BEAUTY 2018

6 - 11 May 2018, La Biodola, Isola d'Elba, Italy

$K \to \pi \nu \bar{\nu}$ from NA62 and KOTO

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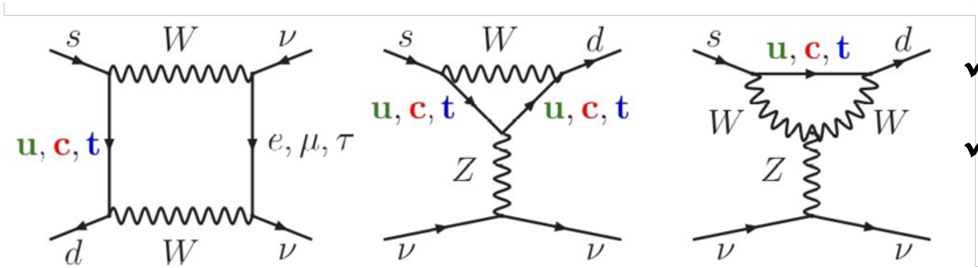
Content

Review of the present experimental status of the $K \rightarrow \pi\nu\bar{\nu}$ decays

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$: first result from NA62 experiment at CERN SPS
- $K_L \rightarrow \pi^0\nu\bar{\nu}$: KOTO experiment at JPARC

Motivations for $K \to \pi\nu\bar{\nu}$

Box & Penguin (one-loop) diagrams



- ✓ FCNC process forbidden at tree level
- ✓ Highly CKM suppressed (BR ~ $|V_{ts}^{*}V_{td}|^2$)
- ✓ Extraction of V_{td} with minimal (few %) non-parametric uncertainty

Theoretically very clean:

- ✓ dominant short-distance contribution
- ✓ hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \nu$)

SM Predictions, error CKM parametric [Buras et al., JHEP 1511 (2015) 033]:

BR($K^+ \to \pi^+\nu\bar{\nu}$) = $(8.4 \pm 1.0) \times 10^{-11}$	BR($K_L \to \pi^0\nu\bar{\nu}$) = $(3.4 \pm 0.6) \times 10^{-11}$

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

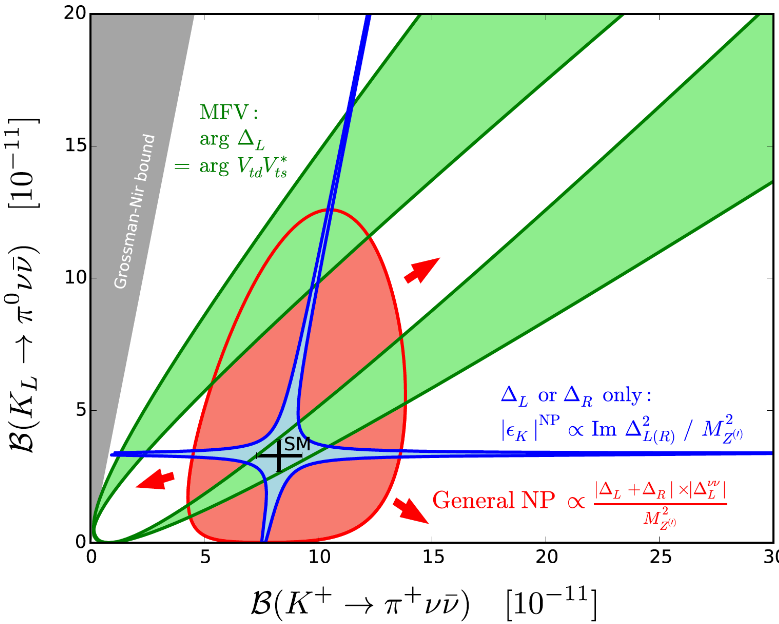
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin(\gamma)}{\sin(73.2^\circ)}\right]^{2}$$

$K \rightarrow \pi\nu\bar{\nu}$: NP Sensitivity

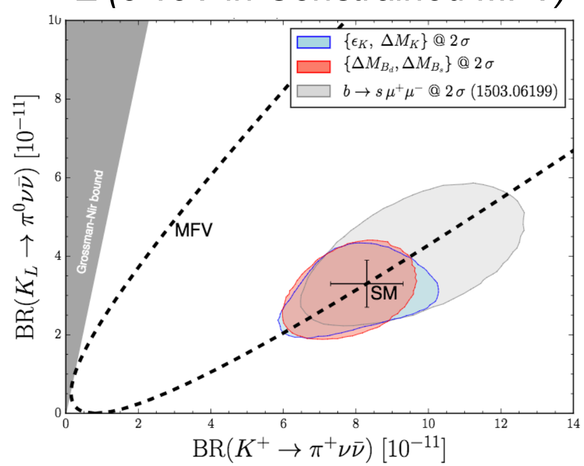
Indirect searches of NP with high precision studies of rare K decays

Measurement of charged ($K^+ \rightarrow \pi^+\nu\nu$) and neutral ($K_L \rightarrow \pi^0\nu\nu$) modes can **discriminate among different NP scenarios**

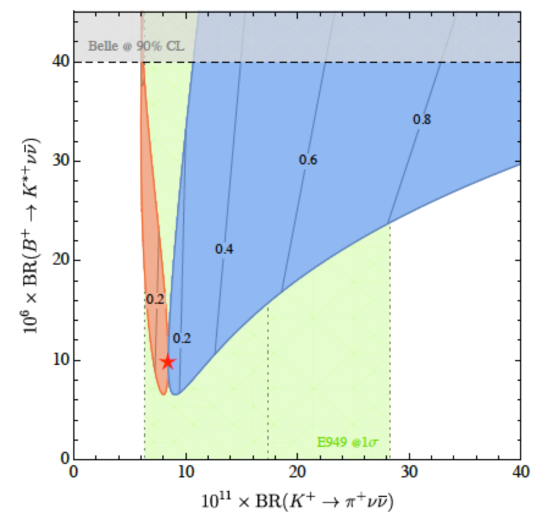
[Buras, Buttazzo, Knegjens, JHEP11 (2015) 166]



Z'(5 TeV in Constrained MFV)



LFU violation



[Isidori et al., Eur. Phys. J. C(2017)77: 618]

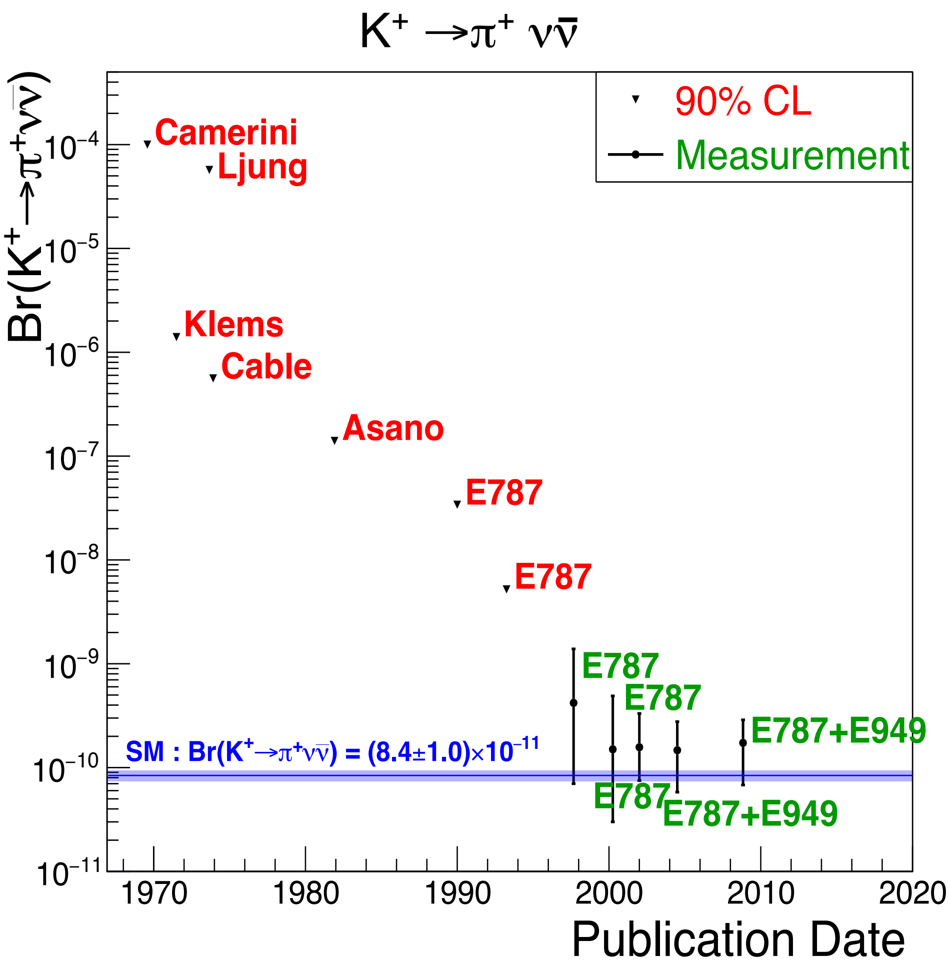
Correlations significantly change for different classes of NP models

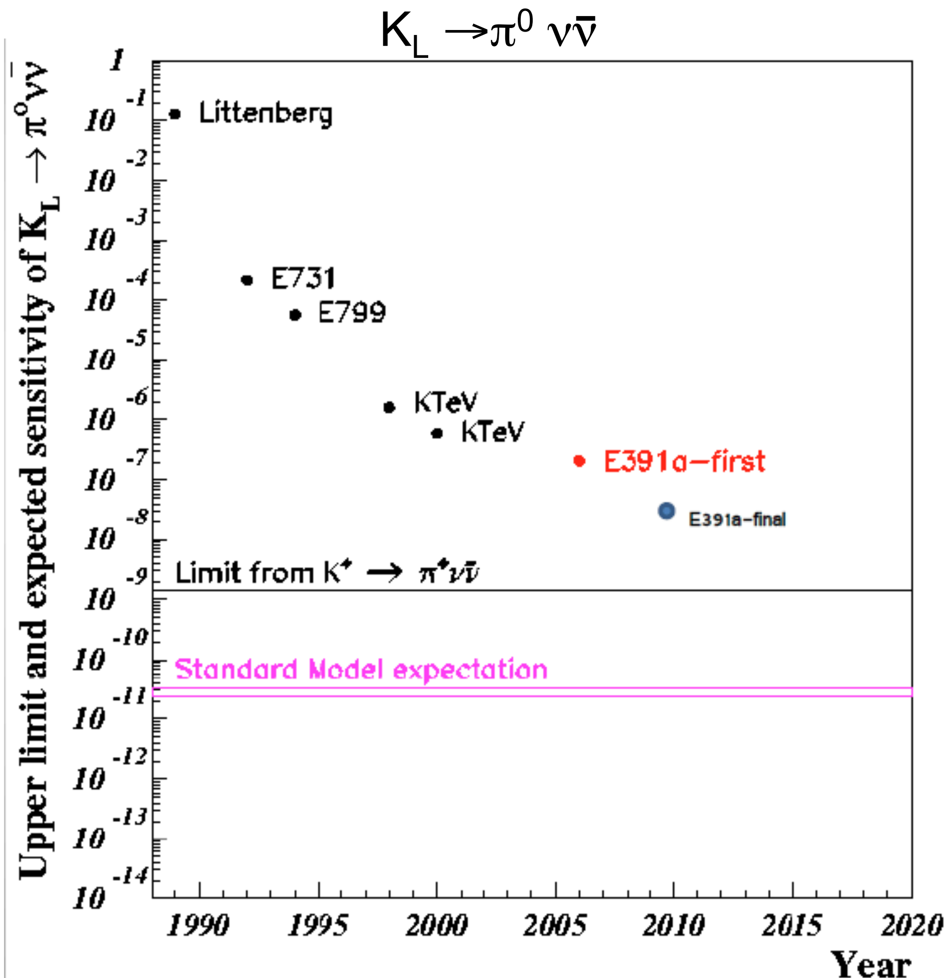
[EPJ C76 (2016) no.4 182]

$K \rightarrow \pi\nu\bar{\nu}$ probes of unique sensitivity for NP models among B and K decays

(NP searches complementary/alternative to LHC)

$K \to \pi\nu\bar{\nu}$ Experimental Status





$BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$BR(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) Phys. Rev. D 81, 072004 (2010)

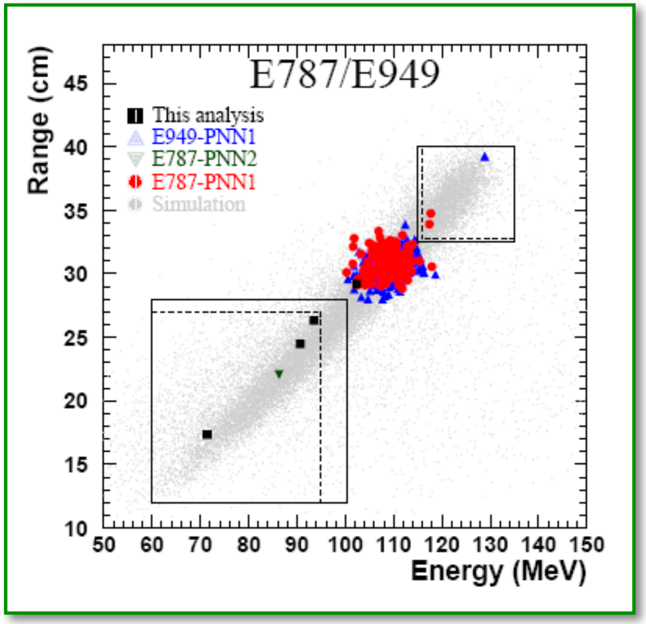
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ in E787/E949

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{THEORY} = (0.84 \pm 0.10) \times 10^{-10}$

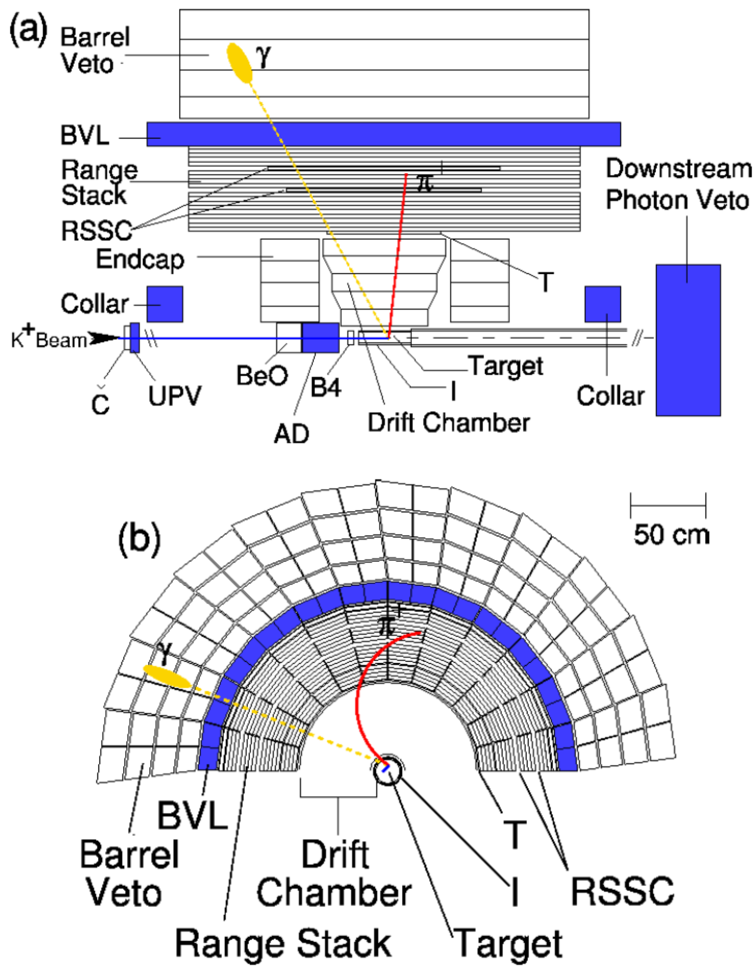
$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{EXP} = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

[E787/E949, Phys.Rev.Lett.101, 191802, 2008]

- based on 7 candidates
- stopped Kaon technique



(7 candidates E787+E949)

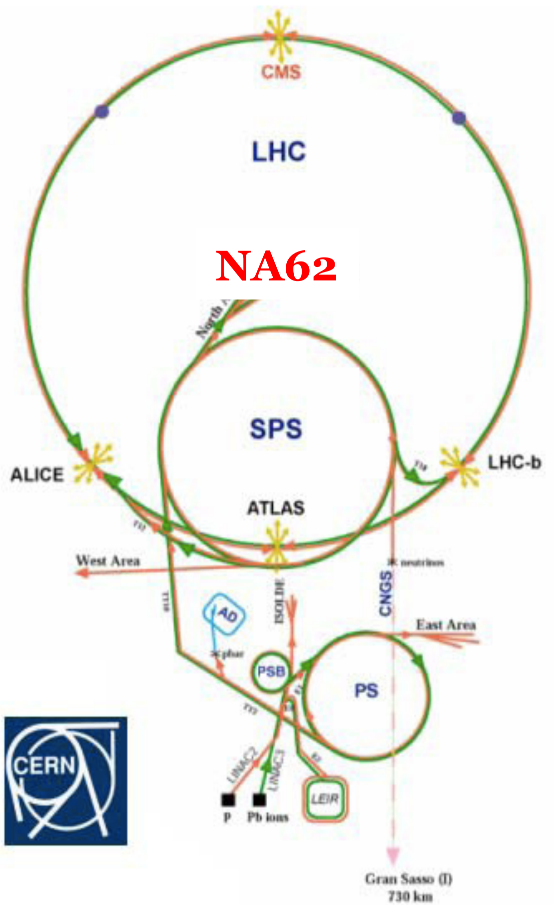


Phys. Rev. D77, 052003 (2008)
Phys. Rev. D 79, 092004 (2009)

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver (UBC)



NA62 Timeline

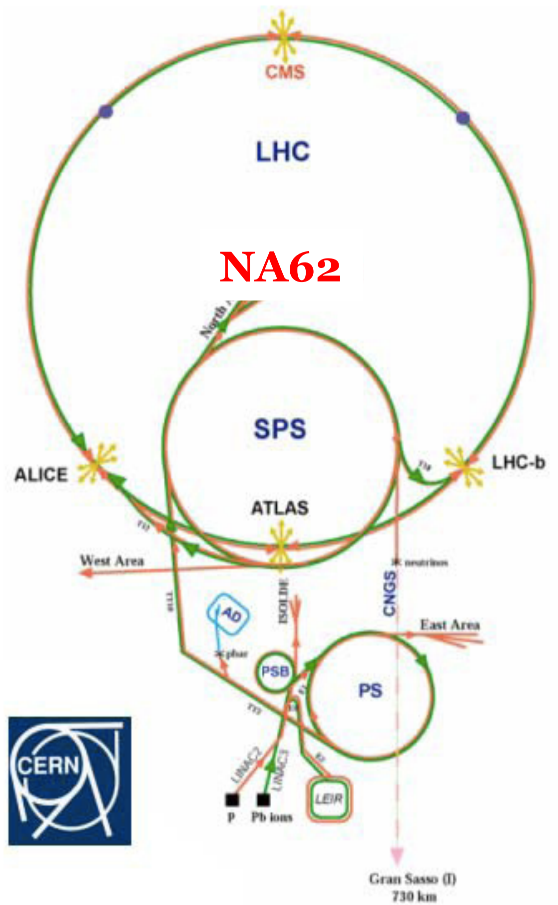
- **Dec 2008 - NA62 Approval**
- **2009 - 2014: Detector R&D, Installation**
- **2015 Commissioning**
- **2016 - 2018: Physics Runs**
- **2021 - 2023 Next Physics Runs (TBA)**

NA62 primary goal: Measure BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)

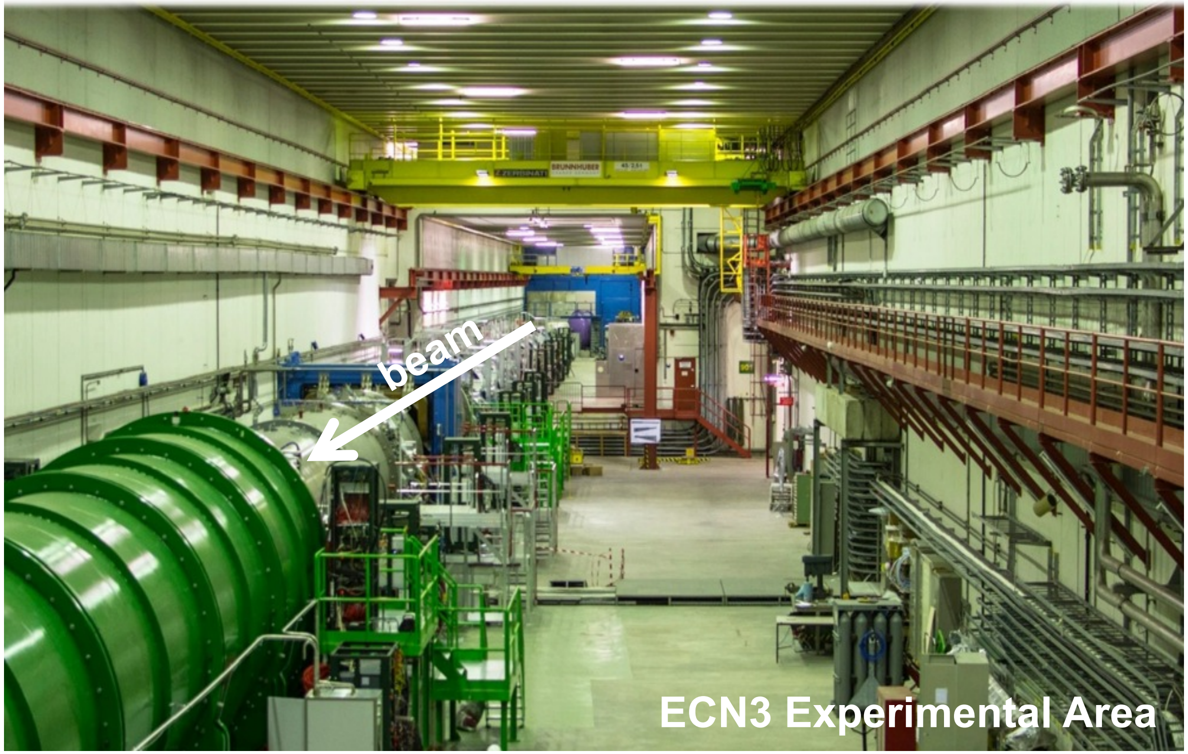
New: K^+ decay-in-flight technique

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS



NA62 Beam line & detectors



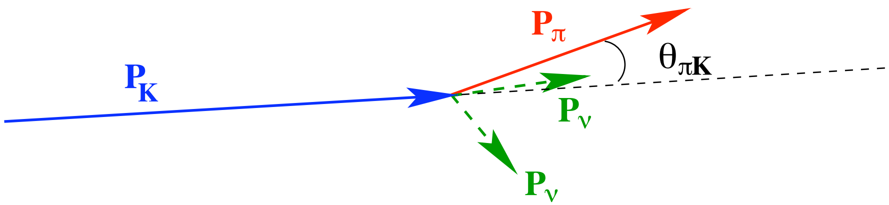
NA62 primary goal: Measure BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)

New: K^+ decay-in-flight technique

$K^+ \to \pi^+ \nu\bar{\nu}$ Signal & Backgrounds

Signal $K^+ \to \pi^+ \nu\bar{\nu}$:

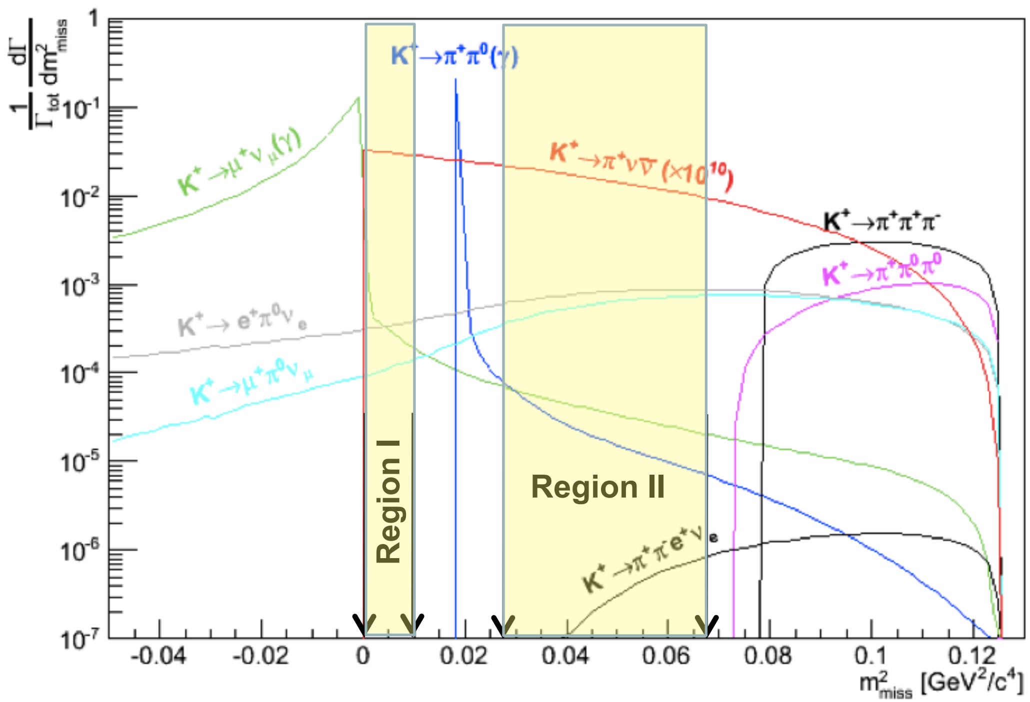
$m^2_{miss} = (P_K - P_\pi)^2$



Main kaon decay backgrounds

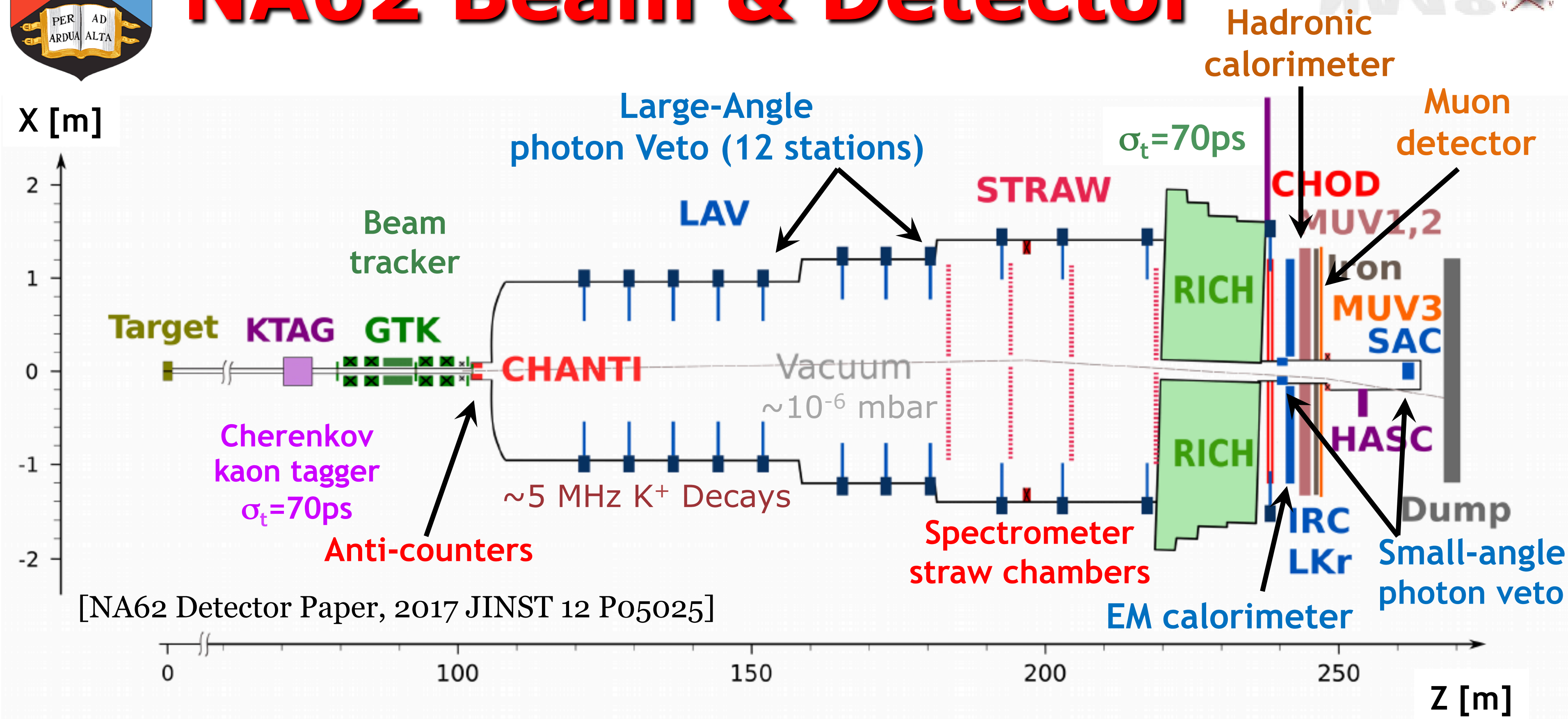
Process	Branching ratio
$K^+ \to \mu^+ \nu_\mu(\gamma)$	63.5%
$K^+ \to \pi^+ \pi^0(\gamma)$	20.7%
$K^+ \to \pi^+ \pi^+ \pi^-$	5.6%
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	4.3×10^{-5}

Sign & Bkg control regions kept blind throughout the analysis



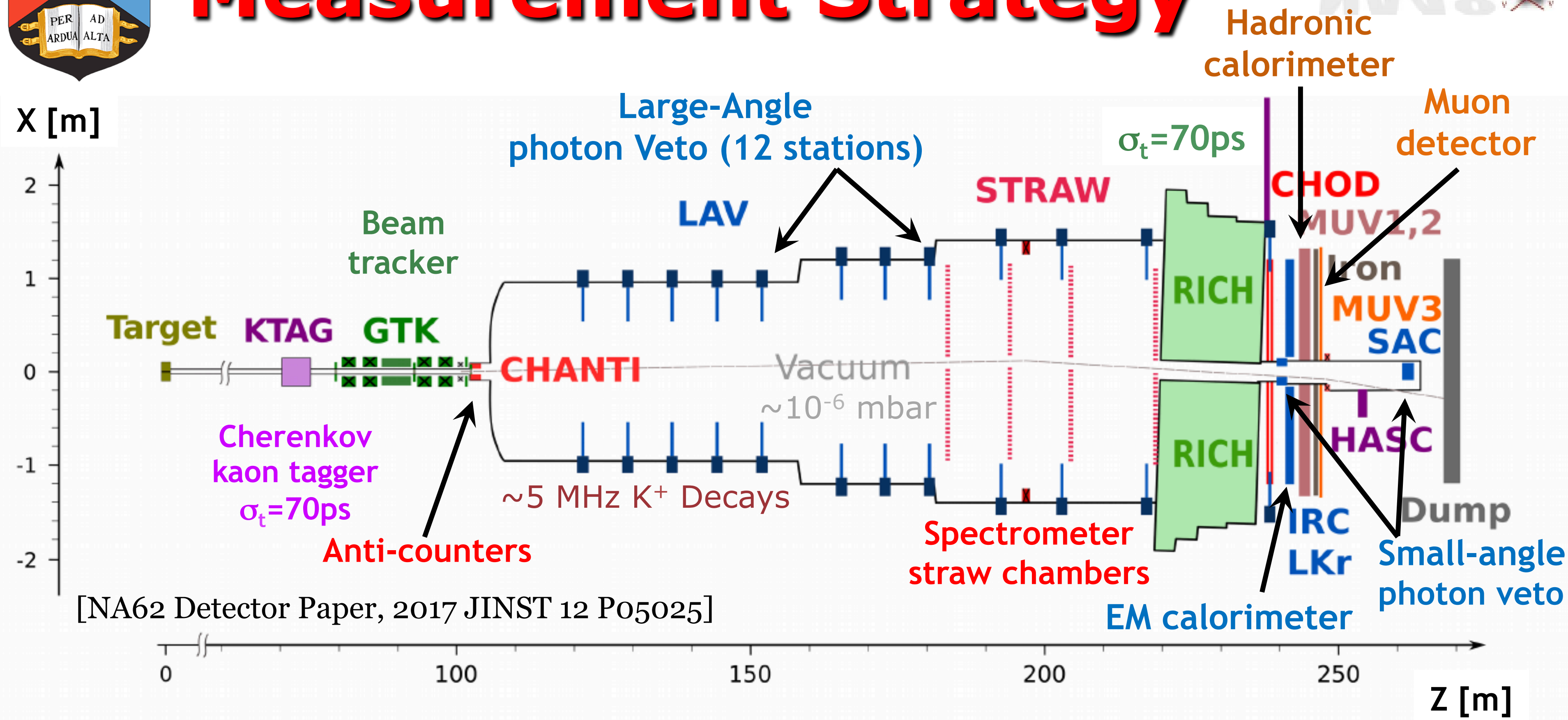
Background rejection relies on **Kinematics** ($15 GeV/c < P_\pi < 35 GeV/c$; m^2_{miss}) used in conjunction with **Particle ID**, **Veto systems** and **sub-ns timing**

NA62 Beam & Detector



- SPS protons on Be target (PoT): 400 GeV/c, ~10^{12} PoT/sec , 3.5 sec/spill
- Un-separated hadron beam: π^+(70%)/K^+(6%)/p(24%)
- 750MHz beam rate @GTK (45MHz K^+ component)
- K^+: 75GeV/c (±1%), divergence < 100μrad, (60 x 30) mm² transverse size
- 10% of K^+ decays in 60 m fiducial volume (FV)

Measurement Strategy



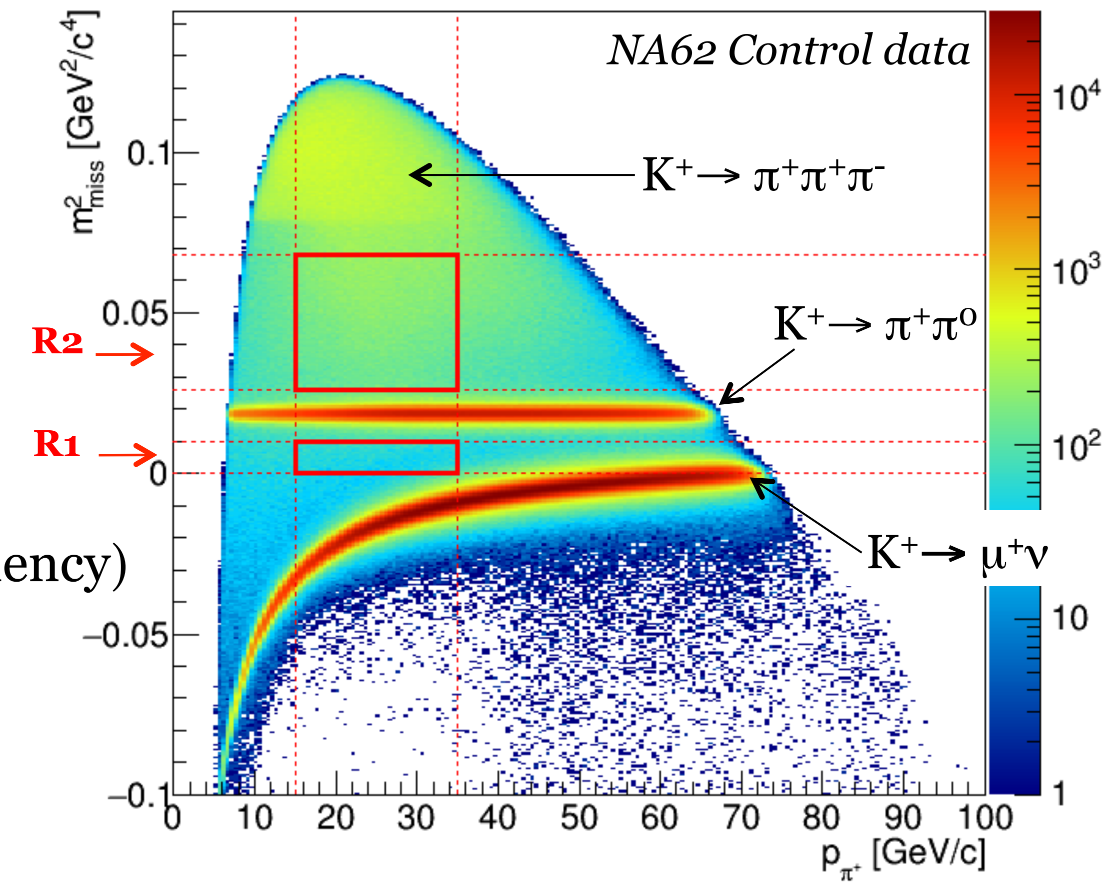
Keystones from detector design:

- Timing between sub-detectors ~ O(100ps)
- Kinematic rejection ~O(10^4) for $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ bkg channels
- Particle ID: muon suppression (from $K \to \mu^+\nu$) > 10^7
- Photon veto: $\pi^0 \to \gamma\gamma$ suppression (from $K^+ \to \pi^+\pi^0$) > 10^7

$K^+ \to \pi^+ \nu \bar{\nu}$ Signal Selection

$m^2_{miss} = m^2_{miss}$ (GTK, STRAW) $= (P_K - P_\pi)^2$
m_π mass hypothesis

Selection criteria:
- Single track topology
- π^+ identification
- Photon rejection
- Multi-track rejection



Performances:
- $\varepsilon(\mu^+) = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon(\pi^0) = 3 \cdot 10^{-8}$
- $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV^2/c^4
- $\sigma_T \sim O(100ps)$

Signal Region 1 (R1), Signal Region 2 (R2)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Signal Regions

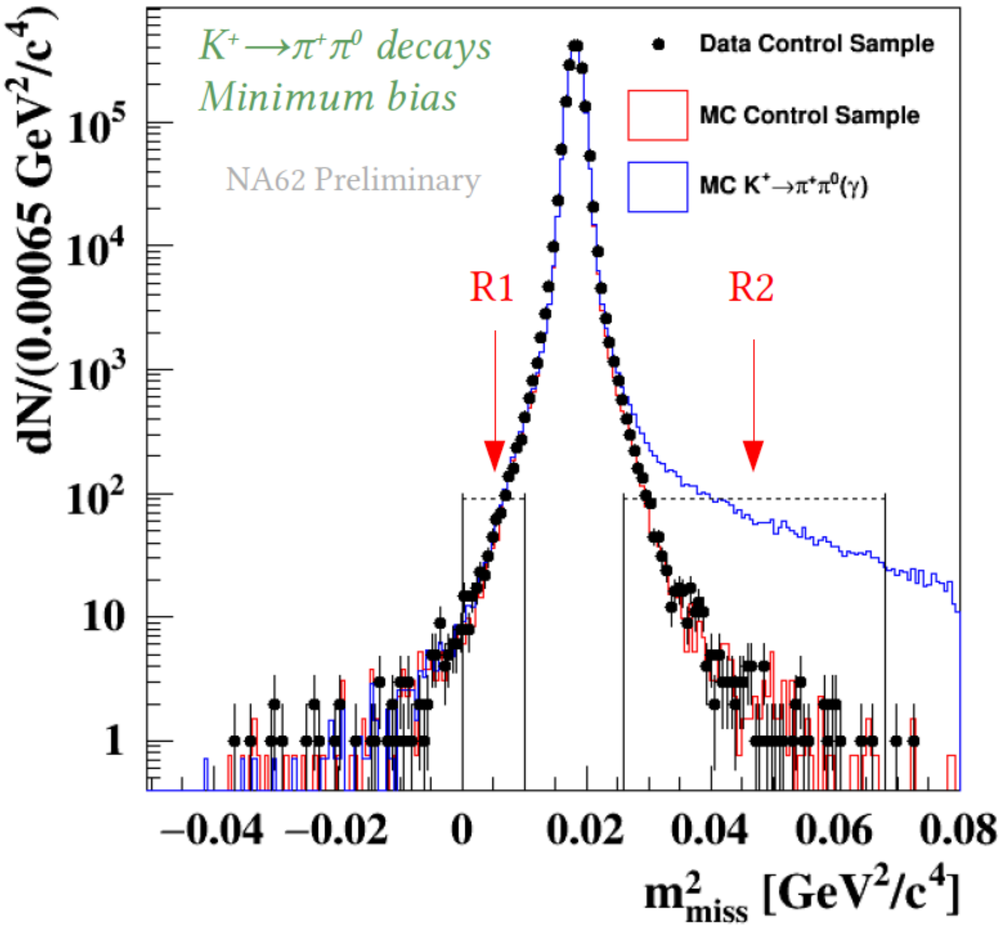
Consider different projections of
$m^2_{miss} = (P_K - P_\pi)^2$

- m^2_{miss} (GTK, STRAW)
- m^2_{miss} (GTK, RICH)
- m^2_{miss} (Beam, STRAW)

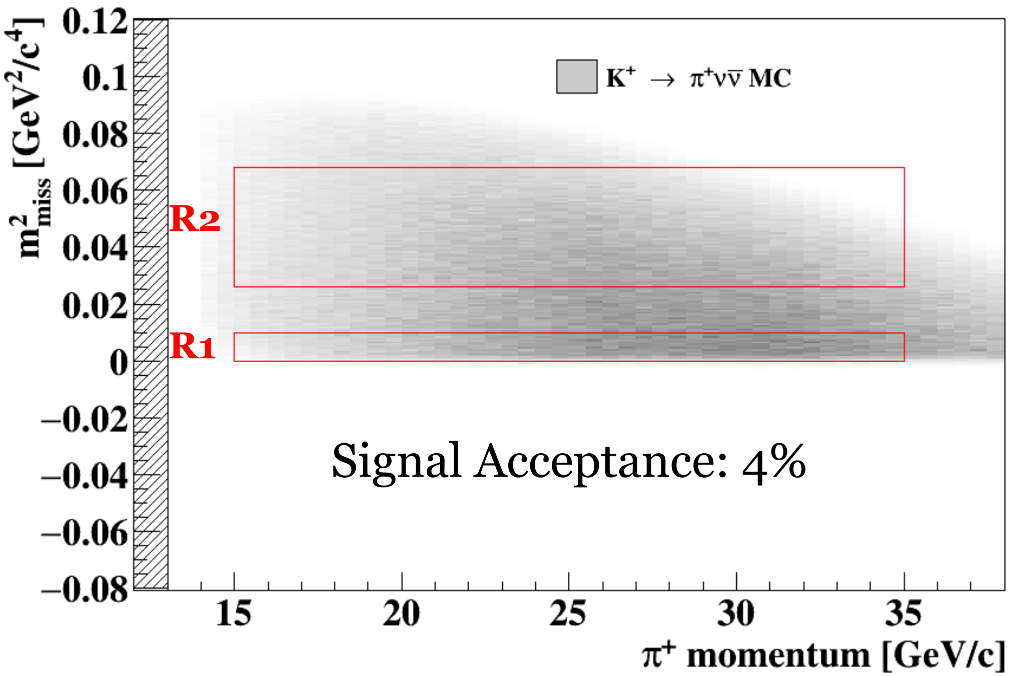
Address non-gaussian tails in the bkg distributions due to mis-reconstruction

Kinematic suppression:

- measured on data
- samples selected using calorimeters
- **$K^+ \rightarrow \pi^+ \pi^0$** $\sim 1 \cdot 10^{-3}$ (resolution tails)
- **$K \rightarrow \mu^+ \nu$** $\sim 3 \cdot 10^{-4}$



Single Event Sensitivity



Source	δSES (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 $\pi+$ interactions	±0.09
Extra activity	±0.02
GTK Pileup simulation	±0.02
Total	±0.24

Control trigger $K^+ \to \pi^+\pi^0$ used for normalisation: acceptance 10%

Number of kaon decays (N_K) in fiducial volume

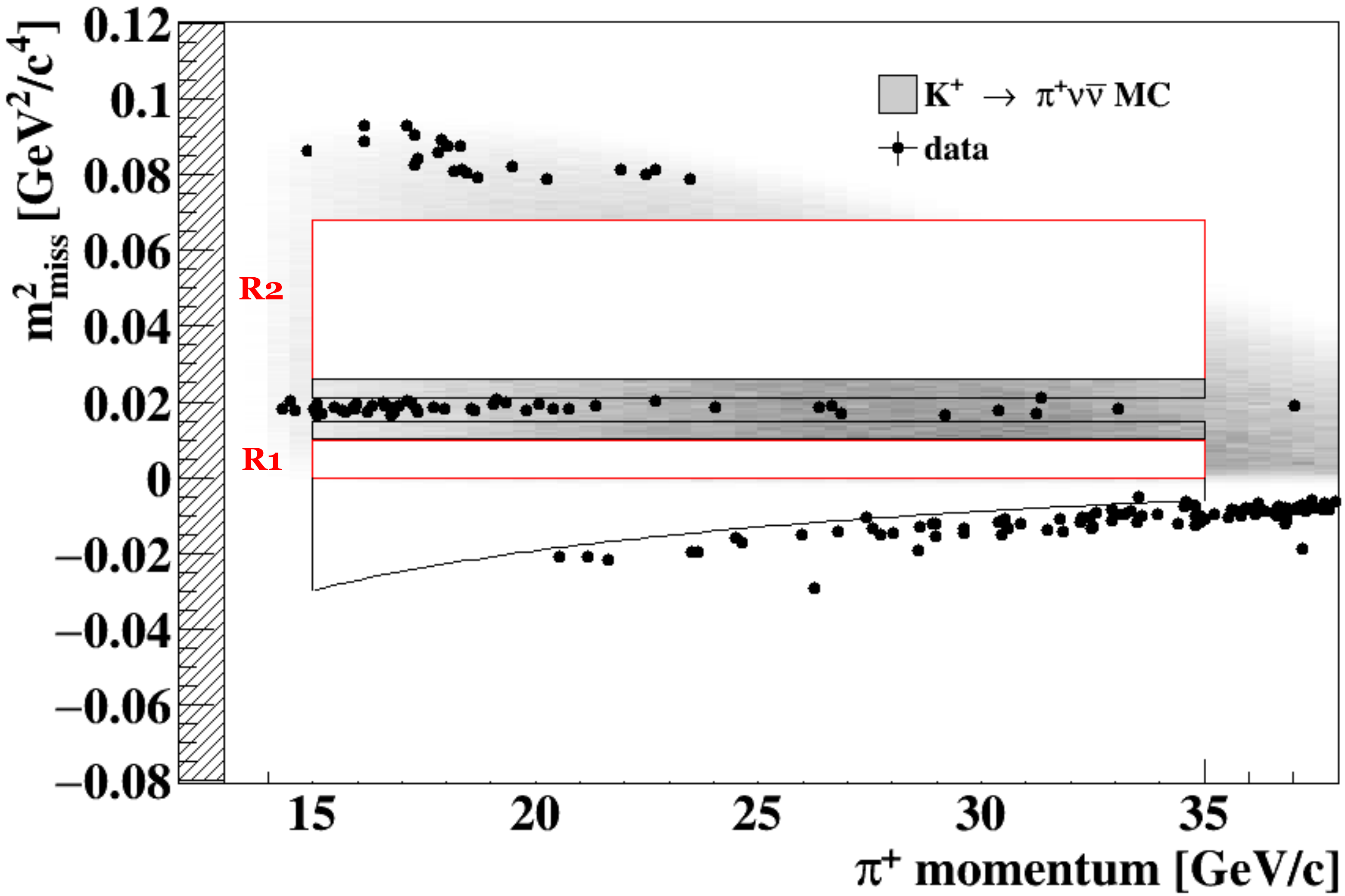
- $N_K = 1.21(2) \times 10^{11}$

Single Event Sensitivity: $SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \times 10^{-10}$

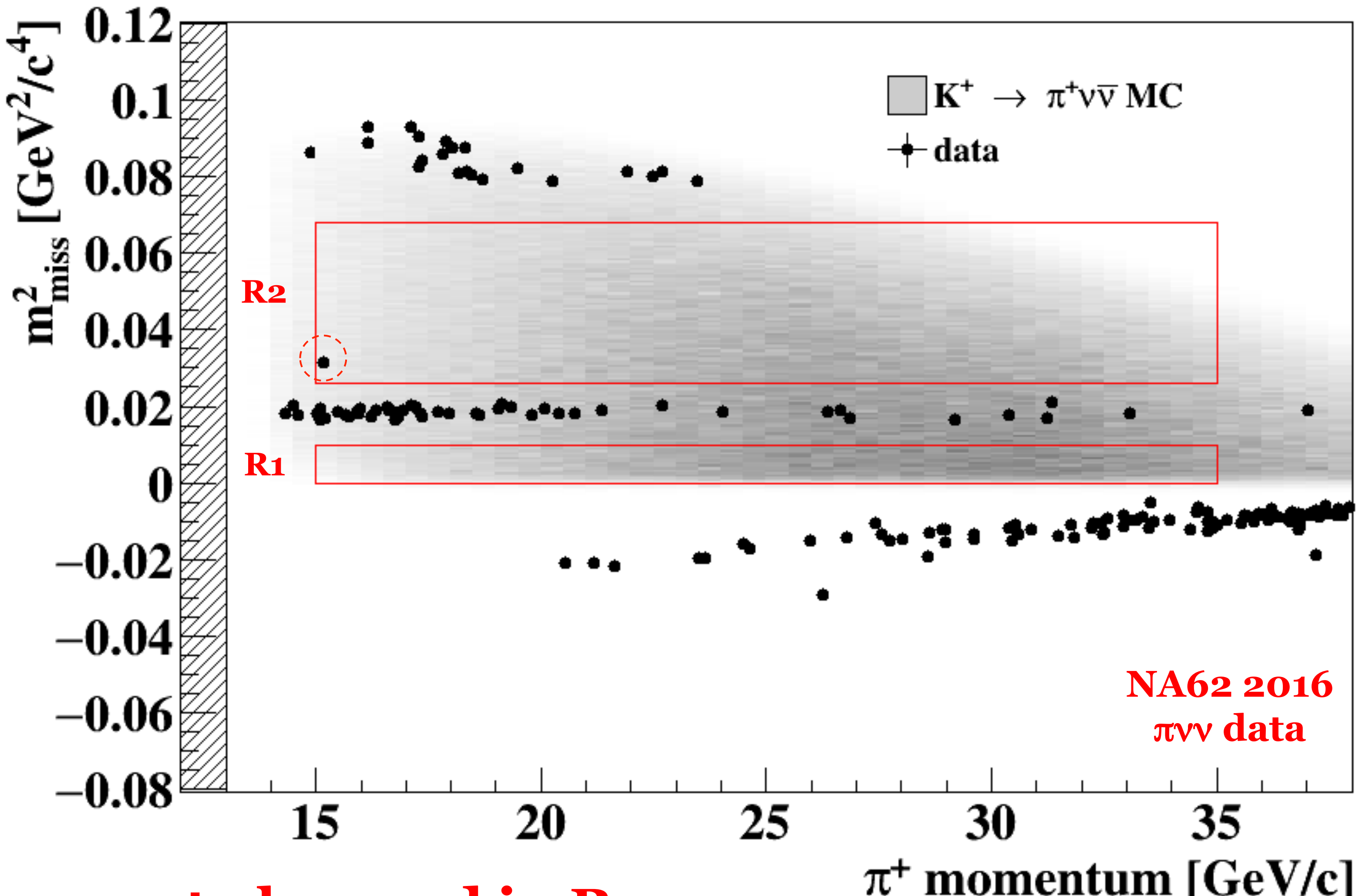
Background Summary

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

$K^+ \to \pi^+ \nu \bar{\nu}$ Results



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Results



One event observed in R2

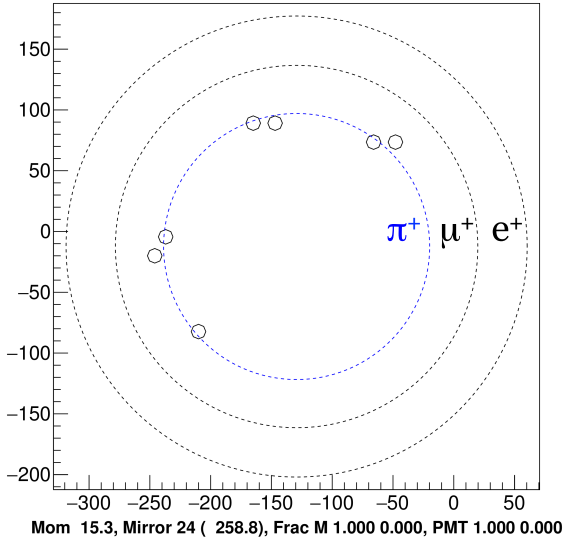
$K^+ \to \pi^+ \nu \bar{\nu}$ Results

- One event observed in signal region R2
- Full exploitation of the CLs method in progress
- The results are compatible with the Standard Model

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

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

RICH ring for the event



For comparison:

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = 28^{+44}_{-23} \times 10^{-11} \text{ @ } 68\% \, CL$$

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

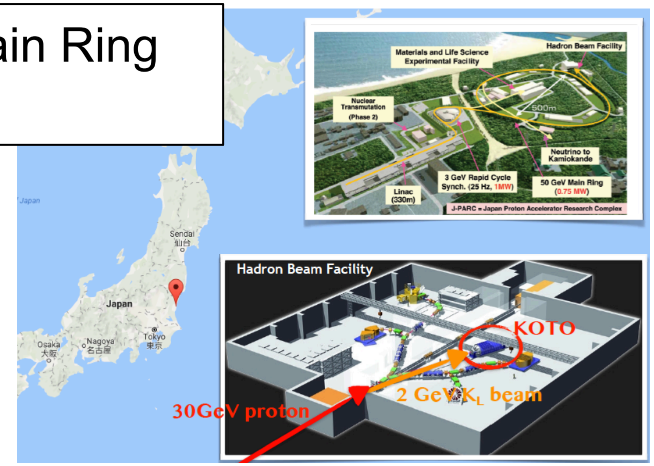
$$BR(K^+ \to \pi^+ \nu \bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

$K^+ \to \pi^+ \nu \bar{\nu}$ Prospects

- Analysis of data collected in 2017 started
  - data sample x 20 larger than presented statistics
  - expect improvements on signal acceptance, efficiency and S/B ratio
- Data taking is ongoing (April-November 2018)
- Expect ~20 SM events before LS2
- Data taking after 2018 to be approved

The KOTO Experiment

Study of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ JPARC 30GeV Main Ring
Goal is to observe few SM events



Primary 30 GeV/c protons on gold target

✓ Intensity (2013) 3 x 10^{13} ppp on target (2s spill)

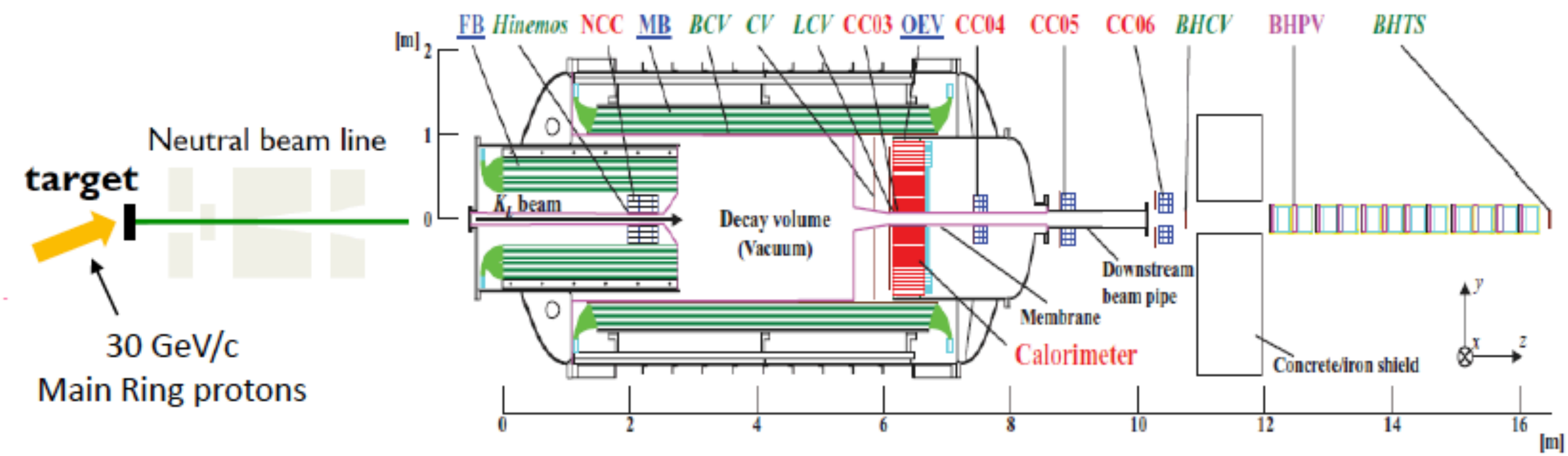
Secondary neutral beam (K_L, neutron, photons)

✓ P = 1.4 GeV/c peak

✓ Transverse size: 80 x 80 mm²

✓ Fiducial decay region ~3 m

Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

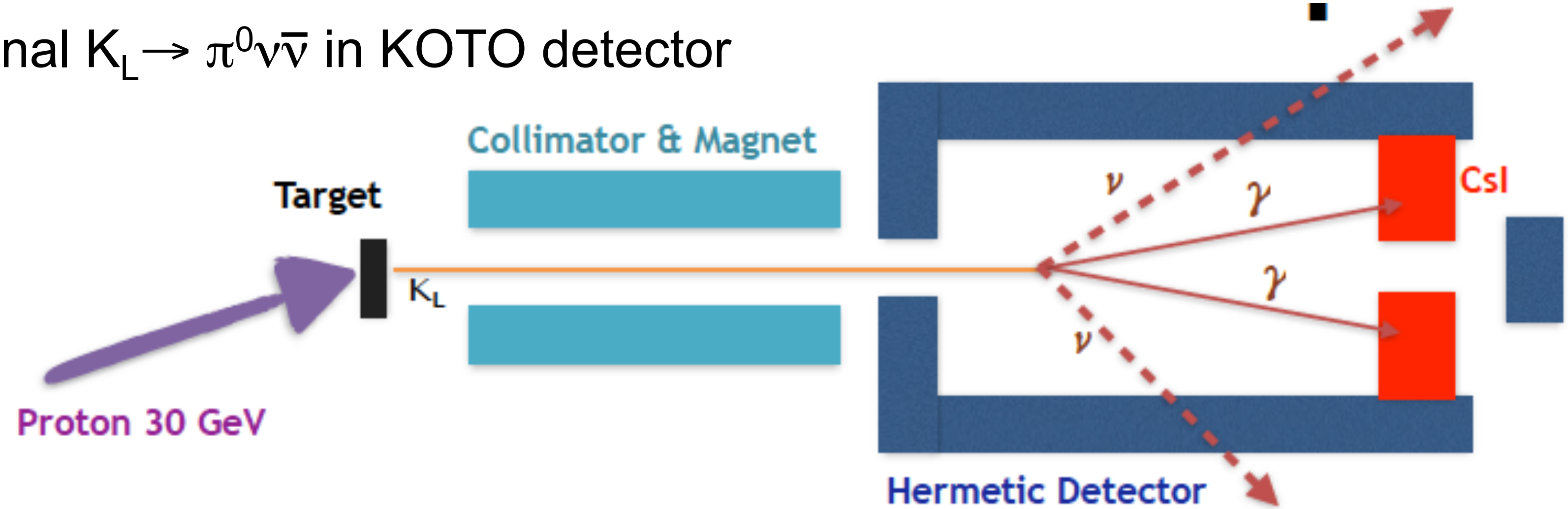


Lead-scintillator sandwich
Plastic scintillator counter
CsI Calorimeter from KTeV

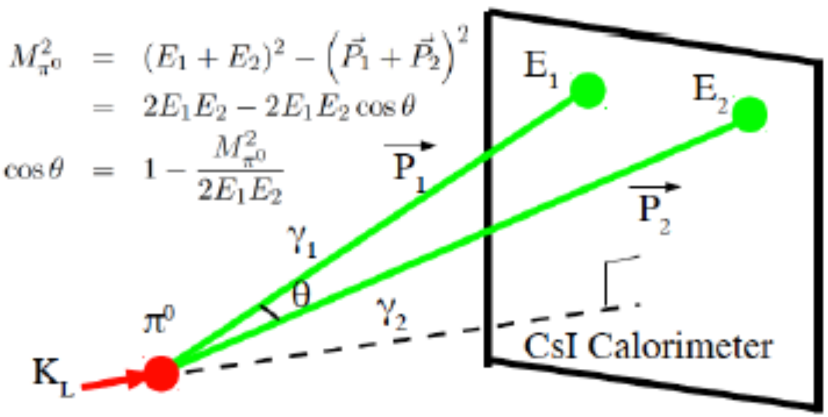
} **Hermetic Veto Systems** → To suppress $K_L \rightarrow \pi^0 \pi^0$

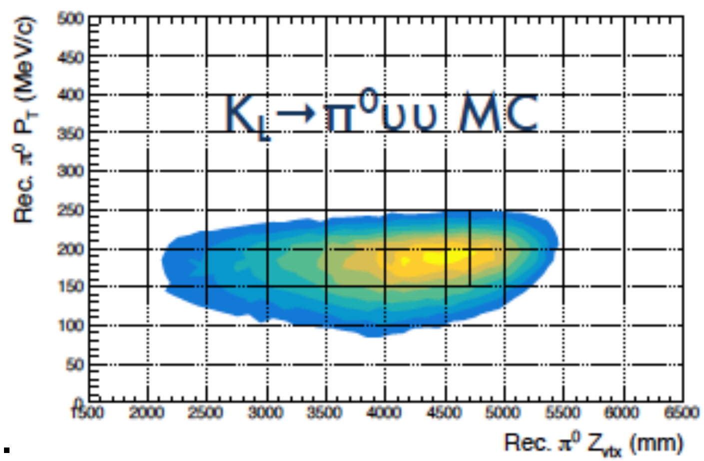
KOTO $K_L \to \pi^0 \nu\bar{\nu}$ Signal

Signal $K_L \to \pi^0 \nu\bar{\nu}$ in KOTO detector



$$M_{\pi^0}^2 = (E_1 + E_2)^2 - \left(\vec{P}_1 + \vec{P}_2\right)^2$$
$$= 2E_1E_2 - 2E_1E_2\cos\theta$$
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$





Assuming 2γ from π^0, calculate Z vertex (Z_{vtx}).

Signal region defined by π^0 Z_{vtx} and transverse momentum (P_T)

KOTO 2013 Result

Data from ~100 hours in 2013 run

✓ $N(K_L)$~2.4 x 10^{11} (**SES 1.3x10^{-8}**)

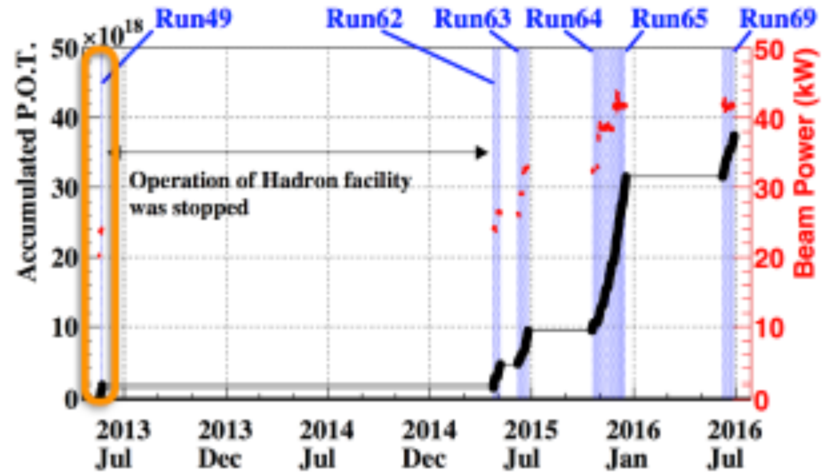
Set upper limit on BR($K_L \to \pi^0 \nu\nu$)

✓ < 5.1 x 10^{-8} (90% C.L.)

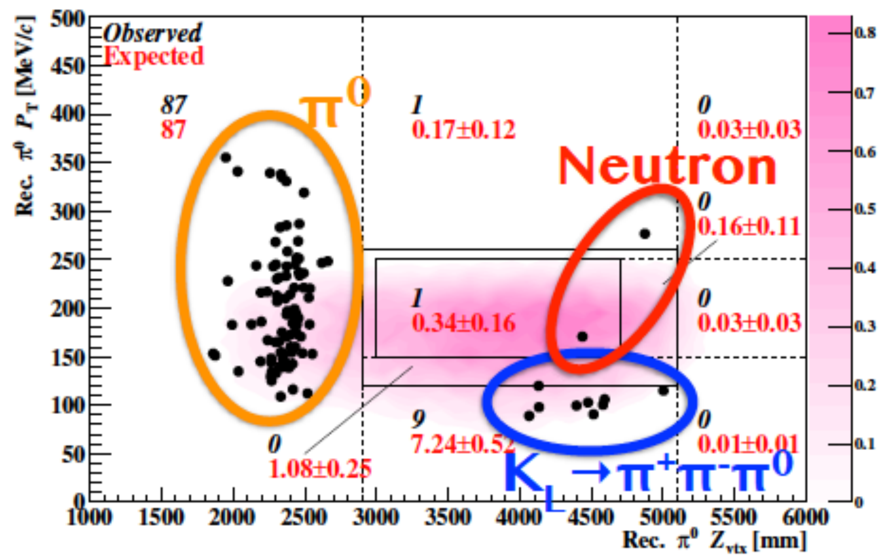
[PTEP 2017, 021C01]

Set upper limit on BR($K_L \to \pi^0 X^0$)

✓ < 3.7 x 10^{-8} (90% C.L.)



Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16

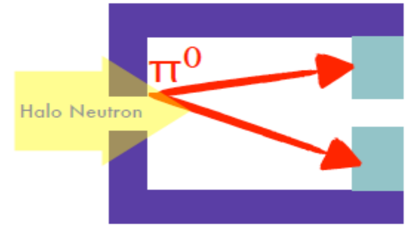


Background in signal region dominated by neutrons

Improvement After 2013

- ✓ Thinner vacuum window (125μm -> 12.5μm) to reduce neutron interaction
- ✓ Beam Profile Monitor for better beam alignment

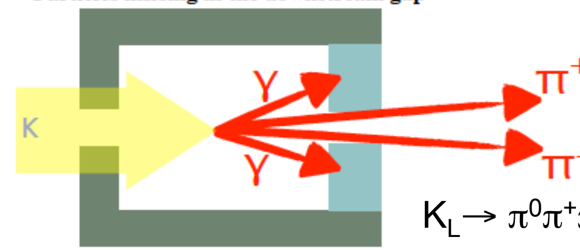
Pion produced at detector upstream



Halo Neutrons hitting the NCC

- ✓ Beam Pipe Charged Veto (BPCV) added
- ✓ 1/10 reduction of $K_L \rightarrow \pi^0\pi^+\pi^-$ background

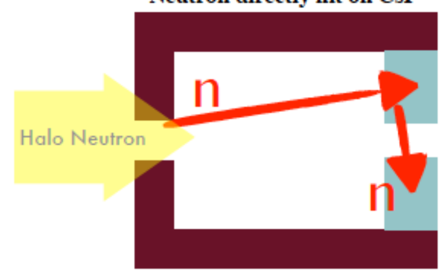
Particles missing in the downstream gap



$K_L \rightarrow \pi^0\pi^+\pi^-$

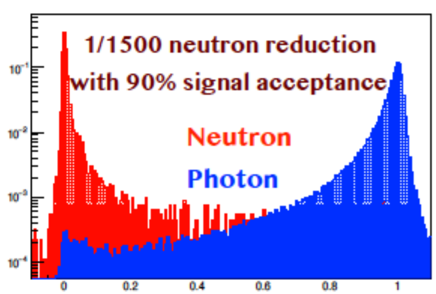
- ✓ Special run with Al target to collect neutron enriched events
- ✓ Better photon – neutron ID in CsI calorimeter

Neutron directly hit on CsI



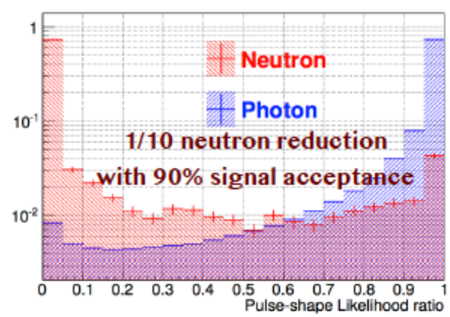
Halo Neutrons hitting the Calo

- Cluster Shape Discrimination



+

- Pulse Shape Discrimination

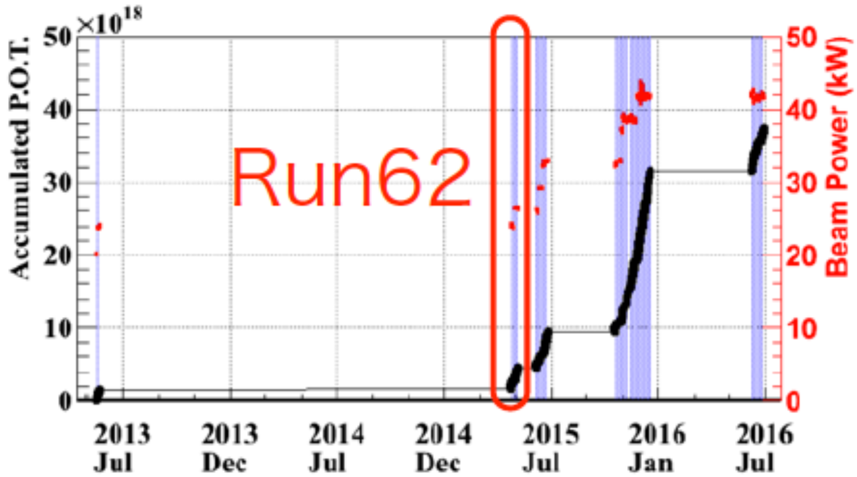


x 5 reduction of neutron background vs 2013 data analysis

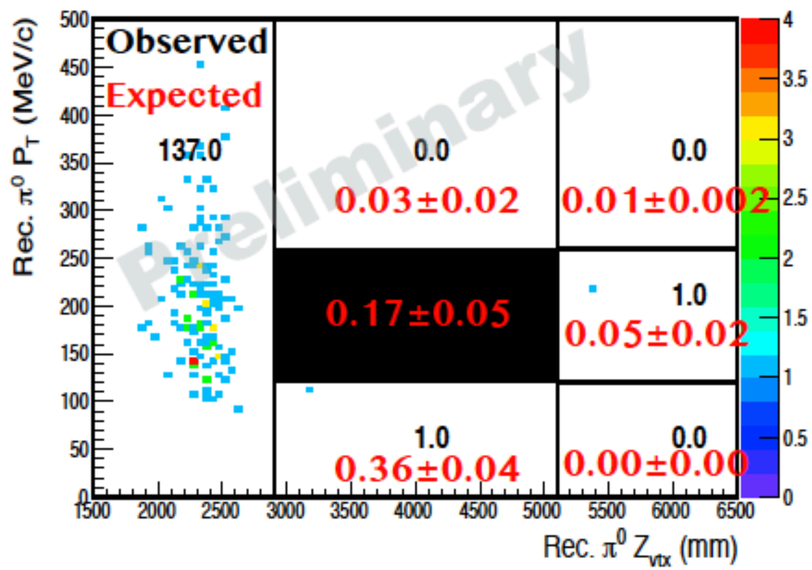
KOTO 2015 Analysis

Based on small subset (run62) of 2015-2016 statistics analysed

- ✓ $N(K_L)$ x1.6 of 2013 run
- ✓ Wider signal region because of better BG rejection
- ✓ Signal acceptance improved by 40%
- ✓ **SES ~ 5.9 x 10^{-9}**



BG in Box	#BG
$K_L \to \pi^0\pi^0$	0.04±0.03
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01
Upstream Events	0.04±0.04
Neutron Events	0.05±0.02
Other BG	Under Estimation



KOTO Prospects

BG in Box	Run62 #BG	Projected #BG
$K_L \to \pi^0\pi^0$	0.04±0.03	7.86
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01	7.86
Upstream	0.04±0.04	7.86
Neutron	0.05±0.02	9.83

Preliminary

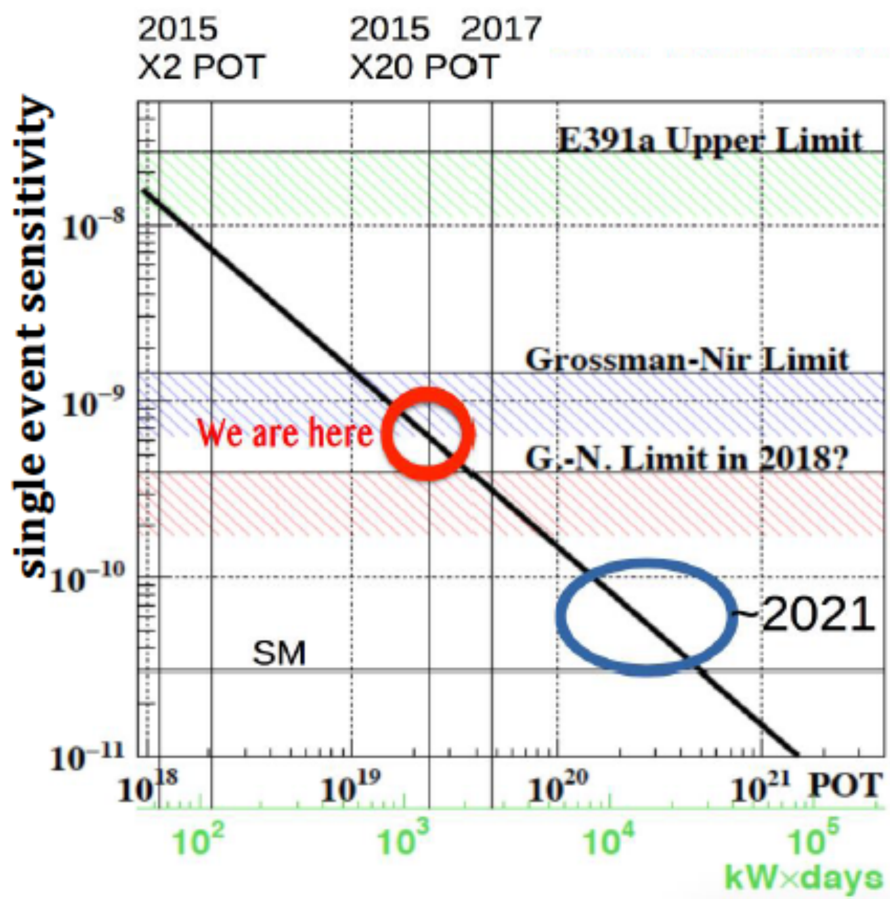
Projected background to SM sensitivity

Upgrades foreseen:

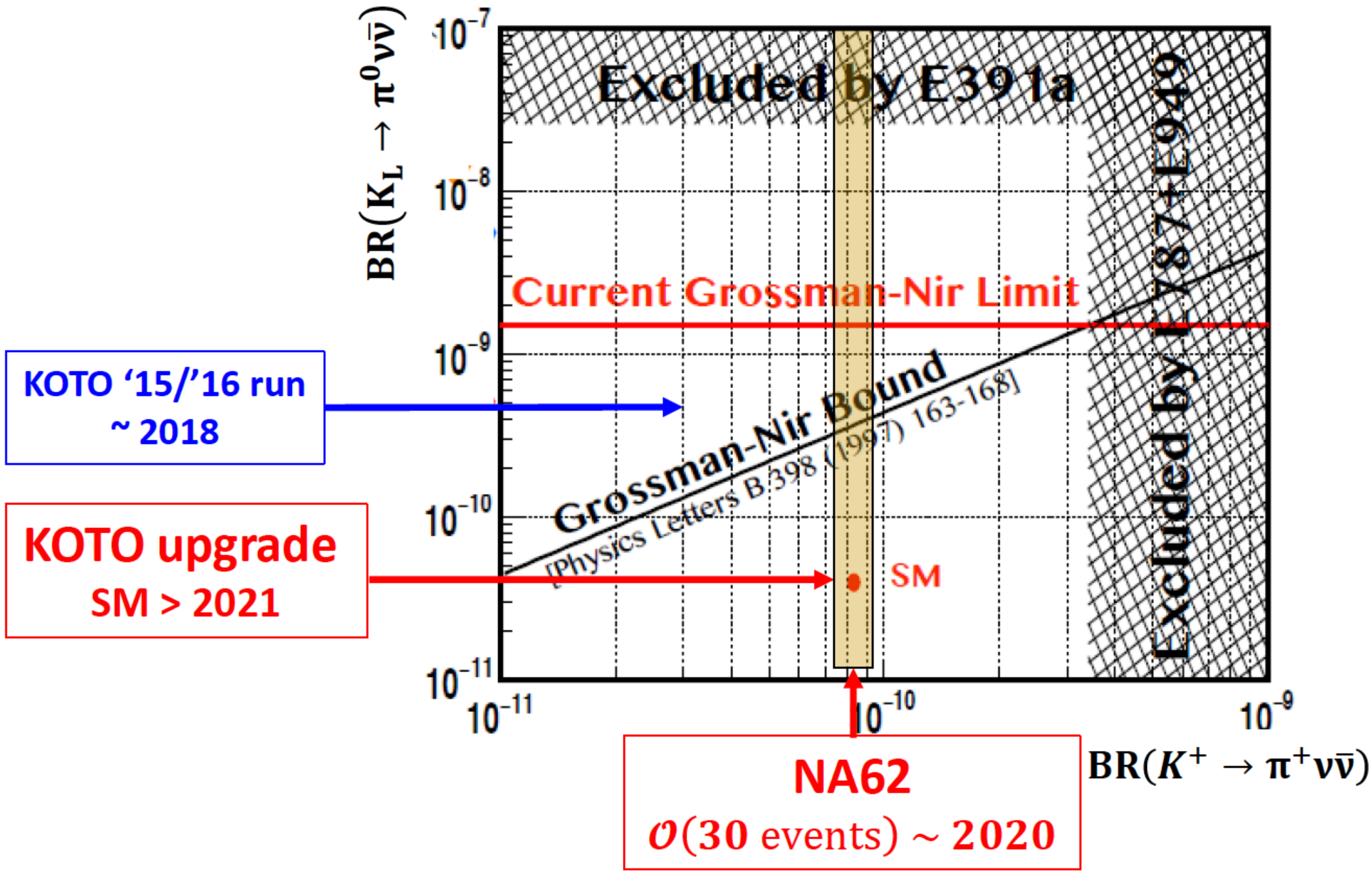
- ✓ New Barrel detector (April 2016)
- ✓ Beam pipe modification (ongoing)
- ✓ CsI both-end readout (2018)
- ✓ JPARC 42kW -> 100kW (2019)

KOTO 2015 - 2016 analysis: < 10^{-9} SES

Upgrades are needed to reach the SM



$K \to \pi \nu\bar{\nu}$ Prospects



Conclusions

- The novel NA62 decay-in-flight technique works
- SM sensitivity for $K^+ \to \pi^+ \nu\bar{\nu}$ reached with the completion of 2016 data analysis
- One event observed in 2016 data (expect 0.3 SM in R1+R2)

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

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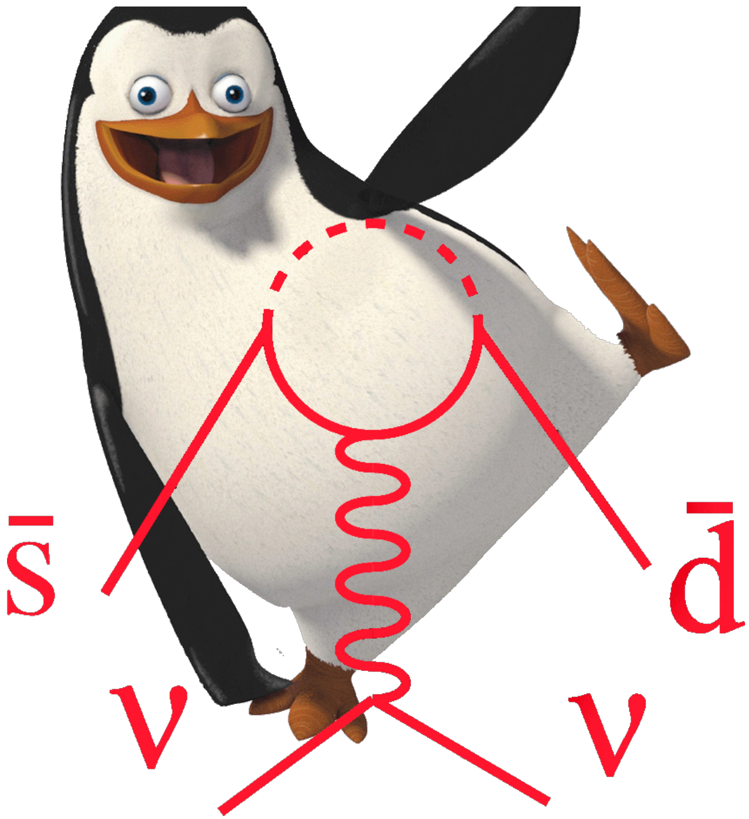
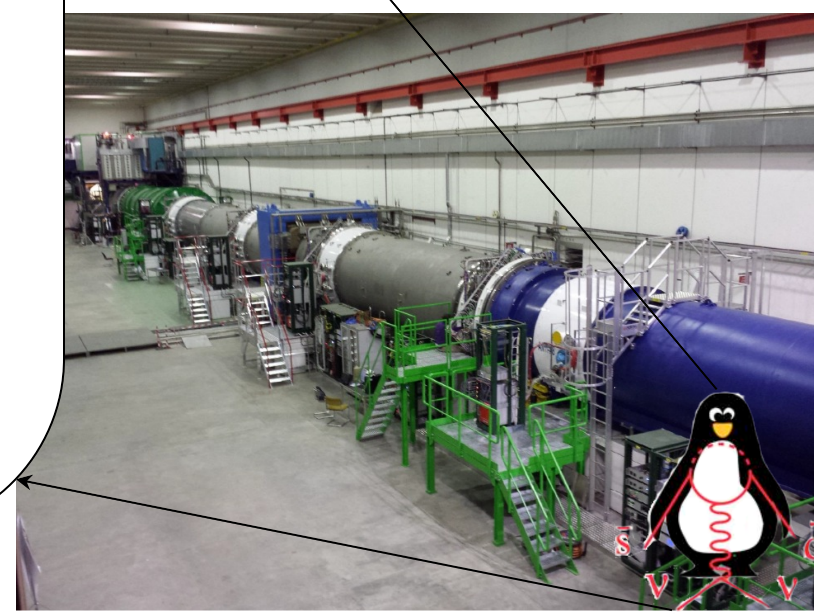
- $K^+ \to \pi^+ \nu\bar{\nu}$: NA62 measurement expected in the next few years
- $K_L \to \pi^0 \nu\bar{\nu}$: KOTO expected to reach $<10^{-9}$ sensitivity soon; SM sensitivity expected by 2021
- **Both experiments are running and data analysis is ongoing**

Conclusions

Stay Tuned !





BEAUTY 2018

6 - 11 May 2018, La Biodola, Isola d'Elba, Italy

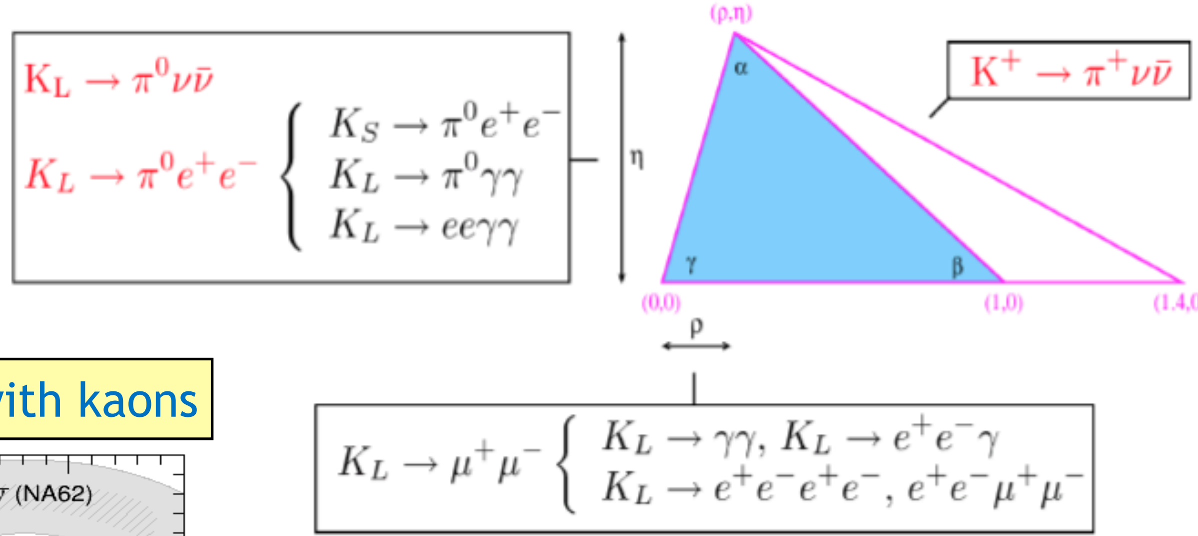
SPARES

Angela Romano, on behalf of the NA62 collaboration

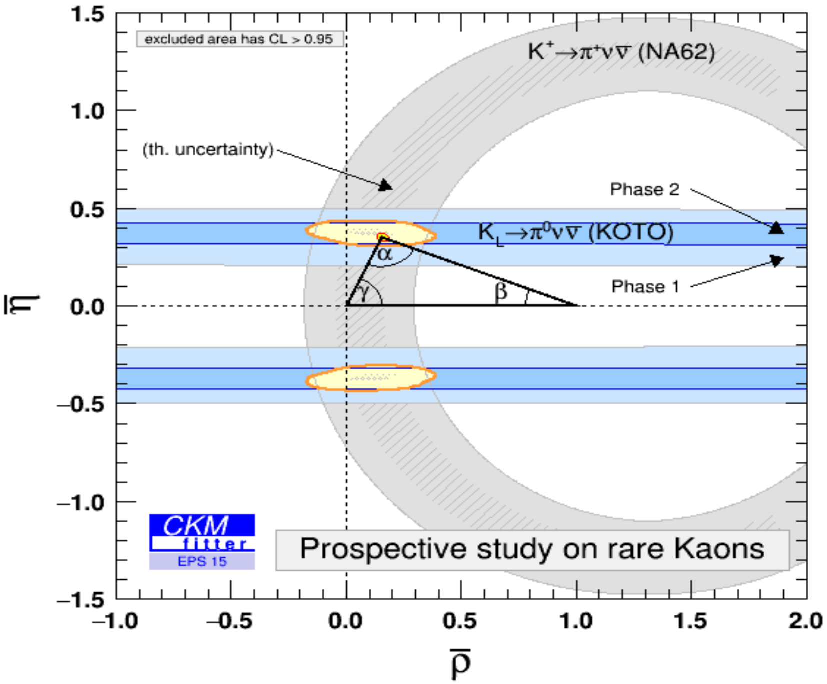
Angela Romano, University of Birmingham (axr@hep.ph.bham.ac.uk)

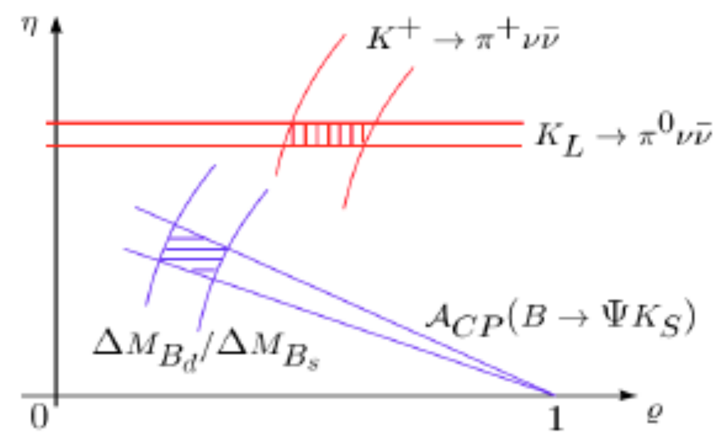
CKM Triangle

Kaons alone
can fully constrain
the CKM triangle



CKM unitarity triangle with kaons





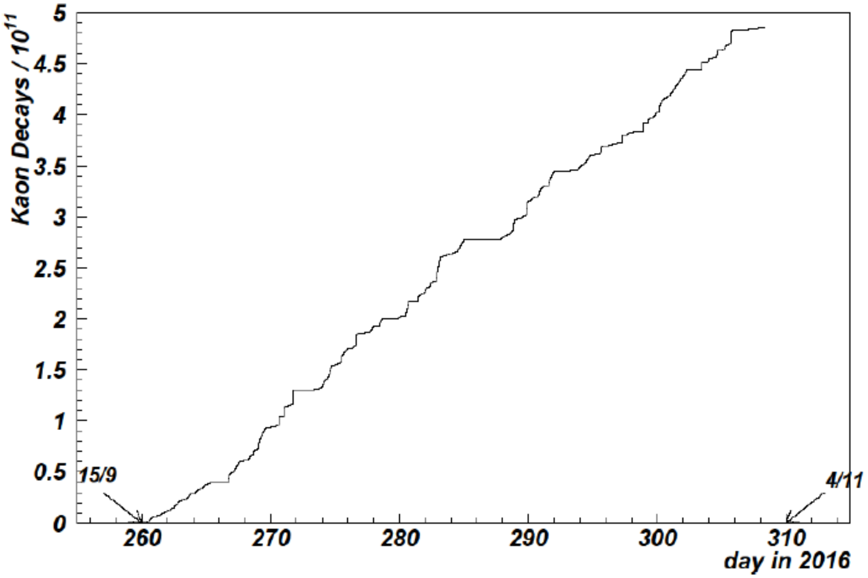
Comparison with B physics can provide hints on NP dynamics

NA62 "Luminosity"

2016 run

13×10^{11} ppp on target (40% nominal)

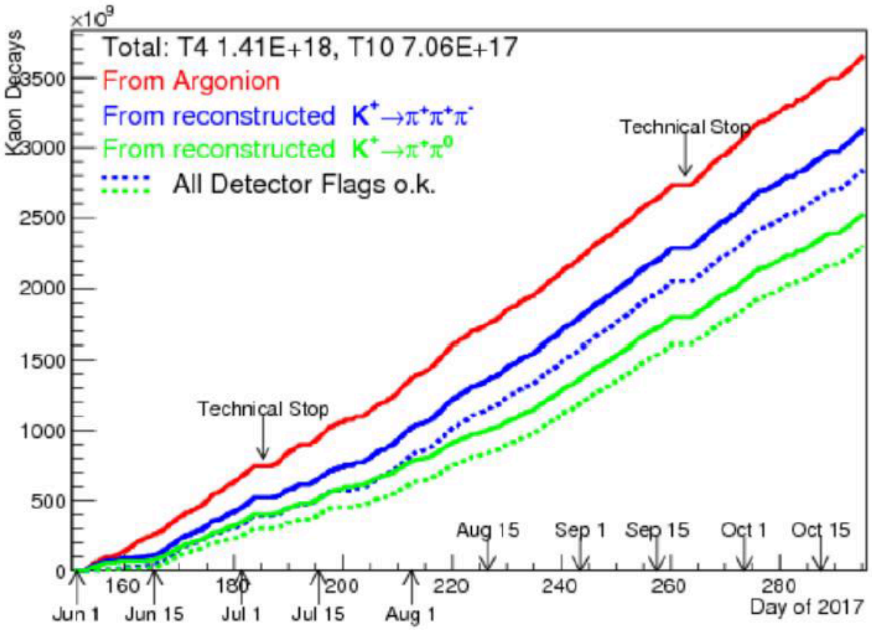
$\sim 1 \times 10^{11}$ K^+ decays useful for $\pi\nu\nu$



2017 run

20×10^{11} ppp on target (60% nominal)

$> 3 \times 10^{12}$ K^+ decays collected



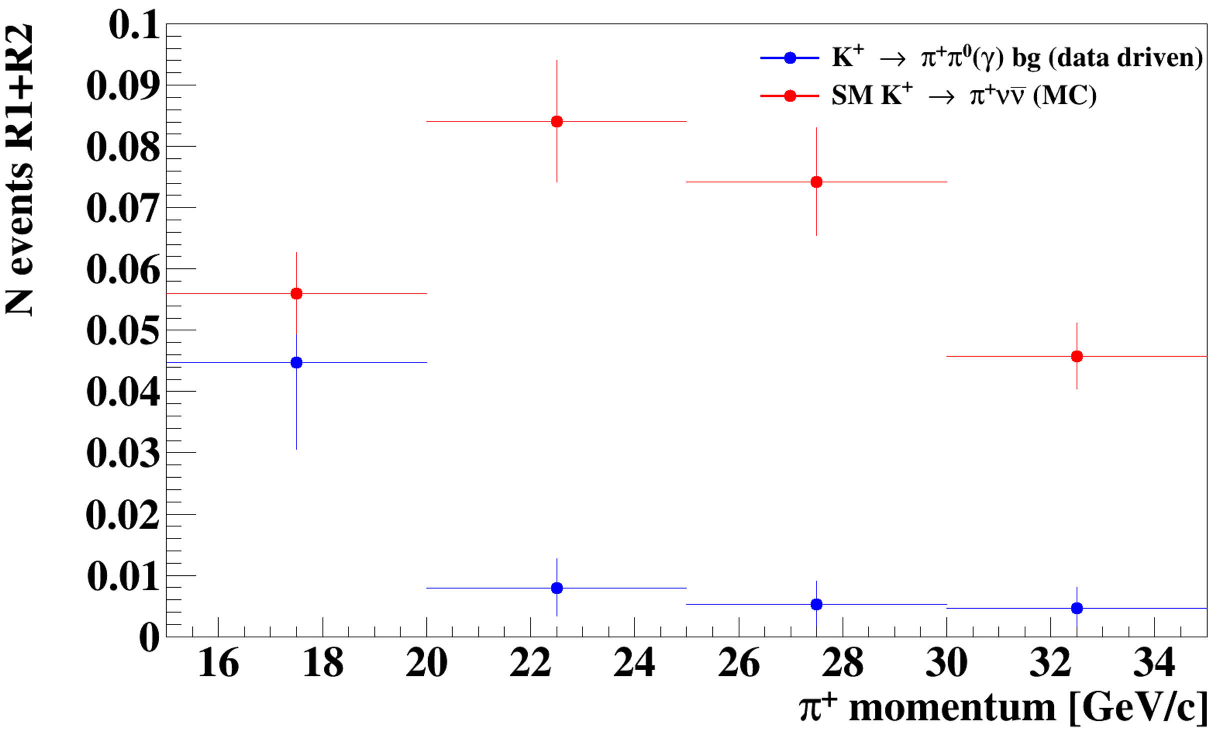
Single Event Sensitivity Results

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

Acceptance $K^+ \rightarrow \pi^+ \nu \bar{\nu}$	4.0 ± 0.1
PNN trigger efficiency	0.87 ± 0.2
Random veto	0.76 ± 0.04

Source	δSES (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 $\pi+$ interactions	± 0.09
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

$K^+ \to \pi^+\pi^0(\gamma)$ Background

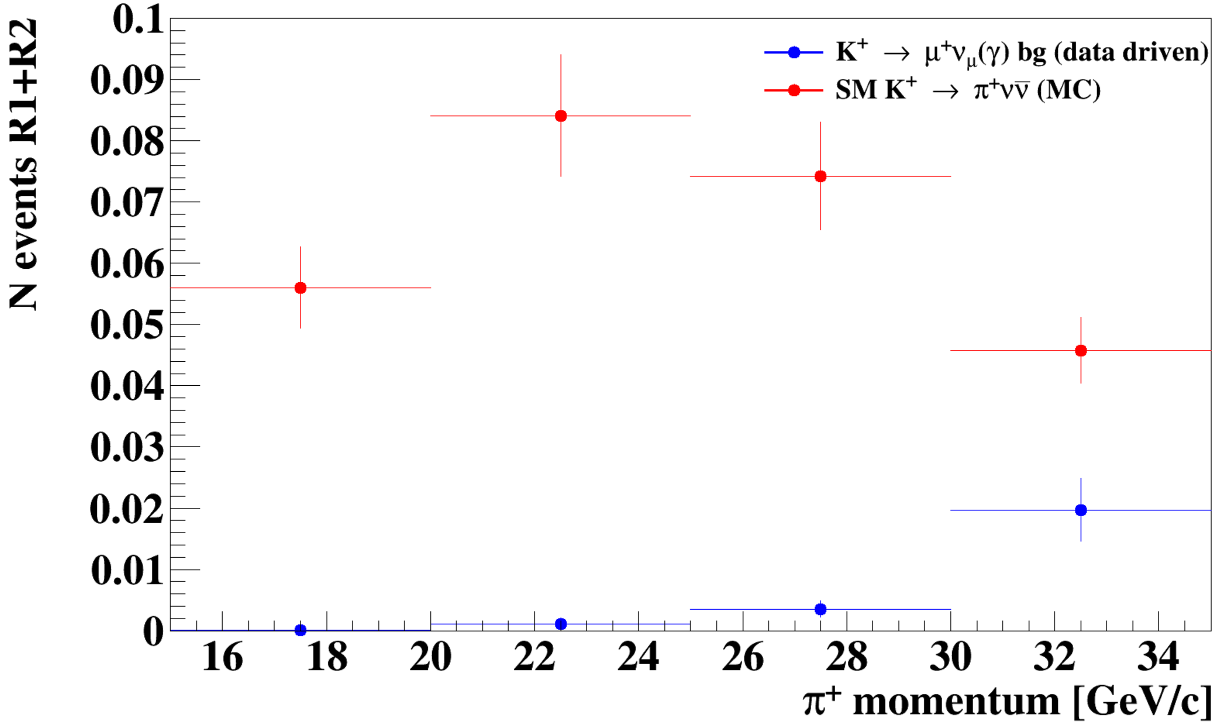


Data driven background estimation

Validation with control region: 1 event observed (1.5 expected)

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

$K^+ \to \mu^+\nu_\mu(\gamma)$ Background



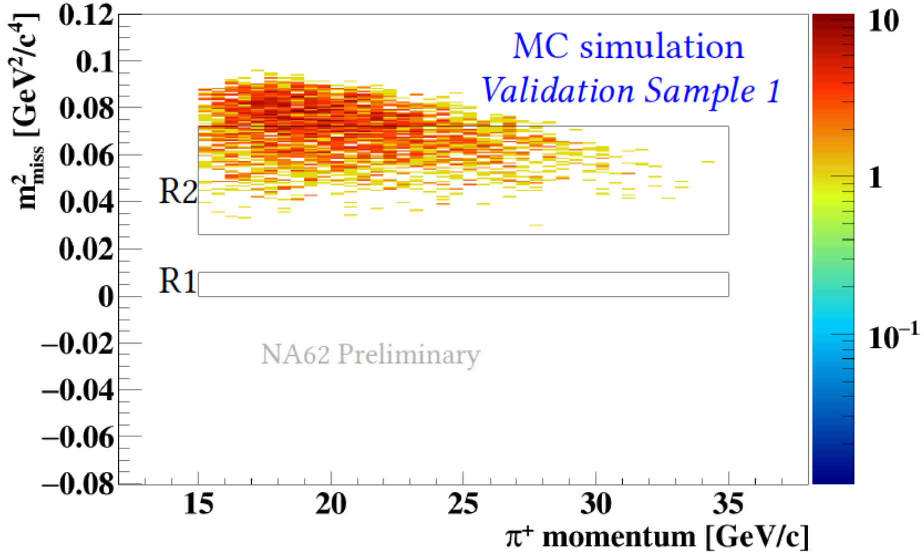
Data driven background estimation

Validation with control region: 2 event observed (1.1 expected)

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

$K^+ \to \pi^+\pi^- e^+\nu_e$ Background

R.Marchevski @ Moriond EW2018



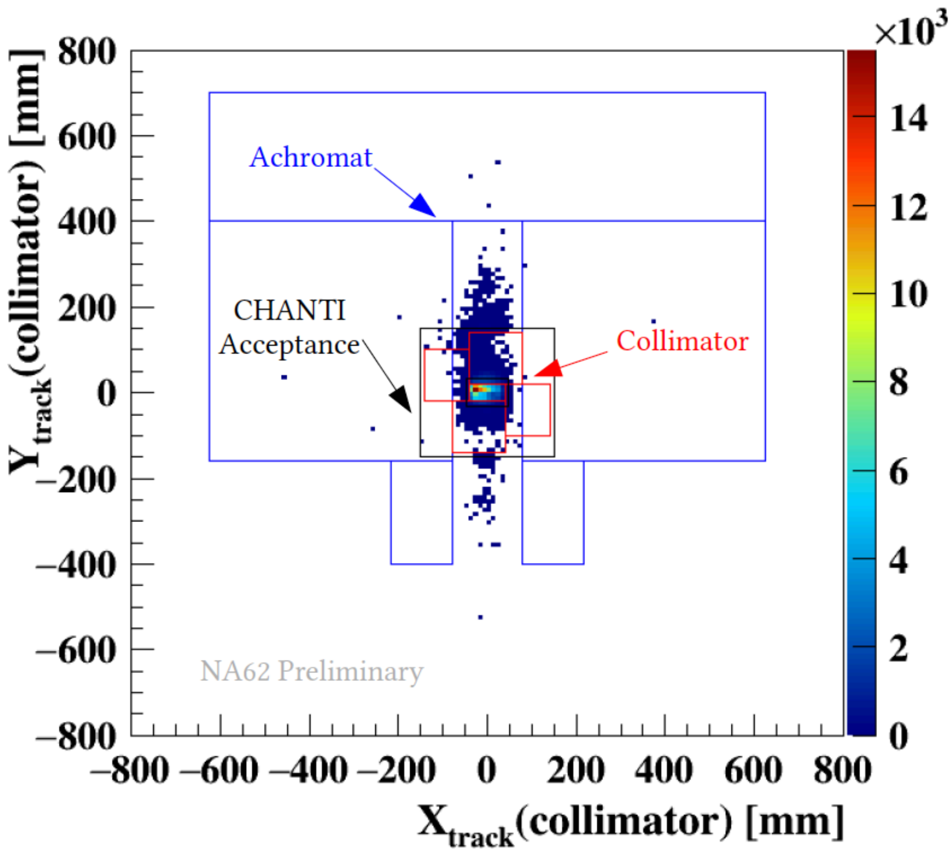
Validation sample	N expected	N observed
1	15.5(4)	8
2	4.0(4)	2
3	3.2(2)	3
4	0.7(1)	1
5	1.2(1)	5

- Background estimated with 400 million MC generated $K^+ \to \pi^+\pi^- e^+\nu_e$ decays
- Good agreement across the 5 validation samples

$$N^{bg}_{K_{e4}} = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$$

Upstream background

R.Marchevski @ Moriond EW2018



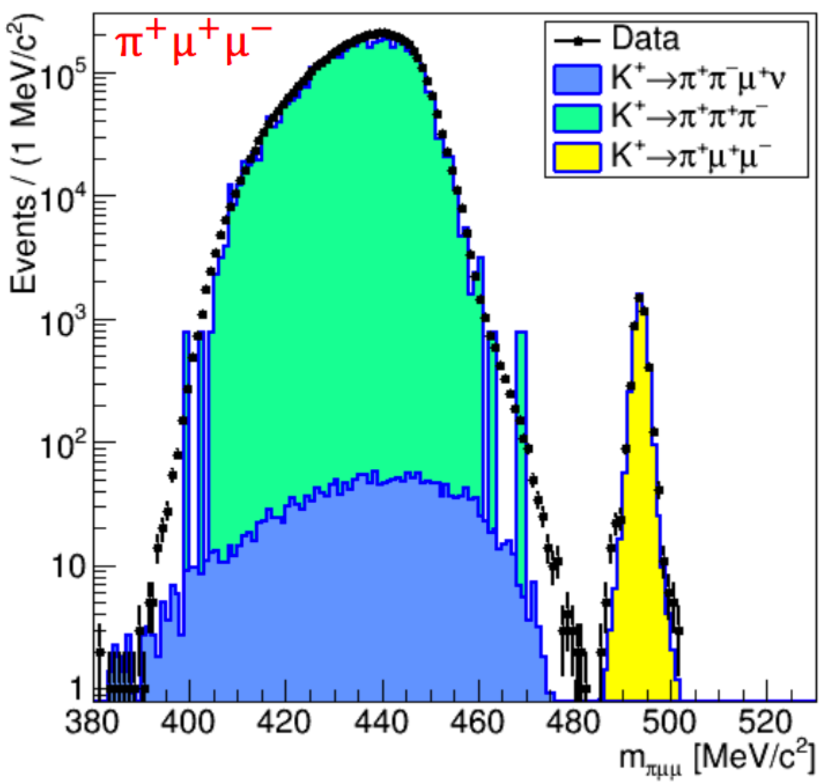
- Accidental particles from the beam line
- Pions from interactions with beam spectrometer material
- Kaon-pion matching and geometrical cuts effective
- Data driven estimation

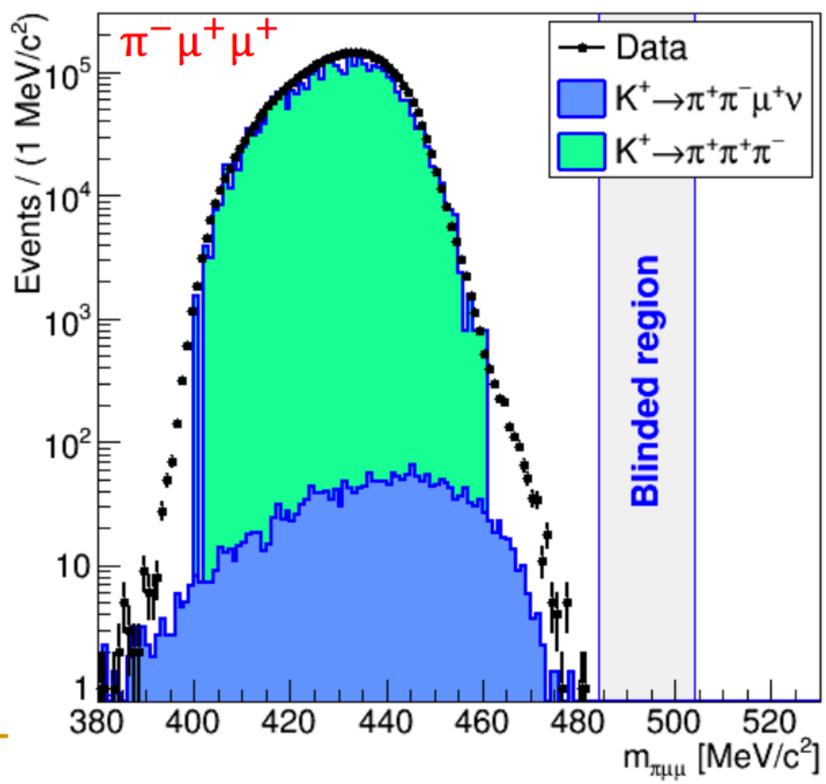
$$N^{bg}_{upstream} = 0.050^{+0.090}_{-0.030}$$

$K^+ \to \pi^+\mu^+\mu^+$

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

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

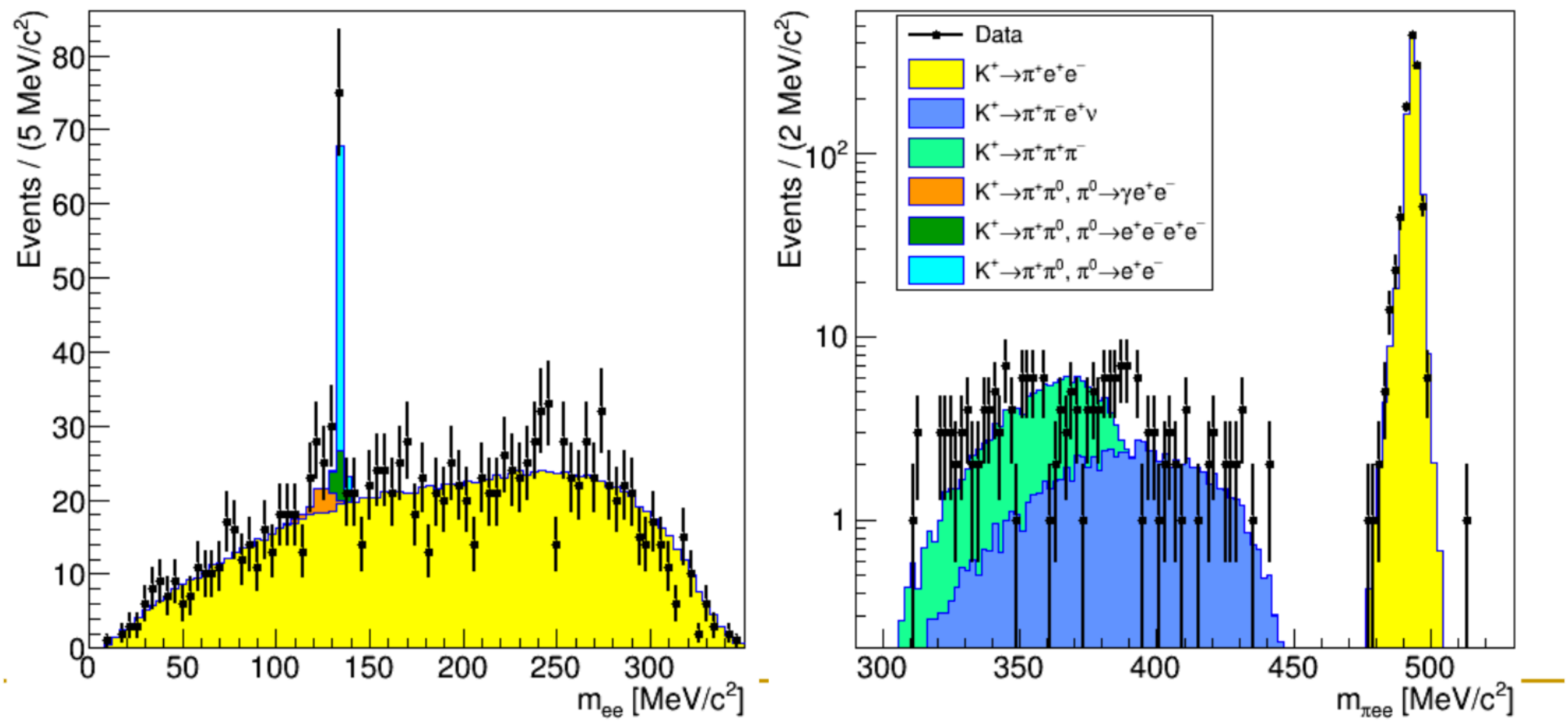




$K^+ \rightarrow \pi^+ e^+ e^+$

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

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



$K^+ \rightarrow e^+\nu$: Lepton Universality

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]

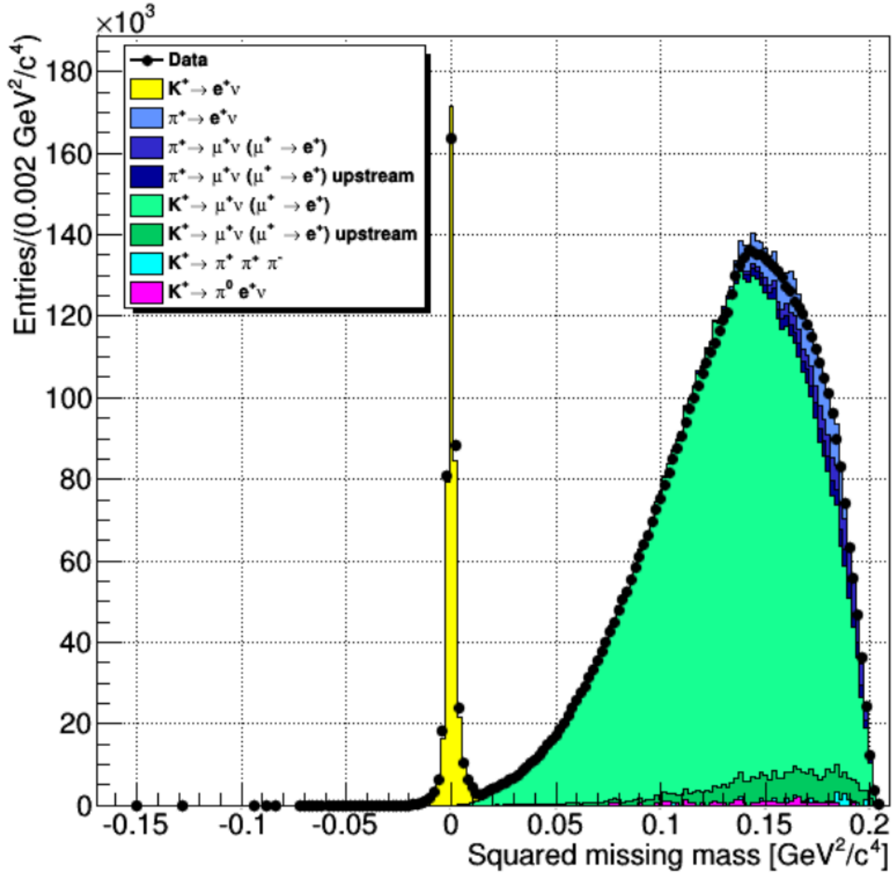
- Experimental Status (2007 NA62):

  $R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

  [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



- Search for HNL production in $K^+ \rightarrow l^+\nu$ in progress [result from 2015 data: Phys. Lett. B778 (2018) 137]