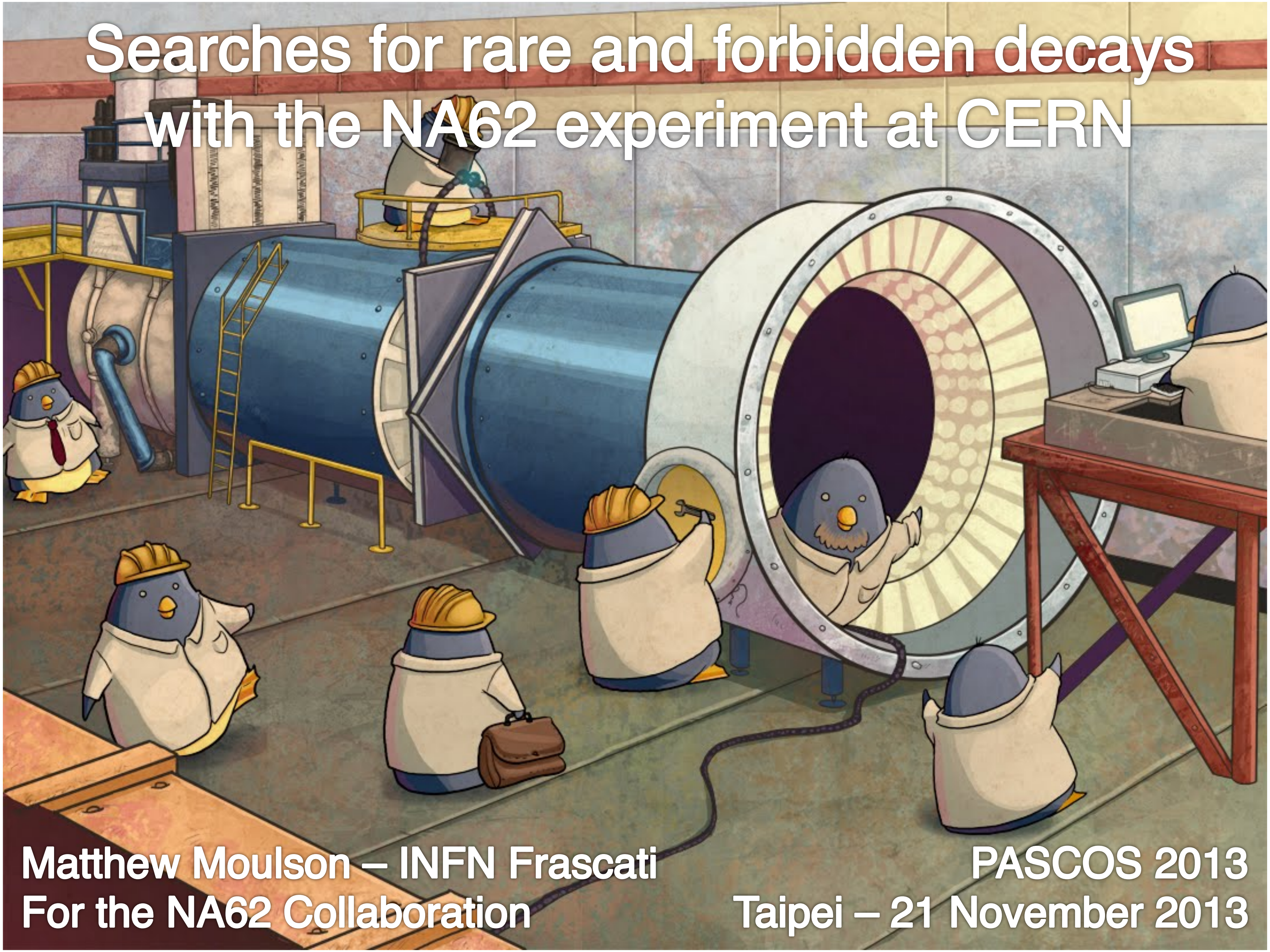
Searches for rare and forbidden decays with the NA62 experiment at CERN



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For the NA62 Collaboration

PASCOS 2013
Taipei – 21 November 2013

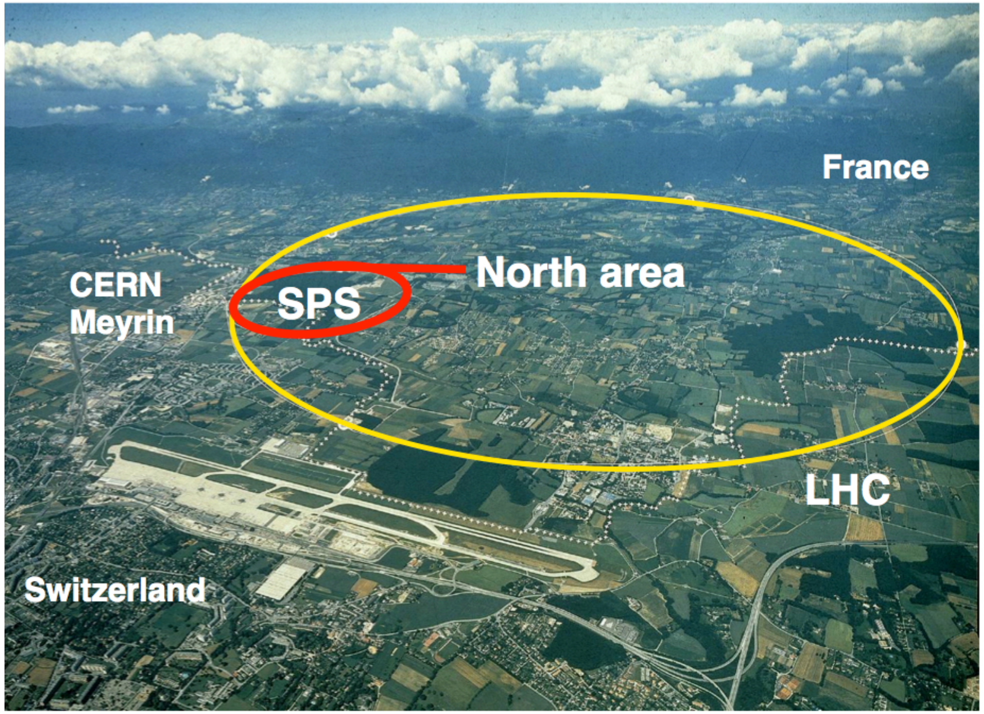
The NA62 experiment at CERN

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

Opportunities to perform additional searches for novel phenomena:

- New-physics contributions in helicity-suppressed decays
- K decays with explicit lepton flavor or number violation (LFNV)
- Forbidden π^0 decays tagged by $K^+ \to \pi^+\pi^0$

Recent history of NA48 experiments at the CERN SPS North Area:



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

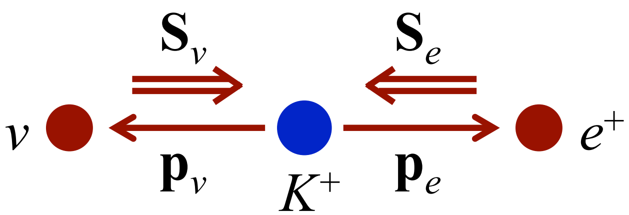
2007-2008 NA62 (using NA48/2)
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$

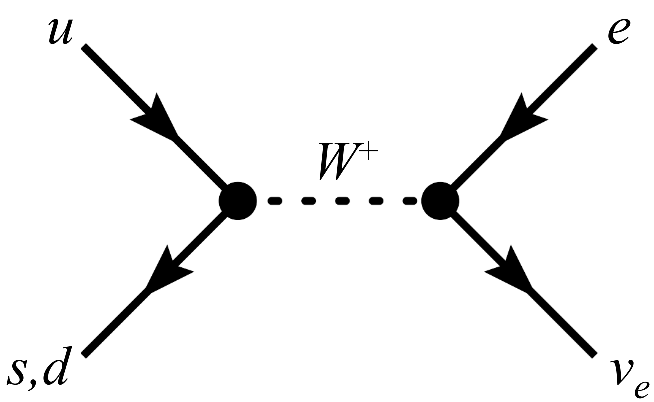
2007-2014 NA62 installation

Fall 2014 NA62 data taking
$K^+ \to \pi^+ \nu\bar{\nu}$

The ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

$K, \pi \to \ell\nu$ decays are helicity suppresed in SM





Standard model prediction for R_K is very precise

- Decay constant f_K cancels from ratio – no hadronic uncertainties
- Only radiative corrections

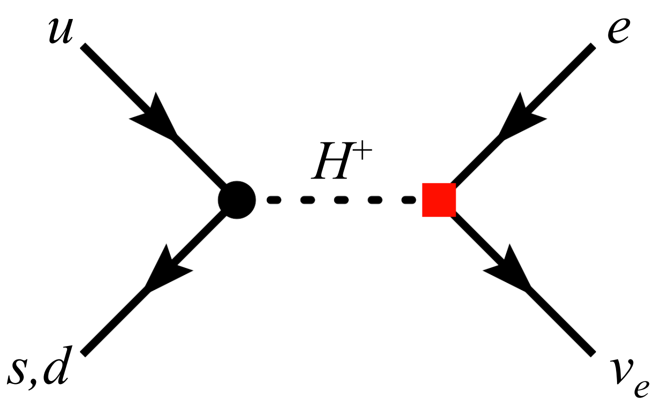
Helicity suppression **Radiative corrections**

$$R_K^{\rm SM} \equiv \frac{\Gamma(K \to e\nu(\gamma_{\rm IB}))}{\Gamma(K \to \mu\nu(\gamma_{\rm IB}))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K^{\rm EM}) = \mathbf{2.477(1) \times 10^{-5}}$$

Cirigliano, Rosell '07

BSM contributions may not be helicity suppressed

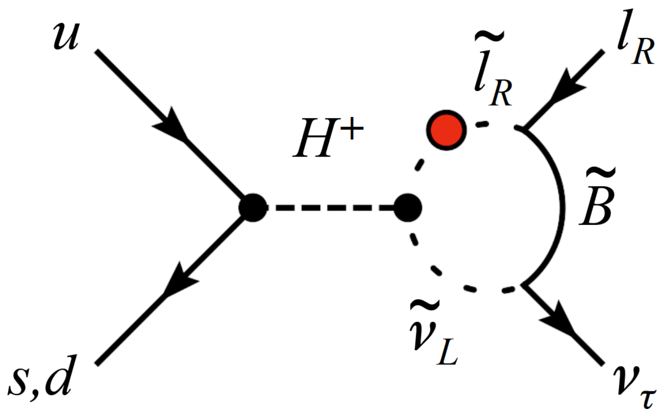
- E.g., scalar H^+ exchange



R_K as a new-physics probe

MSSM with R parity **Masiero, Petronzio & Paradisi '06**

LFV contribution arises in effective H^+ coupling at one loop



Experimentally, neutrino flavor is not measured

$$R_K^{\mathrm{LFV}} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \approx \frac{\Gamma_{\mathrm{SM}}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{\mathrm{SM}}(K \to \mu\nu_\mu)}$$

Coupling depends on mass of ℓ with flavor of ν

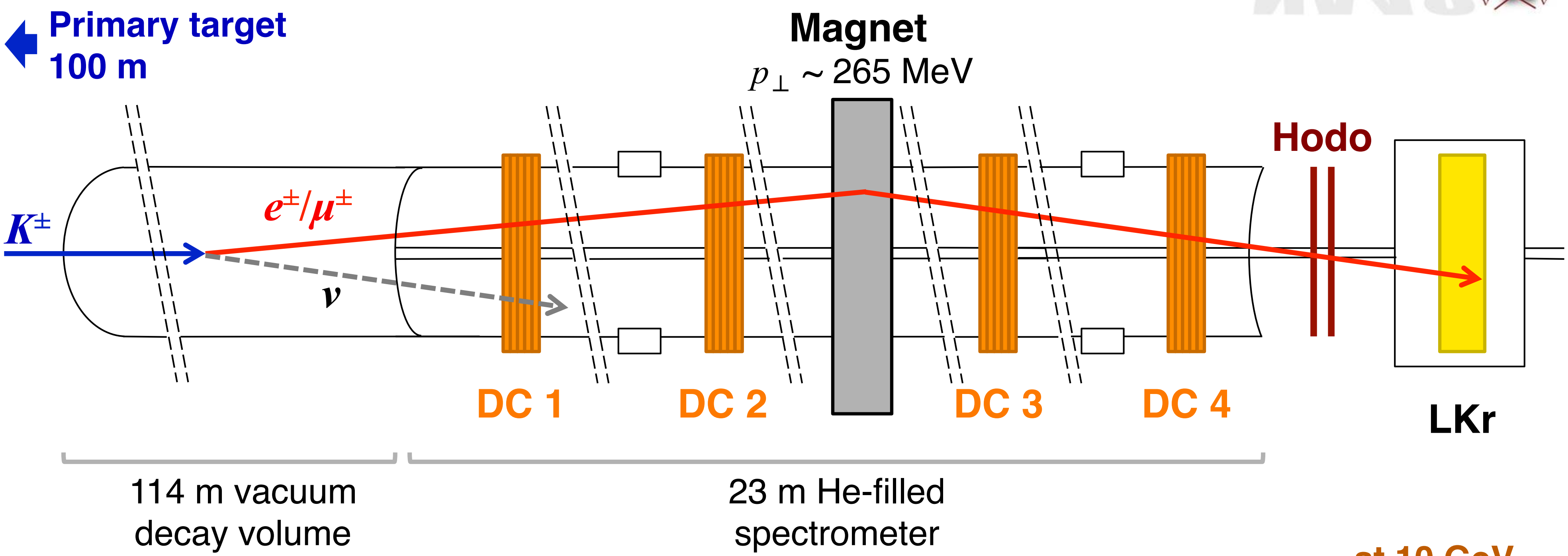
$$eH^+\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$R_K^{\mathrm{LFV}} \approx R_K^{\mathrm{SM}} \left[1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} |\Delta_R^{31}|^2 \tan^6\beta\right]$$

O(1%) effect on R_K for $\Delta_{13} \sim 5\times10^{-4}$ $\tan\beta \sim 40$ $M_{H+} \sim 500$ GeV

High degree of interest in precision measurements of R_K (better than 1%)

NA48 setup used by NA62 for R_K



		at 10 GeV
Drift chambers	$\sigma(p)/p = 0.48\% \oplus 0.009\%\ p$ [GeV]	0.48%
	$\sigma_{x,y} = 90$ µm	
LKr calorimeter	$\sigma_E/E = 3.2\%/\sqrt{E}$ [GeV] $\oplus$ $9\%/E$ [GeV] $\oplus$ 0.42%	1.4%
	$\sigma_x = \sigma_y = 4.2$ mm$/\sqrt{E} \oplus 0.6$ mm	1.5 mm
Hodoscope	Fast trigger, good time resolution (150 ps)	

$K_{\ell 2}$ event selection

Basic selection criteria:

1 track in fiducial volume

Closest distance to beam axis < 3.5 cm

$13 < p < 65$ GeV

No other clusters in LKr

$K_{e2}/K_{\mu 2}$ separation:

Kinematic identification

$M^2_{\text{miss}} = (p_K - p_\ell)^2$

$-0.010 < M^2_{\text{miss}}(\ell) < +0.013$

Exact cuts depend on p_ℓ

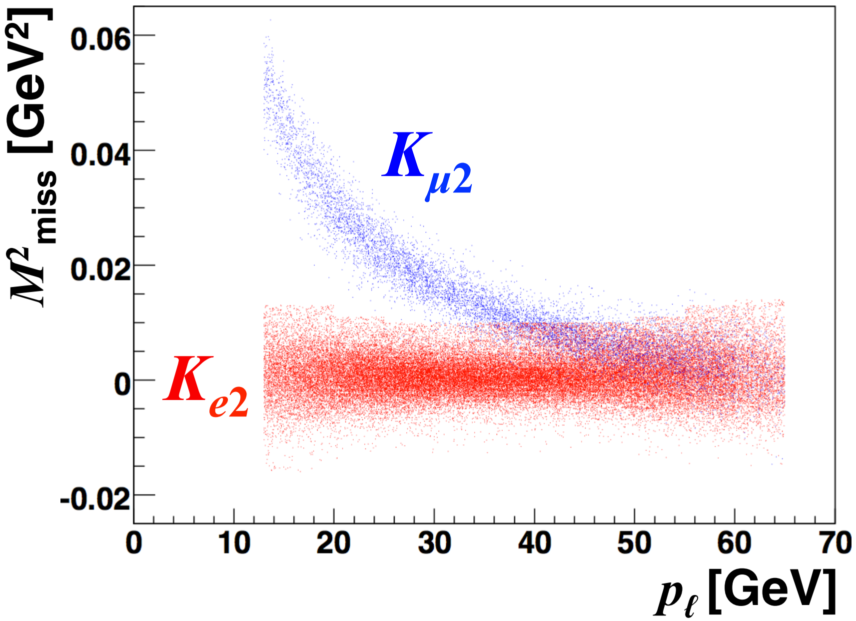
Use avg $\mathbf{p}_K$ measured with $K_{\pi 3}$

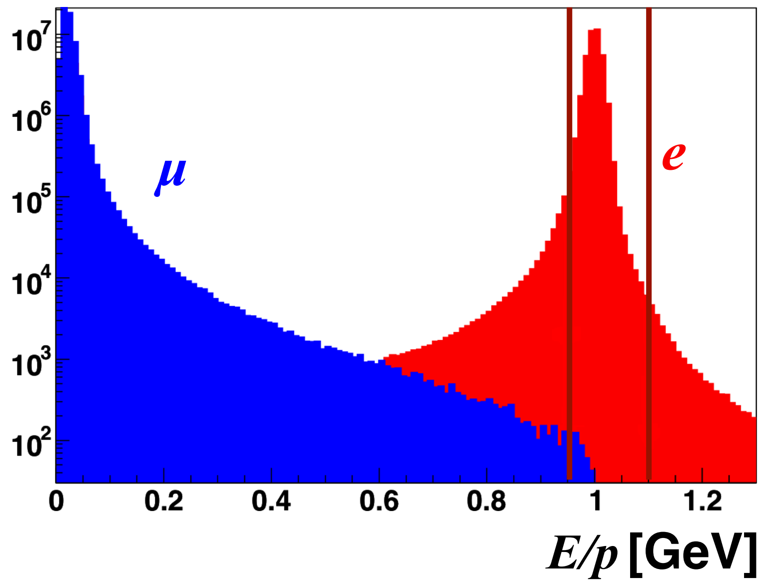
Energy deposition in LKr

$0.95 < E/p < 1.10$ for e

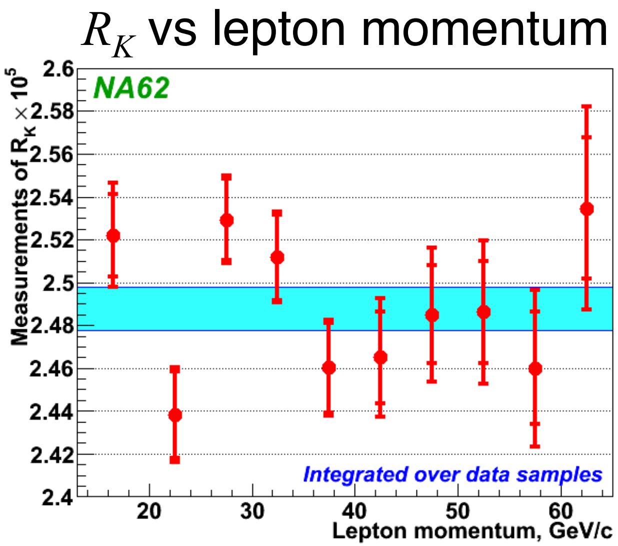
$E/p < 0.85$ for μ

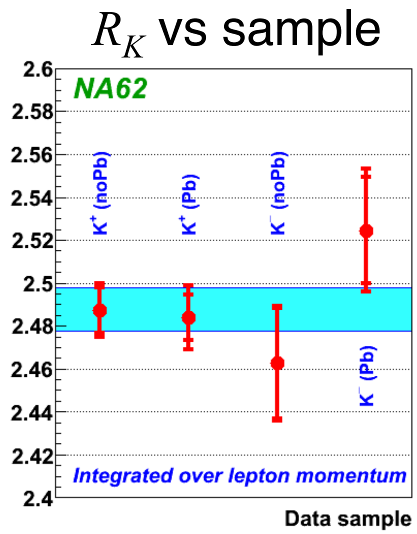
μ suppression ~10^6

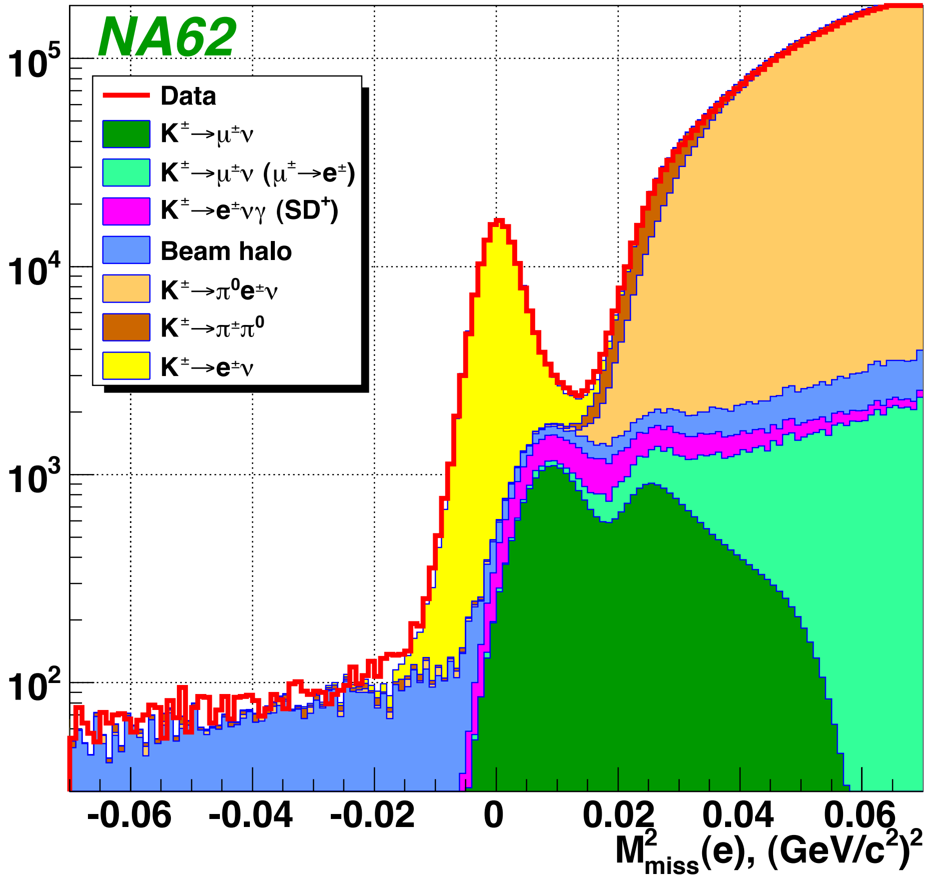




NA62 results for R_K







Fit to 40 measurements gives χ^2**/ndf=47/39**
4 data samples × 10 momentum bins

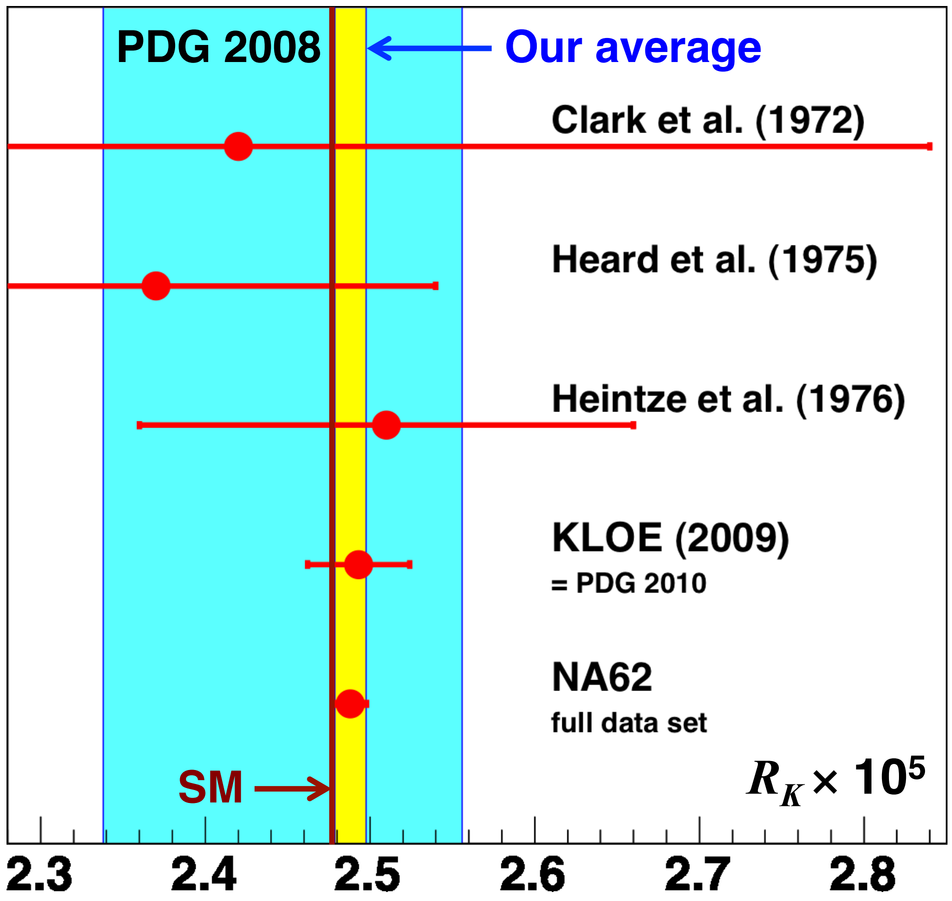
146k K_{e2} candidates (mainly K^+)
Background: B/(S+B)=(10.95±0.27)%
Electron ID efficiency: (99.28±0.05)%

$$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$$
$$= 2.488(10) \times 10^{-5}$$

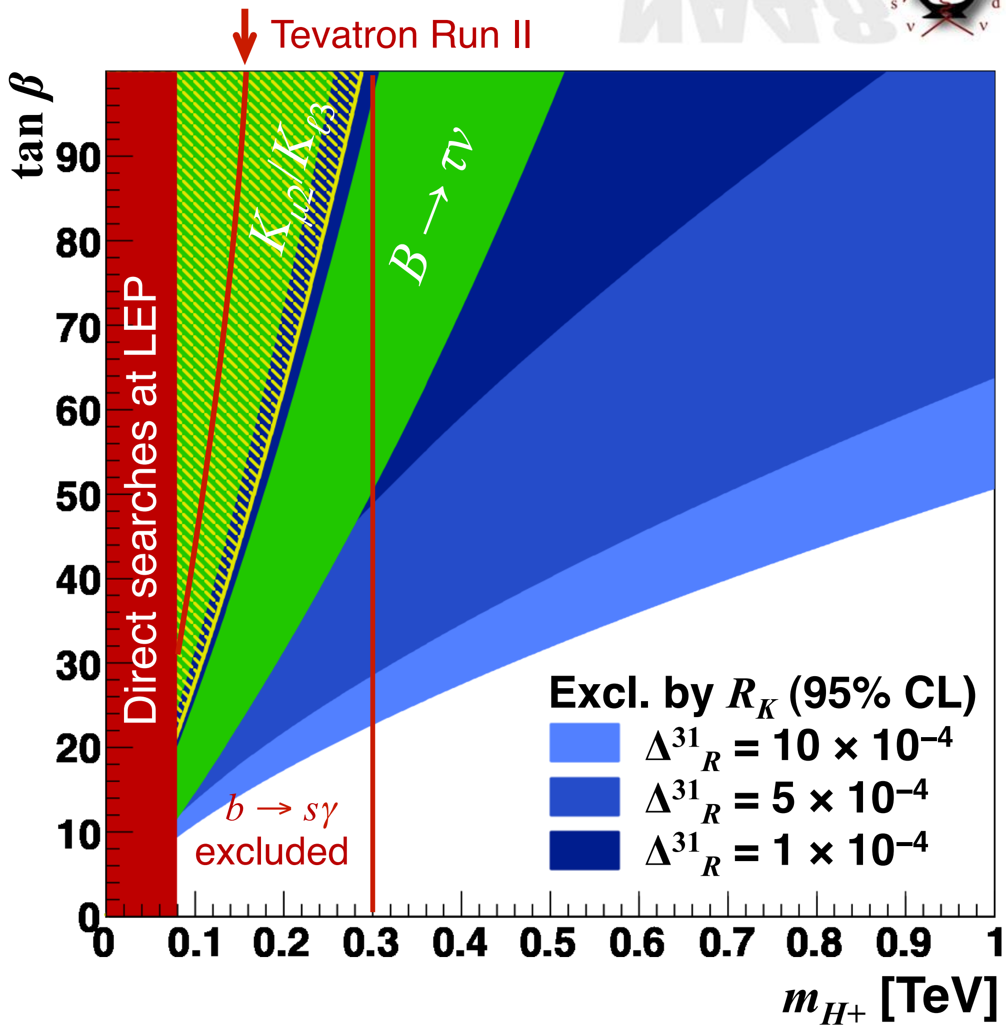
0.4% overall precision

Final result: PLB 719 (2013)
Supersedes result from PLB 698 (2011)
Overall uncertainty reduced by 25%

R_K: world average



Average	$R_K \times 10^5$	$\delta R_K/R_K$
PDG 2008	2.447±0.109	4.5%
Current	**2.488±0.009**	**0.4%**



MSSM with R parity

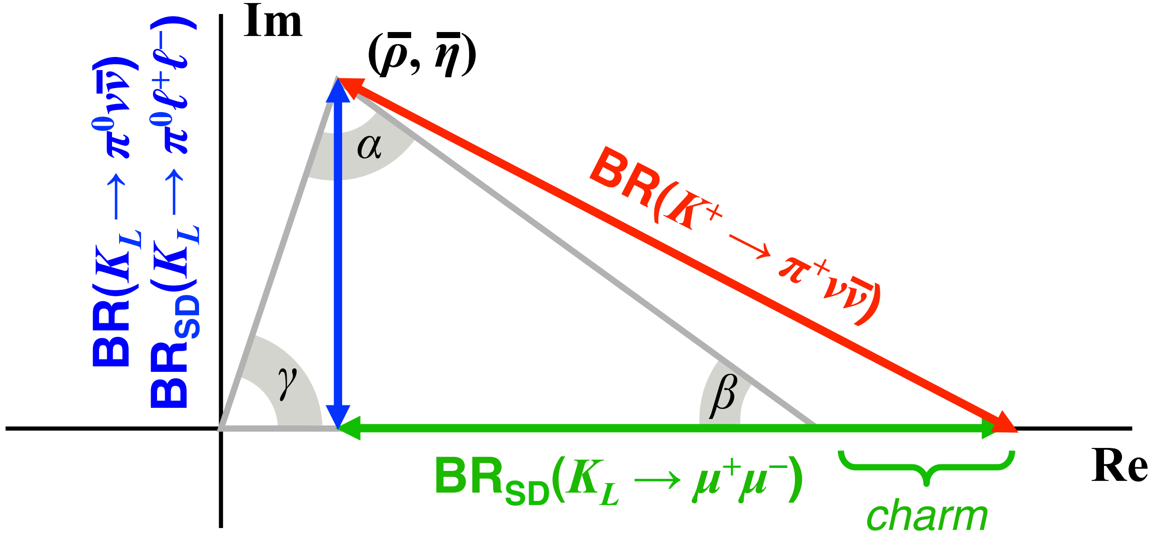
$$R_K^{\mathrm{LFV}} \approx R_K^{\mathrm{SM}} \left[1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} |\Delta_R^{31}|^2 \tan^6\beta \right]$$

Rare kaon decays

FCNC processes dominated by Z-penguin and box diagrams

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

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

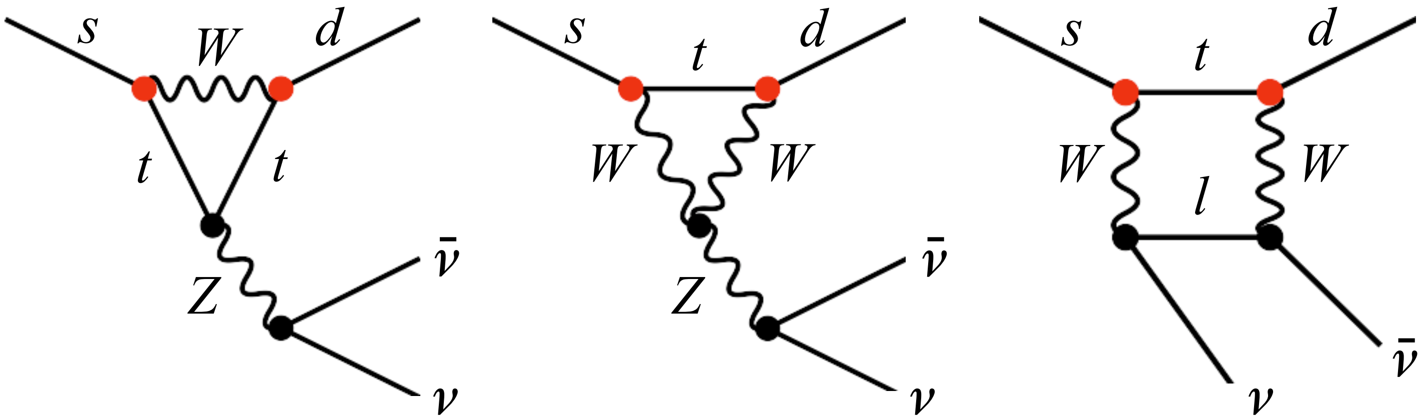


Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	40%	20%	681 ± 32	684 ± 11
$K_L \to \pi^0 e^+e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 12
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	<26000†

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

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

NA62



$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

Loop functions favor top contribution

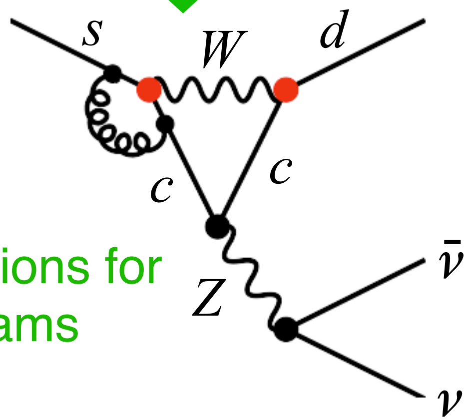
$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \quad \leftarrow \not{CP}$$

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

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

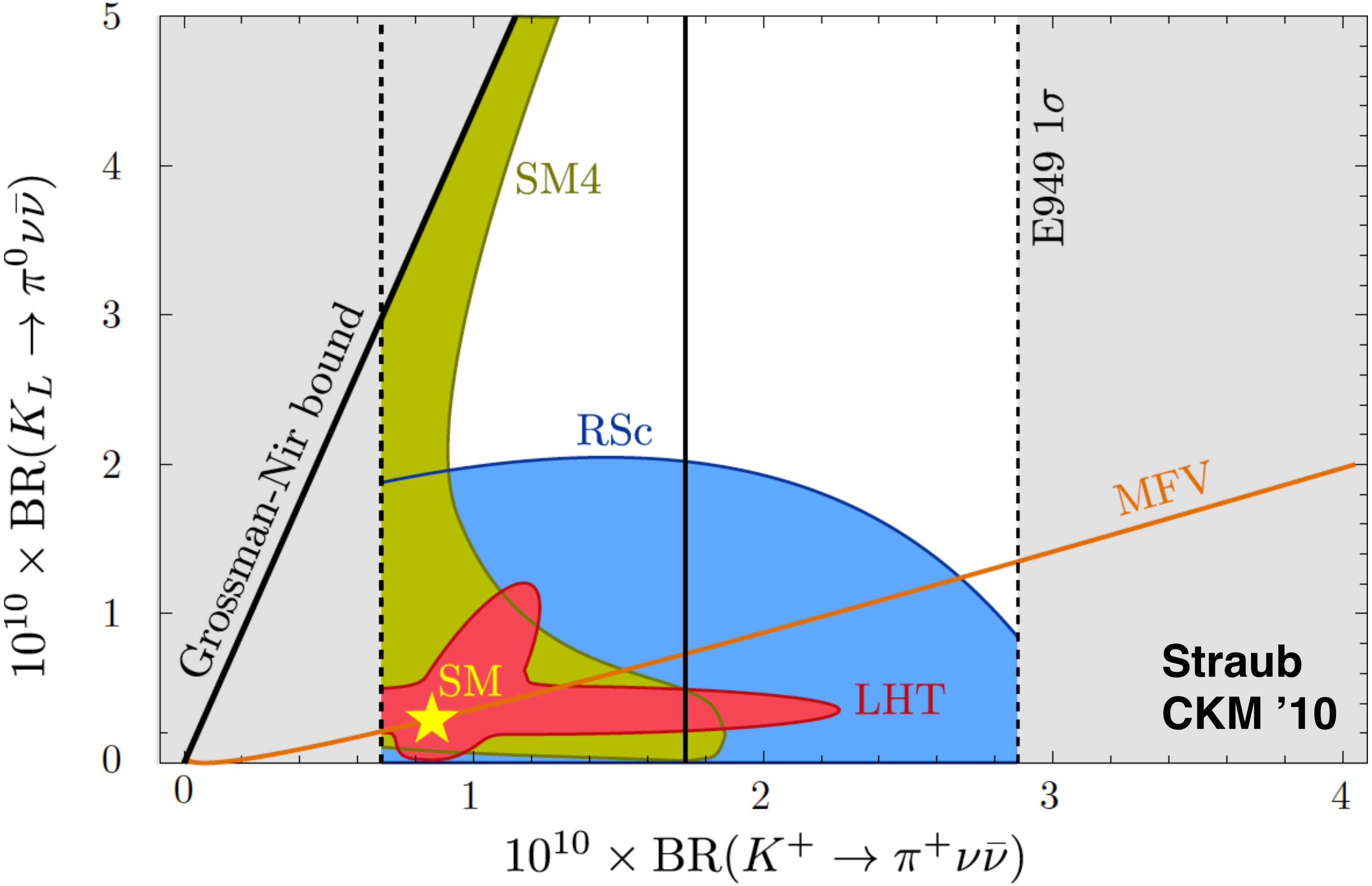
QCD corrections for charm diagrams contribute to uncertainty



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

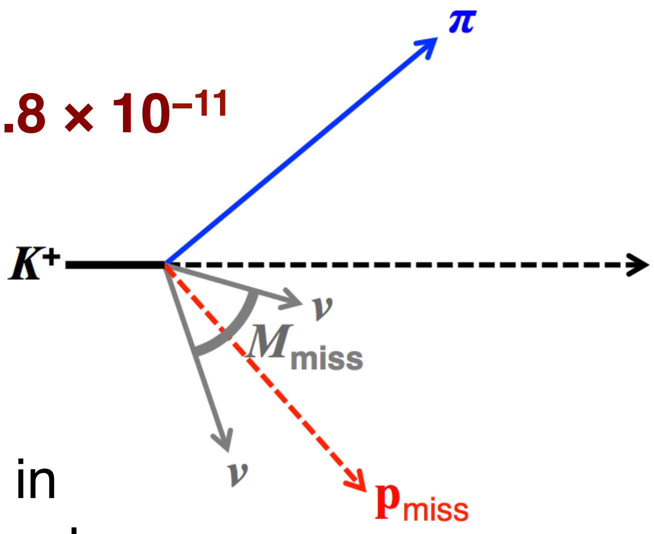
LHT: Littlest Higgs with T parity (Blanke '10)

RSc: Custodial Randall-Sundrum (Blanke '09)

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

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

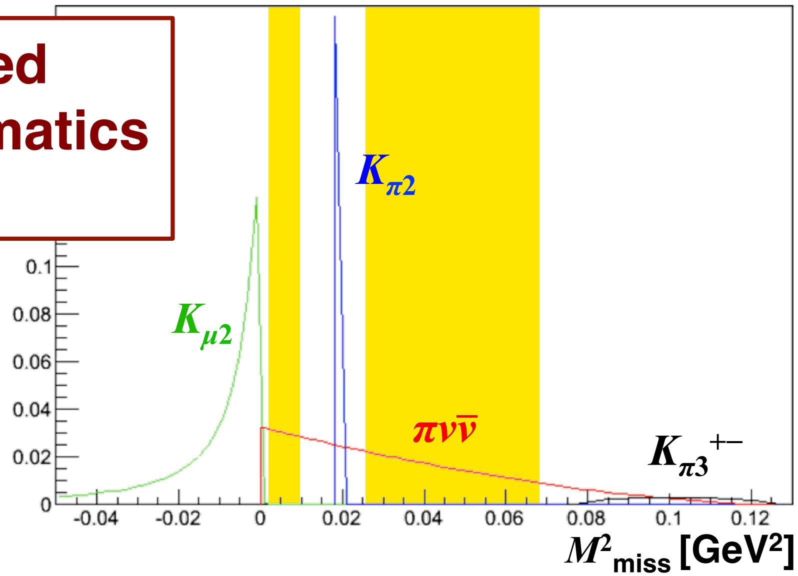
Decay backgrounds

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}

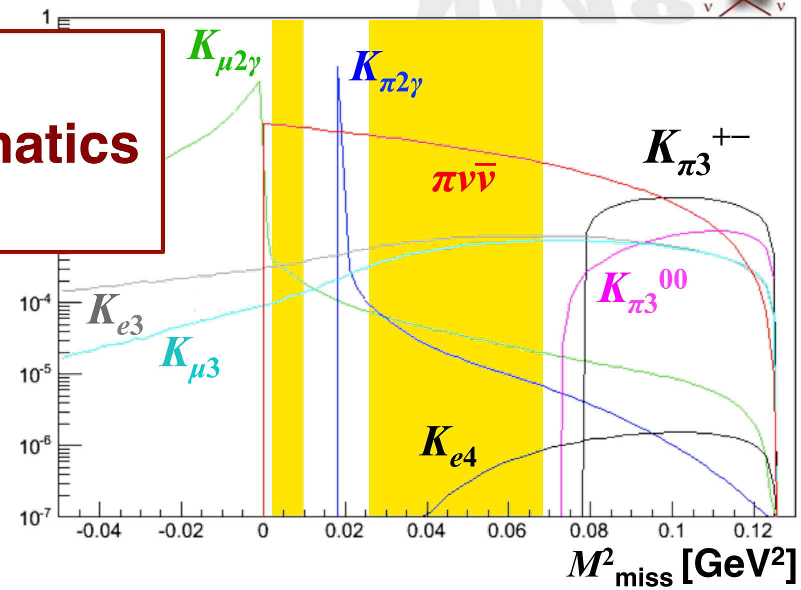
Other backgrounds
- Beam-gas interactions
- Upstream interactions

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

Closed kinematics 92%



Open kinematics 8%



$m^2_{miss} = 0$ 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

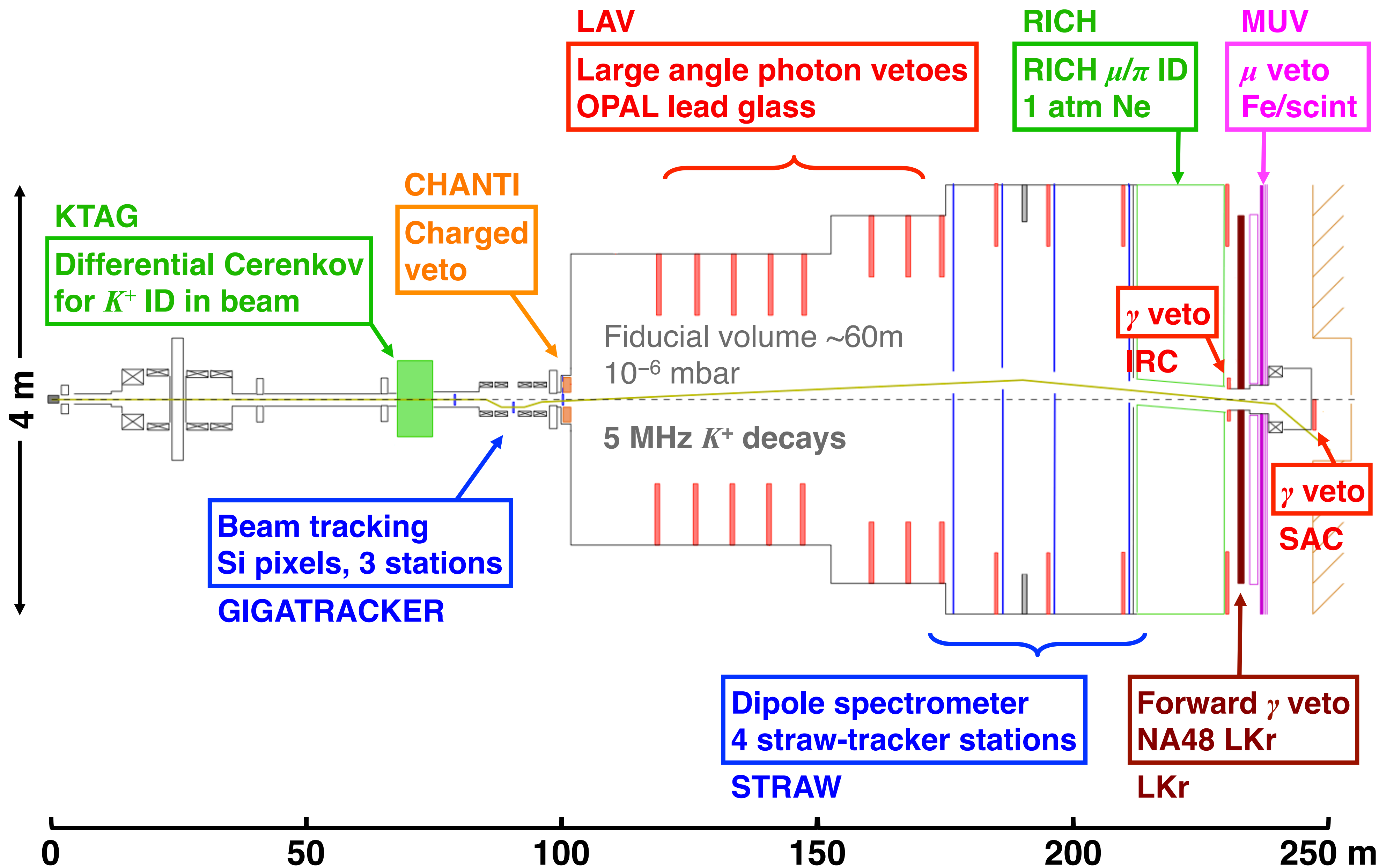
Rejection from kinematics alone: 10^{-4} at best

(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



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 {
- **525 MHz π**
- **170 MHz p**
- **45 MHz K**

Decay volume

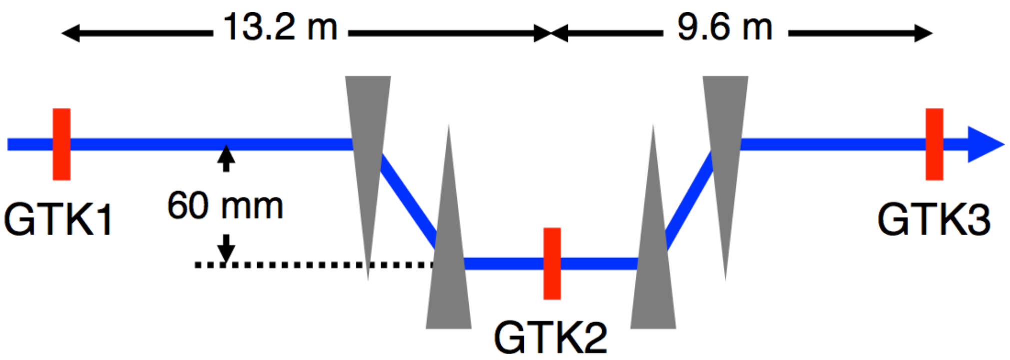
- 60 m long, starting at z = 102 m from target
- 10% of K^+ decay in FV ($\beta\gamma c\tau$ = 560 m)

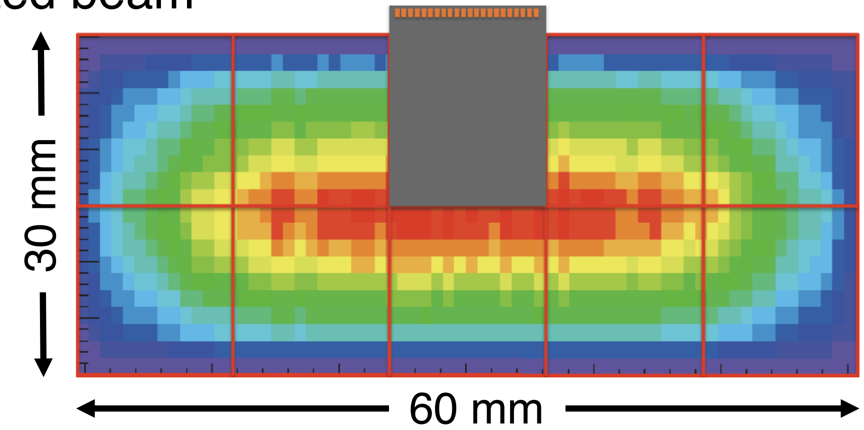
4.5 × 10^{12} K^+ decays/yr = 45× NA48/2

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 → σ_p/p **~ 0.2%,** σ_θ **= 16 μrad**

Secondary tracking: 4 straw chambers in vacuum

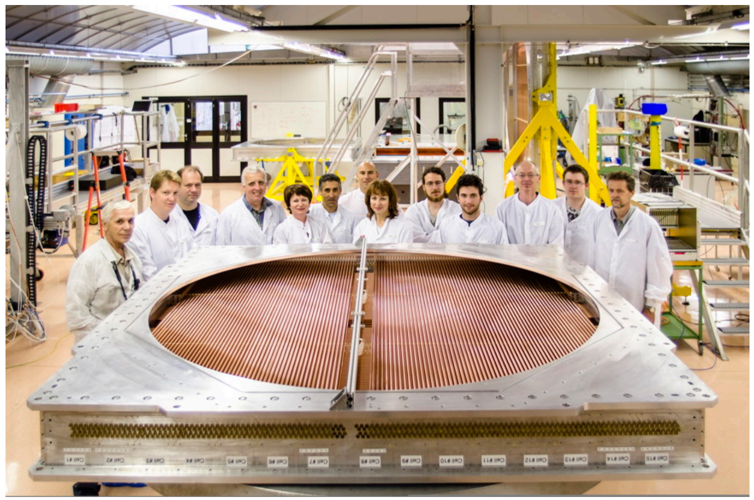
4 chambers, 2.1 m in diameter
16 layers (4 views) of straws per chamber

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

➡

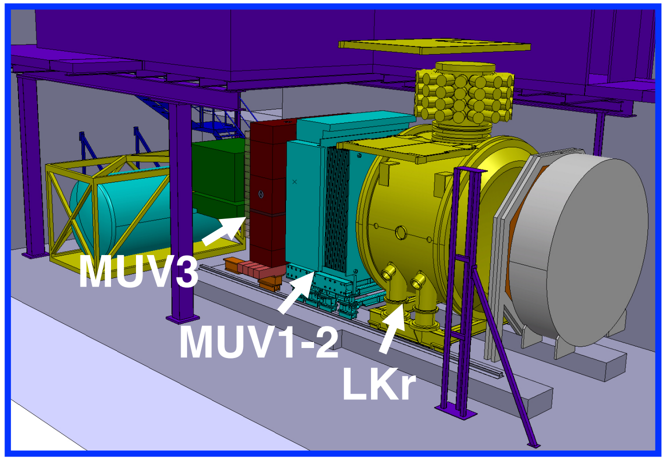
σ_p/p **= 0.32% ⊕ 0.008%** p
$\sigma_{\theta(K\pi)}$ **= 20-50 μrad**

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

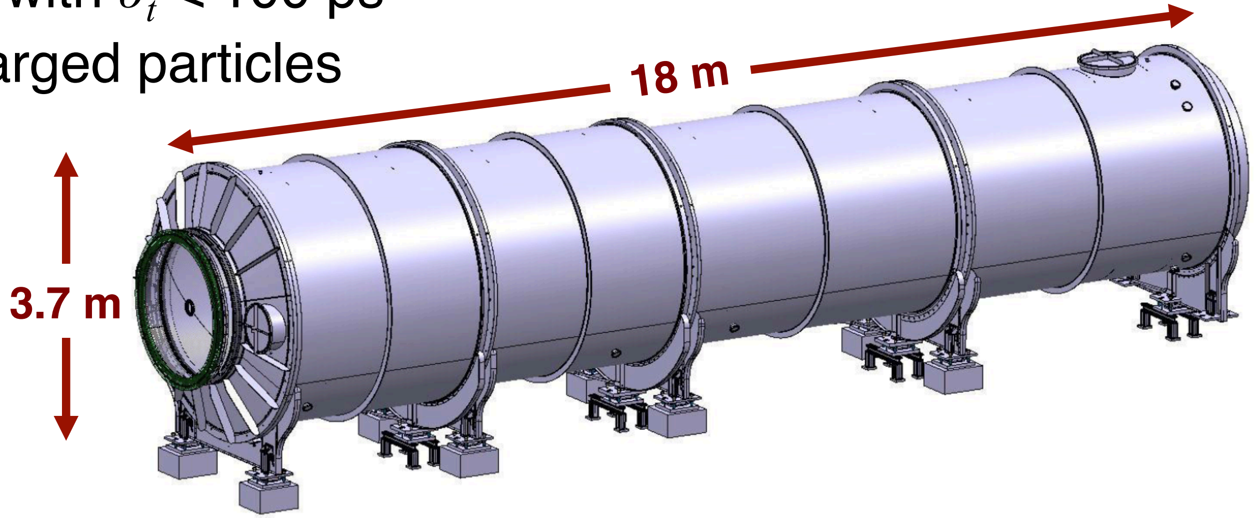
- Used offline to provide principal veto for $K \to \mu\nu$
- Rejects μ to 10^{-5}

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



Beam timing and PID

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

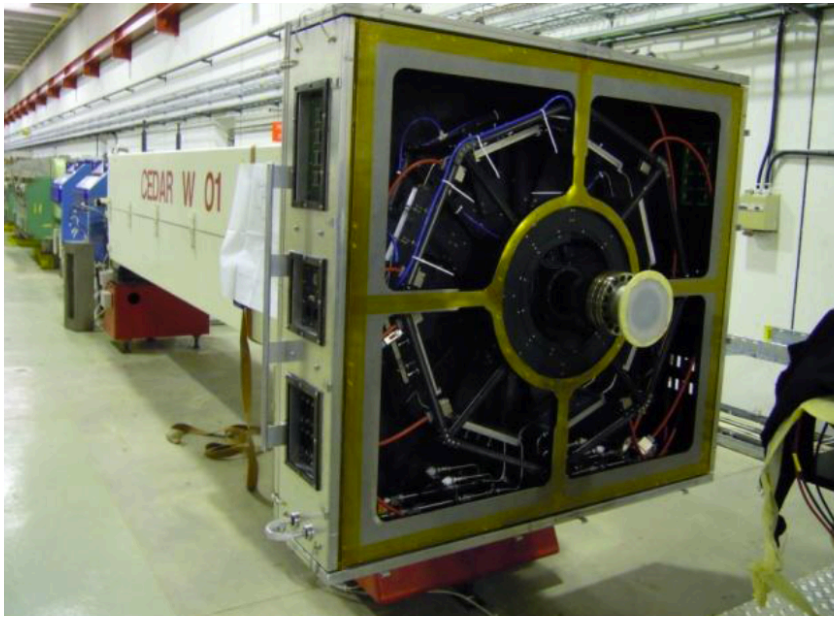
Matching downstream π track to wrong beam particle leads to 3× increase in $\sigma(m_{miss})$

Use detectors with good time resolution to avoid mismatching:

Gigatracker:	σ_t **< 200 ps/station**	Mismatch probability < 1%
KTAG:	σ_t **< 100 ps**	Still accounts for half of kinematic
RICH:	σ_t **< 100 ps**	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^{-8} 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

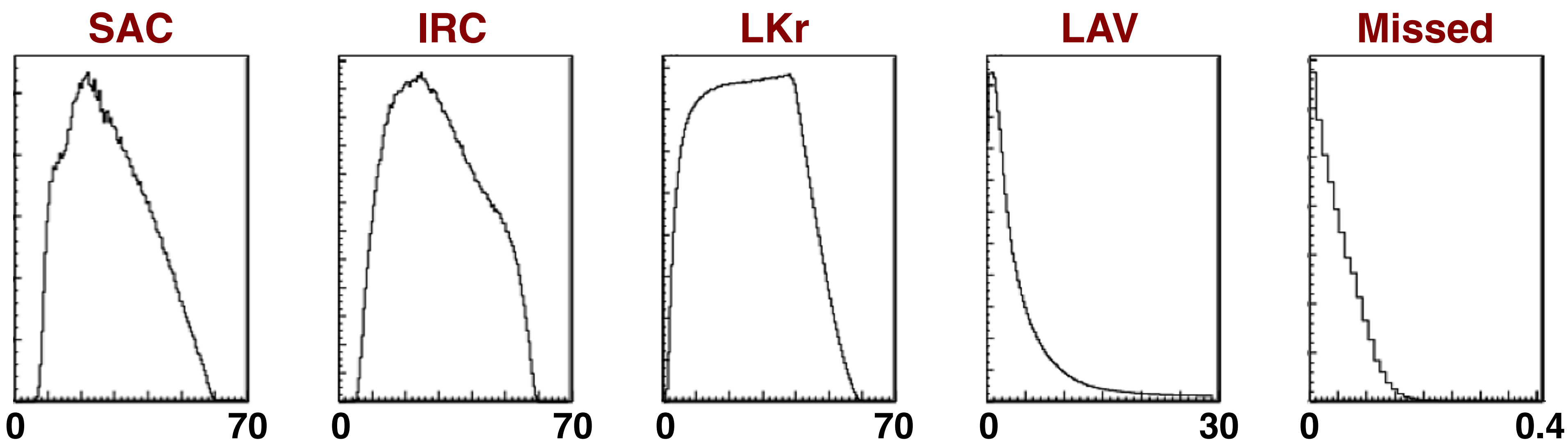
BR($K^+ \to \pi^+\pi^0$) = 21%

- 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

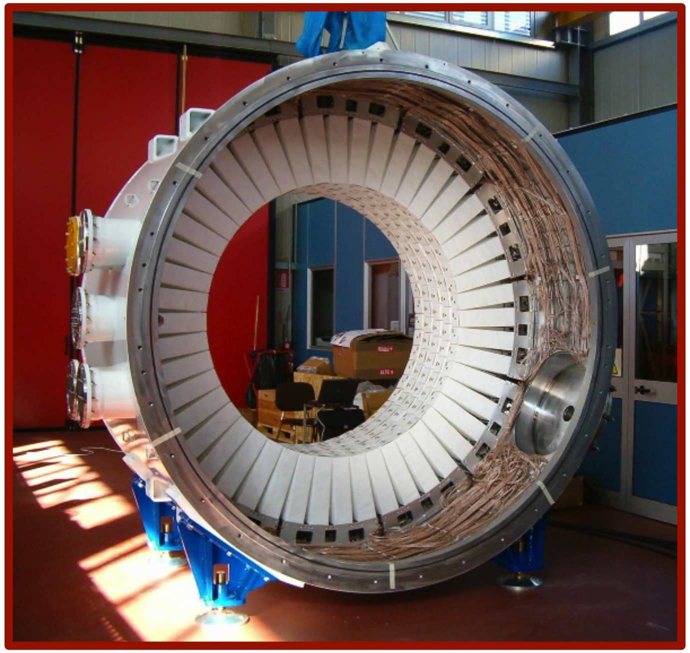
Photon energy deposited in detector [GeV]



Photon veto detectors

Large-angle vetoes (LAV)

$8.5 < \theta < 50$ mrad



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

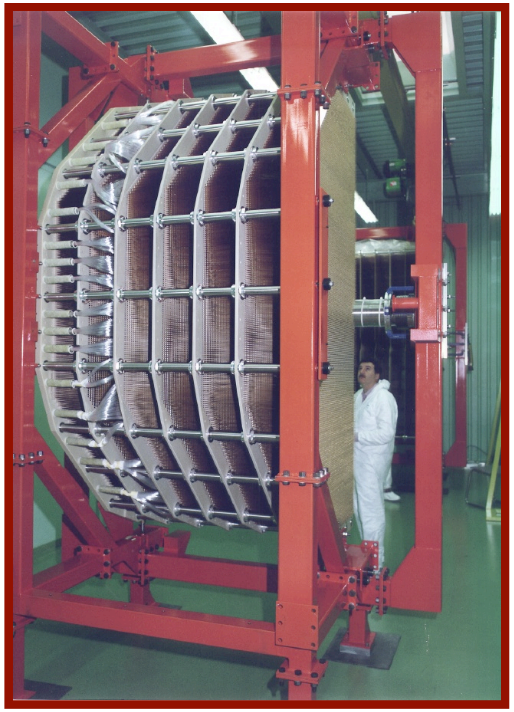
4-5 rings/station of lead glass blocks salvaged from OPAL EM barrel calorimeter

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

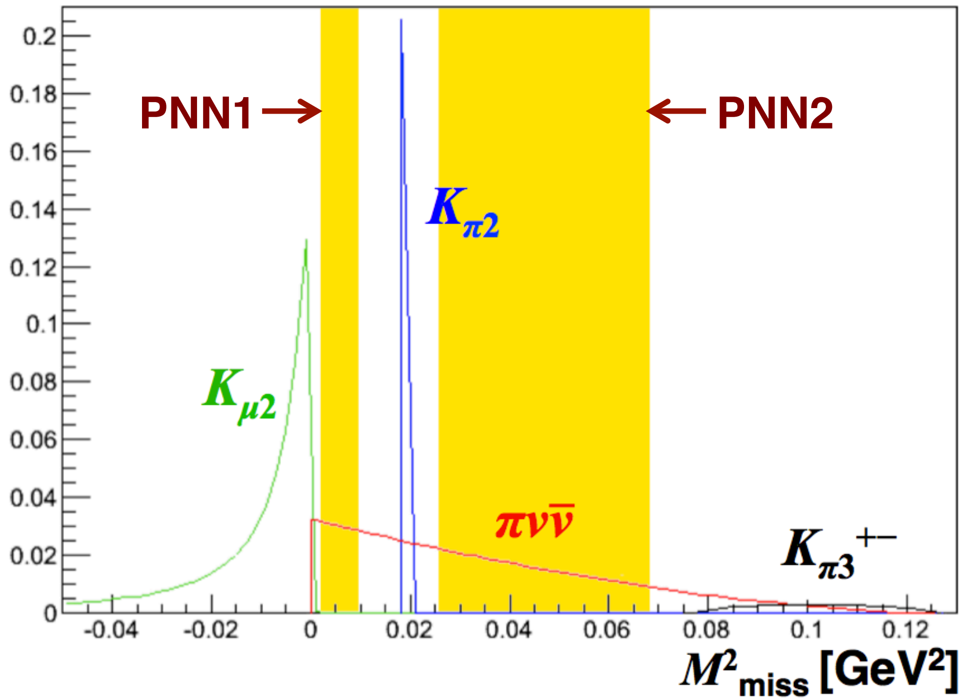
Readout towers 2×2 cm^2 - 13248 channels

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



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_π < 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	
$K^+ \rightarrow \pi^+\pi^0$	10%
$K^+ \rightarrow \pi^+\pi^0\gamma_{IB}$	3%
$K^+ \rightarrow \mu^+\nu$	2%
$K^+ \rightarrow \mu^+\nu\gamma_{IB}$	1%
$K^+ \rightarrow \pi^+\pi^+\pi^-$	< 1%
K^+_{e4}, other 3 track decays	< 1%
K^+_{e3}, $K^+_{\mu 3}$	negligible
Total	**< 20%**

Prospects to improve on R_K

New detectors for $K \rightarrow \pi\nu\bar{\nu}$ will significantly increase background rejection

RICH:

100× more suppression of background from $K_{\mu 2}$ with catastrophic bremsstrahlung

Hermetic photon vetoes:

$K_{e2\gamma}$(SD+) reduced 35× by detecting radiative γ explicitly in LAV, IRC, SAC

Beam spectrometer & CEDAR:

Precise time measurements of incoming kaons and decay products

Reduces beam halo to negligible level

Only significant remaining background: $K_{\mu 2}$ with $\mu \rightarrow e$ decay in flight

~0.3%, well understood

NA62 will have abundant statistics

Required statistical uncertainty ~0.05% (~4M K_{e2} candidates)

Required kaon decay flux: N_K **~ 10^{12}**

Expected NA62 kaon flux: N_K **~ 10^{13}**

~1 month of data taking sufficient

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.

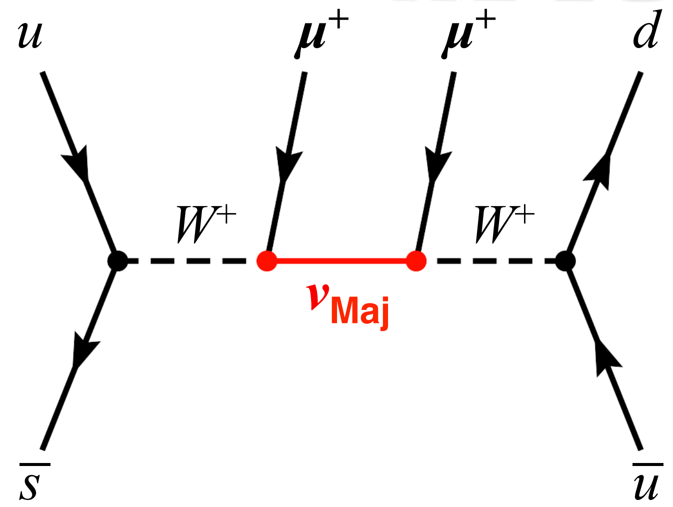
NA62 single-event sensitivities: **~10^{-12} for K^+ decays**, **~10^{-11} for π^0 decays**

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

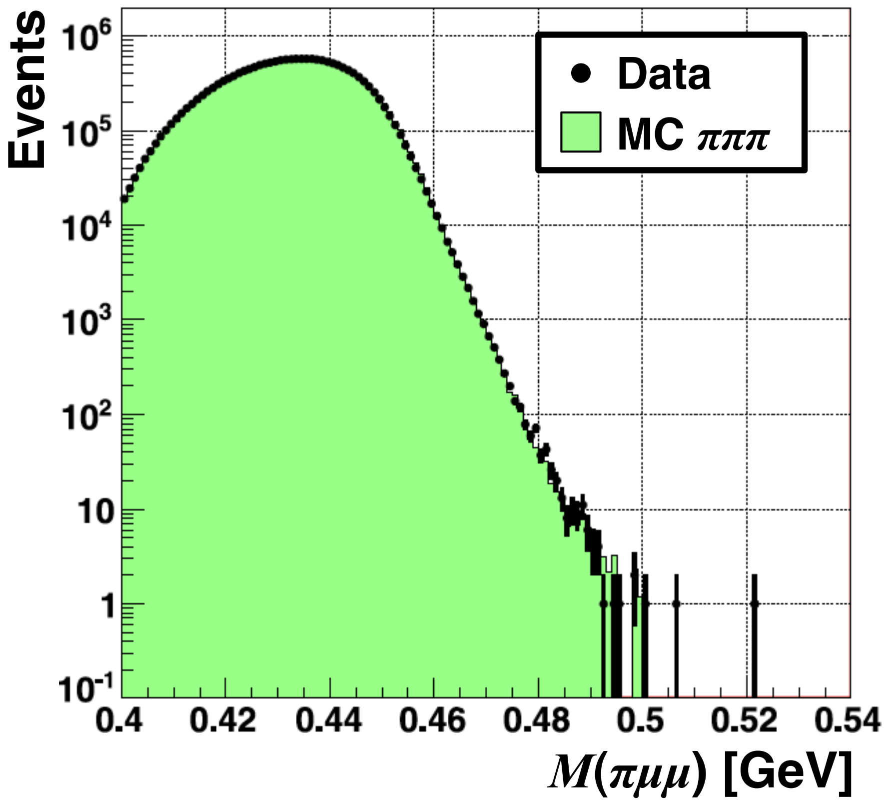
LNV in $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ could provide evidence for Majorana nature of neutrino

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				
$\pi^0 \to 3\gamma$	$BR_{90CL} < 3.1\times10^{-8}$	Crystal Box	Forbidden	Violates C
$\pi^0 \to 4\gamma$	$BR_{90CL} < 2\times10^{-8}$	Crystal Box	BR ~ 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

Rare π^0 decays in NA62

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

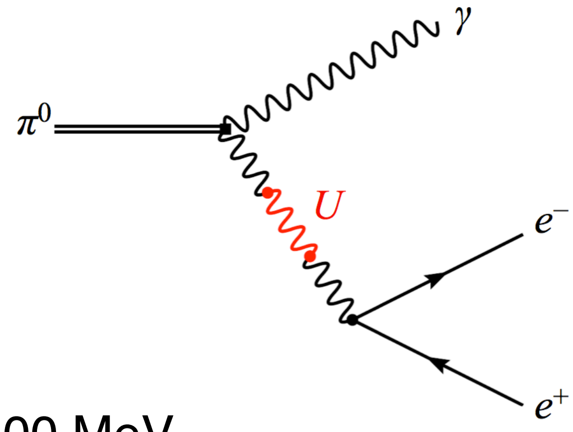
New, light vector gauge boson with weak couplings to charged SM fermions

Could mediate interactions of dark-matter constituents

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

Mass resolution M_{ee} ~ 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 × 10^{-10}

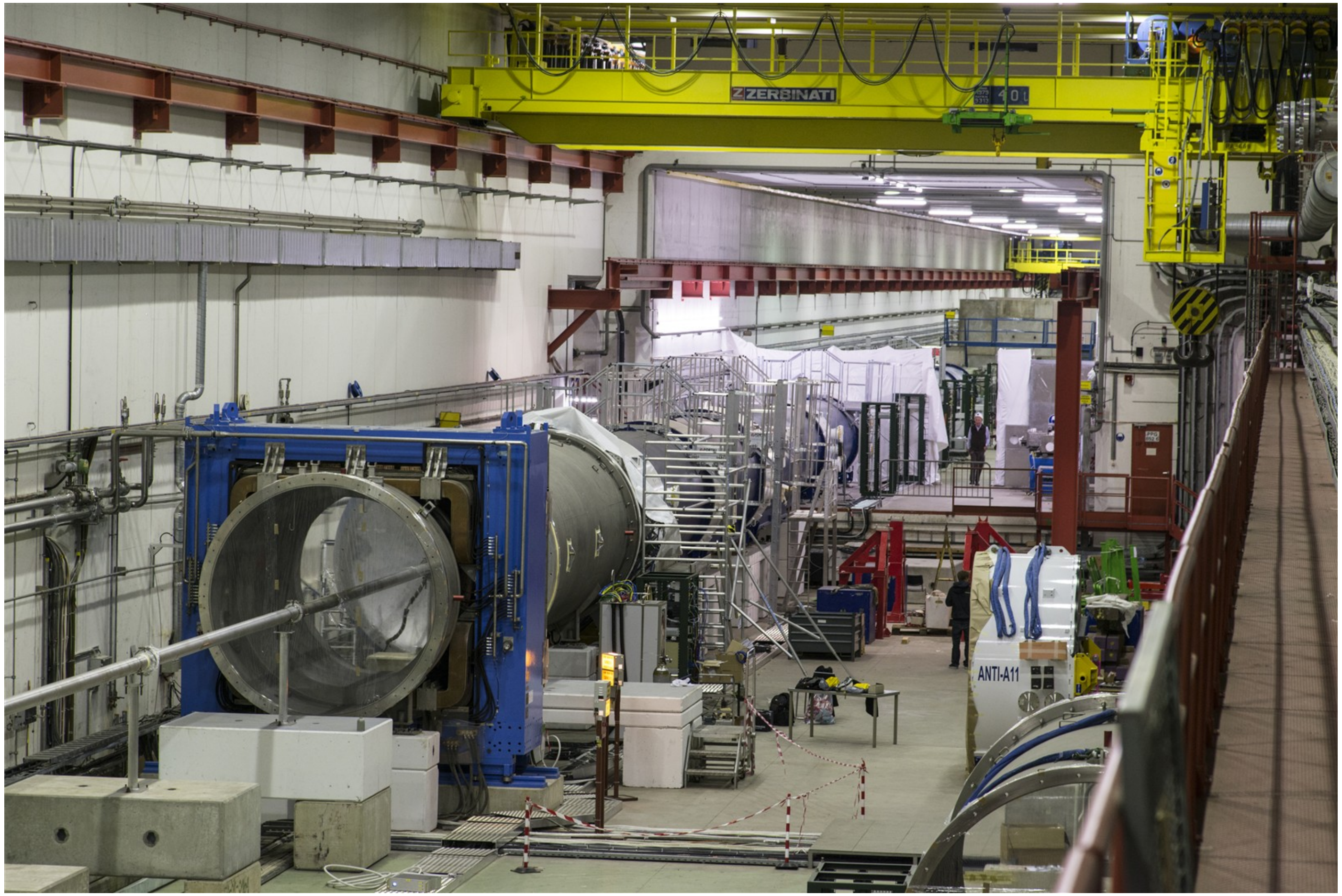
Astrophysics/cosmology: < 3 × 10^{-13}

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 (9/12), 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

- Highly suppressed
- Precisely calculated in the Standard Model
- NP predictions complementary to those from B physics in many cases

NA62 has measured R_K to 0.4%

- SM prediction is still 10× more precise than the measured value
- NA62 will improve precision to the 0.2% level with the $K^+ \to \pi^+ \nu\bar{\nu}$ setup

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

- Single event sensitivities ~10^{-12} for LFNV decays and improved sensitivity for related searches

NA62 will begin taking data in fall 2014