CKM & CPV in kaon and light flavour: status and prospects

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NA62

CKM matrix and first row unitarity

$$-\frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu W_\mu^+ V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Separate class of precision tests

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$\approx 2 \times 10^{-5}$

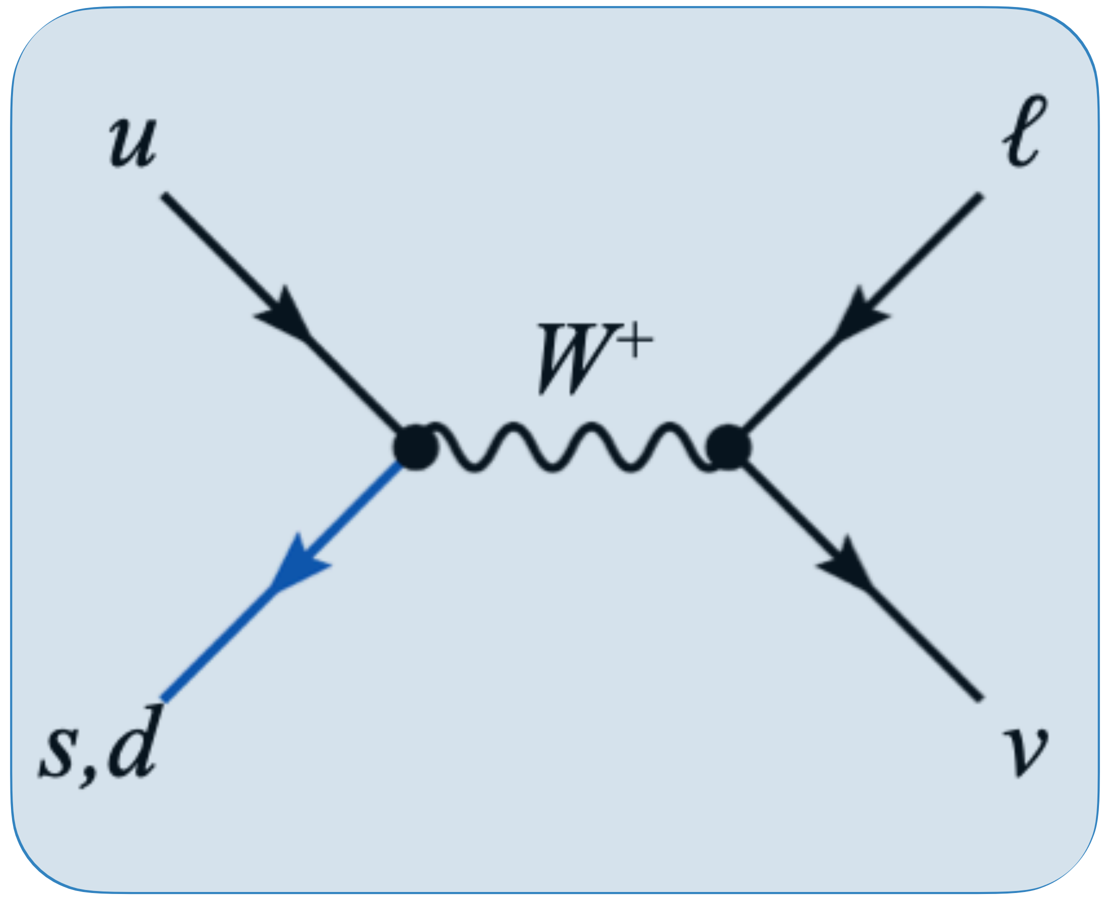
$$\Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 - 1$$

V_{us} and V_{ud} are the most accurately known elements of the CKM matrix

CKM first row as probe for new physics

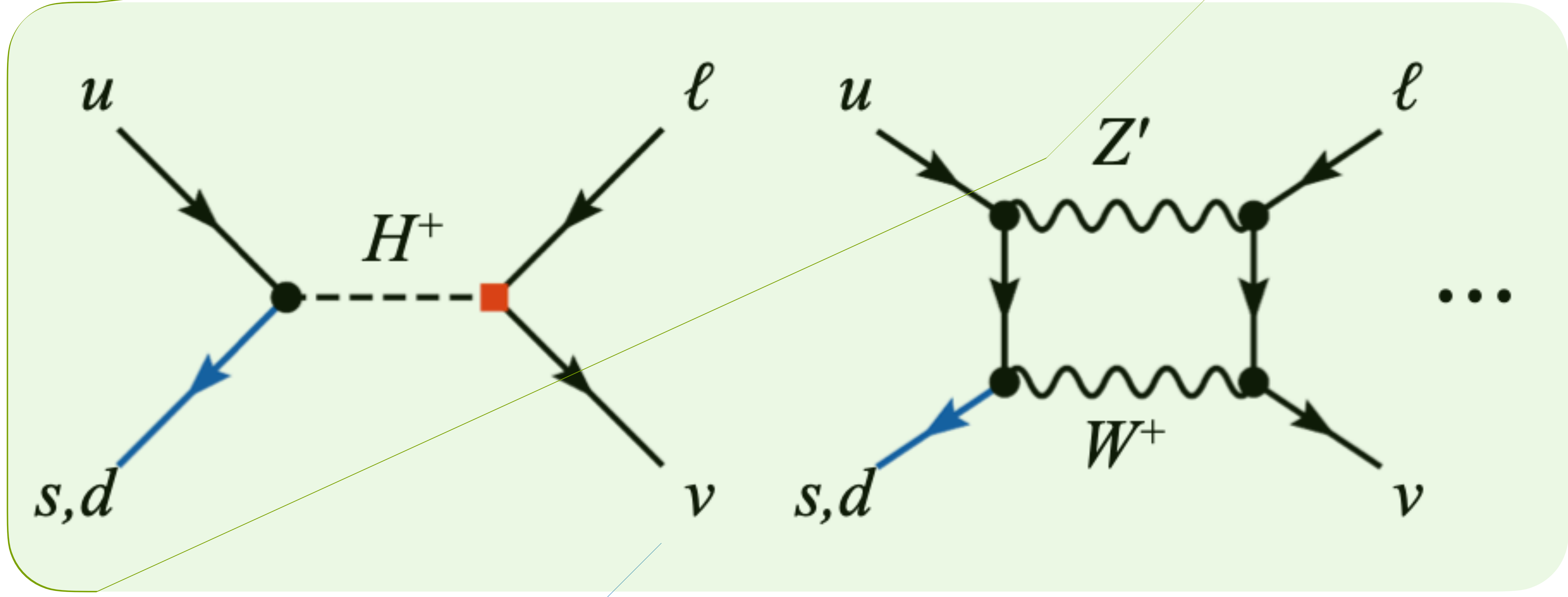
1st row provides the most stringent test of universality & sensitivity to new physics

SM



+

BSM scenario



Universality → Is G_F from the μ decay equal to G_F from K, π and nuclear β decay?

$$|V_{ud}|^2 + |V_{us}|^2 = 1 + O\left(\frac{(M_W^2/g^2)}{\Lambda^2}\right)$$

BSM effect scale as

$(M_W^2/g^2)/\Lambda^2$

For measurement of Δ_{CKM} with total uncertainty σ

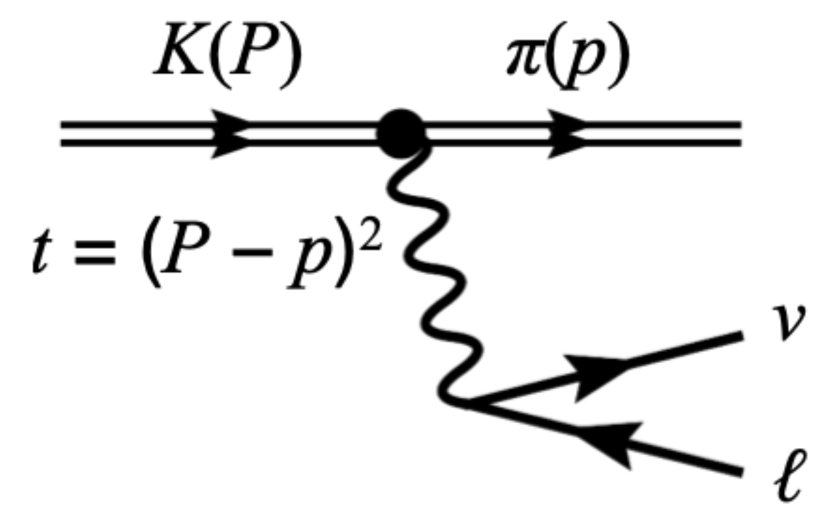
For $\sigma \sim 10^{-4} \rightarrow$ probe $\Lambda \sim 20\,TeV$

CKM in Kaon sector

Kaon semileptonic decays $K_{\ell 3}$

Master formula

$$\Gamma(K \to \pi \ell \nu(\gamma)) = \frac{G_F^2 M_K^5 C_K^2}{192\pi^3} |V_{us}|^2 S_{EW} |f_+^{K\pi}(0)|^2 I_{K\ell}^{(0)} \left(1 + \delta_{EM}^{K\ell} + \delta_{SU(2)}\right)$$



C_K Isospin factor

S_{EW} Short distance electroweak RCs

From theory

$f_+^{K\pi}(0)$ $K\pi$ form factor at $t = 0$

$\delta_{EM}^{K\ell}$ Long-distance electromagnetic RC

$\delta_{SU(2)}$ SU(2) symmetry breaking

From experiments

$\Gamma(K \to \pi \ell \nu(\gamma))$

Rates with well-determined treatment of radiative decays:

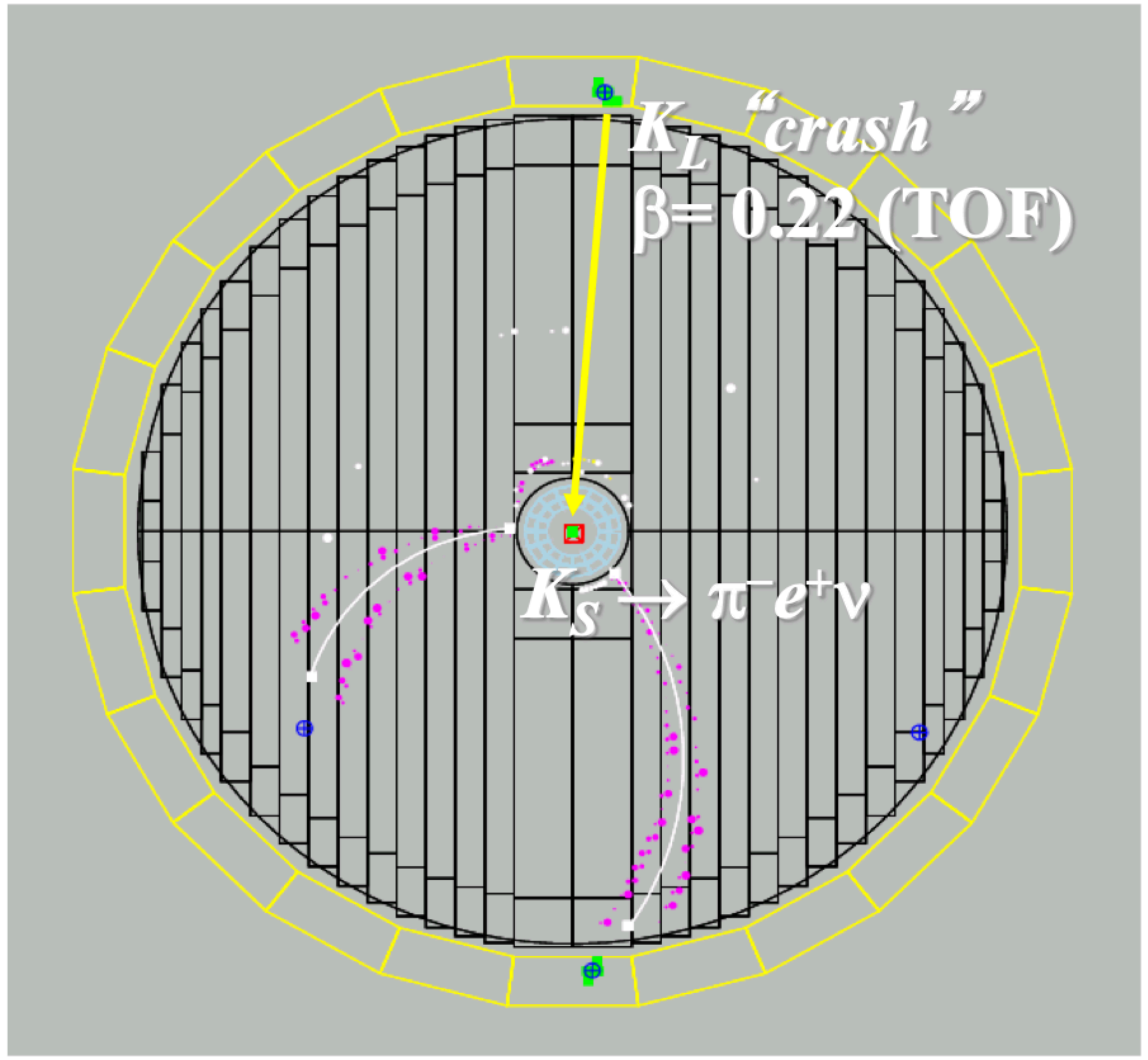
- K_S, K_L, K^+ BR
- K lifetime

$I_{K\ell}^{(0)}$

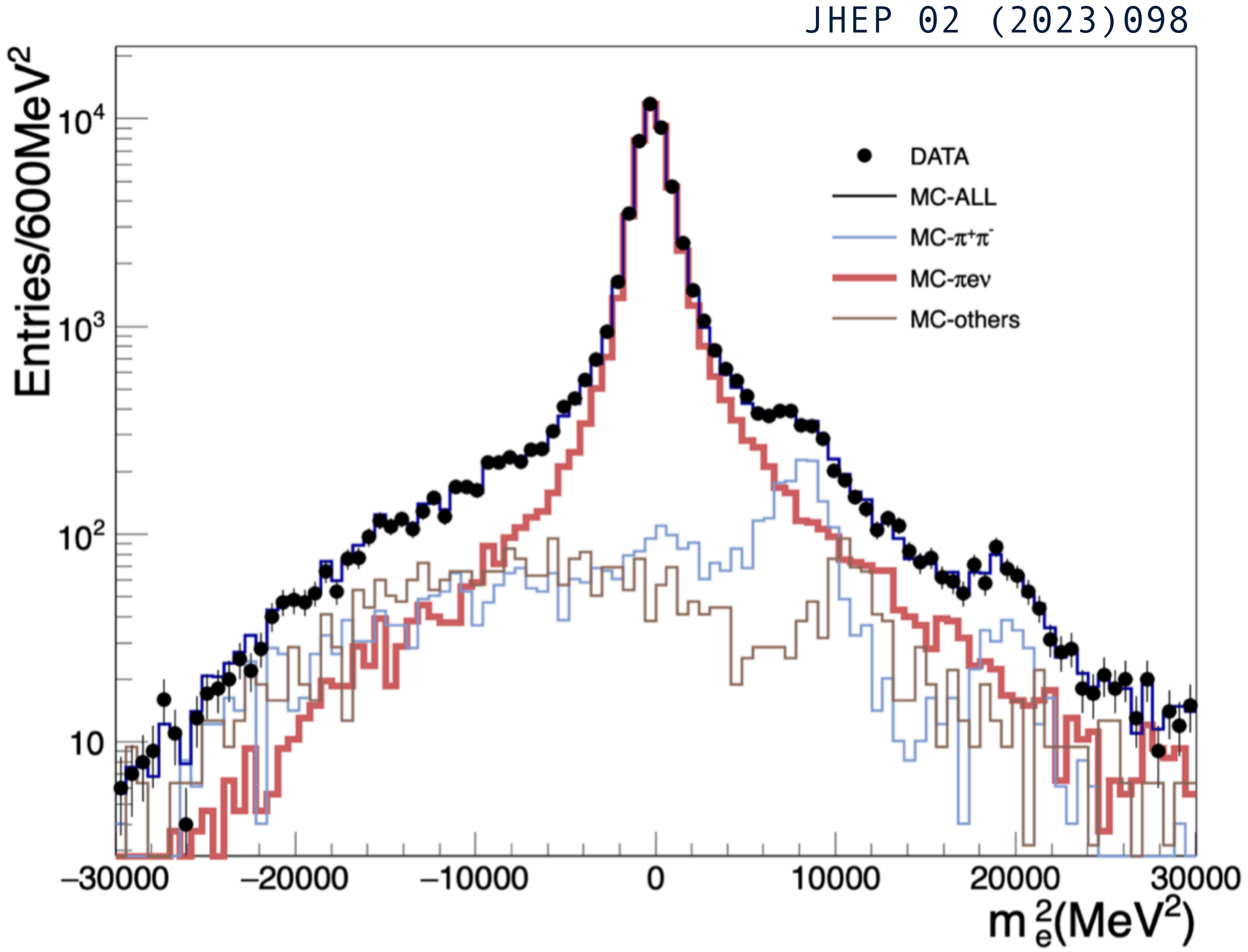
Integral of form factor over phase-space.

KLOE/KLOE-2 measurement of $\mathscr{B}(K_S \to \pi \ell \nu)$

Daϕne is a phi-factory: $e^+e^- \to \phi \to K_S K_L$



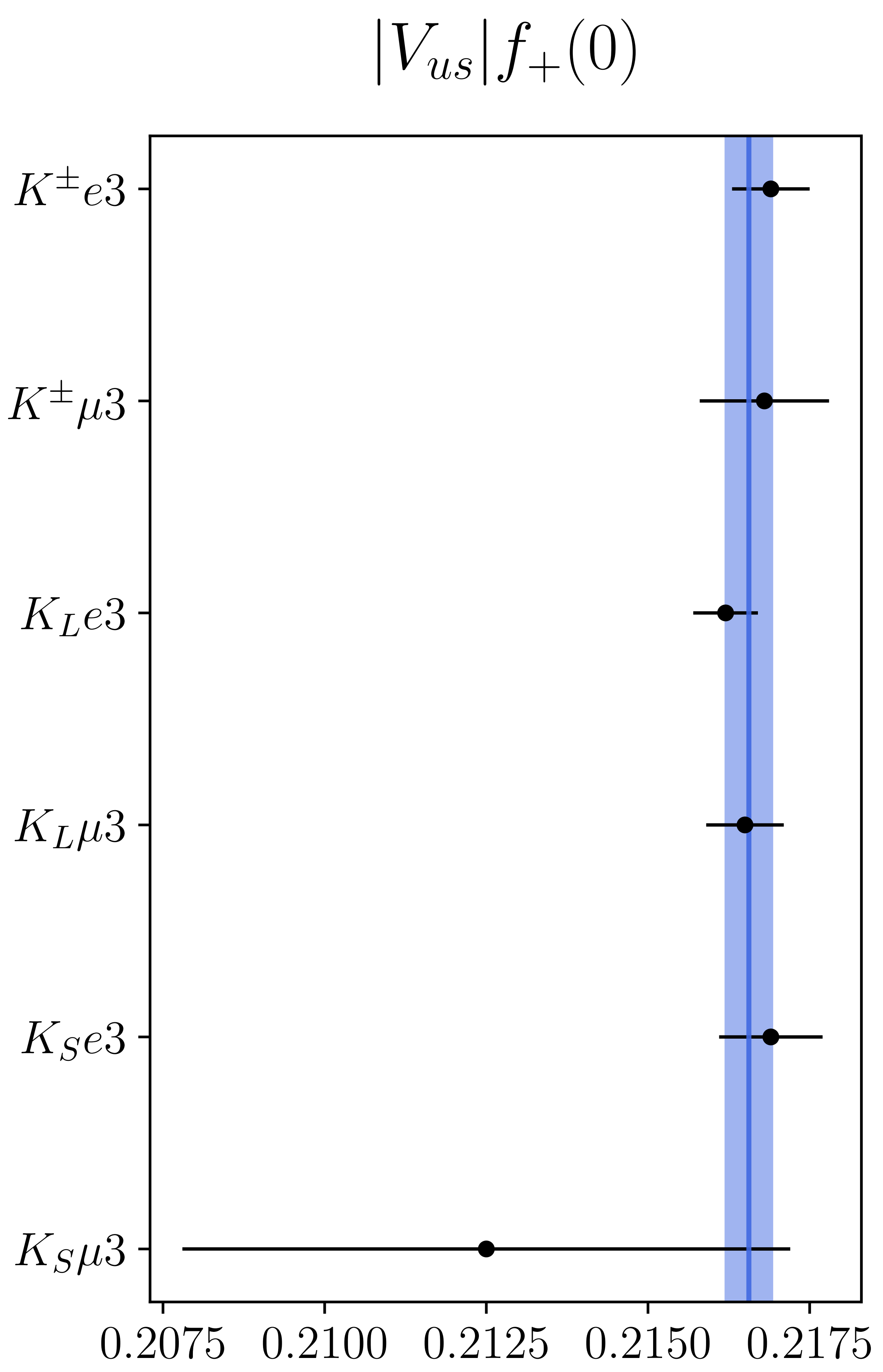
- Select signal with kinematic BDT and ToF $\pi\ell$ assignment
- Fit to $m_\ell = (E_{K_S} - E_\pi - p_{miss})^2 - p_\ell^2$
- $K_S \to \pi^+\pi^-$ as normalisation channel



- **First measurement** of $\mathscr{B}(K_S \to \pi\mu\nu) = (4.56 \pm 0.20) \times 10^{-4}$, based on 1.6 fb^{-1}
- **Recent result** $\mathscr{B}(K_S \to \pi e \nu) = (7.153 \pm 0.037_{stat} \pm 0.044_{styst}) \times 10^{-4}$, based on 1.6 + 0.4 fb^{-1}

PRLB 804 (2024)
JHEP02(2023)098

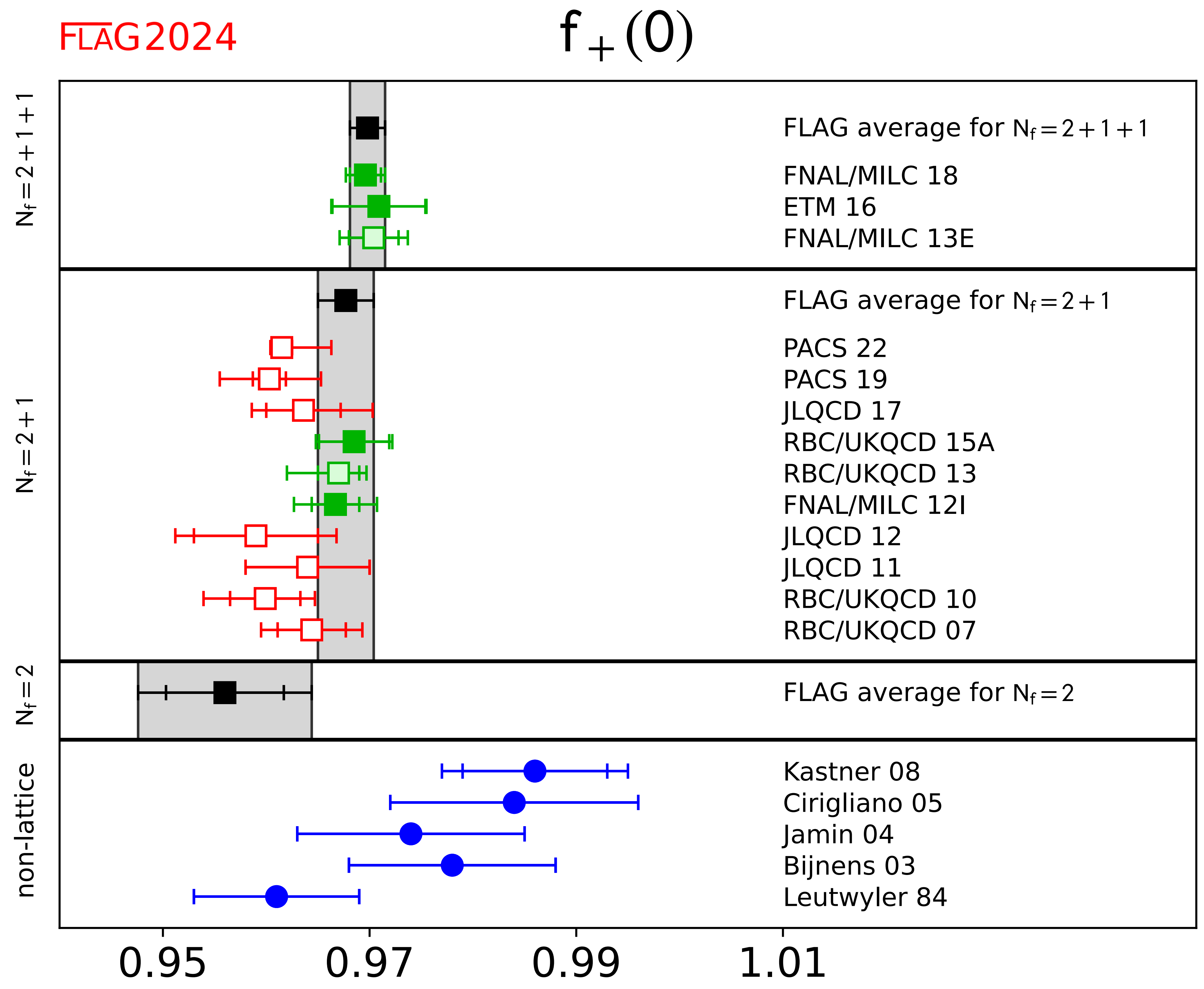
$|V_{us}|f_+(0)$ and $f_+(0)$ from world data



EPJC(69)399–424(2010)

Decay mode	$\|V_{us}\|f_+(0)$
$K^{\pm}e3$	0.2169(6)
$K^{\pm}\mu3$	0.2168(10)
K_Le3	0.2162(5)
$K_L\mu3$	0.2165(6)
K_Se3	0.2169(8)
$K_S\mu3$	0.2125(47)

Average: $|V_{us}|f_+(0) = 0.21656(35) \quad \chi^2/ndf = 1.89/5(86\%)$



Kaon/pion leptonic decay $(K_{\mu 2}/\pi_{\mu 2})$

$$\frac{|V_{us}|f_{K^+}}{|V_{ud}|f_{\pi^+}} = \left[\frac{\Gamma_{K_{\mu 2}}}{\Gamma_{\pi_{\mu 2}}}\frac{M_{\pi^+}}{M_{K^+}}\right]^{1/2} \frac{1-m_\mu^2/M_{\pi^+}^2}{1-m_\mu^2/M_{K^+}^2}(1-\delta_{EM}/2-\delta_{SU(2)}/2)$$

From theory

f_K/f_π — K^+/π^+ decay constants

$\delta_{EM}^{K\ell}$ — Long-distance electromagnetic RC

$\delta_{SU(2)}$ — Strong isospin breaking

From experiments

$\Gamma(K_{\mu 2}), \Gamma(\pi_{\mu 2})$

Rates with well-determined treatment of radiative decays:

- Branching ratios $\mathscr{B}(K_{\mu 2}), \mathscr{B}(\pi_{\mu 2})$ and lifetimes $\tau_{K^\pm}, \tau_{\pi^\pm}$
  - Use $K^\pm$ info from fits
  - Use $\pi^\pm$ info from PDG

Kmu2 BR dominated by one measurement (KLOE)
Km3/Kmu2 BR measurement at 0.2% would have significant impact

$$\frac{|V_{us}|f_{K^+}}{|V_{ud}|f_{\pi^+}} = 0.27679(28)_{BR}(20)_{corr}$$

Need to reduce the impact of the theoretical input in the error budget

Unitarity tests ingredients

From $K_{\ell 3}$

$$|V_{us}| = 0.22330(35)_{exp}(39)_{LAT}(8)_{RC+IB}(53)_{TOT}$$

From $K_{\mu 2}$

$$\frac{|V_{us}|}{|V_{ud}|} = 0.23108(23)_{exp}(42)_{LAT}(16)_{RC+IB}(51)_{TOT}$$

From super-allowed beta decays $0^+ \rightarrow 0^+$

$$|V_{ud}|_\beta = = 0.97367(11)_{exp}(13)_{\Delta_R^V}(27)_{NS}\ (32)_{total}$$

From neutron decay

(τ_n and G_A/G_V as experimental inputs)

$$|V_{ud}|_{n,best} = 0.97413(13)_{\Delta R}(35)_{\lambda}(20)_{\tau_n}$$

good agreement

$$|V_{ud}| = 0.97384(26)$$

(*) Not included in the talk

Multiple ways of testing unitarity

$$\Delta^{(1)}_{CKM} = |V_{ud}|^2_{\beta} + |V_{us}|^2_{K_{\ell 3}} - 1$$

$$\Delta^{(2)}_{CKM} = |V_{ud}|^2_{\beta}\left(\frac{1}{|V_{us}/V_{ud}|^2_{K_{\mu 2}}} + 1\right) - 1$$

$$\Delta^{(3)}_{CKM} = |V_{us}|^2_{K_{\ell 3}}\left(\frac{1}{|V_{us}/V_{ud}|^2_{K_{\mu 2}}} + 1\right) - 1$$

$\Delta^{(1)}_{CKM} = -0.00176(56)$	$\Delta^{(2)}_{CKM} = -0.00098(58)$	$\Delta^{(3)}_{CKM} = -0.0164(63)$
-3.1σ discrepancy	-1.7σ discrepancy	-2.6σ discrepancy

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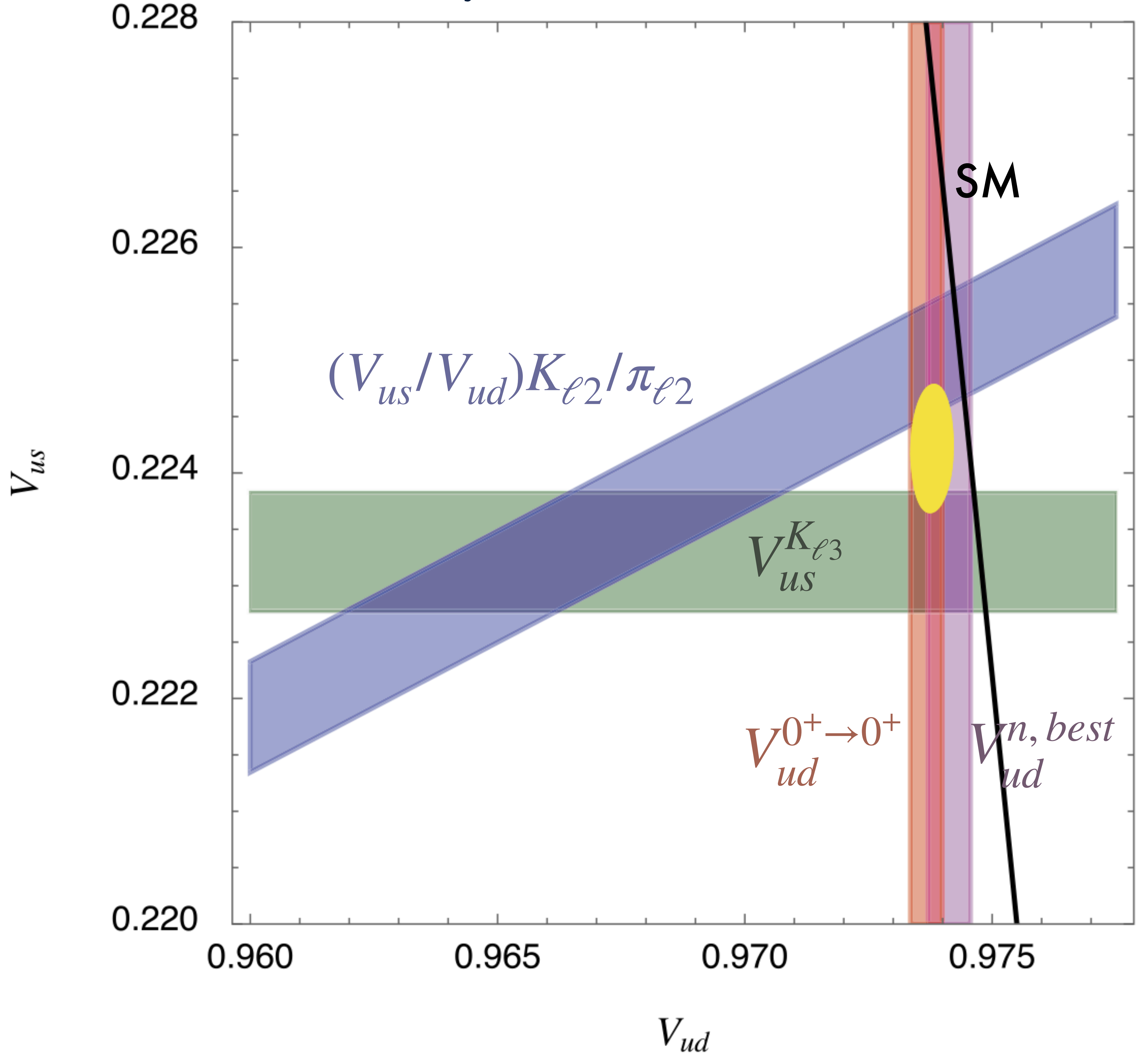
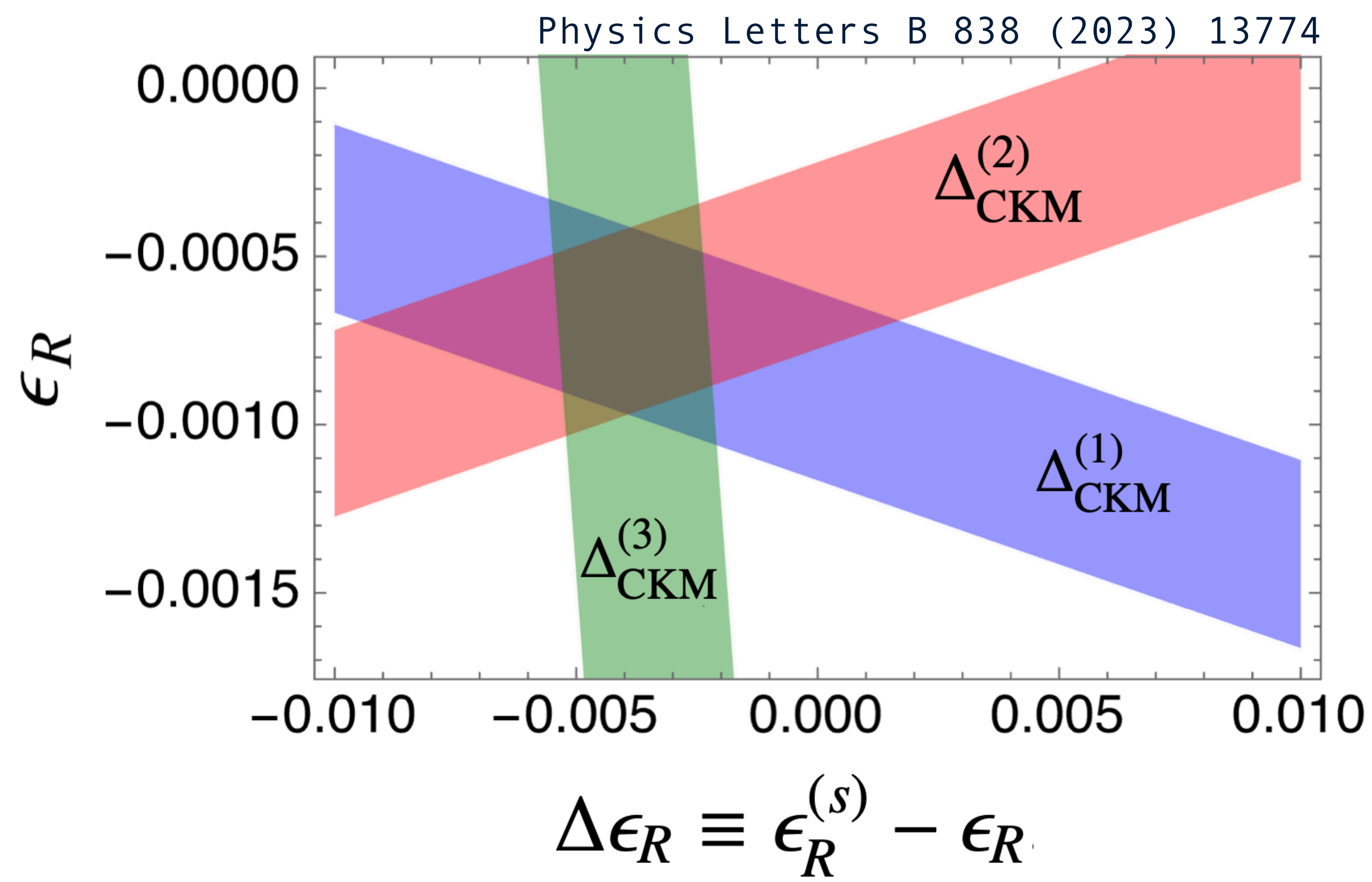


Global fit 2.8σ discrepancy

Cabibbo universality and BSM physics

$$\Delta^{(1)}_{CKM} = 2\epsilon_R + 2\Delta\epsilon_R |V_{us}|^2$$
$$\Delta^{(2)}_{CKM} = 2\epsilon_R - 2\Delta\epsilon_R |V_{us}|^2$$
$$\Delta^{(3)}_{CKM} = 2\epsilon_R + 2\Delta\epsilon_R (2 - |V_{us}|^2)$$



From current fit

$$\epsilon_R = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Zero hypothesis excluded with 3.1σ significance

CKM future in the Kaon/pion panorama

Measuring $R_{K_{\mu3}/K_{\mu2}}$ at NA62

Urgent need for additional information on the compatibility of $K_{\ell 2}$ and $K_{\ell 3}$ data

Proposed measurement

$$R_{K_{\mu3}/K_{\mu2}} = \frac{\mathcal{B}(K^+ \to \pi^0 \mu^+ \nu)}{\mathcal{B}(K^+ \to \mu^+ \nu)}$$

Impact of the measurement

$$(R_{K_{\mu3}/K_{\mu2}})^{-1/2} \propto 1 - 2\Delta\epsilon_R$$

sensitive search for RH currents

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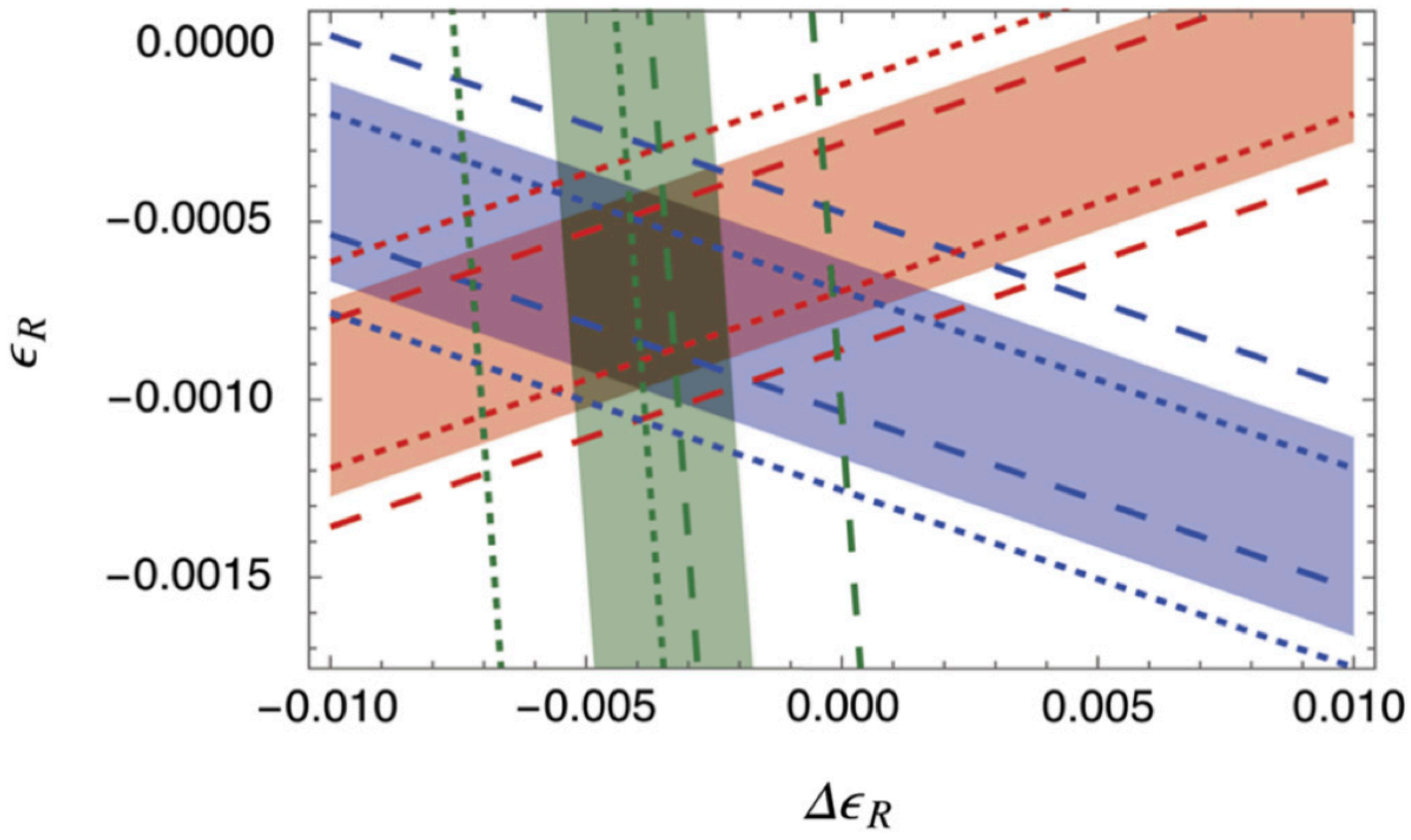


Why NA62 is suitable?

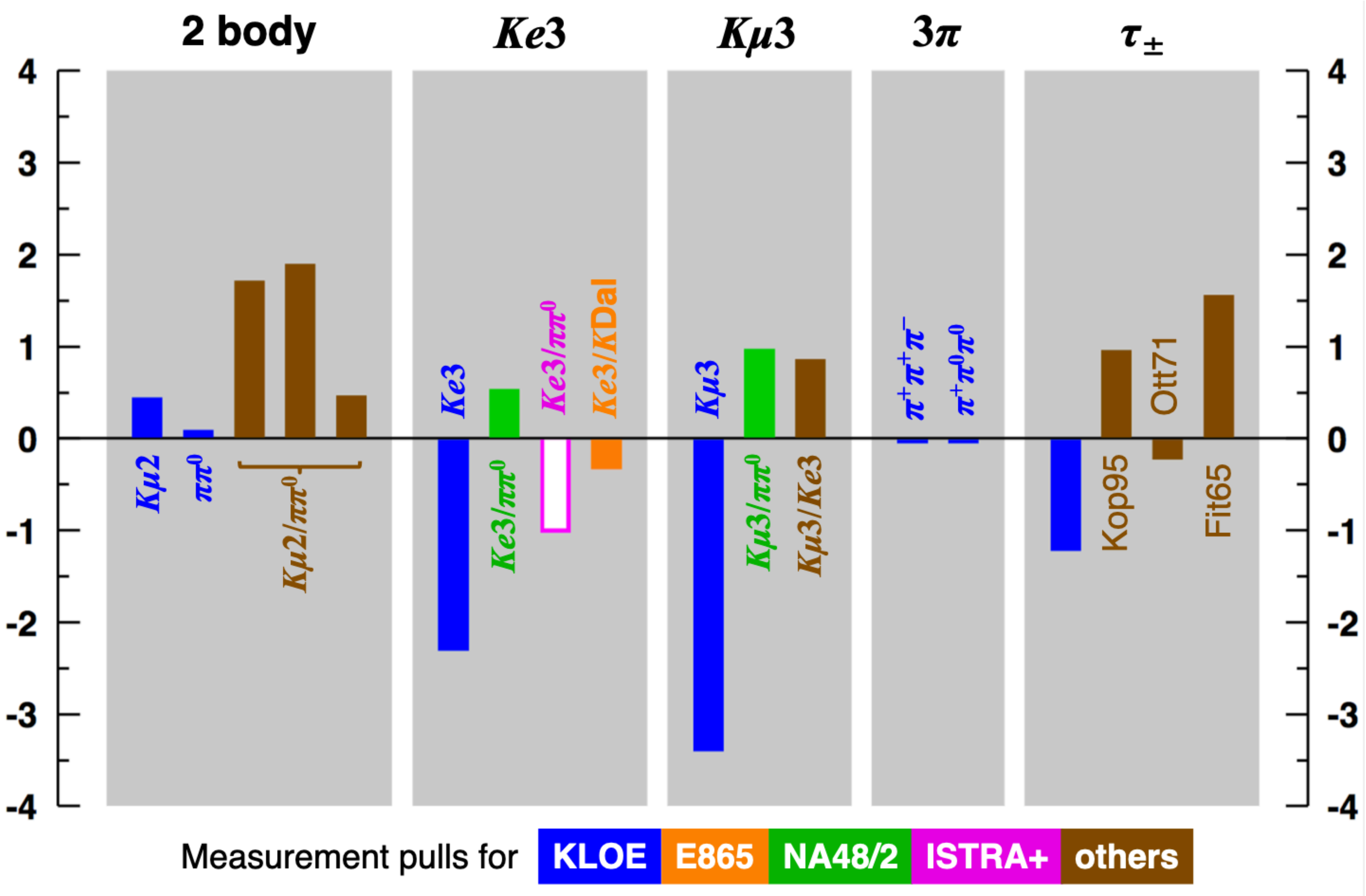
- Only running experiment on K^+ physics
- Good control of systematics
- Single analysis framework

Competitive with only 2 weeks of data taking

NA62 and CKM 1st row: many opportunities

NA62 can perform a suite of measurements of common kaon decays

- Add several new ratios to over-constrain fits with good control of systematics
- Use single analysis framework, data-set to maximise systematics cancellations



Inputs vs fit results for K^+

Strategy

select single positively charged tracks for measuring all decays

- Reduced systematics by using of minimum bias trigger with no PID
- Cleaner environment with higher statistics by taking low-intensity run without downscaling

NA62 low intensity operation

Why NA62 is suitable?

- Only running experiment on K^+ physics
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Competitive with only 2 weeks of data taking

NA62 2024 Low Intensity

Intensity

1.4 avg intensity (1.8% of standard intensity, 1.3% of nominal max intensity)

Total T10 POT collected: 2.6212e+15

Trigger stream

Minimum Bias trigger arrangement:

- CTRL: CHOD, D=50
- Mask2: L0: NewCHOD(Q1) ; L1: STRAW_OneTrack , D = 1
- Physics trigger reference detector = NewCHOD
- L1 does NOT contain KTAG

Pion beta decay: $\pi^+ \rightarrow \pi^0 e^+ \nu_e$

Master formula

$$\Gamma(\pi^+ \rightarrow \pi^0 e^+ \nu_e(\gamma)) = \frac{G_F^2 |V_{ud}|^2 M_{\pi^\pm}^5 |f_+^\pi(0)|^2}{64\pi^3}(1 + \Delta_{RC}^{\pi\ell}) I_{\pi\ell}$$

- Clear theoretically
- Challenging experimentally

- **PIBETA 2004** extracted $|V_{ud}|$ measuring the $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ branching ratio with $\pm 0.6\,\%$ precision

$$|V_{ud}| = 0.9739(27) \left[\frac{\mathscr{B}(\pi^+ \rightarrow e^+ \nu_e(\gamma))}{1.2325 \times 10^{-4}} \right]^{1/2}$$

D. Pocanic et al., Phys. Rev. Lett. 93, 181803 (2004), [hep-ex/0312030]

Normalised using the very precise measured

$$\mathscr{B}(\pi^+ \rightarrow e^+ \nu_e(\gamma)) = 1.2325(23) \times 10^{-4}$$

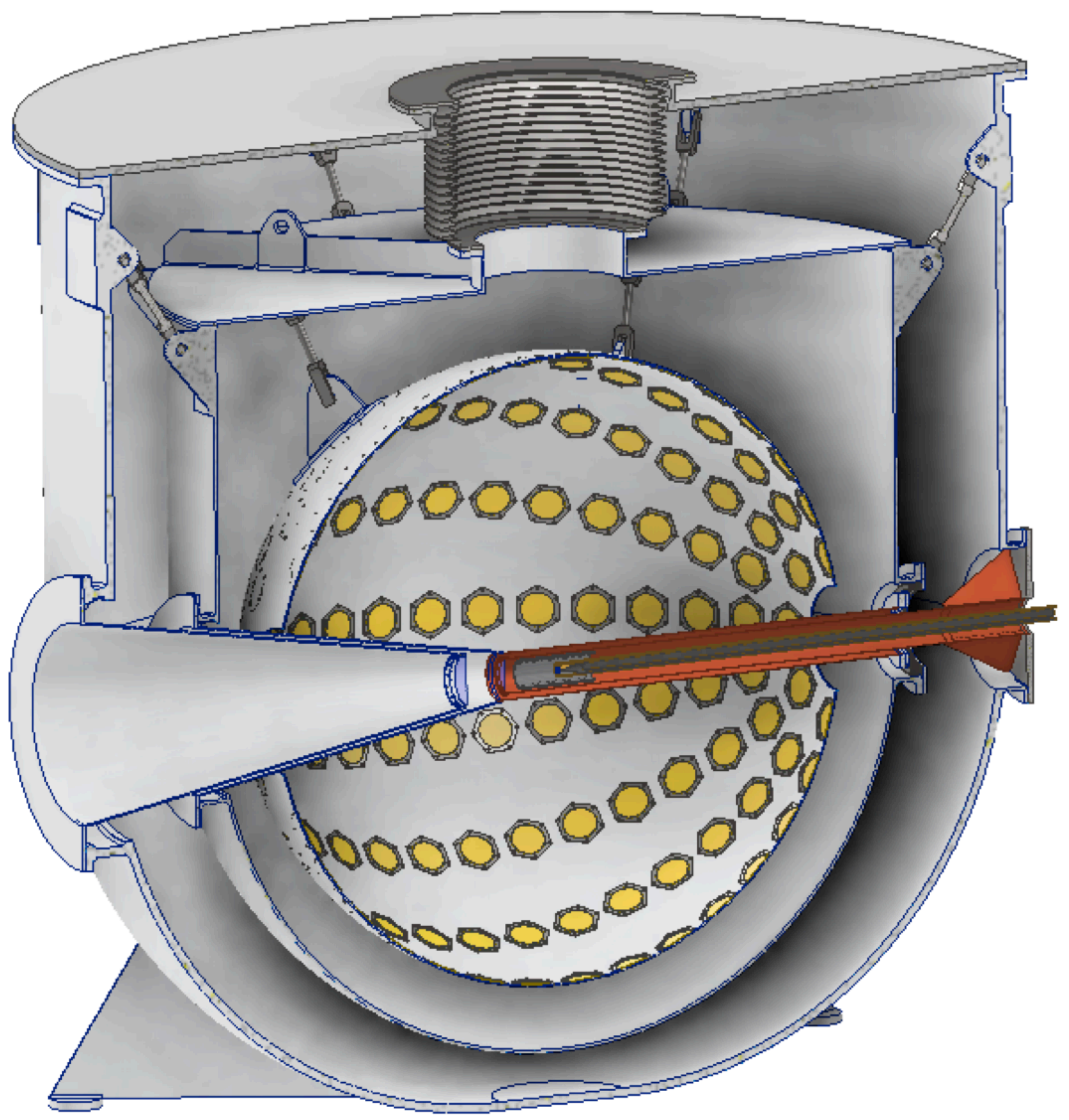
W. J. Marciano and A. Sirlin, Phys. Rev. Lett. 71, 3629 (1993)

Theory is in great shape (0.3% total error on V_{ud})

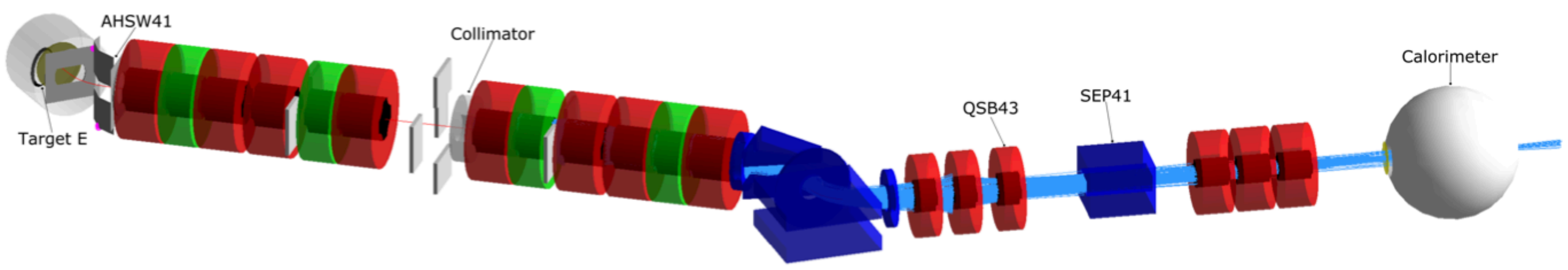
$$|V_{ud}| = 0.97386(281)_{BR}(9)_{\tau_\pi}(14)_{RC}(28)_{I_\pi}\,[283]_{total}$$

Experiment needs order of magnitude improvement in precision to be competitive

PIONEER: a next-generation pion decay experiment



Physics programme



What is PIONEER? [Proposal]

- PSI experiment
- intense pion beam + active target
- Tracker and LXe calorimeter

Data taking will start in about 5 yrs

Phase 1

$$R^{\pi}_{\mu/e} = \frac{\Gamma(\pi \to \mu\nu(\gamma))}{\Gamma(\pi \to e\nu(\gamma))}$$

- Experimental precision improvement by a factor of 15 to 0.01% level
- NP at the PeV scale can be probed

Phase 2 (high intensity π^+ beam)

$$\mathscr{B}r(\pi^+ \to \pi^0 e^+ \nu)$$

- Improve the precision by three times
- CKM matrix unitary check → 10 times improvement in Phase III (theoretically cleanest |Vud| test)

Conclusions

The Cabibbo angle is the cornerstone of the CKM matrix and the Cabibbo universality test is a precision tool to explore what may lie beyond the Standard Model

However...

- Need for experimental and theoretical investigations! Progress is expected on multiple fronts:
  - ➡ Experiment: neutron, K, π, τ
  - ➡ Theory: lattice QCD+QED for neutron, K, π; EFT+ 'ab-initio' methods for nuclei

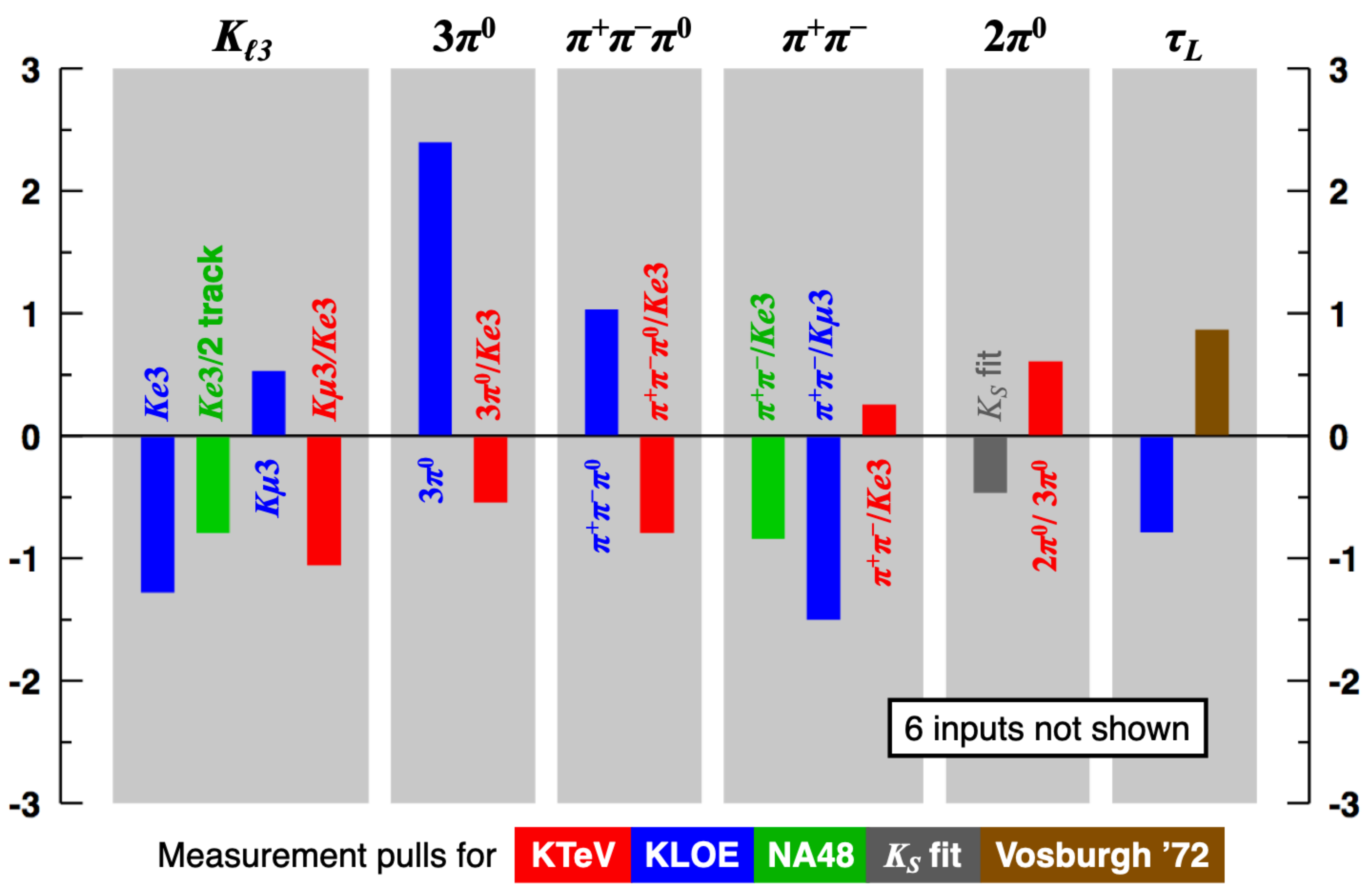
Ongoing experimental and theoretical efforts promise exciting developments

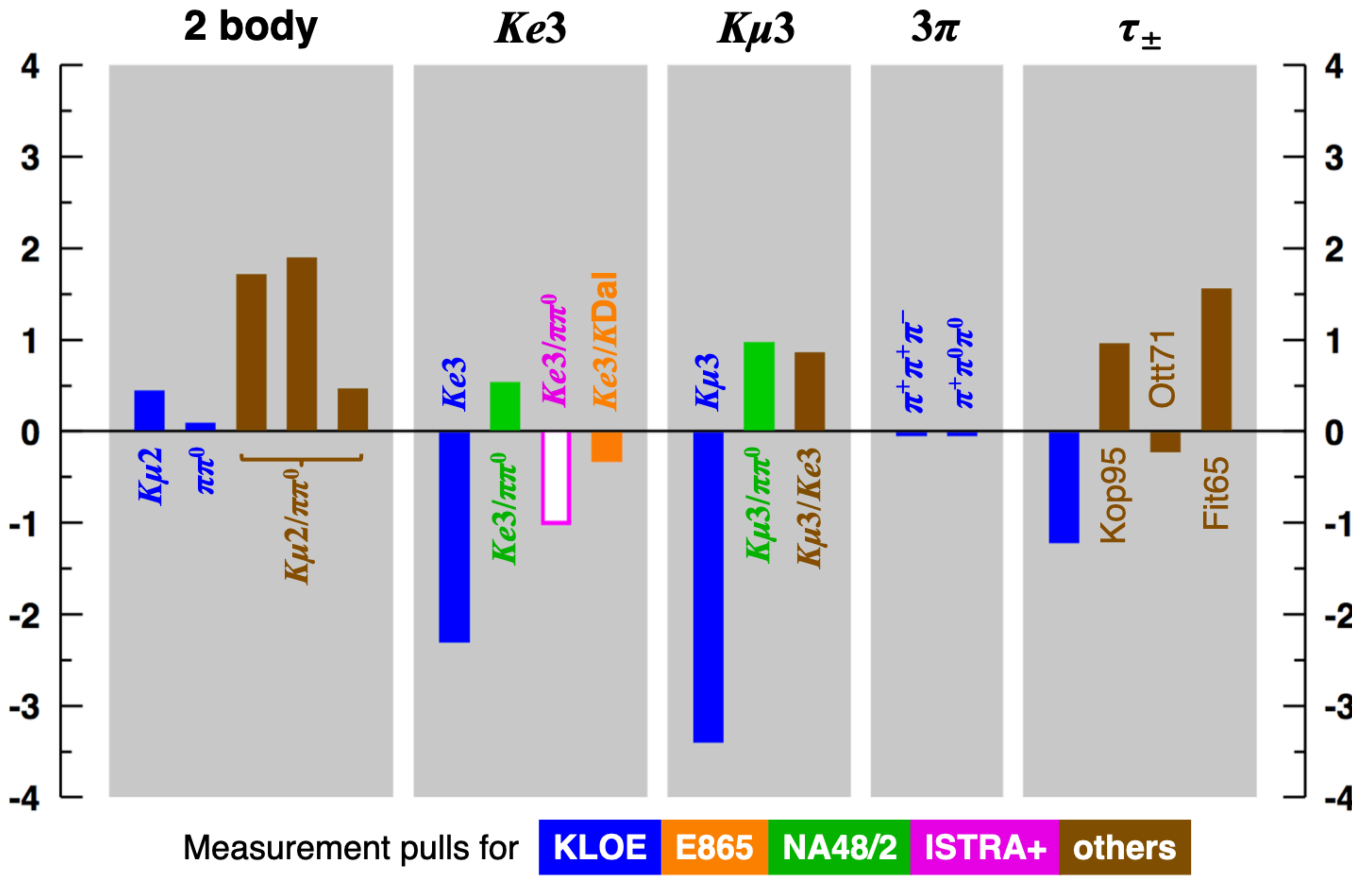
Spares

Fits to K_L and $K^{\pm}$ rate data : input data vs fit

Master formula

$$\Gamma(K \to \pi \ell \nu(\gamma)) = \frac{G_F^2 M_K^5 C_K^5}{192\pi^3} |V_{us}|^2 S_{EW} |f_+^{K^0\pi^-}(0)|^2 \, I_{K\ell}^{(0)} \left(1 + \delta_{EM}^{K\ell} + \delta_{SU(2)}^{K\pi}\right)$$





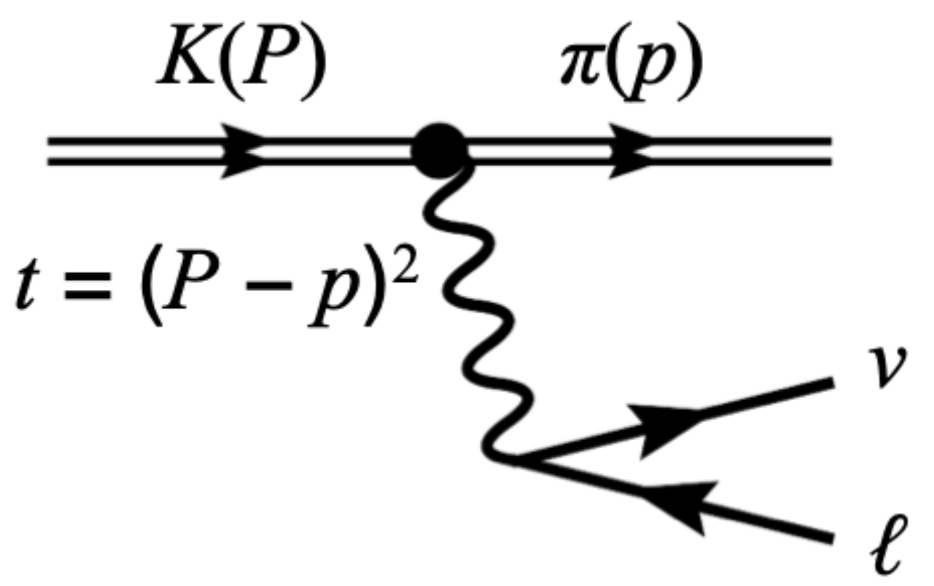
Error budget in $|V_{us}|f_+(0)$

			Approx. contrib. to % err from:			
		% err	**BR**	τ	Δ	**Int**
$K_L e3$	**0.2162(5)**	**0.23**	0.09	0.20	0.02	0.05
$K_L \mu 3$	**0.2165(6)**	**0.26**	0.15	0.18	0.02	0.07
$K_S e3$	**0.2169(8)**	**0.39**	0.38	0.02	0.02	0.05
$K_S \mu 3$	**0.2125(47)**	**2.2**	2.2	0.02	0.02	0.08
$K^{\pm} e3$	**0.2169(6)**	**0.30**	0.27	0.06	0.11	0.05
$K^{\pm} \mu 3$	**0.2168(10)**	**0.47**	0.45	0.06	0.11	0.08

$K_{\ell 3}$ form factors

Phase space factor

$$I_{K\ell}^{(0)} = \int_{m_\ell^2}^{(M_K^2-M_\pi^2)^2} \frac{dt}{M_K^8}\bar{\lambda}^{3/2}\left(1+\frac{m_\ell^2}{2t}\right)\left(1-\frac{m_\ell^2}{t}\right)^2\left[\bar{f}_+^2(t)+\frac{3m_\ell^2\Delta_{K\pi}^2}{(2t+m_\ell^2)\bar{\lambda}}\bar{f}_0^2(t)\right]$$

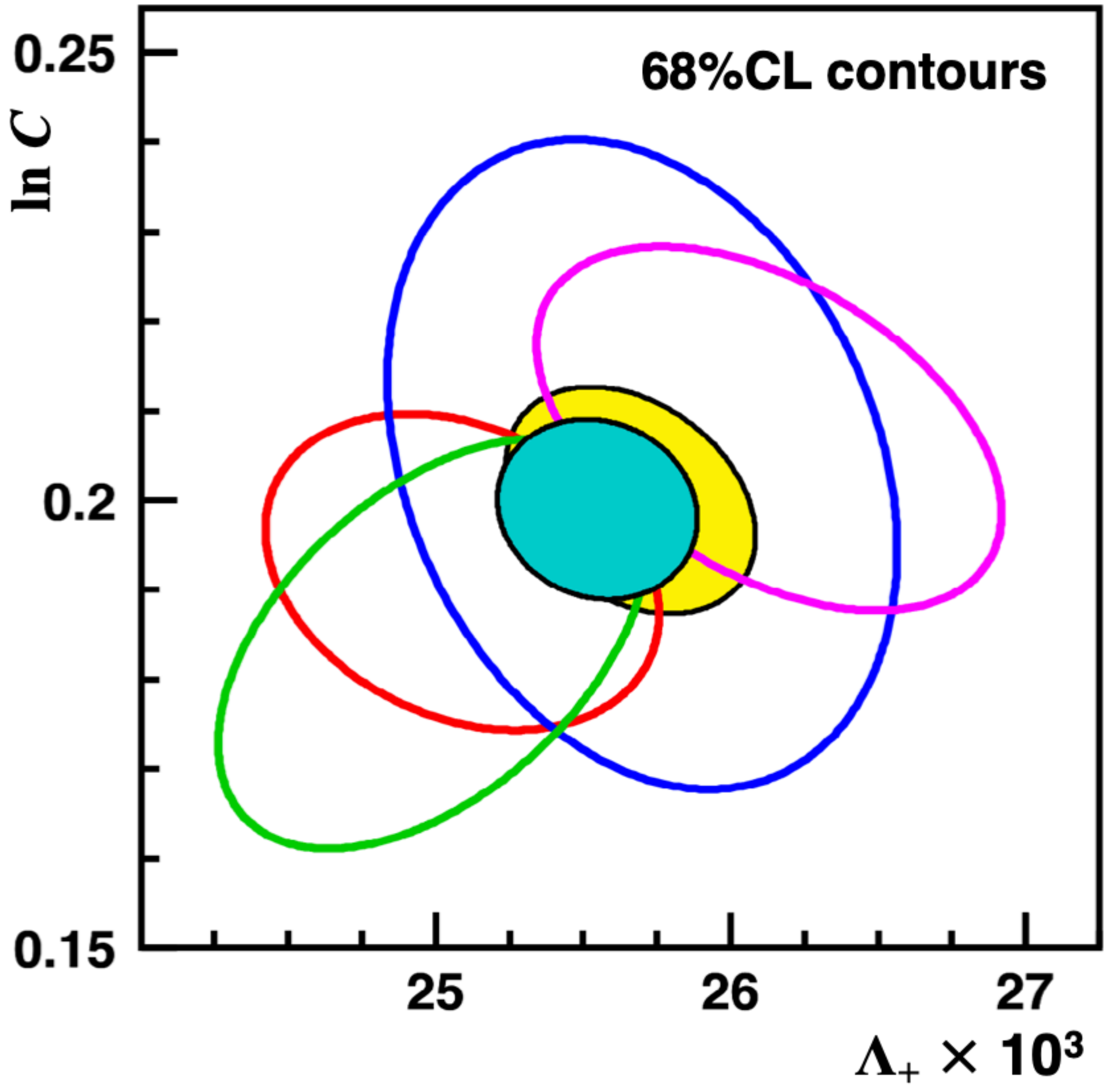


$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}\left(\Lambda_+ - H(t)\right)\right]$$

$$\tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2}\left(\ln C - G(t)\right)\right]$$

$K_{\ell 3}$ avgs from KTeV KLOE ISTRA+ NA48/2

NA48 K_{e3} data included in fits but not shown



2010 fit | Current

$\Lambda_+ \times 10^3$	=	25.55 ± 0.38
$\ln C$	=	0.1992(78)
$\rho(\Lambda_+, \ln C)$	=	−0.110
χ^2/ndf	=	7.5/7 (38%)

Mode	Update
$K^0{}_{e3}$	0.15470(15)
$K^+{}_{e3}$	0.15915(15)
$K^0{}_{\mu 3}$	0.10247(15)
$K^+{}_{\mu 3}$	0.10553(16)

Right handed currents

Find set of ε's so that Vud and Vus bands meet on the unitarity circle

$$|\bar{V}_{ud}|_i^2 = |V_{ud}|^2\left(1 + \sum_\alpha + C_{i\alpha}\epsilon_\alpha\right)$$

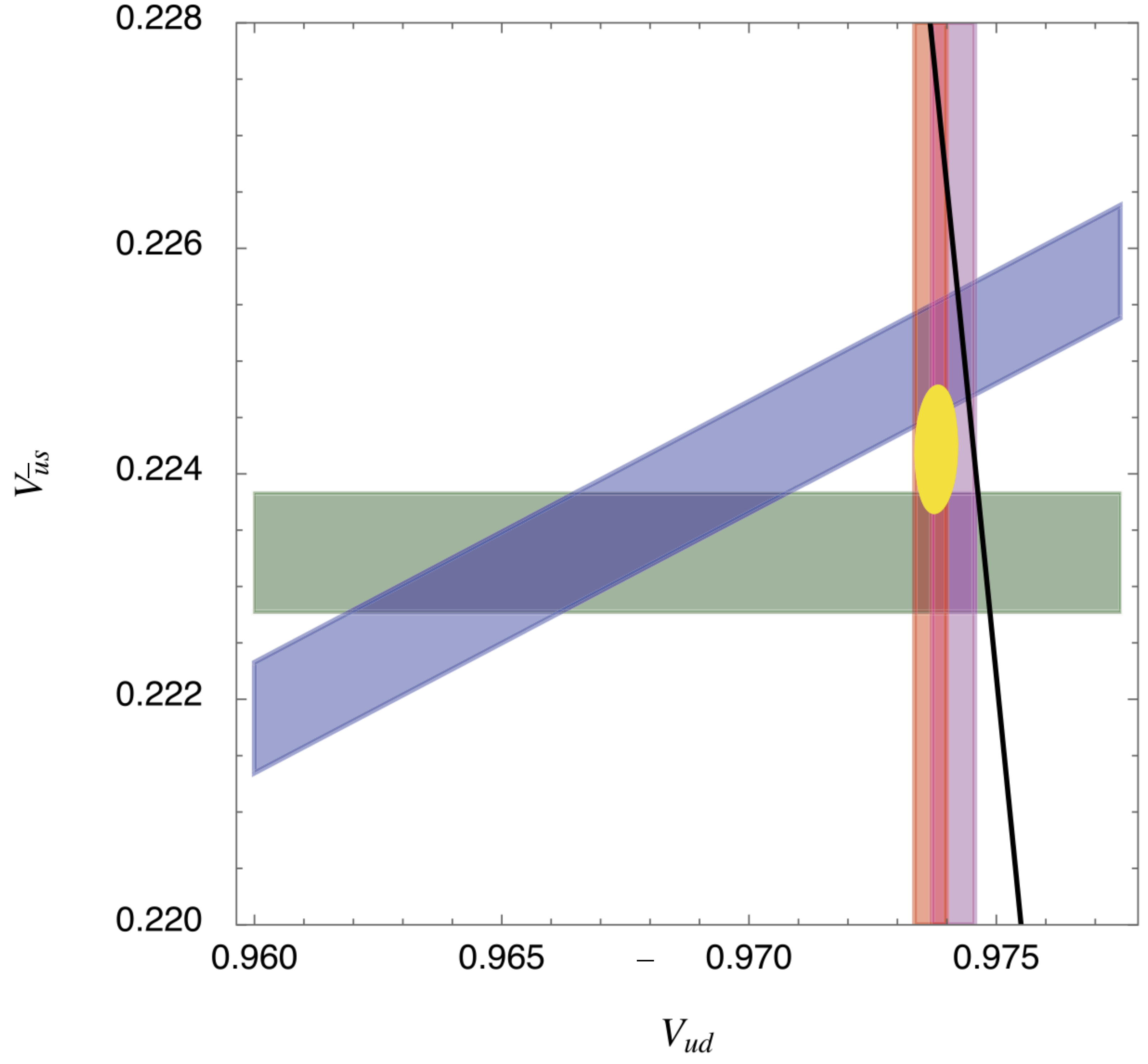
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2\left(1 + \sum_\alpha + C_{j\alpha}\epsilon_\alpha\right)$$

Channel-dependent CKM elements extracted in the 'SM-like analysis'

Elements of the unitary CKM matrix

Known coefficients

BSM effective couplings



RH (V+A) quark currents

- CKM elements from vector(axial) channels are shifted by $1 - \epsilon_R$ $(1 + \epsilon_R)$
- V_{us}/V_{ud}, V_{ud} and V_{us} shift in correlated way

Tensions in the $V_{ud} - V_{us}$ plane

$$\Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 - 1$$

Global fit 2.8σ discrepancy

A little bit of history

- Until ~2018, bands *did* intersect in the same region on the unitarity circle (< 2σ)
- **Main changes since then:**
  - **V_{ud} decreased (radiative corrections in nuclear & neutron increased with smaller uncertainty, dispersive)**
  - V_{us} from $K_{\ell 3}$ decreased ($< V >$ increased with smaller uncertainty, 2+1+1 lattice QCD)

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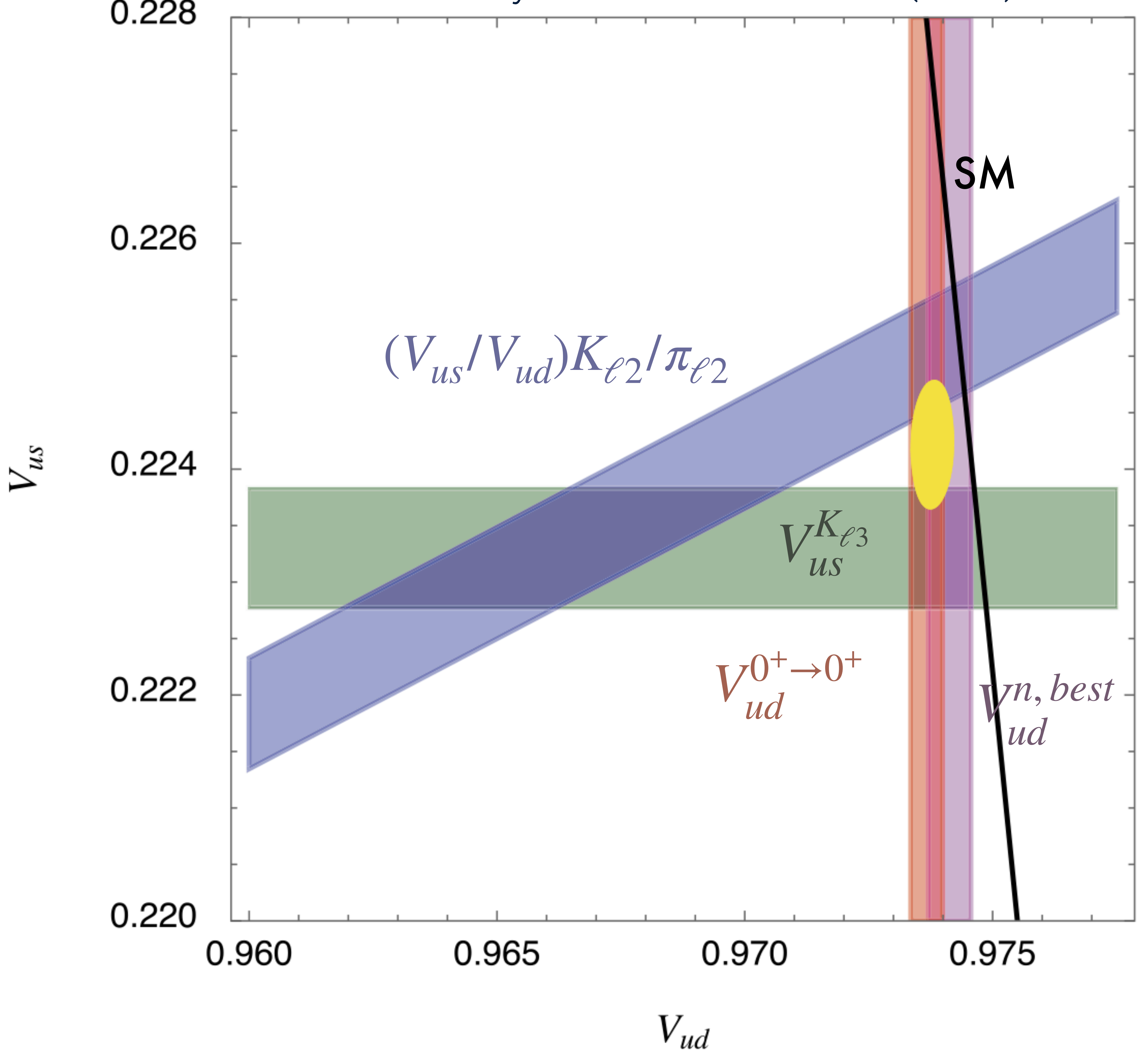

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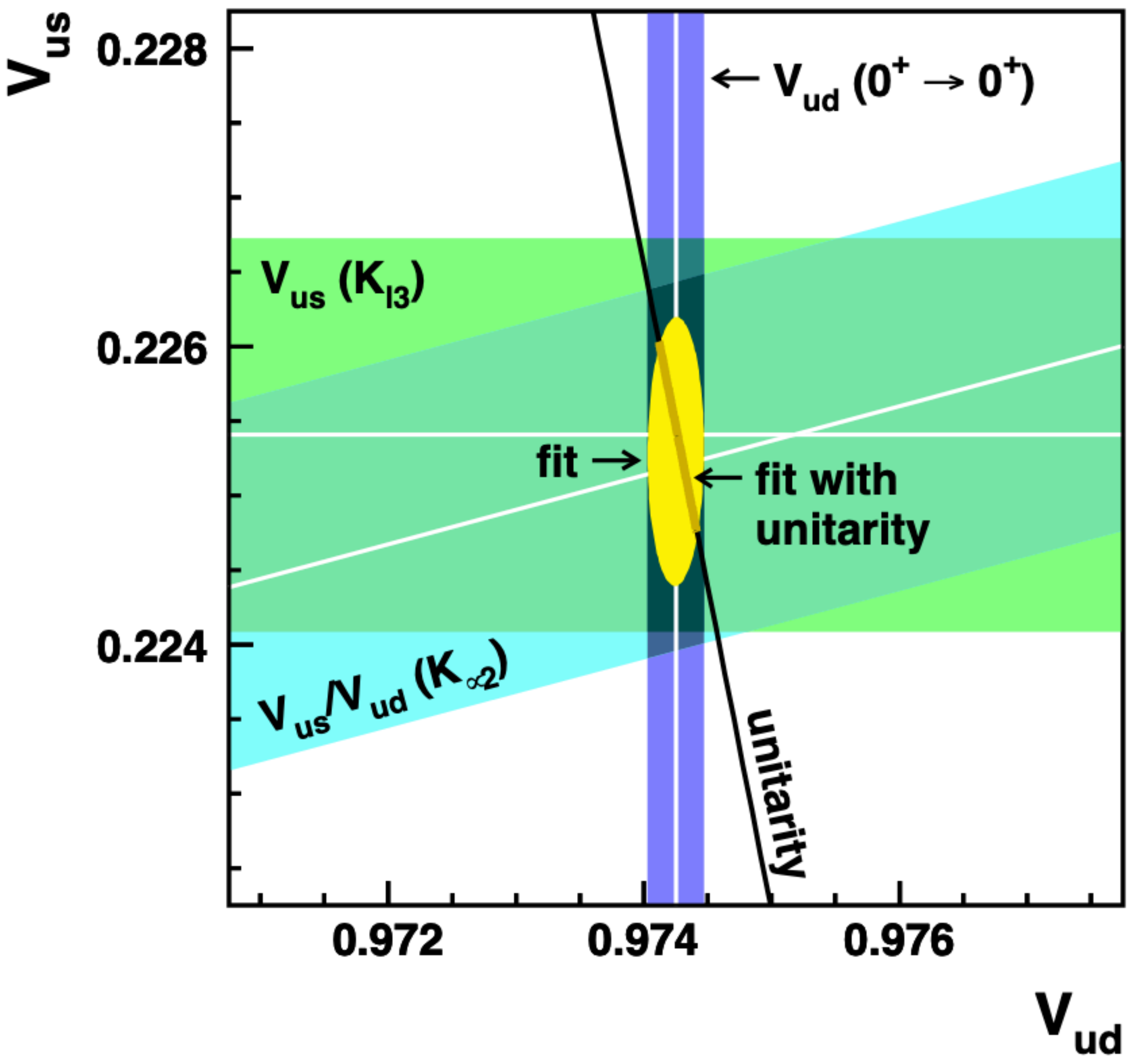
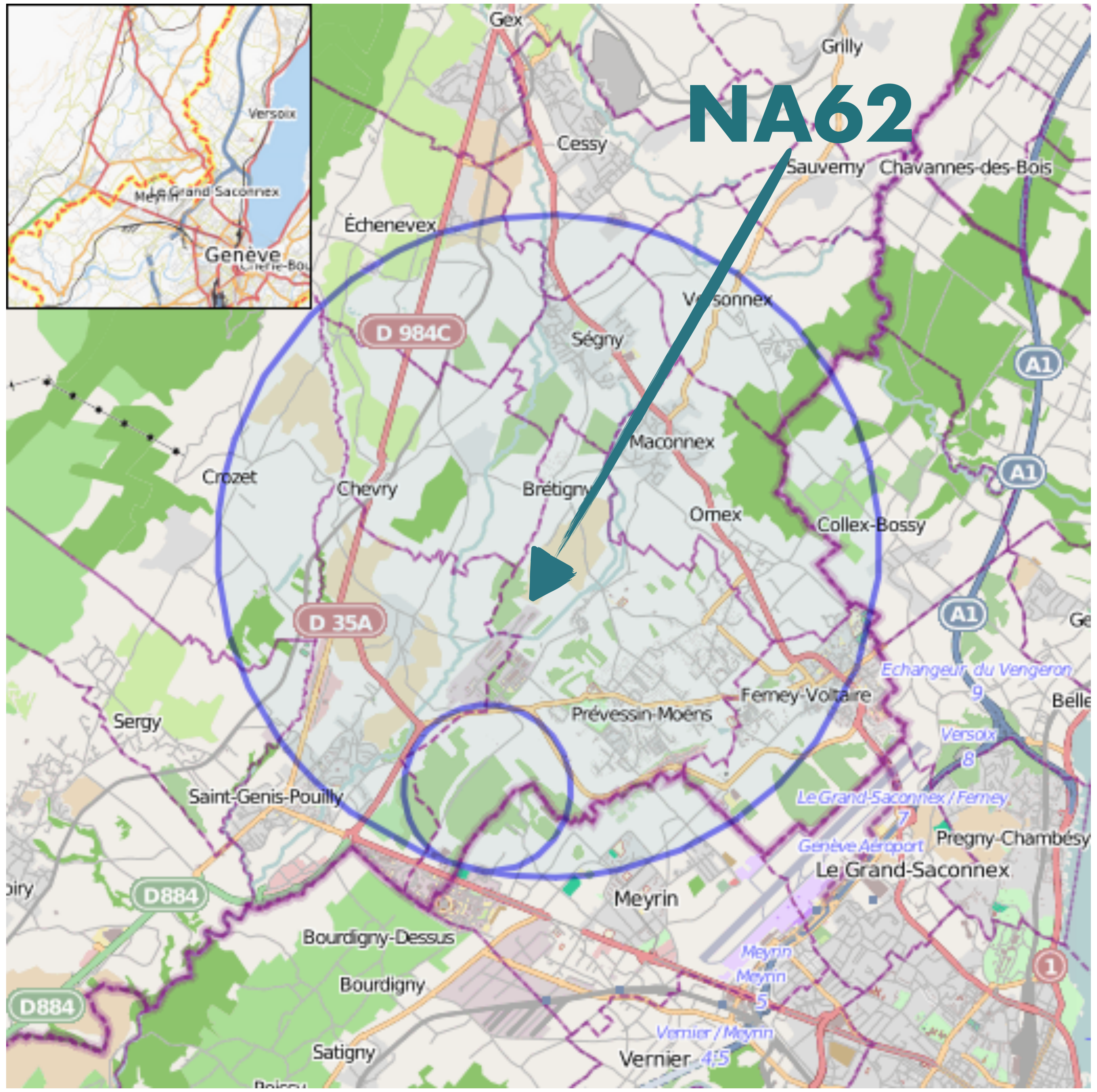


A Kaon factory at CERN



- Beam from the SPS: **400 GeV/c protons** on Be target
- Secondary 75 GeV/c beam hadrons (70% π, 24% p and **6%** K)
- **Decay in flight:** Kaons decay in a 60 meters long volume

The main aim of NA62 is to study the FCNC process $K^+ \to \pi^+ \nu \bar{\nu}$

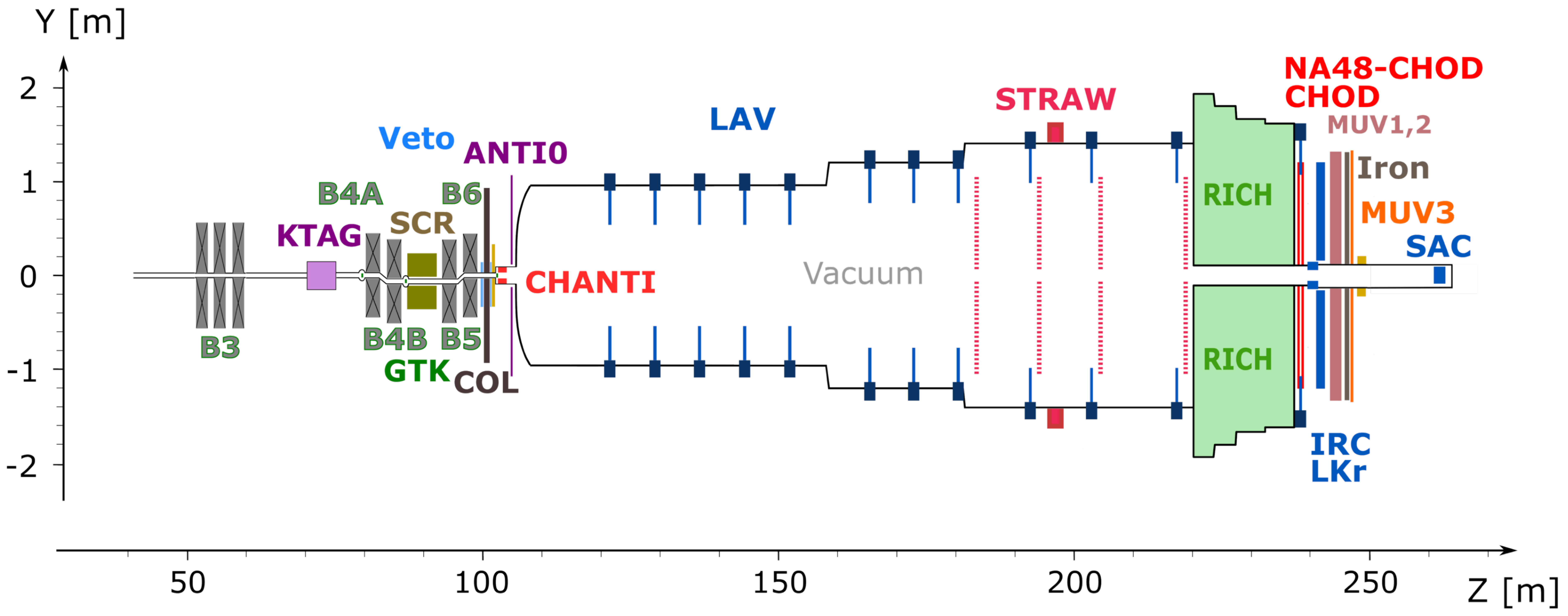
Theory [arXiv:2109.11032] $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$

NA62 [JHEP06 (2021) 093] $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.4^{+4.0}_{-3.4\,stat} \pm 0.9_{syst}) \times 10^{-11}$

Timeline of the NA62 Experiment:

2009-2014	2016-2018	2019-2021	2021-LS3
Detector R&D Installation	Run1	LS2 upgrade	Run 2

NA62 detector



Performances

- GTK-KTAG-RICH time resolution $\mathcal{O}(100\,ps)$
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for $15 < p(\pi^+) < 35\ GeV$
- $\mathcal{O}(10^8)$ π rejection for $E(\pi^0) > 40\,GeV$

Resolution

- Spectrometer $\sigma_p/p = (0.30 \oplus 0.005 \times p)\,\%$ [GeV/c]
- CHOD and NewCHOD resolution of 600 and 200 ps
- LKr $\sigma_E/E = (4.8/\sqrt{E} \oplus 11/E \oplus 0.9)\,\%$ [GeV]