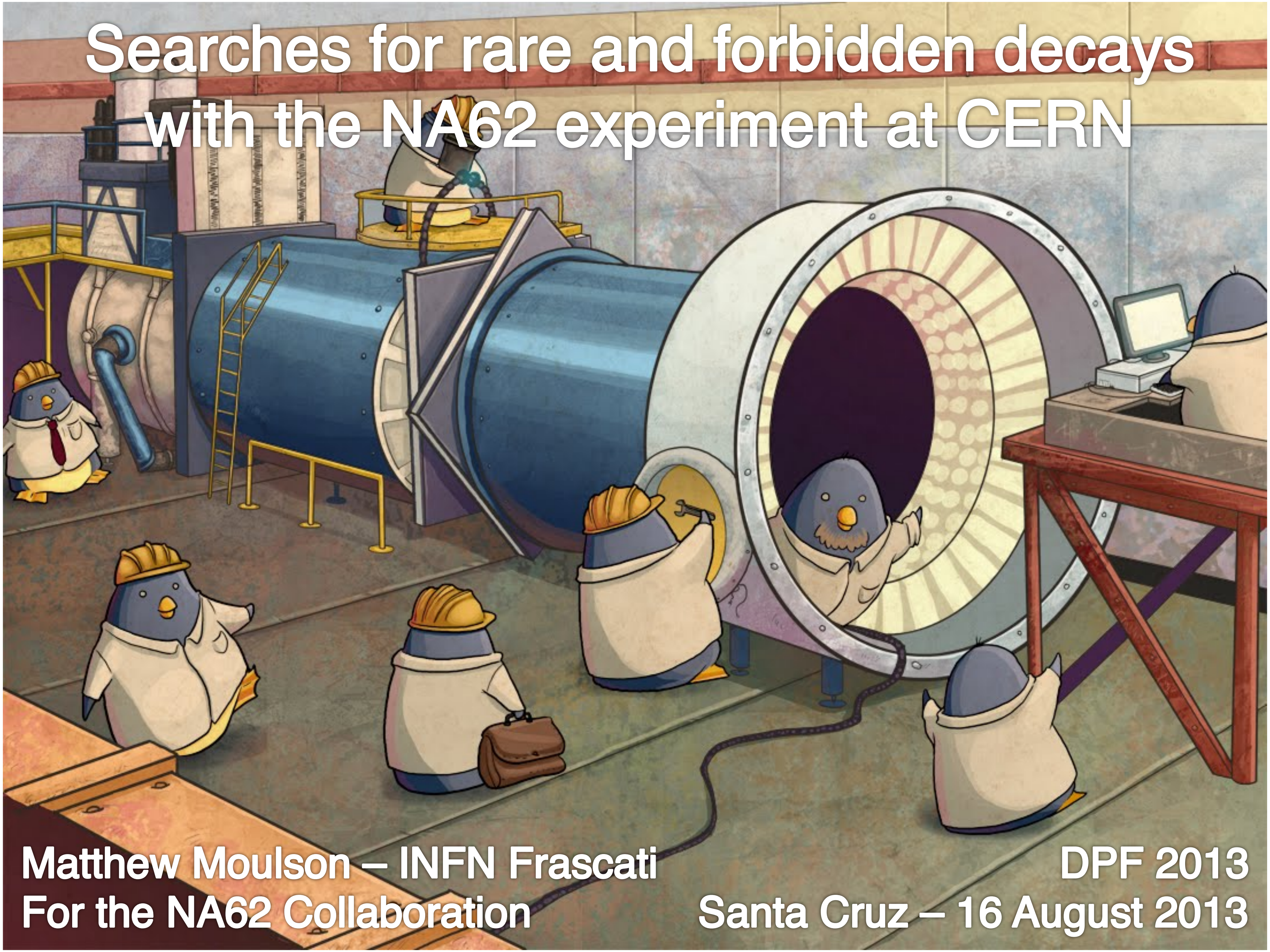
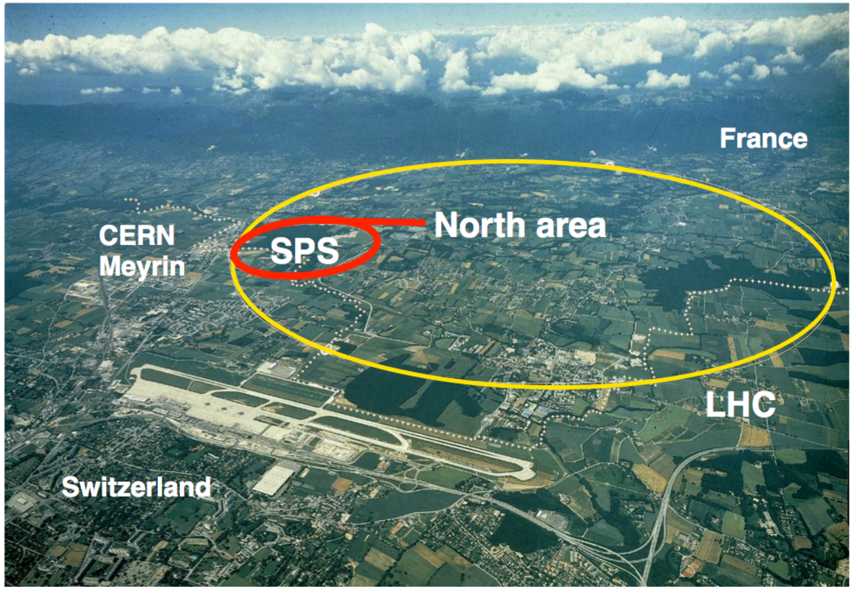
Searches for rare and forbidden decays with the NA62 experiment at CERN



Matthew Moulson – INFN Frascati
For the NA62 Collaboration

DPF 2013
Santa Cruz – 16 August 2013

The NA62 experiment at CERN



1997-2002 NA48, NA48/1
Simultaneous K_S, K_L beams
Re ε'/ε, 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:

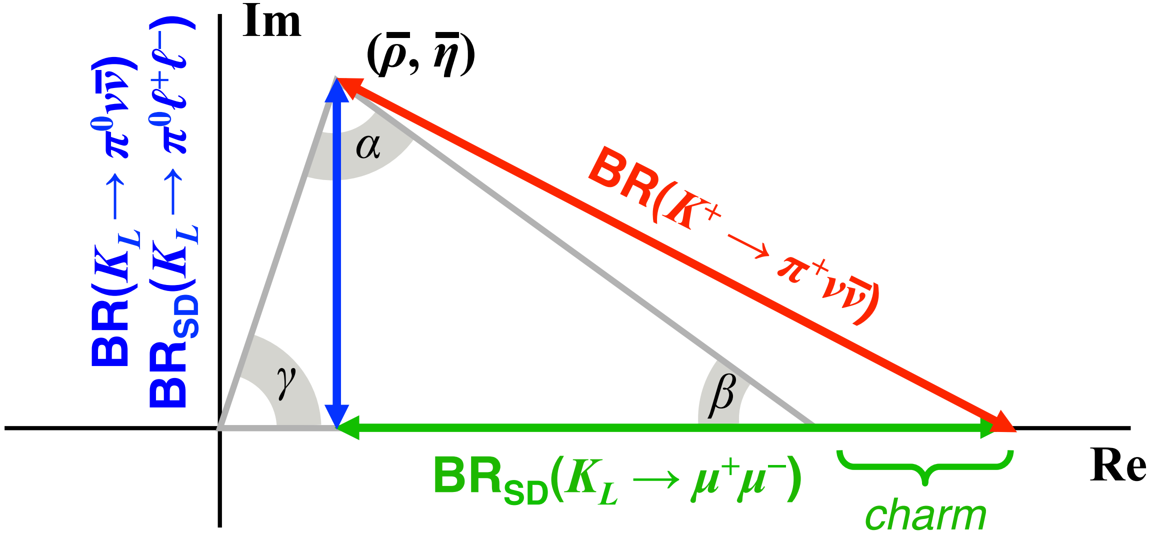
- K decays with explicit lepton flavor or number violation **(LFNV)**
- Forbidden π^0 decays tagged by $K^+ \to \pi^+\pi^0$

Rare kaon decays

FCNC processes dominated by Z-penguin and box diagrams

Short-distance amplitudes related to $\mathrm{V}_{\mathrm{CKM}}$ with minimal non-parametric uncertainty

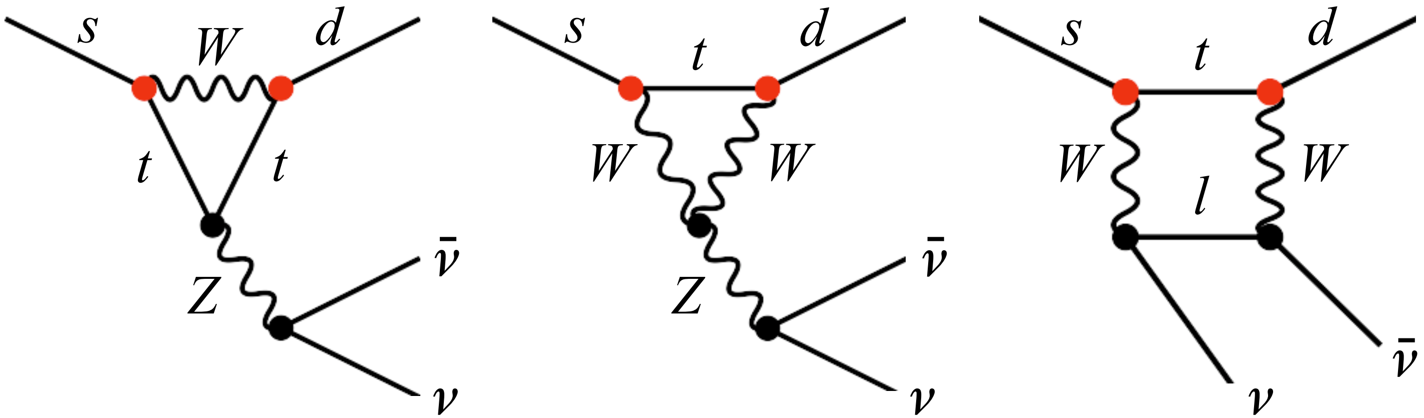
Rate measurements overconstrain $\mathrm{V}_{\mathrm{CKM}}$ and may provide evidence for new physics



Decay	$\Gamma_{\mathrm{SD}}/\Gamma$	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	$< 28^{\dagger}$
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	$< 38^{\dagger}$
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 12
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	$<26000^{\dagger}$

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

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



$$\lambda = V_{us}$$

$$\lambda_c = V_{cs}^* V_{cd}$$

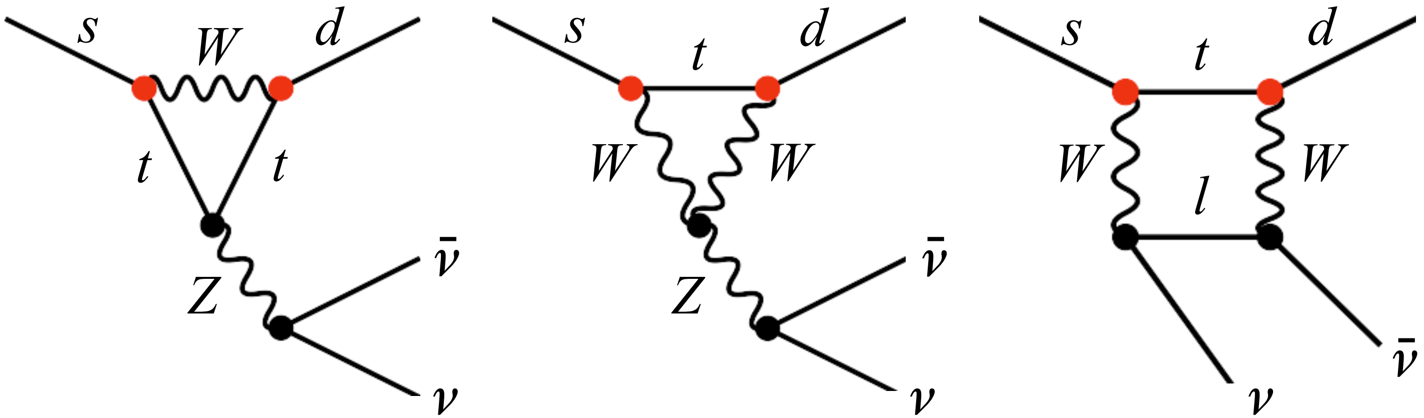
$$\lambda_t = V_{ts}^* V_{td}$$

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

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

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

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



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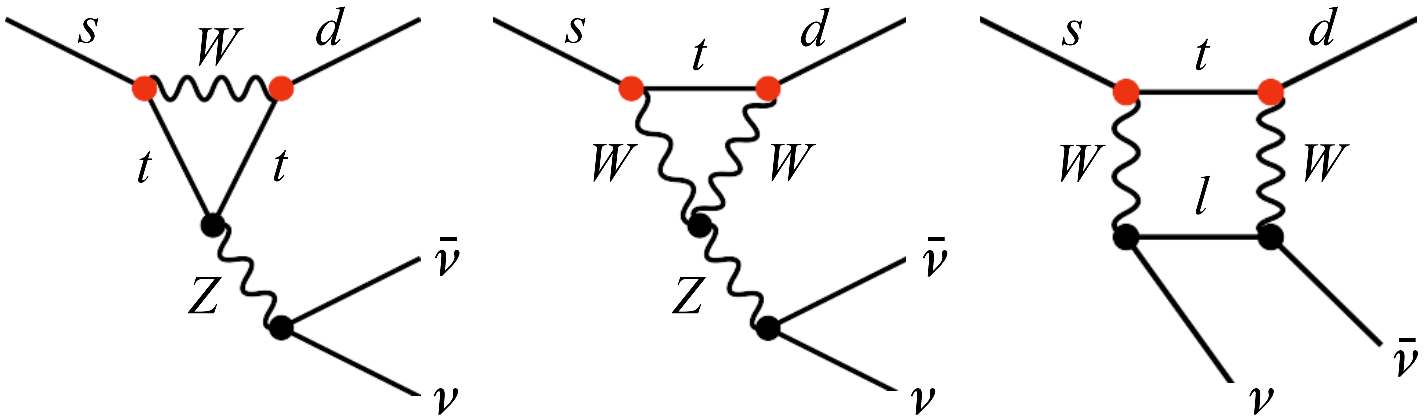
$$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

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

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

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



$$\lambda = V_{us}$$
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Loop functions favor top contribution

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

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

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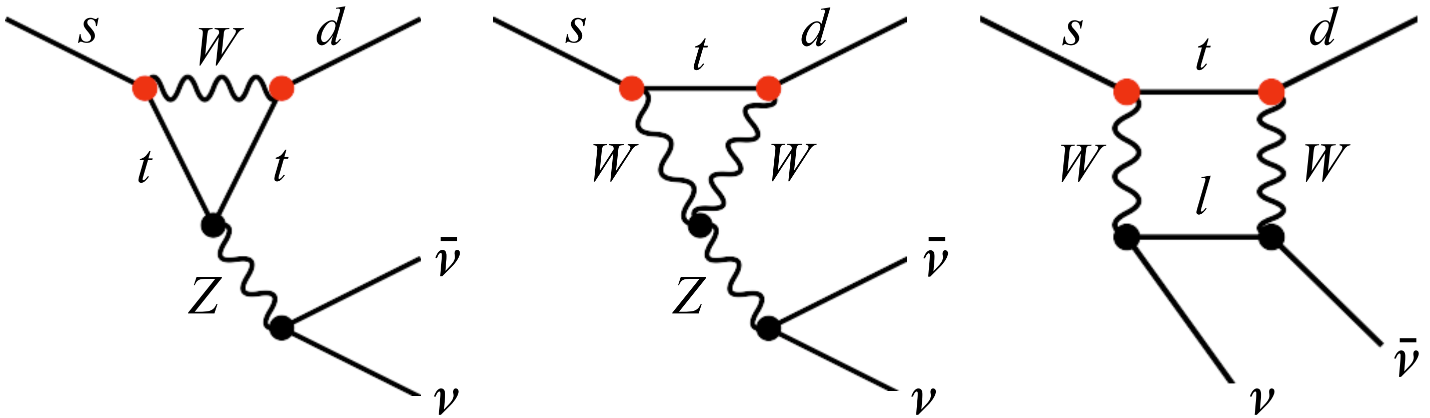
Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation

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



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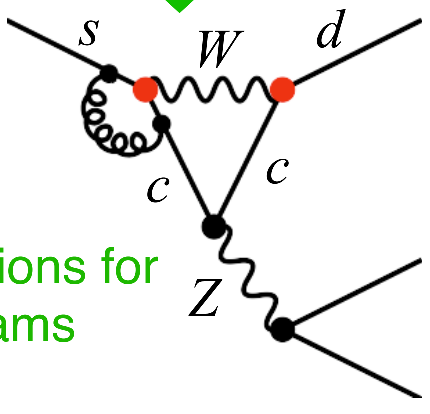


$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$

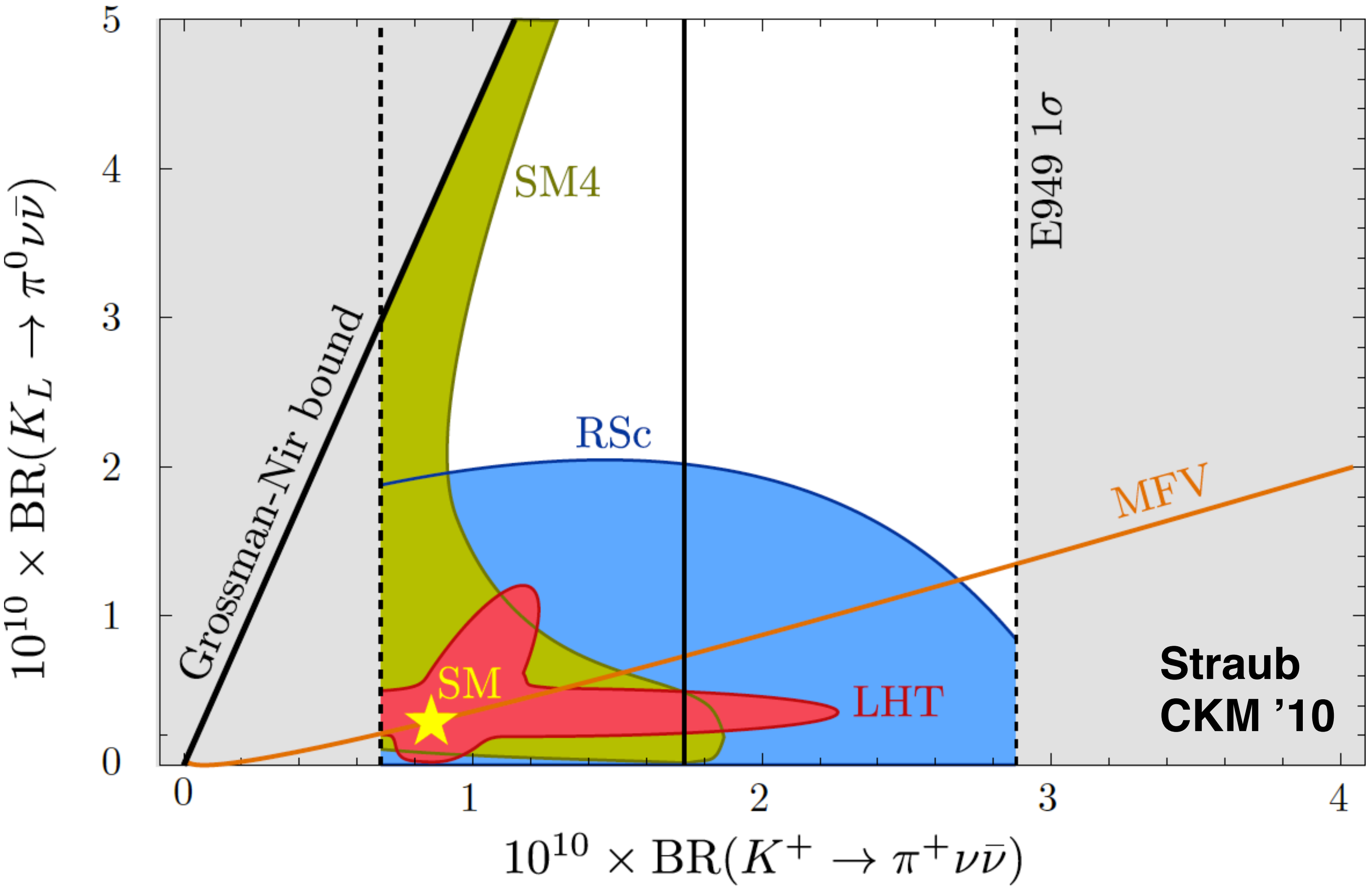
Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation

QCD corrections for charm diagrams contribute to uncertainty

$K \to \pi\nu\bar{\nu}$ 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)

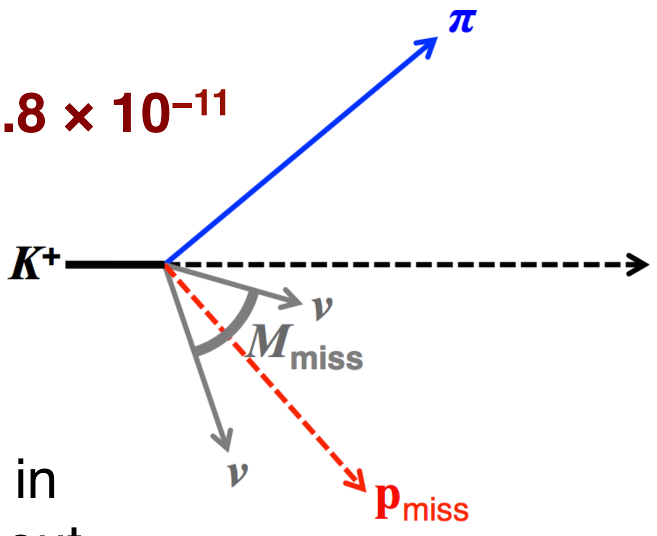
LHT: Littlest Higgs with T parity (Blanke ’10)

RSc: Custodial Randall-Sundrum (Blanke ’09)

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

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

Signal:
BR_{SM} ~ 7.8 × 10^{-11}



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

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%

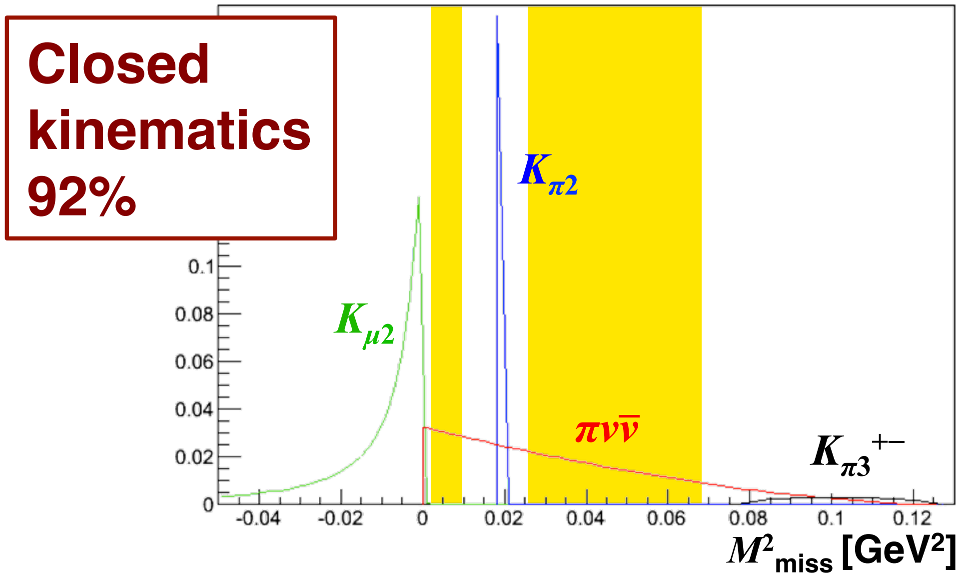
Decay backgrounds

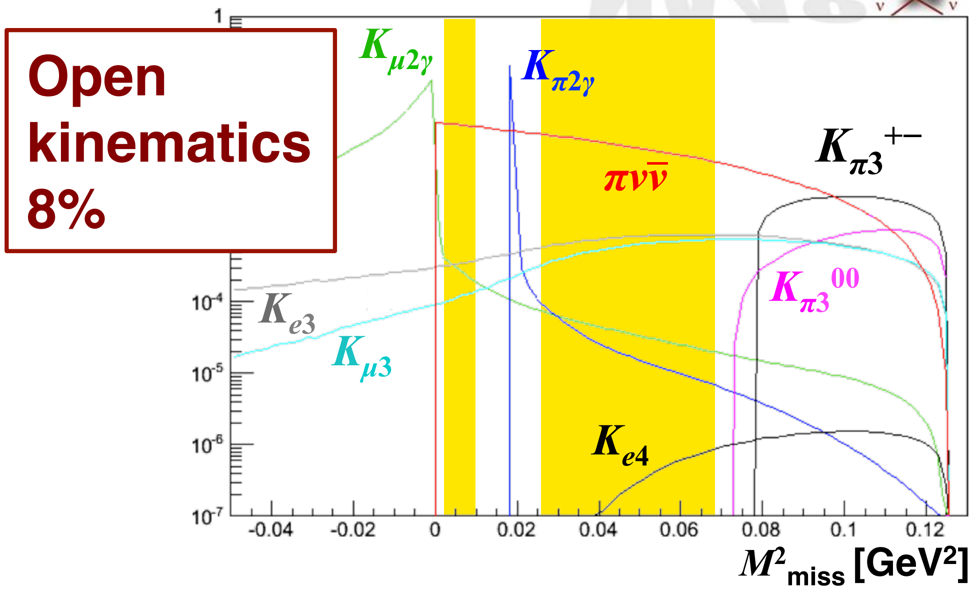
Mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1 × 10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2 × 10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4 × 10^{-5}
$e^+\nu(\gamma)$	1.5 × 10^{-5}

Other backgrounds

Beam-gas interactions
Upstream interactions

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


Closed kinematics 92%


Open kinematics 8%

$m^2_{\text{miss}} = 0$ 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

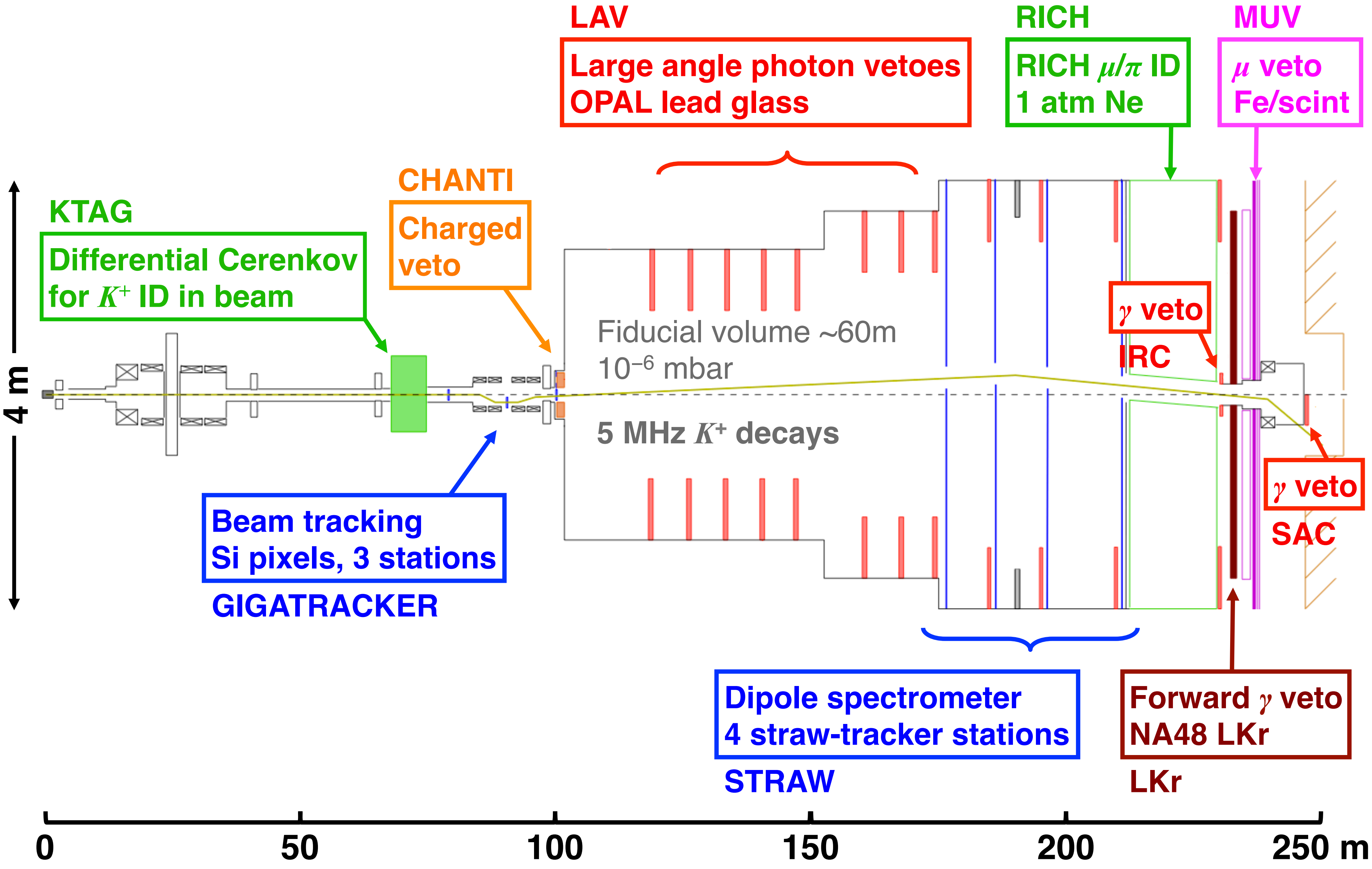
Rejection from kinematics alone: 10^{-4} at best

(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



LAV

Large angle photon vetoes
OPAL lead glass

RICH

RICH μ/π ID
1 atm Ne

MUV

μ veto
Fe/scint

CHANTI

Charged veto

KTAG

Differential Cerenkov for K^+ ID in beam

Fiducial volume ~60m
10^{-6} mbar

5 MHz K^+ decays

γ veto

IRC

γ veto

SAC

4 m

Beam tracking
Si pixels, 3 stations

GIGATRACKER

Dipole spectrometer
4 straw-tracker stations

STRAW

Forward γ veto
NA48 LKr

LKr

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)

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

Decay volume

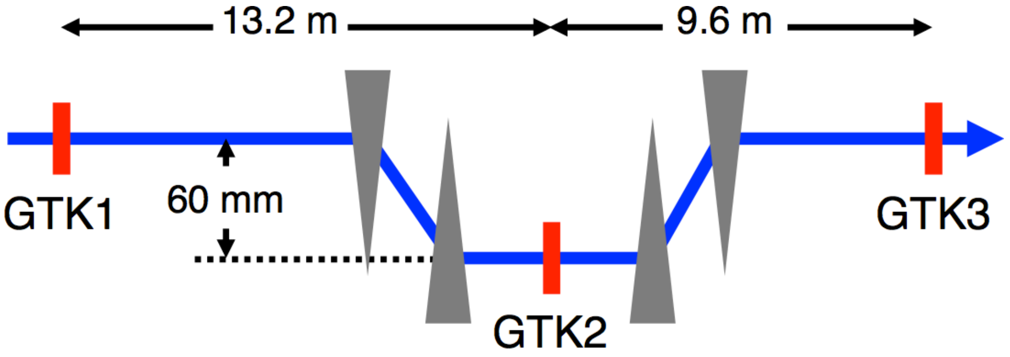
- 60 m long, starting at z = 102 m from target
- 10% of K^+ decay in FV ($\beta\gamma c\tau$ = 560 m)

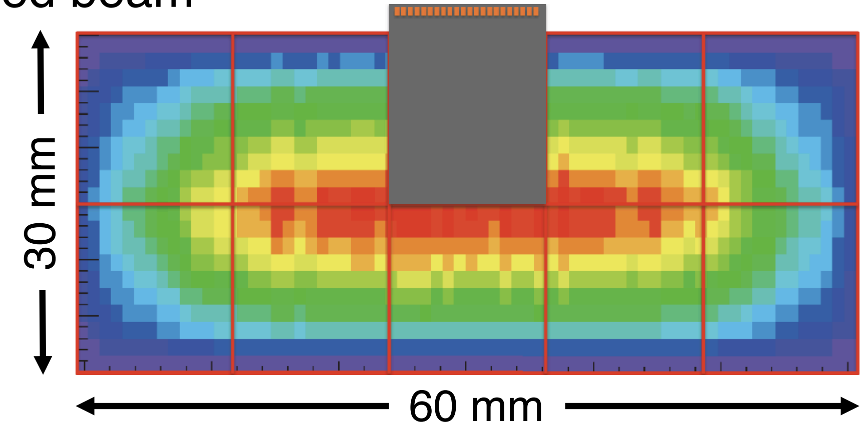
4.5 × 10^{12} K^+ decays/yr = 45× NA48/2

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 → $\boldsymbol{\sigma_p/p}$ **~ 0.2%,** $\boldsymbol{\sigma_\theta}$ **= 16 μrad**

Secondary tracking: 4 straw chambers in vacuum

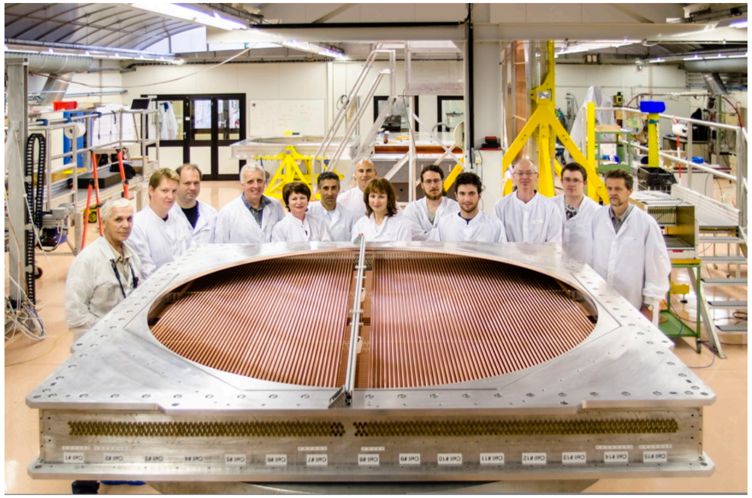
4 chambers, 2.1 m in diameter
16 layers (4 views) of straws per chamber

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

⇒

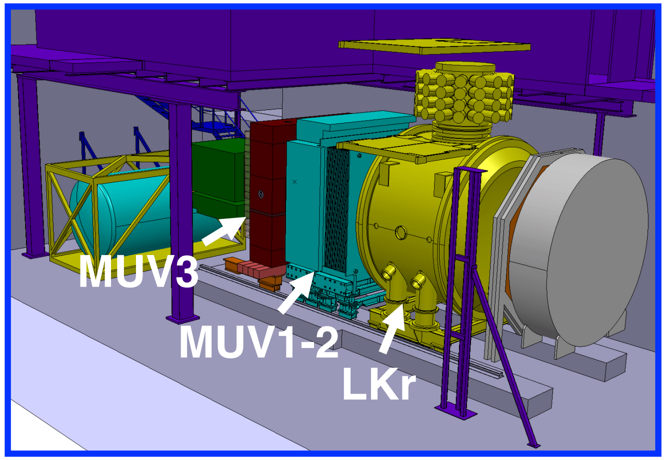
$\boldsymbol{\sigma_p/p}$ **= 0.32% ⊕ 0.008%** $\boldsymbol{p}$
$\boldsymbol{\sigma_{\theta(K\pi)}}$ **= 20-50 μrad**

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

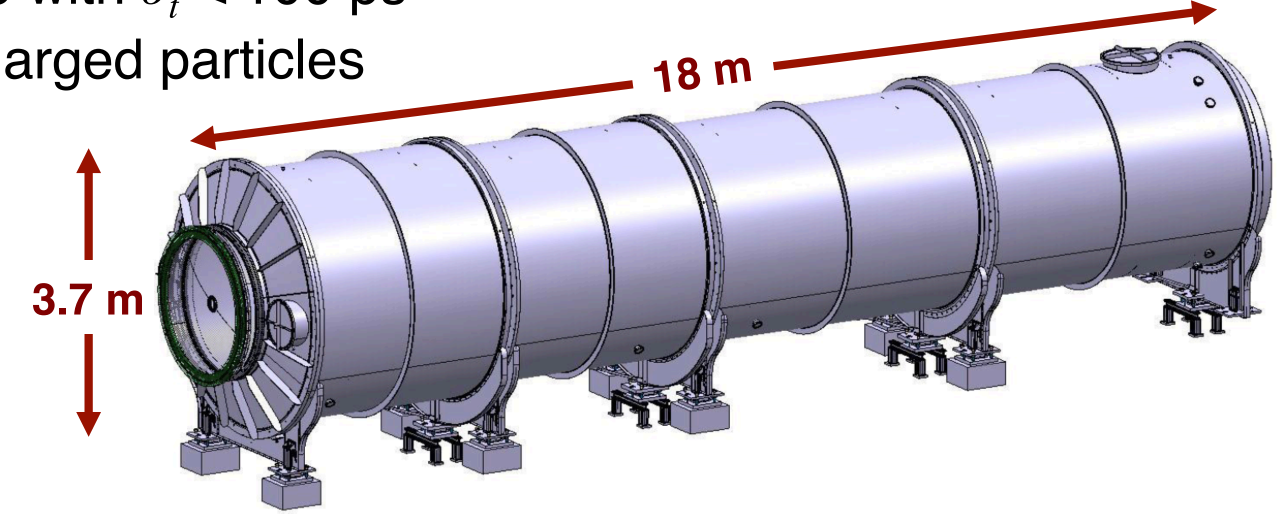
- Used offline to provide principal veto for $K \to \mu\nu$
- Rejects μ to 10^{-5}

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



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 $\sigma(m_{\text{miss}})$

Use detectors with good time resolution to avoid mismatching:

Gigatracker: $\boldsymbol{\sigma_t < 200}$ **ps/station**
KTAG: $\boldsymbol{\sigma_t = 100}$ **ps**
RICH: $\boldsymbol{\sigma_t < 100}$ **ps**

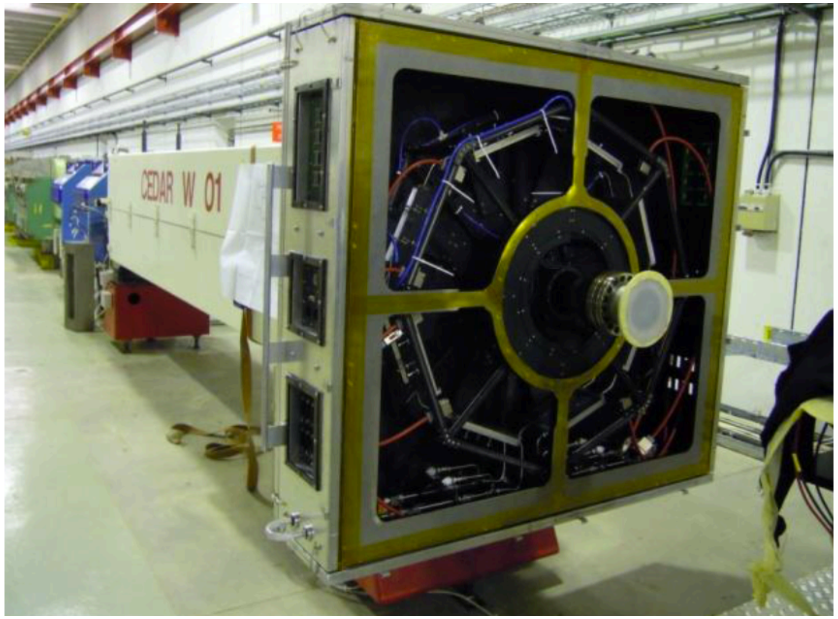
Mismatch probability < 1%

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



Hermetic photon vetoes

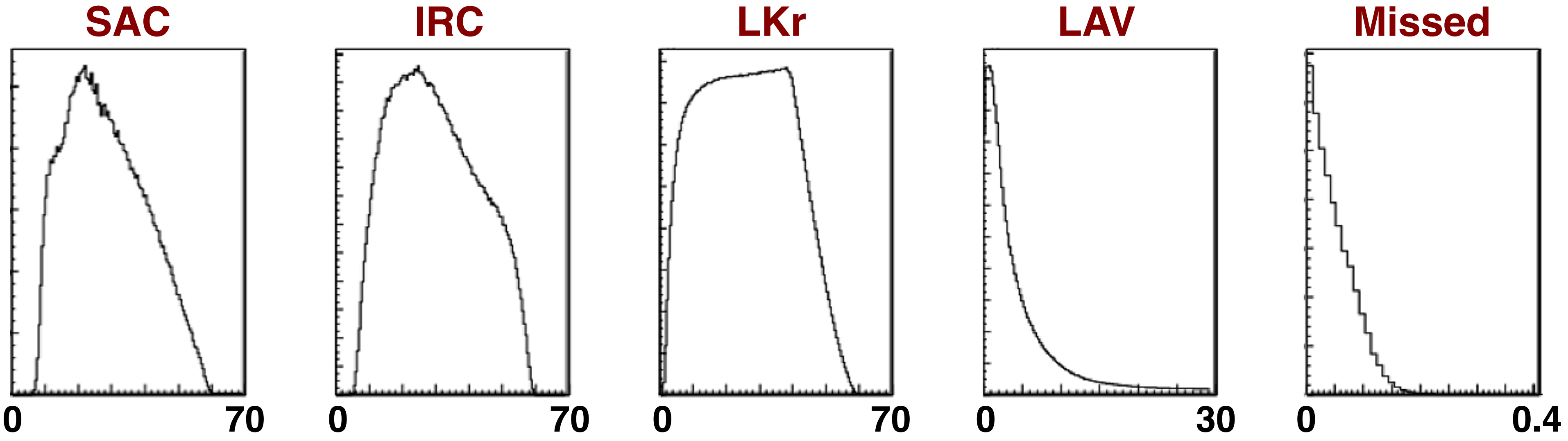
BR($K^+ \rightarrow \pi^+\pi^0$) = 21%

- Kinematic rejection (M^2_{miss}) = 10^{-4}
- Cut $p_{\pi+} < 35$ GeV gives **$\pi^0 \rightarrow \gamma\gamma$** 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 – ε
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

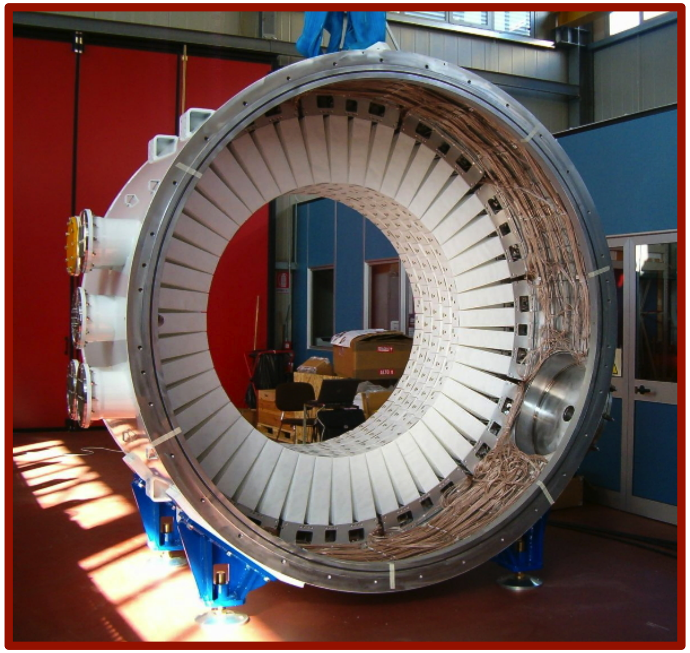
Photon energy deposited in detector [GeV]



Photon veto detectors

Large-angle vetoes (LAV)

$8.5 < \theta < 50$ mrad



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

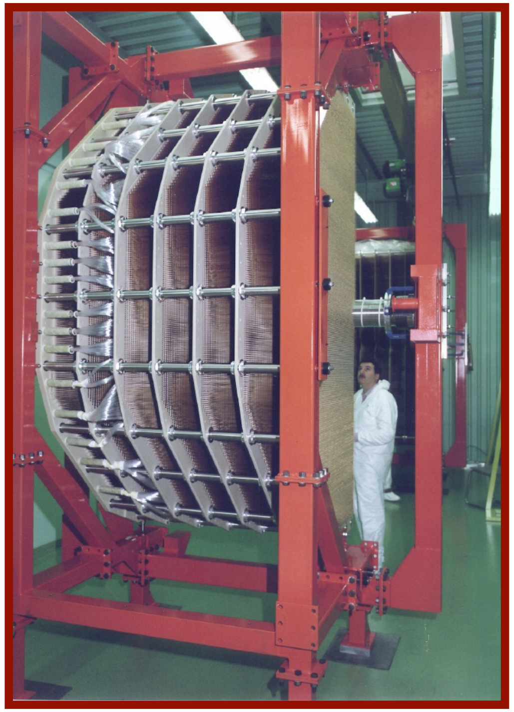
4-5 rings/station of lead glass blocks salvaged from OPAL EM barrel calorimeter

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

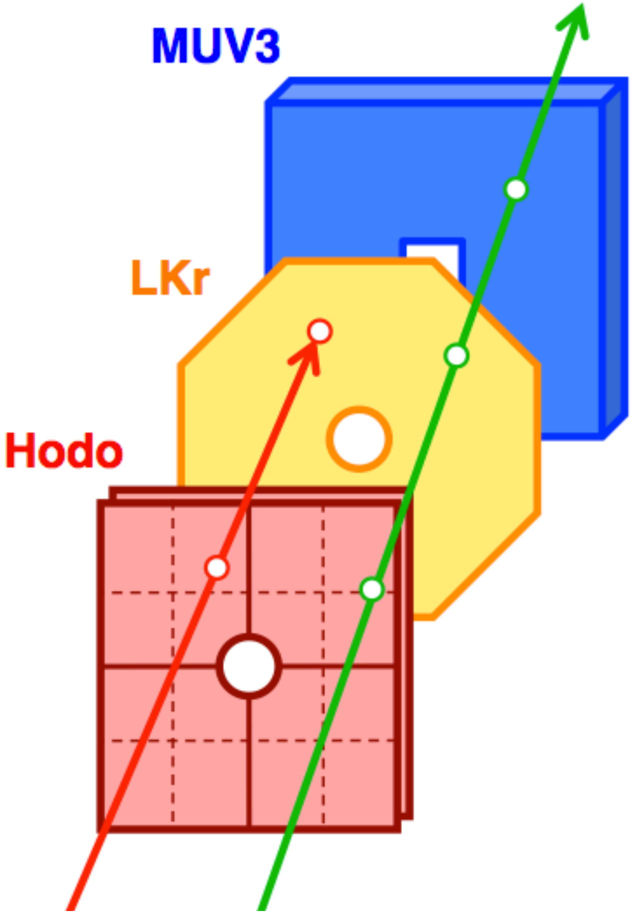
1–ε for γ with $E > 10$ GeV: $< 8 \times 10^{-6}$

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

Trigger and data acquisition

Example L0 trigger primitives:

$\mathbf{Q}_n$	Hits in at least n Hodo quadrants
$\mathbf{LKR}_n(x)$	At least n LKr clusters with energy $E > x$ GeV
$\mathbf{MUV}_n$	Hits in at least n MUV3 pads



10 MHz L0 primitives

L0

Implemented on digital readout card

Example L0 trigger for $K^+ \to \pi^+ \nu\bar{\nu}$:

$\mathbf{Q}_1 \cdot \mathbf{LKR}_1 \cdot \overline{\mathbf{MUV}}$

1 MHz L0 output

L1

Asynchronous

Implemented in L1 trigger processor PC

100 kHz L1 output

L2

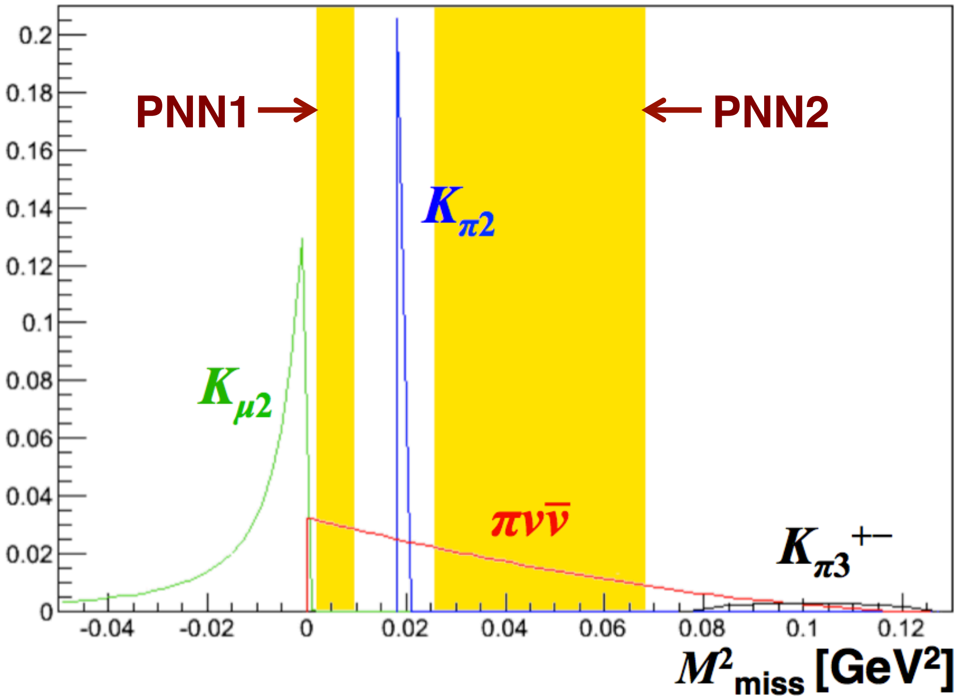
Asynchronous

Implemented in event builder PC

First level to correlate information from different subdetectors

O(kHz) L2 output to disk

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



Acceptance: ~12%

3% in PNN1 region

9% in PNN2 region

50% loss from momentum cut

Detector inefficiencies included

45 signal events/yr

- 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

Expected backgrounds	
$K^+ \to \pi^+\pi^0$	10%
$K^+ \to \pi^+\pi^0\gamma_{\text{IB}}$	3%
$K^+ \to \mu^+\nu$	2%
$K^+ \to \mu^+\nu\gamma_{\text{IB}}$	1%
$K^+ \to \pi^+\pi^+\pi^-$	< 1%
K^+_{e4}, other 3 track decays	< 1%
K^+_{e3}, $K^+_{\mu3}$	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%
$\pi^0 \to \mu^+e^-$	3.8×10^{-10}	KTeV	~2%
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}		

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

NA62 single-event sensitivities:

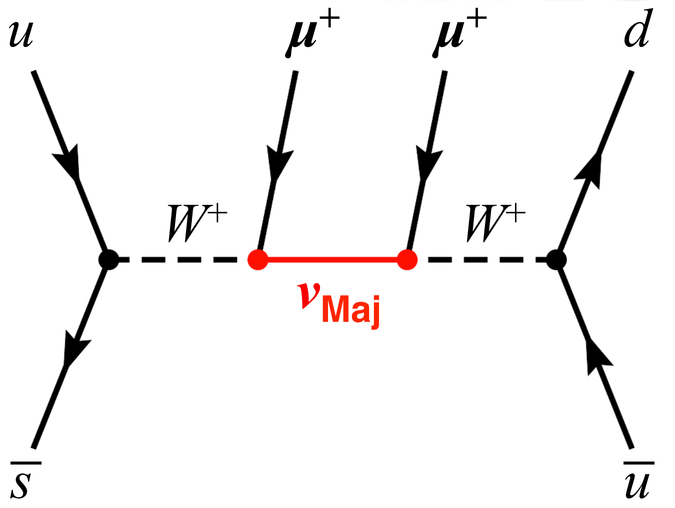
~10^{-12} for K^+ decays
~10^{-11} for π^0 decays

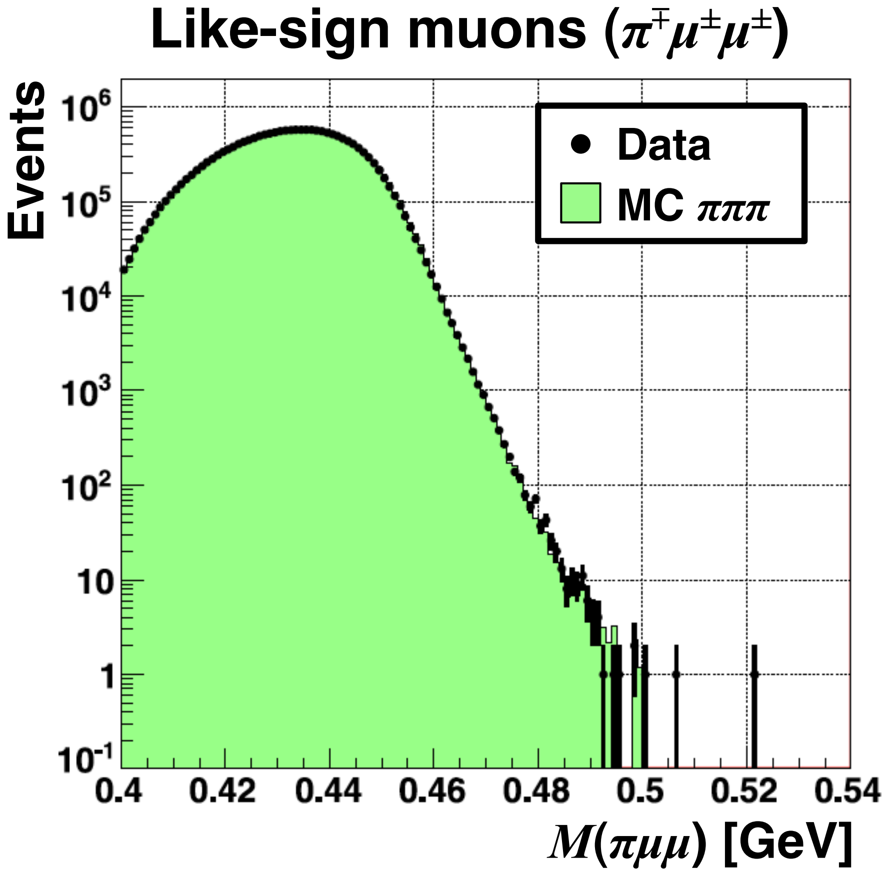
Lepton number violation: $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$

LNV in $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ 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 $\pi \rightarrow \mu$ decays
- 1 of $\pi \rightarrow \mu$ 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}

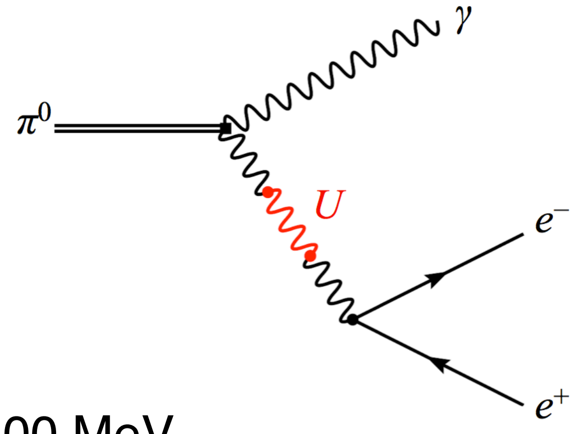
Rare π^0 decays in NA62

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

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) $< 2.7 \times 10^{-7}$ 90%CL

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

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

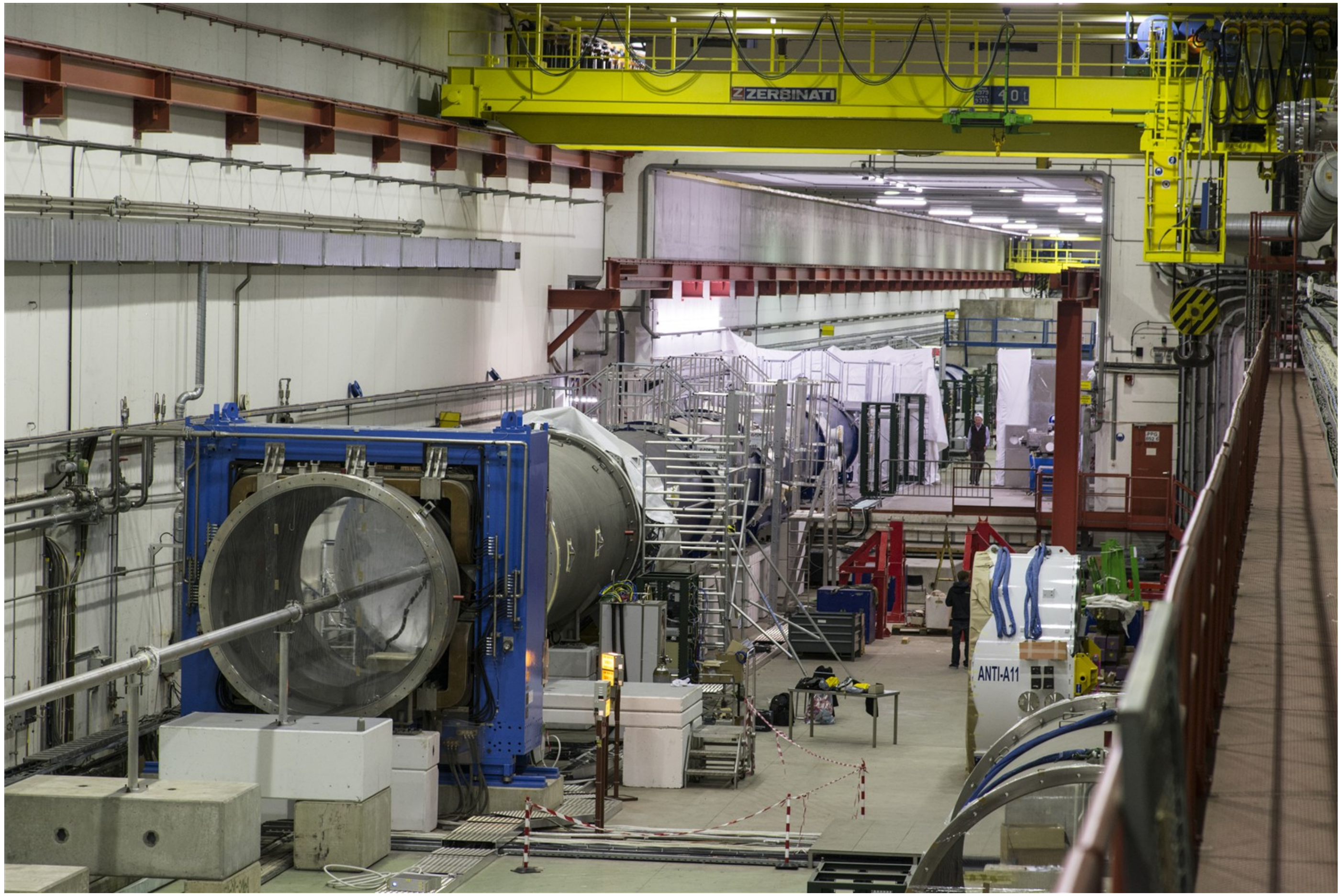
Astrophysics/cosmology: $< 3 \times 10^{-13}$

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

Experimental status



Installing/installed: **KTAG, LAV (8/12), LKr (readout), SAC**
Under construction: **CHANTI, STRAWS, RICH, IRC, MUV**
Advanced design stage: **Gigatracker**

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