Precision measurements with Kaons at CERN

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Precision measurements with Kaons at CERN

1. First measurement of $K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$ [PRELIMINARY]
2. New study of $K^+ \rightarrow \pi^0 e^+ \nu\gamma$ [PRELIMINARY]
3. Measurement of $K^+ \rightarrow \pi^+\mu^+\mu^-$ [PRELIMINARY]

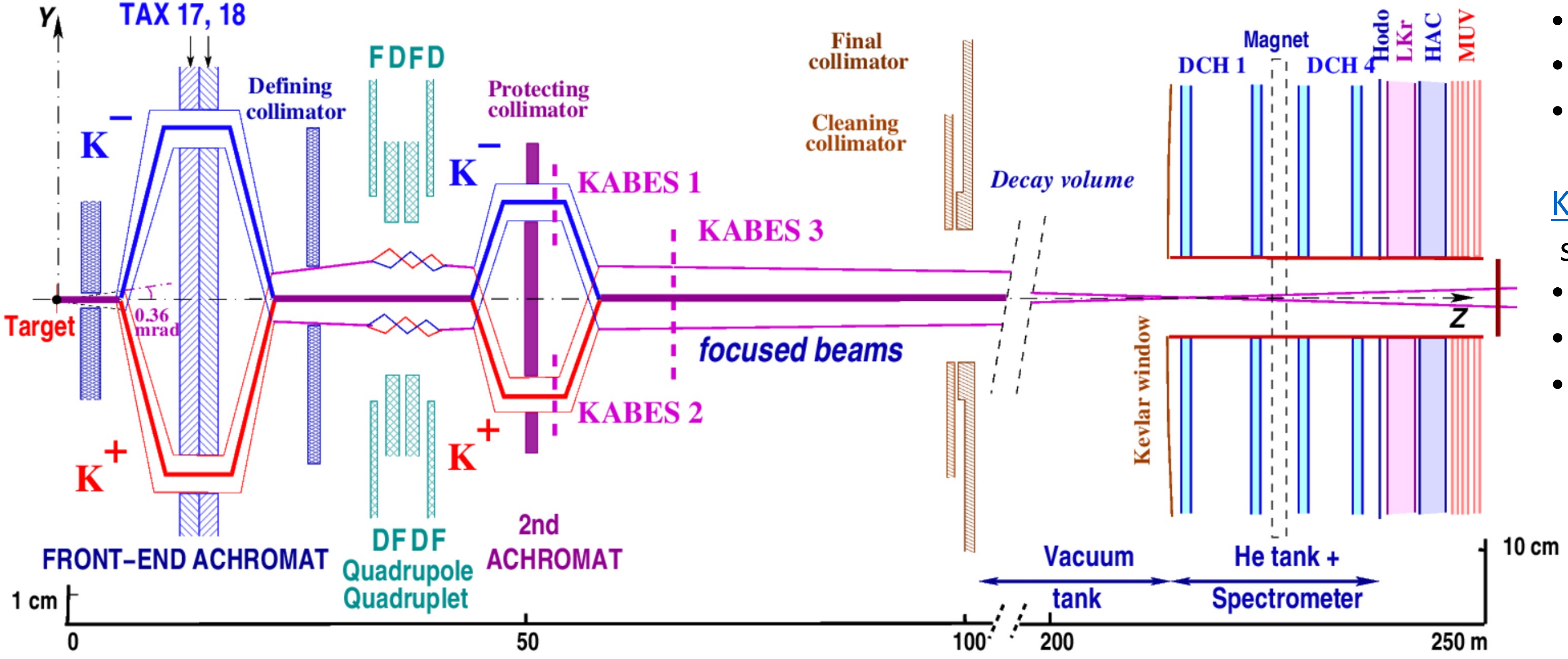
Kaon physics at CERN

- Significant history of kaon physics experiments in the CERN North Area (NA)
- Today I will show results from NA48/2 and NA62

Recent history of NA kaon experiments

1984 ↓ 1990	NA31 (K_S/K_L)	First evidence of direct CPV
1997 ↓ 2001	NA48 (K_S/K_L)	**Re ε'/ε** Discovery of direct CPV
2002	NA48/1 (K_S/hyperons)	Rare $\mathbf{K_S}$ and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV Rare $\mathbf{K^+}$ / $\mathbf{K^-}$ decays
2007 ↓ 2008	NA62 R_K phase (K^+/K^-)	$\mathbf{R_K = K^{\pm}_{e\nu}/K^{\pm}_{\mu\nu}}$
2016 ↓ 2018	NA62 (K^+)	$\mathbf{K^+ \rightarrow \pi^+ \nu\nu}$ Rare $\mathbf{K^+}$ and $\mathbf{\pi^0}$ decays

The NA48/2 beamline



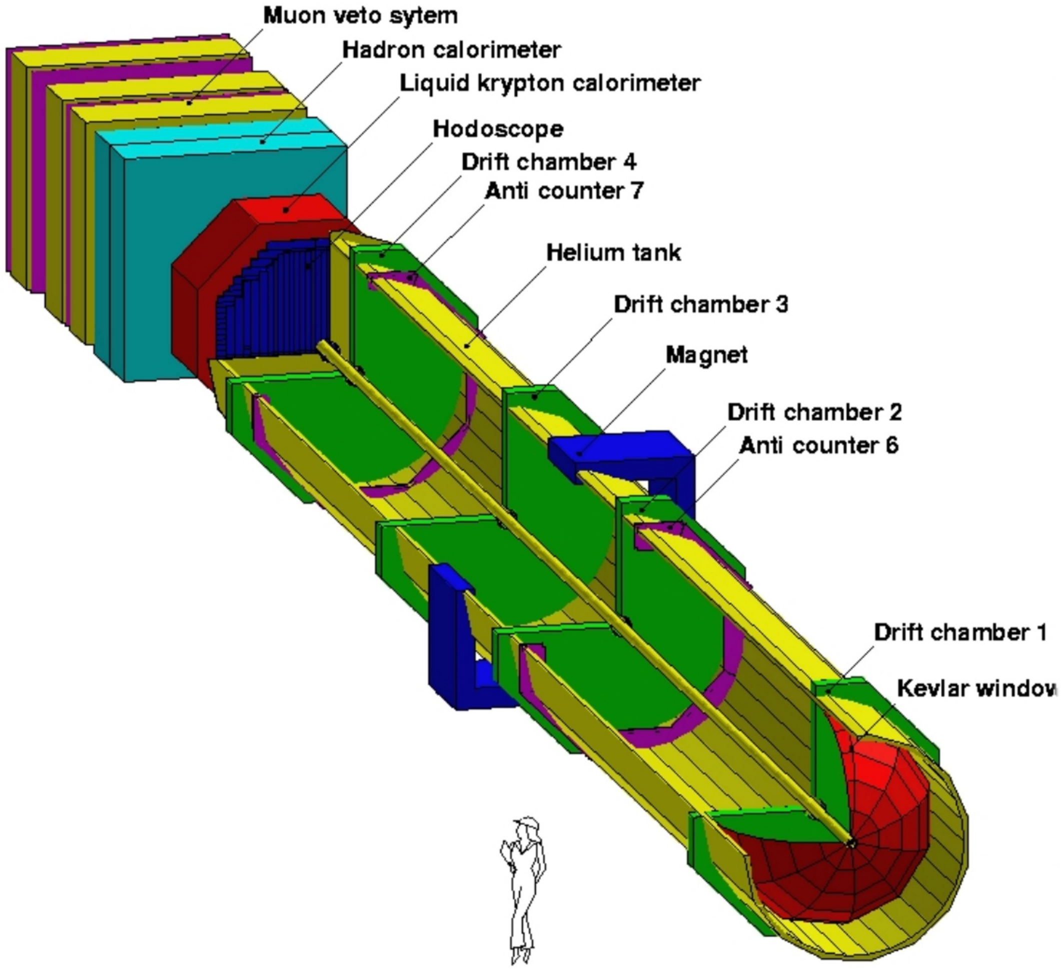
Two charged beams:

- 6% of $K^{\pm}$
- $\langle P_K \rangle \approx 60\ \text{GeV}/c$
- $\Delta P_K / \langle P_K \rangle \approx \pm 3.8\%$

KABES (kaon beam spectrometer):

- $\sigma(X, Y) \sim 800 \mu m$
- $\sigma(P_K) \sim 1\%$
- $\sigma(T) \sim 600 \text{ps}$

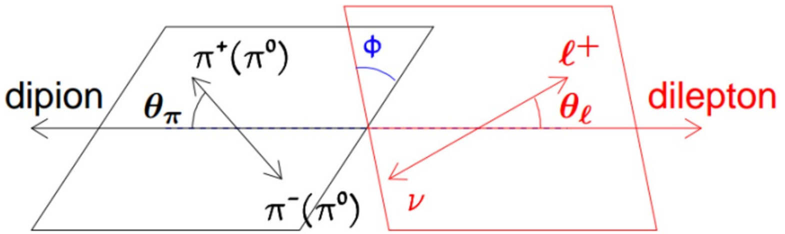
The NA48/2 detector



- Magnetic spectrometer (drift chambers DCH1–DCH4):
  - $\sigma(X, Y) \sim 90\ \mu$m per chamber
  - $\sigma(P_{DCH})/P_{DCH} = (1.02 \oplus 0.044 \cdot P_{DCH})\%$ (P_{DCH} in GeV/c)
- Scintillator hodoscope (HOD):
  - $\sigma(T) \sim 150$ ps
- Liquid Krypton EM calorimeter (LKr):
  - $\sigma_x = \sigma_y = (0.42/\sqrt{E_\gamma} \oplus 0.06)$ cm
  - $\sigma(E_\gamma)/E_\gamma = (3.2/\sqrt{E_\gamma} \oplus 9.0/E_\gamma \oplus 0.42)\%$ (E_γ in GeV)
- Hadronic calorimeter, muon system MUV.

First measurement of $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$

$K \to \pi\pi\mu\nu (K_{l4})$ depends on F, G, R, H form-factors.
Cabibbo-Maksymowicz variables: S_π (dipion mass squared), S_l (dilepton mass squared) and angles θ_π (in the dipion frame), θ_l (in the dilepton frame), ϕ.



- For $K^{00}_{\mu 4}$, s-wave for $\pi^0\pi^0$, there are no dependence on $\cos\theta_\pi, \phi$, and only F and R contribute.
- Unlike K^{00}_{e4} case, R plays some role due to μ mass.

K_{l4} mode	BR $[10^{-5}]$	N_{cand}	
$K_{e4}{}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
$K_{e4}{}^{00}$	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}{}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}{}^{00}$	?	0	

$K^{00}_{\mu 4}$: first observation, ChPT test, check of R presence, potential study of $\pi\pi$ rescattering effects in the $F(S_\pi)$.

$K_{\mu 4}$: huge bkg $K^{\pm} \to \pi\pi(\pi^{\pm} \to \mu^{\pm}\nu)$.

- To simulate $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ decays, can use parameterisation of $F(S_\pi, S_\ell)$ from K^{00}_{e4} measurements [NA48/2 JHEP 08 (2014) 159]
- The only available source of $R(S_\pi, S_\ell)$ is ChPT calculation [J. Bijnes, G. Colangelo, J. Gasser, Nucl. Phys. B 427 (1994) 427]

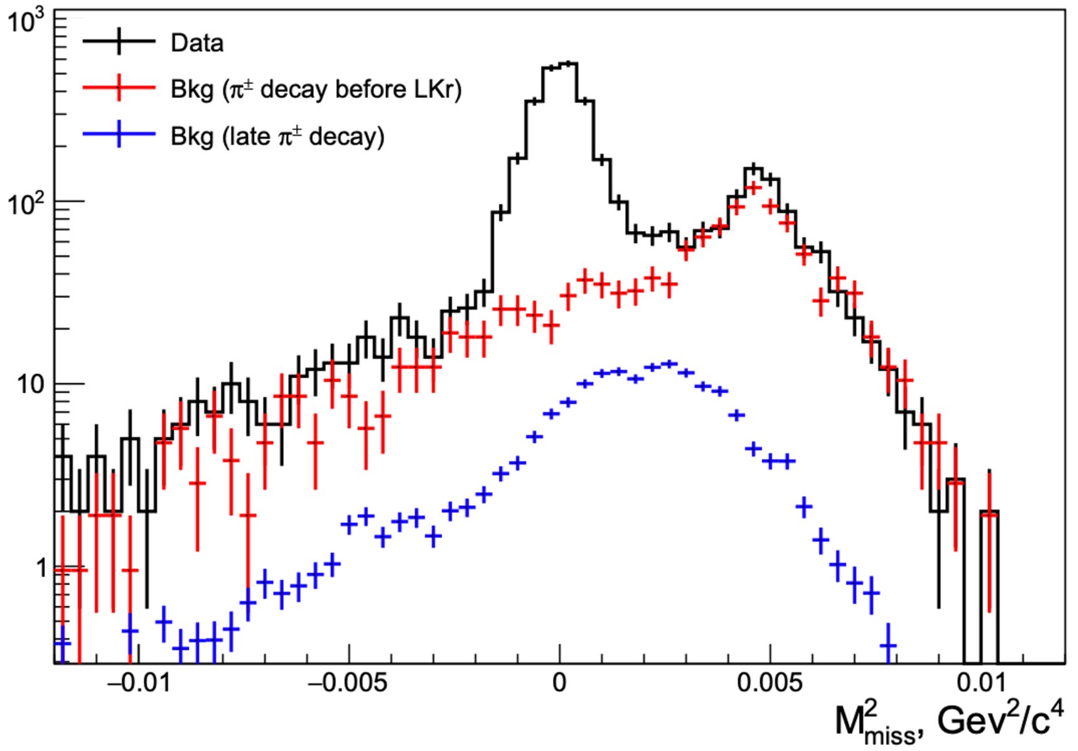
Event selection

- Signal is $K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$
- Normalised to $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

- Event selection: 4 isolated photons consistent with $2\pi^0$ matched in time and space with a KABES beam track and a DCH track with associated MUV response

- The main background is $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ with $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ decay-in-flight before LKr
- Cuts imposed on 3-pion mass and p_T, missing mass, and $\cos(\theta_{\ell})$

- Number of background events extracted from a fit to missing mass sidebands



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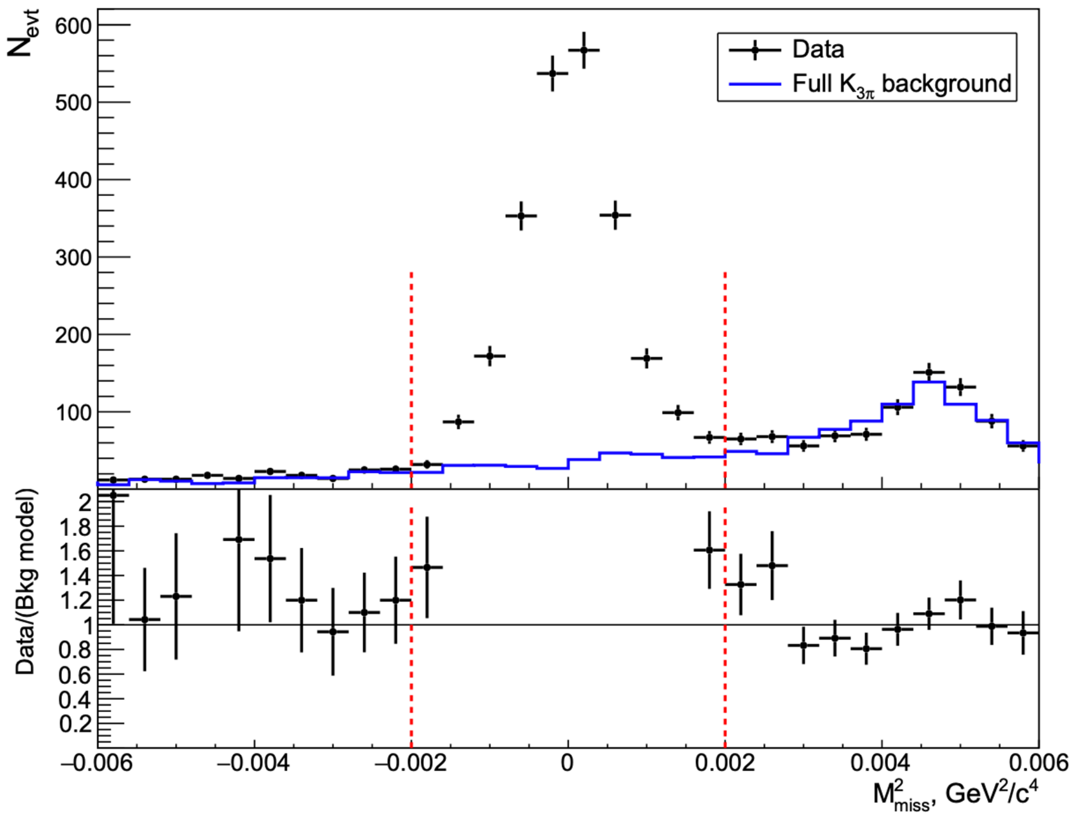
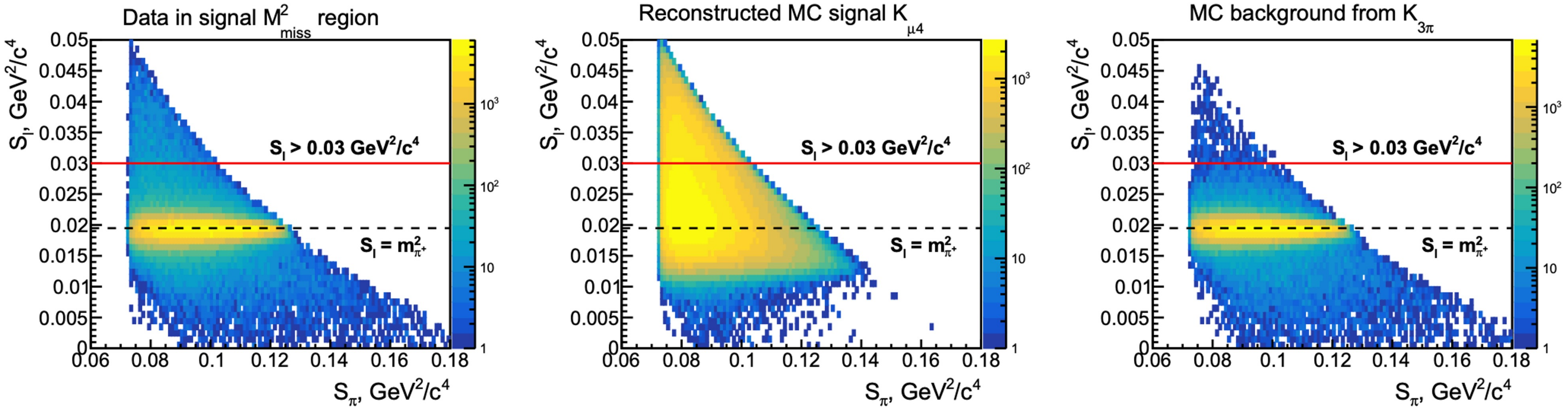
- Cuts imposed on 3-pion mass and p_T, missing mass, and $\cos(\theta_\ell)$

- Number of background events extracted from a fit to missing mass sidebands

2437 candidates in signal region
$354 \pm 33_{stat}$ background events



Full and restricted phase-space



- The branching ratio is measured for the restricted phase space $S_l^{true} > 0.03\ \mathrm{GeV}^2/c^4$.
- Extrapolation to the full phase space depends on the theory.

Ingredients to the branching ratio

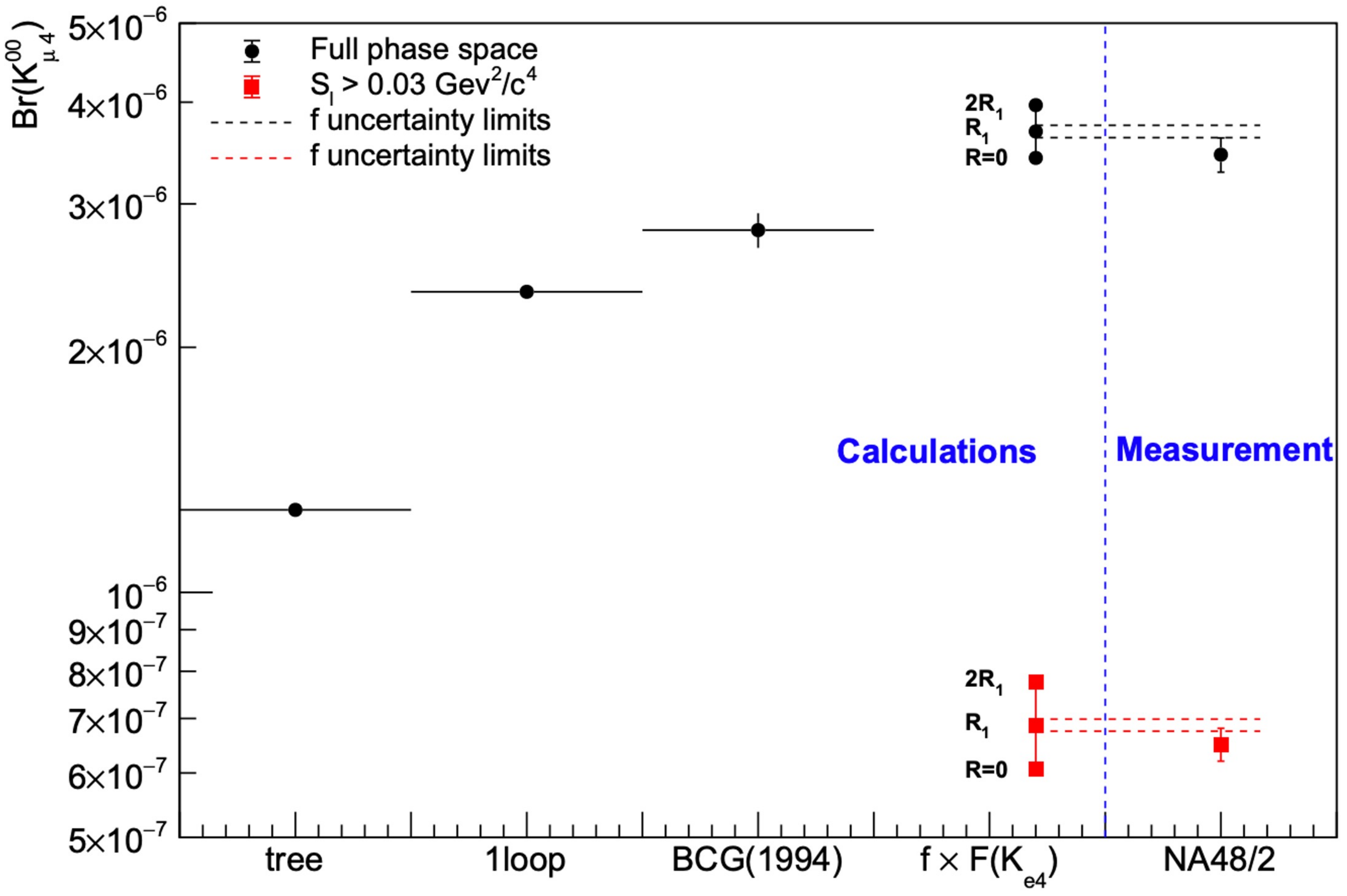
$$BR(K^{00}_{\mu 4}) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig} \cdot BR(K^{00}_{3\pi}).$$

- Extracted signal $N_S = N_{Sign.\ cand.} - N_{Bkg} = 2437 - (354 \pm 33_{stat}) = 2083 \pm 59_{stat}$ events;
  - Signal/Background is $5.89 \pm 0.66_{stat}$;
- Number of normalization events $N_N = 72.99 \times 10^6$;
- Normalization acceptance $A_N = (4.477 \pm 0.002)\%$;
- Signal acceptance for the restricted phase space $A^r_S = (3.453 \pm 0.007)\%$;
- Signal acceptance for the full phase space $A_S = (0.651 \pm 0.001)\%$;
- Trigger correction (extracted with control triggers) $K_{trig} = K_{CHT} \cdot K_{NUT} = (0.998 \pm 0.002) \cdot (1.0007 \pm 0.0007) = 0.999 \pm 0.002$;
- PDG $BR(K^{00}_{3\pi}) = (1.760 \pm 0.023)\%$;

Systematic uncertainties

	Full phase space		$S_l > 0.03$ GeV^2/c^4	
$BR(K_{\mu 4})$ central value $[10^{-6}]$	3.45		0.651	
	$\delta BR[10^{-6}]$	$\delta BR/BR$	$\delta BR[10^{-6}]$	$\delta BR/BR$
Data stat. error	0.10	2.85%	0.019	2.85%
MC stat. error	0.01	0.21%	0.001	0.21%
Trigger	0.01	0.18%	0.001	0.18%
Background	0.10	2.96%	0.019	2.96%
Accidentals	0.01	0.32%	0.002	0.32%
MUV inefficiency	0.06	1.65%	0.011	1.65%
Form Factor modelling	0.05	1.37%	0.001	0.14%
$BR(K_{3\pi})$ error (external)	0.05	1.31%	0.009	1.31%
Total error	0.17	4.83%	0.030	4.64%

Comparison to theory predictions

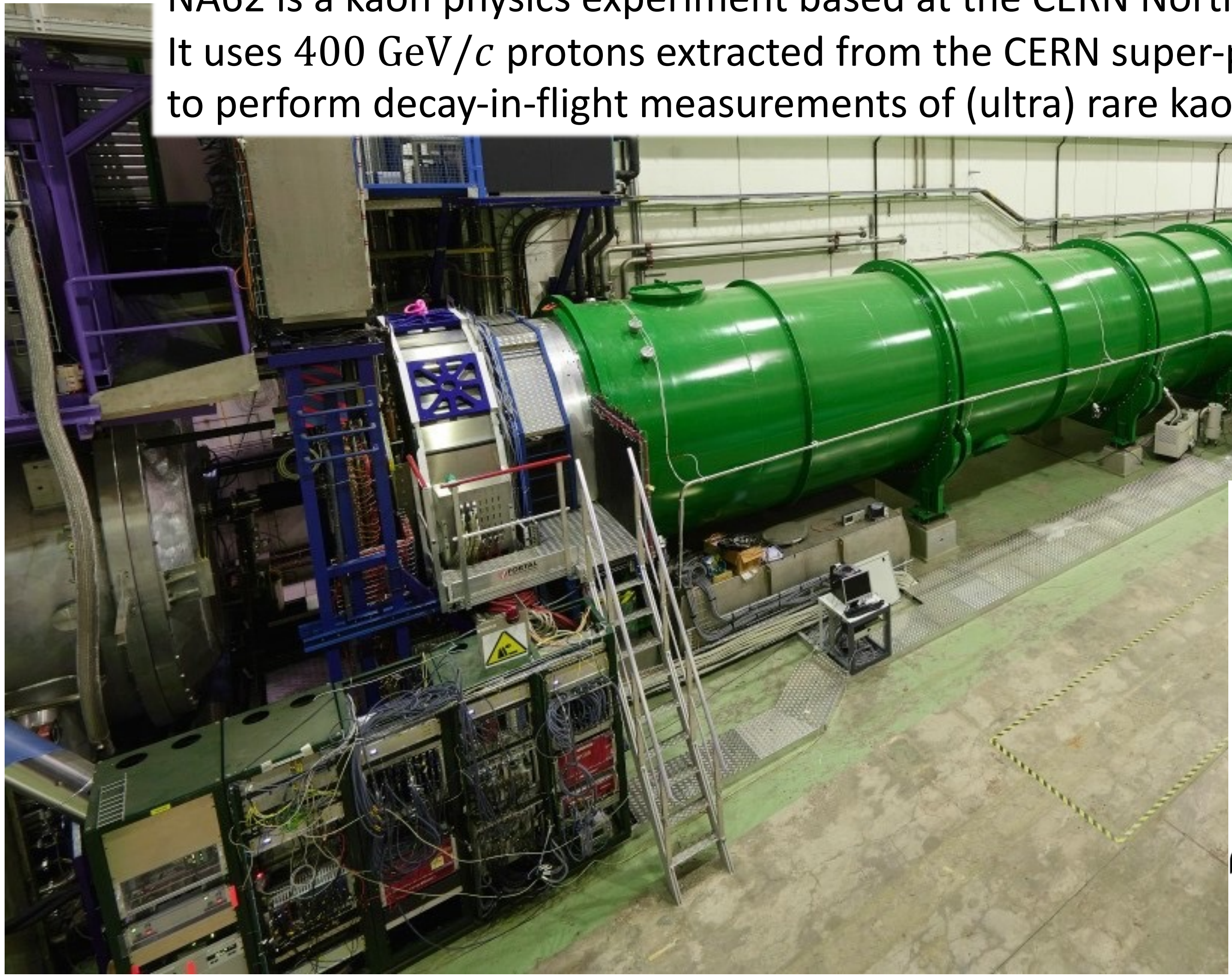


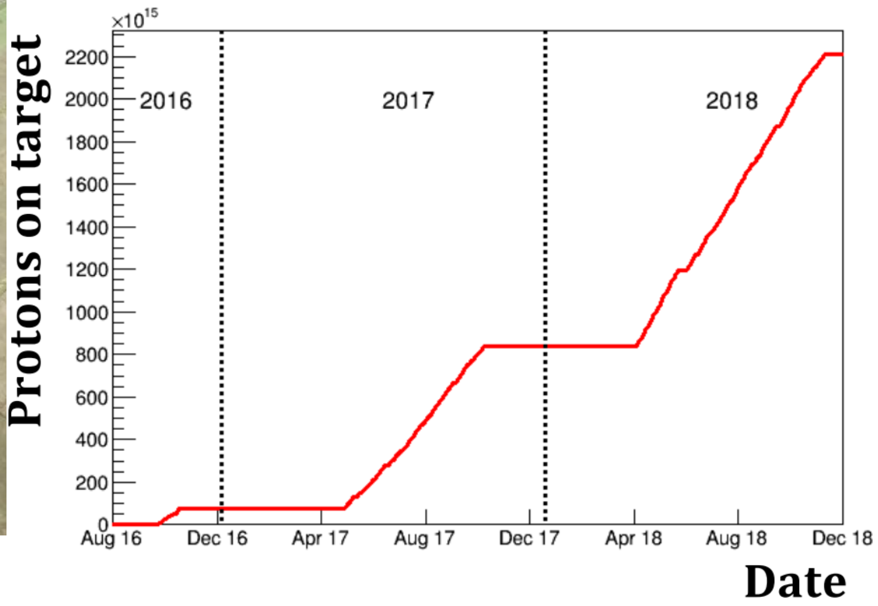
Theory:

- J. Bijnens, G. Colangelo, J. Gasser, Nucl. Phys. B, 427 (1994) 427:
  - Tree approximation;
  - 1-loop;
  - BCG(1994): 'beyond 1-loop' with measured F from [Rosselet etc. Phys. Rev. D 15 (1977) 574].
- Re-calculated now:
  - $F(K_{e4})$ from NA48/2 (2015);
  - $R_1 = R(1loop)$;
  - 1-loop (F,R) phase;
  - 2020 PDG constants.

The NA62 experiment

NA62 is a kaon physics experiment based at the CERN North Area (NA)
It uses $400\ \mathrm{GeV}/c$ protons extracted from the CERN super-proton synchrotron (SPS) to perform decay-in-flight measurements of (ultra) rare kaon decays



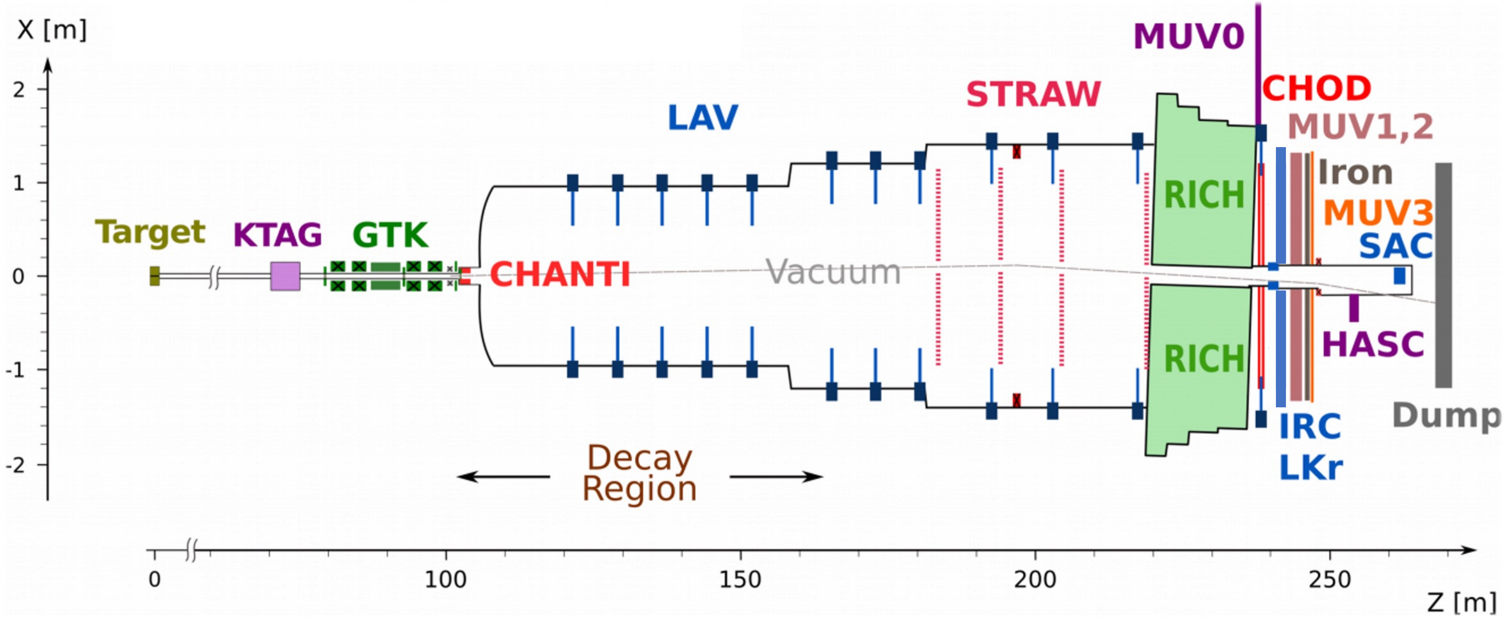


The NA62 detector

[*JINST* **12** P05025]

400 GeV/c protons from CERN SPS

Slow extraction in 'spills' of 5 seconds



- Proton-target interactions + achromatic selector forms secondary hadron beam with $p \approx 75\ GeV/c$
  - There are 750MHz of particles in the secondary beam; 6% are K^+ (45MHz)
- Measurement of all beam particles by kaon tagger **KTAG** and beam-particle tracker **GTK**
- About 15% of K^+ decay within the $\sim 75\text{m}$ vacuum **decay region**, which defines the experiments **fiducial volume**
- Measurement of K^+ decay products by the **STRAW** tracker and **CHOD** detectors
- Particle identification by the **RICH**, the **LKr** and **MUV** calorimeters, and the **MUV3** detector
- Hermetic photon veto provided by the **LAV, LKr, IRC, SAC** photon detectors

New study of $K^+ \to \pi^0 e^+ \nu\gamma$

[Nucl. Phys. B 396 (1993) 81]
[Phys. Rev. D 65 (2002) 054038]
[Eur. Phys. J. C 50 (2007) 557]
[Phys. Atom. Nucl. 74 (2011) 1214]

- The $K^+ \to \pi^0 e^+ \nu\gamma$ decay is a radiative decay described in ChPT, with the photon produced either via direct emission (DE) and inner bremstrahlung (IB)
- The IB amplitude diverges when $E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$
- Measure branching fraction ratio $\mathrm{R} = BR(\pi^0 e^+ \nu\gamma)/\mathrm{BR}(\pi^0 e\nu)$ in 3 kinematic regions R_j

DE (a) + IB (b) + INT

arxiv:2010.07983

Range	E_γ cut	$\theta_{e,\gamma}$ cut	$O(p^6)$ $ChPT$ $[10^{-2}]$	$ISTRA+$ $[10^{-2}]$	OKA $[10^{-2}]$
R_1	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
R_2	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
R_3	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

Phys. Atom. Nucl.70, 29 (2007)

New study of $K^+ \to \pi^0 e^+ \nu\gamma$

- The decay is also sensitive to a T-odd observable ξ, with asymmetry in ξ defined as A_ξ

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

- Expect $|A_\xi| < 10^{-4}$ in SM and beyond; non-zero due to NLO electromagnetic corrections

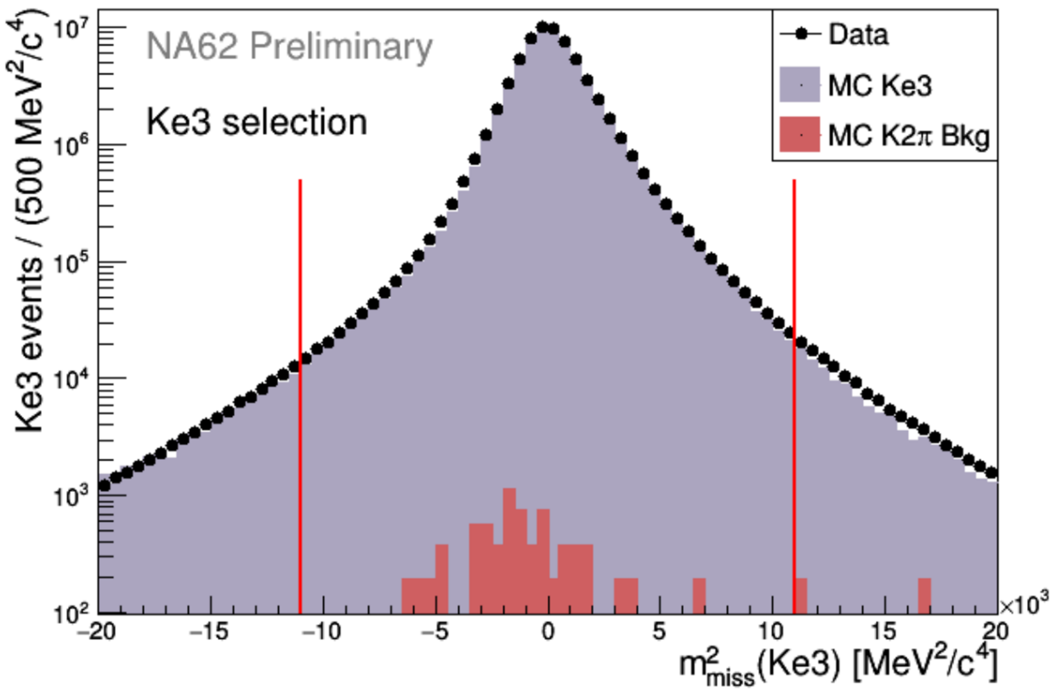
- Exisiting measurement from ISTRA+

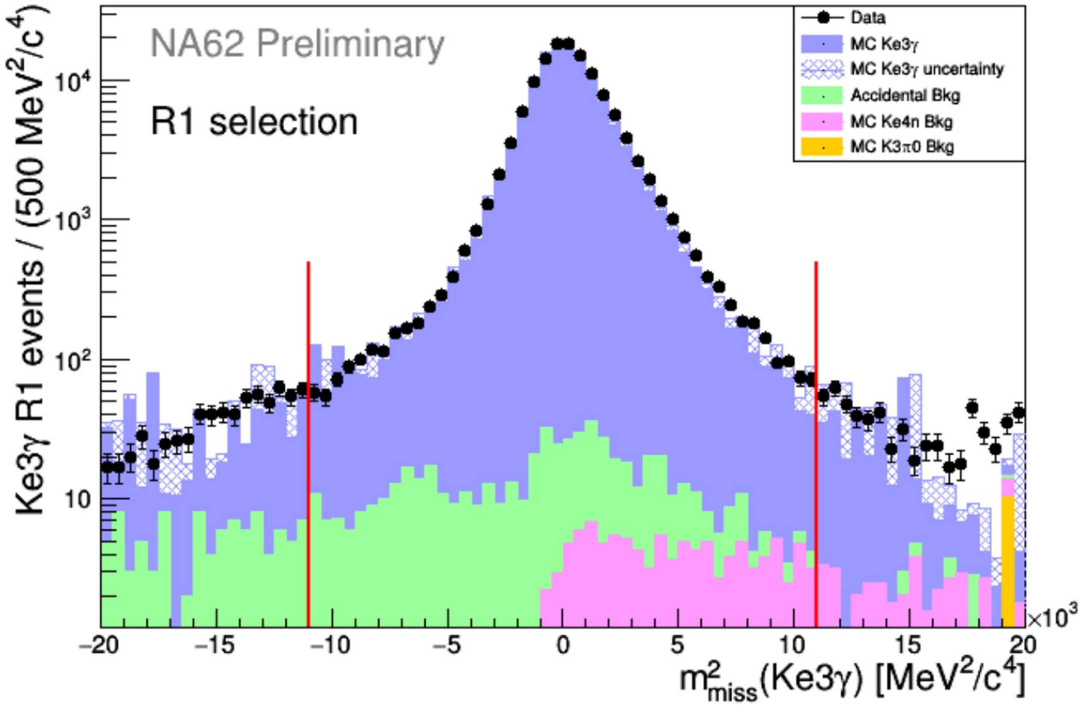
$$A_\xi^{ISTRA+}(R3) = 0.015 \pm 0.021$$

- No measurement in regions 1 or 2

Event selection

- Branching fraction measurements normalised to $K^+ \to \pi^0 e^+ \nu$
- Event selection based on K^+ associated to e^+, $\pi^0 \to \gamma\gamma$ reconstructed in LKr
- Radiative γ must be in-time with the event and isolated; other activity not allowed to suppress $K^+ \to \pi^0\pi^0 e^+ \nu$; cuts to remove γ from bremstrahlung and supress $K^+ \to \pi^+\pi^0\pi^0$ and $K^+ \to \pi^+\pi^0$
- Obtain 66M normalisation events and 130k signal events (R1) with 0.5% background contamination



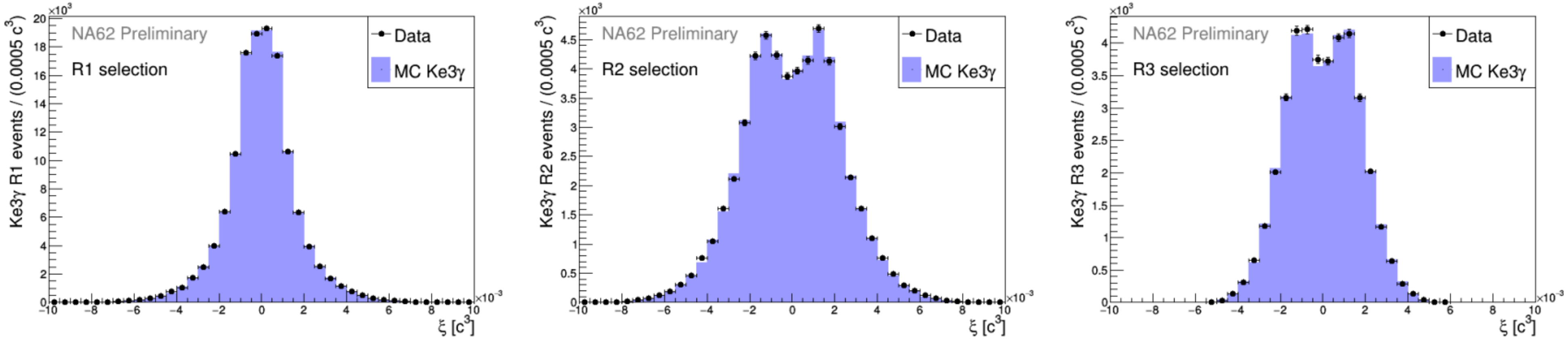


Results and systematics

	$O(p^6)$ *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%

Measurements of A_ξ



	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 $(\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

- First ever measurements of R_1 and R_2 T-asymmetry
- R_3 T-asymmetry precision improved by a factor greater than 3

Measurement of $K^+ \to \pi^+\mu^+\mu^-$

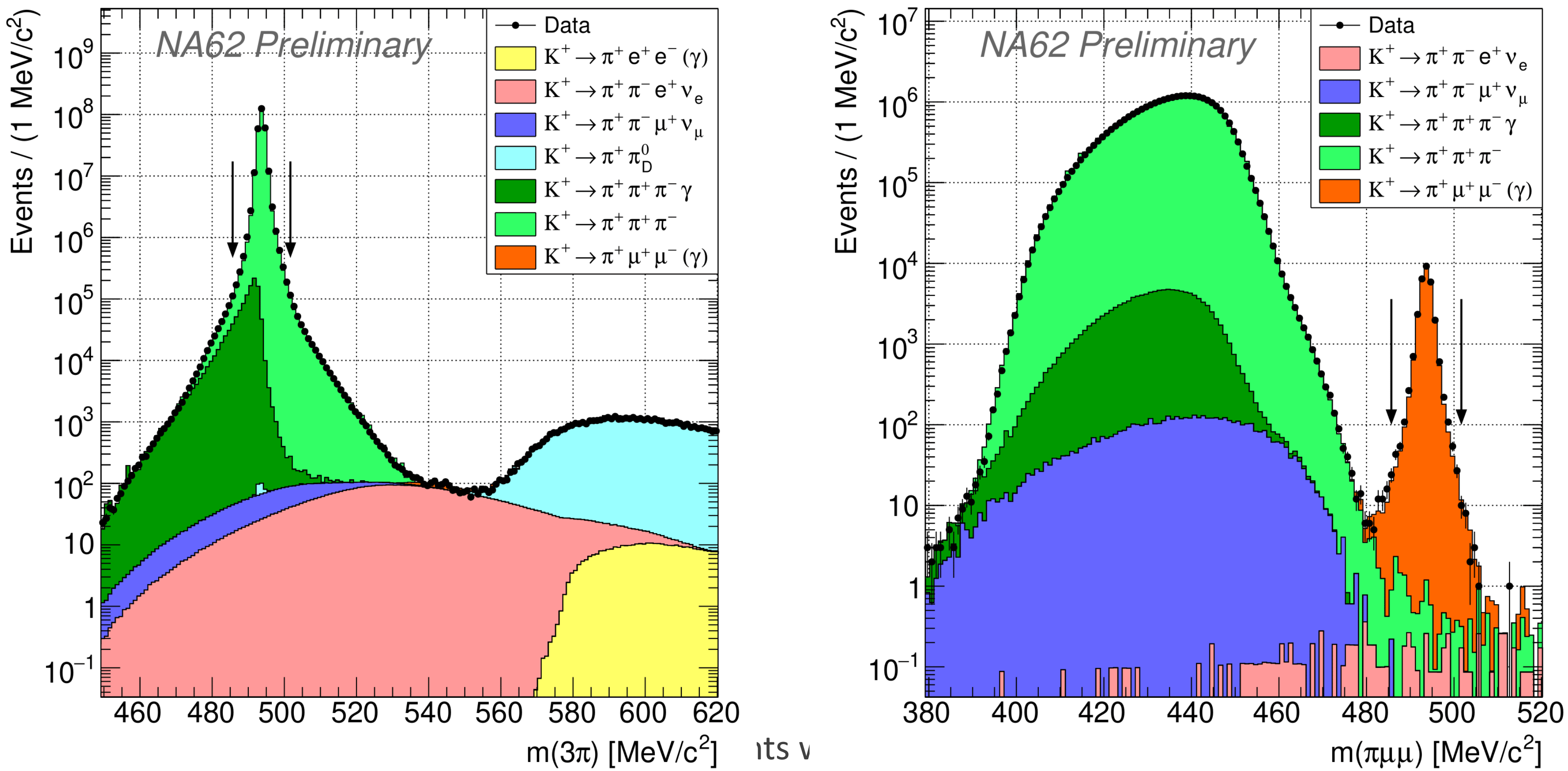
- The $K^+ \to \pi^+\ell^+\ell^-$ decay is a *Flavour Changing Neutral Current* $s \to d\ell\ell$ process
- The SM branching fraction is $\mathrm{O}(10^{-7})$; dominated by long-distance effects
  [Nucl. Phys. B291 (1987) 692–719], [JHEP 08 (1998) 004], [Phys. Part. Nucl. Lett. 5 (2008) 76–84], [Eur. Phys. J. C70 (2010) 219–231]

- The form factor is parameterised by two coefficients: a_+ and b_+

- Short distance physics can be extracted by comparing a_+ and b_+ between $\pi^+\mu^+\mu^+$ and $\pi^+e^+e^-$ as the SM predicts them to be identical: a probe of *Lepton Flavour Universality*
- The a_+ parameter can be related to B anomalies (assuming MFV) [Phys. Rev. D 93, 074038 (2016)]
- Largest uncertainty on a_+ is in the dimuon mode

Event selection

- Normalised to $K^+ \rightarrow \pi^+\pi^+\pi^-$. Events selected by reconstructing three-track vertices, and looking for associated K^+ and muon signatures. Kinematic cuts to further suppress $K^+ \rightarrow \pi^+\pi^+\pi^-$ backgrounds
- $\mathbf{2.78{\times}10^8}$ normalisation events, **28011** signal events (9x larger than earlier measurement)



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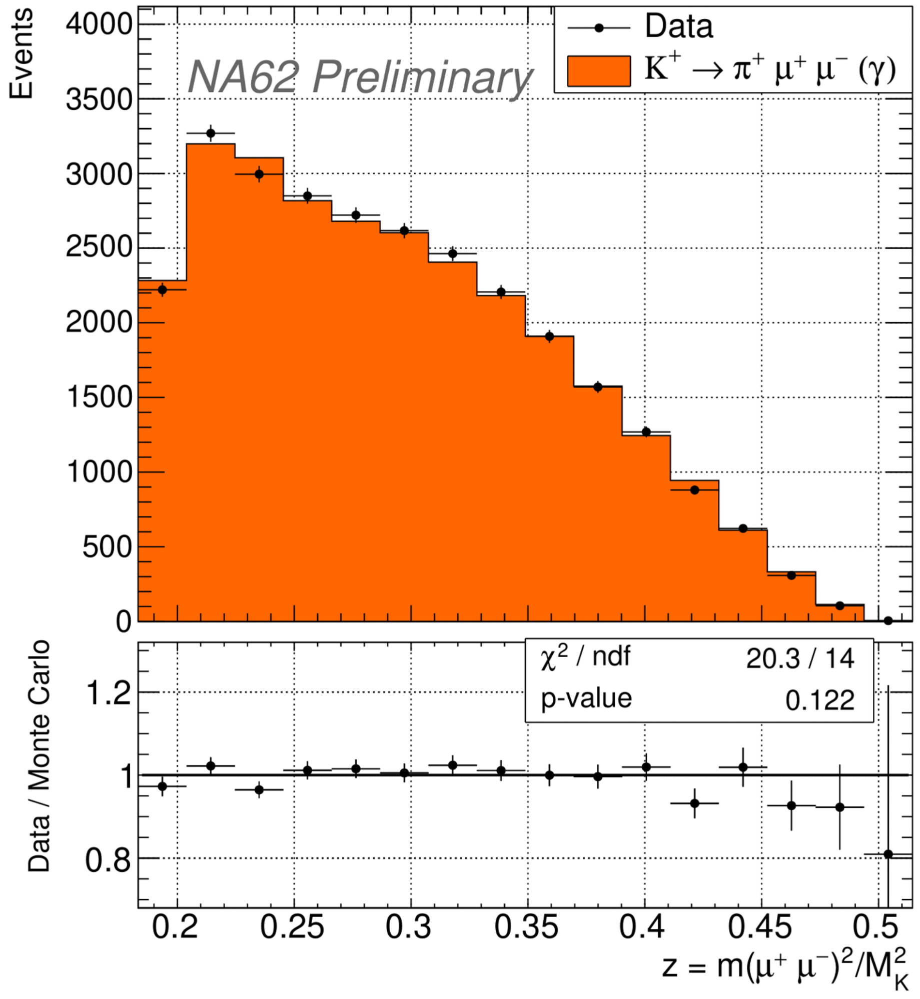
Fit to the form-factor parameters



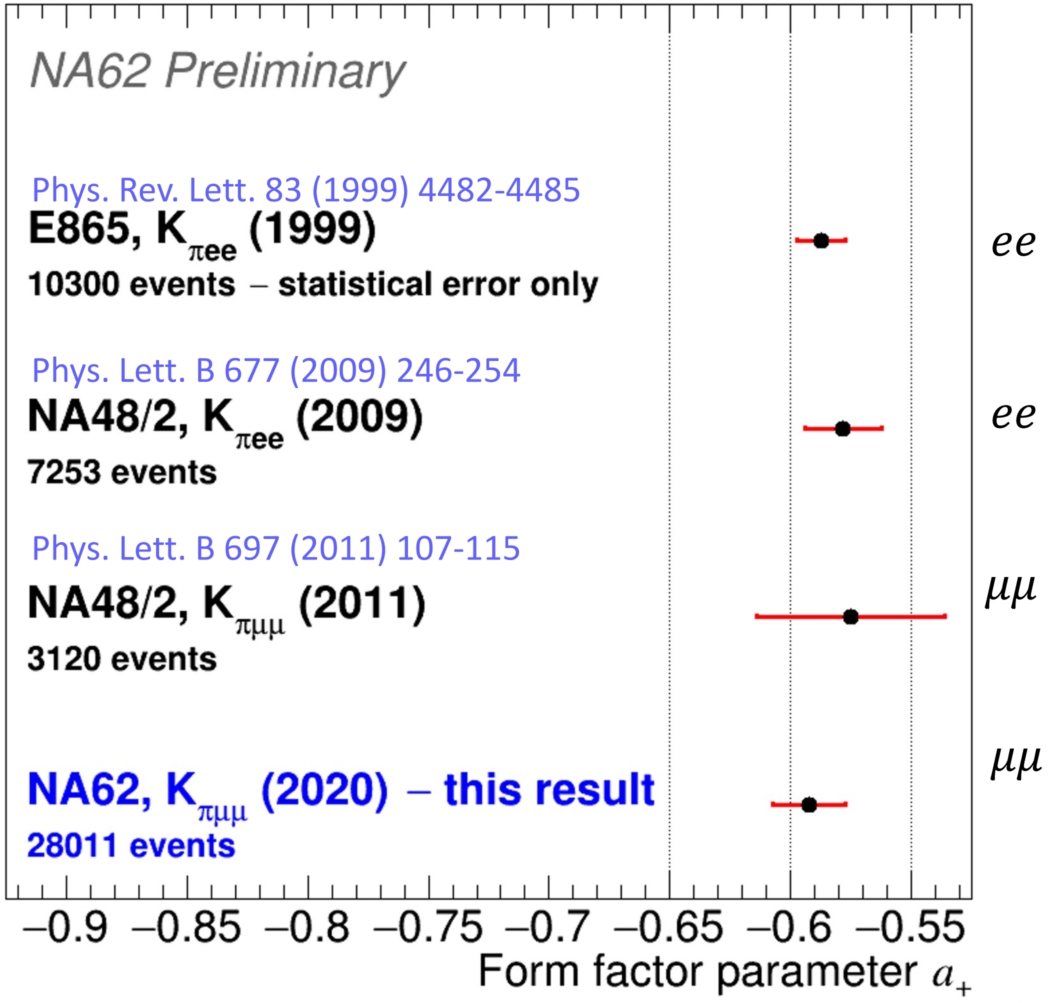
Fitting procedure:

- z spectrum of simulated $K^+ \to \pi^+\mu^+\mu^-$ events reweighted to best fit the data by minimising $\chi^2(a, b)$

	a	b	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa	δb	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam & pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	0.000	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error on $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

Comparison with existing measurements

- The NA62 measurement of $a_+^{\mu\mu}$ is the worlds most precise determination
- The result is consistent with the earlier NA48/2 measurement, and is consistent with existing measurements of a_+^{ee}
- No indication of discrepancy with SM predictions, including LFU violation



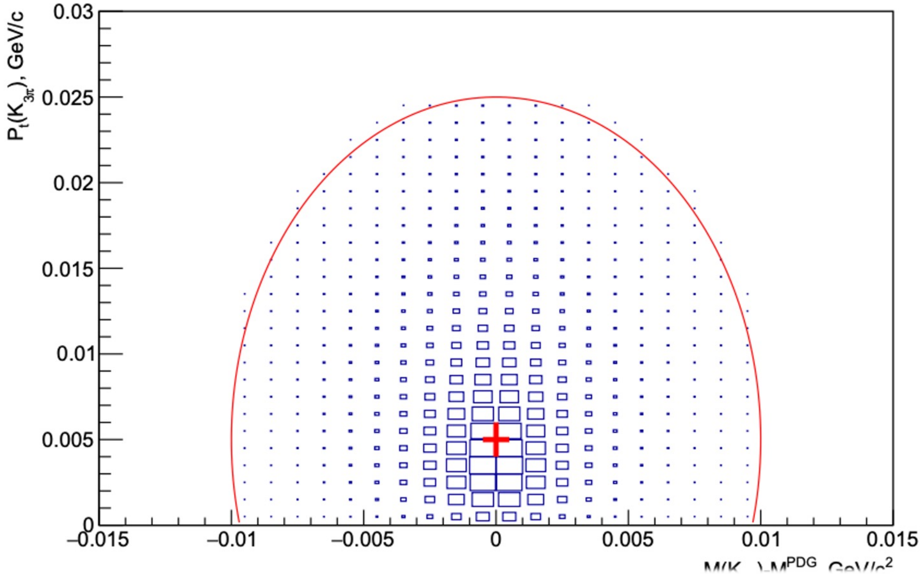
Summary

1. First observation and BR measurement of $K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$ by NA48/2 [PRELIMINARY]
   - Restricted phase-space:
     $$BR(S_\ell > 0.03) = \left(0.65 \pm 0.019_{stat} \pm 0.024_{syst}\right)\times10^{-6} = (0.65 \ \pm 0.03)\times10^{-6}$$
   - Full phase-space result:
     $$BR = \left(3.4 \pm 0.10_{stat} \pm 0.13_{syst}\right)\times10^{-6} = (3.4 \ \pm 0.2)\times10^{-6}$$
   - Consistent with contribution from R form-factor, as expected from ChPT.

2. New study of $K^{+} \rightarrow \pi^0 e^{+}\nu\gamma$ by NA62 [PRELIMINARY]
   - Precision of R_j measurements improved by factors between 2.0 and 3.6
   - First T-asymmetry measurements in R_1 and R_2, improved result on R_3 by factor 3
   - T-asymmetry results compatible with zero

3. Measurement of $K^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ by NA62 [PRELIMINARY]
   - Most precise measurements of a_+ and b_+ parameters and branching ratio
   - No hints of lepton non-universality

- Signal $K_{\mu 4}$ is $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$
- Normalization $K_{3\pi}$ is $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$
- Trigger chain: L1 trigger using HOD and LKr, followed by L2 trigger using DCH for online momentum calculation.
- Event selection: 4 isolated photons consistent with $2\pi^0$ in time-spatial matching with a KABES beam track and a DCH track.

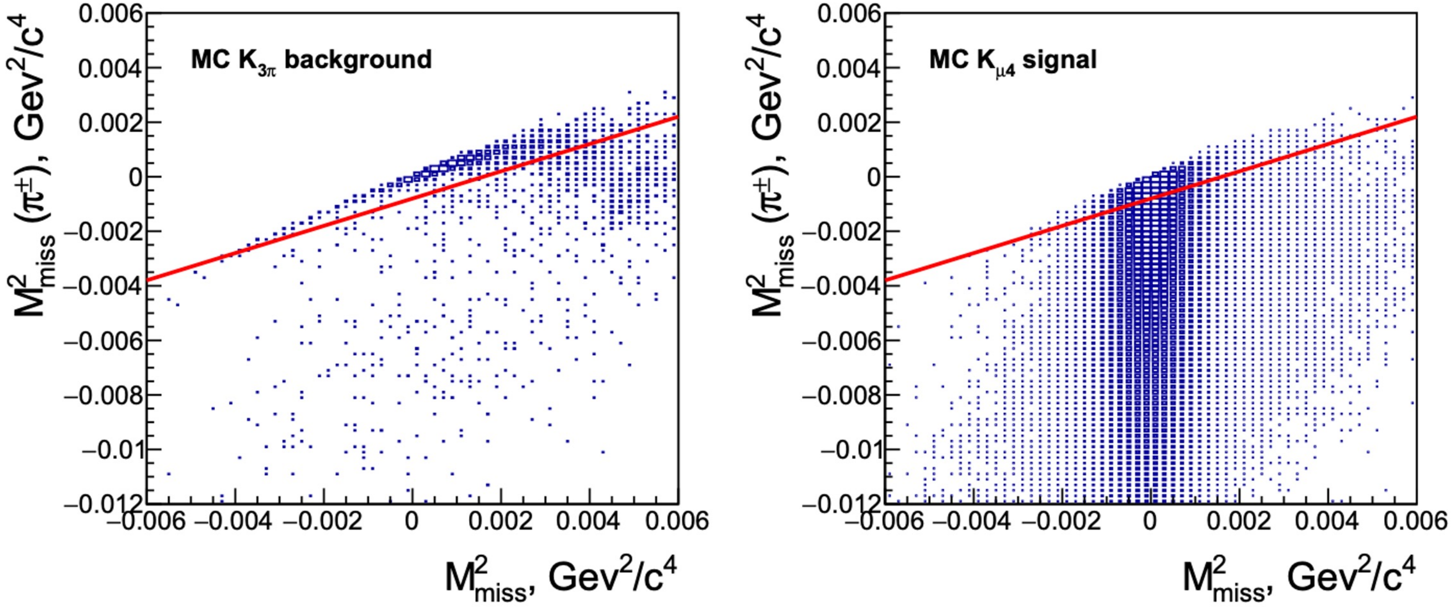


Normalization $K_{3\pi}$ kinematic selection ellipse:

- center:
  - $M(K_{3\pi}) = M_K^{PDG}$
  - $P_t = 5$ MeV$/c$
- semi-axes:
  - $\Delta M(K_{3\pi}) = 10$ MeV$/c^2$
  - $\Delta P_t = 20$ MeV$/c$
- 72.99×10^6 $K_{3\pi}$ selected data events.

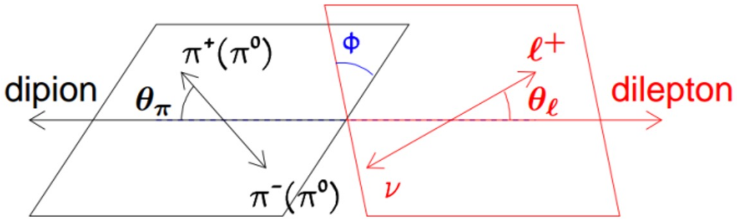
- Off the $K_{3\pi}$ kinematic ellipse
- DCH track has associated MUV response

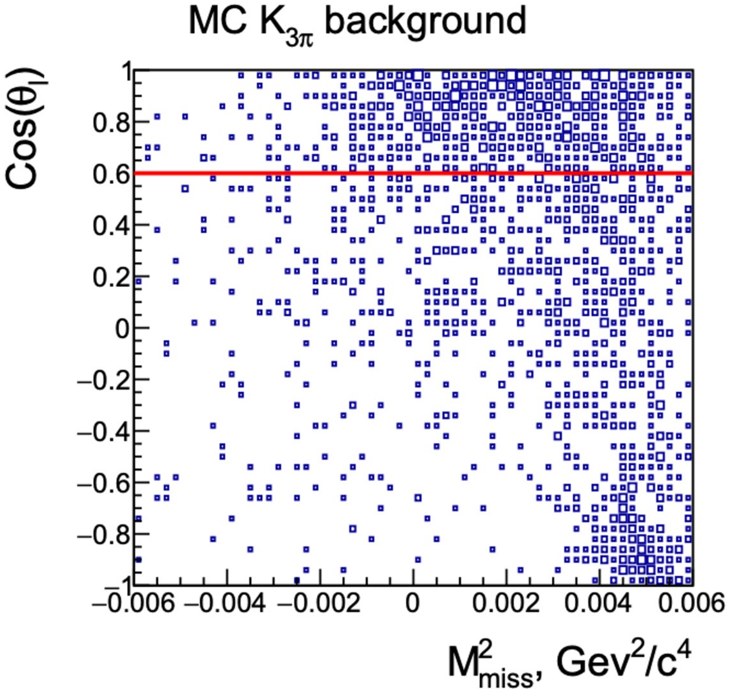
$$M^2_{miss} = (\mathrm{P}_K - \mathrm{P}(\pi^0_1) - \mathrm{P}(\pi^0_2) - \mathrm{P}(\mu^\pm))^2 \qquad M^2_{miss}(\pi^\pm) = (\mathrm{P}_K - \mathrm{P}(\pi^0_1) - \mathrm{P}(\pi^0_2) - \mathrm{P}(\pi^\pm))^2$$

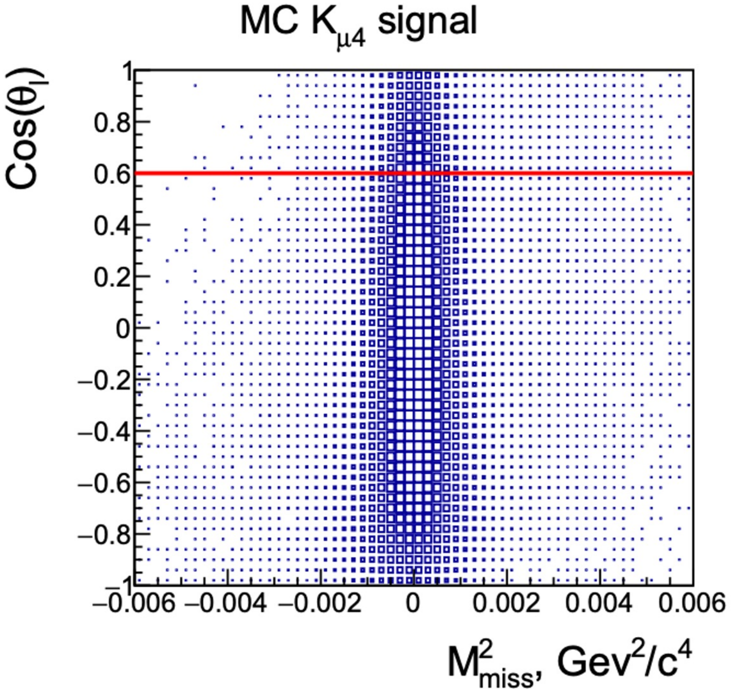


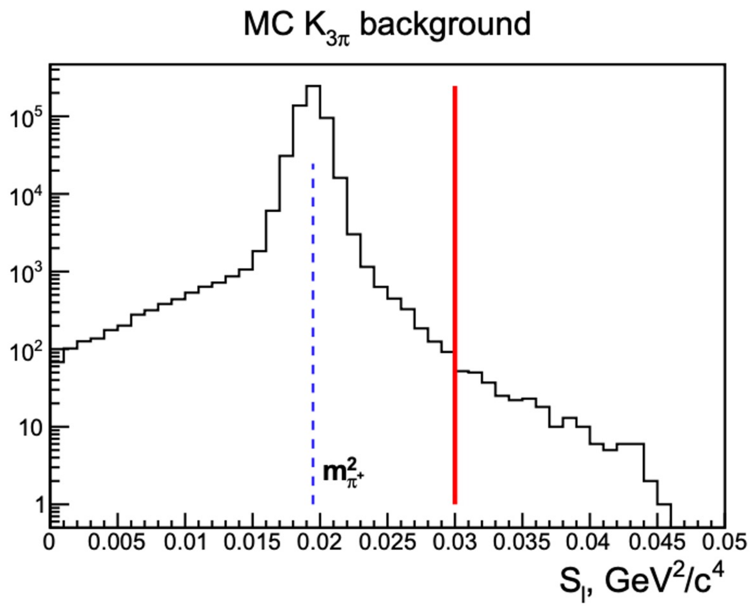
- $M^2_{miss}(\pi^\pm) < 0.5 M^2_{miss} - 0.0008\ \mathrm{GeV}^2/c^4$

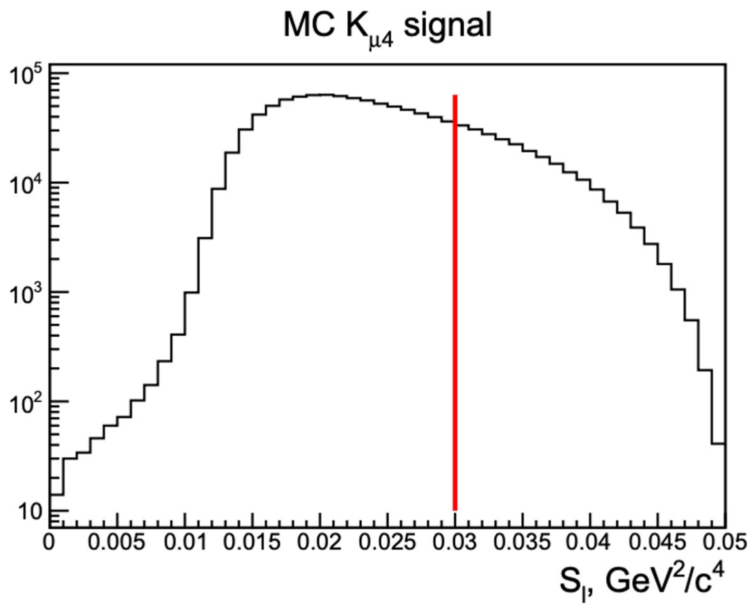
- $cos(\Theta_l) < 0.6$











- $S_l = m(\mu\nu)^2 > 0.03$ GeV$^2/c^4$ (to reject $\pi^{\pm} \to \mu^{\pm}\nu$).
- 3718 $K_{\mu 4}$ data candidates selected
- 2437 data candidates in M^2_{miss} signal region [-0.002,0.002] GeV$^2/c^4$
- The MC M^2_{miss} signal region contains 98.2% of all selected MC events

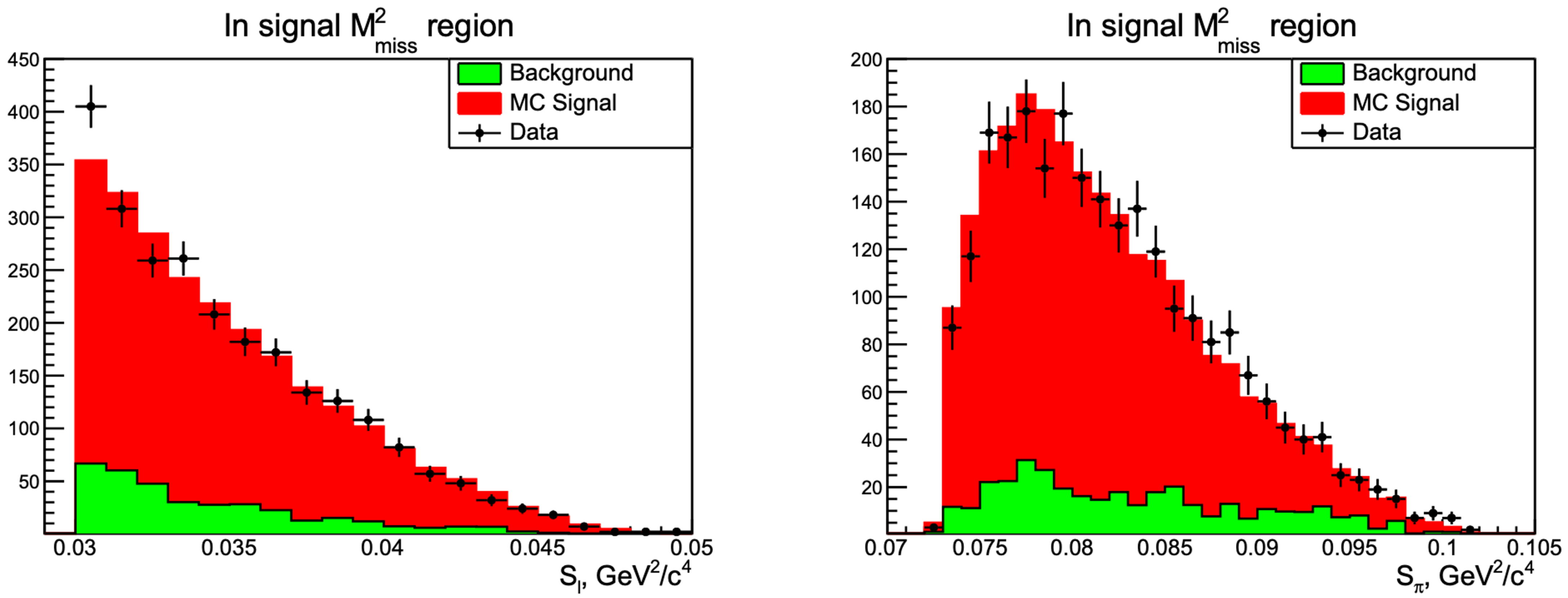


Figure: 1D projections comparison for $S_l > 0.03\ \mathrm{GeV}^2/\mathrm{c}^4$

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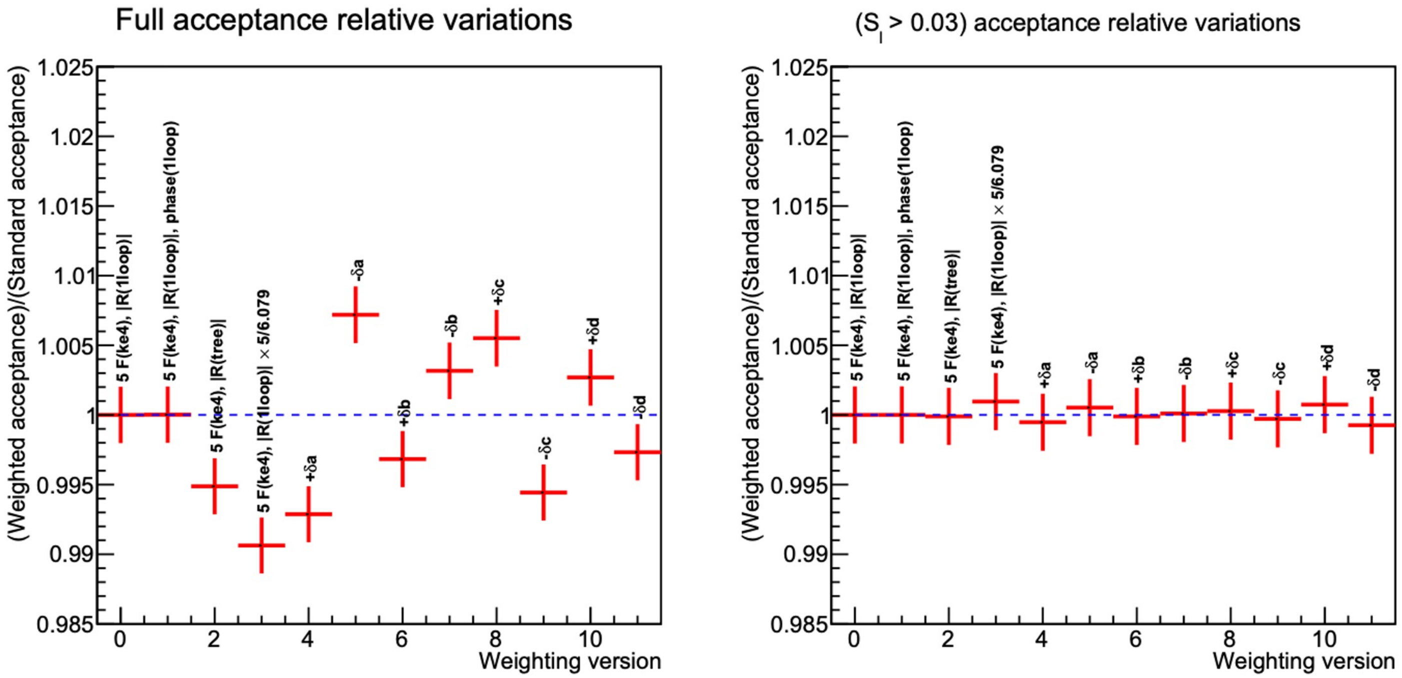
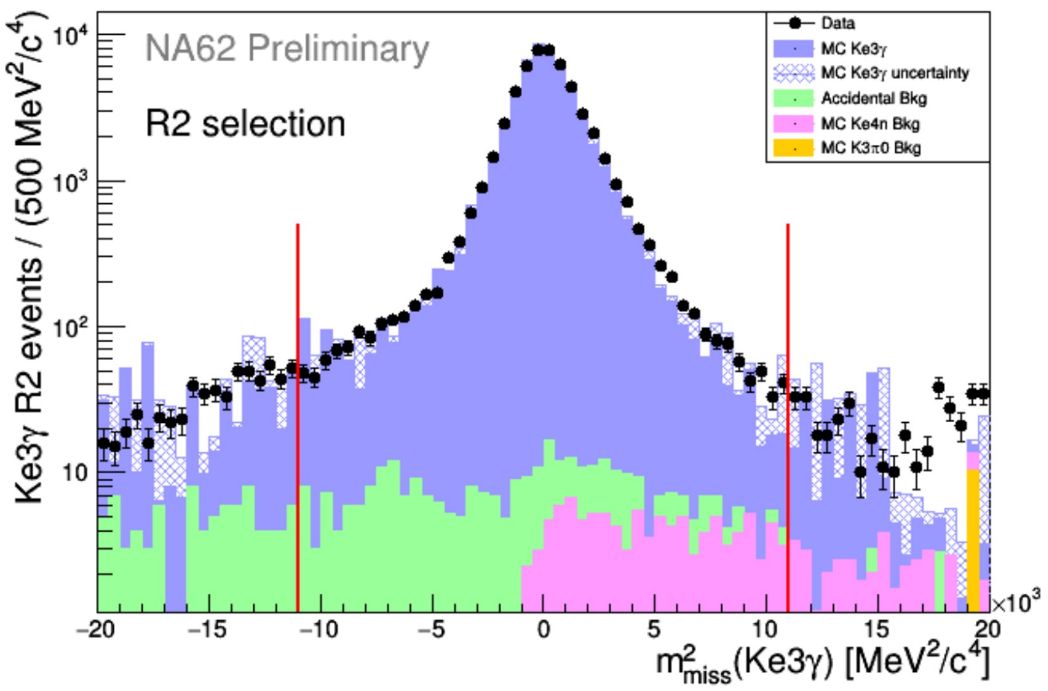
The absolute normalization is also measured $F = f \times F(K_{e4})$, $f = 6.079 \pm 0.055$.

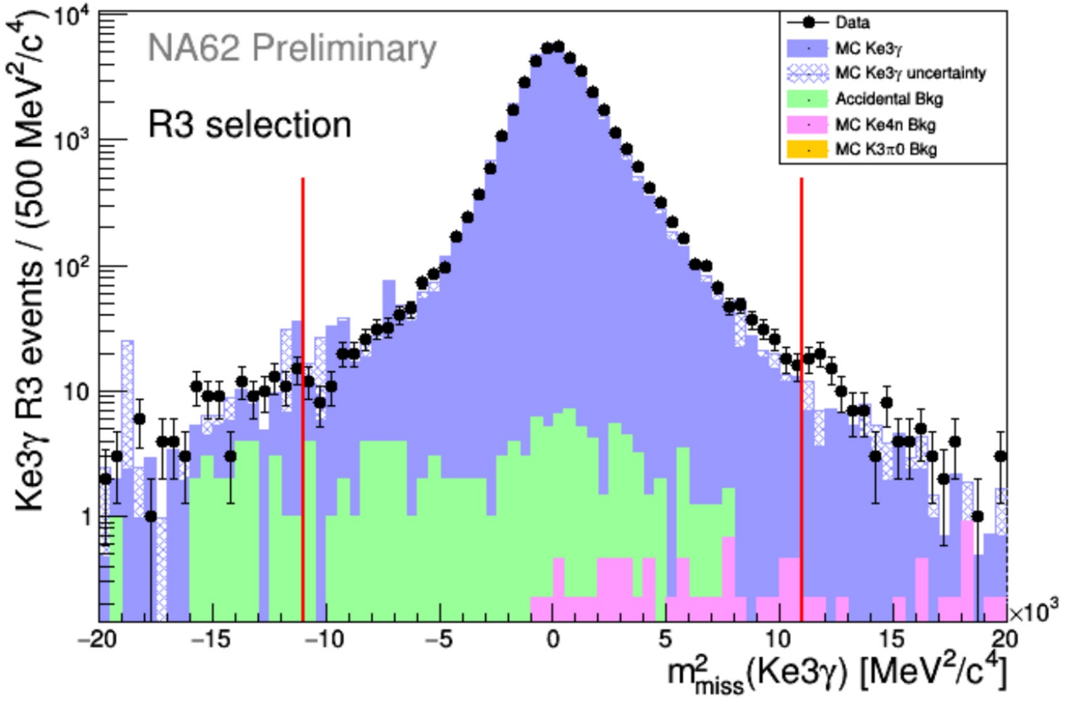
$$F(K_{e4}) = \begin{cases} (1 + aq^2 + bq^4 + c \cdot S_l/4m_{\pi^+}^2) \text{ for } q^2 \geq 0 \\ (1 + d\sqrt{|q^2/(1+q^2)|} + c \cdot S_l/4m_{\pi^+}^2) \text{ for } q^2 < 0 \end{cases}$$

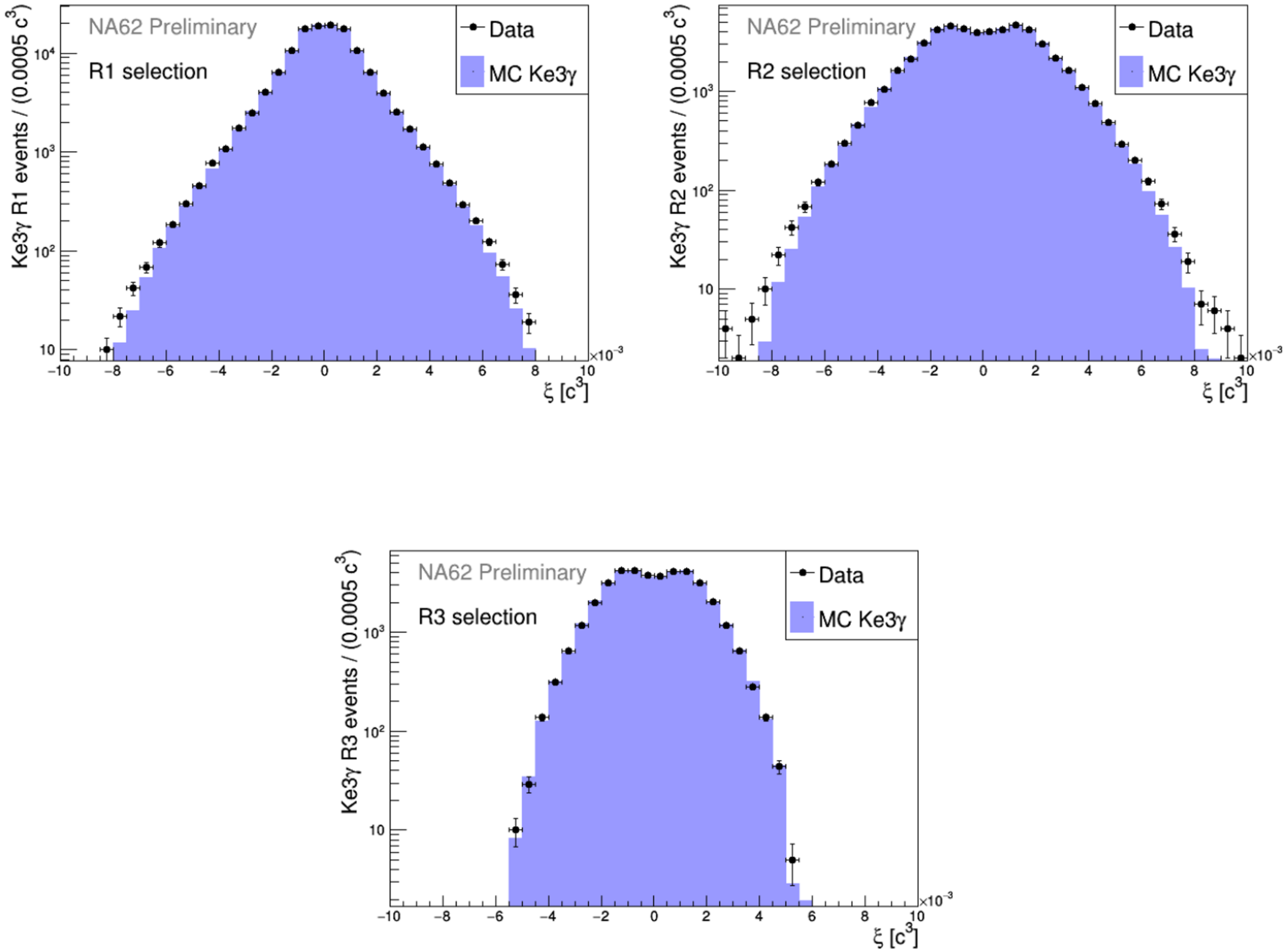
where $q^2 = S_\pi/4m_{\pi^+}^2 - 1$.

- Decay generator was modified by MC events weighting.
- The acceptance spread is taken as systematics.



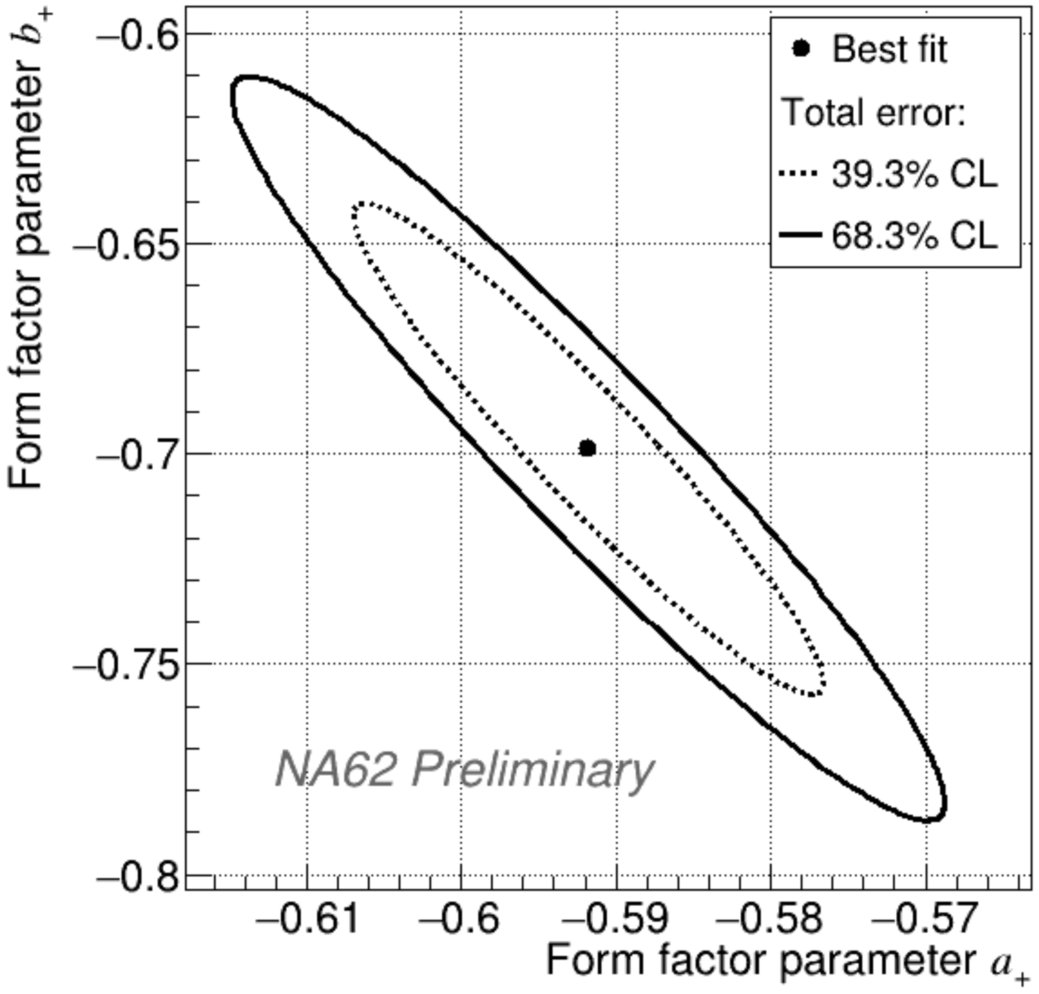

NA62 Preliminary
R2 selection
Data
MC Ke3γ
MC Ke3γ uncertainty
Accidental Bkg
MC Ke4n Bkg
MC K3π0 Bkg
Ke3γ R2 events / (500 MeV²/c⁴)
m²miss(Ke3γ) [MeV²/c⁴]
×10³

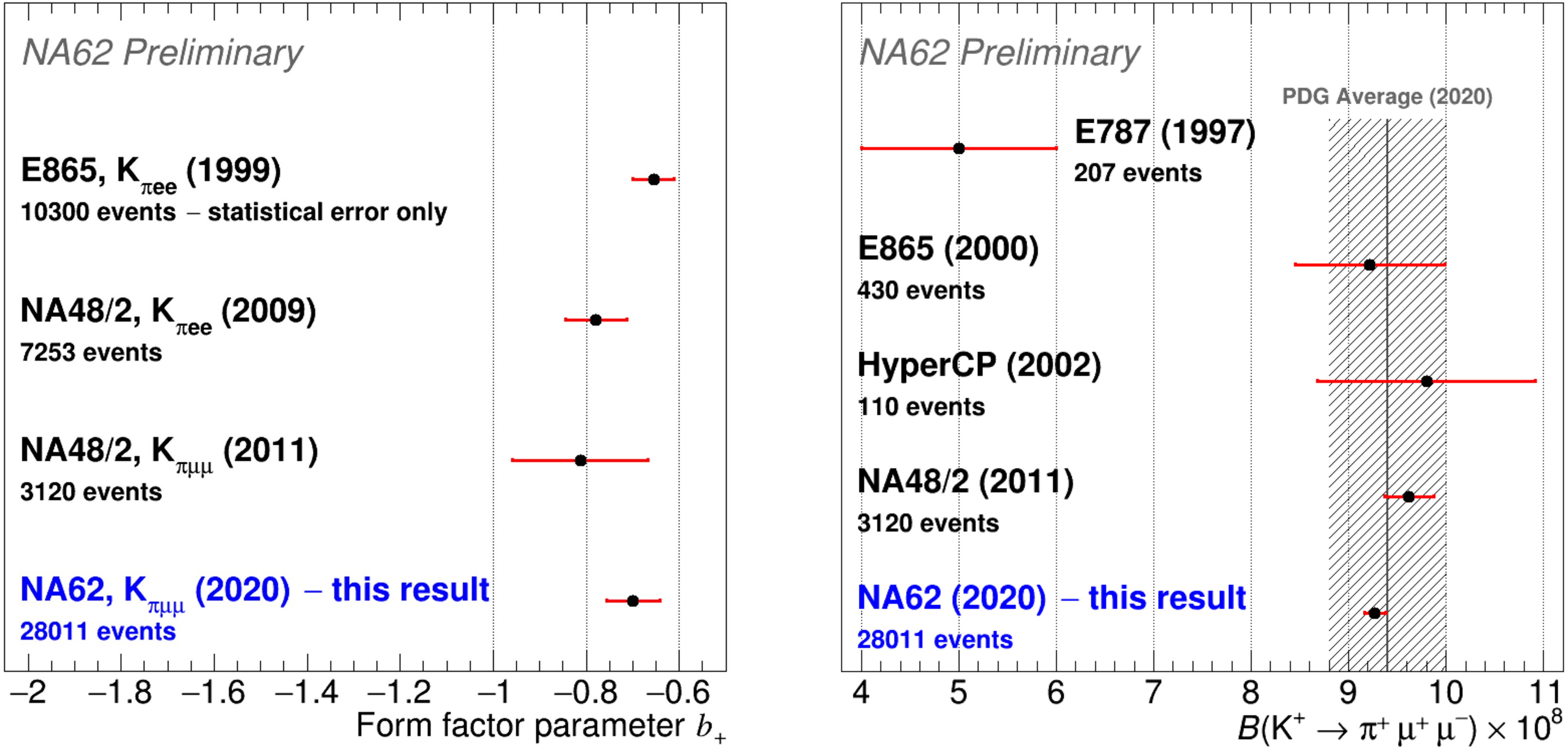

NA62 Preliminary
R3 selection
Data
MC Ke3γ
MC Ke3γ uncertainty
Accidental Bkg
MC Ke4n Bkg
MC K3π0 Bkg
Ke3γ R3 events / (500 MeV²/c⁴)
m²miss(Ke3γ) [MeV²/c⁴]
×10³


NA62 Preliminary
R1 selection
Data
MC Ke3γ
Ke3γ R1 events / (0.0005 c³)
ξ [c³]
×10⁻³
NA62 Preliminary
R2 selection
Data
MC Ke3γ
Ke3γ R2 events / (0.0005 c³)
ξ [c³]
×10⁻³
NA62 Preliminary
R3 selection
Data
MC Ke3γ
Ke3γ R3 events / (0.0005 c³)
ξ [c³]
×10⁻³

	a	b	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa	δb	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam & pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	0.000	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error on $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

Note: a_+ measurement limited by statistical uncertainty




NA62 Preliminary
E865, K_πee (1999)
10300 events − statistical error only
NA48/2, K_πee (2009)
7253 events
NA48/2, K_πμμ (2011)
3120 events
NA62, K_πμμ (2020) − this result
28011 events
−2 −1.8 −1.6 −1.4 −1.2 −1 −0.8 −0.6
Form factor parameter b_+
NA62 Preliminary
PDG Average (2020)
E787 (1997)
207 events
E865 (2000)
430 events
HyperCP (2002)
110 events
NA48/2 (2011)
3120 events
NA62 (2020) − this result
28011 events
4 5 6 7 8 9 10 11
$B(K^+ \to \pi^+ \mu^+ \mu^-) \times 10^8$