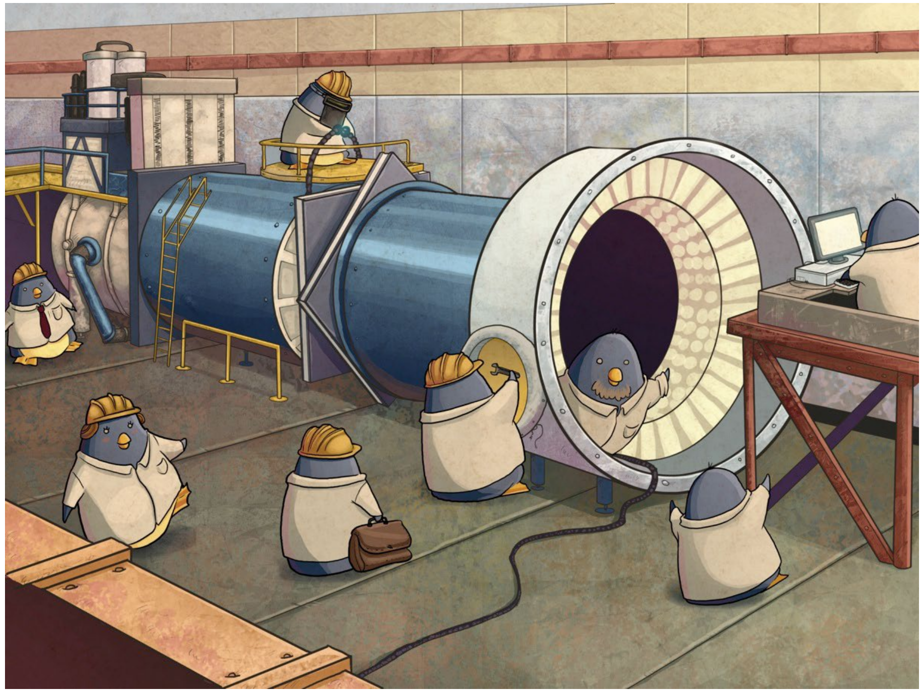
Observation of the of $K^+ \to \pi^+ \upsilon\bar{\upsilon}$ decay and measurement of its branching ratio at NA62



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Vietnam Flavour Physics Conference 2025

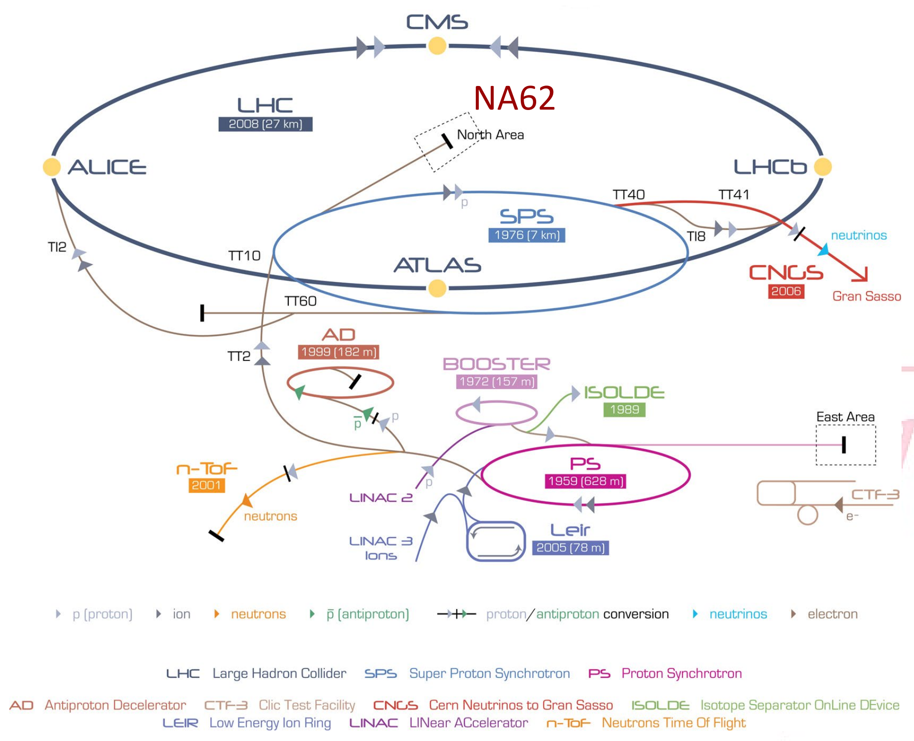
The NA62 Experiment

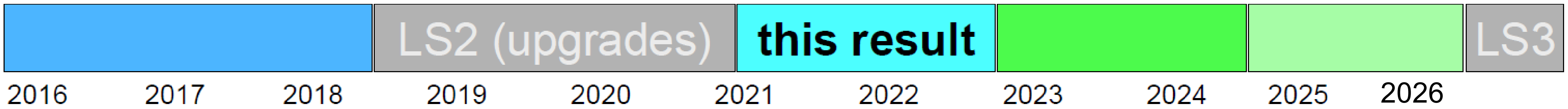
- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)
- Broader physics program: LFV / LNV in K^+ decays, precision measurements and hidden sector particles searches.

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

NA62 Timeline

- 2008 NA62 Approval
- 2014 NA62 Pilot Run (partial layout)
- 2015 Commissioning run
- 2016 Commissioning + Physics run (45 days)
- 2017 Physics run (160 days)
- 2018 Physics run (217 days)
- 2021 Physics run (85 days [10 beam dump])
- 2022 Physics run (215 days).
- 2023 Physics run (150 days [10 beam dump]).
- 2024 Physics run just finished (204 days [10 beam dump]).
- 2025 Physics run on going.
- 2026 Last Physics run



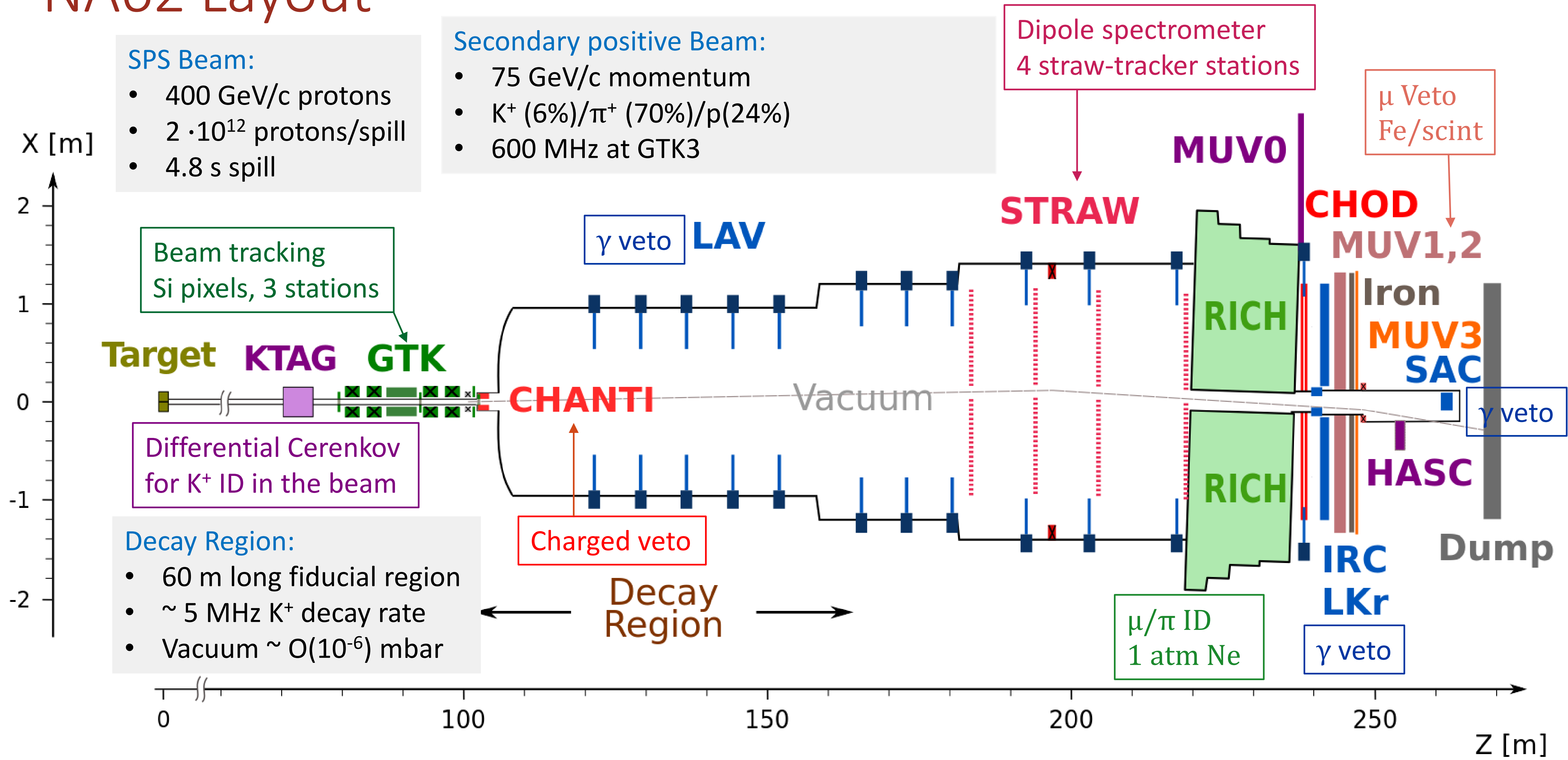


NA62 Layout

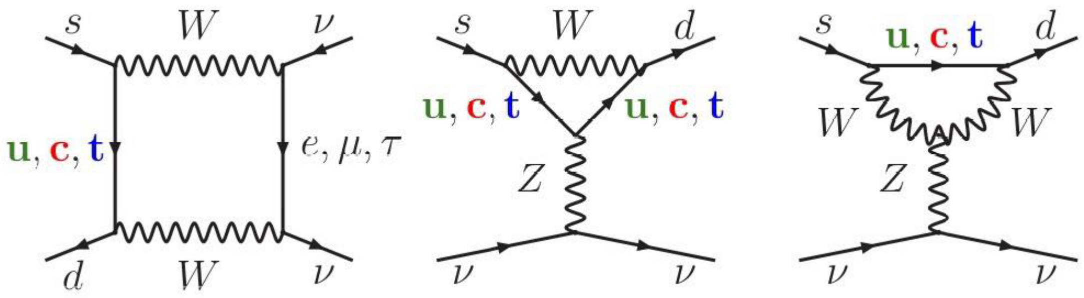
SPS Beam:
- 400 GeV/c protons
- 2 $\cdot 10^{12}$ protons/spill
- 4.8 s spill

Secondary positive Beam:
- 75 GeV/c momentum
- K^+ (6%)/π^+ (70%)/p(24%)
- 600 MHz at GTK3

Decay Region:
- 60 m long fiducial region
- ~ 5 MHz K^+ decay rate
- Vacuum ~ O(10^{-6}) mbar



The $K^+ \to \pi^+ \upsilon\bar{\upsilon}$ decay



- High sensitivity to New Physics
- FCNC process forbidden at tree level
- Highly CKM suppressed (BR ~ $|V_{ts} x V_{td}|^2$)

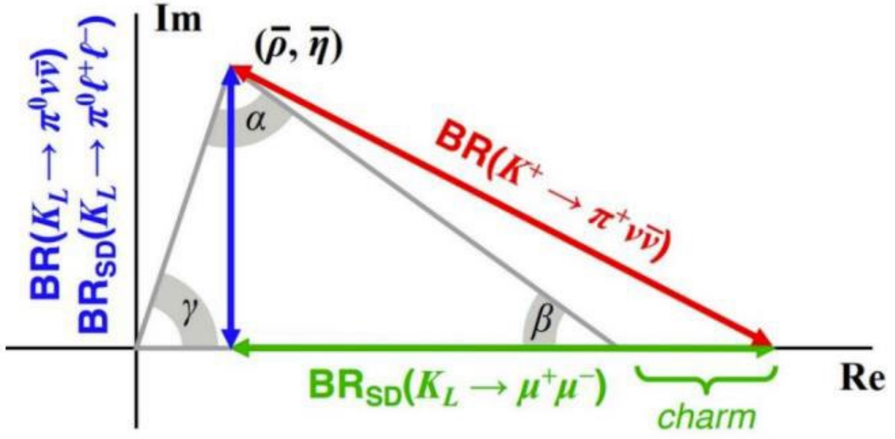
- Very clean theoretically: Short distance contribution
- hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \upsilon$)
- Precise SM predictions:
  - $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{Buras} = (8.60 \pm 0.42) \times 10^{-11}$

    [Buras et al. EPJC 82 (2022) 7, 615]
  - $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{D'ambrosio} = (7.86 \pm 0.61) \times 10^{-11}$

    [D'Ambrosio et al. JHEP 09 (2022) 148]
- Experimental status:

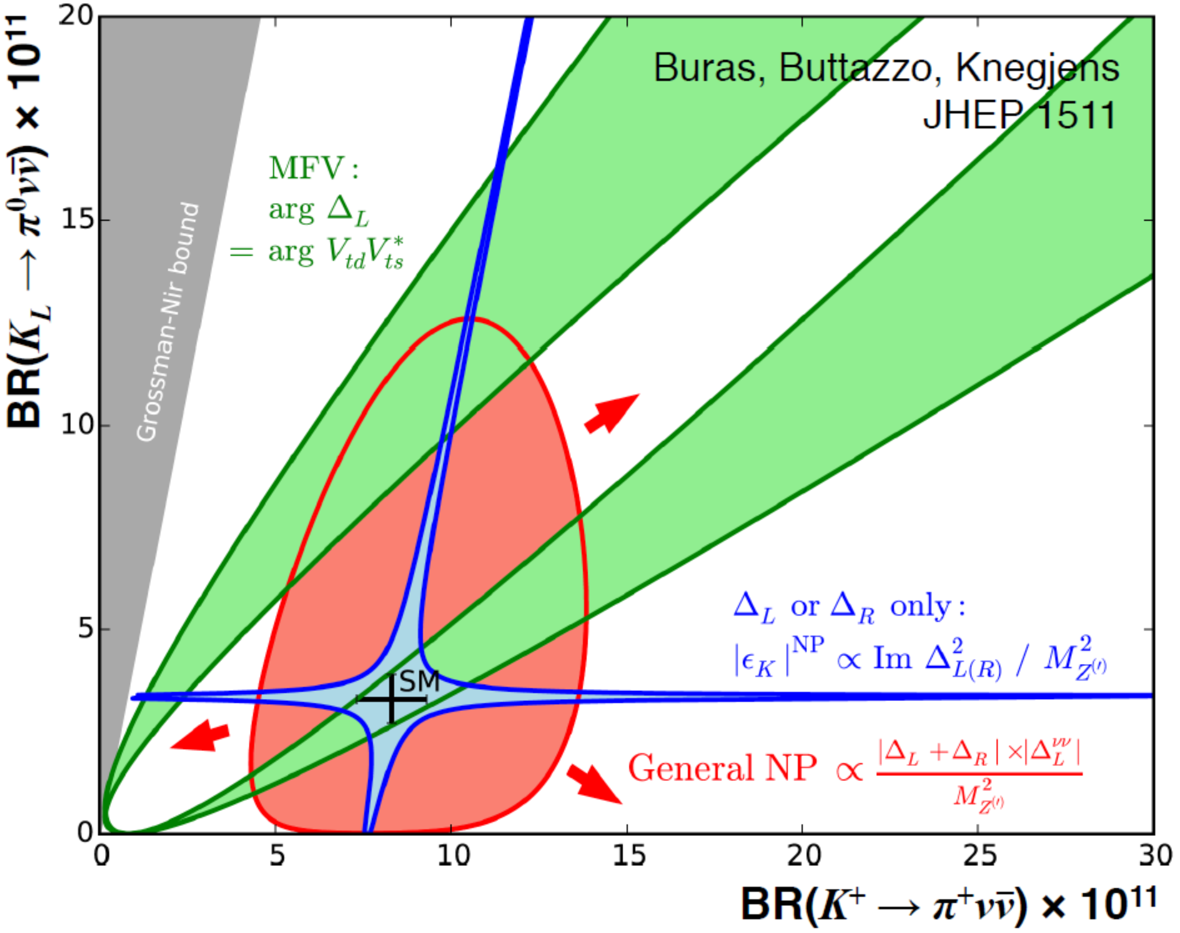
$BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{NA62(2016\text{-}18\ data)} = (10.60^{+4.1}_{-3.5}) \times 10^{-11}$

[JHEP 06 (2021) 093]



$K^+ \to \pi^+\upsilon\bar{\upsilon}$ and New Physics

Measurement of charged ($K^+ \to \pi^+\upsilon\bar{\upsilon}$) and neutral ($K_L \to \pi^0\upsilon\bar{\upsilon}$) modes can **discriminate among different NP scenarios**

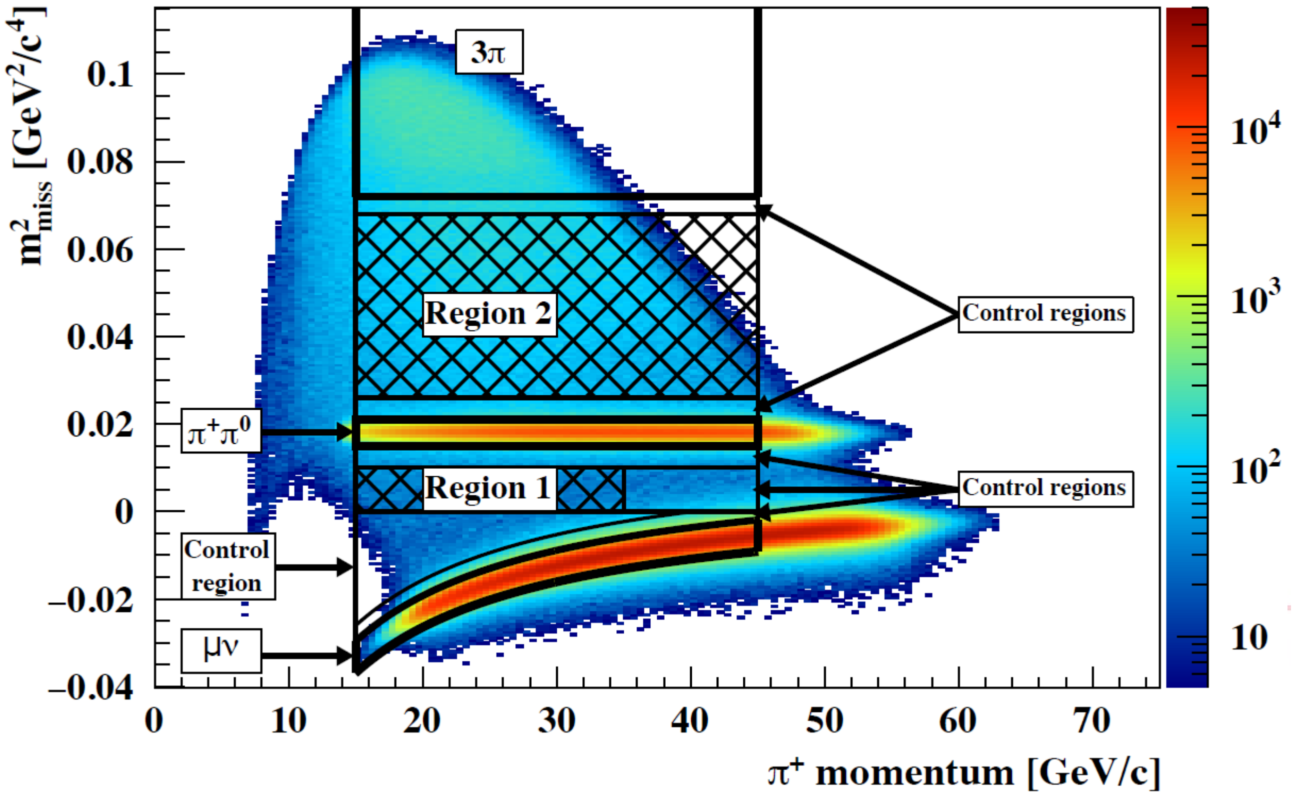


- Models with CKM-like flavor structure (Models with MFV)
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Custodial Randall-Sundrum
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- Simplified Z, Z' models
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity
  [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models
  [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks
  [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- MSSM analyses
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]

Analysis strategy

analysis key points:

- highly boosted decay ($\gamma \sim 150$)
- Large undetectable missing energy (neutrinos)
- All energy from visible particles must be detected
- Hermetic detector coverage
- 2 signal regions in m^2_{miss}
- $15 < P_{\pi^+} < 45$ GeV/c
- 60 m long decay region



Performance:

- 10^{-3} GeV^2/c^4 m^2_{miss} resolution
- $> 10^4$ kinematic background suppression
- $> 10^8$ Muon suppression
- $> 10^8$ π^0 (from $K^+ \rightarrow \pi^+\pi^0$) suppression
- O(100 ps) timing between sub-detectors

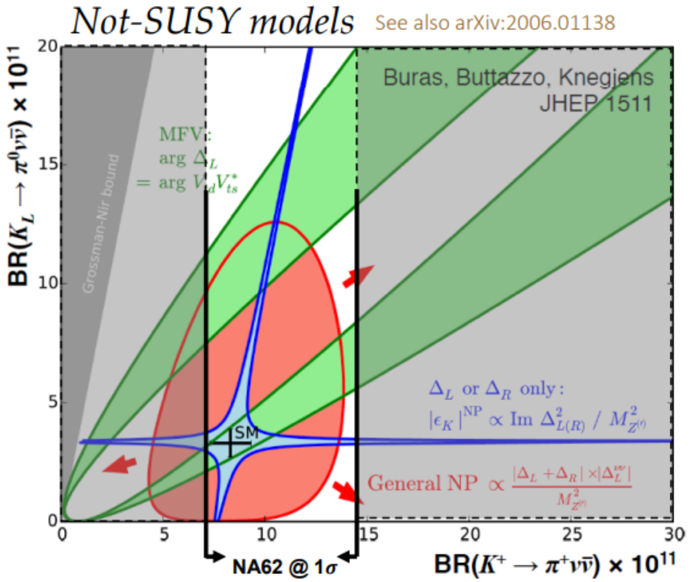
Process	*Branching ratio*
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	0.2067
$K^+ \rightarrow \mu^+\nu(\gamma)$	0.6356
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.0558
$K^+ \rightarrow \pi^+\pi^-e^+\nu$	$4.25 \cdot 10^{-5}$

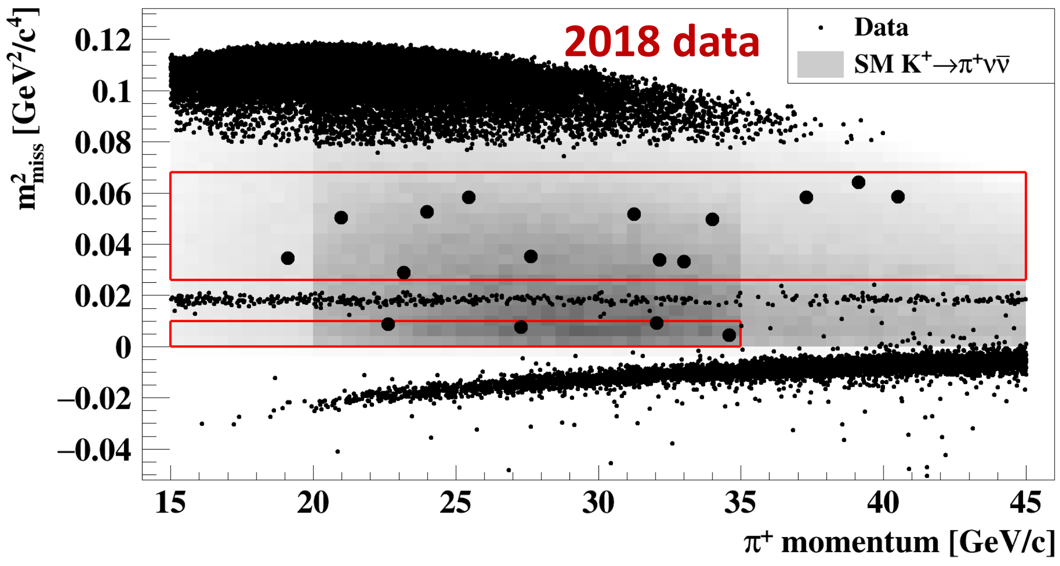
$K^+ \rightarrow \pi^+\nu\bar{\nu}$: RUN1 result (2016 -2018)

[JHEP 06(2021) 093]

Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

$N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes: $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$



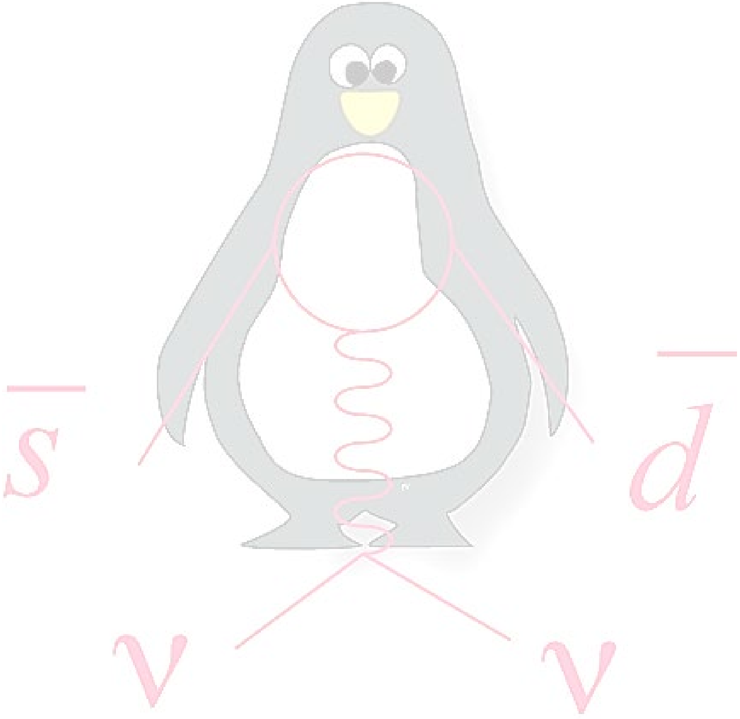


Statistical combination:

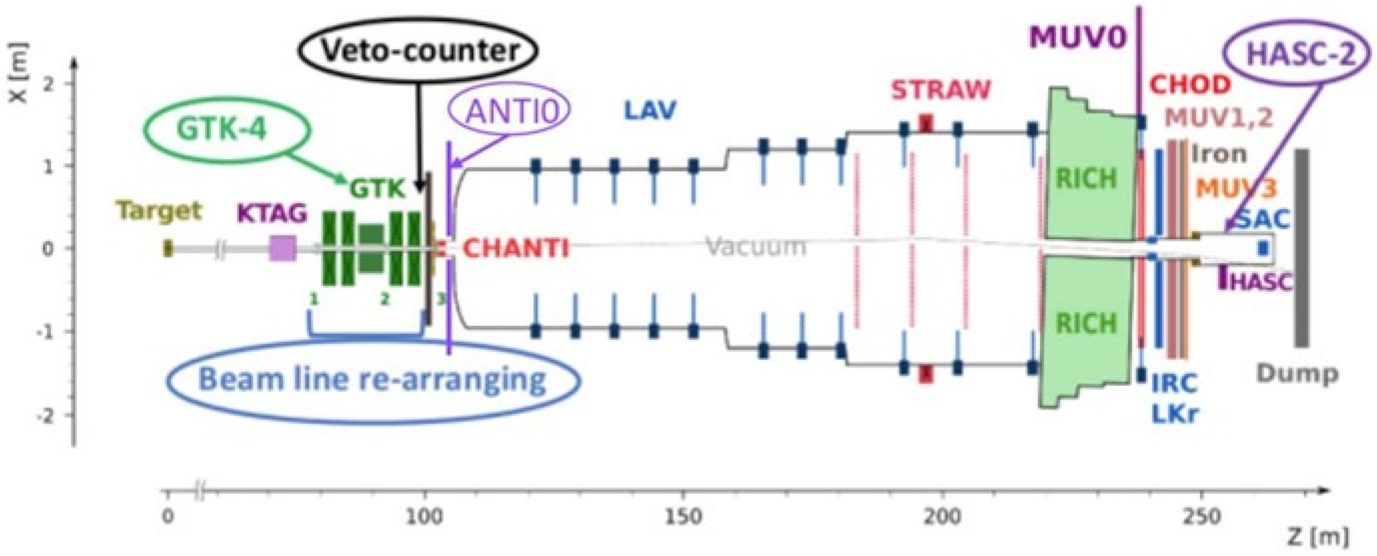
$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\%\ CL$$

Background-only hypothesis: $p = 3.4 \times 10^{-4} \Rightarrow$ significance = 3.4σ

RUN2 Upgrades



Improvements for RUN2



Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^-e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

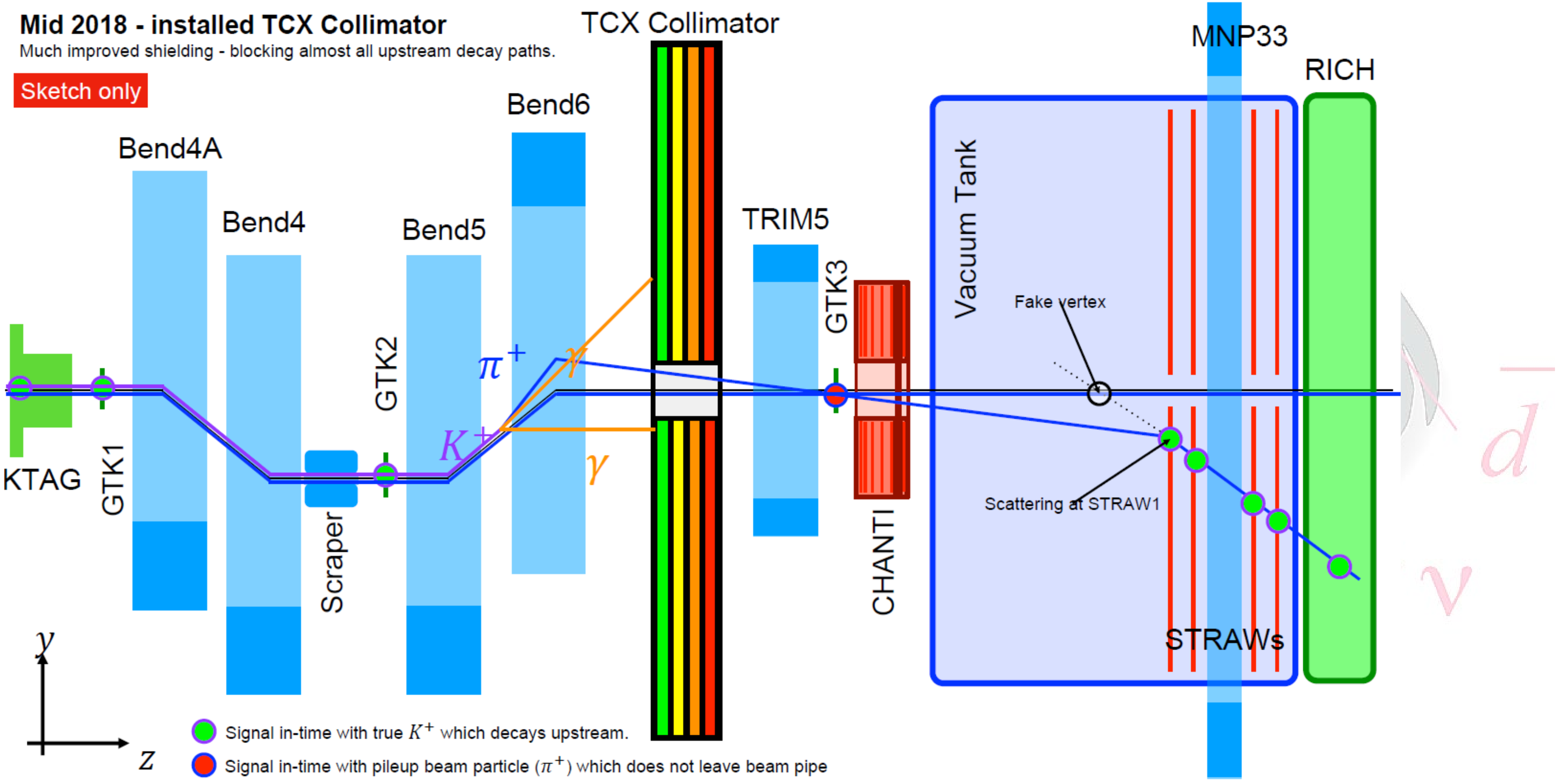
Largest backgrounds:
1. Upstream
2. Decay $K^+ \to \pi^+\pi^0$

- **New GTK station:** GTK4
- **PID improved:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ-detector) ⟶ random veto and acceptance
- **New vetoes:** upstream (VetoCounter, ANTI0) and downstream HASC2
- **New collimator**
- **New L0 Trigger Processor:** L0TP+
- **New L1 trigger algorithms:** STRAW and LAV

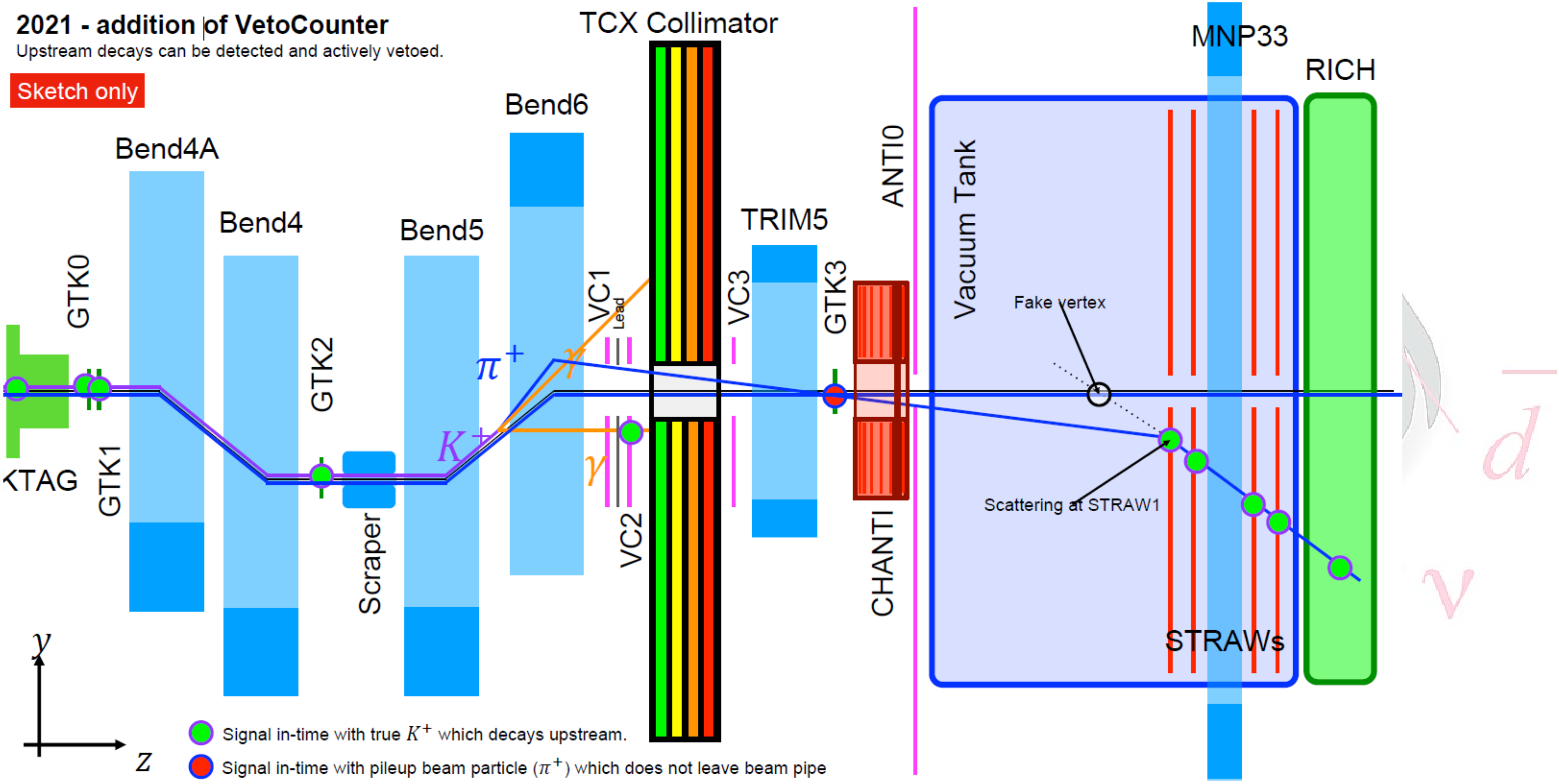
⟹
- trigger efficiency
- Bandwidth exploitation

Then:
- **Intensity increased** by ~35% with respect to 2018 [450 → 600 MHz].
- Improvements to the **trigger configuration.**

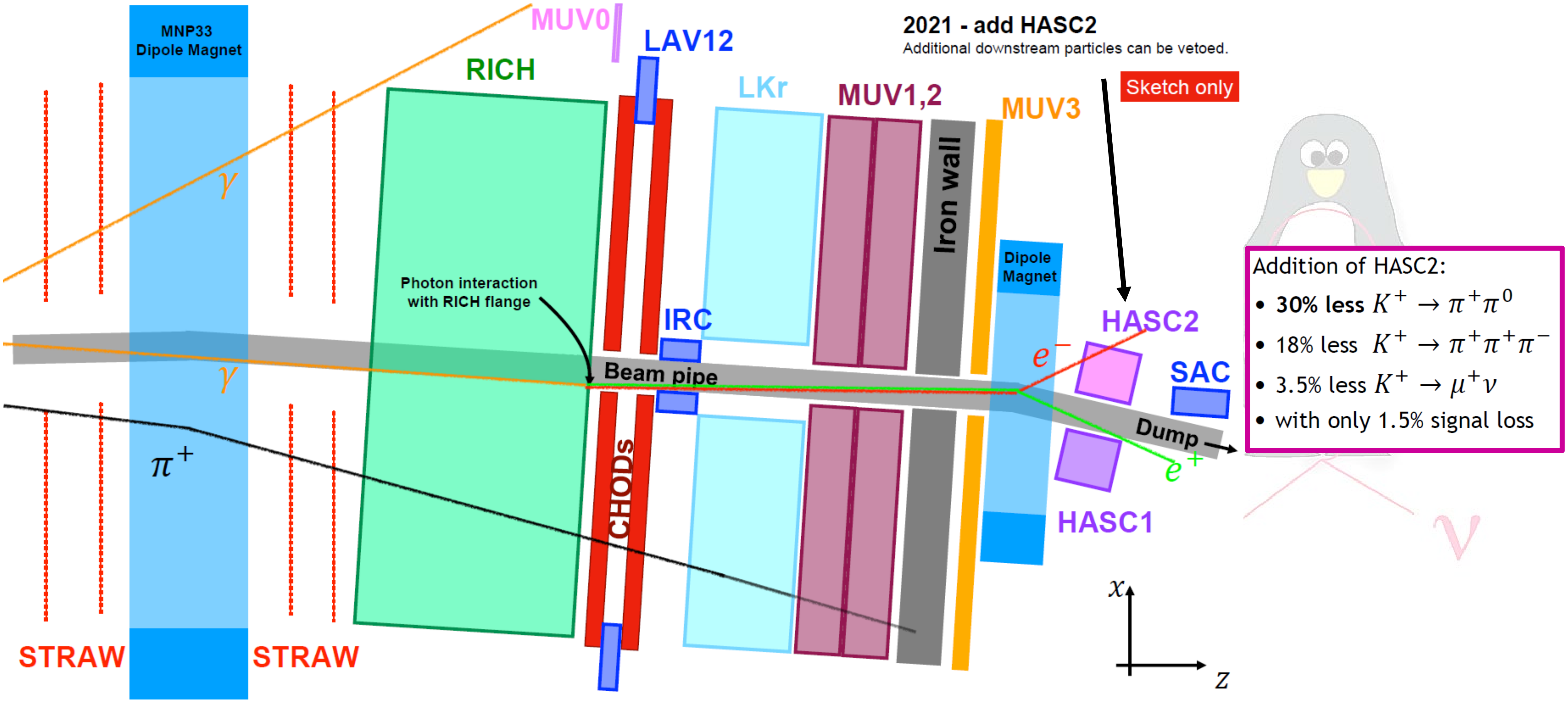
new collimator



New Upstream Vetoes



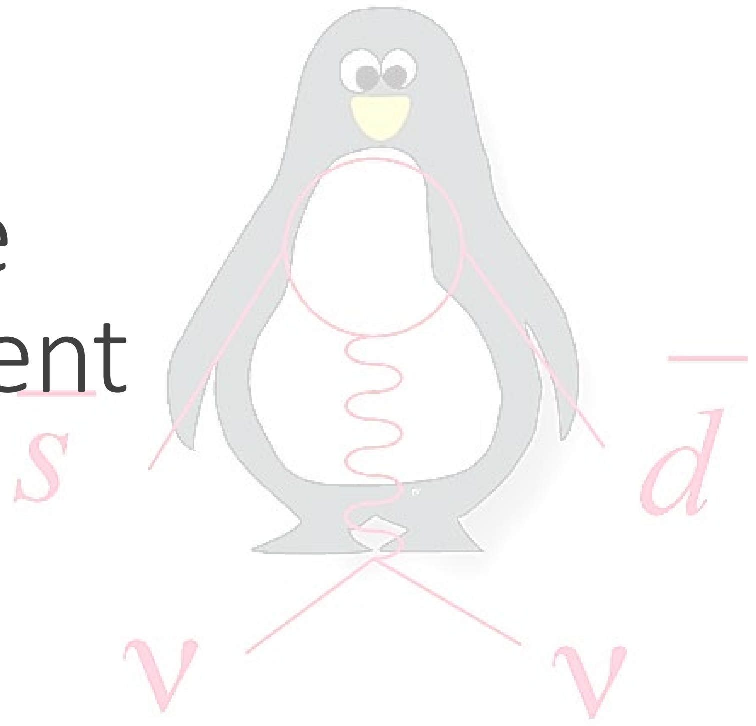
New donwstream Veto



Addition of HASC2:

- **30% less $K^+ \to \pi^+\pi^0$**
- 18% less $K^+ \to \pi^+\pi^+\pi^-$
- 3.5% less $K^+ \to \mu^+\nu$
- with only 1.5% signal loss

Last updates about the $K^+ \to \pi^+\upsilon\bar{\upsilon}$ measurement



Data 2021-22: single event sensitivity

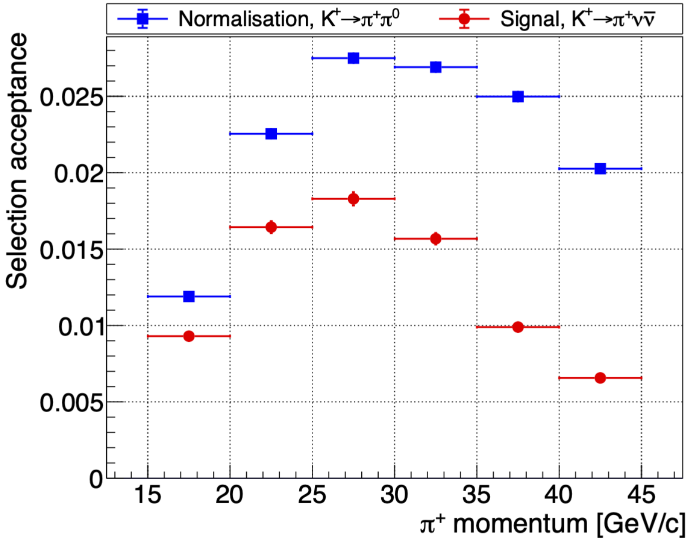
$$N_{\pi\nu\nu}^{SM,exp} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \boxed{\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}} (N_{\pi\pi}\times D_0)\boxed{\varepsilon_{trig}}\boxed{\varepsilon_{RV}}$$

$N_{\pi\pi}$	Normalisation $K^+ \to \pi^+\pi^0$	2.0×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	2.9×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.6 \pm 0.2)\%$
ε_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.6 \pm 0.6)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$

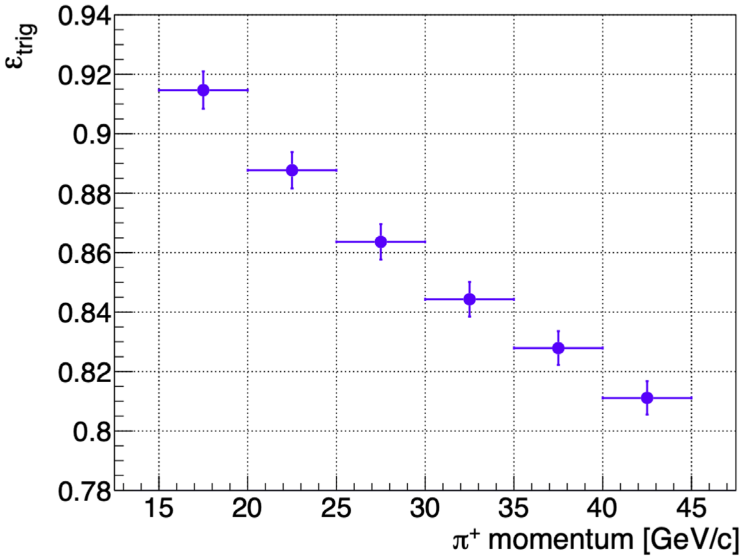
Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

2021-22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$

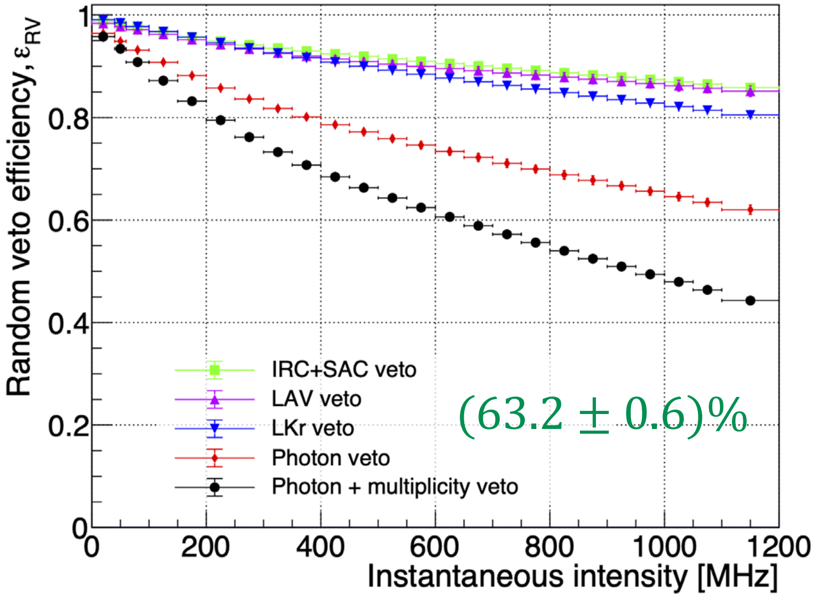
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$



Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	**+15%**
Signal	(6.37±0.64)%	(7.62±0.22)%	**+20%**

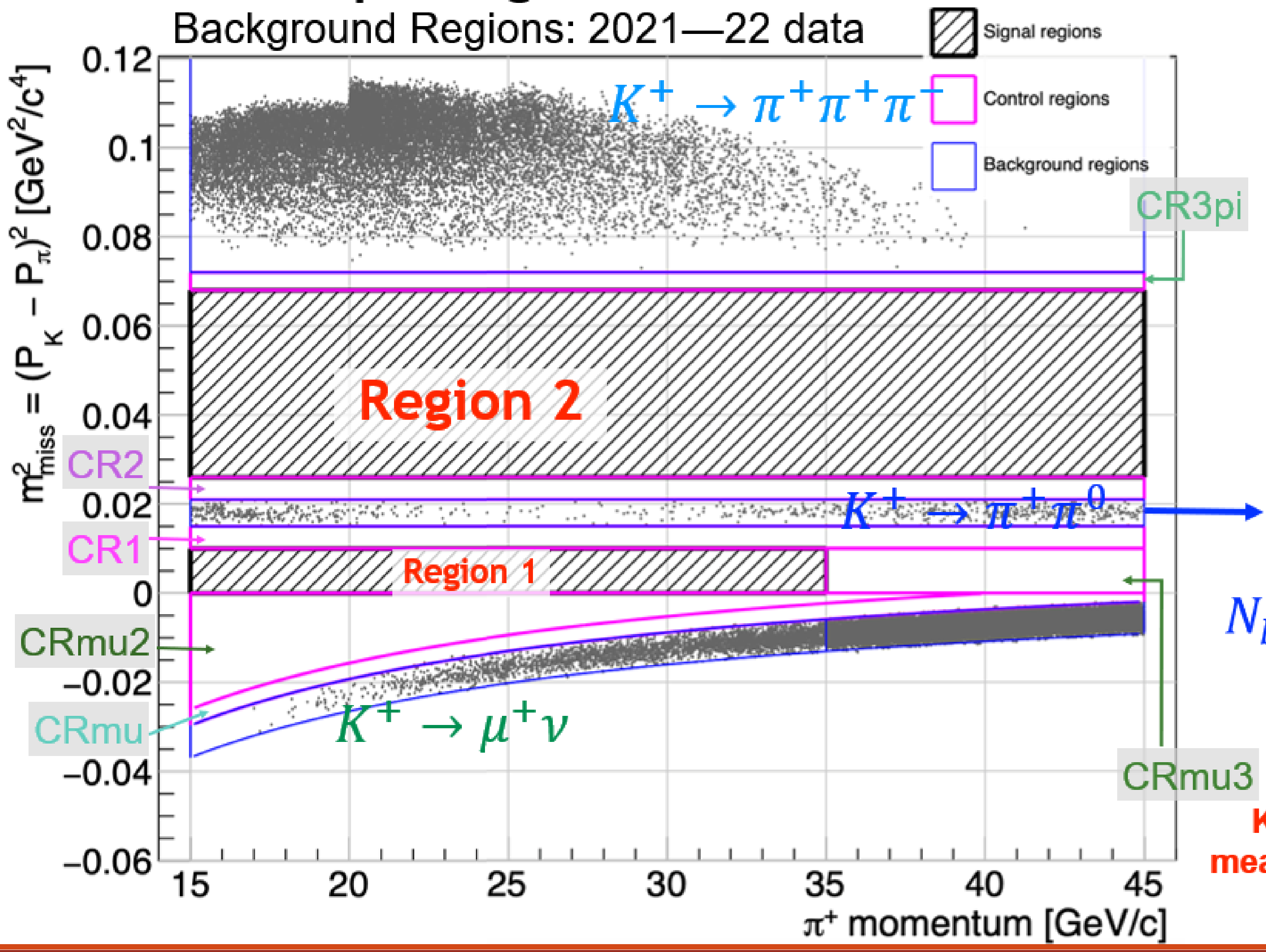


$\varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$



Background regions

Events passing $\pi\nu\nu$ selection



Backgrounds from kinematic misreconstruction tails in m^2_{miss}

Number of events passing signal selection in background region

Control sample events in Signal Regions

$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

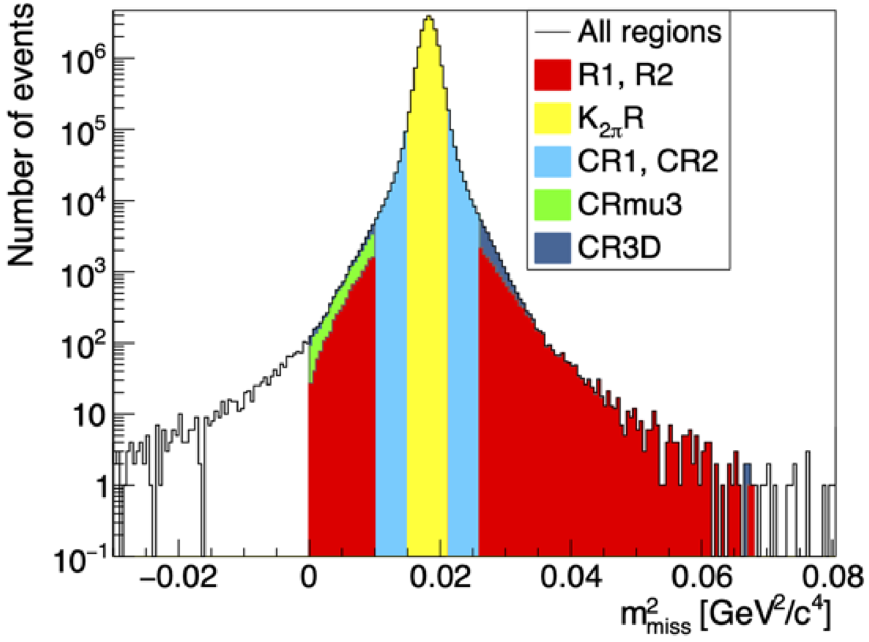
Kinematic tail fraction: measured in control sample

Control sample events in Background Region

Backgrounds from kinematic tails

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

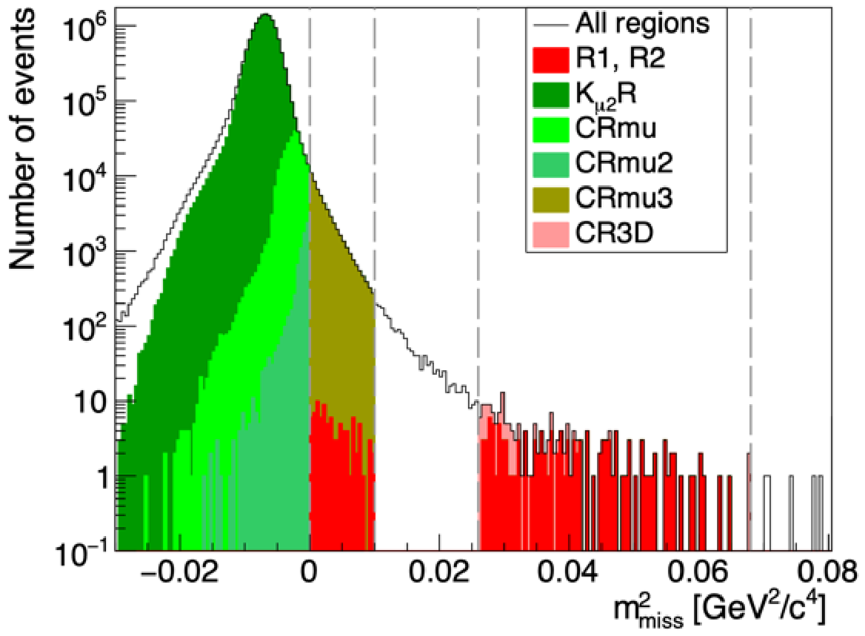
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \to \pi^+\pi^0) = 0.76 \pm 0.04$$

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

control sample of $K^+ \to \mu^+\nu$ events with RICH PID=π^+ and Calo PID=μ^+:



- <1% contribution from $K^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\nu$

$$N_{bg}(K^+ \to \mu^+\nu) = 0.87 \pm 0.19$$

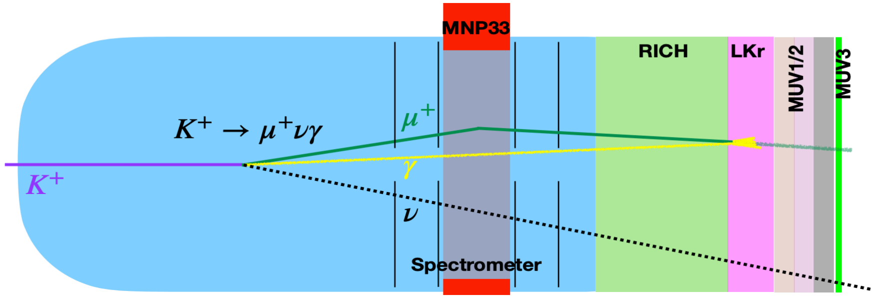
$K^+ \to \pi^+\pi^+\pi^-$

- Use MC to measure f_{tail}:

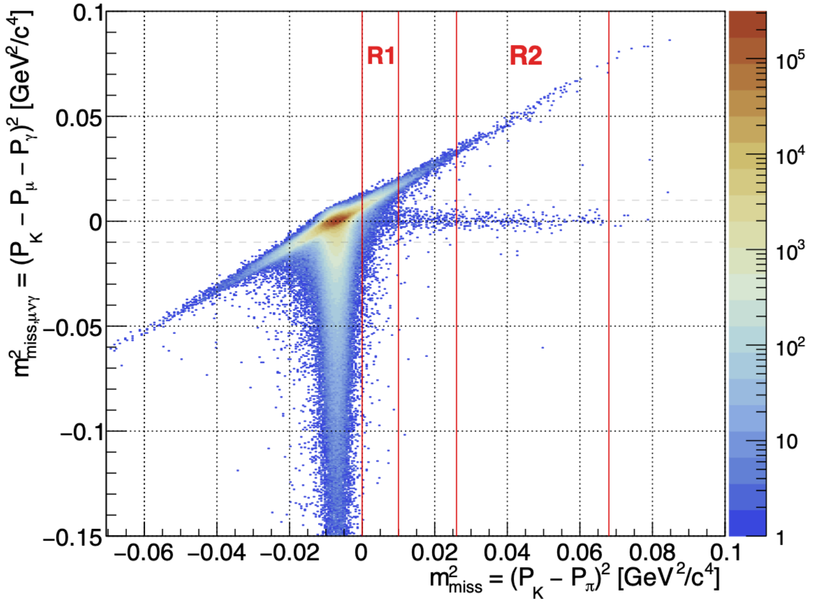
$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

Radiative decays: $K^+ \to \pi^+\pi^0\gamma$ & $K^+ \to \mu^+\nu\gamma$

- $K^+ \to \pi^+\pi^0\gamma$: **not included in "kinematic tails" estimation if the radiative photon is detected in LAV, LKr, IRC or SAC.**
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: tails from MC + measured single photon rejection efficiency : $N_{bg}(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$
  - Validation: m^2_{miss} control regions (CR1,2)
- $K^+ \to \mu^+\nu\gamma$: **not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr, leading to misID as π^+**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
    - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
  - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.82 \pm 0.43$
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π^+ bin).



- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35 GeV/c$ in Region 2 relative to 2016—18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.



Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N	Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)
f_{cda}	Scaling factor : bad cda —> good cda
P_{match}	Probability to pass $K+ - \pi+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

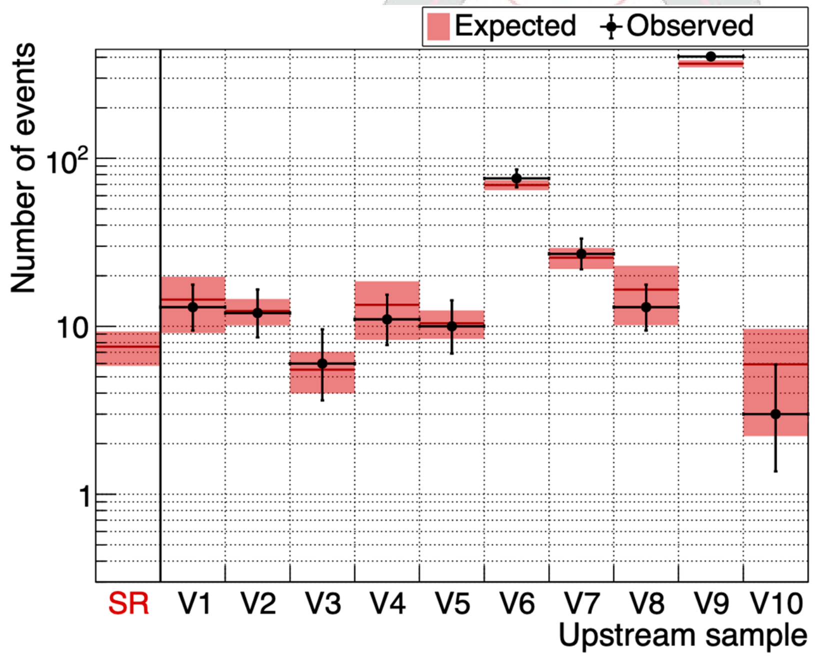
$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73\%$

$$\boxed{N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}}$$

- **Upstream reference sample contains all known upstream mechanisms.**
- N provides normalisation.
- f_{CDA} **depends only on geometry.**
- P_{match} **depends on** $(\Delta T_+, N_{GTK})$.

VALIDATION SAMPLES:

invert & loosen upstream vetos to enrich with different mechanisms



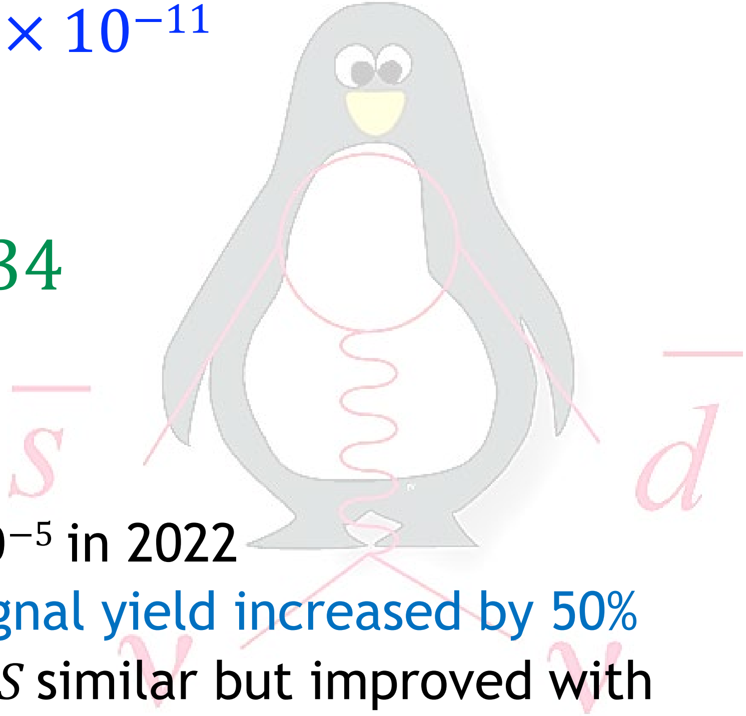
Summary of expectation

Backgrounds

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

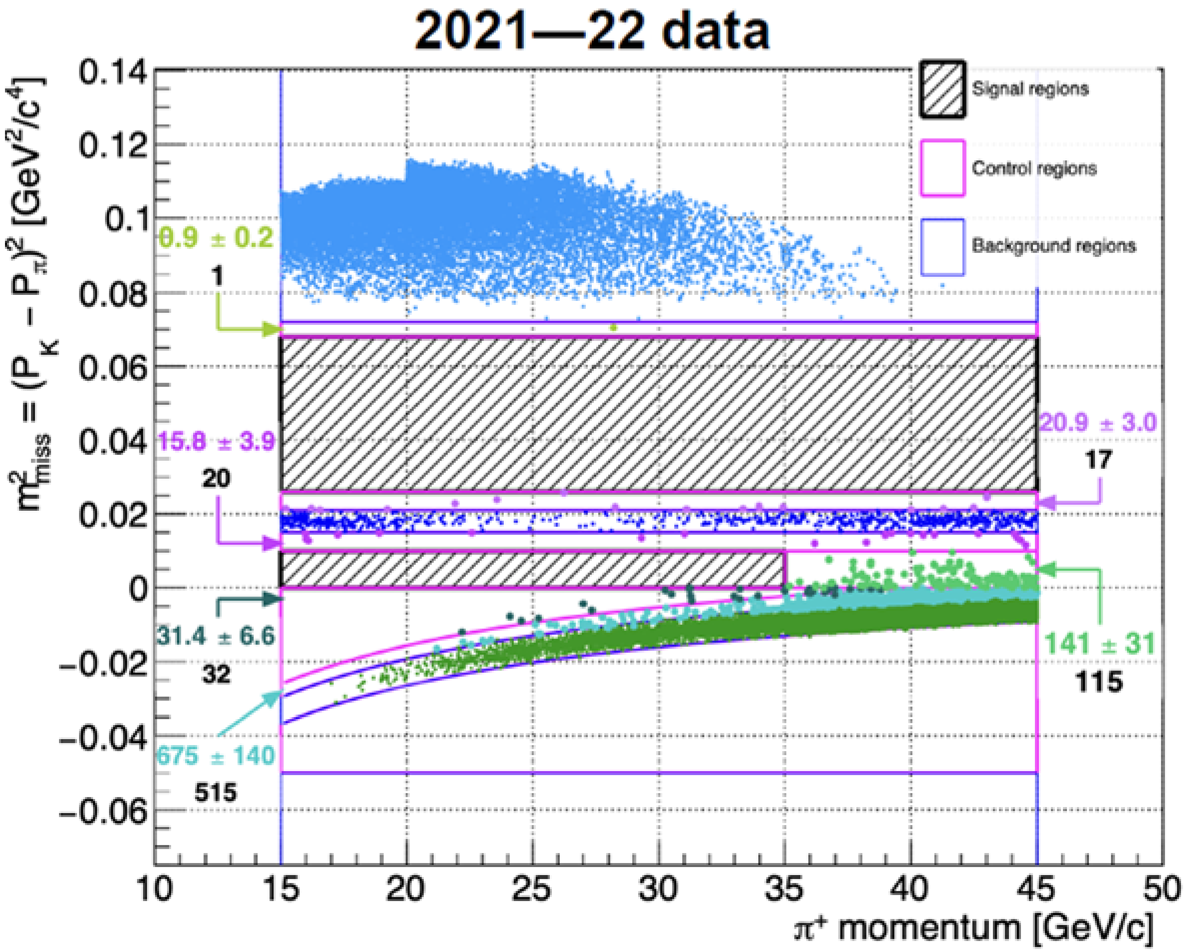
$$\mathcal{B}_{SES} = (0.848 \pm 0.029) \times 10^{-11}$$

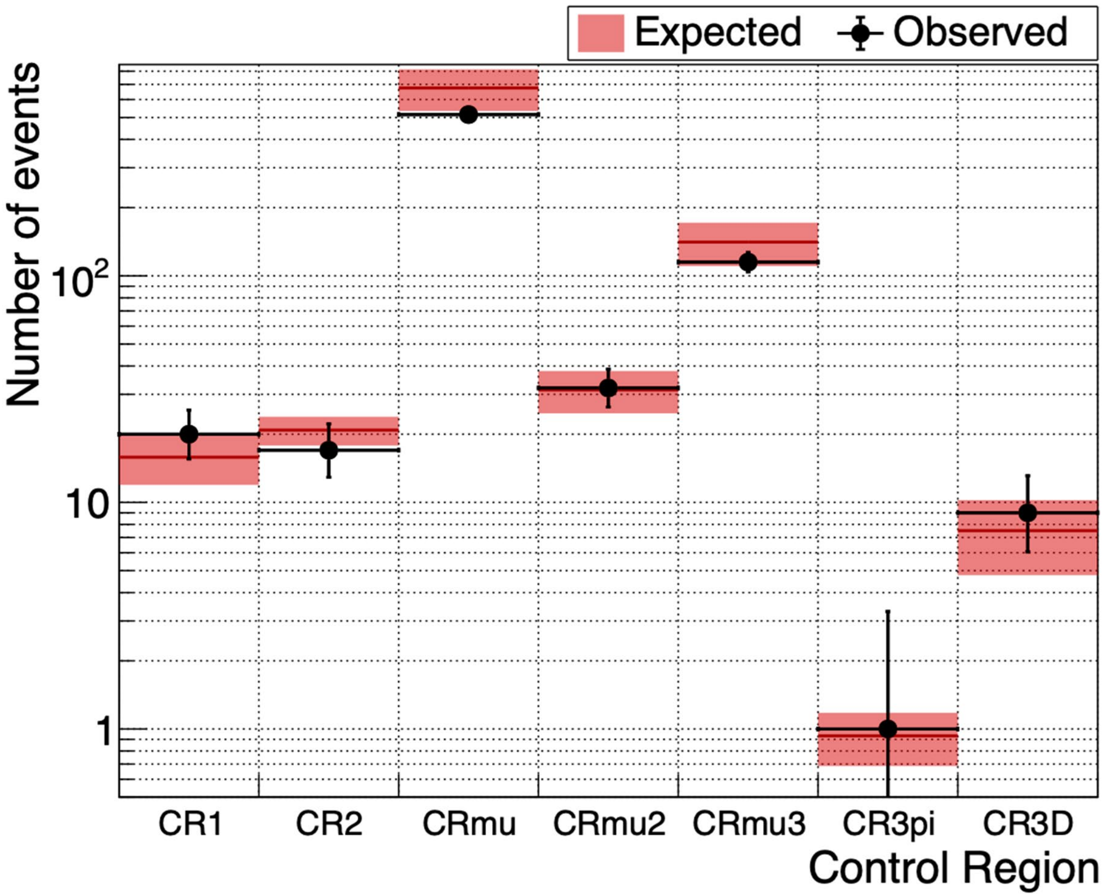
$$N_{\pi\nu\nu} = 9.91 \pm 0.34$$



- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS burst: 2.5×10^{-5} in 2022
- c.f. 1.7×10^{-5} in 2018. $\Rightarrow$ signal yield increased by 50%
- Sensitivity for BR $\sim \sqrt{S+B}/S$ similar but improved with respect to 2018 analysis, for same amount of data

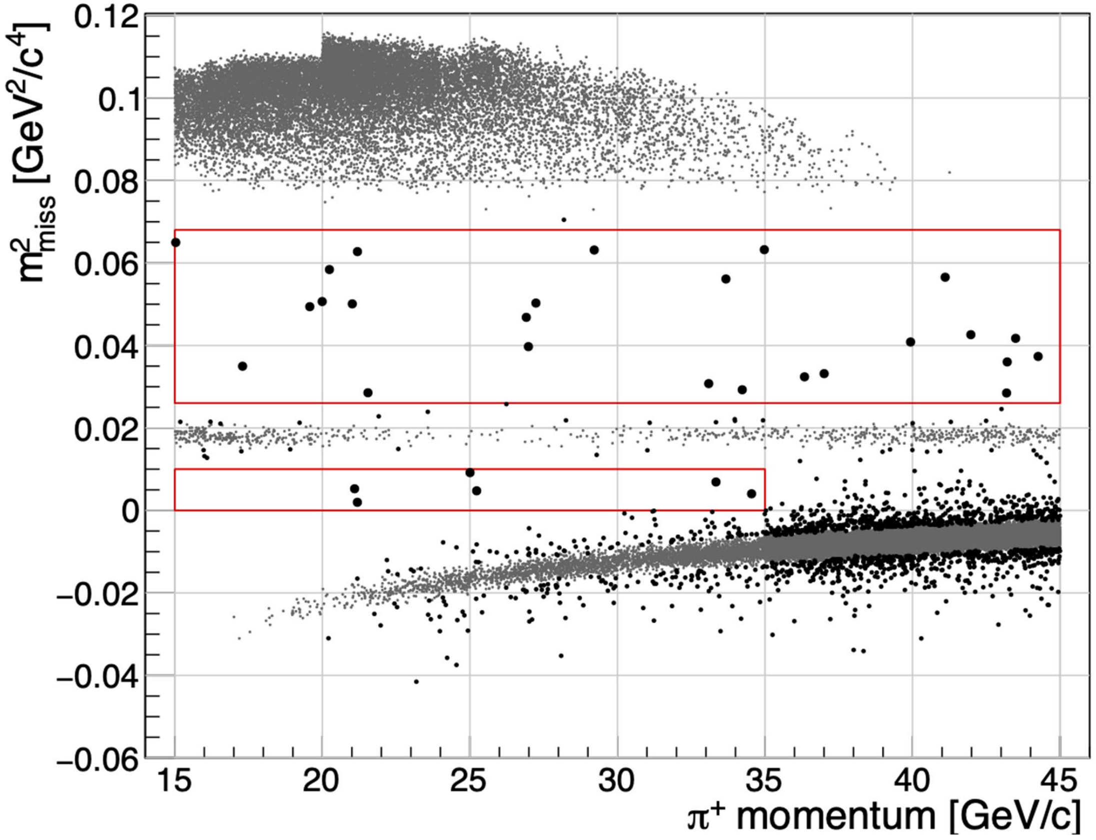
Control regions

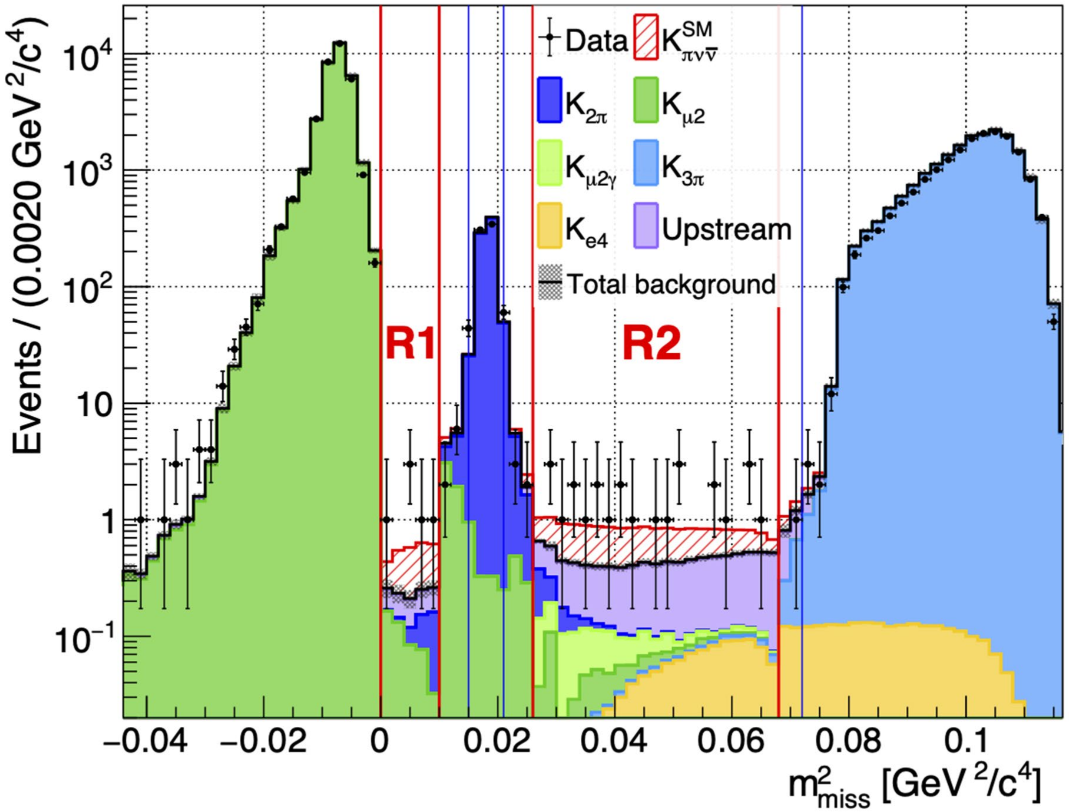




Good agreement in control regions validates background expectations

Result: events observed





Expected SM signal $N^{SM}_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$

Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed: N_{obs} = 31

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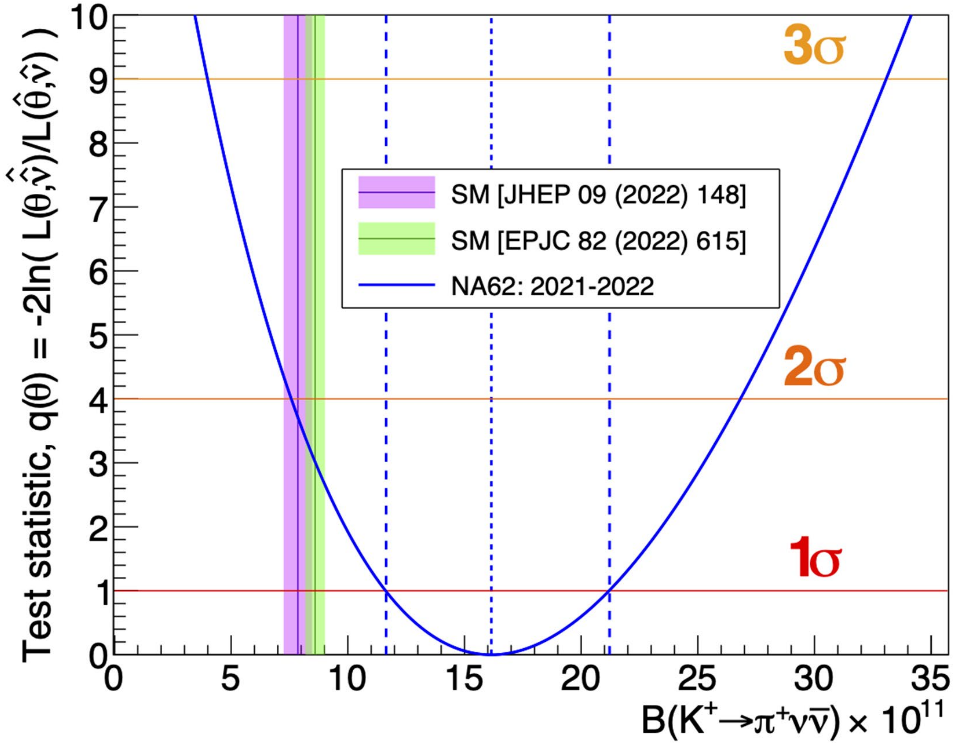
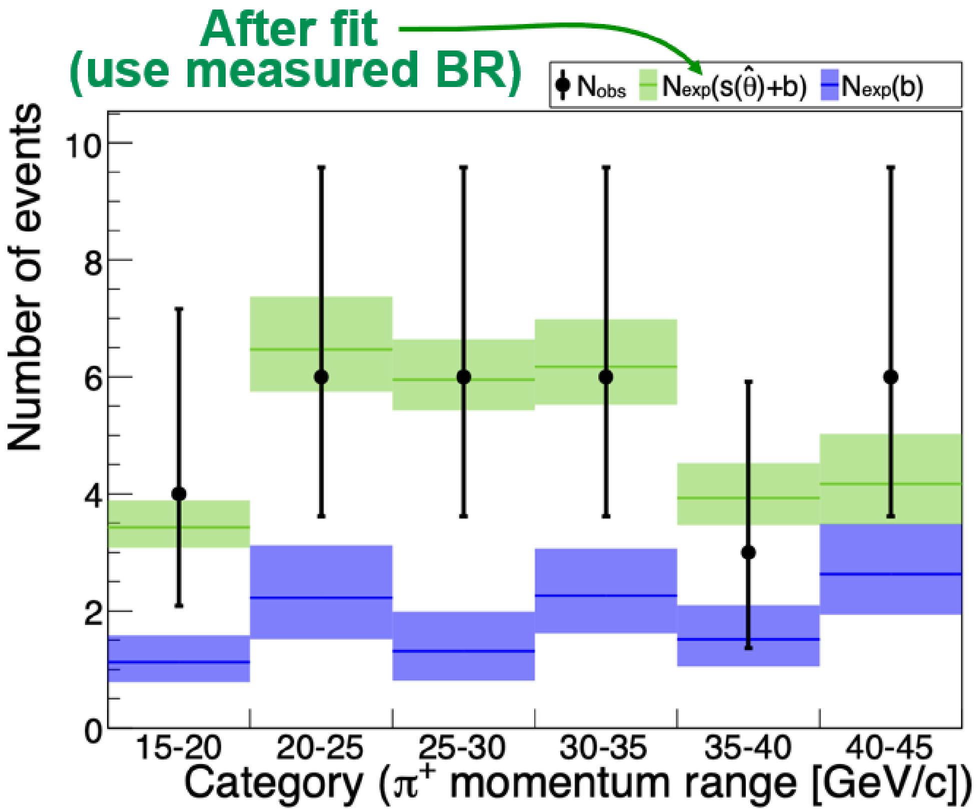
Result: 2021-22 Data

Measure $\mathcal{B}_{\pi\nu\nu}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$



6 (momentum bin) categories



$$\mathcal{B}_{21-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11} = \left(16.2\ \left({}^{+4.9}_{-4.3}\right)_{stat}\ \left({}^{+1.4}_{-1.4}\right)_{syst}\right) \times 10^{-11}$$

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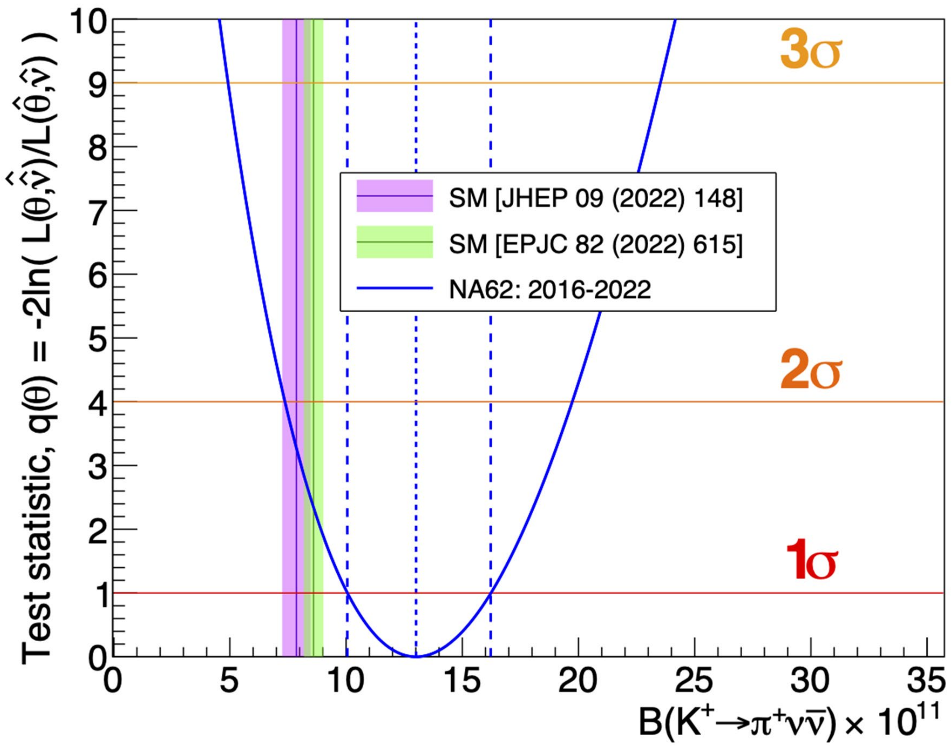
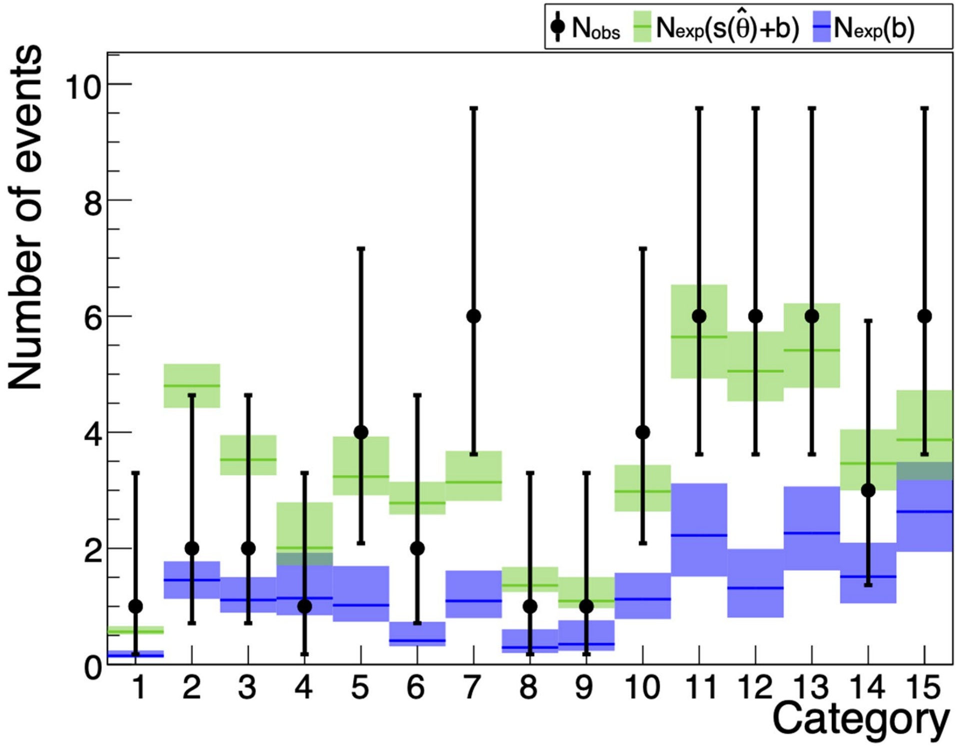
Combining NA62 results: 2016-22

Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$





$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.3})_{syst}) \times 10^{-11}$$

Background-only hypothesis p-value = 2×10^{-7} ⇨ significance $Z > 5$

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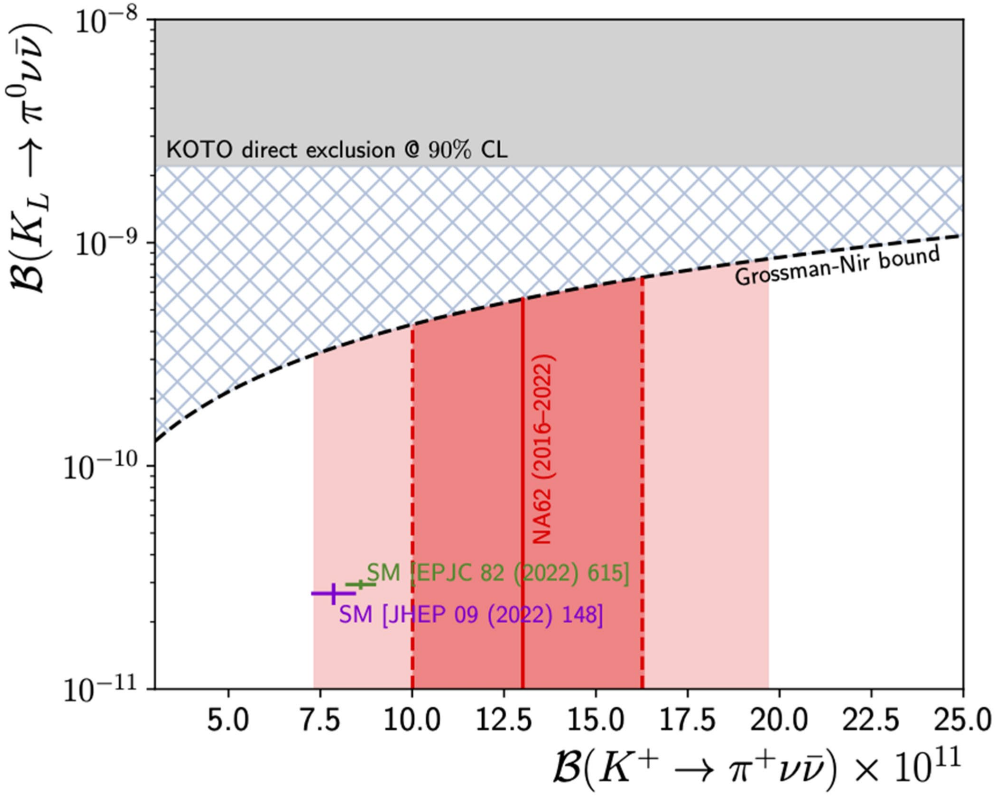
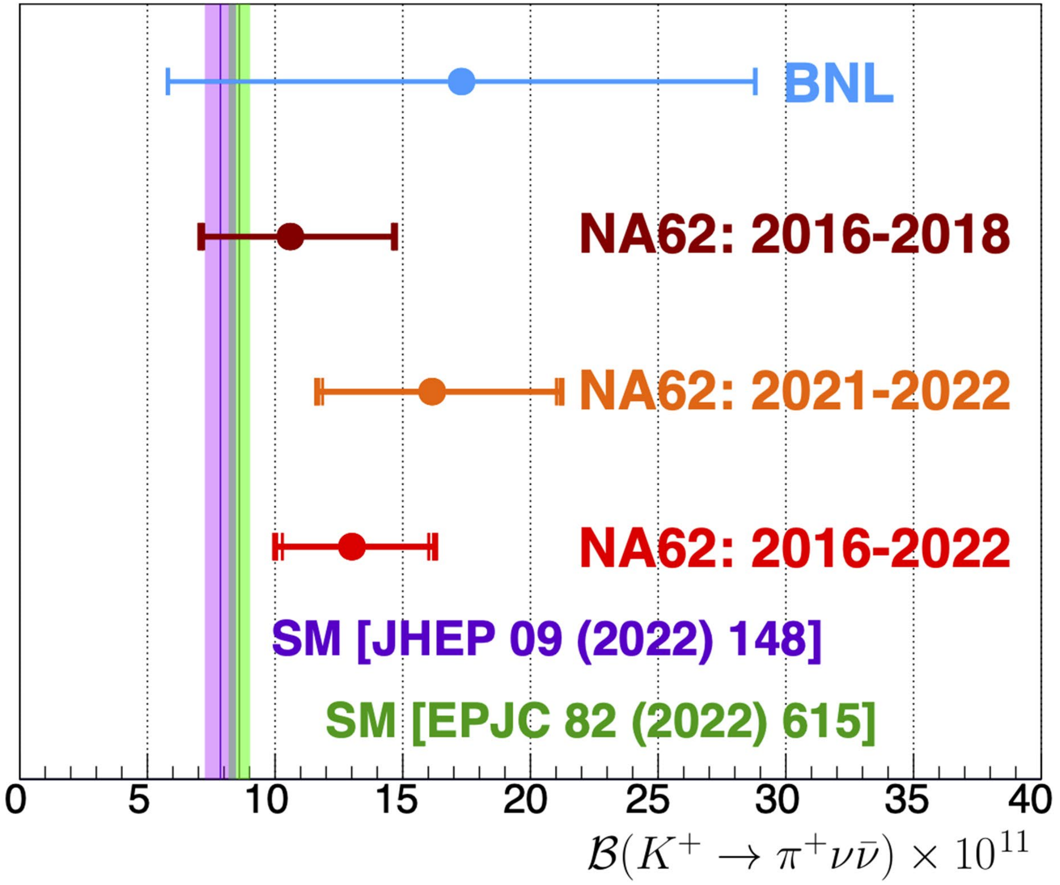
Results in context

- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: from 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5
- First observation of $K^+ \to \pi^+\nu\bar{\nu}$ decay





$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

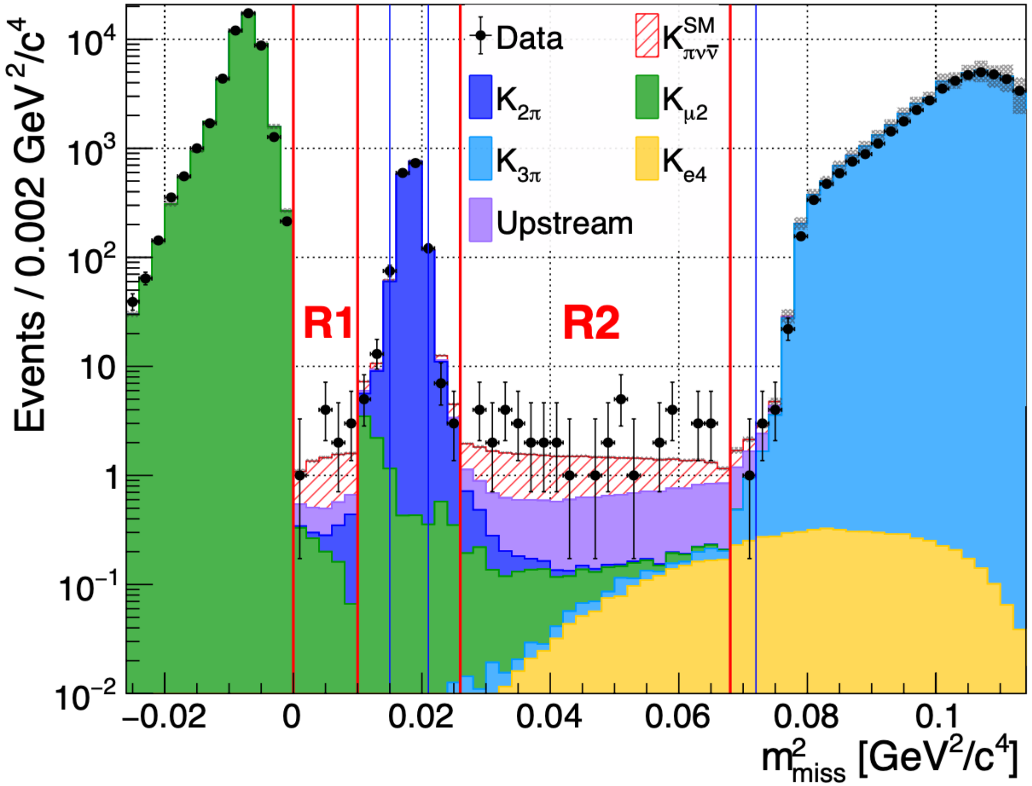
Need full NA62 data-set to clarify SM agreement or tension

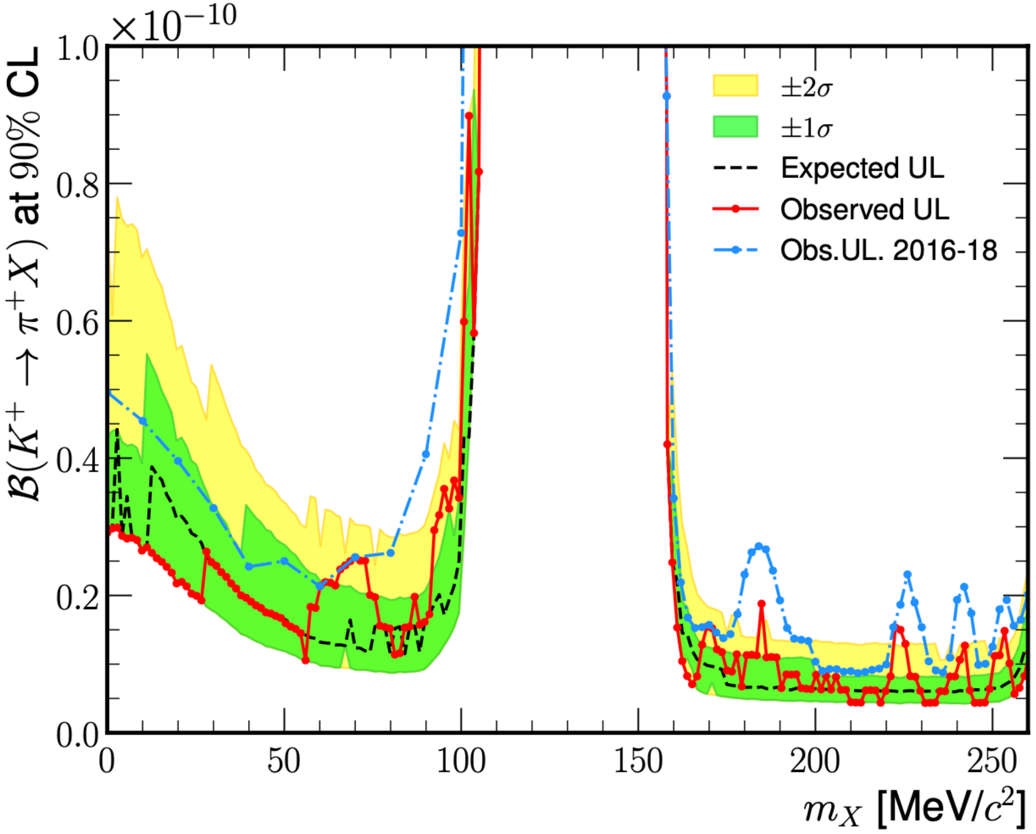
2023—LS3 data-set collection & analysis in progress...

$K^+ \to \pi^+ X$, with invisible X

arXiv:2507.17286

- Interpretation of $K^+ \to \pi^+ \nu\bar{\nu}$ result (2016–2022 data);
- Peak search: $K^+ \to \pi^+ \nu\bar{\nu}$ is the main background;
- The number of background events is estimated using SM branching ratio;
- m_X hypotheses separated by 1.4 MeV/c^2



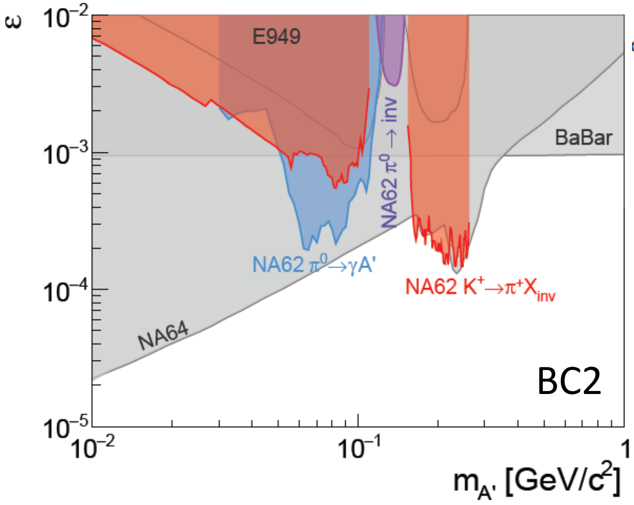


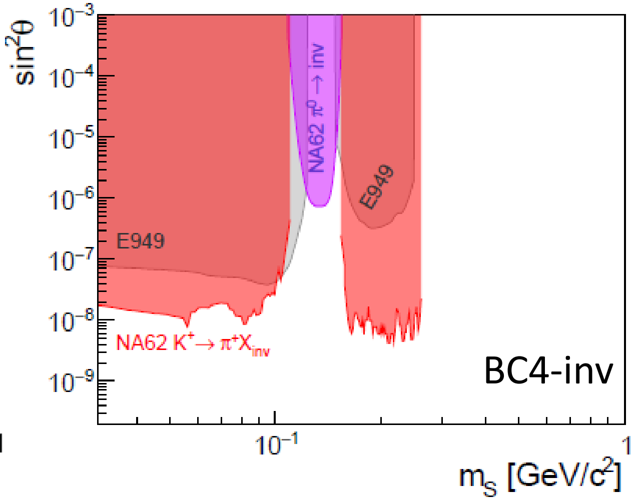
Model-independent constraints

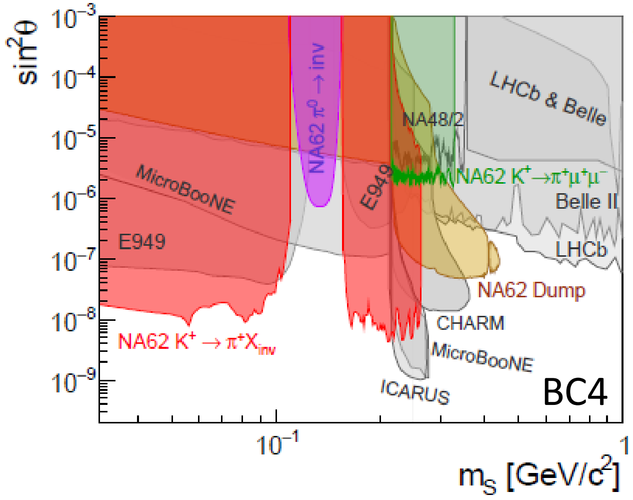
$K^+ \to \pi^+ X$, models interpretation

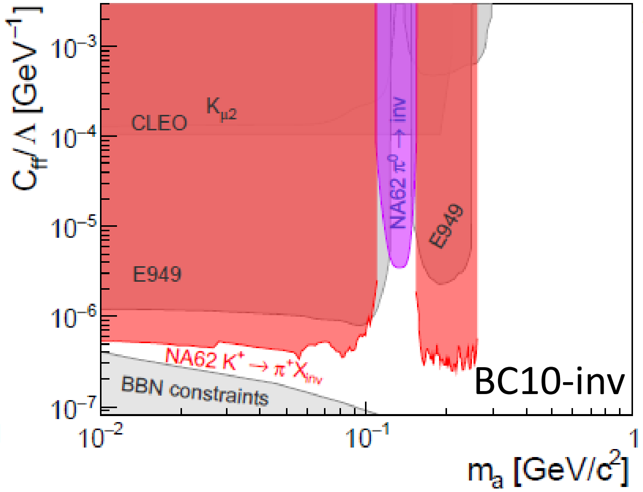
arXiv:2507.17286

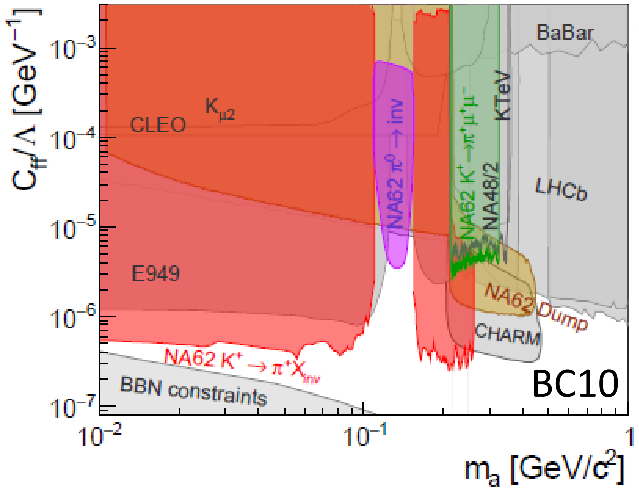
Benchmark	BSM particle (X)	Type	Coupling to SM	Search
BC2	dark photon (A')	vector	ε	invisible
BC4	dark scalar (S)	scalar	θ	invisible, $\mu^+\mu^-$
BC4-inv	dark scalar (S)	scalar	θ	invisible
BC10	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible, $\mu^+\mu^-$
BC10-inv	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible
BC11	axion-like particle (a)	pseudoscalar	C_{GG} (to gluons)	invisible, $\gamma\gamma$

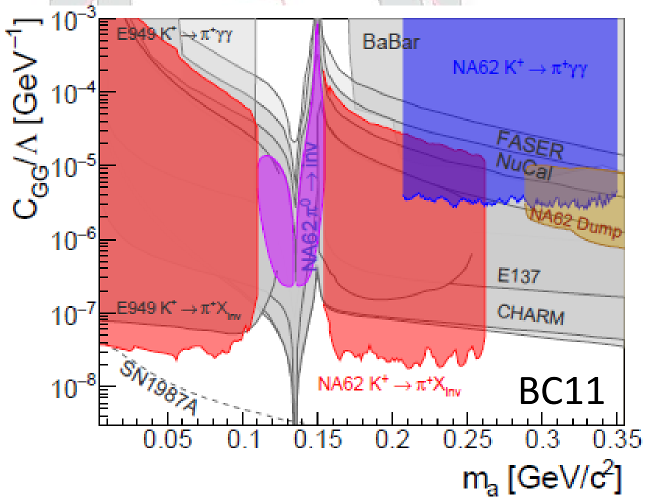






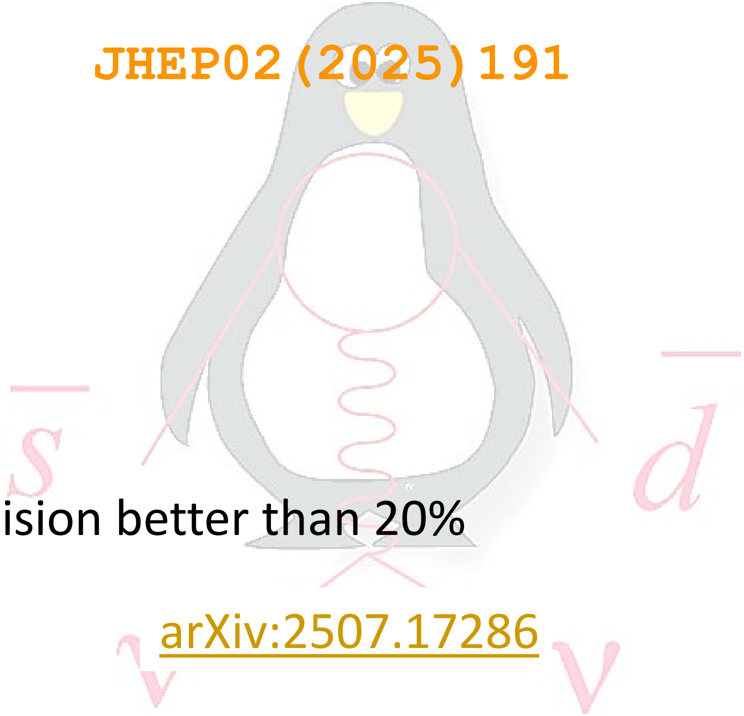






Conclusion

- Last study of $K^+ \rightarrow \pi^+\upsilon\bar{\upsilon}$ decay using NA62 2021—22 dataset:
  - Improved signal yield per SPS spill by 50%.
- Combined with 2016—18 data for full 2016—22 results:
  - $N_{bg} = 18^{+3}_{-2}$, N_{obs} = 51
  - $BR^{16-22}_{\pi\upsilon\bar{\upsilon}} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5
  - 25% relative precision achieved
- Need full NA62 data-set to clarify SM agreement or tension
  - 2023—LS3 data-set collection & analysis in progress, to achieve precision better than 20%
- Search in the hidden sectors using $K^+ \rightarrow \pi^+X$ decay
  - Interpretation of $K^+ \rightarrow \pi^+\upsilon\bar{\upsilon}$ result (2016–2022 data)



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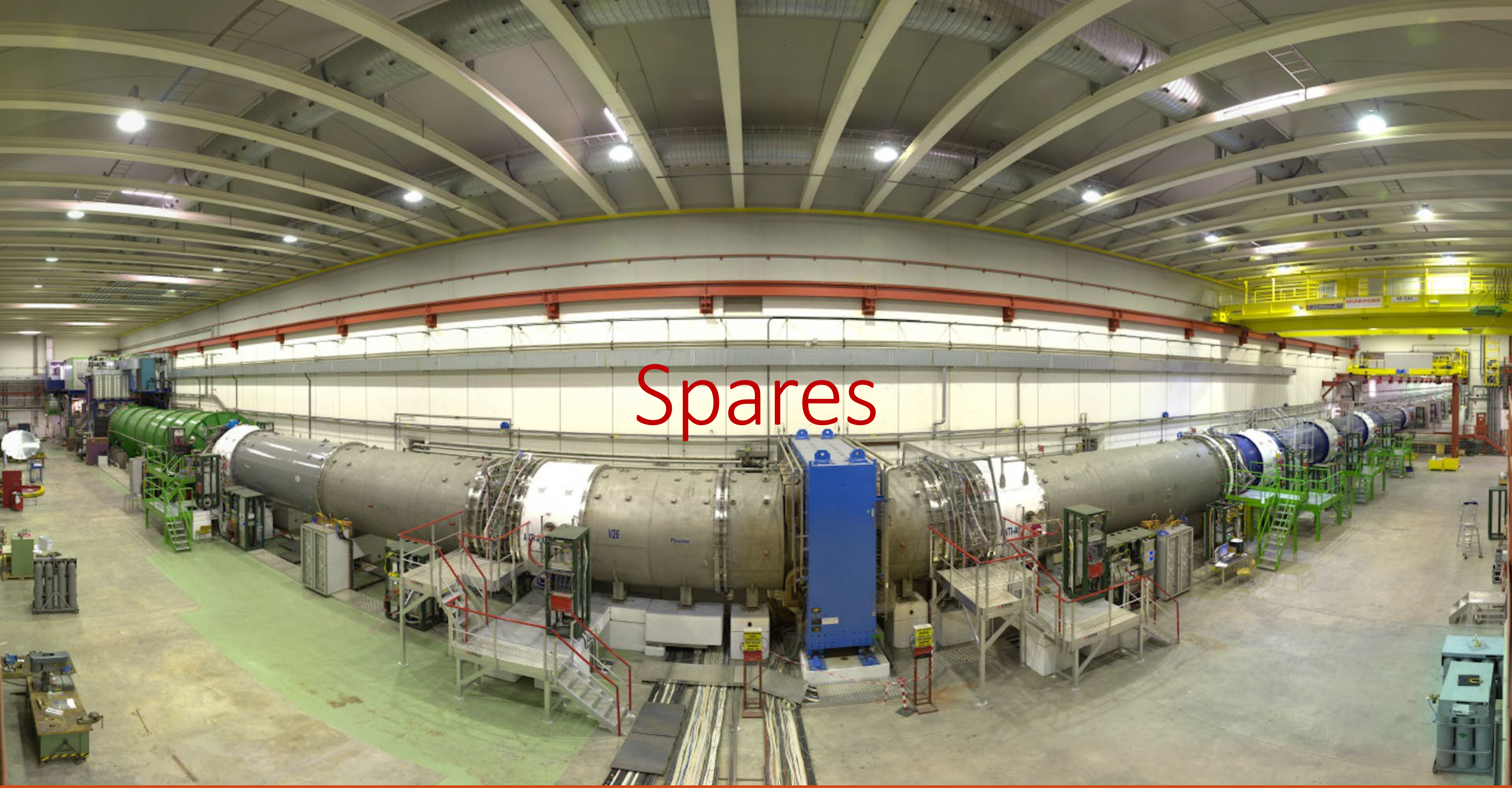
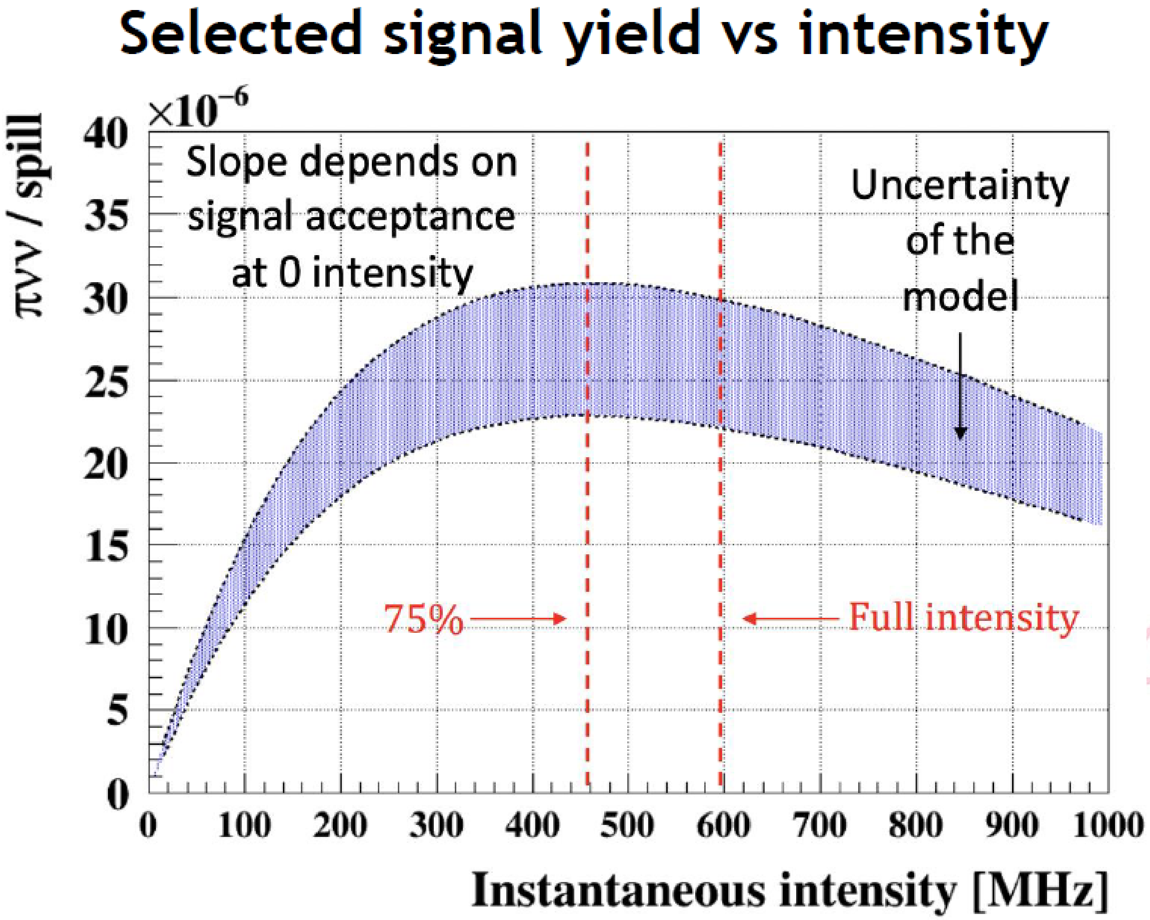


Spares

Optimum NA62 intensity

- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From August 2023 operate at optimal intensity** (~75% of full) to maximise $\pi\nu\nu$ sensitivity
  - Maximise signal yield
  - lower expected background
  - Higher DAQ efficiency

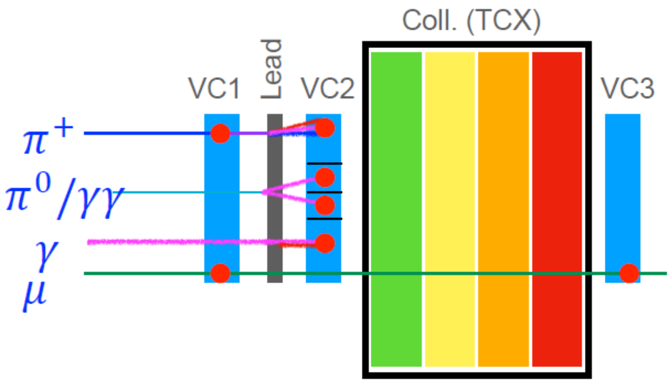


Studies of **2021 - 22 data** at high intensity **were crucial** to establish optimal intensity

New upstream vetos: VetoCounter & ANTI0

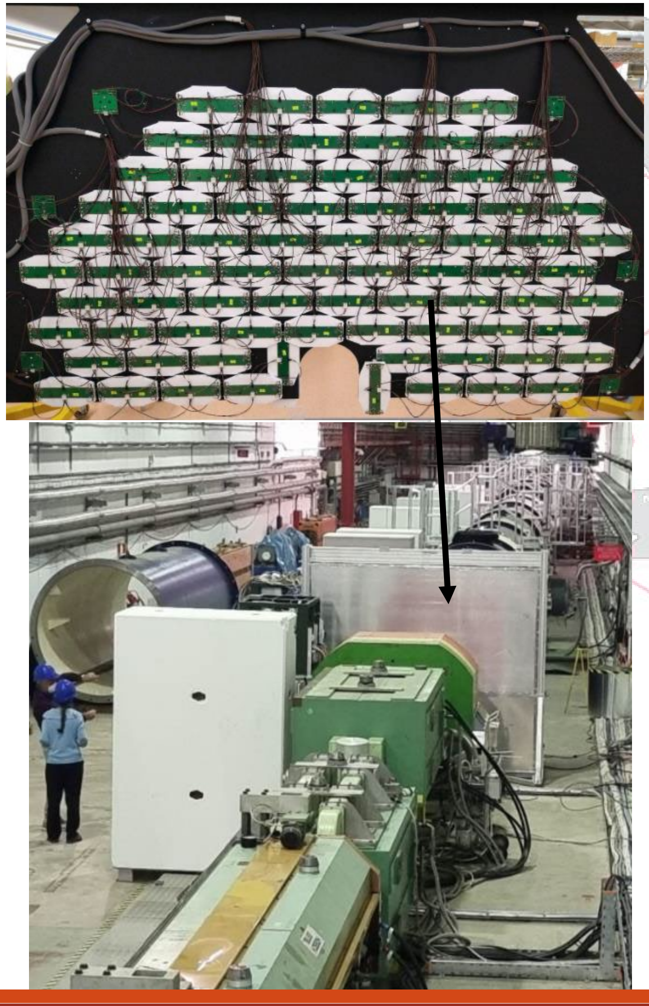
VetoCounter

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



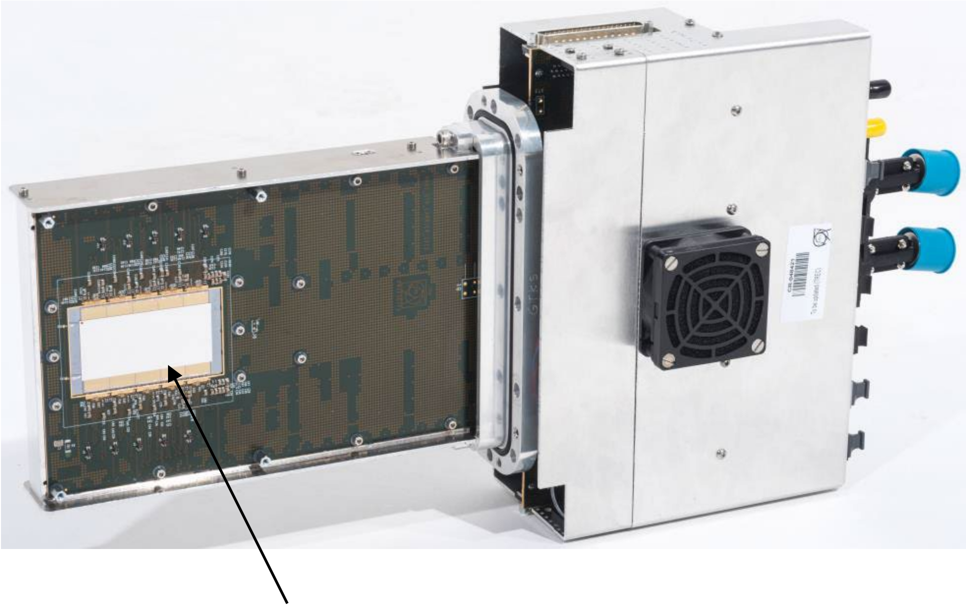
ANTI0

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

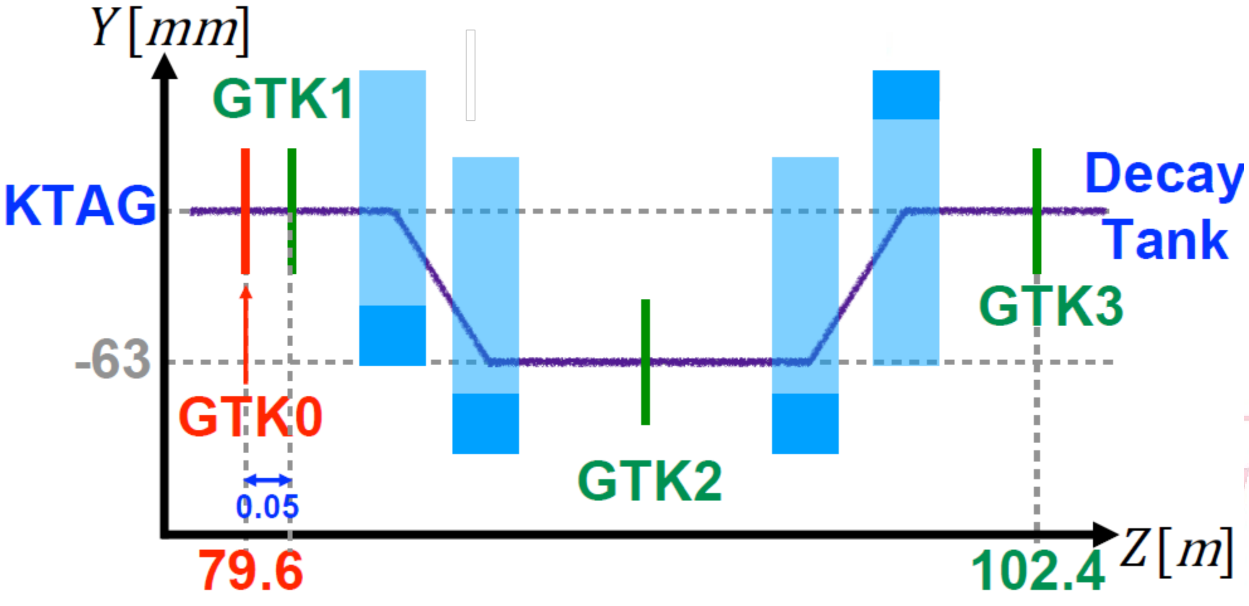


4^{th} GTK station

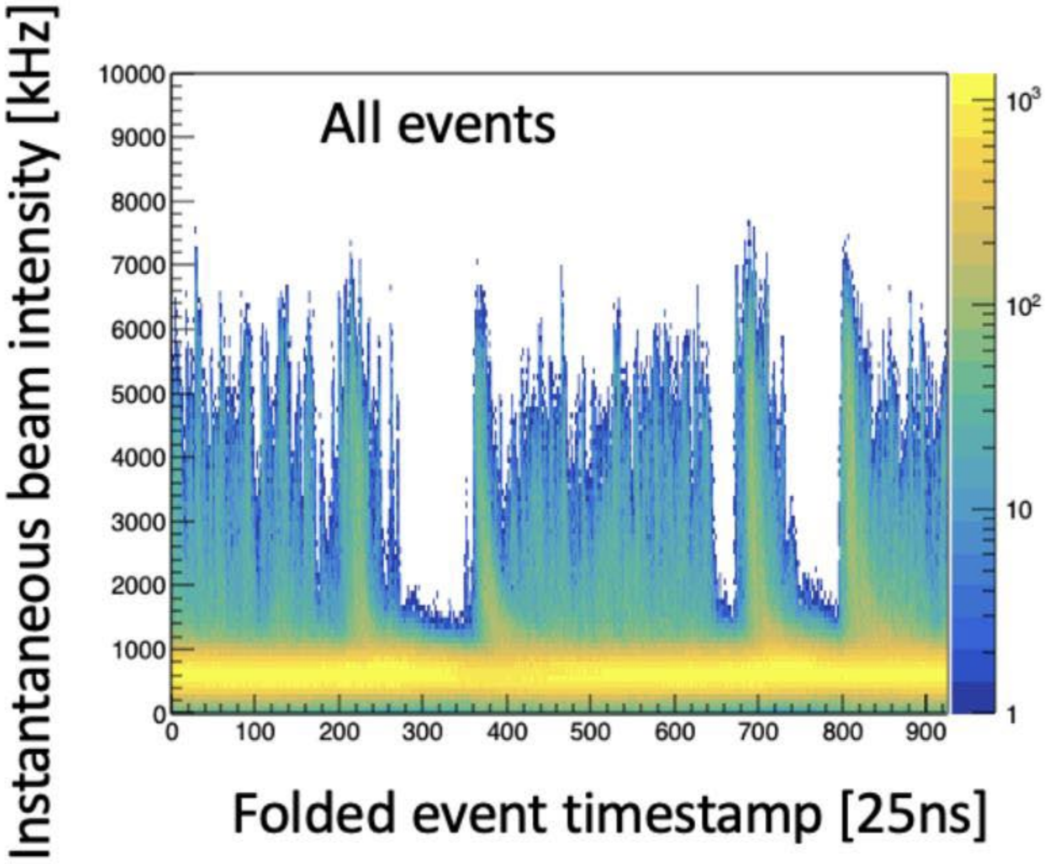
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
- Measures K^+ 3-mom and time
- 4th GTK station improves efficiency and pileup resilience.

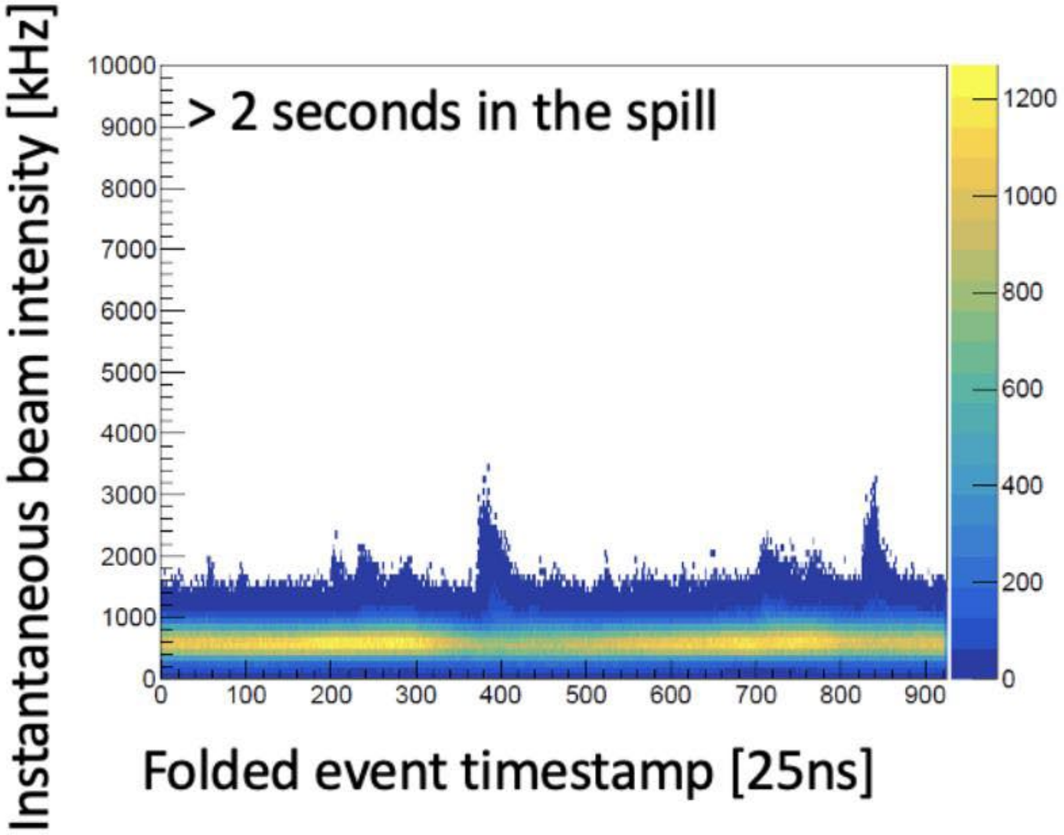


Si Pixels ~(30x60 mm active area)



2021 instantaneous beam intensity





- Remove events in first 1s of 4.8s spill for 2021 data only.
- DAQ overwhelmed by instantaneous rates up to 10x higher than design.