

Exotics Searches at Low Energy

Kaons, Muons,Taus

Zuoz, August 14, 2018

Augusto Ceccucci/CERN

Forward

- I take “exotic searches at low energy” to mean subjects with sensitivity to BSM which are not LHC or atomic/molecular physics
- Outline
 - Kaon Physics: CP-Violation and CKM
 - Kaon Physics: Rare Decays
 - Muon / Tau Rare Decays
 - Muon internal conversion
 - g-2 ...

The Flavours of SM

Fermions (Matter)				Bosons	
Quark	u up	c Charm	t top	elettromagnetic γ photon	$1\text{keV} = 10^3 \text{ eV}$
	d down	s strange	b bottom	strong g gluon	$1\text{MeV} = 10^6 \text{ eV}$
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	weak W W boson	$1\text{GeV} = 10^9 \text{ eV}$
	e electron	μ muon	τ tau	weak Z Z boson	$m_P \sim 938 \text{ MeV}$
Generation	I	II	III	Higgs boson	
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History, CP, BAU, ε & ε' , CPT

Kaons and Standard Model

- Today we tend to forget, but many aspects of the Standard Model (SM) were built on the properties of the strange mesons:
 - Parity Violation (paradox θ - τ)
 - Strong production and weak decay
 - Strangeness and the quark model
 - Violation of di CP in $K_L \rightarrow 2\pi$: superweak or milliweak?
 - Absence of FCNC \rightarrow GIM mechanism
 - Direct CP violation ($\varepsilon'/\varepsilon \neq 0$)
 - Best bounds on beyond SM (BSM) physics

Strangeness (Gell Mann, Pais)

ϑ_0	$S = +1$	According to Jim Cronin, during a seminar at Chicago, Gell Mann introduced S as a quantum number conserved by the strong and violated by the weak interactions with both states $S= +/-1$ decaying into $\pi^+ \pi^-$
$\bar{\vartheta}_0$	$S = -1$	E. Fermi: “ If both decay into $\pi^+ \pi^-$, how can they be different?”

PHYSICAL REVIEW

VOLUME 97, NUMBER 5

MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* Department of Physics, Columbia University, New York, New York

AND

A. PAIS, Institute for Advanced Study, Princeton, New Jersey

(Received November 1, 1954)

At any rate, the point to be emphasized is this: a neutral boson may exist which has the characteristic θ^0 mass but a lifetime $\neq \tau$ and which may find its natural place in the present picture as the second component of the θ^0 mixture.

One of us, (M. G.-M.), wishes to thank Professor E. Fermi for a stimulating discussion.

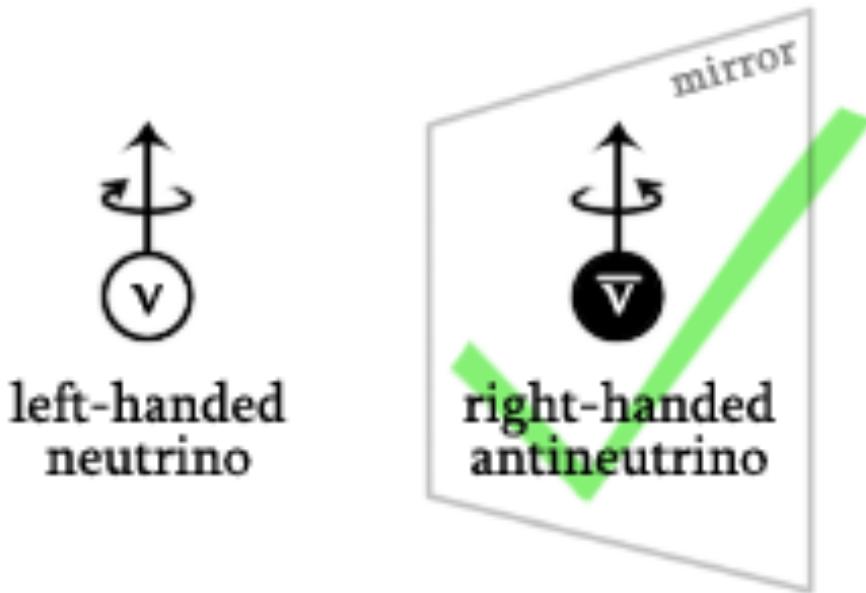
The conservation of C [CP from 1957...] distinguishes the two eigenstates

$$\vartheta_1 = \frac{1}{\sqrt{2}}(\vartheta_0 + \bar{\vartheta}_0) \rightarrow \pi\pi$$

$$\vartheta_2 = \frac{1}{\sqrt{2}}(\vartheta_0 - \bar{\vartheta}_0) \rightarrow \pi\pi\pi$$

$$\theta_{1,2} \rightarrow K_{1,2}$$

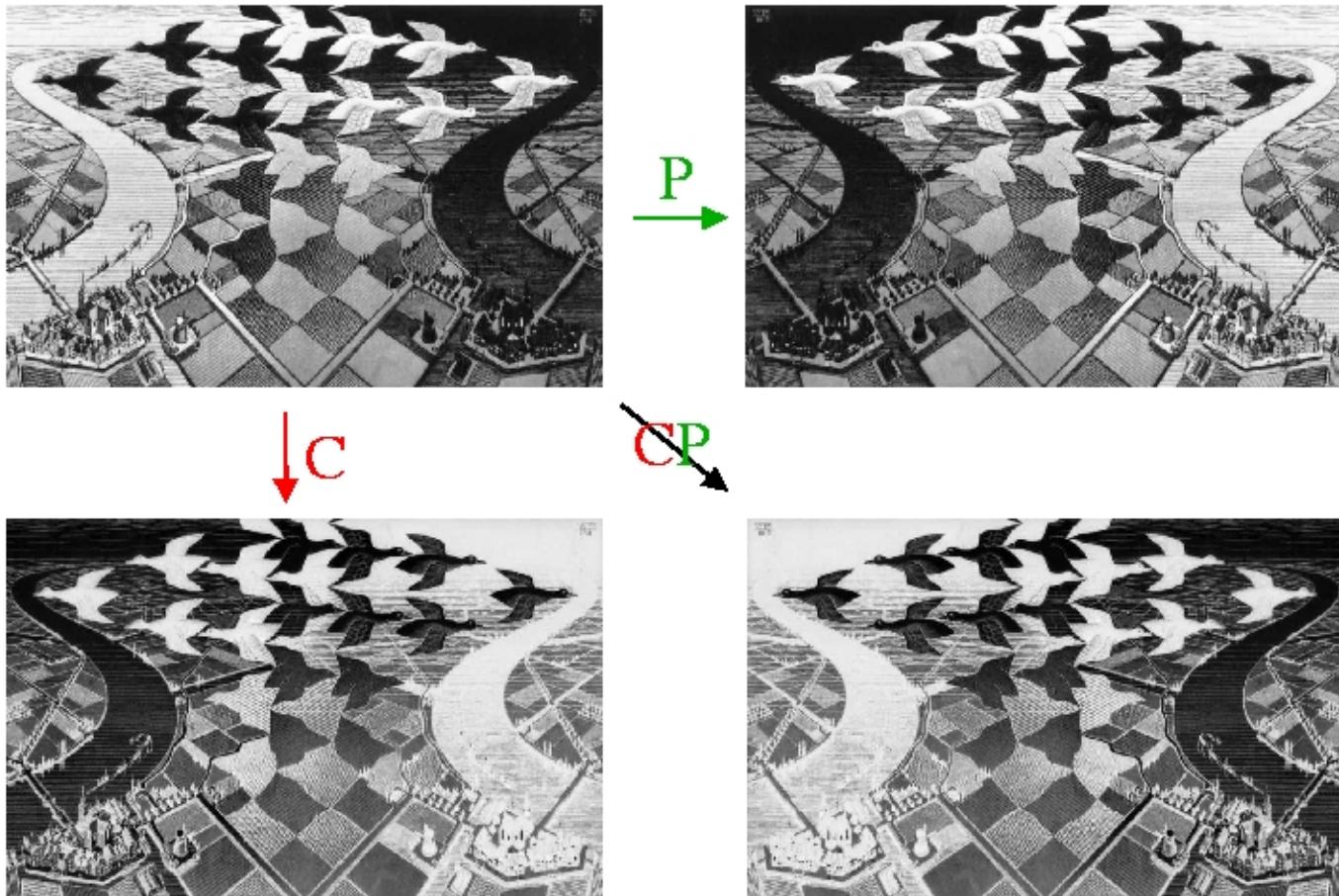
P & C



L. Landau, 1957: "Has is well known, the unusual properties of K-mesons have created a perplexing situation in modern physics....Invariance of the interactions with respect to **combined inversion (CP)** leaves space completely symmetrical....

To save the simmetry of space in view of parity (P) violation, Landau posited the simmetry for the combined operation of parity (P) and charge conjugation (C) → **CP Conservation**

CP Symmetry



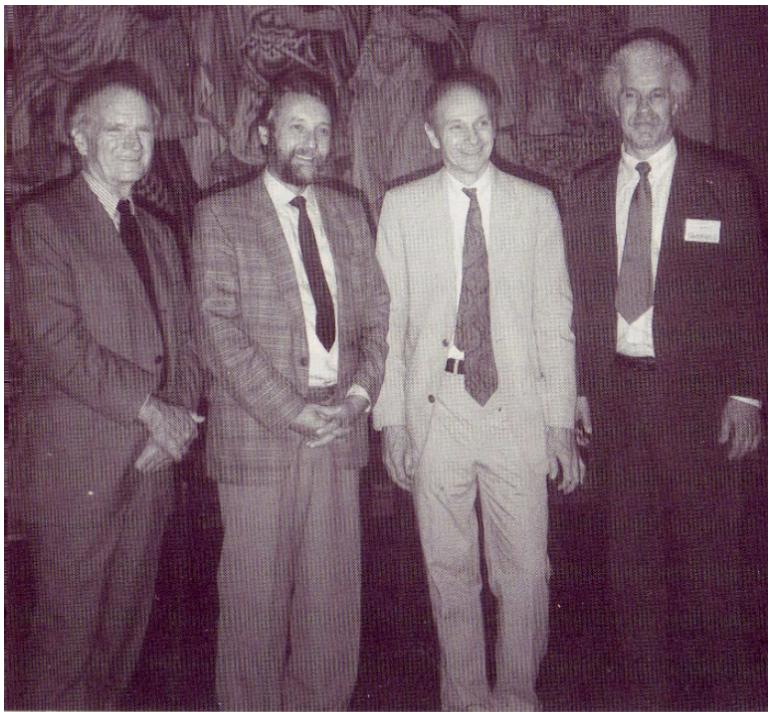
From Gino Isidori:

<http://scienzapertutti.lnf.infn.it/P1/schedaCP.html>

1964

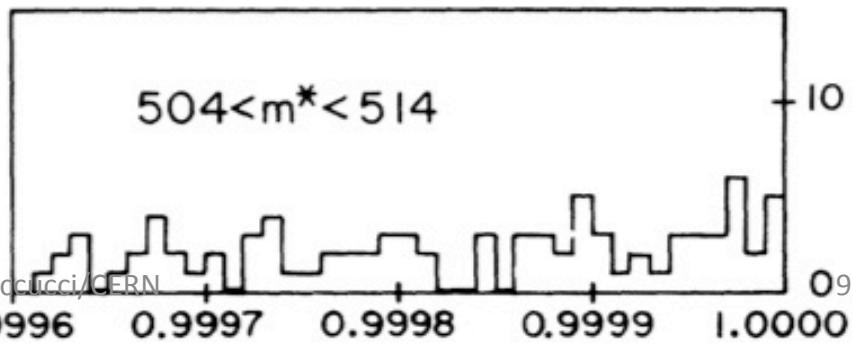
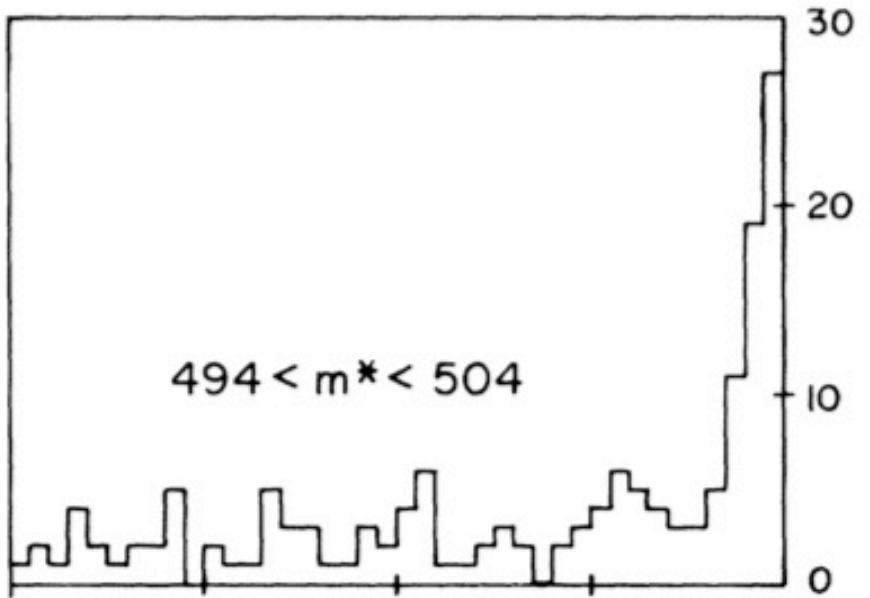
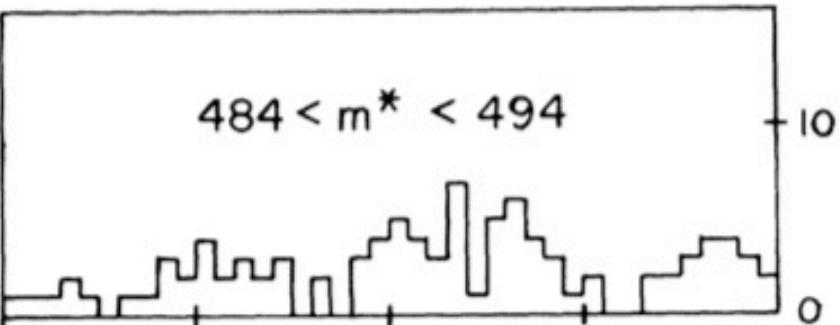
5211 $K_2 \rightarrow \pi^+ + \pi^-$ candidates

The long-lived neutral kaon decays into two pions $\sim 0.2\%$ of the times



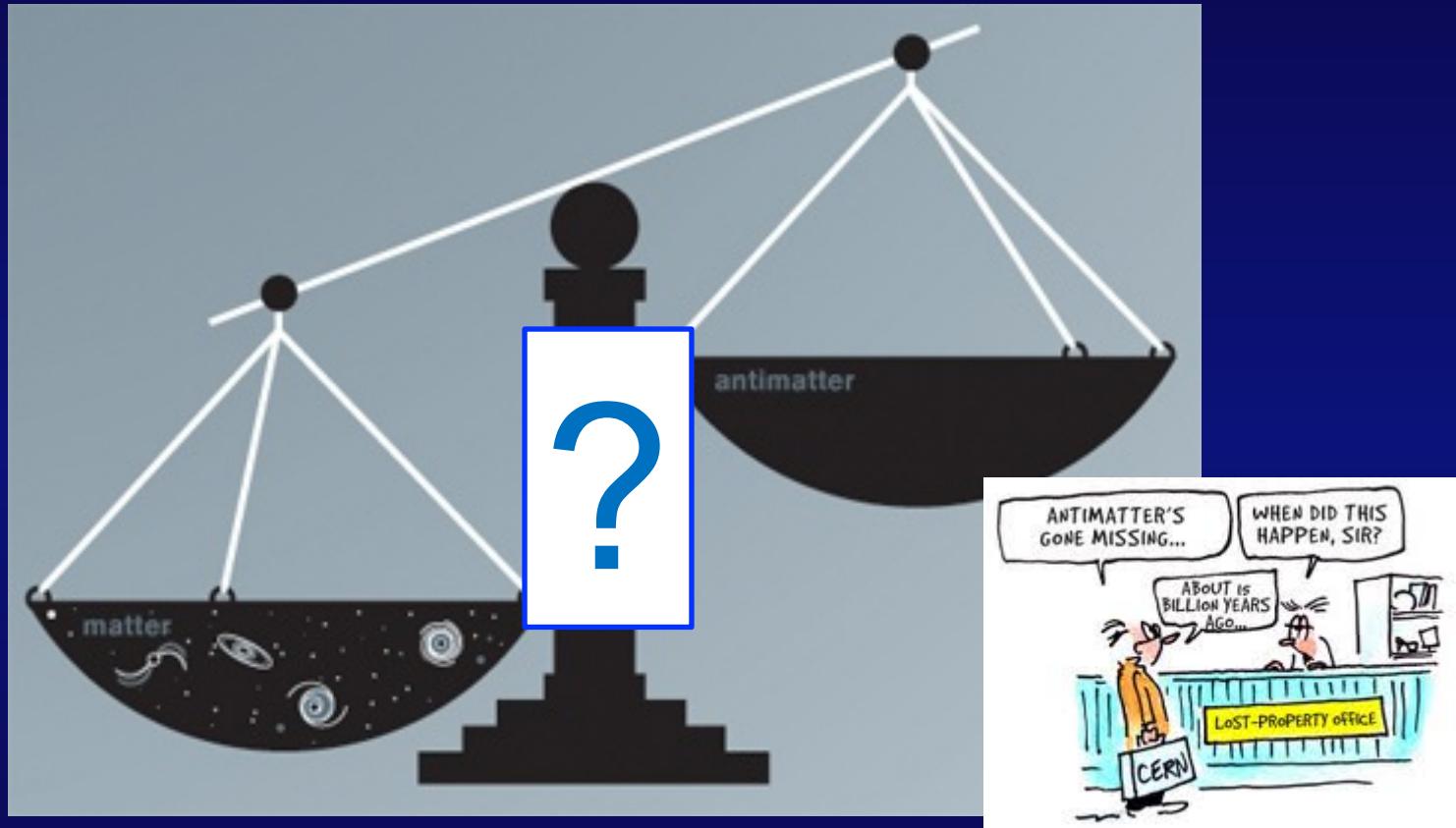
From left : Val Fitch, René Turlay, Jim Cronin and Jim Christenson.

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Compelling Puzzle: Baryon Asymmetry of the Universe (BAU)



$$n_{\text{quark}} - n_{\text{antiquark}} / n_{\text{quark}} \text{ (Proto Universe)} \sim n_{\text{baryon}} / n_{\text{photon}} \text{ (Today)} \sim 5 \times 10^{-10}$$

Why CP-Violation is so cool



**Andrei Sakharov (1967) conditions
for BAU:**

**To allow the development of an
asymmetry between matter and
anti-matter**

- 1. Violation of Baryonic Number**
- 2. Thermodynamic Non-equilibrium**
- 3. Violation of C & CP**

The ratio of the decay amplitudes of K_2^- to K_1^- to $\pi^+ \pi^-$
 $\pi^0 \pi^0$ is given by:

$$\eta_{+-} = \epsilon + \frac{i}{\sqrt{2}} \frac{\text{Im } A_2}{A_0} e^{i(\delta_2 - \delta_0)} = \epsilon + \epsilon'$$

$$\eta_{00} = \epsilon - i\sqrt{2} \frac{\text{Im } A_2}{A_0} e^{i(\delta_2 - \delta_0)} = \epsilon - 2\epsilon'$$

By 1965 $|\eta_{+-}|$ measured to be
 $(2.04 \pm 0.14) \times 10^{-3}$
 and coherence established

Jim Cronin

If $\epsilon' \gg \epsilon$ then $|\eta_{00}| = 2 |\eta_{+-}|$
 If ϵ'/ϵ small then $|\eta_{00}/\eta_{+-}| = |1 - 3\epsilon'/\epsilon|$
 If superweak $\epsilon' = 0$

CP Violation and the neutral K mesons

$$|K_{S,L}\rangle = \frac{1}{\sqrt{(1+|\varepsilon|^2)}} [(1+\varepsilon)|K^0\rangle \pm (1-\varepsilon)|\bar{K}^0\rangle] \quad \phi_{SW} \approx \tan^{-1} \frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L} \approx (43.52 \pm 0.05)^\circ$$

$$\eta_{+-} = \varepsilon + \varepsilon' \quad \eta_{+-} = A(K_L^0 \rightarrow \pi^+ \pi^-)/(K_S^0 \rightarrow \pi^+ \pi^-)$$

$$\eta_{00} = \varepsilon - 2\varepsilon' \quad \eta_{00} = A(K_L^0 \rightarrow \pi^0 \pi^0)/(K_S^0 \rightarrow \pi^0 \pi^0)$$

$$\varepsilon = \tilde{\varepsilon} + i \frac{\text{Im } A_0}{\text{Re } A_0} \quad \text{Indirect} \quad A_{0,2} = A(K^0 \rightarrow \pi\pi, I=0,2)$$

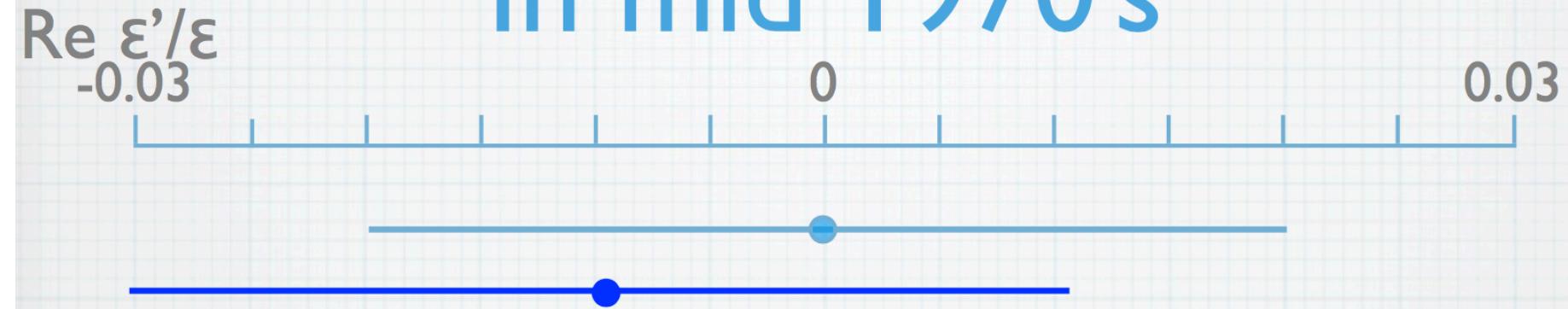
$$\sqrt{2}\varepsilon' = ie^{i(\delta_2 - \delta_0)} (\text{Re } A_2 / \text{Re } A_0) \times (\text{Im } A_2 / \text{Re } A_2 - \text{Im } A_0 / \text{Re } A_0)$$

$$R = \frac{\Gamma(K_L^0 \rightarrow \pi^0 \pi^0)/\Gamma(K_S^0 \rightarrow \pi^0 \pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+ \pi^-)/\Gamma(K_S^0 \rightarrow \pi^+ \pi^-)} = |\eta_{00}/\eta_{+-}|^2 \approx 1 - 6 \text{Re } \varepsilon'/\varepsilon \quad \text{Direct}$$

Double ratio technique where systematics drop out to first order

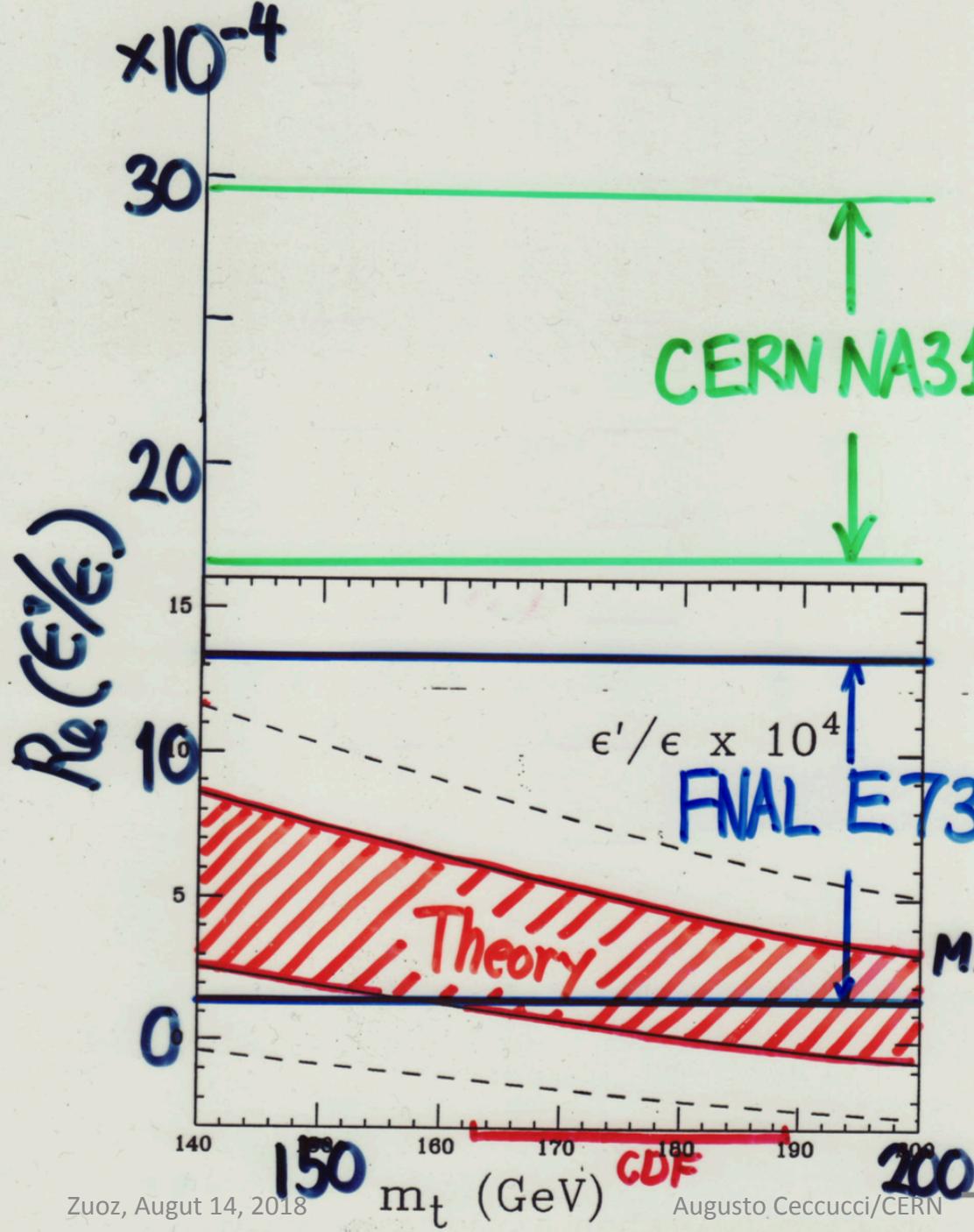
Taku Yamanaka

In mid 1970's



Kleinknecht, Ann. Rev. Nucl. Sci., 26, I (1976)

- * “It is not easy to improve substantially the experimental precision. A decision between superweak and milliweak models of CP violation will therefore probably have to come from other experimental information outside the K^0 system.”

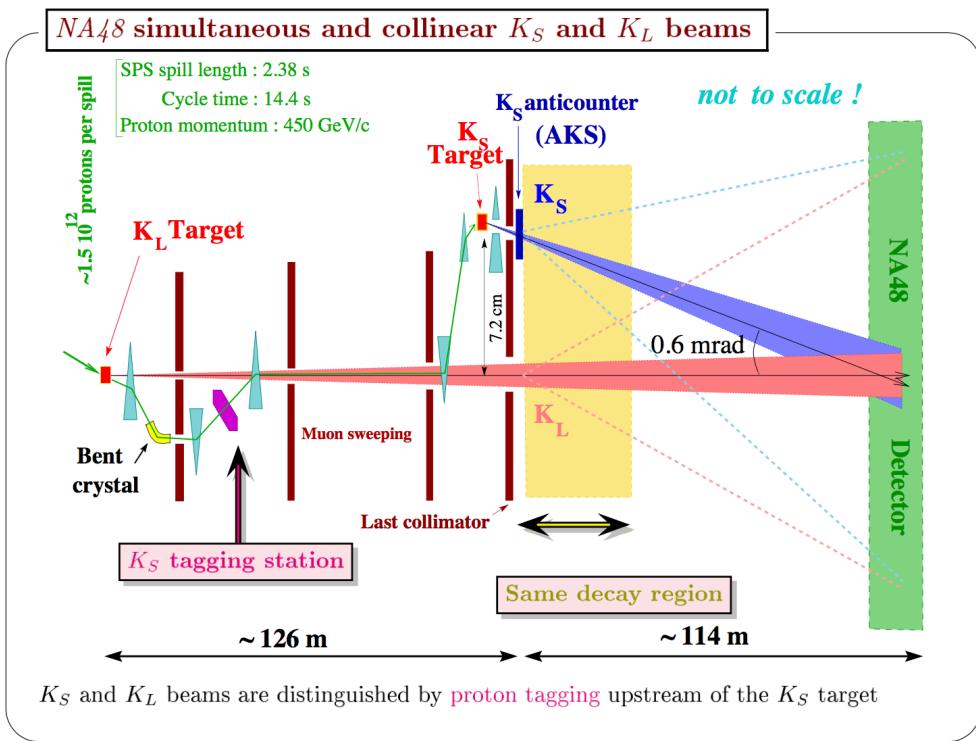


Massive new experiments launched
In the early '90s
to clarify the puzzle

CERN NA48

FNAL KTeV

NA48



- Two beams and two target
- Simoultaneous detection of K_L , K_S into $\pi^+\pi^-$ and $\pi^0\pi^0$
- K_S decay distinguished by proton tagging (30 MHz)
- 0.1% background levels

Electrode structure (half) of the Liquid Krypton Calorimeter, **now used by NA62, cold (~120 K) since 1998**

Final Results:

$$\frac{\Gamma(K_L \rightarrow \pi^+ \pi^-) / \Gamma(K_S \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^0 \pi^0) / \Gamma(K_S \rightarrow \pi^0 \pi^0)} = \left| \frac{\eta_{+-}}{\eta_{00}} \right|^2 \approx 1 + 6Re(\epsilon'/\epsilon).$$

$$Re(\epsilon'/\epsilon) = [19.2 \pm 1.1(stat) \pm 1.8(syst)] \times 10^{-4} \\ = [19.2 \pm 2.1] \times 10^{-4}.$$

KTEV

$$Re(\epsilon'/\epsilon) = (14.7 \pm 1.4 \pm 0.9 \pm 1.5) \times 10^{-4} \\ = (14.7 \pm 2.2) \times 10^{-4}.$$

VALUE (units 10^{-3})

DOCUMENT ID

TECN

COMMENT

1.66 ±0.23 OUR FIT Error includes scale factor of 1.6.**1.68 ±0.20 OUR AVERAGE** Error includes scale factor of 1.4. See the ideogram below.

1.92 ±0.21

1.47 ±0.22

0.74 ±0.52 ±0.29

2.3 ±0.65

1 ABOUZAID 11 KTEV Assuming CPT

BATLEY 02 NA48

GIBBONS 93B E731

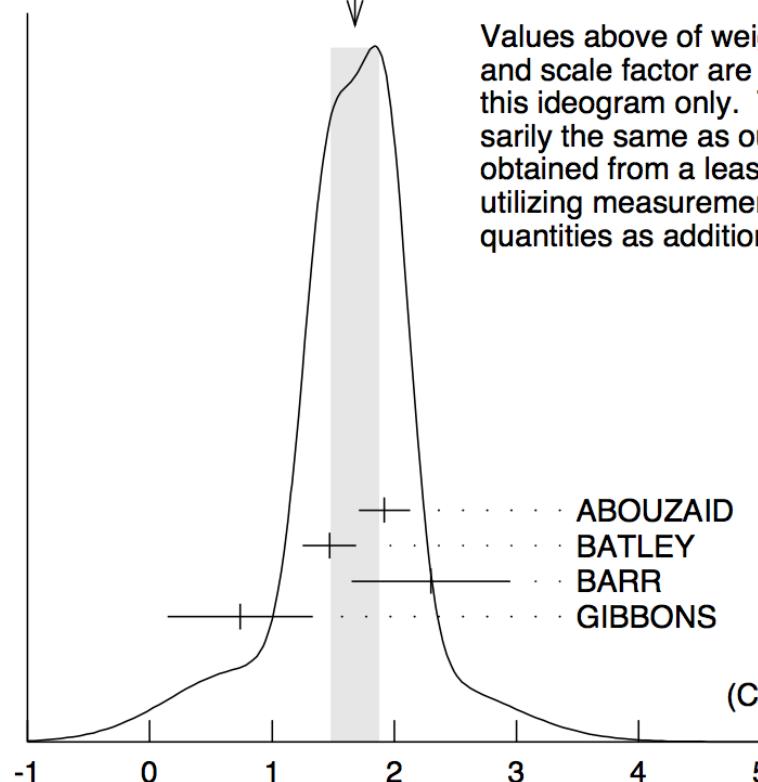
• • • We use the following data for averages but not for fits. • • •

2,3 BARR 93D NA31

 ϵ'/ϵ PDG 2018

WEIGHTED AVERAGE
 1.68 ± 0.20 (Error scaled by 1.4)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.



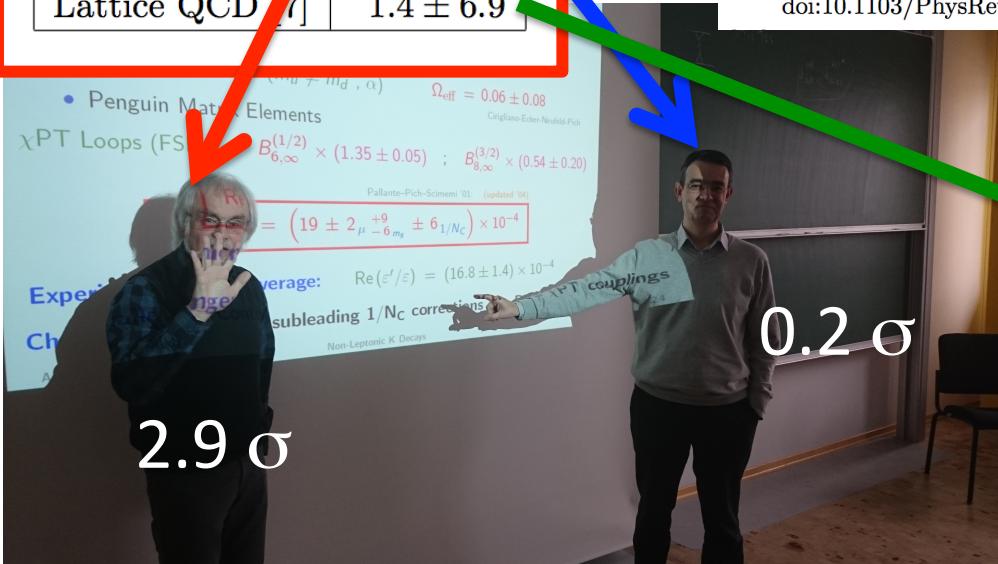
$$\text{Re}(\epsilon'/\epsilon) = (1 - |\eta_{00}/\eta_{+-}|)/3$$

Re(ε'/ε): Theoretical Predictions

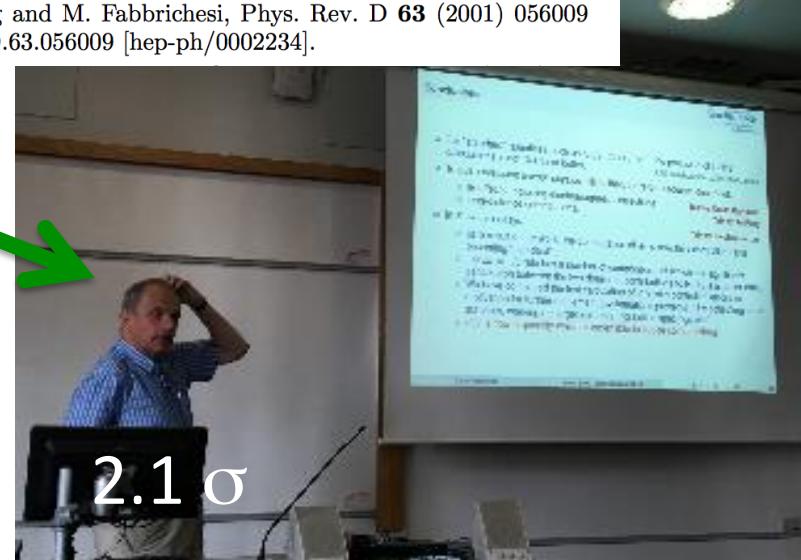
$$\frac{\varepsilon'}{\varepsilon} = 10^{-4} \left[\frac{\text{Im } \lambda_t}{1.4 \cdot 10^{-4}} \right] \left[a(1 - \hat{\Omega}_{eff})(-4.1 + 24.7B_6^{(1/2)}) + 1.2 - 10.4B_8^{(3/2)} \right]$$

Re ε'/ε	(10^{-4})
Experiments	16.6 ± 2.3
Buras et al. [9]	1.9 ± 4.5
KNT [10]	1.1 ± 5.1
Pich et al. [8]	15.0 ± 7.0
BEF [11]	22.0 ± 8.0
Lattice QCD [7]	1.4 ± 6.9

- [7] Z. Bai *et al.* [RBC and UKQCD Collaborations], Phys. Rev. Lett. **115** (2015) no.21, 212001 doi:10.1103/PhysRevLett.115.212001 [arXiv:1505.07863 [hep-lat]].
- [8] H. Gisbert and A. Pich, arXiv:1712.06147 [hep-ph].
- [9] A. J. Buras, M. Gorbahn, S. Jger and M. Jamin, JHEP **1511** (2015) 202 doi:10.1007/JHEP11(2015)202 [arXiv:1507.06345 [hep-ph]].
- [10] T. Kitahara, U. Nierste and P. Tremper, JHEP **1612** (2016) 078 doi:10.1007/JHEP12(2016)078 [arXiv:1607.06727 [hep-ph]].
- [11] S. Bertolini, J. O. Eeg and M. Fabbrichesi, Phys. Rev. D **63** (2001) 056009 doi:10.1103/PhysRevD.63.056009 [hep-ph/0002234].



A. Buras and T. Pich, MITP Mainz, "NA62 Physics Handbook"



C. Sachraida, Kaon2016:
" ε'/ε is now a quantity which is amenable to lattice calculations"

Experiment: $\sim 1.7 \times 10^{-3}$ SM Predictions: ??

CPT?

NA48/1 PLB 610 (2005)

$$(1 + i \tan \phi_{SW}) [\text{Re}(\epsilon) - i \text{Im}(\delta)] = \sum_{\substack{\text{final} \\ \text{states } f}} A(K_L \rightarrow f)^* A(K_S \rightarrow f) / \Gamma_S$$

Bell-Steinberger relation

$$\mathcal{E}_S = \mathcal{E} + \delta$$

$$\mathcal{E}_L = \mathcal{E} - \delta$$

α_f	$10^3 \times \text{Re}(\alpha_f)$	$10^3 \times \text{Im}(\alpha_f)$
$\alpha_{+-} = \eta_{+-} \text{Br}(K_S \rightarrow \pi^+ \pi^-)$	1.146 ± 0.015	1.084 ± 0.016
$\alpha_{00} = \eta_{00} \text{Br}(K_S \rightarrow \pi^0 \pi^0)$	0.511 ± 0.008	0.488 ± 0.008
$\alpha_{+-\gamma} = \eta_{+-\gamma} \text{Br}(K_S \rightarrow \pi^+ \pi^- \gamma)$	0.003 ± 0.000	0.003 ± 0.000
$\alpha_{l3} = 2 \frac{\tau_S}{\tau_L} \eta_{+-0}^* \text{Br}(K_L \rightarrow \pi l \nu) \times [\text{Re}(\epsilon) - \text{Re}(y) - i(\text{Im}(x_+) + \text{Im}(\delta))]$	-0.001 ± 0.007	0.005 ± 0.006
$\alpha_{+-0} = \frac{\tau_S}{\tau_L} \eta_{+-0}^* \text{Br}(K_L \rightarrow \pi^+ \pi^- \pi^0)$	0.000 ± 0.002	0.000 ± 0.002
$\alpha_{000} = \frac{\tau_S}{\tau_L} \eta_{000}^* \text{Br}(K_L \rightarrow 3\pi^0)$	-0.001 ± 0.007	0.001 ± 0.008
$\sum \alpha_f$	1.658 ± 0.024	1.581 ± 0.025

ϵ Violates CP

δ Violates CP e CPT

$$\text{Im}(\delta) = (-0.2 \pm 2.0) \times 10^{-5},$$

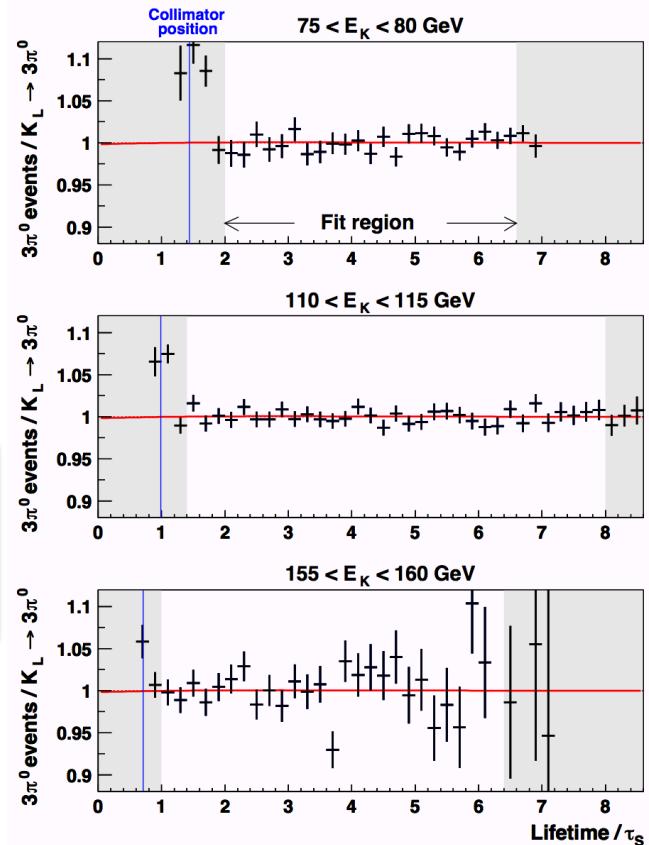
$$\text{Re}(\epsilon) = (166.4 \pm 1.0) \times 10^{-5}.$$

$$m_{K^0} - m_{\bar{K}^0} = (-0.2 \pm 2.8) \times 10^{-19} \text{ GeV}/c^2,$$

$$I_{3\pi^0}(t) \propto e^{-\Gamma_L t} + |\eta_{000}|^2 e^{-\Gamma_S t}$$

$$+ 2 D(p) (\text{Re}(\eta_{000}) \cos(\Delta m t) - \text{Im}(\eta_{000}) \sin(\Delta m t))$$

$$\times e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t}$$





Kaons & CKM, Cabibbo Angle (V_{us}), *Unitarity Tests & Room for “exotics”*

Cabibbo-Kobayashi-Maskawa (CKM) Quark Mixing

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

PDG 2018

$$|V_{ud}| = 0.97420 \pm 0.00021$$

$$|V_{us}| = 0.2243 \pm 0.0005$$

$$|V_{cd}| = 0.218 \pm 0.004$$

$$|V_{cs}| = 0.997 \pm 0.017$$

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$$

$$|V_{ub}| = (3.94 \pm 0.36) \times 10^{-3}$$

$$|V_{tb}| = 1.019 \pm 0.025$$

$0^+ \rightarrow 0^+$ super-allowed nuclear β decays

Kaon semi-leptonic and leptonic decays

semi-leptonic D decays and neutrino/antineutrino

Average of semi-leptonic D and leptonic D_s decays

Combination of exclusive and inclusive B decays

Comb. of exclusive and inclusive charmless B decays

Single top-quark production cross-section

V_{td} & V_{ts} accessible from FCNC processes (loops)

If V is unitary:

$n \times n$ real parameter

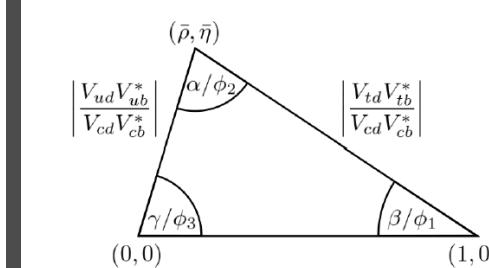
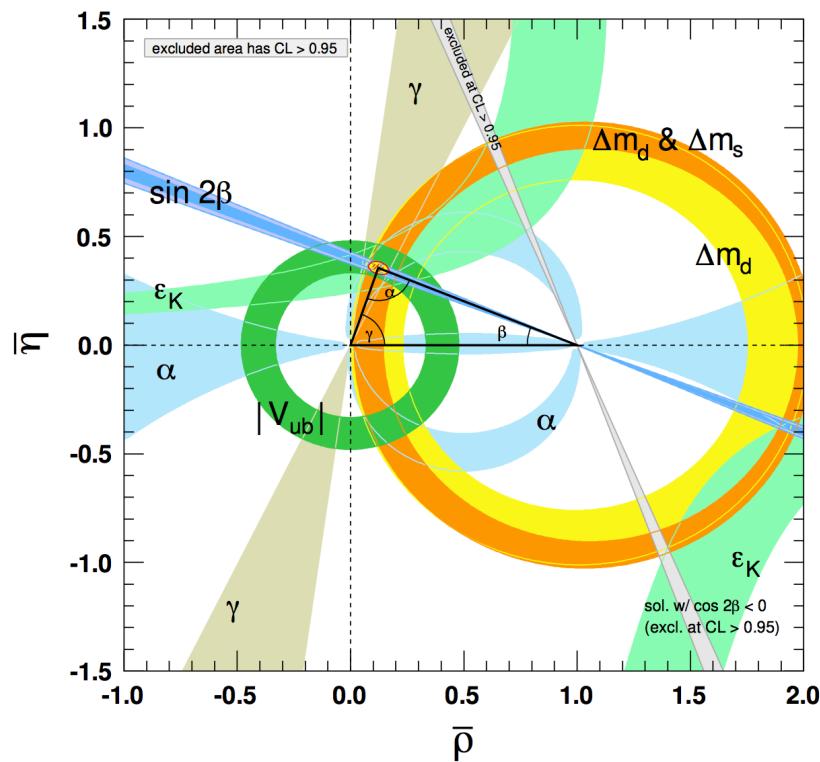
$2n-1$ unphysical phases

$n(n-1)/2$ rotation angles

$(n-1)(n-2)/2$ complex phases

For $n > 2$ CP Violation is automatically possible!

Constraints on the UT



$$\beta = \phi_1 = \arg \left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)$$

$$\alpha = \phi_2 = \arg \left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right)$$

$$\gamma = \phi_3 = \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$

PDG 2018

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

The unique measure of CP-Violation in the SM is the area of the Unitarity Triangle (Jarliskog invariant J)

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

Leptonic Decays & V_{us}

$$\frac{\Gamma(K \rightarrow \ell \bar{\nu}_\ell)}{\Gamma(\pi \rightarrow \ell \bar{\nu}_\ell)} = \left(\frac{|V_{us}|}{|V_{ud}|} \right)^2 \left(\frac{f_K}{f_\pi} \right)^2 \frac{m_K \left(1 - \frac{m_\ell^2}{m_K^2} \right)^2}{m_\pi \left(1 - \frac{m_\ell^2}{m_\pi^2} \right)^2} \left[1 + \frac{\alpha}{\pi} (C_K - C_\pi) \right]$$

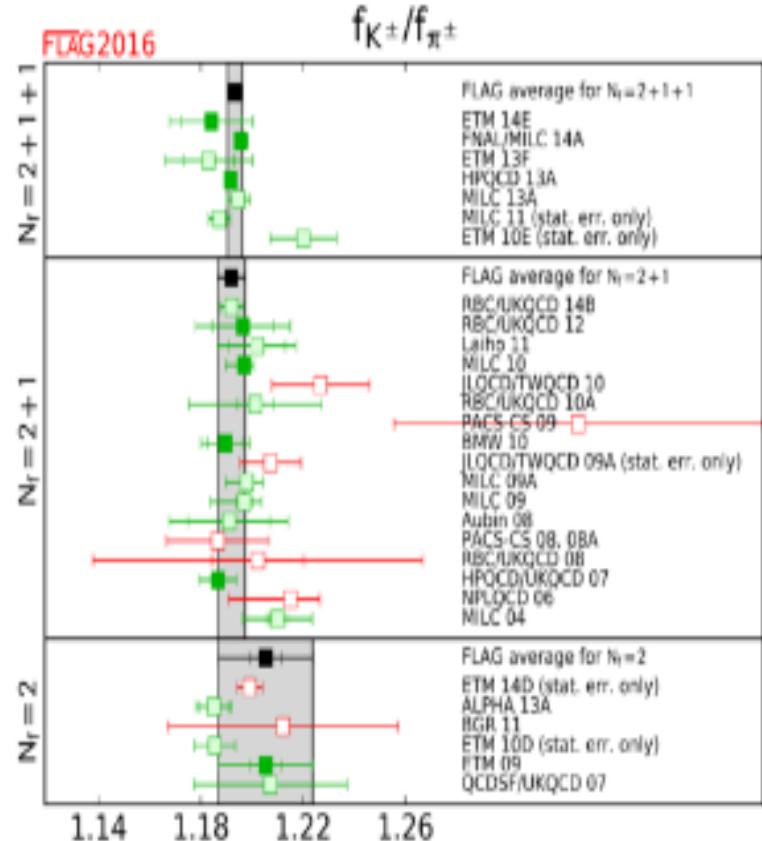
Lattice QCD input (FLAG 2016)

Using typical inputs
(Blucher and Marciano, PDG2017):

$$\frac{\Gamma(K \rightarrow \mu\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} = 1.3367(29)$$

$$\frac{f_{K^+}}{f_{\pi^+}} = 1.1933(29) \quad N_f = 2+1+1$$

$$V_{us} = 0.2253(7)$$

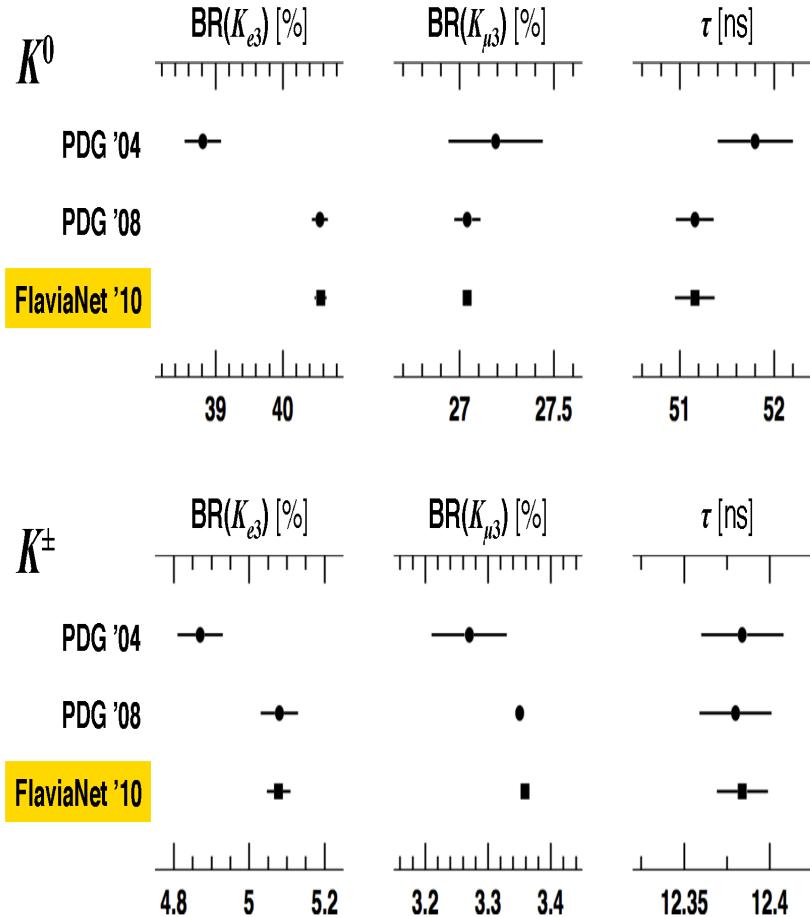


Semileptonic K decays and V_{us}

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi_3} S_{EW} (1 + \delta_K^\ell + \delta_{SU2}) C^2 |V_{us}|^2 f_+^2(0) I_K^\ell$$

Input from Experiment		Input from Theory	
$\Gamma(K_{3(\gamma)})$	Rates with well determined radiative corrections	$f_+(0)$	Hadroni matrix element (form factor) at zero momentum transfer ($\tau = 0$)
	•Branching Ratios	δ_{SU2}	Form factor correction for SU(2) breaking
	•Lifetimes		
$I_{K\ell}(\{\lambda\}_{K\ell})$	Integral of form factor over phase space: parameterizes evolution in τ	$\delta_{K\ell}^I$	Long distance EM effects
		$C^2=1$ (1/2) for neutral (charged) kaons	
	• K_{e3} : Only λ_+ (or $\lambda_+', \lambda_''$)		
	• $K_{\mu 3}$: Need λ_+ and λ_0		

Evolution of Experimental Input Semileptonic Decays

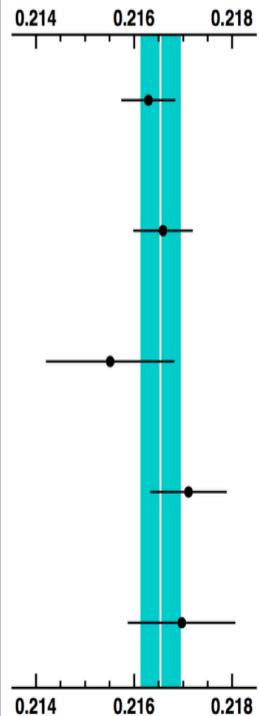


"V_{us} Revolution" with experimental input changing ~ 5% in some cases....Input from many experiments:

BNL865, KTeV, ISTRA+, KLOE, NA48, NA48/2

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

$|V_{us}|f_+(0)$

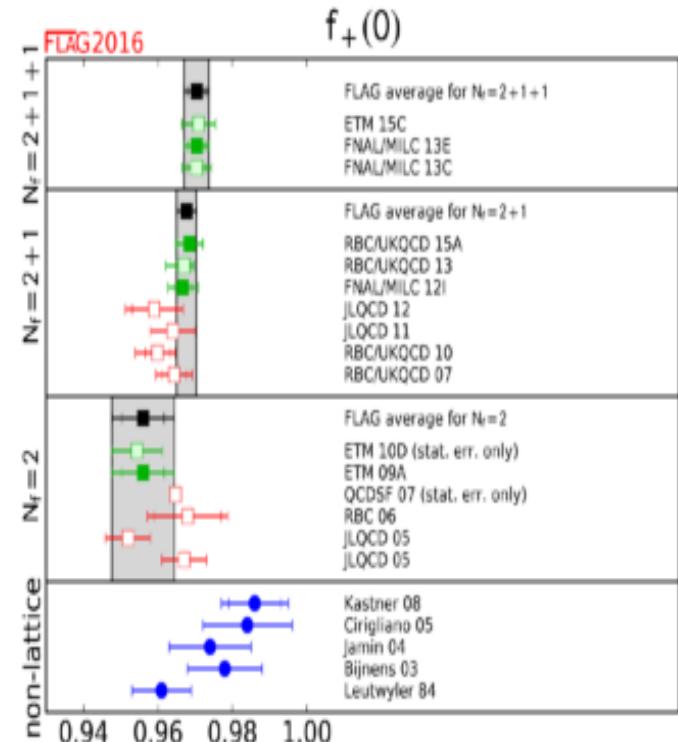


		% err	Approx. contrib. to % err from:			
			BR	τ	Δ	Int
$K_L e3$	0.2163(6)	0.25	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06
$K_S e3$	0.2155(13)	0.61	0.60	0.02	0.11	0.05
$K^\pm e3$	0.2171(8)	0.36	0.27	0.06	0.22	0.05
$K^\pm \mu 3$	0.2170(11)	0.51	0.45	0.06	0.22	0.06

Average: $|V_{us}|f_+(0) = 0.21654(41)$ $\chi^2/\text{ndf} = 1.54/4$ (82%)

Experimental determination of V_{us} from kaon decays – M. Moulson (Frascati) – CKM 2016, Mumbai, 1 December 2016

27



QCD su reticolo (FLAG 2016)

$$V_{us} = 0.2231(4)_{ex}(7)_{latt}$$

For: $f_+(0) = 0.9704(32)$ $N_f = 2+1+1$
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CKM Constraints at low energy

(PDG2018, Blucher&Marciano)

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)(2)$
first error from V_{ud} , second from V_{us}
- Exotic Muon Decays: since they are not considered in the G_μ extraction and CKM unitarity works:

$$\text{BR(exotic muon decays)} < 0.0014 \text{ 95% CL}$$

- New Heavy Quark Mixing:
 $|V_{uD}| < 0.04 \text{ 95% CL}$
- V_{us} determinations from tau decays:
0.2216(15) (2 σ below unitarity)

Rare Kaon Decays, new physics in loops?

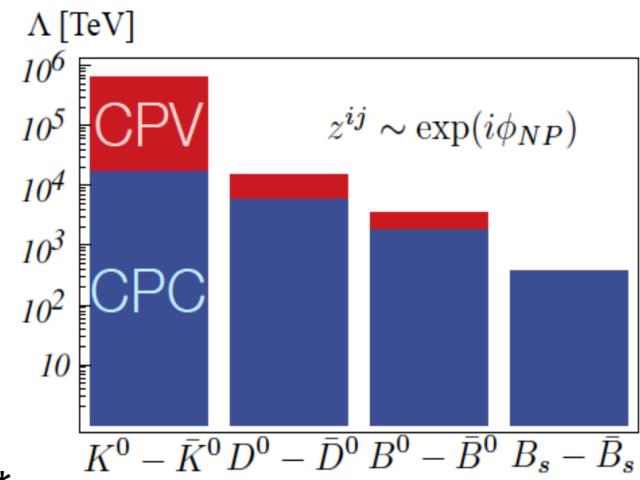
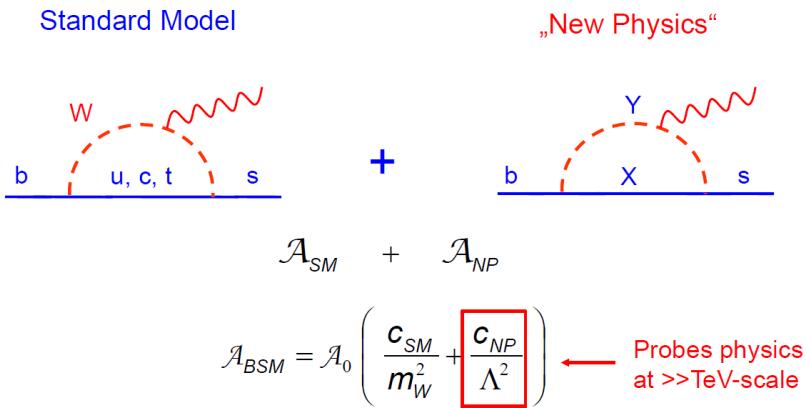
Search for New Physics..Indirectly

- **Discoveries are almost always anticipated by arguments and indirect evidence:**
 1. GIM: Charm \sim GeV
 2. Limits of Fermi theory: $\rightarrow W, Z @ \sim 100$ GeV
 3. CP-Violation \rightarrow 3rd generation of quarks
 4. Flavor, EW fit: $m(\text{top}) \sim 170$ GeV
 5. EW fit: $m(H) = 100 +/- 30$ GeV
- Now that guidance from indirect evidence has dried up... we are left with arguments:
 - Hierarchy problem: NP close to EW scale
 - WIMP miracle: NP close to EW scale
 - Unification of gauge couplings
- **We need to keep studying rare and forbidden processes to look for deviations from the SM predictions**

Bounds from Flavour Physics

Isidori and Teubert, arXiv:1402.2844

$$\mathcal{A}(\psi_i \rightarrow \psi_j + X) = \mathcal{A}_0 \left[\frac{c_{\text{SM}}}{M_W^2} + \frac{c_{\text{NP}}}{\Lambda^2} \right]$$



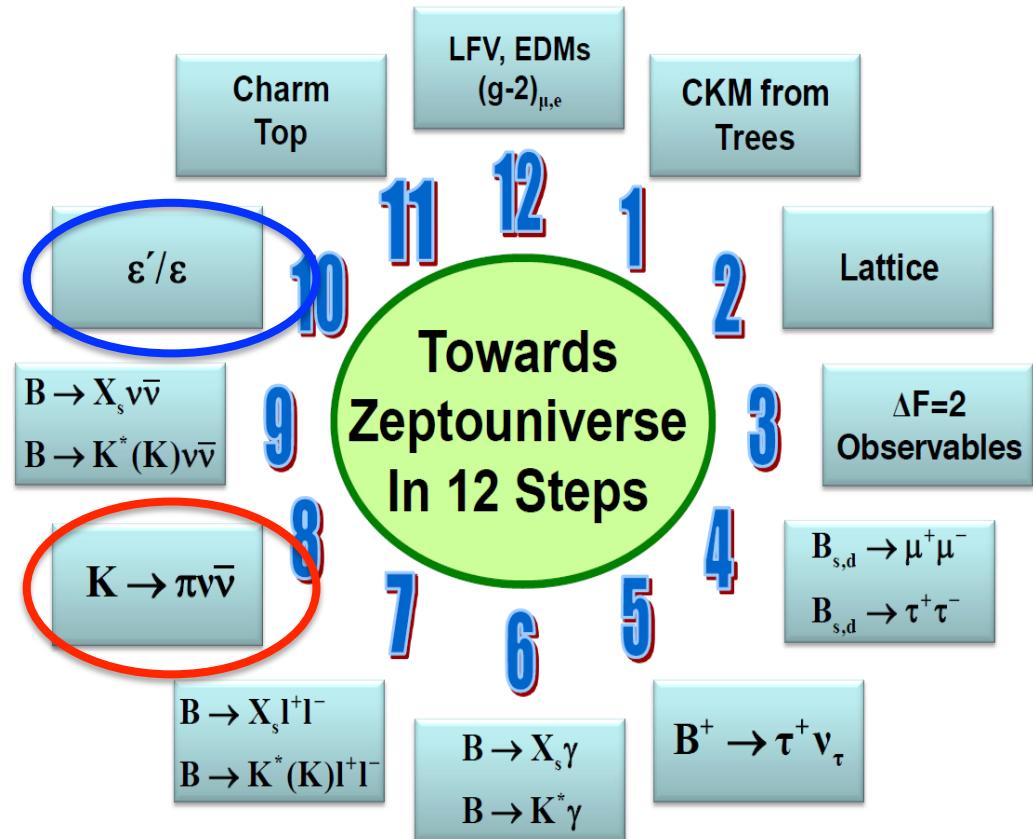
Cannot test Λ and c_{NP} at the same time

Operator	Bounds on Λ in TeV ($c_{\text{NP}} = 1$)		Bounds on c_{NP} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; q/p _D, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d}; \sin(2\beta)$ from $B_d \rightarrow \psi K$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s}; \sin(\phi_s)$ from $B_s \rightarrow \psi \phi$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

Rare Kaon Decays

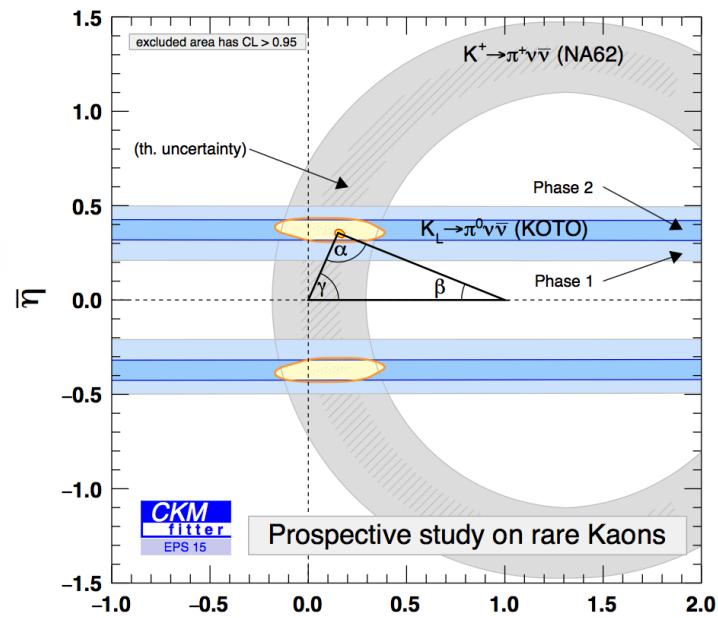
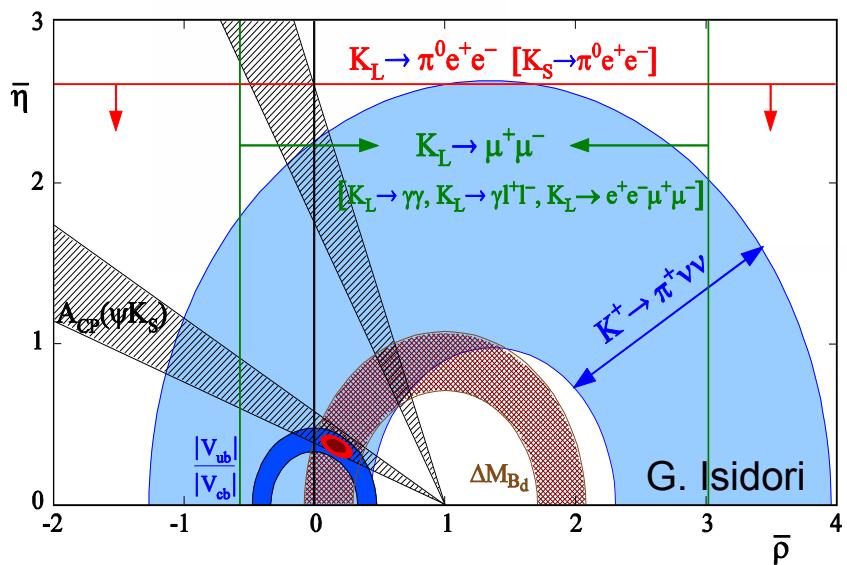
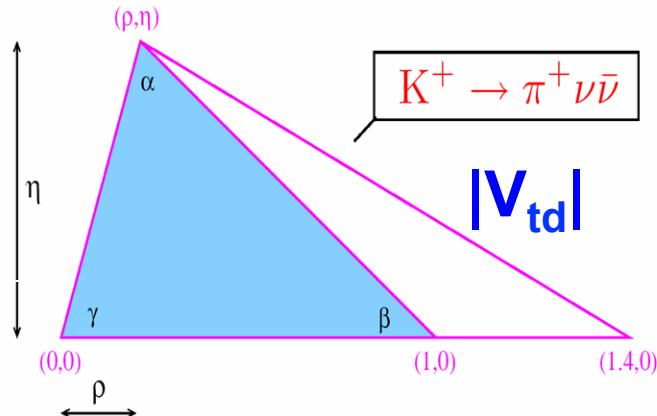
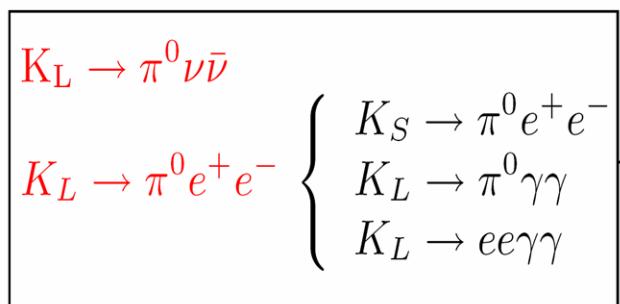
- ϵ'/ϵ is very sensitive to BSM
- Hopefully lattice QCD will allow one to make a precise prediction
- For the time being it remains a **qualitative test** of SM
- On the other hand, **rare kaon decays** are sensitive to BSM and they are precisely calculable in SM \rightarrow **quantitative test**

K e Zepto-Universe (10^{-21})



A. Buras

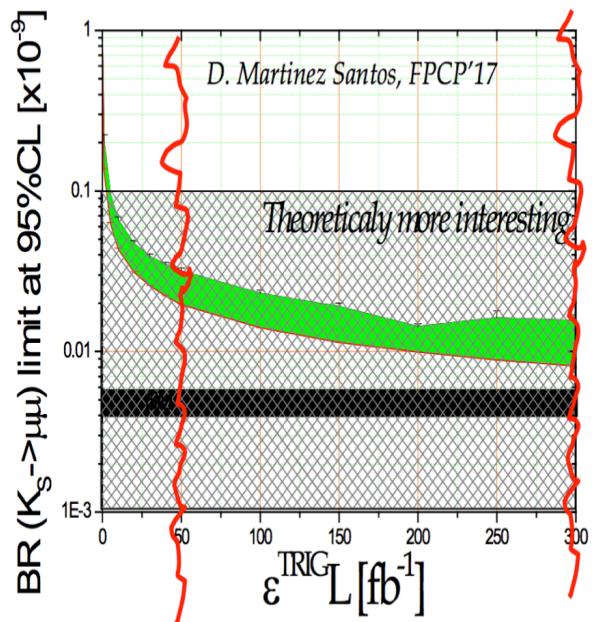
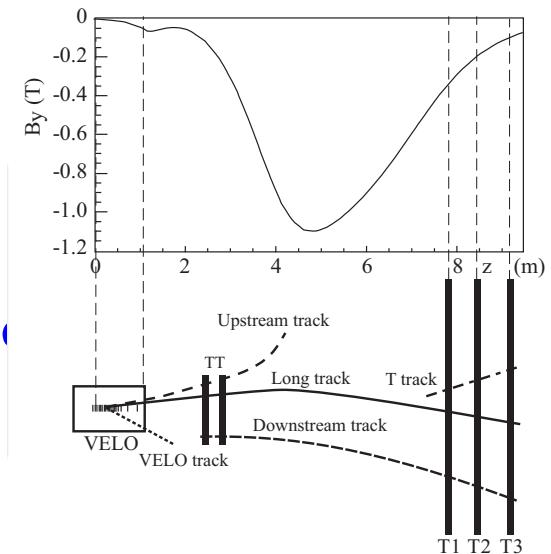
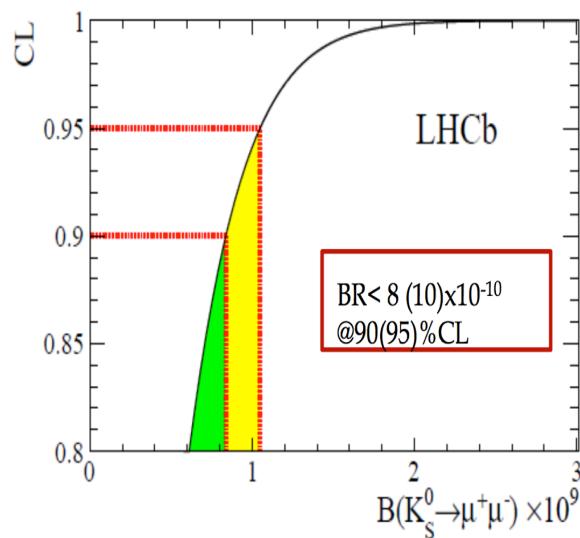
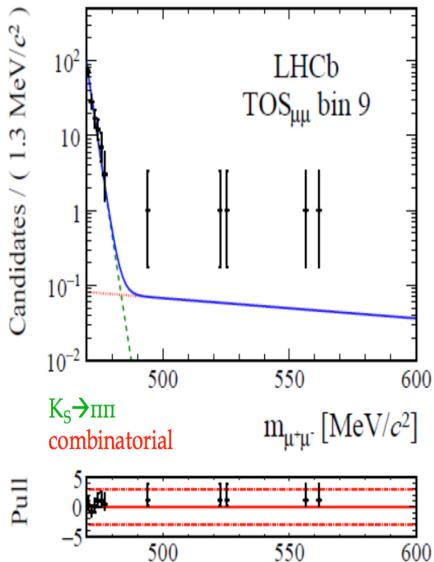
Kaon Rare Decays (Overview)



K Rare Decays as quantitative test complementary to B physics

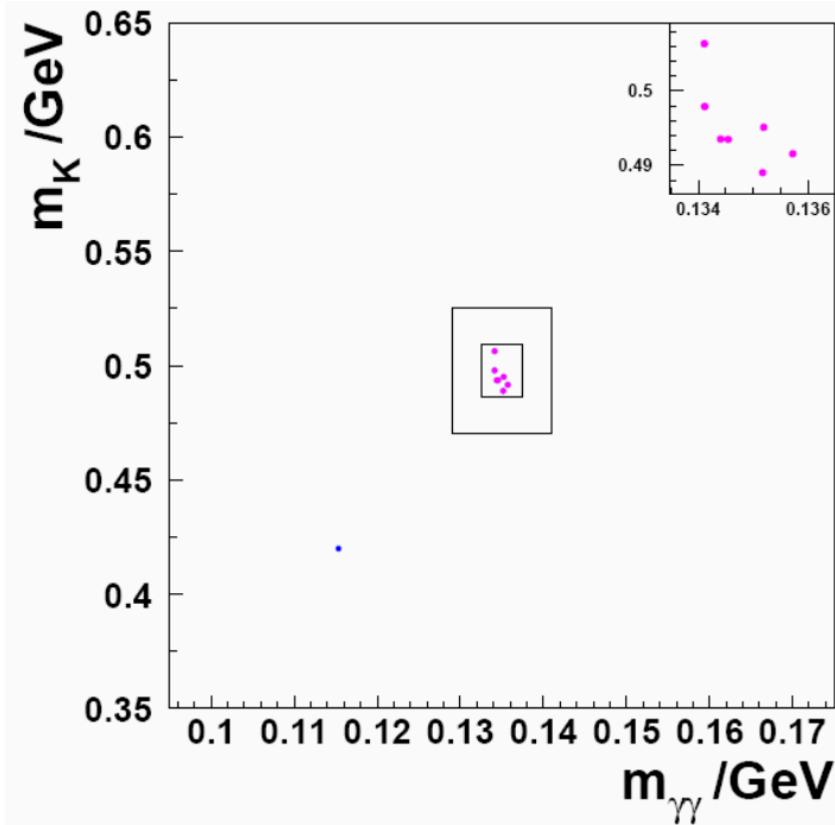
LHCb: $K_s^0 \rightarrow \mu^+ \mu^-$

- $10^{13} K_s^0/\text{fb}^{-1}$!!!
- Can use “long tracks” to reconstruct K_s^0
- Trigger limitations will be overcome thanks to the LHCb upgrade



Phase-II-upgrade

NA48/1

BR($K_S \rightarrow \pi^0 e^+ e^-$)

0 events found in control region
7 events found in signal region

Probability BG only $\sim 10^{-10}$

FIRST OBSERVATION OF
 $K_S \rightarrow \pi^0 e^+ e^-$ with $m_{ee} > 165 \text{ MeV}$

$$\text{BR}(K_S \rightarrow \pi^0 e^+ e^-)_{m_{ee} > 165} = (3.8^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9}$$

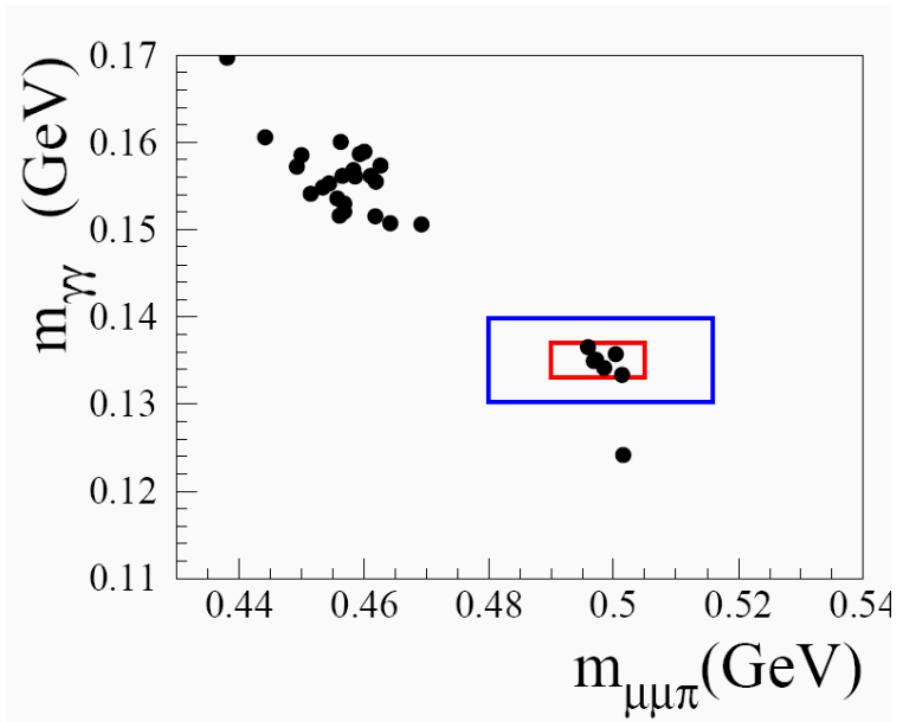
Using MonteCarlo
with unit form factors

$$\text{BR}(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(\text{stat.}) \pm 0.3_{\text{syst}} \pm 0.8_{\text{theory}}) \cdot 10^{-9}$$

PLB 599 (2004)

NA48/1

BR($K_S \rightarrow \pi^0 \mu^+ \mu^-$)



0 events found in control region
6 events found in signal region

FIRST OBSERVATION OF
 $K_S \rightarrow \pi^0 \mu^+ \mu^-$

$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.9^{+1.5}_{-1.2}(stat.) \pm 0.2_{syst}) \cdot 10^{-9}$$

a_s and K_L estimates

- ✓ a_s can be extracted using both decays:

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = 5.2 \cdot 10^{-9} a_s^2 \Rightarrow |a_s| = 1.06^{+0.26}_{-0.21} + 0.07$$
$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = 1.2 \cdot 10^{-9} a_s^2 \Rightarrow |a_s| = 1.55^{+0.38}_{-0.32} + 0.05$$

- ✓ The results are compatible taking into account experimental errors
- ✓ Using $|a_s|$ and current value of $\text{Im}(\lambda_t)$

$$BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} = (17_{IND} \pm 9_{INT} + 5_{DIR}) \cdot 10^{-12}$$

$$BR(K_L \rightarrow \pi^0 \mu^+ \mu^-)_{CPV} = (9_{IND} \pm 3_{INT} + 1_{DIR}) \cdot 10^{-12}$$



Cf. PDG (KTeV) $BR(K_L \rightarrow \pi^0 ee) < 2.8 \cdot 10^{-10} \text{ 90%CL}$

M. Raggi NA48 Collaboration

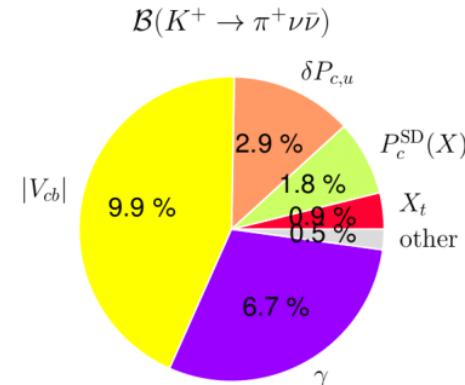
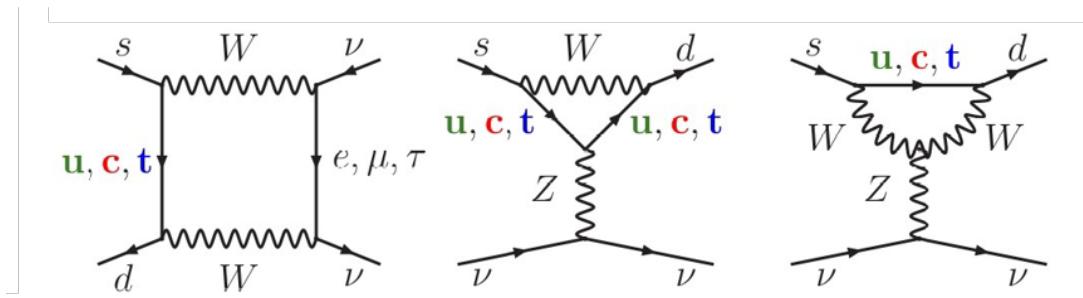
$BR(K_L \rightarrow \pi^0 \mu\mu) < 3.8 \cdot 10^{-10} \text{ 90%CL}$

Kaon Rare Decays: Scenarios

- The $K_L \rightarrow \pi^0 e^+ e^- (\mu^+ \mu^-)$ is very difficult to pursue not only because of the K_S component but also because of irreducible radiative backgrounds ($ee\gamma\gamma$, $\mu\mu\gamma\gamma$)
- $K^+ \rightarrow \pi^+ \nu\nu$ is very important but experimentally not easy:
 1. Within the SM it measures $|V_{td}|$ with small theoretical error
 2. it is sensitive to new physics because the SM contribution is very suppressed
- The study of this rare decays has been done, so far, with decays at rest (DAR)
- The CERN experiment NA62 is studying it with decays in flight
- $K_L^0 \rightarrow \pi^0 \nu\nu$ measures by itself the height of the unitarity triangle. Experimentally is even more challenging

The FCNC process $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

Theoretical error budget
[Buras. et. al., JHEP11\(2015\)033](#)



- FCNC loop processes: $s \rightarrow d$ coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions:
[\[Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 \(2011\)\]](#)
[\[Buras. et. al., JHEP11\(2015\)033\]](#)

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

- Experimental result:
[\[Phys. Rev. D 79, 092004 \(2009\)\]](#)

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

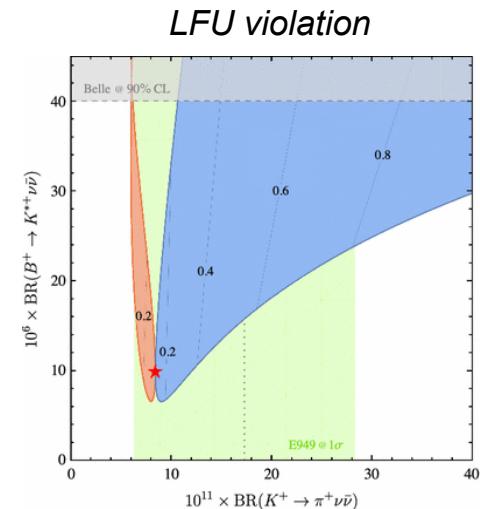
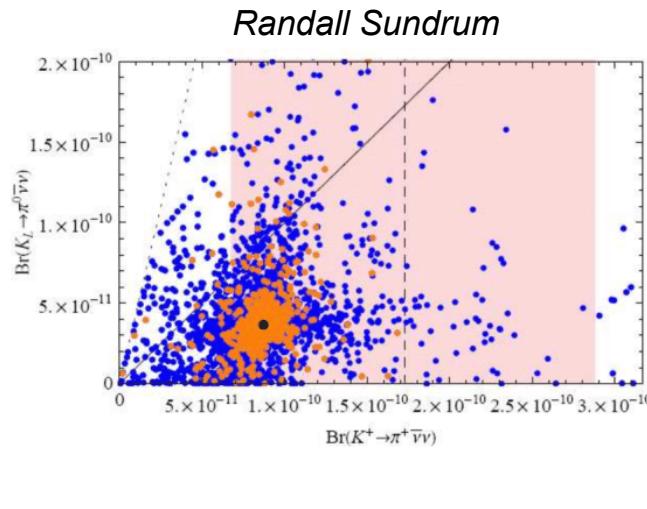
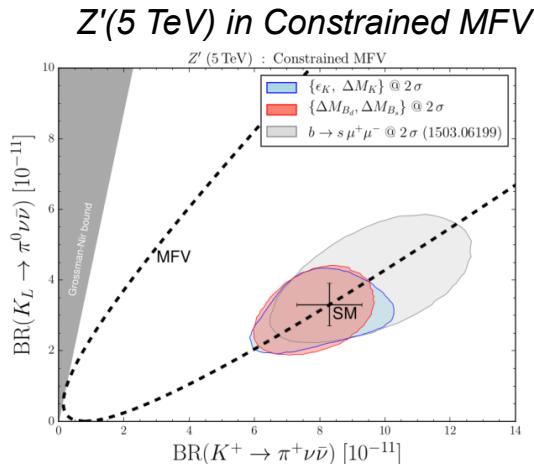
$$K_L \rightarrow \pi^0 \nu\bar{\nu}$$

$$\stackrel{\text{TH}}{BR} = (3.4 \pm 0.6) \times 10^{-11}$$

EX
 $BR < 2600 \times 10^{-11}$ 90%CL
 KEK 391a, PRD81 (2010)

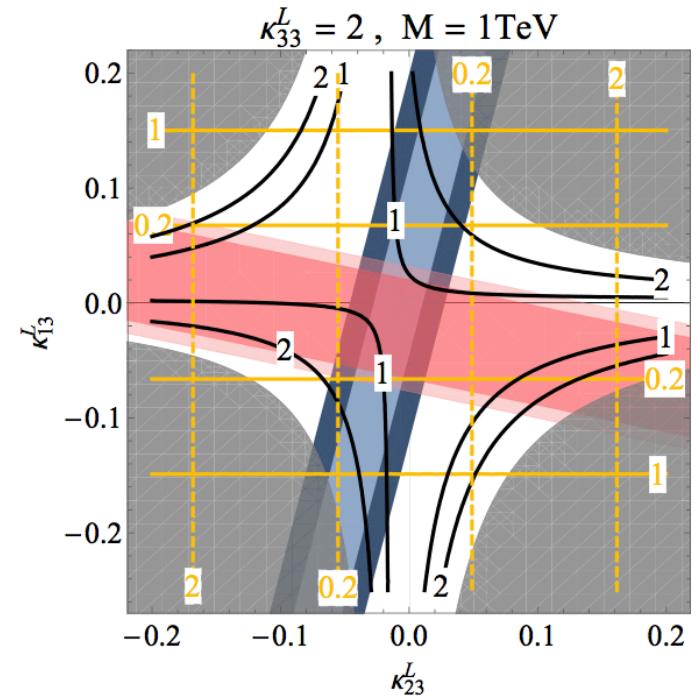
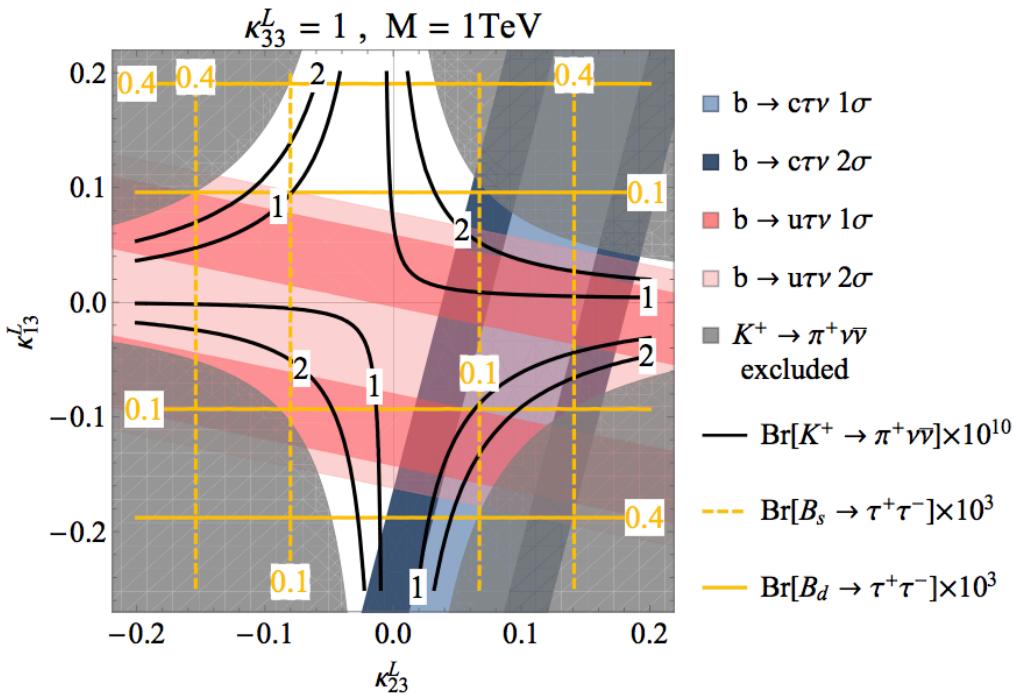
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Beyond the Standard Model

- Custodial Randall-Sundrum [[Blanke, Buras, Duling, Gemmeler, Gori, JHEP 0903 \(2009\) 108](#)]
- MSSM analyses [[Blazek, Mata, Int.J.Mod.Phys. A29 \(2014\) no.27](#)], [[Isidori et al. JHEP 0608 \(2006\) 064](#)]
- Simplified Z, Z' models [[Buras, Buttazzo,Knegjens, JHEP11\(2015\)166](#)]
- Littlest Higgs with T-parity [[Blanke, Buras, Recksiegel, Eur.Phys.J. C76 \(2016\) 182](#)]
- LFU violation models [[Isidori et al., Eur. Phys. J. C \(2017\) 77: 618](#)]
- Constraints from existing measurements (correlations model dependent)
 - ★ Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches



Loop Effects from Vector Leptoquarks

arXiv:1007.02068 A. Crivelling, C. Greub, F. Saturnino



Techniques for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

“Stopped”

- Work in Kaon rest frame
- High Kaon purity
(Electro-Magneto-static Separators) possible
- Compact Detectors

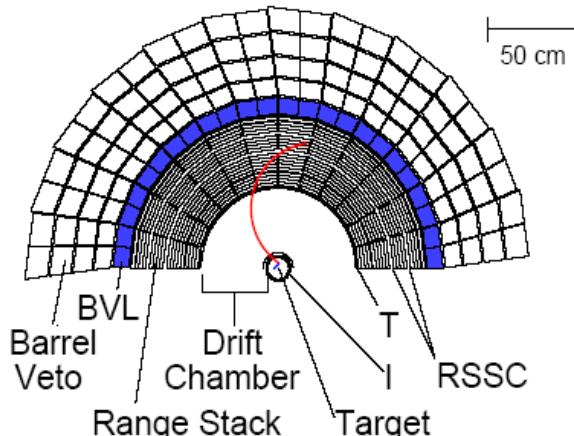
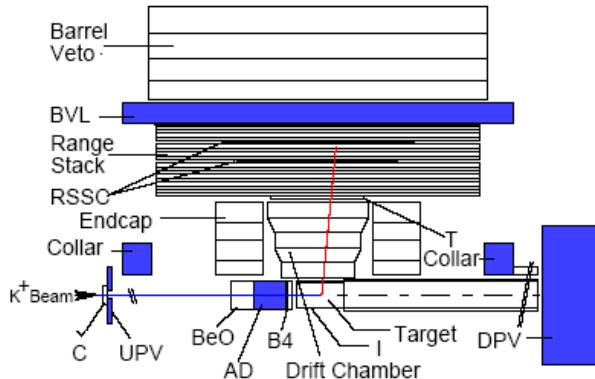
“In-Flight”

- Decays in vacuum (no scattering, no interactions)
- RF separated (very difficult) or unseparated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped; Spark Chambers
	KEK	$< 1.4 \times 10^{-7}$	Stopped; $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	AGS	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	Stopped; PPN1+PPN2
NA62	SPS	Taking Data	In-Flight; Unseparated

E787/E949 Technique

“The entire AGS beam of 65×10^{12} (p/ spill) at a momentum of 21.5 GeV/c was delivered to the E949 K⁺ production target”



- Duty Factor: 2.2 s / 5.4 s \sim 40%
- 1 int. length Pt target
- Before separators: 500 π : 500 p : 1 K
- After separators: Purity **K:π ~ 3-4 : 1**
- Incoming **710 MeV/c** K⁺ identified by Č and slowed down by BeO and Active Degrader
- **~27%** K⁺ stopped in the target (1.6 MHz)
- 1 T solenoid

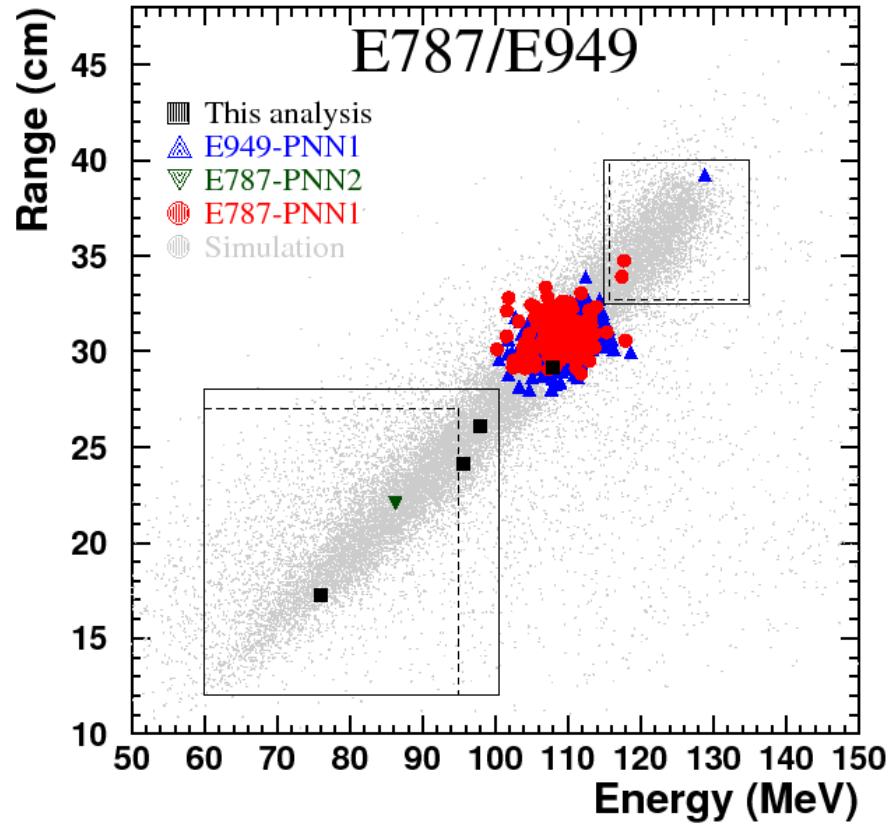
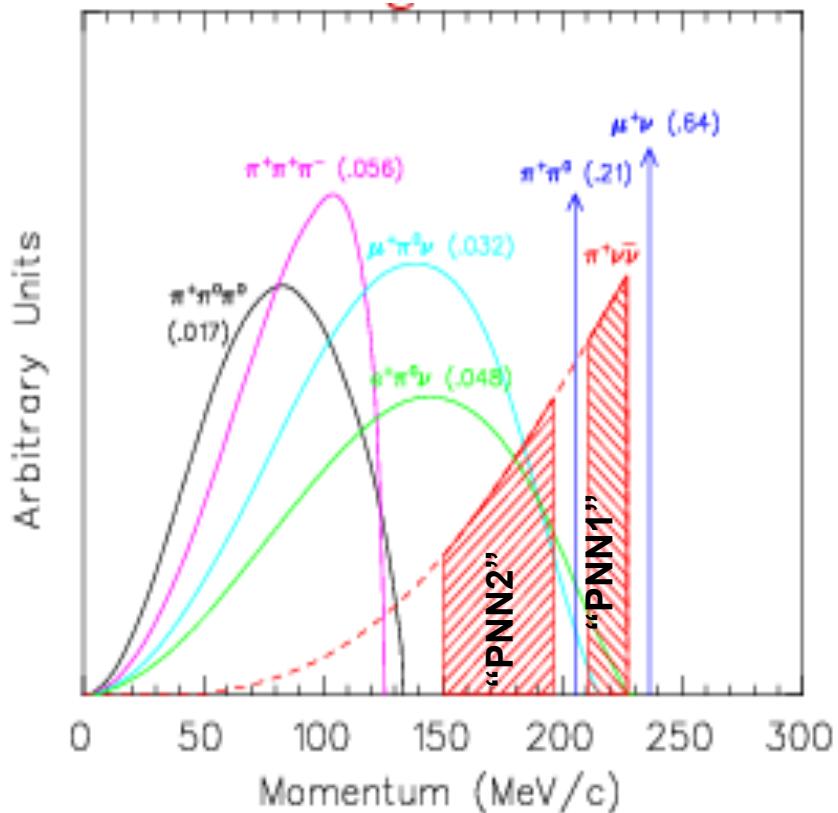
K⁺: Č x B4 x Target

π⁺: Delayed Coincidence
Range
Energy
Momentum
 $\pi^+ \rightarrow \mu^+ \rightarrow e^+$

E787/E949: Final Result

arXiv:0903.0030v1

PRD79:092004, 2009

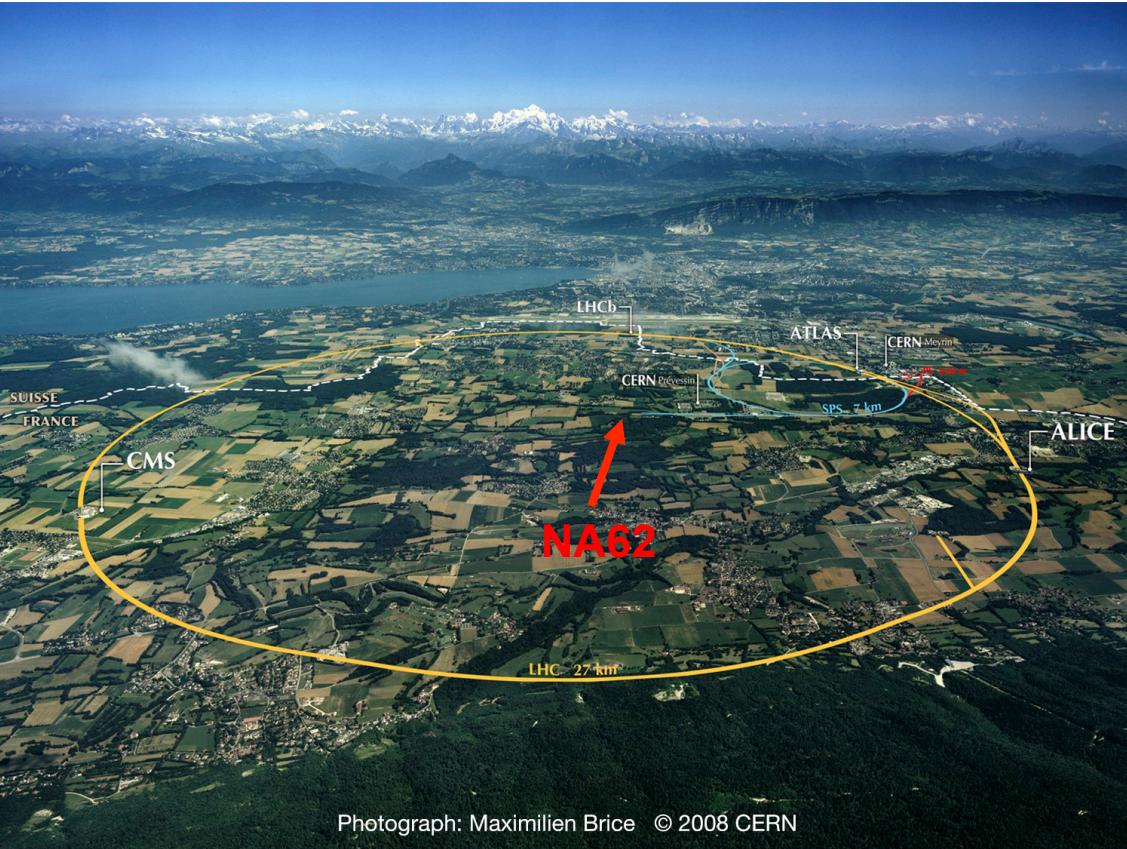


$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Kaon physics @ NA62

14-'18 NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

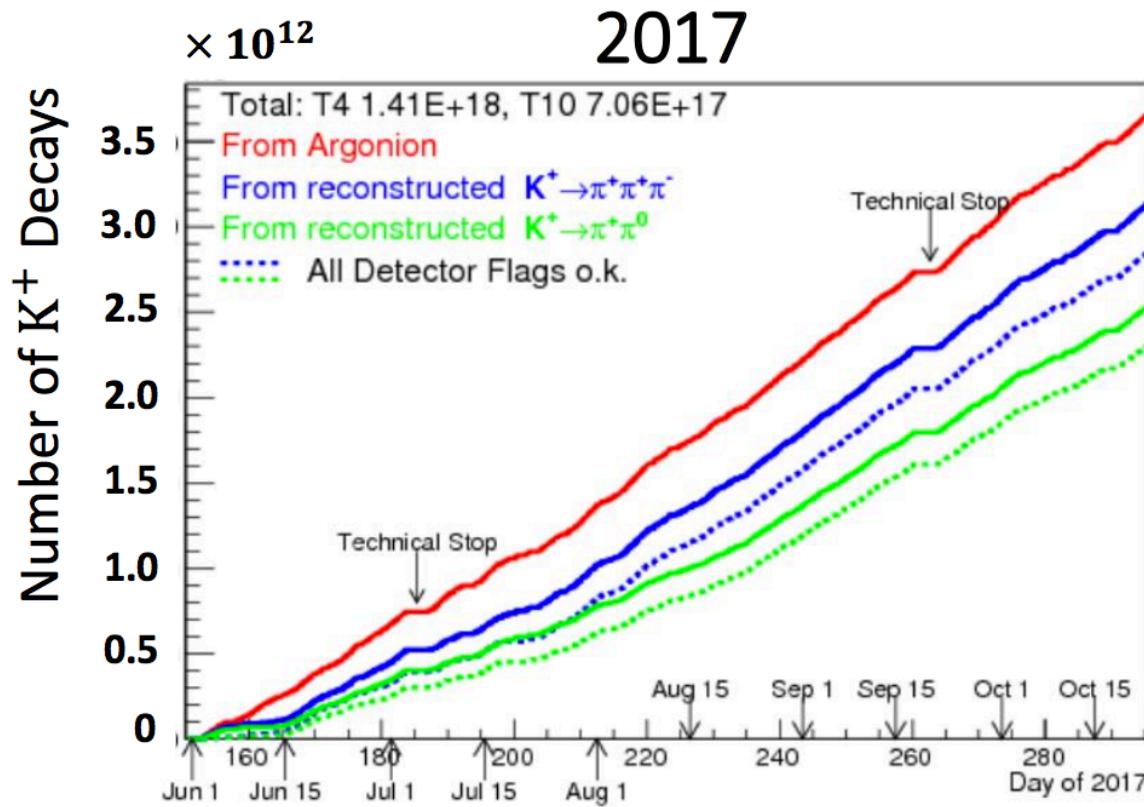
- ★ 2014 Pilot run
- ★ 2015 Commissioning run
- ★ Full detector installation completed in September 2016
- ★ First $\pi \nu \bar{\nu}$ dataset in 2016
(Covered here)
- ★ Continuous data-taking until the end of 2018



~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

NA62 Data Taking

- 2016: 13×10^{11} ppp on target (40% nominal) $\sim 1 \times 10^{11} K^+ \text{ decays useful for } \pi\nu\bar{\nu}$
2017: 20×10^{11} ppp on target (60% nominal) $> 3 \times 10^{12} K^+ \text{ decays collected}$

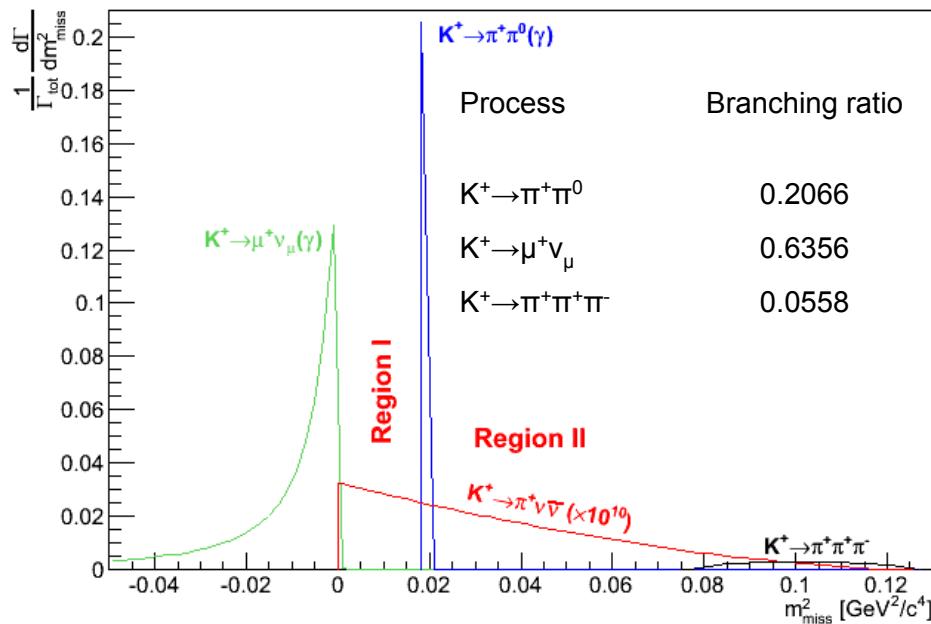
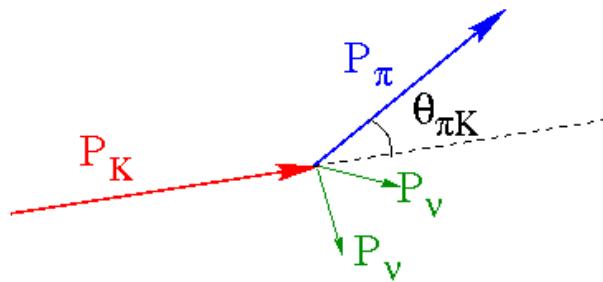


- 2018 Data Taking until November 11
- 218 days of protons (full SPS run!)

Analysis strategy

NEW

Decay in flight technique $m_{\text{miss}}^2 = (P_K - P_{\pi^+})^2$



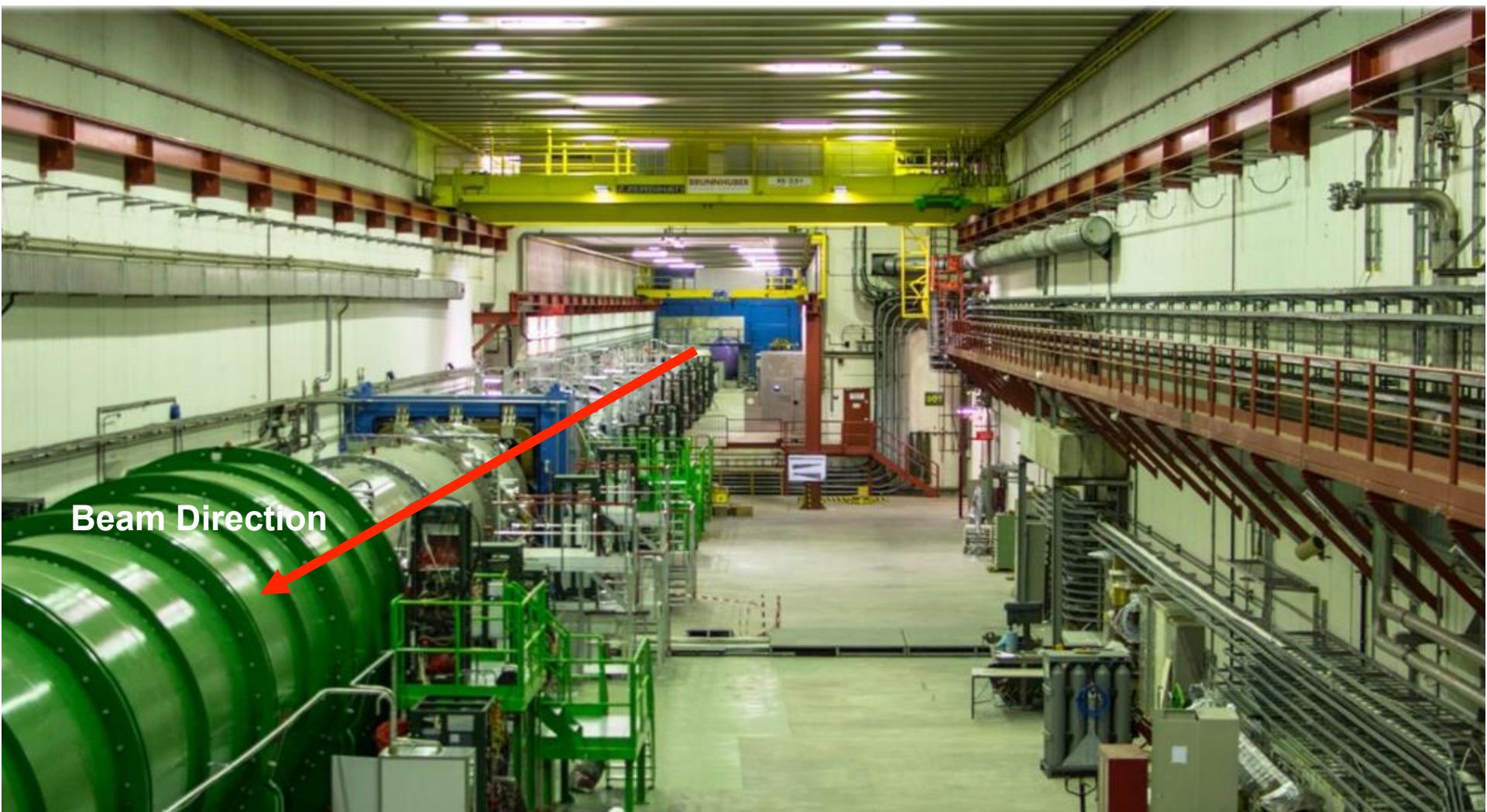
Keystones of the analysis:

- ★ Timing between sub-detectors $\sim O(100 \text{ ps})$
- ★ Kinematic suppression $\sim O(10^4)$
- ★ Muon suppression $> 10^7$
- ★ π^0 suppression (from $K^+ \rightarrow \pi^+ \pi^0$) $> 10^7$

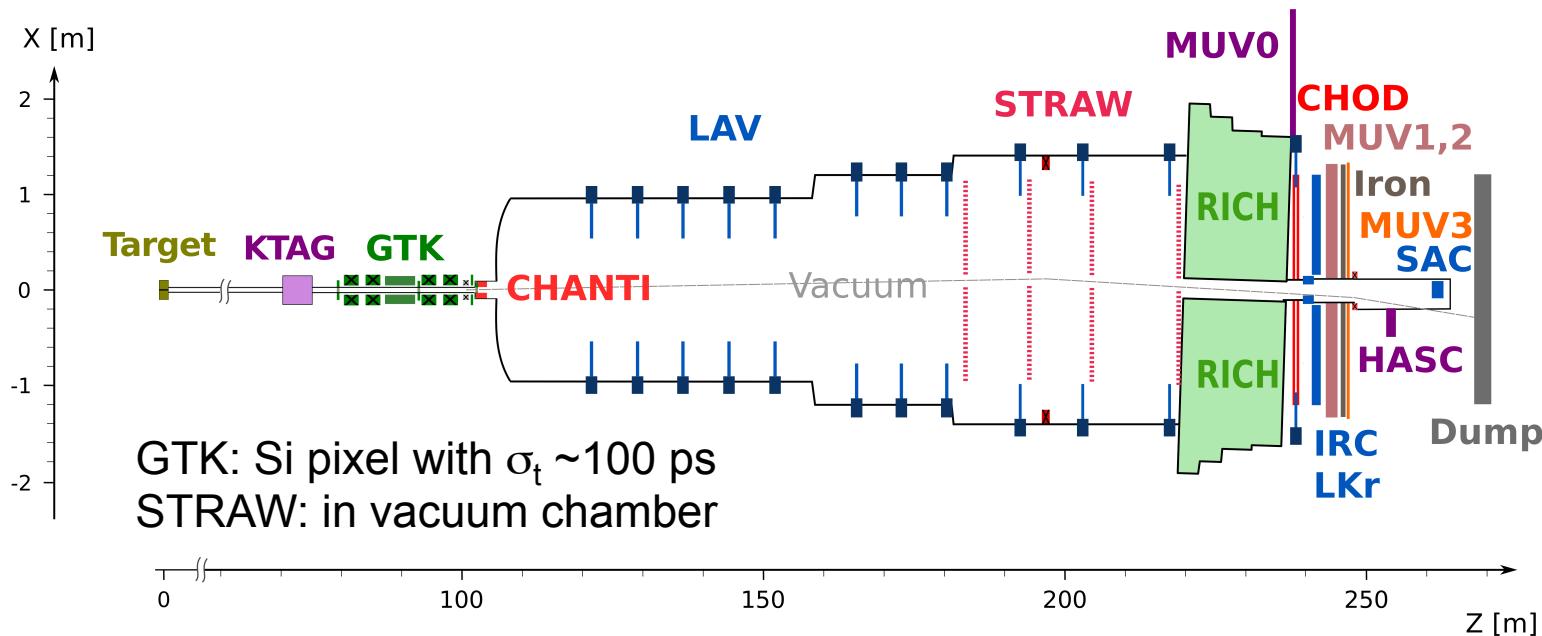
Signal and background control regions are kept blind throughout the analysis

- + $15 < P_{\pi^+} < 35 \text{ GeV}/c$
- + Particle ID(Cherenkov detectors)
- + Particle ID(Calorimeters)
- + Photon veto

NA62 beam and detector

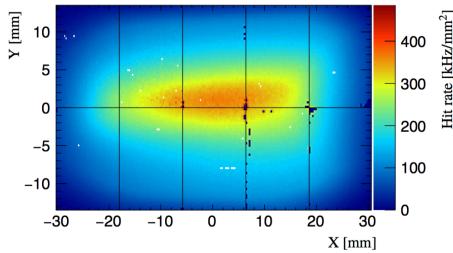


NA62 beam and detector



■ SPS Beam:

- ★ 400 GeV/c protons
- ★ 2.10^{12} protons/spill
- ★ 5s spill [3s eff.] / ~ 16 s



■ Secondary positive Beam:

- ★ 75 GeV/c momentum, 1 % bite
- ★ 100 μ rad divergence (RMS)
- ★ 60x30 mm² transverse size
- ★ K⁺(6%)/p⁺(70%)/p(24%)
- ★ For 33x10¹¹ ppp on T10

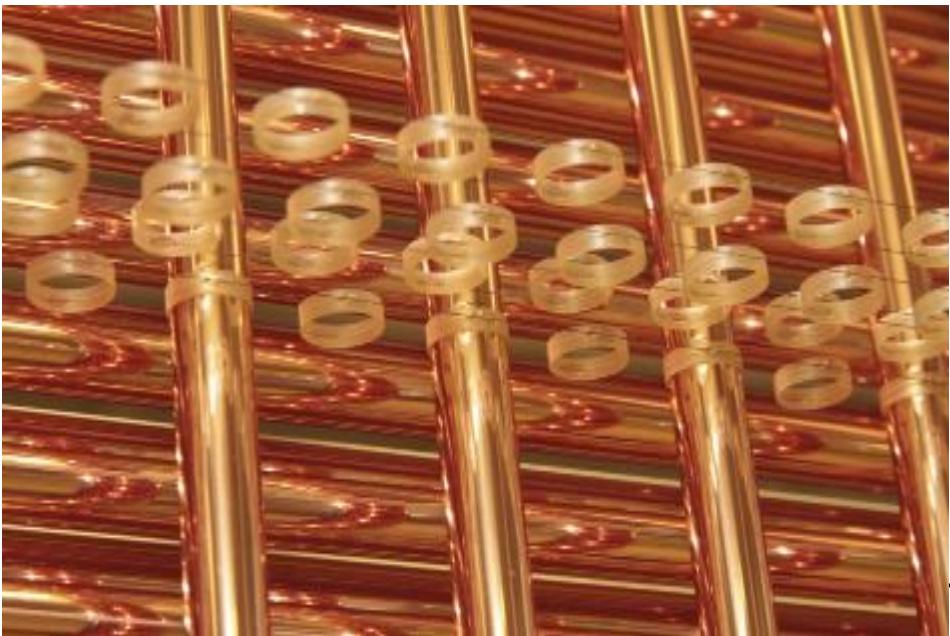
→ 750 MHz at GTK3

■ Decay Region:

- ★ 60 m long fiducial region
- ★ ~ 5 MHz K⁺ decay rate
- ★ Vacuum $\sim O(10^{-6})$ mbar

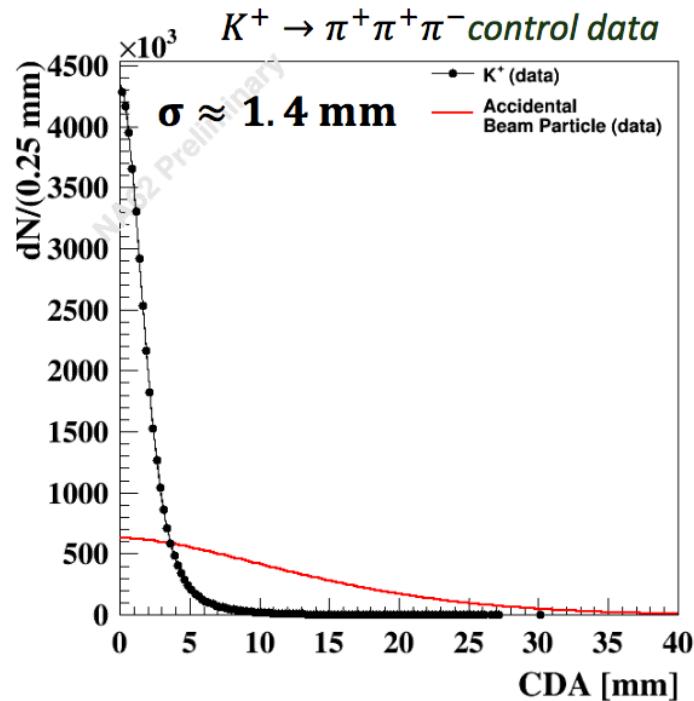
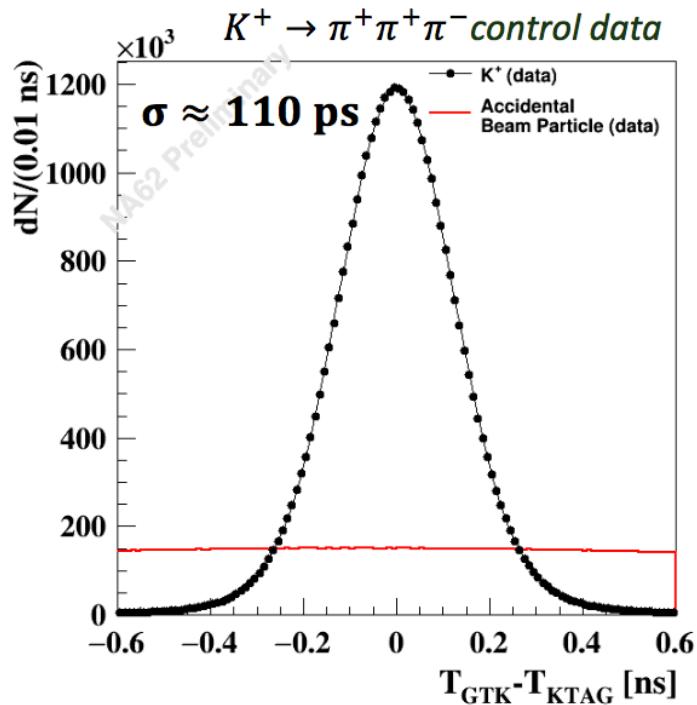
Detector and Performances: [arXiv:1703.08501](https://arxiv.org/abs/1703.08501)

NA62 Straws Tracker

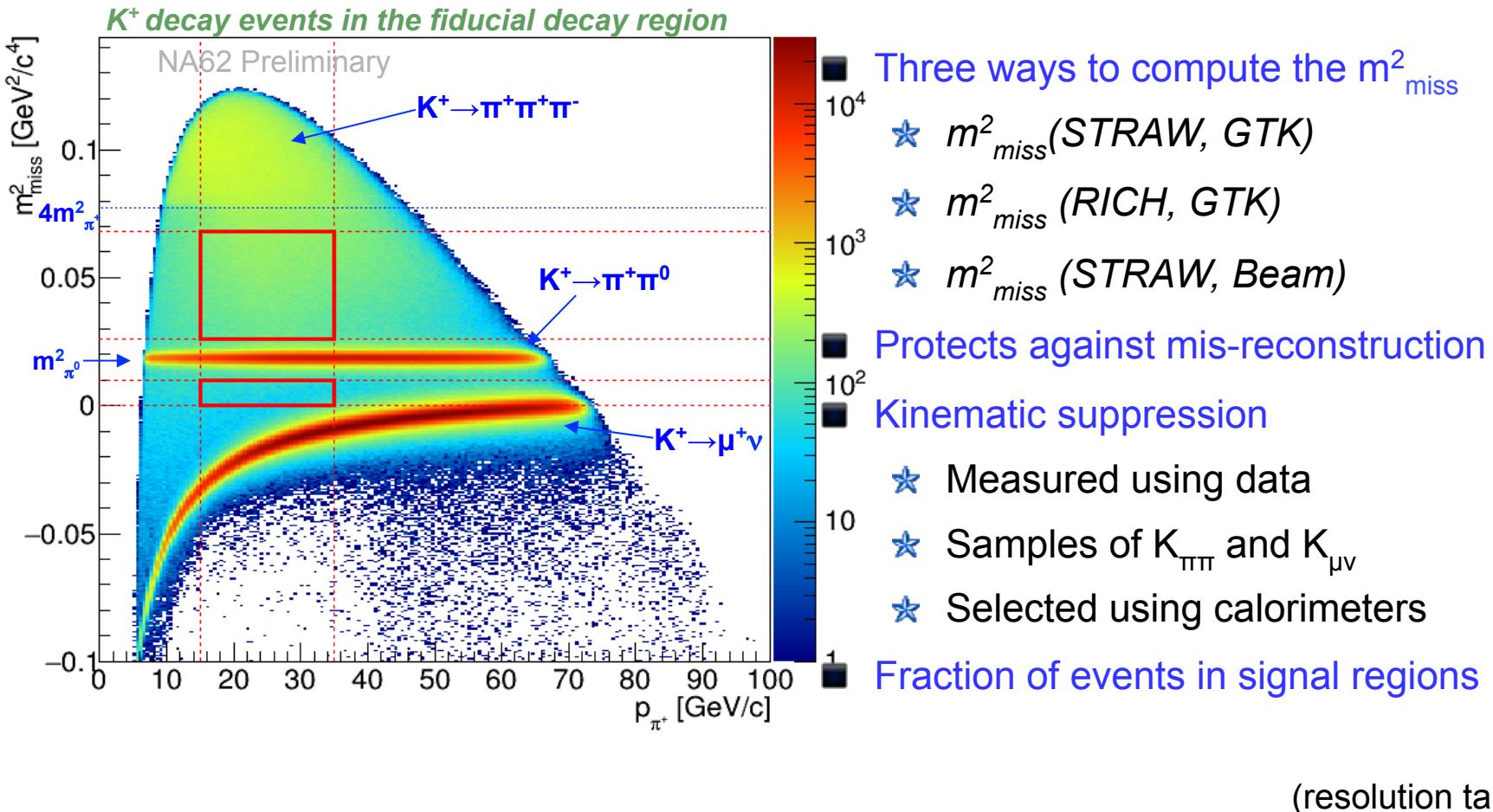


Kaon – Pion Matching (Time and Space)

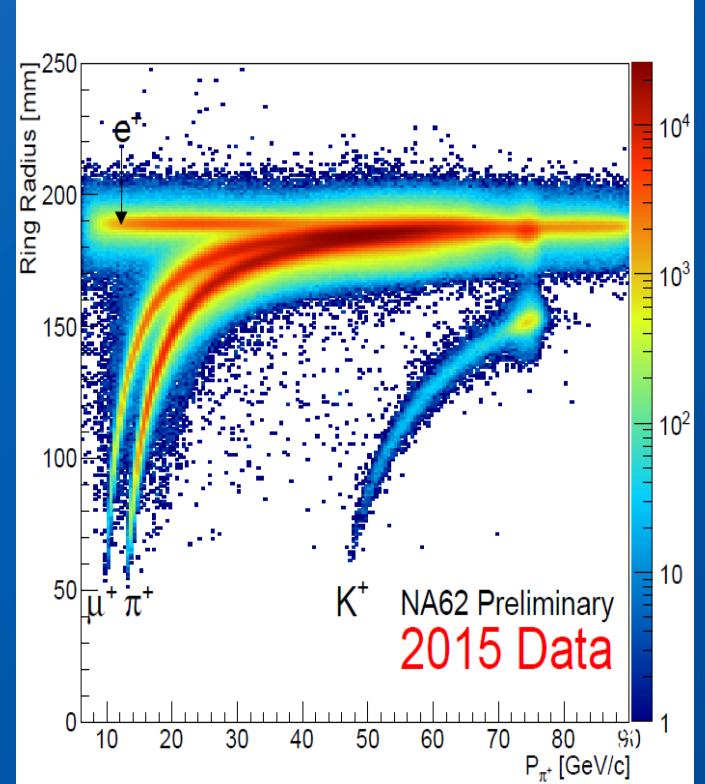
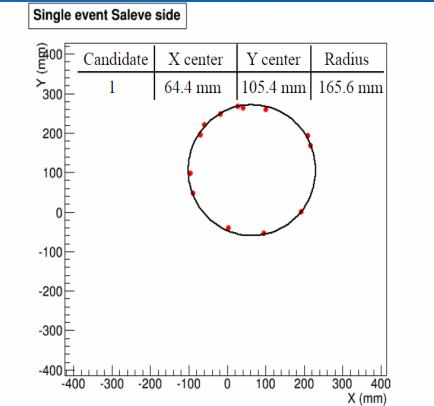
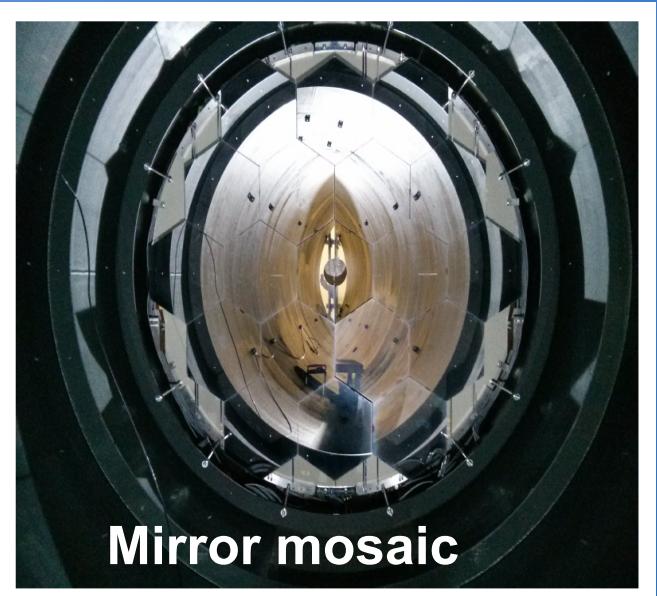
- KTAG – GigaTracker – RICH time matching \rightarrow Kaon decay time (t_{decay})
- GigaTracker – Straw Spectrometer spatial matching (Closest Distance of Approach, CDA)
- 1% (<3.5%) K^+ mis-tag if K^+ track (not) present, dependent on beam intensity
- 75% K^+ reconstruction and ID efficiency



Signal Region Definition

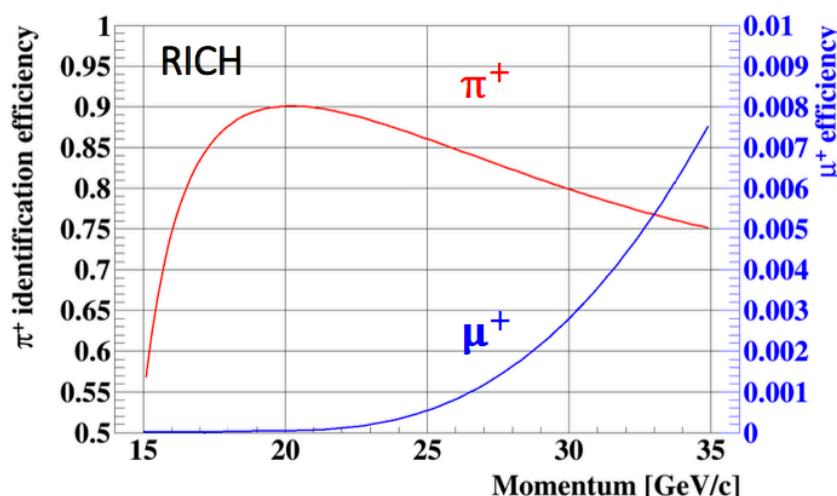
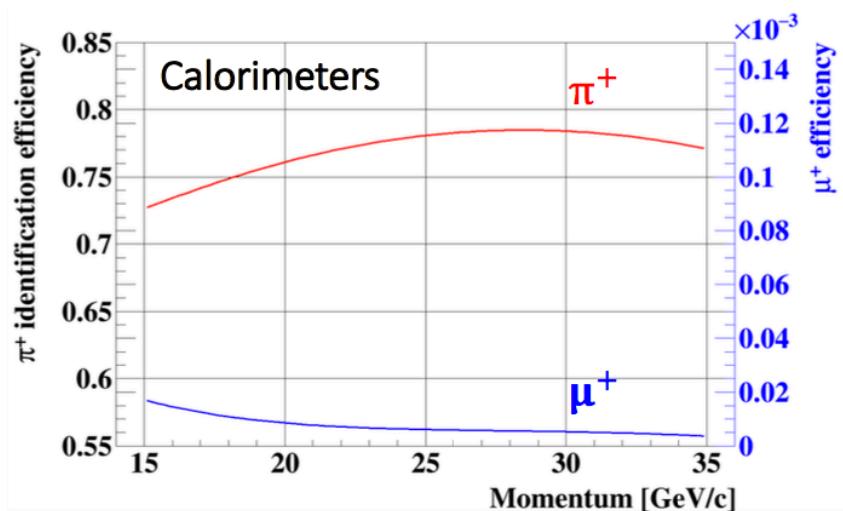


NA62 RICH

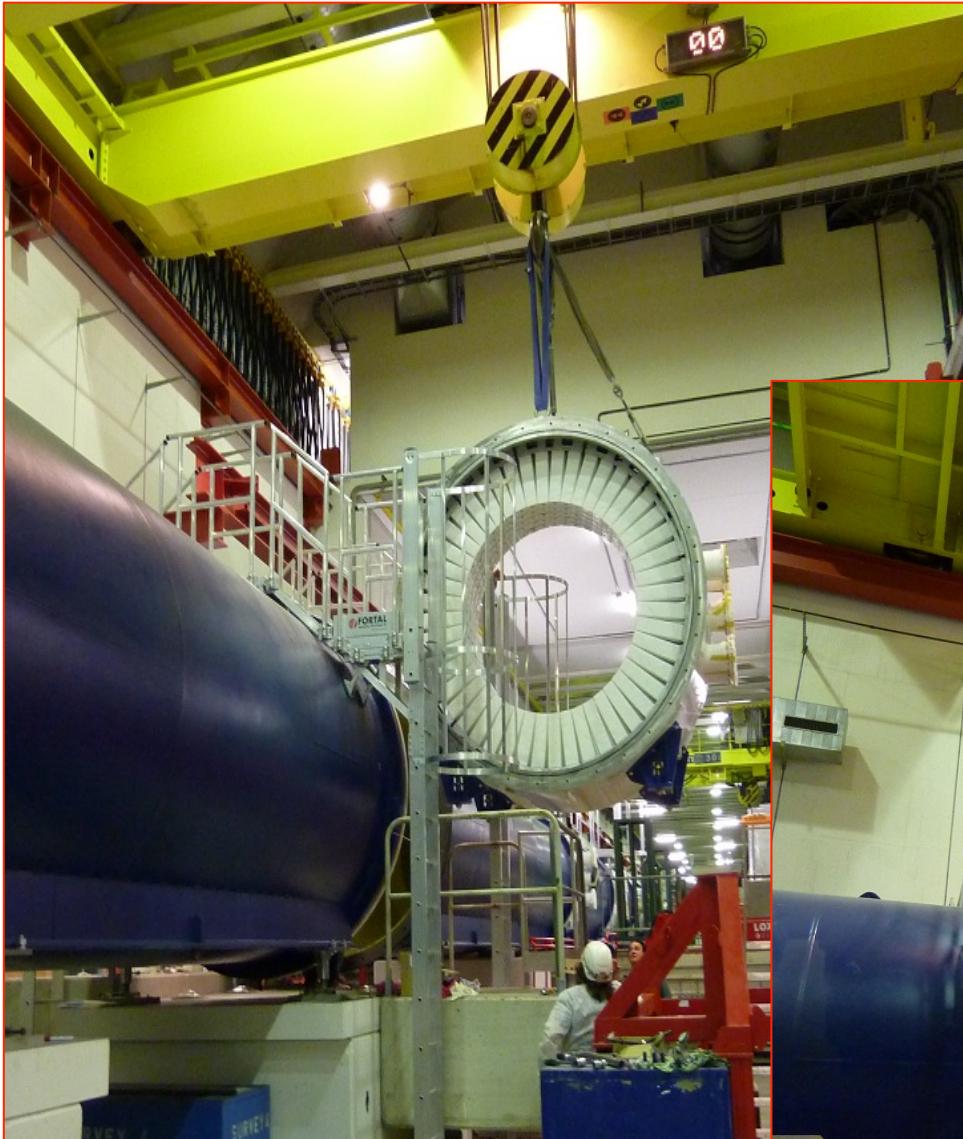


Particle Identification

PID	π^+ efficiency	μ^+ efficiency
Calorimeters	77%	$0.6 \cdot 10^{-5}$
RICH	80%	$2.5 \cdot 10^{-3}$

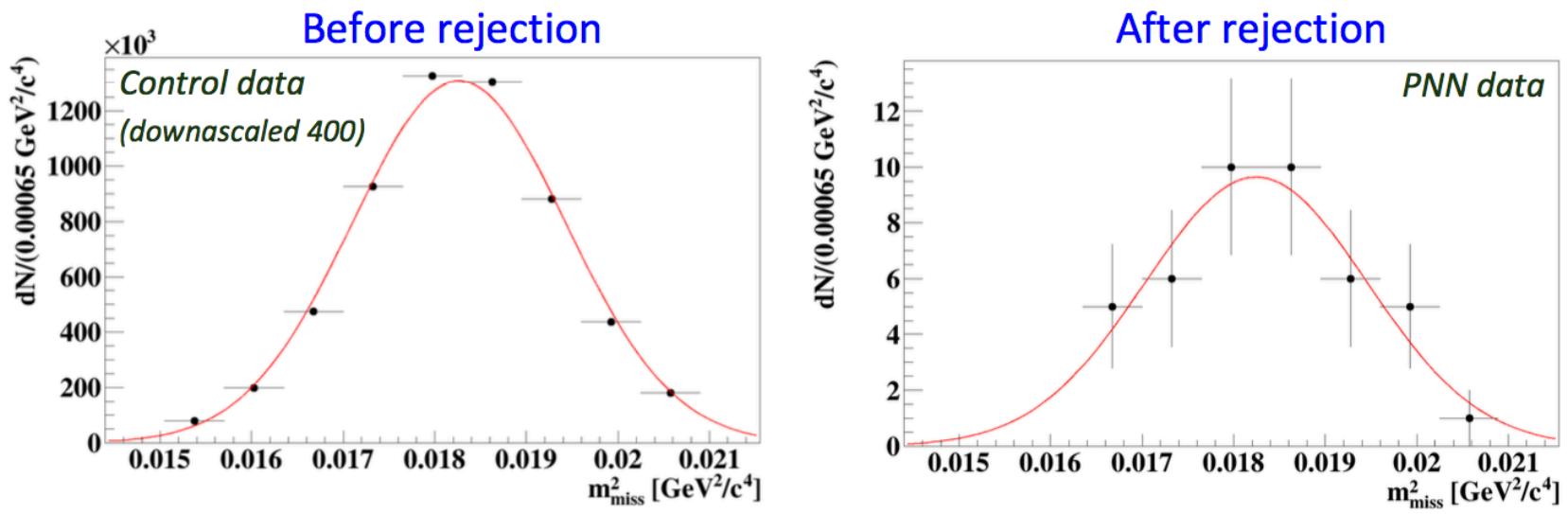


π^0 Rejection



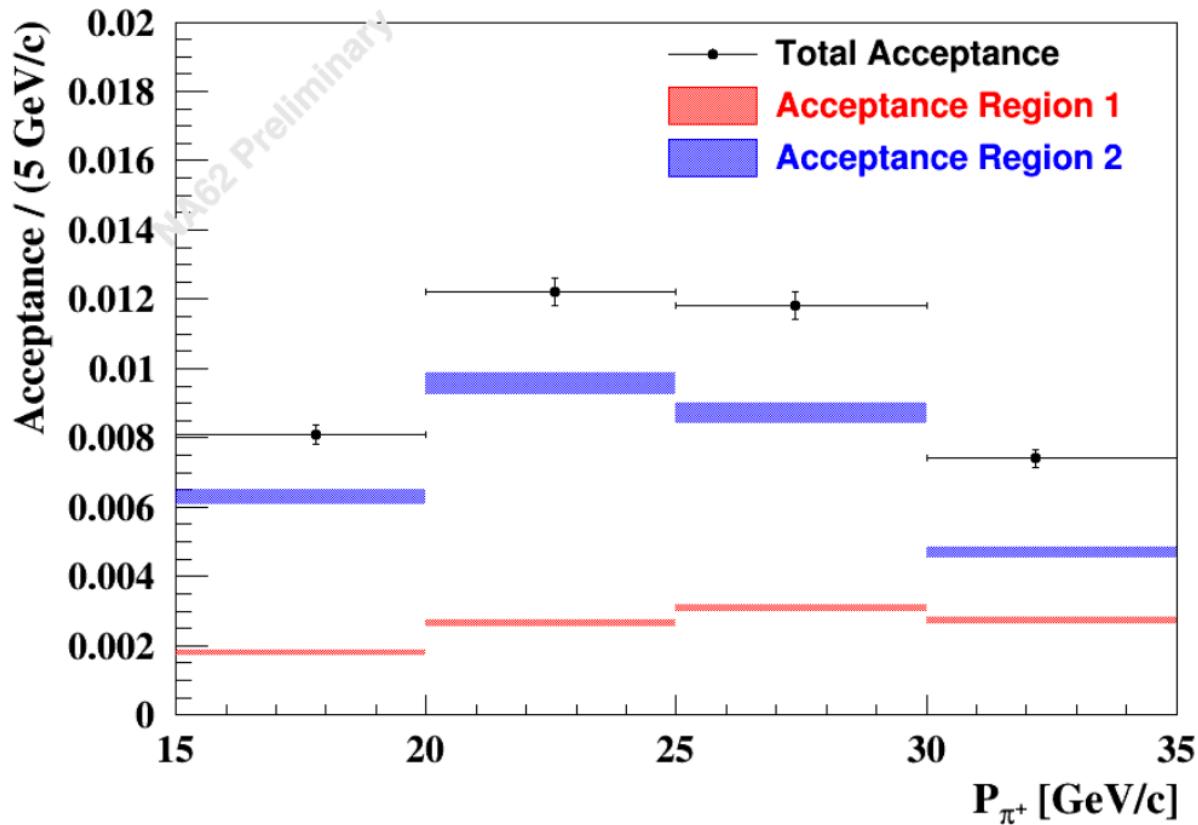
Photon Rejection

- Timing coincidence with signals in LKr, LAV, SAV not associated to π^+ and t_{decay}
- Coincidences of signals in LKr and hodoscopes not associated to π^+ , in time with t_{decay}
- No hits in time in HASC and MUVO (off-acceptance veto); segments rejection in Straw
- Typical timing coincidences: $\pm 3 \div \pm 10$ ns; energy dependent time cut in LKr
- Fraction of surviving $K^+ \rightarrow \pi^+\pi^0$ (15 – 35 momentum range) : $\sim 2.5 \cdot 10^{-8}$
- High suppression of $K^+ \rightarrow \pi^+\pi^+\pi^-$, $K^+ \rightarrow \pi^+\pi^-e^+\nu$

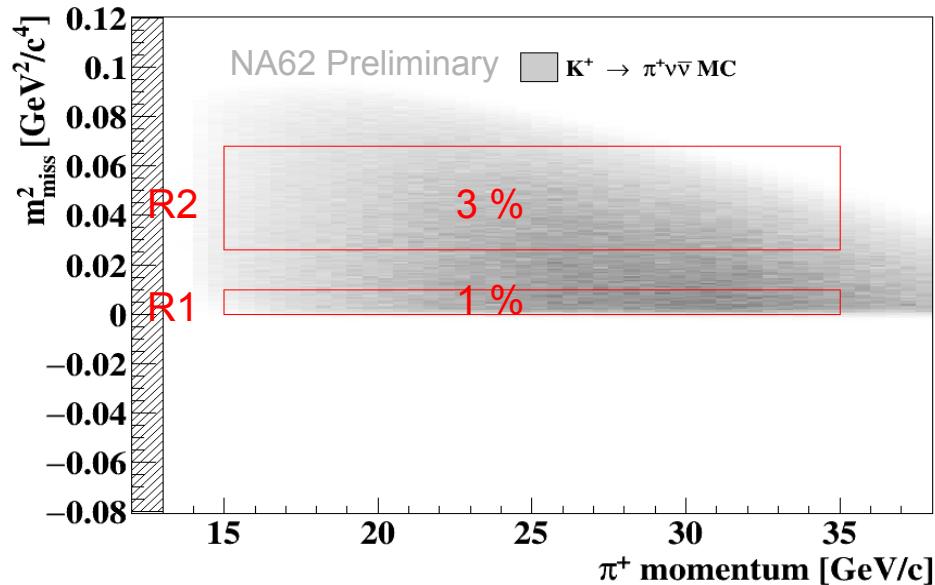


Signal Acceptance

Computed with MC assuming a vector form factor
Including PID and interaction losses



Single Event Sensitivity (SES)



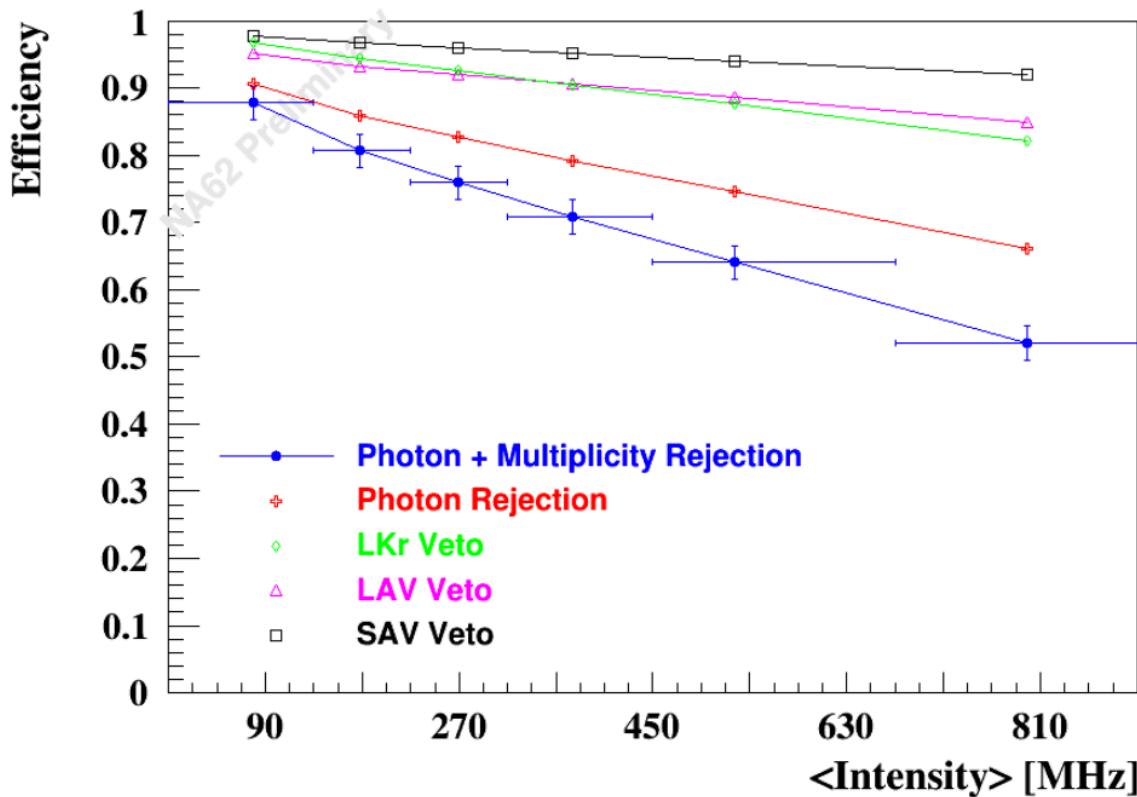
Source	$\delta \text{SES} (10^{-10})$
Random Veto	± 0.17
N_K	± 0.05
Trigger efficiency	± 0.04
Definition of $\pi^+\pi^0$ region	± 0.10
Momentum spectrum	± 0.01
Simulation of π^+ interactions	± 0.09
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

- Signal acceptance : 4 % (before random veto)
- Normalization acceptance : 10 %
- Control triggered $\text{K}^+ \rightarrow \pi^+\pi^0$ used for normalization
- Number of kaon decays in the fiducial volume : $N_K = 1.21(2) \times 10^{11}$

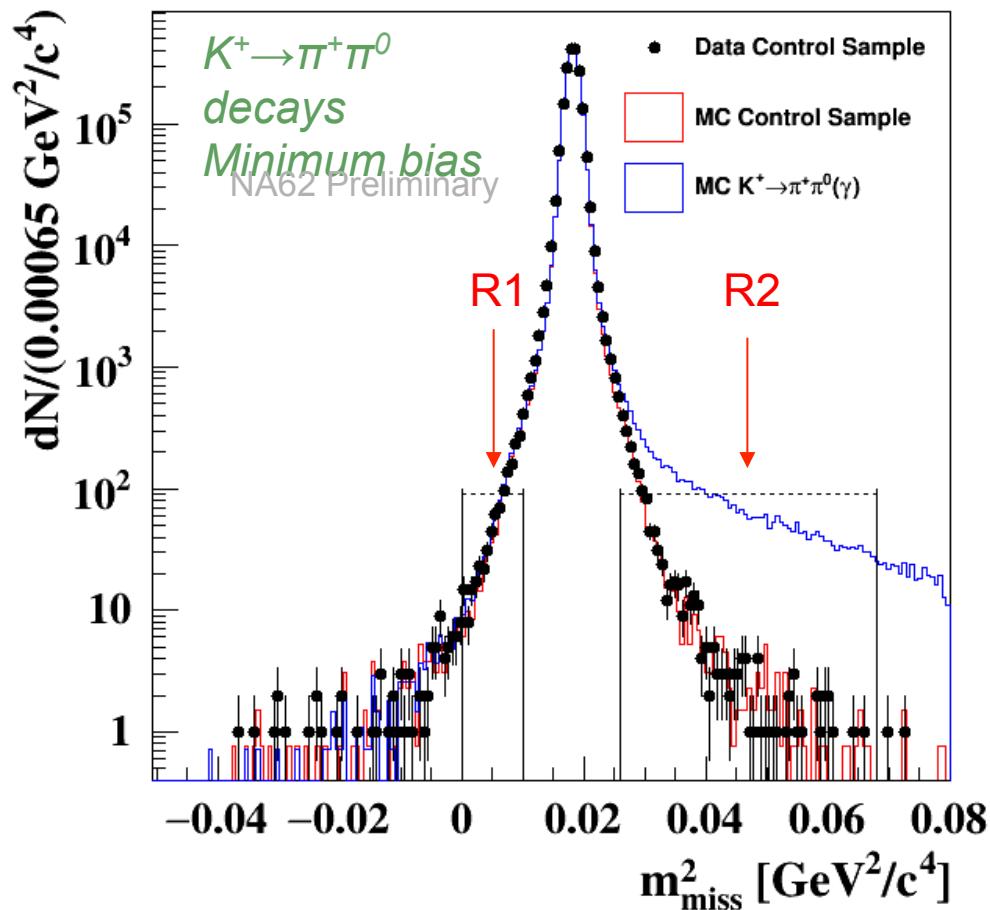
$$SES = (3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \cdot 10^{-10}$$

Random Veto

- Random signal losses due to $\gamma +$ multiplicity rejection measured with $K^+ \rightarrow \mu^+ \nu$
- $\langle \epsilon_{RV} \rangle = 0.76 \pm 0.04$ independent from P_{π^+} , dependent on instantaneous intensity



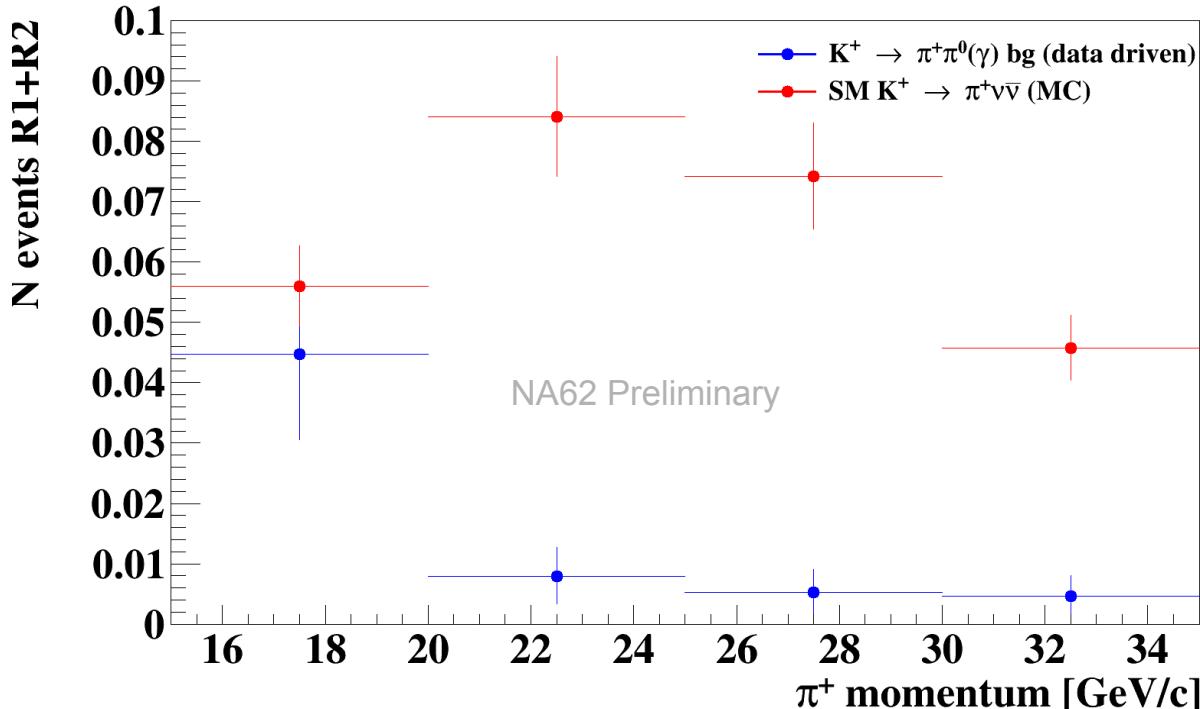
$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ background



$$N_{\pi\pi}^{\text{exp}}(\text{region}) = N(\pi^+ \pi^0) \cdot f^{\text{kin}}(\text{region})$$

- Kinematic rejection independent from photon rejection
- $N(\pi^+ \pi^0)$: events (data) in $\pi^+ \pi^0$ region after $\pi^+ \nu \bar{\nu}$ selection
- f^{kin} : tails, from $\pi^+ \pi^0$ control sample selected on data tagging the π^0
- $f^{\text{kin}}(R1 + R2) \sim 10^{-3}$ [not radiative]
- Radiative: $\pi^0 + \gamma \rightarrow \times 30 \pi^0$ rejection in R2

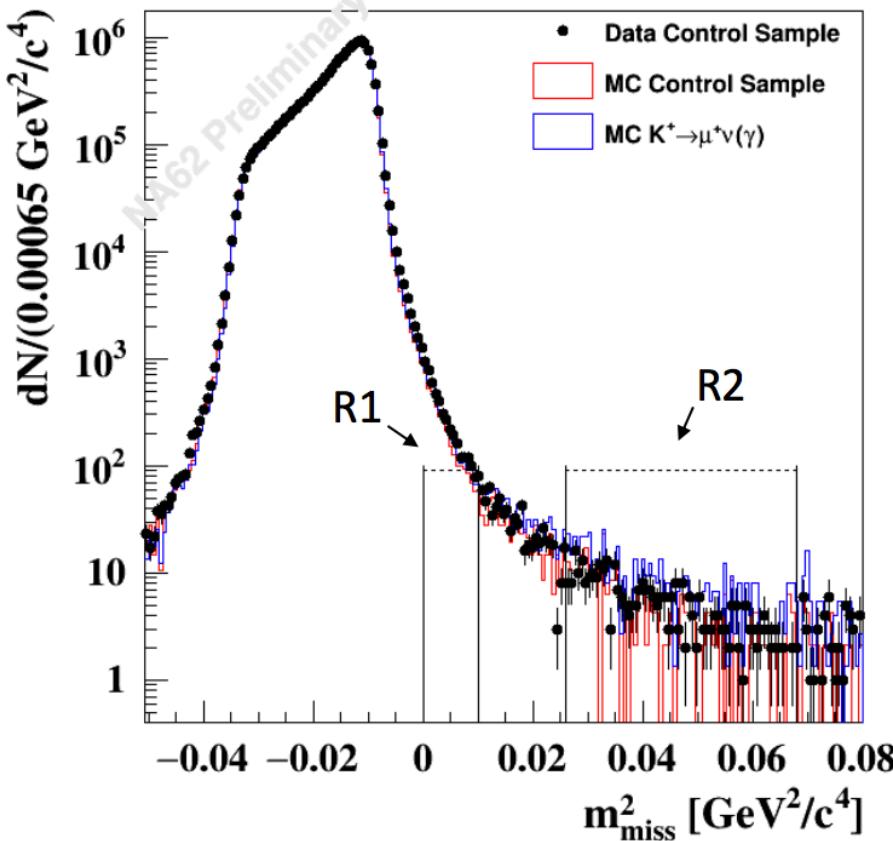
$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ background



- Data driven background estimation
- Control region validation: 1 event observed (1.46 +/- 0.17 expected)

$$N_{\pi\pi(\gamma)}^{bg} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$

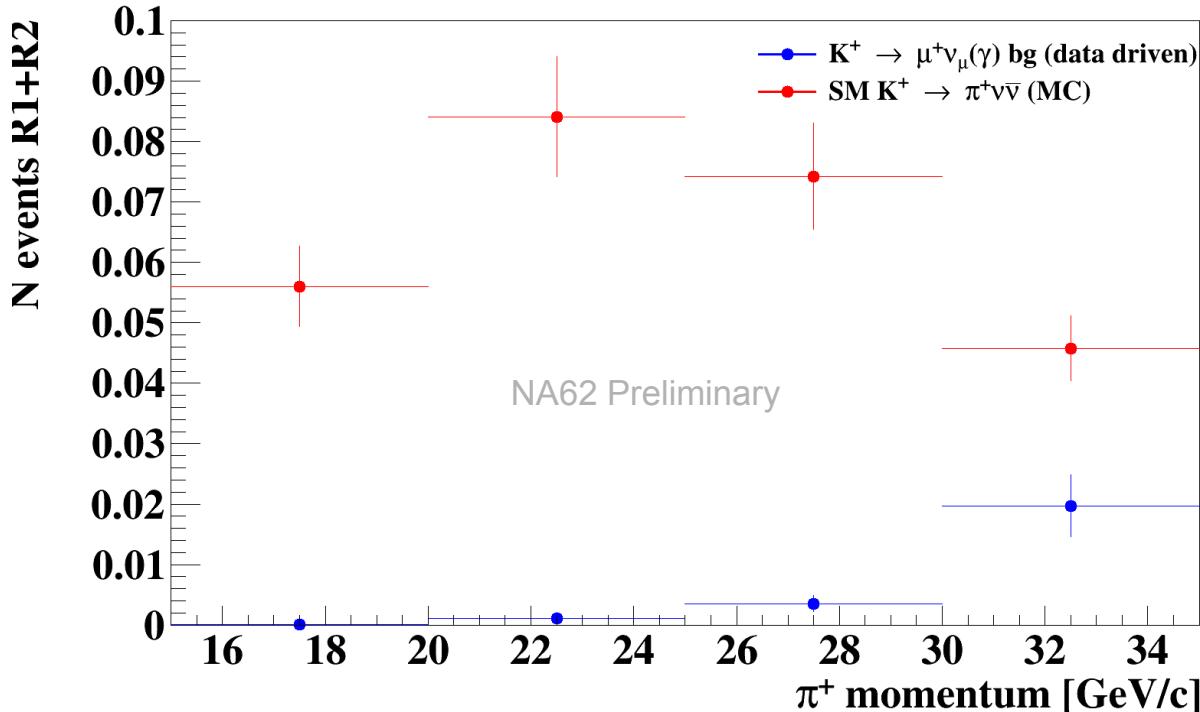
$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ background



$$N_{\mu\nu}^{\text{exp}}(\text{region}) = N(\mu^+ \nu) \cdot f^{\text{kin}}(\text{region})$$

- Kinematic rejection independent from particle identification
- $N(\mu^+ \nu)$: events (data) in $\mu^+ \nu$ region after $\pi^+ \nu \bar{\nu}$ selection
- f^{kin} : tails, from $\mu^+ \nu$ control sample selected on data with μ^+ – ID in calo
- $f^{\text{kin}}(R1) \sim 10^{-5}, 10^{-3} [15, 35] \text{ GeV}/c$
- $f^{\text{kin}}(R2) \sim \mathcal{O}(10^{-5})$
- Radiative included in f^{kin}

$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ background

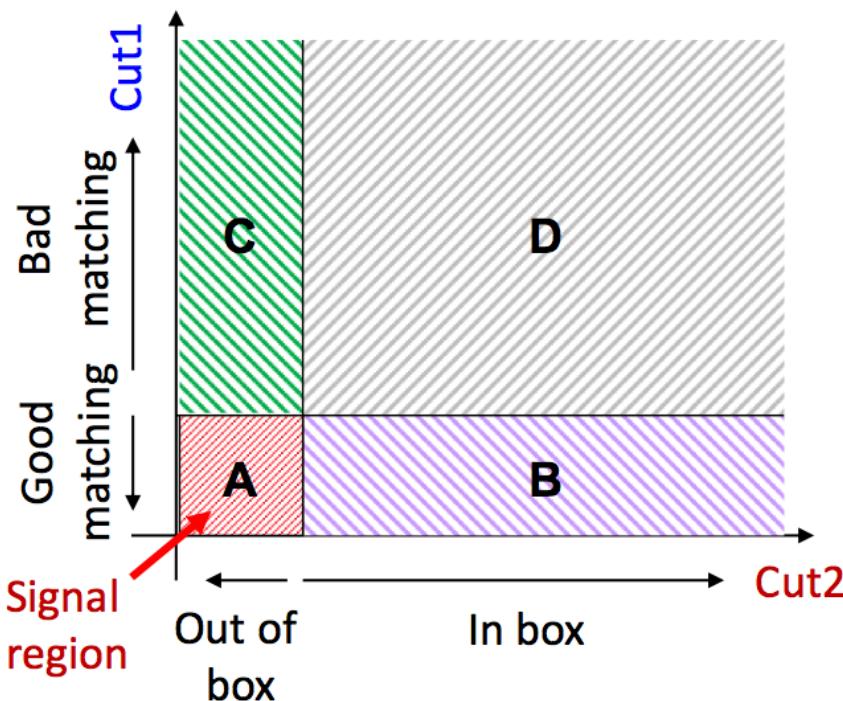


- Data driven background estimation
- Control region validation: 2 event observed (1.02 +/- 0.16 expected)

$$N_{\mu\nu(\gamma)}^{bg} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

Upstream Background: Estimation

- Bifurcation on PNN triggered data inverting: $K - \pi$ matching (Cut1); box cut (Cut2)
- BCD: reference sample, A: signal region
- Hypothesis Cut1 and Cut2 independent
- Procedure validated using different sets of values for Cut1 – Cut2



$$A(\text{exp}) = \frac{B \cdot C}{D}$$

↓

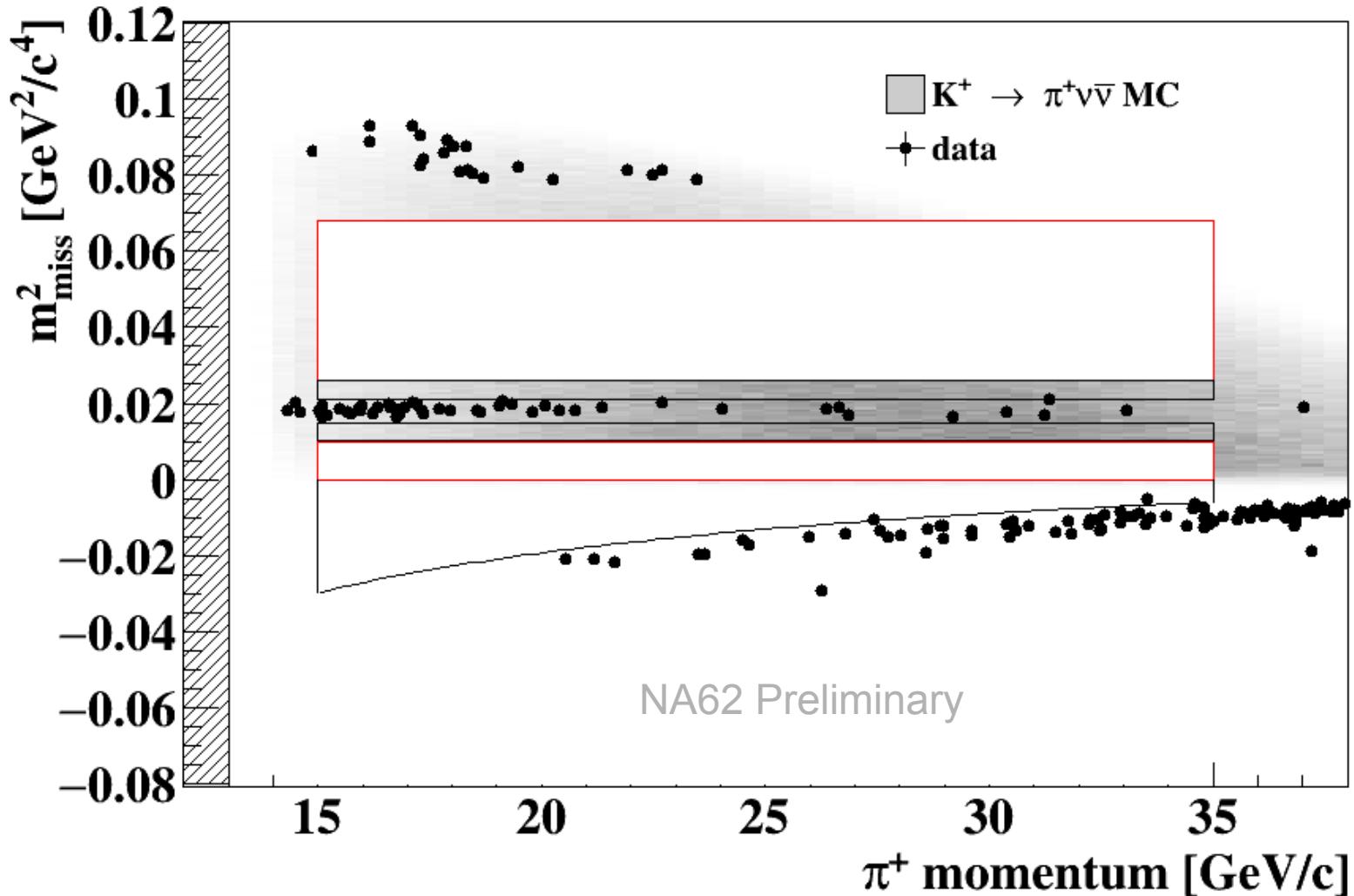
$$N_{\text{upstream}}^{\text{exp}} = 0.050^{+0.090}_{-0.030} |_{\text{stat}}$$

Background summary

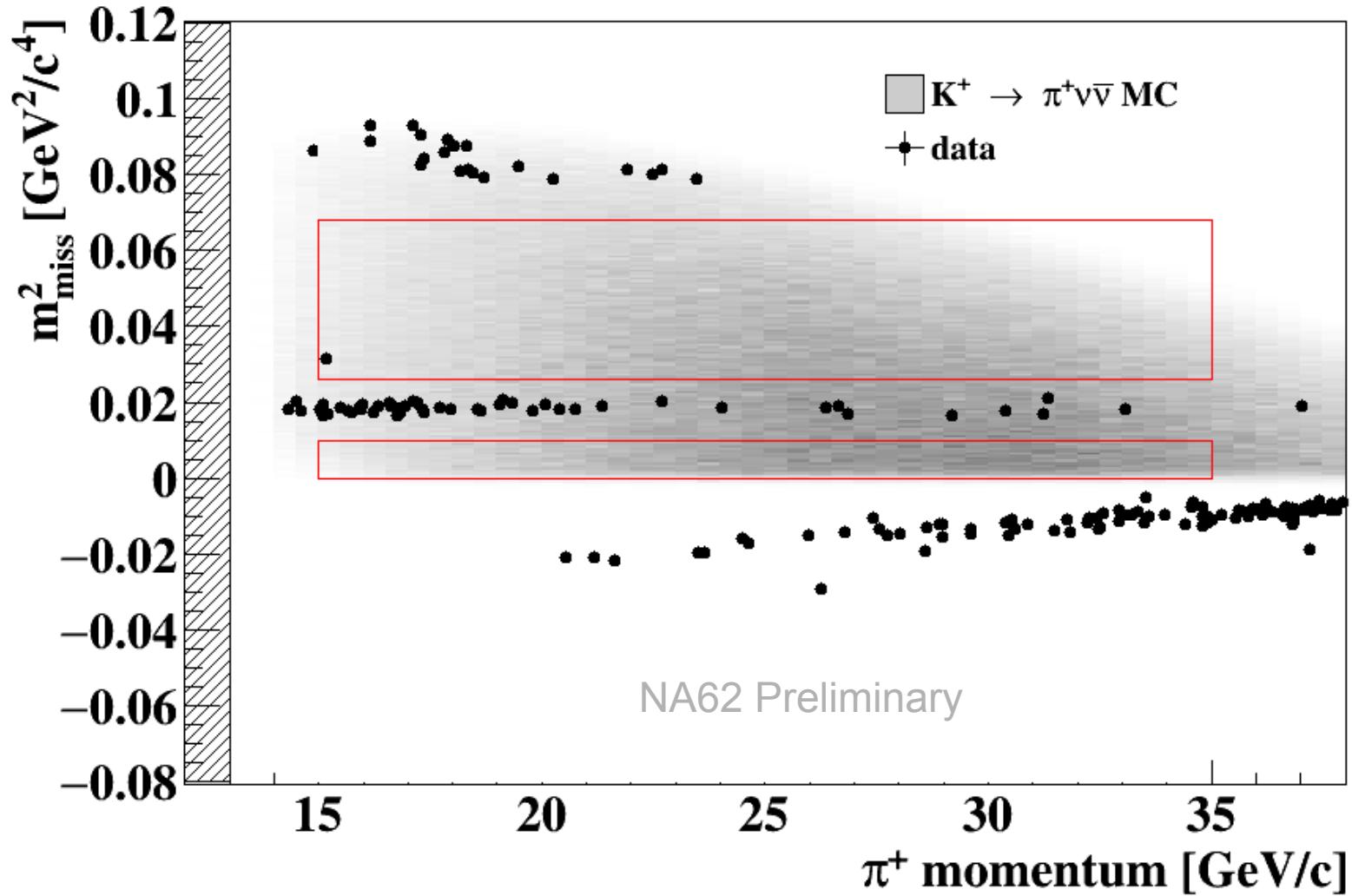


Process	Expected events in R1+R2
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \rightarrow \mu^+ \nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017} _{stat} \pm 0.009_{syst}$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030} _{stat}$

Results

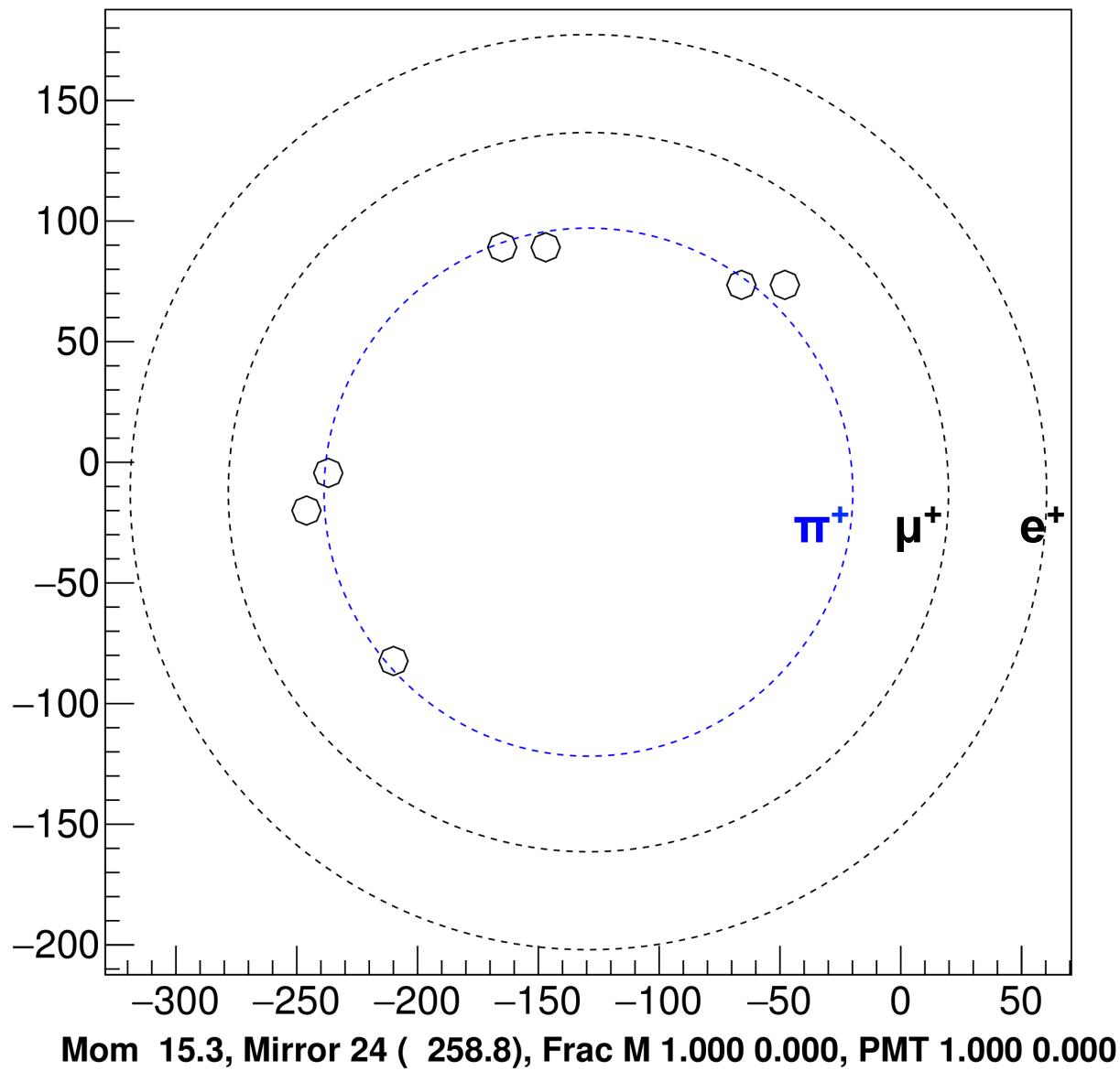


Results



One event observed

Results: RICH ring for the event



Results

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

- One event observed in Region 2
- Full exploitation of the CLs method in progress
- The results are compatible with the Standard Model
- For comparison: $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 28^{+44}_{-23} \times 10^{-11}$ @ 68% CL

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ (BNL, "kaon decays at rest")

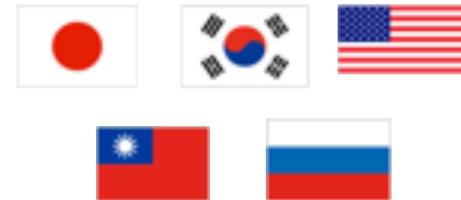
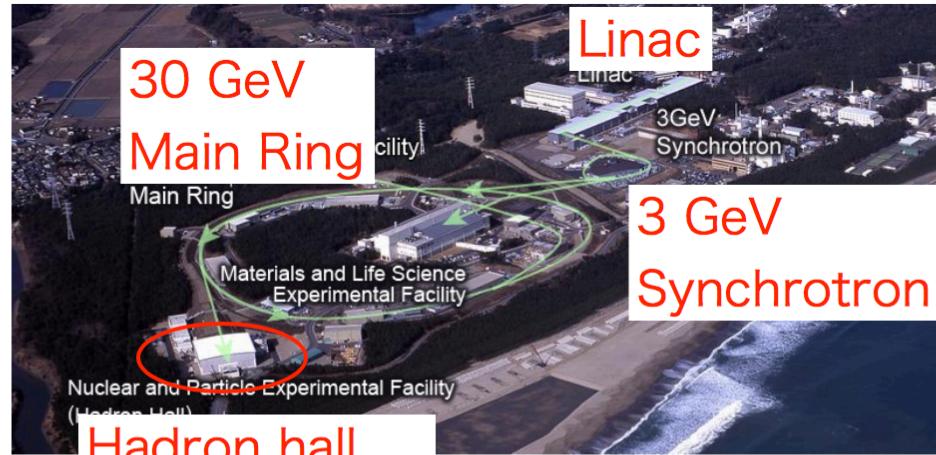
Bottom Line: the novel NA62 in-flight technique works

One event observed in 2016 data

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ @ 95\% CL}$$

- Processing of 2017 data ongoing
 - 20 more than the presented statistic
 - Upstream background reduction expected
 - Methods to improve signal efficiency under study
- 2018 data
 - Further mitigation of the upstream background is expected
 - Processing on parallel with data-taking: monitor of data quality
 - Final 2018 reprocessing expected by beginning 2019
- Expected about 20 SM events from the 2017+2018 data sample
 - Input to the European Strategy for Particle Physics
 - Solid extrapolation to the ultimate sensitivity of NA62 achievable after LS2

KOTO EXPERIMENT

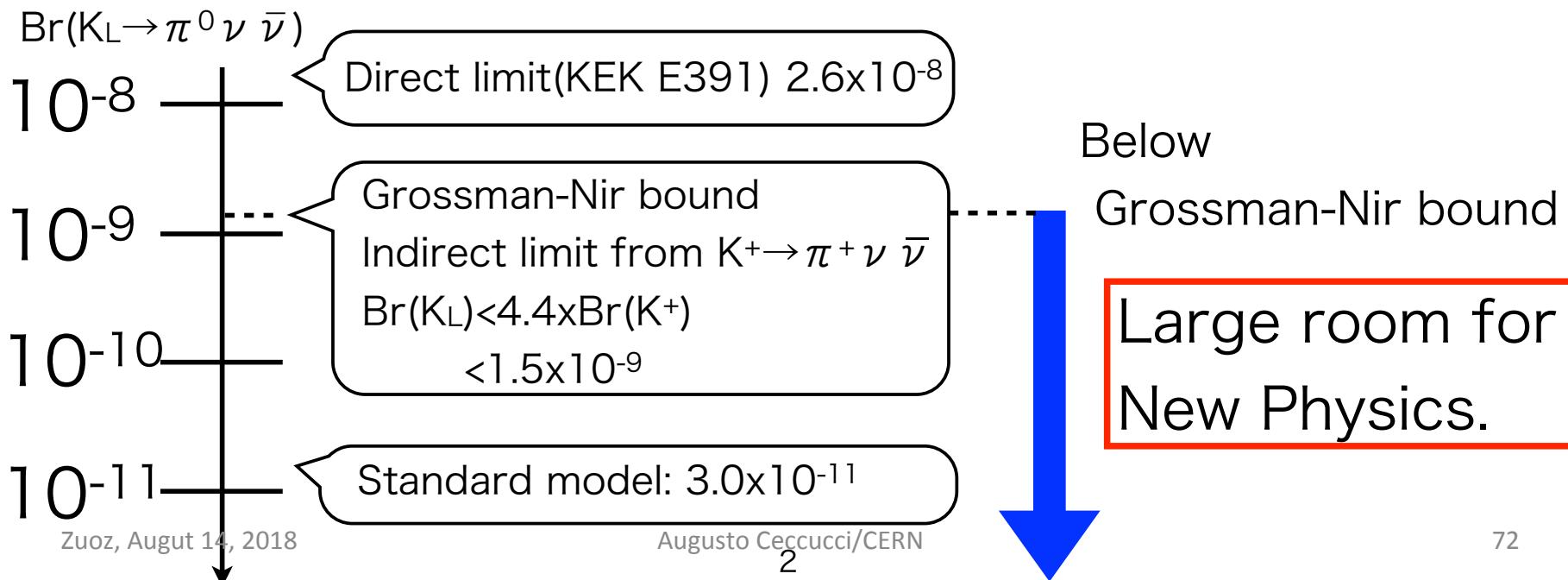


Collaboration photo
at J-PARC(June. 2018)

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

- Breaks CP symmetry directly
- Suppressed in the SM
- Small theoretical uncertainty: 2%

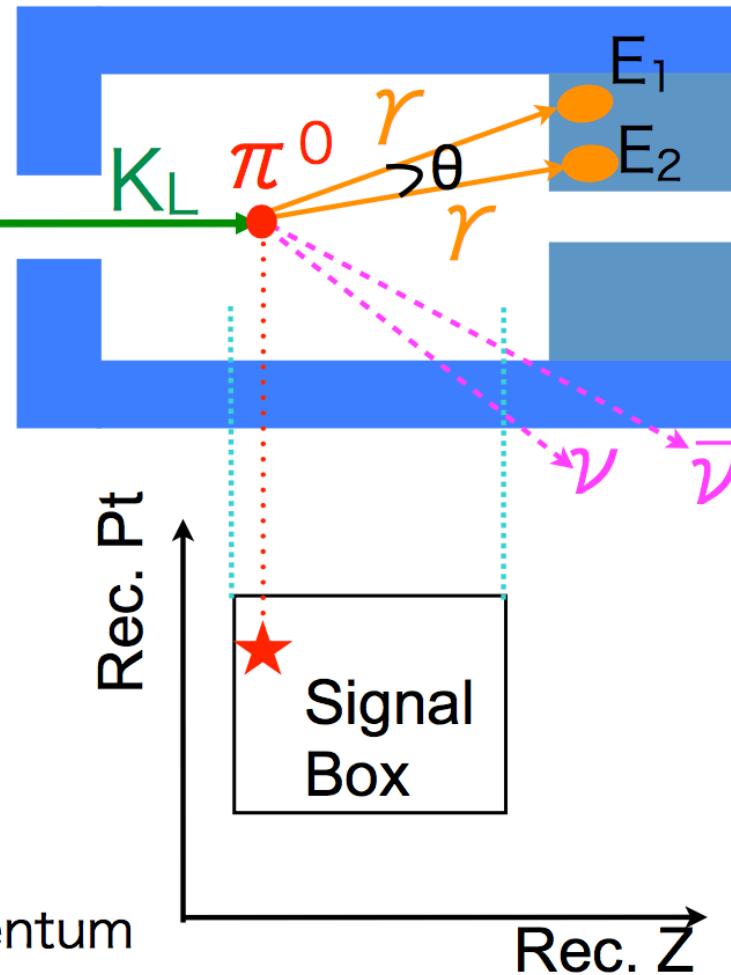
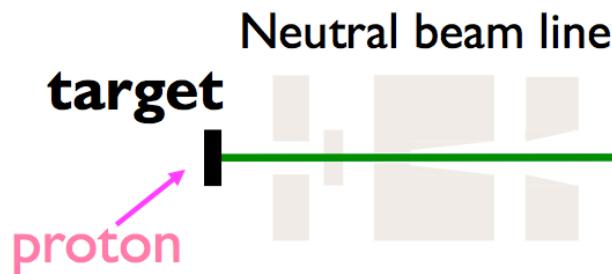
-> Sensitive to New Physics



KOTO Principle

K. Shiomi, ICHEP 2018

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay



“ $2\gamma + \text{Nothing} + \text{Pt}$ ”

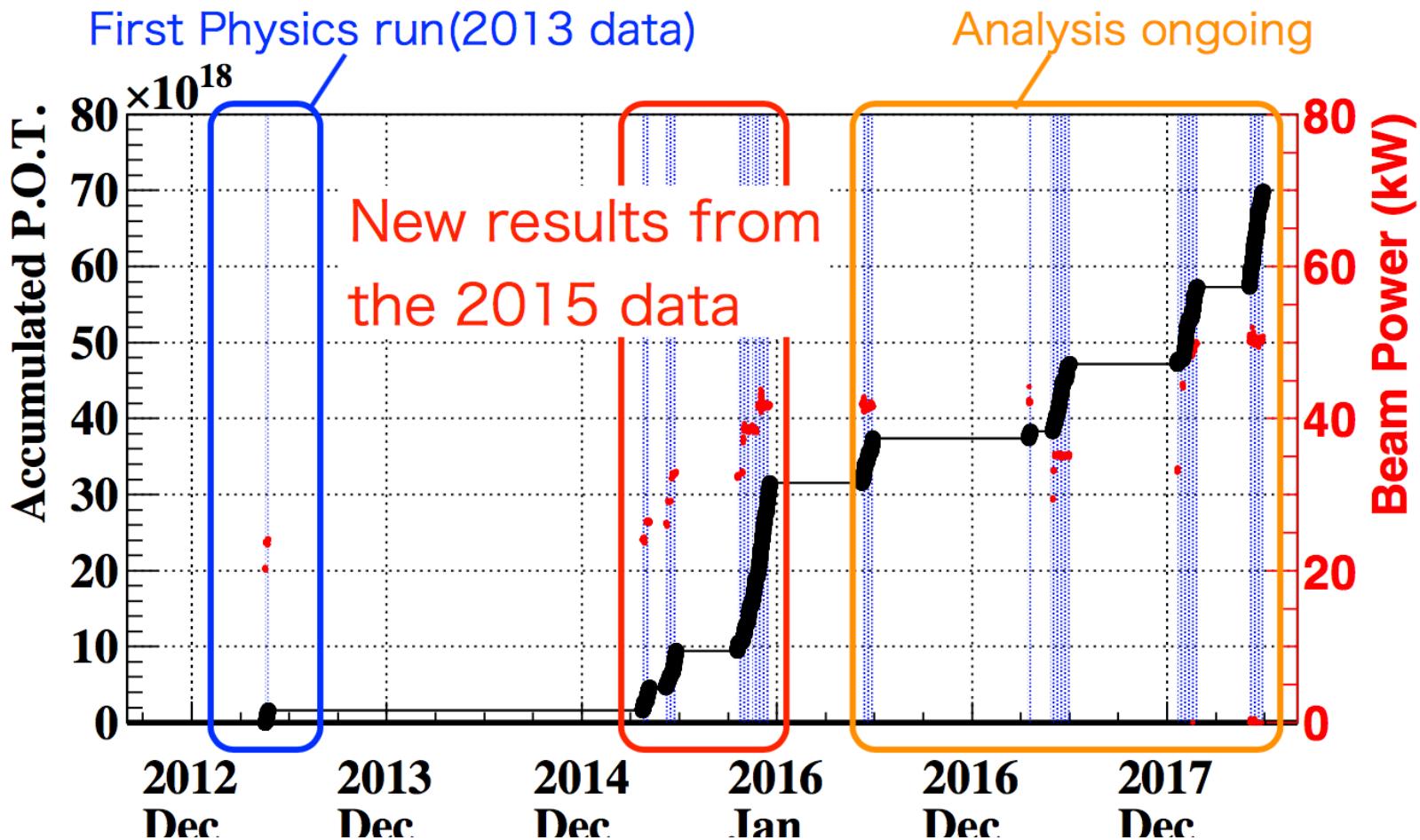
Assuming 2γ from π^0 ,

Calculate z vertex.

$$M^2(\pi^0) = 2E_1 E_2 (1 - \cos \theta)$$

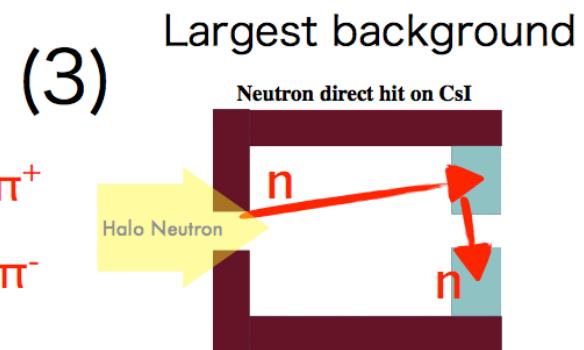
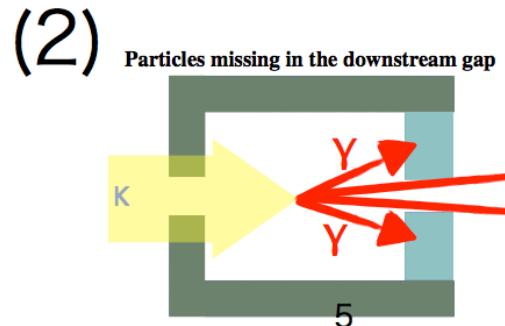
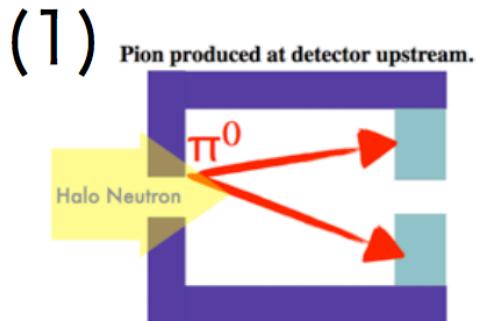
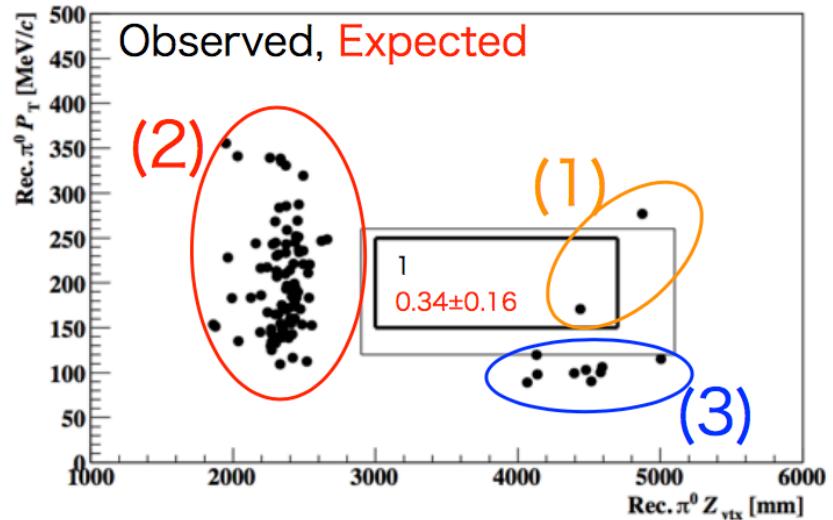
Calculate π^0 transverse momentum

KOTO DATA TAKING



Results of first physics run

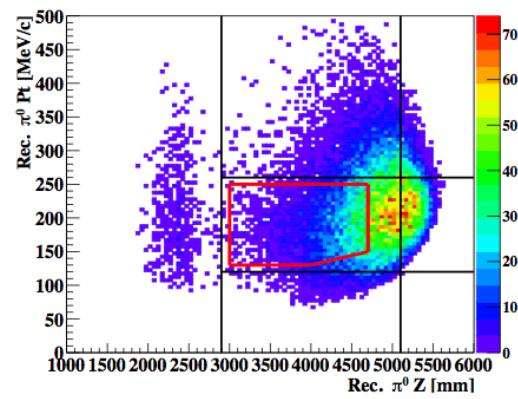
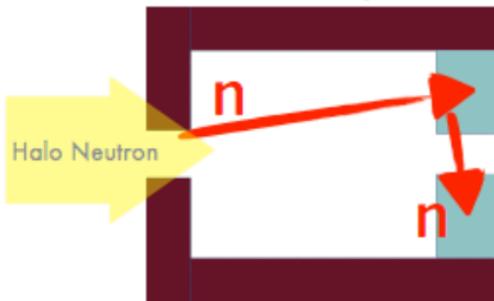
- 2013 100h data
(PTEP 2017 021C01)
- Observed/**Expected**=**1/0.34**
- $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8}$
(90% C.L.)



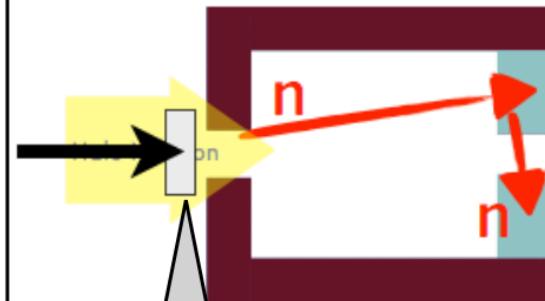
Halo neutron background

-Collected control samples to study of neutron clusters

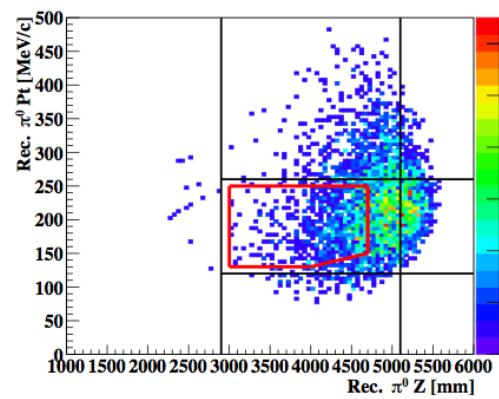
BG mechanism in physics run



Special run to take control sample

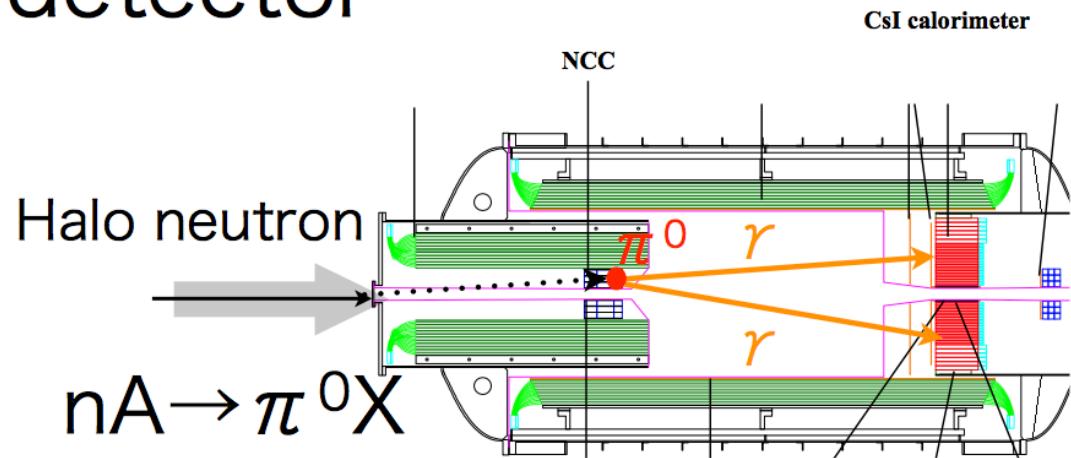


With 10mm Al plate inserted
in the neural beam

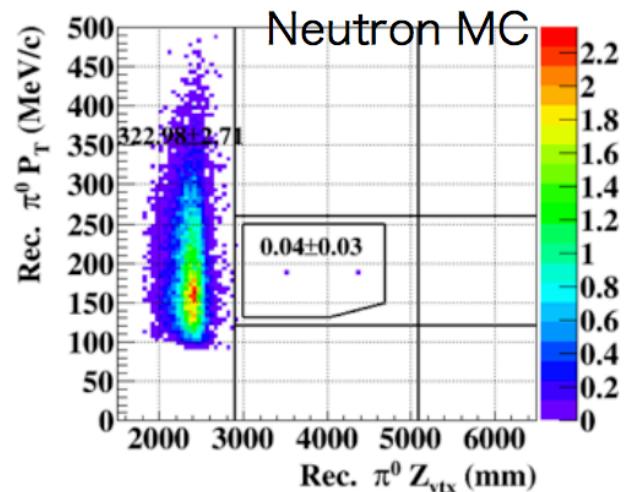


9

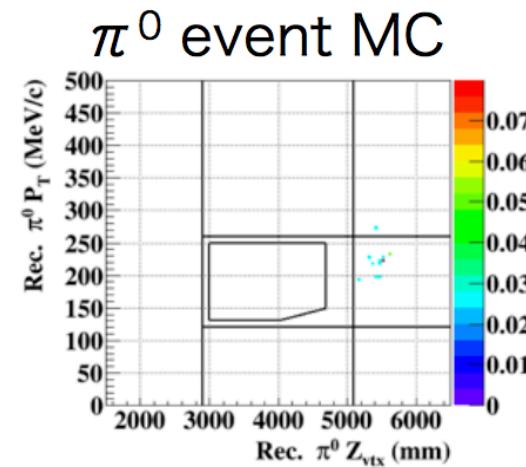
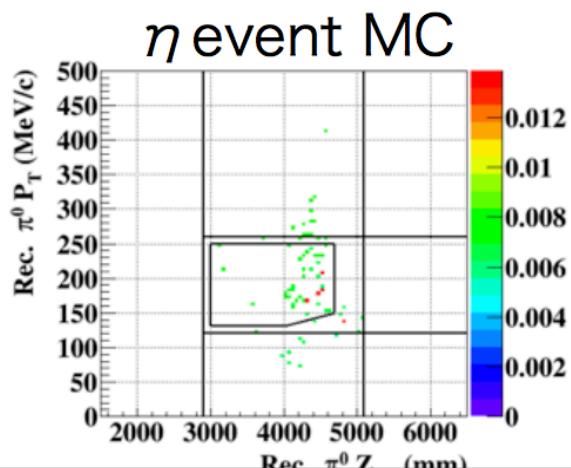
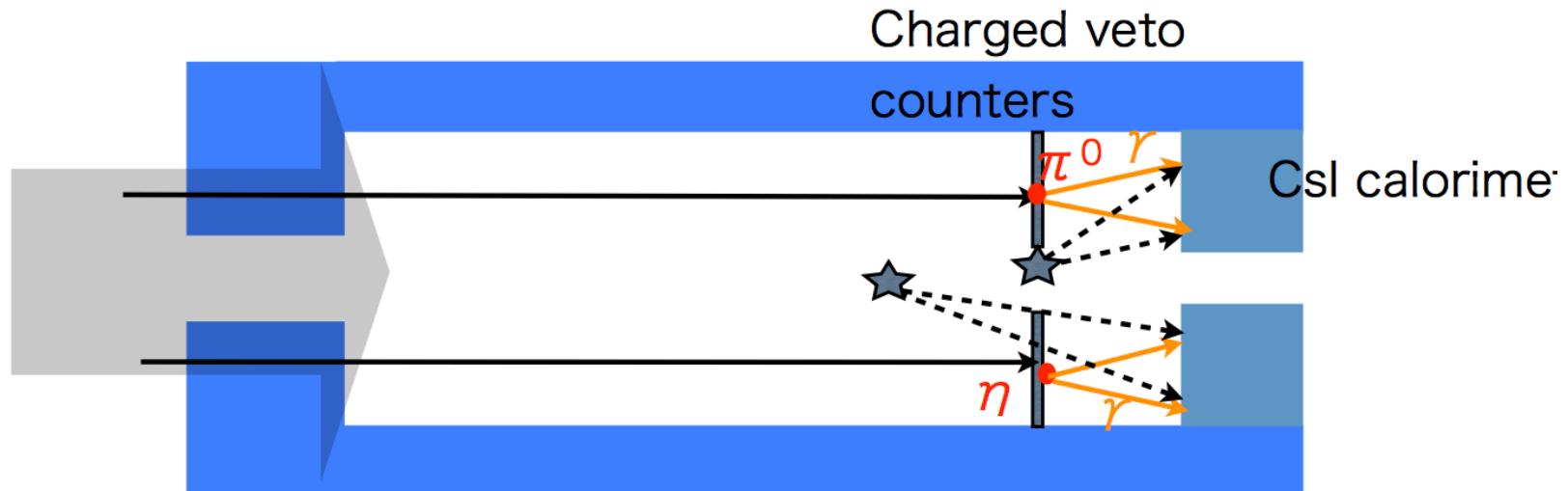
Halo neutron hitting upstream detector



- The number of upstream events expected in the signal box
 - 0.04 ± 0.03



Halo neutron hitting the materials near the CsI Calorimeter



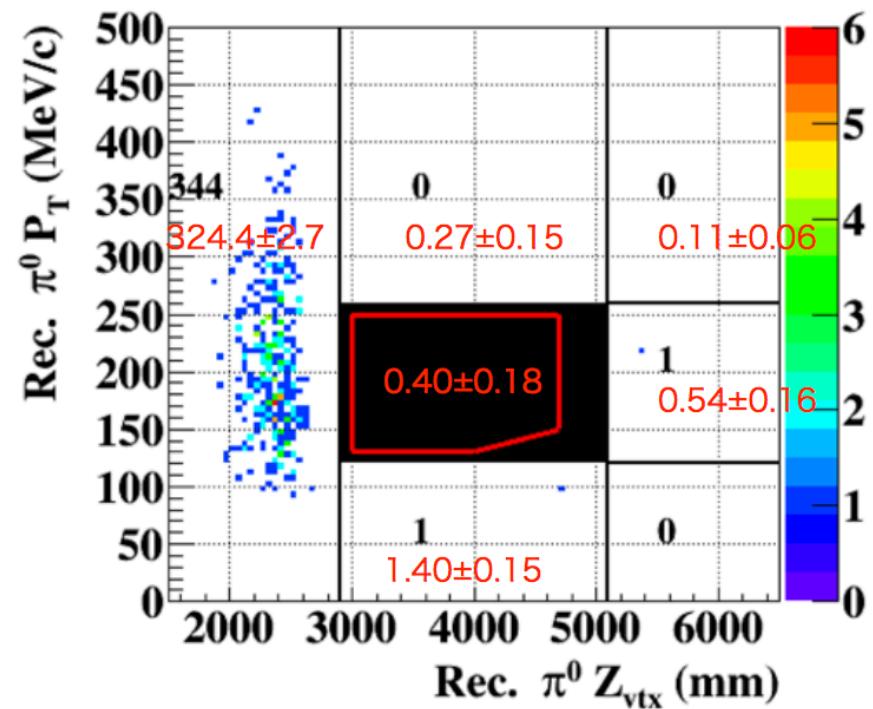
14

Preliminary

Results of 2015 analysis

Summary of background inside the signal box

background source	#BG
Halo neutron hitting CSI	0.24 ± 0.17
Halo neutron hitting upstream detectors	0.04 ± 0.03
η background	0.03 ± 0.02
$KL \rightarrow \pi^+ \pi^- \pi^0$	0.05 ± 0.02
$KL \rightarrow 2\pi^0$	0.02 ± 0.02
other BG sources	0.02 ± 0.02
Sum	0.40 ± 0.18



S.E.S: 1.3×10^{-9}

cf. Grossman-Nir bound $< 1.5 \times 10^{-9}$

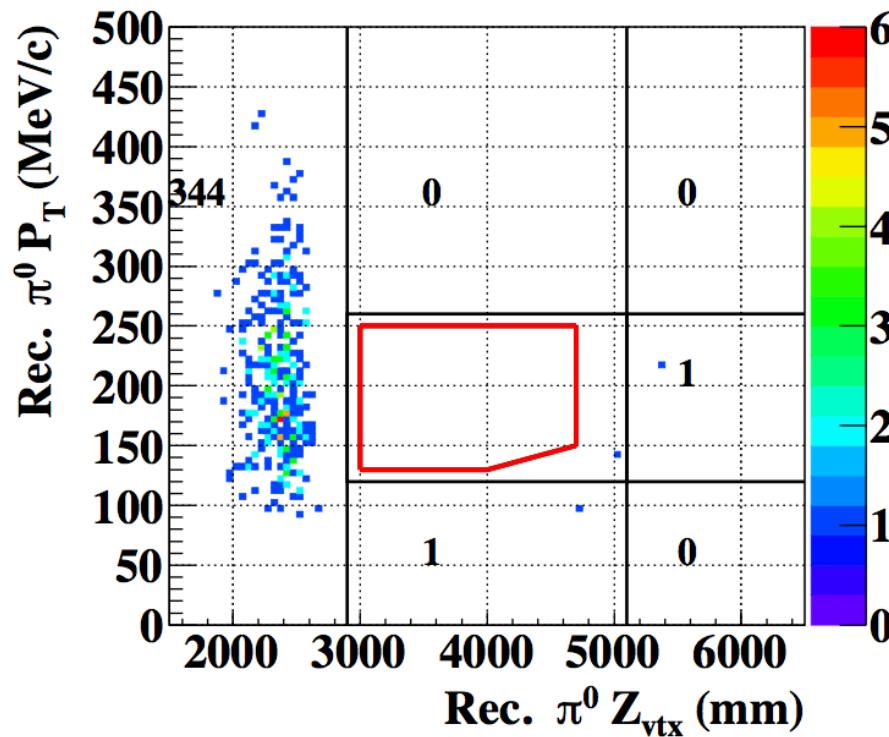
Open the signal box

- No signal candidate observed

Preliminary

- $\text{BR} < 3.0 \times 10^{-9}$ @90% C.L.

S.E.Sx 2.3
with Poisson statistics

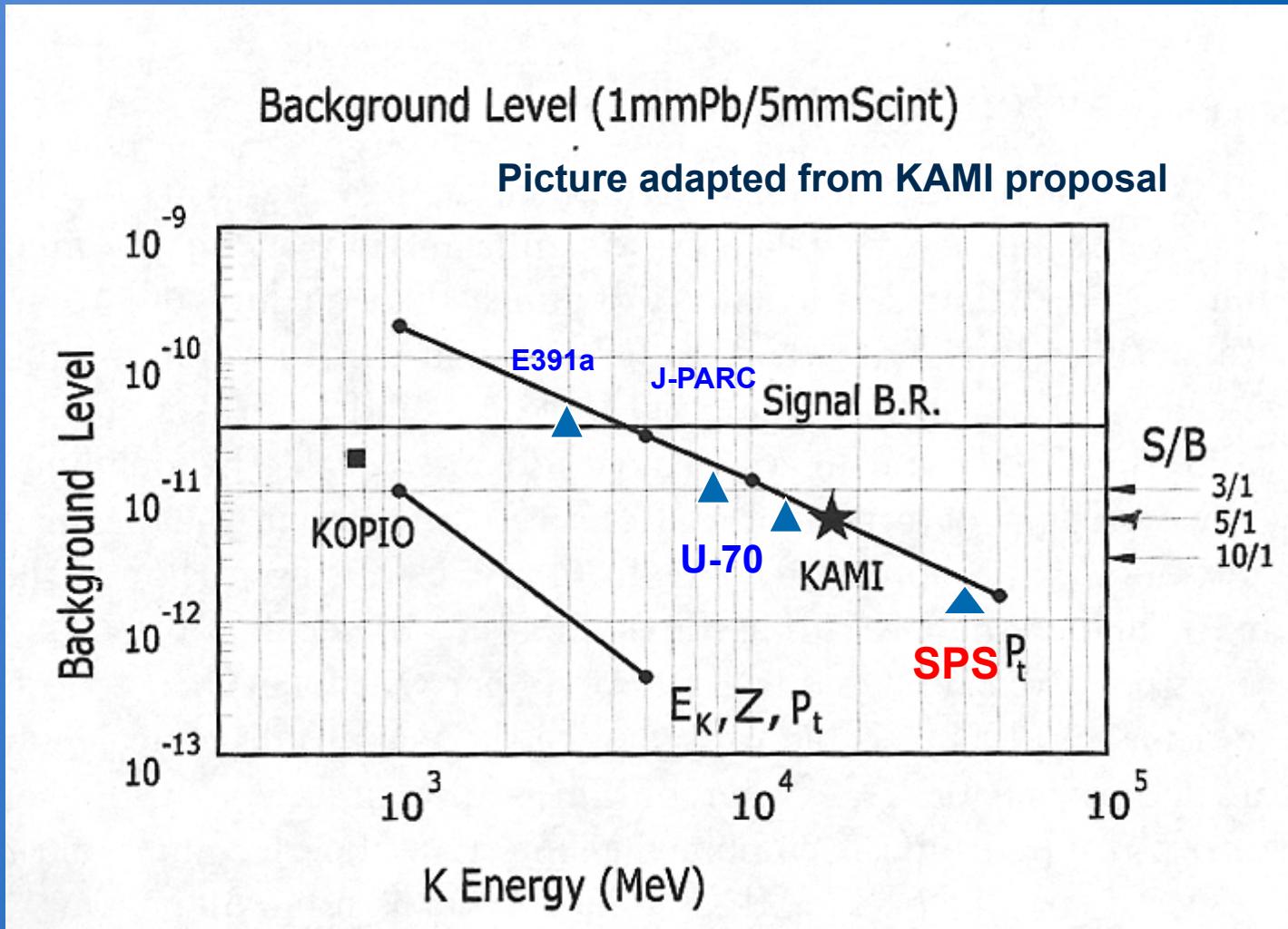


KOTO Prospect

- 2016-2018 data analysis is ongoing
- 1.5x (physics data), 10x (neutron data)
->With 2015-2018 data, we can reach S.E.S of 5×10^{-10}
- From this summer
 - We will upgrade detectors to suppress background.
 - Ex. Calorimeter upgrade against neutron BG.
 - We will improve analysis to recover acceptance
 - Beam power will increase from 50kW to 90kW gradually, after installing a new production target to the Hadron Hall in 2019.
->We aim to go below 10^{-10} in a timely manner

Talk Detector R&D 7/7 14:24 by Kotera
Poster D26 by Mari

$K_L \rightarrow \pi^0 \nu \bar{\nu}$: Comparison of Techniques



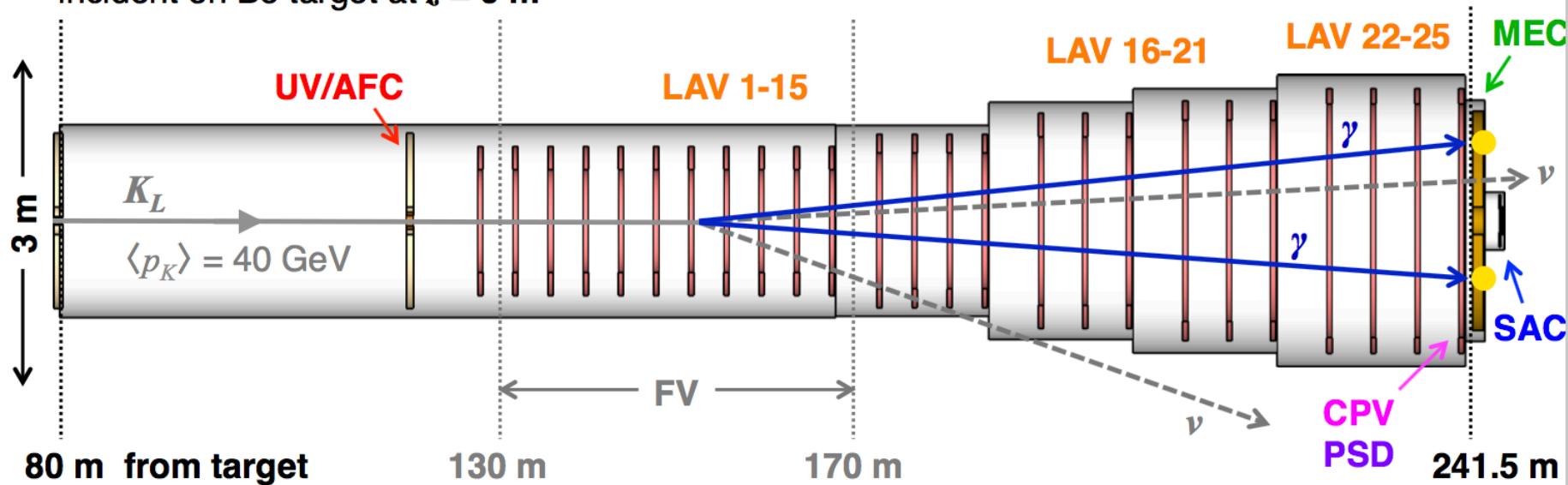
**KLEVER@SPS SES is unique if the E391a/KOTO technique is established
KOPIO (Time of Flight) technique at the needs 100 ps long proton bunches**

A $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment at the SPS

K_LEVER

400-GeV SPS proton beam (2×10^{13} pot/16.8 s)
incident on Be target at $z = 0$ m

M. Moulsson, ICHEP 2018



Main detector/veto systems:

K_LEVER target sensitivity:

5 years starting Run 4

60 SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$

$S/B \sim 1$

$\delta\text{BR}/\text{BR}(\pi^0 \nu \bar{\nu}) \sim 20\%$

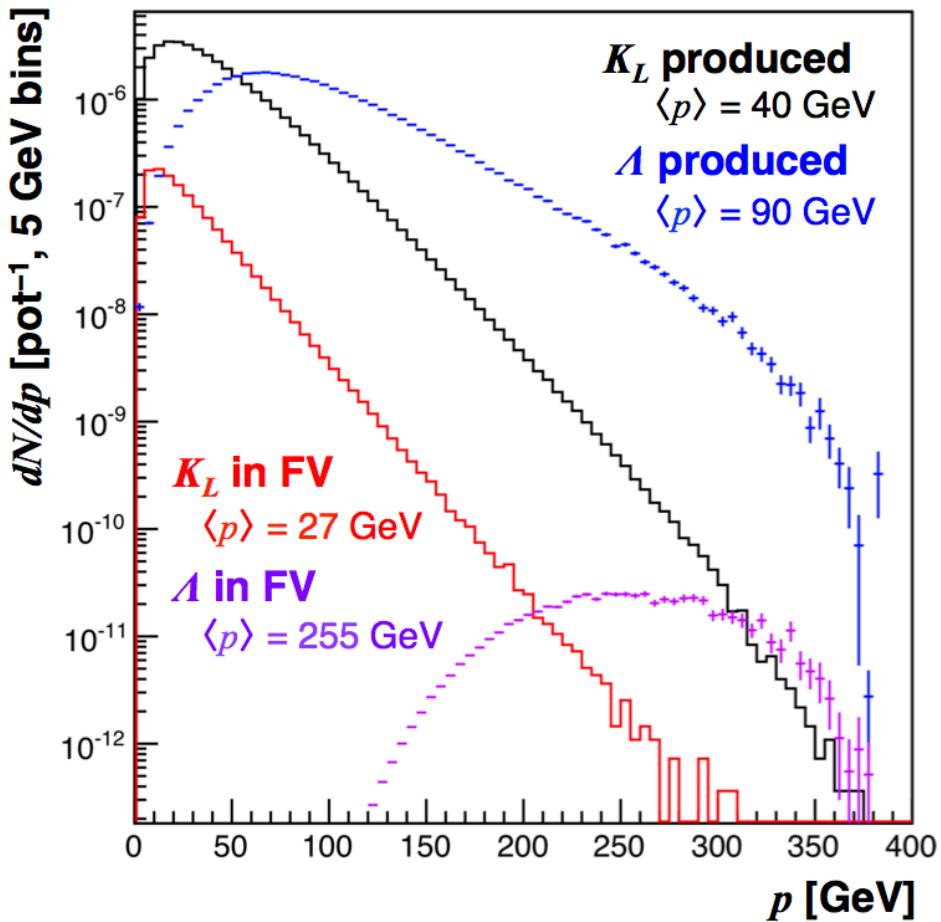
UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

Beam and intensity requirements

K_LEVER

K_L and Λ fluxes in beam

FLUKA simulation



10^{19} pot/year (= 100 eff. days)

E.g.: 2×10^{13} ppp/16.8 s

$\times 5$ years

Augusto Ceccucci/CERN

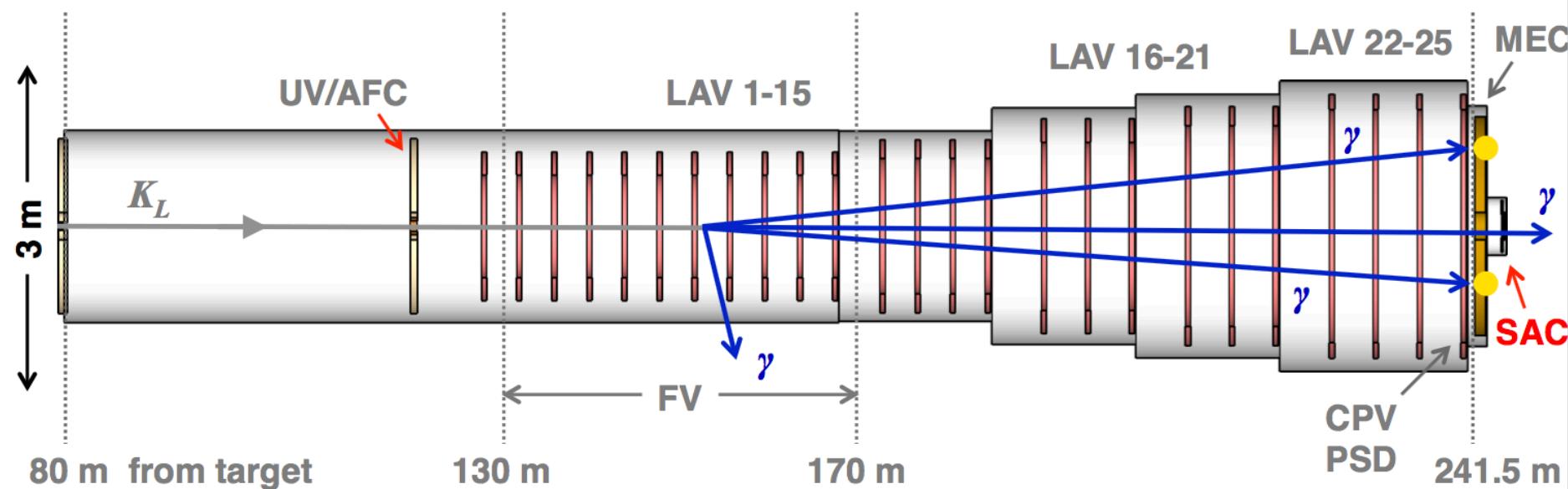
- 400 GeV p on 400 mm Be target
- Production at $\theta = 8.0$ mrad:
 - As much K_L production as possible
 - Low ratio of n/K_L in beam ~ 3
 - Reduce Λ production and soften momentum spectrum
- Solid angle $\Delta\theta = 0.4$ mrad
 - Large $\Delta\theta$ = high K_L flux
 - Maintain tight beam collimation to improves p_\perp constraint for background rejection
- $2.1 \times 10^{-5} K_L$ in beam/pot
- Probability for decay inside FV $\sim 2\%$
- Acceptance for $K_L \rightarrow \pi^0\nu\nu$ decays occurring in FV $\sim 10\%$



60 $K_L \rightarrow \pi^0\nu\nu$ events

Small-angle photon veto

K_LEVER



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γ s from $K_L \rightarrow \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. 1 – ε
$\gamma, E > 5 \text{ GeV}$	50	10^{-2}
$\gamma, E > 30 \text{ GeV}$	2.5	10^{-4}
n	430	–

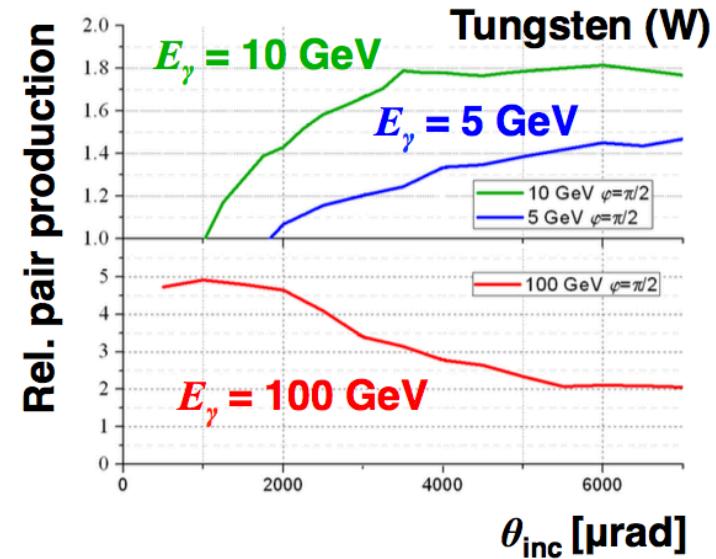
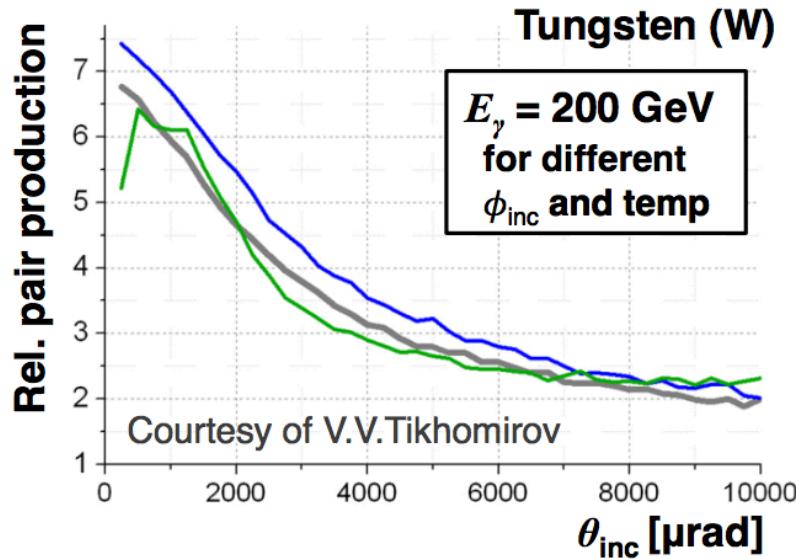
Baseline solution:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

Efficient γ conversion with crystals

KLEVER

Coherent effects in crystals enhance pair-conversion probability



Use coherent effects to obtain a converter with large effective λ_{int}/X_0 :

1. Beam photon converter in dump collimator

Effective at converting beam γ s while relatively transparent to K_L

2. Absorber material for small-angle calorimeter (SAC)

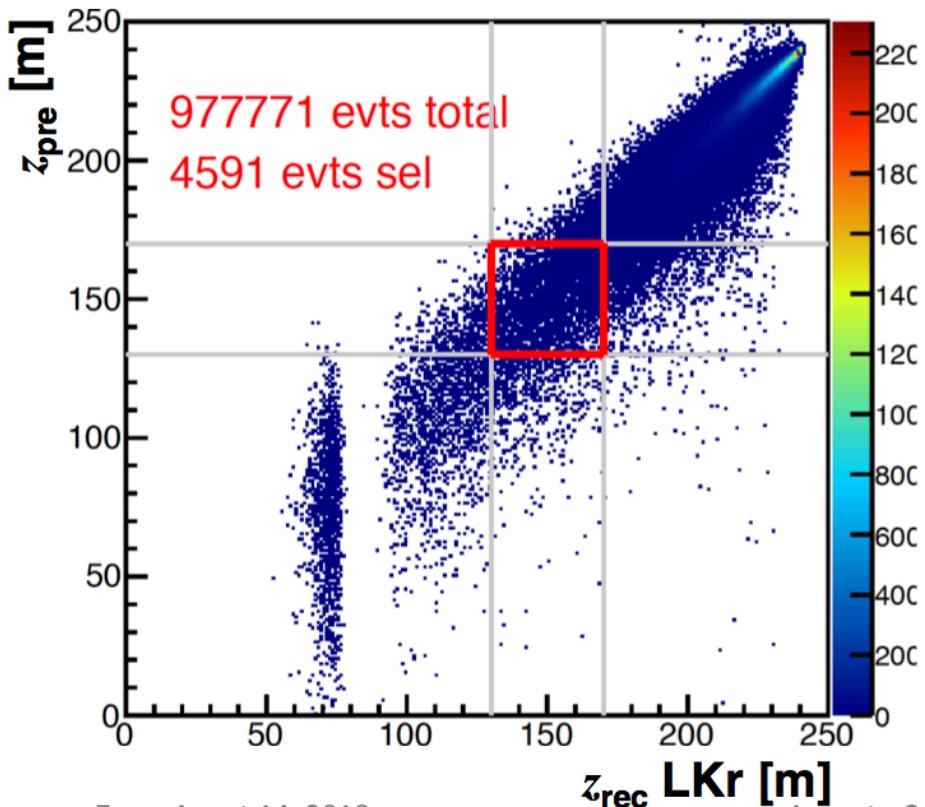
Must be insensitive as possible to high flux of beam neutrons while efficiently vetoing high-energy γ s from K_L decays

Preshower background rejection

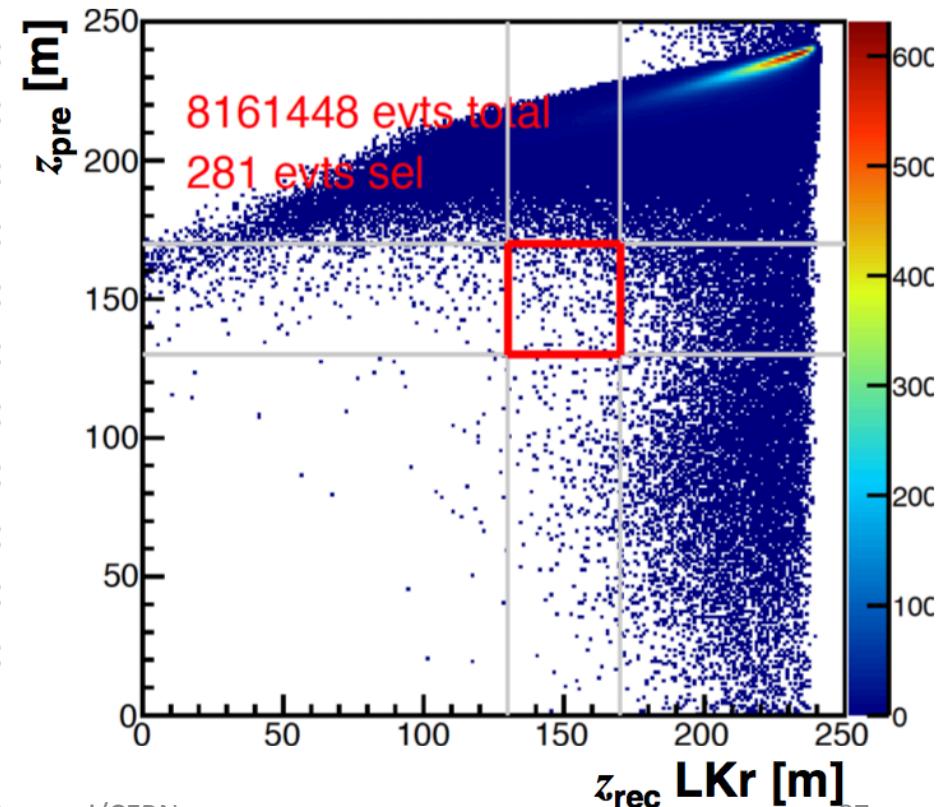
Preshower vertex z_{pre} vs. LKr vertex z_{rec}
 z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi^0}$

- $K_L \rightarrow \pi^0\pi^0$, 1 year equivalent
- No cuts on FV, p_\perp , r_{\min}

Even pairs (2 γ from same π^0)
1 γ converts in preshower



Odd pairs (2 γ s from different π^0)
1 γ converts in preshower

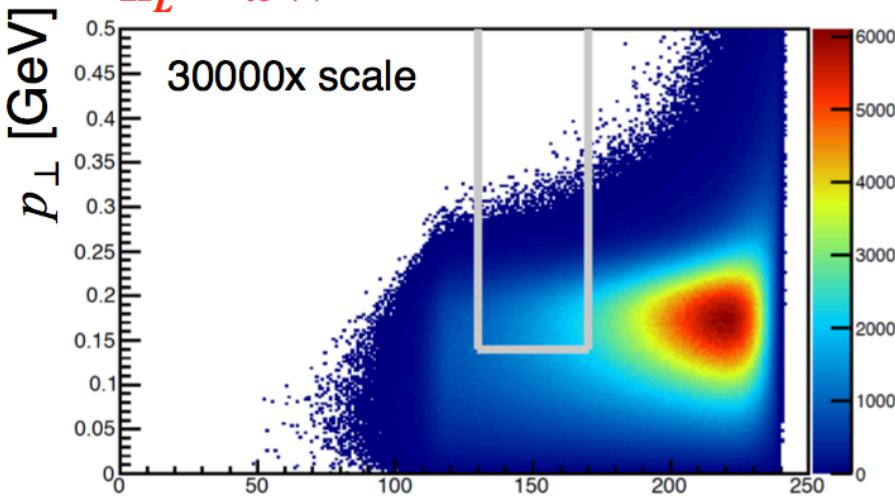


Basic signal selection

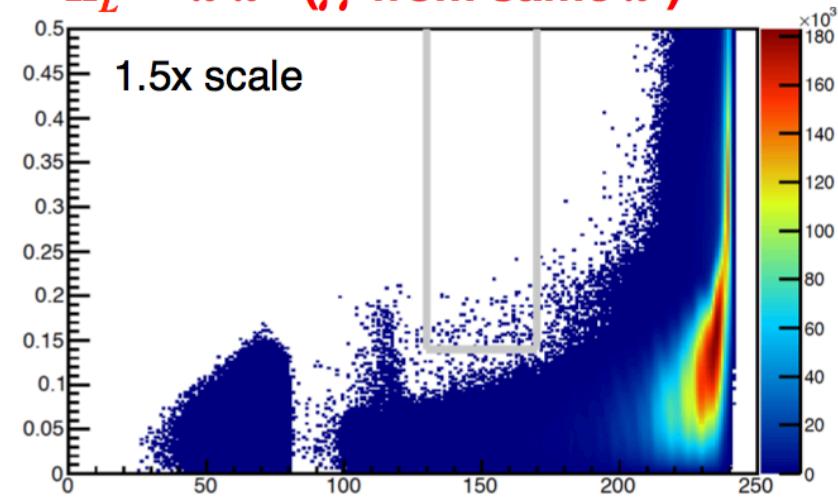
KLEVER

No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and p_{\perp} cuts

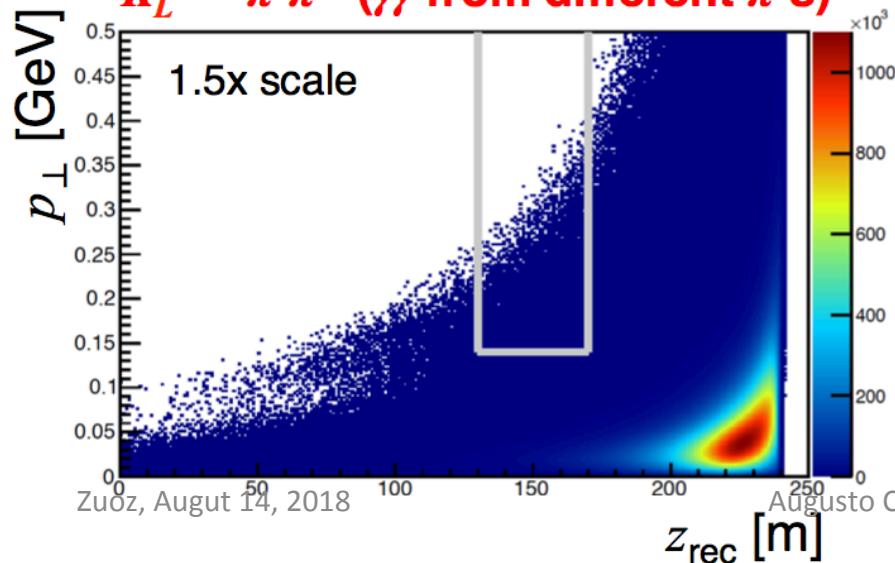
$K_L \rightarrow \pi^0 \nu \bar{\nu}$



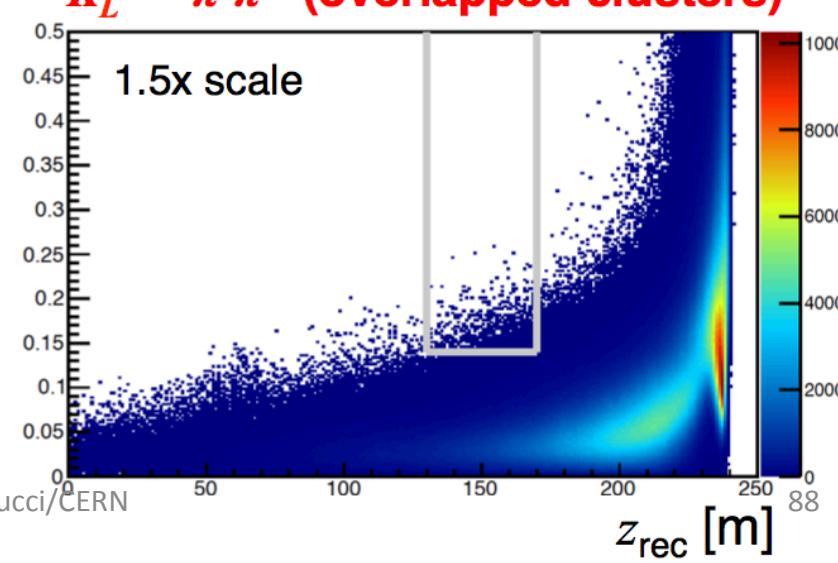
$K_L \rightarrow \pi^0 \pi^0$ ($\gamma\gamma$ from same π^0)



$K_L \rightarrow \pi^0 \pi^0$ ($\gamma\gamma$ from different π^0 s)



$K_L \rightarrow \pi^0 \pi^0$ (overlapped clusters)

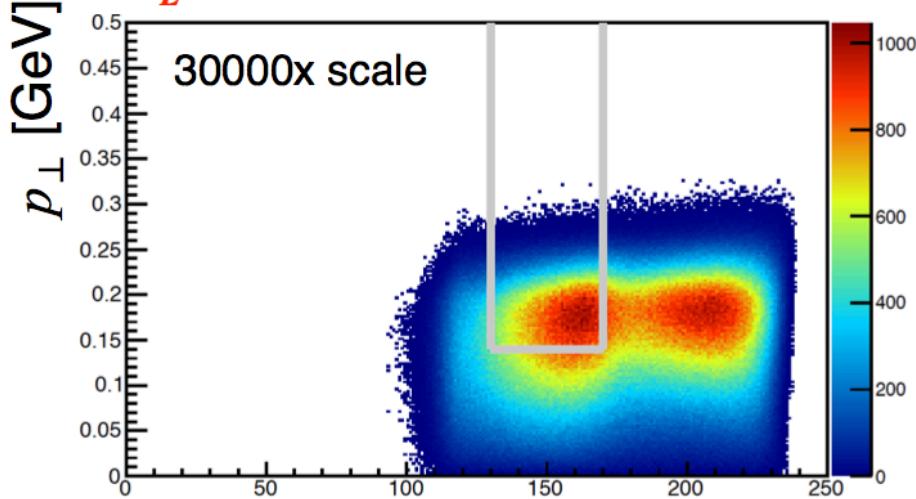


Additional background rejection

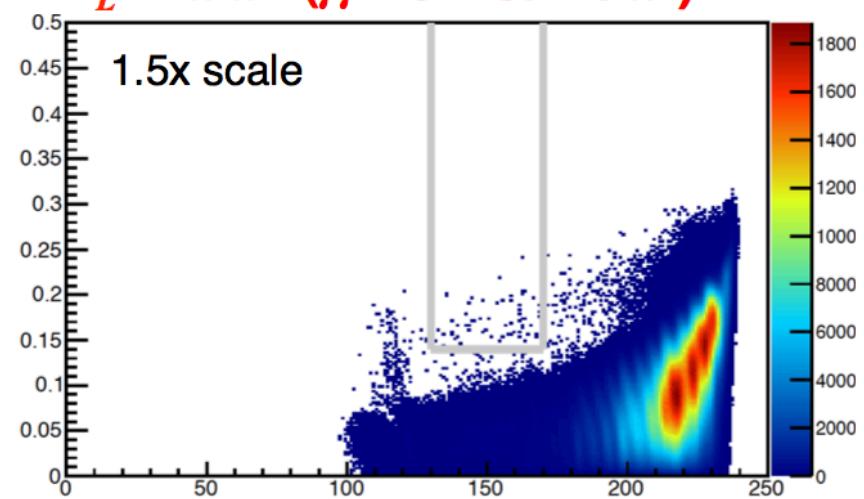
K_LEVER

Cluster radius $r_{\text{MEC}} > 35 \text{ cm}$ – Require z_{PSD} in FV if PSD hit available

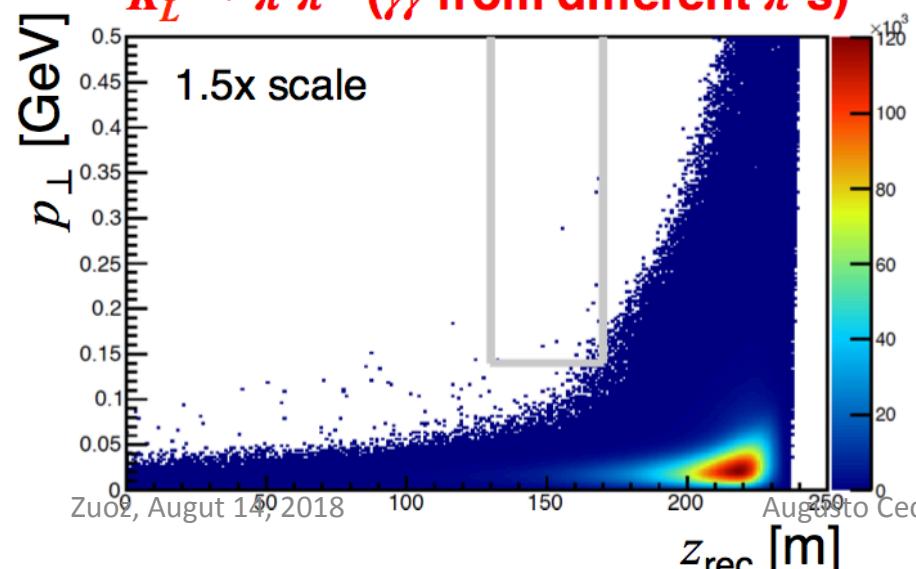
$K_L \rightarrow \pi^0 \nu \bar{\nu}$



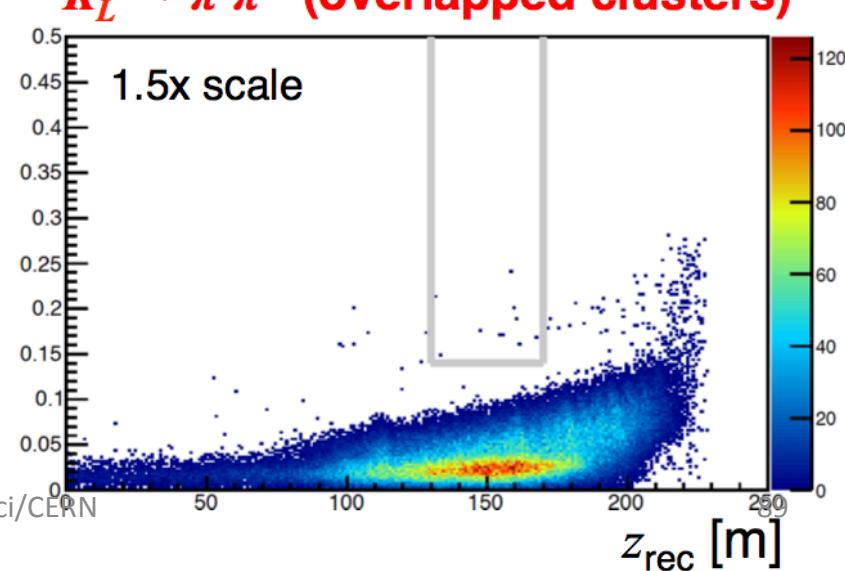
$K_L \rightarrow \pi^0 \pi^0$ ($\gamma\gamma$ from same π^0)



$K_L \rightarrow \pi^0 \pi^0$ ($\gamma\gamma$ from different π^0 's)



$K_L \rightarrow \pi^0 \pi^0$ (overlapped clusters)



Status and timeline

Project timeline – target dates:

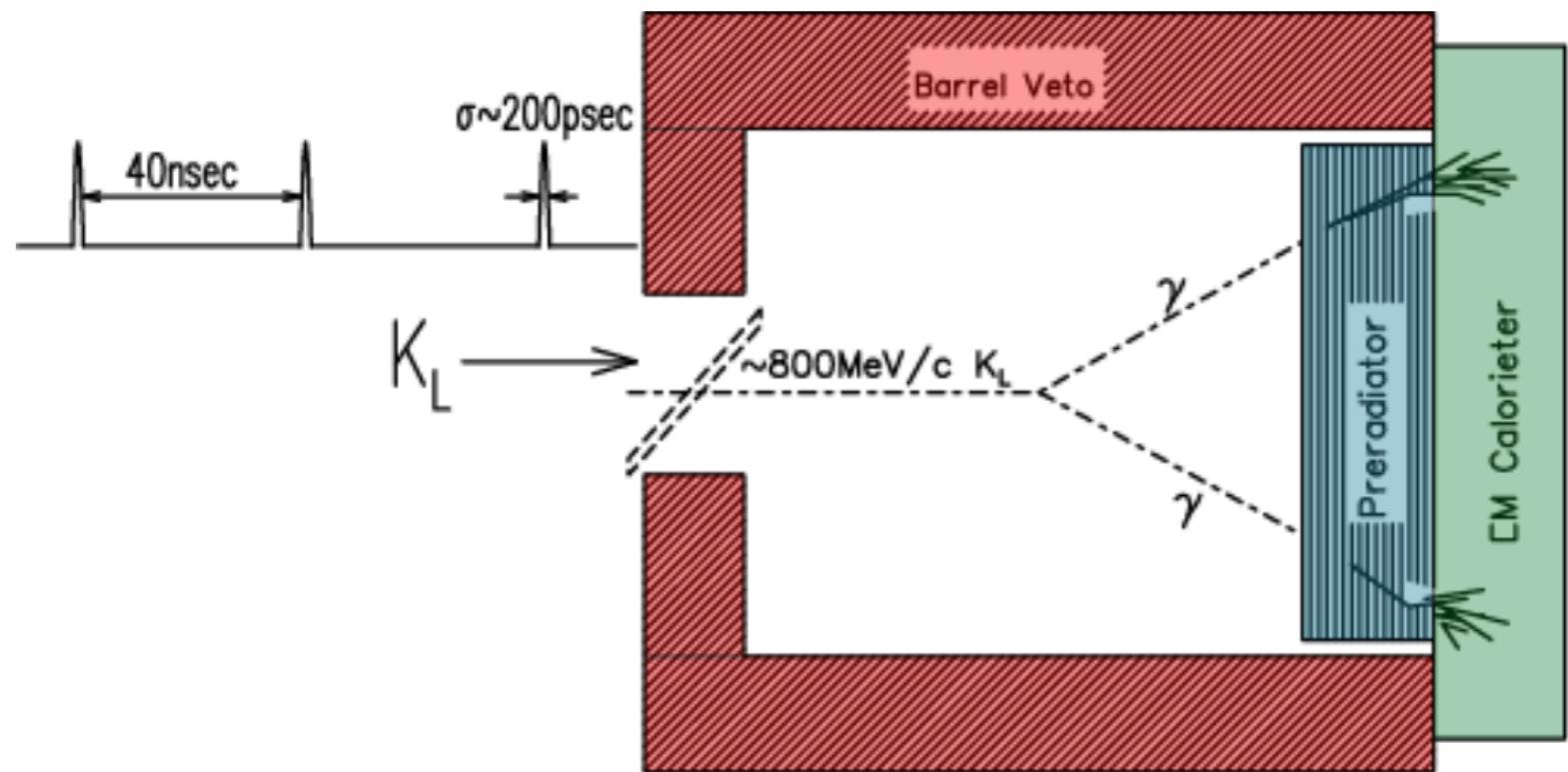
2017-2018	Project consolidation and proposal <ul style="list-style-type: none">• Participation in Physics Beyond Colliders• Beam test of crystal pair enhancement• Input to European Strategy for Particle Physics• Expression of Interest to CERN SPSC
2019-2021	Detector R&D
2021-2025	Detector construction <ul style="list-style-type: none">• Possible K12 beam test if compatible with NA62
2024-2026	Installation during LS3
2026-	Data taking beginning Run 4

Most groups participating in NA62 have expressed interest in KLEVER
We are actively seeking new collaborators!

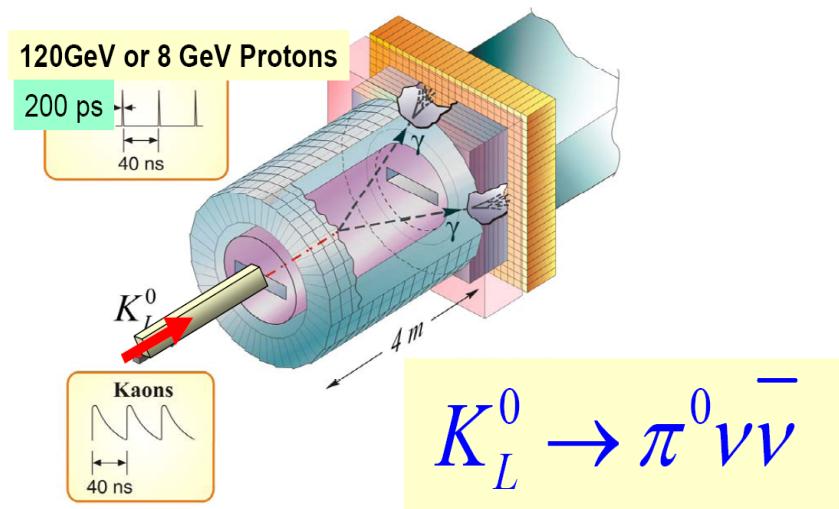
Other techniques for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- The techniques of KOTO and KLEVER are a bit “brute force” because there are no additional constraint (the momentum of the K_L is unknown)
- PHI Factory: $e^+e^- \rightarrow \phi \rightarrow K_S K_L$
Advantage: Monochromatic K_L , large acceptance
Negative: small cross section, luminosity is way too low at $\sqrt{s} \sim 1.02$ GeV
- “KOPIO”

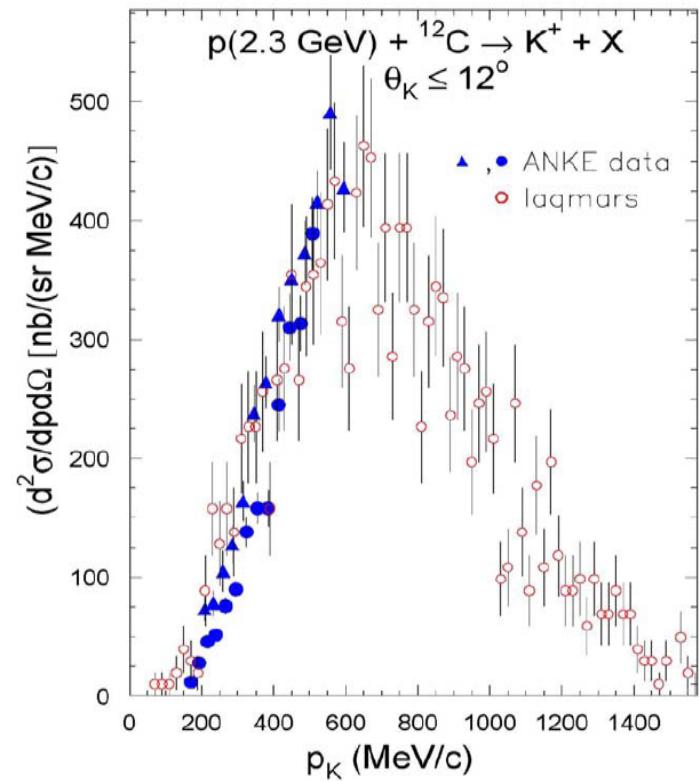
KOPIO Concept



KOPIO Concept



- KOPIO-like: TOF to determine Kaon Energy
- Knowledge of E_K allows rejection of two body decays
- Pointing Calorimeter
- 4π veto for neutral and charged particles
- Small Beam instead of flat beam



- Ideal for a CW p LINAC ~3 GeV
- Excellent bunch timing
- High flux of low energy K_L^0

Outlook

- Still waiting for lattice QCD calculation for ε'/ε
- Precision on unitarity tests involving kaons approaching 0.1%, contribution due to V_{ud} no longer negligible, nice interplay of lattice QCD and experiments
- On the kaon rare decay side:
 - LHCb is competitive for rare decays with $\mu\mu$ in the final state
 - NA62 is taking data and aims to make a $\text{Br}(K^+ \rightarrow \pi^+ \nu\nu)$ measurement at the level of 10% to bridge the large gap existing between theory and experiment
 - KOTO aims to steadily improve the limits on $\text{Br}(K_L \rightarrow \pi^0 \nu\nu)$
 - There are plans to propose to measure $\text{Br}(K_L \rightarrow \pi^0 \nu\nu)$ at the SPS (KLEVER)
 - The nice KOPIO concept is currently not pursued

Lepton Universality, Flavour and Number Violation in K decays

NA62 sensitivity for LFNV decays



Decays in FV in
2 years of data $\left\{ \begin{array}{l} 1 \times 10^{13} K^+ \text{ decays} \\ 2 \times 10^{12} \pi^0 \text{ decays} \end{array} \right.$ Single-event sensitivity
1/(decays × acceptance)

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \rightarrow \pi^+ \mu^+ e^-$	1.3×10^{-11}	BNL 777/865	$\sim 10\%$
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	BNL 865	
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	BNL 865	$\sim 10\%$
$K^+ \rightarrow \pi^- e^+ e^+$	6.4×10^{-10}	BNL 865	$\sim 5\%$
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	1.1×10^{-9}	NA48/2	$\sim 20\%$
$K^+ \rightarrow \mu^- \nu e^+ e^+$	2.0×10^{-8}	Geneva Saclay	$\sim 2\%$
$K^+ \rightarrow e^- \nu \mu^+ \mu^+$	no data		$\sim 10\%$
$\pi^0 \rightarrow \mu^+ e^-$	3.6×10^{-10}	KTeV	$\sim 2\%$
$\pi^0 \rightarrow \mu^- e^+$			

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

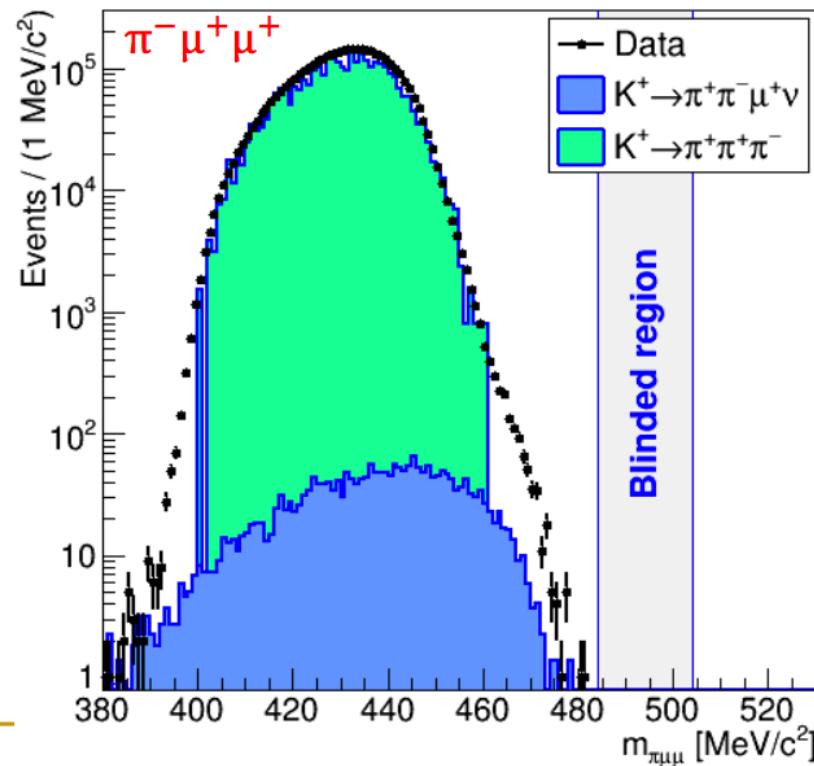
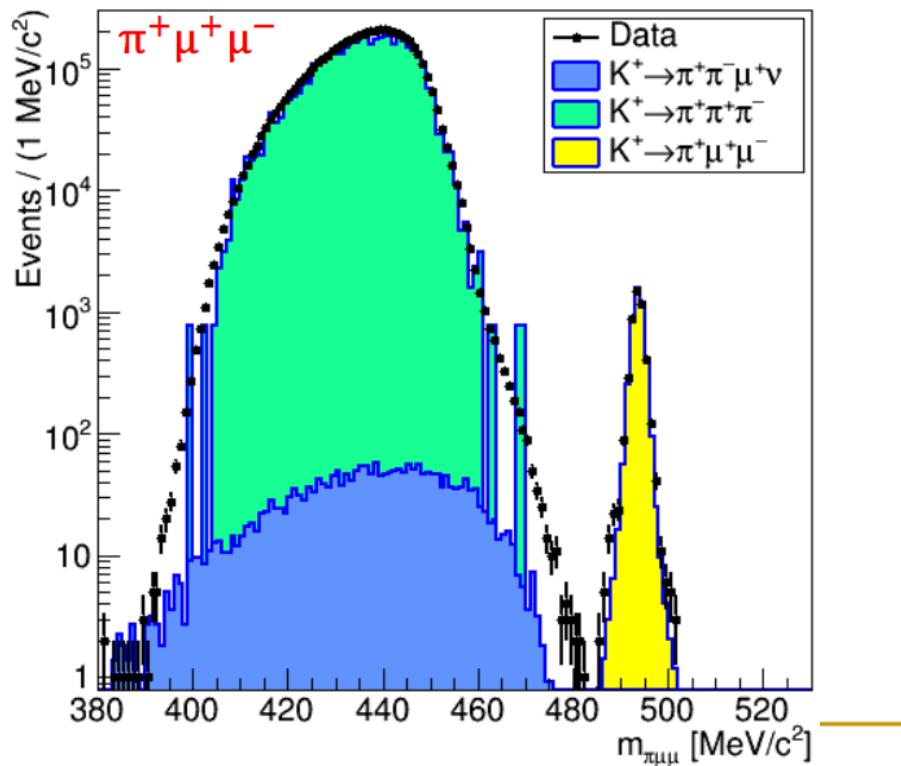
NA62 single-event sensitivities:

$\sim 10^{-12}$ for K^+ decays
 $\sim 10^{-11}$ for π^0 decays

Rare and Forbidden Decays: $K \rightarrow \pi \mu \mu$

50% 2016 + 25% 2017 Data: $N_K = 6.3 \times 10^{11}$

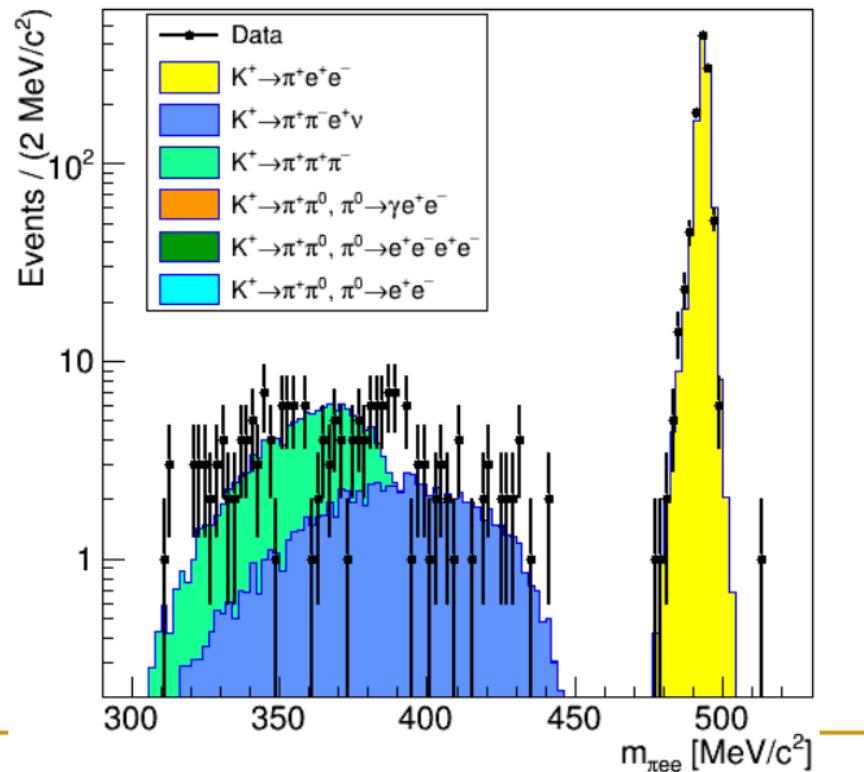
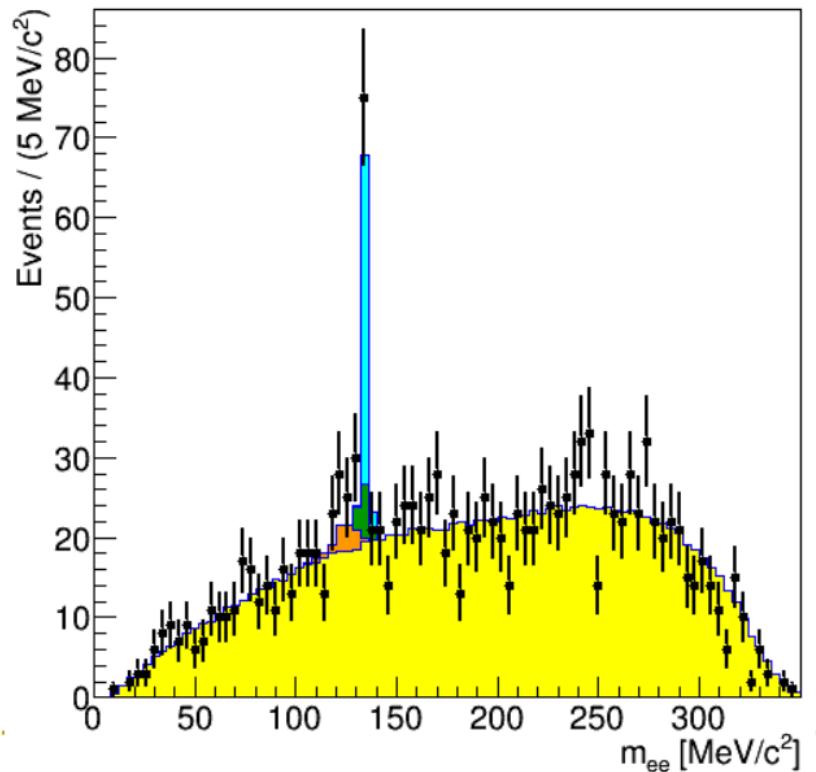
- World-largest $K^+ \rightarrow \pi^+ \mu^+ \mu^-$: $\sim 4.6 \times 10^3$ events ($BR \sim 10^{-7}$)
- Expected 10K; competitive measurement
- Search for $K^+ \rightarrow \pi^- \mu^+ \mu^+$ is not limited by background: $SES = 2 \times 10^{-11}$
- Sensitivity to $K^+ \rightarrow \pi^+ S$, $S \rightarrow \mu^+ \mu^-$: $SES \sim 10^{-10}$ for lifetimes up to $\mathcal{O}(1 \text{ ns})$



Rare and Forbidden Decays: $K \rightarrow \pi ee$

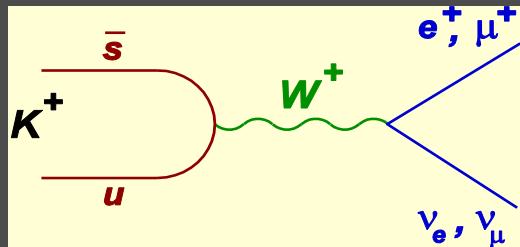
50% 2016 + 25% 2017 Data: $N_K = 1.3 \times 10^{11}$

- Background – free $\sim 1.1 \times 10^3$ events for $m_{ee} > 140$ MeV/c² ($BR \sim 3 \times 10^{-7}$)
- First observation at $m_{ee} < 140$ MeV/c²
- Sensitivity to $BR(K^+ \rightarrow \pi^+ X) BR(X \rightarrow e^+ e^-)$, $10 < m_X < 100$ MeV/c²: $\mathcal{O}(10^{-9})$
- Search for $K^+ \rightarrow \pi^- e^+ e^+$ is not limited by background: $SES = 2 \times 10^{-10}$



Lepton Universality: $R_K = K_{e2}/K_{\mu 2}$

SM

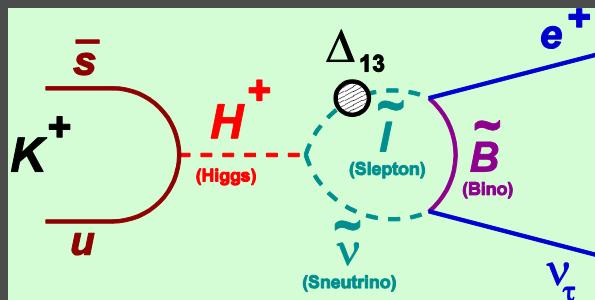


$$R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}})$$

$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

Cirigliano & Rosell PRL 99 (2007) 231801

BSM,
LFV



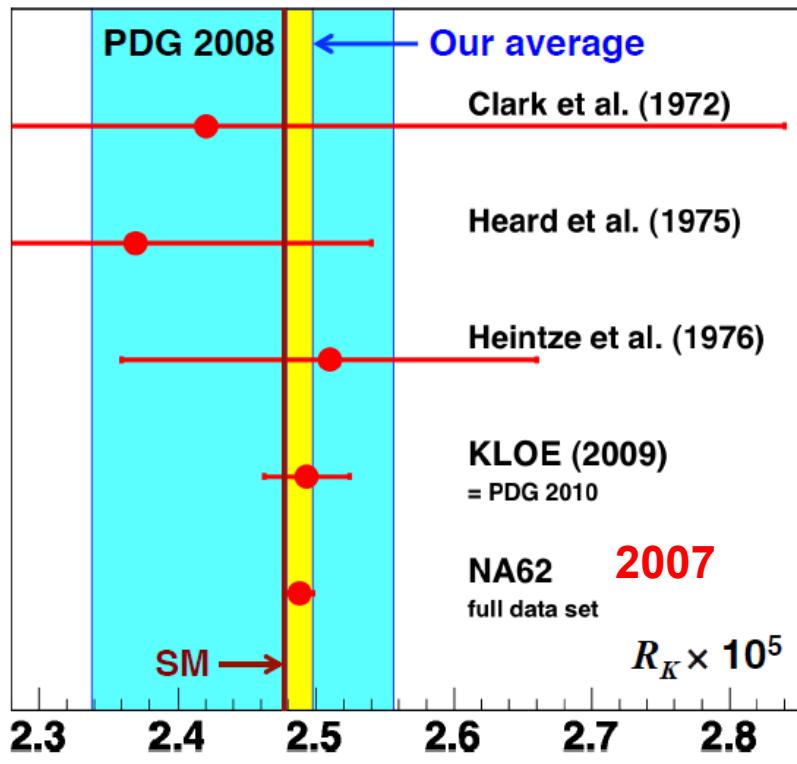
e.g. Masiero, Paradisi Petronzio
PRD 74 (2006) 011701,
JHEP 0811 (2008) 042

$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

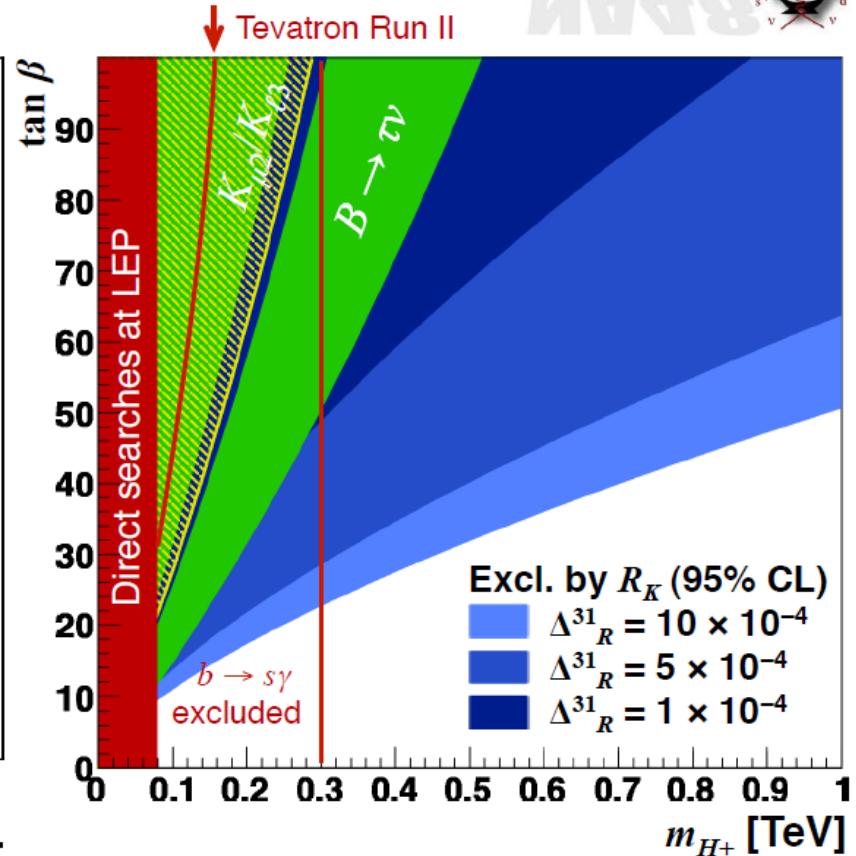
Example:

$(\Delta_{13}=5 \times 10^{-4}, \tan\beta=40, M_H=500 \text{ GeV}/c^2)$
lead to $R_K^{\text{MSSM}} = R_K^{\text{SM}}(1+0.013)$.

R_K : world average



Average	$R_K \times 10^5$	$\delta R_K / R_K$
PDG 2008	2.447 ± 0.109	4.5%
Current	2.488 ± 0.009	0.4%



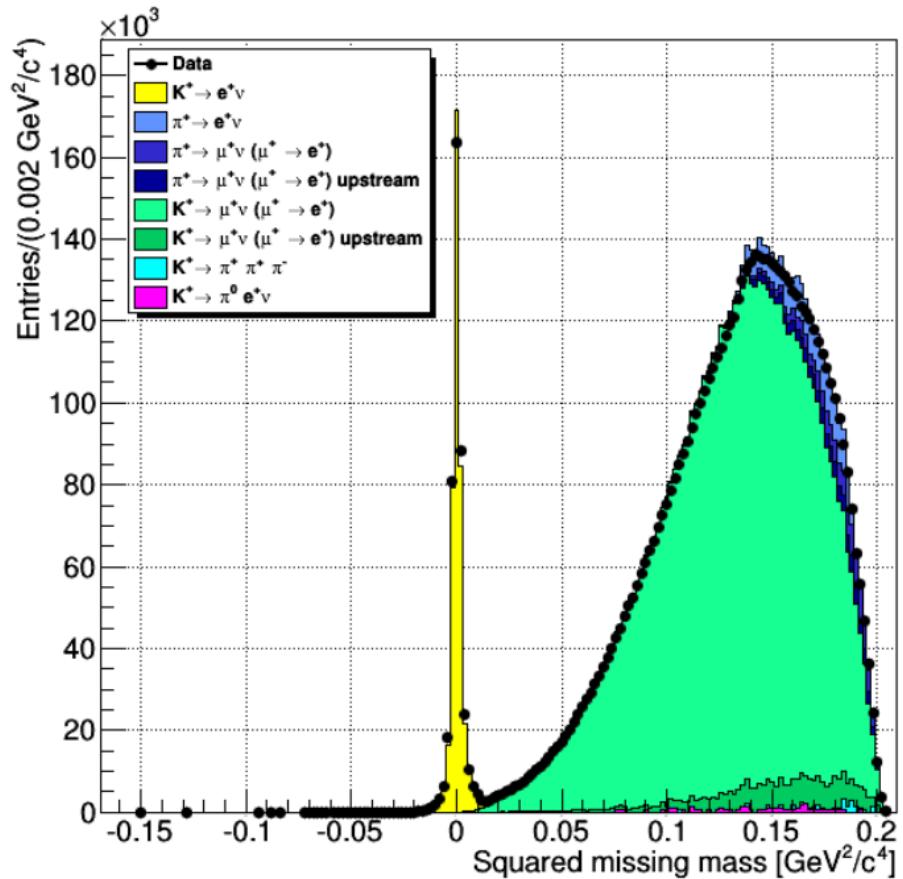
MSSM with R parity

$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} |\Delta_R^{31}|^2 \tan^6 \beta \right]$$

Prospects: R_K

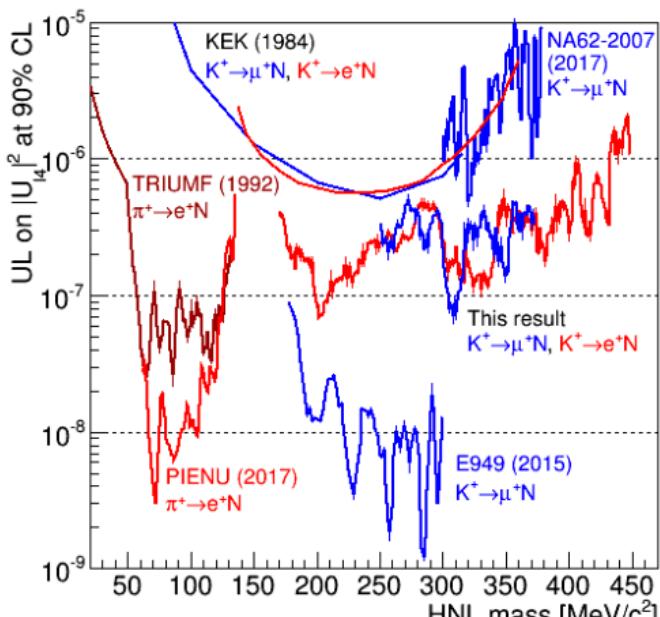
25% 2017 Data: $N_K = 3 \times 10^{11}$, world largest sample of $K^+ \rightarrow e^+ \nu$ 4×10^5

- Study of lepton universality in K :
 $R_K \equiv \Gamma(K^+ \rightarrow e^+ \nu) / \Gamma(K^+ \rightarrow \mu^+ \nu)$
- Theory (SM) :
 $R_K = (2.477 \pm 0.001) \times 10^{-5}$
[Phys. Rev. Lett. 99 (2007) 231801]
- Experimental Status (2007 NA62):
 $R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5}$
[Phys. Lett. B 719 (2013) 326]
- NA62 Present: novel method to measure R_K using $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ for normalization
- No systematics uncertainties that limited the 2007 NA62 measurement



Exotics: HNL, Darks Particles, ALPs,...

Search for Heavy Neutral Leptons from K decays



$$|U_{l4}|^2 = \frac{\mathcal{B}(K^\pm \rightarrow l^\pm N_4)}{\mathcal{B}(K^\pm \rightarrow l^\pm \nu_\mu) \rho_l(m_{N_4})}$$

Analysis of NA62-R_K 2007 Data (Phys. Lett. B772 (2017) 712)

- About 60 million K⁺ decays in the fiducial volume
- Improved limits on |U_{l4}|² for m_{N₄} ∈ (300, 375) MeV/c²

Analysis of NA62 2015 Data (Phys. Lett. B778 (2018) 137)

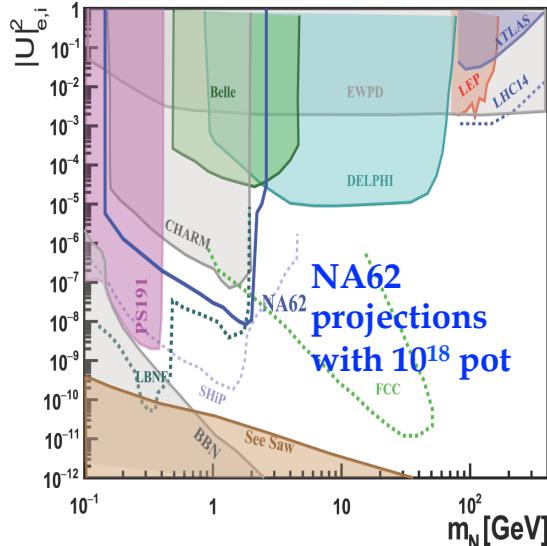
- About 300 million K⁺ decays in the fiducial volume
- New limits on |U_{l4}|² reaching 10⁻⁶ – 10⁻⁷ for m_{N₄} ∈ (170, 448) MeV/c² (K⁺ → e⁺ N₄) and for m_{N₄} ∈ (300, 373) MeV/c² (K⁺ → μ⁺ N₄)

Future prospects

- Major analysis improvements with NA62 2016–2018 high intensity data (beam tracker fully commissioned)

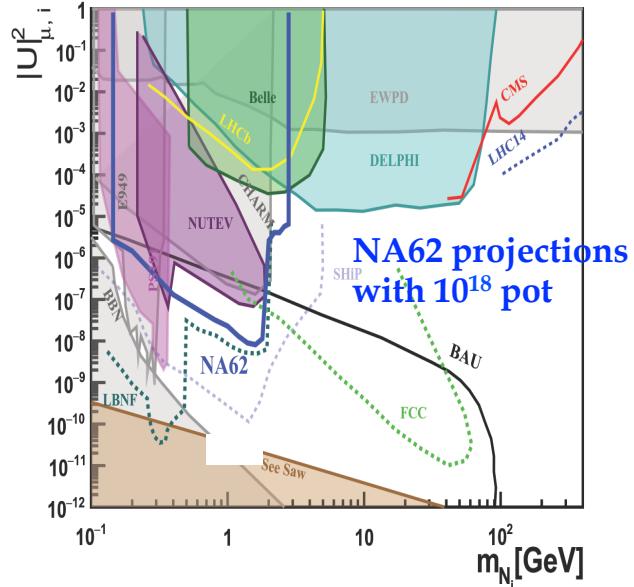
Heavy Neutral Leptons in NA62 (Dump)

Scenario 1



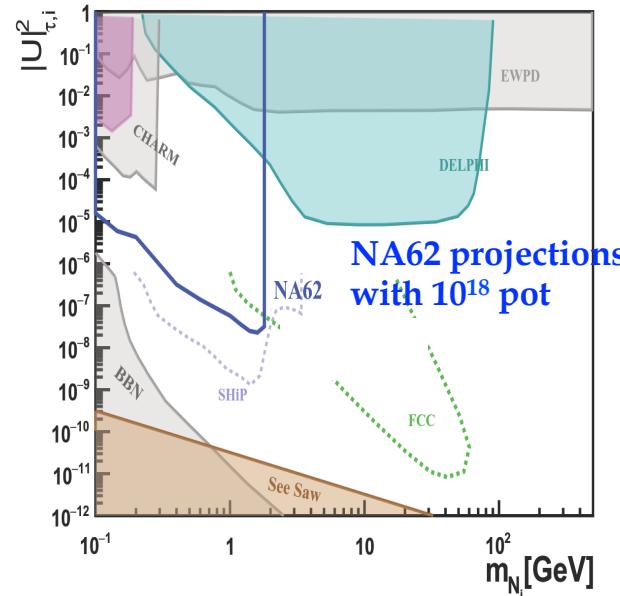
$U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$
Normal hierarchy of active ν masses

Scenario 2



$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$
Normal hierarchy of active ν masses

Scenario 3



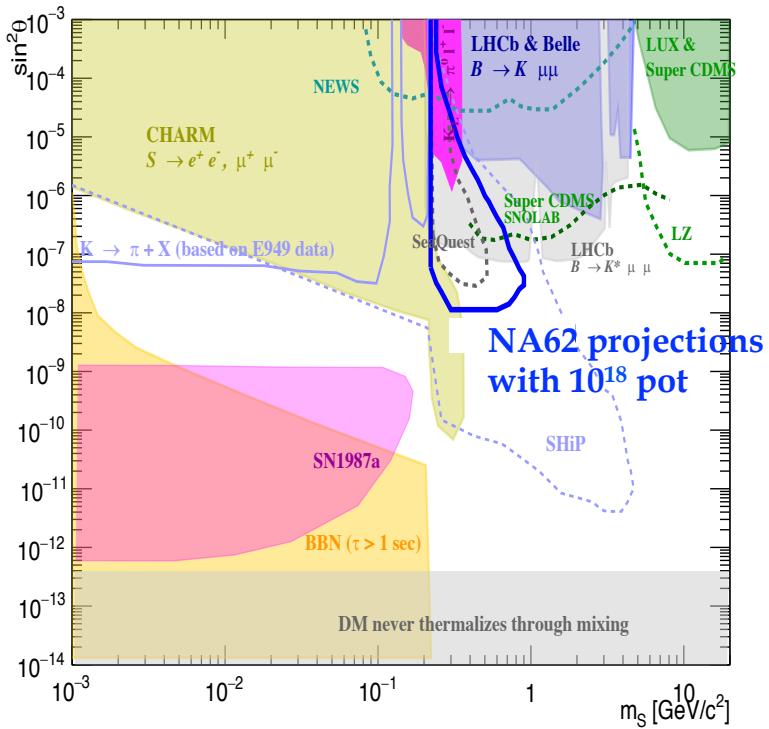
$U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$
Normal hierarchy of active ν masses

These sensitivities assume to detect all 2-track final states, including open channels, and zero background

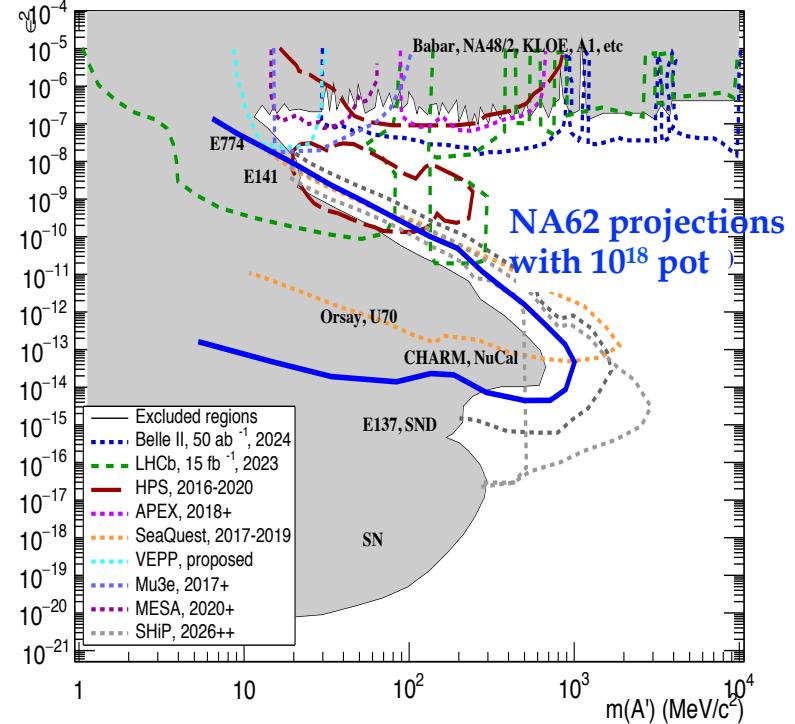
Window of Opportunity to search for HNL above the K mass in the near future

NA62 sensitivity with 10^{18} POT

Dark Scalar:



Dark Photon:



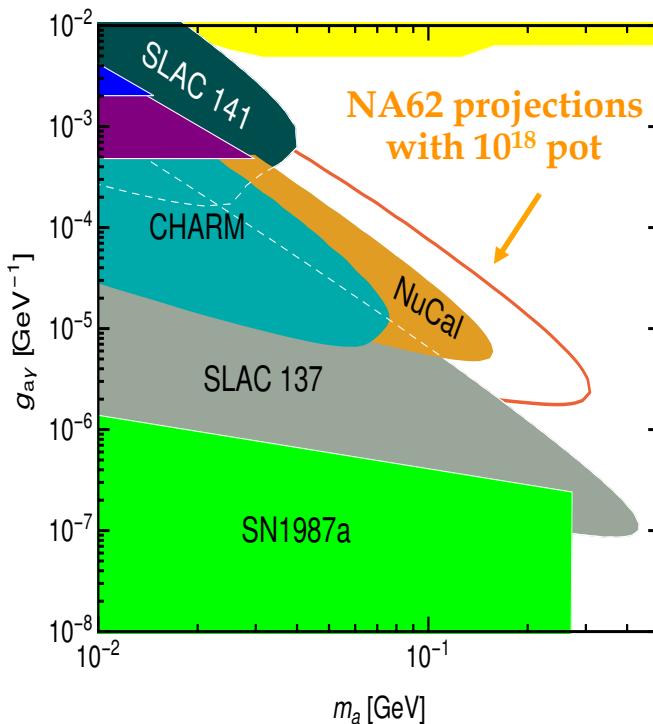
The Dark Scalar sensitivity plot assume all 2-track final states, with zero background

The Dark Photon projections are for di-muon final state only and (still) miss the inclusion of the two dominant production processes (QED, QCD): the curve is very conservative!

NA62-Dump sensitivity for ALPs $\rightarrow \gamma\gamma$



- ALP production via Primakoff effect at target;
- Search for ALP $\rightarrow \gamma\gamma$ in NA62 fiducial volume, account for geometrical acceptance
- Assume zero-background, evaluate expected 90%-CL exclusion plot



**B. Dobrich et al.,
JHEP 02 (2016) 018**

Significant potential for Axion Like Particles searches