C_i using RGE

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu) O_i$$

Wilson coefficients

local operators

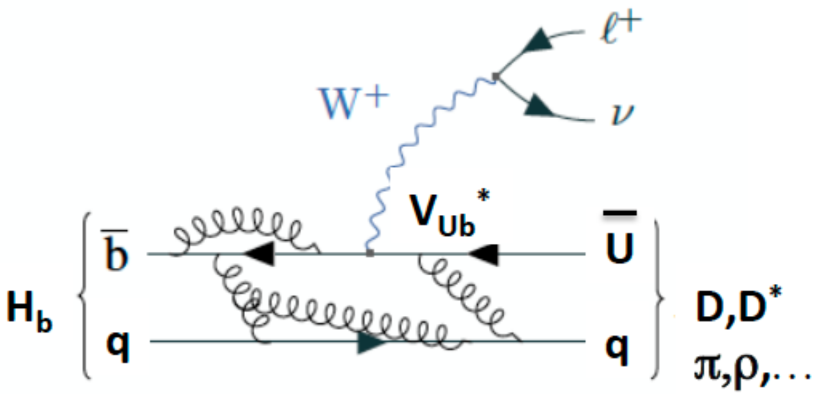
- Matrix elements of the operators through non perturbative approaches
  - Lattice QCD
  - QCD sum rules
  - Quark models

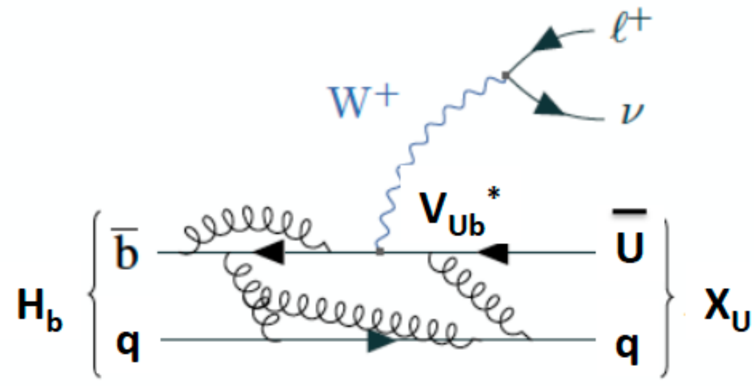
- Effective theories of QCD→approximate symmetries at work
  - HQET
  - ChPTh
  - $1/N_c$

substantial INFN contribution to all the items

Passato prossimo/presente

Determining CKM elements
The case of V_{ub} and V_{cb}





U=u,c

Exclusive determination

- Non perturbative input: form factors
  - lattice, QCDSR, combined methods
  - approximate symmetries

Inclusive determination

- HQ expansion + optical theorem
- non perturbative input: HQE parameters
- fitted from experimental distributions

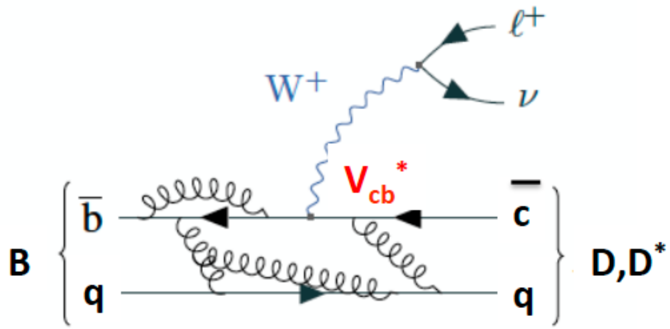
$$\Gamma(H_b \to X\ell^- \bar{\nu}_\ell) = \Gamma_b \left\{ C_0 + \frac{\mu_\pi^2}{m_b^2} C_{\mu_\pi^2} + \frac{\mu_G^2}{m_b^2} C_{\mu_G^2} + \frac{\rho_D^3}{m_b^3} C_{\rho_D^3} + \frac{\rho_{LS}^3}{m_b^3} C_{\rho_{LS}^3} \right\}$$

Passato prossimo/presente

V_{cb} : exclusive determination

Heavy Quark systems

- $m_b >> \Lambda_{QCD}$
- approximate symmetries of QCD
  HQ spin and flavour symmetries



Effective theory: **HQET**

- expansion parameters: $1/m_b$ and $\alpha_s(m_b)$
- B→D,D* : 6(+4) independent form factors reduced to 1
- Isgur-Wise function normalized $\xi(q^2_{max})=1$
- corrections at $O(1/m_b^2)$ Luke's theorem (1990)

analogous to the
Ademollo-Gatto theorem (1964)
based on $SU(3)_F$ for light quarks

$$f_+^{K\to\pi}(q^2=0) = 1 + \mathcal{O}\big((m_s - m_u)^2\big)$$

Passato prossimo/presente

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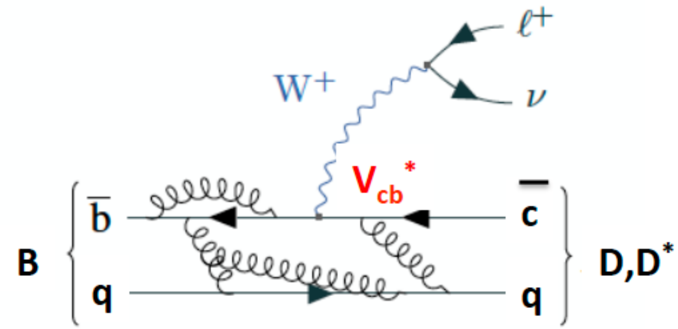

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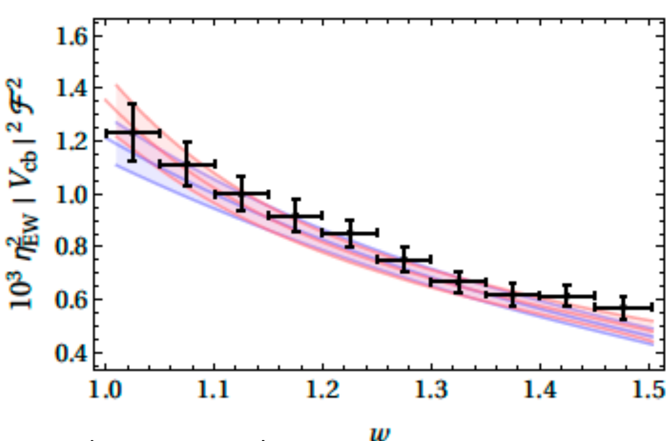
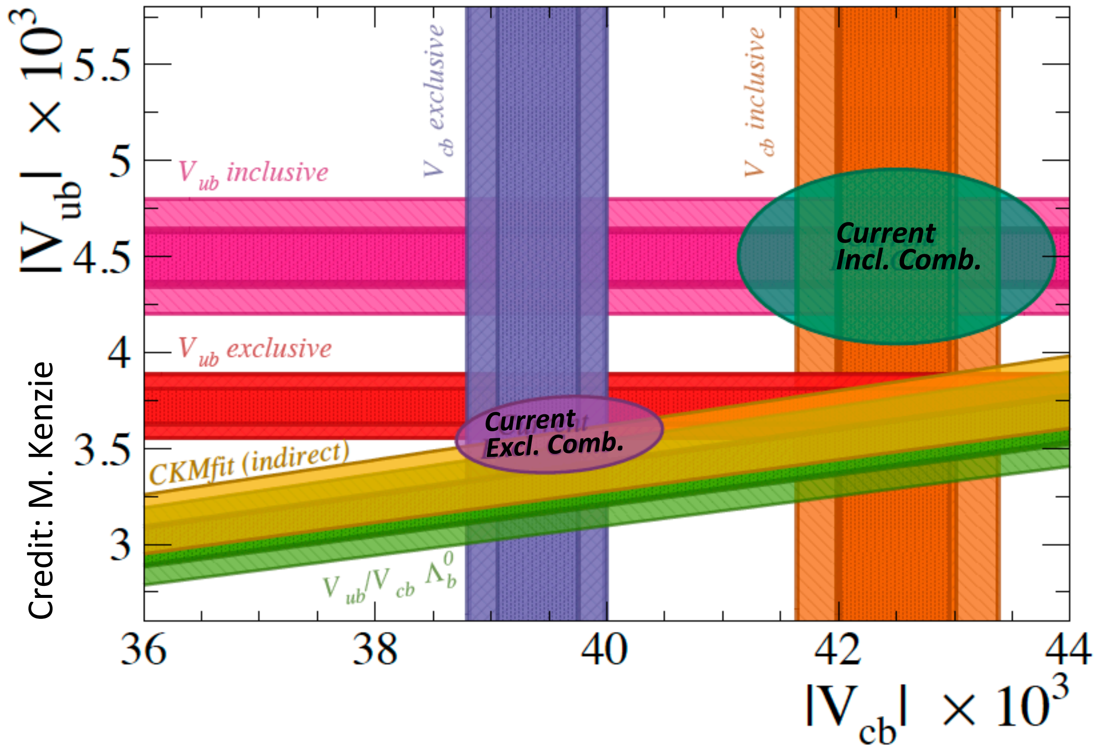


credit D. Bigi et al

Isgur Wise function

$$\frac{d\Gamma(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}{dw} = \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2 \chi(w) \eta_{EW}^2 \mathcal{F}^2(w) |V_{cb}|^2$$

Passato prossimo/presente



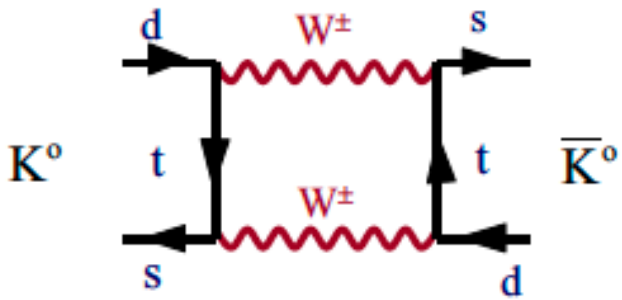
Credit: M. Kenzie

no consensus on the origin of the discrepancy

- violation of quark hadron duality (inclusive calculation)
- parametrization of the FF → role of the HQE (exclusive modes)
  → does not apply to V_{ub}
- improve the determination of FF, e.g. lattice+unitarity (exclusive modes)
- NP?

CP violation in the Kaon sector

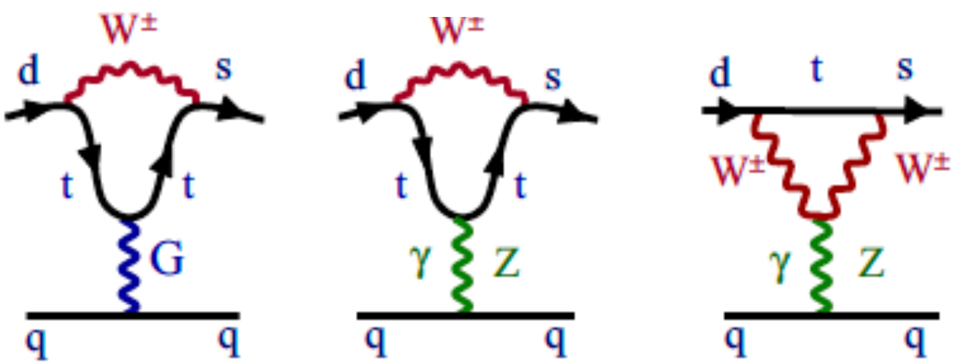
Indirect (mixing)



ΔM_K

ε_K

Credit: A.J. Buras



$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$

direct (amplitudes)

$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}\,.$$

$$(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (14 \pm 5) \times 10^{-4}\,, \qquad (\mathrm{ChPT}-2019).$$

old *anomaly* in flavour physics

$$(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (5 \pm 2) \cdot 10^{-4}\,, \qquad (\mathrm{DQCD}-2020).$$

$$(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (21.7 \pm 8.4) \times 10^{-4}\,, \qquad (\mathrm{RBC\text{-}UKQCD}-2020),$$

Passato prossimo/presente

The quest for NP: **basic questions**

- Flavor puzzle: can we explain the hierarchy of masses and mixings?
  - Frogatt-Nielsen (1979): new U(1) symmetry broken by a spurion horizontal symmetry (different fermion generations have different U(1) charges)
  - Warped extra dimensions (1999): fermion masses depend on their localization in the extra dimension
  - …

- Why 3 generations?
  - 331 models: anomaly cancelation + asymptotic freedom of QCD imposes $N_{gen}=N_c$

- no suitable candidate for dark matter in SM
  - SUSY LSP a suitable candidate
  - Extra-dimensions : KK 1- modes (e.g. $\gamma^{(1)}$)

- Gauge coupling unification, Higgs mass, inclusion of gravity….

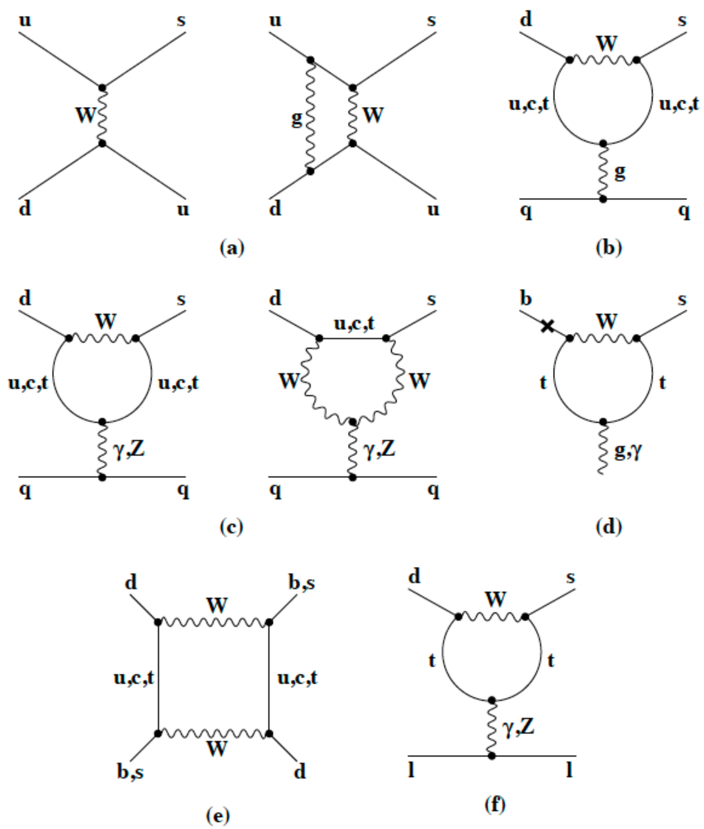
Passato prossimo/presente

The search for new Physics:
Look at rare decays e.g. FCNC: b→ s,d   s→d

$$B_{s,d} \to \mu^+\mu^- \qquad B \to (K, K^*, X_s)\nu\bar{\nu} \qquad B \to (K^*, X_s)\gamma \qquad B \to (K, K^*, X_s)\ell^+\ell^-$$

$$K_L \to \mu^+\mu^- \qquad K_L \to \pi^0\ell^+\ell^-$$

...

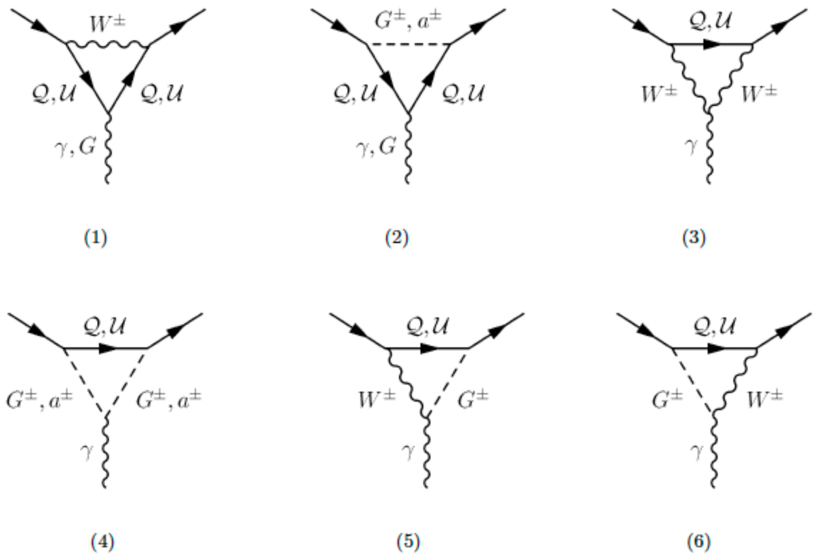


- SM: QCD corrections
  Important contributions from INFN groups

- NP: i) new operators
  ii) modified Wilson coefficients
  iii) new phases

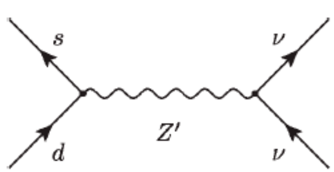
Passato prossimo/presente

parameter space of many NP models constrained
Ex: model with extra dimensions → KK modes

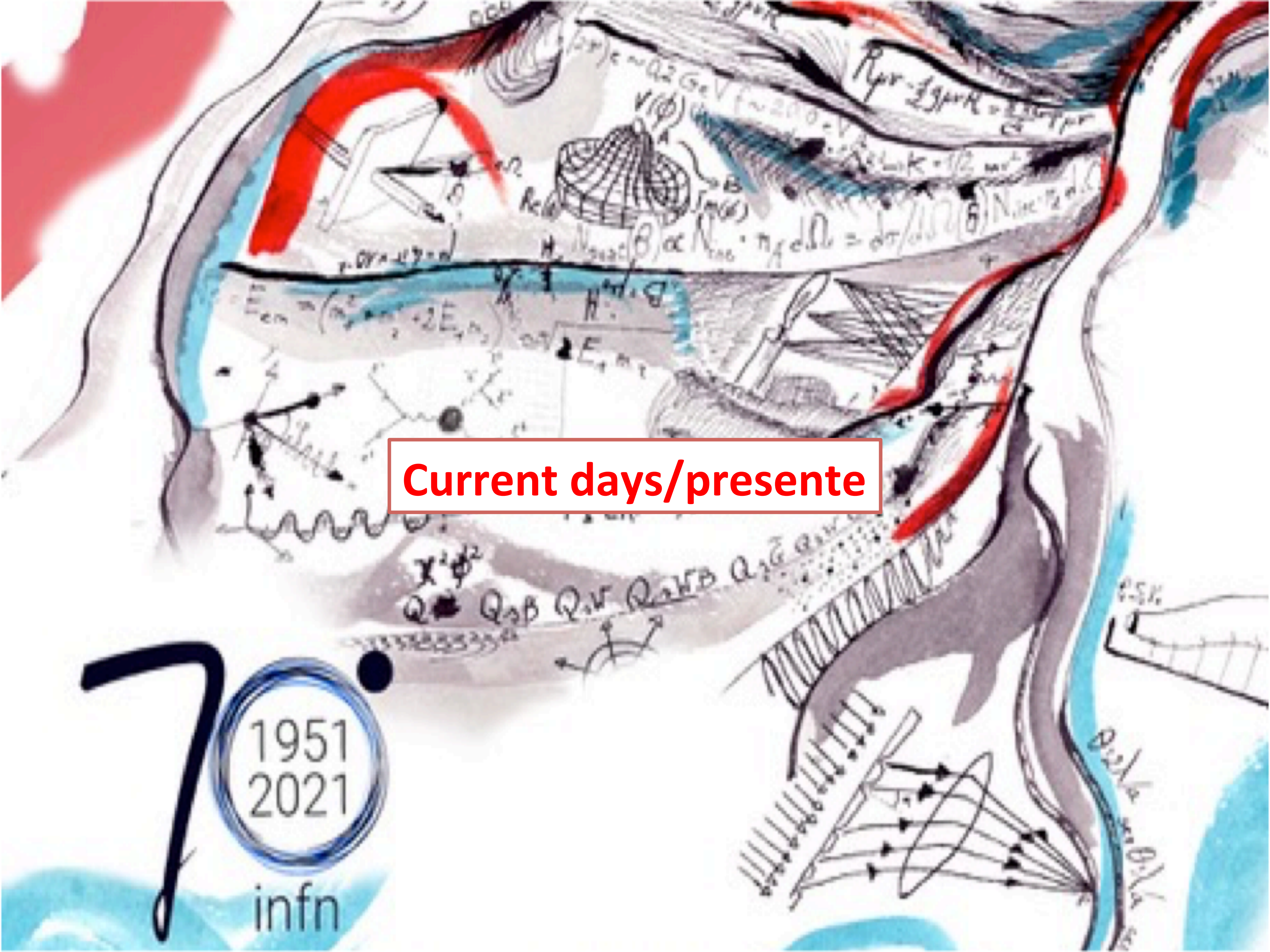


bounds on the size of the ED

Ex: a new neutral gauge boson with tree level FCNC



bounds on the couplings

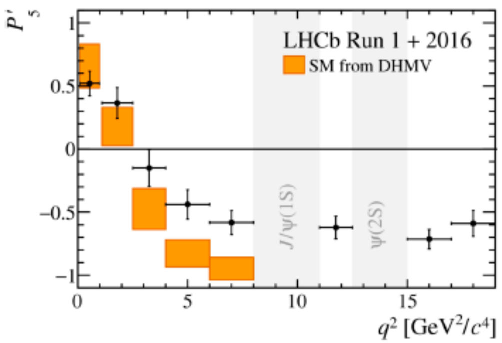


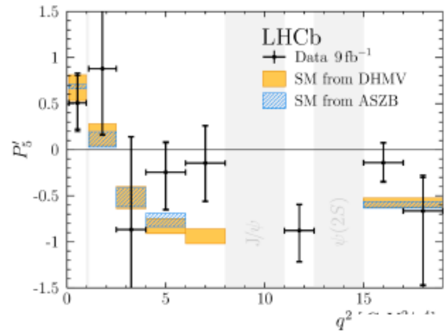
Current days/presente

presente

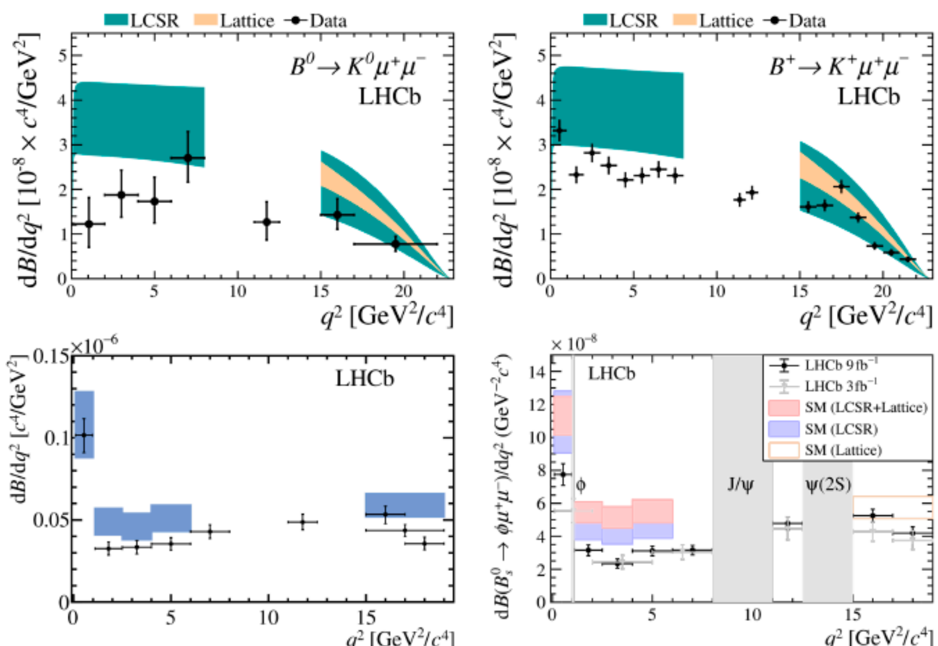
Tiny deviations observed

angular distributions in B → K* μ+ μ-





branching ratios



$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_{9\ell'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

possibility:
deviations reproduced
shifting $C_9^{(')} - C_{10}^{(')}$

- compare different NP predictions
- check correlations with other observables

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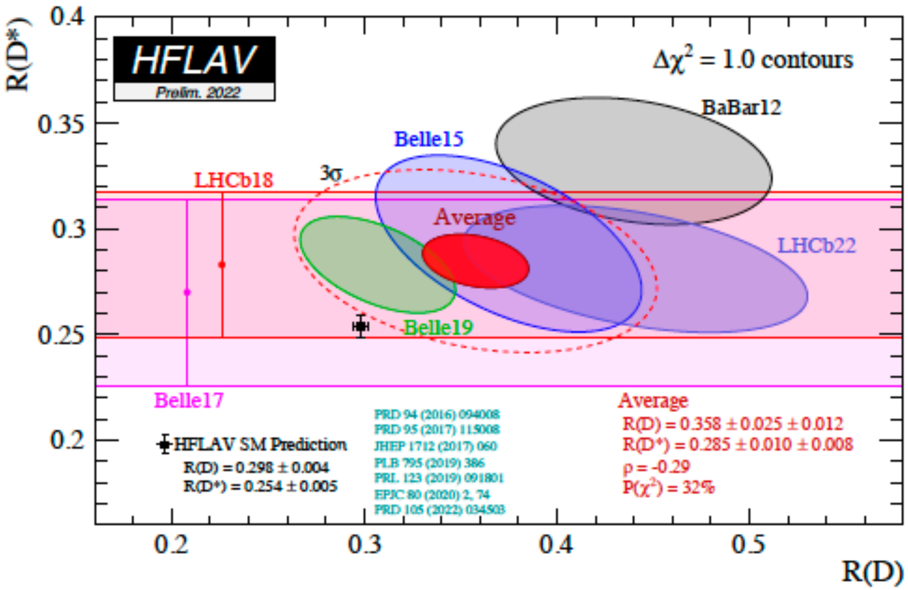
Passato prossimo/presente

unexpected surprises: hints of NP in tree-level modes

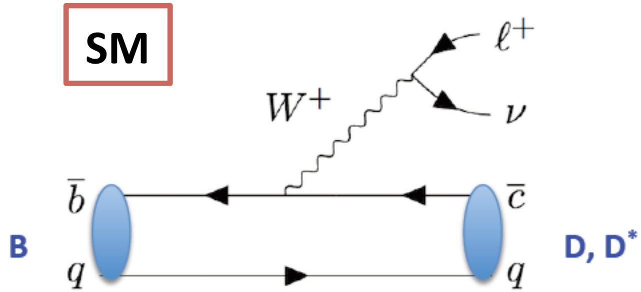


3.2 σ away from SM

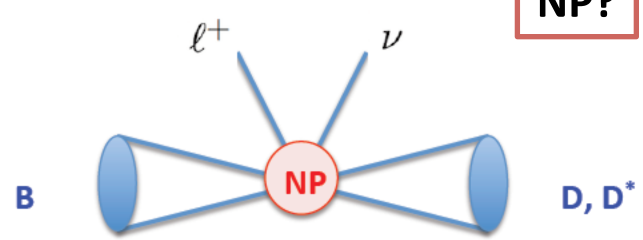
$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell)}$$

$$\mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

SM



NP?



Passato prossimo/presente

unexpected surprises: Lepton Flavour Universality Violation?

SM

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

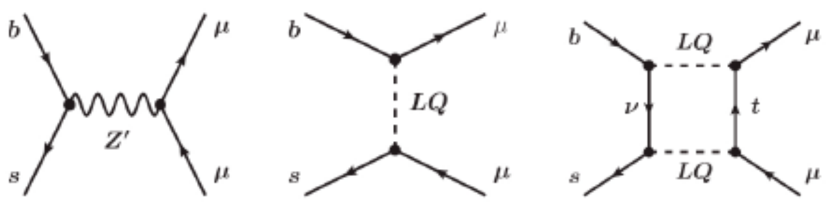
LHCb

$$R_K = 0.846 \pm^{0.042}_{0.039}\,(\mathrm{stat}) \pm^{0.013}_{0.012}\,(\mathrm{sys}) \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2/\mathrm{c}^4$$

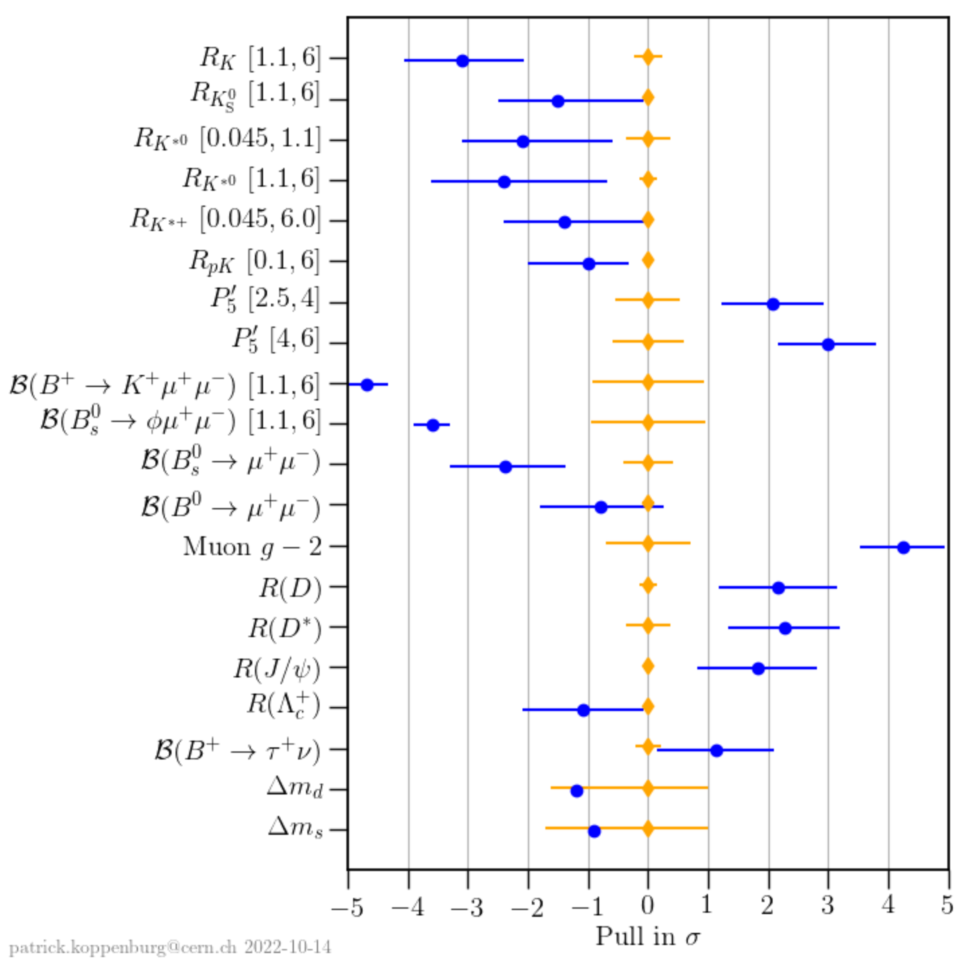
$$R_{K^{*0}} = 0.66 \pm^{0.11}_{0.07} \pm 0.03 \qquad q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2/\mathrm{c}^4$$

$$R_{K^{*0}} = 0.69 \pm^{0.11}_{0.07} \pm 0.05 \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2/\mathrm{c}^4$$

- ✧ point to violation of LFU
- ✧ in SM accidental symmetry violated only by the Yukawa term
- ✧ possible candidates: leptoquarks or Z' with non universal couplings to leptons



Presente



- correlated pattern of deviations from SM predictions?
- common origin of the anomalies?

  ex. V_{cb} , V_{ub} puzzles correlated with observed anomalies in tree-level modes?
- look also for processes forbidden in SM: LFV decays $\tau \to 3\mu$, $\mu \to e\gamma$ …

Presente: effective theory viewpoint

Standard Model Effective Field Theory

SM as an effective theory valid up to a scale Λ

The theory above Λ should reduce to the SM at low energies

- Operators in terms of SM fields + RH neutrinos
- Invariant under the SM gauge group

Weinberg operator

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{(5)}}\mathcal{O}^{(D=5)} + \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i^{(D=6)} + \ldots$$

NP

$$\overbrace{\underbrace{\mathcal{L}^{kin} + \mathcal{L}^{gauge} + \mathcal{L}^{Higgs}} + \underbrace{\mathcal{L}^{Yukawa}}}$$

accidental symmetries

- violates accidental symmetries
- source of (SM) CP violation
- fermion mass terms

Presente: effective theory viewpoint

new operators contribute to different processes

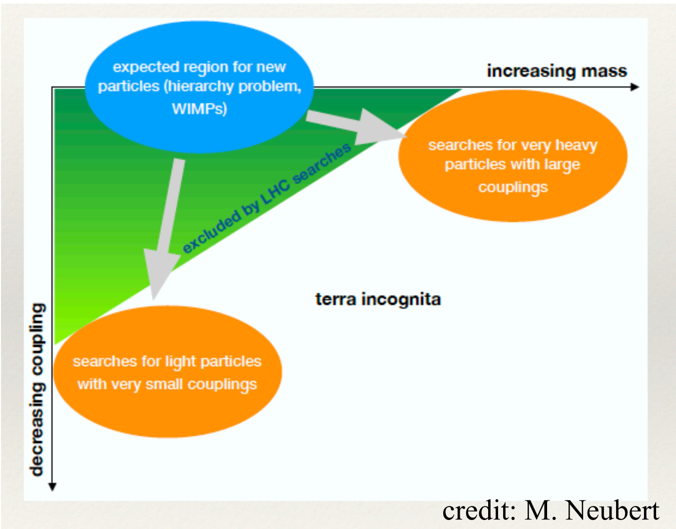
$$
\begin{aligned}
H_{\rm eff}^{b\to u\ell\nu} = \frac{G_F}{\sqrt{2}} V_{ub} \Big\{ & (1+\epsilon_V^\ell)(\bar u\gamma_\mu(1-\gamma_5)b)\,(\bar\ell\gamma^\mu(1-\gamma_5)\nu_\ell) \\
& + \epsilon_S^\ell(\bar u b)\,(\bar\ell(1-\gamma_5)\nu_\ell) + \epsilon_P^\ell(\bar u\gamma_5 b)\,(\bar\ell(1-\gamma_5)\nu_\ell) \\
& + \epsilon_T^\ell(\bar u\sigma_{\mu\nu}(1-\gamma_5)b)\,(\bar\ell\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell)\Big\} + h.c.
\end{aligned}
$$

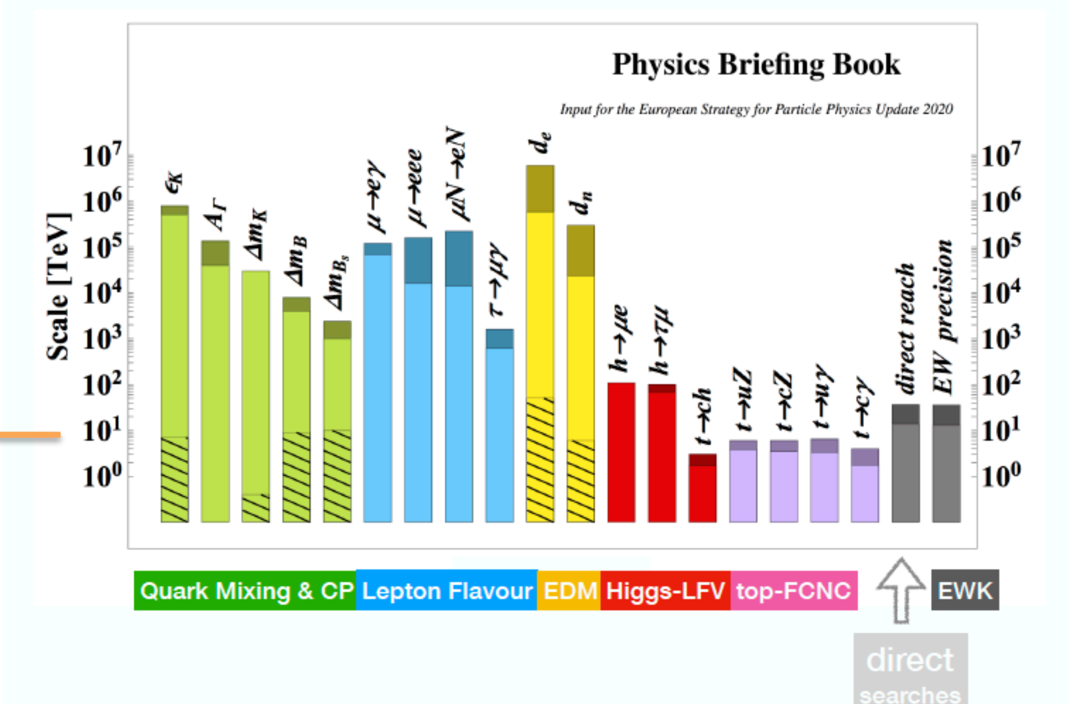
	ϵ_V^ℓ	ϵ_S^ℓ	ϵ_P^ℓ	ϵ_T^ℓ
$B^- \to \ell^-\bar\nu_\ell$	✔		✔	
$\bar B \to \pi\ell^-\bar\nu_\ell$	✔	✔		✔
$B \to \rho\ell\bar\nu_\ell$	✔		✔	✔
$B \to a_1\ell\bar\nu_\ell$	✔	✔		✔

Presente: effective theory viewpoint

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{(5)}}\mathcal{O}^{(D=5)} + \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i^{(D=6)} + \dots$$

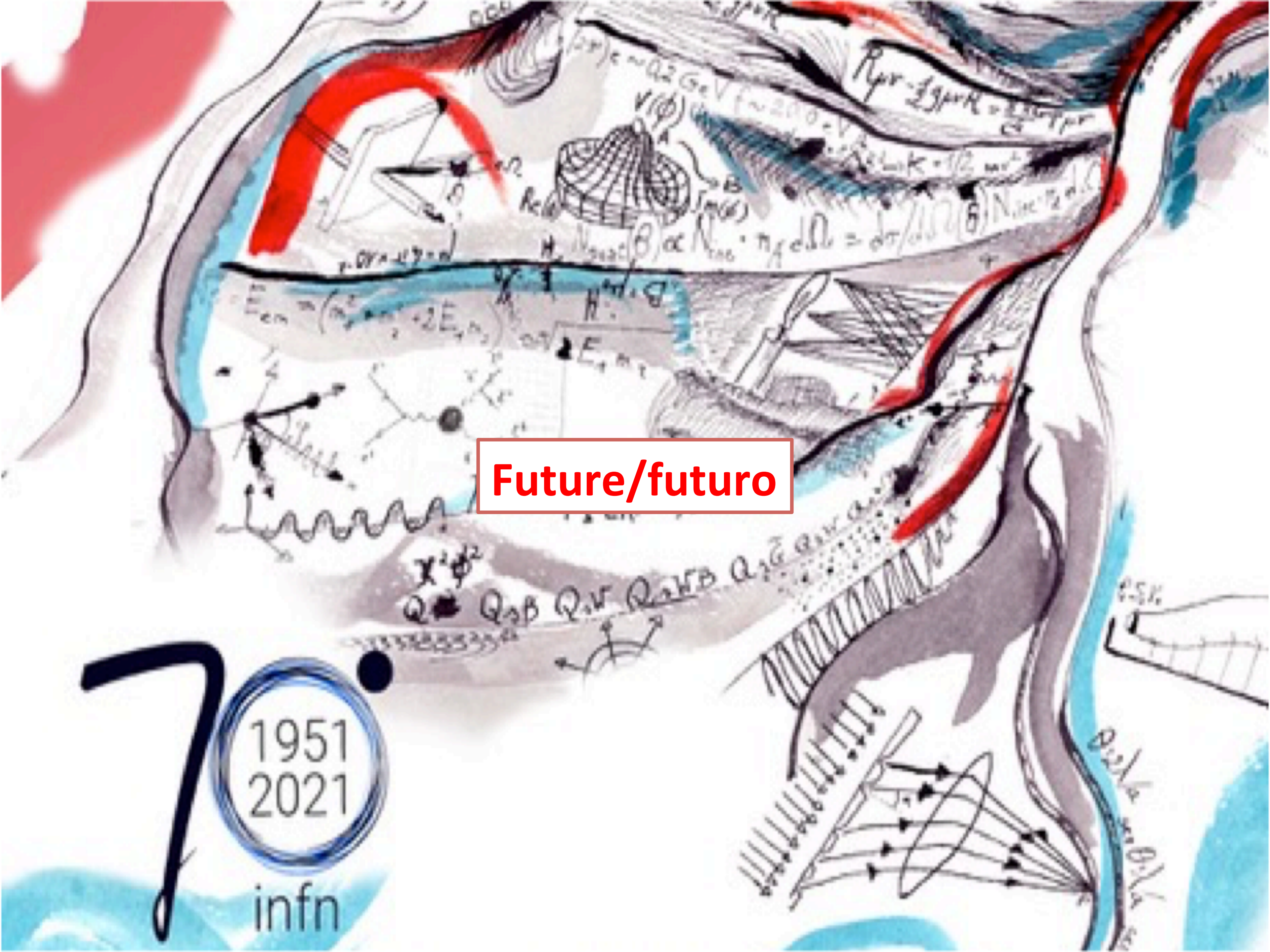
coupling/mass





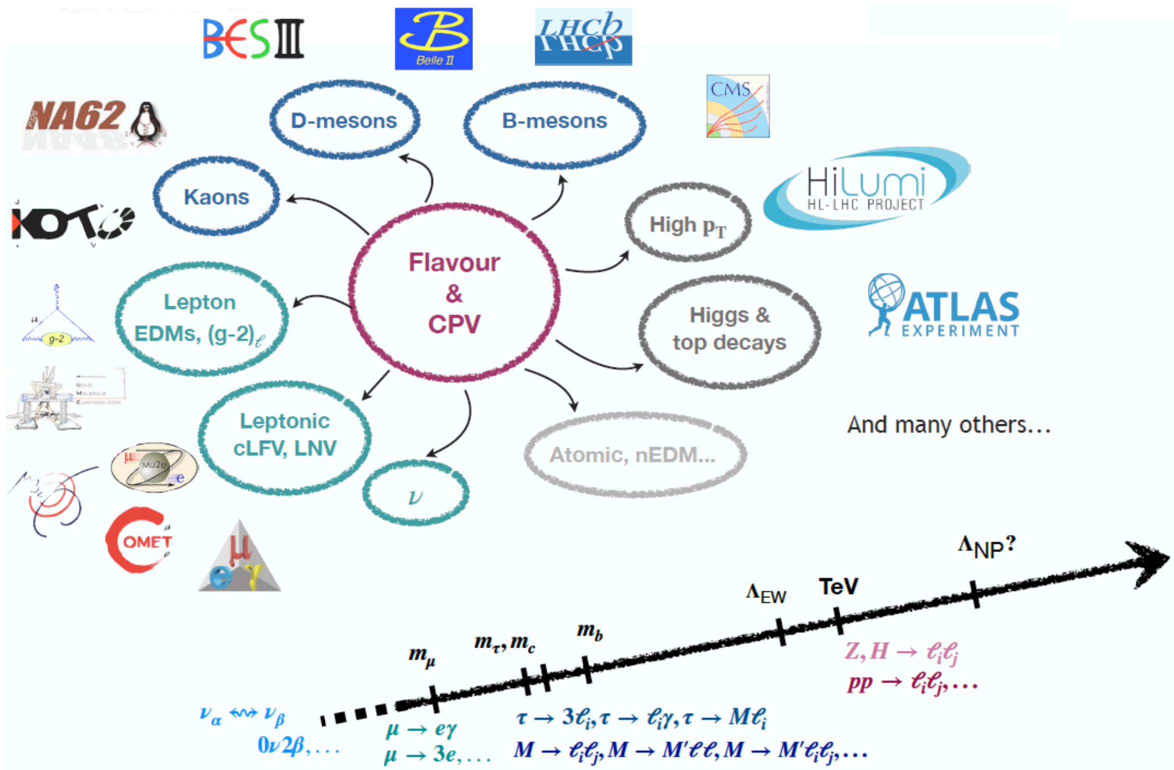
flavour may access high scales

Future/futuro



Perspectives

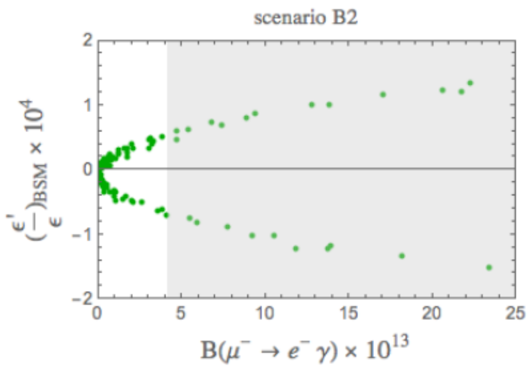
rich landscape of experiments



credit: A. Teixeira

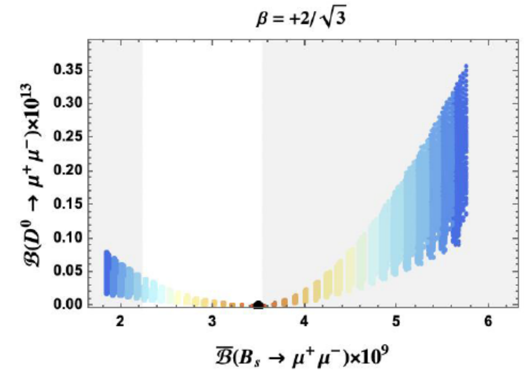
Perspectives: a personal view

Short-term directions

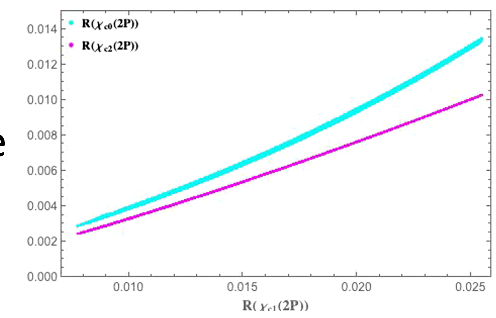


Explore correlations among observables
e.g.

- quark/lepton flavour correlations between rare/forbidden modes



- Many unanswered questions in the charm sector
  - ➢ role of long distance effects
  - ➢ ΔA_{CP} to be understood
  - ➢ null-tests
  - ➢ relations with B, K Physics: model independent (SMEFT) or in specific NP scenario



- important synergy: exotic spectroscopy
- ➢ many new exotic candidates discovered
- ➢ production in weak decays can shed light on the structure

Perspectives: a personal view

Synergies with other areas of particle Physics, e.g. Astroparticle Physics & cosmology

- neutrino Physics
- multimessanger astrophysics
- dark matter searches
- gravitational waves

INFN physicists will be major players