Kaon Physics Prospects

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UK HEP Forum

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Outline

- The Past
- The Present
- Future Prospects

Kaon Physics: a Building Block of the Standard Model

- Discovery of strange particles *[Nature 160 4077 (1947) 855]*
- Postulation of neutral meson oscillation *[PR 97 (1955) 1387]*
- θ - τ puzzle: first hint of P violation *[PR 104 (1956) 254]*
- Discovery of CP violation in the K^0 mixing *[PRL 13 (1964) 138]*
- 3 quark-model to describe the observed meson / baryon spectra *[PL 8 (1964) 214]*
- c quark prediction to explain the observed BR of $K_L \rightarrow \mu^+\mu^-$ *[PRD 2 (1970) 1285]*
- Discovery of CP violation in the K^0 decay *[PLB 206 (1988) 169]*

Kaon Physics: the last 20 Years

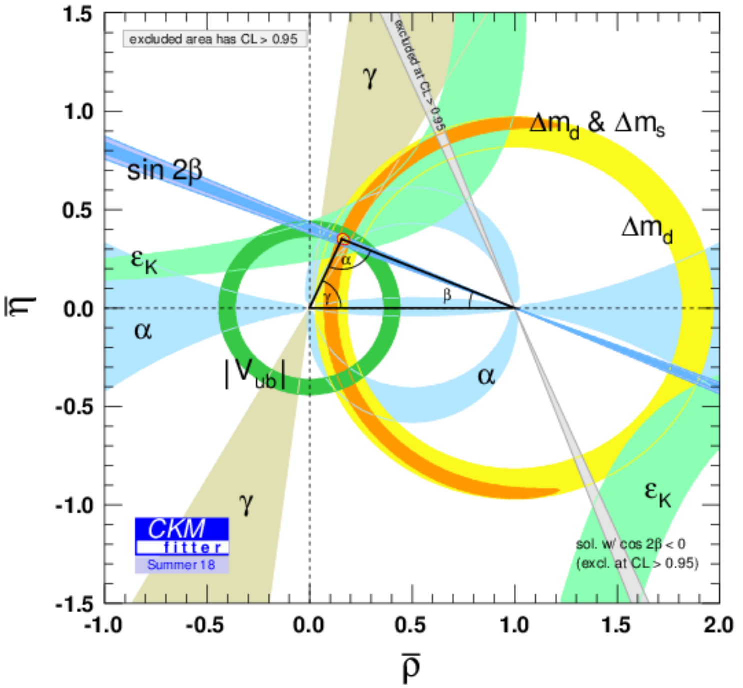
- Measurement of CP violation
- Test of CPT symmetry invariance
- Low energy QCD (e.g. χPT)
- Precision test of the CKM unitarity
- Test of lepton universality and flavour violation
- Rare K decays: SM and beyonds

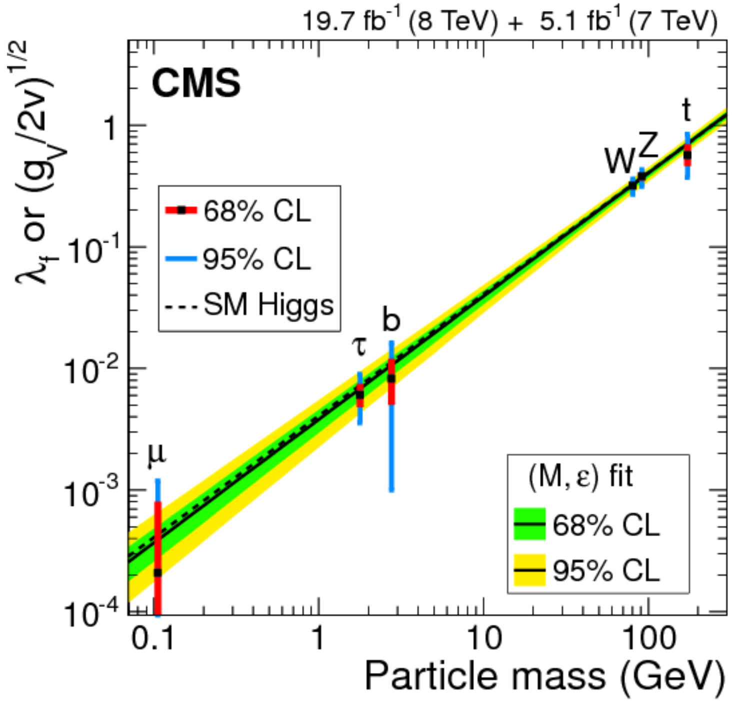
KAON «Factories»:

1997-2014 CERN SPS (NA48), CERN LEAR (CPLEAR), FNAL (KTeV), LNF (KLOE, KLOE2), BNL (E787, E865, E949), KEK (E391), Protvino (ISTRA+)

2014-today CERN SPS (NA62), JPARC (KOTO), CERN LHC (LHCb, K_S rare decay program)

Particle Physics Today





Electroweak sector (LEP, LHC, Tevatron)

QCD sector (LEP, Hera, LHC)

Yukawa sector (Babar/Belle, Tevatron, LHC)

Higgs sector (LHC)

Dark matter / energy

Matter – antimatter asymmetry

ν mass and oscillations

Hierarchy problem

Direct / Indirect New Physics searches

Snapshots from

“The Past”

CP Violation in K^0: Re ε'/ε

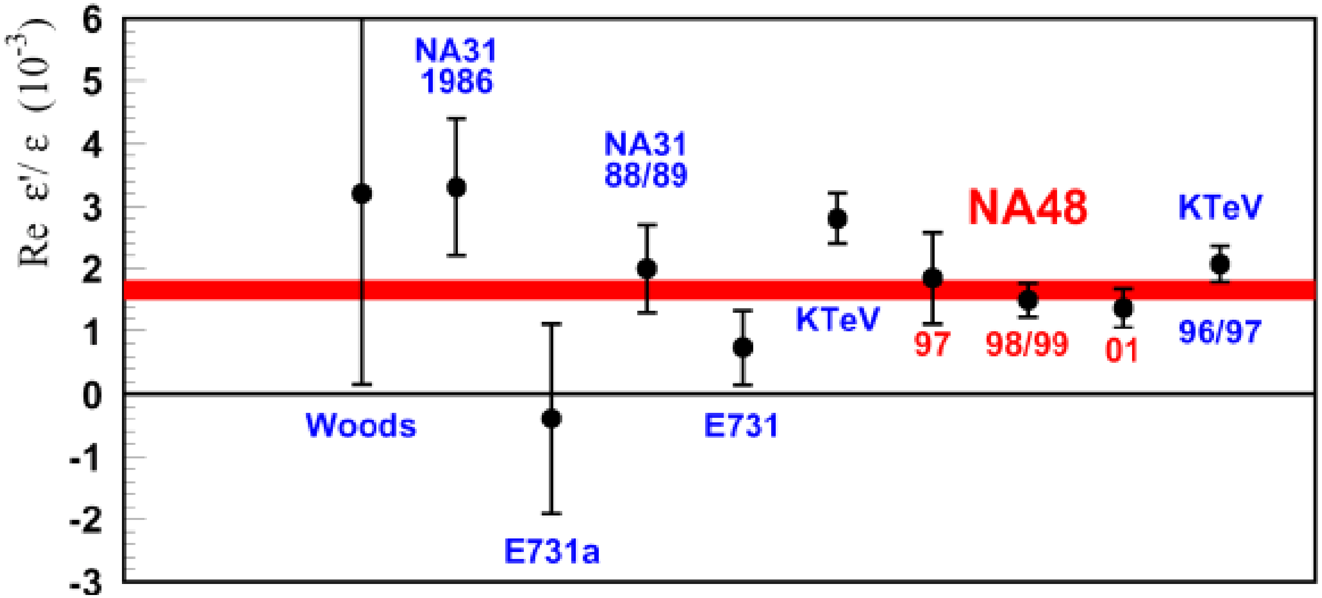
Experimental measurement (NA48 - KTeV): Re $\varepsilon'/\varepsilon = (1.66 \pm 0.23) \times 10^{-3}$

[Phys. Lett. B 544 (2002) 97, Phys. Rev. D 83 (2010) 092001]

$$\eta_{+-} = A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-)$$

$$\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0)$$

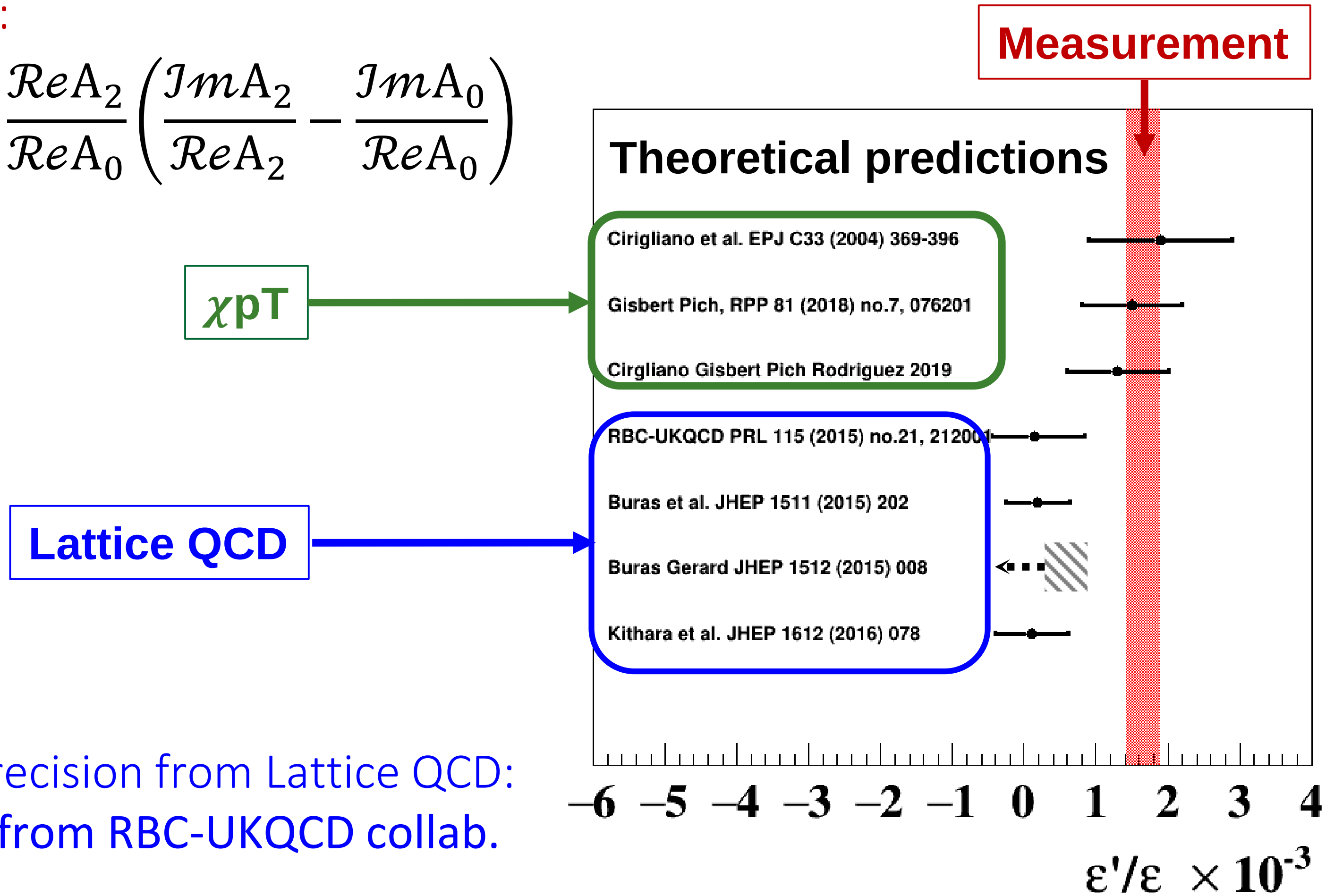
$\Rightarrow$ $|\eta_{00}/\eta_{+-}|^2 \approx 1 - 6Re\,\varepsilon'/\varepsilon$



CP Violation in K^0: Still "The Past" ?

Theory challenge:

$$\sqrt{2}\varepsilon' = ie^{i(\delta_2-\delta_0)} \frac{\mathcal{R}e A_2}{\mathcal{R}e A_0}\left(\frac{\mathcal{I}m A_2}{\mathcal{R}e A_2} - \frac{\mathcal{I}m A_0}{\mathcal{R}e A_0}\right)$$



Best expected precision from Lattice QCD:
new calculation from RBC-UKQCD collab.
expected soon

Kaon Physics and V_{us}

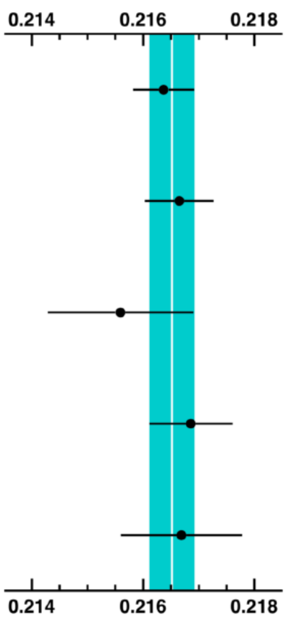
$|V_{us}|$, $K \to \pi l \nu$ (K_{l3})

$$\Gamma\left(K \to \pi l \nu[\gamma]\right) = Br(K_{l3})/\tau = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K |V_{us}|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}\left(1 + 2\Delta_{\mathrm{EM}}^{Kl} + 2\Delta_{\mathrm{SU(2)}}^{K\pi}\right)$$

$\frac{|V_{us}|}{|V_{ud}|}$, $K \to l\nu$ (K_{l2})

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi_{\mu 2(\gamma)}} m_{K^\pm}}\right)^{1/2} \frac{1 - m_\mu^2/m_{\pi^\pm}^2}{1 - m_\mu^2/m_{K^\pm}^2}\left(1 - \frac{1}{2}\delta_{\mathrm{EM}} - \frac{1}{2}\delta_{SU(2)}\right)$$

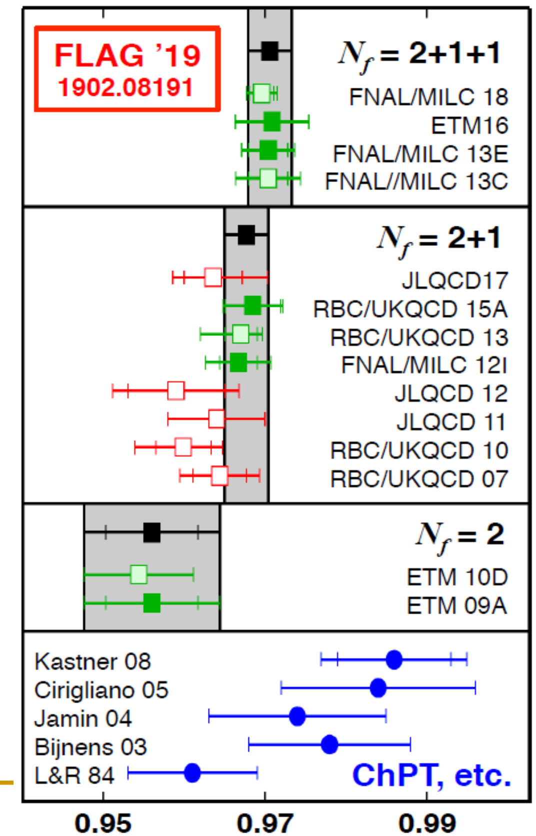
BR and form factor measurements from NA48, KLOE, KLOE2, ISTRA++, KTeV



		% err	BR	τ	Δ	Int
$K_L e3$	0.2164(6)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
$K_S e3$	0.2156(13)	0.61	0.60	0.02	0.11	0.05
$K^\pm e3$	0.2169(8)	0.35	0.27	0.06	0.21	0.05
$K^\pm \mu 3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

Average: $|V_{us}| f_+(0)$ = 0.21652(41) χ^2/ndf = 0.98/4 (91%)

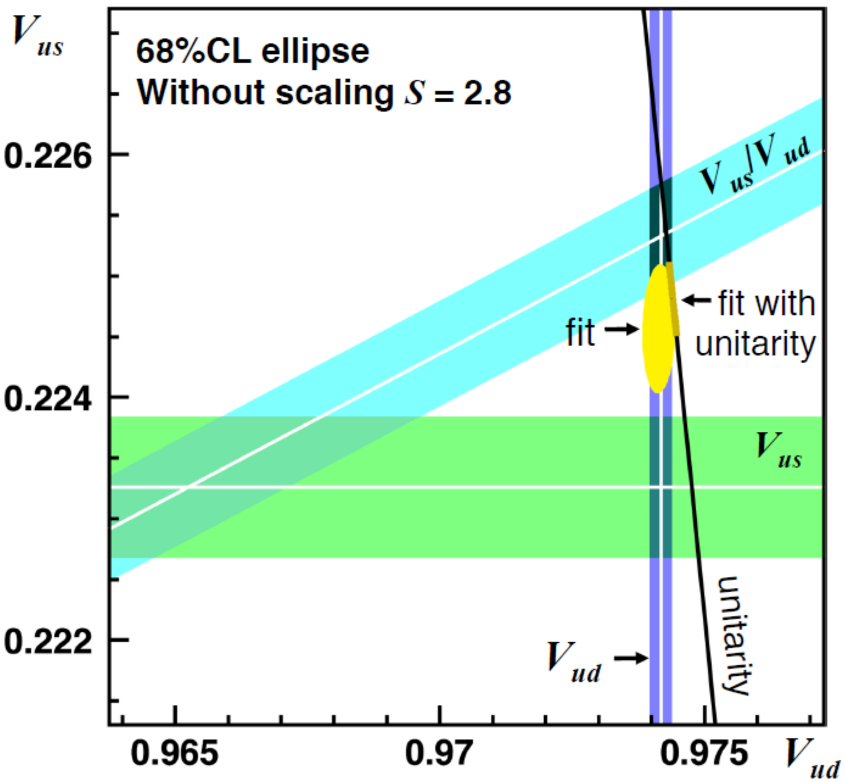
$f_+(0)$ computations



Passerman @ KAON 2019

Kaon Physics and CKM Unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM} \qquad \Delta \sim \frac{c_n}{g^2}\frac{M_W^2}{\Lambda^2} \leq 10^{-2} - 10^{-3} \longleftrightarrow \Lambda\text{~1-10 TeV}$$



Passerman @ KAON 2019

$f_+(0)$, f_K/f_π from χpT

V_{us} fit to the measurements (K_{l3})

V_{us}/V_{us} fit to the measurements (K_{l2})

V_{ud} from nuclear $0^+ \to 0^+$ transitions

$V_{ud} = \mathbf{0.97414(21)}$

$V_{us} = \mathbf{0.22456(35)}$

χ^2/ndf = 8.0/1 (0.5%)

$\Delta_{CKM} = \mathbf{-0.00062(45)}$

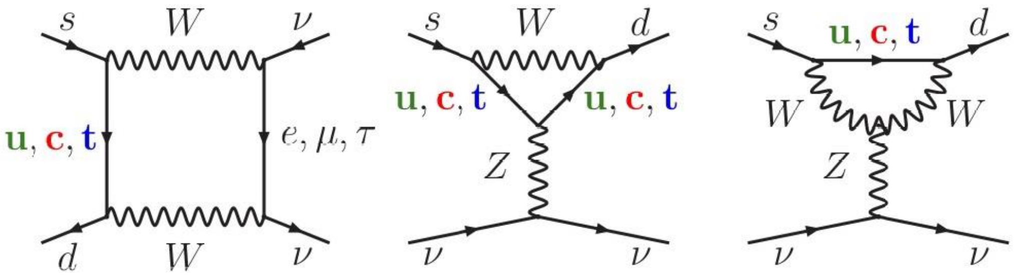
-1.4σ

3σ tension if the most recent determination of V_{ud} is used Passerman @ KAON 2019

“The Present”

$K \to \pi\nu\bar{\nu}$ decays: a theoretically 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 11 (2015) 33]

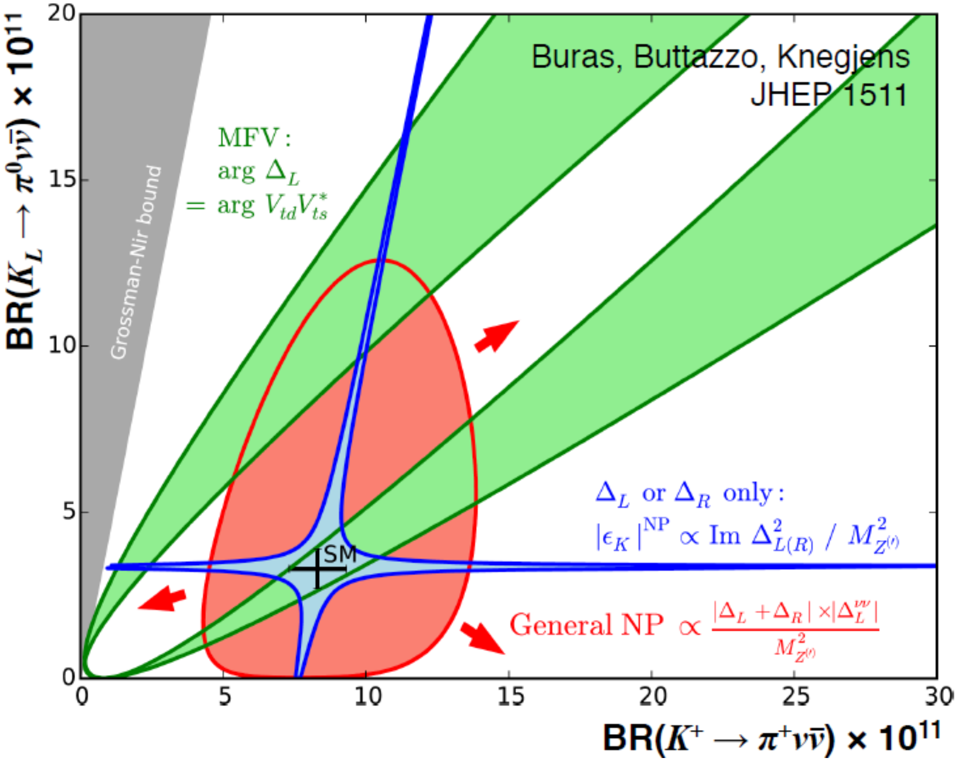
$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11}\left(\frac{|V_{cb}|}{0.0407}\right)^{2.8}\left(\frac{\gamma}{73.2°}\right)^{0.74} = (0.84 \pm 0.10)\cdot 10^{-10}$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11}\left(\frac{|V_{ub}|}{0.00388}\right)^{2}\left(\frac{|V_{cb}|}{0.0407}\right)^{2}\left(\frac{\sin\gamma}{\sin 73.2°}\right)^{2} = (0.34 \pm 0.06)\cdot 10^{-10}$$

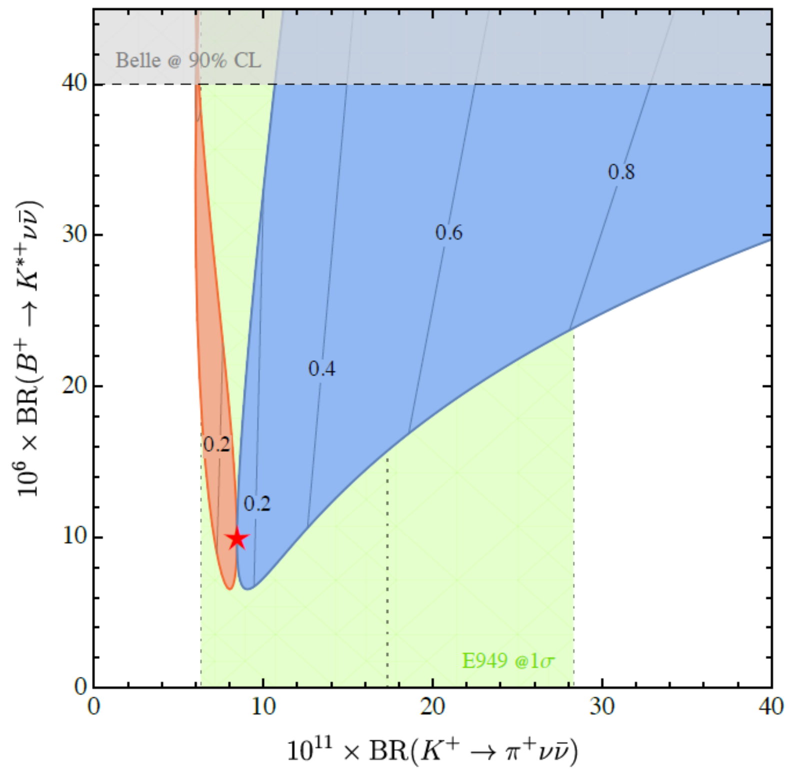
$K \to \pi\nu\bar{\nu}$ and New Physics

- High sensitivity to NP (non MVF): significant variations wrt SM possible
- Model-dependent correlations of possible variations of K^+ and K_L BR
- Weak constraints from other flavour observables

Not-SUSY models



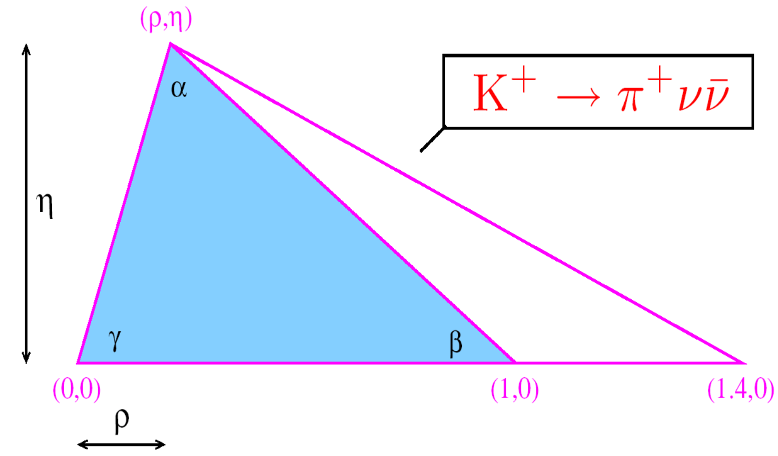
LFU violation



$K \to \pi\nu\bar{\nu}$ and CKM

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

$$K_L \to \pi^0 e^+ e^- \left\{ \begin{array}{l} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to ee\gamma\gamma \end{array} \right.$$



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

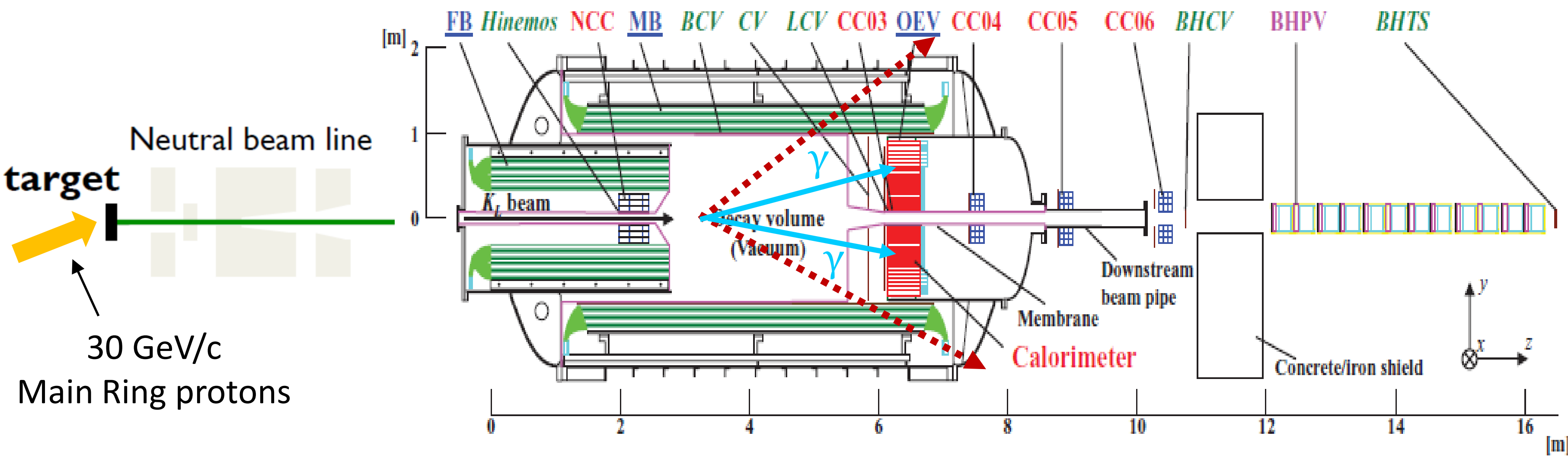
$$K_L \to \mu^+\mu^- \left\{ \begin{array}{l} K_L \to \gamma\gamma,\ K_L \to e^+e^-\gamma \\ K_L \to e^+e^-e^+e^-,\ e^+e^-\mu^+\mu^- \end{array} \right.$$

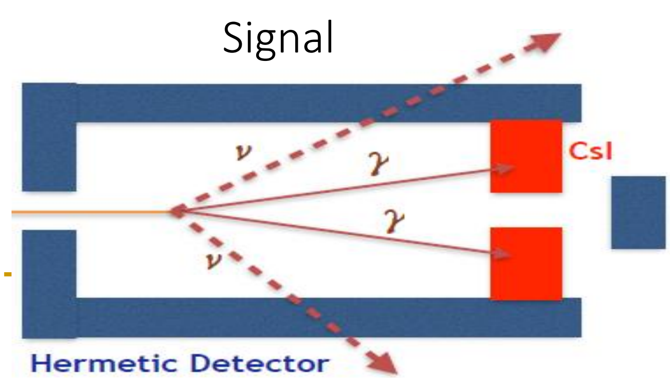
CKM fit using $K \to \pi\nu\nu$ ONLY

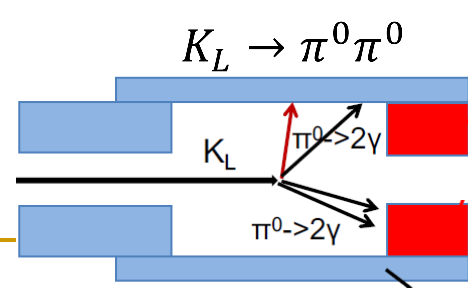
NP flavour dynamics from comparison of CKM fit with K and B

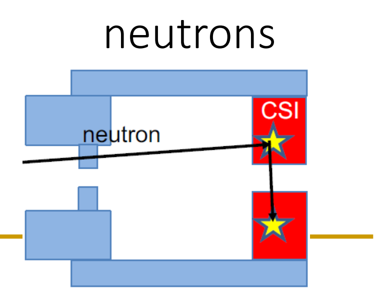
$K_L \to \pi^0\nu\bar{\nu}$: KOTO @ JPARC

Goal: Observe SM $K_L \to \pi^0\nu\bar{\nu}$

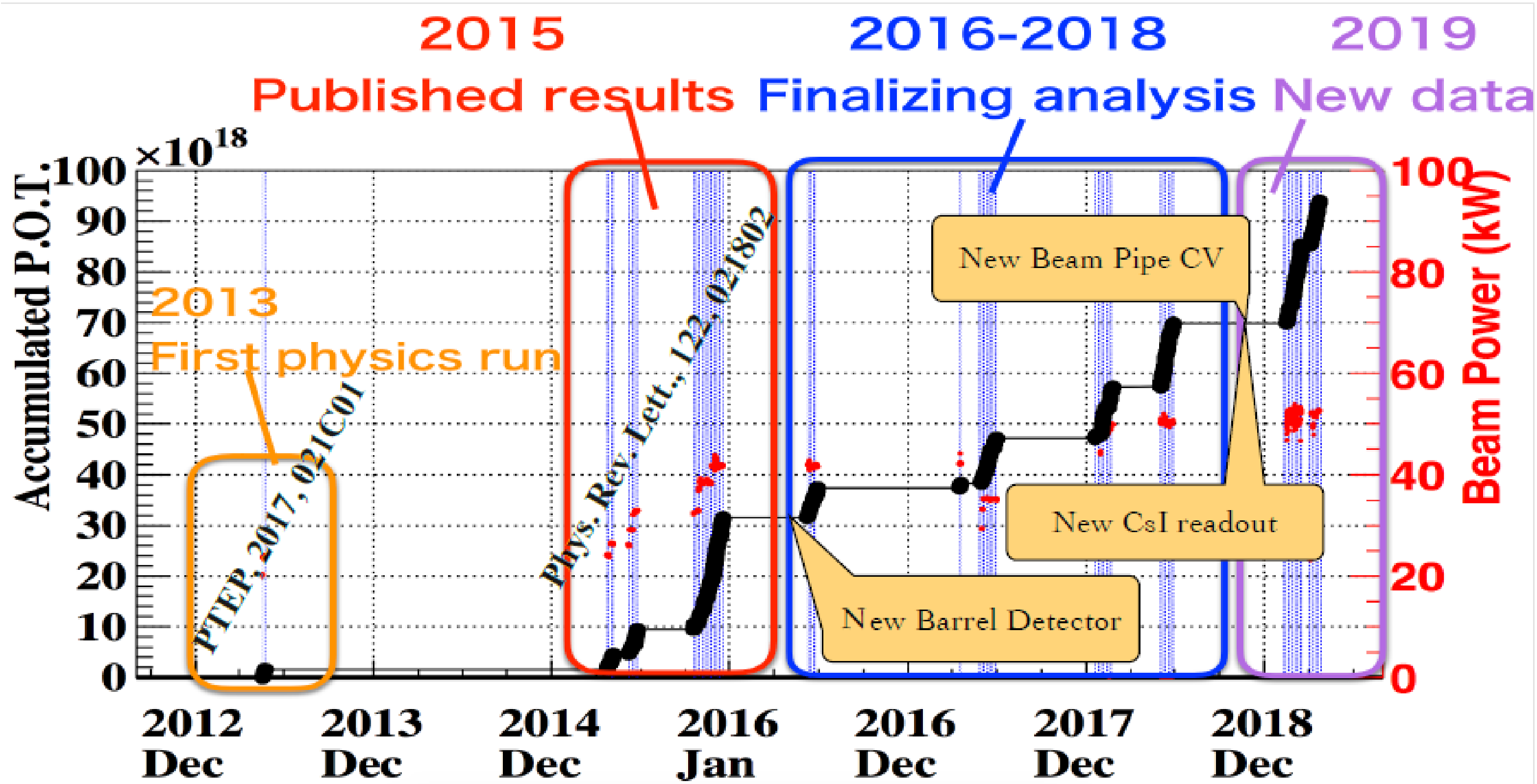








$K_L \to \pi^0 \nu\bar{\nu}$: KOTO @ JPARC



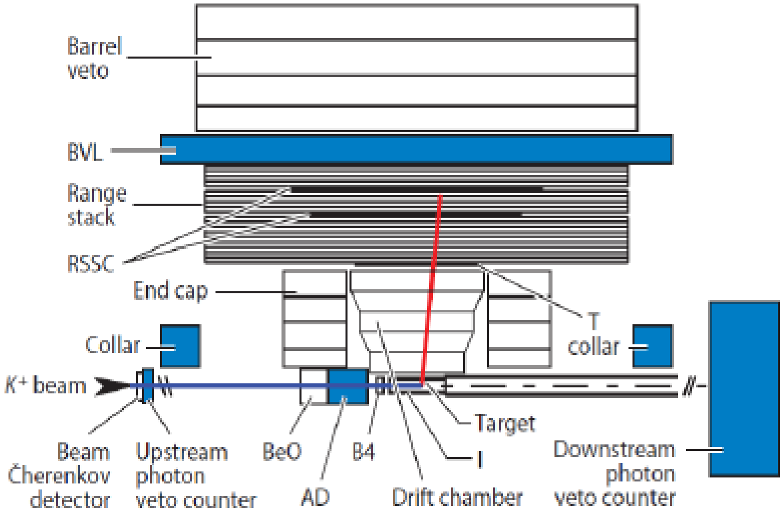
- 2015 Single event sensitivity: $(1.30 \pm 0.01_{stat} \pm 0.14_{syst}) \times 10^{-9}$
- 2015 result: $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ (90% C.L.)

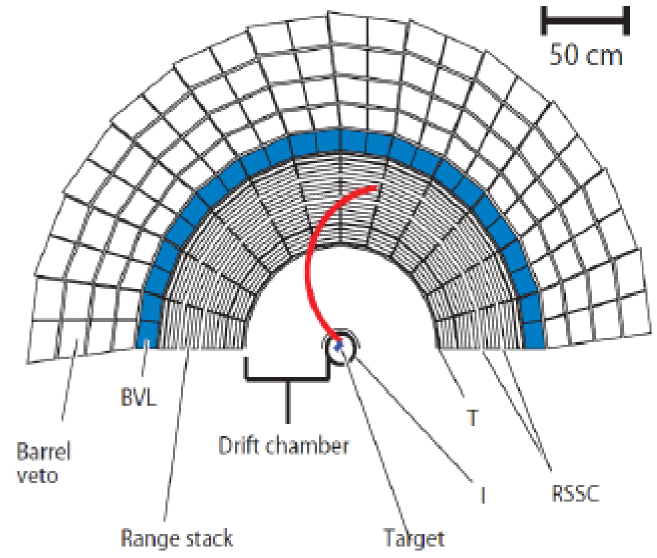
[Phys. Rev. Lett. 122, 021802 (2019)]

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: from the Past to the Present

- The past: Stopping Kaon Technique
- The present: Decay-in-flight Technique

$K^+ \to \pi^+\nu\bar{\nu}$: E787/949 @ BNL Stopping Kaon



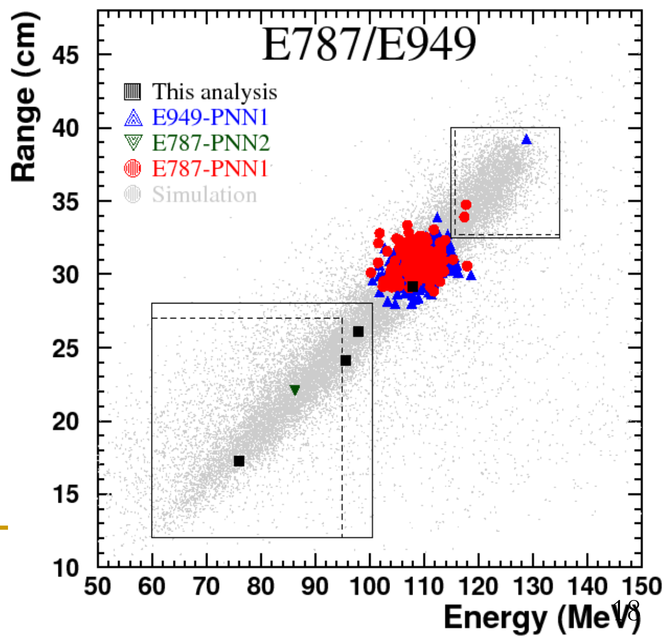


- Single Event Sensitivity: $\sim 0.8 \cdot 10^{-10}$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 3.35 \times 10^{-10} \text{ (90\% CL)}$$
$$BR(K^+ \to \pi^+\nu\bar{\nu}) = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$$

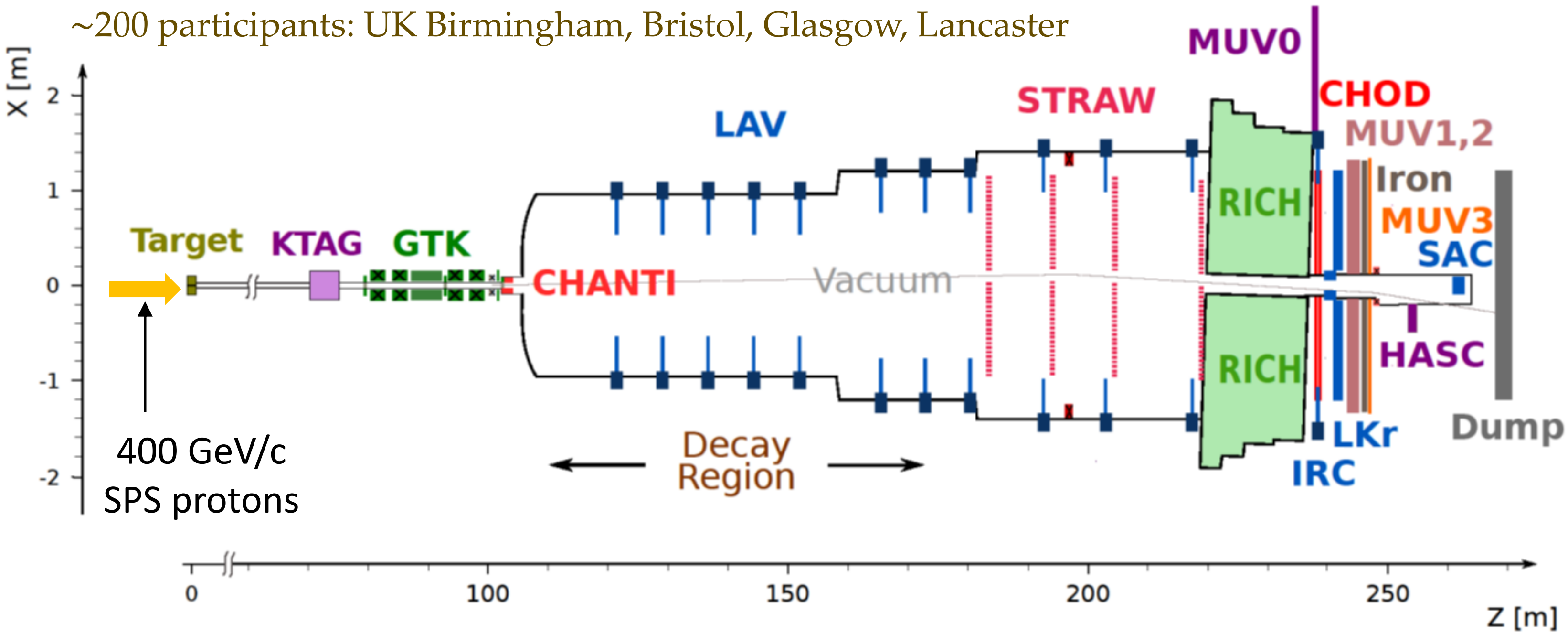
Phys. Rev. D 77, 052003 (2008),

Phys. Rev. D 79, 092004 (2009)



$K^+ \to \pi^+ \nu\bar{\nu}$: NA62 @ CERN SPS, Decay in Flight

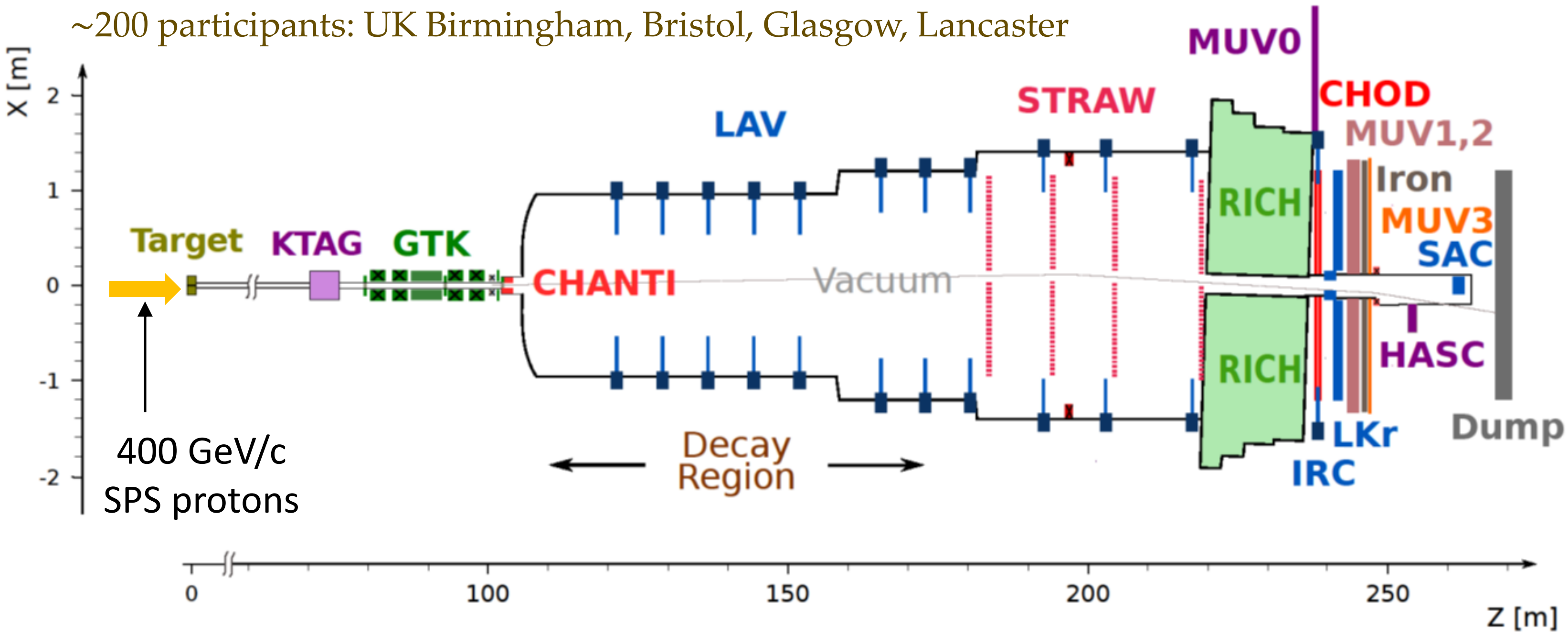
~200 participants: UK Birmingham, Bristol, Glasgow, Lancaster



Typical Intensity	19×10^{11} ppp (450 MHz @ GTK3)
Incoming K^+, 75 GeV/c, 1% rms	Timing by KTAG (σ_t~70 ps); position/momentum by GTK
Outing π^+	Timing by RICH (σ_t~70 ps); position/momentum by STRAW
γ/multitrack veto (LAV, LKr, IRC, SAC, HASC)	$\pi^0 \to \gamma\gamma$ suppression $\sim 1.4 \times 10^{-8}$
Particle ID (RICH, LKr, MUV1,2,3)	μ^+ suppression $\sim 10^{-8}$

$K^+ \to \pi^+ \nu\bar{\nu}$: NA62 @ CERN SPS, Decay in Flight

~200 participants: UK Birmingham, Bristol, Glasgow, Lancaster

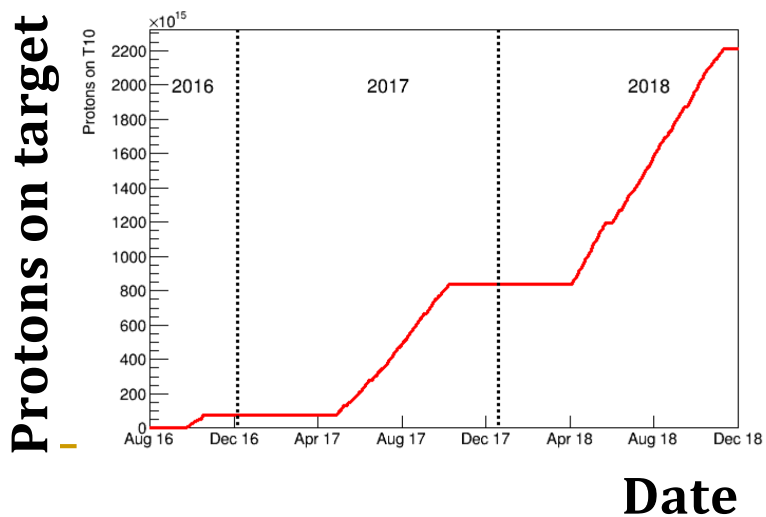


Three years of $K^+ \to \pi^+ \nu\bar{\nu}$ data taking:

2016: $\sim 1 \times 10^{11}$ K^+ decays

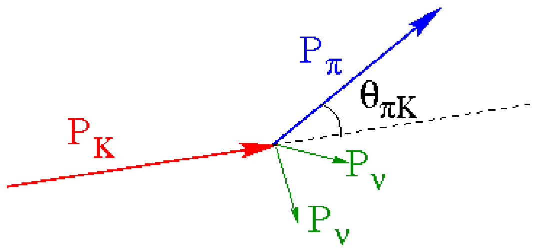
2017: $\sim 2 \times 10^{12}$ K^+ decays

2018: $\sim 4 \times 10^{12}$ K^+ decays

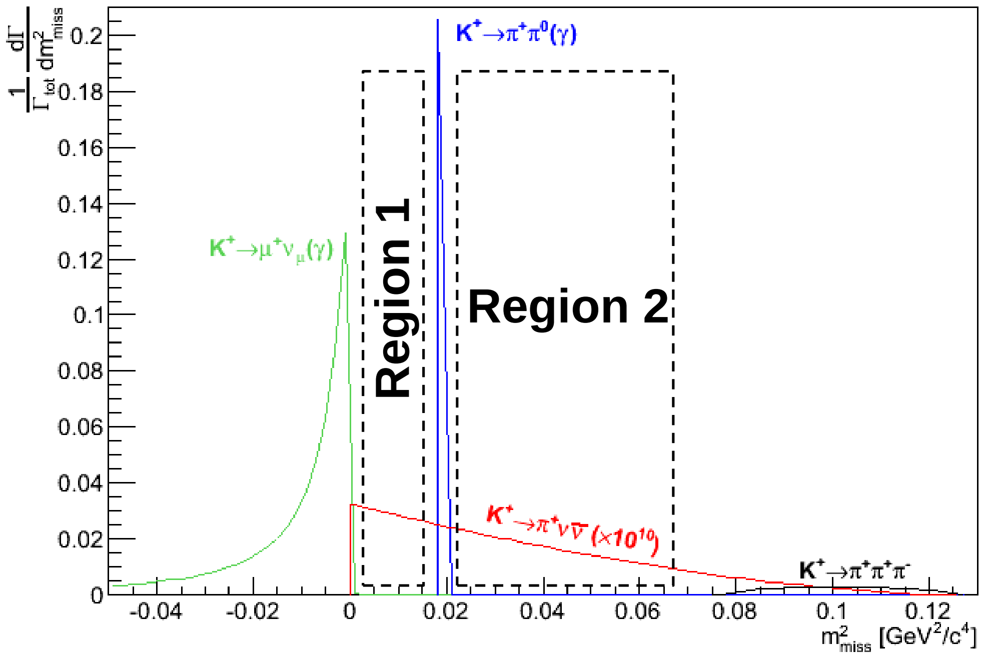


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay in flight

$$m_{miss}^2 = (P_{K^+} - P_{\pi^+})^2$$



Principal Decays	*Branching ratio*
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	0.2067 ± 0.08
$K^+ \rightarrow \mu^+\nu(\gamma)$	0.6356 ± 0.11
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.05583 ± 0.024
$K^+ \rightarrow \pi^+\pi^0\pi^0$	0.01760 ± 0.023
$K^+ \rightarrow \pi^0 e^+\nu$	0.0507 ± 0.04
$K^+ \rightarrow \pi^0\mu^+\nu$	0.03352 ± 0.033
$K^+ \rightarrow \pi^+\pi^- e^+\nu$	$(4.247 \pm 0.024) \cdot 10^{-5}$



+

Particle ID (Cerenkov)

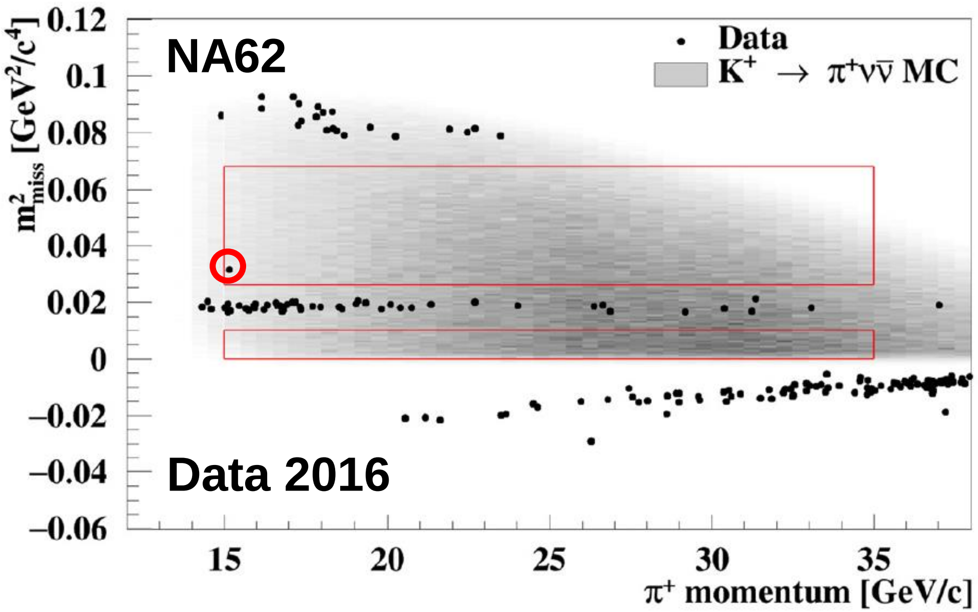
Particle ID (Calorimeters)

Photon Veto

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

NA62: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Data Analysis

- 2016 DATA: Proof-of-principle of the decay in flight technique



$$S.E.S.^* = (3.15 \pm 0.24) \times 10^{-10}$$

$$N_{\pi\nu\nu}^{expected} = 0.267 \pm 0.020 \pm 0.032_{ext}$$

$$N_{bckg} = 0.152^{+0.092}_{-0.033}\Big|_{stat} \pm 0.013_{syst}$$

1 event observed in signal region

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

Phys. Lett. B 791, 156 (2019)

- 2017 Data: new result presented recently

G.R. KAON2019 10/09/2019
CERN EP Seminar 23/09/2019

2 trigger streams: PNN (highly selective for signal), CONTROL (minimum-bias)

Full blind analysis procedure (like for 2016 analysis)

* S.E.S. = Single Event Sensitivity

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

m^2_{miss}: π^+/K^+ 3-momentum from Straw/Gigatracker, π^+ mass hypothesis

K^+ decays selected no PID and γ/multi-track rejection

Selection

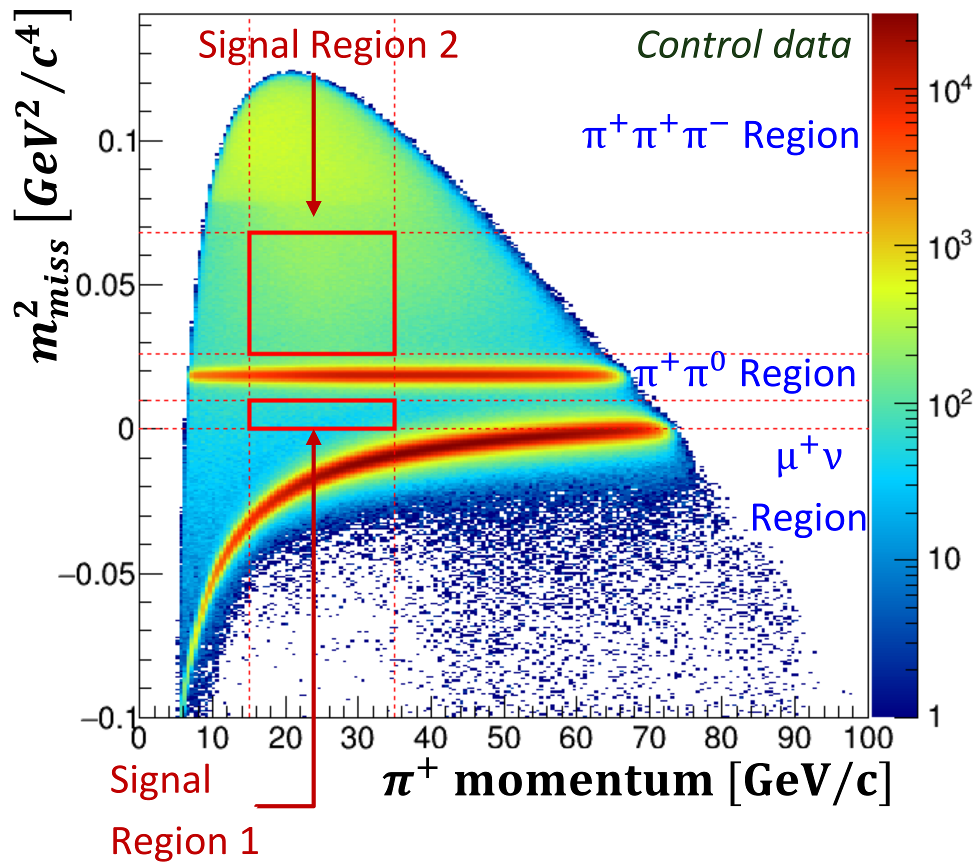
K^+- π^+ matching

K^+ decays in the decay volume

π^+ identification (PID)

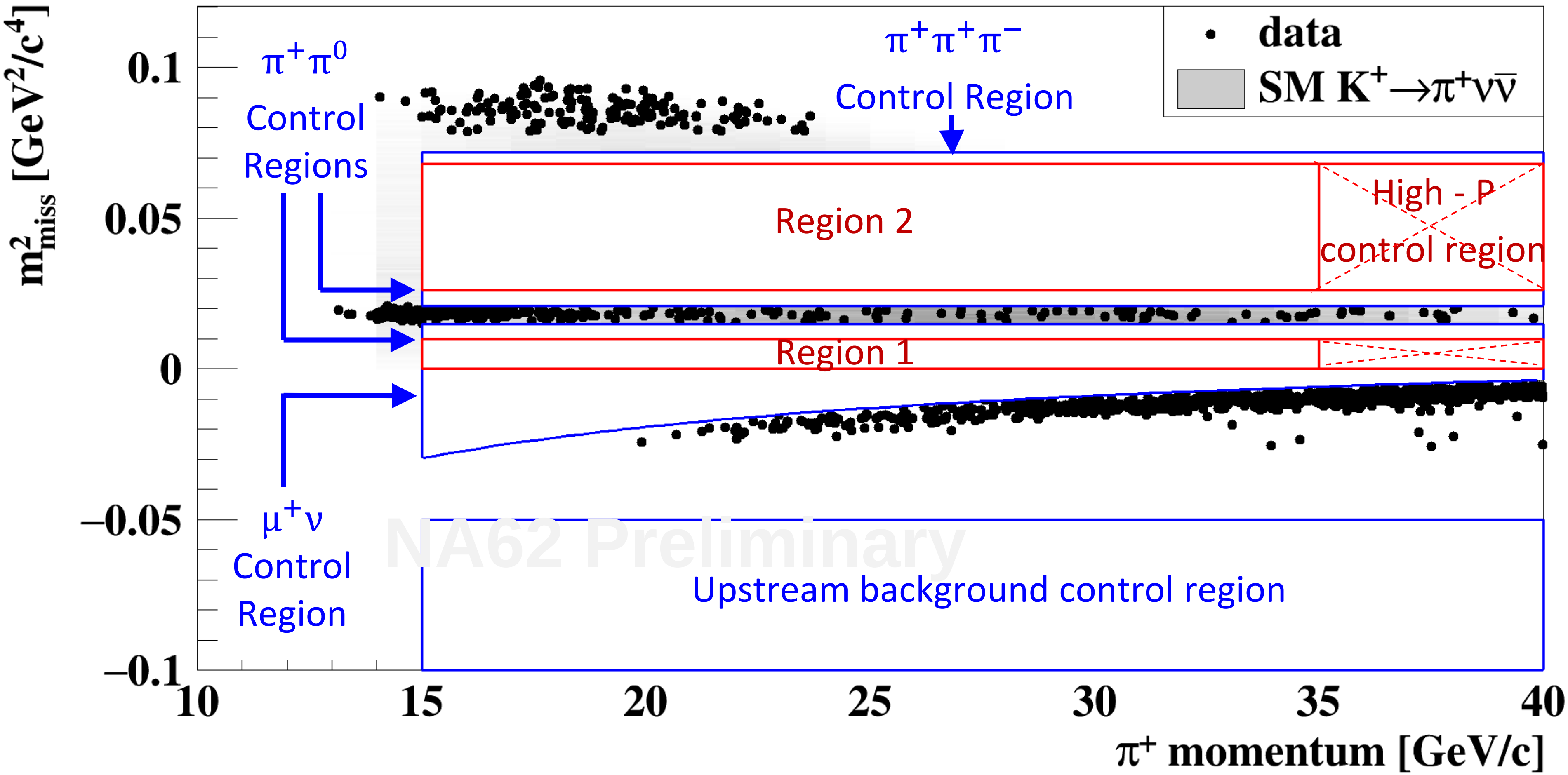
photon rejection

Multi-track rejection



NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ 2017 Data after selection

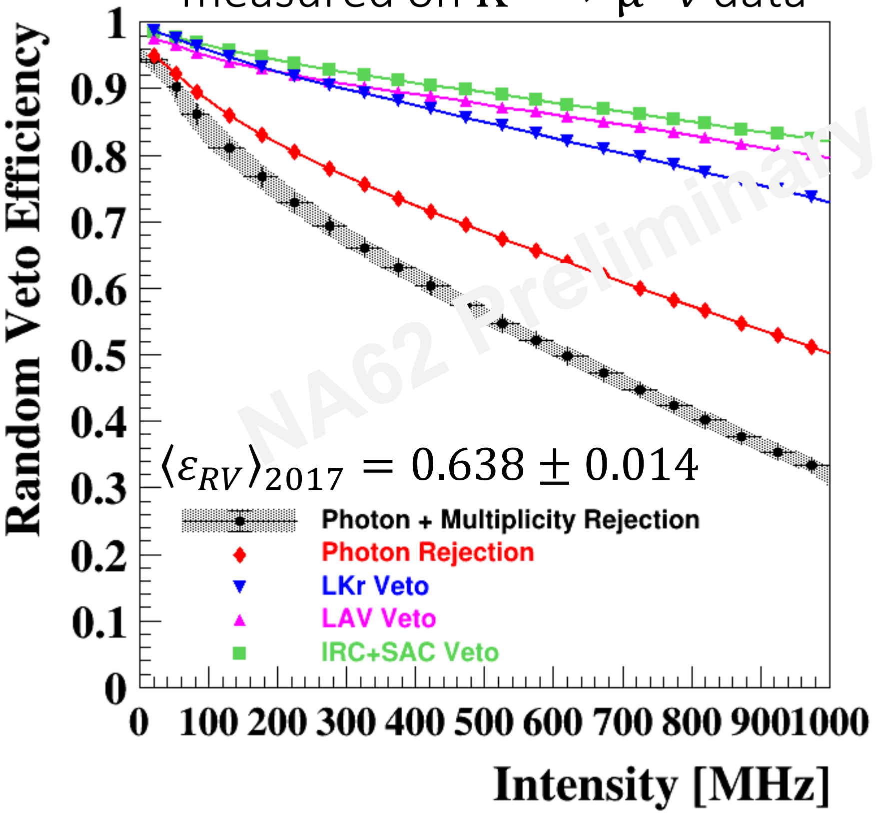
Control and signal regions MASKED



NA62: 2017 Single Event Sensitivity

- $\pi\nu\nu$ normalised to $\pi^+\pi^0$
- SES depends linearly on: PNN trigger efficiency, random veto efficiency

measured on $K^+ \to \mu^+\nu$ data



$$S.E.S. = (0.389 \pm 0.021) \times 10^{-10}$$

$$N_{\pi\nu\nu}^{exp} = 2.16 \pm 0.12 \pm 0.26_{ext}$$

** Vector form factors*

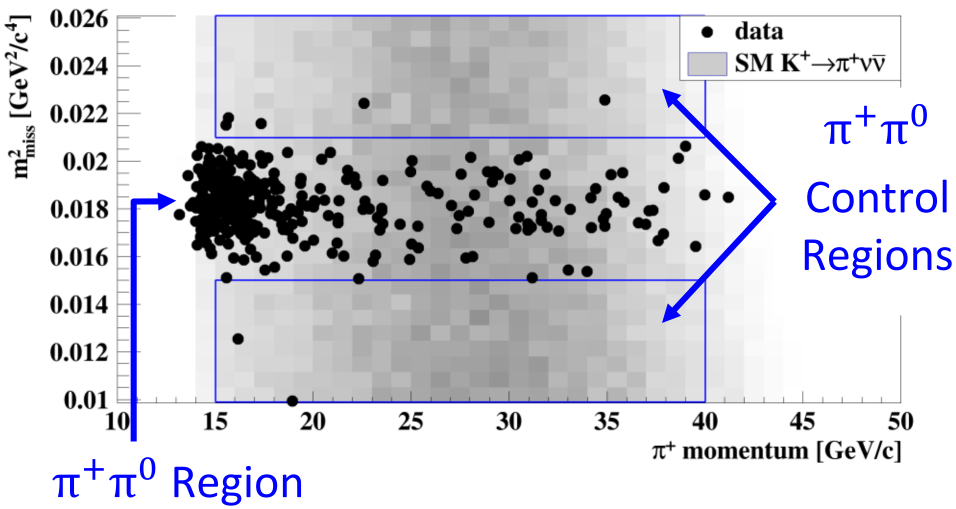
NA62: 2017 Expected Background

Process	Expected events
$K^+ \to \pi^+ \nu\overline{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.11 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu_\mu(\mu^+ \to e^+\text{decay})$	$0.04 \pm 0.02_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

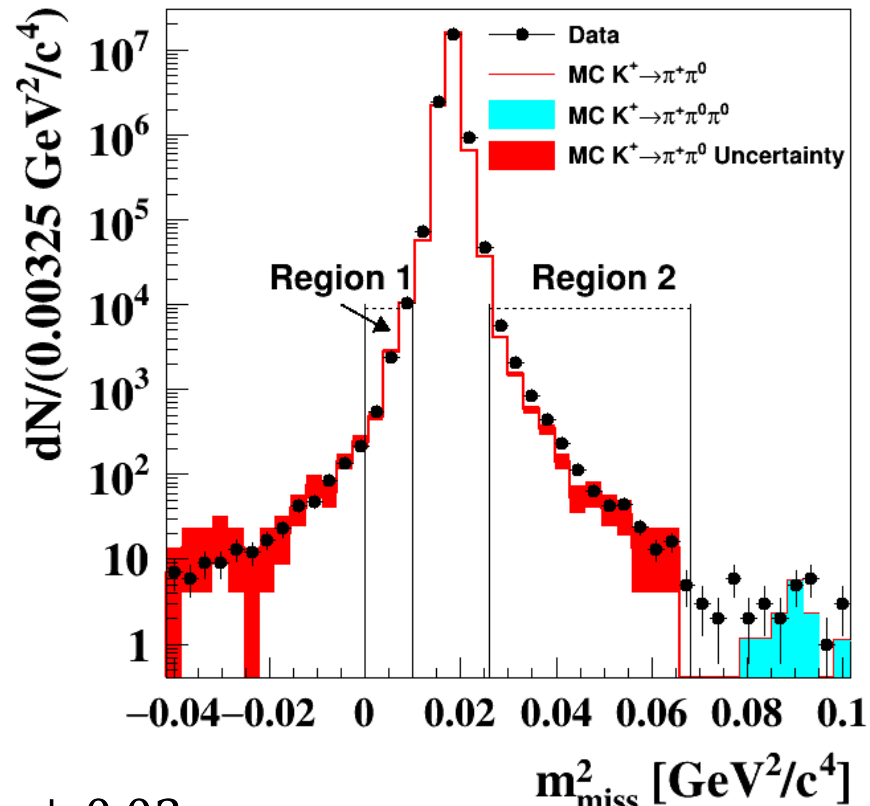
Example: $K^+ \rightarrow \pi^+\pi^0$ Background

- Estimated from DATA. Hypotesis: kinematic and π^0 rejection independent
- Corrections for correlation due to radiative γ

$K^+ \rightarrow \pi^+\pi^0$ after $\pi\nu\nu$ selection



$K^+ \rightarrow \pi^+\pi^0$ to study m^2_{miss} kine tails

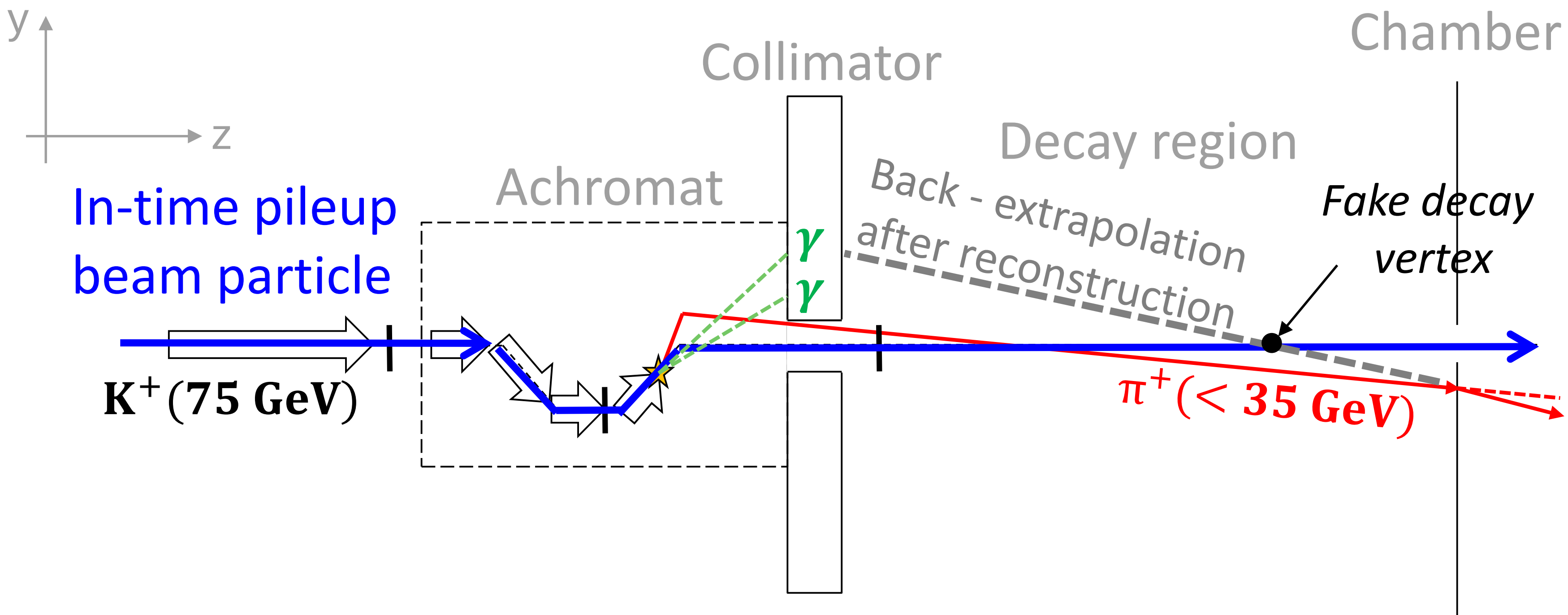


$\pi^+\pi^0$ expected control region: 7.6 ± 0.7

$\pi^+\pi^0$ observed control region: 7

$\pi^+\pi^0$ expected signal region $0.29 \pm 0.03_{stat} \pm 0.03_{syst}$

Example: Upstream Background



- K^+ decays/interacts in the achromat
- Secondary π^+ downstream
- Beam elements block additional particles
- π^+ scattering in straw chamber 1

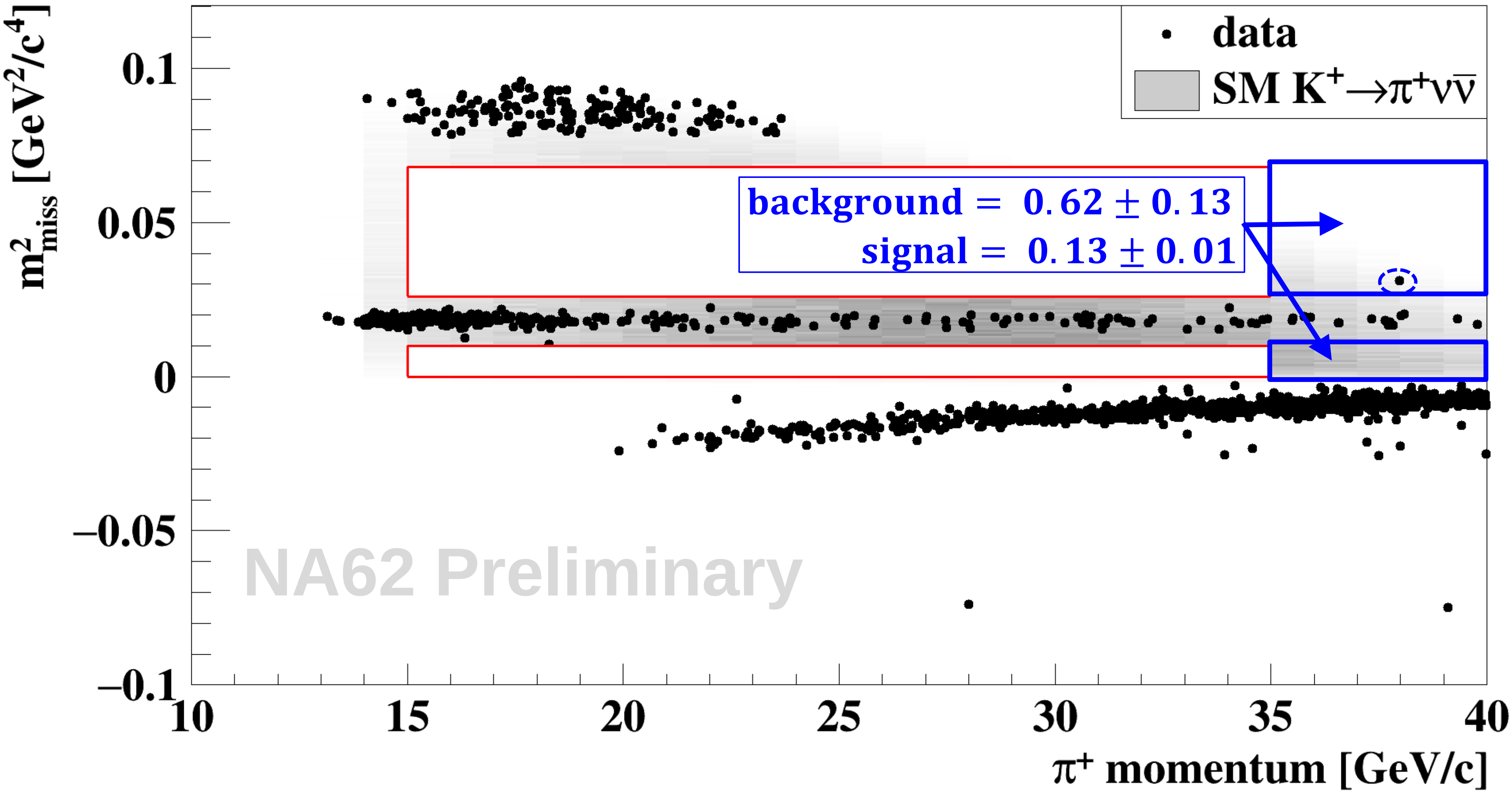
→ Count events on data with inverted $K - \pi$ matching

- Pileup beam particle tagged as K^+

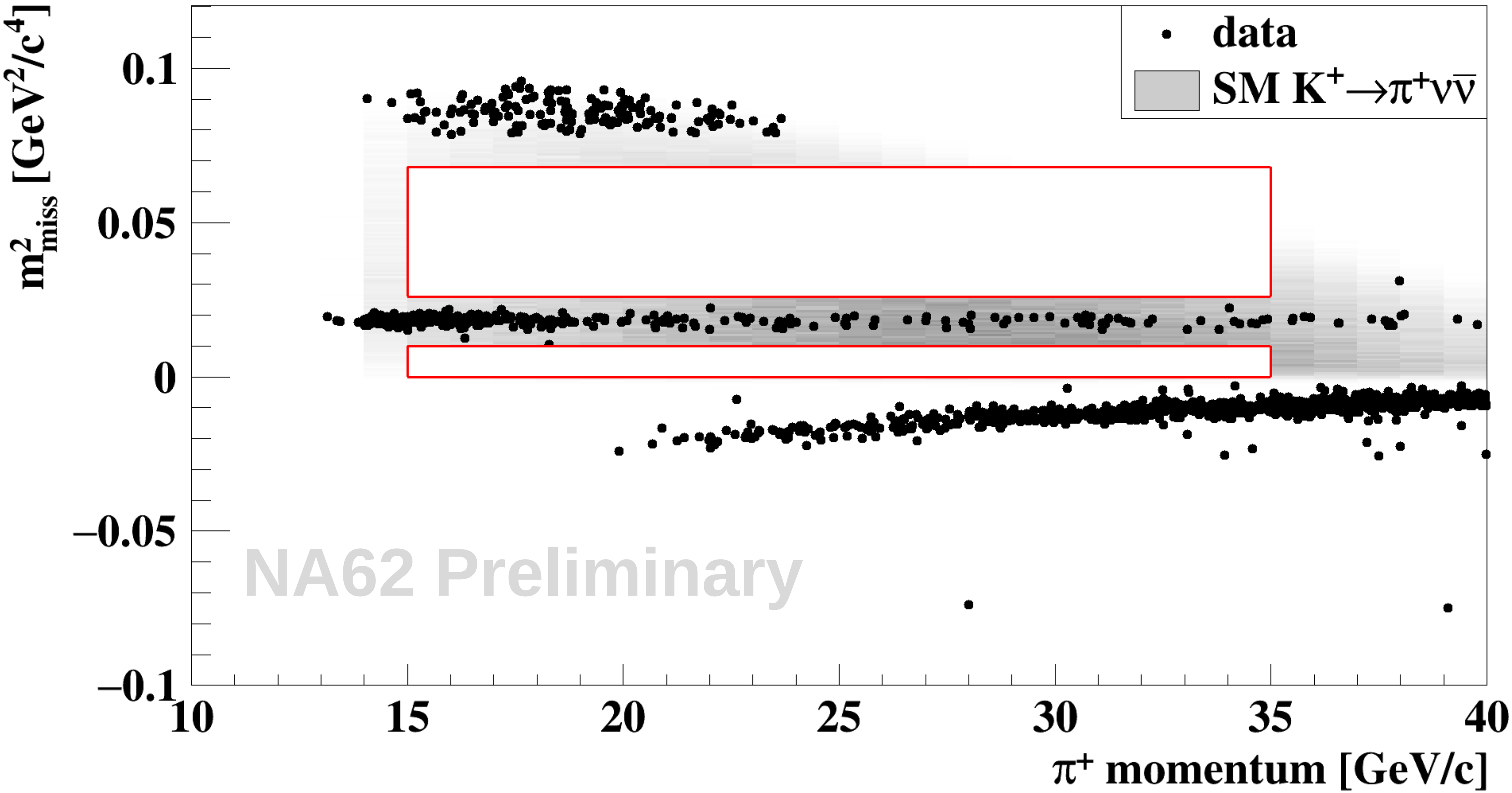
→ Estimate the probability to occur from data/simulation

NA62: 2017 Background Validation

Signal and background evaluated in the 35-40 GeV/c signal-like regions

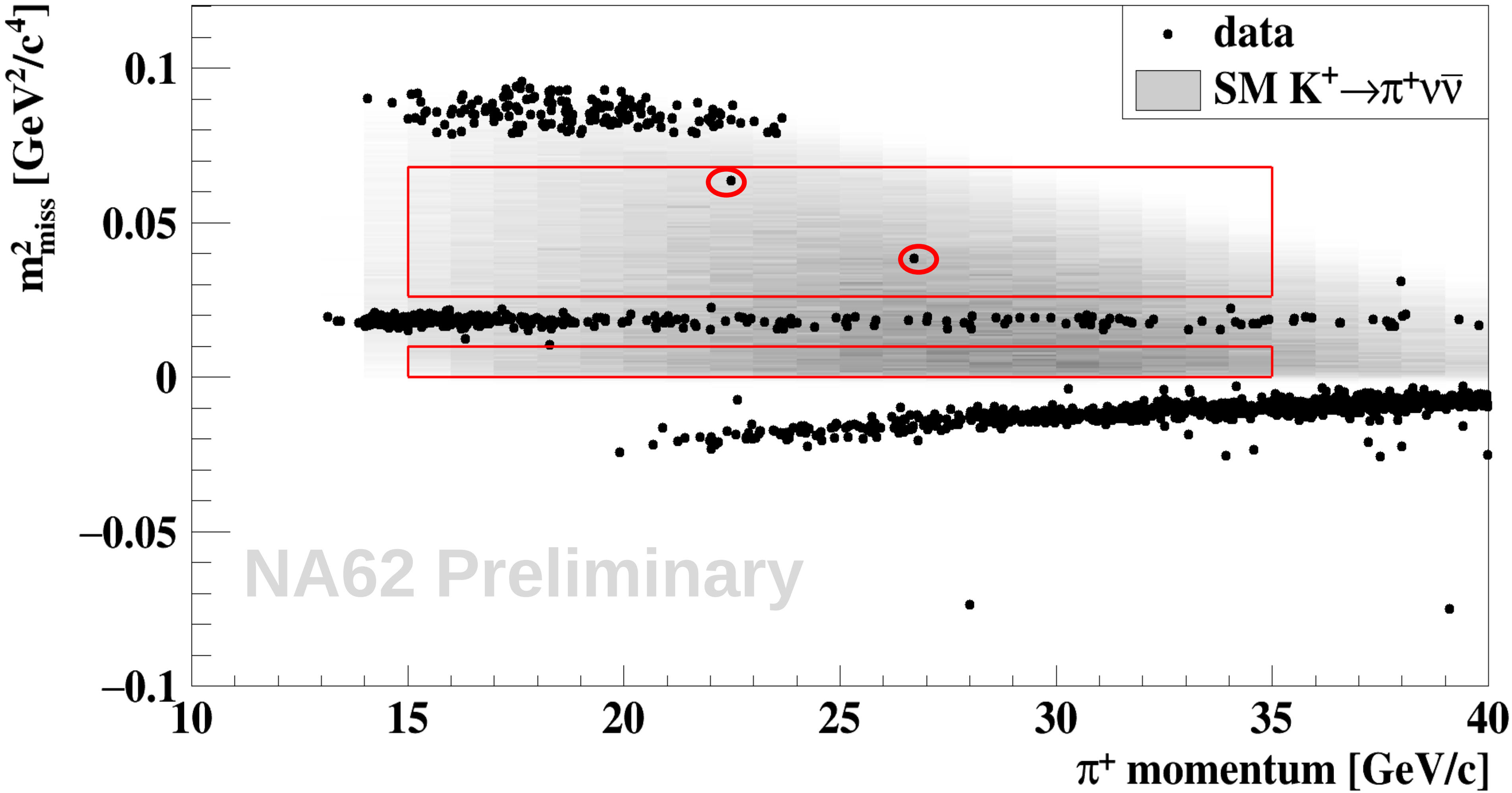


Opening the Box

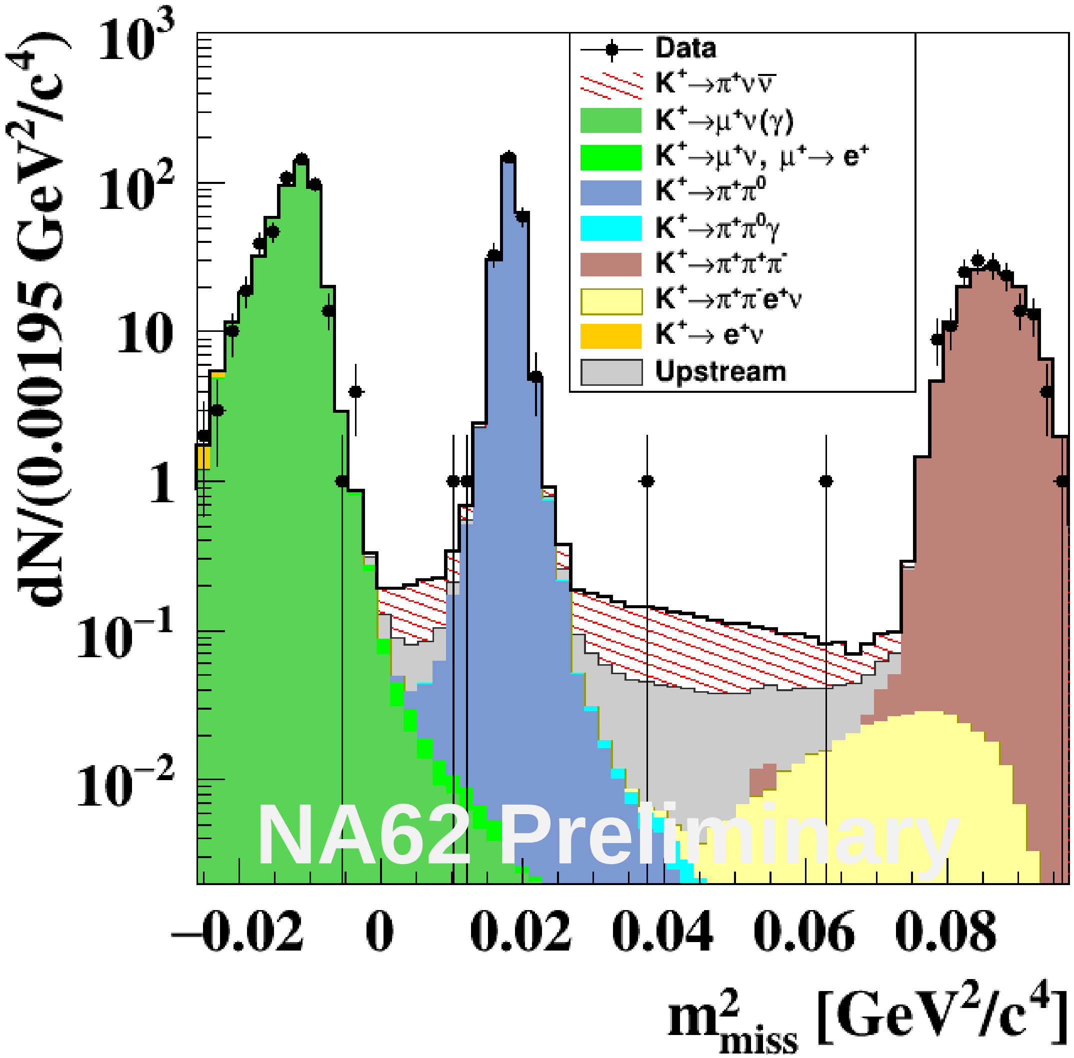


NA62: 2017 Box Opened

2 events observed in signal region



m^2_{miss} Signal and Background



NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ 2016+2017 Result

- Combination of 2016 and 2017 data

Events observed	3
Single event sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected background	1.65 ± 0.31

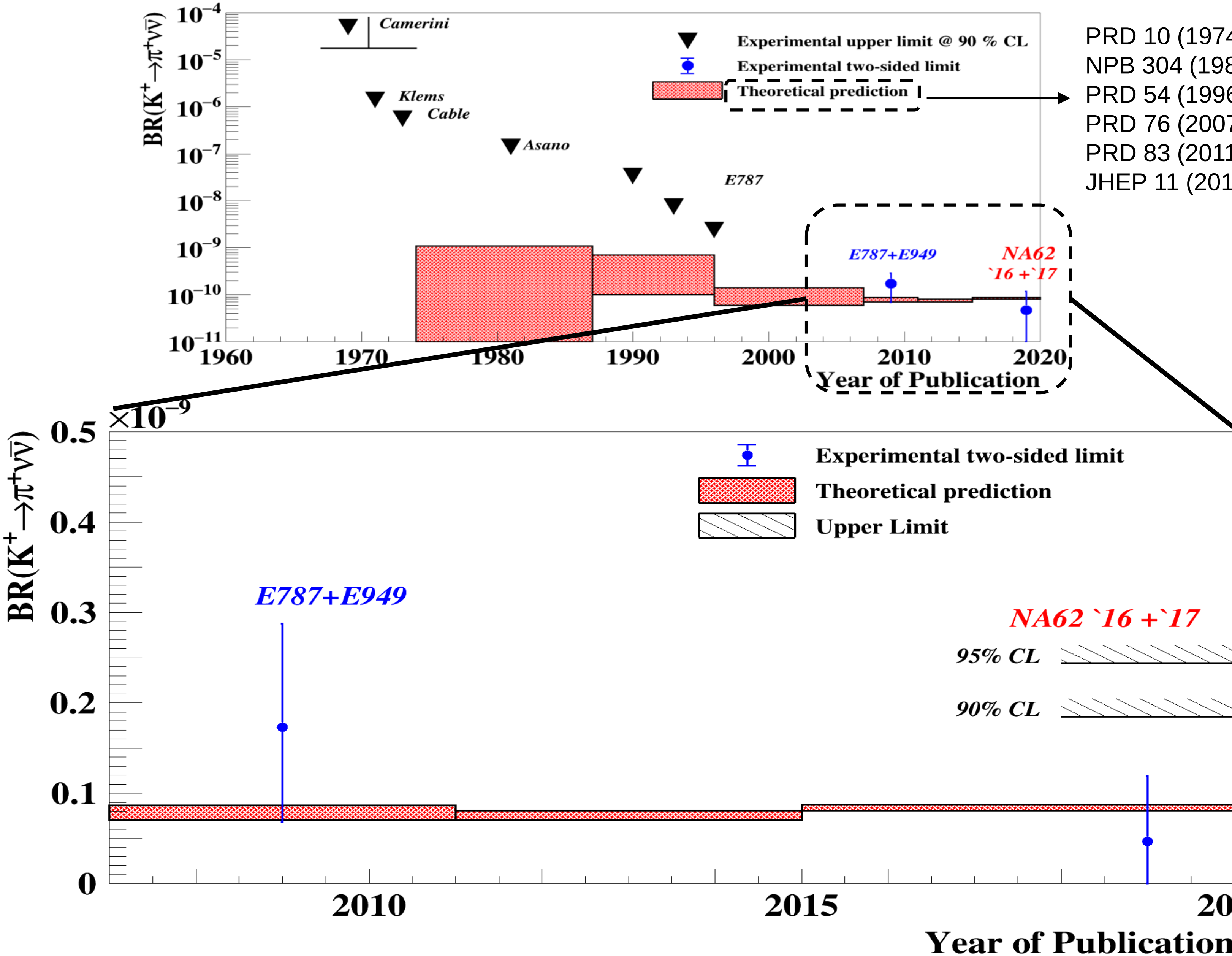
- Upper limits (CLs method)

Observed	Expected (background only)	CL
$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$	$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.32 \times 10^{-10}$	90%
$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \times 10^{-10}$	$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.62 \times 10^{-10}$	95%

- Two-sided 68% band: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$

- Search for $K^+ \to \pi^+ X$, with X «dark» scalar on-going

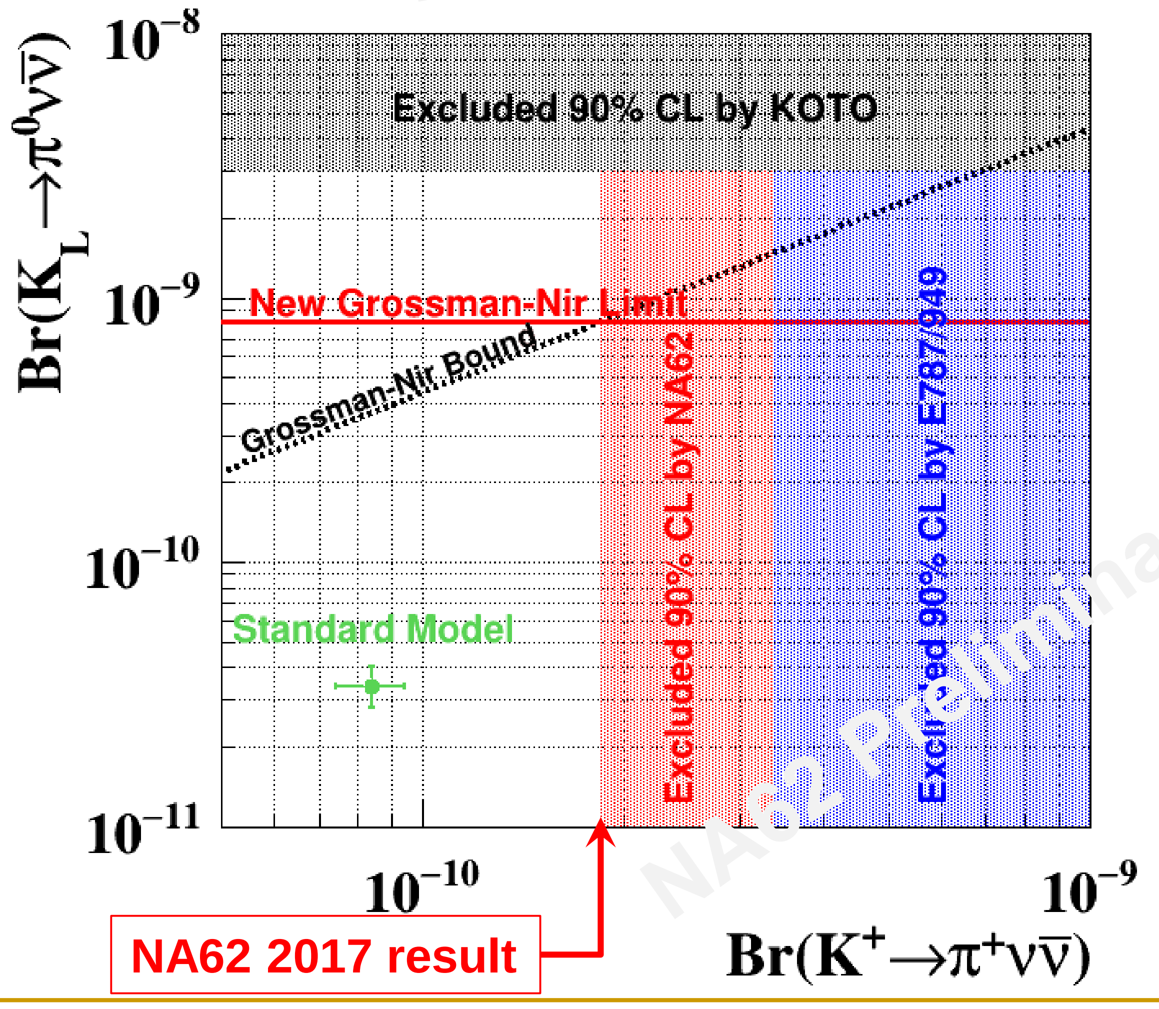
$K^+ \to \pi^+ \nu\bar{\nu}$ History



PRD 10 (1974) 897
NPB 304 (1988) 205
PRD 54 (1996) 6782
PRD 76 (2007) 034017
PRD 83 (2011) 034030
JHEP 11 (2015) 33

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ Today

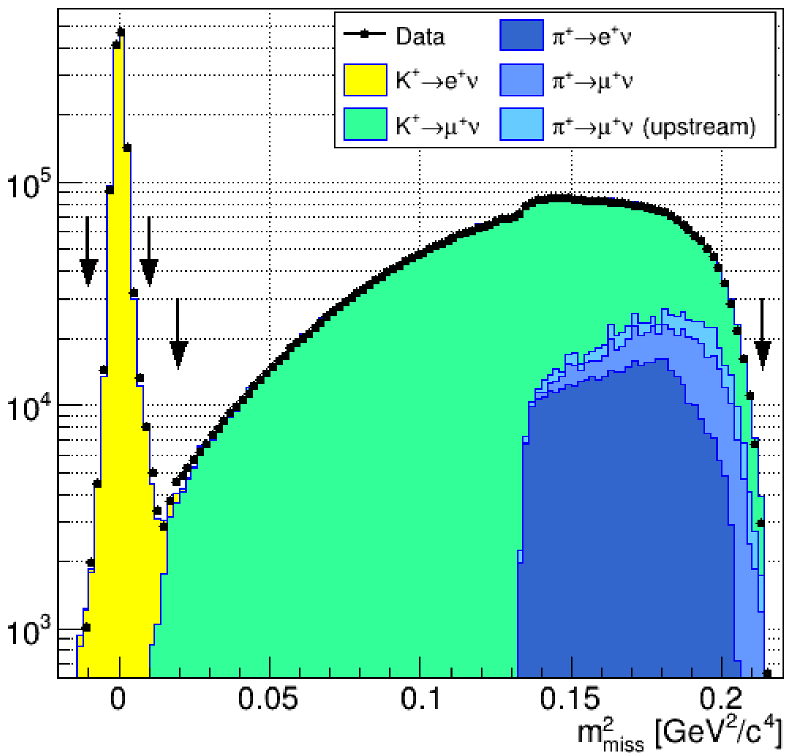
- New Grossman – Nir limit: $Br(K_L \to \pi^0 \nu\nu) < 8.14 \times 10^{-10}$ @ 90% CL

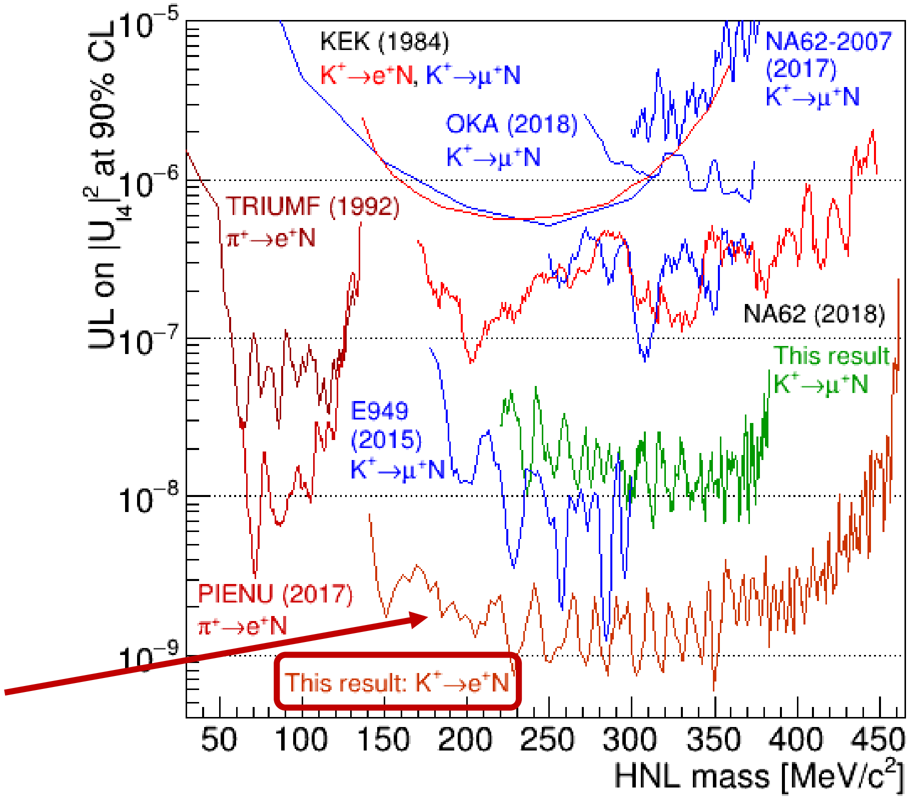


Beyond $K \to \pi\nu\nu$: HNL production @ NA62

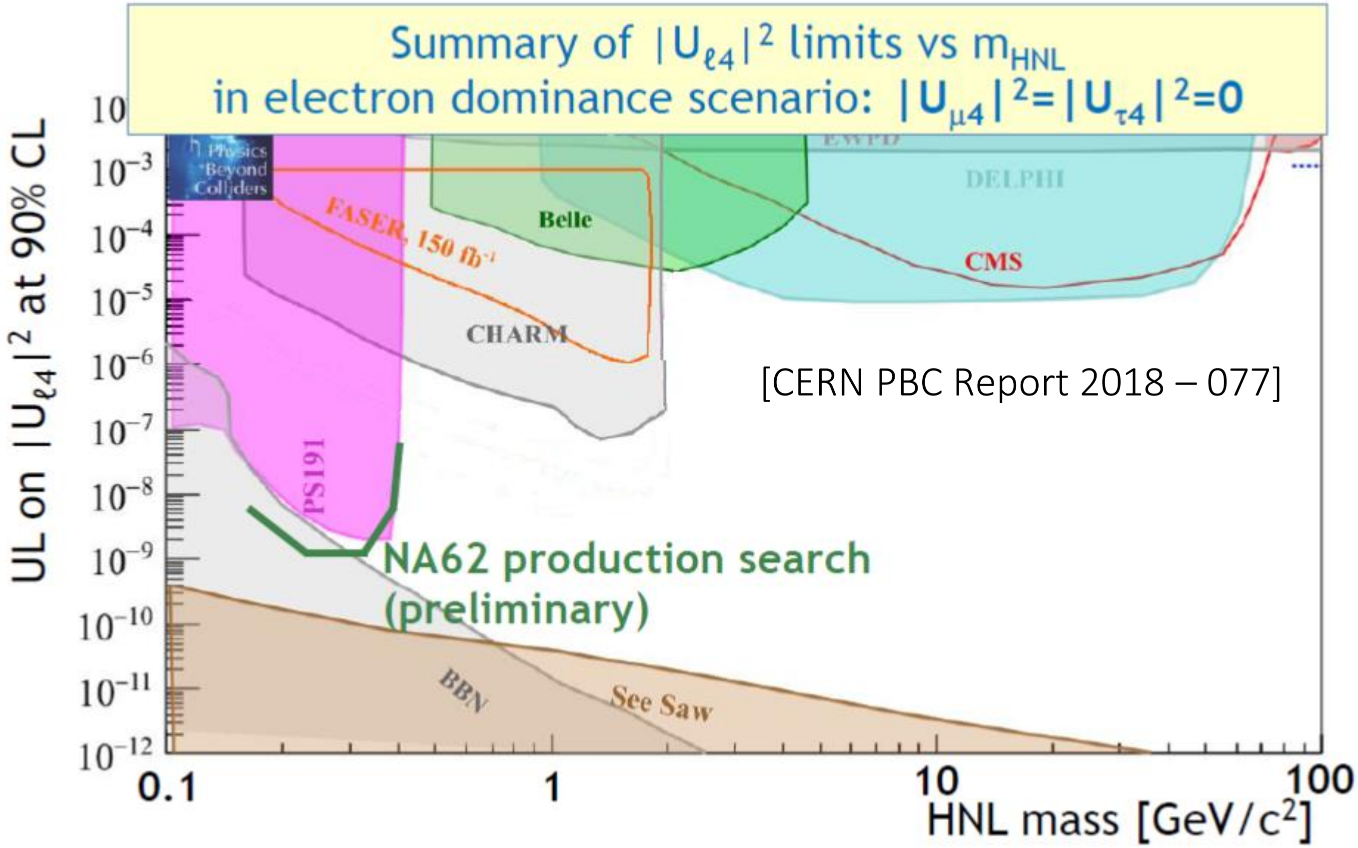
- Search for HNL in $K^+ \to e^+\nu$ and $K^+ \to \mu^+\nu$: NA62 (2016+2017)
- Peak search on the missing mass spectrum out of the peak

$K^+ \to e^+\nu$





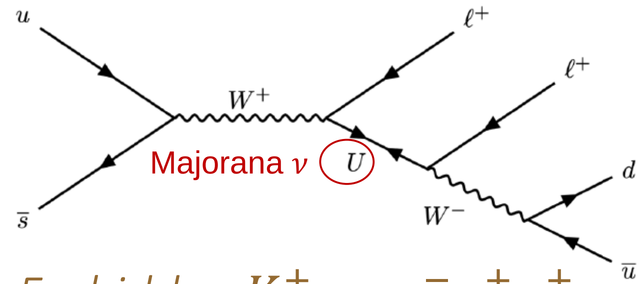
HNL production vs decay searches



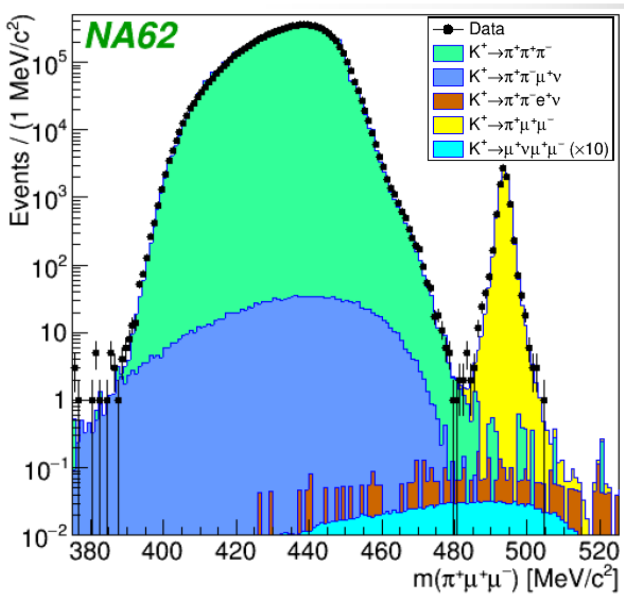
- Direct searches require model – dependent assumptions
- Exhausting the BBN-allowed range up to 300 $\mathrm{MeV/c^2}$
- T2K has improved the PS191 limits > 360 $\mathrm{MeV/c^2}$ [arXiv:1902.07598]

Beyond K → πνν: LFV @ NA62

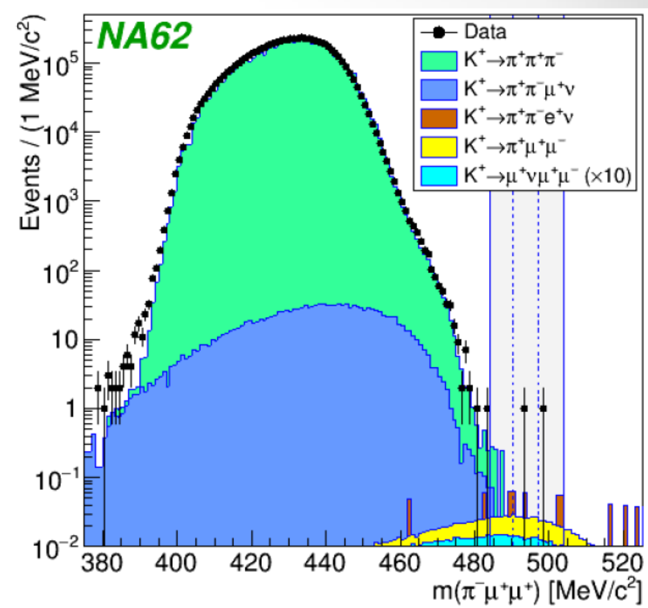
- Search for forbidden decays $K^+ \to \pi^- l^+ l^+$
- 2017 data analyzed
- $\times$ 2,3 factor improvements on U.L.



SM allowed $K^+ \to \pi^+\mu^+\mu^-$



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



$BR(K^+ \to \pi^- e^+ e^+) < 2.2 * 10^{-10}$ @ 90% CL
$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 * 10^{-11}$ @ 90% CL

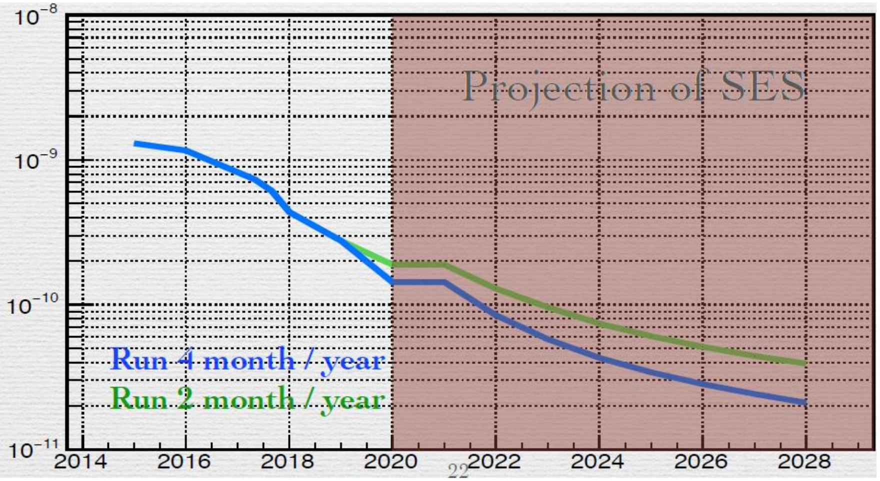
[PLB 797 (2019) 134794]

Future Prospects

$K \to \pi\nu\bar{\nu}$ Medium Term Prospects (<2026)

- $K^+ \to \pi^+\nu\bar{\nu}$ @ NA62
  - Goal 2016+2017+2018 data: O(10) events
    - 2018 data: 2 × 2017 statistics; analysis optimization under study
  - Goal 2021 – 2025 run: O(50) events (if at least 3 years of data taking)
    - Definition of the NA62 run schedule under discussion
    - Suppression of upstream background under study; increase of intensity

- $K_L \to \pi^0\nu\bar{\nu}$ @ KOTO
  - Goal 2016 → 2019 data: O(10) sensitivity increase
    - Background under study
  - Goal >2019 run: SM SES (1 SM event observation)
    - JPARC power increase

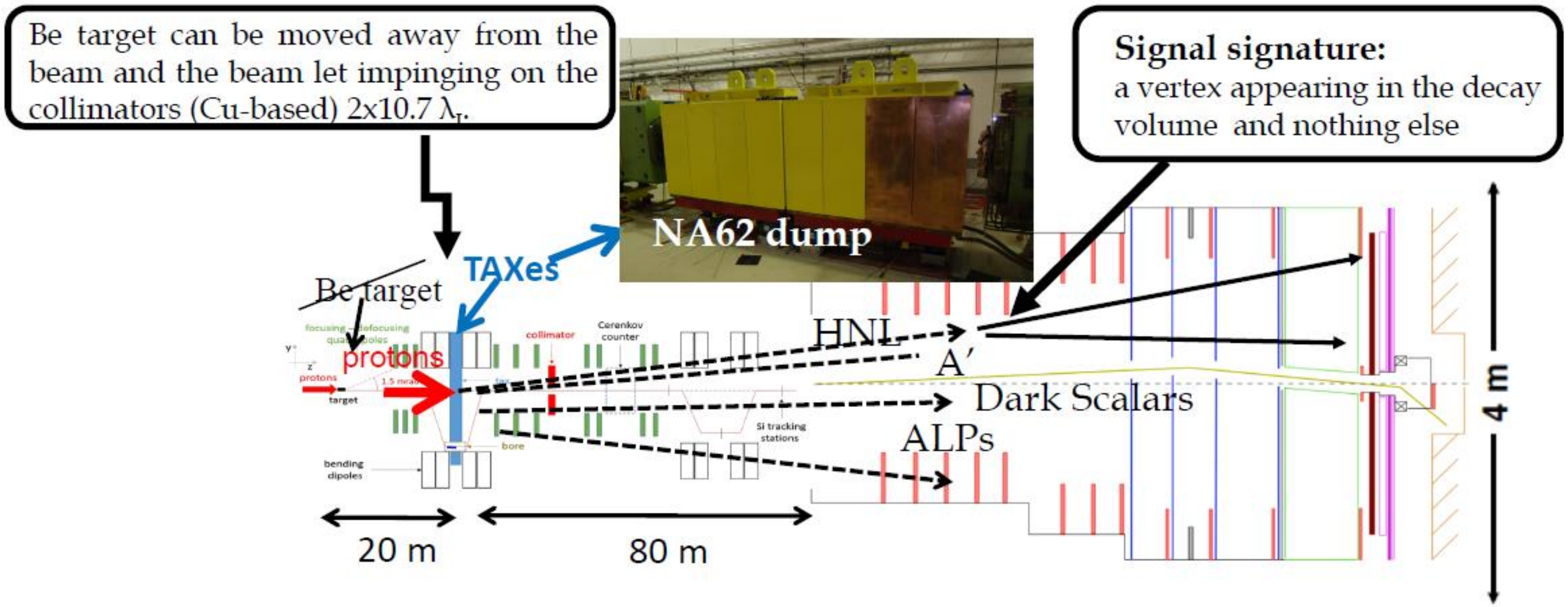


Beyond $K \to \pi\nu\bar{\nu}$: Forbidden /Rare Decays @ NA62

Forbidden LFV - LNV	$K^+ \to \pi^- e^+ e^+$ / $K^+ \to \pi^- \mu^+ \mu^+$
	$K \to \pi\mu e$
HNL production	$K^+ \to \mu^+ N$ / $K^+ \to e^+ N$
Rare decays	$K^+ \to \pi^+ \gamma\gamma$
	$K^+ \to \pi^+ e^+ e^-$ / $K^+ \to \pi^+ \mu^+ \mu^-$
	$K^+ \to l_1^+ \nu l_2^+ l_2^-$, $l_{1,2} = e, \mu$
	$K^+ \to e^+ \nu(\gamma)$, $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$
	$K^+ \to \pi^0 e^+ \nu\gamma$, $K^+ \to \pi^+ e^+ e^- \gamma$, $K^+ \to \pi^+ \pi^+ \pi^- \gamma$

- Forbidden: $10^{-11} \div 10^{-12}$ sensitivity (>2021)
- Rare:
  - largest statistical samples for some of the decays available (e.g. $K^+ \to e^+\nu$)
  - >2021 entering high precision era for all rare decays

Beyond $K \to \pi\nu\bar{\nu}$: Dark Sector Searches @ NA62

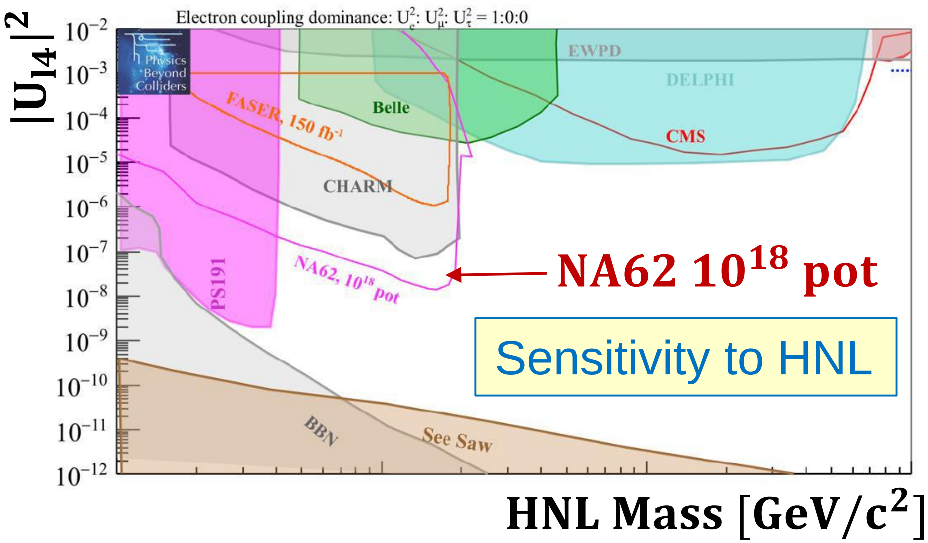


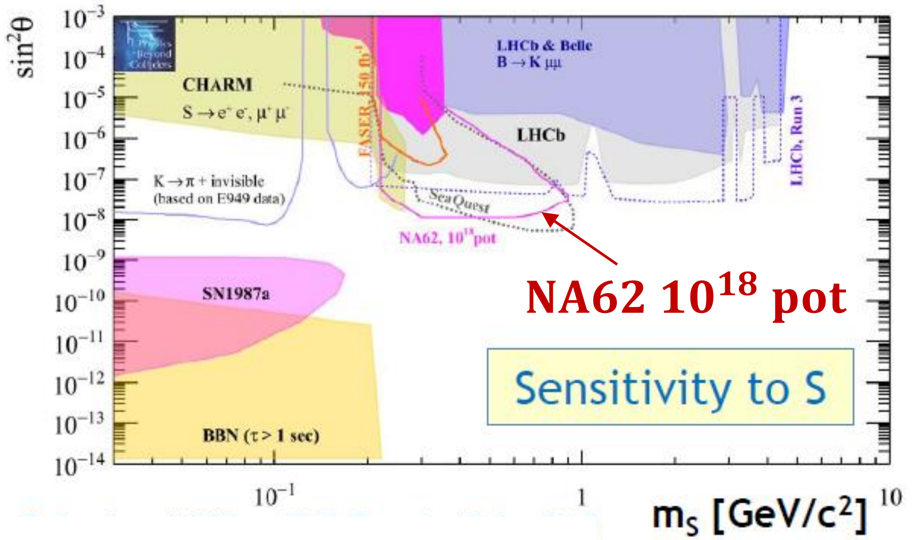
NA62 in dump mode (not exactly K physics... but **<u><2026 time scale</u>**)

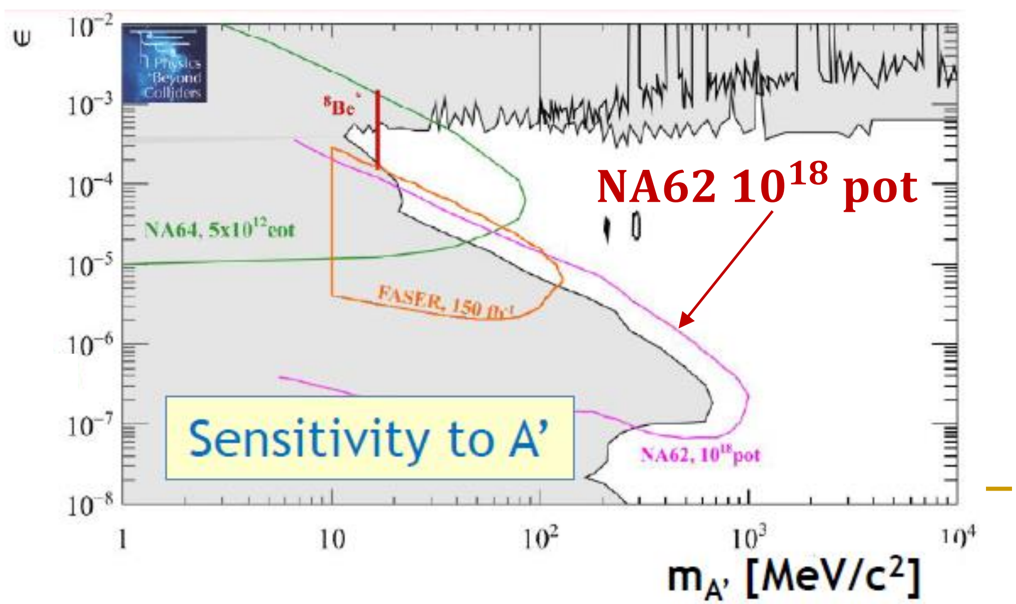
- \>2021 Goal: collect 10^{18} proton on target (3 months of data taking after 2021)
- Extend dark particle mass range $> M_K$ (D and B associated production)
- Searches: HNLs, Dark Scalar (S), Dark Photon (A'), Axion-like (ALP)

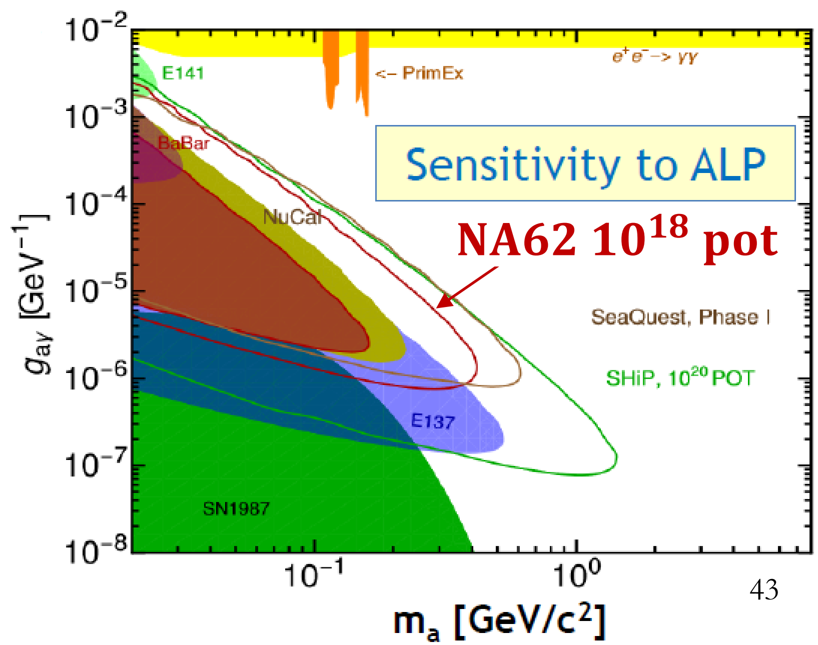
Bridge towards future dump facilities (e.g. SHIP)

Beyond $K \to \pi\nu\bar{\nu}$: NA62-dump Prospects





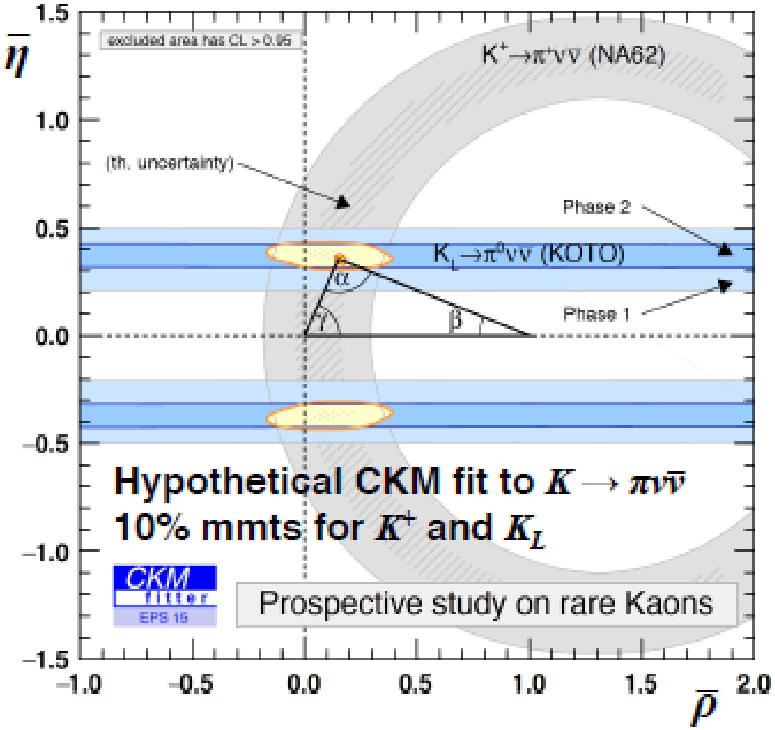




$K \rightarrow \pi\nu\bar{\nu}$ The Big Picture

- <10% precision measurement of $BR(K^+ \rightarrow \pi^+\nu\bar{\nu})$ can test NP up to O(100 TeV) (model - independent)

- BR measurement of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$ can give insights about the NP flavour structure



$K^+ \rightarrow \pi^+\nu\bar{\nu}$ Long Term Prospect (>2026)

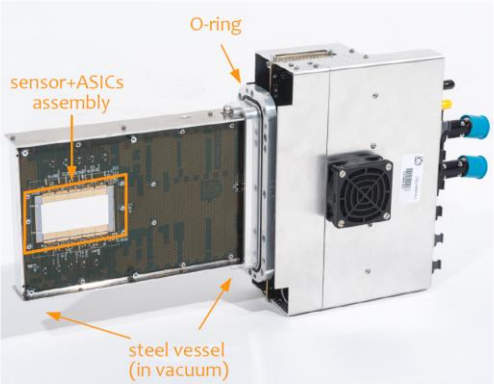
- O(200) events: NA62 @ 4 times the intensity («NA62×4»)

- Advantage:
  - NA62 is the most intense existing kaon facility
  - The decay in flight technique works well for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- Issues:
  - Make NA62 resiliant to intensity effects:
  - Background: time resolution must scale accordingly O(<40 ps)
  - Signal: improve significantly the random veto efficiency

$K^+ \to \pi^+ \nu\bar{\nu}$: «NA62×4»

- Detector R&D example: beam tracker
- Si pixel stations mounted on the beam



	NA62	NA62×4
Beam Particle Rate	750 MHz	3 GHz
Peak Beam Particle Flux	2.0 MHz/mm^2	8.0
Hit Time Resolution	< 200 ps	< 50 ps

- Time resolution (NA62)

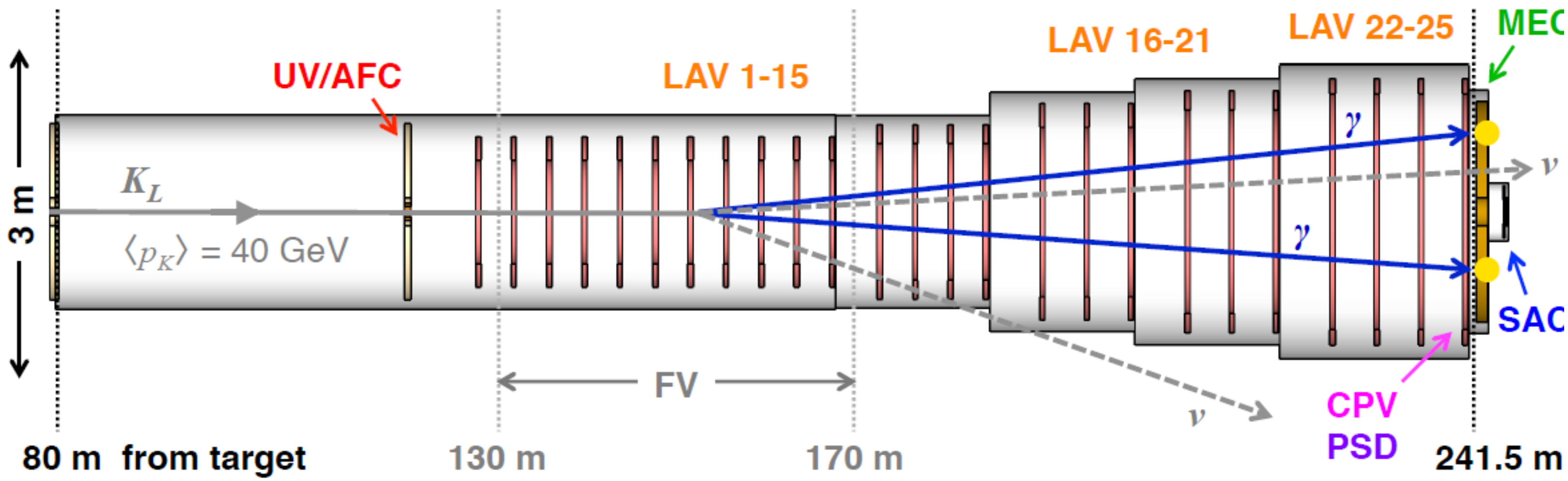
$$\sigma = \sqrt{\sigma^2_{TDC} + \sigma^2_{electronic} + \sigma^2_{WeightingField} + \sigma^2_{Straggling}}$$
$$= \sqrt{28^2 + 75^2 + 85^2 + 100^2} = 150\ \mathrm{ps}$$

- Straggling ⇒ thinner sensor (NA62 200 μm)
- WeightingField ⇒ different electrode design
- Electronic ⇒ reduce S/N

- Possible R&D in synergy with similar projects for HiLumi

$K_L \to \pi^0 \nu\bar{\nu}$ Long Term Prospect

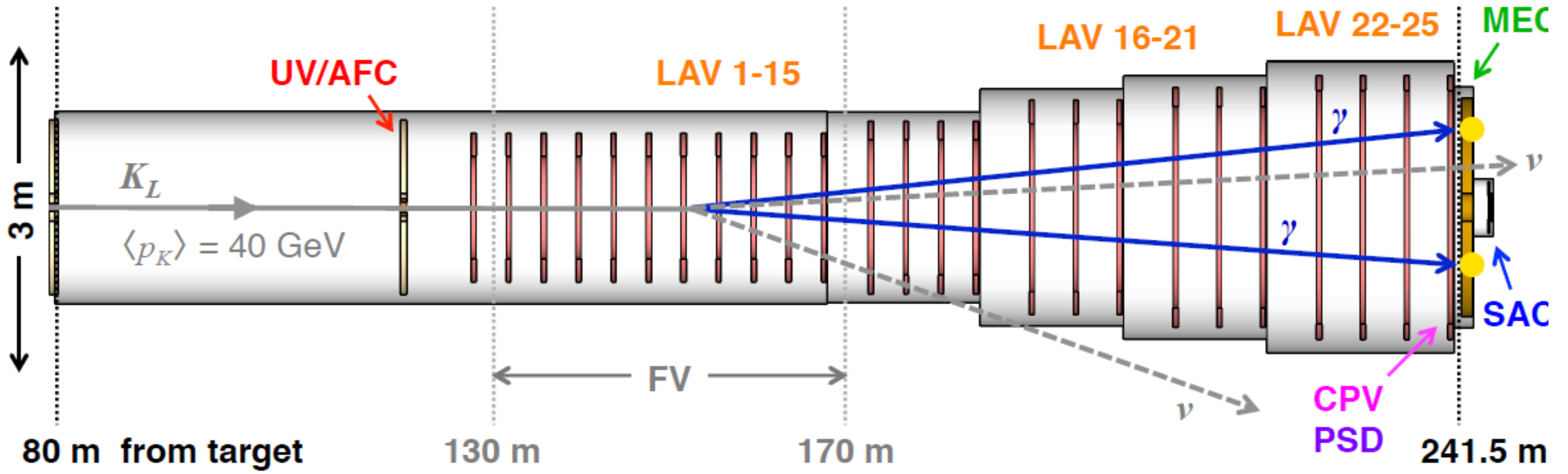
- O(60) events: KLEVER @ CERN



- Idea
  - KOTO-like technique at high energy
- Advantage:
  - CERN SPS can deliver enough protons on target
  - Photon rejection benefits from higher energy than KOTO

$K_L \to \pi^0 \nu\bar{\nu}$ Long Term Prospect

- O(60) events: KLEVER @ CERN



- Idea
  - KOTO-like technique at high energy
- Issues:
  - New photon detectors wrt NA62; avoid pileup from high photon rate
  - No kinematic constraint for signal ⇒ photon rejection critical, but full geometrical coverage not possible over >100 m

Conclusions

- 70 years of Kaon Physics have made the history of the particle physics
- Today
  - Kaon Physics, and NA62 in particular, has started the search for new physics at the highest mass scales
- Tomorrow
  - Kaon Physics can reach new physics at the highest mass scale
  - NA62 can initiate the future quest of new physics in the dark sector
- UK
  - had a leading role in the past of kaon physics (NA48)
  - has a leading role in the present of kaon physics (NA62)
  - is setting the bar to lead the future of kaon physics