Searches for rare and forbidden decays with the NA62 experiment at CERN

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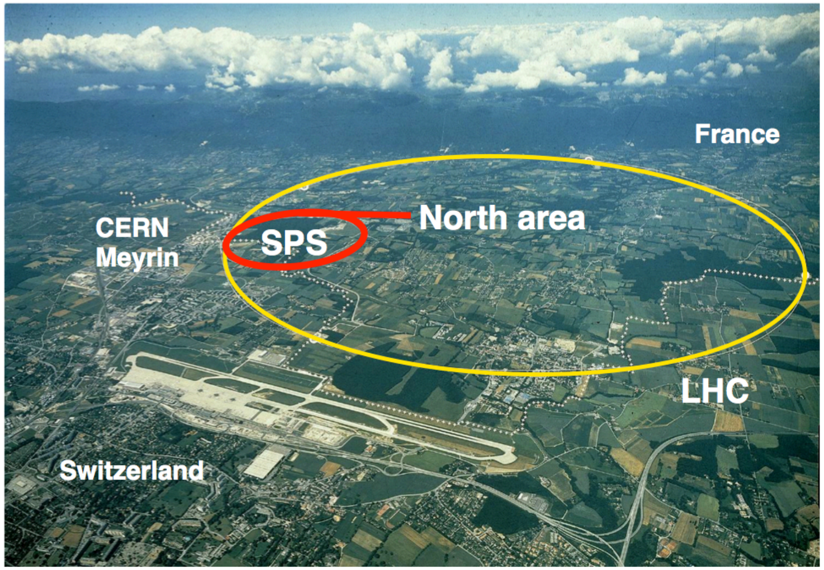
Paolo Massarotti
Università degli studi di Napoli "Federico II"
And INFN Napoli

On behalf of the *NA62 collaboration*:
Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, Stanford, Sofia, Turin

The NA62 experiment at CERN



1997-2002 NA48, NA48/1
Simultaneous K_S, K_L beams
$\mathrm{Re}\ \varepsilon'/\varepsilon$, rare K_S and hyperon decays

2003-2004 NA48/2
Simultaneous K^+, K^- beams
Direct CP violation, rare $K^\pm$ decays

2007-2008 NA62 (using NA48/2)
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

Primary NA62 goal: Detect ~100 $K^+ \to \pi^+ \nu\bar{\nu}$ decays with S/B ~ 10

BR($K^+ \to \pi^+ \nu\bar{\nu}$)$_{\mathrm{SM}}$ ~ 10^{-10}
- Minimal theoretical uncertainty
- Precise measurement of unitarity triangle for K system

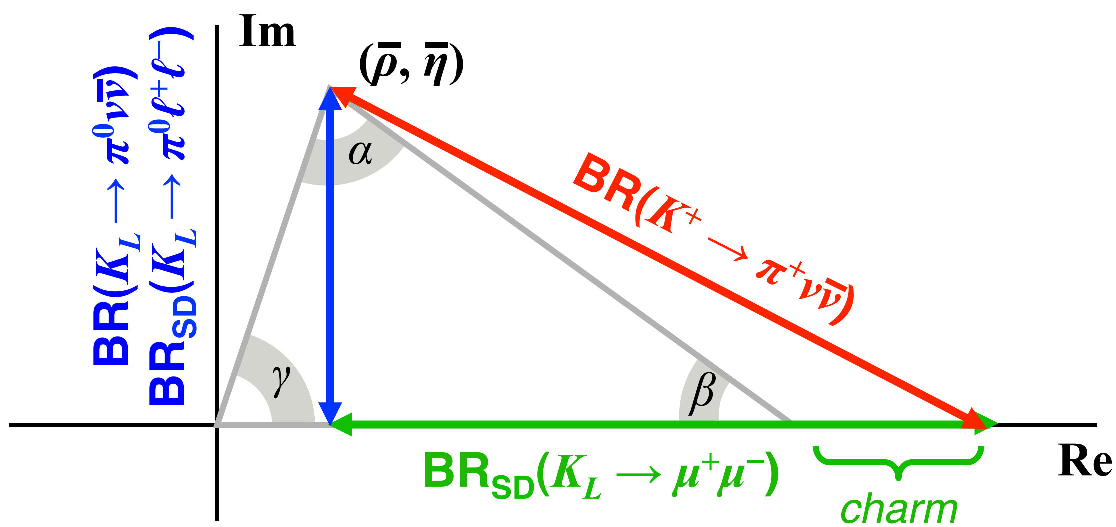
Opportunity to perform additional searches for novel phenomena:
- K decays with explicit lepton flavor or number violation **(LFNV)**
- Forbidden π^0 decays tagged by $K^+ \to \pi^+\pi^0$

Rare kaon decays

FCNC processes dominated by Z-penguin and box diagrams

Short-distance amplitudes related to $\mathbf{V_{CKM}}$ with minimal non-parametric uncertainty

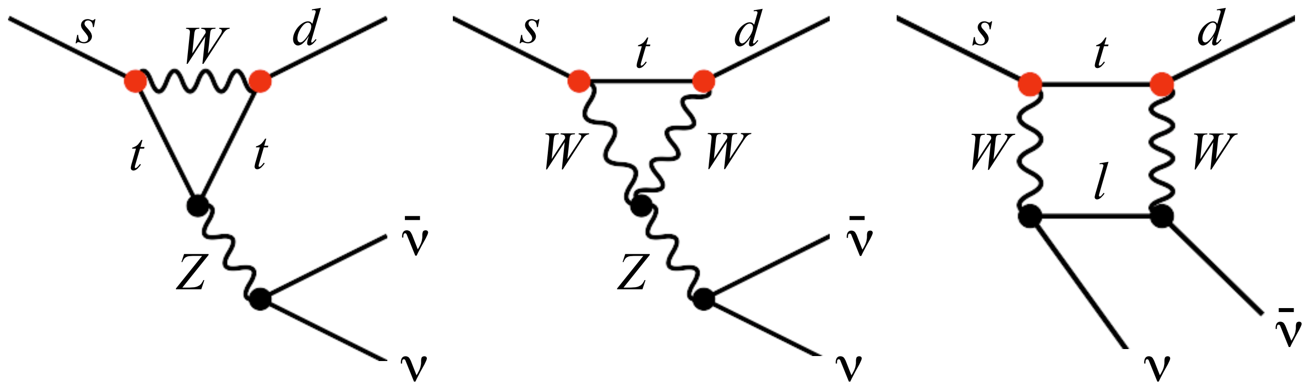
Rate measurements overconstrain V_{CKM} and may provide evidence for new physics



Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	40%	20%	681 ± 32	684 ± 11
$K_L \to \pi^0 e^+e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 12
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	<2600†

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

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



$$\lambda = V_{us}$$
$$\lambda_c = V^*_{cs} V_{cd}$$
$$\lambda_t = V^*_{ts} V_{td}$$

$$x_q \equiv m_q^2/m_W^2$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

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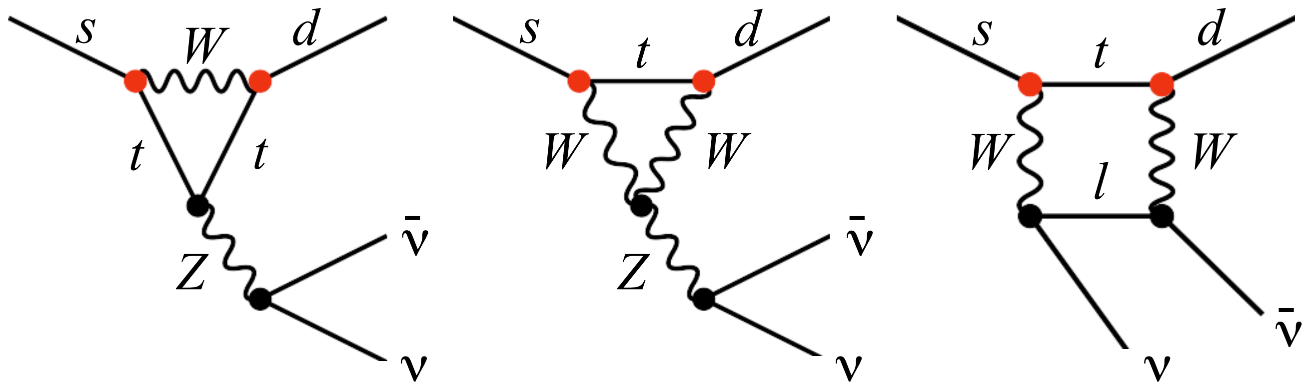

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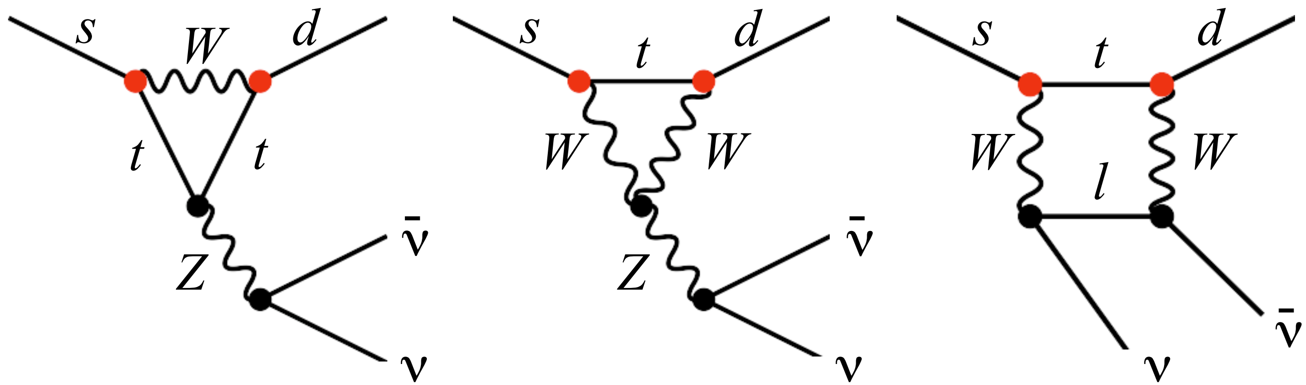
$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \lambda^8$$

Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation

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



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Loop functions favor top contribution

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$$BR(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \cancel{CP}$$

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 BR(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$

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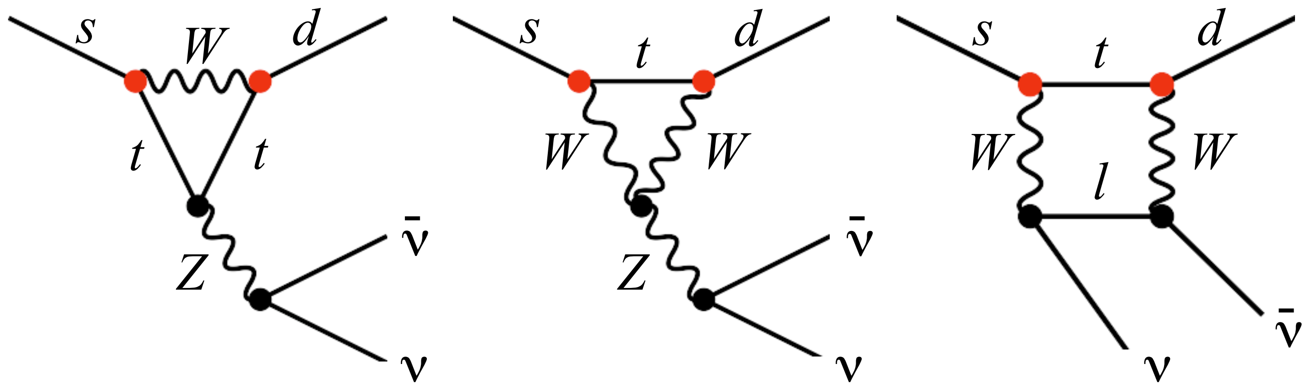

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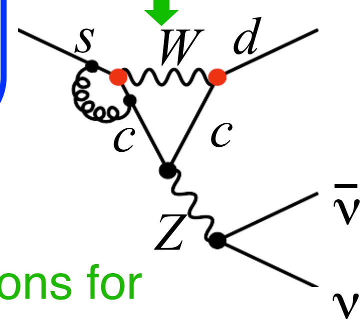
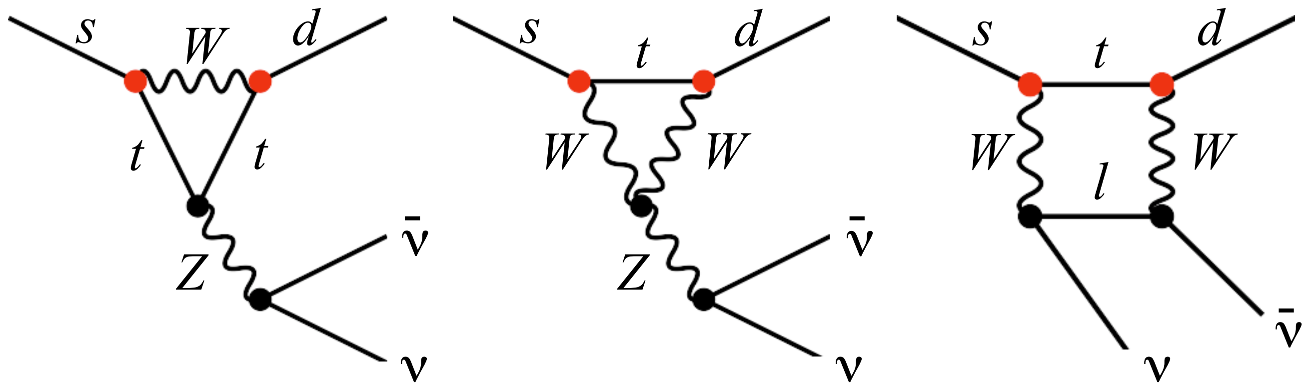


QCD corrections for charm diagrams contribute to uncertainty

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



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Loop functions favor top contribution

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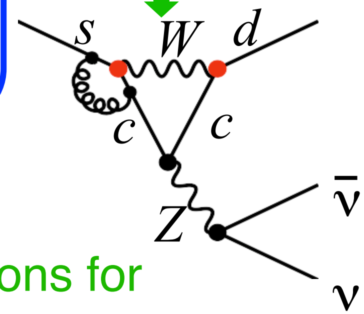
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \boxed{\kappa_+} \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \boxed{\frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X)} \right)^2 \right] = (7.81^{+0.80}_{-0.71} \pm 0.29)$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \boxed{\kappa_L} \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \cancel{CP} \qquad = (2.43^{+0.40}_{-0.37} \pm 0.06)$$



$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \lambda^8$$

Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation

QCD corrections for charm diagrams contribute to uncertainty

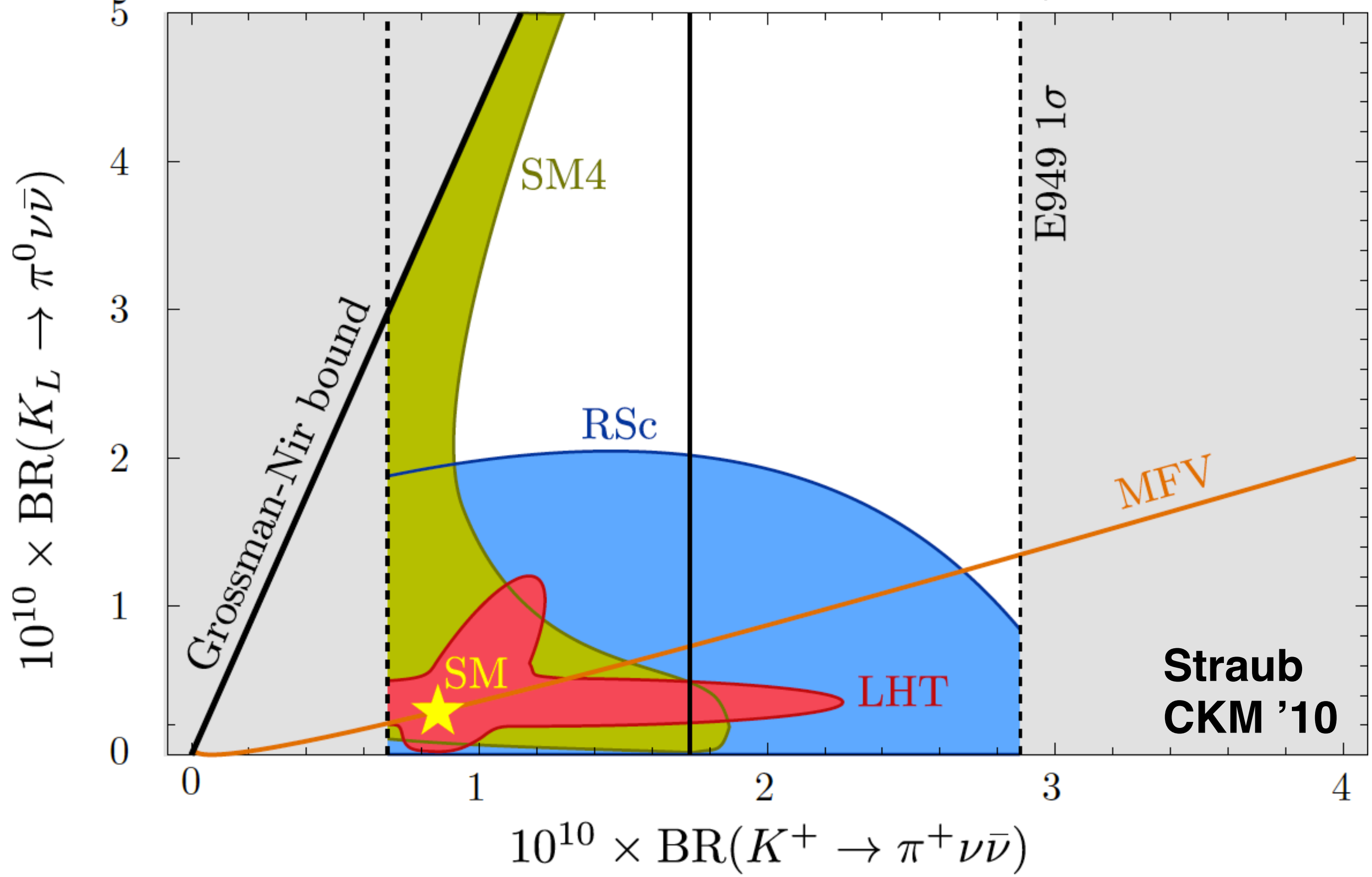
SM prediction (10-11 units)

***[Brod, Gorbahn and Stamou Phys. Rev D 83, (2011)** 034030]*

$K^+ \to \pi^+ \nu\bar{\nu}$ and new physics

New physics affects BRs differently for different channels

Multiple measurements can discriminate among NP scenarios



SM4: SM with 4th generation (Buras et al. '10)

LHT: Littlest Higgs with T parity (Blanke '10)

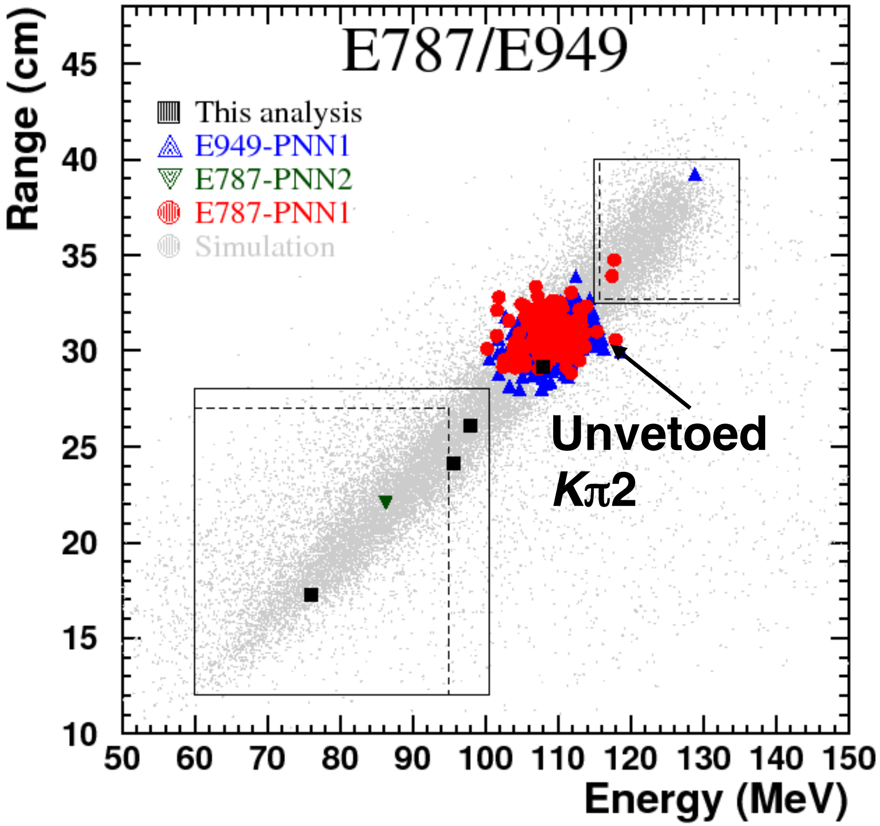
RSc: Custodial Randall-Sundrum (Blanke '09)

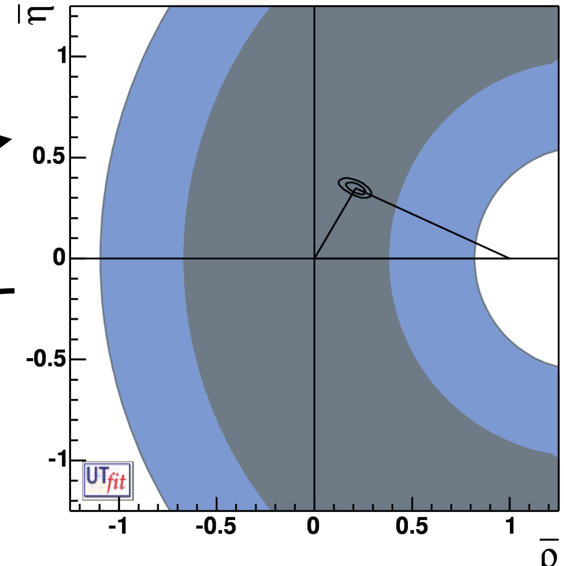
MFV: Minimal flavor violation (Hurth et al. '09)

Experimental status for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

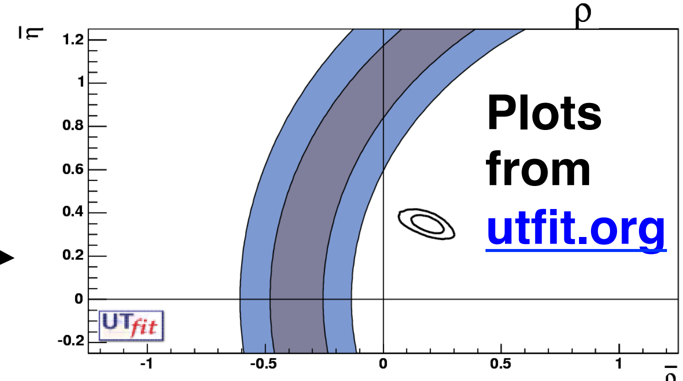
In 2008, combine E787 (1995-8 runs) & E949 (12-weeks run in 2001) results

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





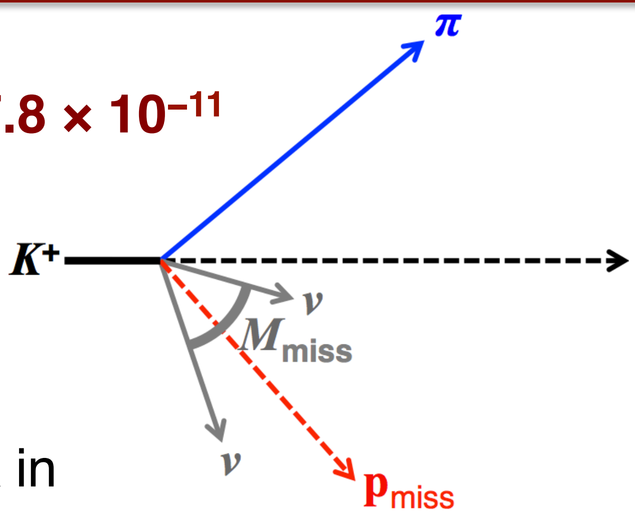
Same central value, 100 evts



Expected bkg 2.6 events, prob. all 7 obs. evts are bkg is ~10^{-3}

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: Signal and background

Signal:
BR_{SM} ~ 7.8 × 10^{-11}



K track in
π track out
No other particles in final state
$M^2_{\text{miss}} = (p_K - p_\pi)^2$

NA62 goal:
Measure BR to 10%

100 signal events
S/B ~ 10

10^{13} K decays with:

Acceptance ~10%
Background rejection ~10^{12}
Background known to ~10%

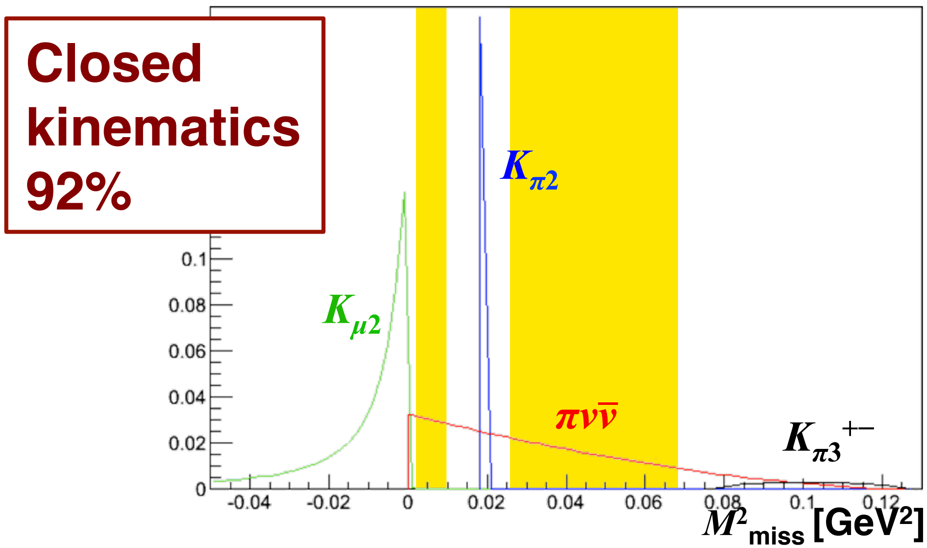
Decay backgrounds

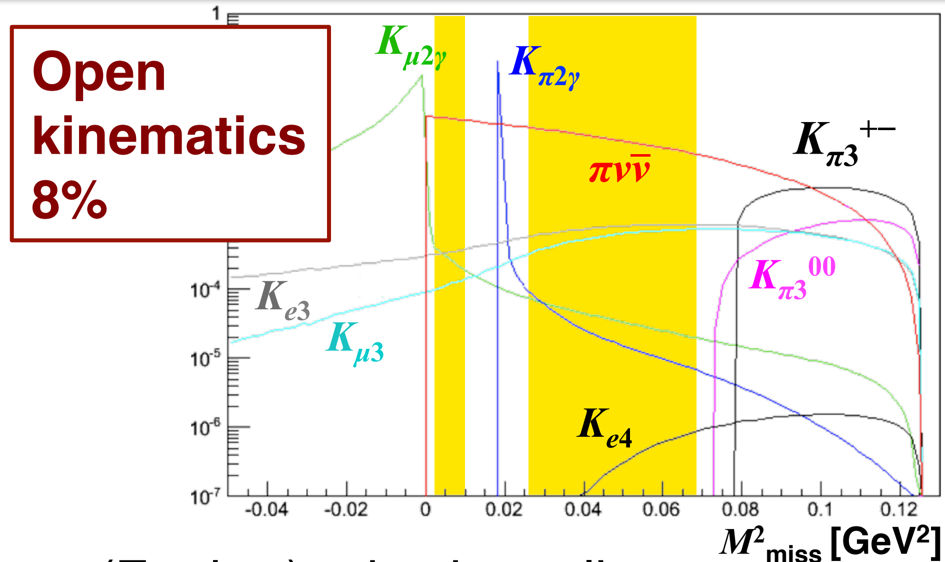
Mode	BR
$\mu^+\nu(\gamma)$	**63.5%**
$\pi^+\pi^0(\gamma)$	**20.7%**
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1 × 10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2 × 10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4 × 10^{-5}
$e^+\nu(\gamma)$	1.5 × 10^{-5}

Other backgrounds

Upstream interactions

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: Background rejection





$m^2_{\text{miss}} = 0$ or m_π^2 to reject $\mu\nu$, $\pi\pi^0$ → 2 fiducial regions in m^2_{miss}

- High resolution m^2_{miss} reconstruction
- Precise measurement of p_K and p_π
- Minimize multiple scattering

High-rate beam tracker
Low-mass spectrometer in vacuum

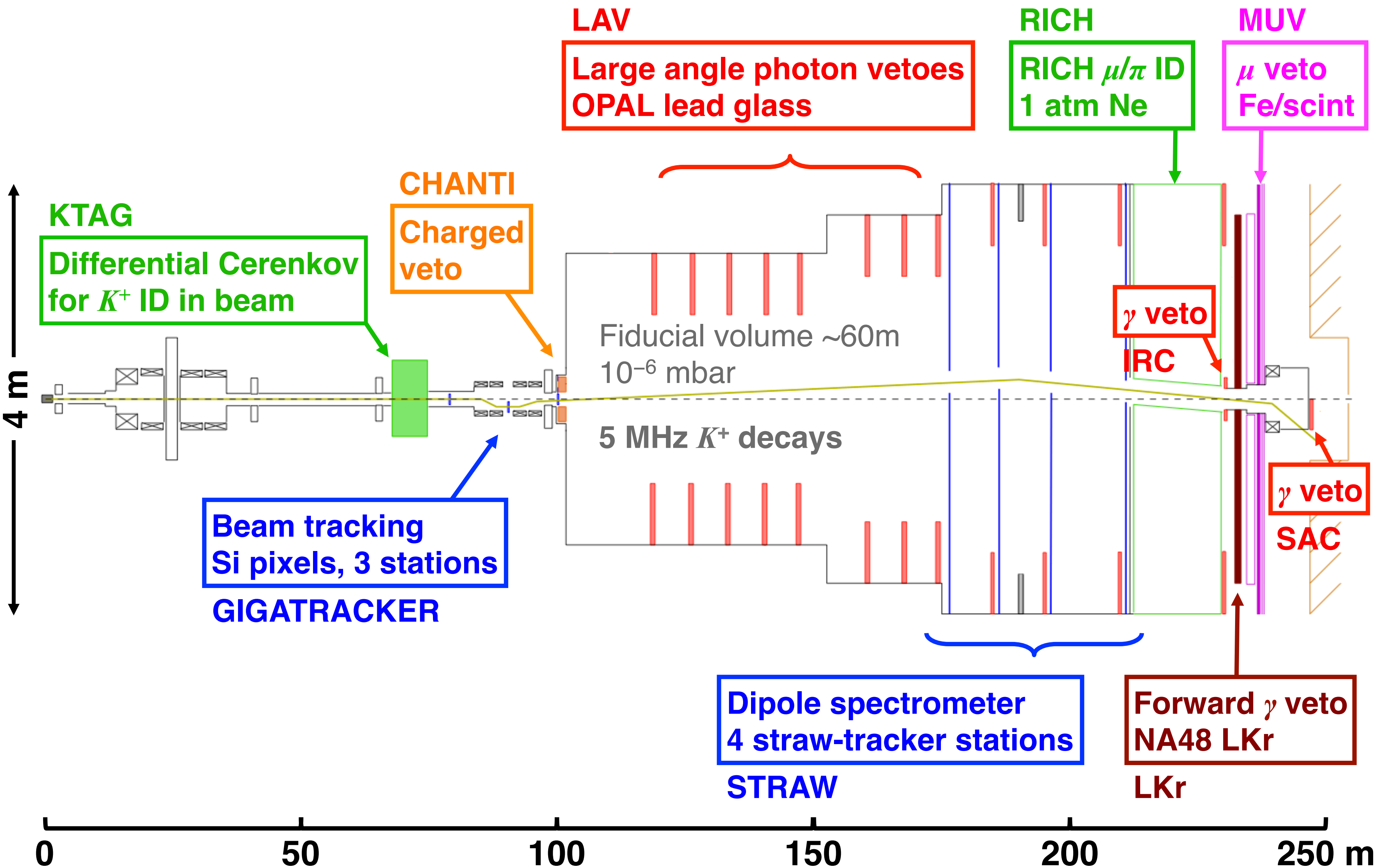
Rejection from kinematics alone: 10^{-4} at best

(Further) rejection relies on PID and vetoes

- Veto detectors for π^0 rejection
- K^+ identification in hadron beam
- Detectors for π/μ separation

Hermetic γ vetoes
Non-destructive beam ID
Secondary particle ID
Muon vetoes

The NA62 experiment at the SPS

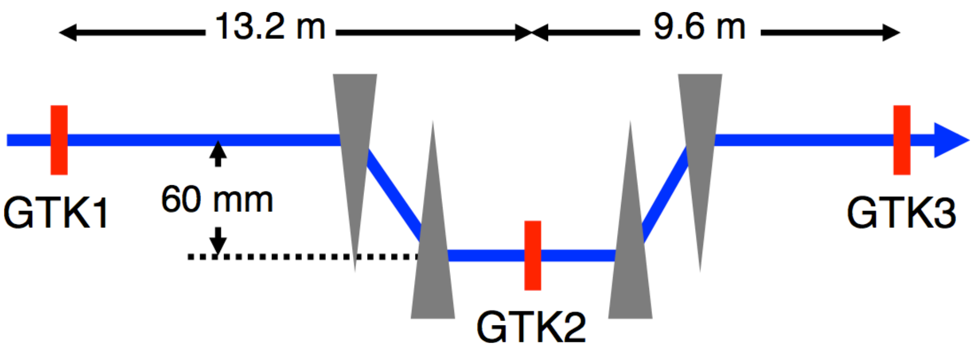


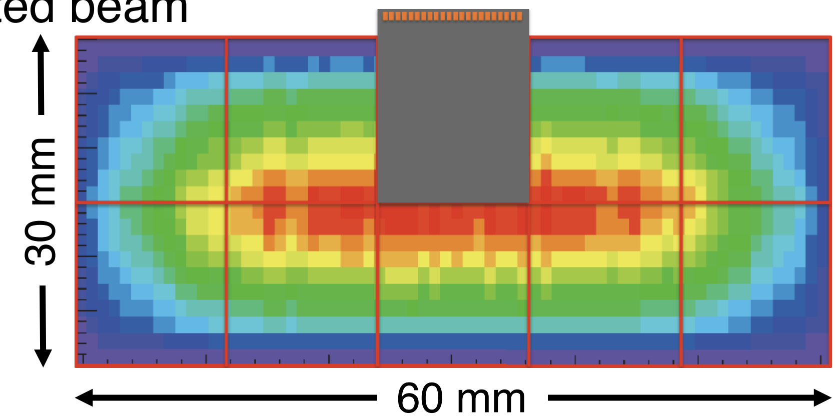
High-rate, precision tracking

Beam tracking: Gigatracker

3 planes of hybrid Si pixel detectors: 1 sensor, 10 bump-bonded readout chips

Tracks individual particles in 750 MHz unseparated beam





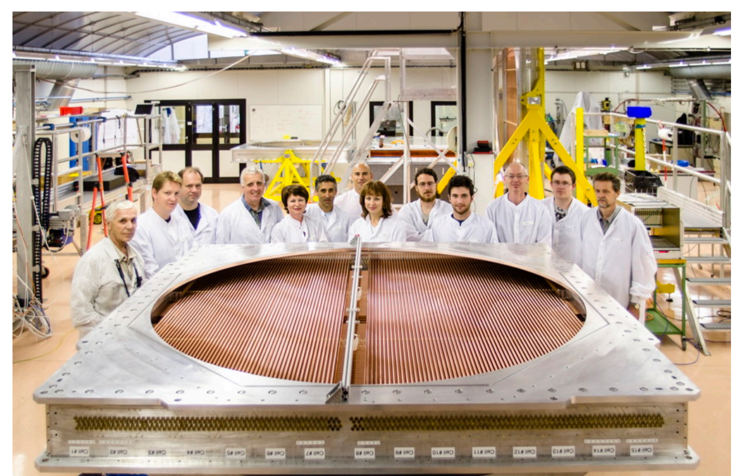
Pixel size 300 × 300 μm² → σ_p/p **~ 0.2%,** σ_θ **= 16 μrad**

Secondary tracking: 4 straw chambers in vacuum

4 chambers, 2.1 m in diameter
16 layers (4 views) of straws per chamber

$\sigma \leq$ 130 μm (1 view)
0.45X_0 per chamber

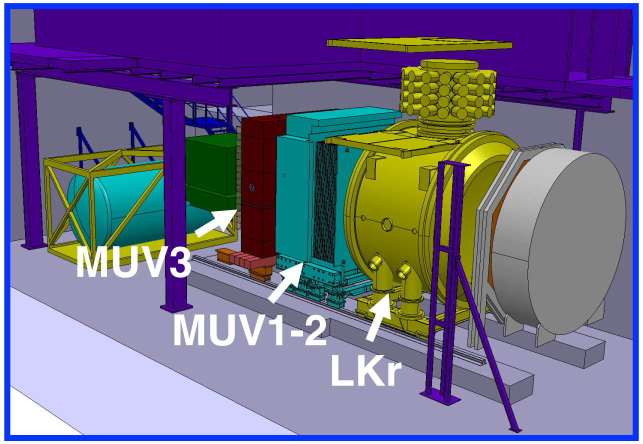
σ_p/p **= 0.32% ⊕ 0.008%** p
$\sigma_{\theta(K\pi)}$ **= 20-50 μrad**



MNP33 dipole: 0.36T ($\Delta p_\perp$ = 270 MeV)

Particle identification

Primary μ/π separation from downstream muon vetoes (MUV)



MUV1-2: Fe/scintillator hadron calorimeter

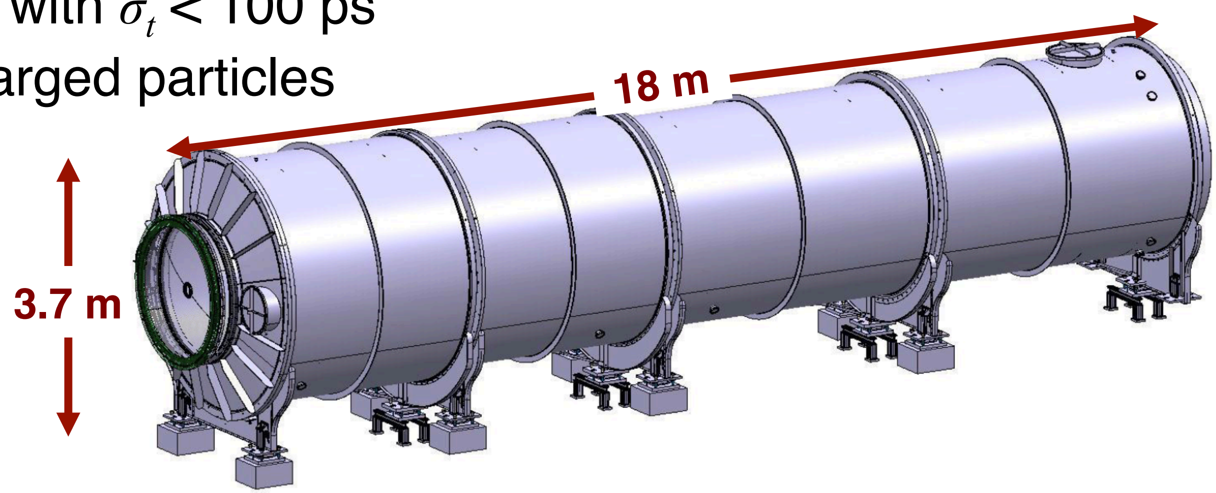
- Used offline to provide principal veto for $K \to \mu\nu$
- Rejects μ to 10^{-5}

MUV3: Fast μ identification for trigger

- Vetoes μ online at 10 MHz with $\sigma_t < 1$ ns

RICH provides additional 10^{-2} μ rejection to exclude $K \to \mu\nu$

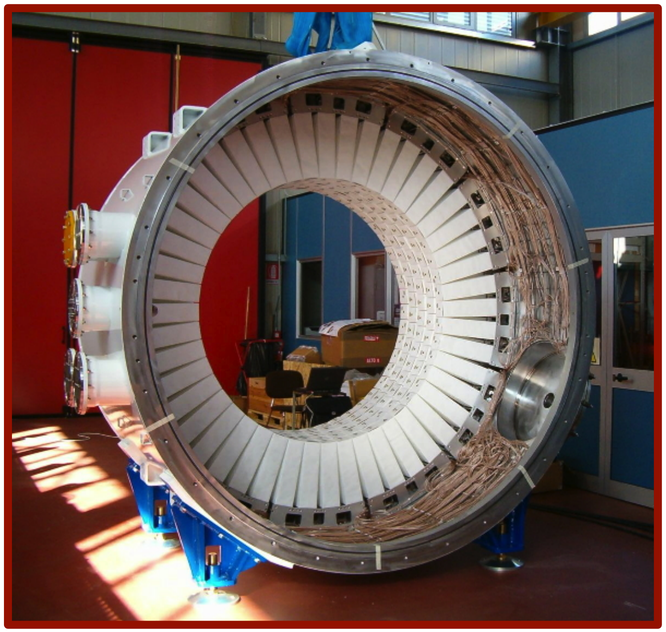
- μ/π separation to better than 1% for $15 < p < 35$ GeV
- Measures π crossing time with $\sigma_t < 100$ ps
- Provides L0 trigger for charged particles
- Ne gas at 1 atm
  $p_{\text{thresh}} = 12$ GeV for π
- 2000 8-mm PMTs on upstream flanges



Photon veto detectors

Large-angle vetoes (LAV)

$8.5 < \theta < 50$ mrad



12 stations at intervals of ~10m along vacuum decay volume

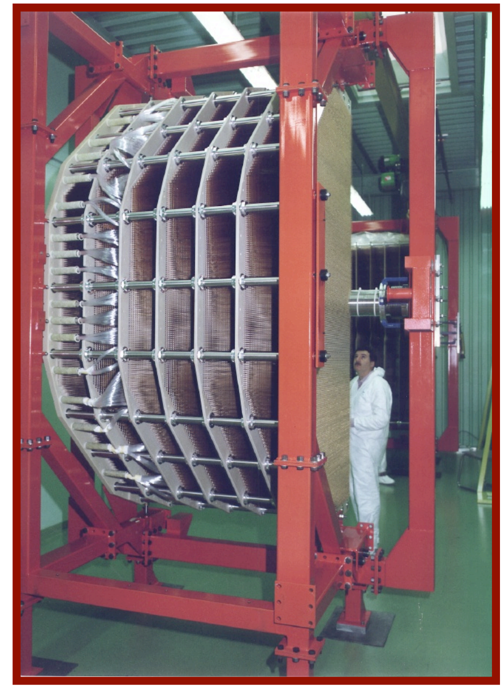
4-5 rings/station of lead glass blocks salvaged from OPAL EM barrel calorimeter

1–ε for e^- at 200 MeV: (1±1) × 10^{-4}

Tagged e^- at Frascati BTF

NA48 liquid krypton calorimeter (LKr)

$1 < \theta < 8.5$ mrad



Quasi-homogeneous ionization calorimeter

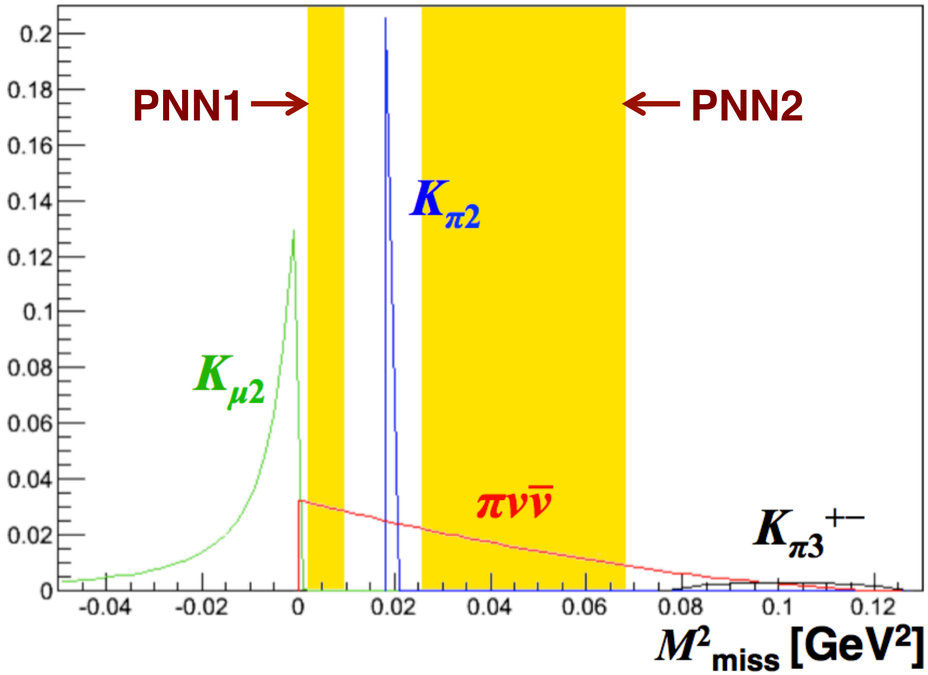
Readout towers 2×2 cm^2 - 13248 channels

Depth 127 cm = 27 X_0

1–ε for γ with E > 10 GeV: < 8 × 10^{-6}

$\pi\pi^0$ and e^- bremsstrahlung events in NA48

Performance for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



- 1 track with $15 < p_\pi < 35$ GeV and π PID in RICH
- No γs in LAV, LKr, IRC, SAC
- No μs in MUVs
- 1 beam particle in Gigatracker with K PID by KTAG
- z_{vtx} in 60 m fiducial volume

Acceptance: ~12%

3% in PNN1 region

9% in PNN2 region

50% loss from momentum cut

Detector inefficiencies included

45 signal events/yr

Expected backgrounds	
$K^+ \rightarrow \pi^+\pi^0$	11%
$K^+ \rightarrow \pi^+\pi^0\gamma_{\text{IB}}$	3%
$K^+ \rightarrow \mu^+\nu$	2%
$K^+ \rightarrow \mu^+\nu\gamma_{\text{IB}}$	1%
$K^+ \rightarrow \pi^+\pi^+\pi^-$	< 2%
K^+_{e4}, other 3 track decays	< 2%
K^+_{e3}, $K^+_{\mu 3}$	negligible
Total	**< 20%**

NA62 sensitivity for LFNV decays

Decays in FV in 2 years of data: **1×10^{13} K^+ decays**, **2×10^{12} π^0 decays**

Single-event sensitivity 1/(decays × acceptance)

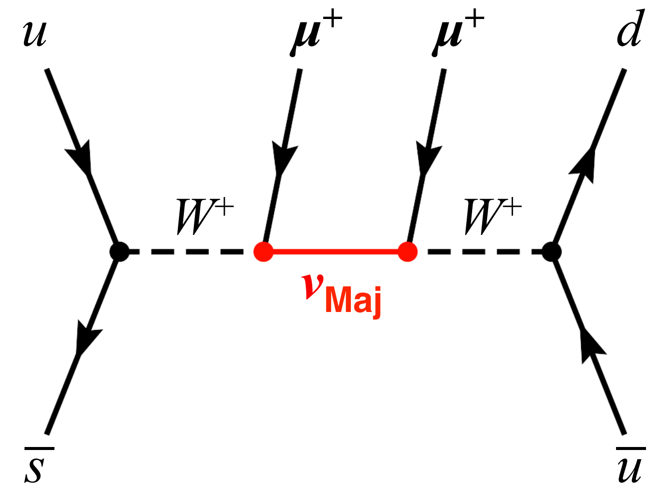
Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	~10%
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	~10%
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	~5%
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	~20%
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva Saclay	~2%
$K^+ \to e^-\nu\mu^+\mu^+$	no data		~10%
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	KTeV	~2%
$\pi^0 \to \mu^-e^+$			

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

NA62 single-event sensitivities: **~10^{-12} for K^+ decays**, **~10^{-11} for π^0 decays**

Lepton number violation: $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$

LNV in $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ could provide evidence for Majorana nature of neutrino

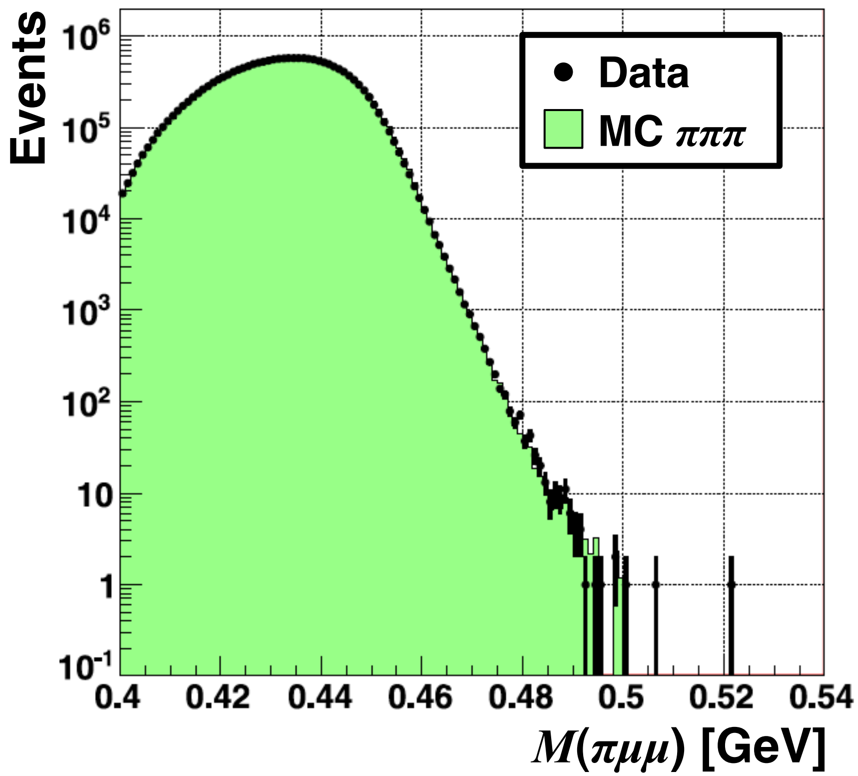


NA48/2 (2011) PLB697

BR($\pi^\mp\mu^\pm\mu^\pm$) < 1.1 × 10^{-9} 90%CL

$\langle M_{\mu\mu}\rangle < 0.3$ TeV

Like-sign muons ($\pi^\mp\mu^\pm\mu^\pm$)



NA48/2

52 candidate events with $M(\pi\mu\mu) \sim m_K$

In agreement with MC background prediction

- Unusual $\pi\pi\pi$ topology with 2 $\pi \to \mu$ decays
- 1 of $\pi \to \mu$ between magnet & last DC

NA62

60× increase in kaon flux

Increased $p_\perp$ kick in will eliminate $K_{\pi 3}$ background without p_π cut

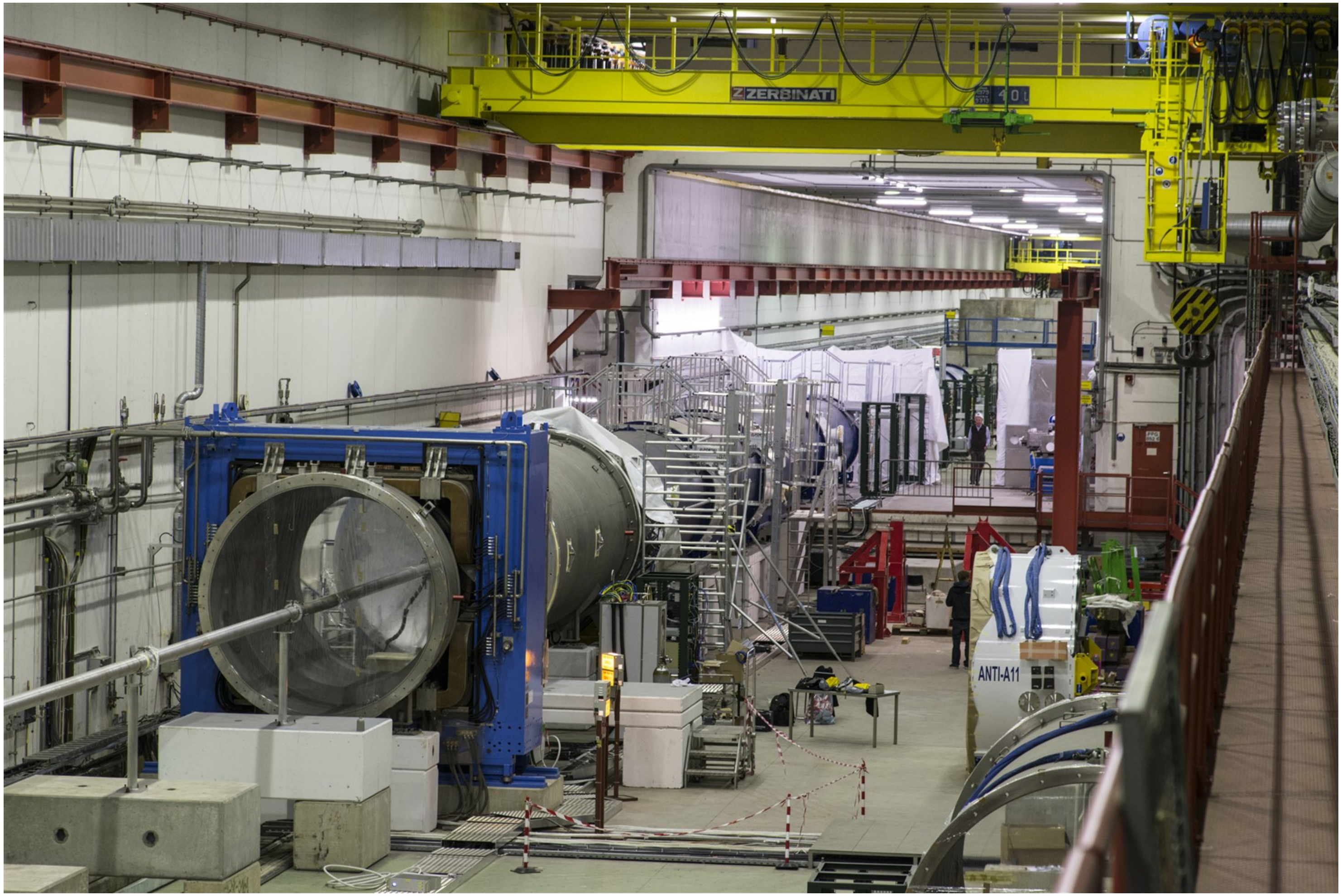
Potential sensitivity ~ 10^{-12}

Rare π^0 decays in NA62

2×10^{12} π^0 decays in FV in 2 years of data will allow substantial improvement of results in many channels

Mode	Current knowledge	Experiment	Expectation in SM	Physics interest
Neutral modes				
$\pi^0 \to 3\gamma$	$BR_{90CL} < 3.1\times10^{-8}$	Crystal Box	Forbidden	Violates C
$\pi^0 \to 4\gamma$	$BR_{90CL} < 2\times10^{-8}$	Crystal Box	$BR \sim 10^{-11}$	Scalar states $\pi^0 \to SS$
$\pi^0 \to$ inv	$BR_{90CL} < 2.7\times10^{-7}$	BNL 949	$BR < 10^{-13}$ (cosm. limit)	N_ν, LFV
Charged modes				
$\pi^0 \to e^+e^-e^+e^-$	$BR = 3.34(16)\times10^{-5}$	KTeV	$3.26(18) \times10^{-5}$	Off-shell vectors
$\pi^0 \to e^+e^-\gamma$	$BR_{95CL}(\pi^0\to U\gamma)$: $< 1\times10^5$, $M_U = 30$ MeV; $< 3\times10^6$, $M_U = 100$ MeV	WASA/COSY	Null result	Dark forces

Experimental status



Installing/installed: **KTAG, LAV (8/12), CHOD, LKr (readout), SAC**

Under construction: **Gigatracker, CHANTI, STRAWS, RICH, IRC, MUV**

NA62 will take 2 years of data starting late 2014

Summary & outlook

Rare kaon decays are powerful probes for new physics

- $K^+ \to \pi^+ \nu\bar{\nu}$ highly suppressed and precisely calculated in the SM

NA62 will measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to 10%

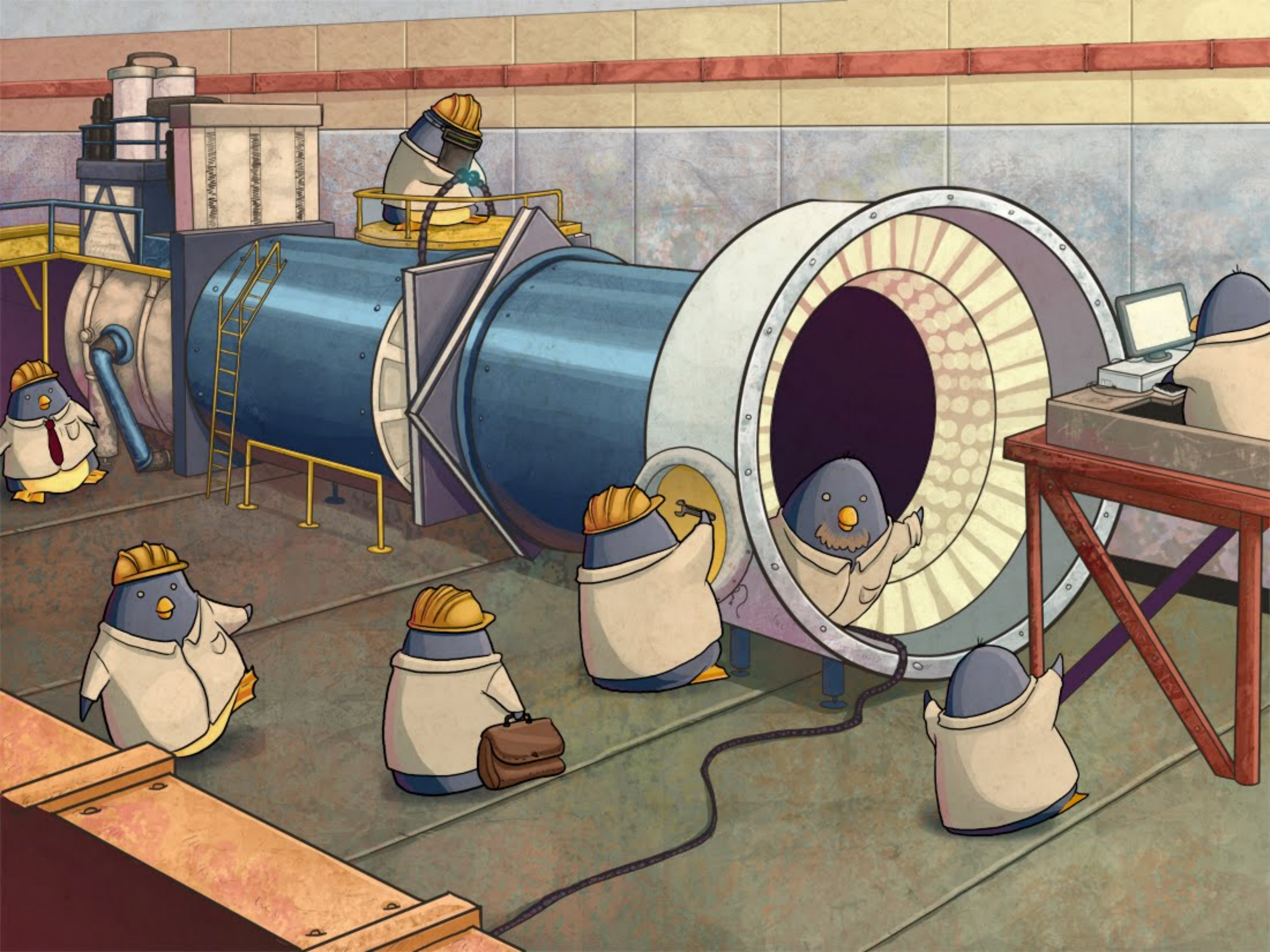
- Will shed light on flavor structure of new physics if discovered at LHC
- May provide evidence for new physics even if not discovered at LHC

NA62 is well adapated to search for other rare/forbidden K and π decays

- Copious production of K^+ and π^0
- Robust background rejection: tracking, PID, vetoes

NA62 will take two years of data starting in late 2014

- ~10^{13} K^+ decays in the fiducial volume
- ~10% acceptance (including trigger efficiency) for LFNV decays
- Single event sensitivities ~10^{-12} for LFNV decays and improved sensitivity for related searches



K12 high-intensity K^+ beamline

Primary SPS proton beam:

- p = 400 GeV protons
- 3 × 10^{12} protons/pulse (3× NA48/2)
- Duty factor ~ 0.3

  Expect similar to 4.8s/16.8 s duty cycle for NA48/2

  Simultaneous beam delivery to LHC

High-intensity, unseparated secondary beam

- Momentum selection chosen to optimize K decays
- p = 75 GeV (1.4× more K^+ than NA48/2)
- $\Delta p/p$ ~ 1% (3× smaller than NA48/2)
- Beam acceptance 12.7 μstr (32× NA48/2)

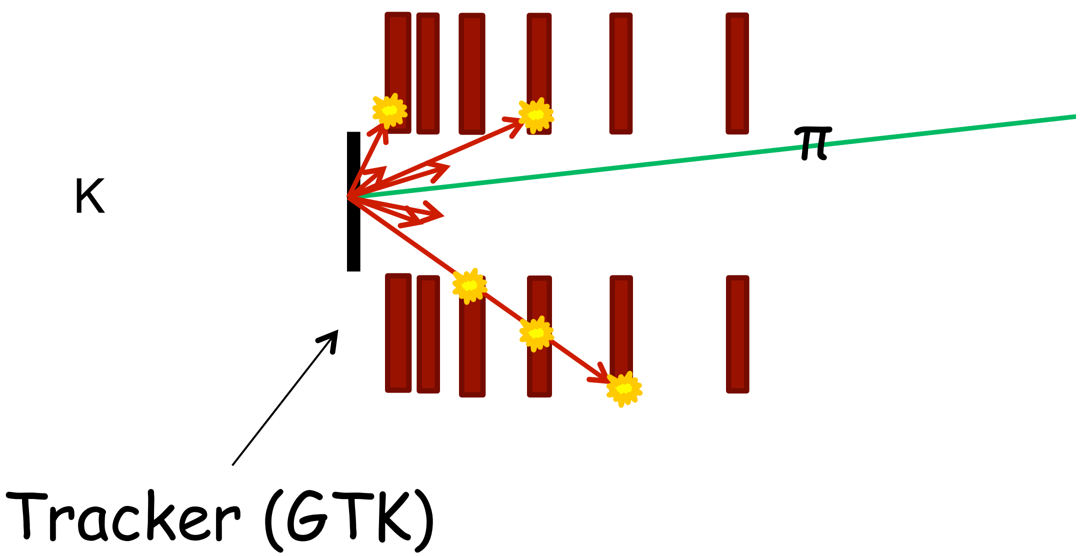
Total rate 750 MHz $\left\{ \begin{array}{l} \textbf{525 MHz } \pi \\ \textbf{170 MHz } p \\ \textbf{45 MHz } K \end{array} \right.$

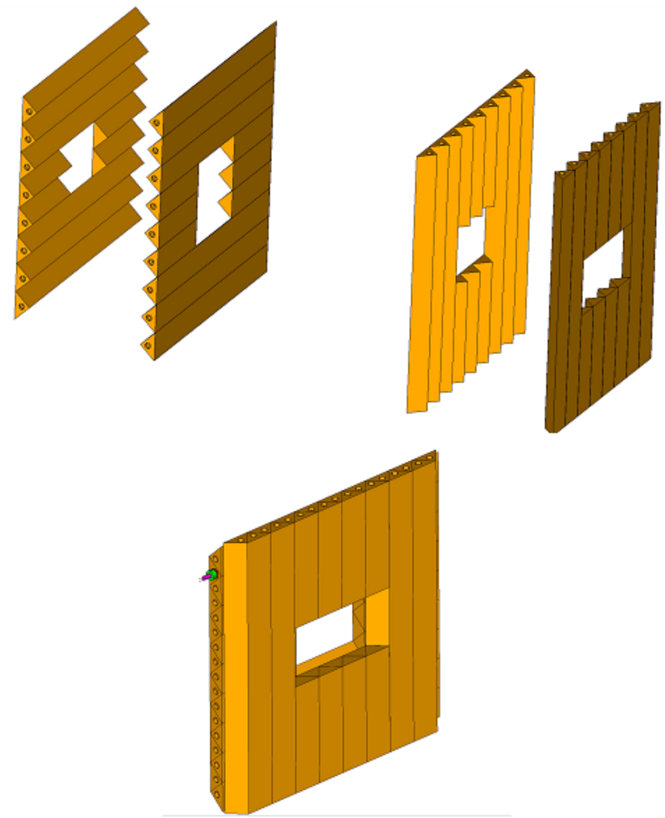
Decay volume

- 60 m long, starting at z = 102 m from target
- 10% of K^+ decay in FV ($\beta\gamma c\tau$ = 560 m)

4.5 × 10^{12} K^+ decays/yr = 45× NA48/2

CHANTI





Hermetic photon vetoes

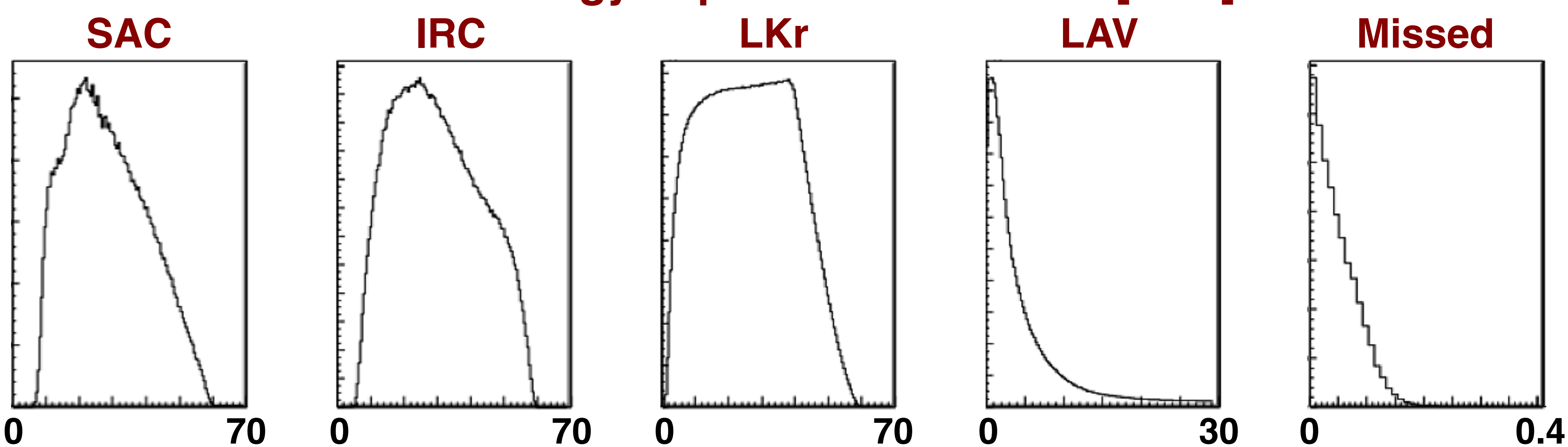
BR($K^+ \to \pi^+\pi^0$) = 21%

- Kinematic rejection (M^2_{miss}) = 10^{-4}
- Cut $p_{\pi+} < 35$ GeV gives $\pi^0 \to \gamma\gamma$ with 40 GeV
- Remaining events have 2γ in one of three configurations:

81.2%	Both γ in forward vetoes
18.6%	1γ in forward vetoes, 1γ in LAVs
0.2%	1γ in LAVs, 1γ undetected

Detector	**θ [mrad]**	**Max. $1 - \varepsilon$**
LAV	8.5 - 50	10^{-4} at 200 MeV
LKr	1 - 8.5	10^{-3} at 1 GeV 10^{-5} at 10 GeV
IRC+SAC	< 1	10^{-4} at 5 GeV

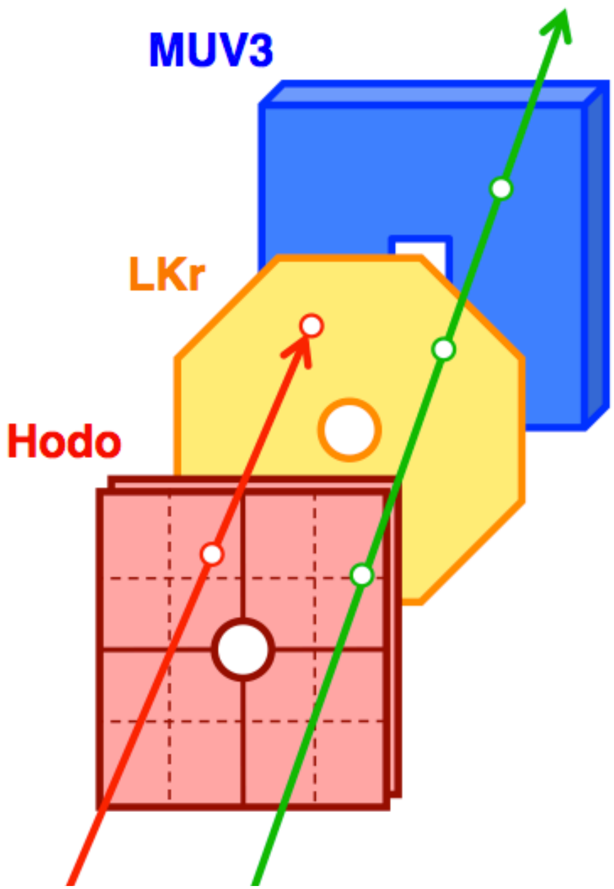
Photon energy deposited in detector [GeV]



Trigger and data acquisition

Example L0 trigger primitives:

Q_n	Hits in at least n Hodo quadrants
$LKR_n(x)$	At least n LKr clusters with energy $E > x$ GeV
MUV_n	Hits in at least n MUV3 pads



10 MHz L0 primitives

L0
Implemented on digital readout card
Example L0 trigger for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$:
$\mathbf{Q_1 \cdot LKR_1 \cdot \overline{MUV}}$

1 MHz L0 output

L1
Asynchronous
Implemented in L1 trigger processor PC

100 kHz L1 output

L2
Asynchronous
Implemented in event builder PC
First level to correlate information from different subdetectors

O(kHz) L2 output to disk

Beam timing and PID

Gigatracker (750 MHz) ← **Must precisely match events** → **Downstream detectors (~10 MHz)**

Matching downstream π track to wrong beam particle leads to 3× increase in $\sigma(m_{miss})$

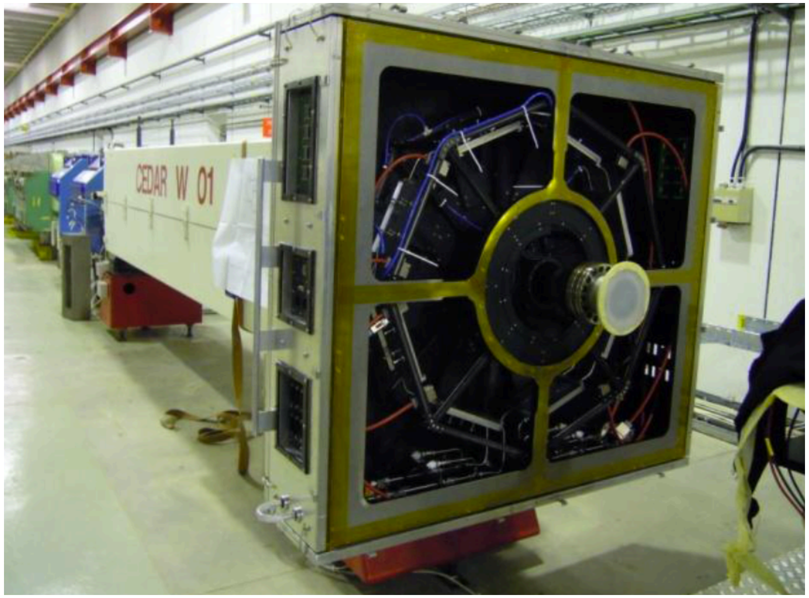
Use detectors with good time resolution to avoid mismatching:

Gigatracker: σ_t **< 200 ps/station**
KTAG: σ_t **= 100 ps**
RICH: σ_t **< 100 ps**

Mismatch probability < 1%
Still accounts for half of kinematic rejection inefficiency

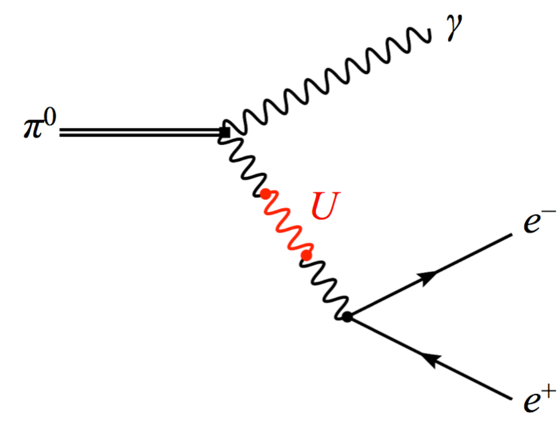
Non-destructive beam PID using KTAG differential Cerenkov counter

- Identifies 45 MHz of K^+ in 750 MHz of unseparated beam
- Beam ID fundamental to suppress background from beam-gas interactions
    Without KTAG, need 10^{-6} mbar vacuum in decay tank!
- Original CEDAR-W design, now running with H_2 at 3.85 bar
- Completely new, high segmentation readout



Rare π^0 decays in NA62

Search for U boson in $\pi^0 \to e^+e^-\gamma$ decay



New, light vector gauge boson with weak couplings to charged SM fermions

Could mediate interactions of dark-matter constituents

Expect to collect ~10^8 $\pi^0 \to e^+e^-\gamma$ decays/year

Mass resolution $M_{ee} \sim 1$ MeV

Potential for ~100× improvement in BR limit for $30 < M_U < 100$ MeV

Search for $\pi^0 \to$ invisible

$\pi^0 \to \nu\bar{\nu}$ forbidden by angular momentum conservation if νs are massless
For a given flavor of massive $\bar{\nu}$, BR($\pi^0 \to \nu\bar{\nu}$) directly related to m_ν

Direct experimental limit:

BNL 949 (2005)

BR($\pi^0 \to$ inv) < 2.7×10^{-7} 90%CL

Inferred limits on BR($\pi^0 \to \nu\bar{\nu}$) from:

Measured ν_τ mass: $< 5 \times 10^{-10}$

Astrophysics/cosmology: $< 3 \times 10^{-13}$

Experimental signature identical to $K^+ \to \pi^+\nu\bar{\nu}$

Only difference: in $K^+ \to \pi^+\pi^0$, $\pi^0 \to$ invisible, π^+ has 2-body decay kinematics

Limit BR($\pi^0 \to$ invisible) to less than 10^{-9}, ~100× better than present limits

NA62 prospects for $\pi^0 \to 3\gamma, 4\gamma$

Main backgrounds: $K \to \pi\pi^0(\gamma)$ and $K \to \pi\pi^0\pi^0$ with $\pi^0 \to 2\gamma$

Trigger

Level 0: Dedicated trigger to reduce rates to acceptable levels while maintaining reasonable efficiencies

E.g., for $\pi^0 \to 3\gamma$: **$\mathbf{Q_1 \cdot LKR_{=3}(1\ GeV)^* \cdot \overline{MUV}}$**

Level 1: Refine using kinematics reconstructed in LKr

$M_{3\gamma}$ vs. p_π^{CM}

Analysis

Use veto detectors to reject extra photons (for $\pi^0 \to 3\gamma$)

Kinematic fit to complete event to provide an additional rejection factor of 10^{-4}

Potential

Sensitivity to BRs ~ 10^{-10}

~100× better than present limits

* Possibly with optimized LKR trigger segmentation

NA62 prospects: $\pi^0 \rightarrow$ invisible

Experimental signature identical to $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

Only difference: in $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow$ invisible, π^+ has 2-body decay kinematics

Trigger

Baseline level-0 criteria same as for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

$$\mathbf{Q_1 \cdot LKR_1 \cdot \overline{MUV}}$$

Refinements possible, e.g., inclusion of LAV at L0 or L1

Dominant contribution to trigger rate is from π^+/γ overlap with 1 missed γ

Analysis

Stringent track-quality requirements for π^+

Cuts on $p_{\pi+}$, $\theta_{\pi+}$ to minimize γs at large angle and increase π^0 rejection

Less help from kinematics than in $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, but hope to improve on NA62 π^0 rejection by at least 10×

Potential

Limit BR($\pi^0 \rightarrow$ invisible) to less than 10^{-9}

~100× better than present limits