NA62 & PIONEER

Vincent Wong (TRIUMF),
on behalf of the Canadian NA62 and PIONEER Collaborations

IPP 50th Anniversary Symposium
28-29 May, 2022
Fairmont Château Laurier

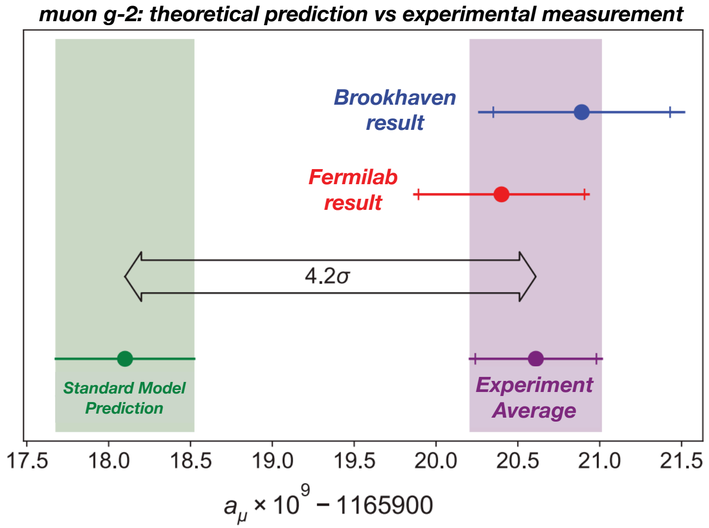
Outline:

1) **Introduction: Tensions in Flavor Physics**
2) **NA62 experiment overview and results**
3) **PIONEER experiment overview and status**
4) **Summary and outlook**

Tensions in Lepton Flavor Universality

Several measurements hinting at the violation of Lepton Flavor Universality and CKM Unitarity:

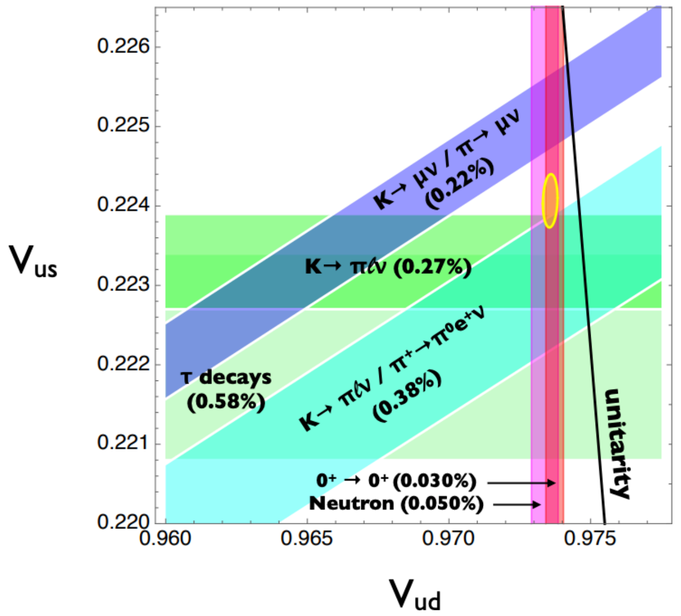
- B-anomalies:
  - $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell^+\bar{\nu})}$ 3.1σ — EPJC 81 (2021) 226, PRL 122 (2019) 191801, arXiv:2103.11769
  - $R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$ 2.1-3.3σ — PRL 126 (2021) 161801, JHEP 08 (2017) 055
- Muon g-2 deviation from SM prediction 4.2σ — PRL 126 (2021) 141801, arXiv:2111.05338
- Cabibbo angle anomaly in CKM unitary 3.7σ
  - Tensions between π^+, K^+, τ and β decay measurements
  - May be related to LFV



A few rare pion and kaon decays that have interesting connections to LFU:

- $K_L^0 \to \pi^0\nu\bar{\nu}$ ~ 10^{-11}
- $K^+ \to \pi^+\nu\bar{\nu}$ ~ 10^{-10}
- $\pi^+ \to e^+\nu(\gamma)$ ~ 10^{-4}
- $\pi^+ \to \pi^0 e^+\nu(\gamma)$ ~ 10^{-8}

Two experiments in this talk
NA62 & PIONEER

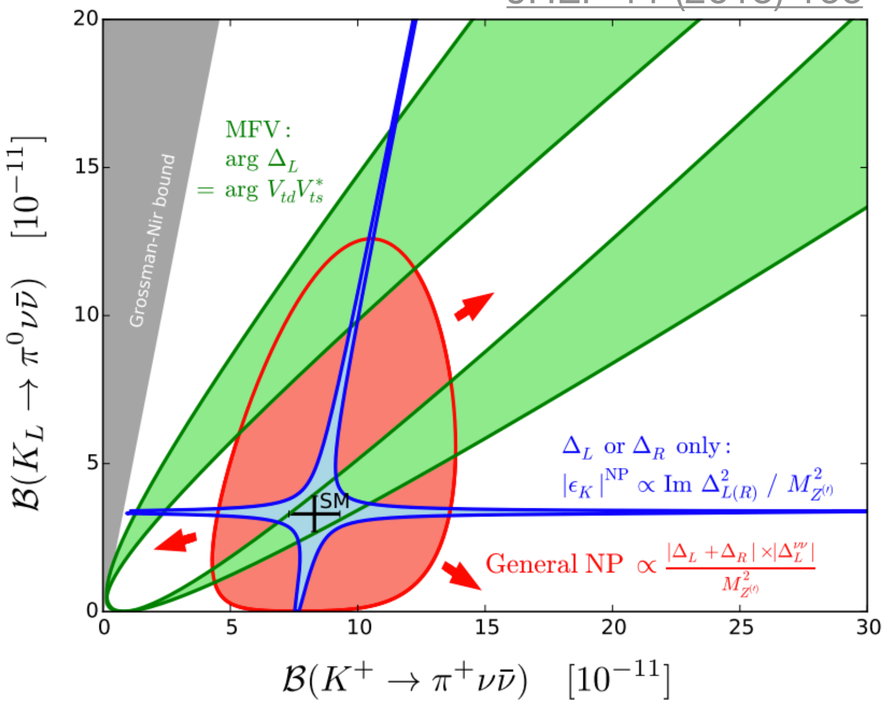


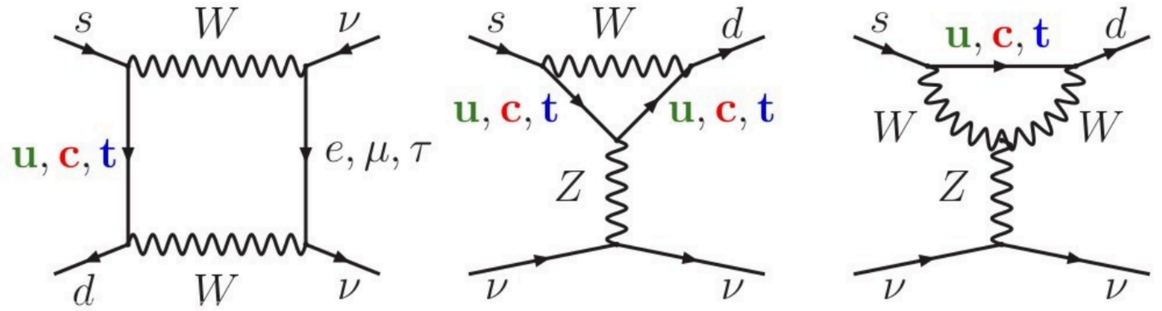
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

- FCNC loop process:
  - $s \to d$ coupling and highest CKM suppression
- Theoretically clean:
  - Free from hadronic uncertainties
  - Hadronic matrix element extracted from the well-known $K^+ \to \pi^0 e^+ \nu$
- Possibly sensitive to new physics at O(100 TeV): Leptoquark, Z', Little Higgs w/ T-parity, Supersymmetry…

arXiv:1802.00786 JHEP 02 (2018) 101 JHEP 12 (2020) 097 JHEP 11 (2015) 166 EPJC 76 (2016) 182 PTEP 12 (2016) 123B02

JHEP 11 (2015) 166





arXiv:2203.10099

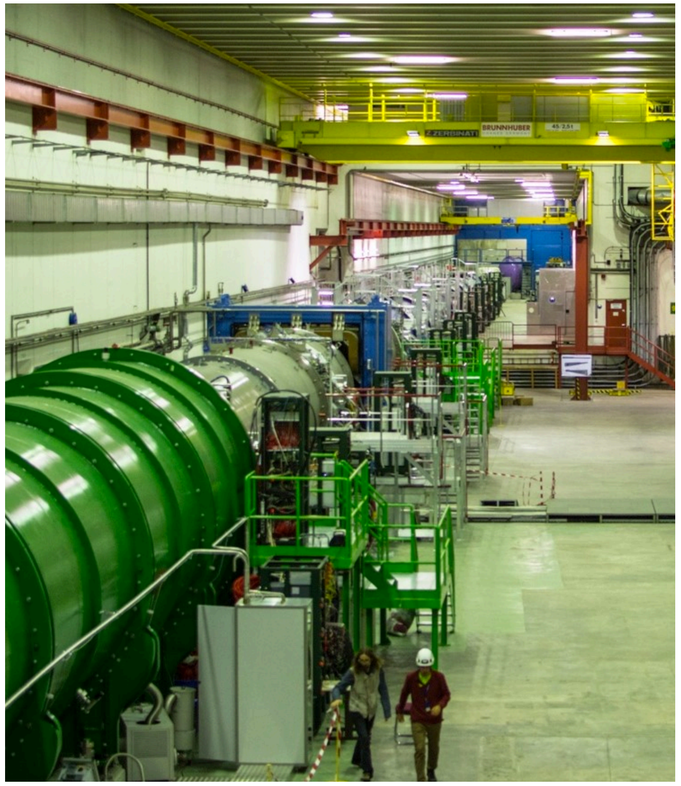
Decay mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}$	8.60 ± 0.42
$K_L \to \pi^0 \nu\bar{\nu}$	2.94 ± 0.15

NA62: High-Intensity Kaon Experiment @ CERN SPS

The CERN Kaon factory:
- Fixed target experiment at CERN SPS
- Kaon decay-in-flight

Currently in NA62:
- ~200 participants and ~30 institutions

The main goal of NA62 is to measure ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% precision.



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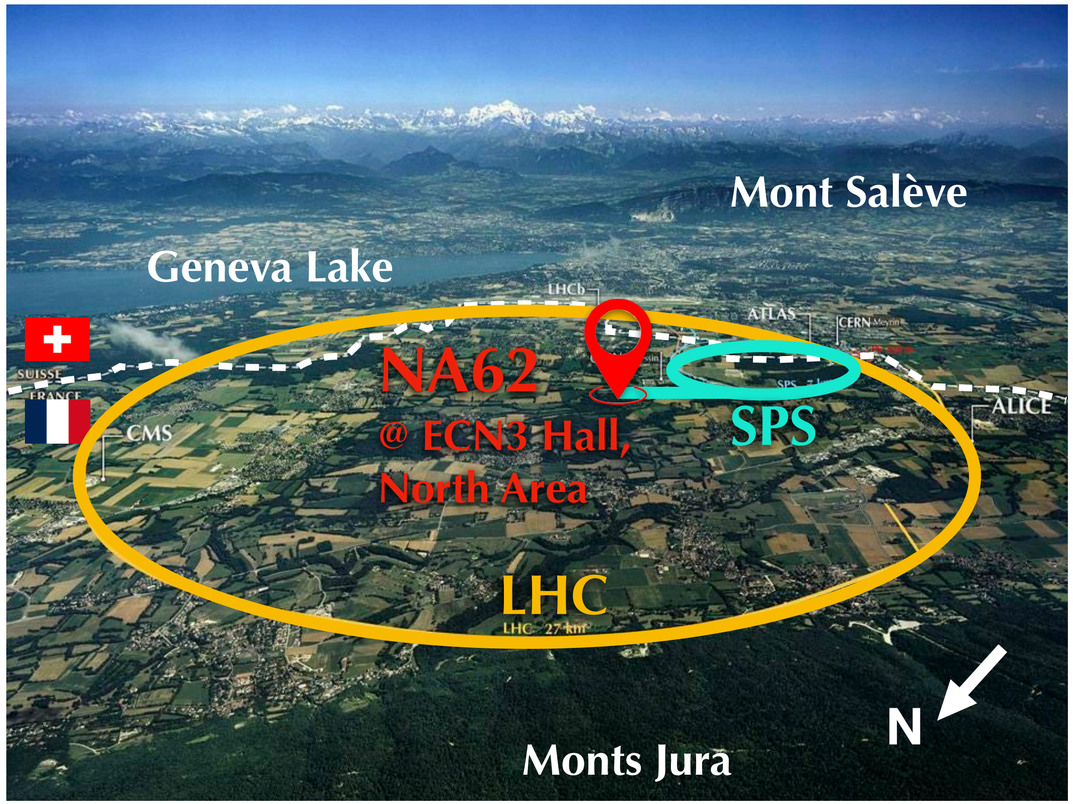
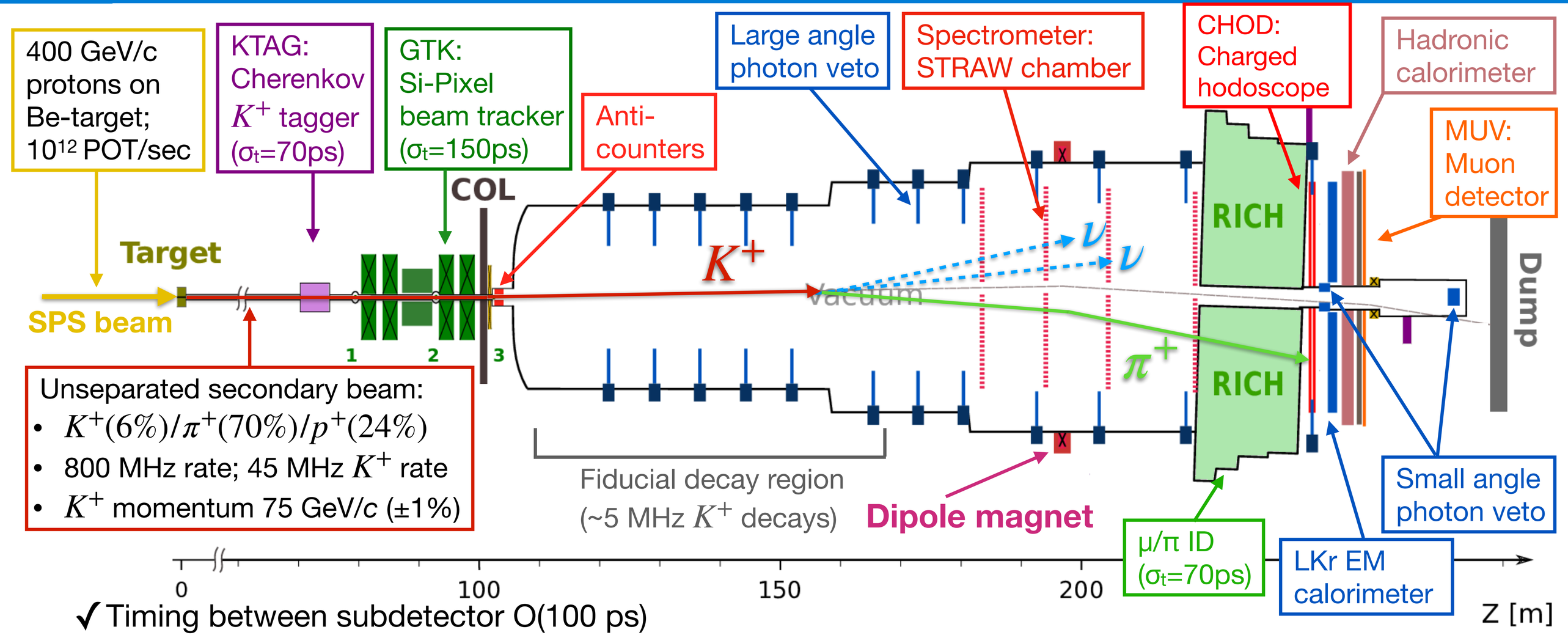


2021-

Earlier CERN Kaon experiments	NA62 R_K phase	NA62 Run 1	NA62 Run 2
since 1986		2016-18	

The NA62 Beam and Detector

JINST 12 (2017) P05025

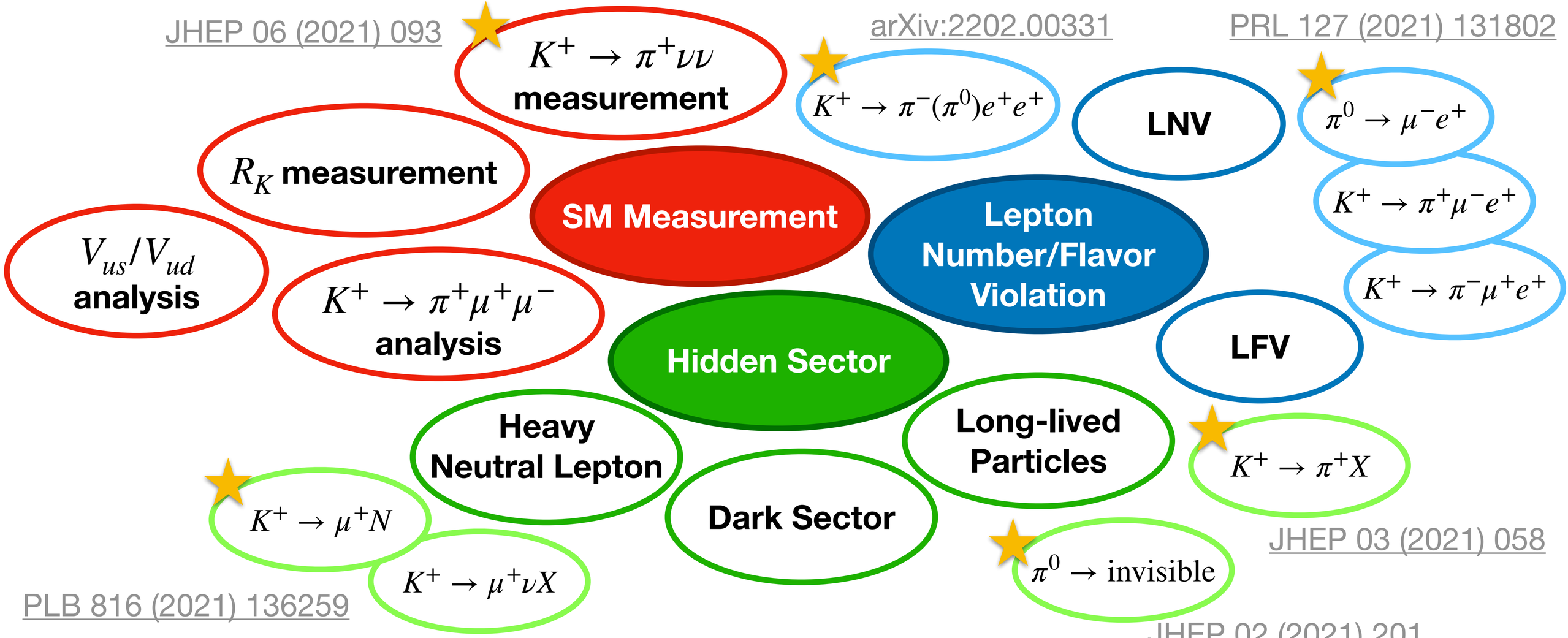


- ✓ Timing between subdetector O(100 ps)
- ✓ Kinematic rejection factor O(10^3) for $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$
- ✓ Hermetic photon veto (LAV+LKr+IRC+SAC): $\pi^0 \to \gamma\gamma$ suppression factor O(10^7) from $K^+ \to \pi^+\pi^0$
- ✓ Particle ID (RICH+LKr+HAC+MUV): muon suppression factor O(10^8) from $K^+ \to \mu^+\nu$

Kaon Physics @ NA62

NA62 has a broad physics programme - SM tests and new physics searches

- Several recent Run 1 results published in 2021-22 (marked by ★)
- More data taking during Run 2 in beam dump mode for MeV-GeV hidden sector



NA62: Run 1 data for $K^+ \to \pi^+\nu\nu$ measurement

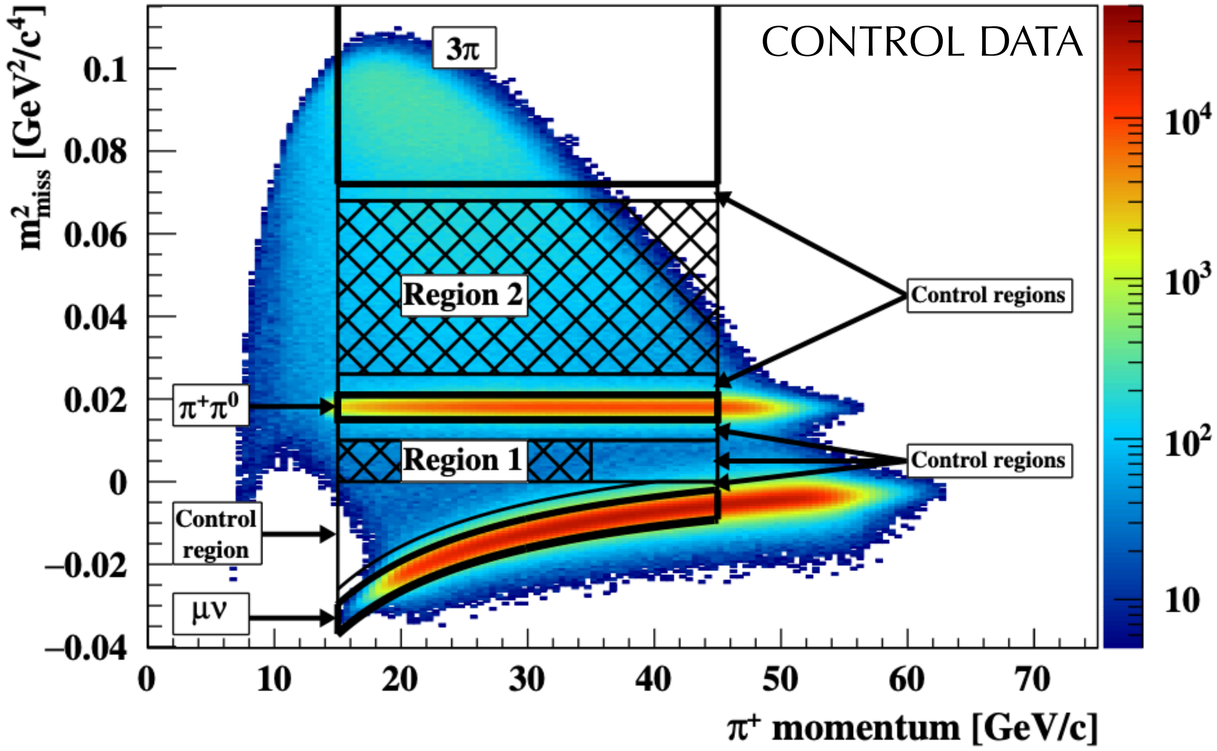
Decay-in-flight technique: $m^2_{\text{miss}} = (P_{K^+} - P_{\pi^+})^2$, assuming π^+ mass for downstream track

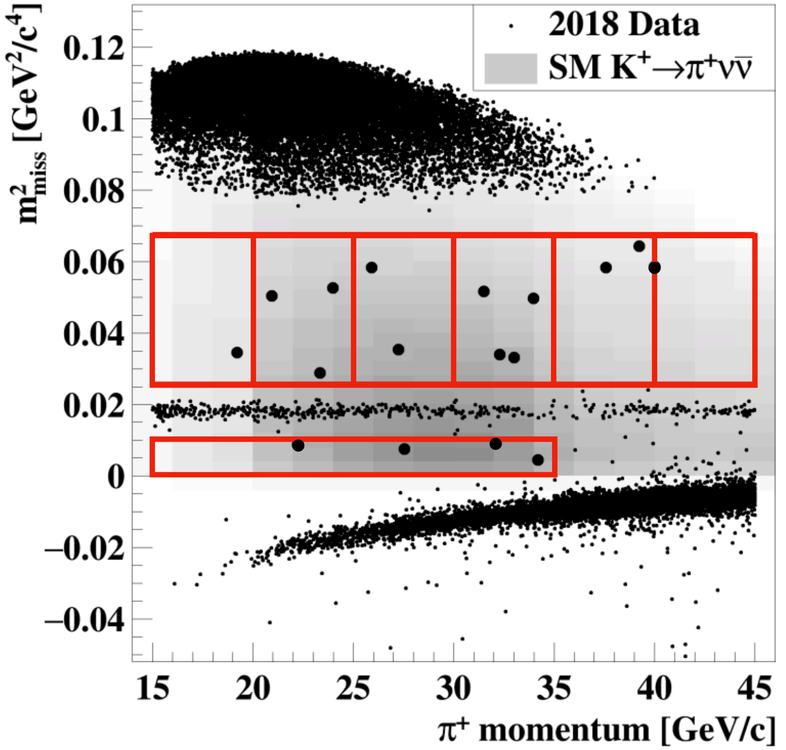
Two-step unblinding procedure:

Background estimation evaluated from control data

→Unblind control regions in the $K^+ \to \pi^+\nu\nu$ data for validation

→Unblind signal regions for final results





Full Run 1 data [JHEP 06 (2021) 093]

$N^{\text{exp}}_{\text{SM } \pi\nu\bar{\nu}} = 10.01 \pm 1.26$

$N^{\text{exp}}_{\text{bkg}} = 7.03^{+1.05}_{-0.82}$

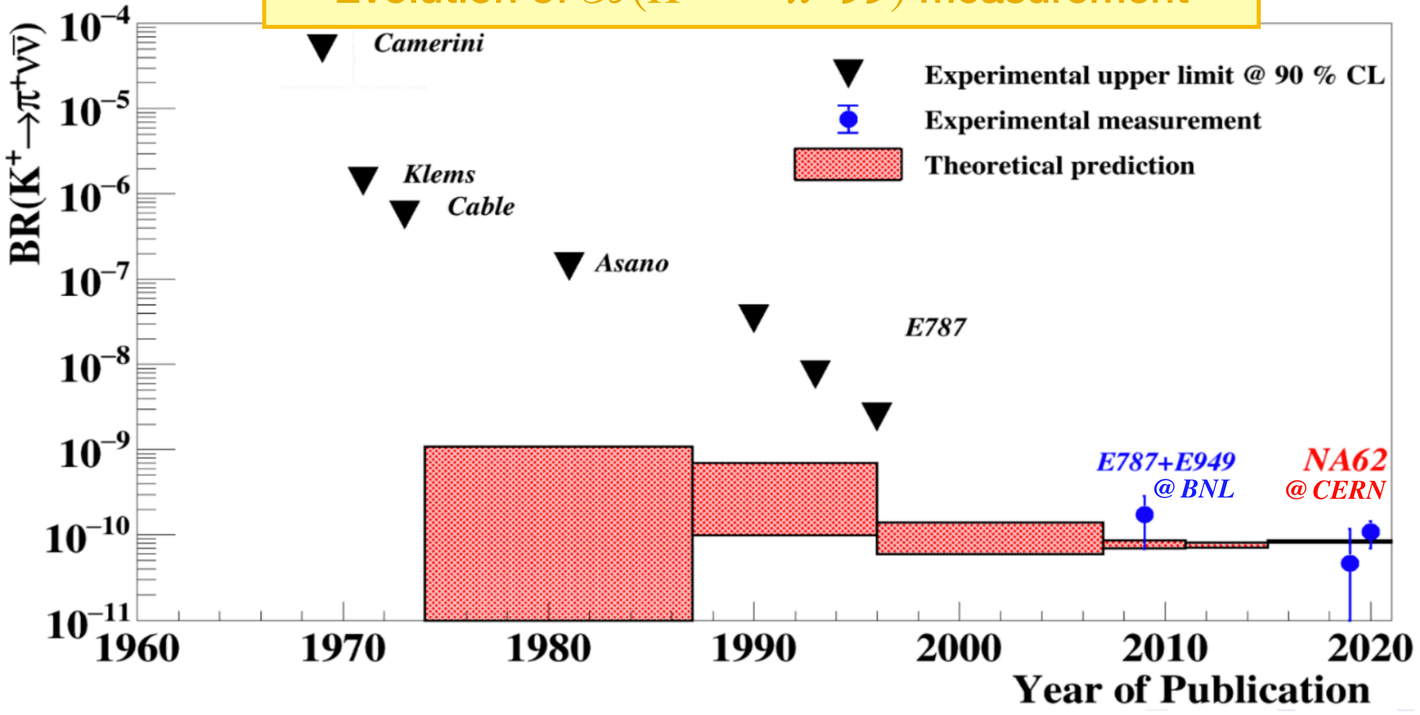
$N^{\text{obs}}_{\text{total}} = 20$ (17 in 2018 data)

NA62: Run 1 Results and Interpretations

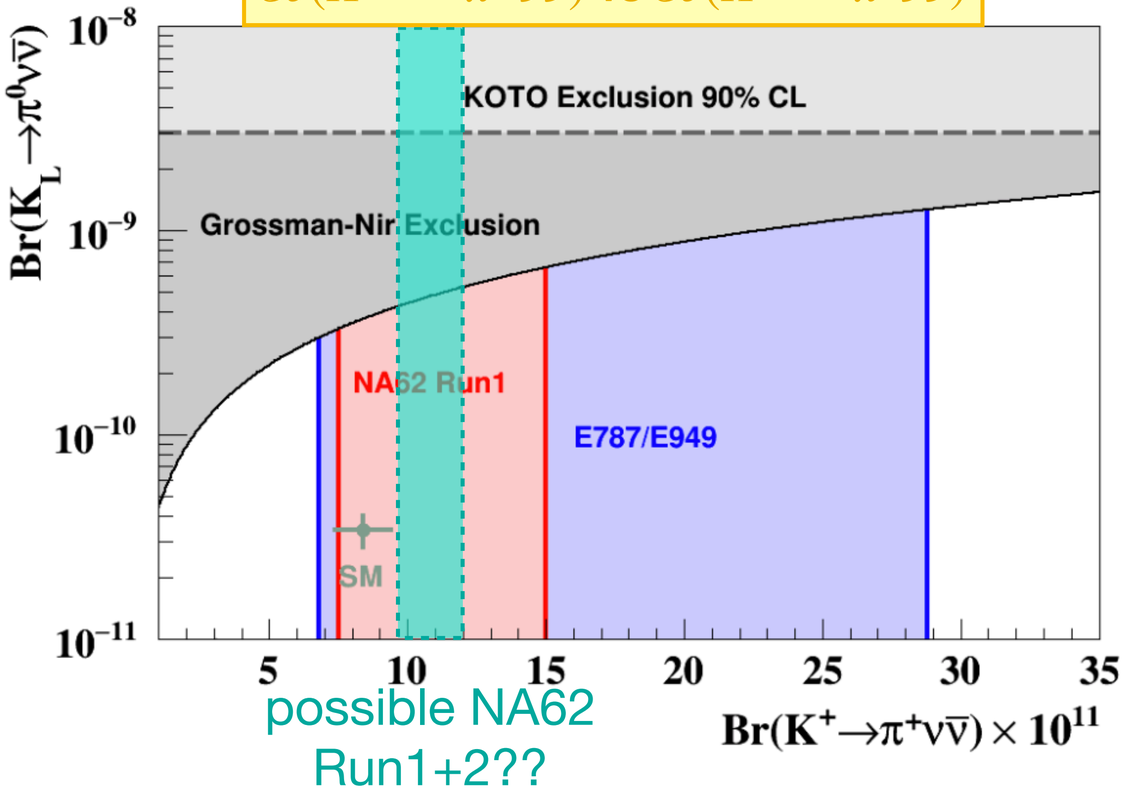
NA62 Run 1 result: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ @ 68% CL

- Strongest evidence so far, with 3.4σ significance

Evolution of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ measurement



$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ vs $\mathcal{B}(K^0 \to \pi^0\nu\bar{\nu})$



possible NA62 Run1+2??

Next target is to achieve 10-20% precision on $K^+ \to \pi^+\nu\bar{\nu}$ measurement by 2025!

PIONEER: Next-Generation Rare Pion Decay Experiment

PIONEER: next generation rare pion decay experiment to address LFUV and CKM unitary with order of magnitude improvements [arXiv:2203.01981]

GOALS:

- **Measure** $R_{e/\mu} = \dfrac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$

$$\sim O(\pm 0.01\%)$$

  - ✓ improve the precision of the best g_e/g_μ test by 10 times
  - ✓ sensitive to BSM up to O(1000) TeV with coupling O(1), e.g. charged Higgs, leptoquarks…

- **Measure** $R_{\pi\beta} = \dfrac{\Gamma(\pi^+ \to \pi^0 e^+\nu)}{\Gamma(\pi^+ \to \text{all})}$

$$\sim O(\pm 0.05\%)$$

  - ✓ comparable to the ±0.03% superallowed beta decay measurement precision on V_{ud}

$R_{e/\mu}^{\text{theory}} = (1.2352 \pm 0.0001) \times 10^{-4}\ (\pm 0.01\%)$ arXiv:2111.05338

$R_{e/\mu}^{\text{exp}} = (1.2327 \pm 0.0023) \times 10^{-4}\ (\pm 0.19\%)$

$\Rightarrow g_e/g_\mu = 0.9989 \pm 0.0009\ (\pm 0.09\%)$ current world average (PDG)

PEN, PIENU goals $R_{e/\mu}^{\text{exp}} \leq \pm 0.1\ \%$

Theoretically cleanest $|V_{ud}|$ measurement (free from nuclear-structure uncertainties)

$R_{\pi\beta}^{\text{exp}} = (1.036 \pm 0.006) \times 10^{-8}\ (\pm 0.62\%)$ PIBETA results PRL 93 (2004) 181803

Superallowed nuclear β-decay measurement at $\pm 0.03\ \%$ level

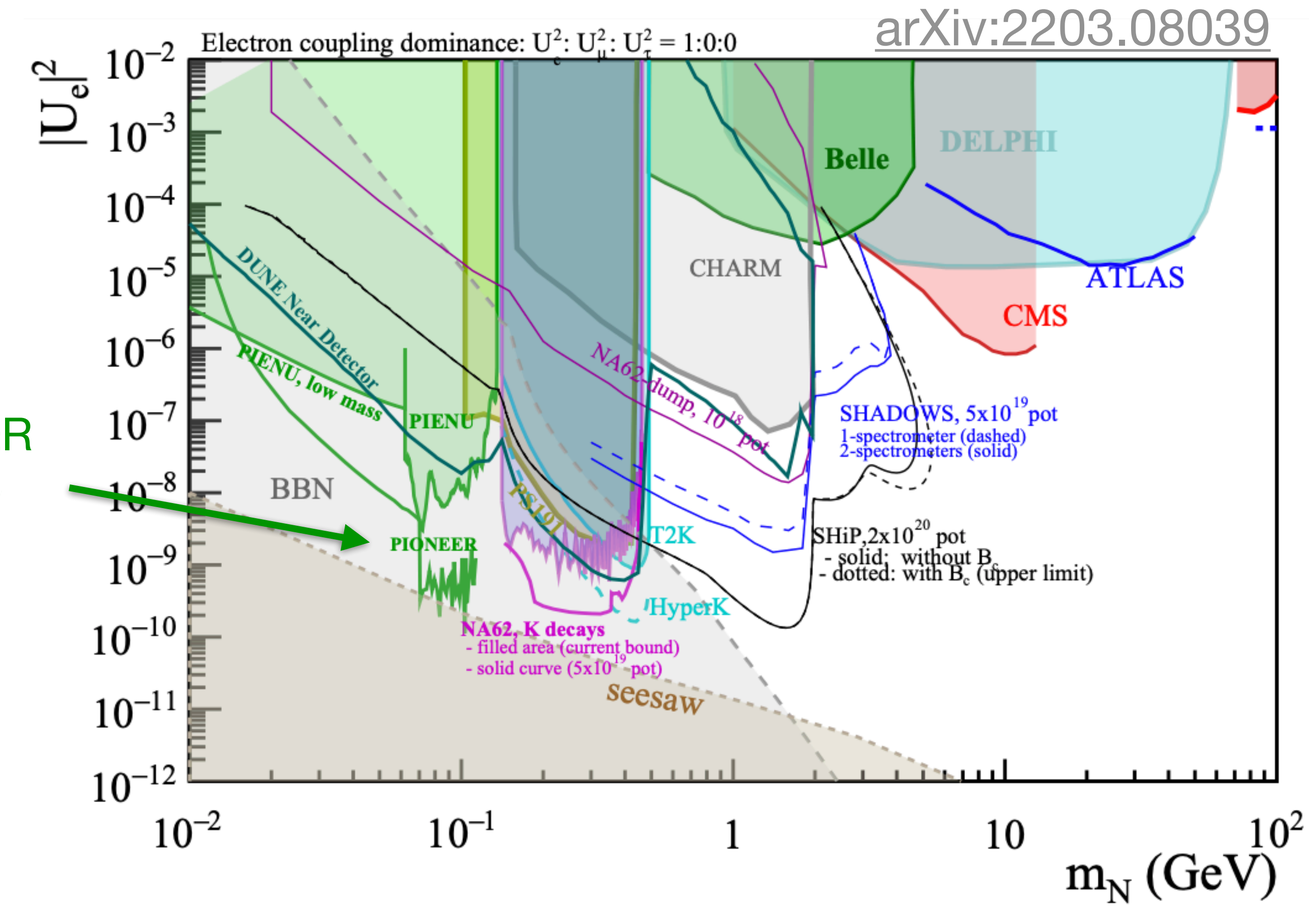
PIONEER: Next-Generation Rare Pion Decay Experiment

PIONEER: next generation rare pion decay experiment to address LFUV and CKM unitary with order of magnitude improvements [arXiv:2203.01981]

GOALS:

- **Improve search sensitivities** by more than an order of magnitude
  - Heavy neutral lepton via $\pi^+ \to (e^+/\mu^+)N$
  - Hidden sector mediator via $\pi^+ \to (e^+/\mu^+)\nu X$
  - Ultra-rare pion decays $\pi^+ \to (e^+/\mu^+)\nu\nu\bar{\nu}$

Stringent limit could be from PIONEER on the HNL mixing angle $|U_e|^2$ below 140 MeV



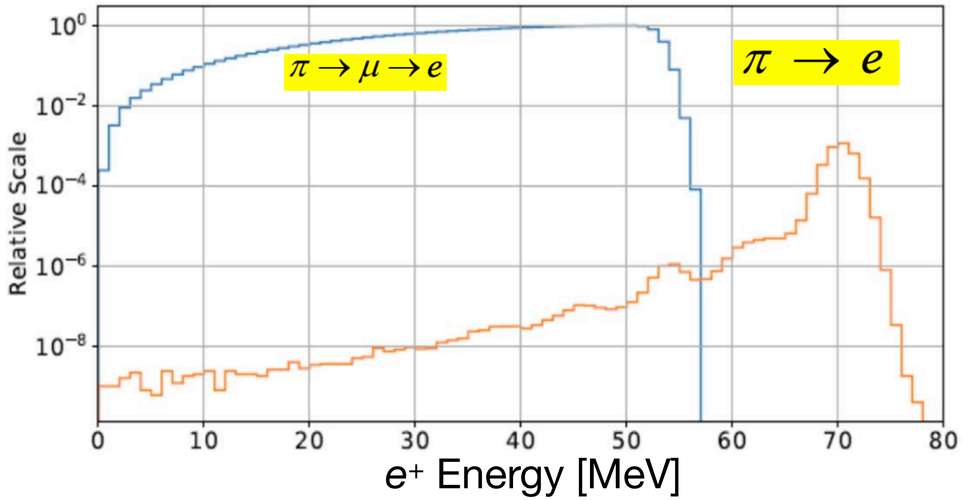
PIONEER: Detector Design

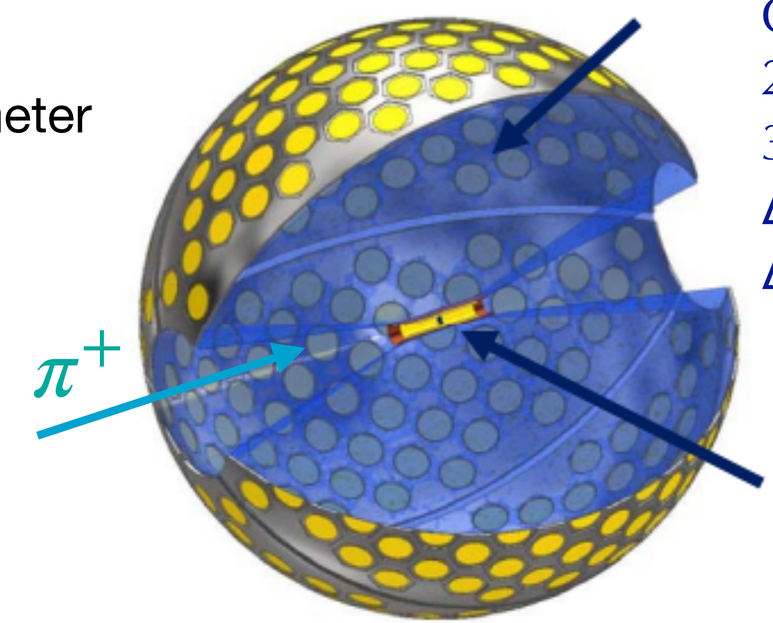
Experimental method illustrated with $\pi^+ \to e^+\nu$:

- Pions decay at rest in an active stopping target
- Positrons are tracked, and its energy is measured in a calorimeter

Principal challenge: Low energy "tail" of $\pi^+ \to e^+\nu$ events under $\pi^+ \to \mu^+(\to e^+\nu\bar{\nu})\nu$ background

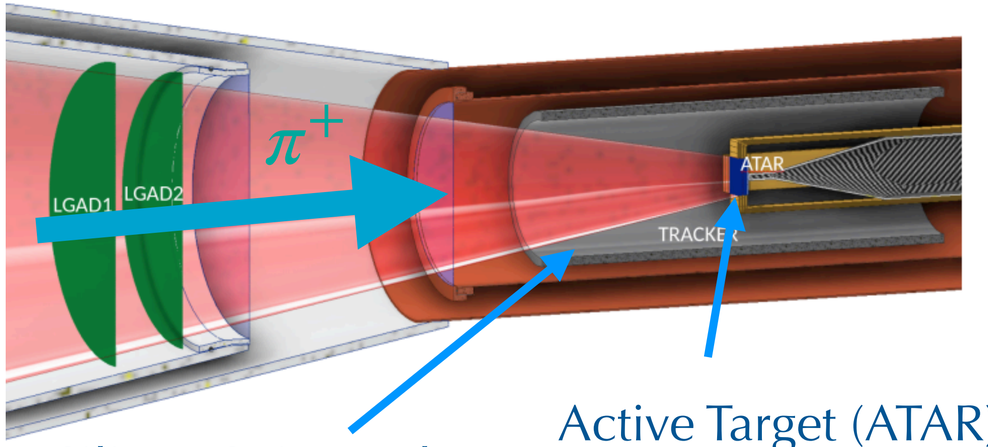
- Silicon active target (ATAR) with 4D tracking
  - reduce pileup effects and $\pi^+ \to e^+\nu$ energy tail correction
  - directly identify $\pi^+ \to \mu^+ \to e^+$ chain
- Calorimeter with high resolution and fast timing
  - improve $\pi^+ \to e^+\nu$ energy tail suppression
- Fast electronics and DAQ $\Rightarrow$ improve efficiency





Calorimeter:
25 X_0
3π-coverage
Δt~100 ps
ΔE/E~1.5%

Active Target and Tracking Layers



Silicon Strip Tracker

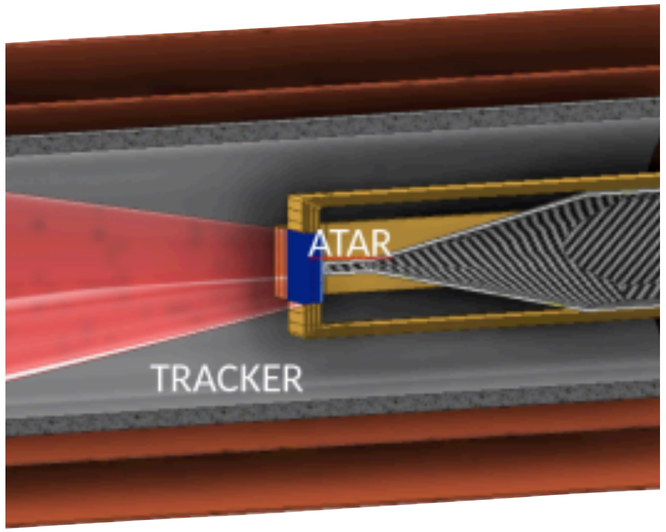
Active Target (ATAR)

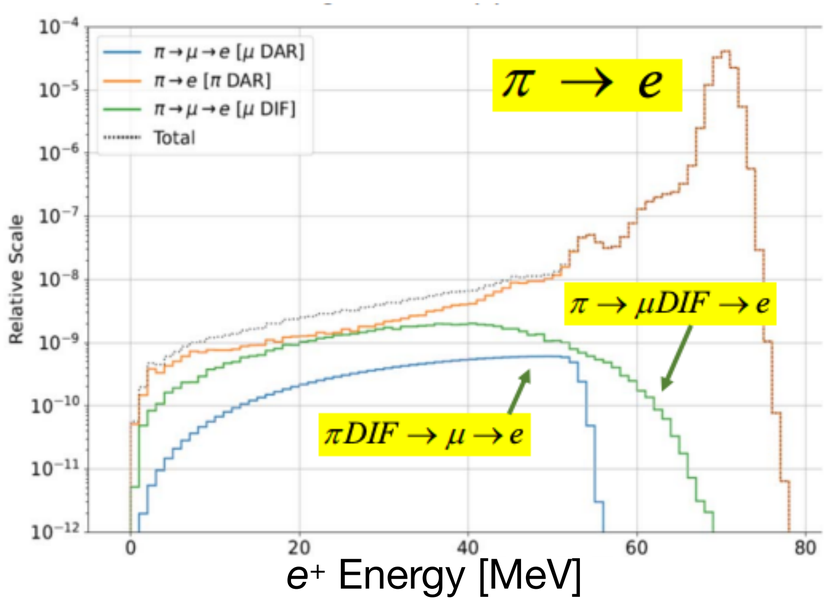
PIONEER: ATAR

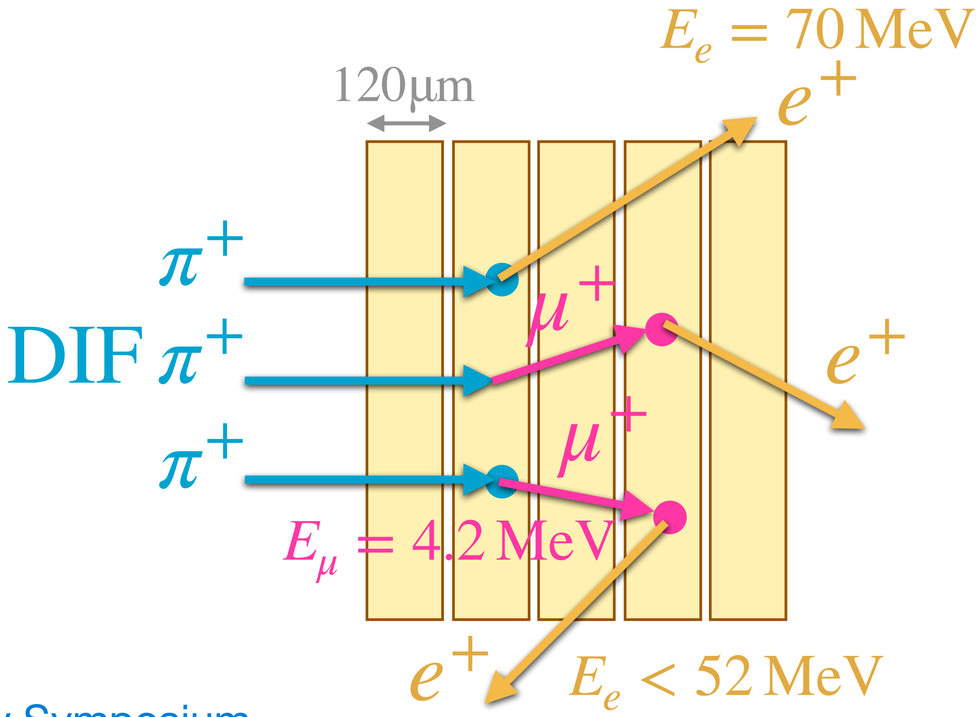
Tentative design:

- 48 layers of thick X/Y strips
  - 100 strips/layer
  - strip size: 120 μm thick x 200 μm wide x 2 cm long
- AC-LGADs (low gain avalanche diode)

Preliminary simulation study shows that strip hit information from ATAR allows strong suppression of $\pi^+ \to \mu^+ \to e^+$ backgrounds (an order of magnitude smaller than $\pi^+ \to e^+\nu$)

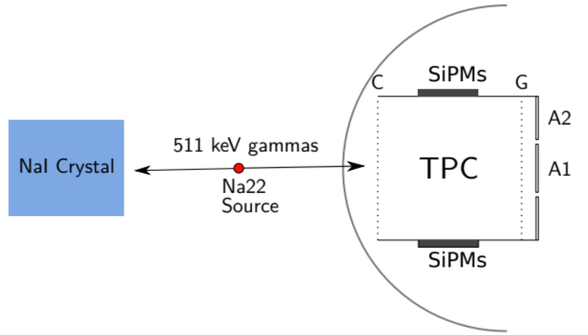


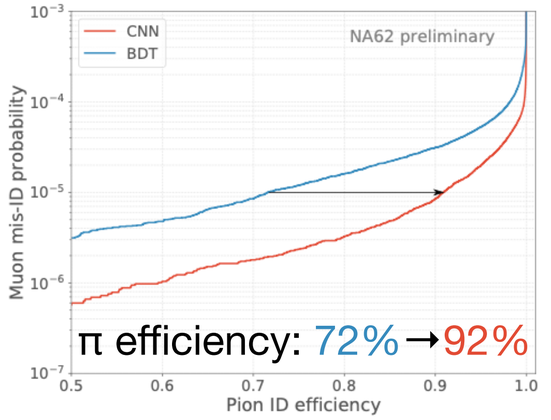




Examples of Contributions from the Canadian Group

- Developed a Liquid Krypton TPC purity monitor system
  - Validated the LKr purity to be < 1 ppb contamination level
    ⇒ allowing refilling and operation of NA62's primary calorimeter
- Improving the PID performance with machine learning (ML) algorithms
  - Developed and implemented a Convolutional Neural Network model based on raw hit data of the calorimeters.
  - Collaborating with UBC Master of Data Science to study the possibility to improve PID eff. by applying ML algorithms on NA62's RICH detector data
- Telescope with high timing and spatial resolution for Silicon Pixel R&D
  - Allow testing of fast-timing silicon sensor (σ_t < 50 ps) for NA62 beam tracker timing upgrade
  - Apply silicon detector techniques to future experiments, e.g. PIONEER and upgrades for HL-LHC
- Studying NA62's sensitivity to V_{us}/V_{ud} measurements
- Initiation and involvement in PIONEER experiment design
  - Simulation studies of ATAR to study its background suppression power
  - LXe calorimeter R&D with simulation and prototype studies





NA62 TDCpix telescope
(70ps timing resolution)

Conclusions & Outlooks: NA62 and PIONEER

- Rare kaon decays at NA62 are excellent probe for new physics beyond Standard Model
  - Run 1 (2016-18) result for $K^+ \to \pi^+\nu\bar{\nu}$ has been presented:
    $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$
  - NA62 resumed data taking in 2021 and will continue till LS3.
    Plan to reach 10-20% precision level for $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ by 2025
  - Rich physics program of rare decay measurements and searches, in addition to the golden channel $K^+ \to \pi^+\nu\bar{\nu}$, e.g. LFV/LNV, HNL, dark sector…

- PIONEER will address Lepton Flavor Universality and CKM unitarity with unprecedented precision
  - Measure $\pi^+ \to e^+\nu/\pi^+ \to \mu^+\nu$ to O(±0.01%), matching the ±0.01% SM theory precision
  - Measure pion beta decay to O(±0.05%), comparable to the ±0.03% superallowed beta decay measurement precision on V_{ud}
  - Search for exotic particles and ultra-rare pion decays, e.g. HNL, ALP, $\pi^+ \to (e^+/\mu^+)\nu\nu\bar{\nu}$

TRIUMF Rare Decay Group

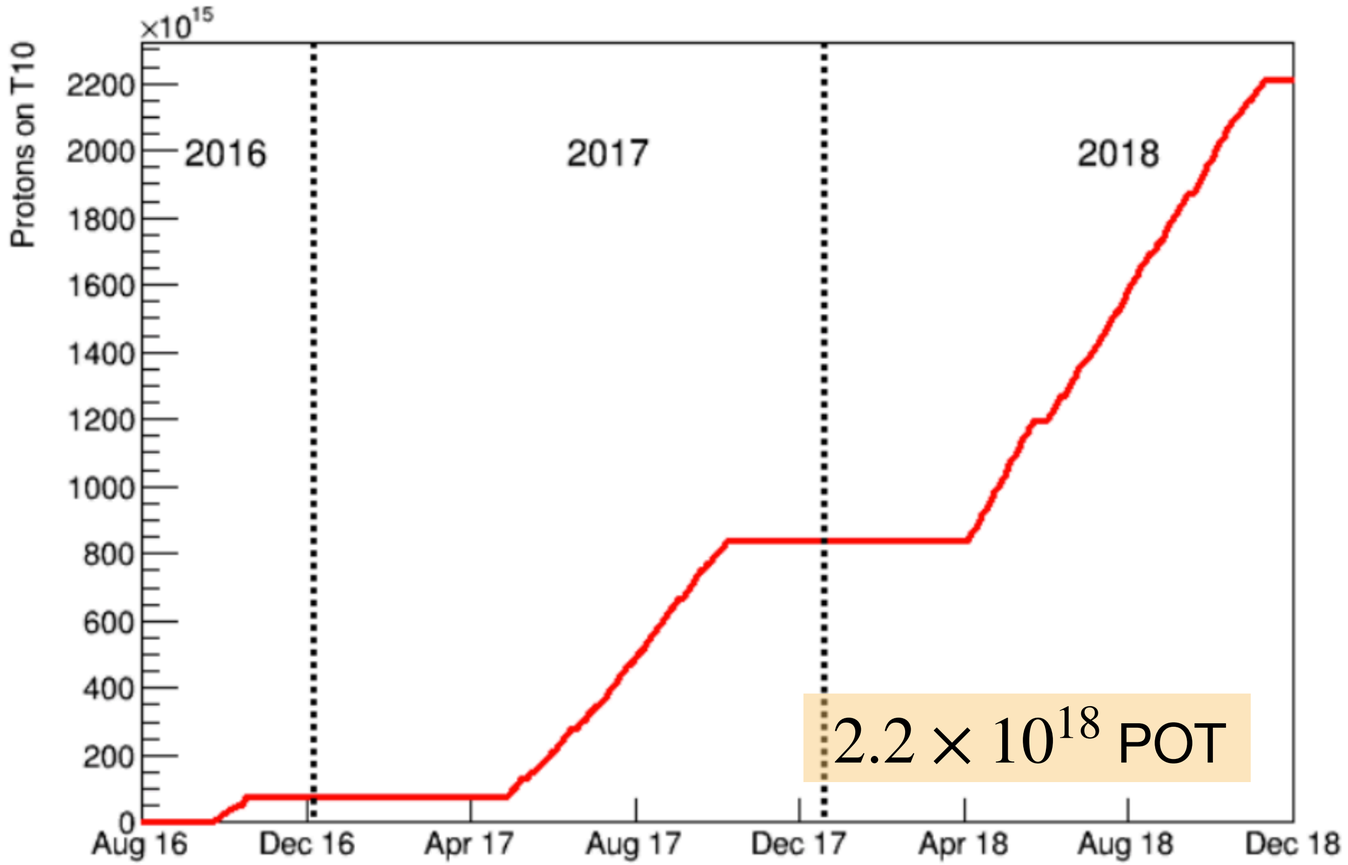
<u>NA62</u>
Faculty: Douglas Bryman (UBC/TRIUMF), Toshio Numao (TRIUMF)
Postdocs: Bob Velghe (TRIUMF), Vincent Wong (TRIUMF)
Students: UBC MDS Capstone

<u>PIONEER</u>
Faculty: Douglas Bryman (UBC/TRIUMF), Chloé Malbrunot (TRIUMF), Toshio Numao (TRIUMF), Katherine Pachal (TRIUMF)
Detector Development Simulation Specialist: Aleksey Sher (TRIUMF)
Postdocs: Bob Velghe (TRIUMF), Vincent Wong (TRIUMF)
Students: UBC undergraduate honors theses

Supported by NSERC, Digital Research Alliance of Canada Resources and TRIUMF detector science/engineering/machine learning group

TRIUMF

NA62 Data Taking



Physics run 2016 (30 days):
40% of nominal intensity
2×10^{11} K^+ decays in fiducial volume

Physics run 2017 (160 days):
60% of nominal intensity
2×10^{12} K^+ decays in fiducial volume

Physics run 2018 (217 days):
70% of nominal intensity
4×10^{12} K^+ decays in fiducial volume

Run 2 physics data taking:
85 days of physics run and 10 days of beam dump mode in 2021

More data on its way in NA62 Run 2 (until Long Shutdown 3)