πνν From NA62 and KOTO

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First Forum on Rare Kaon Decays

Edinburgh, 22/02/2018

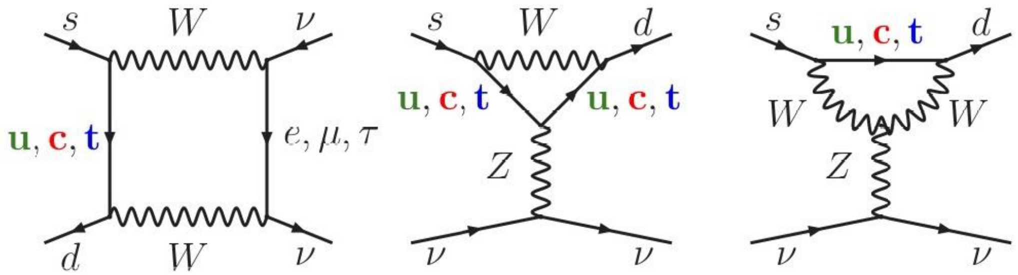
Contents

- Review of the present experimental status of the $K \rightarrow \pi\nu\bar{\nu}$ decays
  - $K^+ \rightarrow \pi^+\nu\bar{\nu}$: NA62 experiment at CERN
  - $K_L \rightarrow \pi^0\nu\bar{\nu}$: KOTO experiment at JPARC

- Future prospects on $K \rightarrow \pi\nu\bar{\nu}$

The K → πνν̄ decays: a theoretical clean environment

- FCNC loop processes: s→d coupling and highest CKM suppression



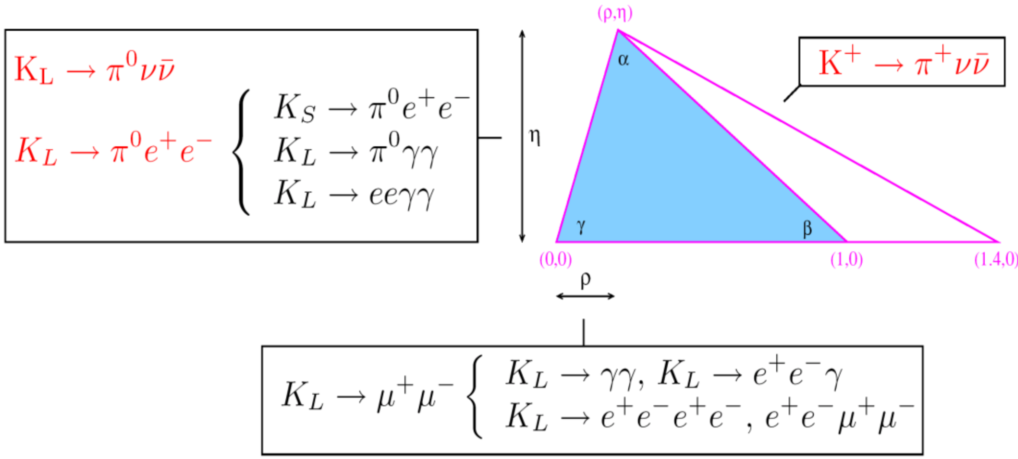
- Very clean theoretically: Short distance contribution. No hadronic uncertainties.

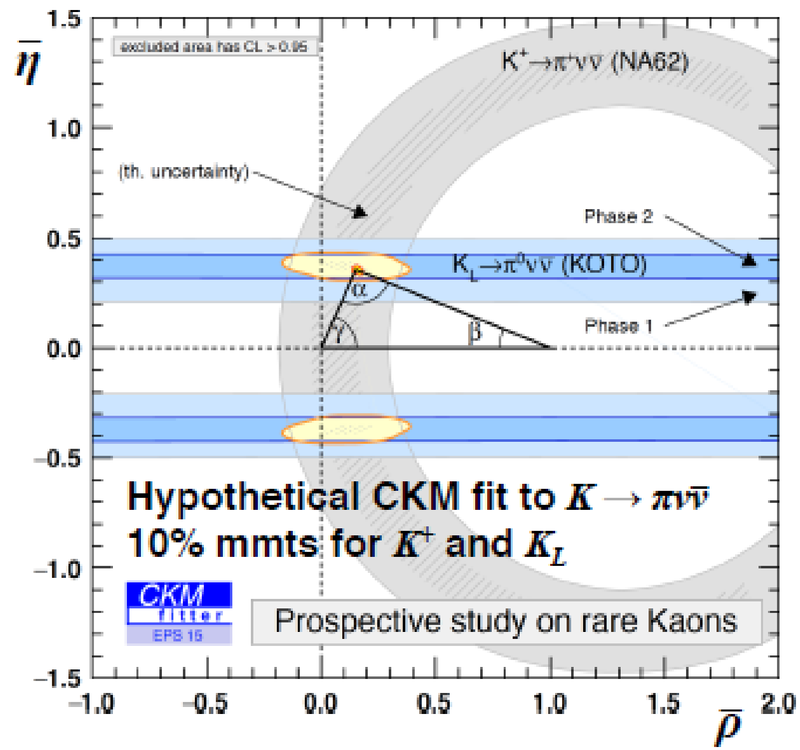
- SM predictions [Buras et al. JHEP 1511 (2015) 33]

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

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6) \cdot 10^{-11}$$

Connection with Flavour Physics





K physics alone can fully constraint the CKM unitarity triangle.

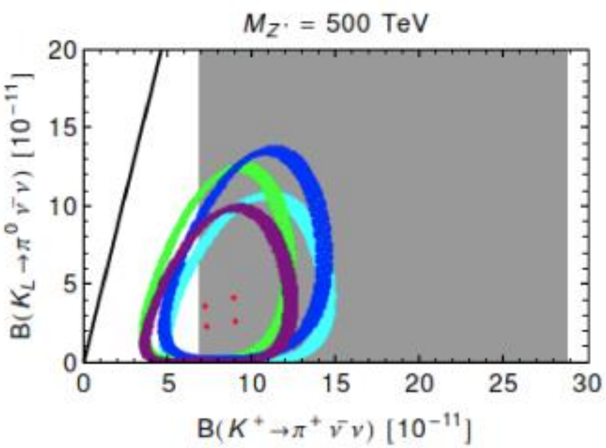
Comparison with B physics can provide description of NP flavour dynamics

$K \to \pi\nu\bar{\nu}$ NP Sensitivity

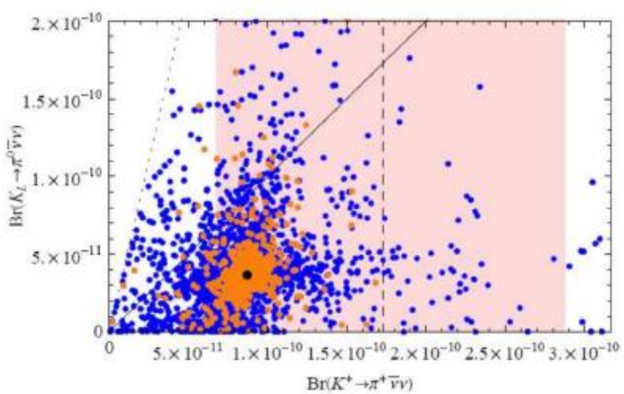
- Simplified Z, Z’ models [Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV [Tanimoto, Yamamoto arXiv:1603.0796, Isidori et al. JHEP 0608 (2006) 064]

- Constraints from existing measurements (correlations model dependent):
  - Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches

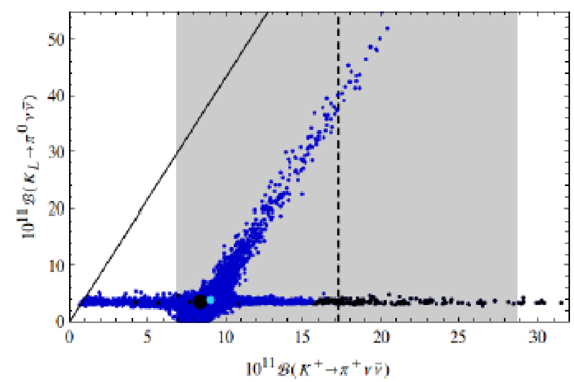
Z’ model



Randall - Sundrum

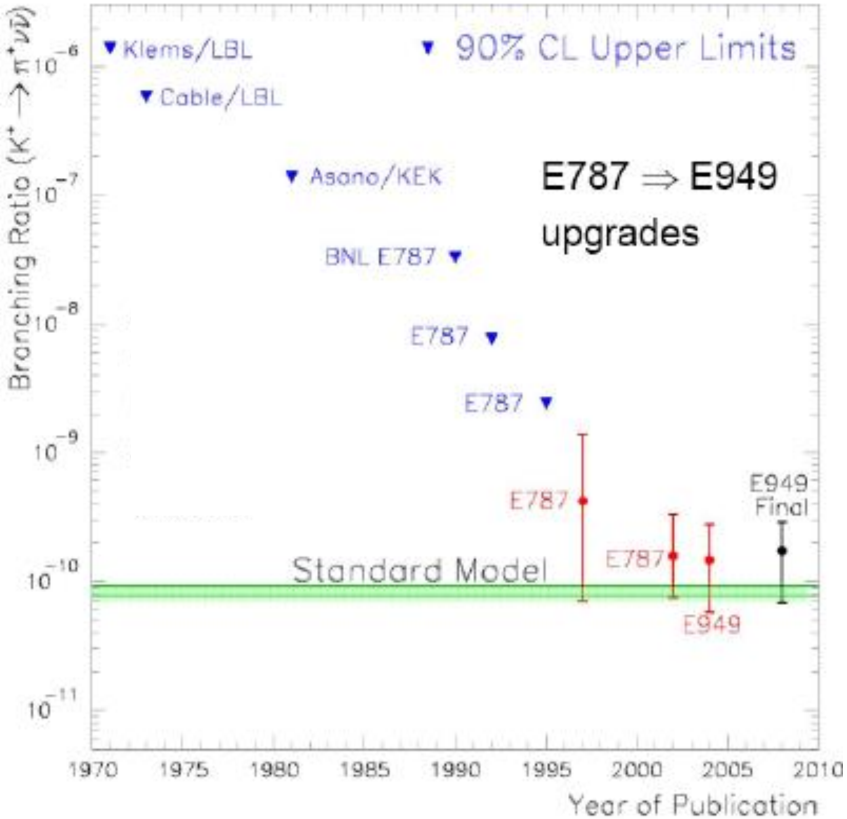


Littlest Higgs

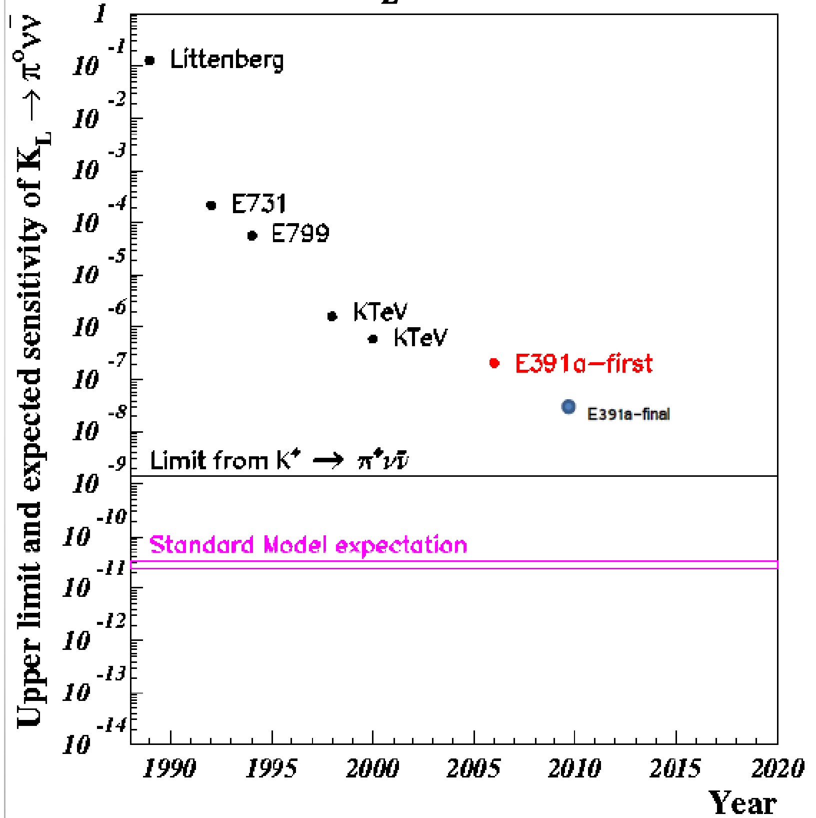


$K \to \pi\nu\bar{\nu}$ Experimental State of the Art

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



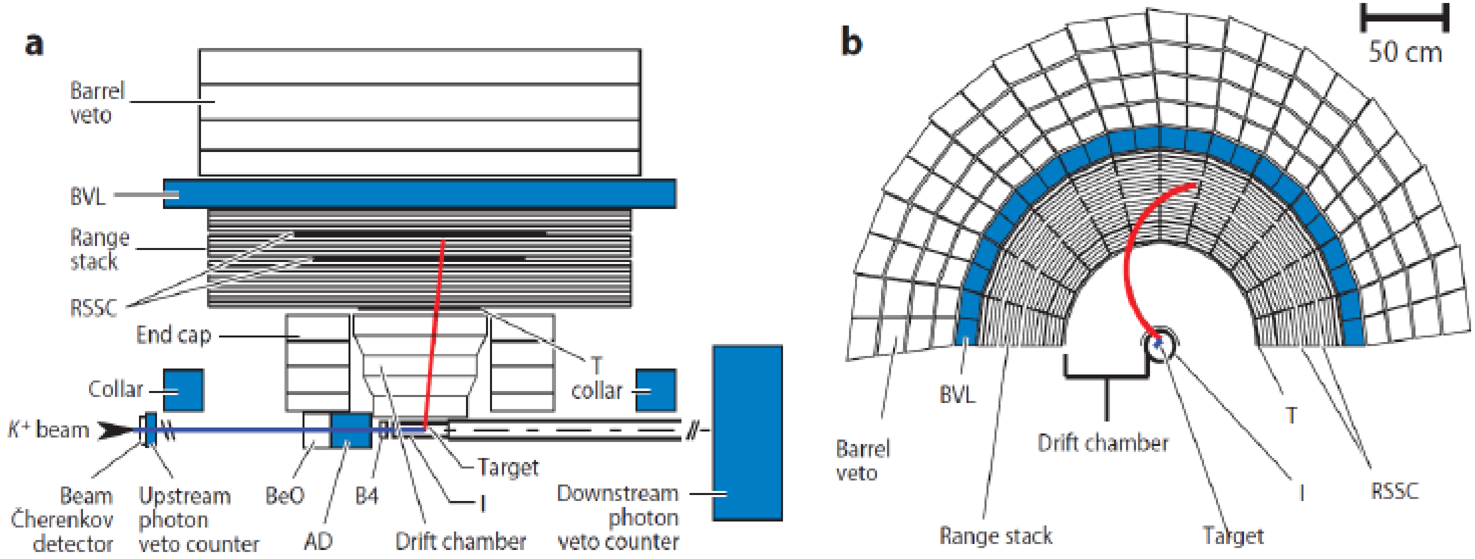
$K_L \to \pi^0\nu\bar{\nu}$



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

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

$K^+ \to \pi^+ \nu\bar{\nu}$: E787 / E949

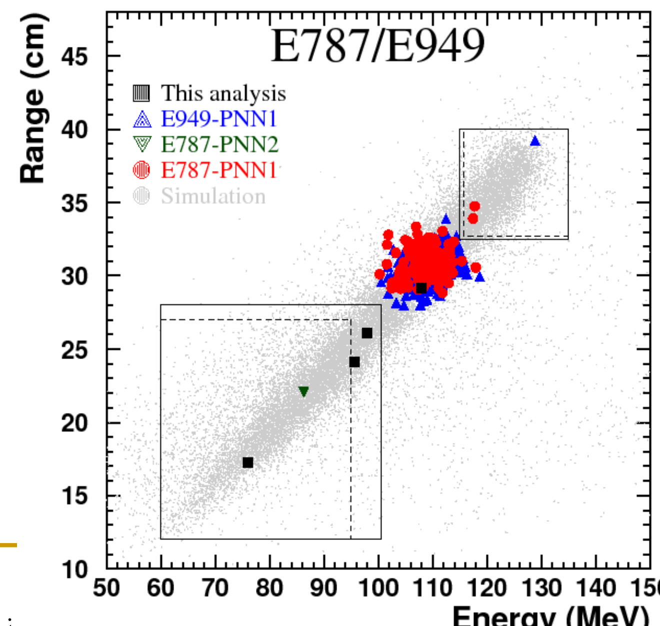


Signal efficiency: 3×10^{-3}

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

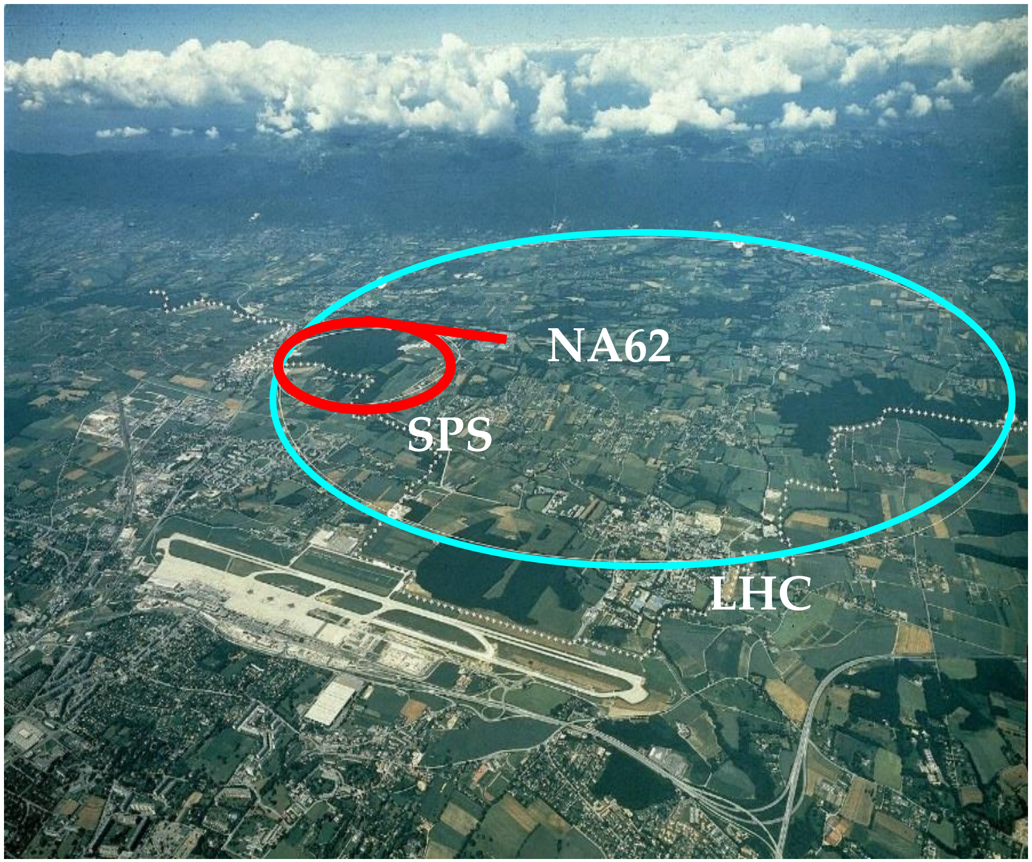
Phys. Rev. D 77, 052003 (2008)

Phys. Rev. D 79, 092004 (2009)



NA62 @ CERN - SPS

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



Primary goal:

$\mathcal{O}(10\%)$ precision BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)

Requirements:

- Statistics: O(100) events
- K decays 10^{13}
- Signal acceptance ~ 10%
- $>10^{12}$ background rejection

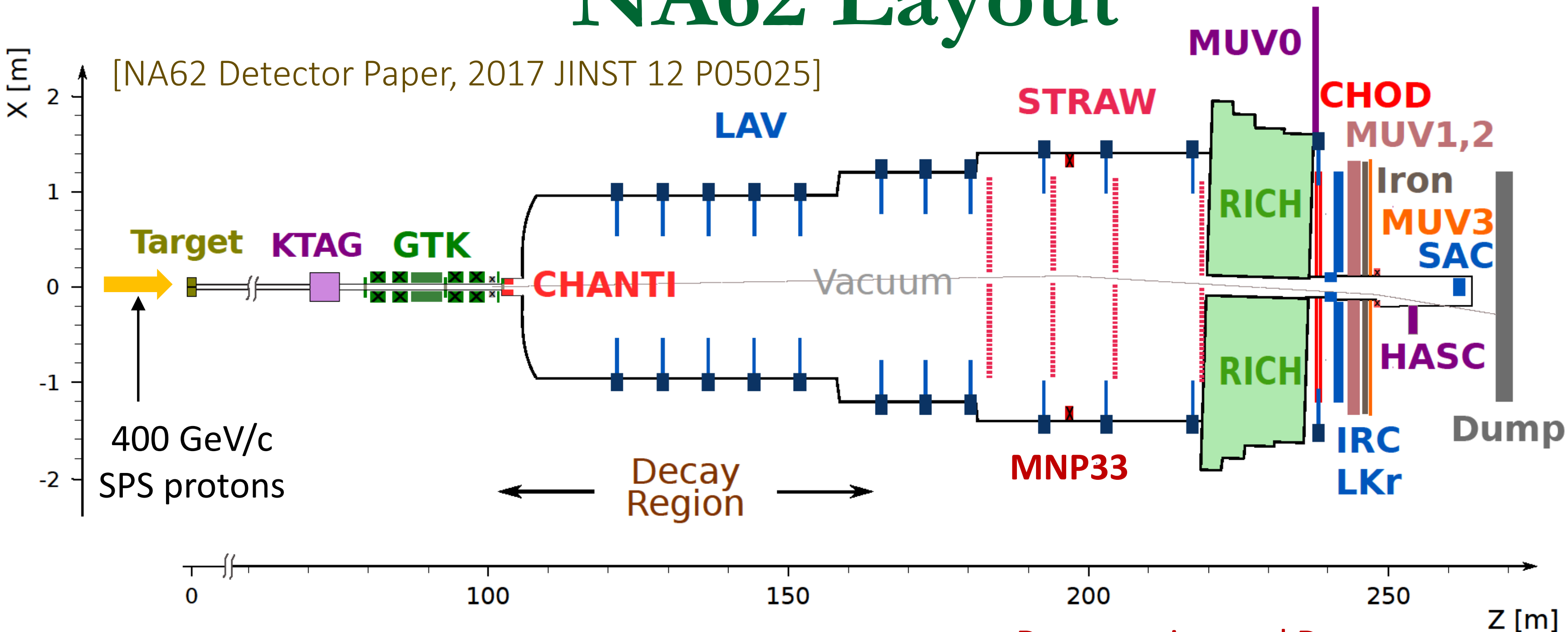
Technique:

K Decay – in – flight

Broader Physics program:

- LFV – LNV in K^+ decays
- Hidden sector particles searches

NA62 Layout



Secondary positive beam

Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 μrad
Transverse Size	$60 \times 30 mm^2$
Composition	$K^+(6\%)/\pi^+(70\%)/p(24\%)$
Nominal Intensity	33×10^{11} ppp (750 MHz at GTK3)

Decay region and Detectors

Fiducial region	60 m
K^+ decay rate	$\sim$ 5 MHz
Vacuum	$\mathcal{O}(10^{-6})$ mbar

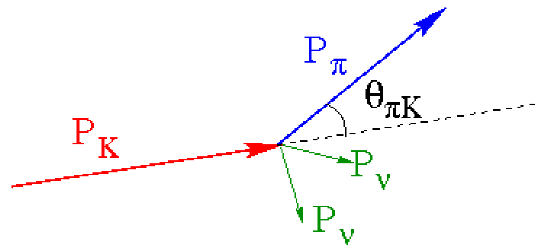
Si pixel beam tracker + Straw tracker

LKr Calorimeter from NA48

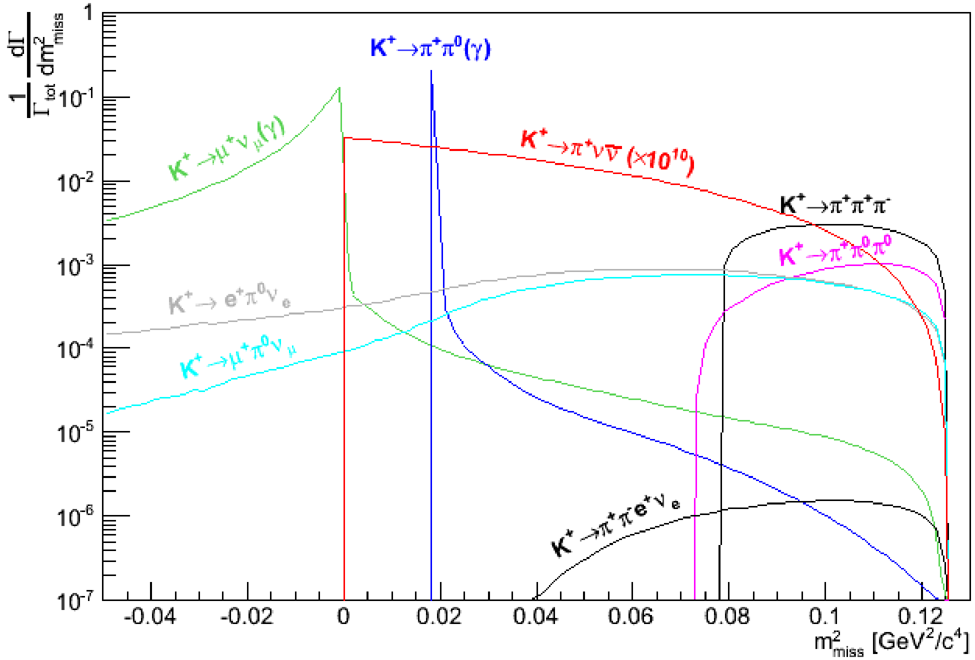
Cerenkov counter for K id, RICH for π/μ id

NA62 $K^+ \to \pi^+ \nu\bar{\nu}$: Analysis Method

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



Process	*Branching ratio*
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558



+

$15 < P_{\pi^+} < 35$ GeV/c

Particle ID (Cherenkov detectors)

Particle ID (Calorimeters)

Photon veto

NA62 Keystones

$\mathcal{O}(100\ \mathrm{ps})$	Timing between sub-detectors
$\mathcal{O}(10^4)$	Background suppression from kinematics
$> 10^7$	Muon suppression
$> 10^7$	π^0 (from $K^+ \rightarrow \pi^+\pi^0$) suppression

Analysis steps

- K^+ Decay Event
- Fiducial Decay Region
- Particle ID: π^+
- Photon rejection & Multiple charged particle rejection
- Kinematic Selection of the Signal Regions

NA62 Runs

2014	Pilot run
2015	Commissioning run
2016	Commissioning + Physics run
2017	Physics run
2018	210 days Physics run scheduled

NA62 «Luminosity»

2016 run

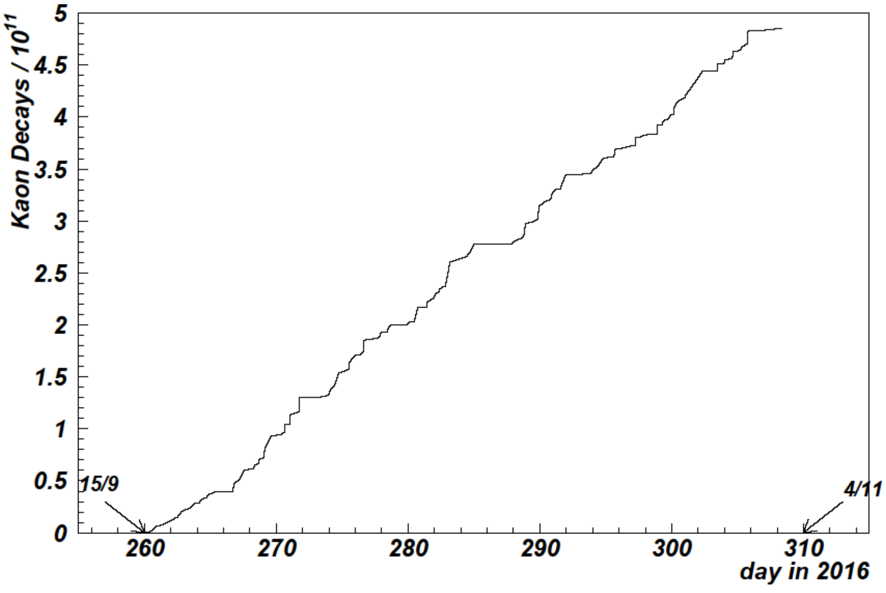
13×10^{11} ppp on target (40% nominal)

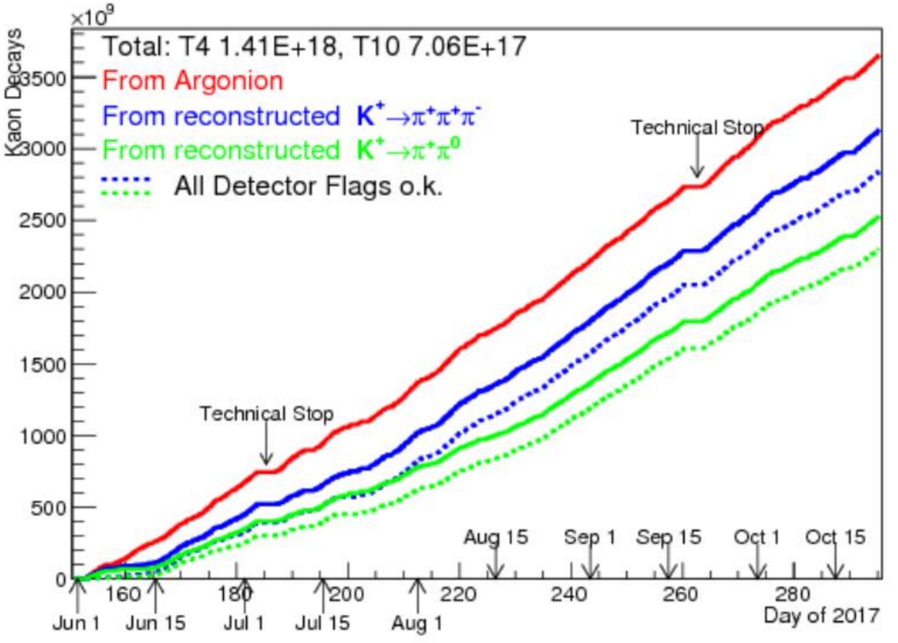
$\approx 2 \times 10^{11}$ K^+ decays useful for $\pi^+\nu\bar{\nu}$

2017 run

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

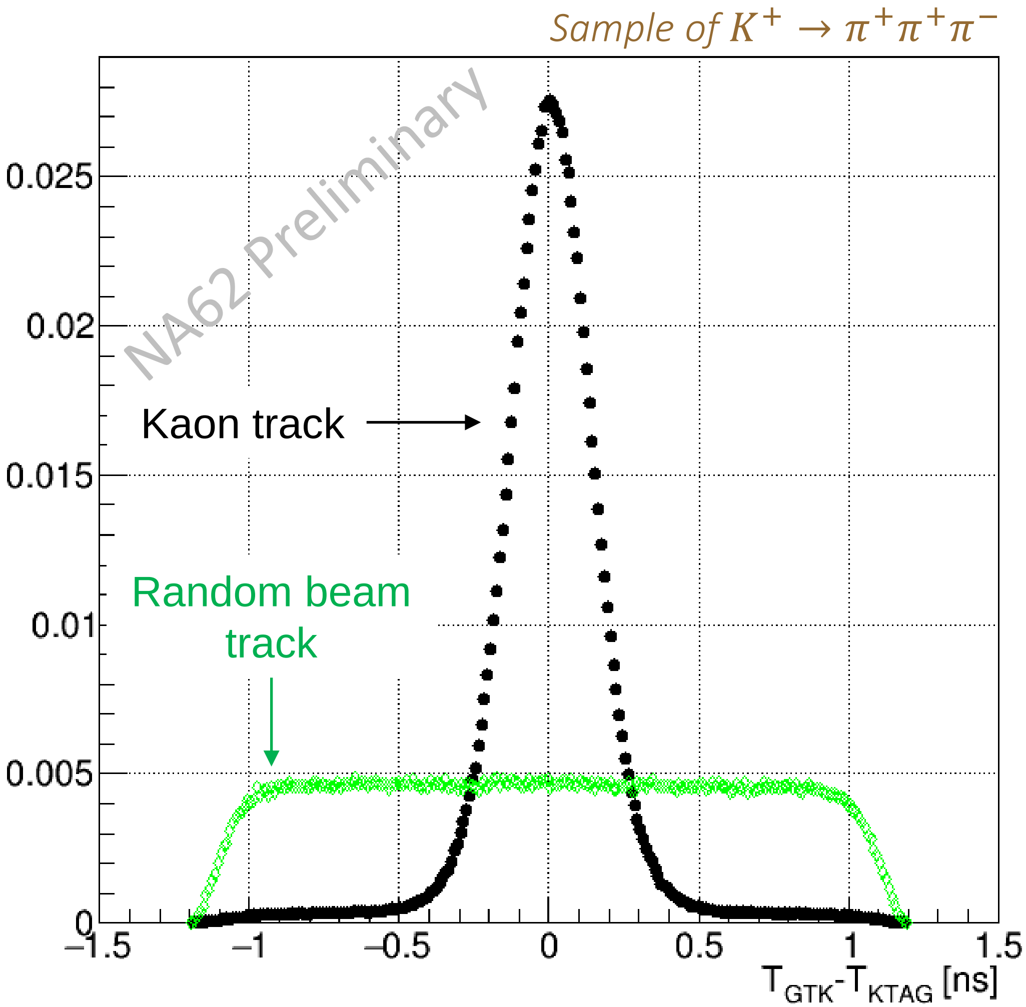
$2 \div 3 \times 10^{12}$ K^+ decays collected





Preliminary results of the analysis of 2×10^{10} K^+decays from 2016 data presented [$\mathcal{O}(10\%)$ 2016 data]

NA62: K/π matching



Timing π^+:

$\sigma(T_{CHOD})\sim250$ ps, $\sigma(T_{RICH})\sim150$ ps

Timing K^+:

$\sigma(T_{KTAG})\sim80$ ps, $\sigma(T_{GTK})\sim100$ ps

Spatial matching:

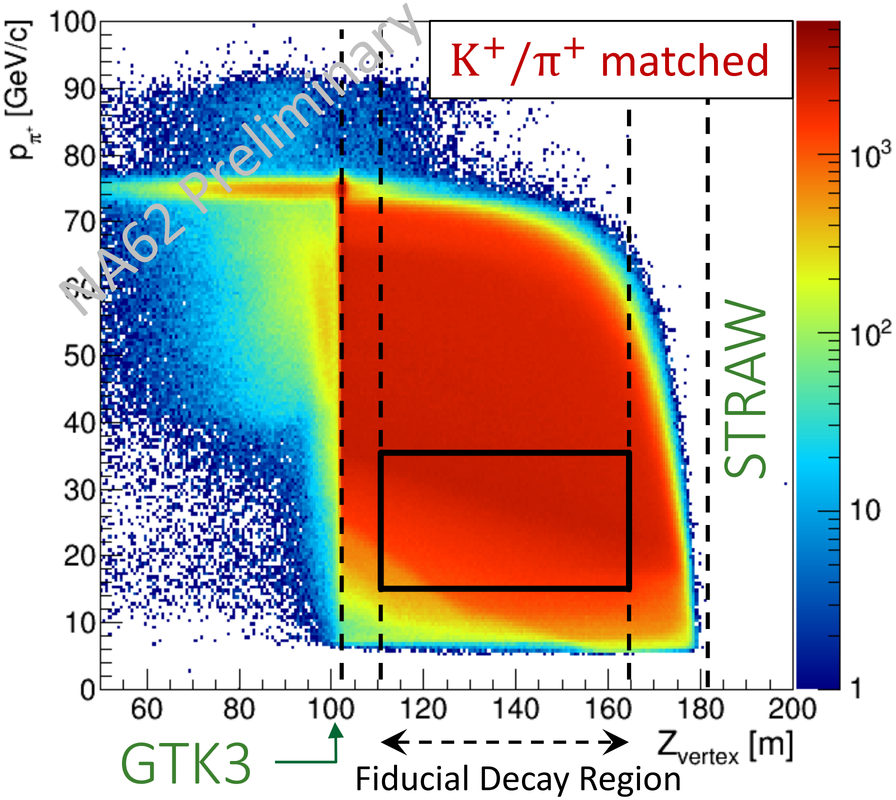
intersection of GTK and Straw track

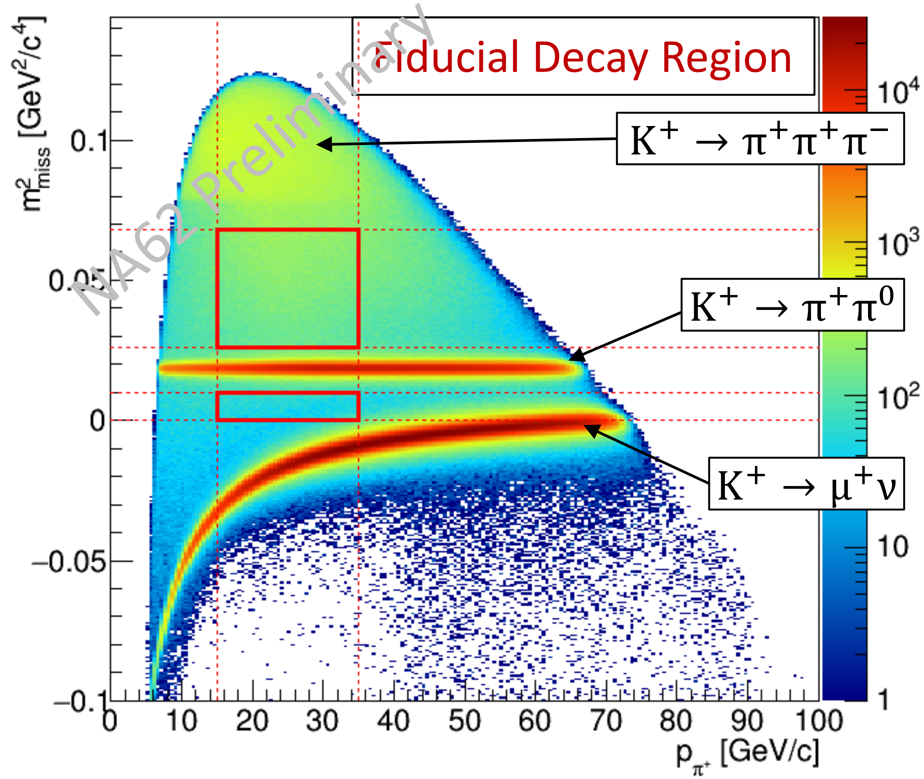
$\sigma(CDA)\sim1.5$ mm

Mis-tagging probability: ~1.7%

[75% efficiency]

NA62: Signal Regions



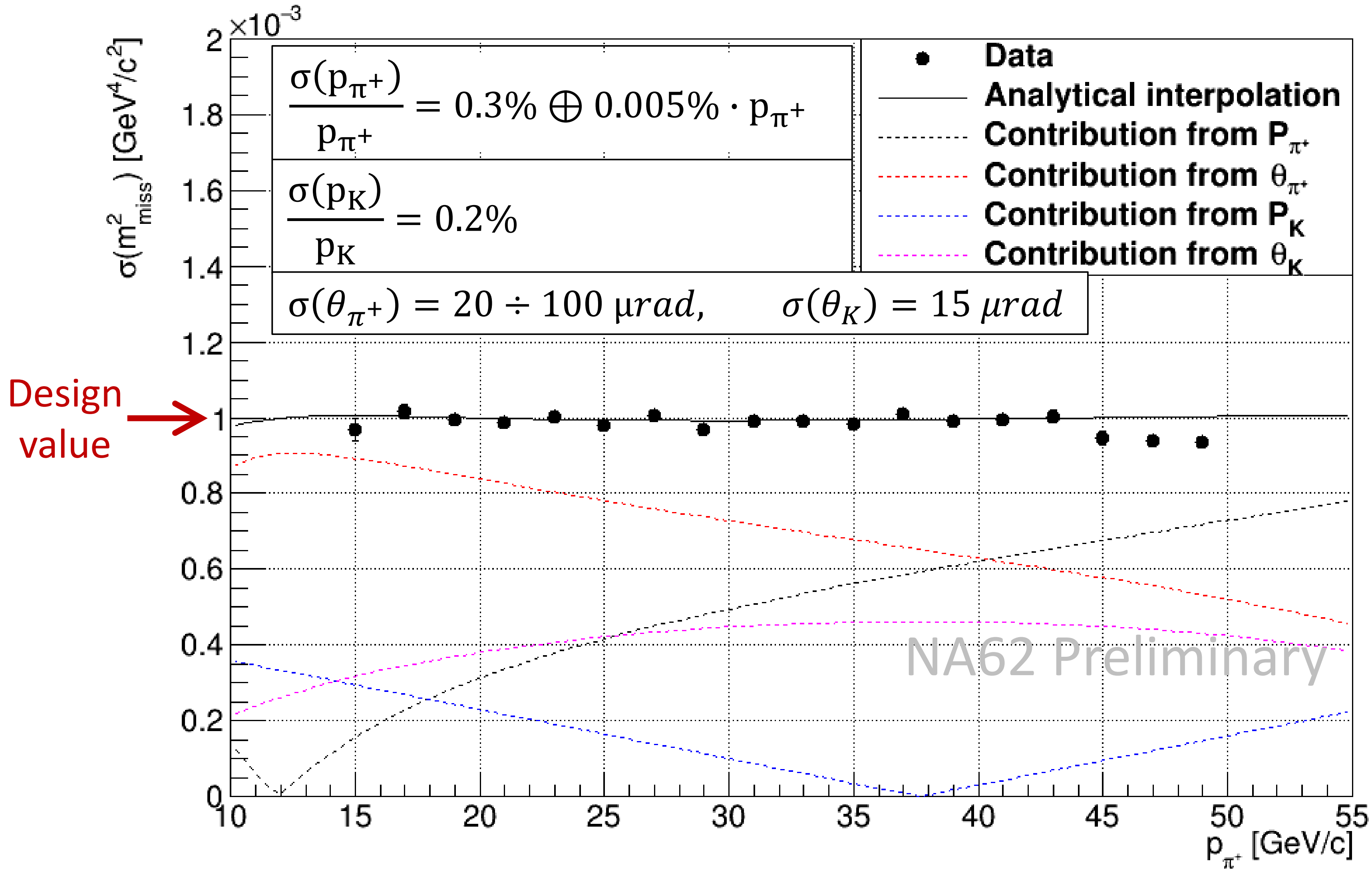


- K^+ decays between GTK3 and Straw
- K^+ decays before GTK3
- Beam particle interactions in GTK3

- Signal region defined by:

$$Z_{vertex} - p_{\pi^+} - m^2_{miss}$$

m^2_{miss} Resolution

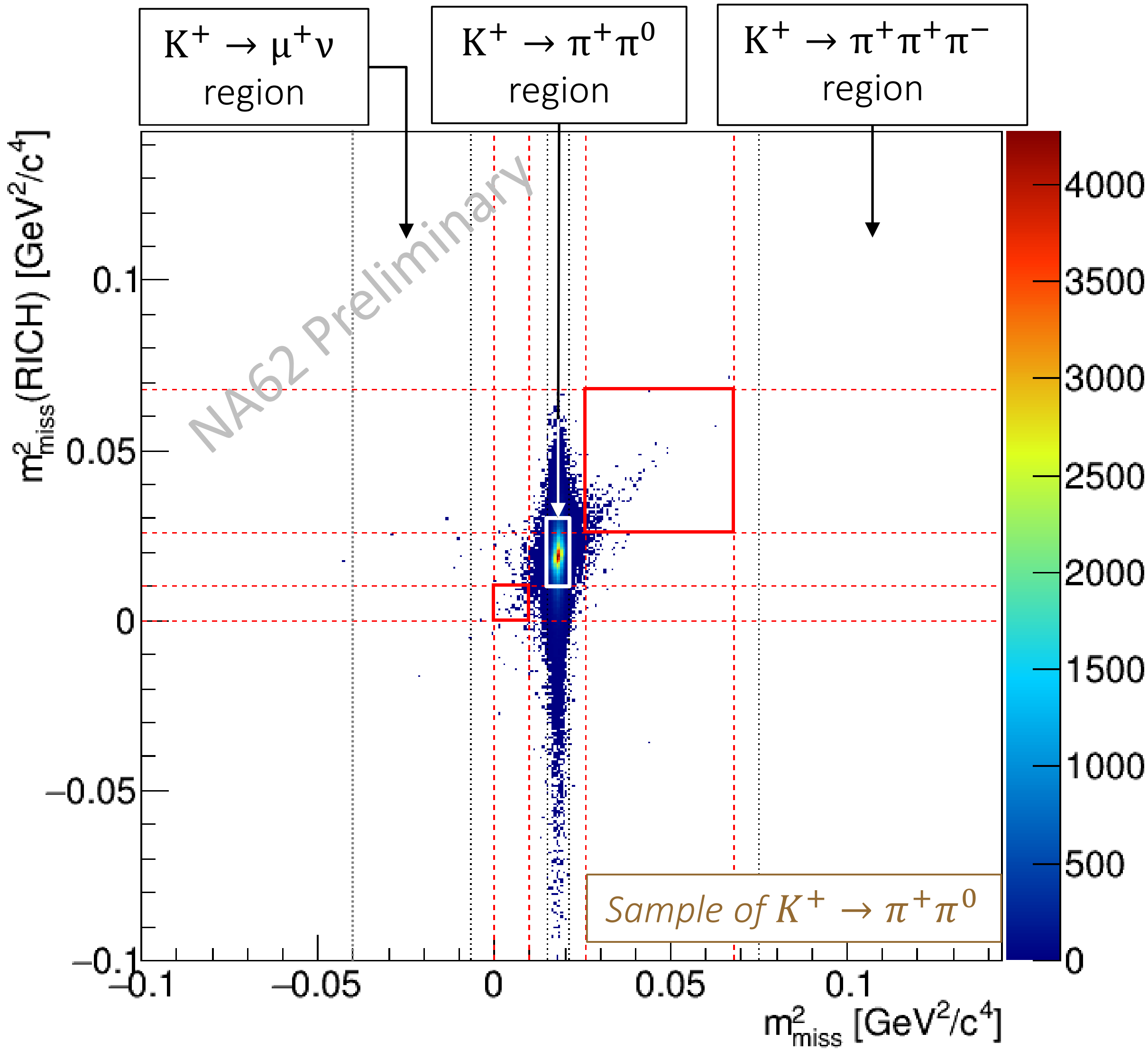


NA62: Kinematics and Backgrounds

m^2_{miss} , p_{π^+}

$m^2_{miss}(\mathrm{RICH})$ p_{π^+} RICH (m_{π^+})

$m^2_{miss}(\mathrm{No\ GTK})$ p_{K^+} nominal



Kinematical suppression

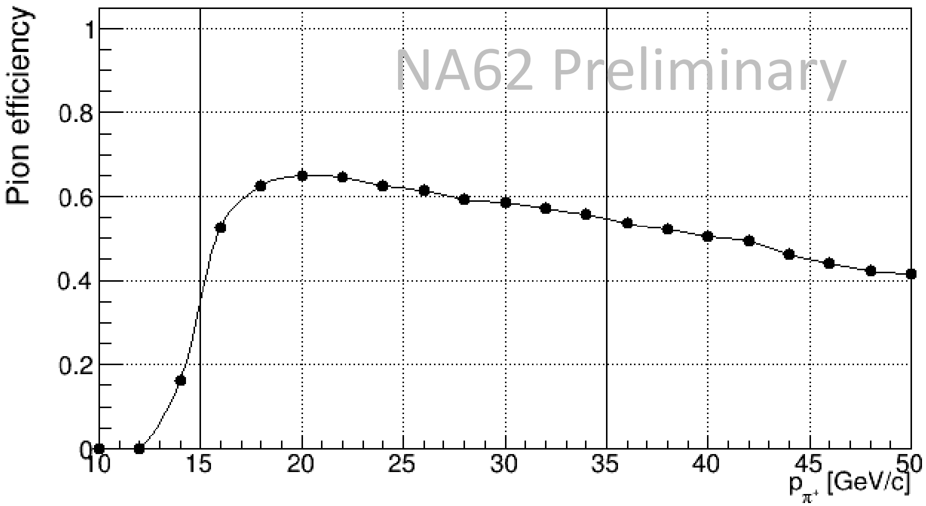
- Measured on data

  $K^+ \to \pi^+\pi^0$ $\sim 6 \times 10^{-4}$

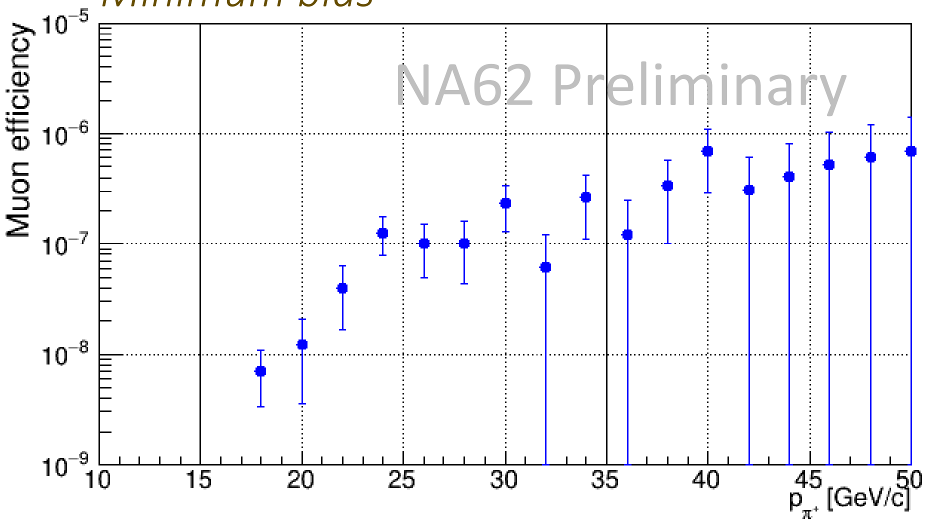
  $K^+ \to \mu^+\nu$ $\sim 3 \times 10^{-4}$

NA62 Particle ID: $\pi^+ - \mu^+$ Separation

Minimum bias



Minimum bias



Particle ID with calorimeters

$\varepsilon(\mu) \div \varepsilon(\pi) \sim 10^{-5} \div 80\%$

- MVA discriminant

Particle ID with RICH

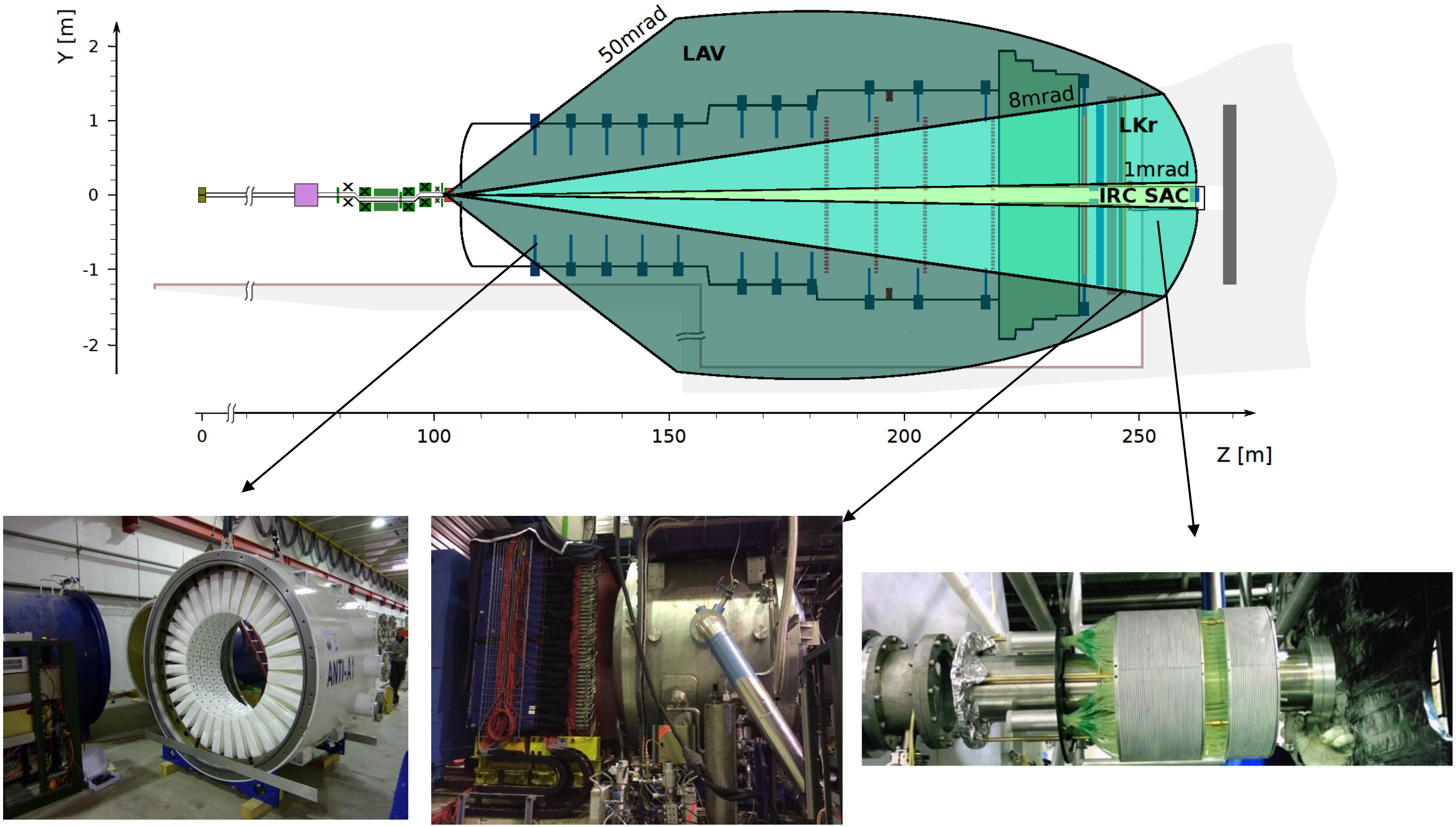
$\varepsilon_{ring}(\pi) \sim 90\%$ [depends on p_{π^+}]

$\varepsilon(\mu) \div \varepsilon_{ID}(\pi) \sim 10^{-2} \div 80\%$

PID performance measurement:

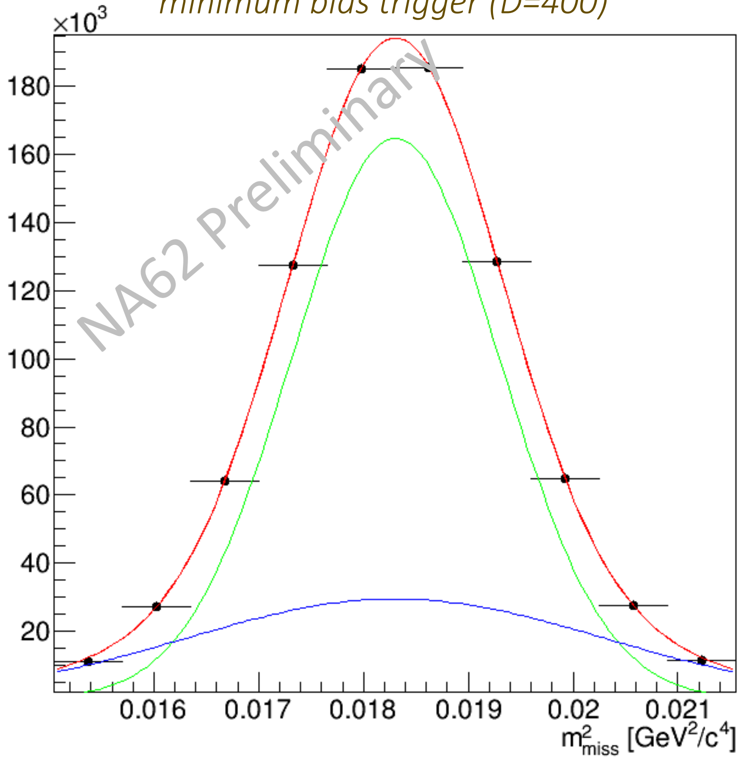
- RICH and calorimeter combined

π^0 Rejection

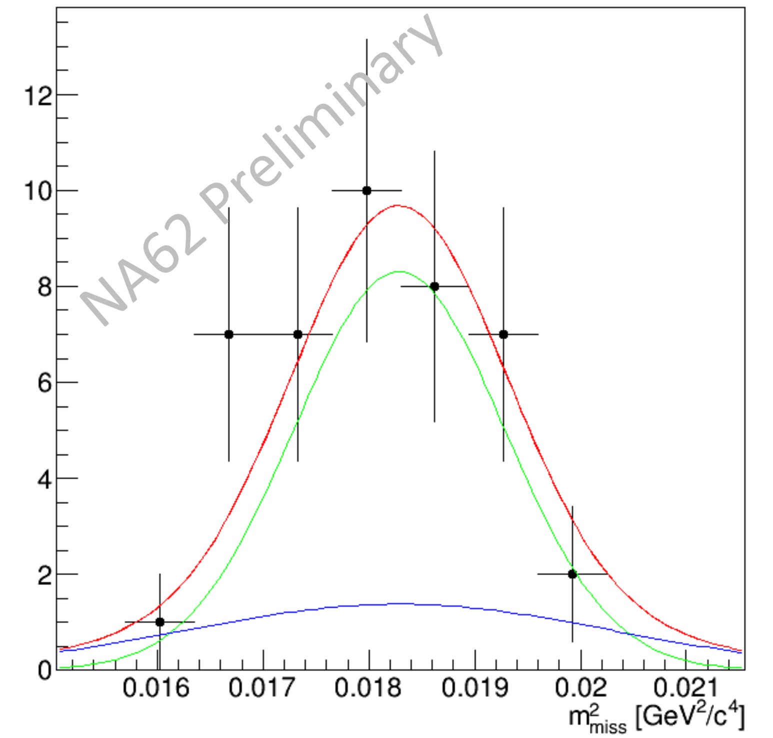


NA62 Photon Rejection

Before γ-reject., minimum bias trigger (D=400)



After γ-reject., PNN Trigger



Photon Veto conditions: LKr, LAV, IRC, SAC + multiplicity in CHOD

π^0 suppression (from $\pi^+\pi^0$)

$\epsilon_{\pi^0} = (1.2 \pm 0.2) \times 10^{-7}$

$[O(10^{-8})$

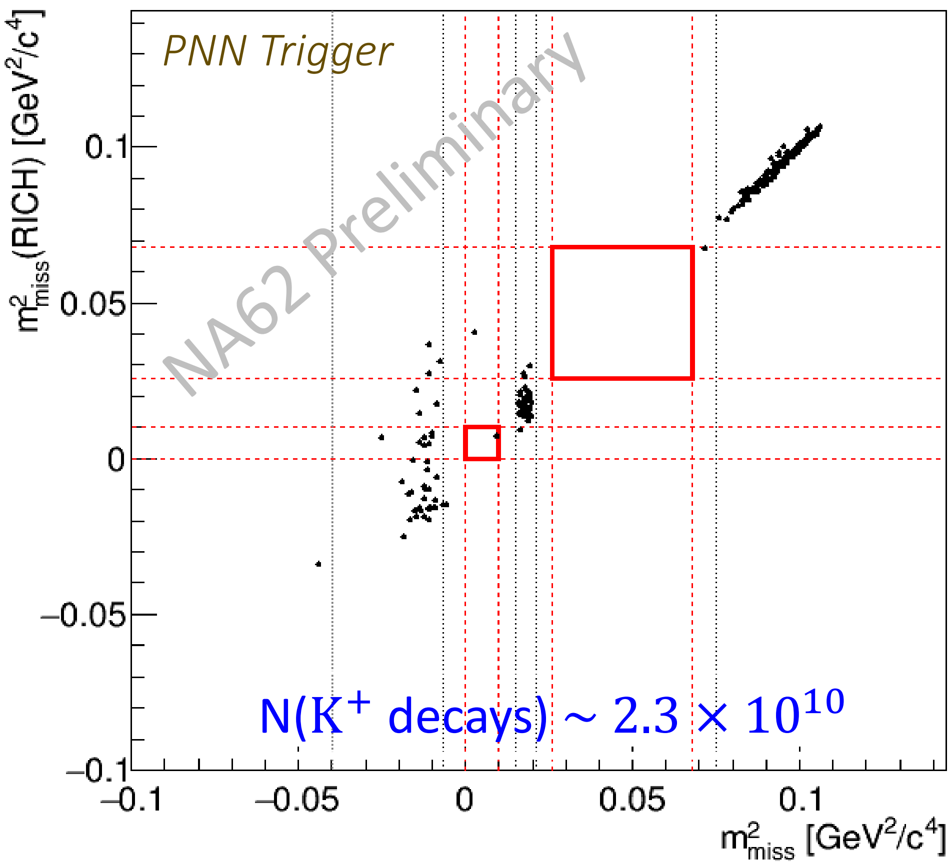
$\pi\nu\nu$ losses (random activity, π interactions)

15 %

$\sim 25 \div 30\%]$

NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ Preliminary Result

O(10%) 2016 statistics



Expected $\pi\nu\nu \approx \mathbf{0.064}$

- Normalization: $K^+ \to \pi^+\pi^0$

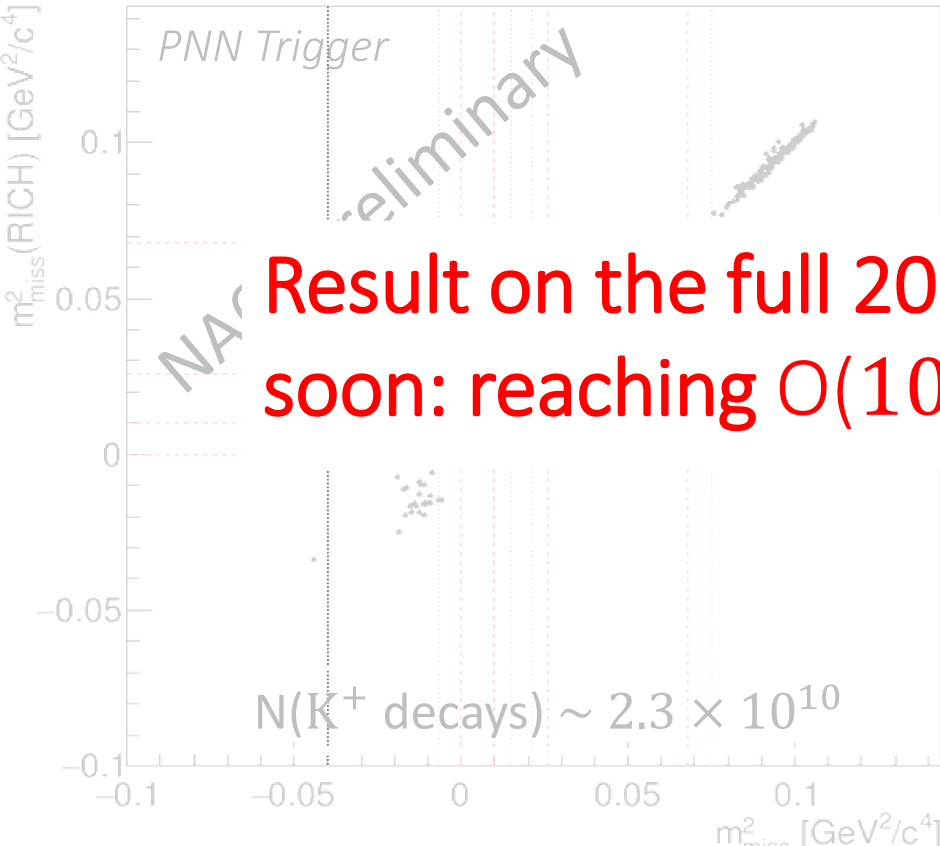
Expected backgrounds:

$K^+ \to \pi^+\pi^0$	0.024
$K^+ \to \mu^+\nu$	0.011
$K^+ \to \pi^+\pi^+\pi^-$	< 0.017
Beam - induced	under study

- Estimated with data – driven methods
- Analysis on-going, further reduction of background expected

NA62 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Preliminary Result

O(10%) 2016 statistics



Expected $\pi\nu\nu \approx \mathbf{0.064}$

- Normalization: $K^+ \rightarrow \pi^+\pi^0$

Expected backgrounds:

7

Beam - induced under study

- Estimated with data – driven methods
- Analysis on-going, further reduction of background expected

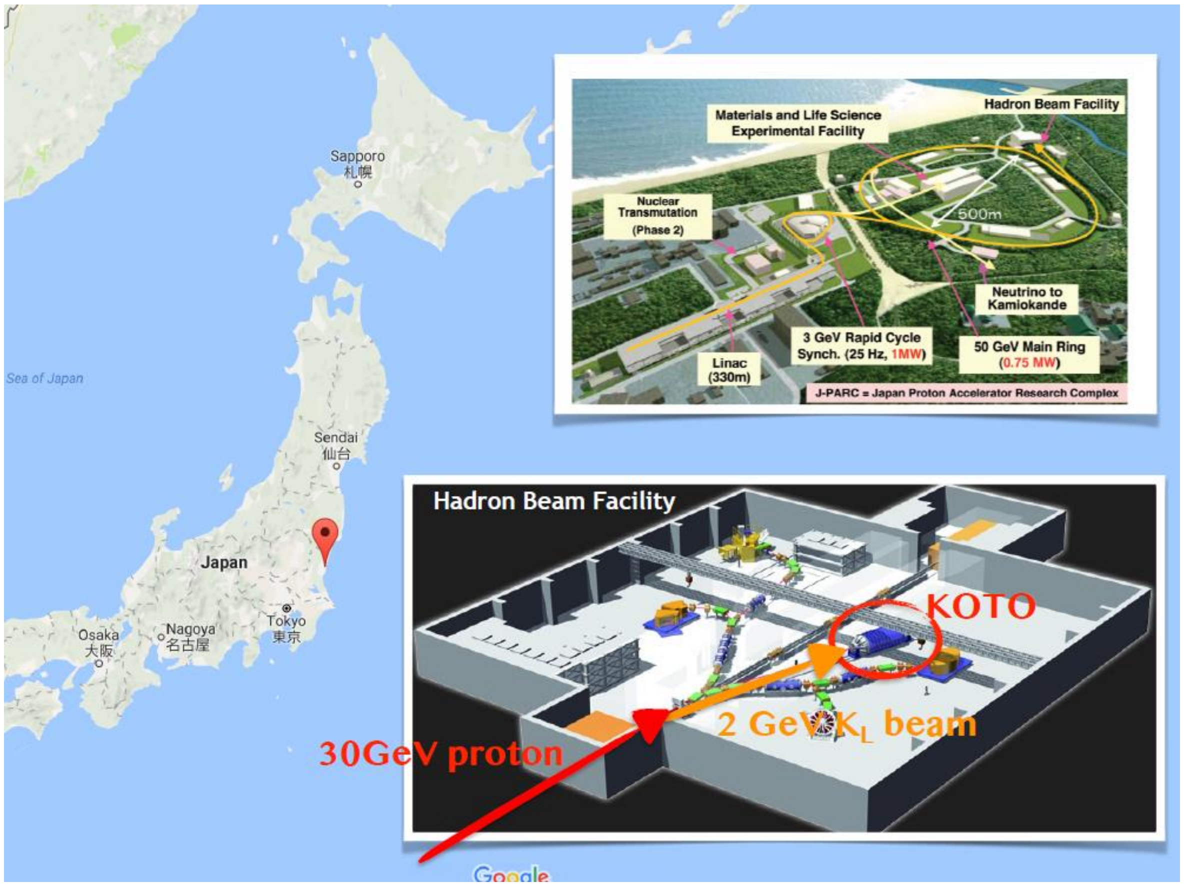
Result on the full 2016 data expected soon: reaching $O(10^{-10})$ SES

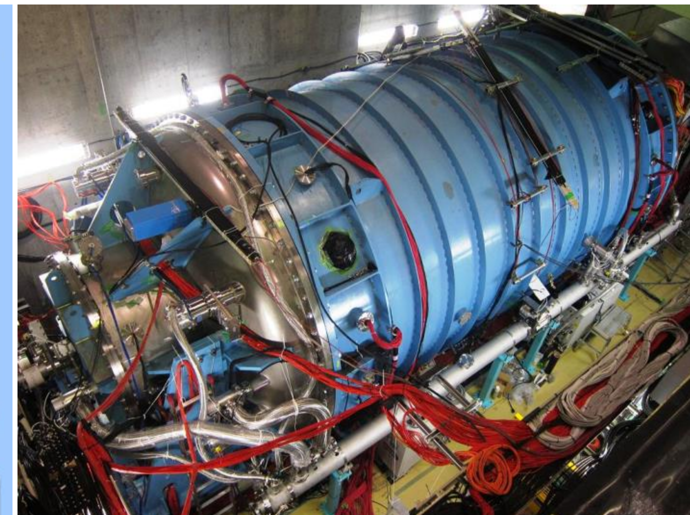
NA62 Prospects

- Completion of the 2016 data analysis: O(10^{-10}) SES
- 2017 5-months run: order of magnitude improvement vs 2016
- 2018: 200 days run allocated (starting in April).

KOTO @ JPARC

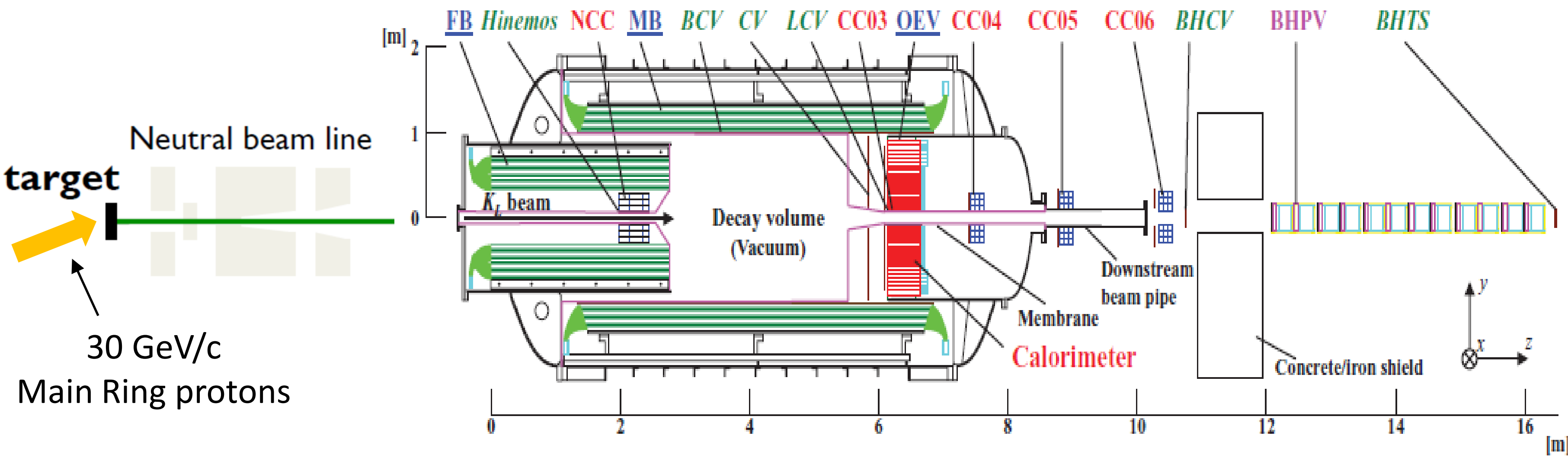
Goal of KOTO: Observe few SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events





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

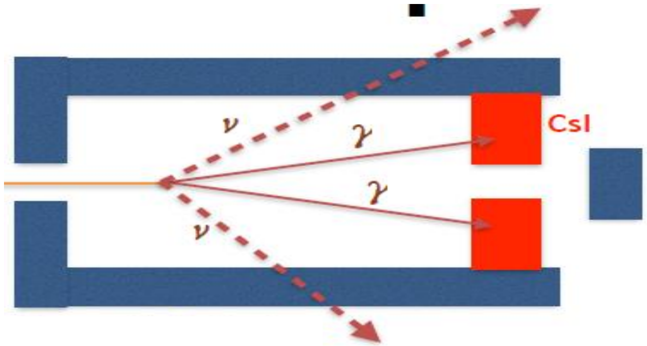
KOTO Layout



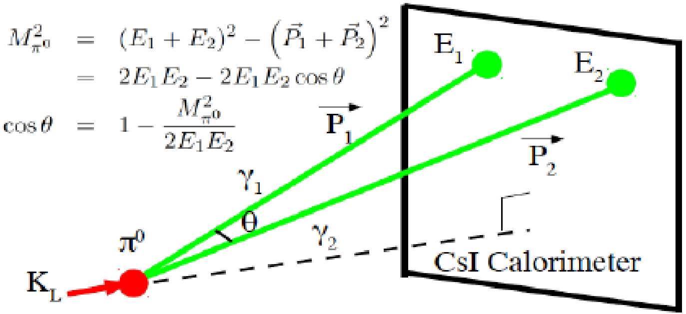
Secondary neutral beam	
Momentum	1.4 GeV/c peak
Angle of production	16°
Transverse Size	$80 \times 80 \text{ mm}^2$
Composition	K_L , neutron, photons
Intensity (2013)	3×10^{13} ppp on target (25 kW)
Intensity (2015/16)	30 / 42 kW

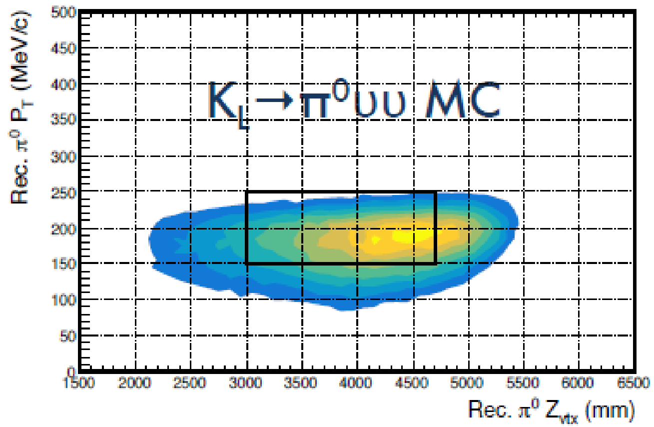
Decay region and Detectors	
Fiducial region	~3 m
Vacuum	5×10^{-7} mbar
CsI Calorimeter from KTeV	
Hermetic γ – veto to suppress $K_L \rightarrow \pi^0\pi^0$	
Waveform digitizer	

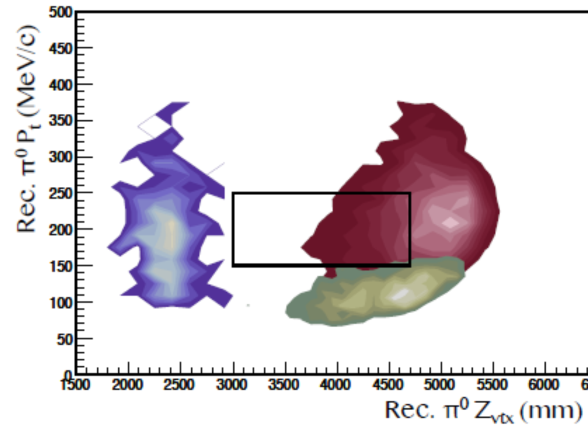
πνν Analysis: the Method



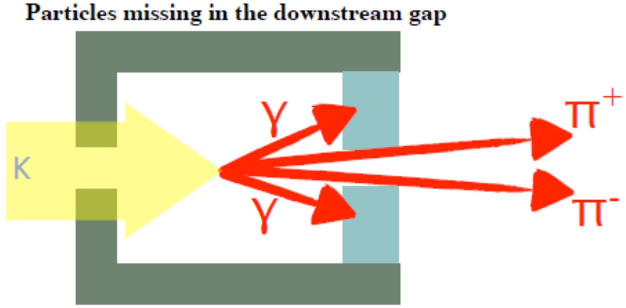
$$M^2_{\pi^0} = (E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2$$
$$= 2E_1E_2 - 2E_1E_2\cos\theta$$
$$\cos\theta = 1 - \frac{M^2_{\pi^0}}{2E_1E_2}$$



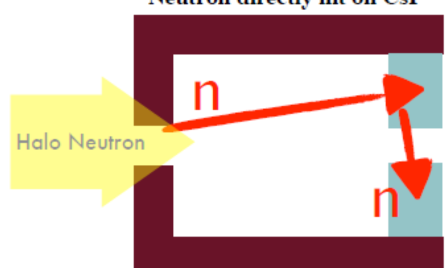




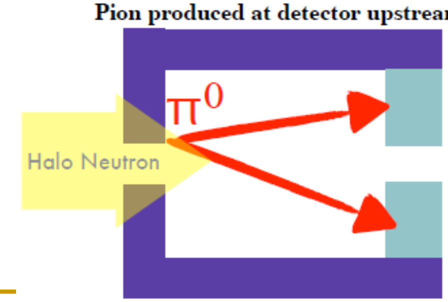
Particles missing in the downstream gap



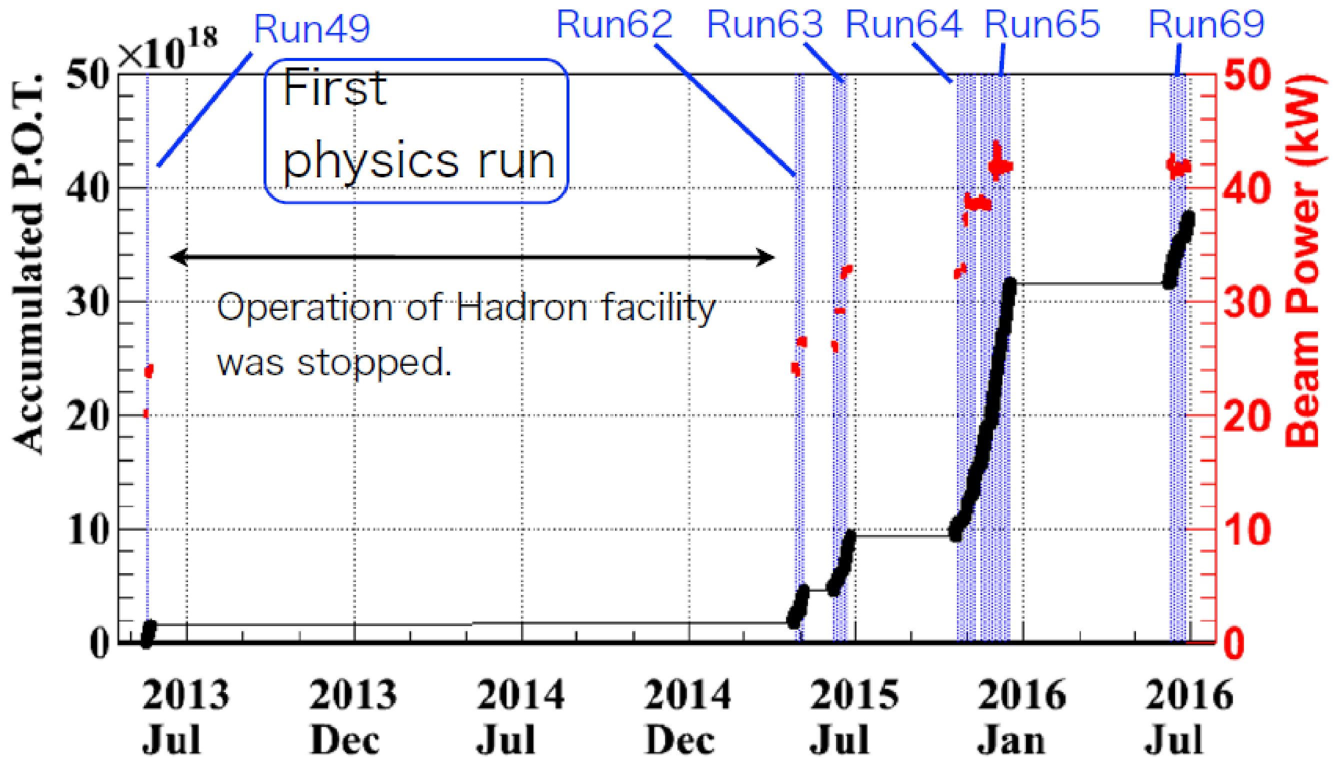
Neutron directly hit on CsI



Pion produced at detector upstream



KOTO Runs

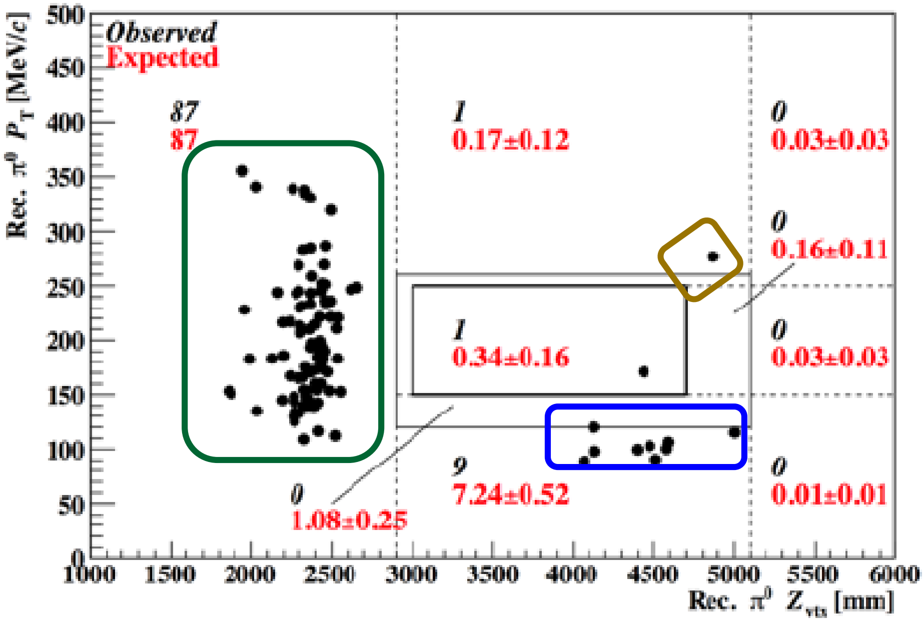


2013	First physics result [PTEP 2017, 021C01]
2015 - 2016	20 × statistics of 2013 run

KOTO 2013 Result

- Data from 2013 run: $\mathrm{N(K_L)} \sim 2.4 \times 10^{11}$, S.E.S 1.3×10^{-8}
- $\mathrm{BR}(\mathrm{K_L} \to \pi^0 \nu\bar{\nu}) < 5.1 \times 10^{-8}$ (90% C. L.) [PTEP 2017, 021C01]
- Background in signal region dominated by neutrons

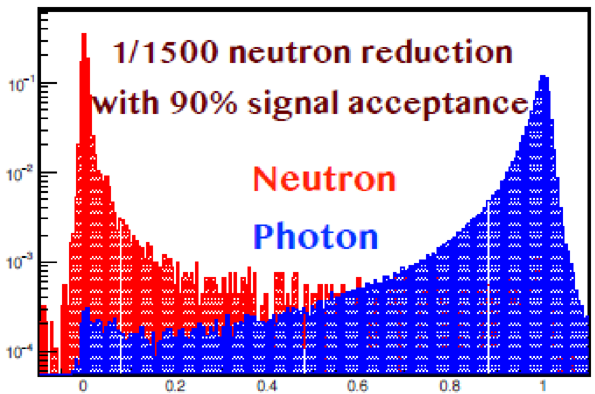
Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15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



KOTO After 2013

- Thinner vacuum window, collimator realignment: reduction of π^0 from neutrons
- Beam pipe charged veto: 1/10 reduction of $K_L \to \pi^+\pi^-\pi^0$
- Special run with Al target to collect neutron – enriched events
- Better Photon – neutron identification in CsI calorimeter

- Cluster Shape Discrimination



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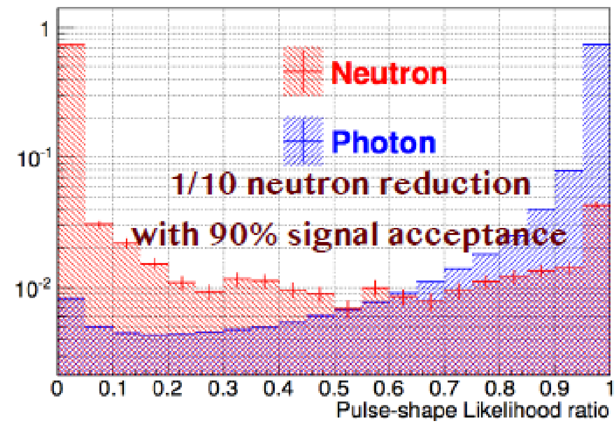
- Pulse Shape Discrimination

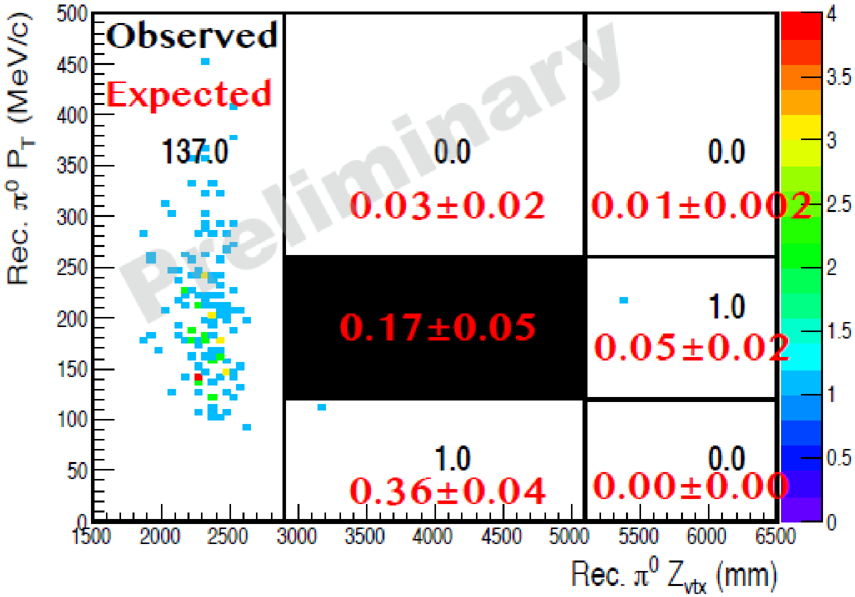


× 5 reduction of neutron background vs 2013 data analysis

KOTO 2015 Analysis

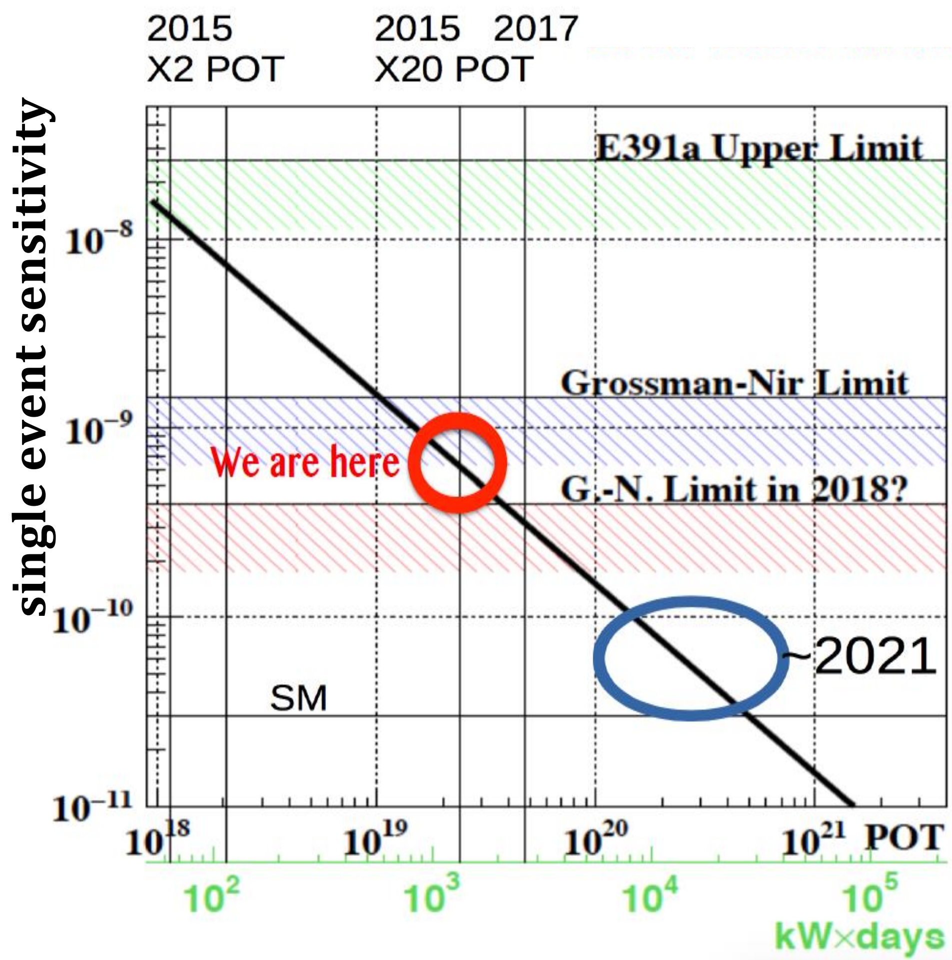
- Small subsample of 2015-2016 statistics analysed (run62)
- $N(K_L) \sim \times 1.6$ of the 2013 run
- Wider signal region thanks to the better γ rejection: +40% signal acceptance
- $S.E.S. \sim 5.9 \times 10^{-9}$

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

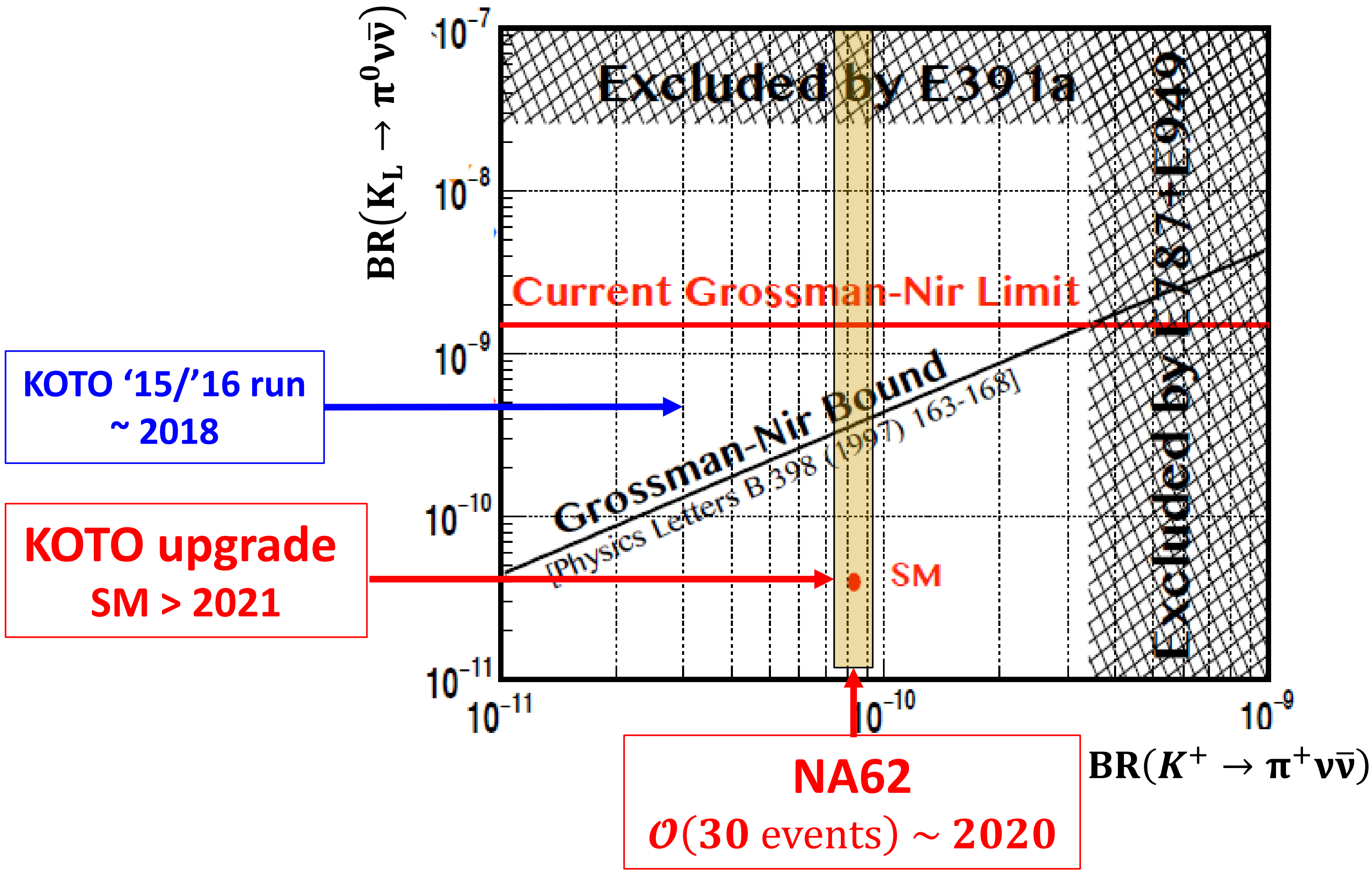


KOTO Prospects

- 2015 – 2016 analysis: < 10^{-9} S.E.S.
- Upgrades to reach SM
  - New barrel detector (April 2016)
  - Beam pipe modification (on going)
  - CsI both end readout (MPPC, 2018)
  - JPARC 42 kW → 100 kW (2019)



$K \rightarrow \pi\nu\nu$ Prospects



Conclusions

Kaon experiments NA62 at CERN and KOTO at JPARC are exploring physics beyond SM primarily via $K \to \pi\nu\nu$ for $10 - 10^3$ TeV scale:

- $K^+ \to \pi^+\nu\bar{\nu}$: NA62 expected to reach the SM sensitivity soon; BR 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 on-going