Istituto Nazionale di Fisica Nucleare
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Experimental overview of CKM metrology from kaon physics

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Contents:
- Experimental status and Cabibbo Angle Anomaly
- Future experimental prospects

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CKM matrix and 1st row unitarity

- SM coupling of quarks and leptons to W:

$$\frac{g}{\sqrt{2}} W_\alpha^+ (\mathbf{U}_L V_{CKM} \gamma^\alpha \mathbf{D}_L + \bar{e}_L \gamma^\alpha \nu_{eL} + \bar{\mu}_L \gamma^\alpha \nu_{\mu L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau L}) + \text{h.c.}$$

Single gauge coupling, g

Unitary CKM matrix

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

$$|V_{CKM}^{ij}| = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.042 \\ 0.009 & 0.041 & 0.9991 \end{pmatrix}$$

[PDG 2023]

- Unitarity condition for 1st row:

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

$$\therefore \Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

$|V_{ud}|^2 \approx 0.949$

$|V_{us}|^2 \approx 0.05$

small

$|V_{ub}|^2 \approx 2 \times 10^{-5}$

$$\therefore \Delta^u_{CKM} \approxeq |V_{ud}|^2 + |V_{us}|^2 - 1 = 0$$

Focus on measurements of V_{ud} and V_{us}

CKM matrix and 1st row unitarity

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Single gauge coupling, g

Unitary CKM matrix

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

- Where $\lambda = V_{us} = \sin\theta_{12} = \sin\theta_{\text{Cabibbo}}$

CKM matrix and 1st row unitarity

- SM coupling of quarks and leptons to W:

$$\frac{g}{\sqrt{2}} W_\alpha^+ (\mathbf{U}_L V_{CKM} \gamma^\alpha \mathbf{D}_L + \bar{e}_L \gamma^\alpha \nu_{eL} + \bar{\mu}_L \gamma^\alpha \nu_{\mu L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau L}) + \text{h.c.}$$

Single gauge coupling, g

Unitary CKM matrix

- Most precise test of CKM unitarity, unitarity of for 1st row:

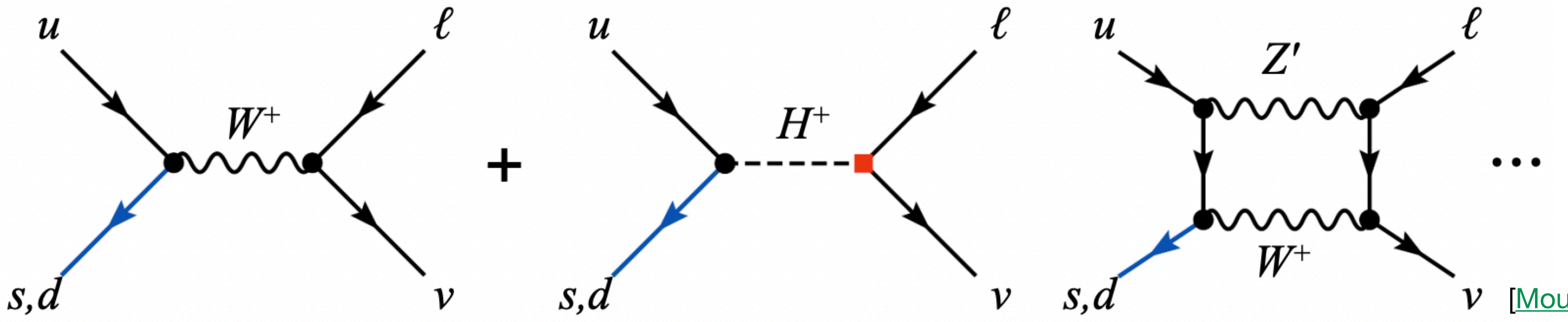
$$\therefore \Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

$|V_{ub}|^2 \approx 2 \times 10^{-5}$

- Universality: is the coupling the same for quarks and leptons?

$$G_\ell^2 = \frac{g_e g_\mu}{m_W^4} \stackrel{?}{=} G_{CKM}^2 = \frac{(g_q g_\ell)^2(|V_{ud}|^2 + |V_{us}|^2)}{m_W^4}$$

- BSM physics can break gauge universality:



[Moulson, CKM23]

CKM matrix and 1st row unitarity

- SM coupling of quarks and leptons to W:

$$\frac{g}{\sqrt{2}} W_\alpha^+ (\mathbf{U}_L V_{CKM} \gamma^\alpha \mathbf{D}_L + \bar{e}_L \gamma^\alpha \nu_{eL} + \bar{\mu}_L \gamma^\alpha \nu_{\mu L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau L}) + \text{h.c.}$$

Single gauge coupling, g

Unitary CKM matrix

- Most precise test of CKM unitarity, unitarity of for 1st row:

$$\therefore \Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$$

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- Universality: is the coupling the same for quarks and leptons?

$$G_\ell^2 = \frac{g_e g_\mu}{m_W^4} \stackrel{?}{=} G_{CKM}^2 = \frac{(g_q g_\ell)^2(|V_{ud}|^2 + |V_{us}|^2)}{m_W^4}$$

- BSM physics can break gauge universality:

$$G_{CKM,ij} \sim G_\ell V_{ij} \sim \frac{g^2}{m_W^2} V_{ij} \qquad \delta G_{CKM,ij} \sim \frac{1}{\Lambda^2}$$

→ **BSM effects scale as** $\frac{m_w^2}{g^2}\frac{1}{\Lambda^2}$

- Measurement of Δ^u_{CKM} with uncertainty σ probes scale $\Lambda \sim \frac{m_W}{g}\frac{1}{\sqrt{\sigma}}$
  - e.g. for $\sigma \sim 10^{-4}$ probe scale $\Lambda \sim 20$ TeV

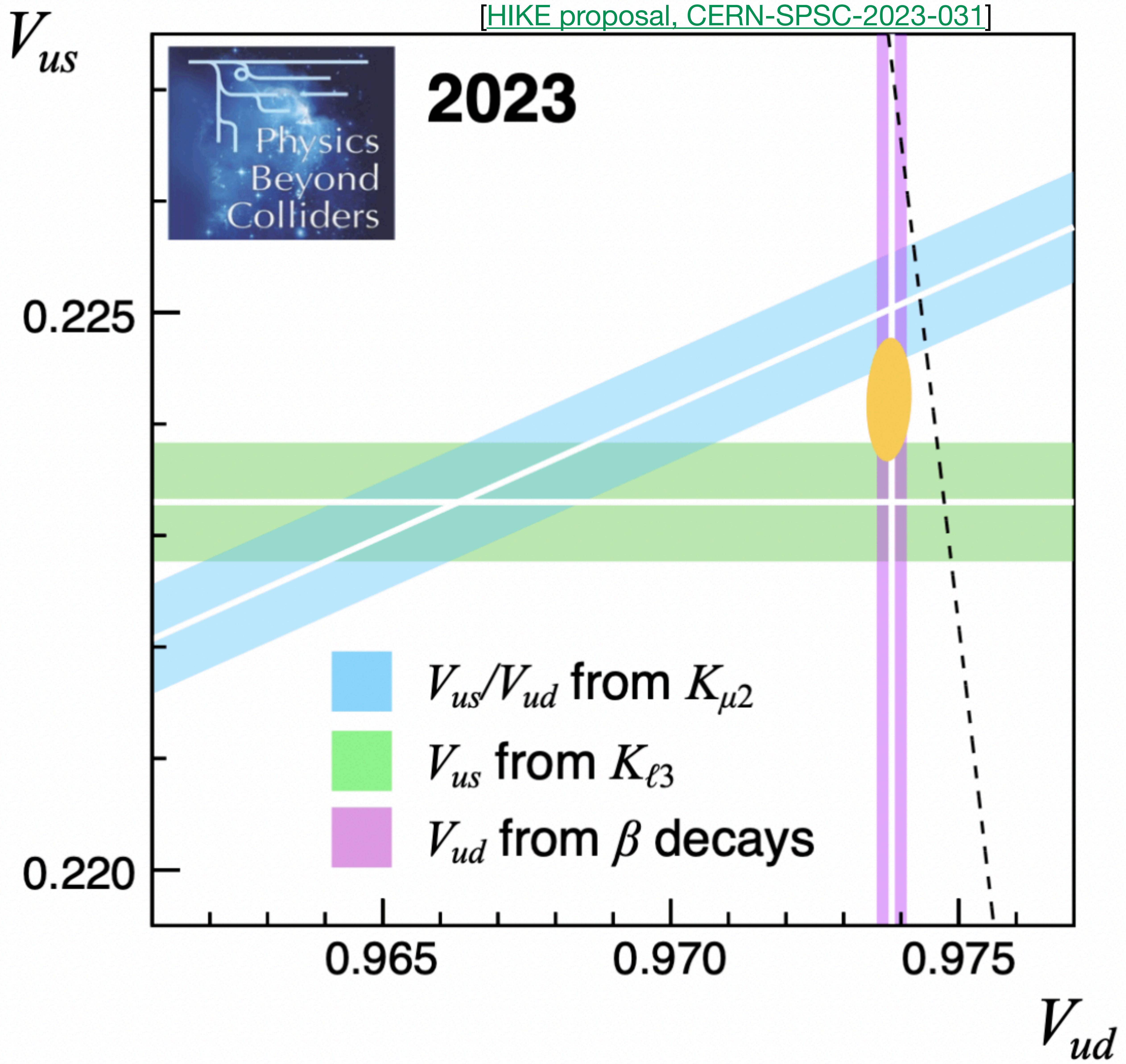
[Moulson, CKM23]

Status of 1st row unitarity test

$$\Delta^{u}_{CKM} \approxeq |V_{ud}|^2 + |V_{us}|^2 - 1 = 0$$

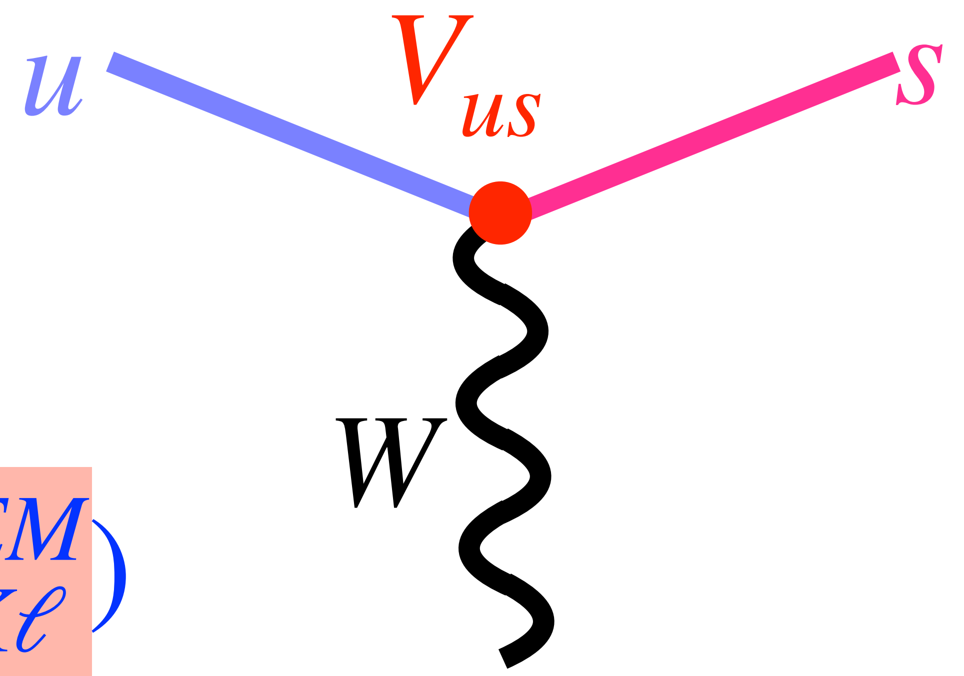
- $\therefore |V_{ud}|^2 + |V_{us}|^2 \approxeq 1$ defines a circle [dotted line]
- Independent methods measuring $|V_{ud}|$ and $|V_{us}|$, and their ratio, should all meet at a point on this circe…
- Discrepancy between measurements constitutes a 3σ deficit in 1st row CKM unitarity : **Cabibbo angle anomaly**.
- A tension with similar significance exists between rates of $K \to \ell\nu$ and $K \to \pi\ell\nu$.

[HIKE proposal, CERN-SPSC-2023-031]



$|V_{us}|$ Measurement

$|V_{us}|$ from $K_{\ell 3}$ decays



$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

- Where $K \in [K^+, K^0]$ and $\ell \in [e, \mu]$. $C_K^2 = \begin{cases} 0.5 & \text{for } K^+ \\ 1 & \text{for } K^0 \end{cases}$.
- $S_{EW} = 1.0232$: universal Short-Distance EW correction

Experimental inputs

- $\Gamma(K \to \pi \ell \nu(\gamma))$: **decay rates** with well-determined radiative decay treatment:
  - $K^{\pm}$,$K_{L,S}$ Branching ratios
  - Kaon lifetimes
- $I_{K_L}(\lambda_{K\ell})$: **integral of form factor over phase-space.**
  - λ terms parameterise t evolution.
  - K_{e3} : only λ_+ (or λ'_+ , λ''_+), $K_{\mu 3}$: need λ_+ and λ_0

Theoretical inputs

- $f_+^{K^0\pi^-}(0)$: hadronic metric element (**form factor**) at 0 momentum transfer (t=0)
- $\Delta_K^{SU(2)}$: **Form-factor correction** for $SU(2)$ breaking
- $\Delta_{K\ell}^{EM}$: **Form-factor correction** for Long-Distance EM effects.

$|V_{us}|$: Kaon decay rates experimental inputs

$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

K_S decays:

- $\mathscr{B}(K_S \to \pi^0\pi^0)$
  $\mathscr{B}(K_S \to \pi^+\pi^-(\gamma))$
- $\mathscr{B}(K_S \to \pi\ell\nu)$, $\ell = e, \mu$
- Lifetime τ_s

K_L decays:

- $\mathscr{B}(K_L \to \pi\ell\nu)$, $\ell = e, \mu$
- $\mathscr{B}(K_L \to \pi^0\pi^0\pi^0)$
- $\mathscr{B}(K_L \to \pi^+\pi^-\pi^0)$
- $\mathscr{B}(K_L \to \pi^+\pi^-(\gamma_{(IB,DE)}))$
- $\mathscr{B}(K_L \to \pi^0\pi^0)$
- $\mathscr{B}(K_L \to \gamma\gamma)$
- Lifetime τ_L

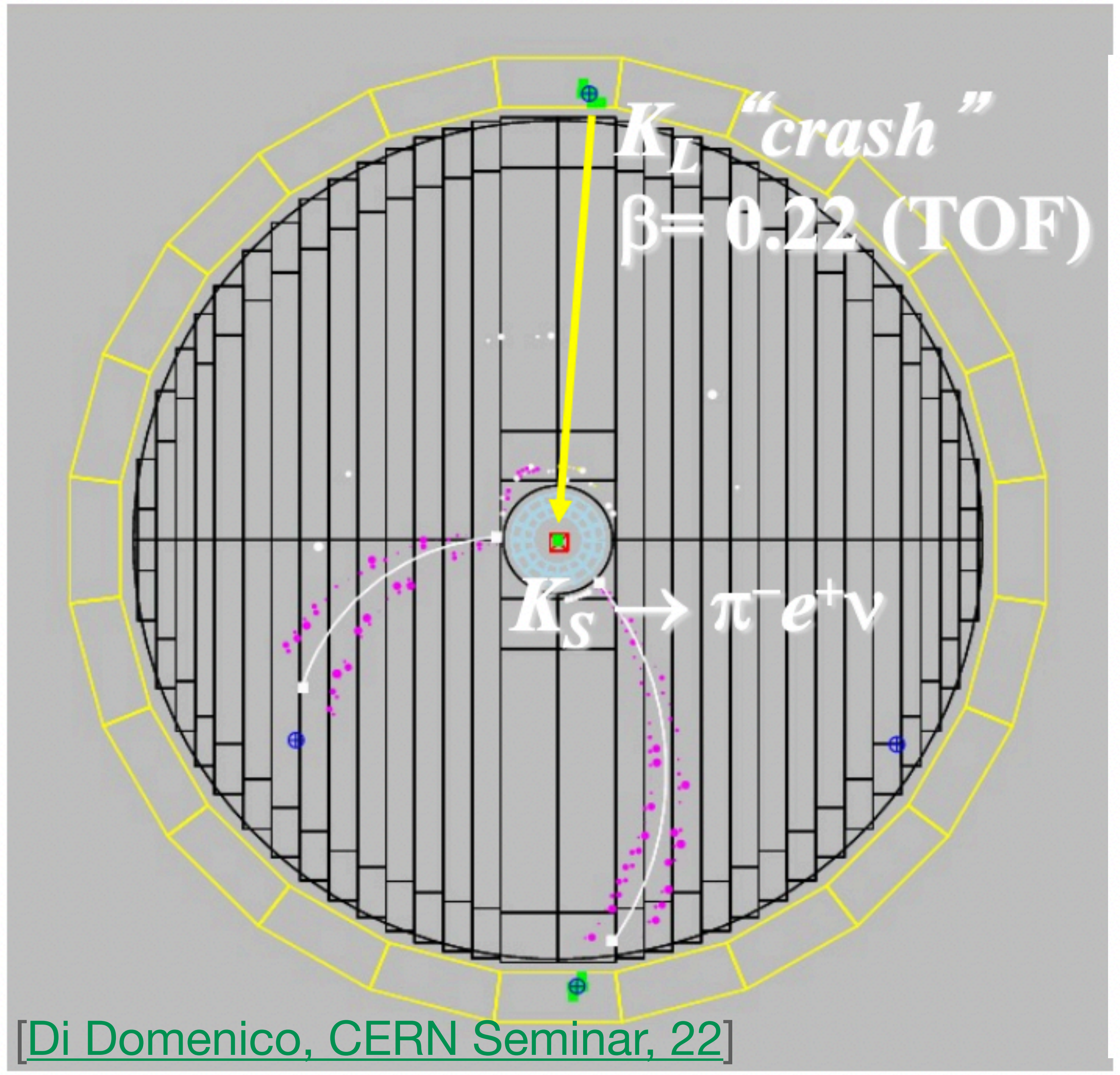
$K^\pm$ decays:

- $\mathscr{B}(K^\pm \to \mu^\pm\nu)$
- $\mathscr{B}(K^\pm \to \pi^\pm\pi^0)$
- $\mathscr{B}(K^\pm \to \pi^\pm\pi^+\pi^-)$
- $\mathscr{B}(K^\pm \to \pi^0\ell^\pm\nu)$, $\ell = e, \mu$
- $\mathscr{B}(K^\pm \to \pi^\pm\pi^0\pi^0)$
- Lifetime $\tau_\pm$

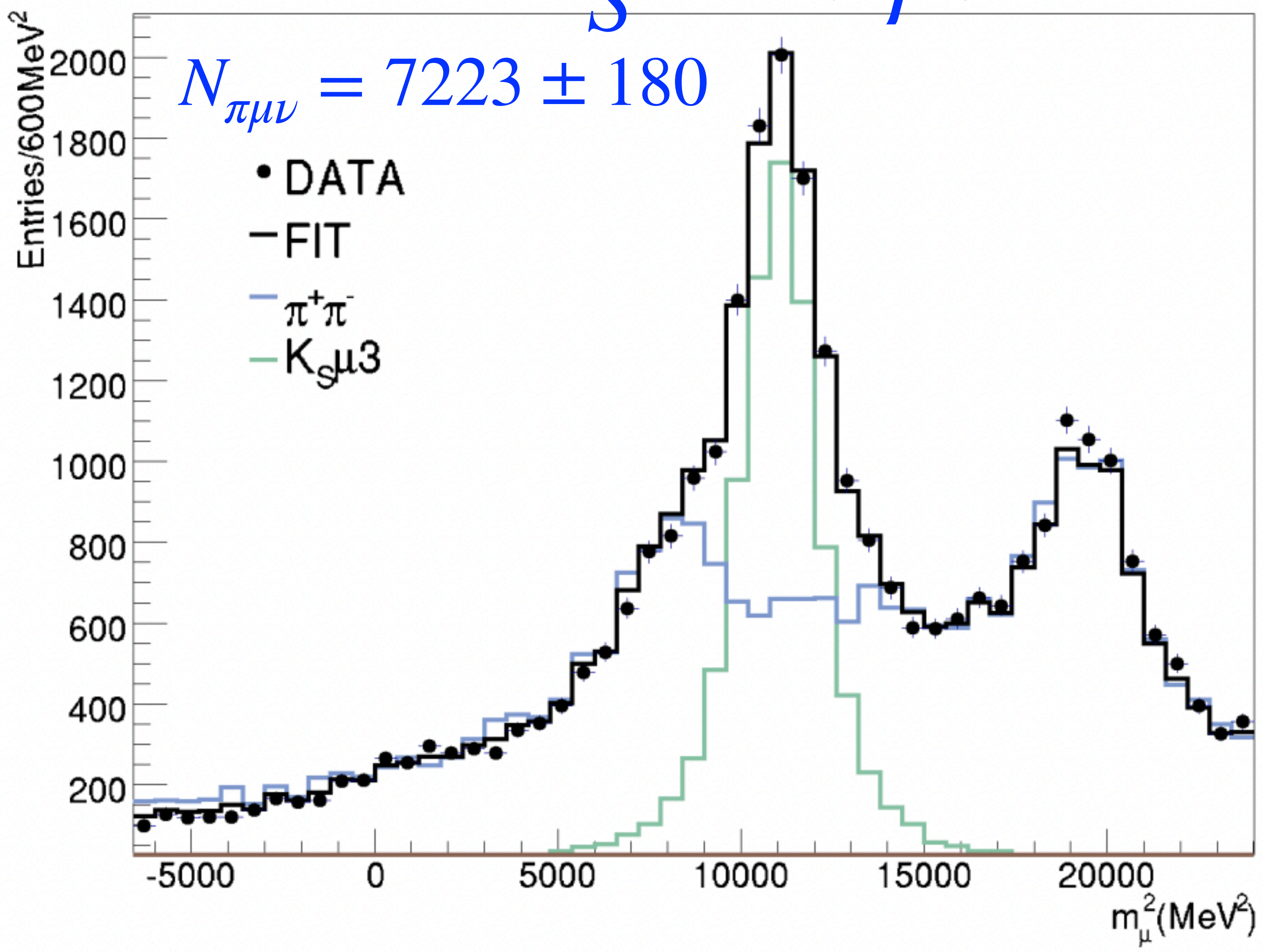
- Use various experimental inputs to fit…

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

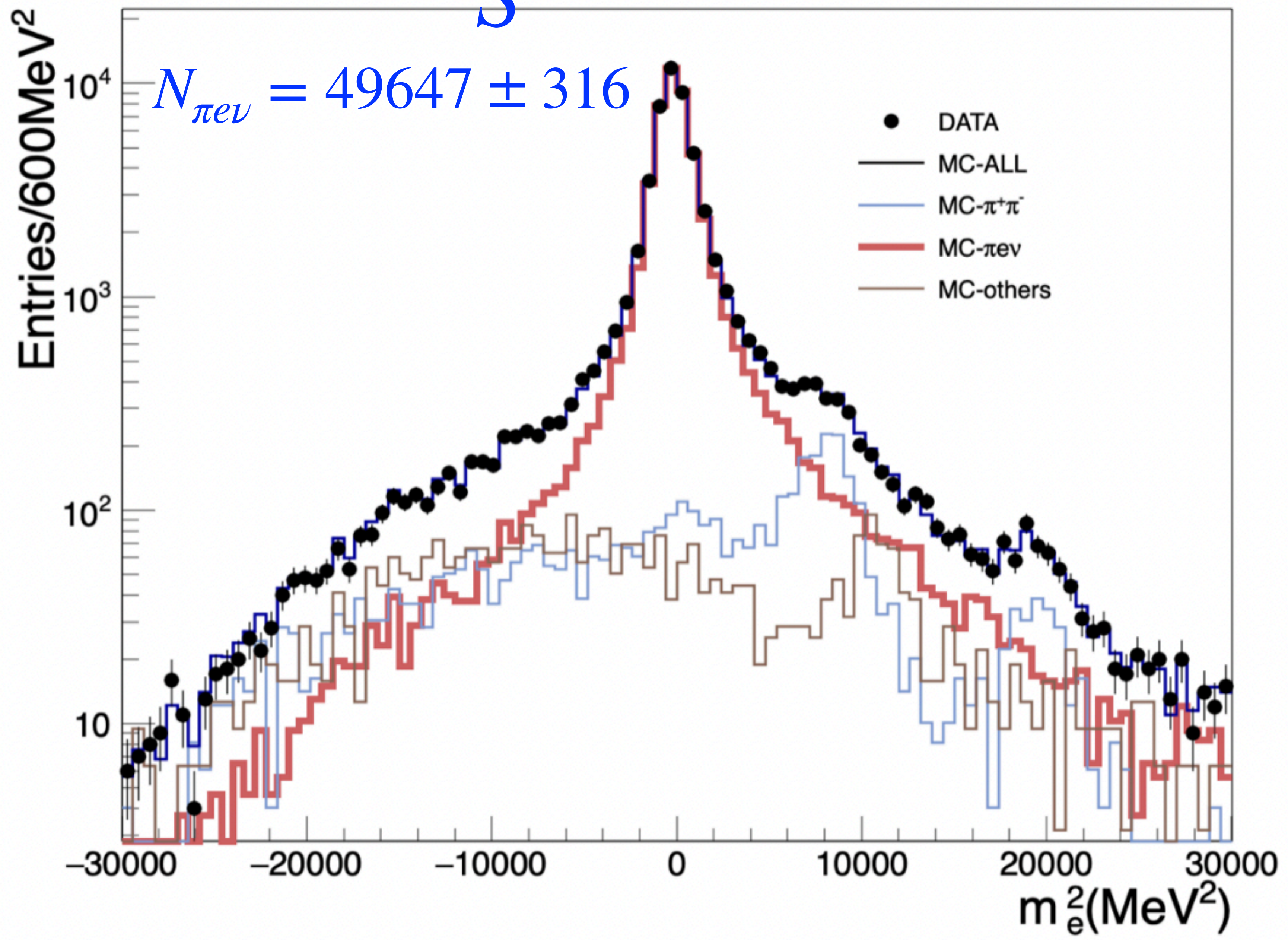
- DAΦNE ϕ-factory at LNF: $e^+e^- \to \phi \to K_S K_L$: tag K_L from "crash" interaction in calorimeter.
- Select signal with kinematic BDT & time-of-flight $\pi\ell$ assignment: fit to $m_\ell^2 = (E_{K_S} - E_\pi - p_{miss})^2 - p_\ell^2$.



$K_S \to \pi\mu\nu$



$K_S \to \pi e \nu$



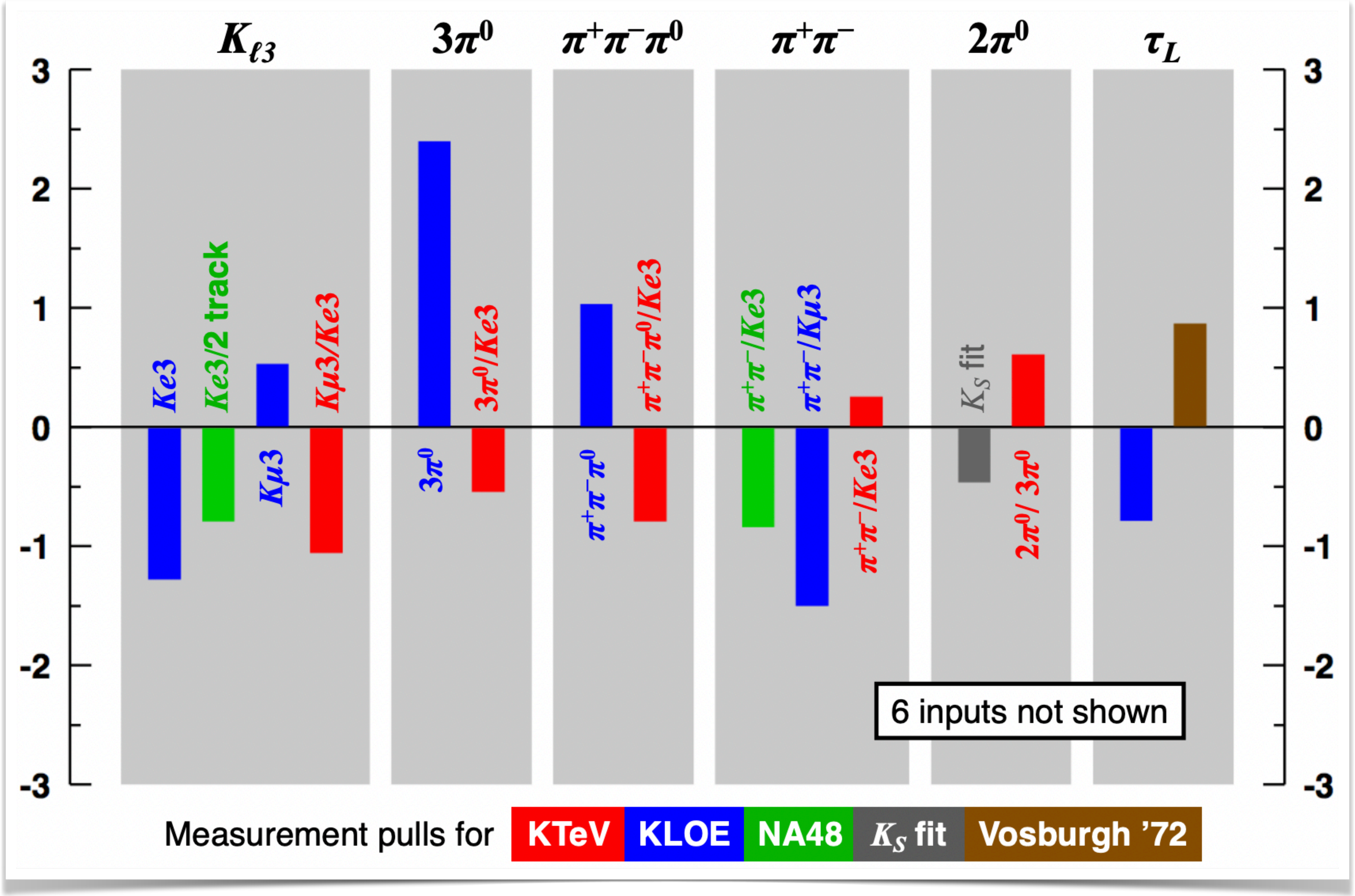
- [PLB 804 (2020) 135378] First measurement of BR: $\mathscr{B}(K_S \to \pi^0 \mu\nu) = (4.56 \pm 0.20) \times 10^{-4}$, based on $1.6\ \mathrm{fb}^{-1}$.
- [JHEP 02 (2023) 098] **recent result**: $\mathscr{B}(K_S \to \pi^0 e\nu) = (7.153 \pm 0.037_{\text{stat}} \pm 0.044_{\text{syst}}) \times 10^{-4}$ [0.8% unc.], based on $1.6\ \mathrm{fb}^{-1}$.
- Both normalised to $\mathscr{B}(K_S \to \pi^+\pi^-)$ [also measured by KLOE]. Used to extract measurements of $|V_{us}|f_+(0)$ (see later).

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

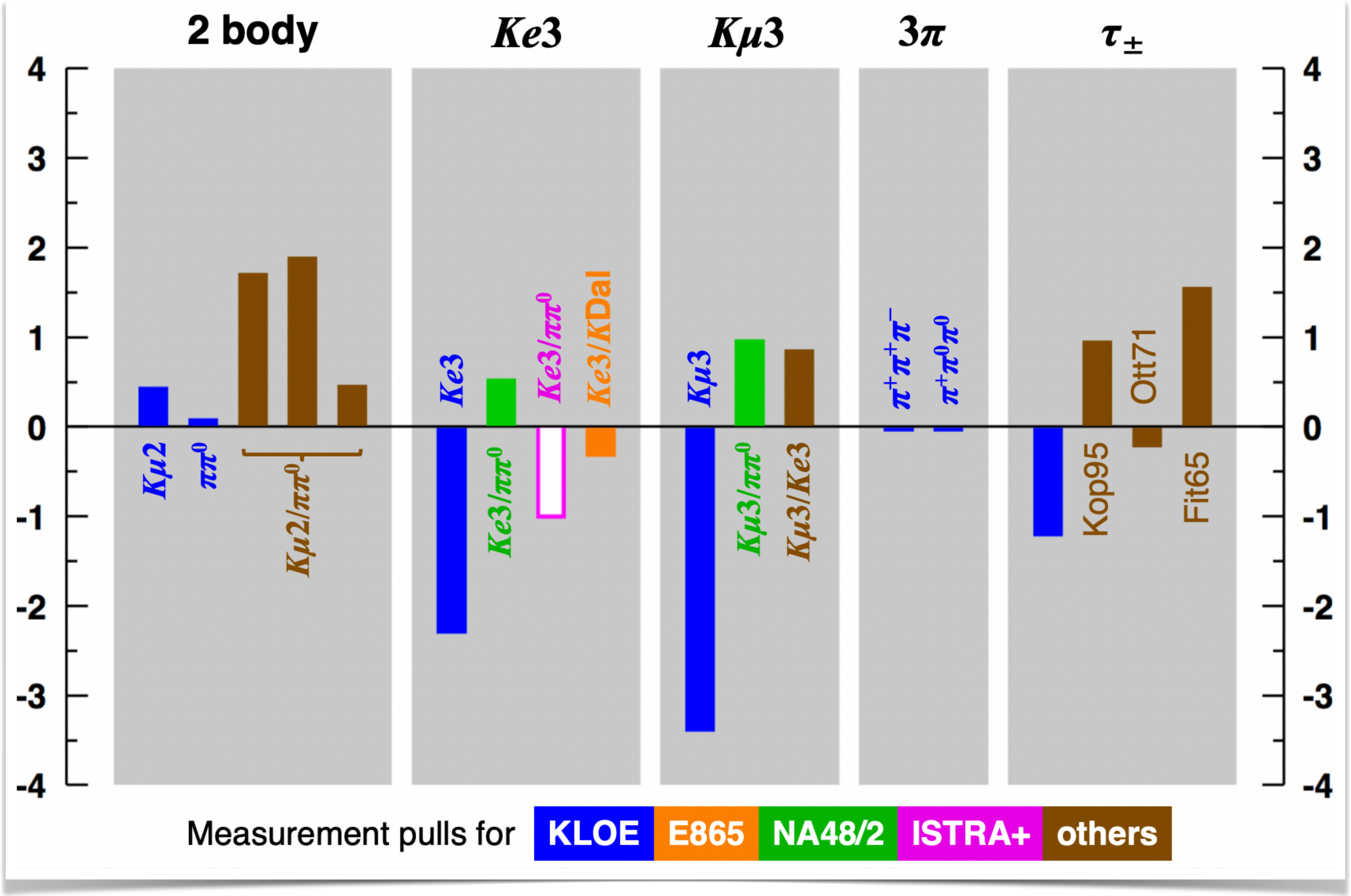
[Moulson, CKM23]

$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

K_L Fit



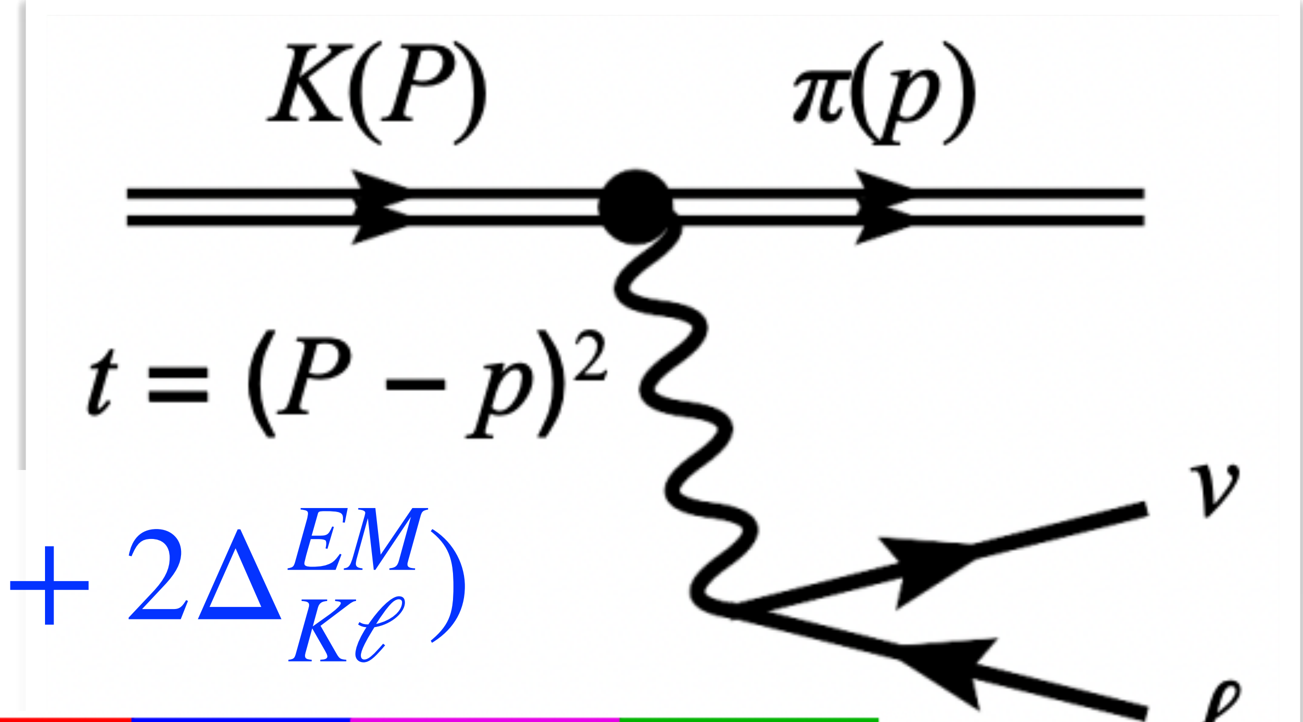
$K^\pm$ Fit



See backups for details of inputs.

$K_{\ell 3}$ Form factors

[Moulson, CKM23]



$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

- Form factor parameterisations

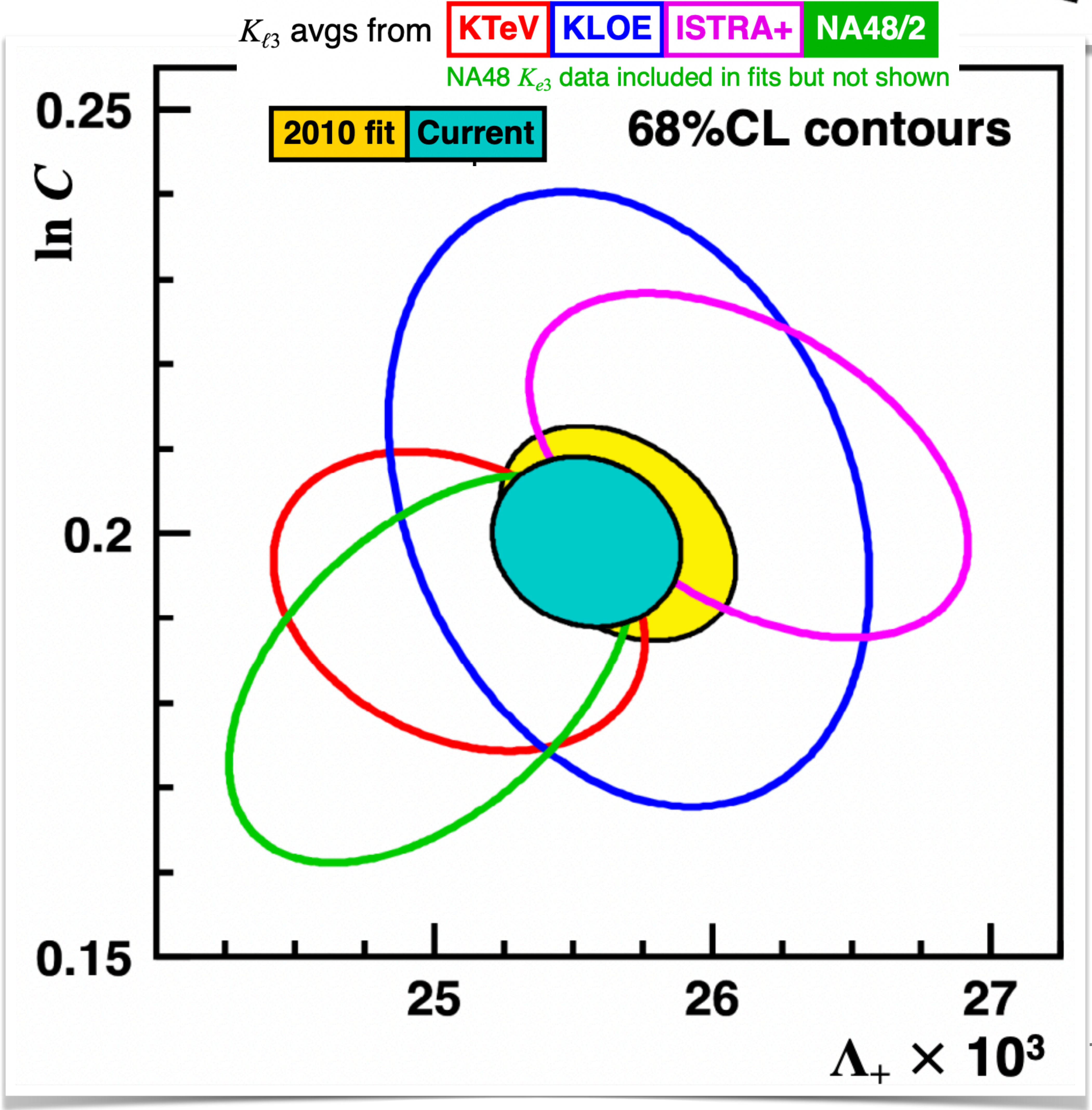
$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2(\Lambda_+ - H(t))}\right], \tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2(\ln C - G(t))}\right].$$

- Current fit:

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

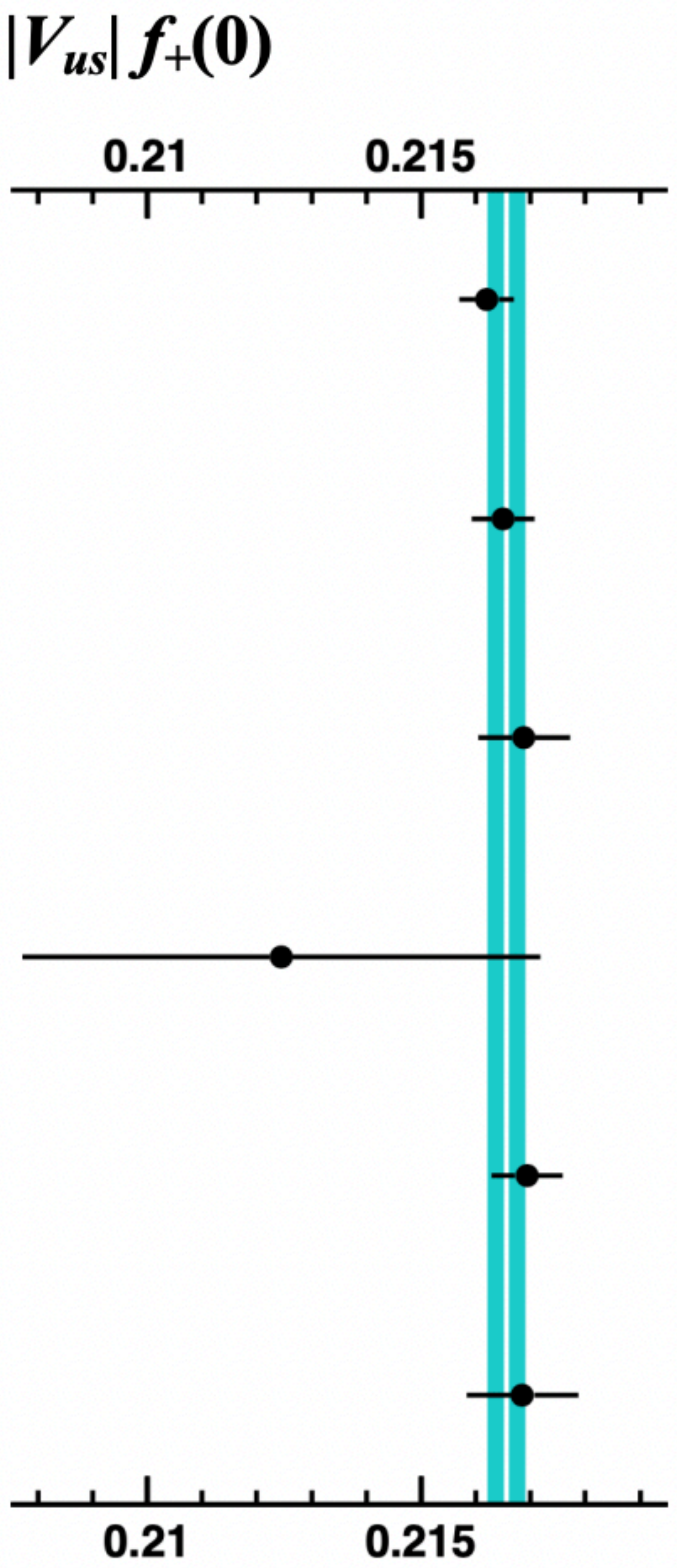
Integrals

Mode	Update	2010
$K^0{}_{e3}$	**0.15470(15)**	0.15476(18)
$K^+{}_{e3}$	**0.15915(15)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10247(15)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10553(16)**	0.10559(17)



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

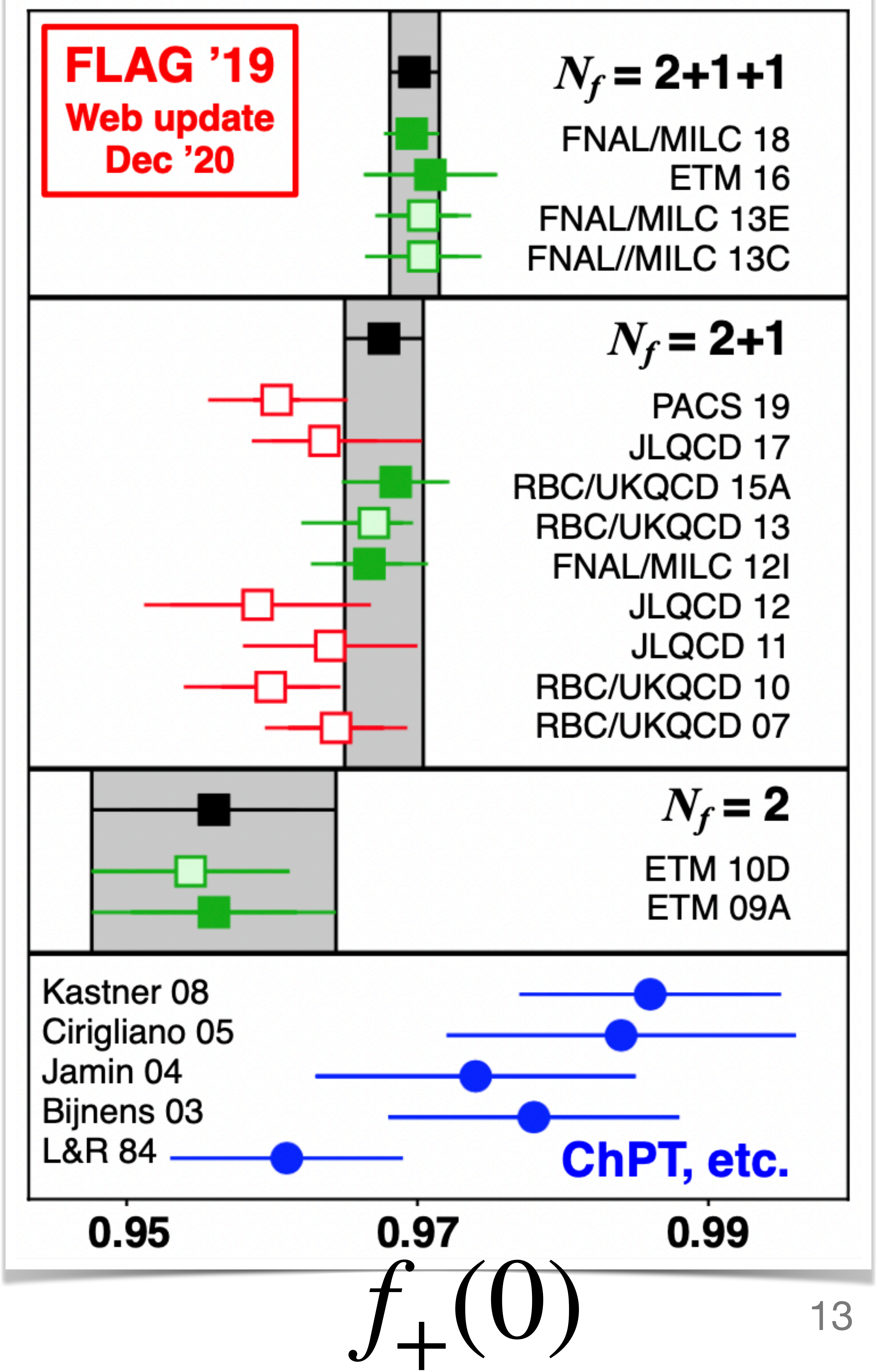
[Moulson, CKM23]



$K_{\ell 3}$ decays

		% err	Approx. contrib. to % err from: 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

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



- See also: [FLAG '21].

$\frac{|V_{us}|}{|V_{ud}|}$ Measurement

$\frac{|V_{us}|}{|V_{ud}|}$ from $K^{\pm} \to \mu^{\pm}\nu$ and $\pi^{\pm} \to \mu^{\pm}\nu$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi_{\mu 2(\gamma)}} m_{K^\pm}}\right)^{\frac{1}{2}} \left(\frac{1 - \frac{m_\mu^2}{m_{\pi^\pm}^2}}{1 - \frac{m_\mu^2}{m_{K^\pm}^2}}\right) \left(1 - \frac{1}{2}\delta_{EM} - \frac{1}{2}\delta_{SU(2)}\right)$$

Experimental inputs

- $\Gamma(K_{\mu 2})$ and $\Gamma(\pi_{\mu 2})$: **decay rates.**
  - **Branching ratios** $\mathscr{B}(K_{\mu 2})$ and $\mathscr{B}(\pi_{\mu 2})$ plus **lifetimes** $\tau_{K^\pm}$ and $\tau_{\pi^\pm}$.
    - Use $K^{\pm}$ info from fits.
    - Use $\pi^{\pm}$ info from PDG.

Theoretical inputs

- f_K/f_π : **ratio of decay constants,** lattice-scale uncertainties cancel.
- δ_{EM} : **Long-Distance EM corrections** for $SU(2)$ breaking.
- $\delta_{SU(2)}$: **Strong isospin breaking** $f_K/f_\pi \to f_{K^\pm}/f_{\pi^\pm}$.

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

[Moulson, CKM23]

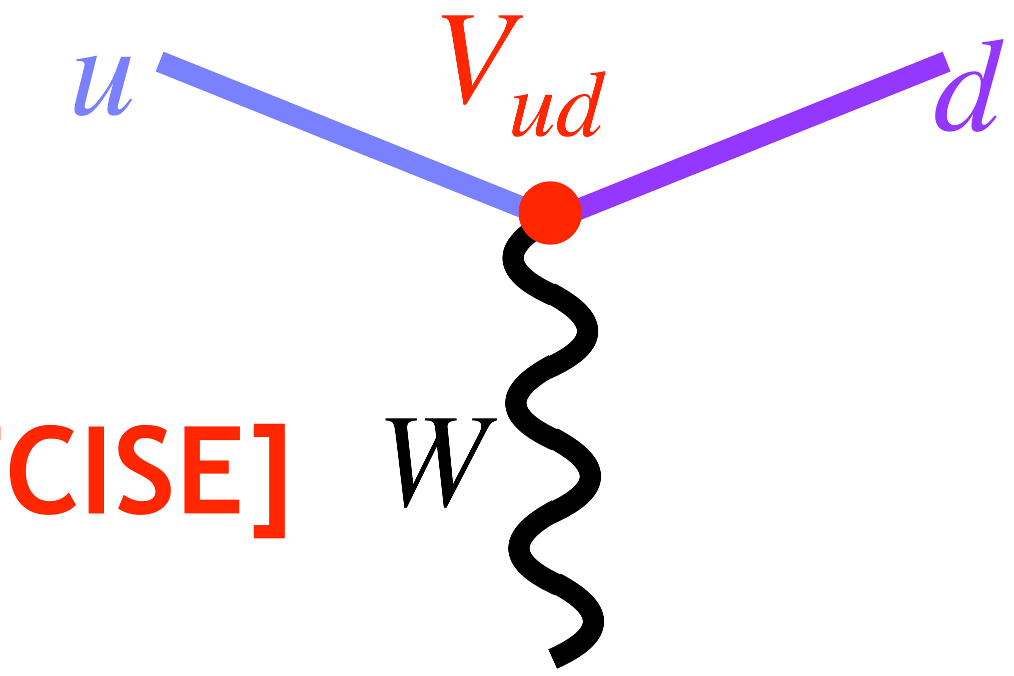
Summary : $|V_{us}|$ and $\frac{|V_{us}|}{|V_{ud}|}$ from Kaon decays

- **From** $K_{\ell 3}$: $|V_{us}| = 0.22330(35)_{\text{exp}}(39)_{\text{lat}}(8)_{\text{IB}}$ [total frac. unc. = 0.24%]
  - With $f_+(0) = 0.9698(17)$.
- **From** $K_{\mu 2}$: $\frac{|V_{us}|}{|V_{ud}|} = 0.23108(23)_{\text{exp}}(42)_{\text{lat}}(16)_{\text{IB}}$ [total frac. unc. = 0.22%]
  - With $f_K/f_\pi = 1.1978(22)$
- Are these results consistent with unitarity? : $\Delta^{(3)}_{CKM} = |V_{us}|^2_{(K_{\ell 3})}\left(\frac{1}{|V_{us}/V_{ud}|^2_{(K\mu 2)}} + 1\right) - 1$
  - Unitarity test: $\Delta^{(3)}_{CKM} = 0$?
  - Find: $\Delta^{(3)}_{CKM} = -0.0164(63)$ i.e. -2.6σ .

Hint of anomaly only from $K_{\mu 2}$ vs $K_{\mu 3}$

$|V_{ud}|$ Measurement

Determinations of $|V_{ud}|$



- $|V_{ud}|$ **from super-allowed** $0^+ \rightarrow 0^+$ **nuclear beta decays** **[MOST PRECISE]**
  - e.g. $^{14}\text{O}(14,8) \rightarrow {}^{14}\text{N}(14,7) + e^+ + \bar{\nu}_e$
  - Measure half-lives and Q-values, determine decay rate factors and then $|V_{ud}|$.
  - Using 15 most precisely measured decays [Phys.Rev.C 102 (2020) 4, 045501] and up-to-date set of radiative corrections [PLB 838 (2023) 137748]:
    $|V_{ud}|_\beta = 0.97367(11)_{\text{exp}}(13)_{\text{Rad.Cor.}}(27)_{\text{Nucl.Struc.}}$

    Fractional uncertainty: $\sigma_{|V_{ud}|}/|V_{ud}| = 3.3 \times 10^{-4}$

- $|V_{ud}|$ **from neutron lifetime** τ_n **and axial-vector/vector coupling** $g_A = G_A/G_V$, (recent precision measurements avoiding inconsistencies [PLB 838 (2023) 137748]):
  - $|V_{ud}|_n = 0.97413(13)_{\text{Rad.Cor.}}(35)_{g_A}(20)_{\tau_n}$

    Fractional uncertainty: $\sigma_{|V_{ud}|}/|V_{ud}| = 4.4 \times 10^{-4}$

- Good agreement, use average: $|V_{ud}| = 0.97384(26)$

  Fractional uncertainty: $\sigma_{|V_{ud}|}/|V_{ud}| = 2.7 \times 10^{-4}$

[PDG23]

Global picture

Status of 1st row unitarity test

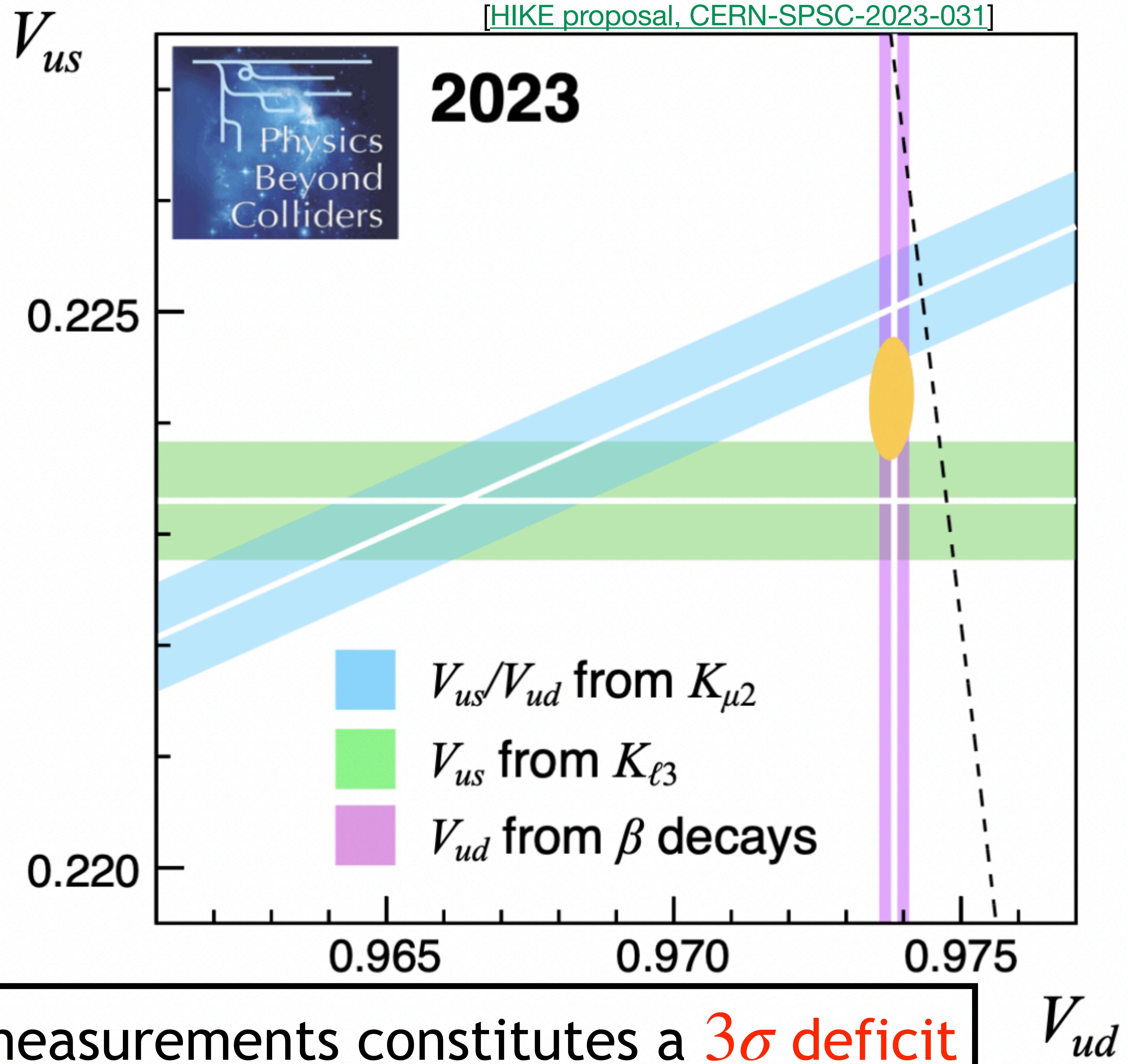
$$\Delta^u_{CKM} \approxeq |V_{ud}|^2 + |V_{us}|^2 - 1 = 0$$

- $\therefore |V_{ud}|^2 + |V_{us}|^2 \approxeq 1$ defines a circle [dotted line]
- Just from kaon decays: -2.6σ discrepancy

$$\Delta^{(3)}_{CKM} = |V_{us}|^2_{(K_{\ell 3})}\left(\frac{1}{|V_{us}/V_{ud}|^2_{(K\mu 2)}} + 1\right) - 1 = -0.0164(63)$$

- Include $|V_{ud}|$ from β decays: -2.8σ discrepancy
  - From fit (yellow blob) without constraint: $[\chi^2/\text{ndf} = 6.4/2 \ \ (4.1\%)]$
    - $\Delta^u_{CKM} = -0.0018(6)$
    - $V_{ud} = 0.97378(26)$, $V_{us} = 0.22422(36)$
    - With scale factor $S = 2.6$:
      - $V_{ud} = 0.9737(8)$, $V_{us} = 0.2242(10)$

[HIKE proposal, CERN-SPSC-2023-031]



- Discrepancy between measurements constitutes a 3σ deficit in 1st row CKM unitarity : **Cabibbo angle anomaly.**

1st row unitarity tests

$$\Delta^u_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$$

$|V_{ub}|^2 \approx 2 \times 10^{-5}$

- 3 observables: $|V_{us}|^2_{(K_{\ell 3})}$, $\left|\frac{V_{us}}{V_{ud}}\right|^2_{(K\mu 2)}$ and $|V_{ud}|_{(\beta)}$, and 2 unknowns V_{ud} and V_{us} .

Therefore construct 3 tests (each $\Delta^{(i)}_{CKM} = 0$ if unitarity holds…)

$$\Delta^{(1)}_{CKM} = |V_{ud}|^2_{(\beta)} + |V_{us}|^2_{(K_{\ell 3})} - 1 = -0.00176(56) \quad [-3.1\sigma]$$

$$\Delta^{(2)}_{CKM} = |V_{ud}|^2_{(\beta)}\left[1 + |V_{us}/V_{ud}|^2_{K\mu 2}\right] - 1 = -0.00098(58) \quad [-1.7\sigma]$$

$$\Delta^{(3)}_{CKM} = |V_{us}|^2_{(K_{\ell 3})}\left(|V_{us}/V_{ud}|^{-2}_{(K\mu 2)} + 1\right) - 1 = -0.0164(63) \quad [-2.6\sigma]$$

Not using any inputs from β decays

[PLB 838 (2023) 137748]

1^{st} row non-unitarity: BSM with RH currents?

- In SM W only couples to Left-Handed chiral fermion states.
- BSM physics with couplings to Right-Handed currents could explain deficits in 1st row unitarity and $K_{\ell 3} - K_{\mu 2}$ difference.
- Define:

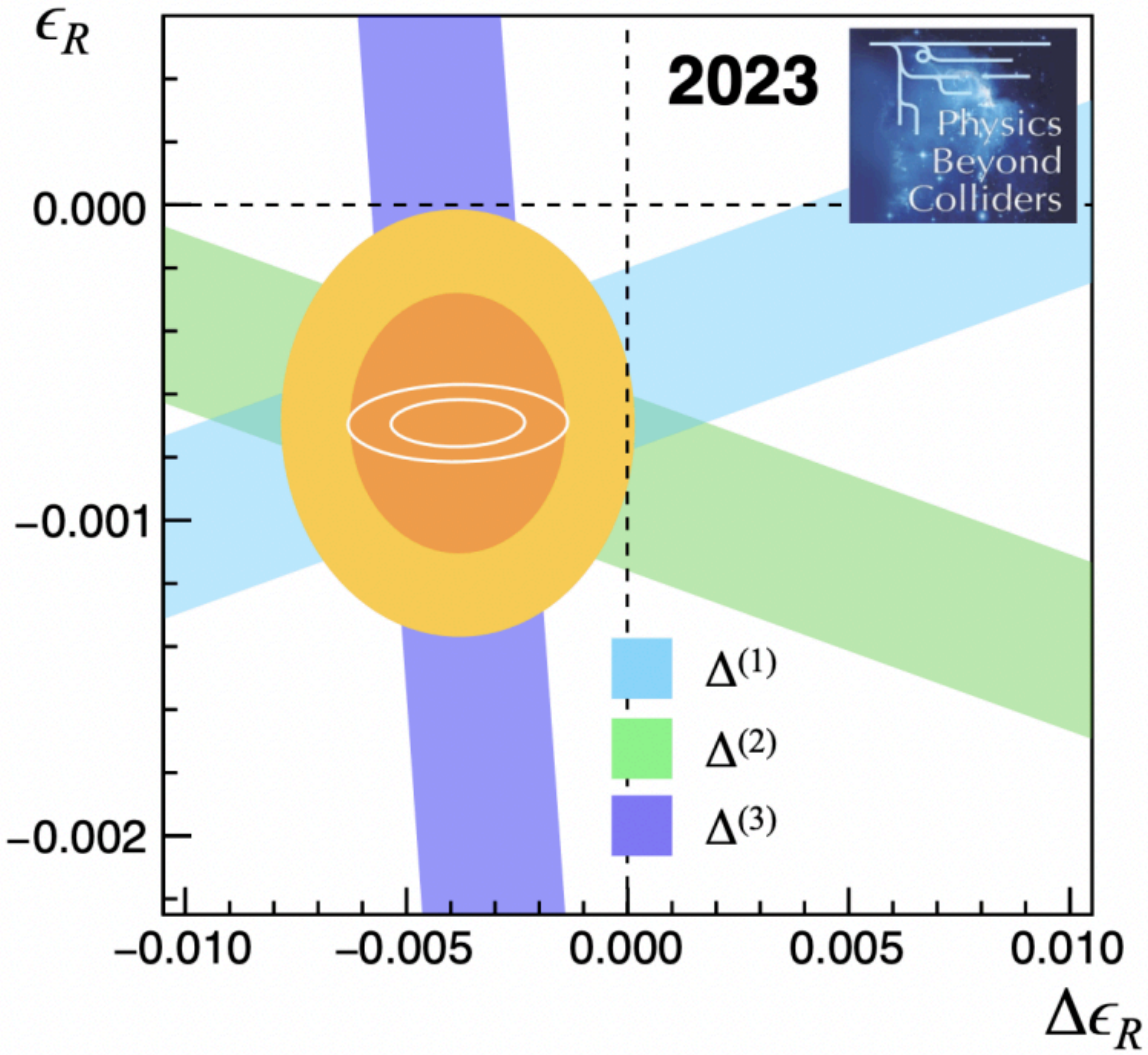
$$\Delta^{(1)}_{CKM} = 2\epsilon_R + 2\Delta\epsilon_R |V_{us}|^2$$

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

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

- Where:
  - ϵ_R = RH currents in u,d sector
  - $\Delta\epsilon_R$ = RH currents in strange sector

- From current fit:
  - $\epsilon_R = -0.69(27) \times 10^{-3}$ (2.5σ)
  - $\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$ (2.4σ)
  - $\epsilon_R = \Delta\epsilon_R = 0$ excluded with 3.1σ significance.



[PLB 838 (2023) 137748]

Future: NA62/HIKE

NA62 and CKM 1st row unitarity : $K_{\mu 3}/K_{\mu 2}$

- NA62 is ideally placed to make a high precision measurement of

$$R^{K_{\mu3}/K_{\mu2}} = \frac{\mathscr{B}(K^+ \to \pi^0 \mu^+ \nu)}{\mathscr{B}(K^+ \to \mu^+ \nu)}$$, with many systematics cancelling.

- This single measurement can have a significant impact: $(R^{K_{\mu3}/K_{\mu2}})^{-1/2} \propto r$ where:

$$r \equiv \left(\frac{1+\Delta^2_{CKM}}{1-\Delta^{(3)}_{CKM}}\right)^{-1/2} = \frac{\left|\frac{V_{us}}{V_{ud}}\right|^2_{(K\mu2)}}{|V_{us}|^2_{(K_{\ell3})}/|V_{ud}|_{(\beta)}} = 1 - 2\Delta\epsilon_R$$

- Uses input from β decays, but provides a qualified statement about consistency of data set.
- Sensitive search for right-handed currents ($\Delta\epsilon_R \neq 0$).

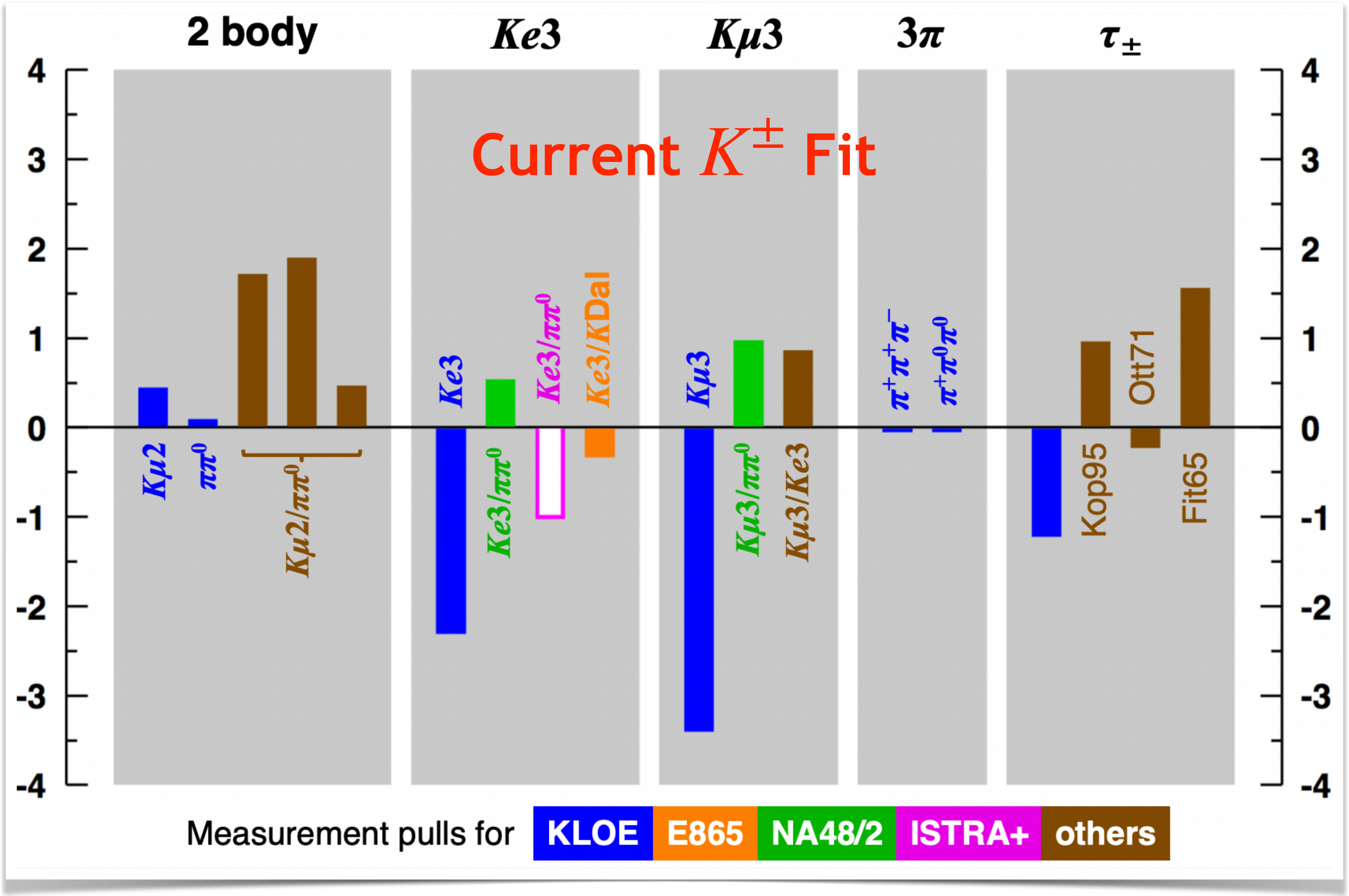
NA62 hypothetical $K_{\mu3}/K_{\mu2}$ to 0.5%:

Result	$\Delta\epsilon_R$		Remarks
Same as fit	$-4.0(1.9)\times10^{-3}$	2.1σ	Almost same precision as result from world average
$+1.5\sigma$	$-0.4(1.9)\times10^{-3}$	0.2σ	$K_{\mu2}, K_{\mu3}, V_{ud}$ consistent: current tensions have experimental origin?
-1.5σ	$-7.6(1.9)\times10^{-3}$	4.0σ	Evidence for right-handed currents contributing to CKM non-unitarity

[PLB 838 (2023) 137748]
[Moulson, CKM23]

NA62 and CKM 1st row unitarity: 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.



- e.g. Target measurements:
  - $K_{\mu 2}/K_{\pi^+\pi^0}$: verify KLOE result with quoted 0.27% uncertainty.
  - $K_{e3}/K_{\pi^+\pi^0}$, $K_{\mu 3}/K_{\pi^+\pi^0}$: currently the $K_{\ell 3}$ have large scale factors in fit.
  - $K_{e3}/K_{\mu 3}$: test of lepton universality

- **With a dedicated, stable, low-intensity data-taking with minimum-bias triggers statistical uncertainties <0.1% in 2 weeks.**

NA62 and CKM 1st row unitarity: 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.

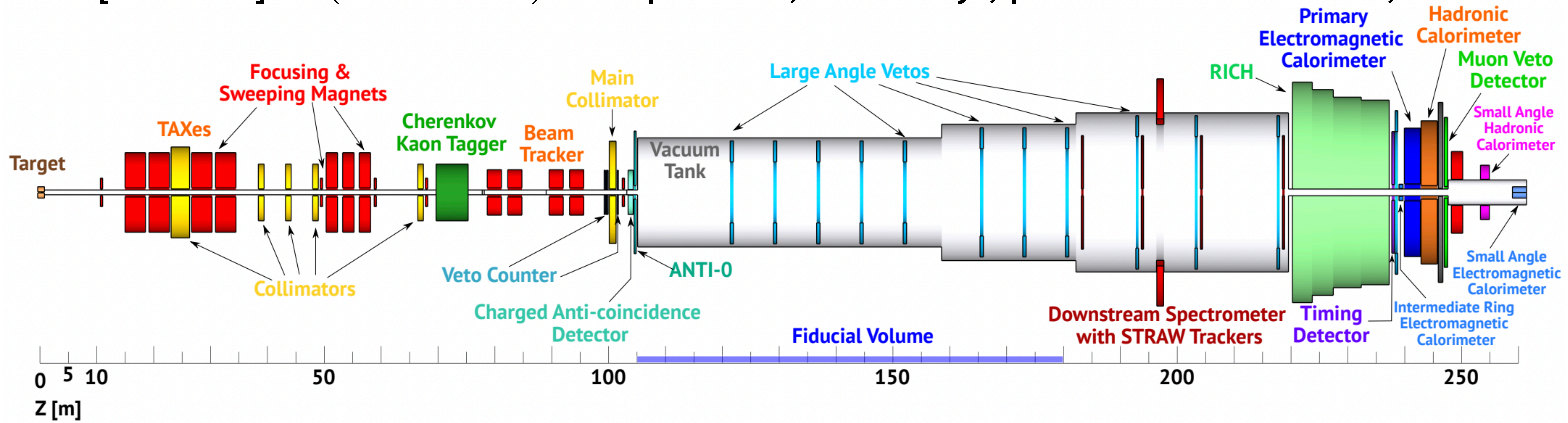
- Alternative strategy, mostly independent of other inputs:
  - $R_A^{K_{\mu 2}} = \dfrac{K^+ \to \mu^+ \nu}{K^+ \to \pi^0 \pi^+ \to \pi^0 \mu^+ \nu}$
  - $R_A^{K_{\mu 3}} = \dfrac{K^+ \to \pi^0 \mu^+ \nu}{K^+ \to \pi^0 \pi^+ \to \pi^0 \mu^+ \nu}$
  - $R^{K_{\mu 3}/K_{\mu 2}} = \dfrac{K^+ \to \pi^0 \mu^+ \nu}{K^+ \to \mu^+ \nu}$ [see previous]
- Minimise systematics looking at modes with/without π^0 and perform simultaneous fit to m^2_{miss} spectra.
- Systematics evaluation ongoing (2017-18 data): expected <0.6%.

- e.g. Target measurements:
  - $K_{\mu 2}/K_{\pi^+\pi^0}$: verify KLOE result with quoted 0.27% uncertainty.
  - $K_{e3}/K_{\pi^+\pi^0}$, $K_{\mu 3}/K_{\pi^+\pi^0}$: currently the $K_{\ell 3}$ have large scale factors in fit.
  - $K_{e3}/K_{\mu 3}$: test of lepton universality

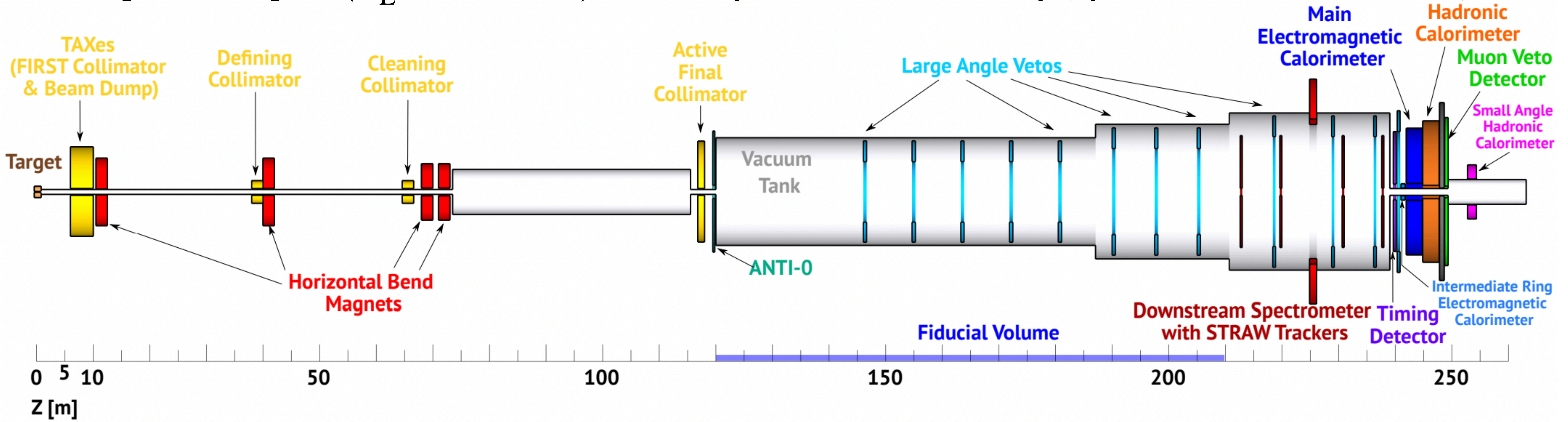
- **With a dedicated, stable, low-intensity data-taking with minimum-bias triggers statistical uncertainties <0.1% in 2 weeks.**

HIKE: long-term kaon programme at CERN

Phase1 [K^+ beam]: $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$ to 5% precision, rare decays, precision measurements, LNV/LFV



Phase2 [K^0 beam]: $\mathscr{B}(K_L \to \pi^0 \ell^+ \ell^-)$ to ~15% precision, rare decays, precision measurements, LNV/LFV



HIKE
High Intensity Kaon Experiments

- + FIPs searches with periodic beam dump running.
- + synergy with SHADOWS [CERN-SPSC-2023-029]

[HIKE proposal, CERN-SPSC-2023-031]

Hypothetical fits after HIKE Phase1+2

HIKE High Intensity Kaon Experiments

K^+ fits after HIKE phase 1

11 input measurements:

- 3 old τ values in PDG
- KLOE τ
- KLOE BR $\pi\pi\pi$, $\pi\pi^0\pi^0$
- **HIKE $\pi\pi^0/\mu\nu$ to 0.4%**
- **HIKE $K_{e3}/\pi\pi^0$ to 0.4%**
- **HIKE $K_{\mu3}/\mu\nu$ to 0.2%**
- **HIKE $K_{\mu3}/\pi\pi^0$ to 0.4%**
- **HIKE $K_{\mu3}/K_{e3}$ to 0.2%**

- Can remove almost all old data.
- [Assume HIKE measurements consistent with $V_{us} = 0.22417$]
- Constraint $\sum \mathscr{B}(K^{\pm}) = 1$ significantly increases fit result for $\mathscr{B}(K_{\mu2})$.
- Results:

χ^2/ndf = 4.90/5 (Prob = 42.8%)

compare current: 25.5/11 (0.78%)

K_L fits after HIKE phase 2

24 input measurements:

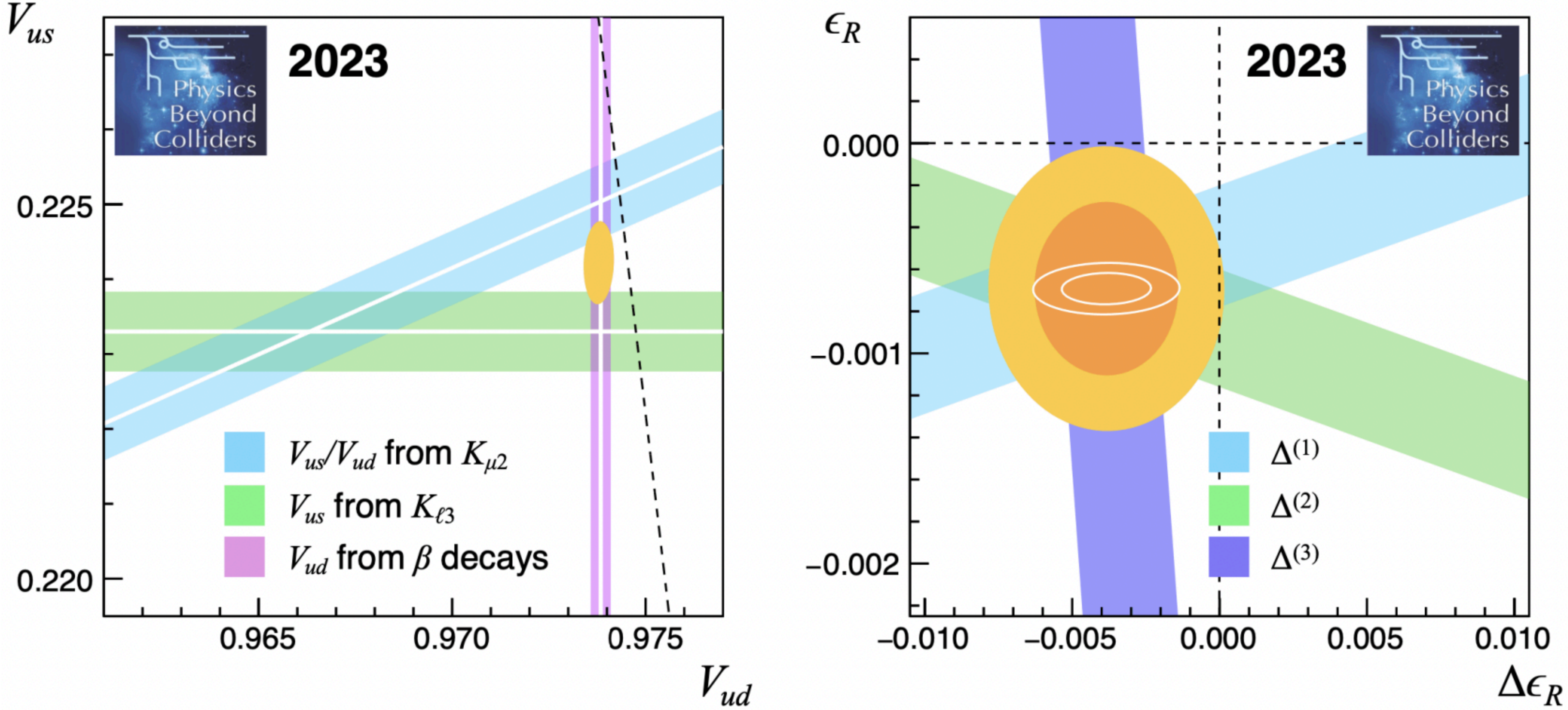
- 21 inputs from current fit
- Hypothetical HIKE measurements chosen to agree with V_{us} = 0.22417:
- **HIKE $K_{\mu3}/K_{e3}$ to 0.3%**
- **HIKE $\pi^+\pi^-/K_{e3}$ to 0.4%**
- **HIKE $\pi^+\pi^-/\pi^+\pi^-\pi^0$ to 0.6%**

- Harder to improve overall fit.
  - $K_{\ell 3}$ modes dominate but $3\pi^0$ and $\pi^+\pi^-\pi^0$ critical for normalisation - with poor systematic cancellation.
- Results:

χ^2/ndf = 30.7/15 (Prob = 0.94%)

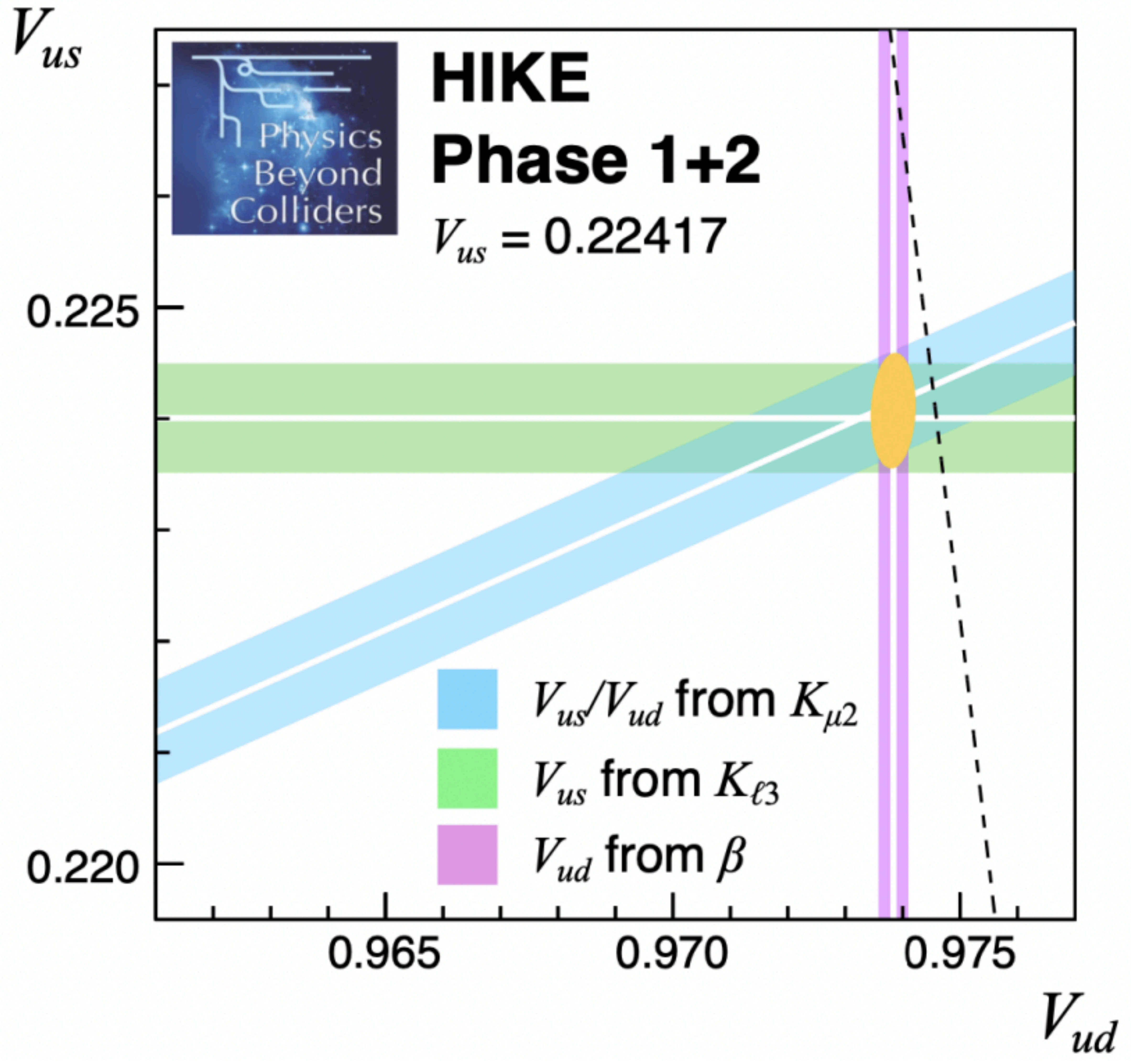
c.f. current 19.8/12 (Prob=7.0%)

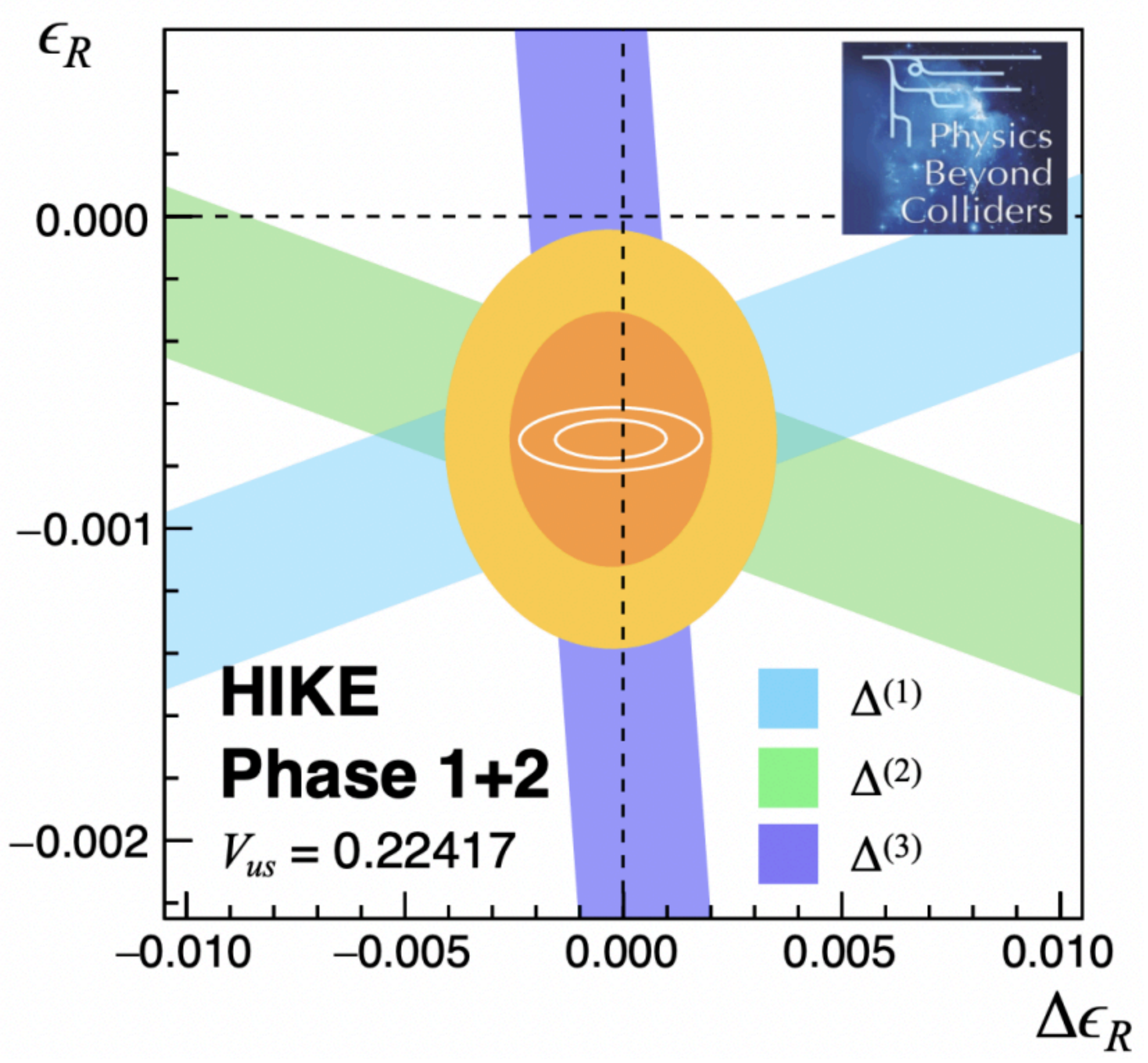
Current status



- Poor agreement of $K_{\mu 3}$ vs $K_{\mu 2}$, unitarity deficit $\approx 2.8\sigma$
- $\epsilon_R = \Delta\epsilon_R = 0$ excluded with 3.1σ significance.

After HIKE Phase1+2 [e.g. hypothetical scenario]





- Good agreement of $K_{\mu 3}$ vs $K_{\mu 2}$, unitarity deficit $\approx 2.7\sigma$ remains.
- $\epsilon_R = \Delta\epsilon_R = 0$ excluded with 2.2σ significance.

Future: Kaon/Pion Experiments

CKM constraints from $\pi^+ \to \pi^0 e^+ \nu_e$ ("pion beta decay")

- **PIBETA experiment at PSI:** $\mathscr{B} = (1.036 \pm 0.004_{\text{stat}} \pm 0.005_{\text{syst}}) \times 10^{-8}$ (0.6% precision) [PRL 93 (2004) 181803].
  - Gives:

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

Normalising to measurement:

$$BR(\pi^+ \to e^+\nu_e(\gamma)) = 1.2325(23) \times 10^{-4}$$

Or theory: $1.2350(2) \times 10^{-4}$

  - \> **Fractional unc. of 0.3% on** $|V_{ud}|$ [PDG], but theory uncertainties are small…

- **PIONEER experiment at PSI** [Snowmass21][proposal, 2203.01981] Approved - starting data-taking in ~5 years…

CKM constraints from $\pi^+ \to \pi^0 e^+ \nu_e$ ("pion beta decay")

- **PIONEER experiment at PSI** [Snowmass21] [proposal, 2203.01981] Approved - starting data-taking in ~5 years. Focusing on $\pi^+ \to \pi^0 e^+ \nu_e$ in phases 2 and 3.
  - Phase1 : $R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$, stopped pions, look for positrons from $\pi^+ \to e^+\nu$ or $\pi^+ \to \mu^+\nu, \mu^+ \to e^+\nu\bar{\nu}$.
  - **Phase2 : measure $\mathscr{B}(\pi^+ \to \pi^0 e^+ \nu_e)$ with 0.2% precision**, looking for back-to-back $\gamma\gamma$ from stopped pions, normalising to $\pi^+ \to e^+\nu$ [same concept as PIBETA].
    - Thus improve $|V_{ud}|$ and $|V_{ud}/V_{us}|$ precision (using ratio $R_V = \frac{\Gamma(K \to \pi l \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))}$) **by factor ~3.**

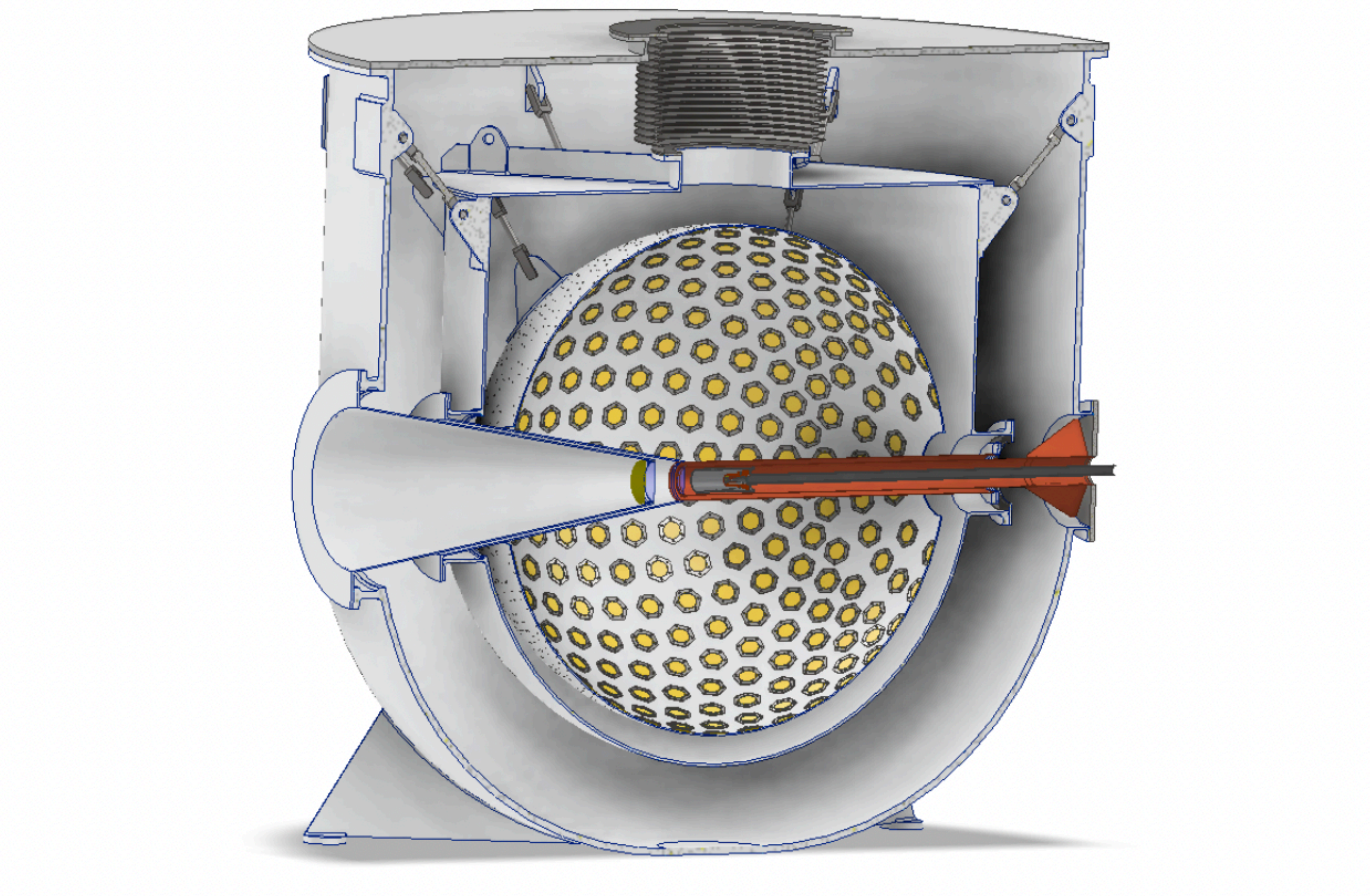
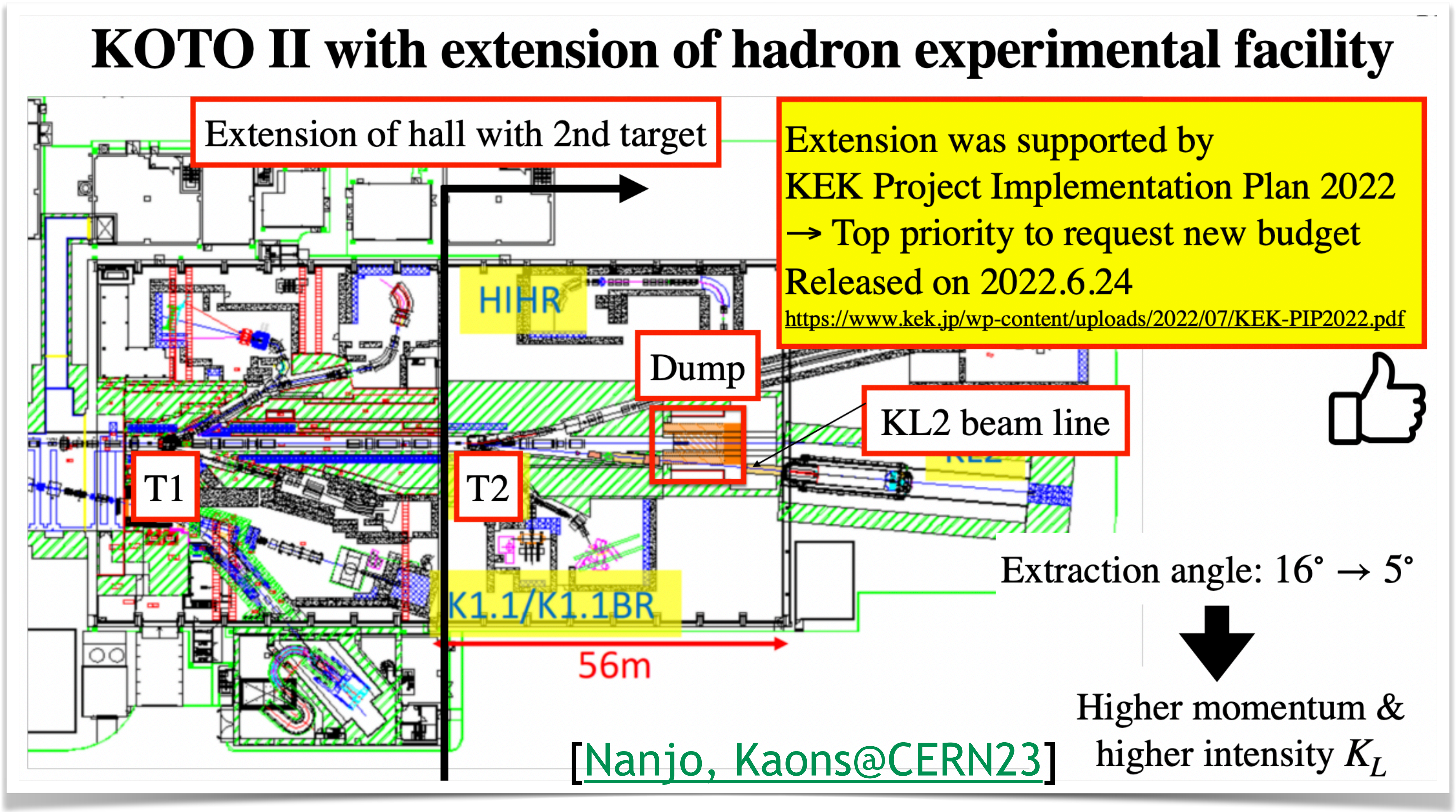


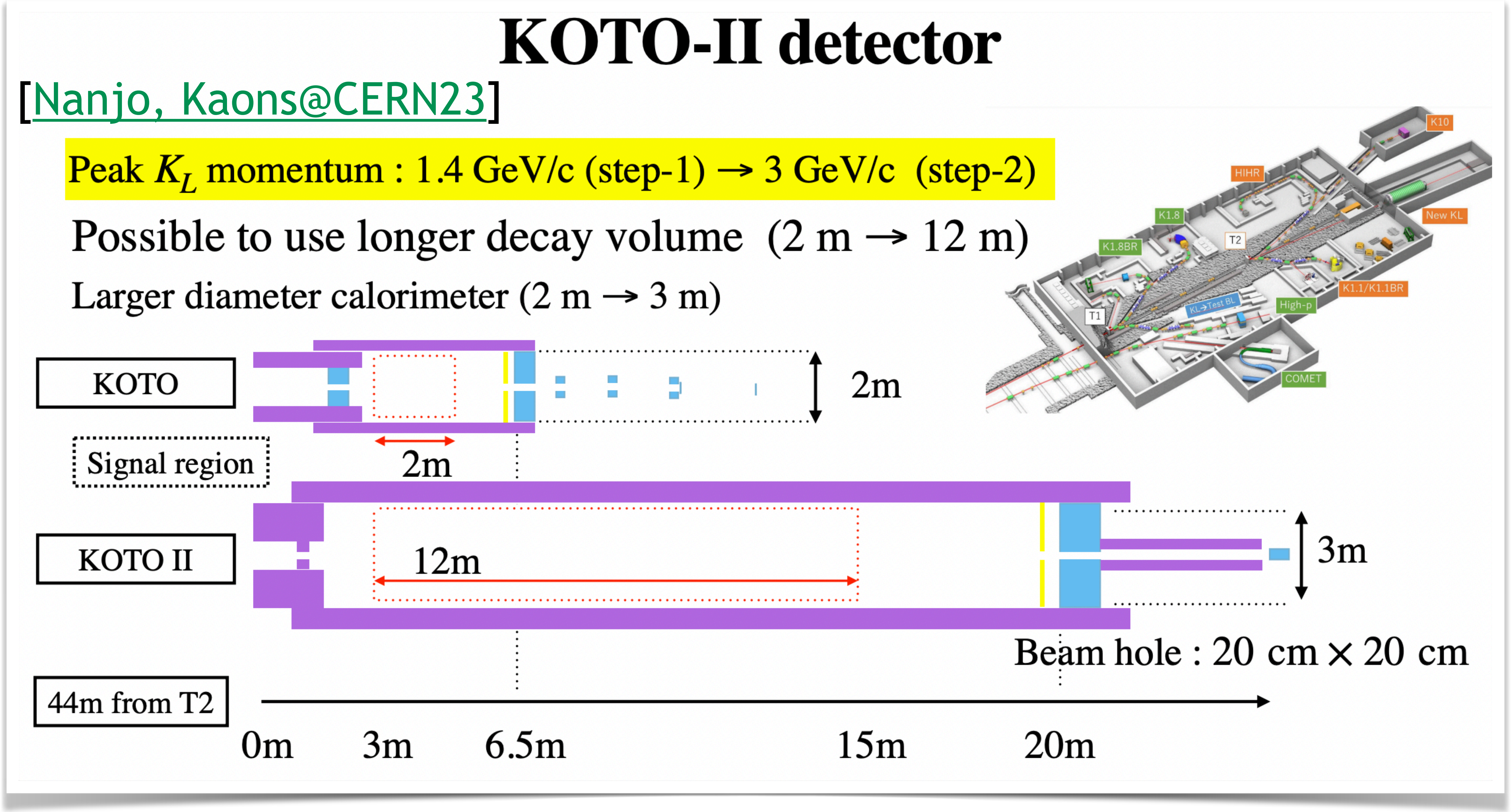
FIG. 4 – PIONEER conceptual design. The sphere is a LXe calorimeter, with the beam entering from the left, and the ATAR at the center. For scale, the lid is 3.05 m diameter. The yellow circles are merely representative of the LXe photosensors; they are not placed accurately.

Challenging long-term goal: reach precision of 0.02% on $|V_{ud}|$ (competitive with super-allowed β decays) by end of phase 3.

Future for neutral kaons?

- **KOTO** currently running at J-PARC, will be followed by **KOTO-2**.
  - Bespoke, highly specialised, design to study $K_L \to \pi^0 \nu \bar{\nu}$.
  - Limited precision for other K_L decays, unlikely to significantly impact fits.





- **HIKE phase2**: Primary objective: $K_L \to \pi^0 \ell^+ \ell^-$, but notable impacts expected.

$$(K_L \to \pi^0 \ell^+ \nu, K_L \to \pi^0 \pi^+ \pi^-, K_L \to \pi^+ \pi^-)$$

Summary

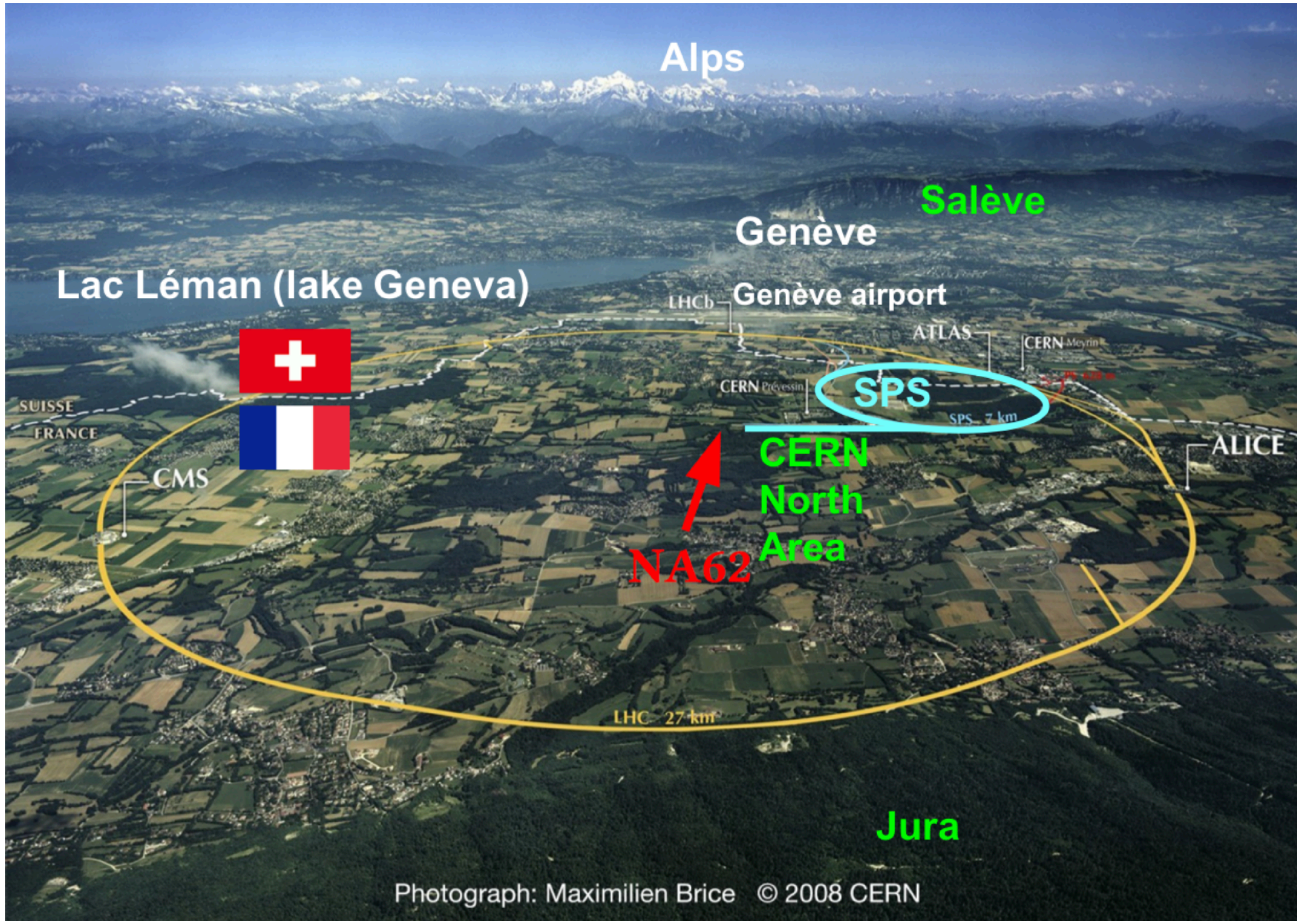
Summary

- **Cabibbo angle anomaly: tension with 1st row unitarity [currently at ~3σ].**
  - + tension in $K_{\mu 3}$ vs $K_{\mu 2}$
- Most precise tests by studying $|V_{us}|^2_{(K_{\ell 3})}$, $\left|V_{us}/V_{ud}\right|^2_{(K\mu 2)}$ and $|V_{ud}|_{(\beta)}$.
  - Key results from combined fits of $K_S, K_L, K^{\pm}$ data.
- Is current tension **experimental** in nature?
  - NA62/HIKE can provide new, high-precision measurements of $K_{\mu 3}/K_{\mu 2}$: **directly tests the tensions** and can have **significant impact on fits.**
  - + Future pion experiments (PIONEER) may challenge $|V_{ud}|$ precision.
- Is tension due to **BSM physics**?
  - Test for right-handed currents established, currently weakly favoured (exclude 0 RH currents at ~3σ)

Supplemental

The NA62 Experiment at CERN

~300 collaborators from ~30 institutions.



- **Primary goal:** measurement of $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - Rare K^+ decays (e.g. $K^+ \to \pi^+ \mu^+ \mu^-$ [JHEP 11 (2022) 011])
  - LNV/(c)LFV decays
  - Exotics (e.g. Dark photon [arXiv:2303.08666])
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]).
  - 2022 Physics run (215 days).
  - 2023 Physics run (just finished!).

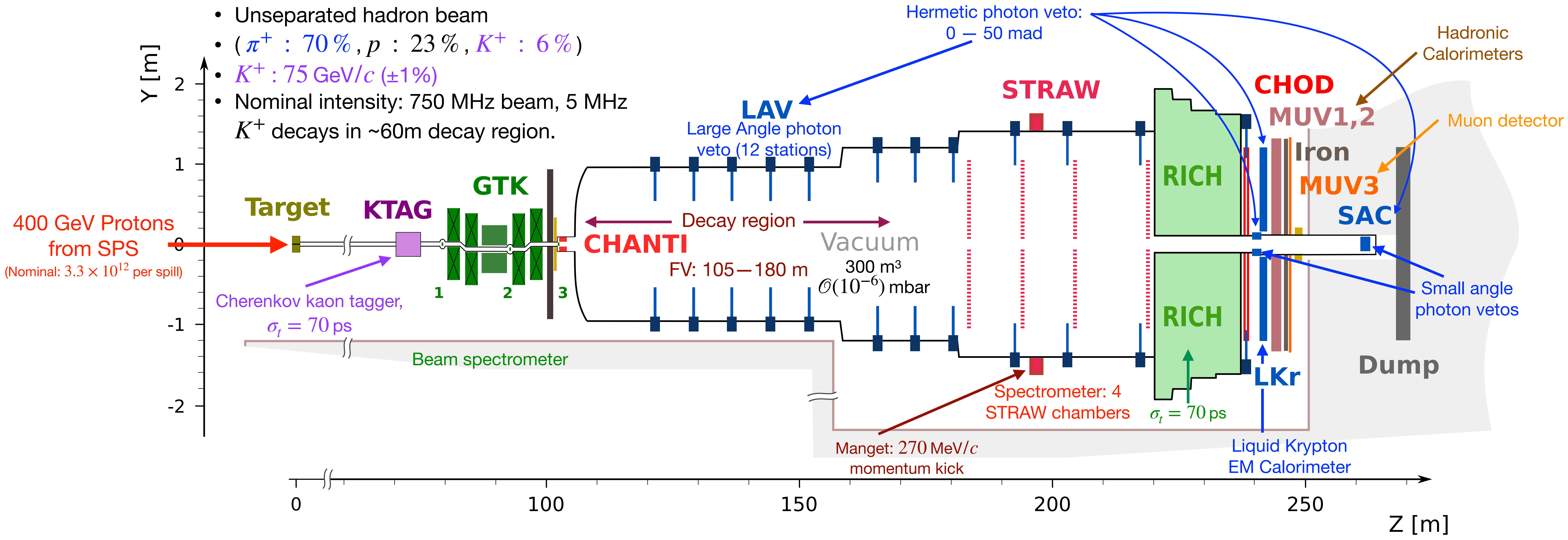
Continues long history of Kaon physics at CERN :

NA31	NA48	NA48/1	NA48/2	NA62-R_K	NA62 Run1	NA62 Run2
1986-98	1977—2001 Discovery of direct CVP	2002	2003-4	2007-8	2016-18	2021…

NA62 Beamline & Detector

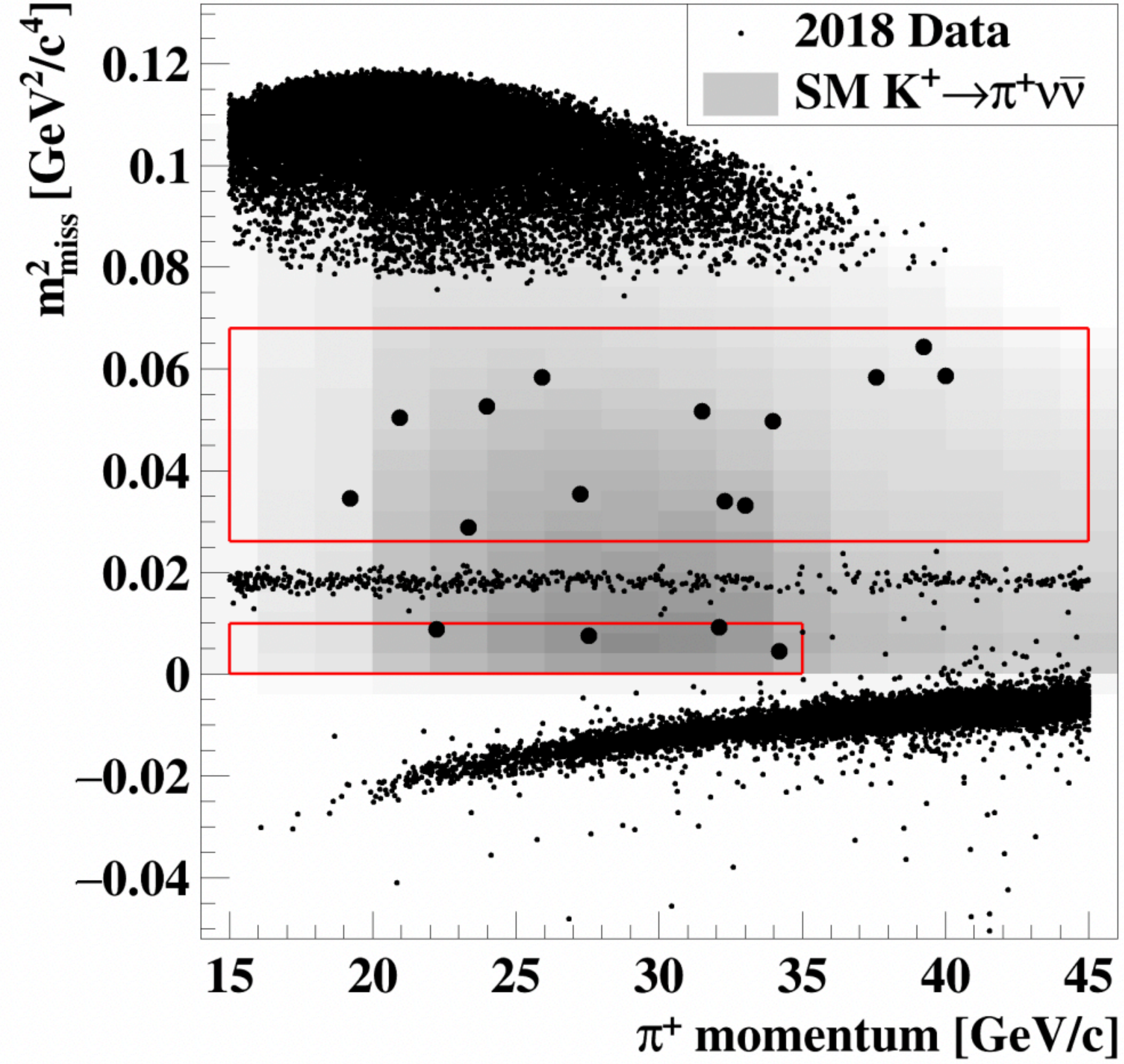
[JINST 12 (2017) 05, P05025]

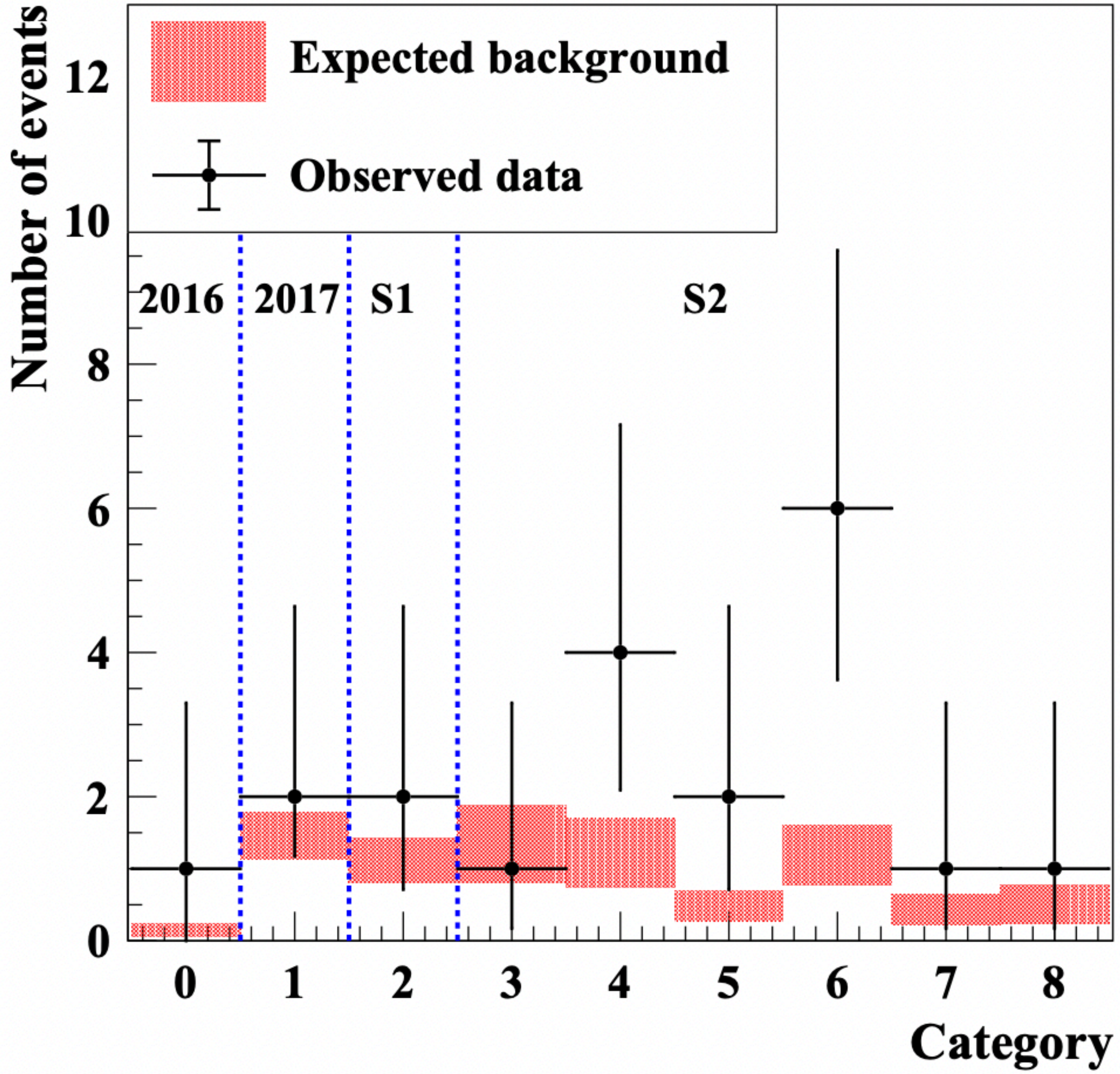
- Unseparated hadron beam
- (π^+ : 70 % , p : 23 % , K^+ : 6 %)
- K^+ : 75 GeV/c (±1%)
- Nominal intensity: 750 MHz beam, 5 MHz K^+ decays in ~60m decay region.



- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV, IRC, SAC (γ)

Run1 (2016—18) $K^+ \to \pi^+ \nu \bar{\nu}$ Results:



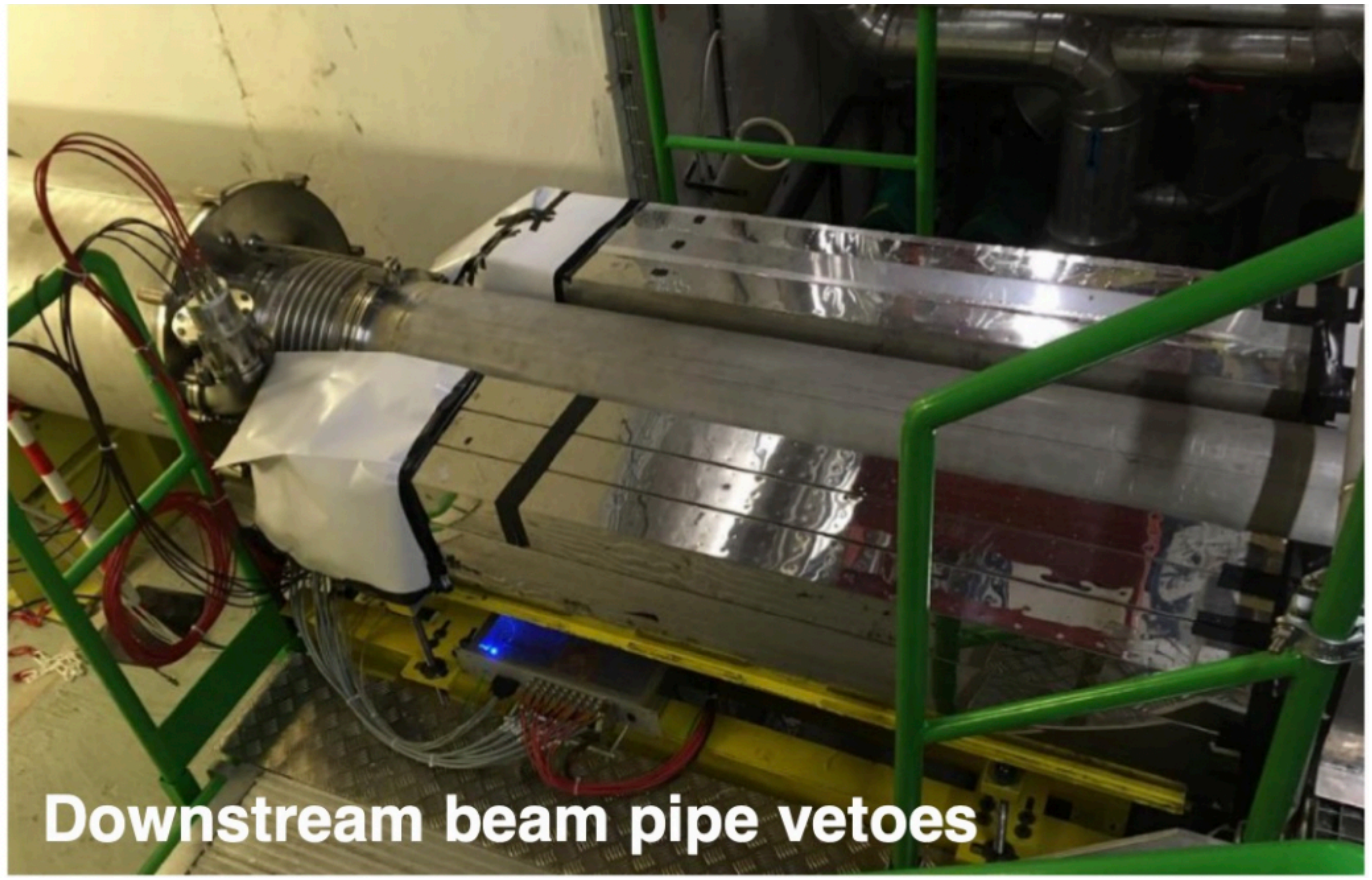


- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$, $N^{exp}_{bkg.} = 7.03^{+1.05}_{-0.82}$: $n_{obs} = 20$
- In background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ signal significance: 3.4σ.
- $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$ @ 68 % CL [JHEP 06 (2021) 093]

NA62 Run2 & The Future

- NA62 technique is firmly established.
- Run2 - target $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$ measurement: $\mathcal{O}(10)\,\%$ **precision**.
  - 4th GTK (Kaon beam tracker) & rearrange beam line elements around GTK achromat.
  - New upstream veto & veto hodoscope upstream of decay volume.
  - Additional veto detector at end of beam-line.
  - Intensity increased by $\sim 30\,\%$ with respect Run1. Matched by trigger updates.
- Improvements to the trigger have led to smaller trigger downscaling factors for multi-track triggers: more data available for CLFV/LNV searches.
- Beyond LS3: High Intensity Kaon Experiment (HIKE) program under development at CERN SPS. [arXiv:2204.13394]

New detectors installed in 2021 for NA62 Run2:



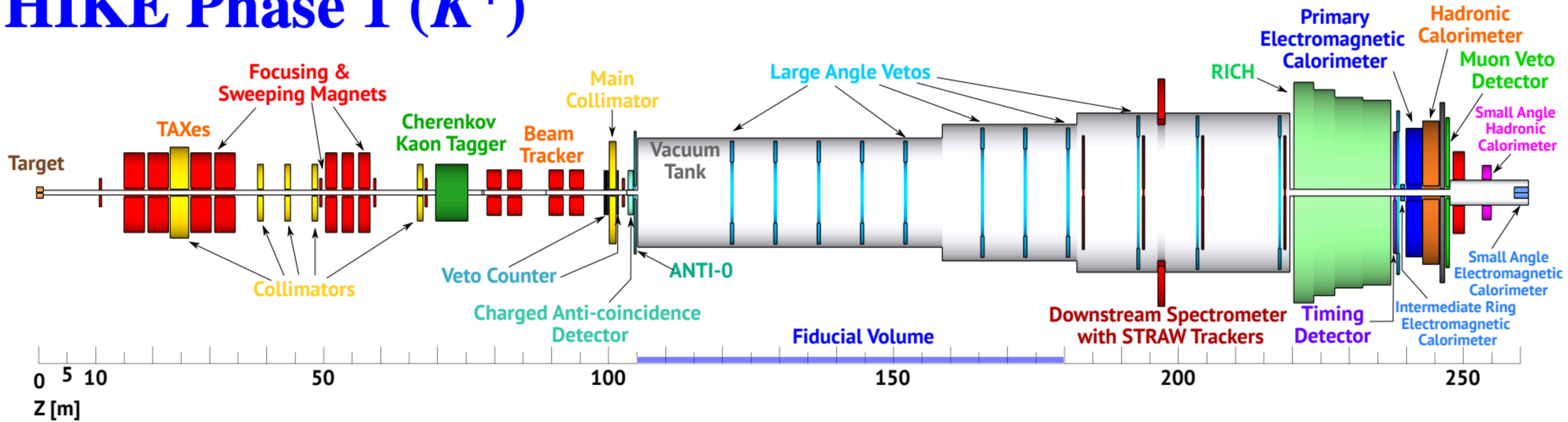
HIKE: High Intensity Kaon Experiments

[HIKE LOI: arXiv:2211.16586, proposal to SPSC under preparation]

High Intensity Kaon Experiments

- Long-term programme of kaon physics at the CERN SPS beyond LS3.
- Beam intensity 4-6 times higher than NA62, detectors with $\mathcal{O}(20)$ ps time resolution.
- Multi-phase **physics program** (K^+ and K_L beams foreseen in different phases):
  - Ultimate precision for $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ measurement, target: $\mathcal{O}(5\%)$ i.e. approx. SM theory precision.
  - $K_L \to \pi^0 \ell^+ \ell^-$ observation and BR measurement.
  - LFUV tests with sub-percent precision.
  - LFV/CLFV searches with $\mathcal{O}(10^{-12})$ sensitivity
  - Measurements of V_{us} and main kaon decay modes.
  - Beam dump physics in synergy with SHADOWS experiment.

HIKE Phase 1 (K^+)



CKM

Fit to K_S rate data

[Moulson, CKM23]

Fit inputs & constraints → **Fit results**

7 input measurements:

- **KLOE '06** BR $\pi^0\pi^0/\pi^+\pi^-$
- **NA48** $\Gamma(K_S \to \pi e \nu)/\Gamma(K_L \to \pi e \nu)$, τ_S
- **KLOE '11** τ_S
- **KTeV '11** τ_S
- **KLOE-2 '22** BR $\pi e \nu/\pi^+\pi^-$ **New!**
- **KLOE-2 '20** BR $\pi \mu \nu/\pi^+\pi^-$

Parameter	Value
BR($\pi^+\pi^-(\gamma)$)	69.20(5)%
BR($\pi^0\pi^0$)	30.69(5)%
BR(K_{e3})	$7.15(6) \times 10^{-4}$
BR($K_{\mu3}$)	$4.56(20) \times 10^{-4}$
τ_S	89.58(4) ns

χ^2/ndf = 0.36/3 (Prob = 95%)

- Constraint: $\sum \mathscr{B}(K_s) = 1$

Fit to K_L rate data

[Moulson, CKM23]

Fit inputs & constraints → **Fit results**

21 input measurements:

- 5 KTeV ratios
- NA48 BR(K_{e3}/2 track)
- 4 KLOE BRs with dependence on τ_L
- KLOE, NA48 BR($\pi^+\pi^-/K_{\ell 3}$)
- KLOE, NA48 BR($\gamma\gamma/3\pi^0$)
- BR($2\pi^0/\pi^+\pi^-$) from K_S fit, Re ε'/ε
- KLOE τ_L from $3\pi^0$
- Vosburgh '72 τ_L
- KTeV BR($\pi^+\pi^-\gamma/\pi^+\pi^-(\gamma)$)
- E731, 2 KTeV BR($\pi^+\pi^-\gamma_{\mathrm{DE}}/\pi^+\pi^-\gamma$)

Parameter	Value	S
BR(K_{e3})	0.4056(9)	1.3
BR($K_{\mu 3}$)	0.2704(10)	1.5
BR($3\pi^0$)	0.1952(9)	1.2
BR($\pi^+\pi^-\pi^0$)	0.1254(6)	1.3
BR($\pi^+\pi^-(\gamma_{\mathrm{IB}})$)	1.967(7) × 10^{-3}	1.1
BR($\pi^+\pi^-\gamma$)	4.15(9) × 10^{-5}	1.6
BR($\pi^+\pi^-\gamma_{\mathrm{DE}}$)	2.84(8) × 10^{-5}	1.3
BR($2\pi^0$)	8.65(4) × 10^{-4}	1.4
BR($\gamma\gamma$)	5.47(4) × 10^{-4}	1.1
τ_L	51.16(21) ns	1.1

χ^2/ndf = 19.8/12 (Prob = 7.0%)

- Constraint: $\sum \mathscr{B}(K_L) = 1$
- c.f. current PDG result (since 09): $\chi^2/\mathrm{ndf} = 37.4/17$ (Prob = 0.30%)

Fit to $K^{\pm}$ rate data

[Moulson, CKM23]

Fit inputs & constraints → **Fit results**

17 input measurements:

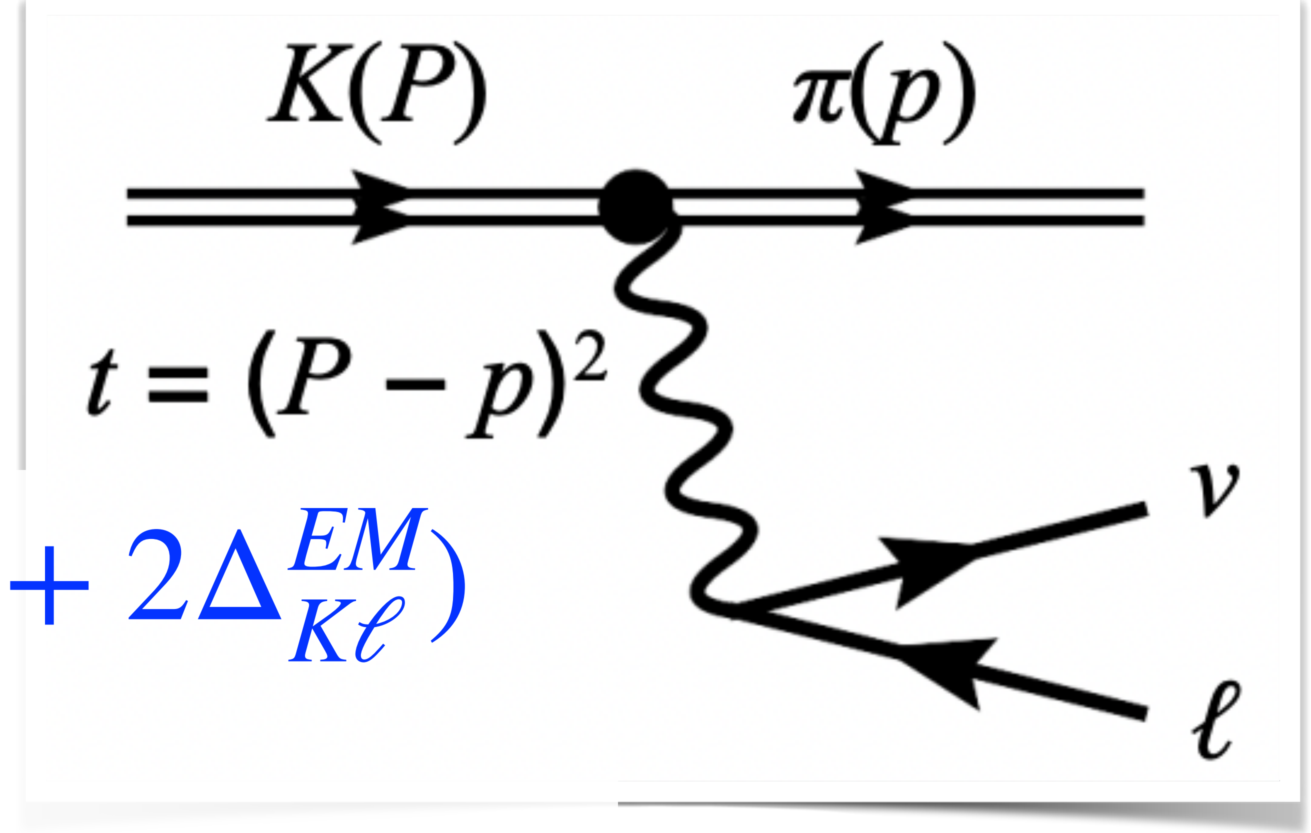
- 3 old τ values in PDG
- KLOE τ
- KLOE BR $\mu\nu$, $\pi\pi^0$
- KLOE BR K_{e3}, $K_{\mu3}$ with dependence on τ
- NA48/2 BR $K_{e3}/\pi\pi^0$, $K_{\mu3}/\pi\pi^0$
- E865 BR K_{e3}/KDal
- 3 old BR $\pi\pi^0/\mu\nu$
- KEK-246 $K_{\mu3}/K_{e3}$
- KLOE BR $\pi\pi\pi$, $\pi\pi^0\pi^0$
- (Bisi '65 BR $\pi\pi^0\pi^0/\pi\pi\pi$ removed)

Parameter	Value	S
BR($\mu\nu$)	63.58(11)%	1.1
BR($\pi\pi^0$)	20.64(7)%	1.1
BR($\pi\pi\pi$)	5.56(4)%	1.0
BR(K_{e3})	5.088(27)%	1.2
BR($K_{\mu3}$)	3.366(30)%	1.9
BR($\pi\pi^0\pi^0$)	1.764(25)%	1.0
$\tau_{\pm}$	12.384(15) ns	1.2

χ^2/ndf = 25.5/11 (Prob = 0.78%)

- Constraint: $\sum \mathscr{B}(K^{\pm}) = 1$
- Note: restricted set of inputs wrt PDG fit (35 inputs, 8 parameters).
- c.f. current PDG result (2016): $\chi^2/\text{ndf} = 53/28$ (Prob = 0.26%)
- Note: negligible change when including ISTRA+ measurements.

$K_{\ell 3}$ Form factors

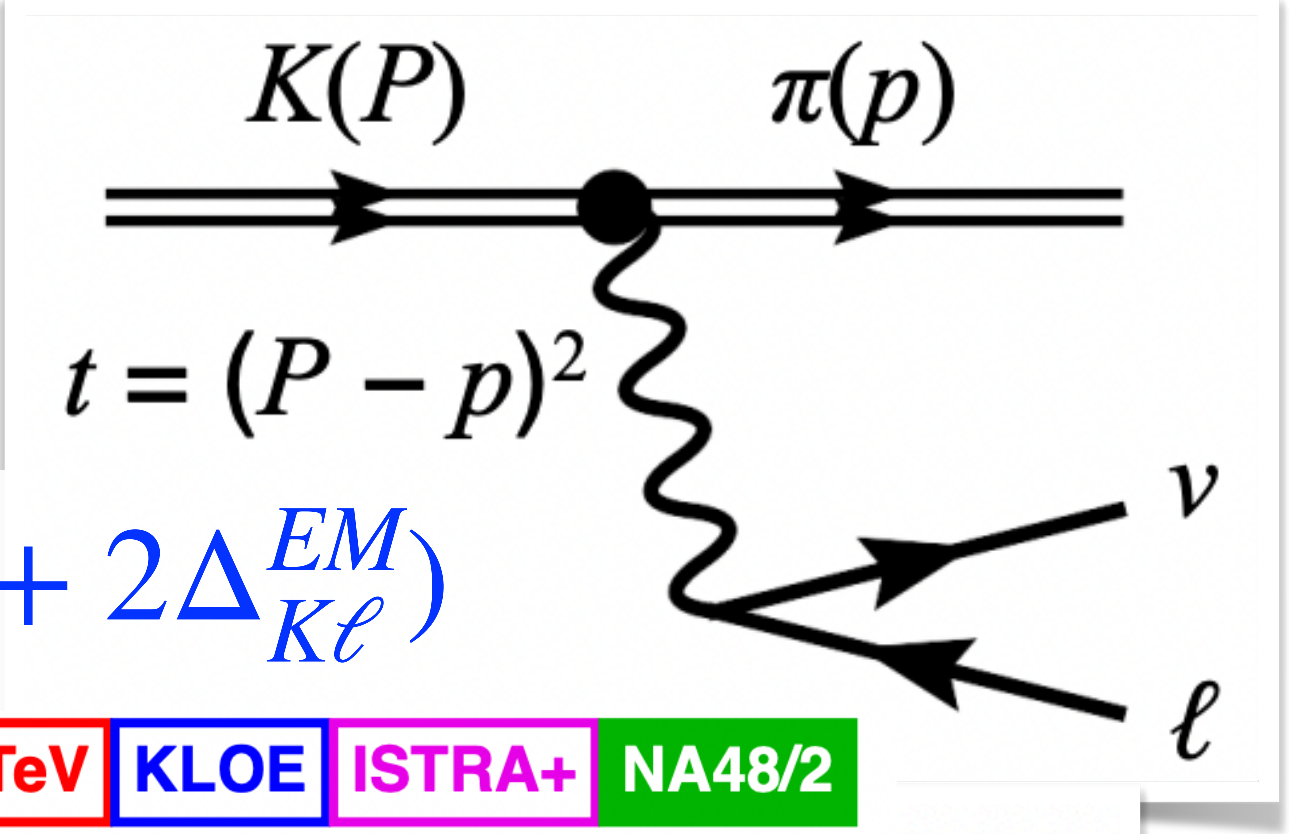


$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

- Hadronic matrix element: $< \pi | J_\alpha | K > = f(0)\left[\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha\right]$
  - K_{e3} decays: only vector form factor $\tilde{f}_+(t)$
  - $K_{\mu 3}$ decays: also need scalar form factor $\tilde{f}_0(t) = \tilde{f}_+ + \tilde{f}_- \dfrac{t}{m_K^2 - m_\pi^2}$
- Parameterise using dispersion relations $\tilde{f}_+(t) = \exp\left[\dfrac{t}{m_\pi^2(\Lambda_+ - H(t))}\right], \tilde{f}_0(t) = \exp\left[\dfrac{t}{m_K^2 - m_\pi^2(\ln C - G(t))}\right].$
  - Where $H(t)$ and $G(t)$ are polynomials from $K\pi$ scattering data, contributing to (but not much) uncertainty in fits.
- Evaluate Integral of form factors over phase-space: $I_{K_L}(\lambda_{K\ell})$ [where λ parameterises t evolution]

$K_{\ell 3}$ Form factors

[Moulson, CKM23]



$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

- Form factor parameterisations

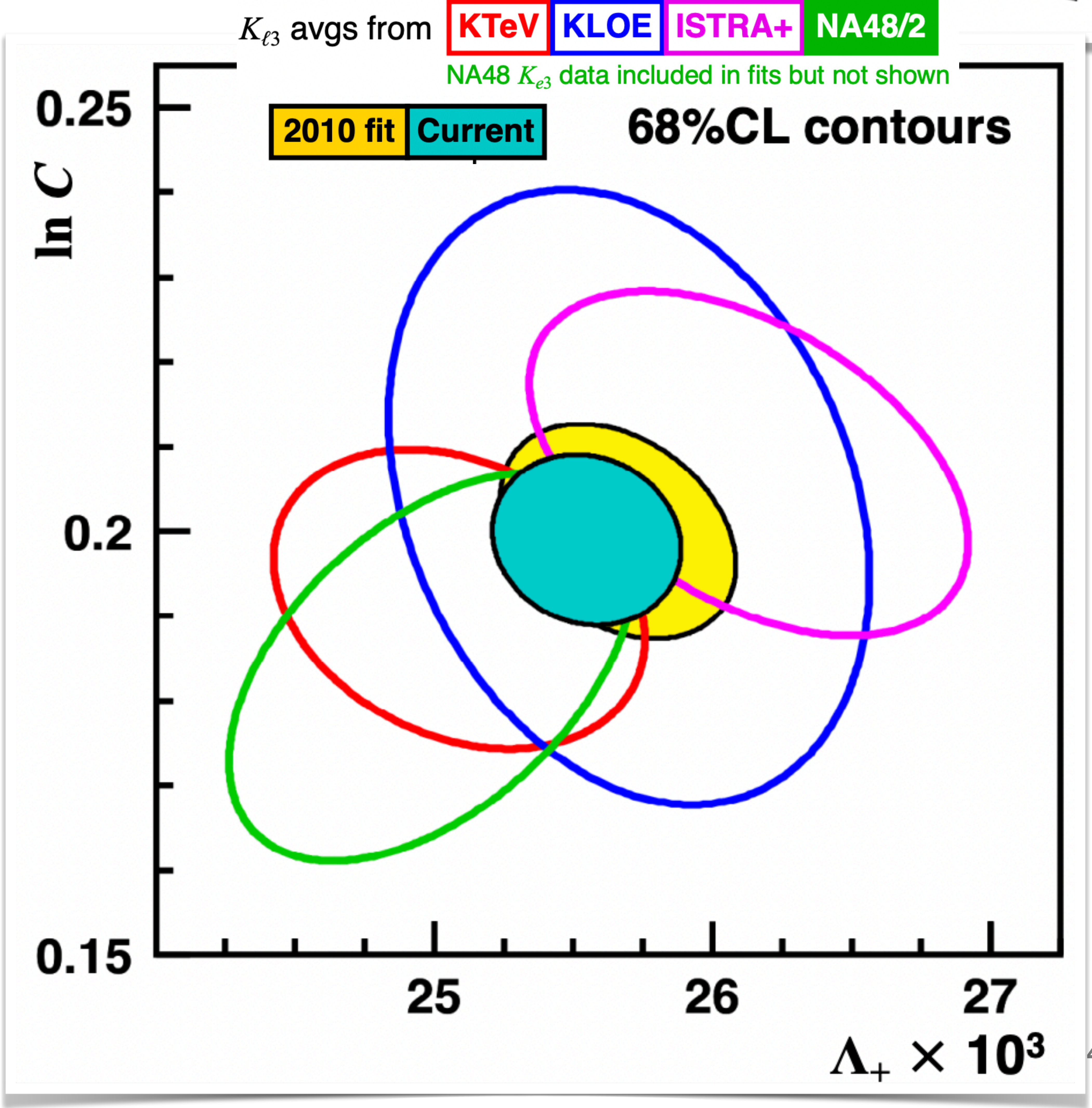
$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2(\Lambda_+ - H(t))}\right], \tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2(\ln C - G(t))}\right].$$

- Current fit:

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

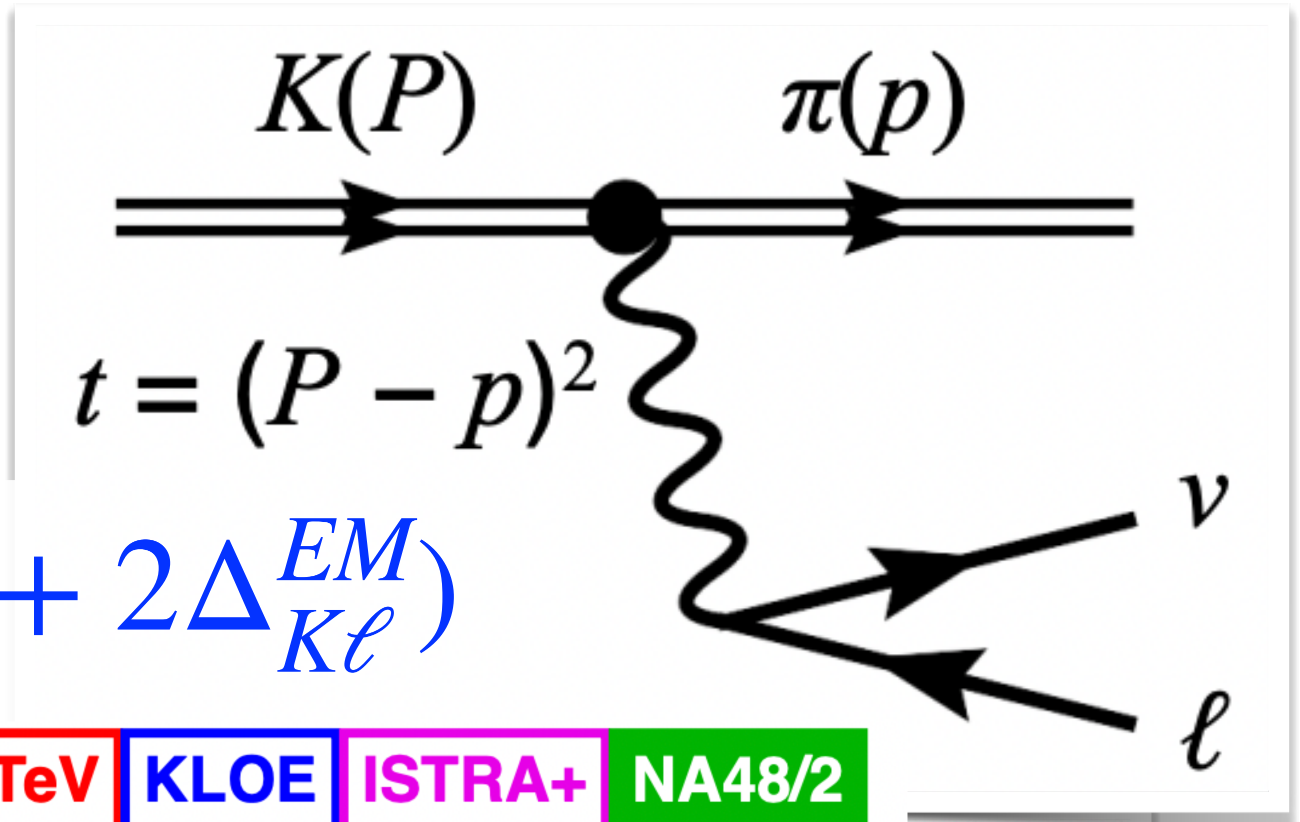
Integrals

Mode	Update	2010
$K^0{}_{e3}$	**0.15470(15)**	0.15476(18)
$K^+{}_{e3}$	**0.15915(15)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10247(15)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10553(16)**	0.10559(17)



$K_{\ell 3}$ Form factors

[Moulson, CKM23]



$$\Gamma(K \to \pi \ell \nu(\gamma)) = |V_{us}|^2 \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |f_+^{K^0\pi^-}(0)|^2 I_{K_L}(\lambda_{K\ell})(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM})$$

- Form factor parameterisations

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

- Current fit:

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

Integrals

Mode	Update	2010
$K^0{}_{e3}$	**0.15470(15)**	0.15476(18)
$K^+{}_{e3}$	**0.15915(15)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10247(15)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10553(16)**	0.10559(17)