STATUS AND FUTURE PROSPECTS FOR RARE KAON DECAY MEASUREMENTS AT NA62

1. The NA62 experiment
2. The main goal: BR($K^+ \to \pi^+\nu\bar{\nu}$)
3. Recent preliminary results and prospects

RENATO FIORENZA (on behalf of the NA62 collaboration)
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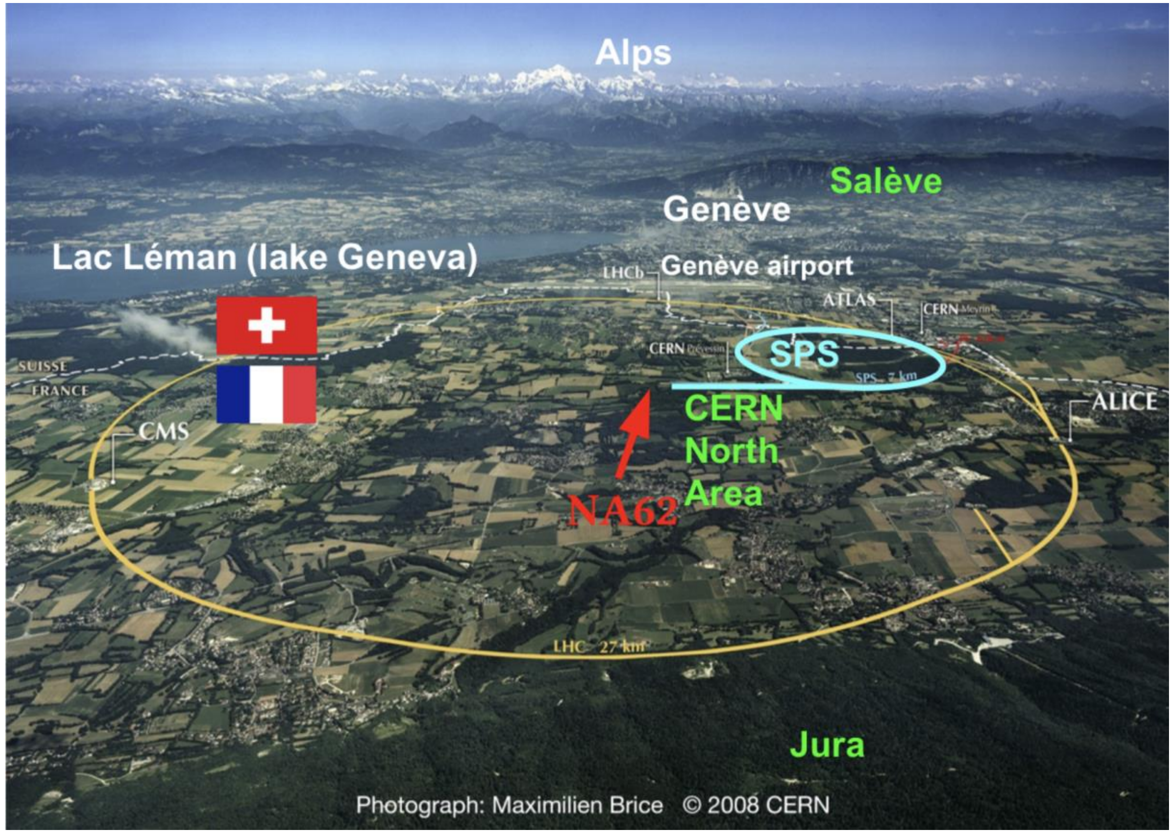
THE NA62 EXPERIMENT



~200 collaborators from ~30 institutes

High-precision kaon experiment

- Technique: Fixed target & decay in flight

Main goal: measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$)

Broad physics program

- Rare K^+ decays
- Search for LNV / LFV
- Direct exotic searches

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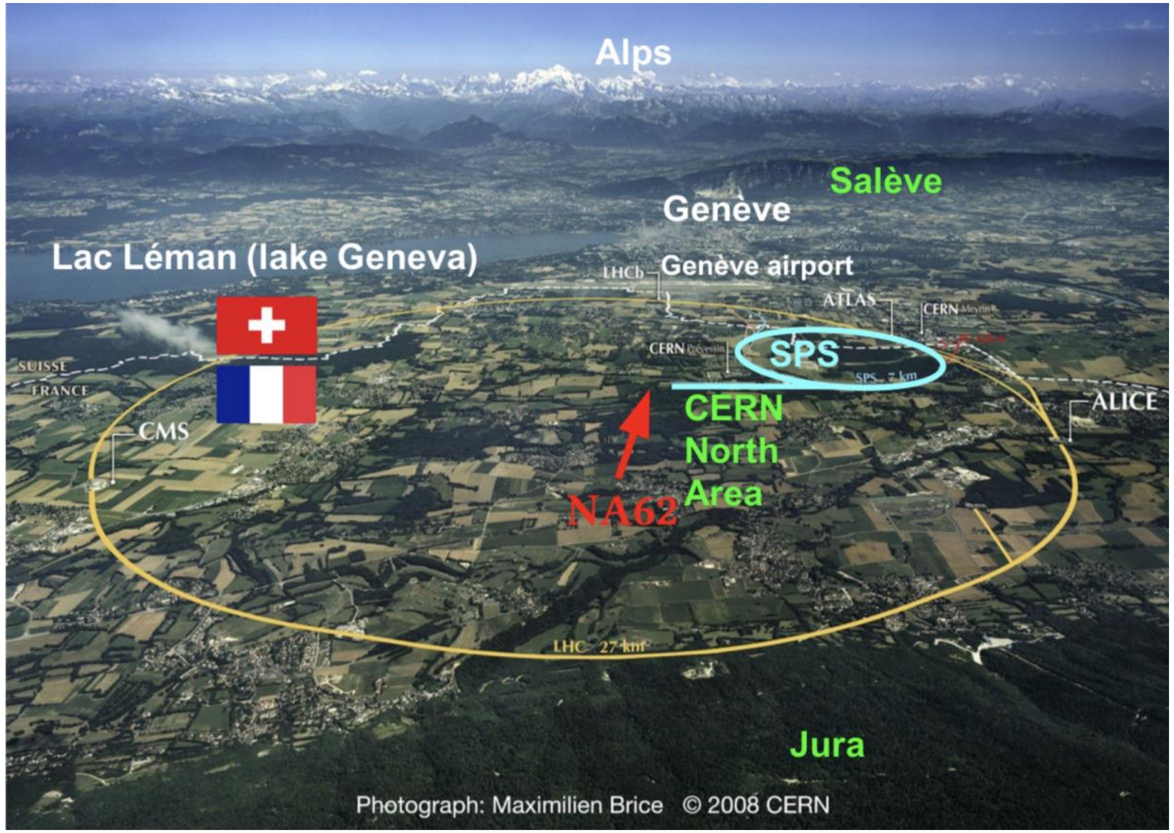

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this talk

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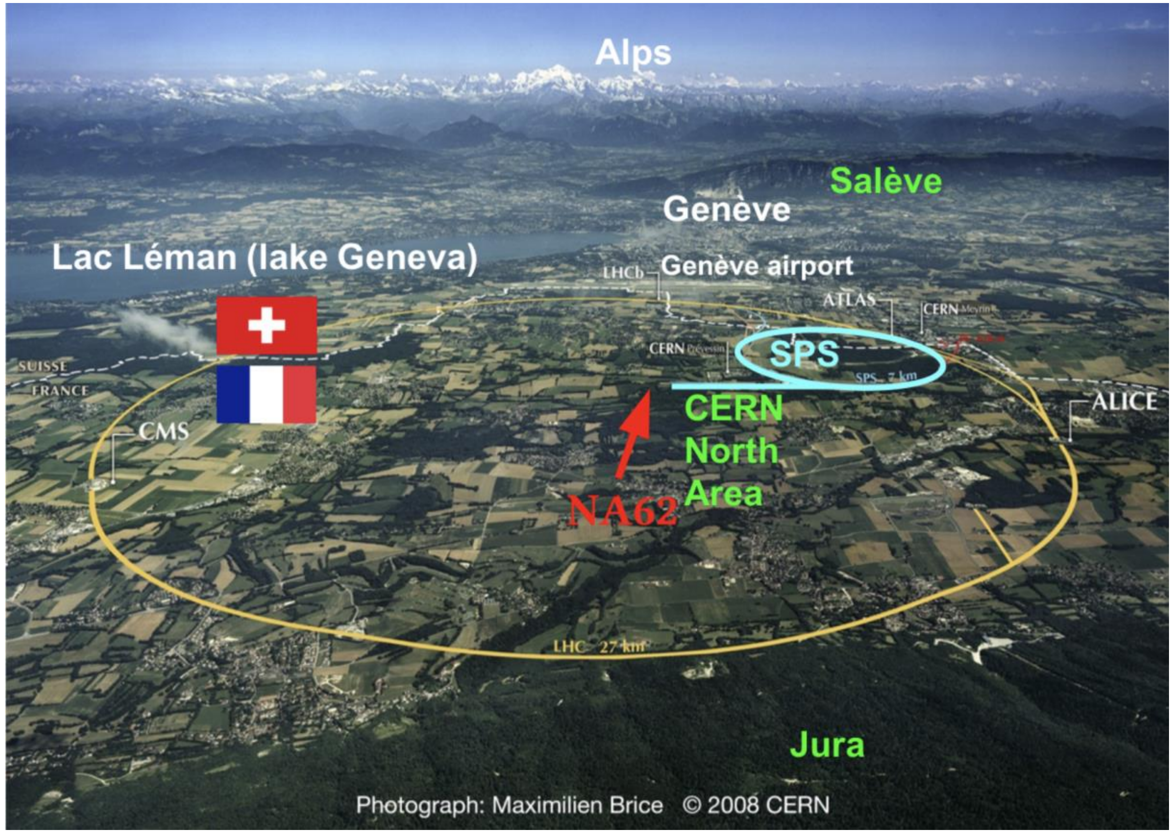

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Broad physics program

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this talk

Commissioning	2016	2017	2018	LS2	2021	2022	2023	2024	2025	2026
	45 days	160 days	217 days	upgrades	85 days	215 days	150 days	204 days		

THE NA62 DETECTOR

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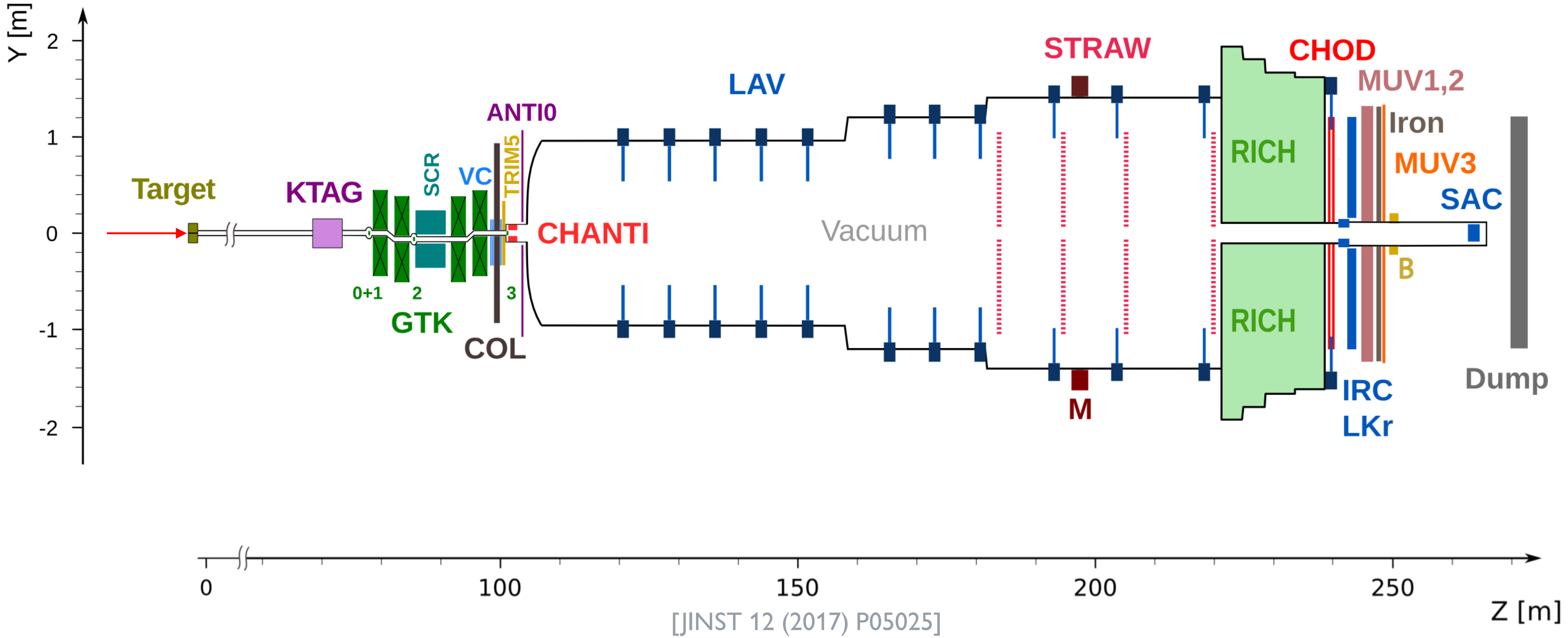
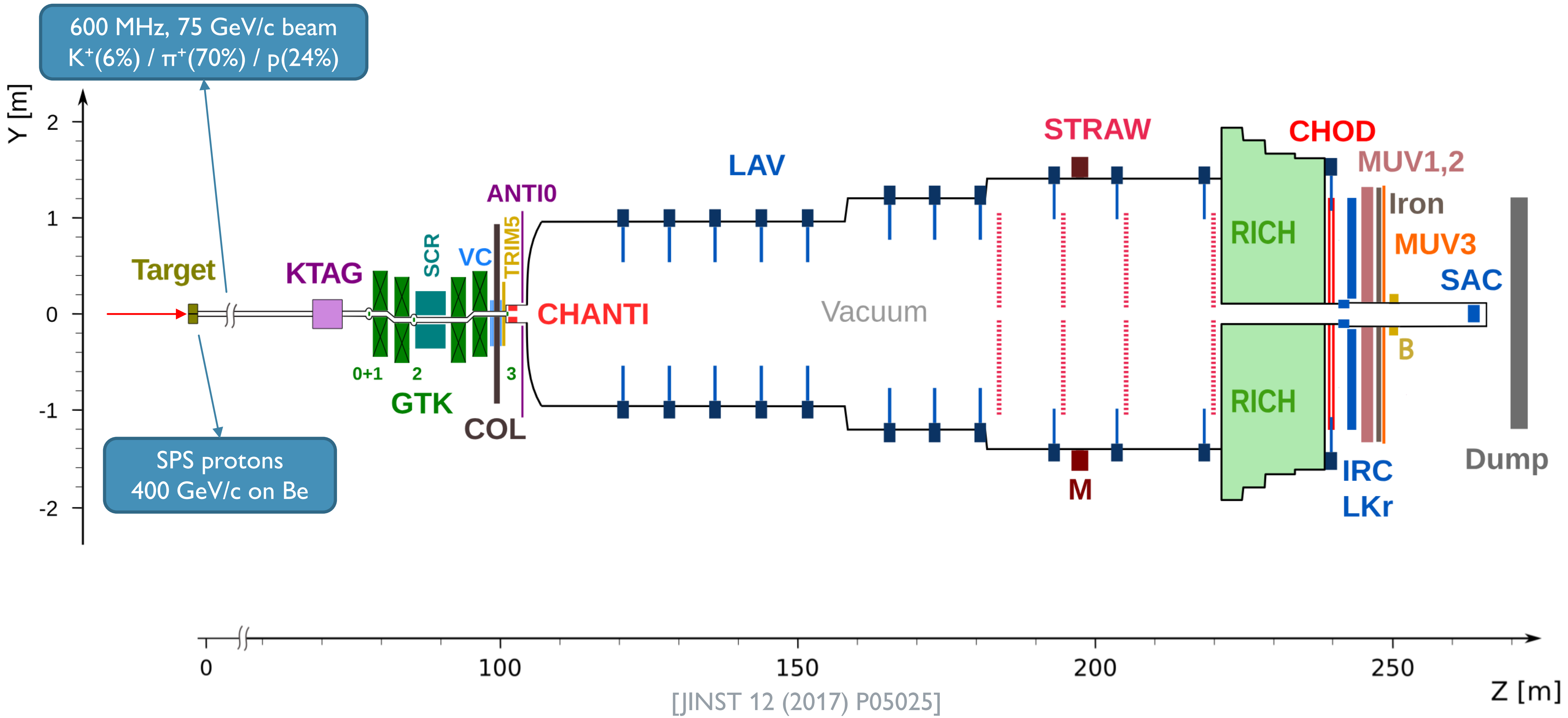


[JINST 12 (2017) P05025]

THE NA62 DETECTOR



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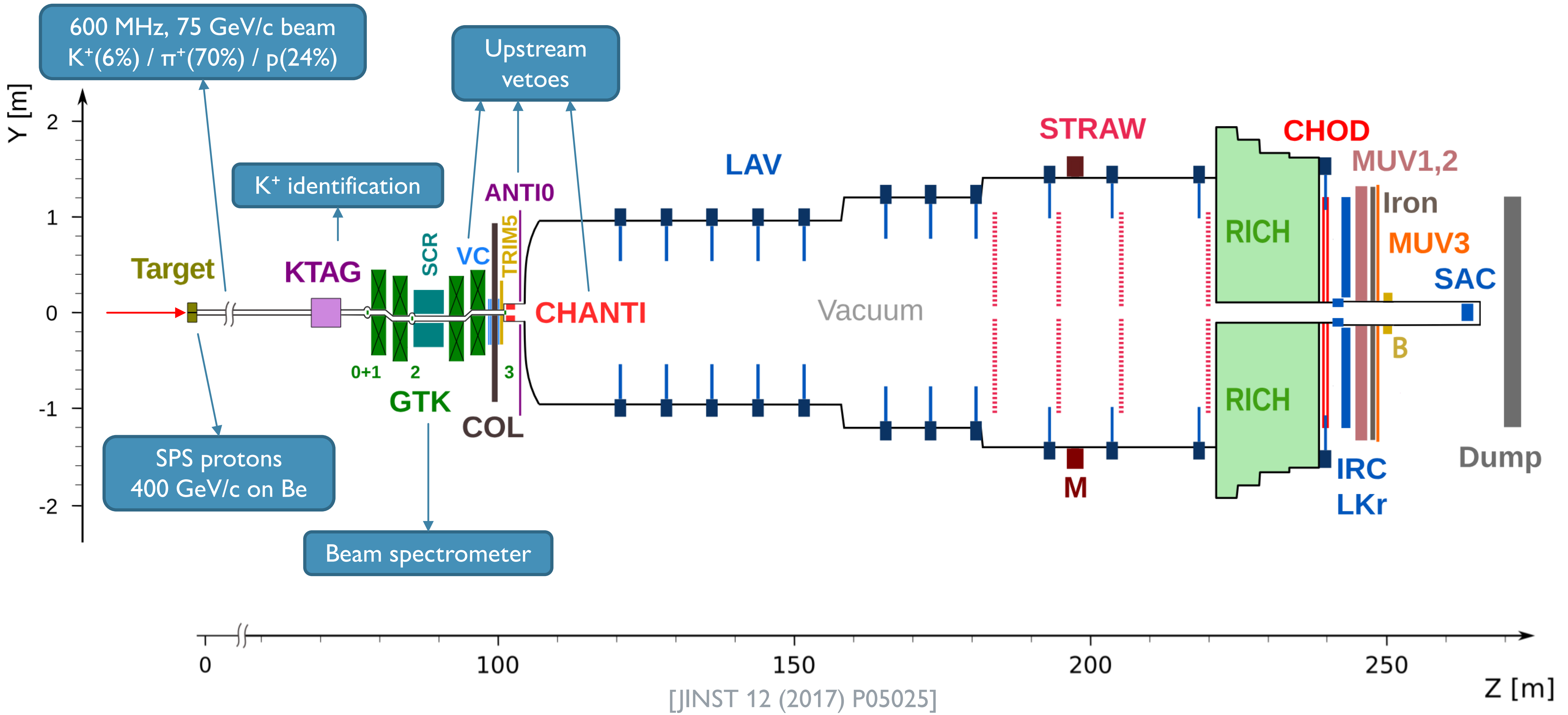

[JINST 12 (2017) P05025]

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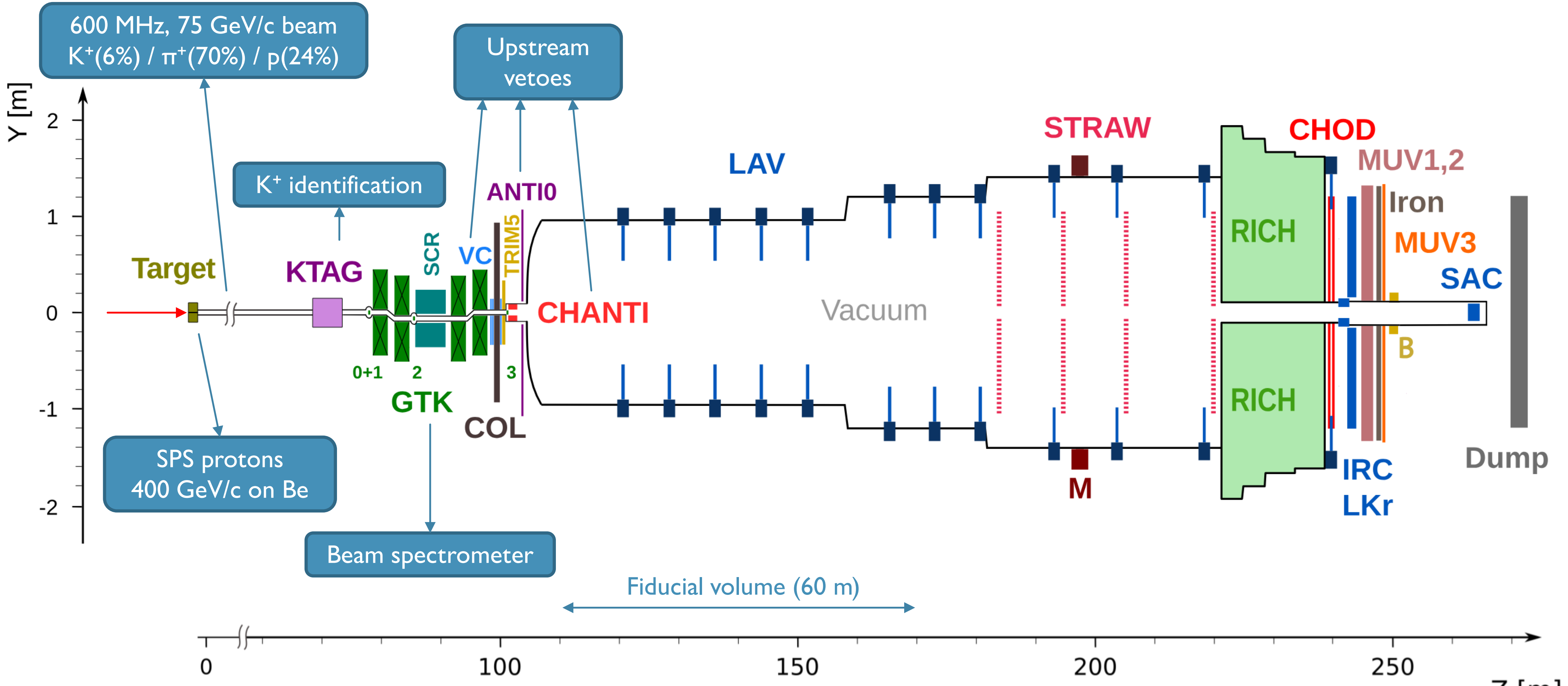
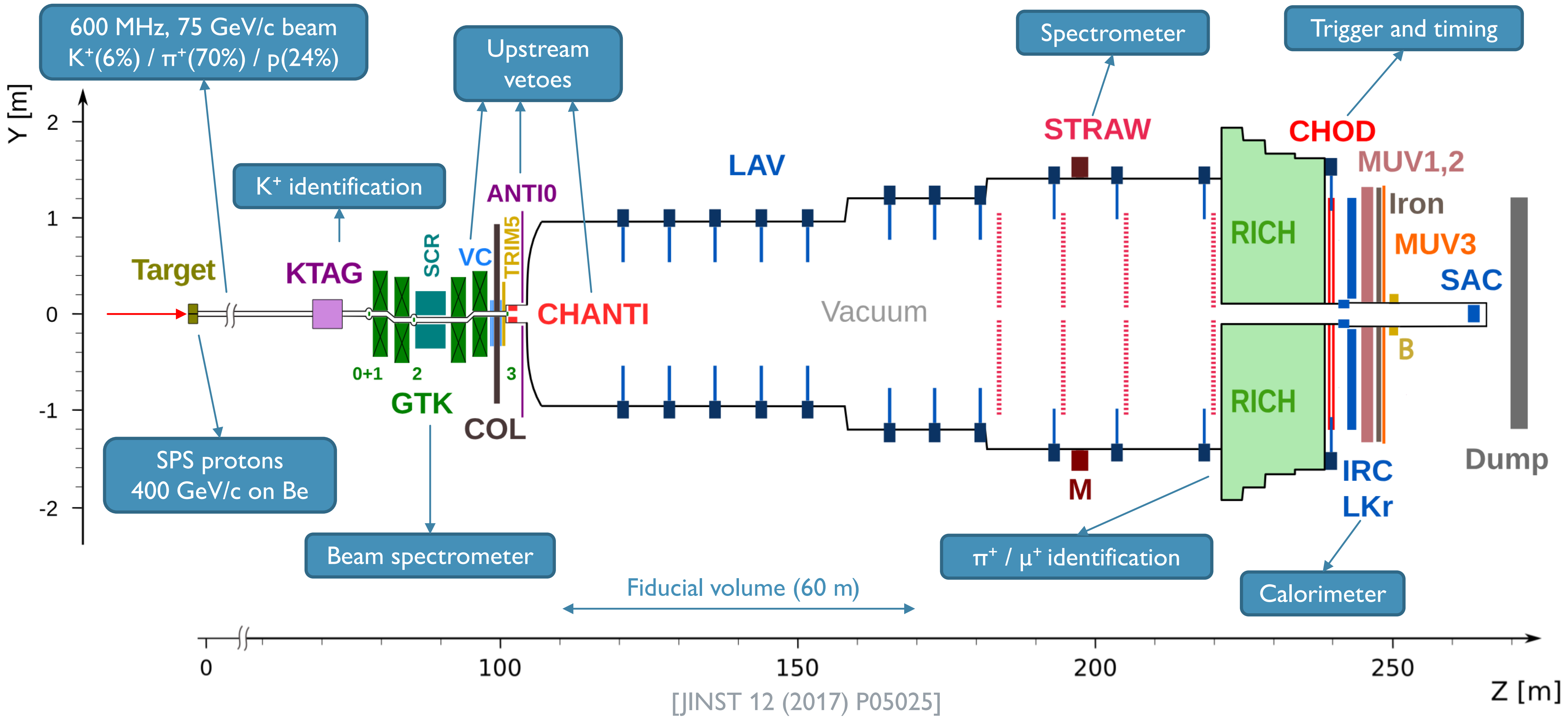


[JINST 12 (2017) P05025]

THE NA62 DETECTOR



[JINST 12 (2017) P05025]

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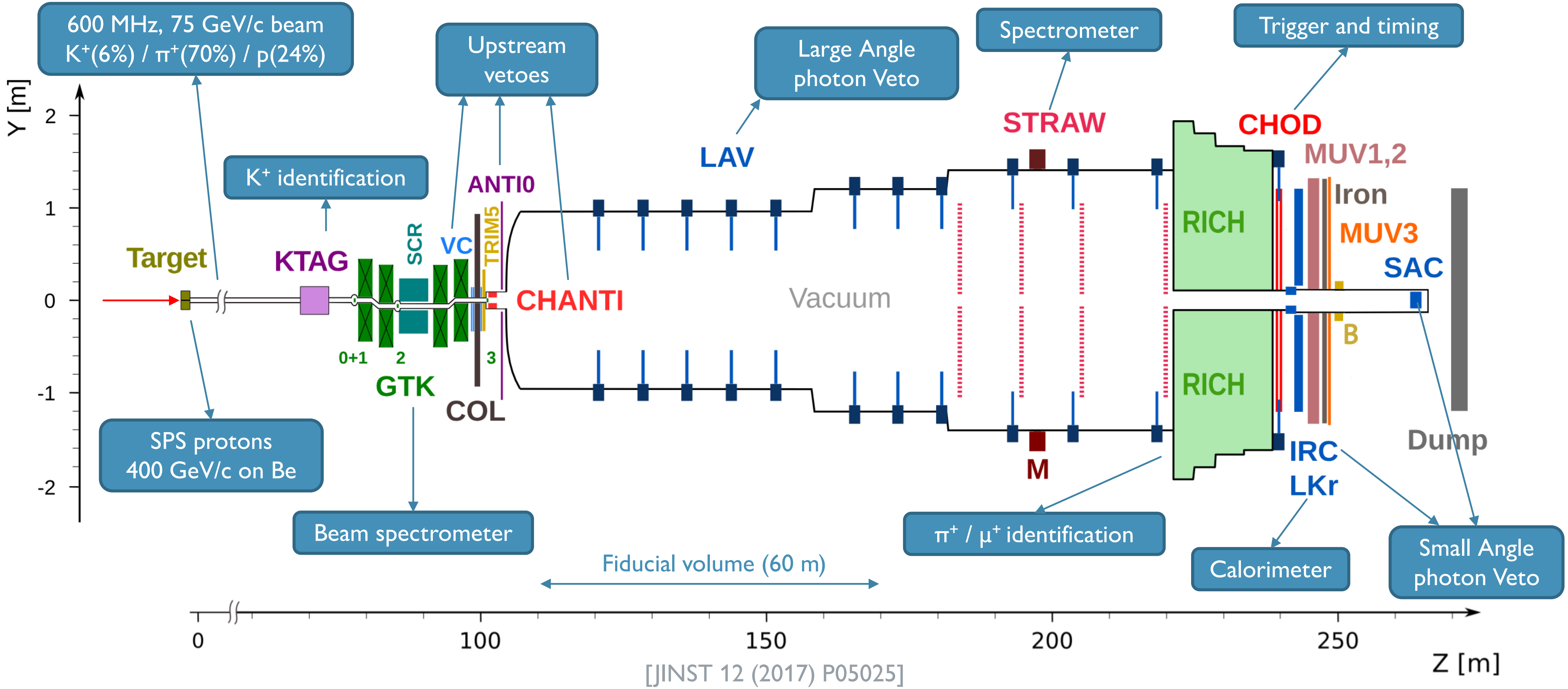
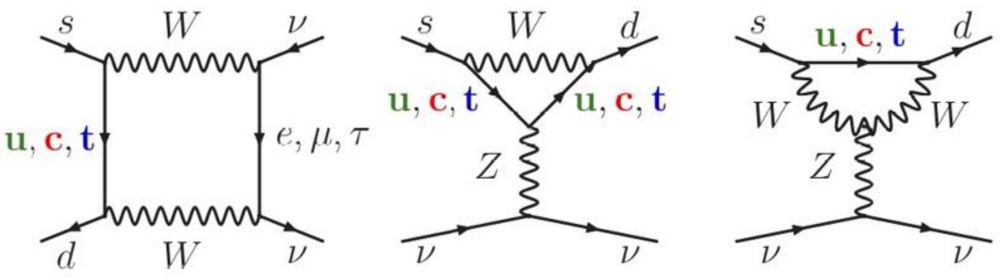


[JINST 12 (2017) P05025]

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

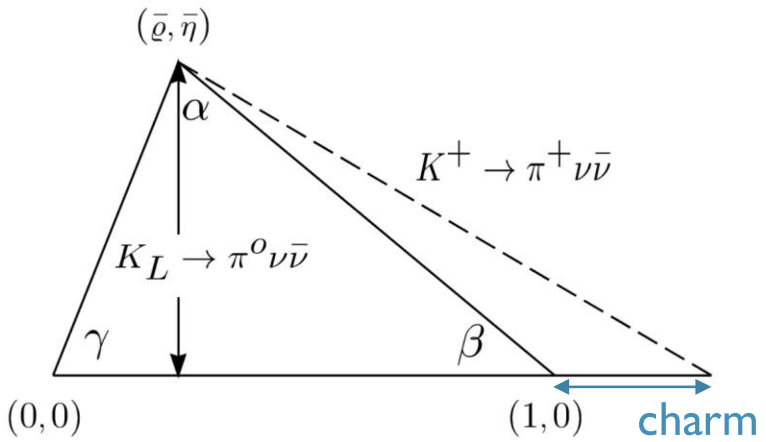
ANALYSIS OF 2021 – 2022 DATA

THE K → $\pi\nu\bar{\nu}$ DECAY: THEORY

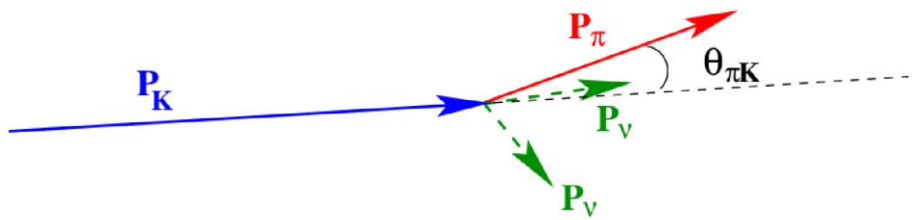


BR×10[11]	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L \to \pi^0\nu\bar{\nu}$
D'Ambrosio et al. [JHEP 09 (2022) 148]	7.86 ± 0.61	2.68 ± 0.30
Buras et al. [EPJC 82 (2022) 615]	8.60 ± 0.42	2.94 ± 0.15
Experimental status	$10.6\ ^{+4.0}_{-3.4}\vert_{stat} \pm 0.9_{syst}$ NA62 2016–2018 [JHEP 06 (2021) 093]	< 220 KOTO 2021 [PRL 134 (2025) 081802]

- FCNC s → d, highly suppressed
- Theoretically clean, dominated by short distance
- Hadronic form factor extracted from $K^+ \to \pi^0\ell^+\nu$
- Choice of CKM parameters affects the SM predictions
- K → $\pi\nu\bar{\nu}$ constrain the unitarity triangle
- Highly sensitive to new physics



EXPERIMENTAL STRATEGY

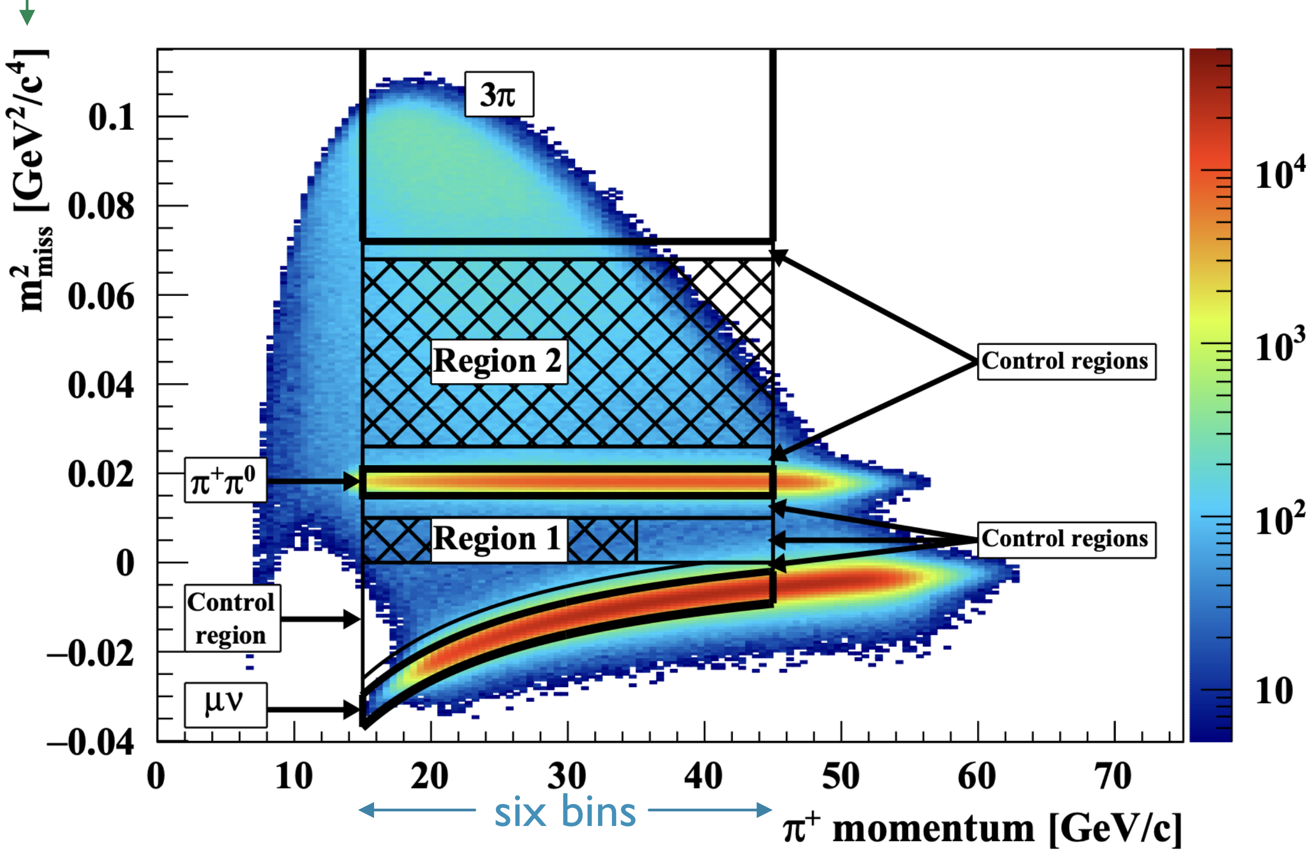


Main K^+ (bkg) decay modes	BR
$K^+ \to \mu^+\nu$	64×10^{-2}
$K^+ \to \pi^+\pi^0$	21×10^{-2}
$K^+ \to \pi^+\pi^+\pi^-$	5.6×10^{-2}
$K^+ \to \pi^+\pi^-e^+\nu$	4.3×10^{-5}

Keystones

- $O(10^4)$ bkg suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ π^0 rejection
- $O(100\text{ ps})$ timing between sub-detectors

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



SIGNAL EXPECTATION

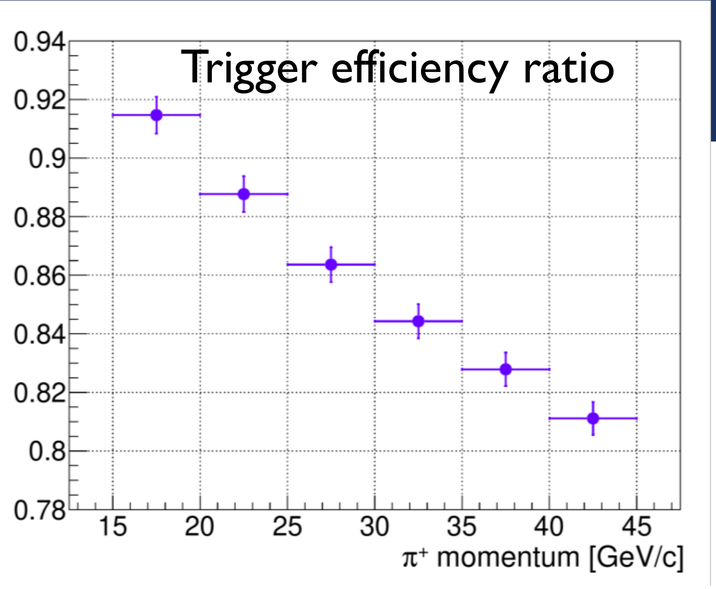
$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi}\, D\, \frac{BR(\pi\nu\nu)}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\, \varepsilon_{trig}\, \varepsilon_{RV}$$

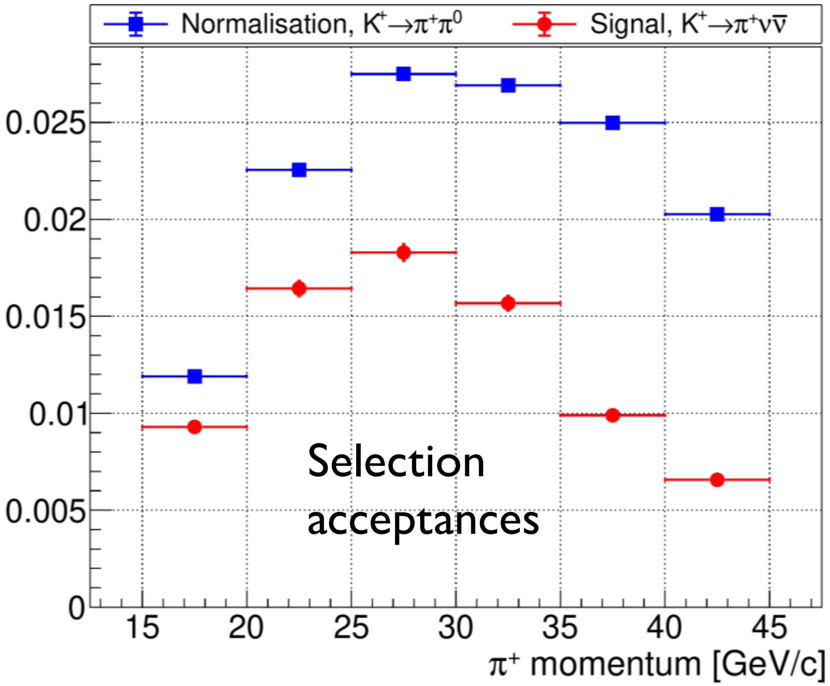
Expected SM signal events

Trigger downscaling

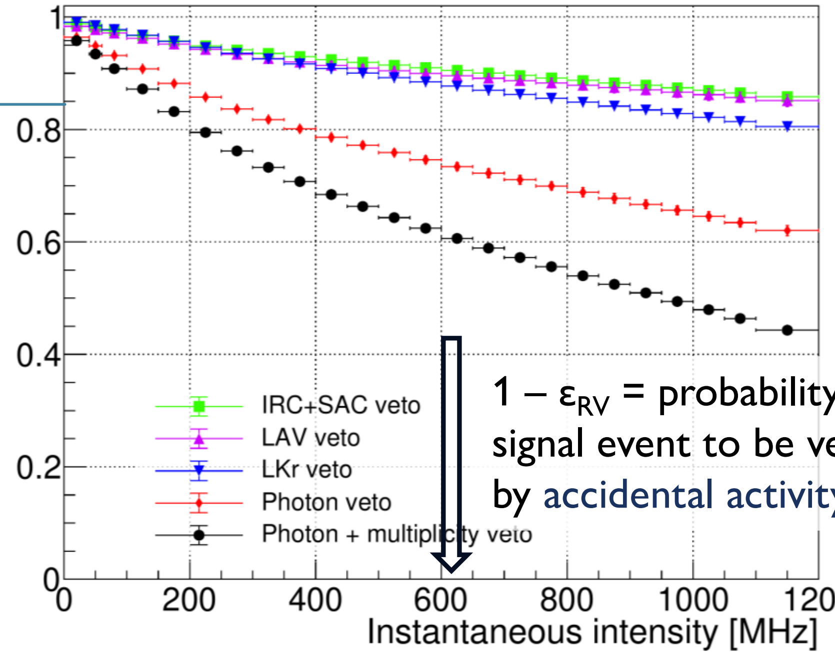
From SM

Normalization $K^+ \rightarrow \pi^+\pi^0$ events





Random veto efficiency



$1 - \varepsilon_{RV}$ = probability of a signal event to be vetoed by accidental activity

SIGNAL EXPECTATION

$$N^{exp}_{\pi\nu\nu} = N_{\pi\pi}\, D\, \frac{BR(\pi\nu\nu)}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\, \varepsilon_{trig}\, \varepsilon_{RV} = 9.91 \pm 0.34$$

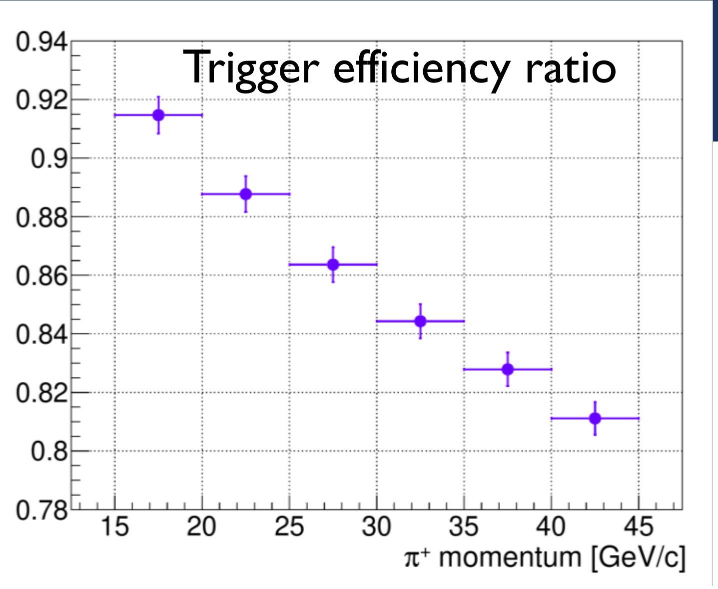
Expected SM signal events

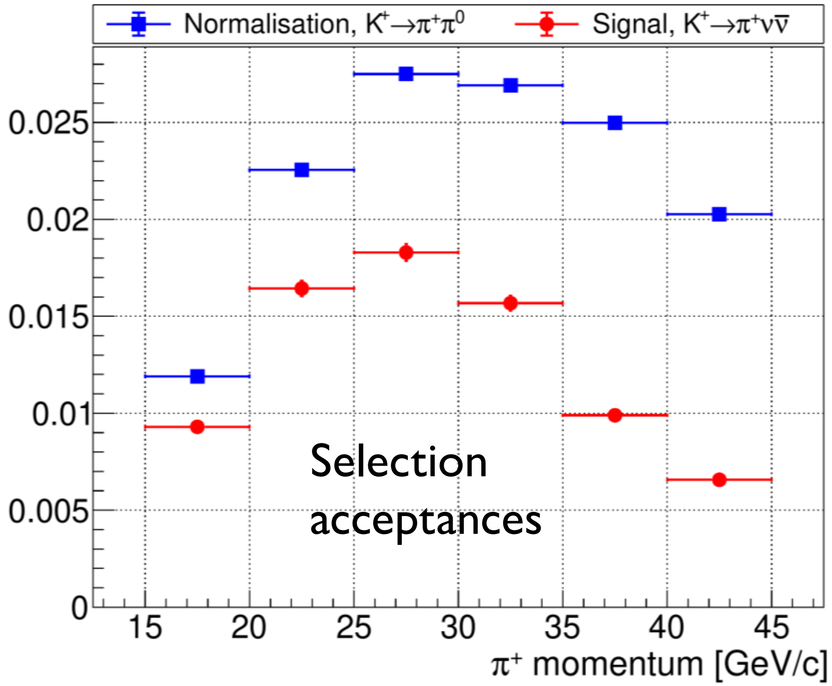
Normalization $K^+ \to \pi^+\pi^0$ events

Trigger downscaling

From SM

2016 – 2018:
$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42$





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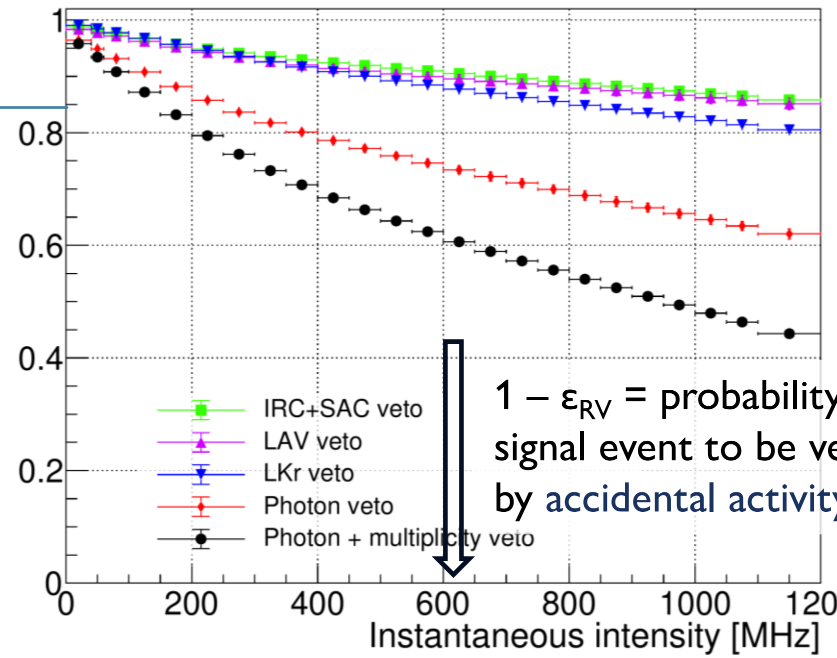

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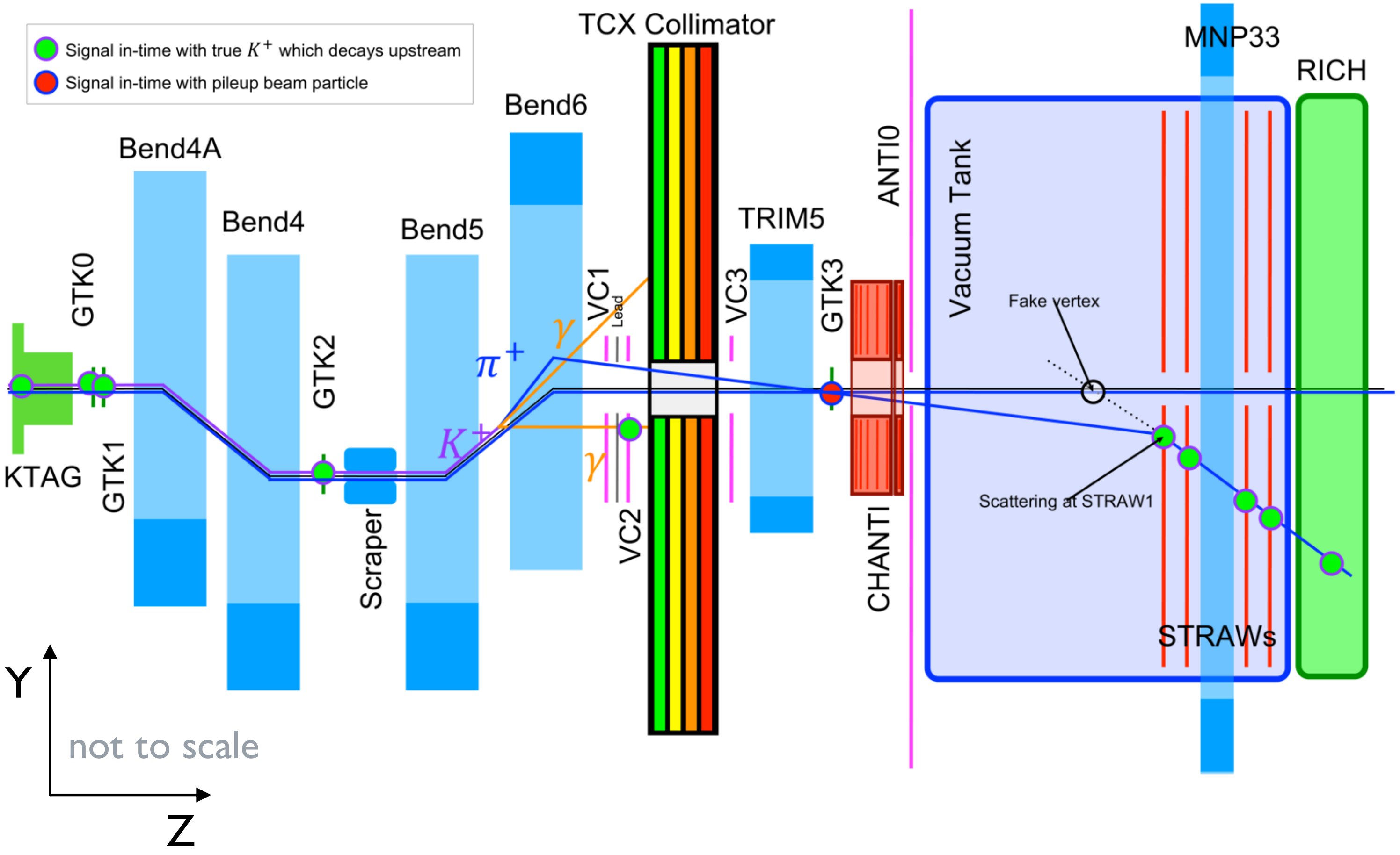
UPSTREAM BACKGROUND



$$N(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

Suppression

- Δt between K^+ and π^+ reconstructed tracks
- Upstream vetoes (VC, CHANTI, ANTI0)
- BDT using spatial infos of K^+, π^+

Estimation

- Fully data-driven
- "Upstream Reference Sample" contains all known generation mechanisms
- Bkg-to-signal probability from data

Validation

- 10 independent samples enriched with different mechanisms

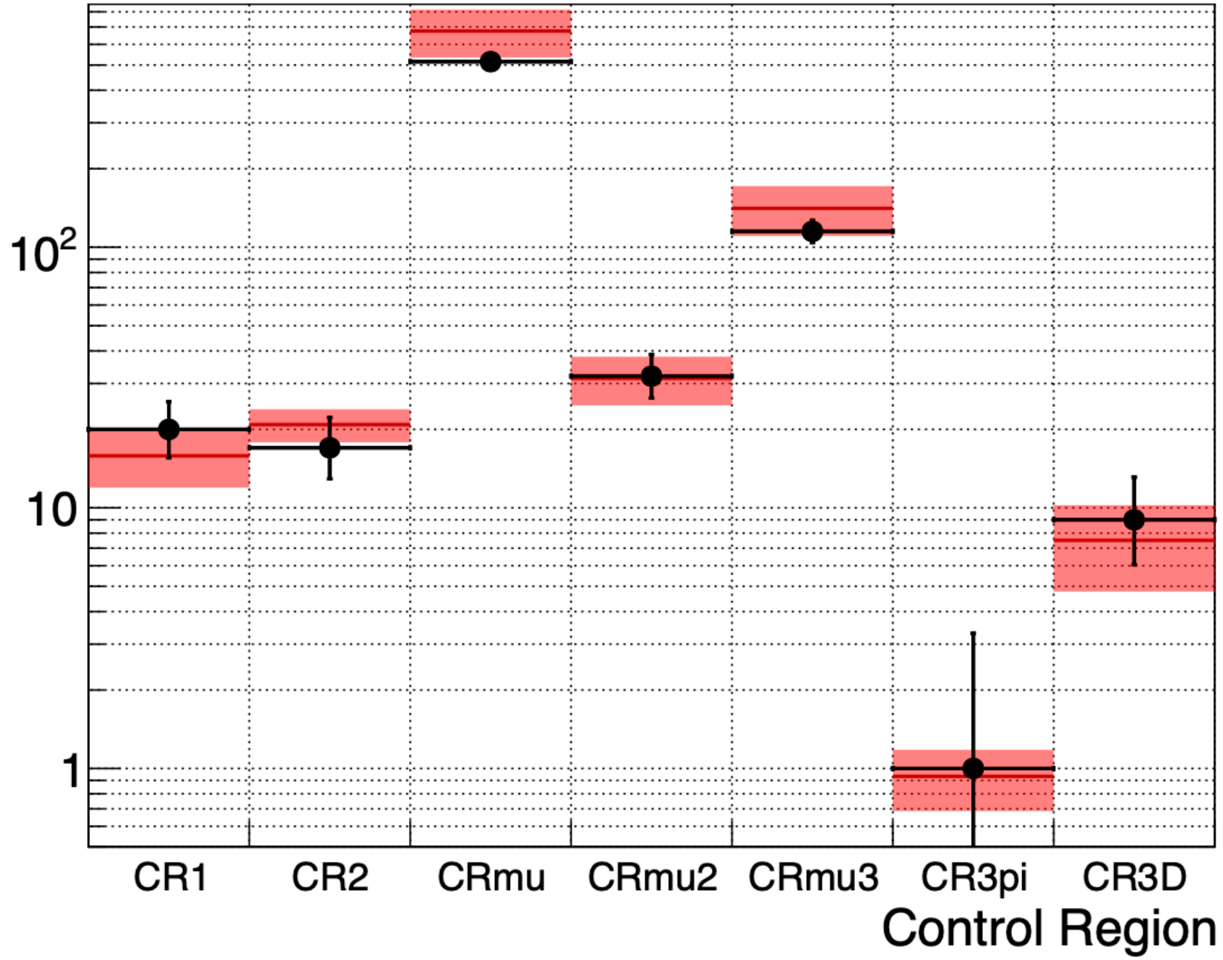
BACKGROUND SUMMARY

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89\,^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4\,^{+2.1}_{-1.8}$
Total background	$\mathbf{11.0\,^{+2.1}_{-1.9}}$
SM signal	9.91 ± 0.34

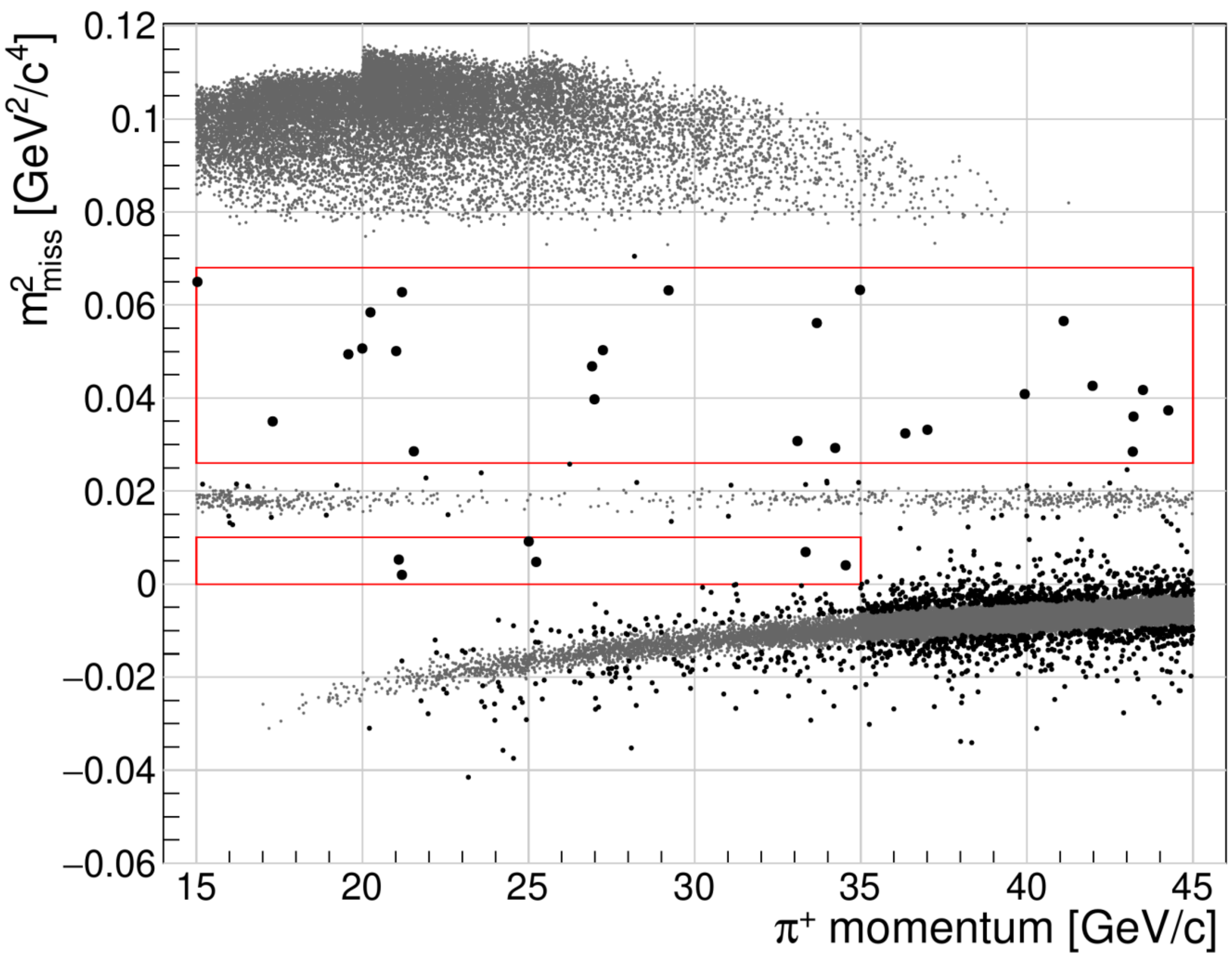
$$\frac{\sqrt{S+B}}{S} \approx 0.5$$

similar to analysis of 2018 data

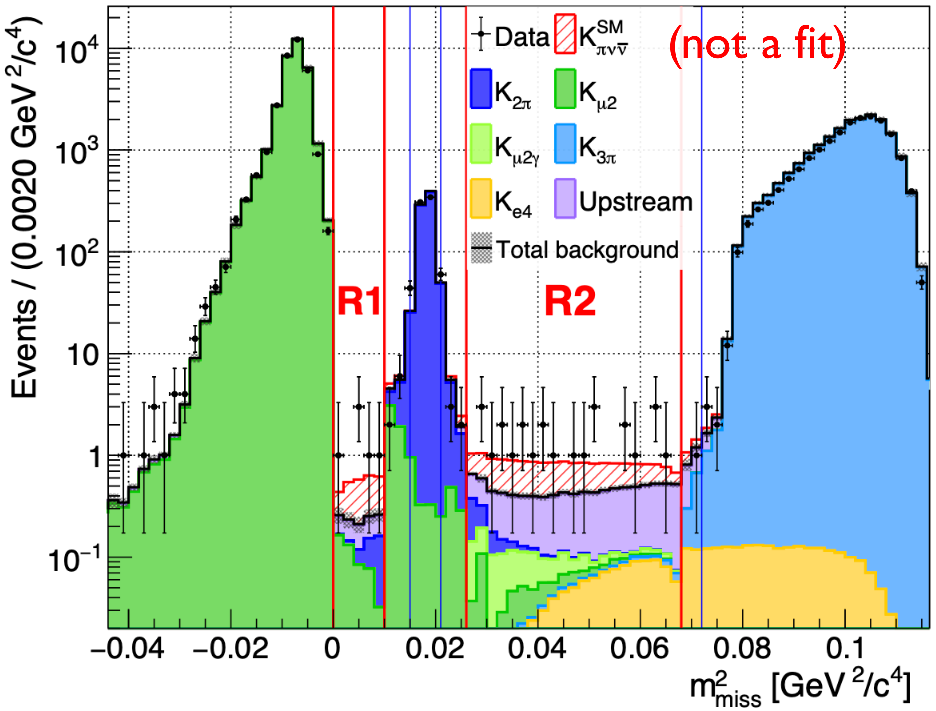
Extensive data-driven validation of background estimations



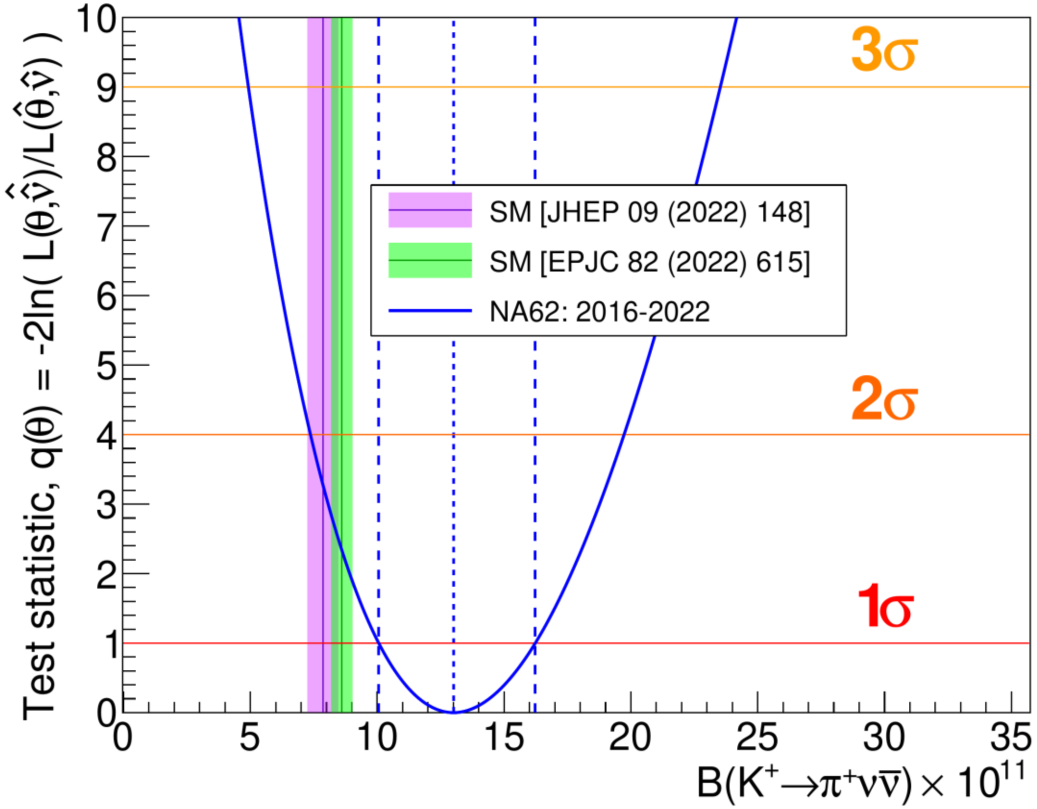
SIGNAL REGIONS

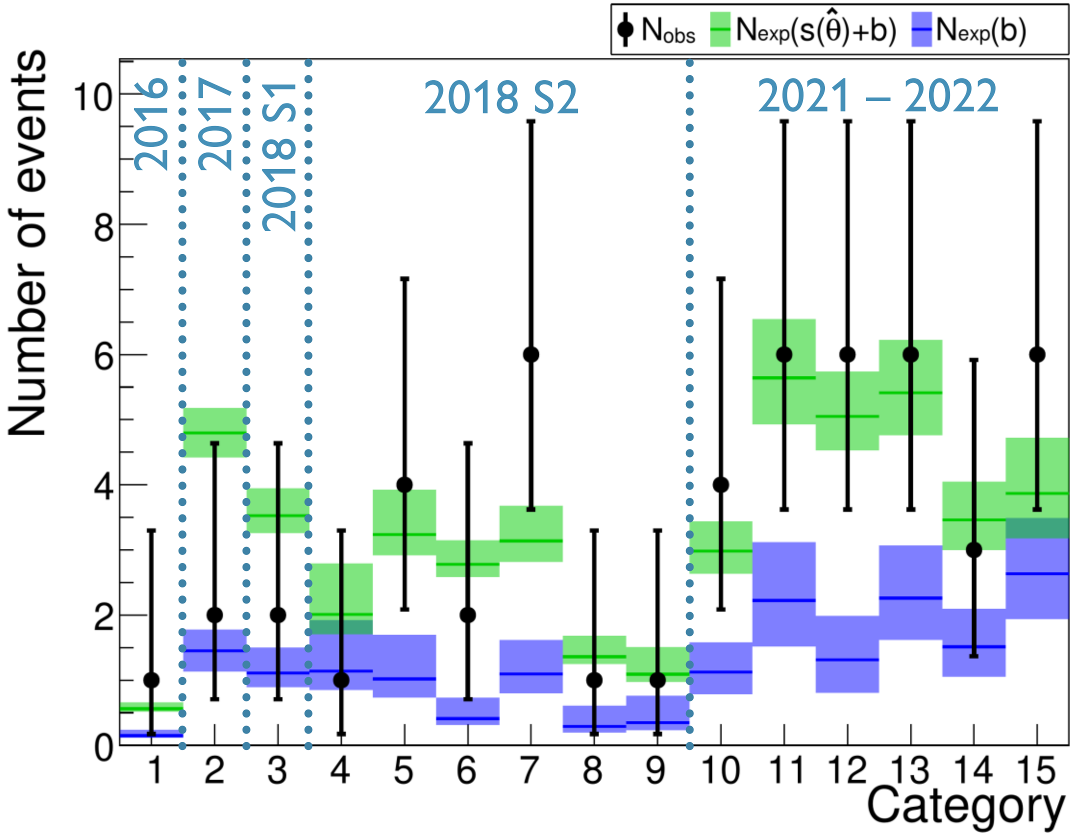


- Expected SM signal: 9.91 ± 0.34
- Estimated background: $11.0\,^{+2.1}_{-1.9}$
- Observed: 31



COMBINING RESULTS: 2016 – 2022 DATA

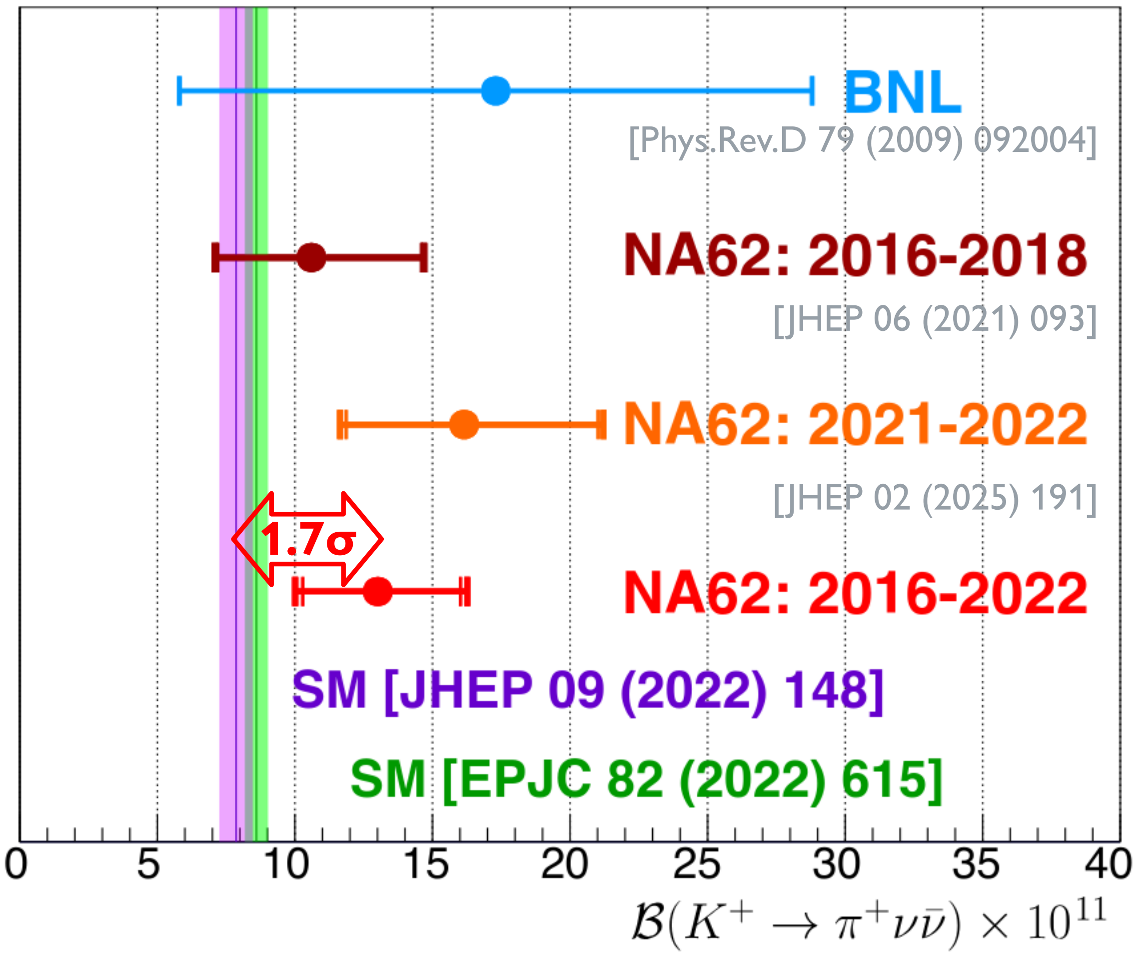


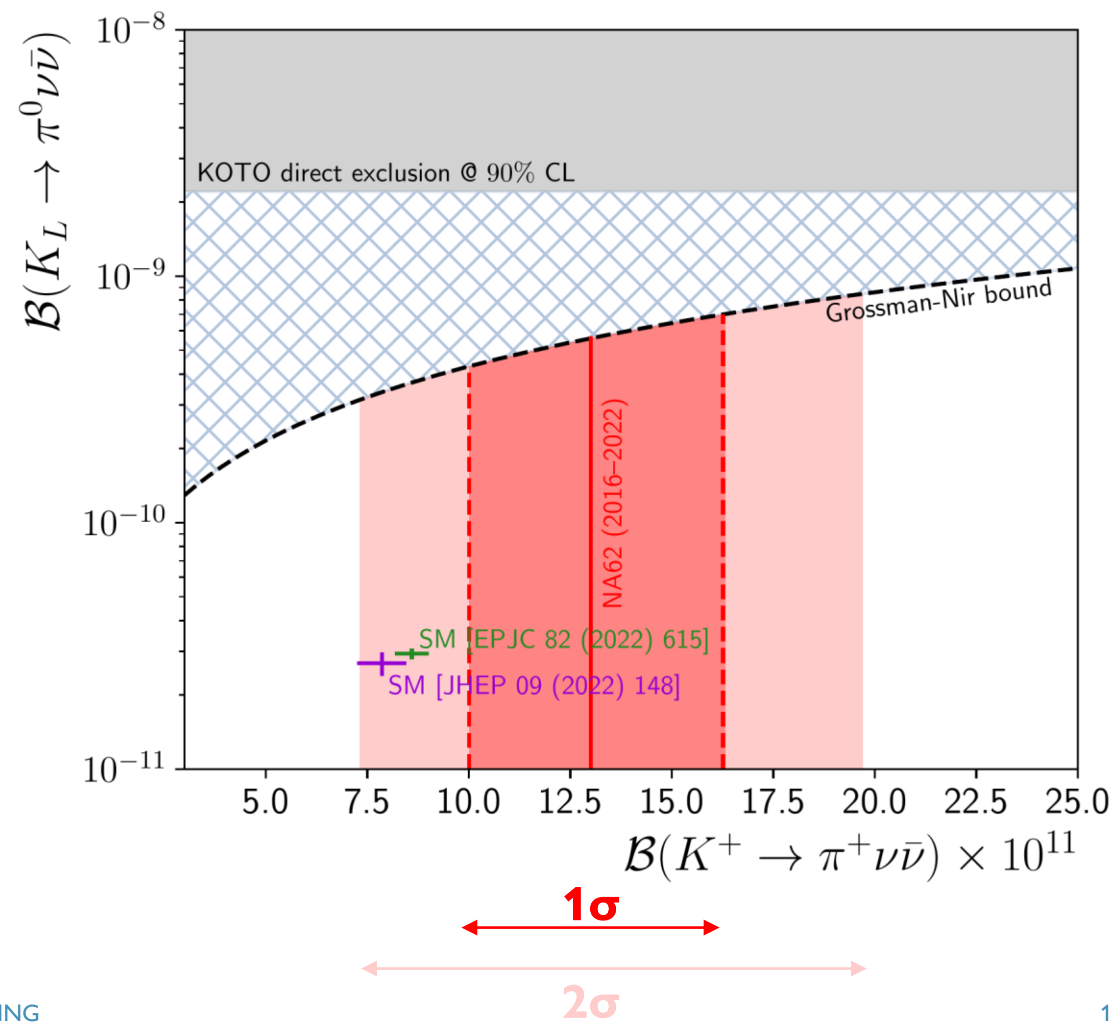


$N_{bkg} = 18\,^{+3}_{-2}$, $N_{obs} = 51$ → Significance > 5σ

$$BR_{2016\text{–}2022} = (13.0\,^{+3.3}_{-3.0}) \times 10^{-11} = (13.0\,^{+3.0}_{-2.7}|_{stat}\,^{+1.3}_{-1.3}|_{syst}) \times 10^{-11}$$

THE GLOBAL PICTURE



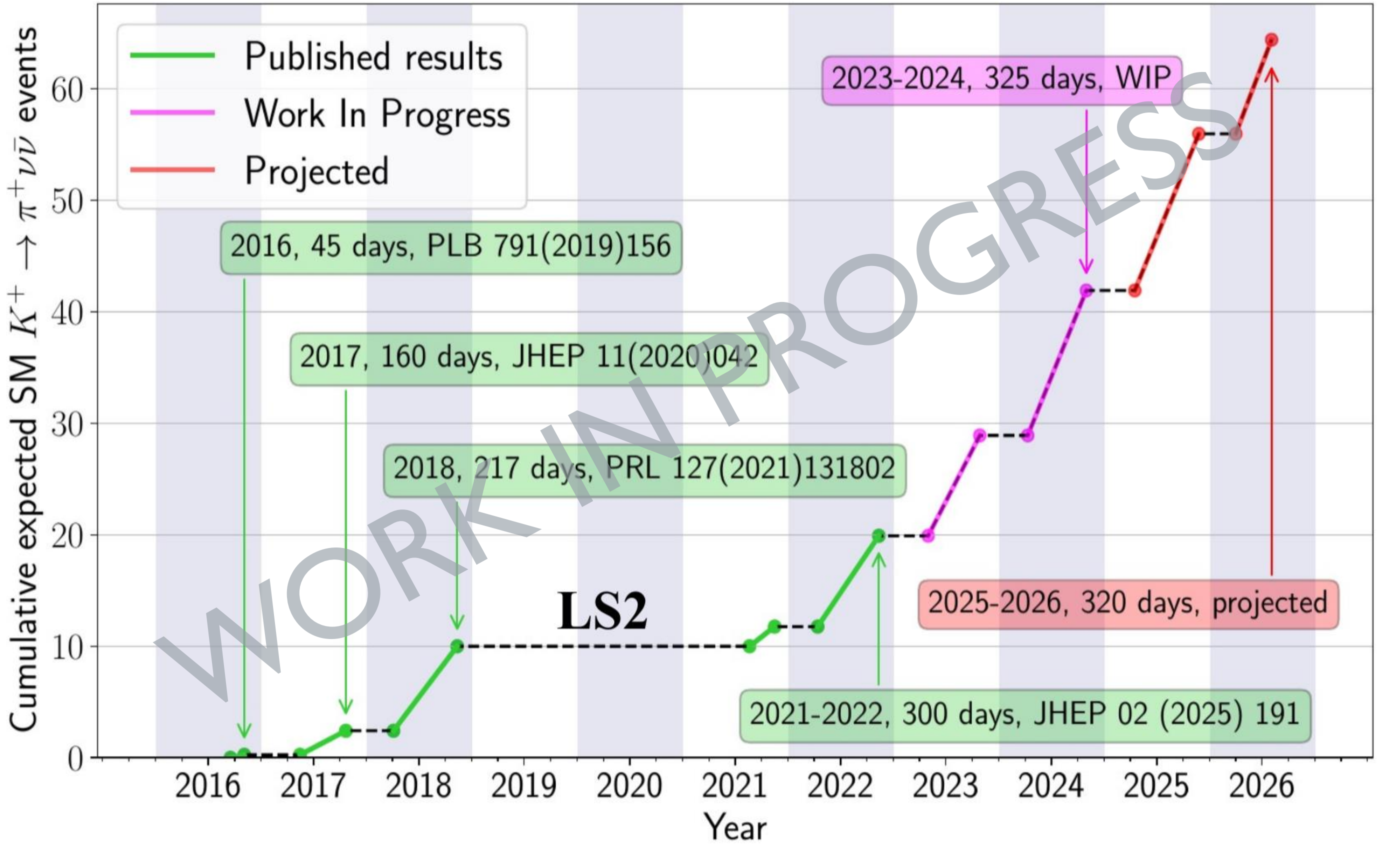


OUTLOOK

Final dataset projection (2016 – 2026):

>60 SM $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events, **>120** candidate events

(assuming same $N_{\pi\nu\nu}$/day as 2024, same B/S as 2022)



Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} >$ $[10^2]$	4.9	4.7	4.4
N_K $[10^{12}]$	2.3	2.5	3.3
ε_{RV}	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill}$ $[10^{-5}]$	2.5	2.5	2.6
$B_{\text{total}}/N_{\pi\nu\nu}$	1.1	1.1	1.0

WORK IN PROGRESS

[2025 SPSC report]

Target:
3x currently published statistics,
<20% BR uncertainty

RECENT PRELIMINARY RESULTS

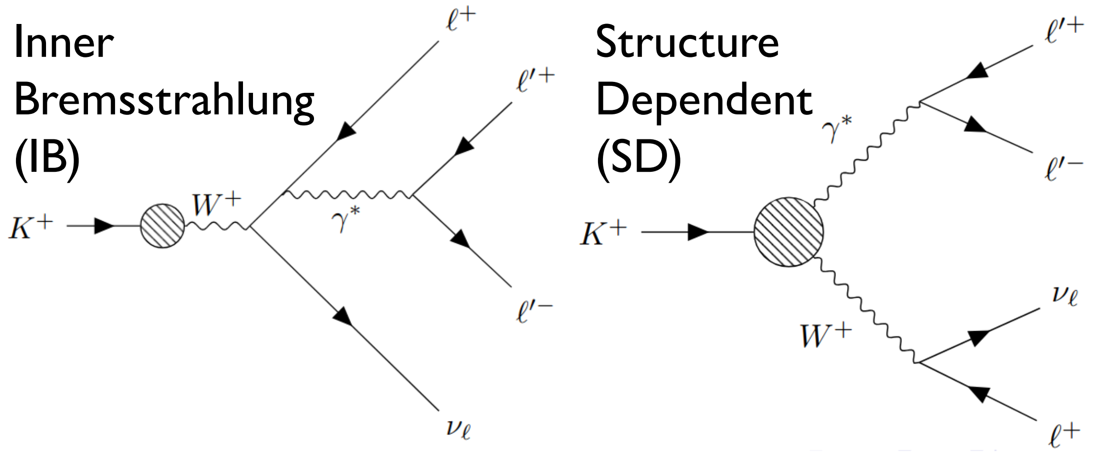
[KAON2025 CONFERENCE]

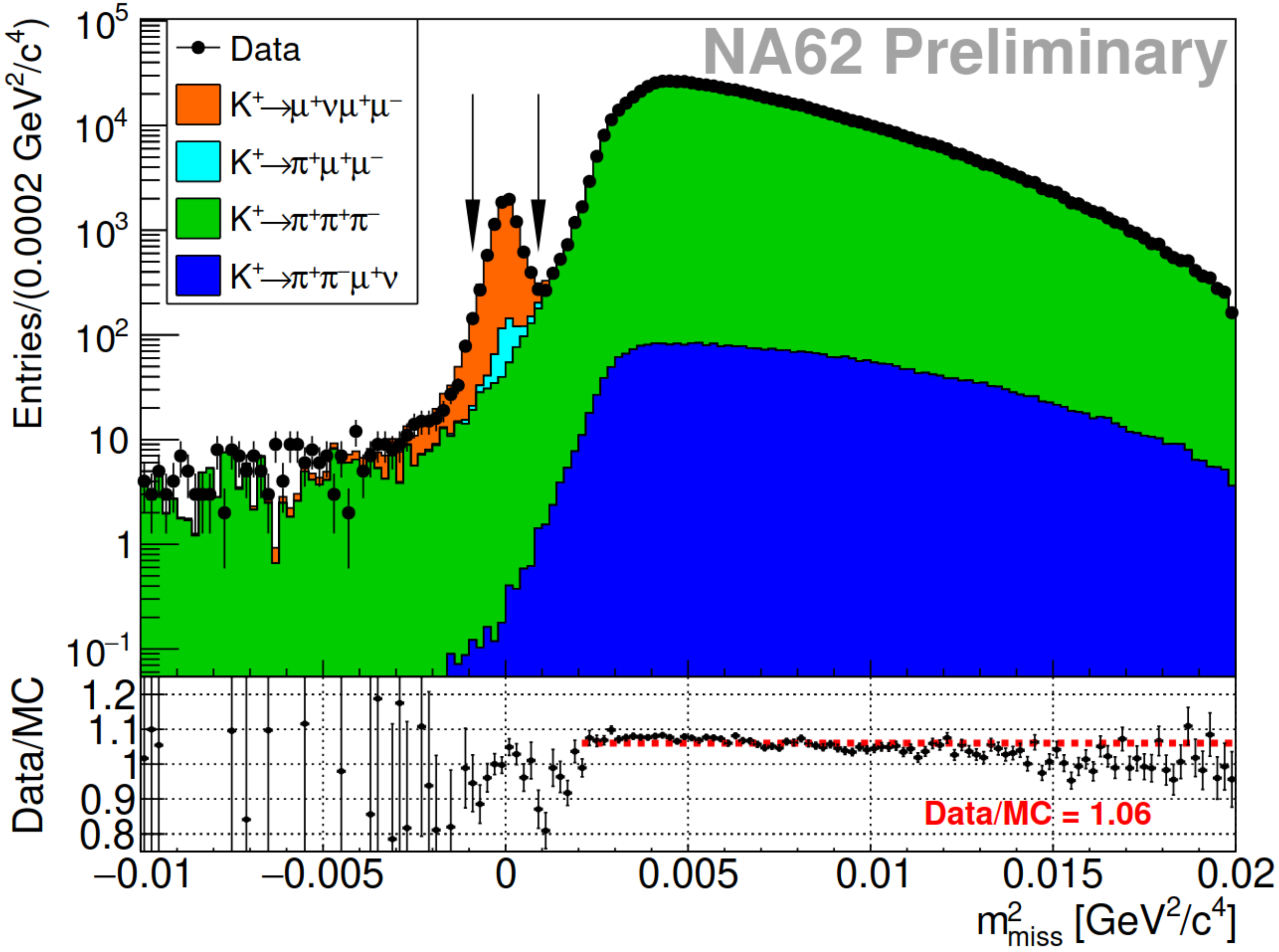
1. $K^+ \to \mu^+\nu\mu^+\mu^-$
2. $K^+ \to e^+\nu\gamma$ (SD^+)
3. $K^+ \to \pi^+\pi^+\pi^-\gamma$
4. $K^+ \to \pi^+\ell^+\ell^-$ (prospects)

$K^+ \to \mu^+\nu\mu^+\mu^-$ ANALYSIS

Inner Bremsstrahlung (IB)

Structure Dependent (SD)

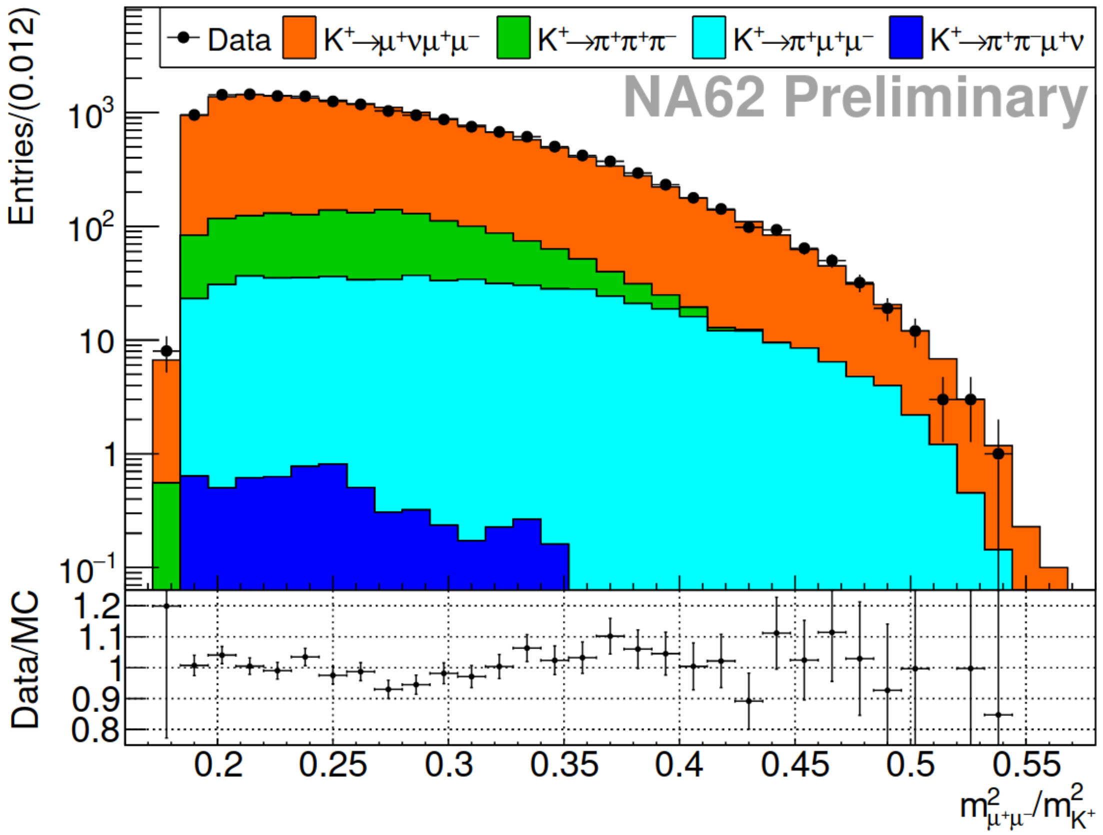




- Dataset: 2017 – 2024
- $N_K = 1.4 \times 10^{13}$
- Normalization channel: $K^+ \to \pi^+\mu^+\mu^-$
- Signal data candidates: 8227
- Background contamination: $892 \pm 11_{stat} \pm 54_{syst}$
- Bkg mechanisms: π decay in flight, mis-ID

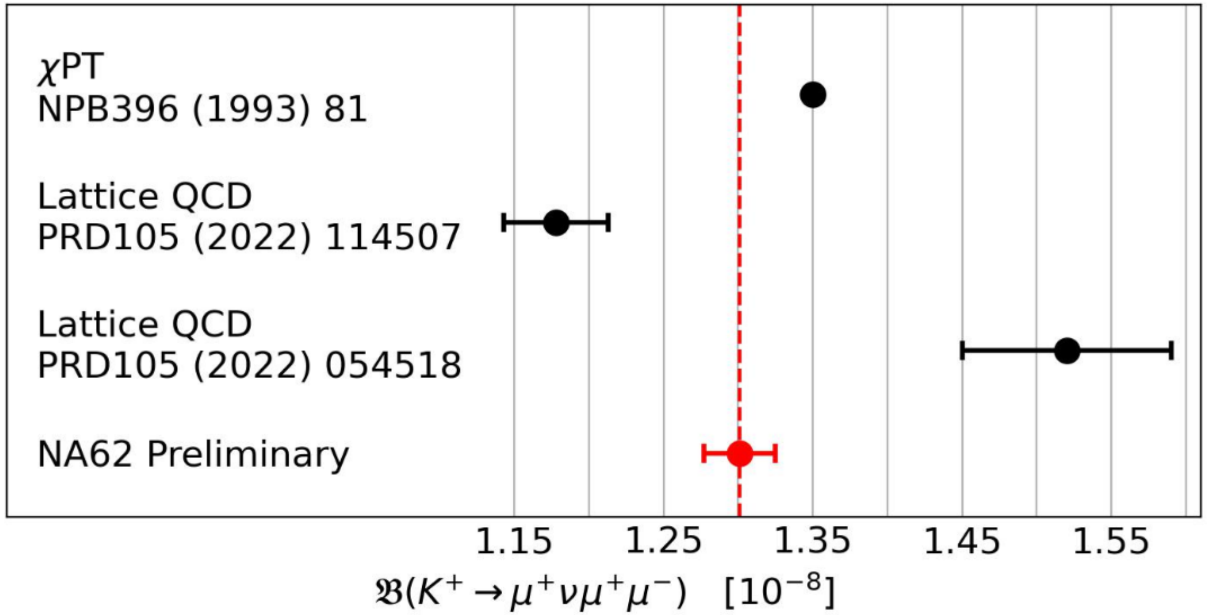
$K^+ \to \mu^+\nu\mu^+\mu^-$

PRELIMINARY RESULTS



First observation of last missing $K^+ \to \ell^+\nu\ell'^+\ell'^-$ decay

Spectrum agrees with $O(p^6)$ ChPT prediction



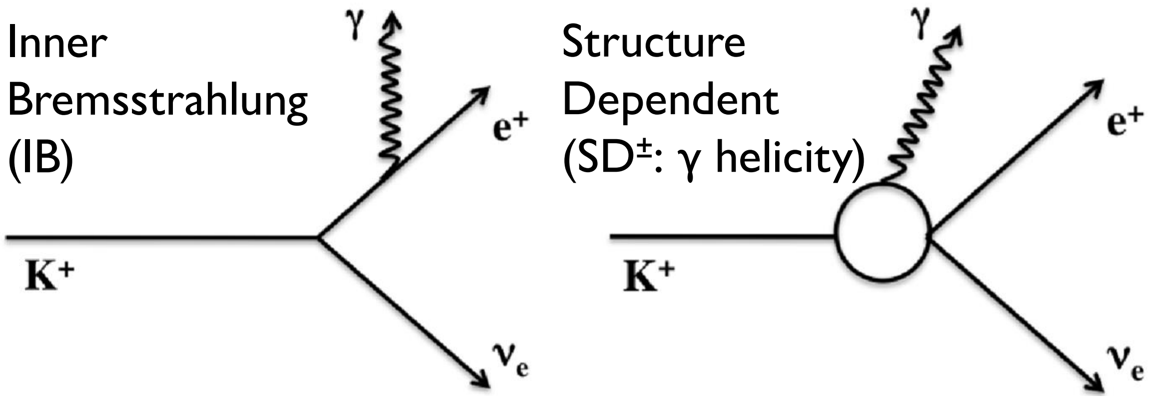
$$BR = (1.301 \pm 0.017_{stat} \pm 0.012_{syst} \pm 0.012_{ext}) \times 10^{-8} = (1.301 \pm 0.024) \times 10^{-8}$$

A. Tomczak's talk at KAON2025

$K^+ \to e^+\nu\gamma$ (SD^+)

Inner Bremsstrahlung (IB)

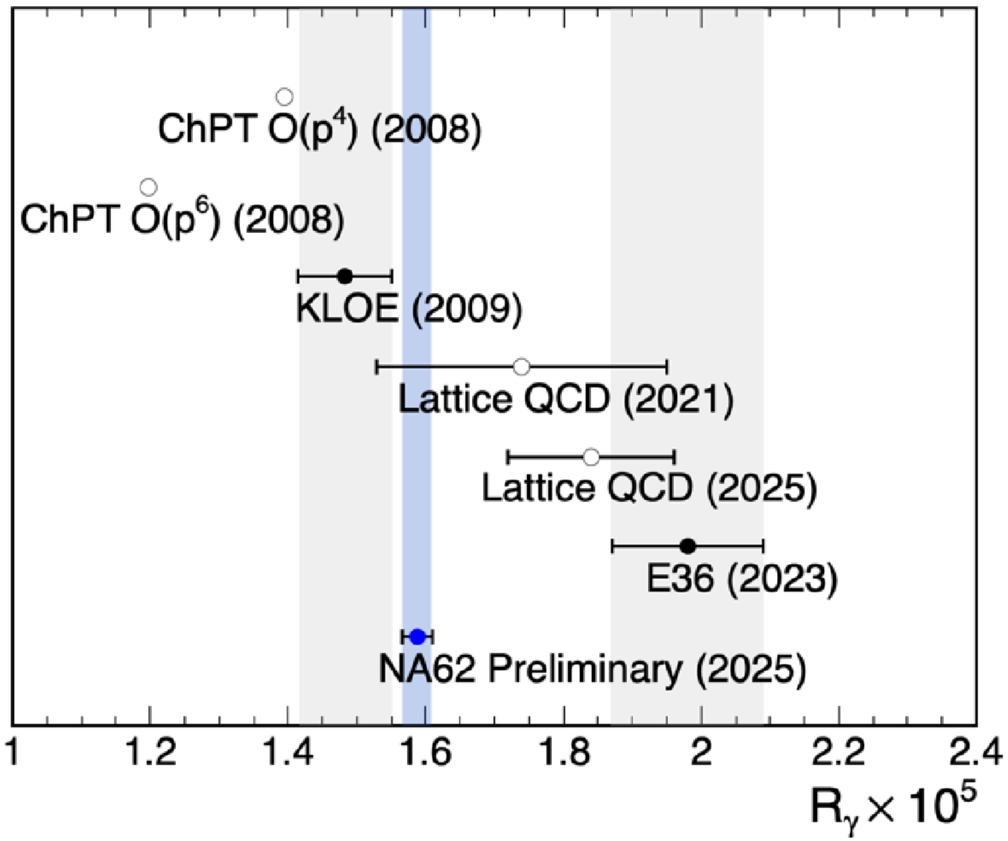
Structure Dependent ($SD^\pm$: γ helicity)



- Dataset: 2017 – 2018
- Normalization: $K^+ \to e^+\nu\pi^0$
- Backgrounds:
  $K^+ \to e^+\nu\pi^0$, $K^+ \to e^+\nu\gamma$ (SD^-), $K^+ \to e^+\nu$, $K^+ \to \pi^+\pi^0$
- Kinematic selection: $X = 2E_e^*/m_K > 0.2$, $Y = 2E_\gamma^*/m_K > 0.93$ (where SD^+ dominates)
- **$BR[K^+ \to e^+\nu\gamma\ (SD^+)] = (0.466 \pm 0.006) \times 10^{-5}$**
- 3.5x improvement in statistical uncertainty
- B/S ~ 0.4% contributes little to total uncertainty
- R_γ precision improved 10x wrt to PDG average

extrapolated to KLOE kinematic selection

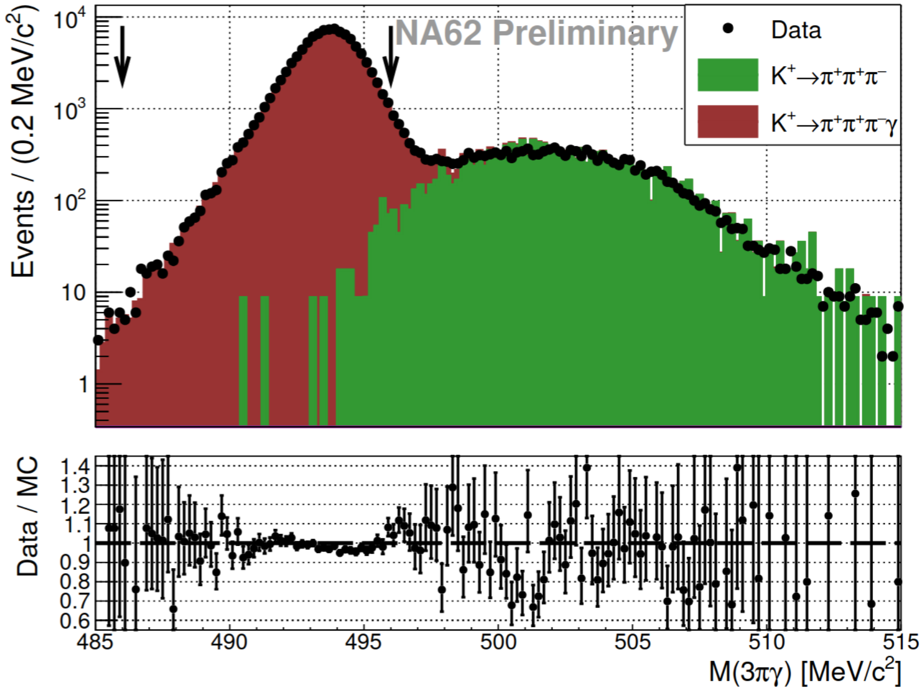
$R_\gamma = \Gamma[K^+ \to e^+\nu\gamma\ (SD^+)] / \Gamma(K^+ \to \mu^+\nu)$

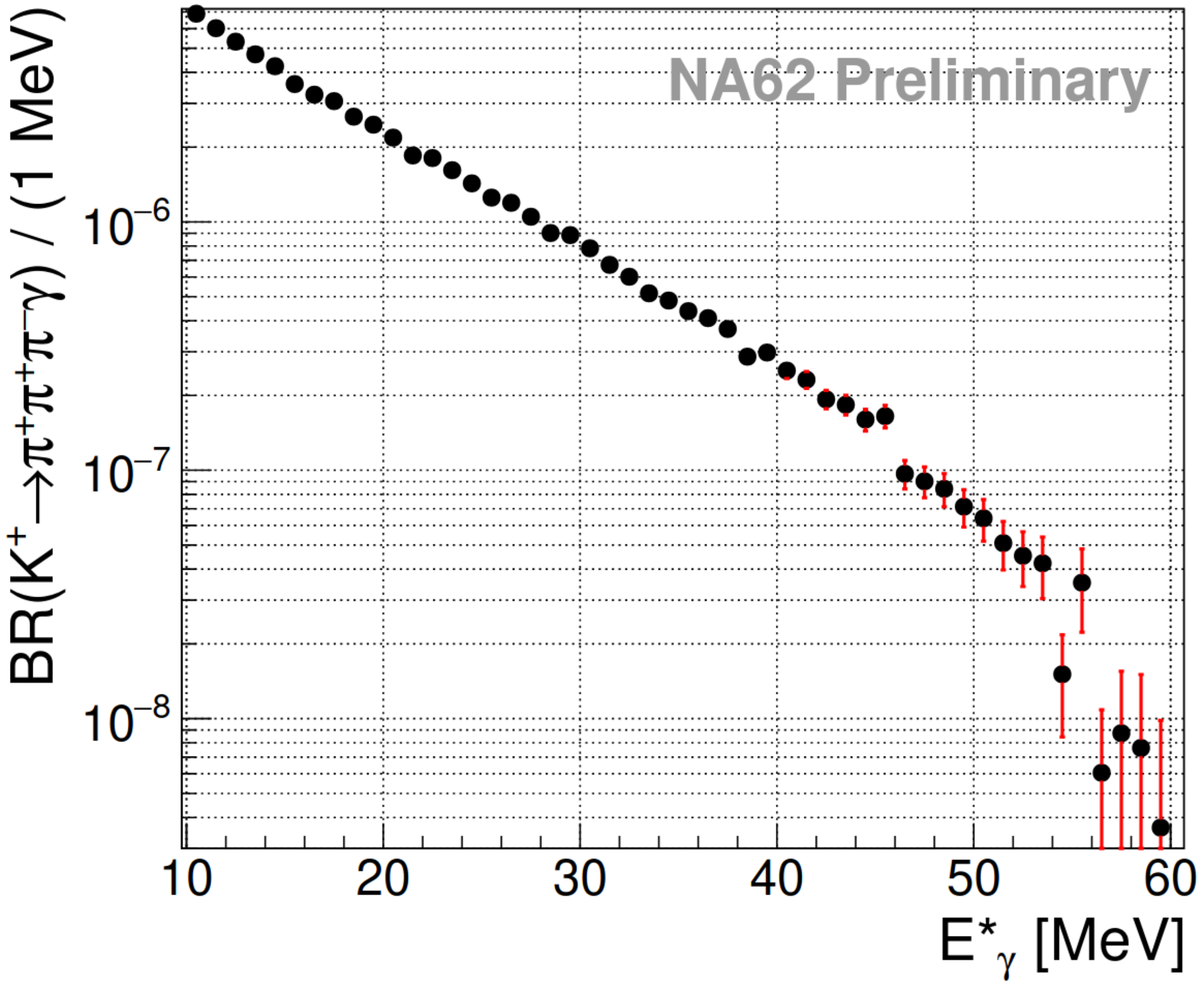


A. Romano's talk at KAON2025

$K^+ \to \pi^+\pi^+\pi^-\gamma$

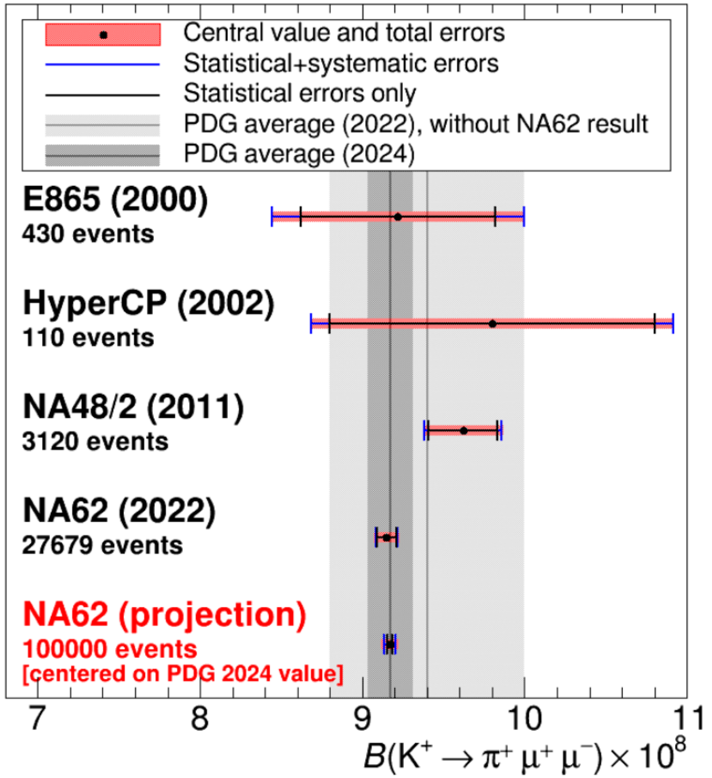
- Dataset: 2017 – 2018
- First measurement in $10 < E^*_\gamma$ / MeV < 30
- Normalization channel: $K^+ \to \pi^+\pi^+\pi^-$
- Bkg < 0.2% for $E^*_\gamma > 10$ MeV
- Good agreement with OKA and with theory

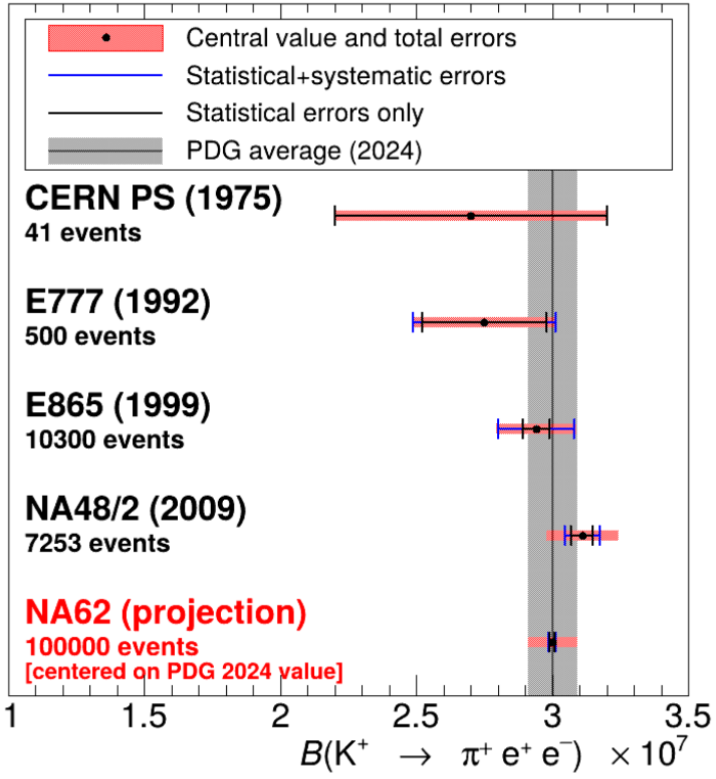


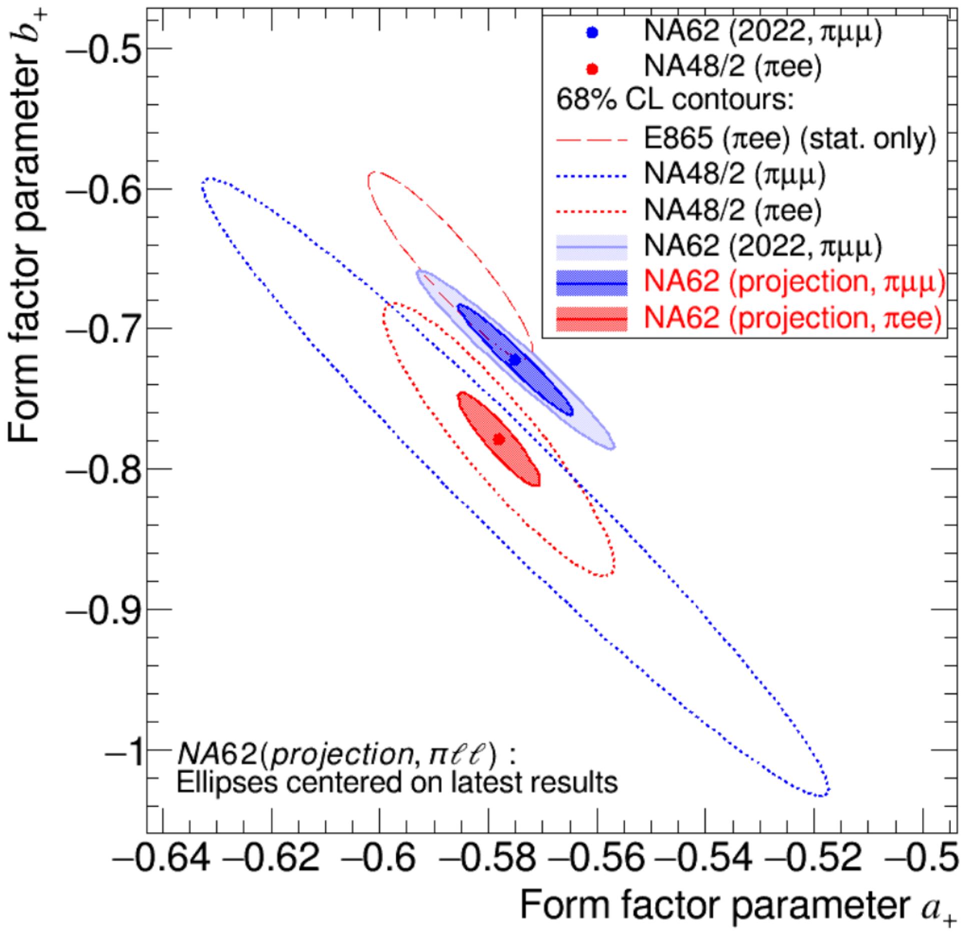


$K^+ \to \pi^+ \ell^+ \ell^-$: PROBING LFUV

FINAL DATASET PROJECTIONS







Expect >100k events per channel,
with negligible background
and ~0.3% syst uncertainty

K. Massri's talk at KAON2025

CONCLUSION

- NA62 is collecting data until LS3, producing the world's largest multi-purpose sample of K^+ decays

- First observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay
- $BR(K^+ \to \pi^+\nu\bar{\nu}) = (13.0\,^{+3.3}_{-3.0}) \times 10^{-11}$ is the smallest BR ever measured at 5σ signal significance
- Expect <20% precision with the final 2016 – 2026 dataset

- First observation of $K^+ \to \mu^+\nu\mu^+\mu^-$: $BR = (1.301 \pm 0.024) \times 10^{-8}$
- $K^+ \to e^+\nu\gamma$ and $K^+ \to \pi^+\pi^+\pi^-\gamma$ studied with unprecedented precision
- The final 2016 – 2026 dataset will allow for stringent tests of the Standard Model, stay tuned!

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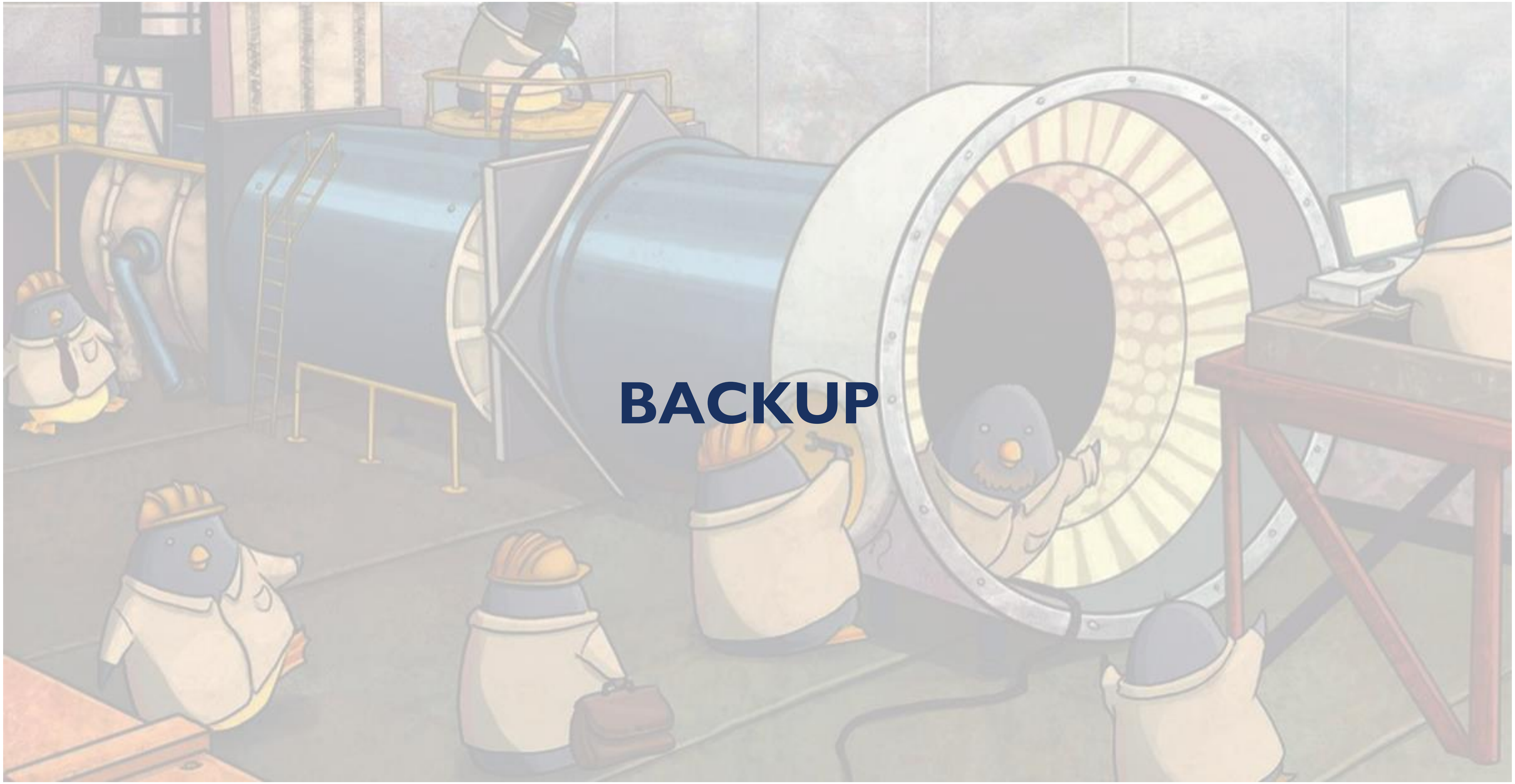
THANK YOU!

BACKUP



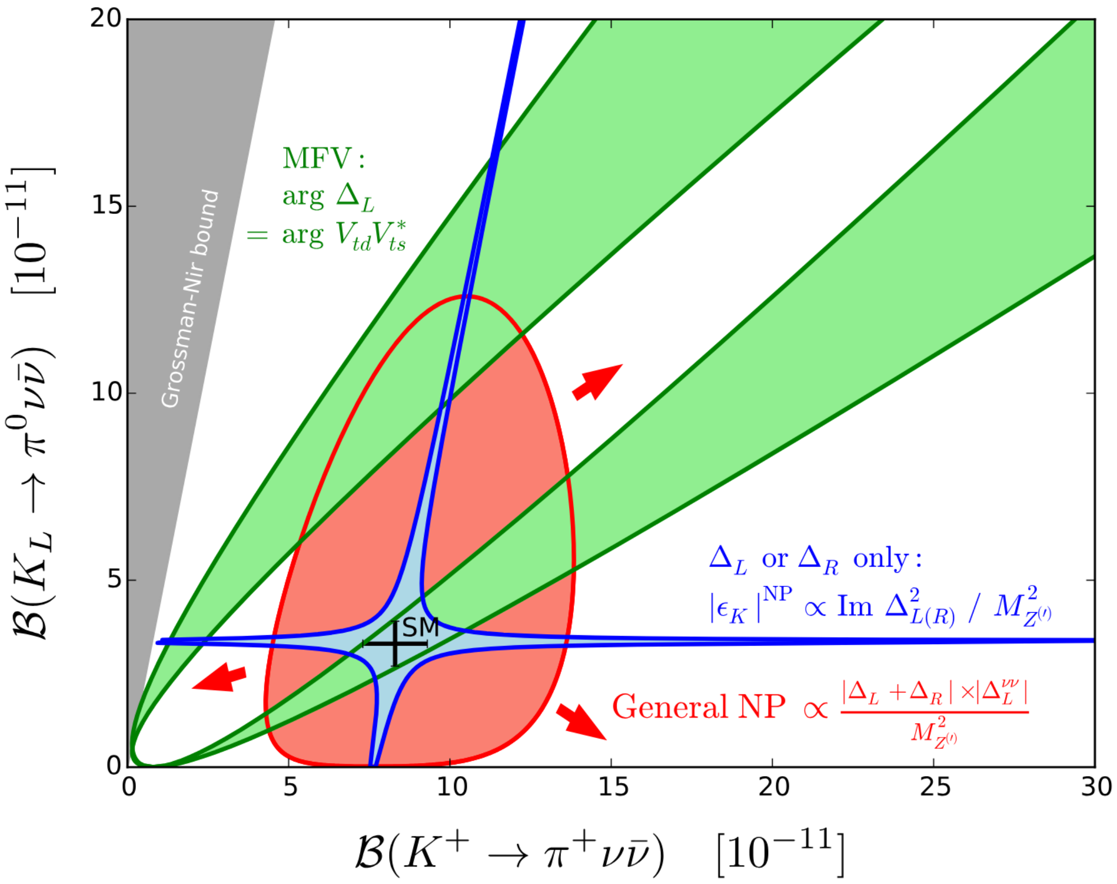
THE K → πνν̄ DECAY: BEYOND THE STANDARD MODEL

Correlation between neutral and charged channels

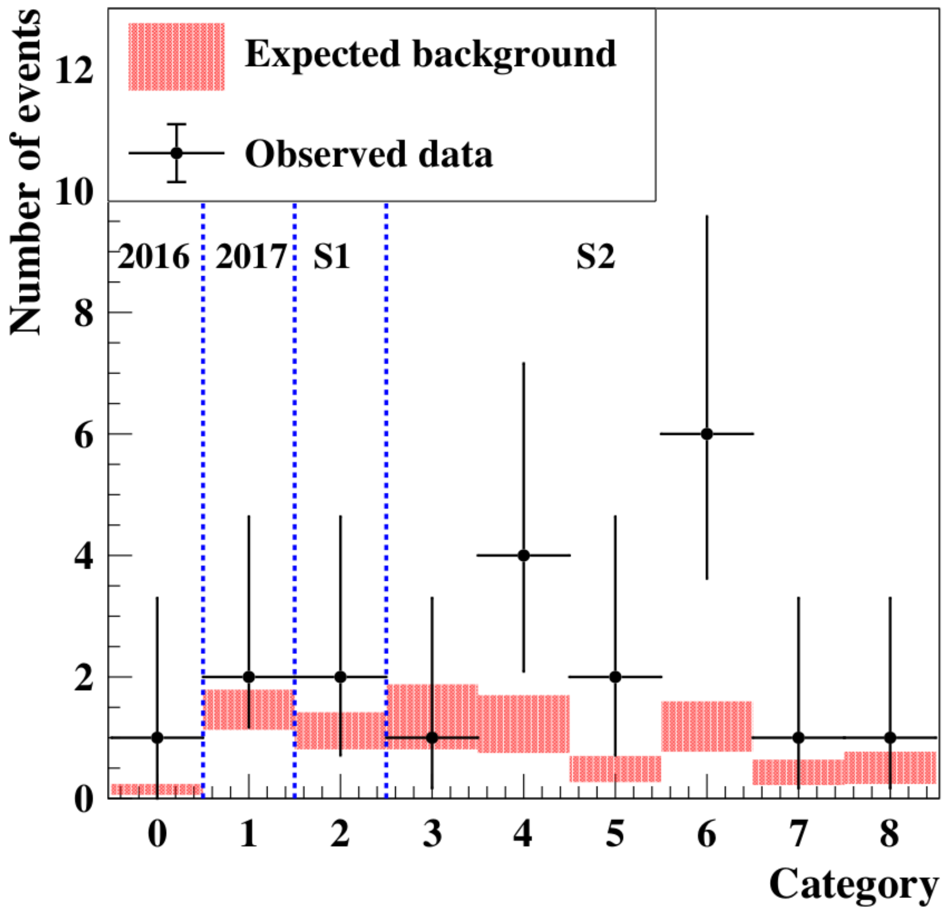
- Model independent Grossman-Nir bound [PLB 398 (1997) 163]

$$\frac{\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})\ /\ \tau_{K_L}}{\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})\ /\ \tau_{K^+}} \lesssim 1$$

- New Z' boson [JHEP 11 (2015) 166]
  - Minimal Flavour Violation: Z' with CKM-like structure
  - Z' with pure LH / RH couplings
  - General Z'
- Leptoquarks [EPJC 82 (2022) 320, PLB 835 (2022) 137525]
- New physics in lepton flavour
  [EPJC 84 (2024) 680, JHEP 10 (2024) 087]



2016 – 2018 DATA RESULTS

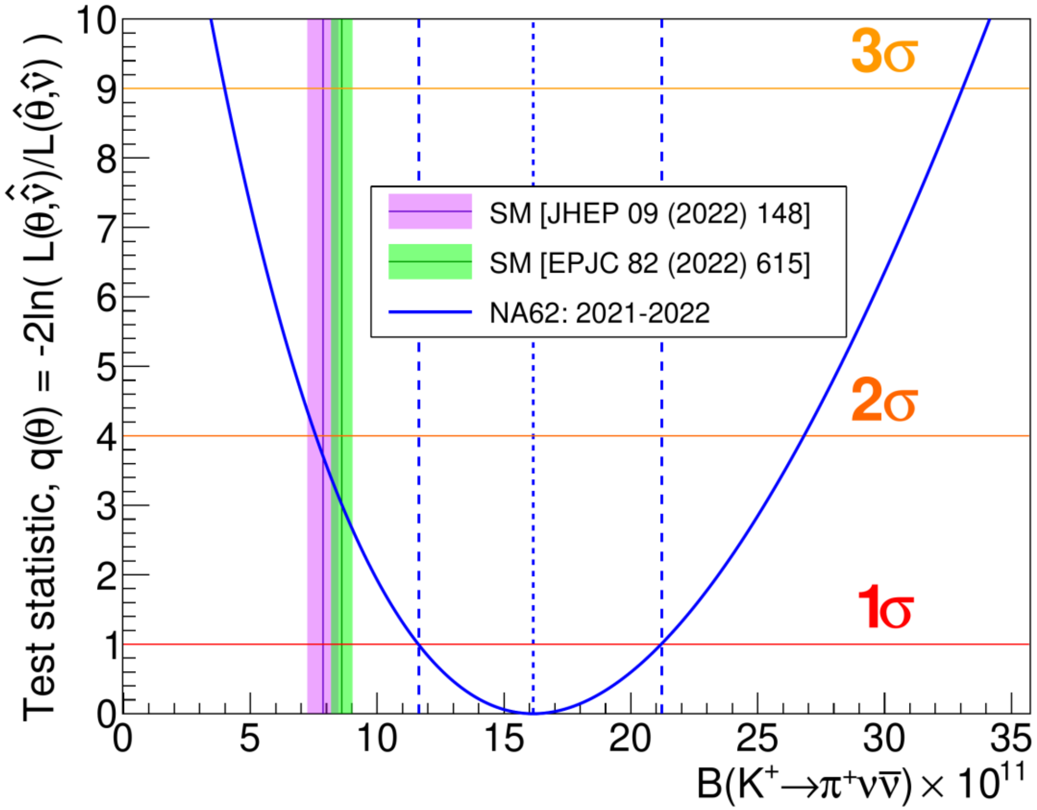


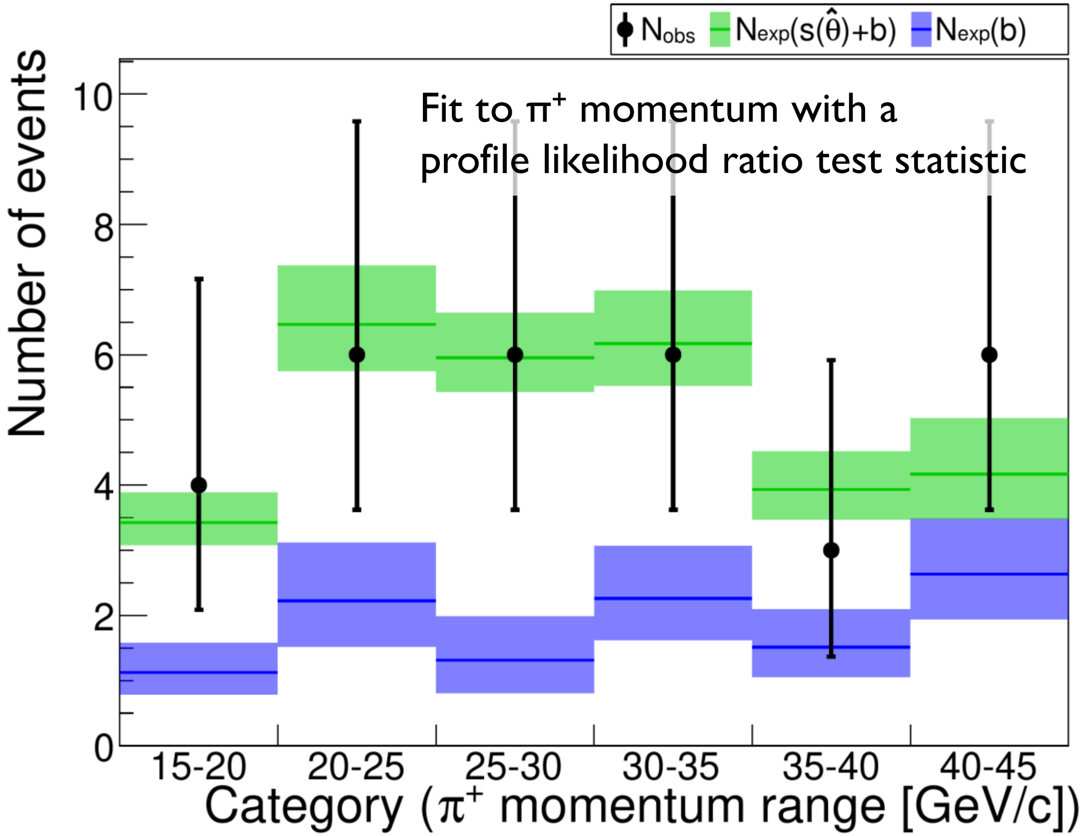
- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16+17+18} = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

[PLB 791 (2019) 156]
[JHEP 11 (2020) 042]
[JHEP 06 (2021) 093]

2021 – 2022 DATA RESULTS





$N_{bkg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$ → Significance: 3.6σ

$$BR_{2021-2022} = (16.2^{+5.1}_{-4.5}) \times 10^{-11} = (16.2^{+4.9}_{-4.3}|_{stat}\, {}^{+1.4}_{-1.4}|_{syst}) \times 10^{-11}$$

2018 DATA SUMMARY

Signal

	Subset S1*	Subset S2*
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\mathrm{trig}}^{\mathrm{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\mathrm{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

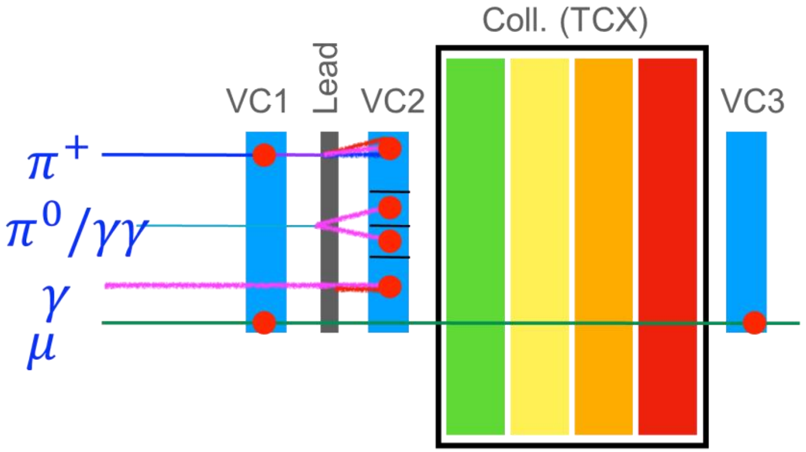
* different hardware configurations

Background

Background	Subset S1*	Subset S2*
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

VETOCOUNTER & ANTI0

[FELIX readout: Streaming Readout Workshop talk 2021]



VetoCounter

- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.

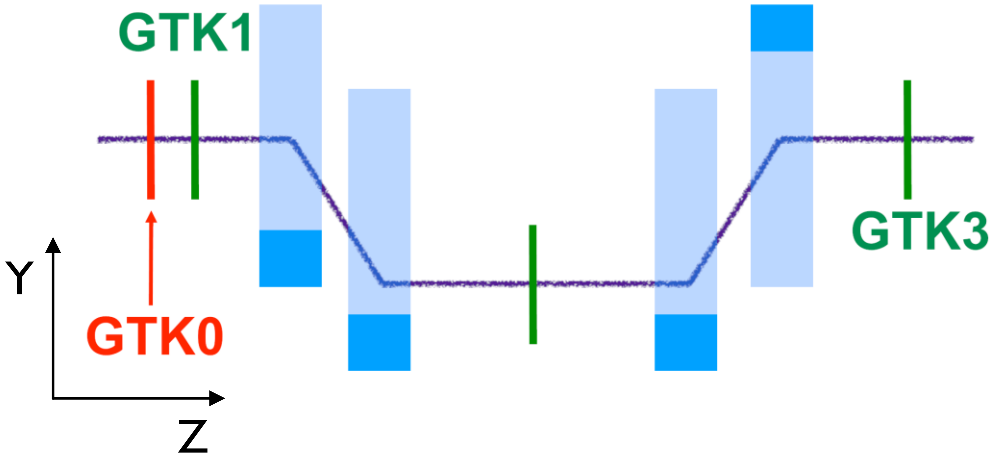
ANTI0

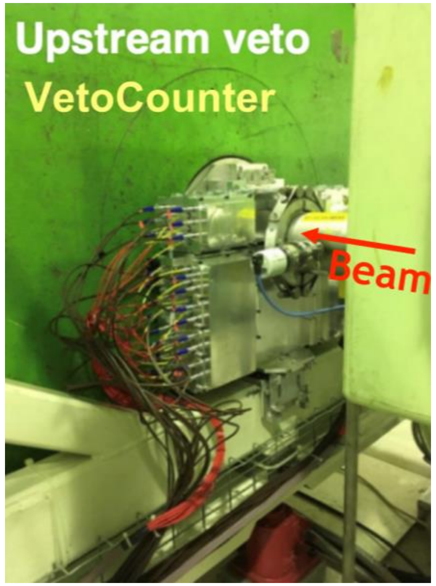
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

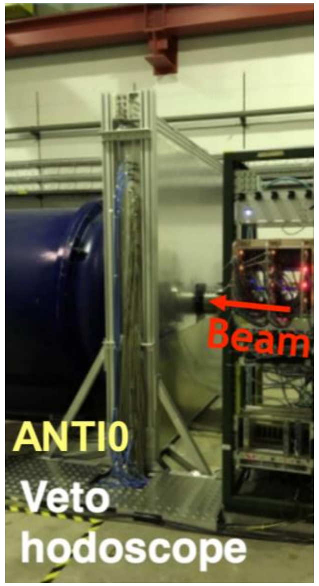
[SPSC report 2023][EP Newsletter, Dec21]

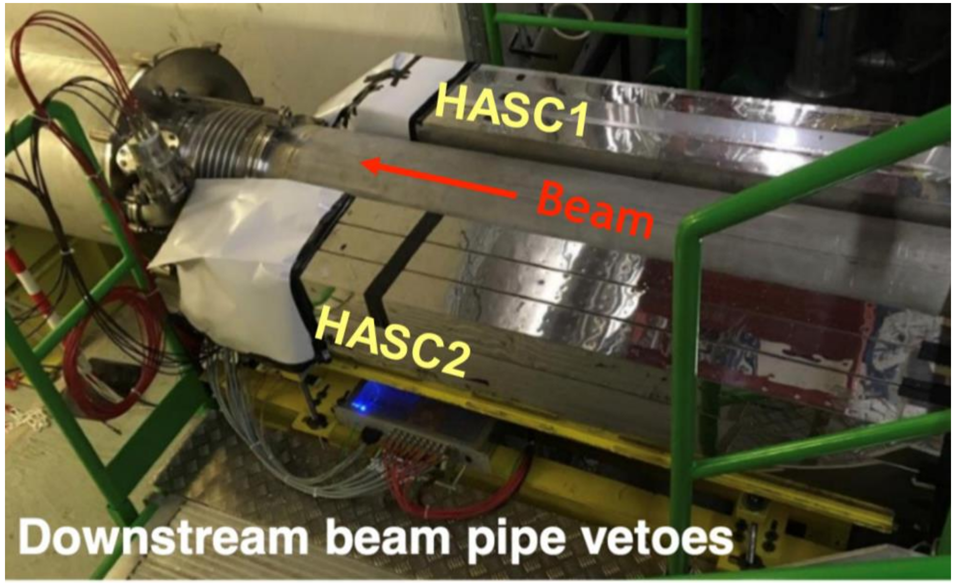
LS2 UPGRADES SUMMARY

- New VetoCounter & ANTI0
- New GTK0 station + GTK2 rearrangement
- New HASC2
- Improvements to trigger system
- Intensity increased by 50% (400 to 600 MHz)

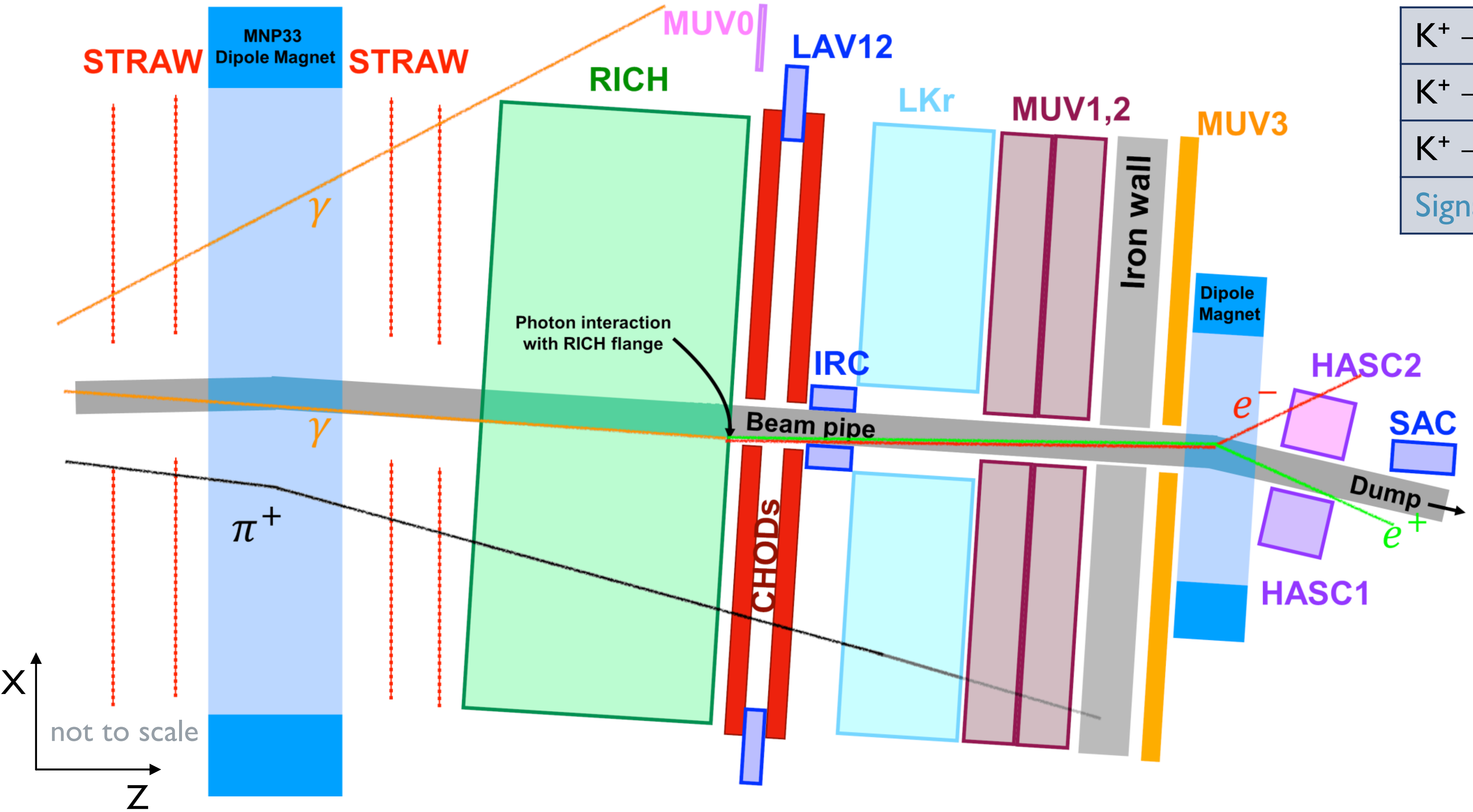






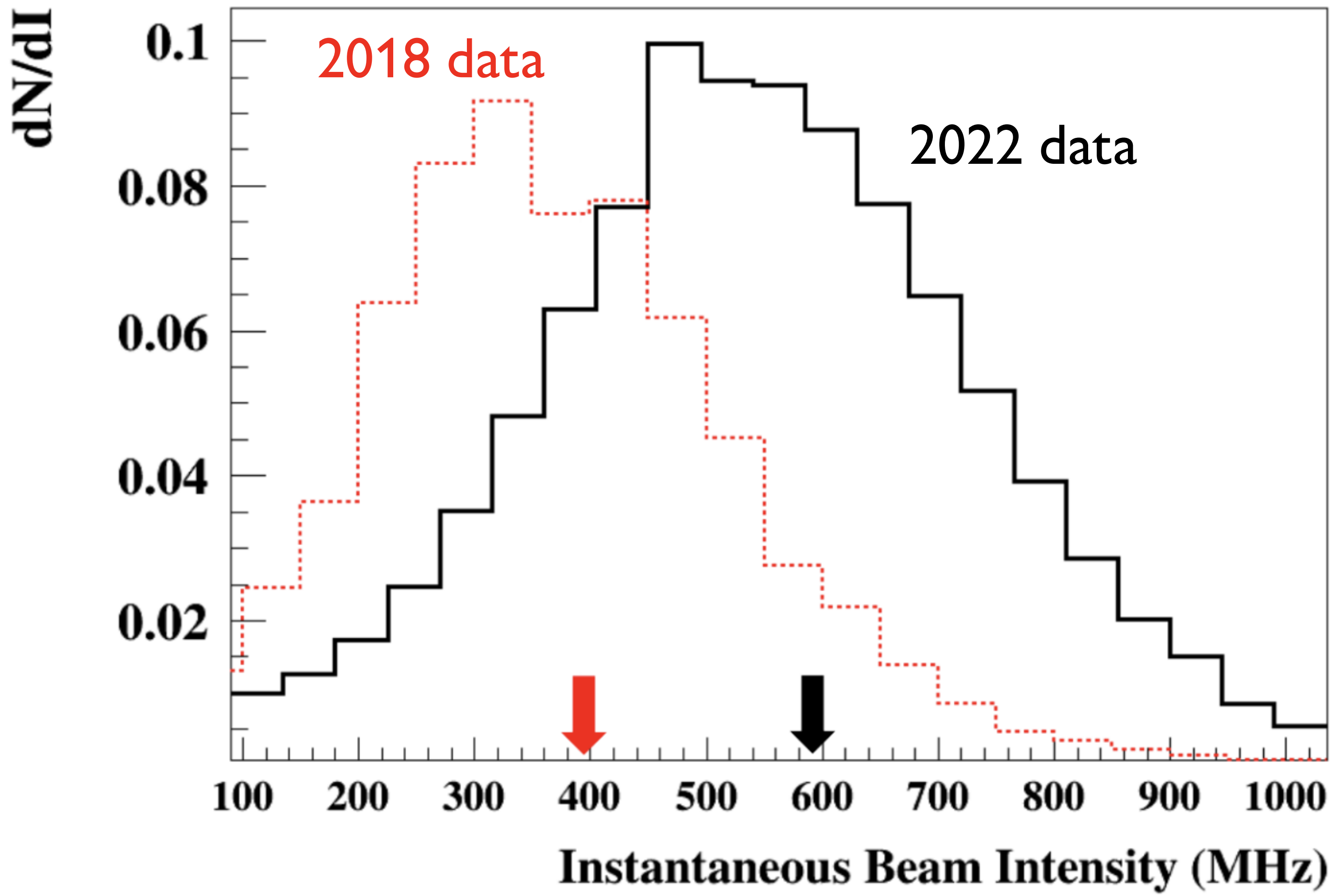


HASC2 ADDITION

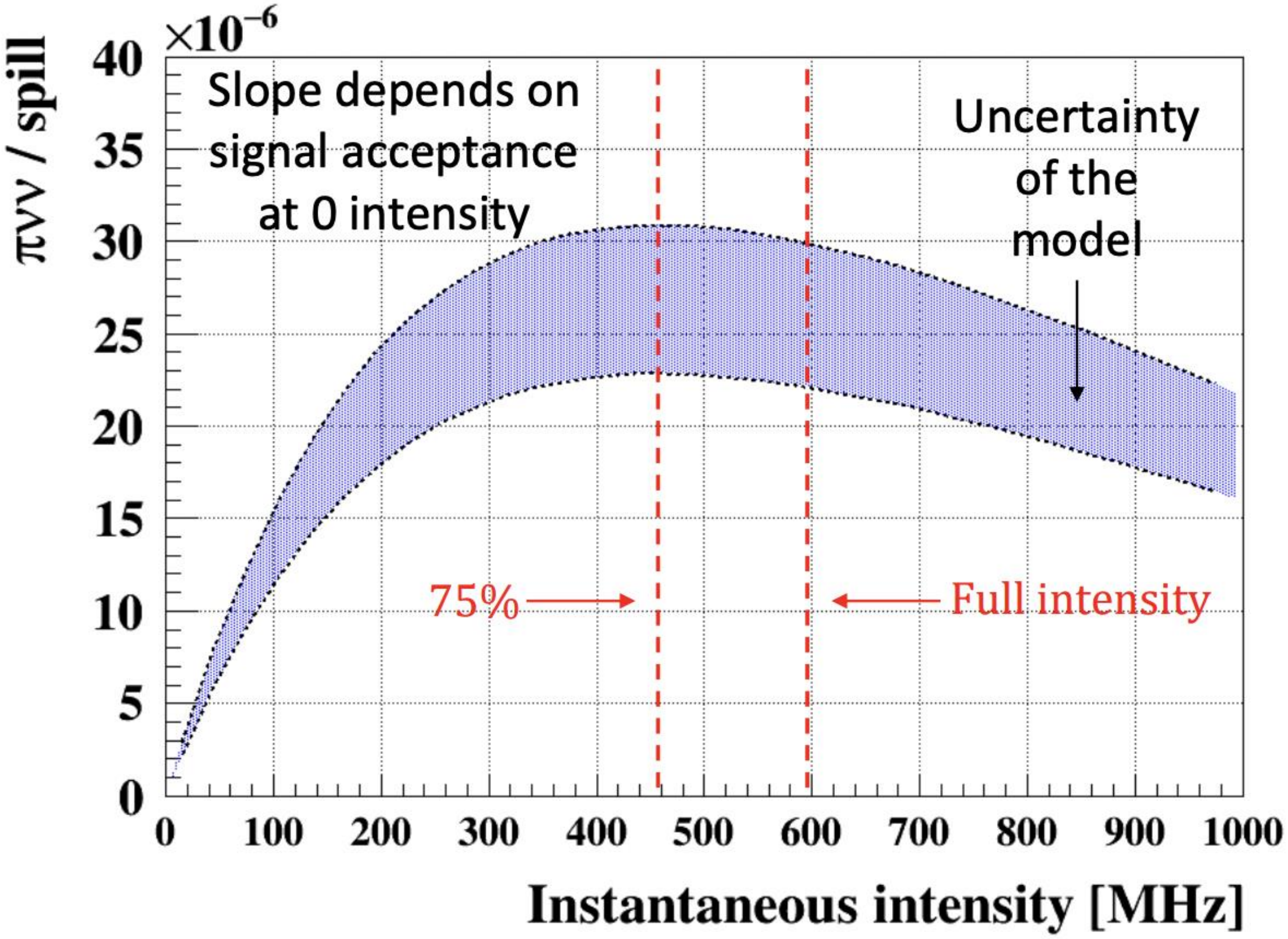


$K^+ \rightarrow \pi^+\pi^0$	-30%
$K^+ \rightarrow \pi^+\pi^+\pi^-$	-18%
$K^+ \rightarrow \mu^+\nu$	-3.5%
Signal	-1.5%

BEAM INTENSITY

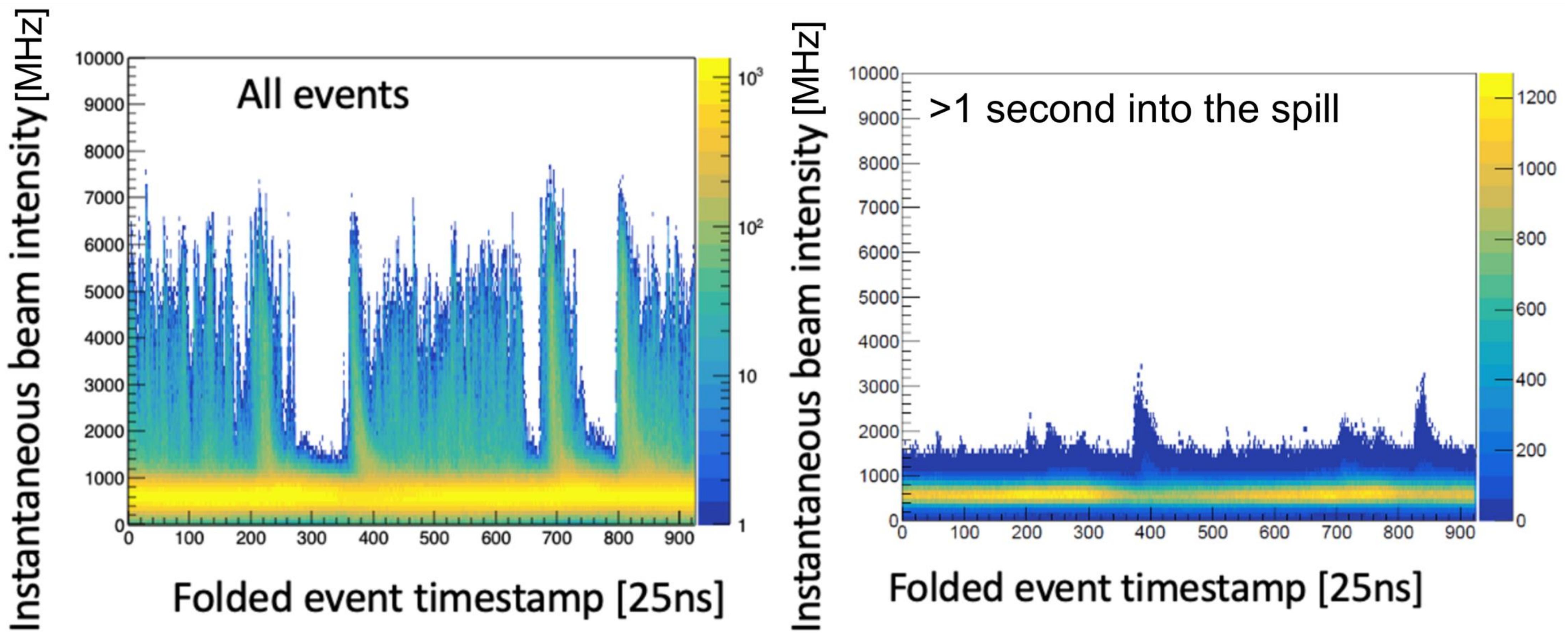


OPTIMUM NA62 INTENSITY



- Saturation due to paralyzable dead time
  - TDAQ dead time
  - Trigger veto
  - Offline veto
- **Operated at 75% intensity (450 MHz) since August 2023**

2021 INSTANTANEOUS BEAM INTENSITY



Removed first 1s of 4.8s spill in 2021 data

SELECTION STRATEGY

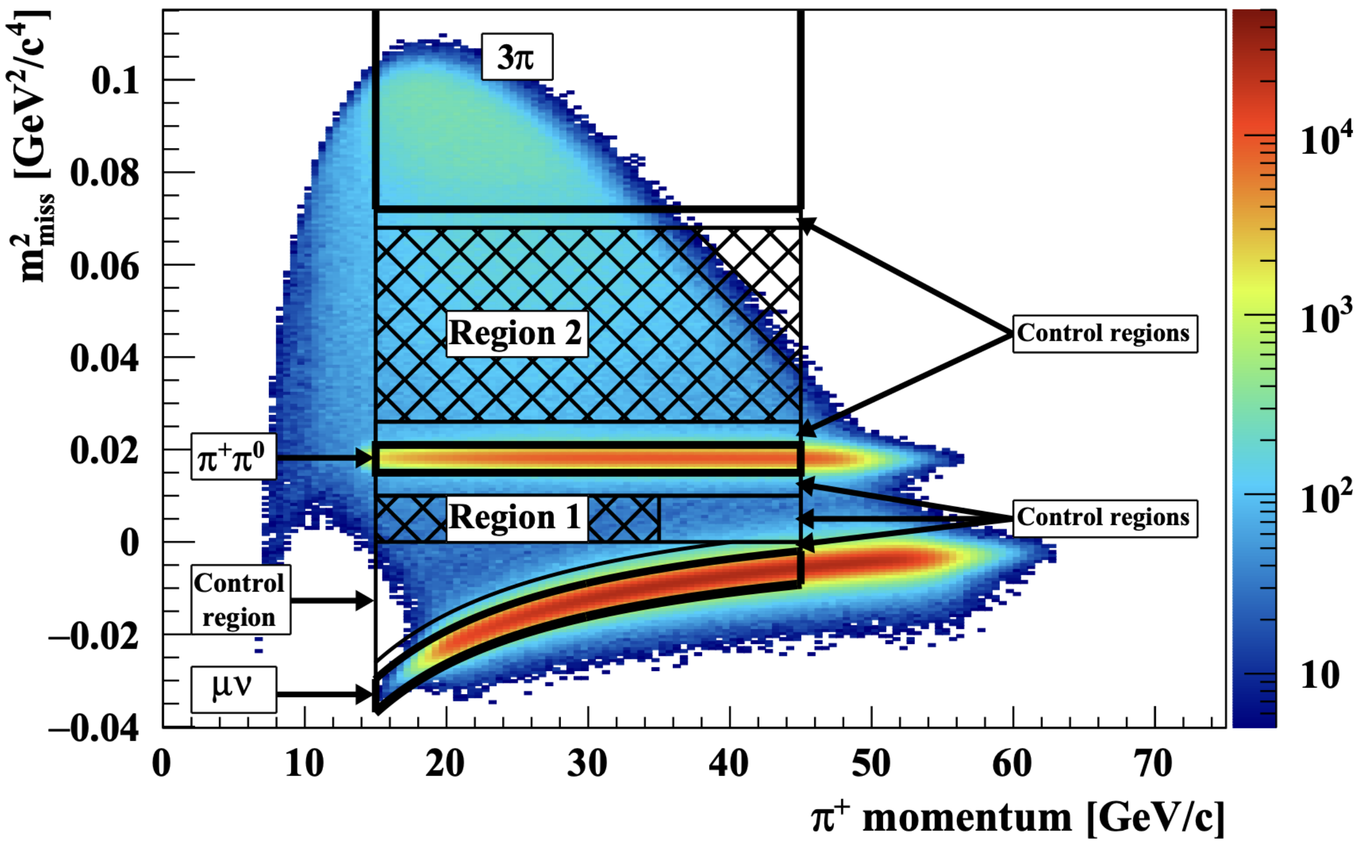
Normalization: $K^+ \to \pi^+\pi^0$

- Normalization trigger: μ^+ veto, K^+ tag
- Require one downstream particle
- π^+ identification (μ^+ rejection)
- Match K^+ track in GTK
- Reconstruct vertex and m^2_{miss}
- Upstream activity veto

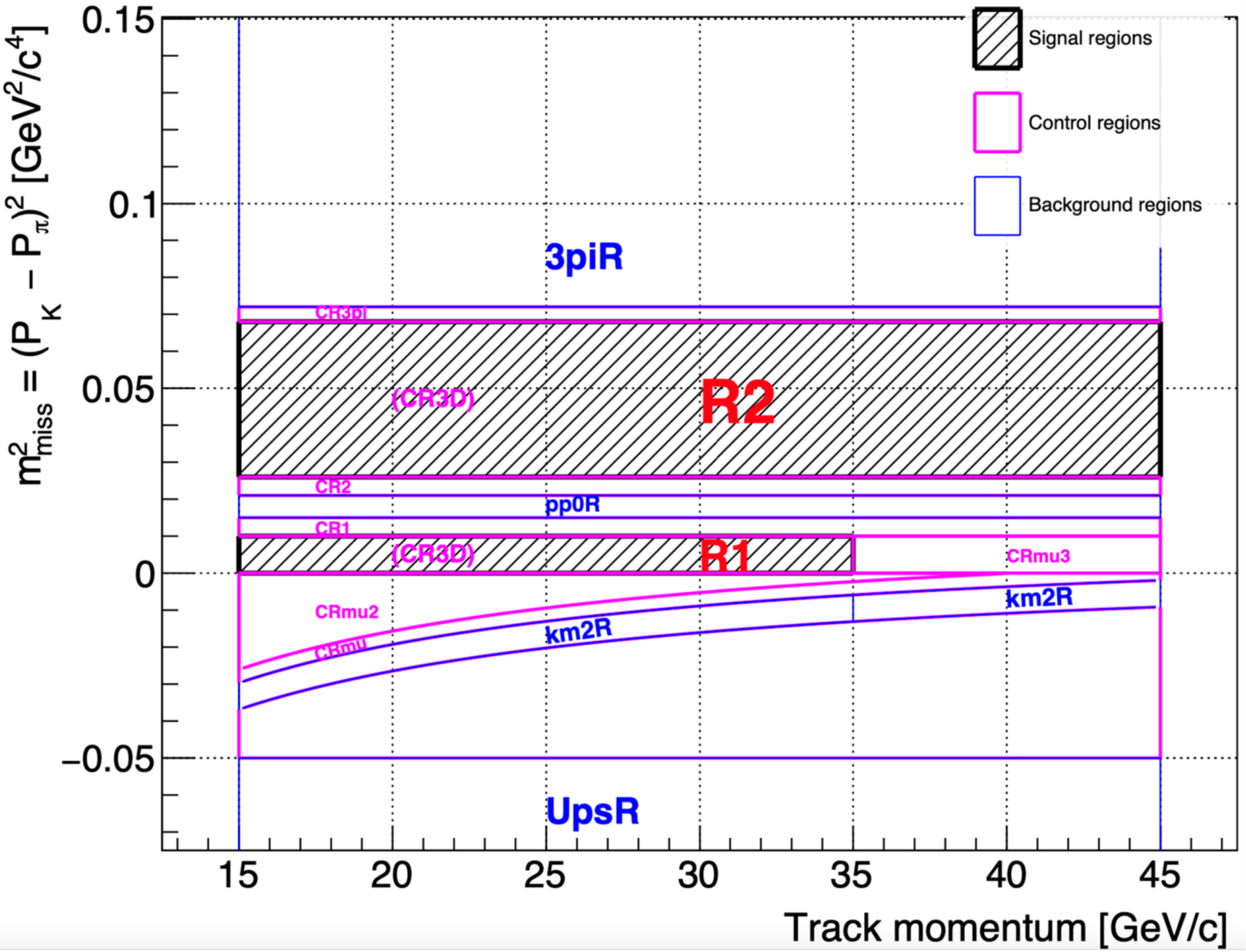
Signal: $K^+ \to \pi^+\nu\bar{\nu}$

- Signal trigger: μ^+ veto, K^+ tag + LKr and LAV veto
- Same selection as normalization
- Photon and multiplicity vetoes

π^+ momentum range: 15 – 45 GeV/c, in 5 GeV/c bins



KINEMATIC REGIONS

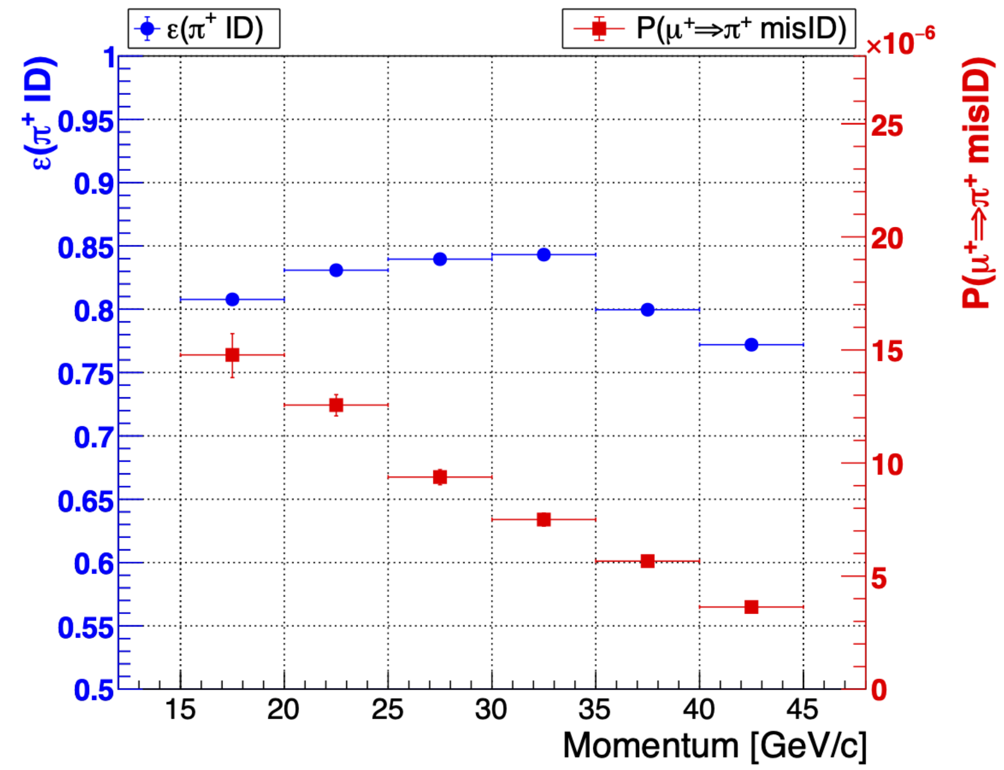


- **Signal regions:**
- **Control regions:**
  - Used to validate background predictions.
- **Background regions:**
  - Used as “reference samples” for some background estimates.

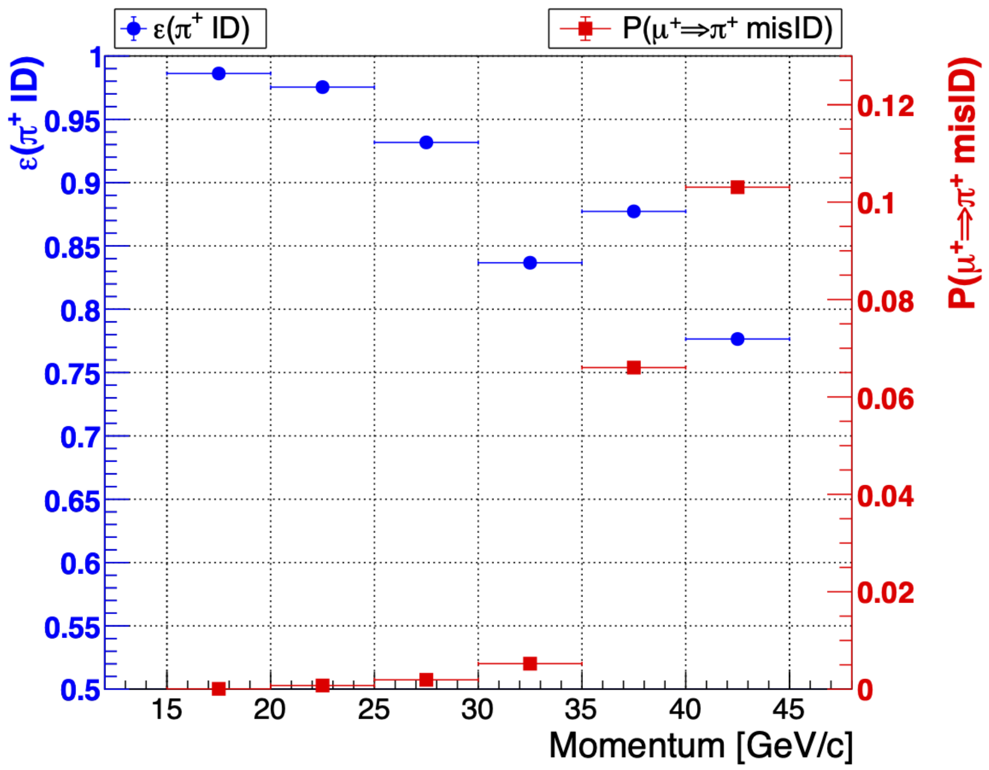
PARTICLE ID PERFORMANCE

Calorimetric

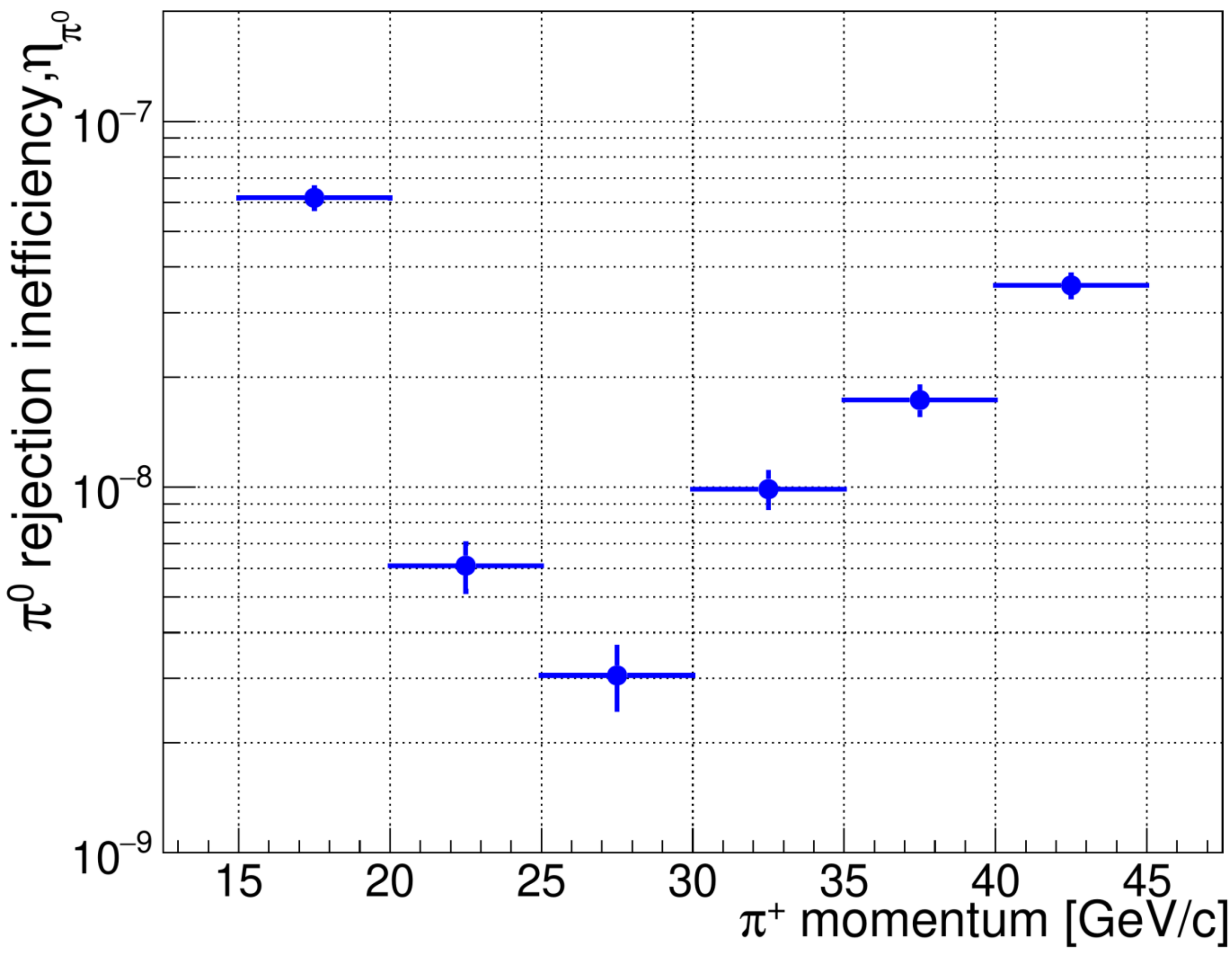
(LKr + MUV12 + MUV3)



RICH



PHOTON VETO PERFORMANCE

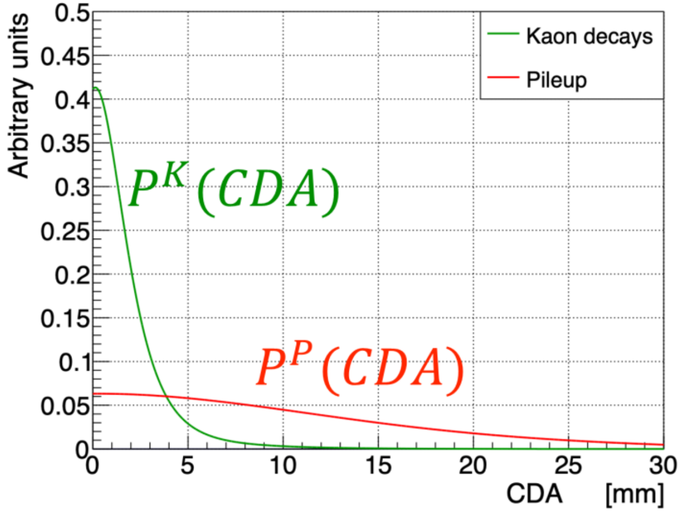


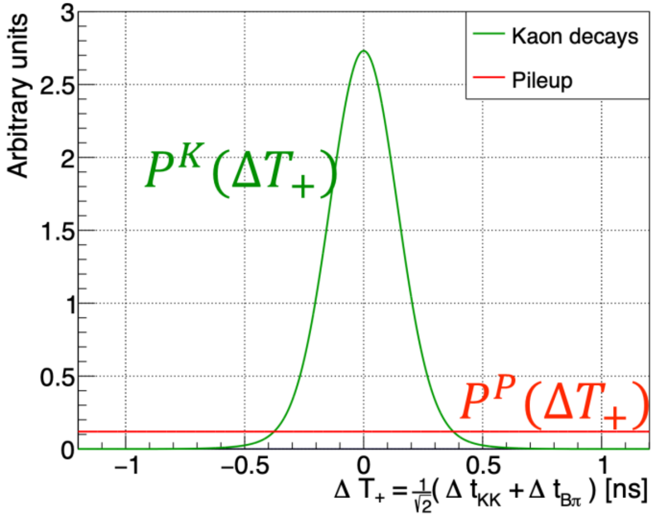
Control sample of $K^+ \rightarrow \pi^+\pi^0$

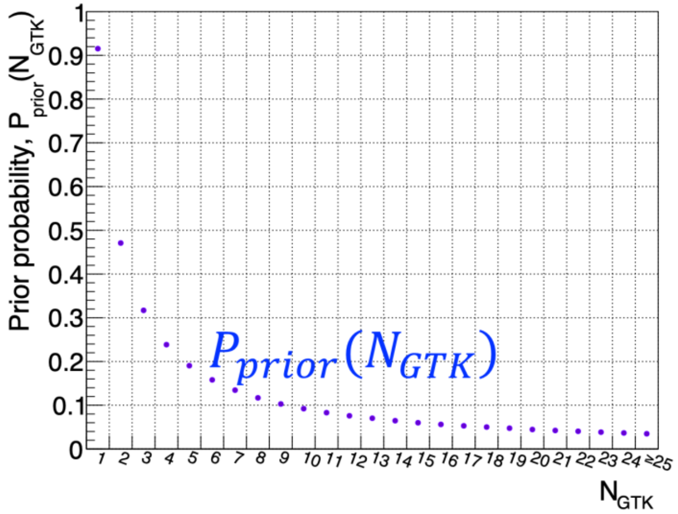
$$\eta_{\pi 0} = (1.72 \pm 0.07) \times 10^{-8}$$

BAYESIAN K - π MATCHING

- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data.



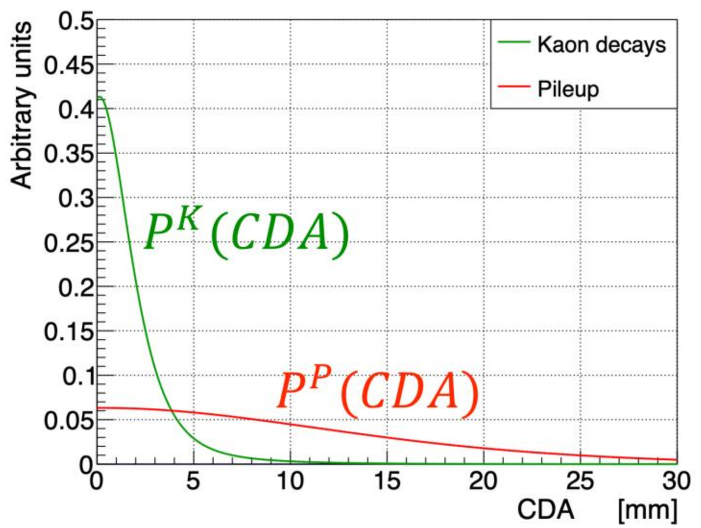




- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

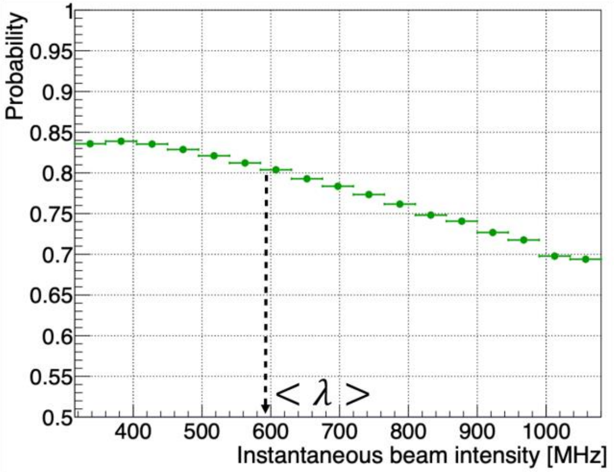
BAYESIAN K - π MATCHING

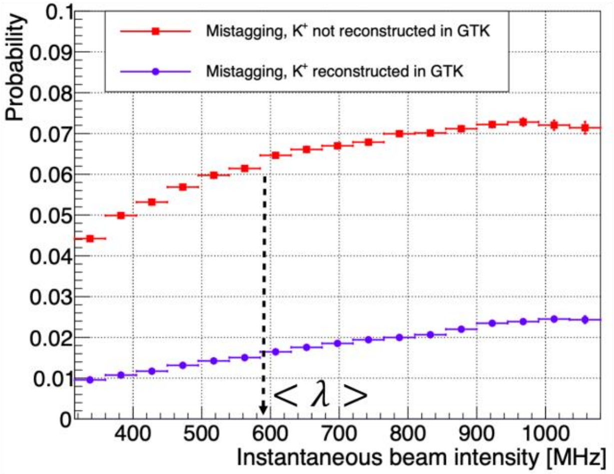
- **Inputs:** matching in space (CDA) & time (ΔT) Prior: pileup (N_{GTK})
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data



- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$

$\varepsilon = 80\%$ $P^P_{mistag} = 6\%$ $P^K_{mistag} = 2\%$





- Efficiency improved (+10%) and mistagging probability maintained.

SIGNAL EXPECTATION

$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi}\, D\, \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}\, \frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\, \varepsilon_{trig}\, \varepsilon_{RV}$$

		analysis of 2018 data:
$N_{\pi\pi}$	$(1.953 \pm 0.005) \times 10^8$	
$A_{\pi\pi}$	13.4%	11.8%
$A_{\pi\nu\nu}$	$(7.62 \pm 0.2)\%$	$(6.37 \pm 0.6)\%$
ε_{trig}	$(85.9 \pm 1.4)\%$	$(89 \pm 5)\%$
ε_{RV}	$(63.2 \pm 0.6)\%$	$(66 \pm 1)\%$
	@ 600 MHz	@ 400 MHz

Improvements wrt analysis of 2018 data:

- Retuned selection and reconstruction
- New trigger configuration
  (common conditions lead to cancellation of systematics)

$\Rightarrow$ ×2 signal yield per SPS spill, ×2 better SES precision

Effective kaon decays

$$N_K = \frac{N_{\pi\pi}\, D}{BR(\pi\pi) A_{\pi\pi}} = (2.85 \pm 0.01) \times 10^{12}$$

Single Event Sensitivity

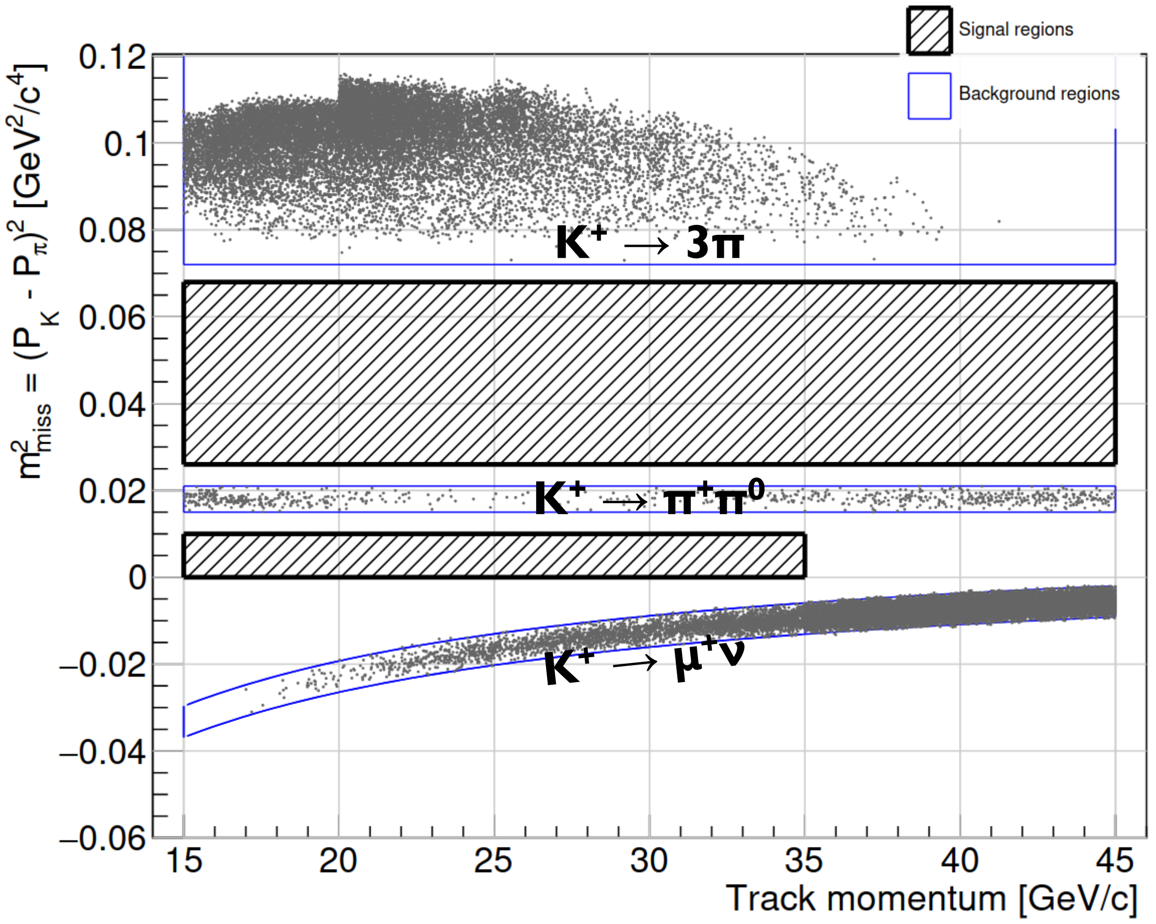
$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}} = (8.48 \pm 0.29) \times 10^{-12}$$

2016 – 2018: $(8.39 \pm 0.54) \times 10^{-12}$

$$N_{\pi\nu\nu}^{exp} = 9.91 \pm 0.34$$

2016 – 2018: 10.01 ± 0.42

BACKGROUND K^+ DECAYS



Events in $\pi^+\pi^0$ region after selection

$$N_{\pi^+\pi^0}(SR) = N(\pi^+\pi^0)\, f_{\pi^+\pi^0}(SR)$$

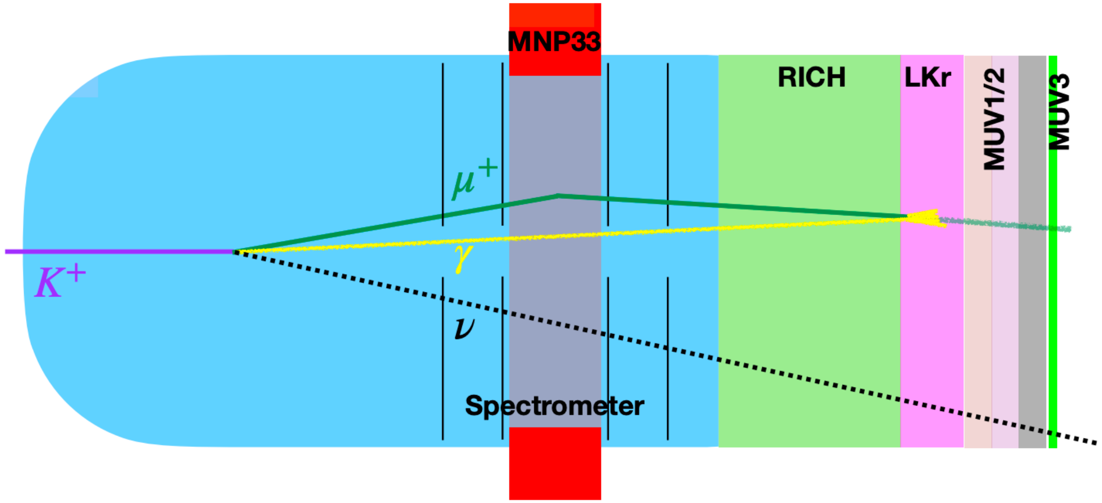
$K^+ \to \pi^+ \pi^0$ events in signal region

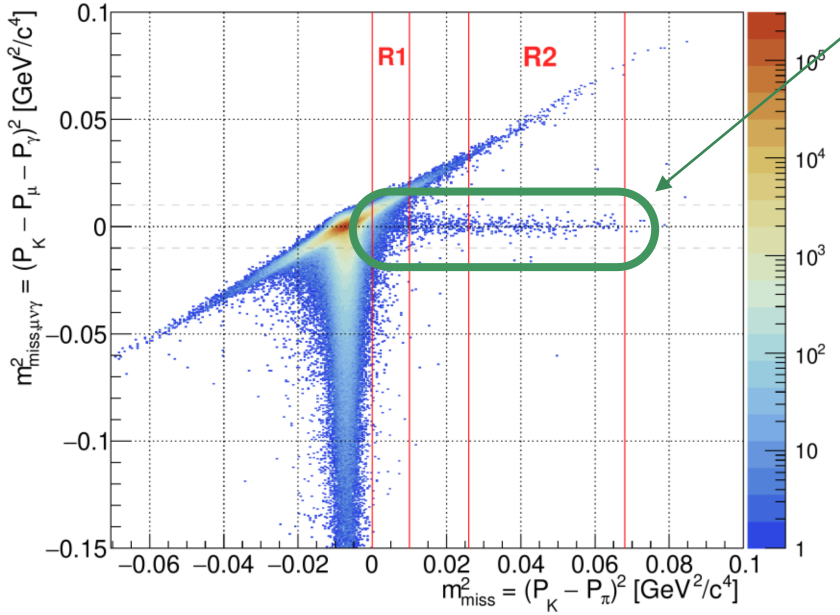
Ratio of events in $\pi^+\pi^0$ region to signal region, measured on control sample

kinematic tail fraction

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05	data-driven
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47	
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03	
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.33}_{-0.27}$	estimated with MC
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01	
$K^+ \to \pi^0\ell^+\nu$	< 0.001	

$K^+ \to \mu^+\nu\gamma$





- $\mu^+\gamma$ cluster mis-ID as π^+
- Not included in kinematic tail control sample
- Particle ID performance degraded at high intensity
- Veto: $m^2_{miss,\mu\nu\gamma} = (P_K - P_\mu - P_\gamma)^2 \approx 0$

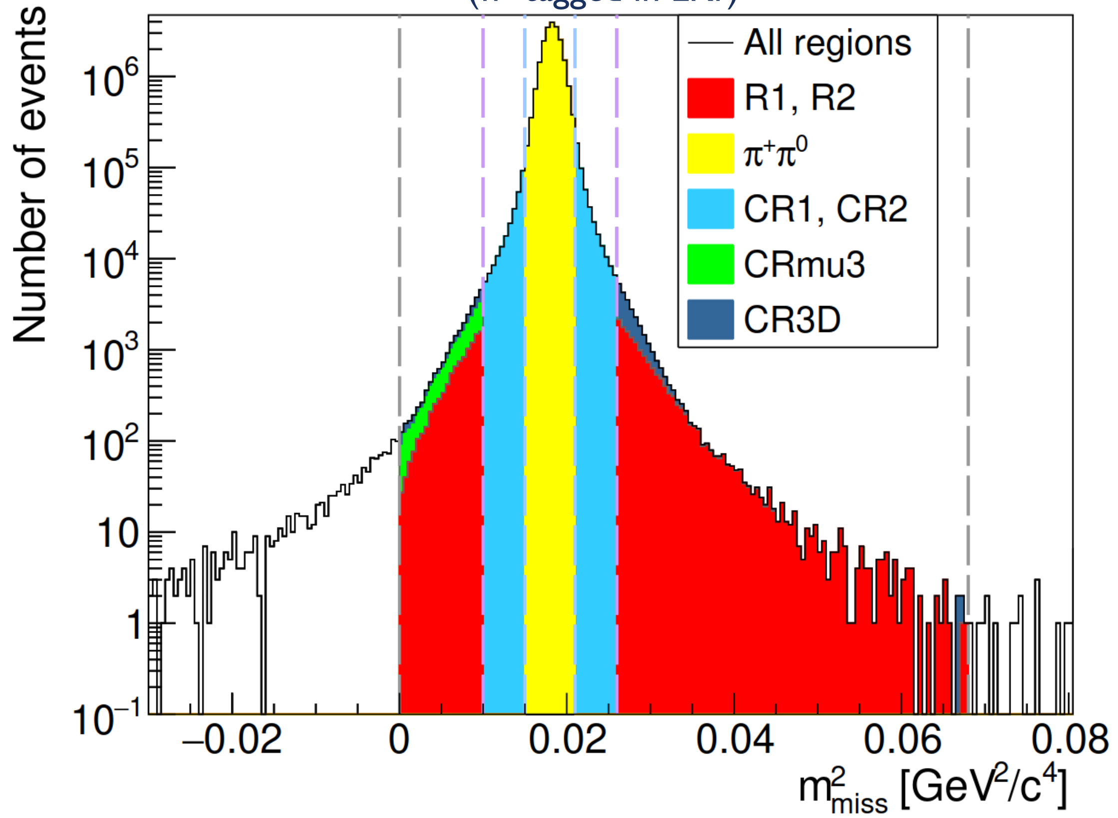
$N(K^+ \to \mu^+\nu\gamma) = 0.82 \pm 0.43$

- Before veto, found excess of events in Region 2 wrt 2016–2018 data
- $K^+ \to \mu^+\nu\gamma$ identified as background and studied with control samples and MC
- Veto added to selection for final analysis

KINEMATIC TAIL FRACTIONS

$K^+ \rightarrow \pi^+\pi^0$ control sample

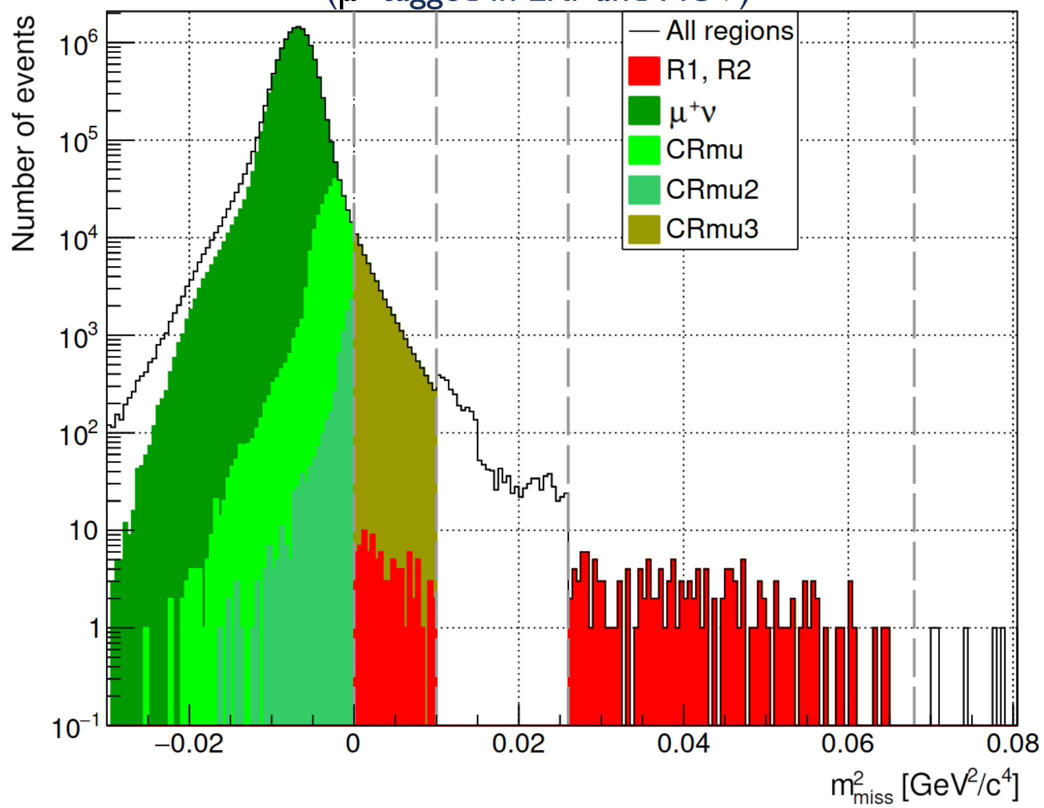
(π^0 tagged in LKr)



$N(K^+ \rightarrow \pi^+\pi^0) = 0.76 \pm 0.04$

$K^+ \rightarrow \mu^+\nu$ control sample

(μ^+ tagged in LKr and MUV)

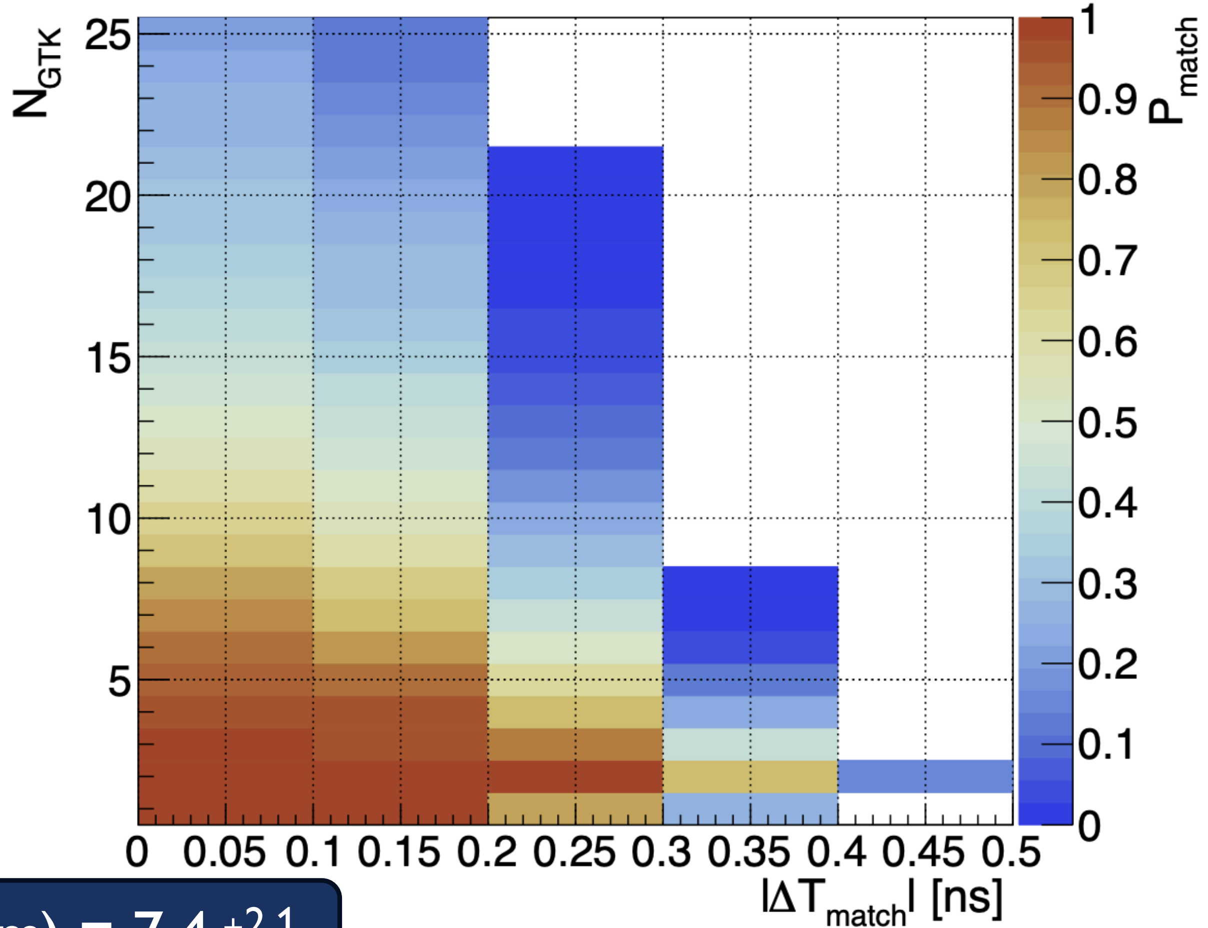


$N(K^+ \rightarrow \mu^+\nu) = 0.87 \pm 0.19$

UPSTREAM BACKGROUND ESTIMATION

$N(\text{Upstream}) = \sum_i N_{URS}(i)\, f_{CDA}\, P_{match}(i)$

$N_{URS} = 51$, $f_{CDA} = 0.20 \pm 0.03$, $\langle P_{match} \rangle = 73\%$



- i: bins of (ΔT, N_{GTK})
- Upstream Reference Sample: signal selection but bad CDA
  - Contains all known upstream background mechanisms
  - Provides normalization
- f_{CDA}: ratio of bad CDA events to good CDA events
  - Extracted from the URS
  - Depends on geometry only
- P_{match}: probability of passing K-π matching criteria
  - Extracted from normalization data

$N(\text{Upstream}) = 7.4\,^{+2.1}_{-1.8}$

UPSTREAM BACKGROUND ESTIMATION

$$N(\text{Upstream}) = \sum_i N_{URS}(i)\, f_{CDA}\, P_{match}(i)$$

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- Upstream Reference Sample: signal selection but bad CDA
  - Contains all known upstream background mechanisms
  - Provides normalization
- f_{CDA}: ratio of bad CDA events to good CDA events
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  - Depends on geometry only
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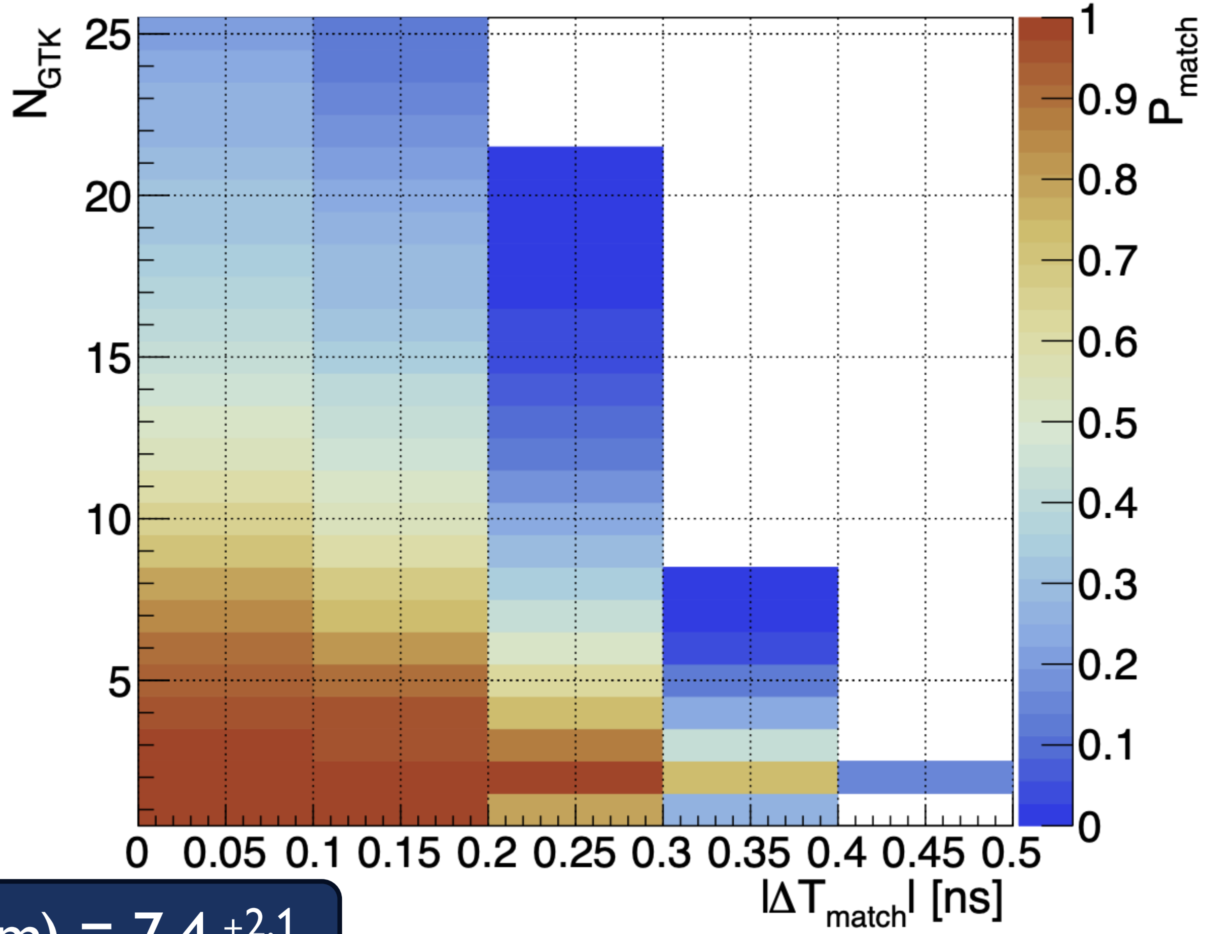

$$N(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

$K^+ \to \pi^+\pi^- e^+\nu$ BACKGROUND

From PDG: 4.3×10^{-5}

From MC: $(1.3 \pm 0.3) \times 10^{-8}$

$$N^{exp}_{\pi\pi e\nu} = N_{\pi\pi}\, D\, \frac{BR(\pi\pi e\nu)}{BR(\pi\pi)}\, \frac{A_{\pi\pi e\nu}}{A_{\pi\pi}}\, \varepsilon_{trig}\, \varepsilon_{RV} = 0.89\,^{+0.33}_{-0.27}$$

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

Experiments

Camerini et al. [PRL 23 (1969) 326-329]
Klems et al. [PRD 4 (1971) 66-80]
Ljung et al. [PRD 8 (1973) 1307-1330]
Cable et al. [PRD 8 (1973) 3807-3812]
Asano et al. [PLB 107 (1981) 159]
E787 :
[PRL 64 (1990) 21-24]
[PRL 70 (1993) 2521-2524]
[PRL 76 (1996) 1421-1424]
[PRL 79 (1997) 2204-2207]
[PRL 84 (2000) 3768-3770]
[PRL 88 (2002) 041803]
E949 (+E787)
[PRL 93 (2004) 031801]
[PRL 101 (2008) 191802]
NA62:
2016 data [PLB 791 (2019) 156]
2016–17 data [JHEP 11 (2020) 042]
2016–18 data [JHEP 06 (2021) 093]
2016–22 data [JHEP 02 (2025) 191]

Theory

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[Prog.Theor.Phys. 65 (1981)]
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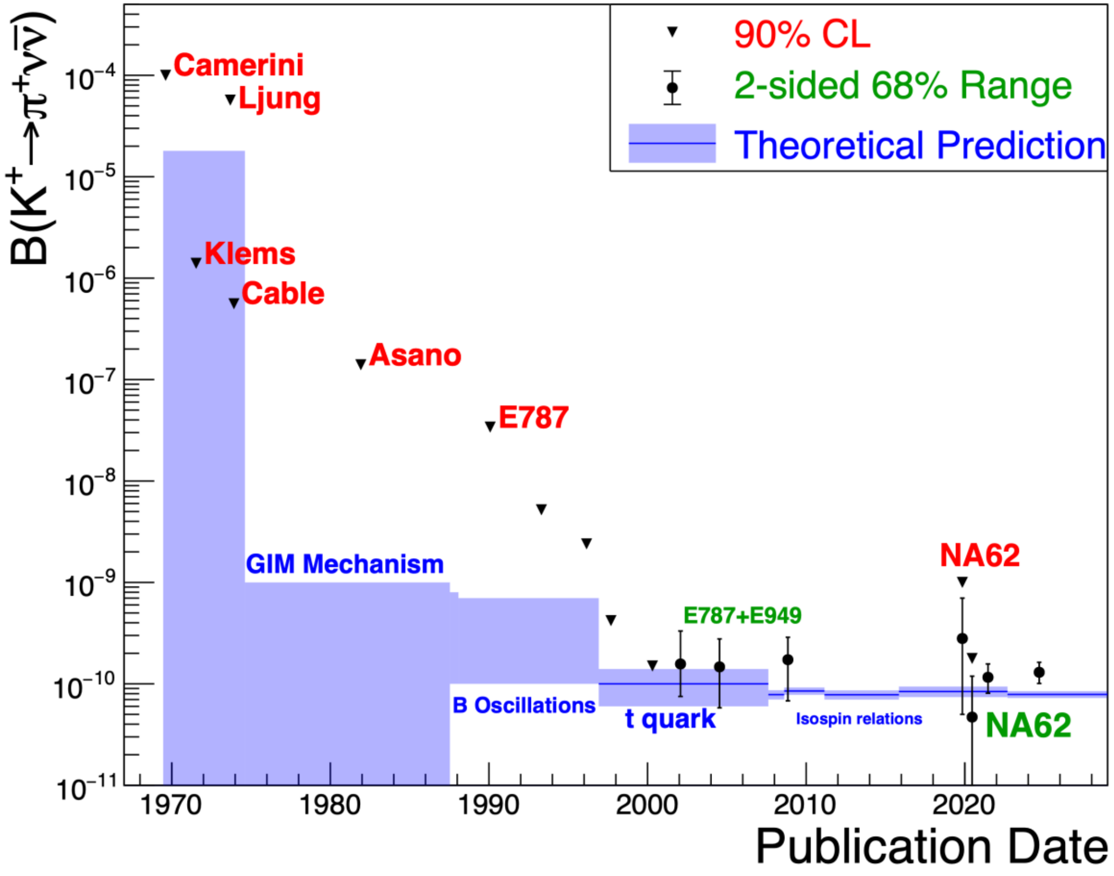
[Nucl.Phys.B 304 (1988) 205-235]
[PRD 54 (1996) 6782-6789]
[PRD 76 (2007) 034017]
[PRD 78 (2008) 034006]
[PRD 83 (2011) 034030]
[JHEP 11 (2015) 033]
[JHEP 09 (2022) 148]



…NOT ONLY $K^+ \to \pi^+\nu\bar{\nu}$

Precision measurements

- $K^+ \to \pi^+\mu^+\mu^-$ JHEP 11 (2022) 011
- $K^+ \to \pi^0 e^+\nu\gamma$ JHEP 09 (2023) 040
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$ PLB 846 (2023) 138193
- $K^+ \to \pi^+\gamma\gamma$ PLB 850 (2024) 138513

Forbidden decays

- $K^+ \to \pi^-\ell^+\ell^+$ PLB 797 (2019) 134794
- $K^+ \to \pi\mu e^+$ & $\pi^0 \to \mu^- e^+$ PRL 127 (2021) 131802
- $K^+ \to \pi^-(\pi^0)e^+e^+$ PLB 830 (2022) 132172
- $K^+ \to \mu^-\nu e^+e^+$ PLB 838 (2023) 137679
- $K^+ \to \pi^0\pi\mu e$ PLB 859 (2024) 139122

Invisible particles

- $\pi^0 \to \gamma A'$ JHEP 05 (2019) 182
- $K^+ \to e^+ N$ PLB 807 (2020) 135599
- $\pi^0 \to$ inv. JHEP 02 (2021) 201
- $K^+ \to \mu^+$ + inv. PLB 816 (2021) 136259

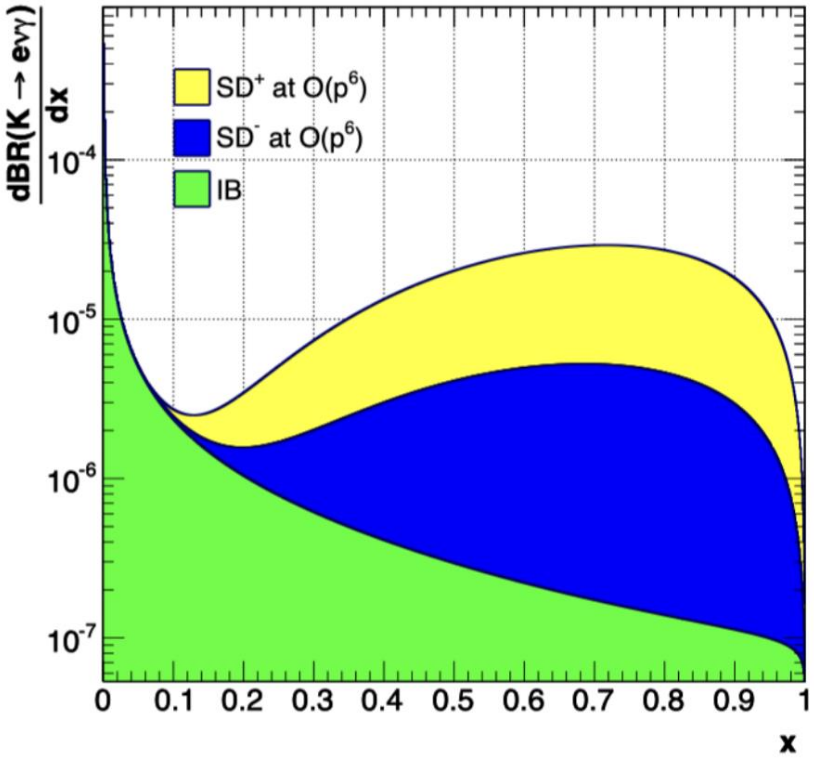
Dump mode

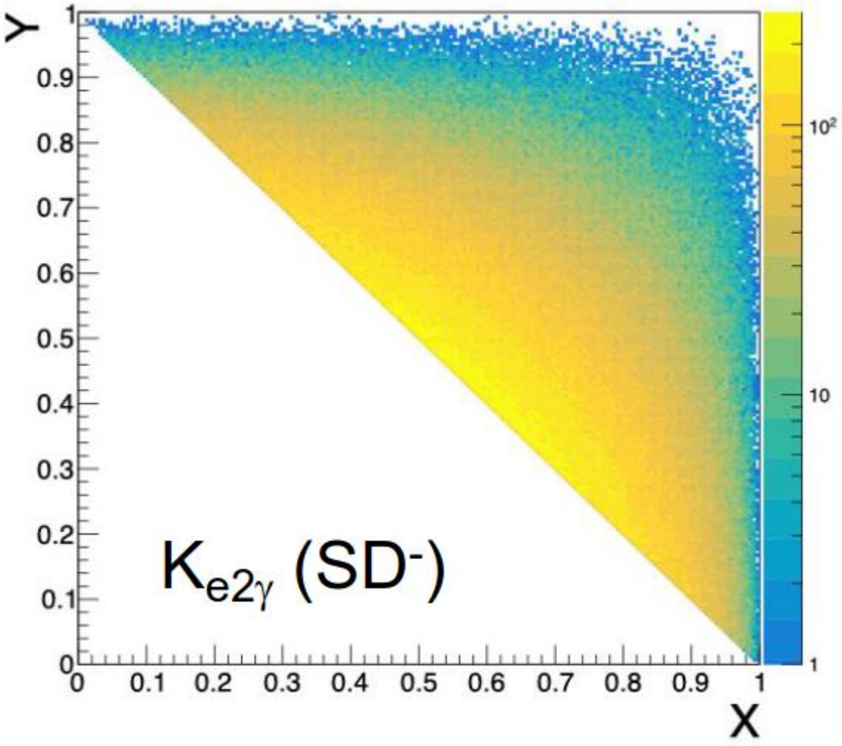
- $A' \to \mu^+\mu^-$ JHEP 09 (2023) 035
- $A' \to e^+e^-$ PRL 133 (2024) 111802
- $A' \to$ hadrons arXiv:2502.04241

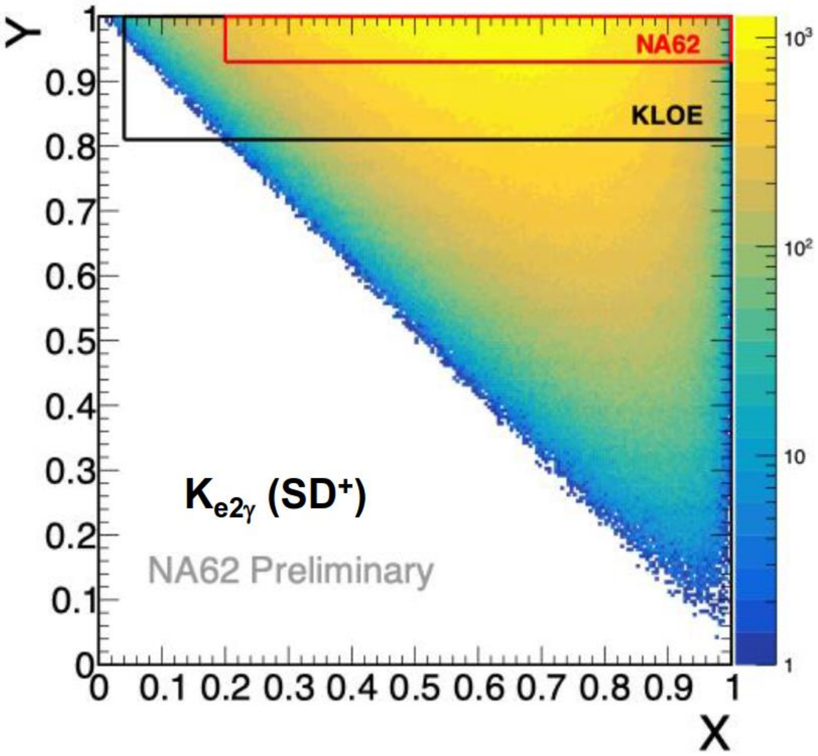
Neutrino tagging:

PLB 863 (2025) 139345

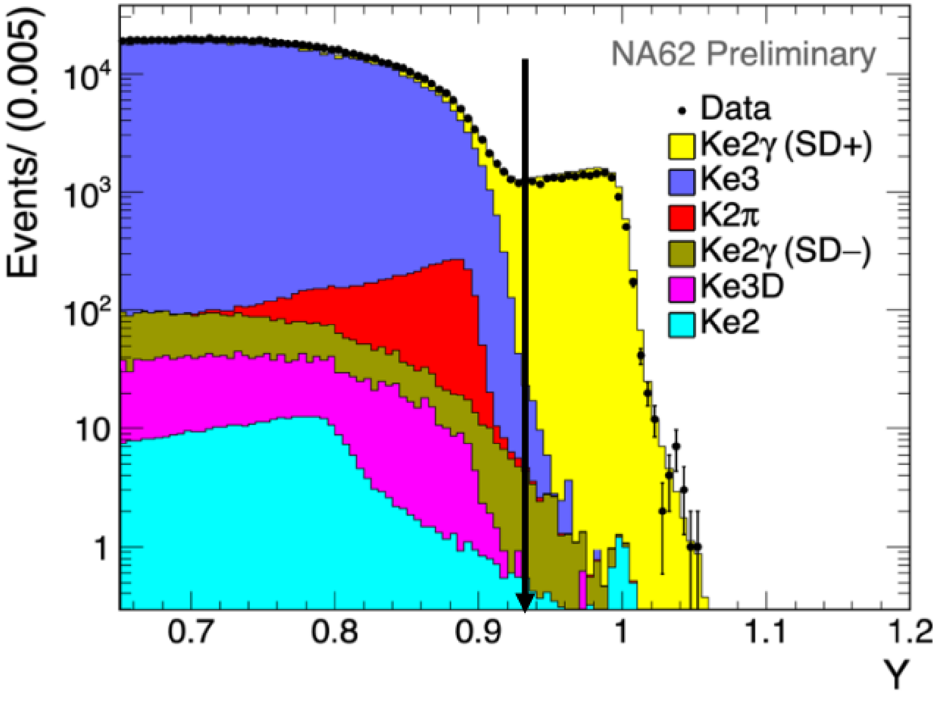
$K^+ \to e^+\nu\gamma$ KINEMATICS

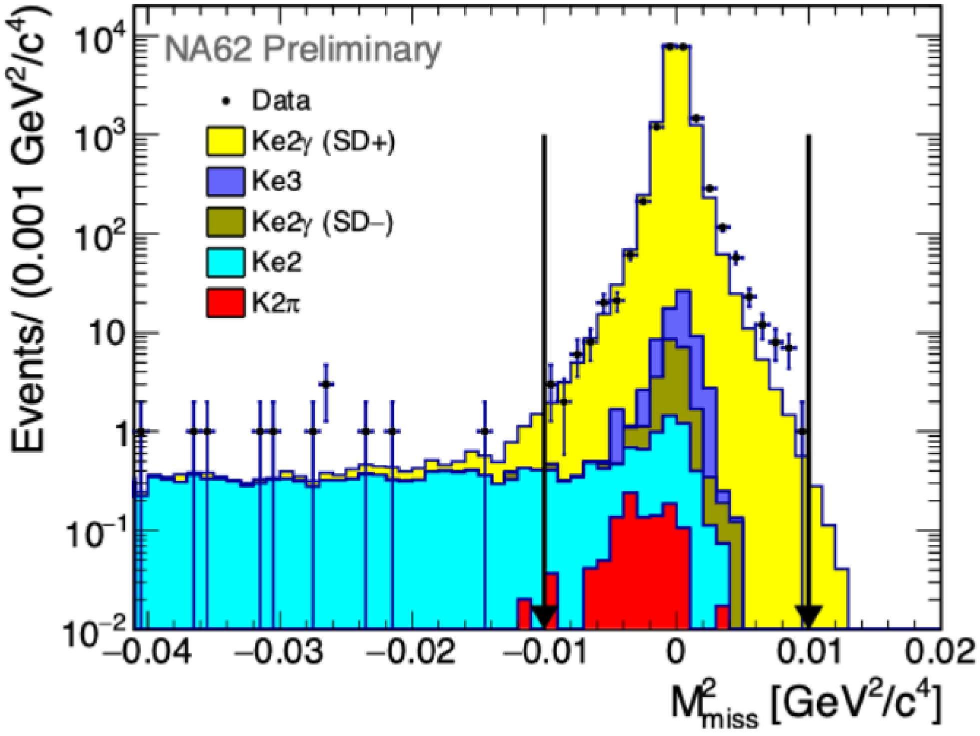






$K^+ \rightarrow e^+\nu\gamma$ ANALYSIS





$N^{obs}_{Ke2\gamma}$	18929
$Acc_{Ke2\gamma}$	14.2 %
B/S	0.4 %

Background source	N^{bkg}
$K^+ \to \pi^0 e^+ \nu$ (K_{e3})	46 ± 7
$K^+ \to e^+ \nu_e \gamma$ $(K_{e2\gamma})$(SD-)	18 ± 3
$K^+ \to e^+ \nu_e$ (K_{e2})	7 ± 1
$K^+ \to \pi^+ \pi^0$ $(K_{2\pi})$	1.1 ± 0.1
Total	72 ± 8

$Y_{max}(K2\pi) = 0.920$
$Y_{max}(Ke3) = 0.925$
Selection: $Y > 0.93$