Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab

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Overview of $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab

- Measure B($K^+ \to \pi^+ \nu \bar{\nu}$) to ±5% using BNL E787/949 method
  - Build a modern **4th generation** detector based on the E949 concept.
  - Reliably estimate the sensitivity and backgrounds of the new experiment by extrapolating from E949 experience
  - Expect 200 events/year at SM branching fraction (100 x E949 sensitivity)
- Use the Tevatron as a Stretcher, filled by the Main Injector, to get high duty factor (≈95%).
  - 10% hit on protons to NOvA; no effect on microBooNE, mu2e, g-2, …
- Avoid civil construction by using an existing hall
  - Several possibilities have been identified
- Use an existing superconducting solenoid.
  - CDF or CLEO is suitable
- Estimated TPC is $53M (FY2010 $); work in progress to reduce capital cost through reuse of existing equipment.
- Proposed schedule has a 3 year construction period.

Outline

- Physics Motivation
- Proposed Technique
- Status of Other Experiments
- Opportunity at the Fermilab complex

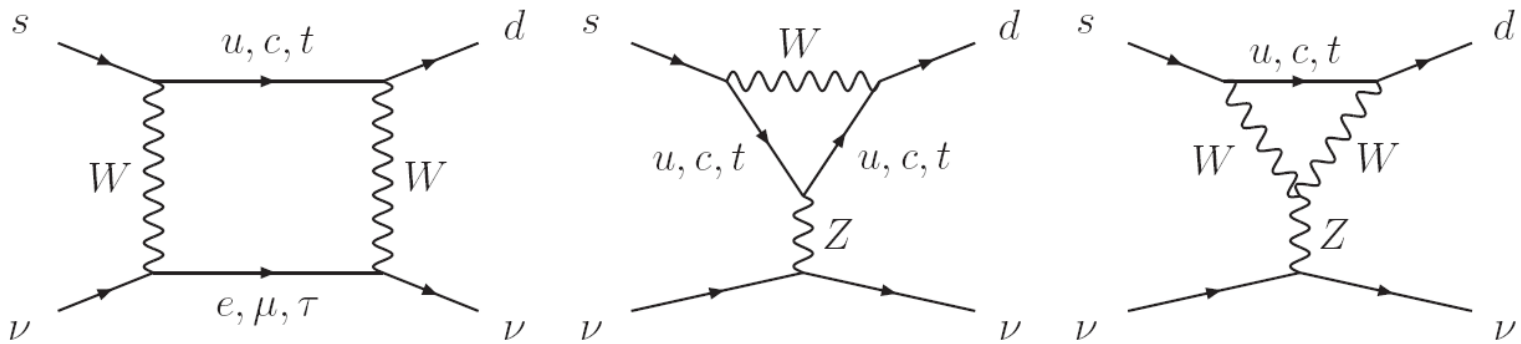
DB

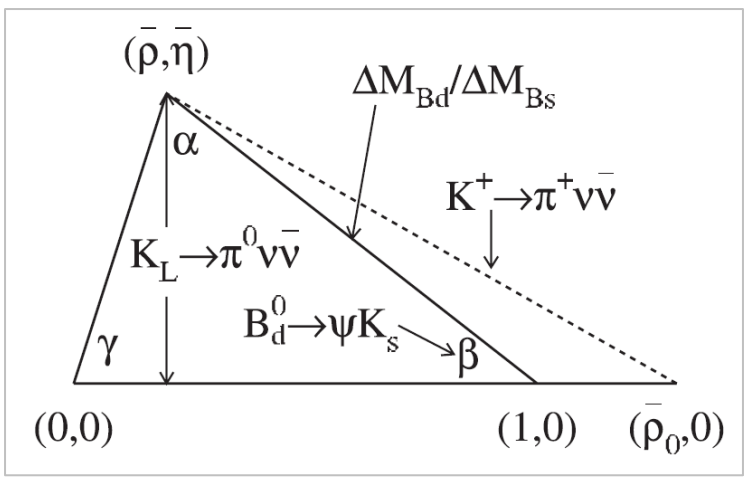
- Tevatron Stretcher
- Kaon Beam
- P966 detector and technique
- Sensitivity and Backgrounds
- Cost and Schedule
- Summary

RT

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

The $K \to \pi\nu\bar{\nu}$ decays are the most precisely calculated FCNC decays.





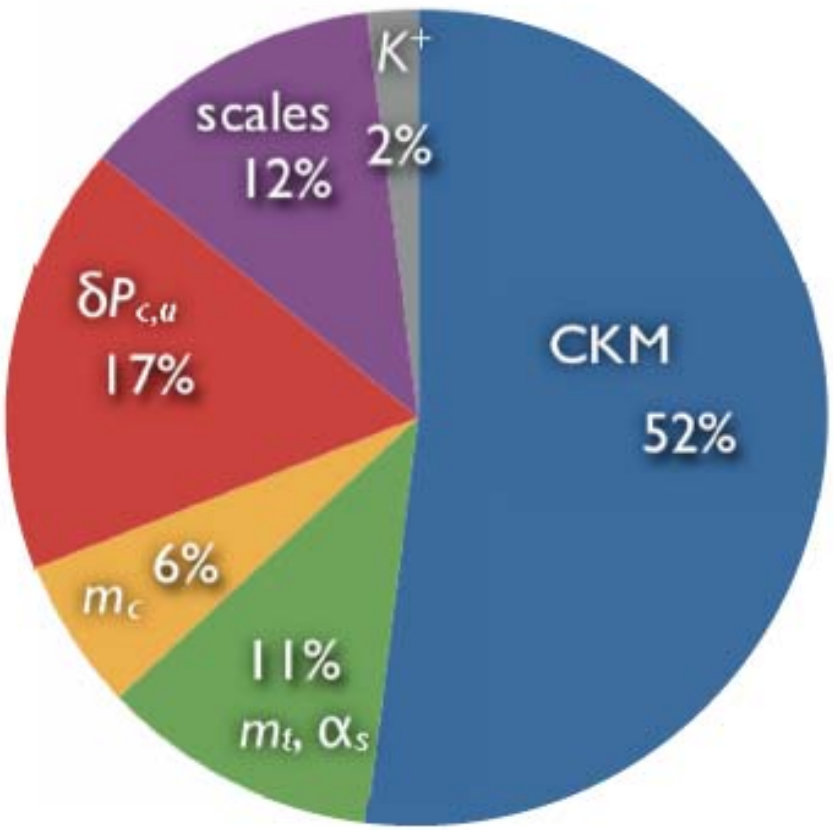
- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- uncertainty from CKM elements (*will improve*)
- **Remains clean in New Physics models** *(unlike many other observables)*

$$\mathrm{BSM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.5 \pm 0.7) \times 10^{-11}$$

Brod and Gorbahn, PRD 78, 034006(2008)

Summary of SM Theory Uncertainties

CKM parameter uncertainties
dominate the error budget today.



With foreseeable improvements, it is reasonable to expect the total SM theory error ≤6%.

A. Kronfeld

Unmatched by any other FCNC process (K or B).

30% deviation from the SM would be a 5σ signal of NP

SM theory error for $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode exceed that for $K^+ \to \pi^+ \nu\bar{\nu}$.

U. Haisch, arXiv:0707.3098

Theoretical Progress

SM Precision

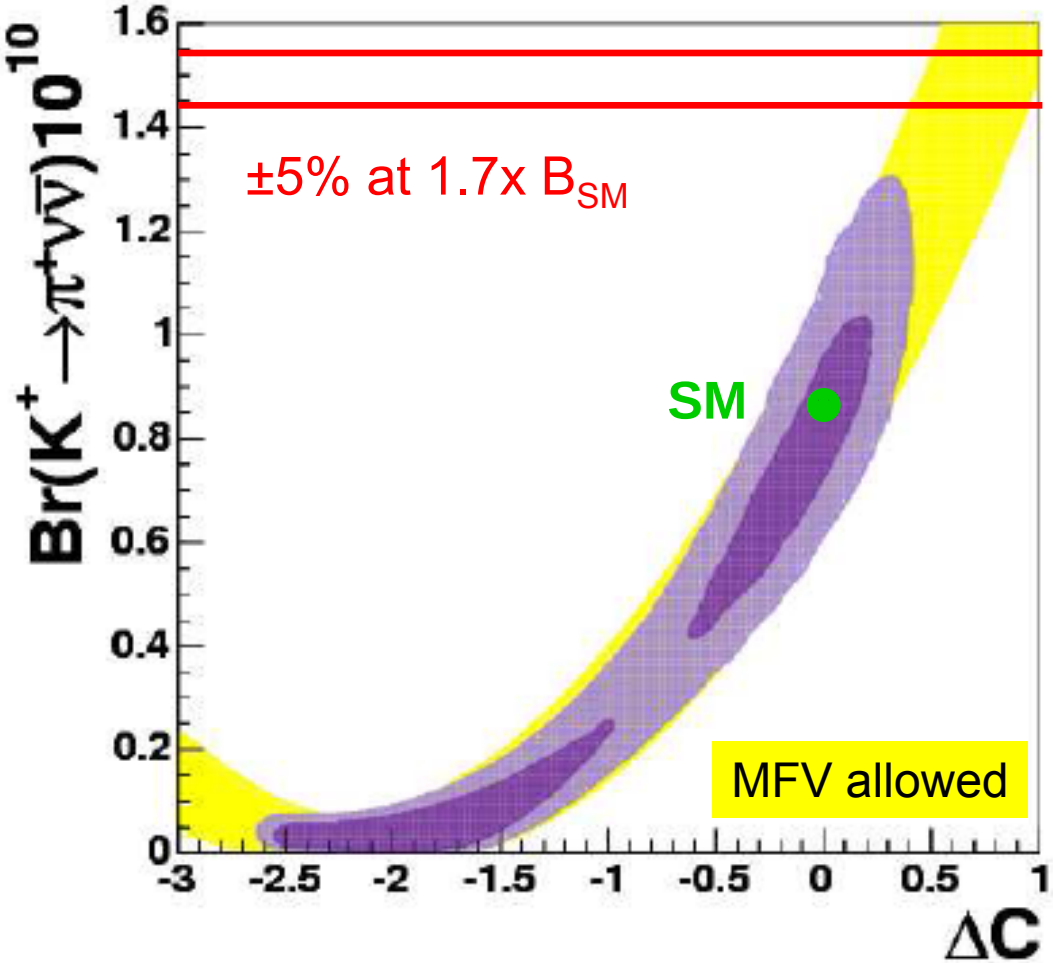
- Buchalla, Buras, 1993
- Lu, Wise, 1994
- Marciano, Parsa, 1996
- Misiak, Urban, 1999
- Buchalla, Buras, 1999
- Falk, Lewandowski, Petrov, 2000
- Isidori, Mescia, Smith, 2005
- Isidori, Martinelli, Turchetti, 2006
- Buras, Gorbahn, Haisch, Nierste, 2006
- Mescia, Smith, 2007
- Bijnens, Ghorbani, 2007
- Kühn, Steinhauser, Sturm, 2007
- Brod, Gorbahn, 2008

BSM Excitement

- Grossman, Nir, 1997
- Buras, Romanino, Silvestrini, 1998
- Buras, Fleischer, 2001
- Grossman, Isidori, Murayama, 2004
- Buras, Ewerth, Jäger, Rosiek, 2004
- Choudhury, Gaur, Joshi, McKellar, ’04
- He, Valencia, 2004
- Bobeth *et al.*, 2005
- Isidori, Mescia, Paradisi, Smith, Trine, 2006
- Blanke, 2009
- And many more—see Buras, Schwab, Uhlig, RMP 2008 for complete refs.

Minimal Flavor Violation (*a highly pessimistic hypothesis*)

Bobeth et al, Nucl Phys B726, 252(2005)



68% and 95% allowed regions for NP, based on $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

The MFV hypothesis assumes that all flavor- and CP-violating effects in New Physics are governed by the SM Yukawa couplings (CKM mixing and phase).

±5% measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$ will provide strong constraints on New Physics within MFV, or demonstrate failure of the MFV hypothesis.

$\Delta C = C - C_{SM}$,
where C characterizes the Z-penguin in b→s

General MSSM with R-parity

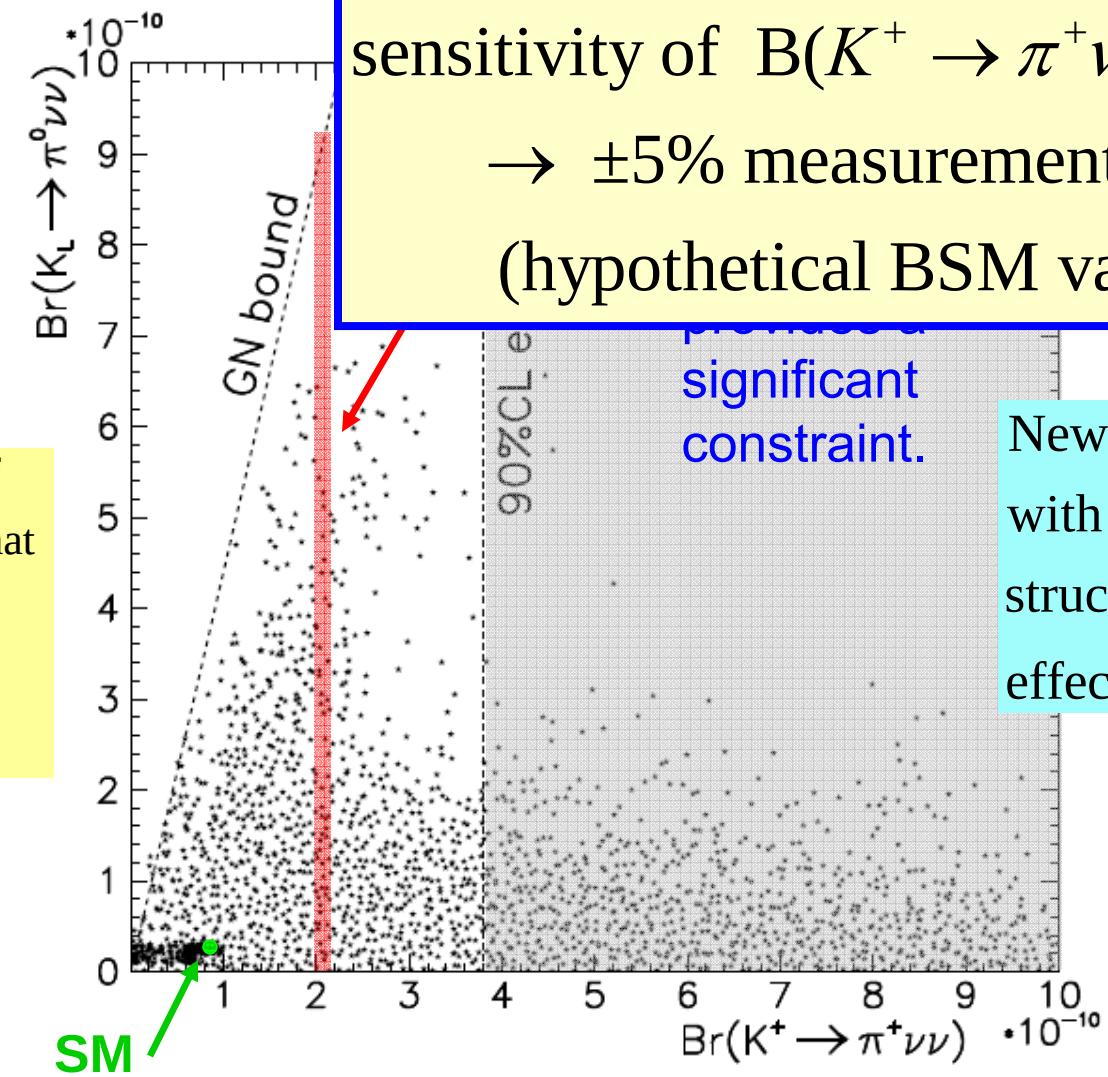
Fermilab P996 will improve the sensitivity of $B(K^+ \to \pi^+ \nu\bar{\nu})$ by >100 !

$\to$ ±5% measurement

(hypothetical BSM value)

Buras et al, NP B714,103(2005)

Points from a scan of MSSM parameters that satisfy experimental constraints except $B(K^+ \to \pi^+ \nu\bar{\nu})$



significant constraint.

New Physics models with generic flavor structure induce large effects in $K^+ \to \pi^+ \nu\bar{\nu}$.

R Parity: $R = (-1)^{2j+3B+L}$.

$K^+ \to \pi^+ \nu\bar{\nu}$ in the LHC Era

New Physics found at LHC

$\Rightarrow$ New particles with unknown flavor- and CP-violating couplings

Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.

New Physics NOT found at LHC

Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

Quark Gen.	Processes to Study NP
1	μ-e Conversion, $\pi \to e\nu$
2	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L^0 \to \pi^0 \nu\bar{\nu}$
3	$b \to s\gamma$, other rare decays

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ have special status because of their small SM uncertainties and large NP reach.

Precision measurement of B($K^+ \to \pi^+ \nu\bar{\nu}$) is an immediate high priority.

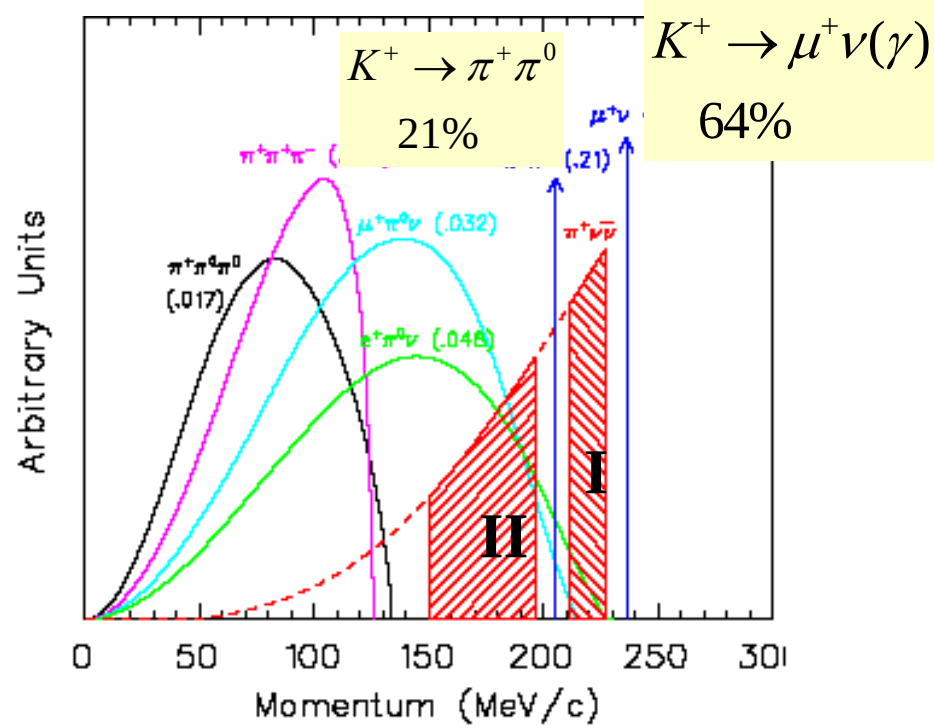
* It is experimentally more accessible than $K_L^0 \to \pi^0 \nu\bar{\nu}$.

* The result can guide the Project-X Intensity Frontier program.

Special Features of Measuring

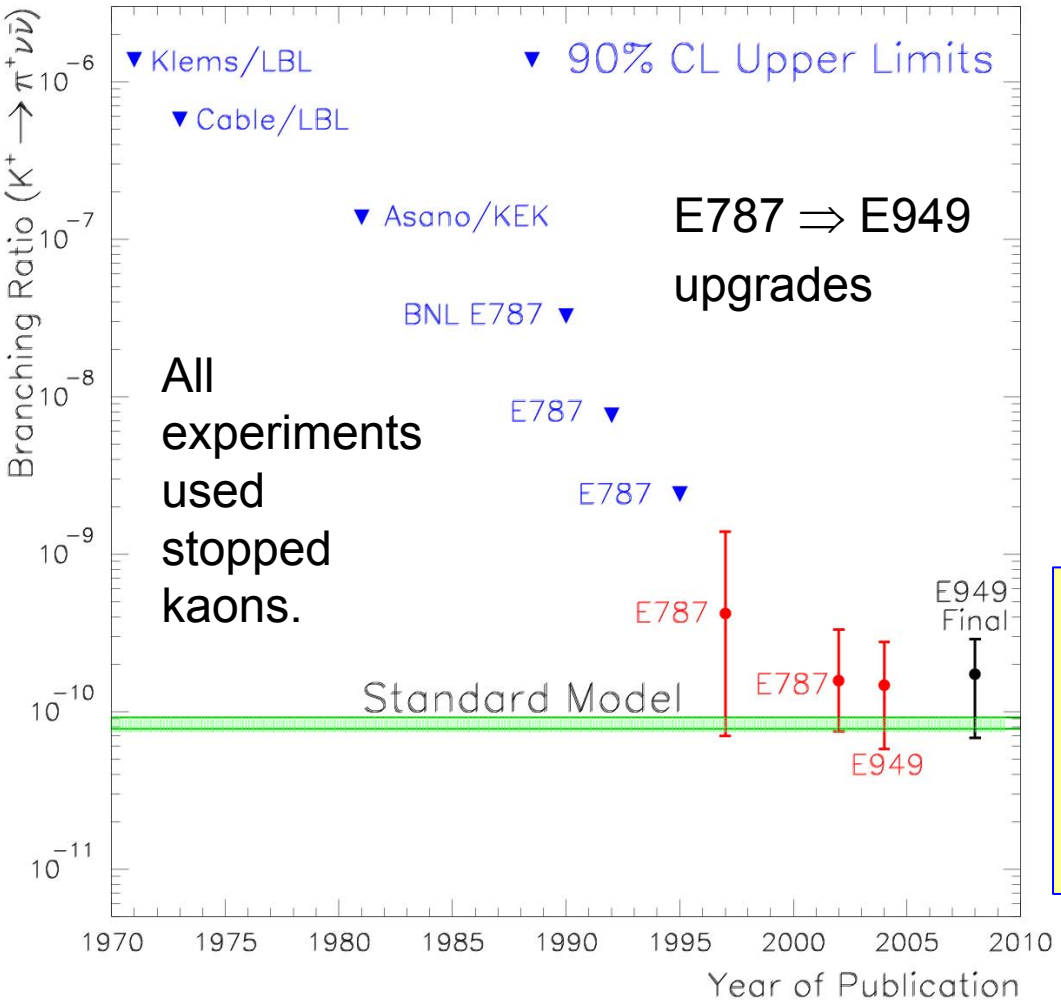
$$K^+ \to \pi^+ \nu \bar{\nu}$$

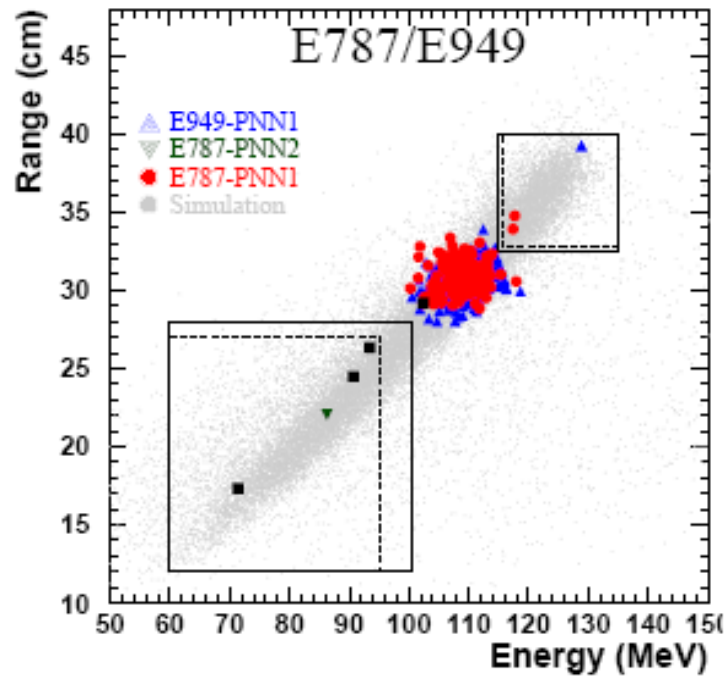
Experimentally weak signature with background processes exceeding signal by >10^{10}



- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+- μ^+- e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency < 10^{-6}
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use "Blind analysis" techniques
  - * Test predictions with outside-the-signal-region measurements
- Evaluate candidate events with S/N function

$K^+ \to \pi^+ \nu\bar{\nu}$ History





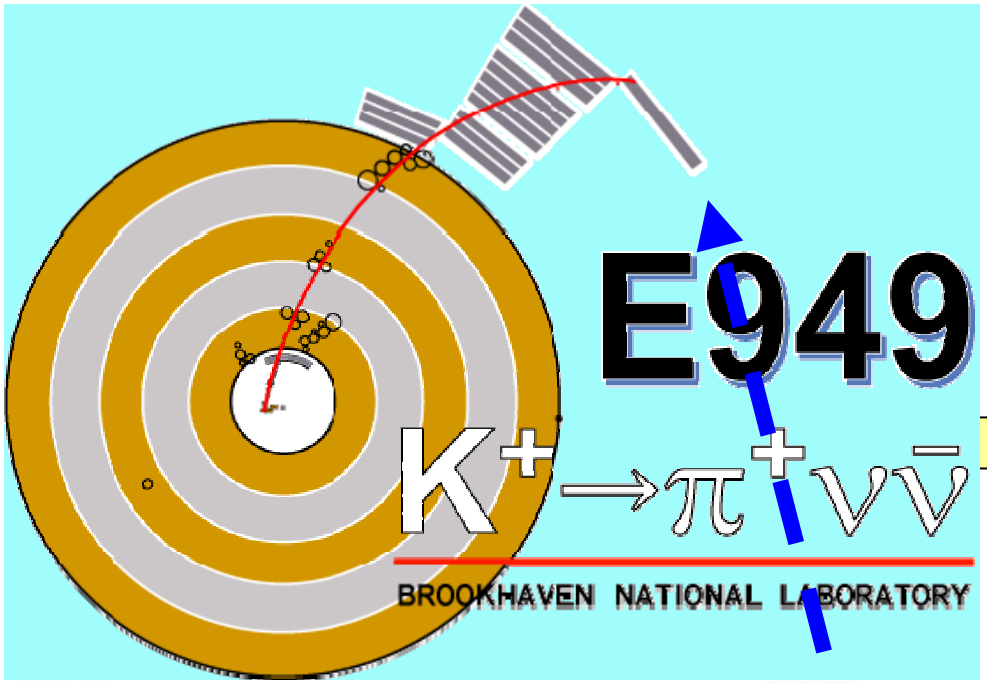
E787/E949 Final: 7 events observed

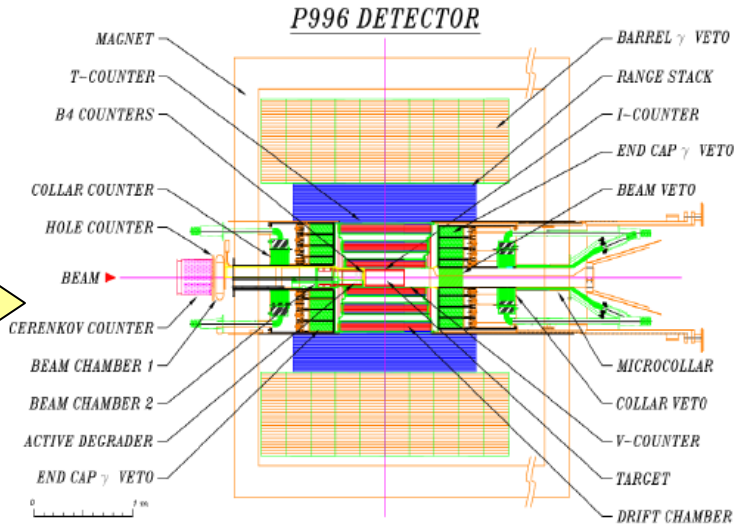
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

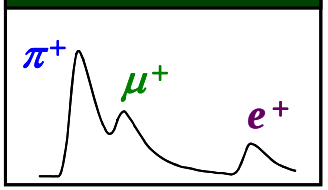
4th generation





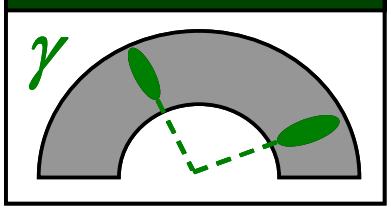
- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks

$\pi^+ \to \mu^+ \to e^+$ Decay Sequence



500 MHz digitizers

4π Photon Veto



Incremental Improvements

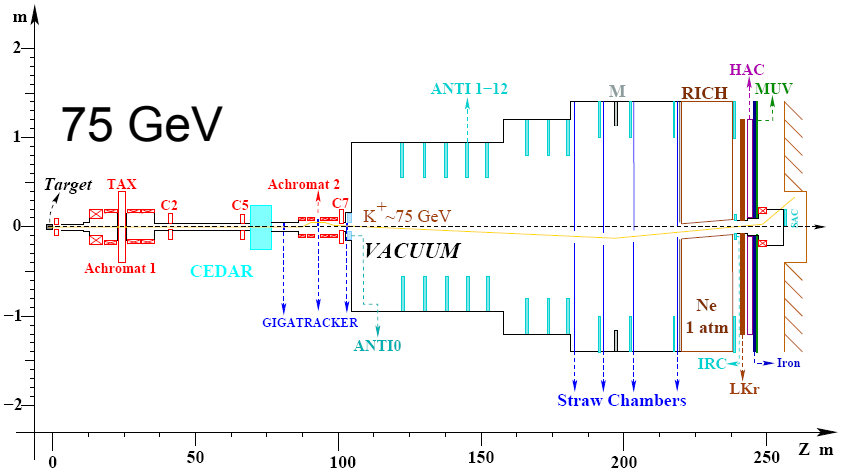
- 550 MeV/c K stopping rate **x5** with comparable instantaneous rate
- Larger solid angle – Acceptance **x 10**
- Finer segmentation, improved resolutions -

Reduced backgrounds

- Overall **100 x** sensitivity

$K^+ \to \pi^+ \nu\bar{\nu}$ at CERN

CERN NA-62 first generation decay-in-flight experiment.



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 50 events/yr at SM
- Under construction; start >2012

$K_L^0 \to \pi^0 \nu\bar{\nu}$ at J-PARC

KOTO: 2nd try with ~same setup as KEK ($B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 2.6 x 10^{-8}$)

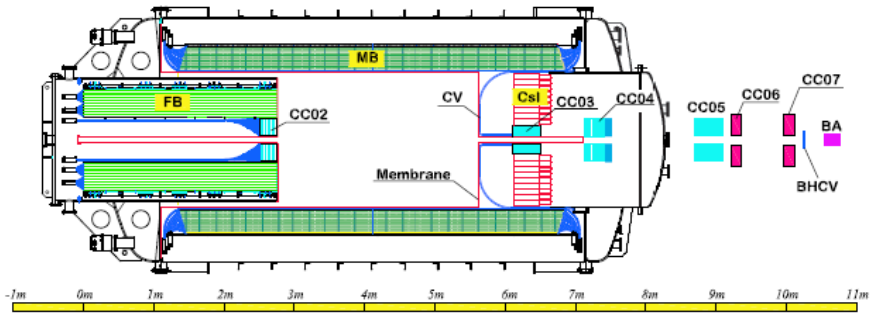


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

- Improved J-PARC Beam line
- (Eventually) higher power
- Aim: 2.8 events (S/B~1) at SM
- Under construction; start >2011

Past experiments like these (at BNL, Fermilab, CERN, PSI, & TRIUMF) have taken several generations (spanning decades) to reach goals.

Why now? Why Fermilab?

LHC discoveries would demand the results from $K^+ \to \pi^+ \nu \bar{\nu}$ and other flavor experiments.

Either New Physics from $K^+ \to \pi^+ \nu \bar{\nu}$ will appear or severe constraints will result.

To be timely, P996 should compete head-to-head with CERN's NA-62 and J-PARC's KOTO "flagship" experiments. P996 is the only comparable effort "guaranteed" to succeed.

- Existing Fermilab facilities (MI and Tevatron) provide an opportunity to make the decisive measurement – no other lab comes close
- Tevatron stretcher operation is viable (if done soon after collider running ends).
- The experiment provides important input for planning the Project-X Intensity Frontier program.
- This experiment will foster rebuilding the U.S. kaon-physics community, essential for the success of Project-X.

Backup Slides

Other Possible P996 Measurements

$$K^+ \to \pi^+ \mu^+ \mu^-$$
$$K^+ \to \pi^+ \gamma\gamma$$
$$K^+ \to \mu^+ \nu\gamma$$
$$K^+ \to \pi^+ \pi^0 \gamma$$
$$K^+ \to \pi^+ X^0$$
$$K^+ \to \pi^+ \gamma\gamma$$
$$K^+ \to \pi^+ \gamma$$
$$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$$
$$K^+ \to \pi^+ H;\ H \to \mu^+ \mu^-$$
$$K^+ \to e^+ \nu \mu^+ \mu^-$$
$$\pi^0 \to \nu\bar{\nu}$$
$$\pi^0 \to \gamma + X^0$$

Other Possible Stretcher Experiments

- Next generation Drell-Yan experiment (follow up of current E906)
- Next generation neutral kaon beam experiment tuned to the interference region to pursue CP and CPT studies in a variety of final states.
- Next generation hyperon experiments, such as a follow-up of the putative evidence for new physics in the $\Sigma^+ \rightarrow p\mu^+\mu^-$ signal or Σ^+ EDM search using bent crystals (Wah, Chicago).
- A $K_L \rightarrow \pi^0 \nu\nu$ experiment if the accelerator pulse timing resolution can be improved (requires R&D).
- $K^+ \rightarrow \pi^0 \mu^+ \nu$ Transverse μ^+ polarization: Stringent test of non-SM time reversal invariance.
- High duty factor test-beam program, which will reduce the cost to NOvA. As configured now the test-beam program will be a 5% hit on NOvA operations, and P996 would be 10%, raising the aggregate hit to 15%. Driving test beams in parallel with P996 will reduce the aggregate NOvA hit to 10% as well as providing better test beams.

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

$$B_{\rm SM}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{\tau_{K^+} M_{K^+}^5}{32\pi^3}(1+\Delta_{\rm EM})\left|f_+^{K^+\pi^+}(0)\right|^2 \mathcal{I}_\nu^+ \left|\frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}Y\right|^2$$

Radiative correction ≅ –0.003

Form factor from Ke3

$$\boxed{Y = V_{td}^* V_{ts} X(x_t) + V_{cd}^* V_{cs}\left[X(x_c) + |V_{us}|^4 \delta P_{c,u}\right]}$$

Top loop ≈70% of BF; NLO in perturbation theory, good to 2%

Charm loop ≈30% of BF; recent calculations reduce error to 2.3%; remaining parametric uncertainty from charm quark mass

Higher dimn charm loop, long-dist u-quark effects; (0.04±0.02)

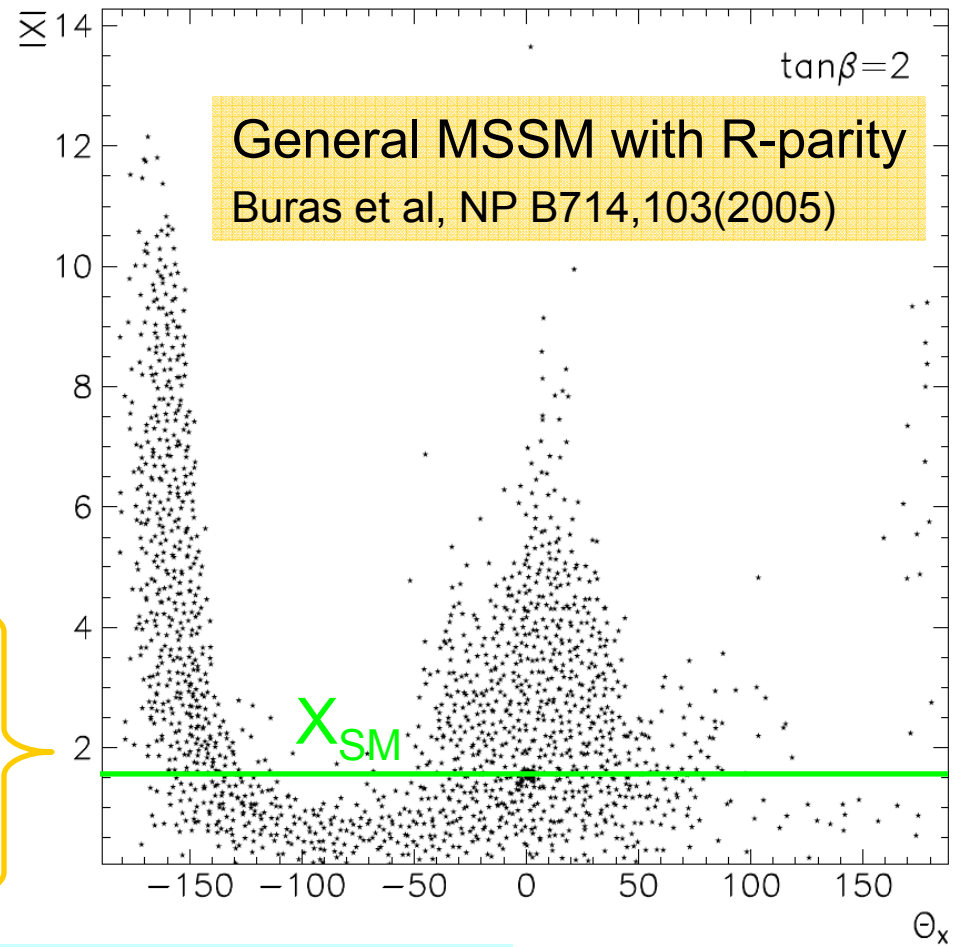
Bottom line - BSM($K^+ \to \pi^+\nu\bar{\nu}$) = (8.5 ± 0.7) x 10^{-10} (9% err)

Sensitivity to New Physics

New Physics can be parameterized by a function $X = |X| e^{i\theta_x}$, which is calculable in perturbation theory for given models.

Significant deviations from the SM are possible.

General MSSM with R-parity
Scan of parameters imposing experimental constraints except B(K⁺→ π⁺ûü)

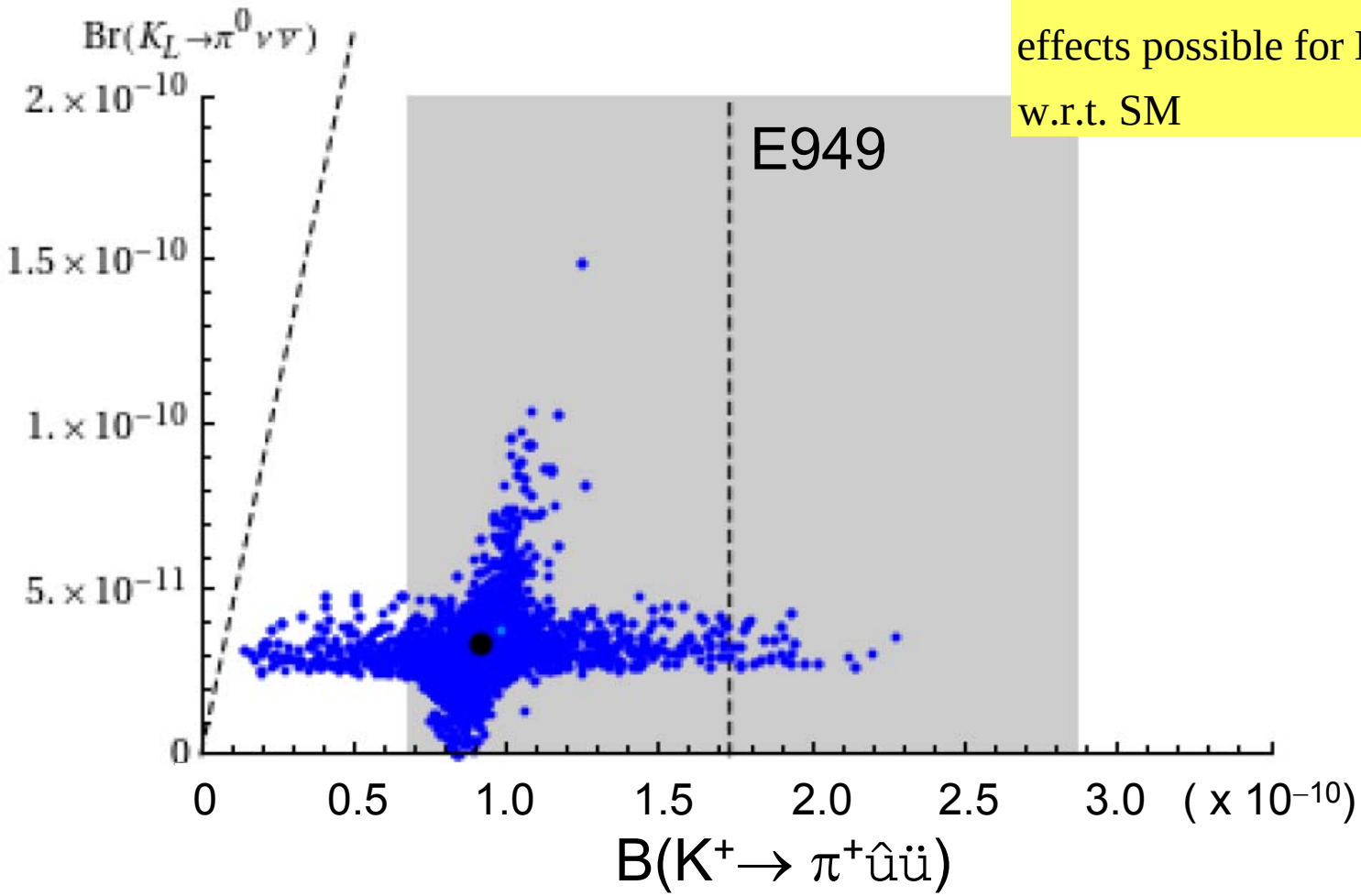


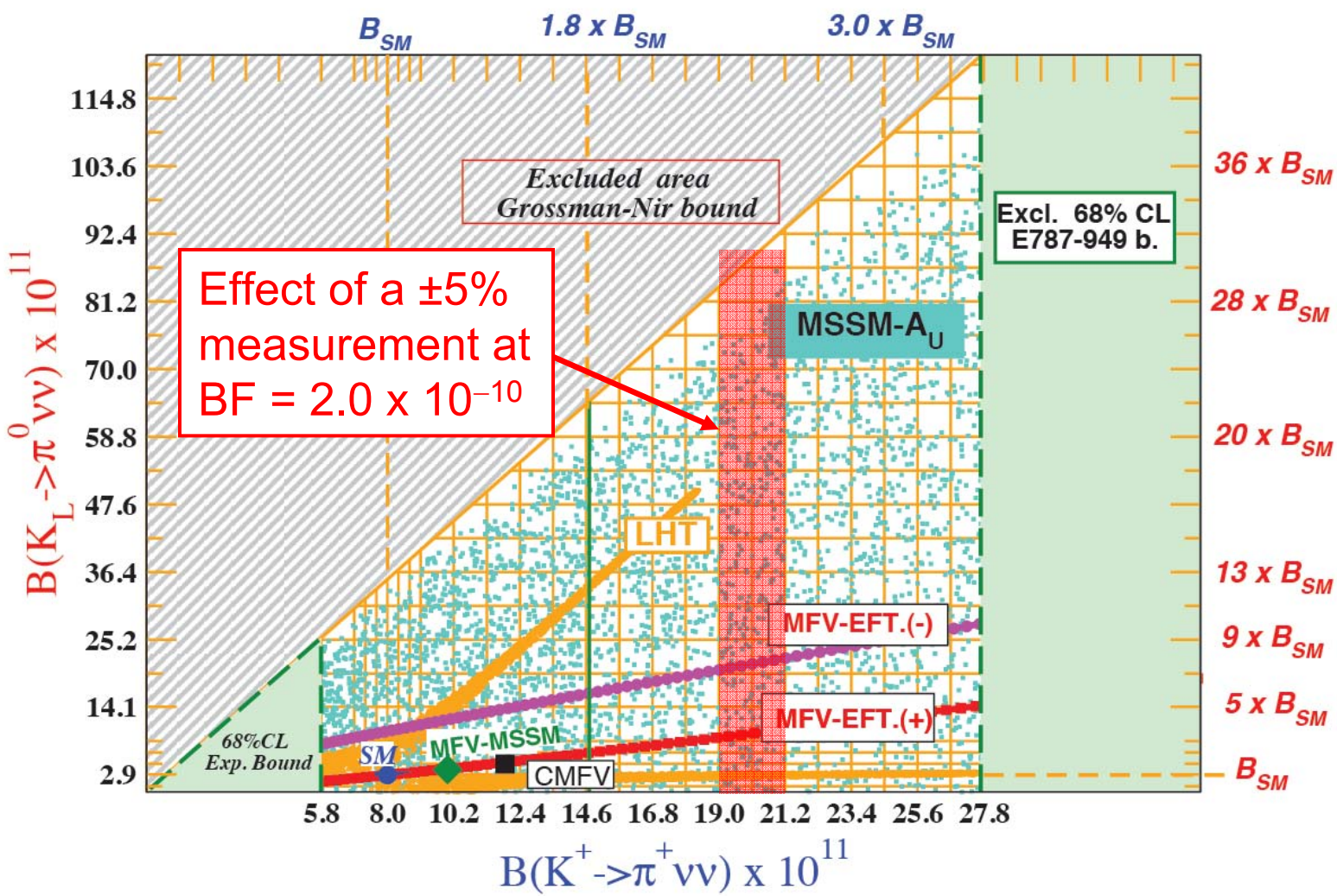
$$B(K^+ \to \pi^+ \nu\bar{\nu}) \propto (X_{SM} + |X| e^{i\theta_x})^2$$

Littlest Higgs model with T-parity

Blanke et al., arXiv:0906.5454

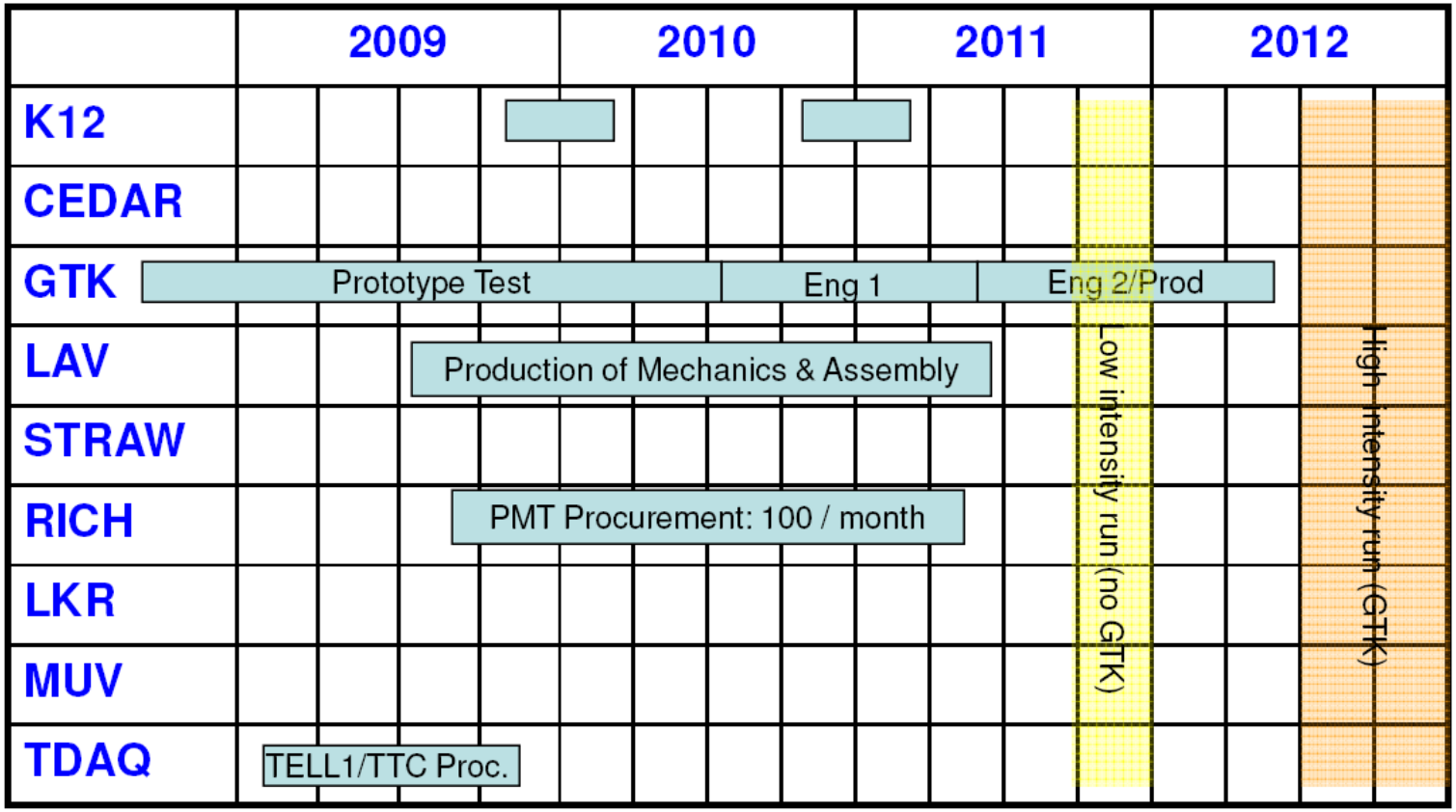
One of many examples of NP scenarios with factor >2-3 effects possible for $B(K^+ \to \pi^+ \nu\bar{\nu})$ w.r.t. SM





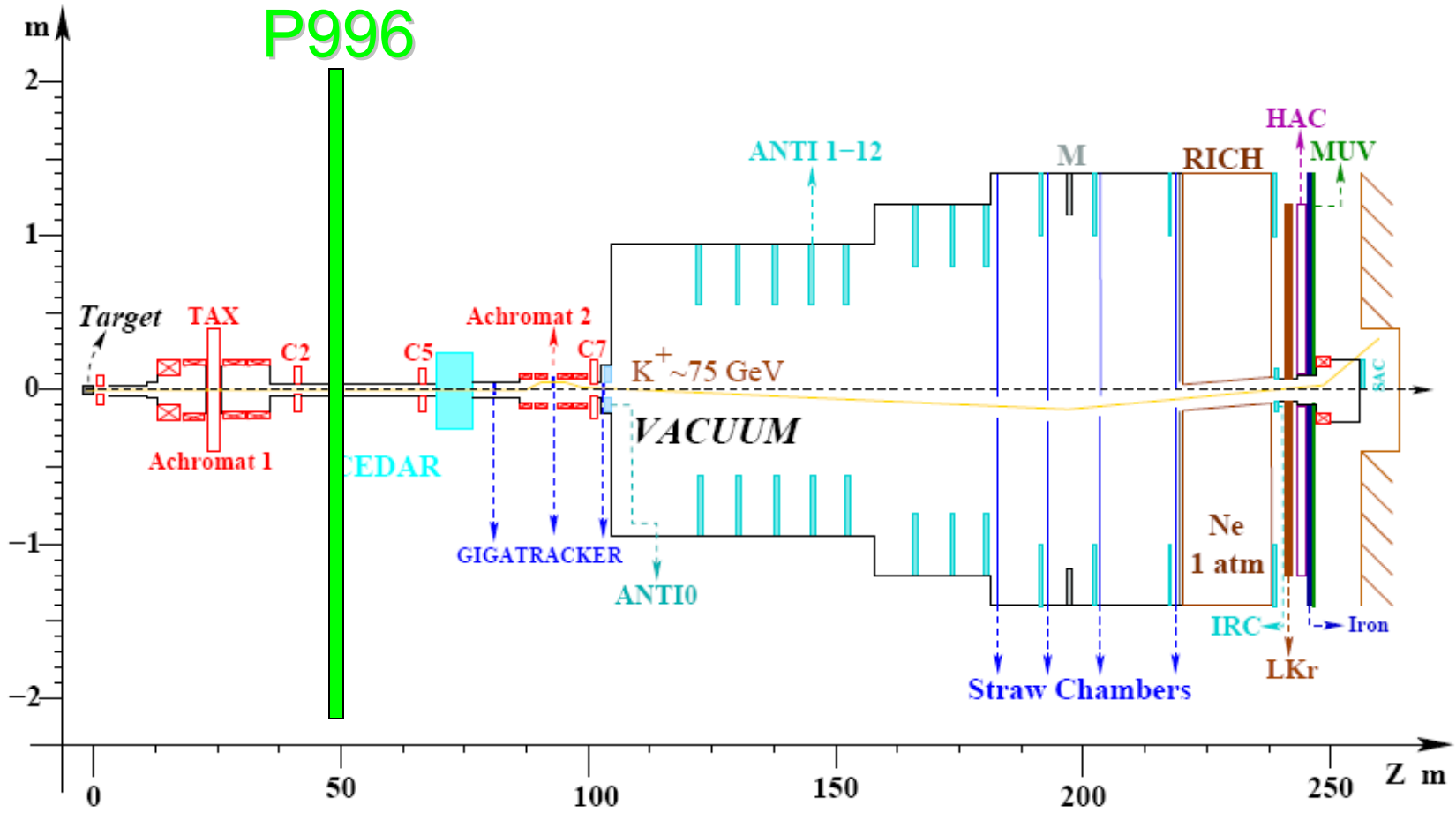
Effect of a ±5% measurement at BF = 2.0×10^{-10}

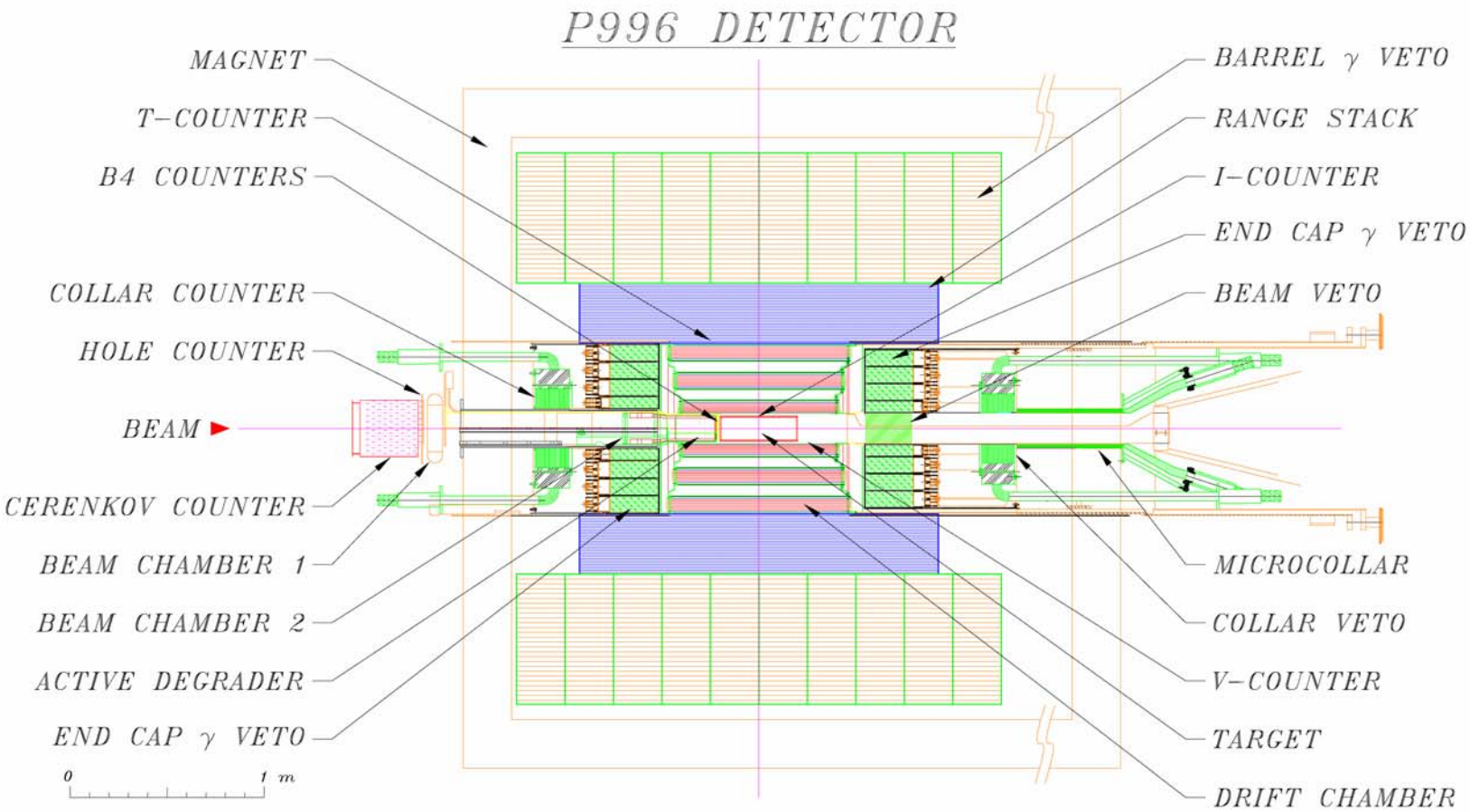
NA-62 Schedule



Source: Augusto Ceccucci, August 2009 (Extreme Beam)

NA-62 Detector Layout




P996 DETECTOR
MAGNET
T–COUNTER
B4 COUNTERS
COLLAR COUNTER
HOLE COUNTER
BEAM
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
ACTIVE DEGRADER
END CAP γ VETO
0
1 m
BARREL γ VETO
RANGE STACK
I–COUNTER
END CAP γ VETO
BEAM VETO
MICROCOLLAR
COLLAR VETO
V–COUNTER
TARGET
DRIFT CHAMBER