First-row CKM unitarity and related measurements from NA62

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on behalf of the NA62 Collaboration

Workshop on status and perspectives of physics at high intensity

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Outline

- Theoretical context and motivations
- The NA62 experiment
- $R_{32} = \Gamma(K_{\mu 3})/\Gamma(K_{\mu 2})$ @ NA62
- K_{l3} form factors @ NA62
- Radiative $K_{e3\gamma}$ decay @ NA62
- V_{us}/V_{ud} @ NA62

First-row CKM unitarity: state of the art [PDG 2022]

CKM matrix - Wolfenstein parametrization

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

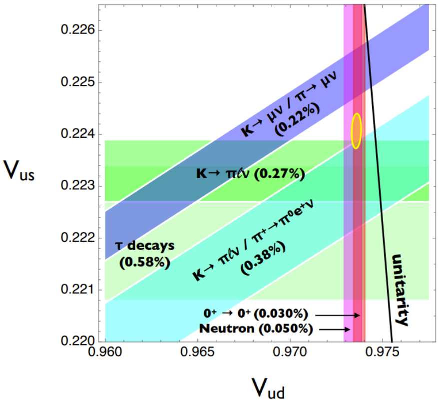
$$\lambda = sin(\theta_{Cabibbo}) = V_{us} = 0.2243 \pm 0.0008$$

$$V_{ud} = 0.97373 \pm 0.00031$$

Most stringent test of unitarity in the CKM matrix

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$$
$$\Delta_{CKM} = (-1.5 \pm 0.6_d \pm 0.4_s) \cdot 10^{-3} \rightarrow 2.1\sigma$$
$$|V_{ub}|^2 < 2 \cdot 10^{-5} \rightarrow \text{negligible}$$

First-row CKM unitarity: state of the art [arXiv:2111.05338v2 (May 2022)]



Global fit output (1σ ellipse):

- $V_{us} = 0.22406 \pm 0.00034$
- $V_{ud} = 0.97357 \pm 0.00027$

Differences with respect to PDG:

- Individual inputs taken from the various channels
- PDG first averages V_{us} from K_{l2} and K_{l3} and gets a first scale factor
- τ data for V_{us} included for the final estimate

$$\Delta_{CKM} = (-1.95 \pm 0.53) \cdot 10^{-3} \rightarrow 3.7\sigma$$

Cabibbo Angle Anomaly

Determination of $|V_{us}|$ from K_{l3} decays ($K \to \pi l \nu$, $l = e, \mu$)

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell + \delta_{SU2}) C^2 \left|V_{us}\right|^2 f_+^2(0) I_K^\ell$$

Inputs from theory

- $f_+(0)$: form factor at zero momentum transfer for the $l\nu$ system
- δ_K^l: form factor correction for long-distance EM effects
- δ_{SU2}: form-factor correction for $SU(2)$ breaking

Inputs from experiments

- Γ_{Kl3}: K_{l3} rates corrected to include radiative IB (form factors crucial to determine the experimental acceptance of the K_{l3} selections)
- I_K^l: phase space integral, based on form factors: higher precision for e (only vector form factor) than for μ (vector and scalar form factors)

Determination of $|V_{us}|/|V_{ud}|$ from $K \to \mu\nu$ and $\pi \to \mu\nu$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_{K^+}}{f_{\pi^+}} = F(m_\mu, m_{\pi^+}, m_{K^+}) \cdot (1 + \delta_{EM} + \delta_{SU2}) \cdot \left[\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)}\right]^{\frac{1}{2}}$$

Inputs from theory

- f_{K^+}/f_{π^+}: ratio of decay constants (cancellation of lattice-scale uncertainties from ratio)
- δ_{EM}: form factor correction for long-distance EM effects
- δ_{SU2}: form-factor correction for $SU(2)$ breaking

Inputs from experiments

- $\Gamma(K \to \mu\nu)$ and $\Gamma(\pi \to \mu\nu)$: rates inclusive of IB radiative corrections

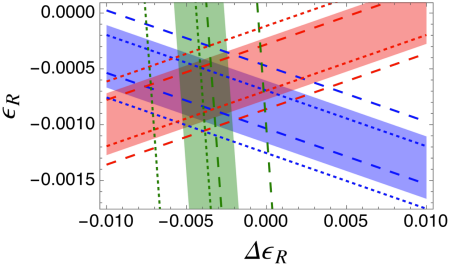
$\Gamma(K^+ \to \pi^0\mu^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ and New Physics scenarios

- In the Standard Model, the W boson couples only to LH chiral fermion states
- New Physics with couplings to RH currents could explain both unitarity deficit and $K_{\mu3}/K_{\mu2}$ difference
- ϵ_R: admixture of RH currents in the non-strange sector
- $\epsilon_R + \Delta_{\epsilon_R}$: admixture of RH currents in the strange sector

[arXiv:2208.11707v1 (Aug 2022)]

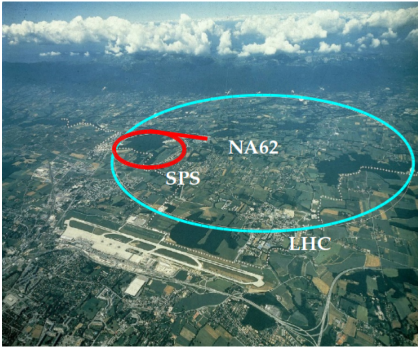
Fit with current inputs

$$\epsilon_R = (-0.69 \pm 0.27) \cdot 10^{-3}\ (2.5\sigma)$$
$$\Delta_{\epsilon_R} = (-3.9 \pm 1.6) \cdot 10^{-3}\ (2.4\sigma)$$



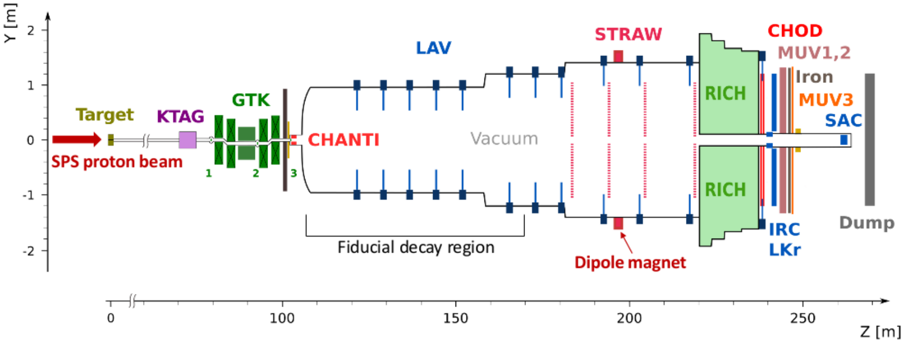
The NA62 experiment at CERN

- Detector installation completed in 2016.
- Run 1: 2016, 2017 and 2018.
- Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement; NA62 programme covers the full K^+ physics.
- Measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ from full Run 1 published: [JHEP 06 (2021) 093].
- Data taking resumed in July 2021, approved until CERN LS3.



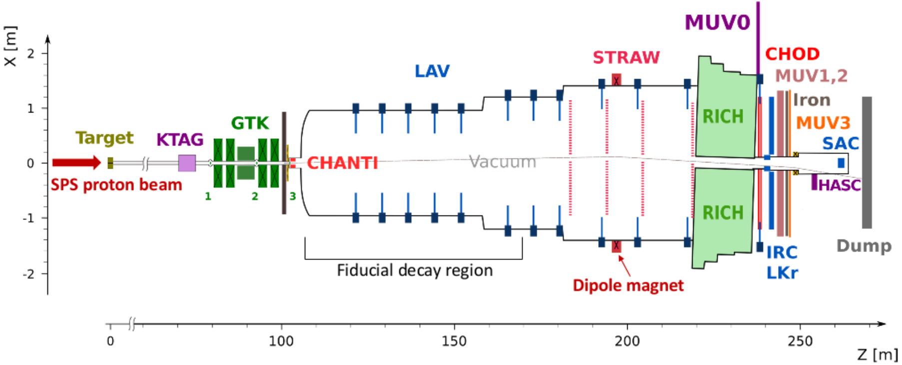
NA62 is located at CERN in the *North Area*, exploiting a 400 GeV/c proton beam extracted from the SPS accelerator.

NA62 beam [2017 JINST 12 P05025]



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% kaons
- Nominal beam particle rate (at GTK3): 750 *MHz* @ 3 s effective spill length
- Average beam particle rate during 2018 data-taking: ∼ 65% of the nominal
- Average beam particle rate during 2022 data-taking: ∼ 100% of the nominal

NA62 detector [2017 JINST 12 P05025]



- KTAG: Cherenkov threshold counter;
- GTK: Si pixel beam tracker;
- CHANTI: stations of plastic scintillator bars;
- LAV: lead glass ring calorimeters;
- STRAW: straw magnetic spectrometer;
- RICH: Ring Imaging Cherenkov counter;
- MUV0: off-acceptance plane of scintillator pads;

- CHOD: planes of scintillator pads and slabs;
- IRC: inner ring shashlik calorimeter;
- LKr: electromagnetic calorimeter filled with liquid krypton;
- MUV1,2: hadron calorimeter;
- MUV3: plane of scintillator pads for muon ID;
- HASC: near beam lead–scintillator calorimeter;
- SAC: small angle shashlik calorimeter.

NA62: possible measurement of $R_{32} = \Gamma(K^+ \to \pi^0 \mu^+ \nu)/\Gamma(K^+ \to \mu^+ \nu)$

State of the art

$R_{32}^{PDG\ 2022\ fit} = 0.0527 \pm 0.0006$ ($\simeq 1\%$ relative uncertainty)

- Measurement statistically dominated by $K^+ \to \pi^0 \mu^+ \nu$ ($\mathcal{B} \simeq 3\%$)
- At the nominal beam intensity NA62 collects about $N_K \sim 10^{10}$ kaon decays per day
- In standard $K \to \pi\nu\nu$ data taking conditions, the minimum bias trigger mask is downscaled by a factor of 600
- In 1 year (i.e. ~ 200 days) of standard data taking a statistical uncertainty smaller than 0.1% could be achieved ($\sim 5 \cdot 10^6$ events), but the systematic uncertainty is above 1%
- Exploring the possibility of **10 days of dedicated data taking**, with minimum bias trigger mask not downscaled, and 1% of nominal beam intensity: $\sim 2 \cdot 10^6$ events with **strong suppression of the systematic uncertainty** → **total uncertainty of 0.5% achievable**

Possible scenarios with measurement of $R_{32} = \Gamma(K^+ \to \pi^0\mu^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ from NA62

$$\left[\frac{\Gamma(K^+ \to \pi^0\mu^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}\right]^{-\frac{1}{2}} \propto (1 - 2\Delta_{\epsilon_R})$$

Possible scenarios with 0.5% precision measurement from NA62

- Result: same as current fit → almost same precision as result from world average
- Result: current fit $+1.5\sigma \to \Delta_{\epsilon_R}$ significance goes to 0.2σ, i.e. have the current tensions "only" an experimental origin?
- Result: current fit $-1.5\sigma \to \Delta_{\epsilon_R}$ significance goes to 4.0σ, i.e. evidence for right-handed currents contributing to CKM non-unitarity

Scalar (f_0) and vector (f_+) form factors

$$f_0(t) = f_0(0)\left[1 + \lambda_0(t/m^2_{\pi^+})\right]$$

$$f_+(t) = f_+(0)\left[1 + \lambda'_+(t/m^2_{\pi^+}) + \frac{\lambda''_+}{2}(t/m^2_{\pi^+})^2\right]$$

State of the art (PDG 2022 fit/average)

- $\lambda_0 = (1.76 \pm 0.25) \cdot 10^{-2}$ for $K_{\mu 3}$:
  ISTRA+ (0.54 M events), NA48/2 (2.3 M events)
- $\lambda'_+ = (2.59 \pm 0.04) \cdot 10^{-2}$ for K_{e3}:
  OKA (5.25 M events), NA48/2 (4.4 M events)
- $\lambda''_+ = (0.186 \pm 0.021) \cdot 10^{-2}$ for K_{e3}:
  OKA (5.25 M events), NA48/2 (4.4 M events)

NA62 will collect ~ 1 order of magnitude higher statistics for K_{l3} decays. Improving the poor precision of the form factors is fundamental for the determination of V_{us}, in particular for the experimental acceptance of the K_{l3} decays.

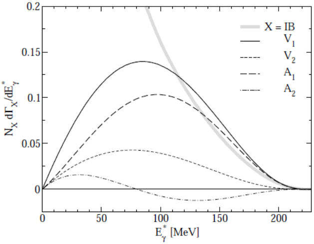
K_{l3} radiative corrections

For V_{us} determination the K_{l3} decays include the radiative correction (IB component), that must be well known both for rates and form factors.

The $K^+ \to \pi^0 e^+ \nu\gamma$ decay

DE (a) + IB (b) + INT

[Kubis et al., EPJ C 50, 557]

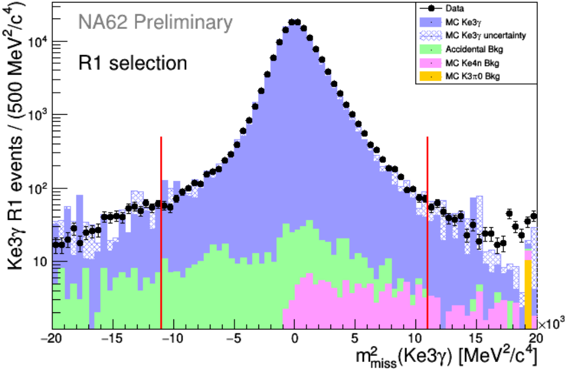


Divergent decay amplitude for $E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$ due to IB component.

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E^j_\gamma, \theta^j_{e,\gamma})}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

The Ke3γ selected sample [PoS(EPS-HEP2021)553]

	E_γ cut	$\theta_{e,\gamma}$ cut
R_1	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10^\circ$
R_2	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20^\circ$
R_3	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$



Selected signal events:

- 130 K in R_1
- 54 K in R_2
- 39 K in R_3

Background contamination:

- $B/S(R_1) \simeq 0.5\%$
- $B/S(R_2) \simeq 0.6\%$
- $B/S(R_3) \simeq 0.3\%$

NA62 preliminary R_j measurements [PoS(EPS-HEP2021)553]

	$O(p^6)$ *ChPT*	ISTRA+	OKA	**NA62 preliminary**
R_1 $(\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 $(\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 $(\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

Uncertainty source	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.5%	0.6%
Acceptances from MC	0.2%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modeling	0.5%	0.6%	0.5%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.6%
Total stat+syst	0.7%	1.0%	0.8%

- Achieved precision on R_j measurements equal/better than 1% relative
- State of the art improved by a factor between 2.0 and 3.6 in terms of relative precision
- Relative discrepancy with theory of 6-7% in all three measurements
- NA62 result for R_2 is half way between the two latest theoretical predictions [Kubis et al., EPJ C 50, 557] and [Khriplovich et al., PAN 74, 1214]

$R_A^{K_{\mu 2}}$ and $R_A^{K_{\mu 3}}$ @ NA62

Ratios related to V_{us}/V_{ud}

$$R_A^{K_{\mu 2}} = \frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)}$$

$$R_A^{K_{\mu 3}} = \frac{\Gamma(K^+ \to \pi^0 \mu^+ \nu)}{\Gamma(\pi \to \mu\nu)}$$

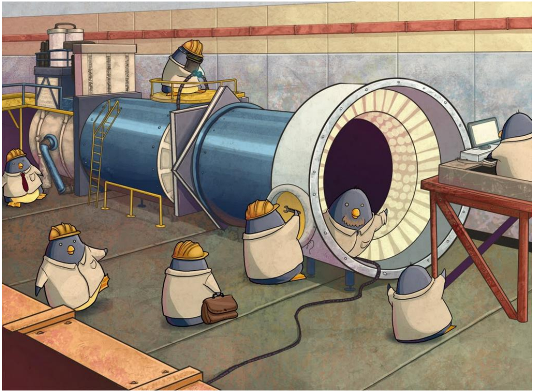
NA62 analysis strategy

- mimimum bias trigger
- $\pi^+ \to \mu^+ \nu$ process reconstructed from $K^+ \to \pi^+ \pi^0$, tagging the π^0
- Cancellation of several systematic uncertainties
- Analysis ongoing on 2017 and 2018 data
- Expected statistical uncertainty $< 1\%$
- Expected systematic uncertainty $O(0.1\%)$
- External uncertainty: knowledge of $\mathcal{B}(K^+ \to \pi^+ \pi^0)$: 0.4%

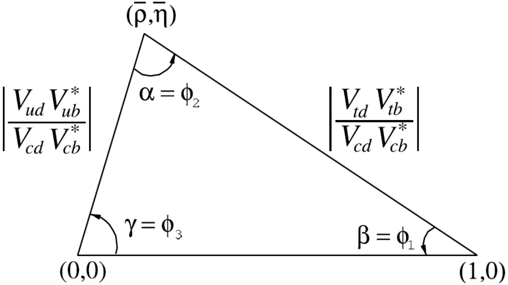
Conclusions

- The CKM unitarity condition represents a strong tool to test our comprehension of the Weak Interaction in the Standard Model.
- There are interesting hints of possible deviation from the unitarity condition, in particular with the first row of the CKM matrix (V_{ud} and V_{us}).
- Kaon physics is the best environment to improve the precision of those measurements.
- The NA62 experiment is collecting the world largest statistics of K^+ decay and can give a fundamental contribution in that context.

SPARES

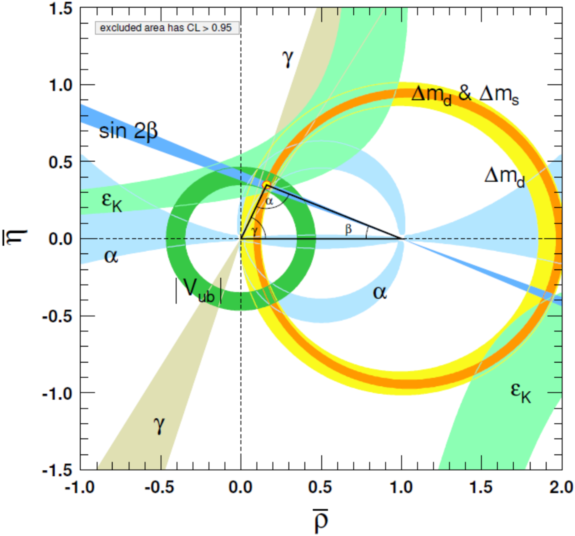


The CKM unitarity triangle

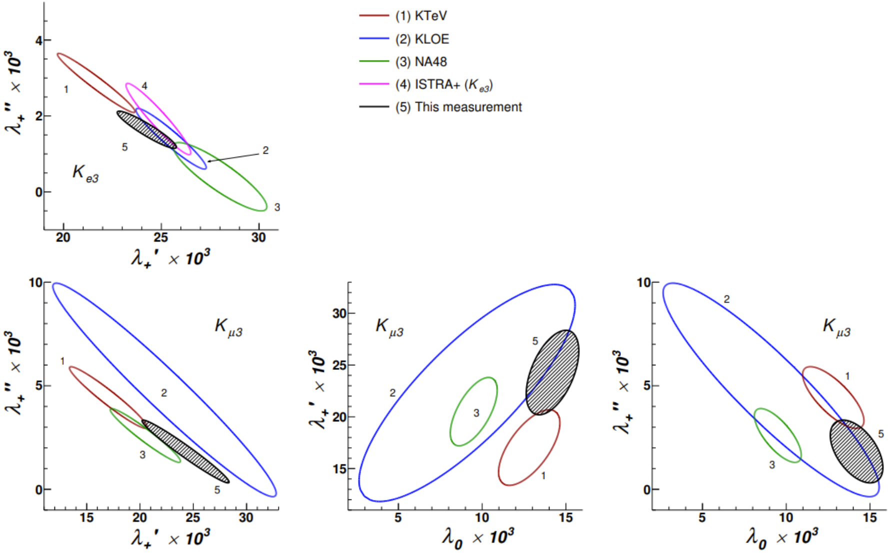


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The CKM unitarity triangle fit [PDG 2022]



Form factors measurements from NA48/2 paper [JHEP10(2018)150]



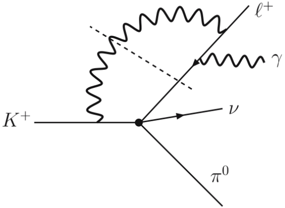
$K^+ \to \pi^0 e^+ \nu \gamma$ decay: T-asymmetry

T-odd observable ξ
(in the kaon rest frame):

$$\xi = \frac{\overrightarrow{p_\gamma} \cdot (\overrightarrow{p_e} \times \overrightarrow{p_\pi})}{m_K^3} \; ; \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

Non-zero A_ξ values due to NLO (one-loop) electromagnetic corrections

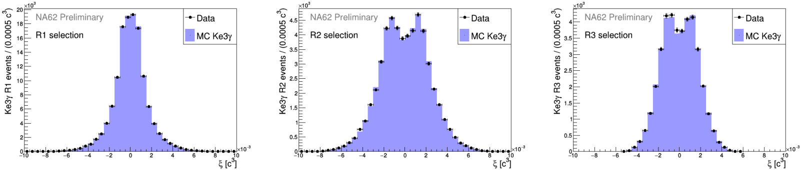
[Muller et al.,
EPJ C 48, 427]



State of the art:

- $|A_\xi^{SM\ and\ beyond}| < 10^{-4}$
- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements provided for R_1 and R_2

NA62 preliminary A_ξ measurements [PoS(EPS-HEP2021)553]



$$A_\xi = A_\xi^{Data} - (A_\xi^{MCreco} - A_\xi^{MCgene}) \simeq A_\xi^{Data} - A_\xi^{MCreco}$$

	R_1 selection	R_2 selection	R_3 selection
A_ξ^{Data} $(\times 10^2)$	0.2 ± 0.3	0.1 ± 0.4	-0.6 ± 0.5
A_ξ^{MCgene} $(\times 10^2)$	-0.01 ± 0.01	0.00 ± 0.02	-0.01 ± 0.02
A_ξ^{MCreco} $(\times 10^2)$	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.5
A_ξ $(\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

- R_3 T-asymmetry precision improved by a factor greater than 3: $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- First measurements ever performed for R_1 and R_2 T-asymmetry