Kaon Physics: What the Future Holds in Probing the Standard Model and Beyond…

FPCP – Lake Placid, NY.

R. Tschirhart
Fermi National Accelerator Laboratory
May 29th , 2009

Kaon Physics:

"The Reports of My Death Are Greatly Exaggerated"

Experiments actively publishing:

E391 @ KEK

E949 @ BNL

KLOE @ Frascati.

KTeV @ Fermilab

NA62 @ CERN

Experiments in preparation:

E14 @ JPARC

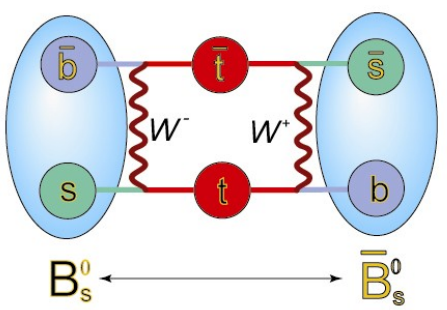
NA62 @ CERN

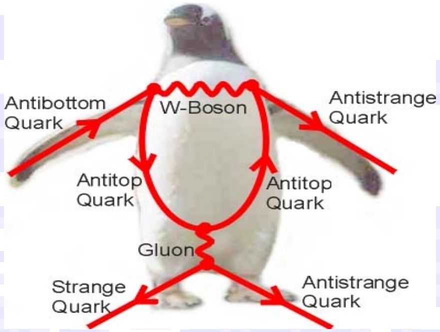
KLOE @ Frascati.

Mark Twain, circa 1897

Kaon Physics Deeply Attacks The Flavor Problem

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??





Sensitivity of the Field Today…

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+\nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \rightarrow \pi^+\bar{\nu}\nu$
- BNL E871: 2×10^{-12} measurement sensitivity of $K_L \rightarrow e^+e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \rightarrow \mu e$

Probing new physics above the 10 TeV scale with ~20 kW of protons

Going after New Physics with Trees and Loops: Notable results from the past six months

(See Zhe Wang's talk Saturday AM)

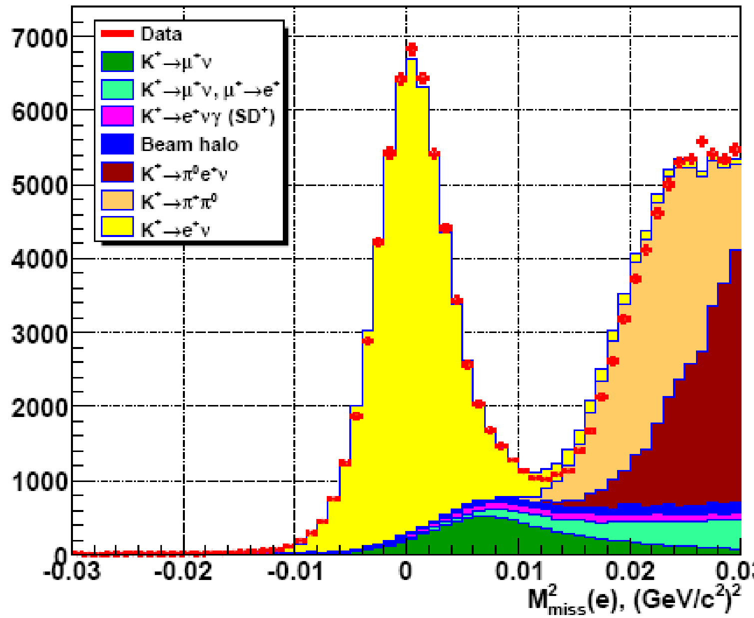
- CERN NA62: Ke2 precision result at summer conferences. Excellent probe of SUSY, particularly charged Higgs.

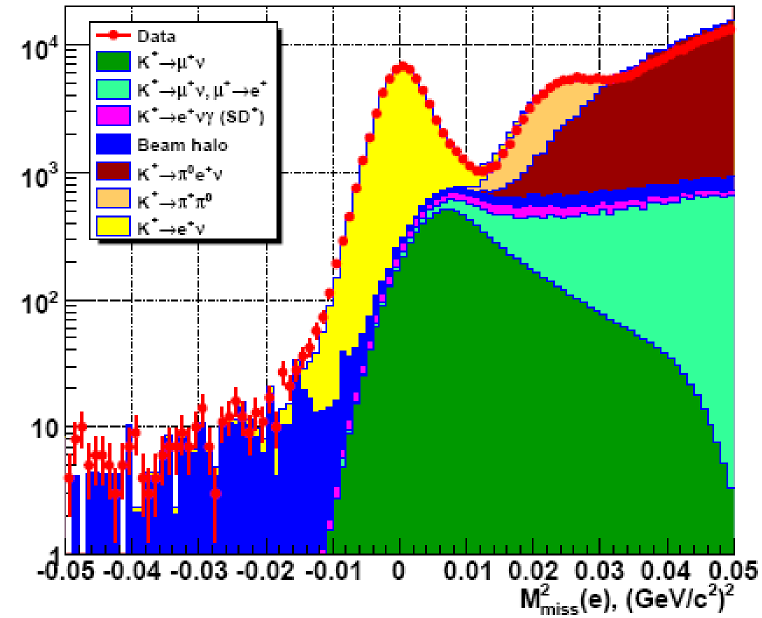
- Frascati KLOE Ke3, Ke2 precision results reported at LaThuile in March. Definitive measures of V_{us} and quark-lepton universality.

- Fermilab KTeV $K_L \rightarrow \pi\pi\mu\mu$ search, closes the window on possible new physics from the HyperCP anomaly: ($\Sigma^+ \rightarrow p^+\mu^+\mu^-$ with a narrow di-muon mass) at Moriond in March.

- BNL E949: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ final result in December 2008, *measurement* with a central value twice (but consistent) with the Standard Model.

CERN NA62: Precision Mesurement of $K^+ \to e\nu$ will be announced soon…





Ke2 background sources:

$K\mu 2$	$(7.4 \pm 0.2)\,\%$
$K\mu 2,\ \mu \to e$	$(1.3 \pm 0.1)\,\%$
$Ke2\gamma$ (SD+)	$(1.6 \pm 0.3)\,\%$
Beam halo	$(1.3 \pm 0.1)\,\%$
Ke3	$0.1\,\%$
$K_{2\pi}$	$(0.6 \pm 0.1)\,\%$

Total Ke2 B/S = 12.3 %

Estimated NA62 total Ke2 sample:

140k K^+ and 20k K^- candidates

Proposal: 150k candidates

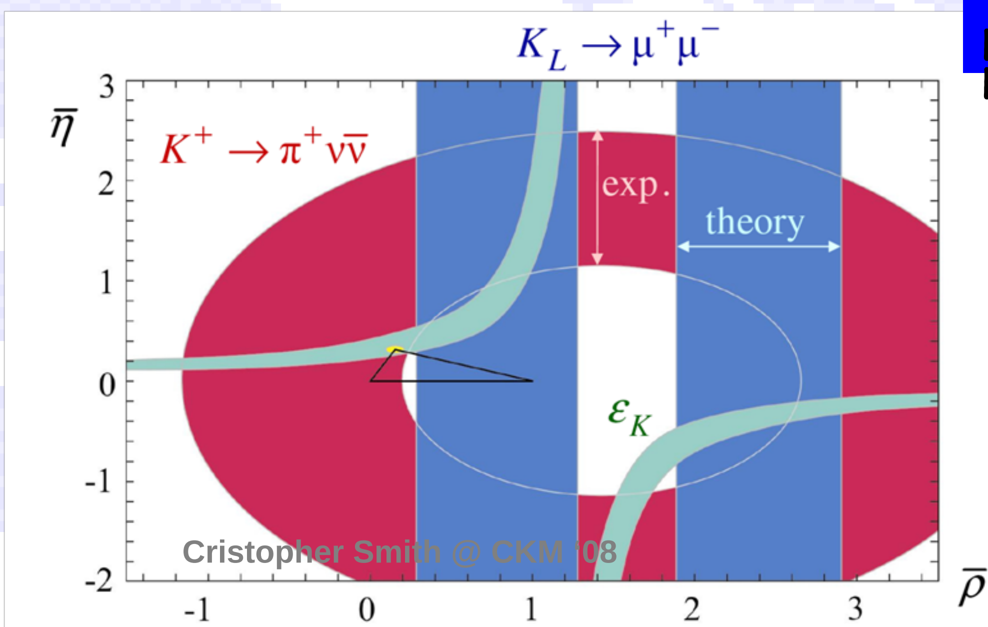
Andreas Winhart, Moriond, March 2009

Test of lepton universality in $K \to l\nu$ decays by NA62 – p. 15

$K \to \pi\nu\bar{\nu}$: Theoretically Pristine and Almost Unexplored

Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \to \pi^+\nu\bar{\nu}(\gamma)$	0.85 ± 0.07 [1]	$1.73^{+1.15}_{-1.05}$ [2]
$K_L^0 \to \pi^0\nu\bar{\nu}$	0.28 ± 0.04 [3]	< 670 (90% CL) [4]

[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
[2] AGS-E787/E949 PRL101 , arXiv:0808.2459
[3] c.f. CKM 08 procs.
[4] KEK-E391a PRL 100, arXiv:0712.4164



$K_L \to \pi^0\nu\bar{\nu}$: $\bar{\eta} < 17$

$K_L \to \pi^0 e^+ e^-$: $\bar{\eta} < 3.3$

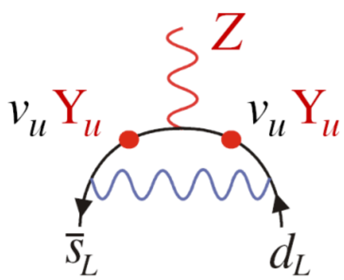
$K_L \to \pi^0 \mu^+\mu^-$: $\bar{\eta} < 5.4$

Proposed:
KOTO (E14) J-PARC

Kaon Rare Decays and NP

(courtesy by Christopher Smith)

C. The Z penguin (and its associated W box)

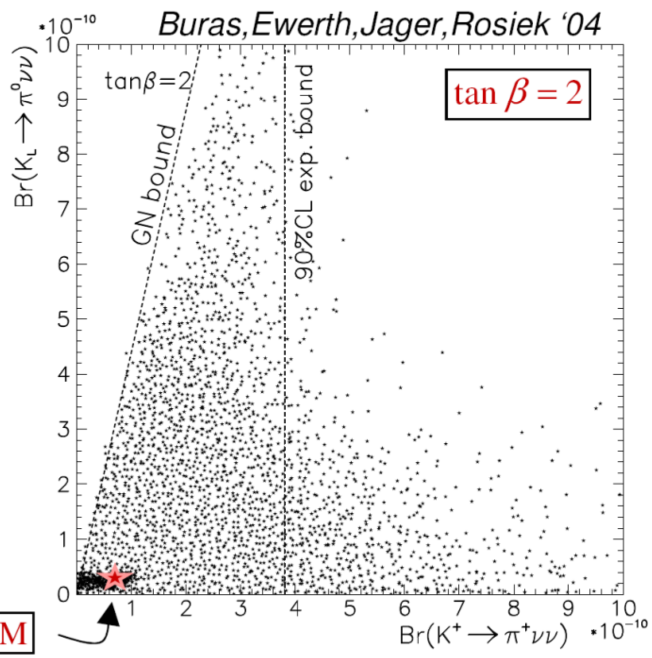


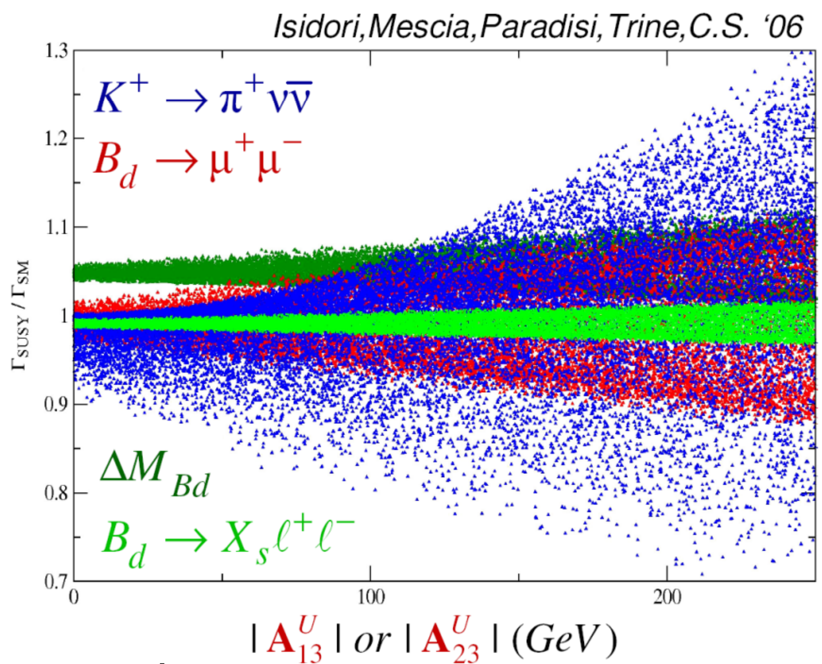
- $SU(2)_L$ breaking: $SM : v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

$$MSSM : v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 \times O(1)\,?$$

$$MFV : v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left|A_0 a_2^* - \cot\beta\mu\right|^2 .$$

- Relatively slow decoupling (w.r.t. boxes or tree).





CERN, 11-5-2009 A. Ceccucci 8

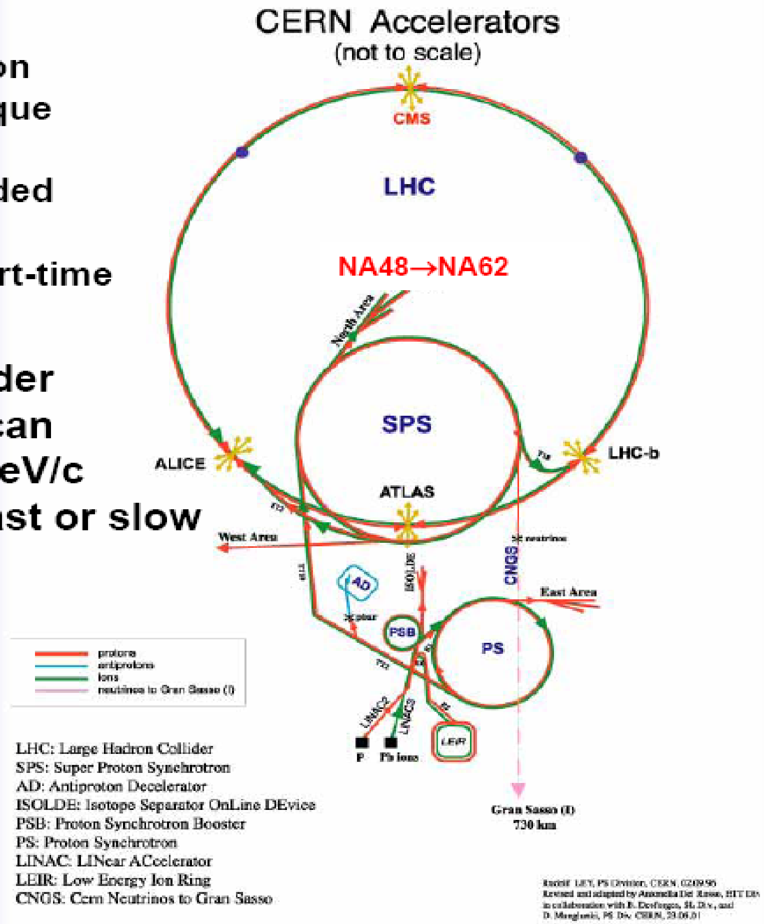
CERN NA62: Precision Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Bern ITP, Birmingham, Bristol, CERN, Dubna, Ferrara, Fairfax, Florence, Frascati, Glasgow, IHEP, INR, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin

The CERN proton Complex is unique

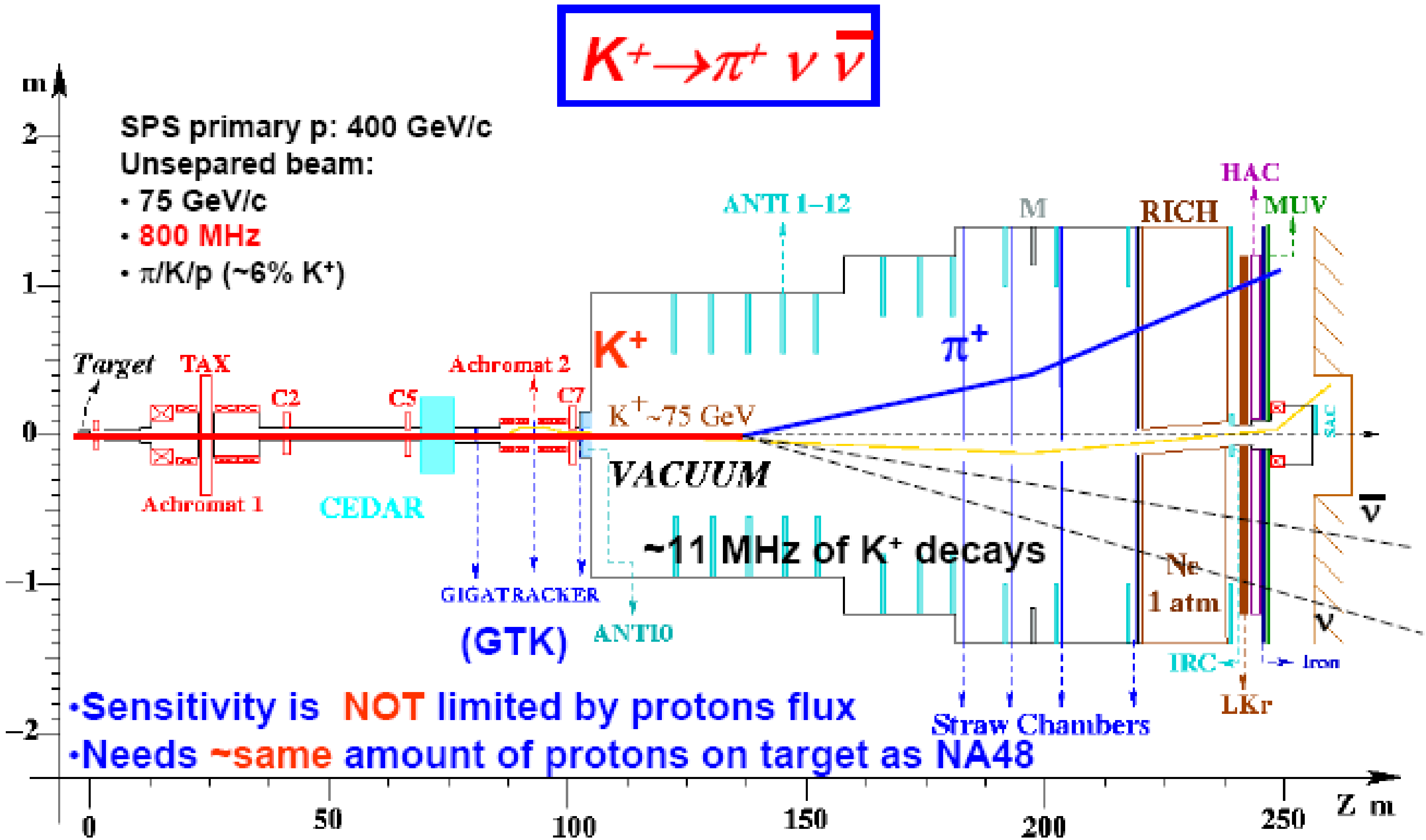
The SPS is needed as LHC proton injector only part-time

For the reminder of the time it can provide 400 GeV/c protons for fast or slow extraction

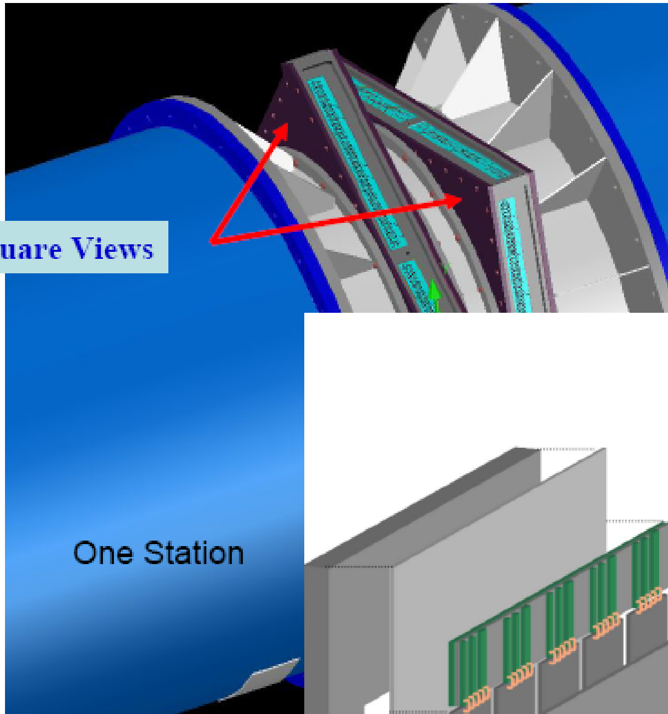


Nota Bene:
NAYY ≡ YYth Experiment Performed at the North Area SPS Extraction site

Proposed Detector Layout

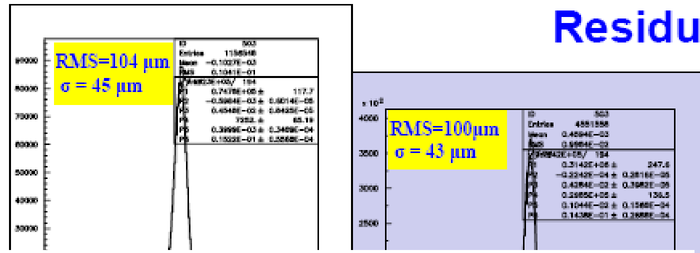


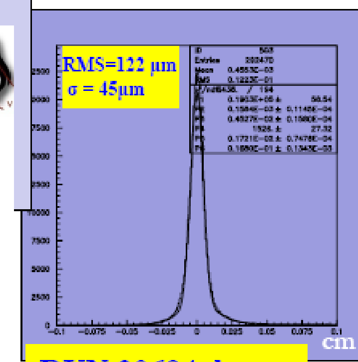
Ultra-low mass, high speed tracking…



800 MHz Beam!

STRAW Prototype: Beam Test

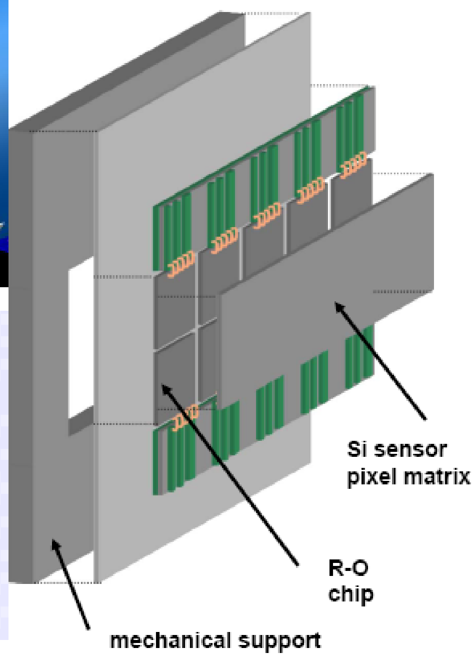


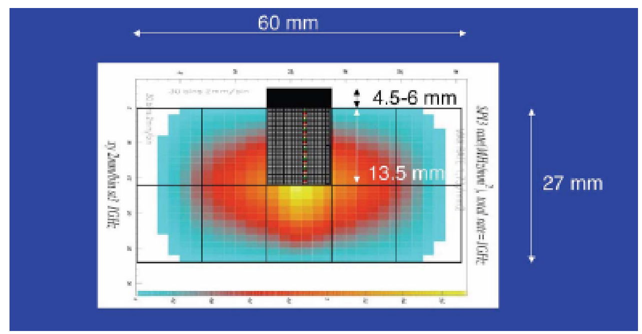


full length Straw Prototype: 2.1 m long Operated in Vacuum

CF$_4$ (10%) Isob. (10%)

GTK Station





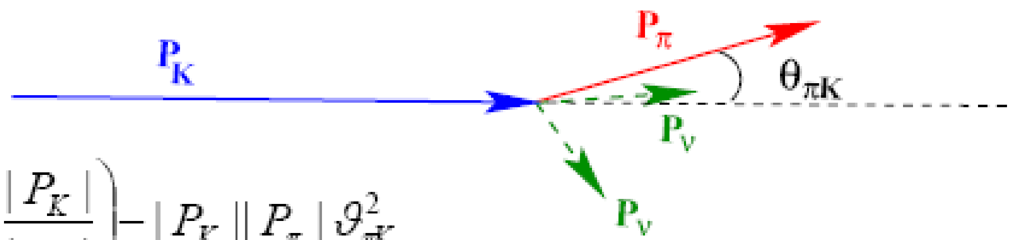
Requirements:

Track and time each beam particle
Time resolution: 200 ps / station
Material Budget: < 0.5 % X_0 / station
Pattern: 300 x 300 μm^2

Two options for the Read-Out:

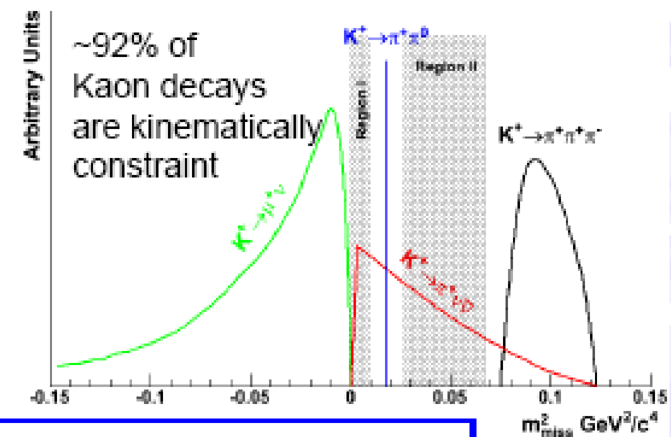
- On-Pixel TDC
- End-of-Column TDC

Background Rejection



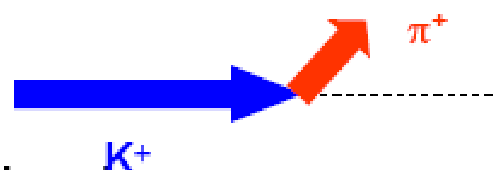
$$m_{miss}^2 \approx m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta_{\pi K}^2$$

Decay	BR
$K^+\rightarrow\mu^+\nu$ ($K_{\mu 2}$)	0.64
$K^+\rightarrow\pi^+\pi^0$ ($K_{\pi 2}$)	0.21
$K^+\rightarrow\pi^+\pi^+\pi^-$ $K^+\rightarrow\pi^+\pi^0\pi^0$	0.07



Signature:

- Incoming high momentum (75 GeV/c) K^+
- Outgoing low momentum (< 35 GeV/c) π^+
- For $K_{\pi 2}$ P(π^0) > 40 GeV/c: it can hardly be missed



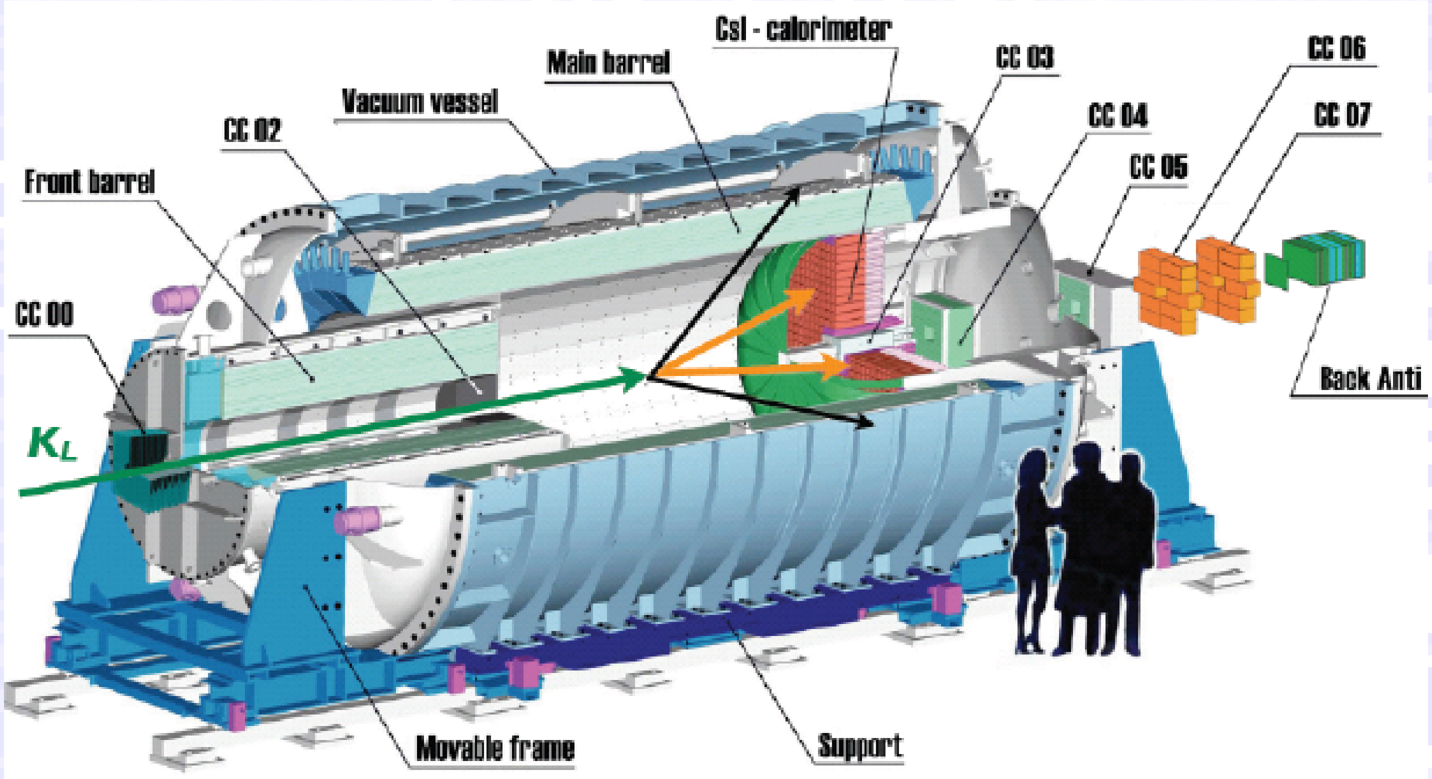
NA62 Sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-8}) $]$	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+(\mu^+)$ $\pi^0 \nu$, others	negligible
Expected background	≤13.5% (≤17%)

Definition of "year" and running efficiencies based on NA48 experience: ~100 days/year; 60% overall efficiency

Construction of key additional sub detectors in 2010, data taking in 2012.

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Neutral Mode: "Nothing-in, Nothing-out"



KEK & JPARC staged attack:

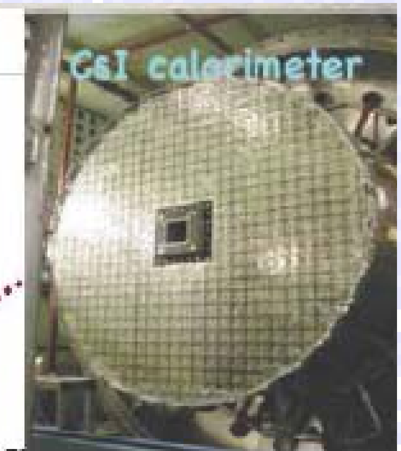
1: Develop techniques at KEK.

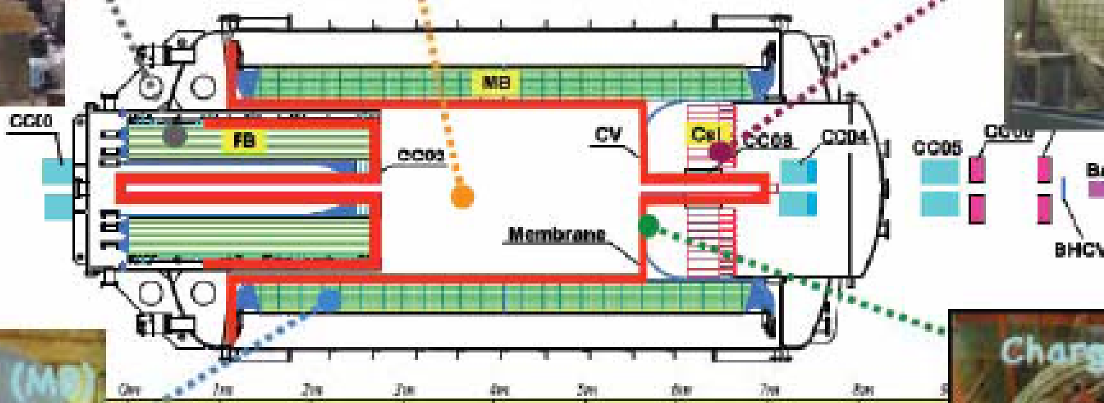
2: Standard Model Sensitivity at JPARC, Phase-I (start 2011)

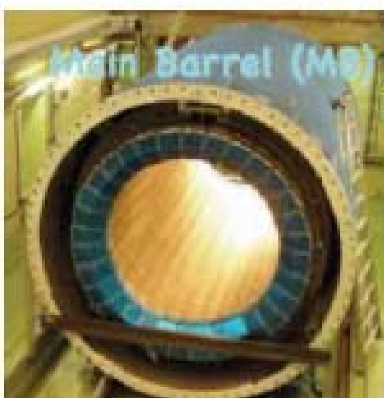
3: Ten's of SM events in Phase-II.

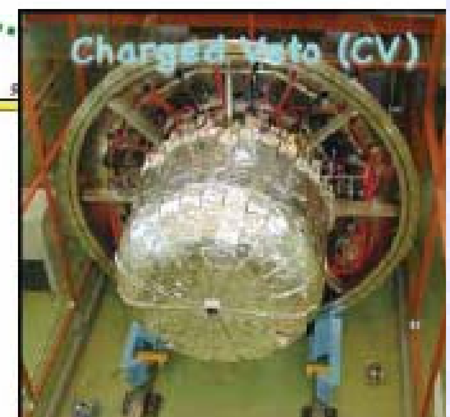
Elements of Hermeticity…

- Decay region
  - High vacuum: 10^{-5} Pa
    - to suppress the background from interactions w/ residual gas





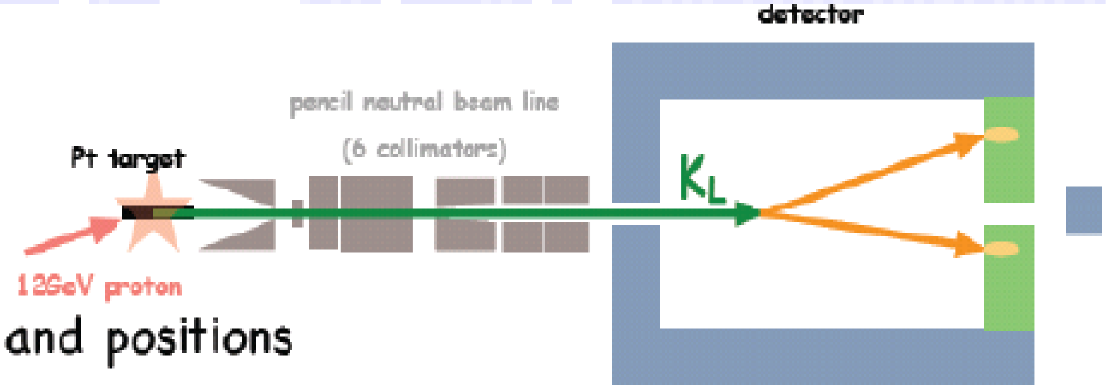




- Detector components
  - Set in the vacuum: 0.1 Pa
    - separating the decay region from the detector region with "membrane": 0.2mmt film

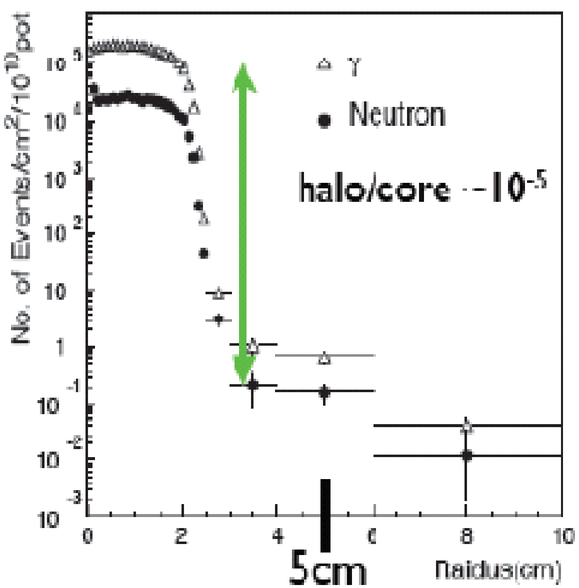
Signal = 2γ + nothing

1. require 2 photons
   - Hermetic veto system

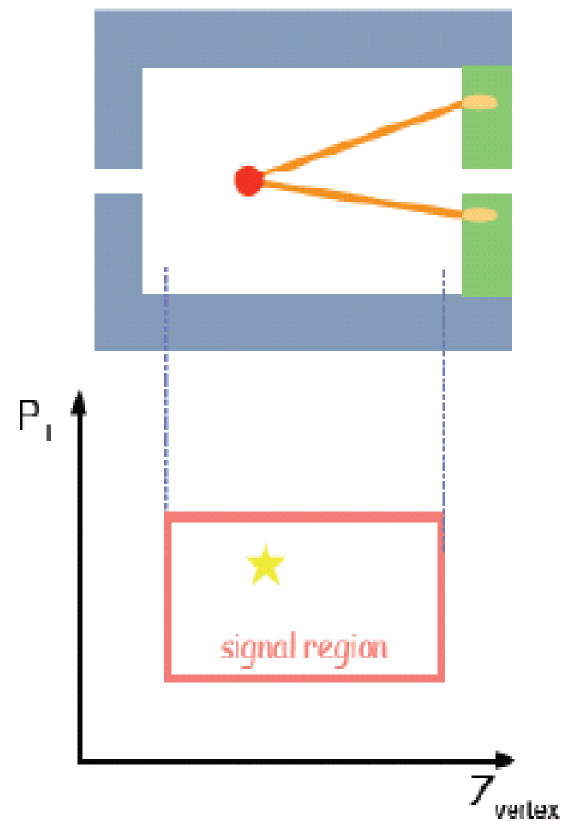


2. measure the photon energies and positions

3. reconstruct the decay vertex on the beamline assuming $M_{2\gamma} = M_{\pi 0}$



4. require missing P_T and the vertex in the fiducial region
   - "Pencil" beam line to improve P_T resolution
     - 8cm diameter @ 16m from the target

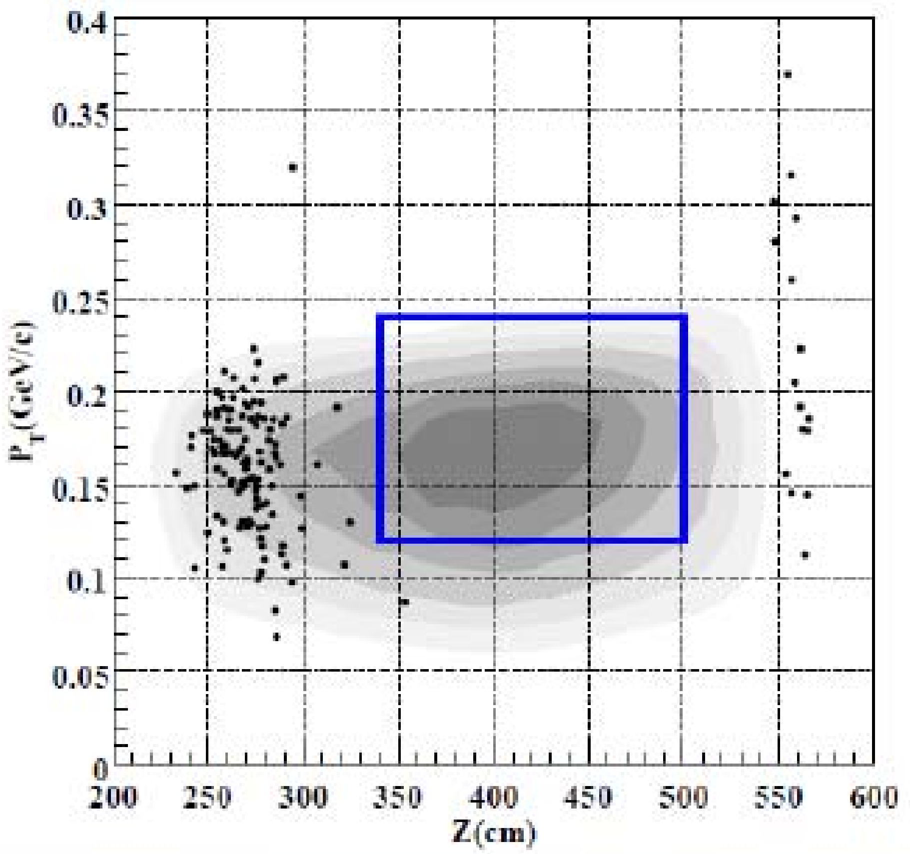


KEK E391a : Result

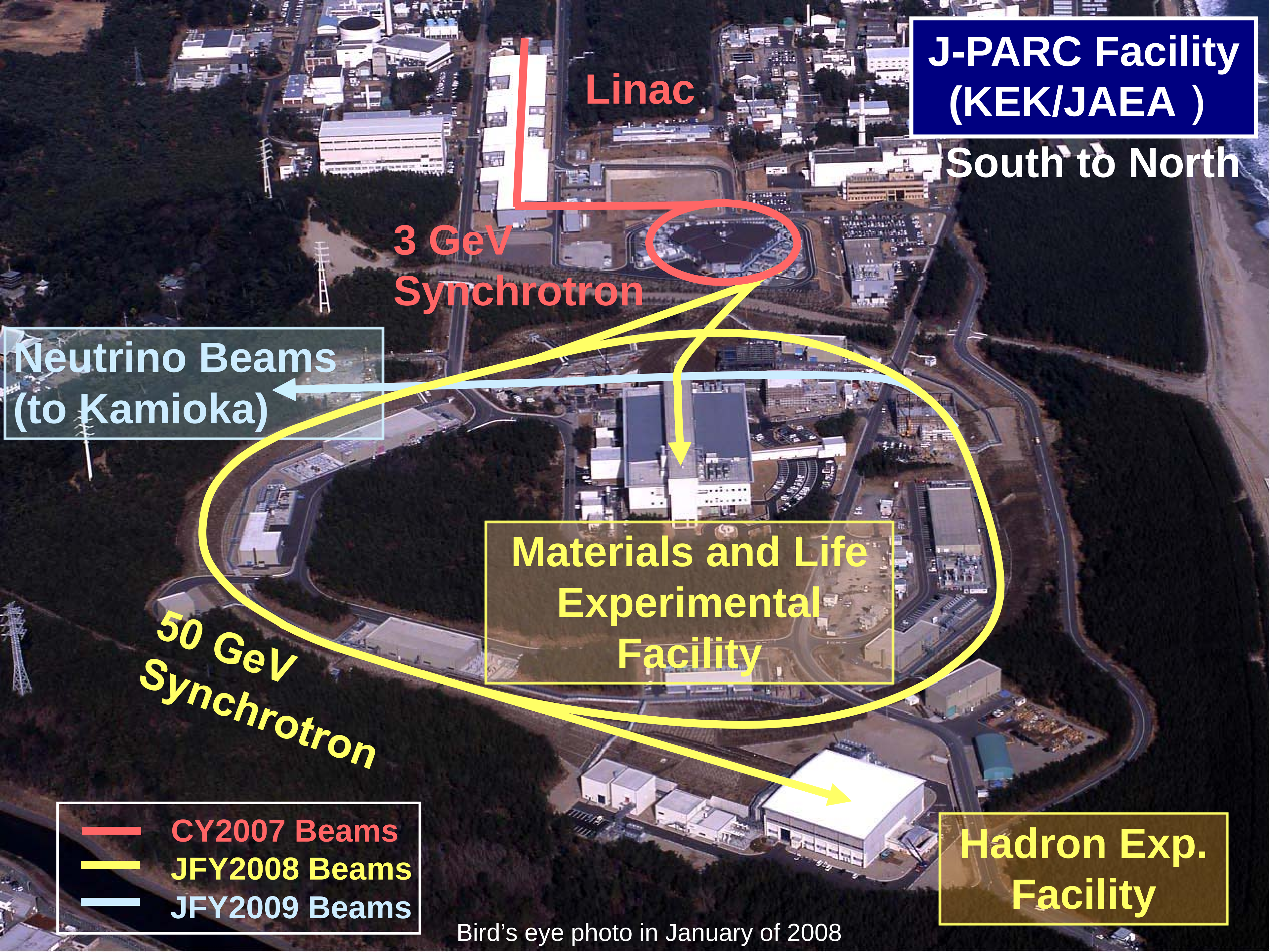
- Open the box
  and
  no event inside

➔ Set upper limit

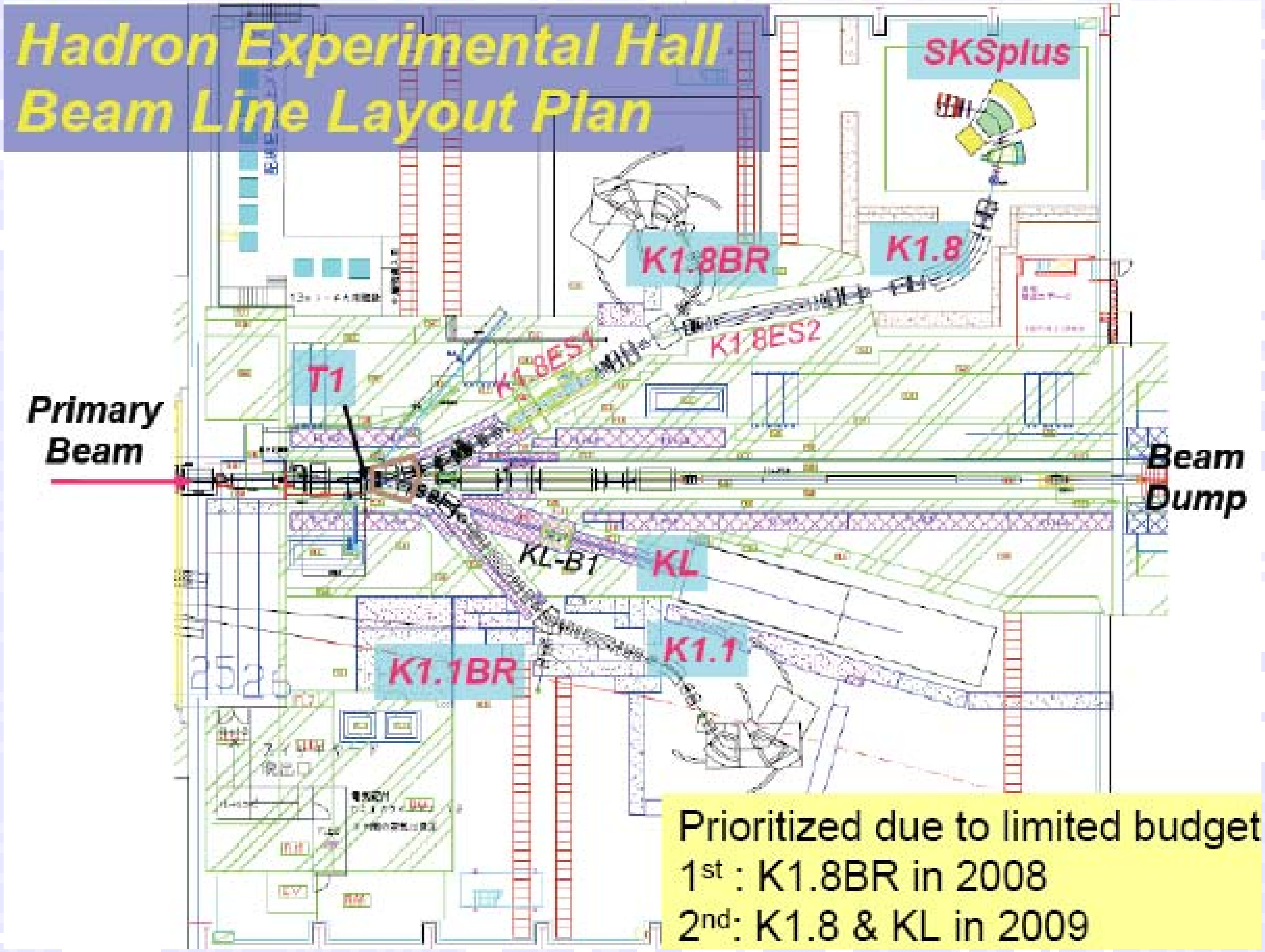
$$BR < 6.7\times10^{-8}$$



E391a has another dataset with similar statistics and it is now on analysis.


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Slow extracted beam established, Measurement of neutral beam properties this fall.



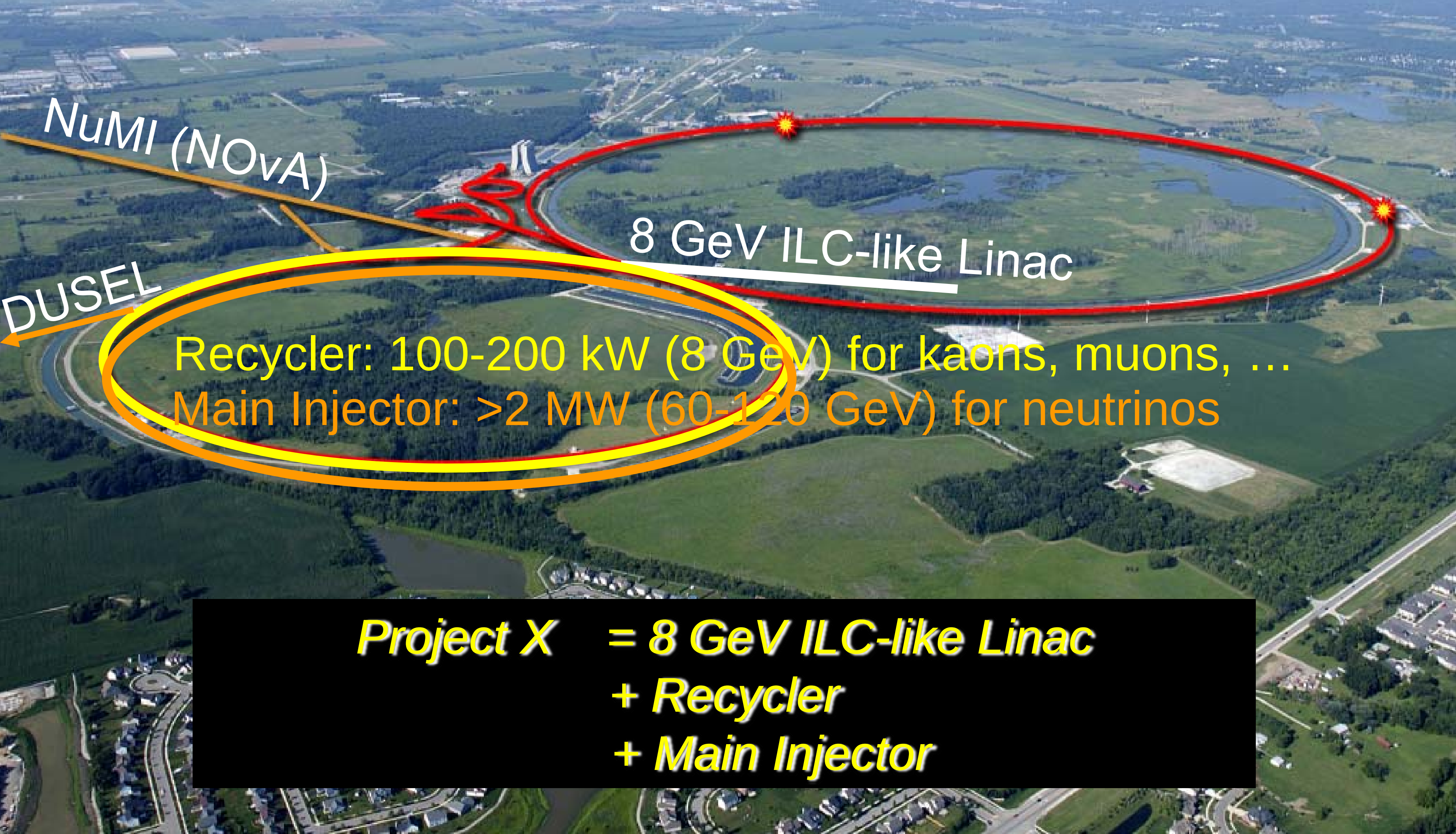
Prioritized due to limited budget
1st : K1.8BR in 2008
2nd: K1.8 & KL in 2009

"Project-X" at Fermilab: A future blow torch of protons…

High Intensity Proton Accelerator – Project X

National Project with International Collaboration

Alignment with ILC Technologies for a shared development effort



Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector

Project-X: A blow-torch of protons...all the time!

Per year

Facility	Duty Factor	Clock hours	Beam hours	Projected # of K → $\pi\nu\bar{\nu}$
☆ CERN-SPS (450 GeV)	30%	1420	405	40 (charged)
Booster Stretcher (8GeV, 16kW)	90%	5550	5000	40 (charged)
Tevatron-Stretcher (120 GeV)	90%	5550	5000	200 (charged)
ProjectX Stretcher (8GeV, 200kW)	90%	5550	5000	250 (charged)
☆ JPARC-I (30 GeV)	21%	2780	580	~1 (neutral)
BNL AGS (24 GeV)	50%	1200	600	20 (neutral)
JPARC-II (30 GeV)	21%	2780	580	30 (neutral)
Booster Stretcher (8GeV, 16kW)	90%	5550	5000	30 (neutral)
ProjectX Stretcher (8GeV, 200kW)	90%	5550	5000	300 (neutral)

☆ **Moving toward full approval.**

J-PARC - Neutrino:Kaon = 50%:50%

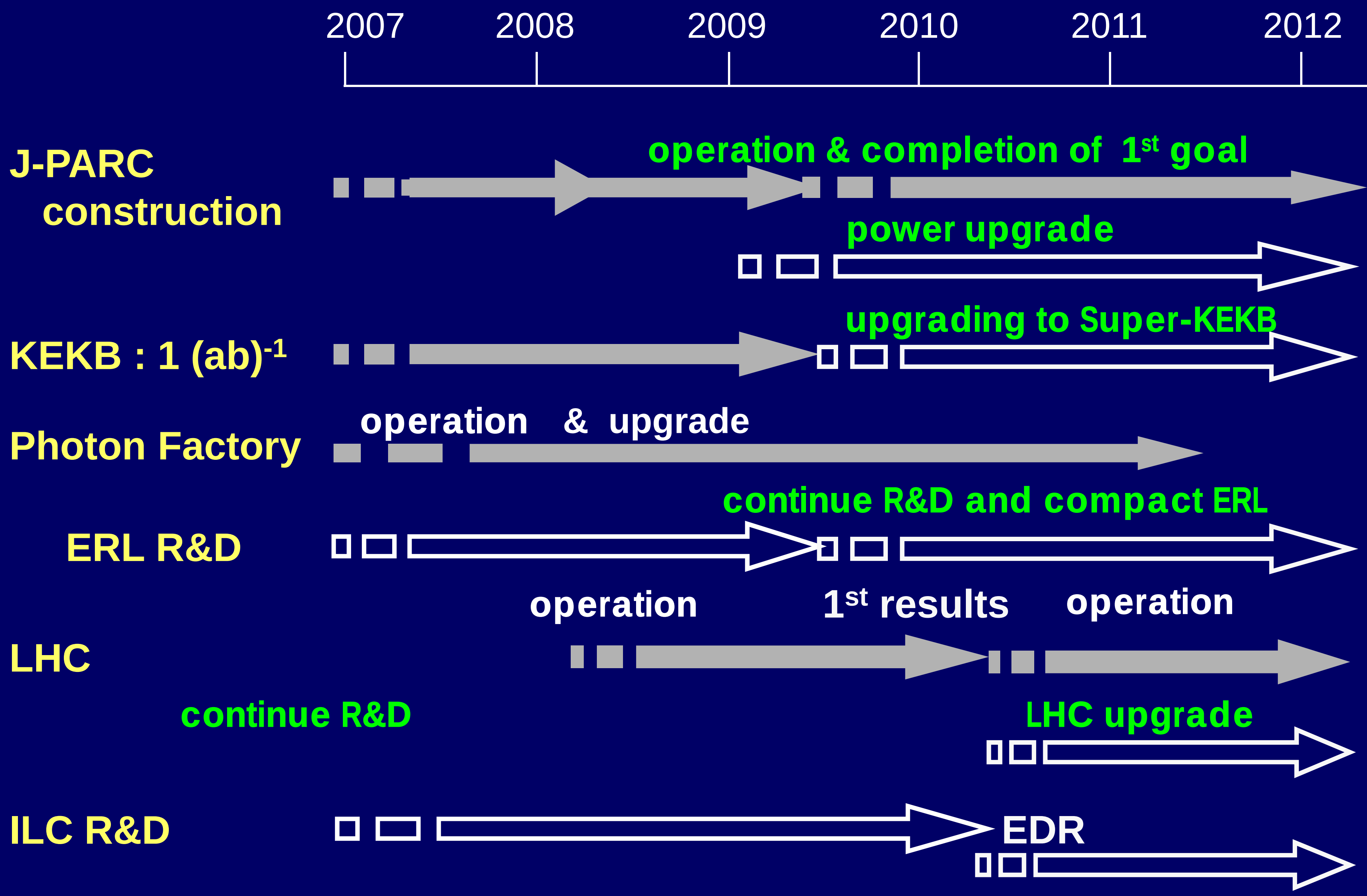
Summary

- Precision measurements and rare decay studies in Kaon physics continue to refine the Standard Model and probe for the new physics we believe is there.
- Existing proton beam facilities will produce kaon beams of exceptional quality and intensity that will propel the field toward precision measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ and Standard Model sensitivity for $K_L \to \pi^0 \nu\bar{\nu}$.
- Measurements at the $K \to \pi\nu\bar{\nu}$ frontier can incisively search and probe new physics — particularly the conundrum of Minimum Flavor Violation.
- Project-X at Fermilab is an opportunity to drive next-generation world-leading experiments that require high intensity, high duty factor muon and kaon beams.

Spare Slides

DG Atsuto Suzuki

KEK Roadmap (July, 2007 : KEK Roadmap Panel led by F. Takasaki)



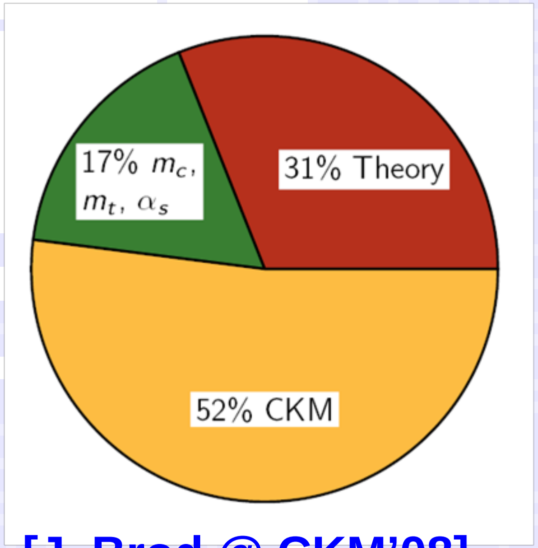
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Physics Motivation

In the Standard Model:

$$B(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)) = k_+ (1+\Delta_{EM}) \times \frac{|V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \,\mathrm{Re} V_{cs}^* V_{cd} (P_c(m_c^2) + \delta P_{c,u})|^2}{\lambda^5}$$

λ= Cabibbo Angle

- NLO QCD [Buchalla, Buras '94], [Misiak, Urban '99], [Buchalla, Buras '99]
- Charm
  - ✓NNLO QCD [Buras, Gorbahn, Haisch, Nierste '06]
  - ✓EW Corrections to P_c [Brod, Gorbahn '08]
- Long Distance
  - ✓|ΔE|< 1% [Mescia, Smith '07]
  - ✓ $\delta P_{c,u}$ +6% [Isidori, Mescia, Smith '05]



[J. Brod @ CKM'08]

•The SM Branching Ratio prediction is precise (~8%) and the intrinsic theory error is small
•The parametric error will be further reduced

Charged Mode, Where we are at Today

BNL program★ has established the process.

The CERN NA48 program evolves **step-by-step** down the sensitivity ladder.

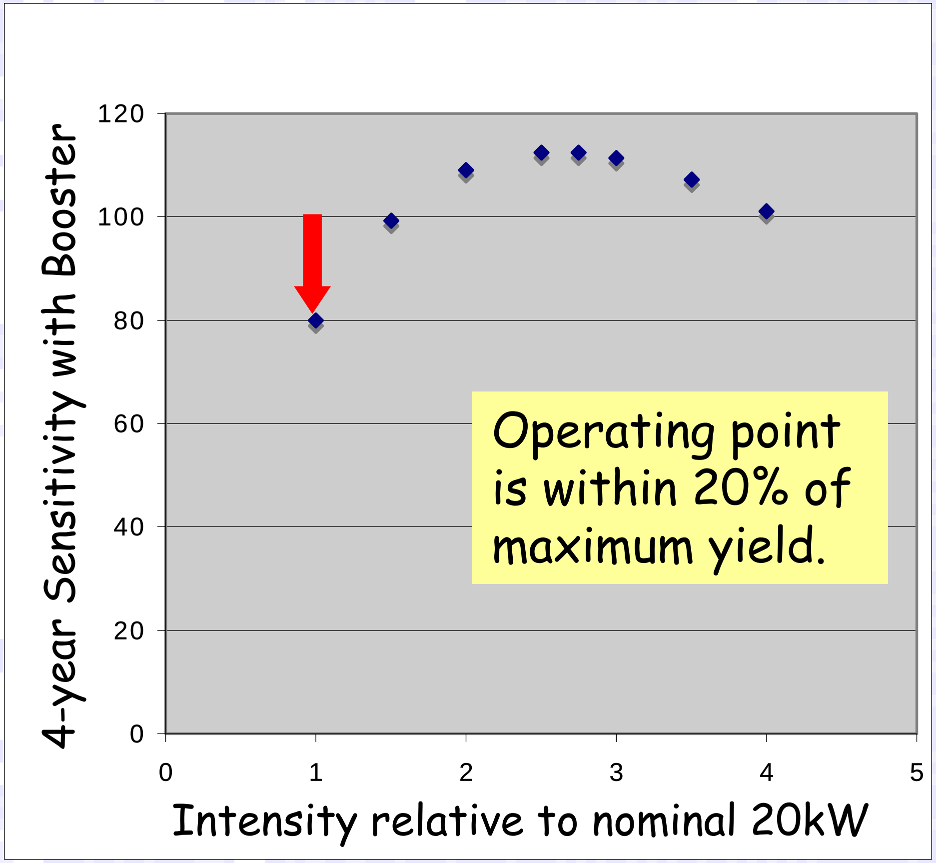
Next generation concepts and designs developed by R&D for the Fermilab CKM experiment.

→ The now approved CERN NA62 experiment marches toward a 100 event measurement early next decade

★ **Measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio. (March 2008)**
Phys.Rev.D77:052003,2008, FERMILAB-PUB-08-065-CD-E

Intensity Dependence of the KOPIO Design

- The KOPIO design is instantaneous rate-limited, primarily due to the large aperture of the neutral beam.
- The sensitivity could be increased by improved detector resolutions.
- **But** the KOPIO design is already not a cheap experiment, large area of detectors, many constraints.
- Could the potentially huge intensity increases of Project-X qualitatively change the picture?



Improved Rate Performance of a "Pencil Beam" TOF Experiment.

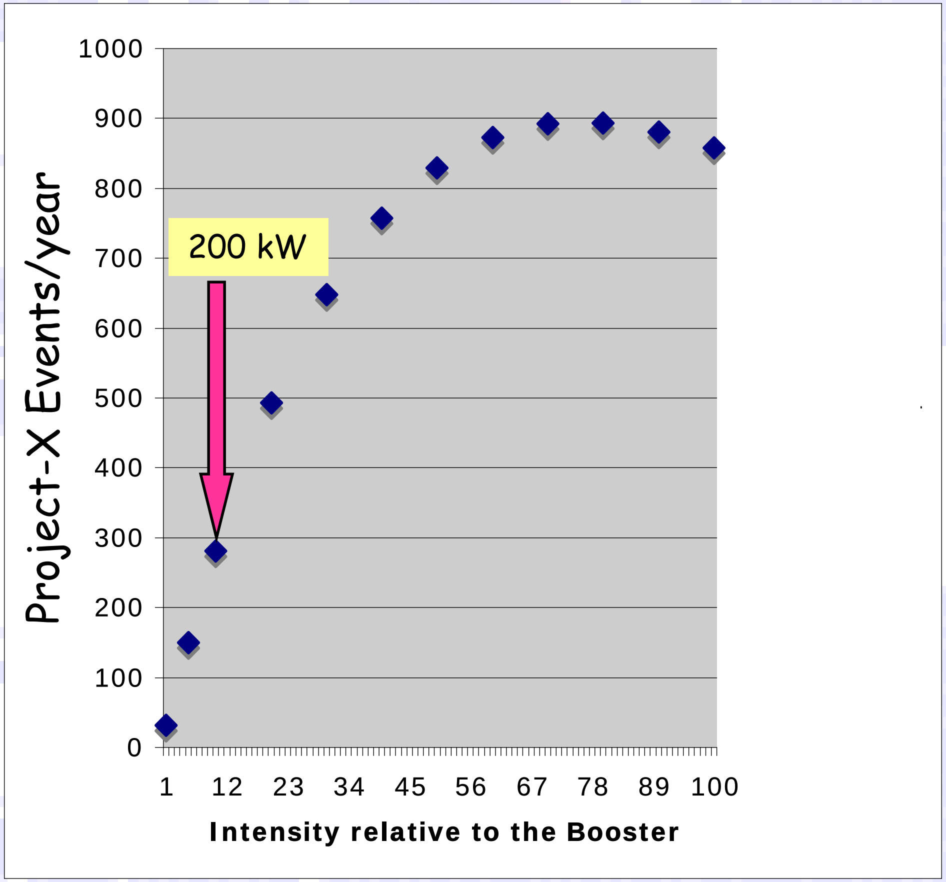
- Booster Power (20 kW):

30 equivalent events per year

- Project-X (200 kW):

300 equivalent events per year

- 200 kW operating point has robust rate performance which can be scaled to much higher beam power.
- Experiment designed with a pencil beam has substantially lower technical risk and likely lower cost.



P5 Preamble on μ's & K's:

"The latest developments in accelerator and detector technology make possible promising new scientific opportunities through measurement of rare processes. Incisive experiments, complementary to experiments at the LHC, would probe the Terascale and possibly much higher energies. Among them are measurements that can be performed at Fermilab—muon-to-electron conversion and rare K decays — as well as participation in overseas B factories."

The P5 Recommendation

" The panel recommends pursuing the muon-to-electron conversion experiment, subject to approval by the Fermilab PAC, under all budget scenarios considered by the panel. The intermediate budget scenario, scenario B, would allow pursuing significant participation in one overseas next-generation B factory. The more favorable funding scenario, scenario C, would allow for pursuing a program in rare K decay experiments."

The Data has put us on the hot seat: Motivates a "Minimal Flavor Violating" Framework

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2}$$

contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

recent analysis: Bona *et al.* '07

If you don't think this is an accident of $\Delta F=2$... ⇒ MFV

G. Isidori, LP-2007

Minimal Flavor Violation strictly constrains New Physics enhancements…less than x2 in SUSY.

Observable	Experiment	MFV bound	SM prediction
$R^{(\mu/e)}(B \to K\ell^+\ell^-) - 1$	0.17 ± 0.28 [59,60][a]	$[-0.004, 0.14]$	$\mathcal{O}(10^{-4})$ [61]
$R^{(\mu/e)}(B \to K^*\ell^+\ell^-) - 1$	0.18 ± 0.26 [59,60][a]	$[-0.002, 0.01]$	~ 0 [47]
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$ [24]	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$
$\mathcal{B}(B \to X_s\tau^+\tau^-)$	–	$< 5 \times 10^{-7}$	$1.6(5) \times 10^{-7}$
$\mathcal{B}(B \to K\nu\bar{\nu})$	[62]	$< 0.4 \times 10^{-4}$	$(0.5 \pm 0.1) \times 10^{-5}$
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	[62]	$< 9.4 \times 10^{-5}$	$(1.2 \pm 0.3) \times 10^{-5}$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	[63]	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

[a] Here we quote naïve averages of the values obtained by the experiments and with symmetrized errors.

Constraints are relaxed but still quite tight with a model independent treatment (Hurth et, al., hep-ph 0807-5039, 2008)

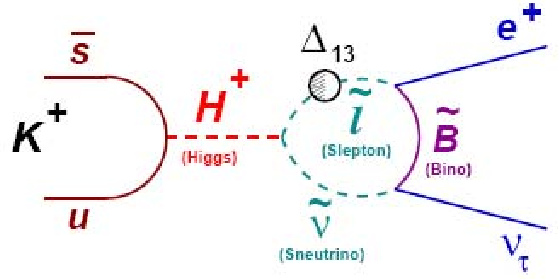
High Premium on flavor physics probes with rock-solid SM predictions.

R_K beyond the SM

Possible scenario in MSSM:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

'Charged Higgs mediated SUSY LFV contributions can be strongly enhanced, in particular in kaon decays into an electron or a muon and a tau neutrino'



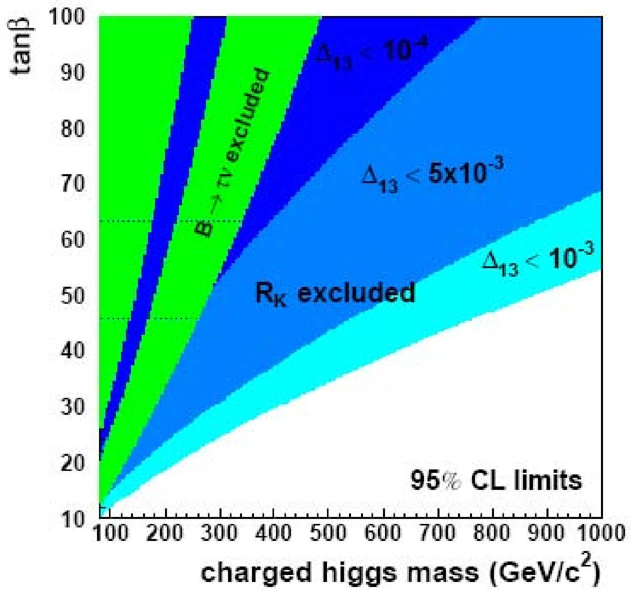
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

A few percent effect possible in large (not extreme) $\tan\beta$ regime with relatively massive charged Higgs

Example:

$\Delta_{13}=5\times10^{-4}$, $M_H=500\,\mathrm{GeV}$, $\tan\beta=40$:

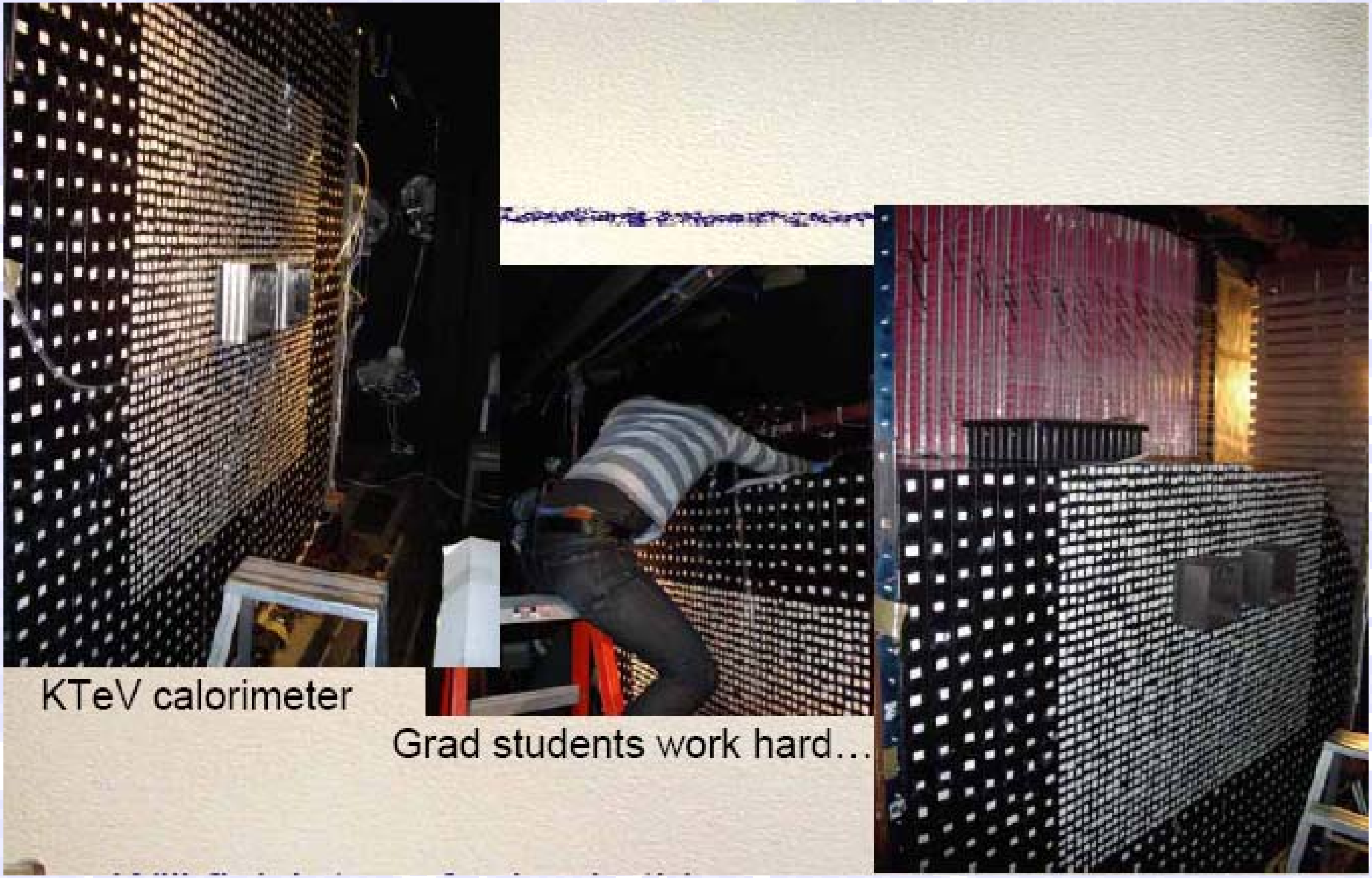
$R_K^{LFV}\approx R_K^{SM}(1+0.013)$



NB: Analogous SUSY effects in pion decay are suppressed by a factor $(m_\pi/M_K)^4\approx6\times10^{-3}$

Andreas Winhart, Moriond, March 2009

Test of lepton universality in $K\to l\nu$ decays by NA62 – p. 3


KTeV calorimeter
Grad students work hard…