Future Kaon Experiments

R. Tschirhart
Fermilab

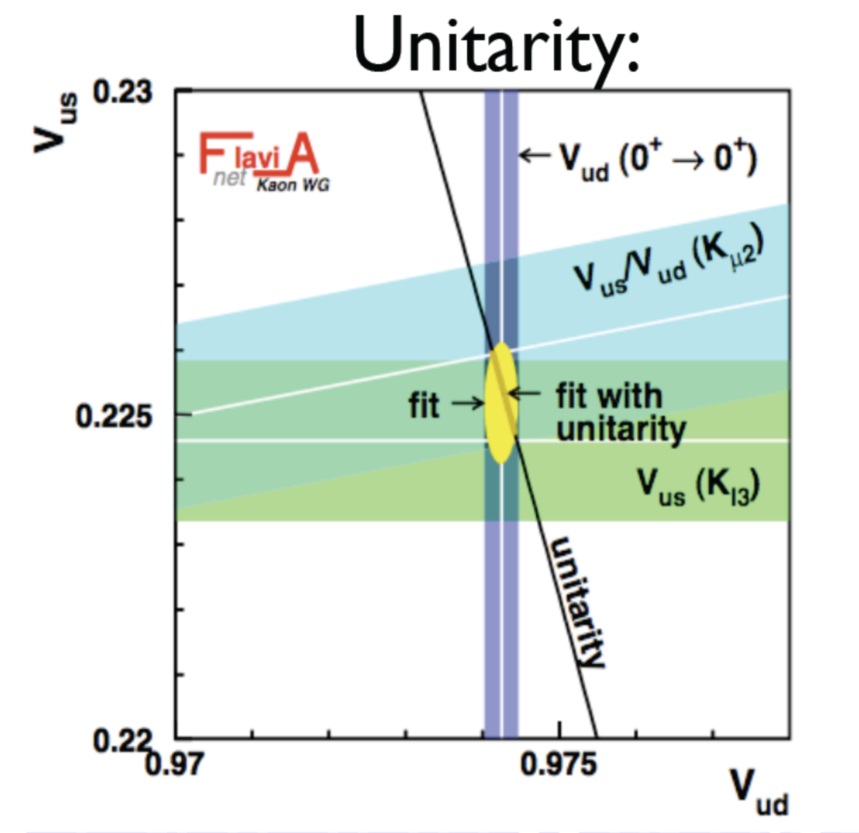
April 27th , 2010

LQCD Targets in Kaon Physics: Now and Then…

- LQCD post-dictions to interpret existing precision measurements.
- LQCD post-dictions to interpret existing measurements that could have large contributions from physics beyond the Standard Model.
- LQCD predictions of future measurements that are highly sensitive to new physics beyond the Standard Model.

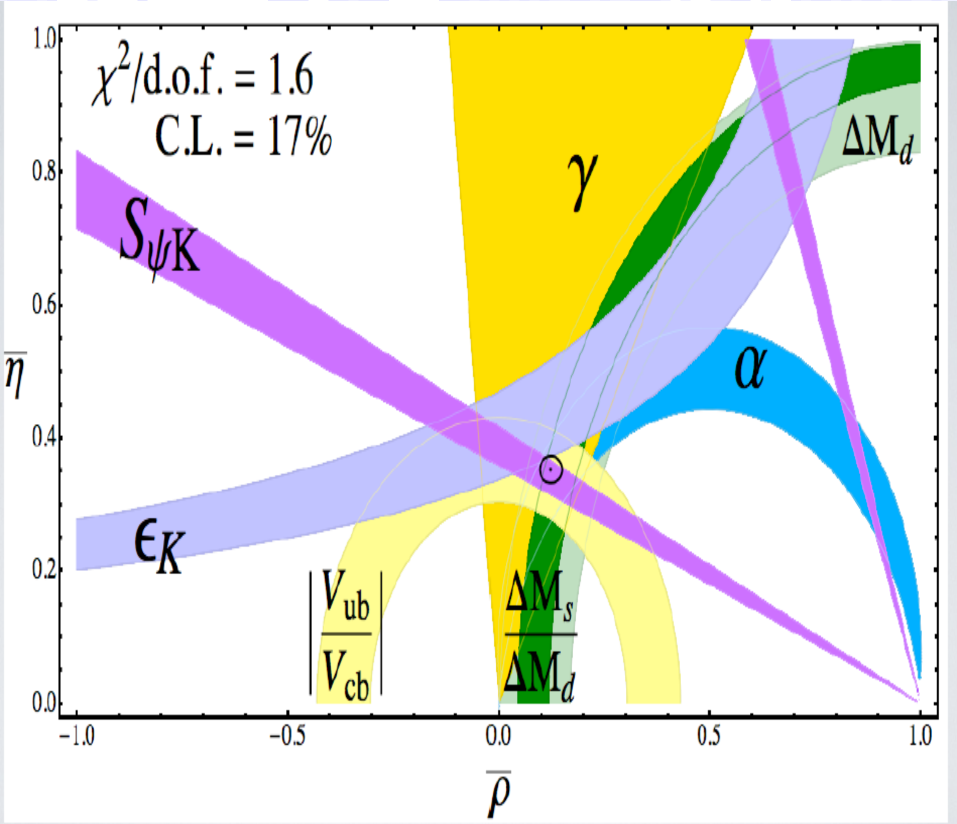
Interpreting Existing Precision Measurements

Enrico Lunghi, LME-2010, Fermilab



Precision unitarity tests require f_K and form-factors

Laiho, Lunghi, Van de Water, arXiv:0910.2928



ε_K interpretation requires B_K, but now limted by $|V_{cb}|$!

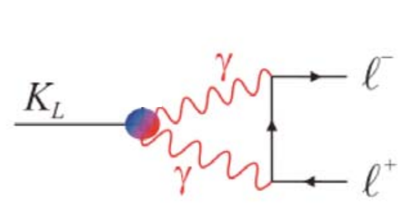
Hiding in Plain Sight…

- $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)$:

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.22) \times 10^{-6}\ ^{*}$$

Large component of this asymmetry might arise from New Physics.

- $K_L \to \mu\mu$:



$$B(K^0_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}\ ^{*}$$

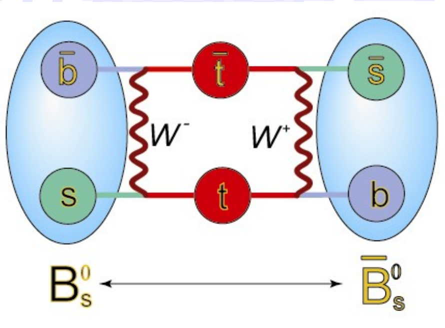
~10% of this amplitude is from 2nd order EW loops…where new physics can contribute.

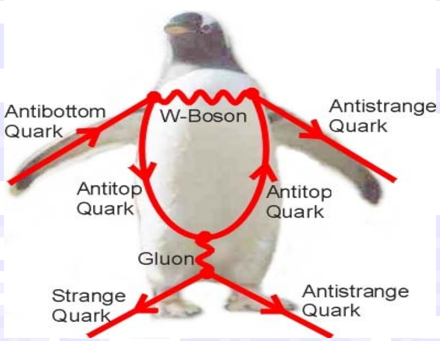
Urban-Art camouflage

* PDG

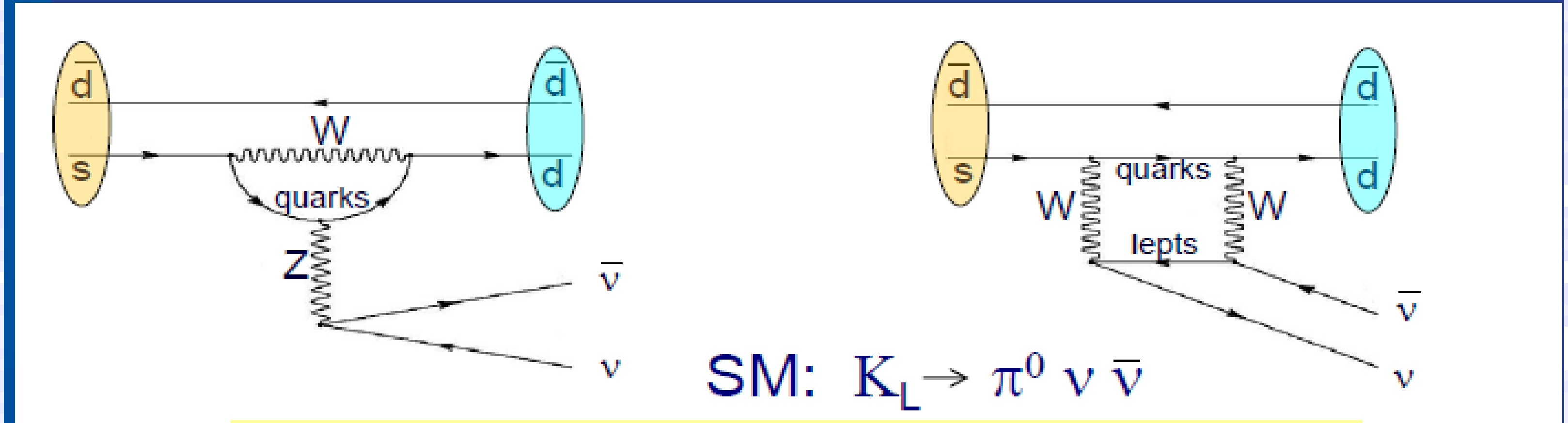
Future Rare Kaon Decay Experiments Deeply Attack The Flavor Problem

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

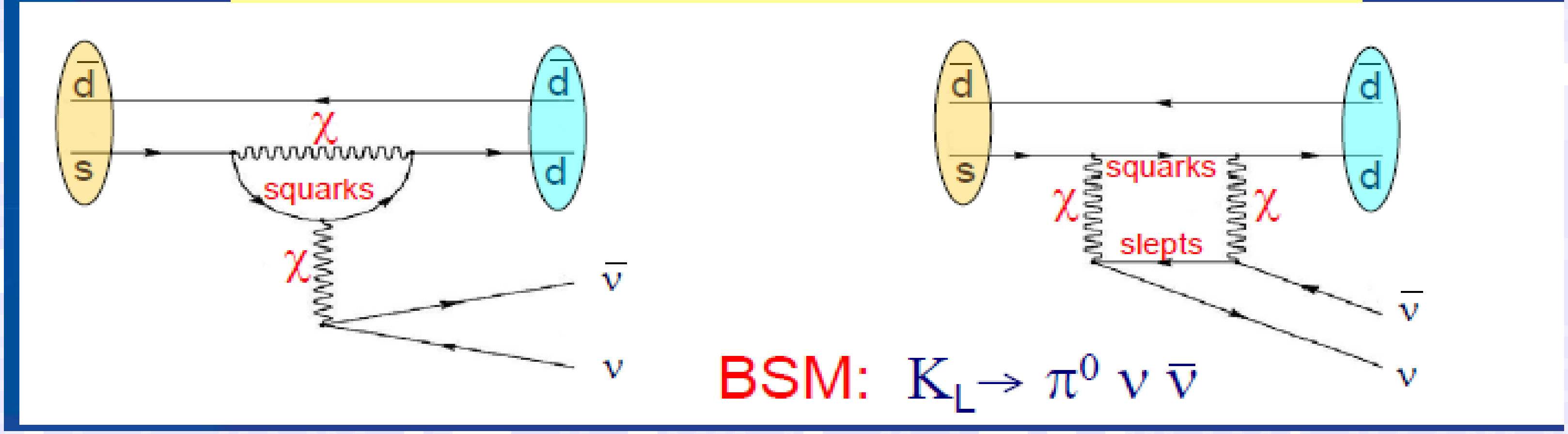




The Window of Ultra-rare Kaon Decays



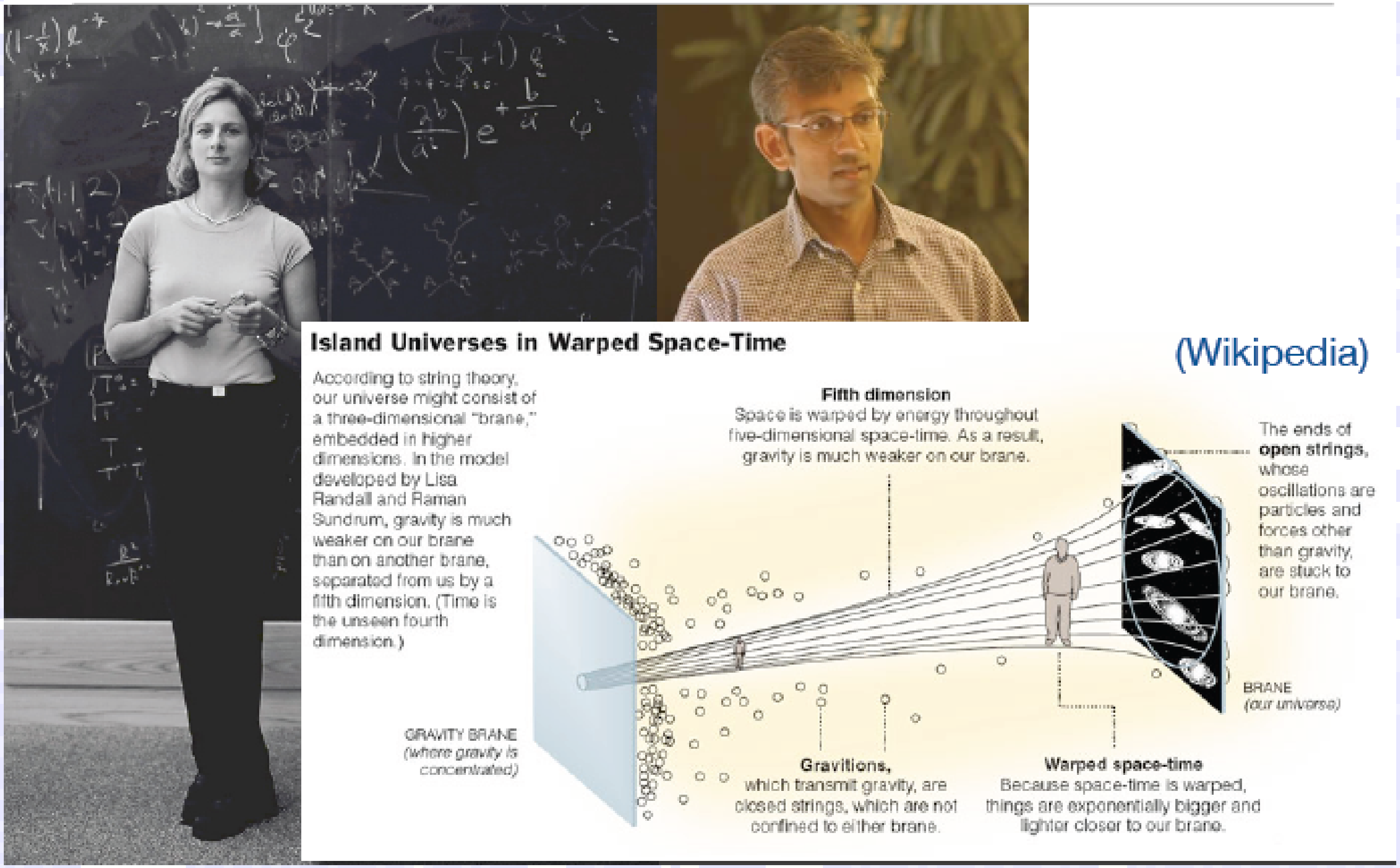
Standard Model rate of 3 parts per 100 billion!



BSM particles within loops can increase the rate by x10 with respect to SM.

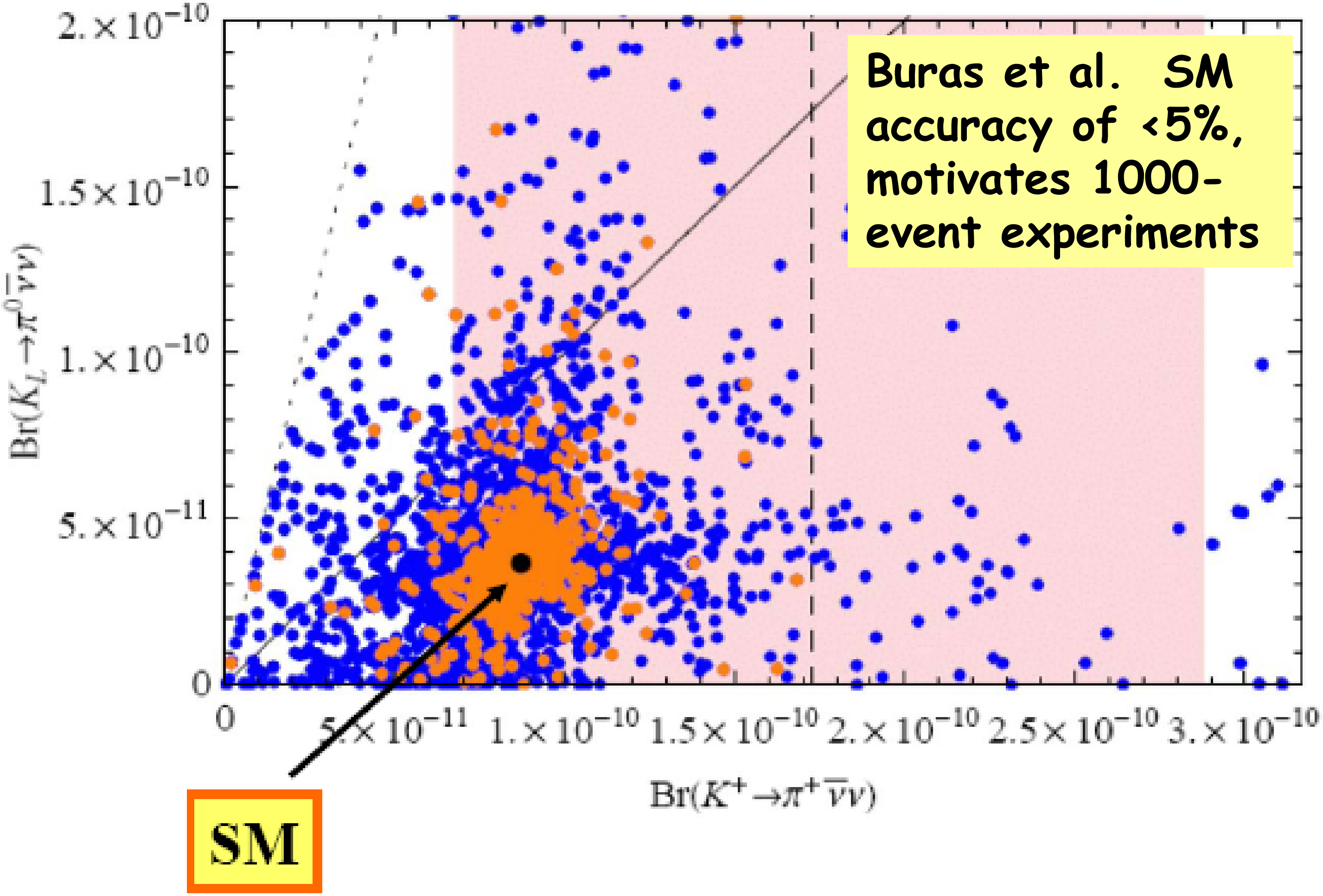
Rates sensitive to many BSMs…e.g, Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea



$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ (RS)

(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

Sensitivity of Kaon Physics 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 $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- BNL E871: 1×10^{-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 a 10 TeV scale with 20-50 kW of protons.

Next goal: 1000-event $\pi\nu\nu$ **experiments...10^{-14} sensitivity**.

Kaon Experiment Goals This Decade

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$: >100 events, first measurement with BSM sensitivity
  CERN NA62 experiment, data taking in 2013.
  1000-event proposal to Fermilab (P996).

- $K^+ \rightarrow \pi^0\mu^+\nu$: Search for T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_x$: Search for anomalous heavy neutrinos.
  JPARC E06 "TREK" experiment, advanced approval.

- $K_L \rightarrow \pi^0\nu\bar{\nu}$: Sensitivity approaching the Standard Model prediction.
  JPARC E14 "KOTO" experiment, advanced approval.

- $K_S \rightarrow \gamma\gamma$: Precision measurement, test of ChPT…LQCD?
  KLOE-2, advanced approval.

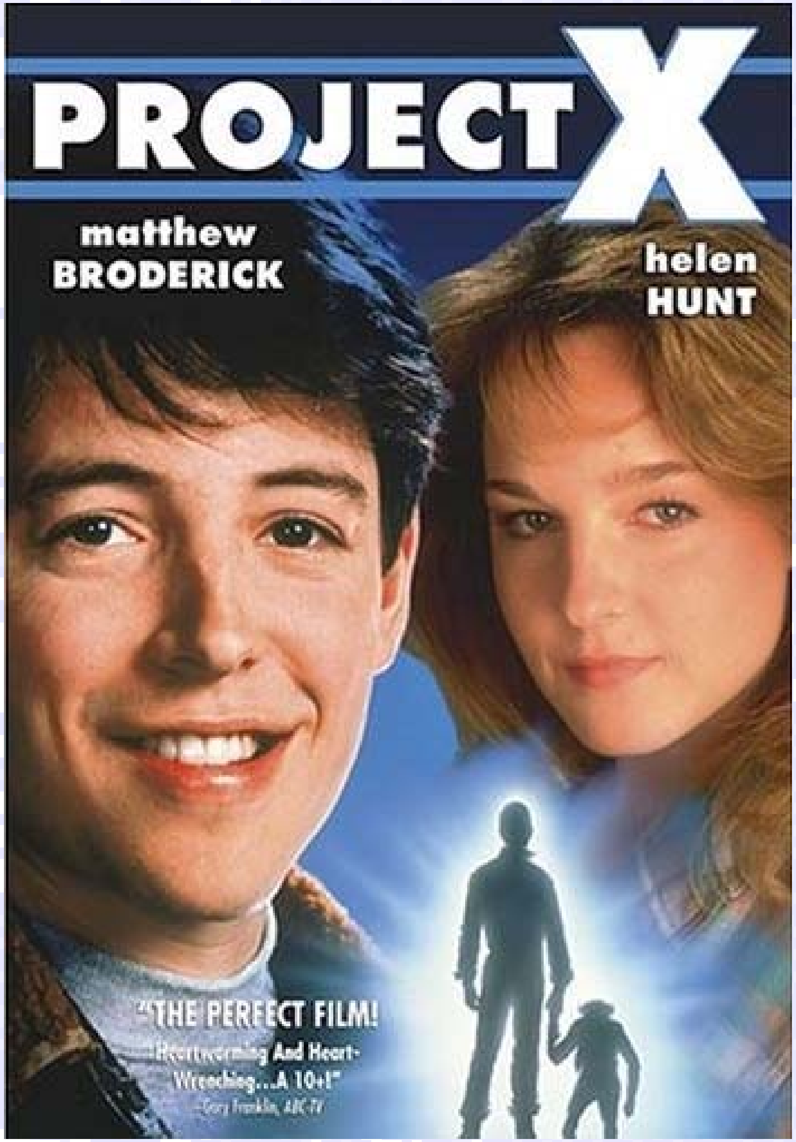
Kaon Physics Measurements Enabled by Project-X, Data Taking in the Next Decade

- $K^+ \rightarrow \pi^+\nu\nu$: >1000 events, Precision rate and form factor….V_{cb} !
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K_L \rightarrow \pi^0\nu\nu$: 1000 events, enabled by high flux & precision TOF.
- $K_2 \rightarrow \pi^0 e^+e^-$: <10% measurement of CP violating amplitude.
- $K_2 \rightarrow \pi^0\mu^+\mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \rightarrow X$: Precision study of a pure K^0 interferometer:
  Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \rightarrow$LFV: Next generation Lepton Flavor Violation experiments

…and more

4th Project-X Physics Workshop: **November 9-10th 2009**

Project-X, What it's not…



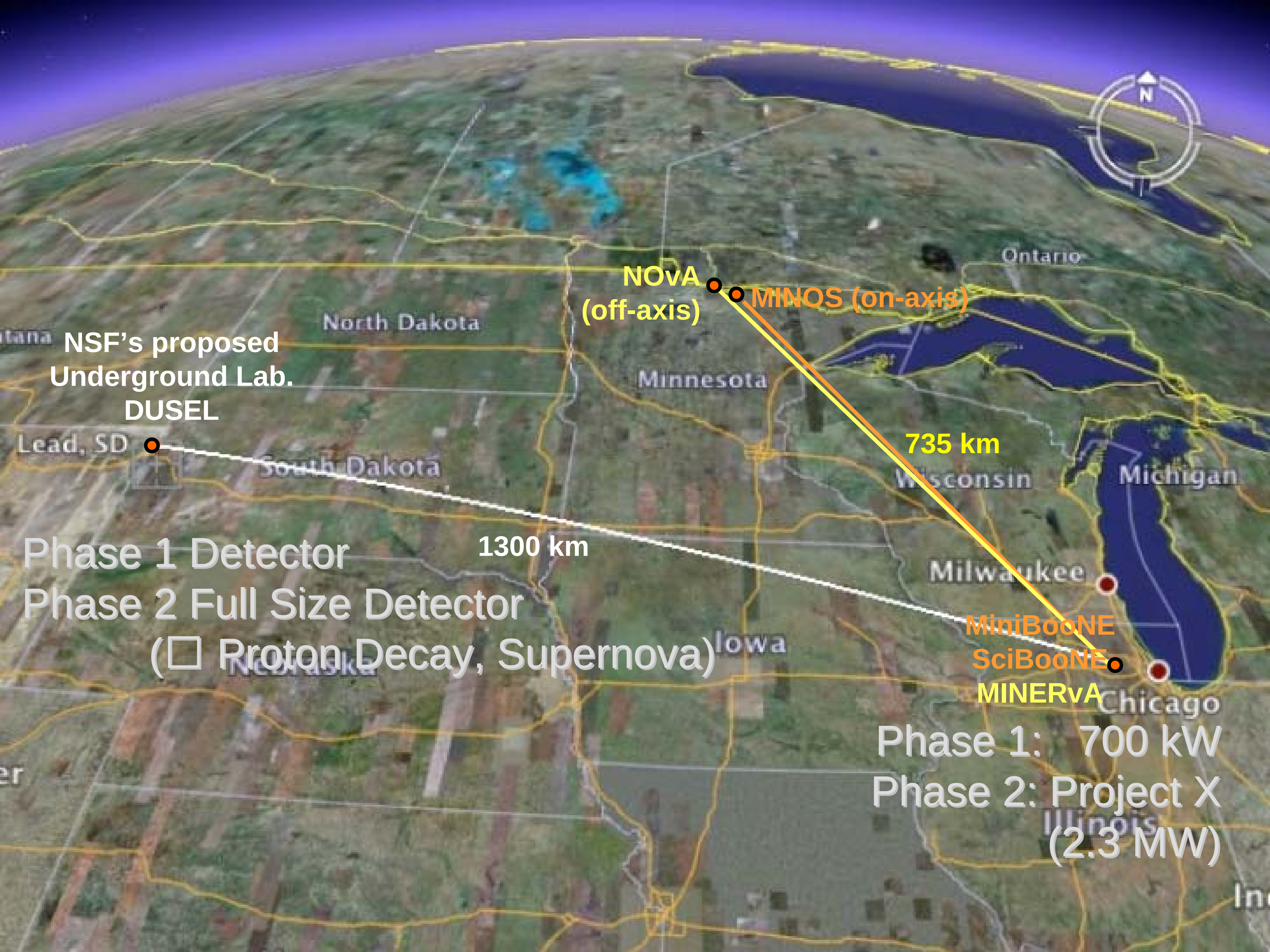
The Project-X Research Program

- ***Long baseline neutrino oscillation experiments:***

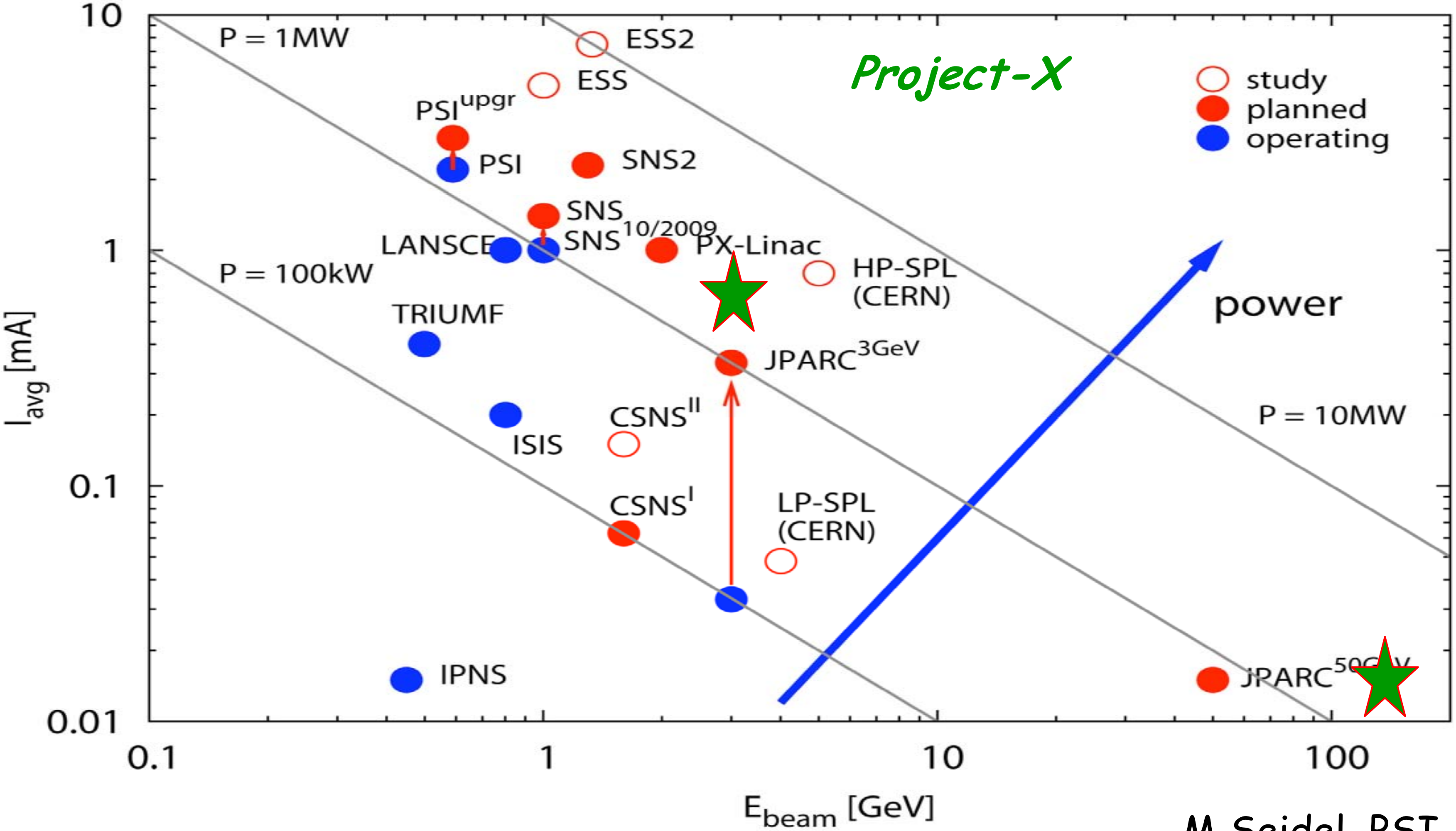
  Driven by a high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams directed toward massive detectors at a distant deep underground laboratory.

- ***Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:***

  These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

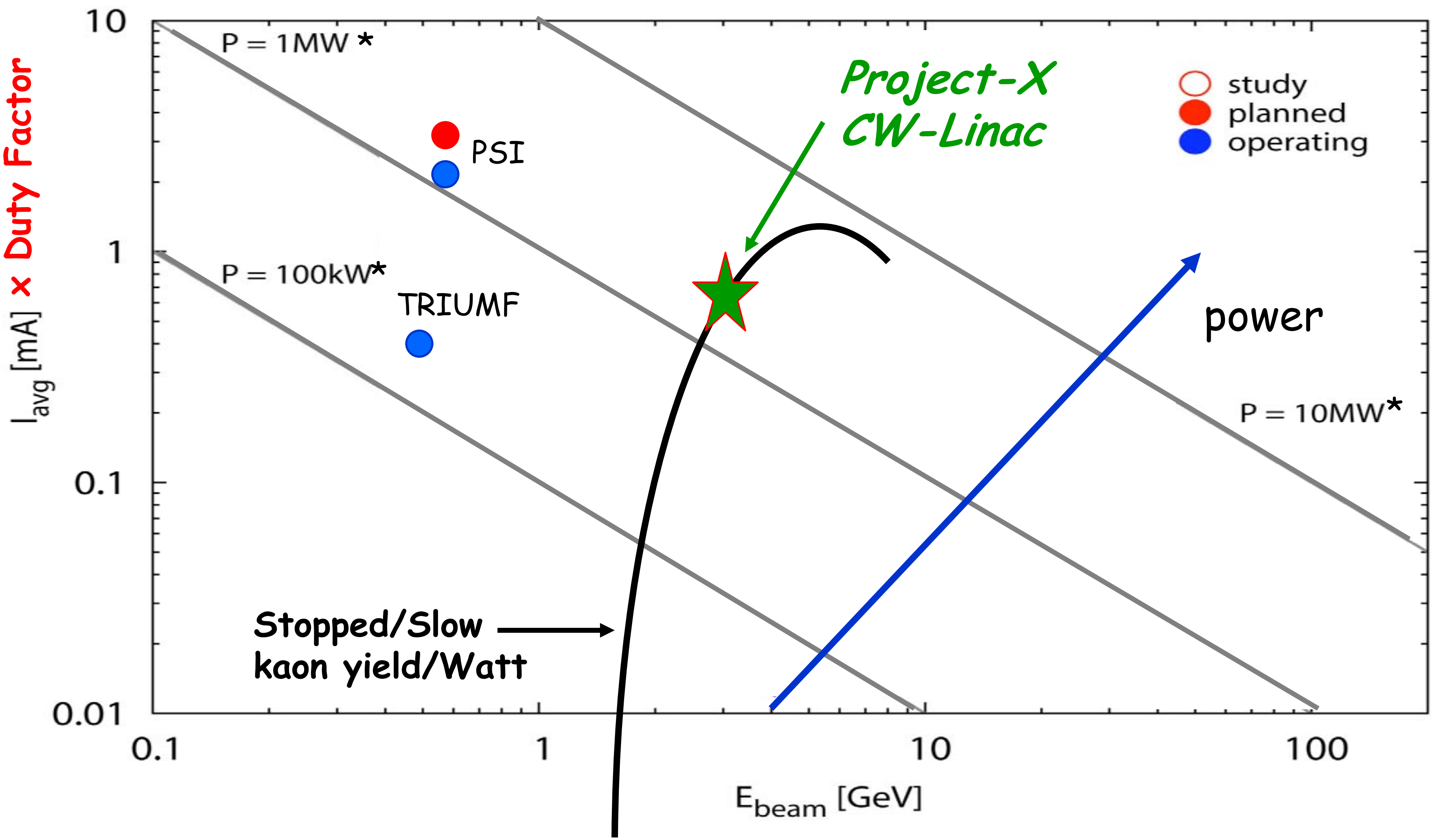

NOvA
(off-axis)
MINOS (on-axis)
NSF's proposed
Underground Lab.
DUSEL
Lead, SD
North Dakota
South Dakota
Minnesota
Wisconsin
Michigan
Ontario
Milwaukee
Iowa
Nebraska
Chicago
Illinois
735 km
1300 km
Phase 1 Detector
Phase 2 Full Size Detector
(□ Proton Decay, Supernova)
MiniBooNE
SciBooNE
MINERvA
Phase 1: 700 kW
Phase 2: Project X
(2.3 MW)

This Science has attracted Competition: The Proton Source Landscape This Decade...



M Seidel, PSI

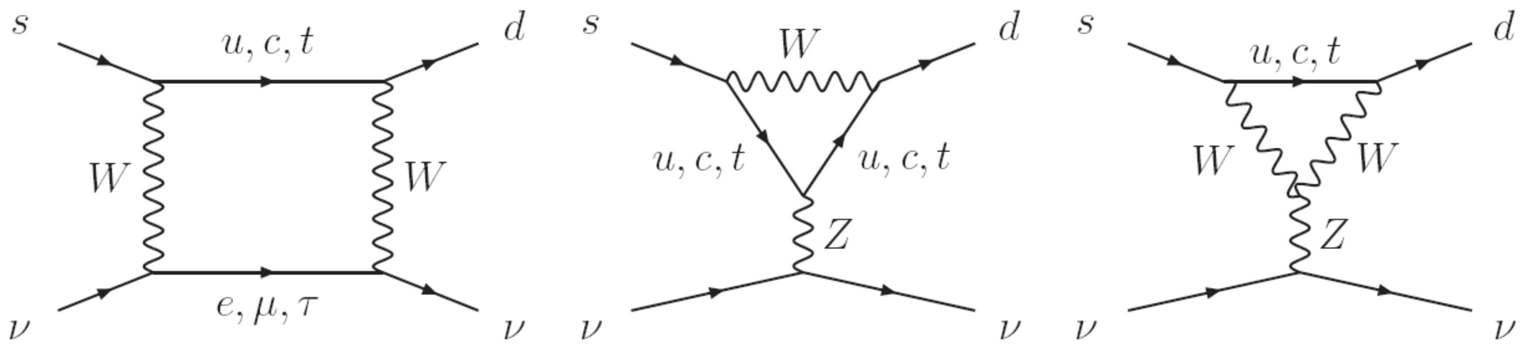
The High Duty Factor Proton Source Landscape This Decade...



* Beam power × Duty Factor

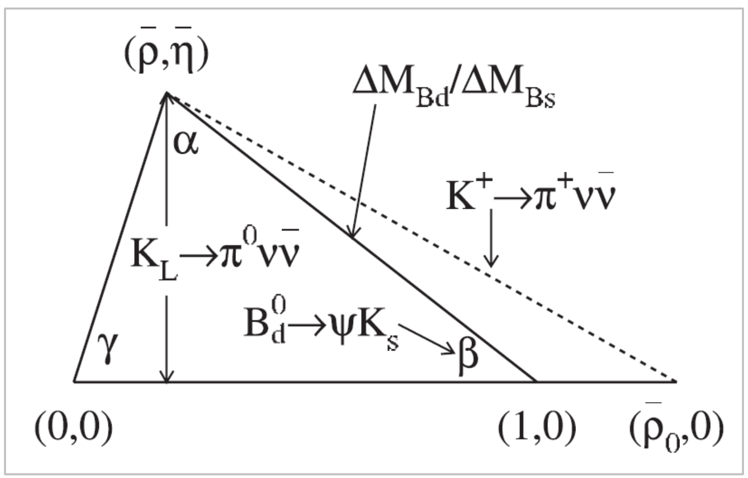
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

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)



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

Bird and Gorbahn, PRD 78, 034006(2008)

Theoretical Progress

SM Precision

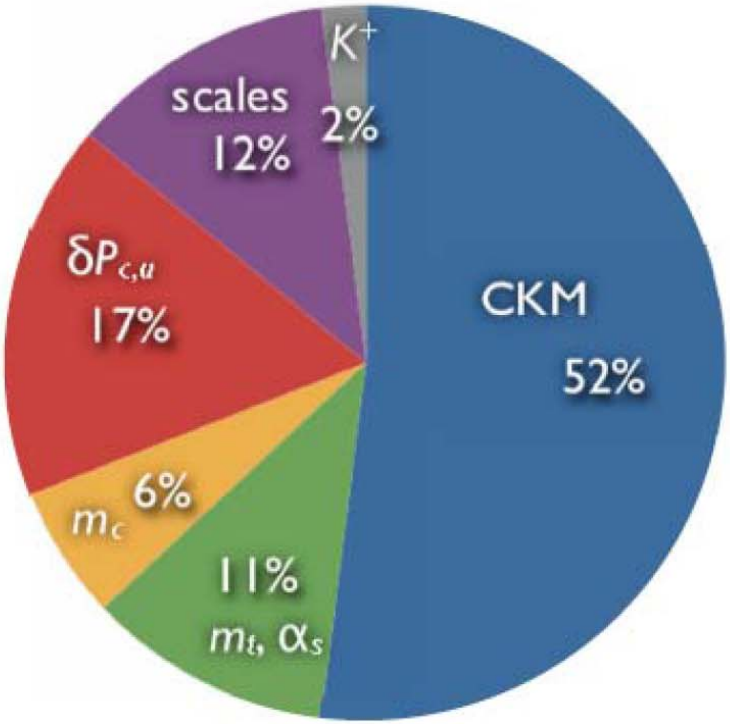
- Buchalla, Buras, 1993
- Lu, Wise, 1994
- Marciano, Parsa, 1996
- Misiak, Urban, 1999
- Buchalla, Buras, 1999
- Falk, Lewandowski, Petrov, 2000
- Isidori, Mescia, Smith, 2005
- Isidori, Martinelli, Turchetti, 2006
- Buras, Gorbahn, Haisch, Nierste, 2006
- Mescia, Smith, 2007
- Bijnens, Ghorbani, 2007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

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

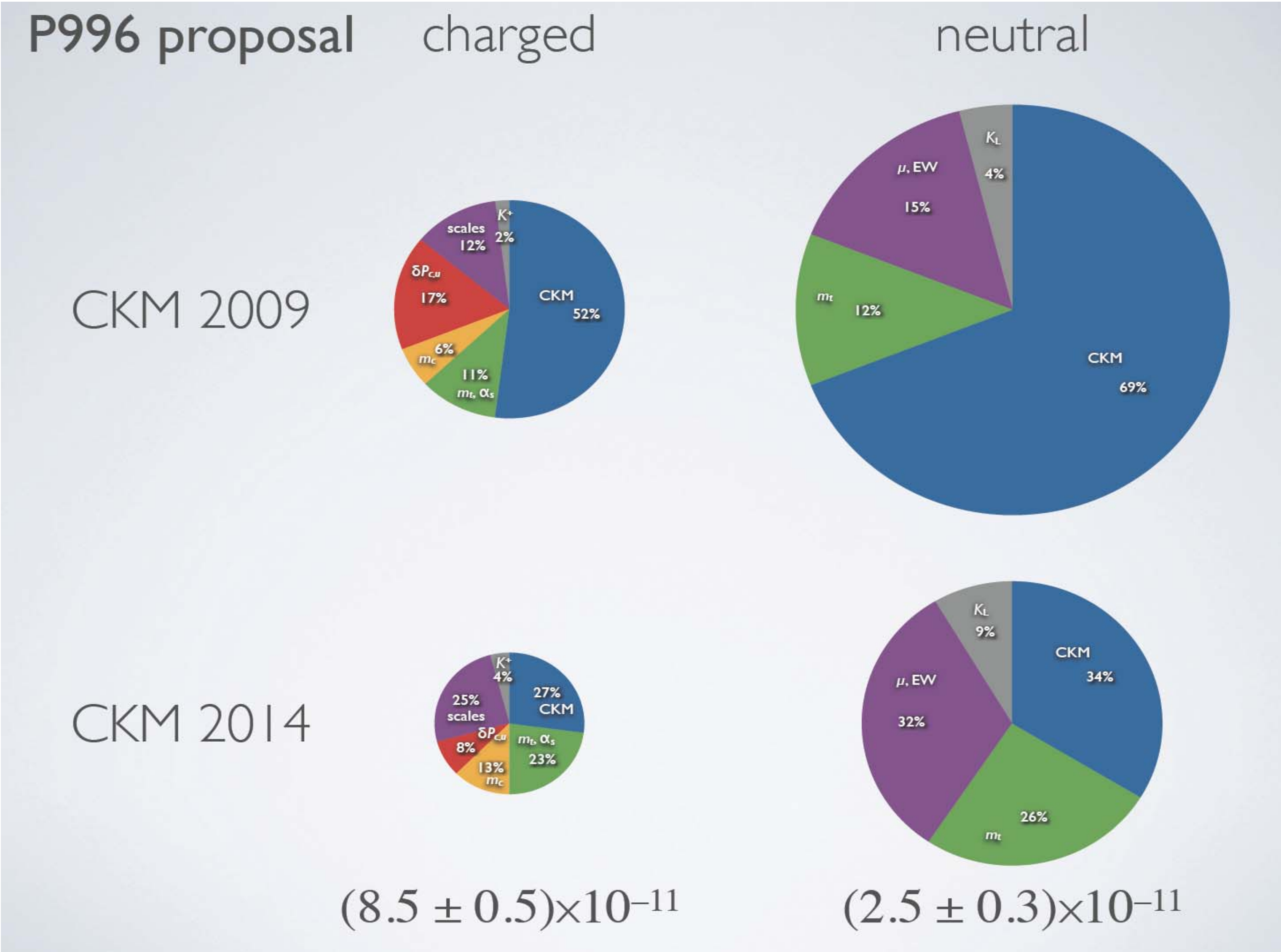
Unmatched by any other FCNC process (K or B).

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

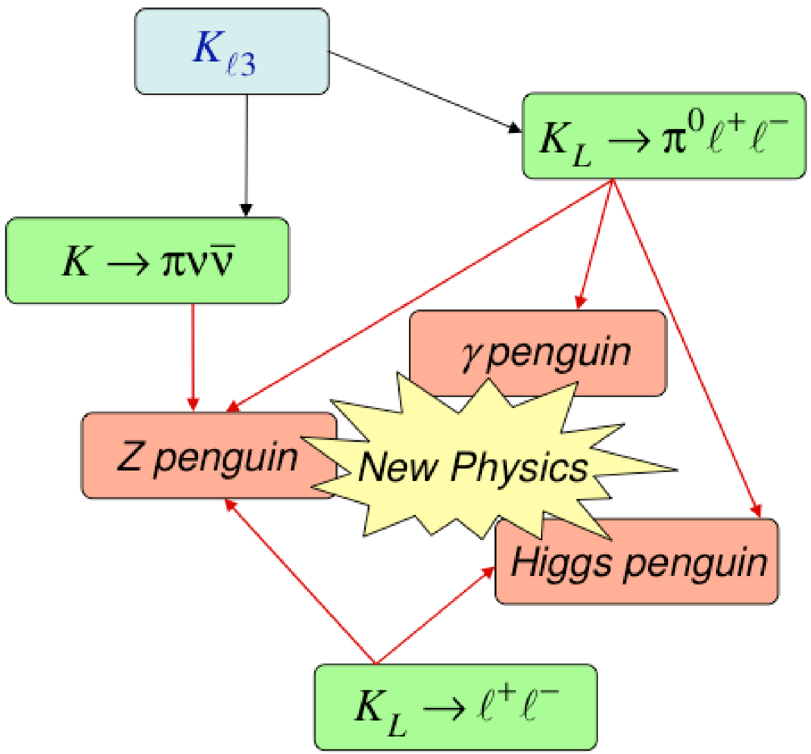
U. Haisch, arXiv:0707.3098

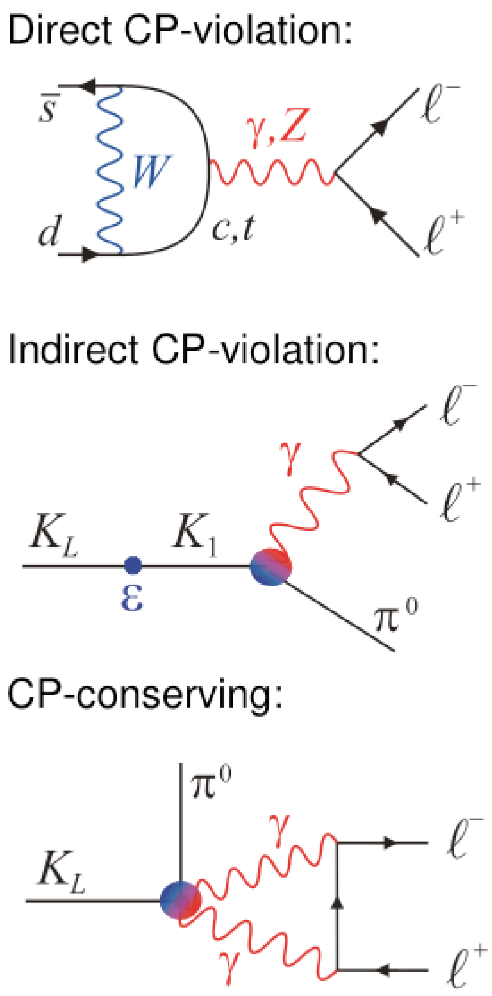
Components of $K \to \pi\nu\bar{\nu}$ Uncertainty in the Standard Model



LQCD and $K_2 \to \pi^0 e^+ e^-$...

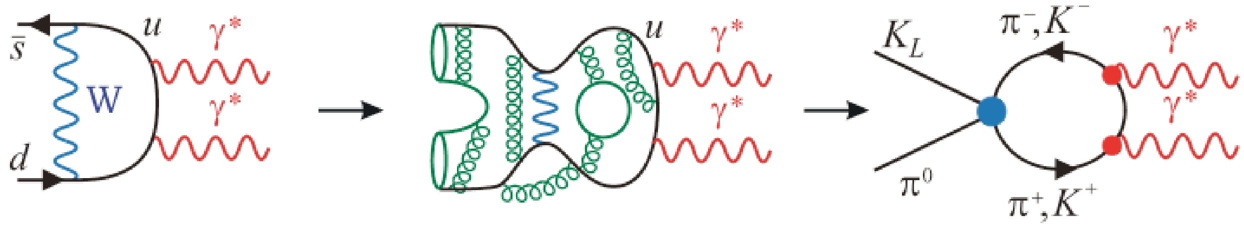
LD in rare K 3/10





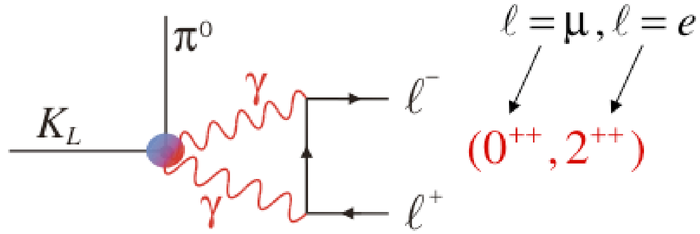
From NA62 Physics-Handbook: Christopher Smith

C. CP-conserving long-distance double photon penguin



LO (p^4) is finite, produces $\ell^+\ell^-$ in a scalar state only (helicity-suppressed),

Higher order estimated using the $K_L \to \pi^0\gamma\gamma$ rate and spectrum:



- Production of $(\mu^+\mu^-)_{0^{++}}$ under control within 30%. *Isidori,Unterdorfer,C.S. '04*

- No signal of $(\gamma\gamma)_{2^{++}}$ implies $(e^+e^-)_{2^{++}}$ is negligible.

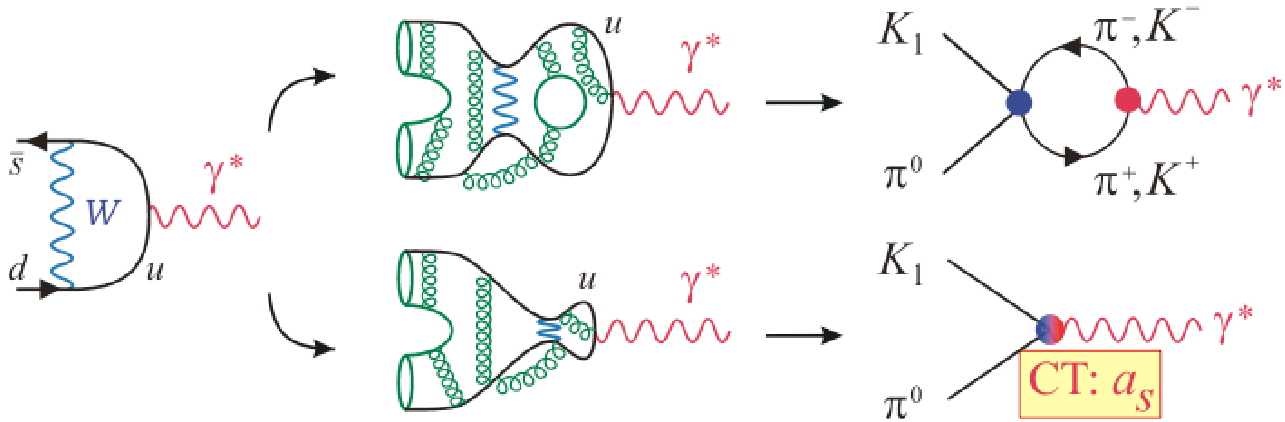
Buchalla,D'Ambrosio, Isidori '03

($K_S \to \gamma\gamma$ is also useful to constrain the p^6 LEC structure)

B. Indirect CPV: Long-distance photon penguin

D'Ambrosio et al. '98

Indirect CP-violation is $K_L \to \varepsilon K_1 \to \pi^0 \ell^+ \ell^-$, related to $K_S \to K_1 \to \pi^0 \ell^+ \ell^-$:



Loops are rather small, a single LEC a_S dominates.

It is fixed from $K_S \to \pi^0 \ell^+ \ell^-$ (up to its sign) measured by NA48:

$$\left.\begin{array}{l} Br(K_S \to \pi^0 e^+ e^-)_{m_{ee} > 165\text{MeV}} = (3.0^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9} \\ Br(K_S \to \pi^0 \mu^+ \mu^-) = (2.9^{+1.4}_{-1.2} \pm 0.2) \times 10^{-9} \end{array}\right\} \to |a_S| = 1.2 \pm 0.2$$

K1 and K2 interference into the *same* $\pi^0 e^+ e^-$ final state can boost the K2 signal out of the $K_L \to \gamma\gamma ee$ background!

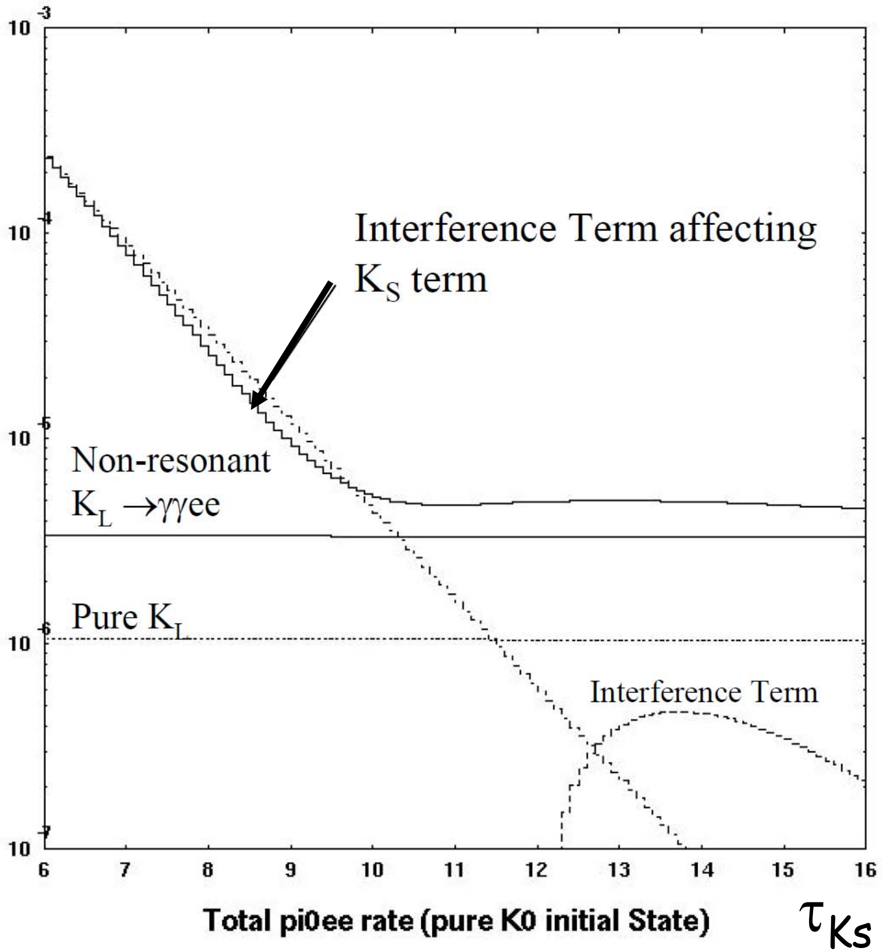
$$\frac{dN}{dt} \sim e^{-t/t_S} + 2D\sqrt{R}\cdot\cos(\Delta\mathrm{m} + \Delta\phi)\mathrm{e}^{-\mathrm{t}(\mathrm{t_S}+\mathrm{t_L})/(2\mathrm{t_S}\mathrm{t_L})} + (R + R_{ee\gamma\gamma})e^{-t/t_L} \quad (5)$$

where D=0.3 (dilution factor), $\Delta m = m_L - m_S$, $\Delta\phi = \phi_S - \phi_L = 57°$ [4], and

$$R = [15.3 - 6.8\frac{\mathrm{Im}(\lambda_\mathrm{t})}{A_S} + 2.8(\frac{\mathrm{Im}(\lambda_\mathrm{t})}{A_S})^2] \cdot 10^{-12}\frac{t_S}{t_L}\frac{1}{5.2\cdot 10^{-9}} \quad (6)$$

$$R_{ee\gamma\gamma} = 10^{-10}\frac{t_S}{t_L}\frac{1}{A_S^2 5.2\cdot 10^{-9}}$$

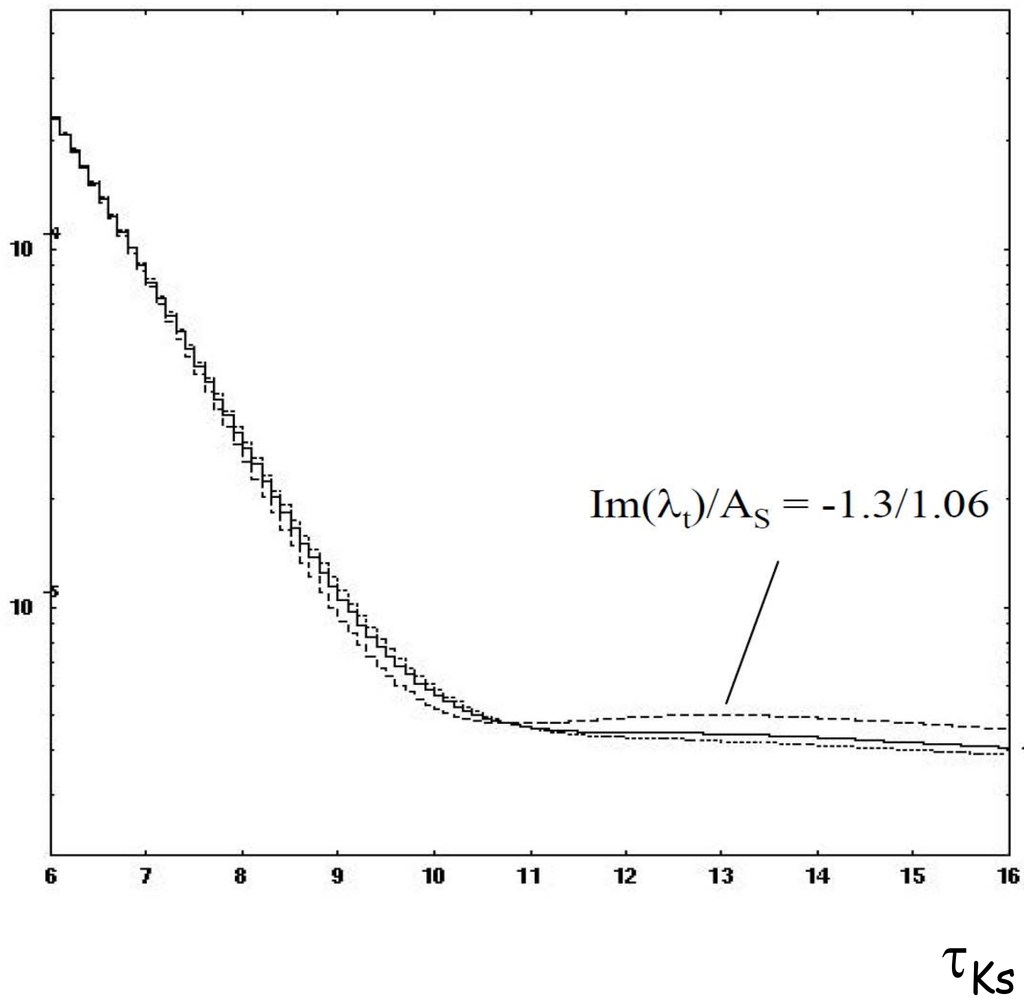
D is the dilution factor. For high energy K production D = 0.3 ; For threshold production D = 1.0



Number of τ_S lifetimes from target

Hogan Nguyen, 4th Project-X workshop.

The Sign of A_S is very important



For $Im(\lambda_t)/A_S$ = +1.3/1.06 there is a great loss of resoluti extracting $Im(\lambda_t)$

$Im(\lambda_t)/A_S$ = +1.3/1.06

$Im(\lambda_t)$ = 0

$Im(\lambda_t)$ in units of 10^{-4}

Summary of LQCD Targets for Kaon Physics

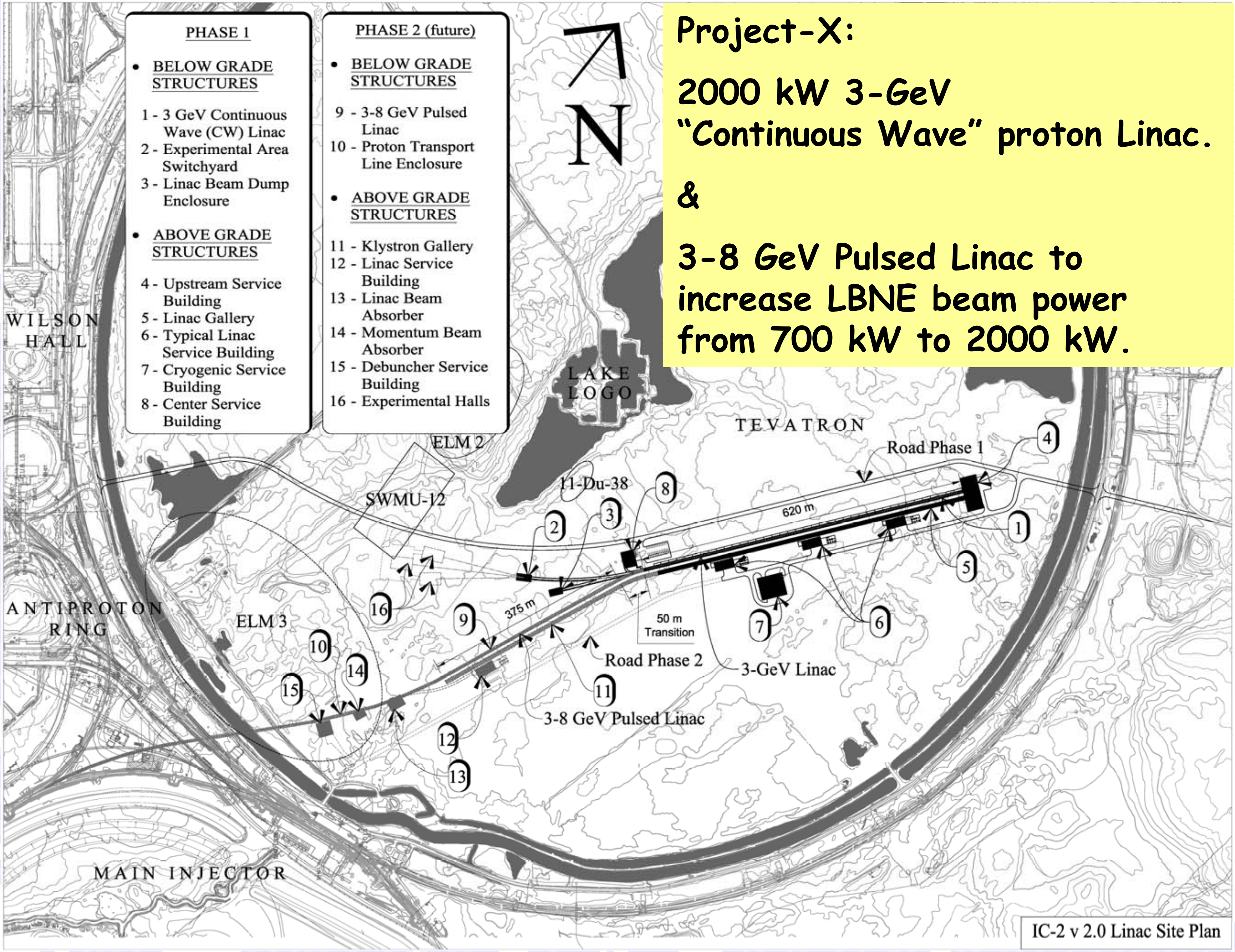
- $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)$!! New Physics could be hiding in plain sight.
- CKM parameters, most notably V_{cb} and V_{ub}. Important for establishing modest measured enhancements of $K\rightarrow\pi\nu\nu$ as new physics. Alternatively a precision measurement of $K\rightarrow\pi\nu\nu$ could ultimately be the best measure of V_{cb} .
- Continued progress on B_K , f_K, and form factors.
- Initiate a campaign on radiative decays. The theoretical understanding of $K_L\rightarrow \gamma^*\gamma^*$ is not robust, and must become solid to interpret $K_L\rightarrow \mu\mu$. Understanding the phase of $K_L\rightarrow \pi^0\gamma^*$ will be critical to developing a Project-X assault on $K_L\rightarrow \pi^0e^+e^-$.

Project-X:

2000 kW 3-GeV “Continuous Wave” proton Linac.

&

3-8 GeV Pulsed Linac to increase LBNE beam power from 700 kW to 2000 kW.

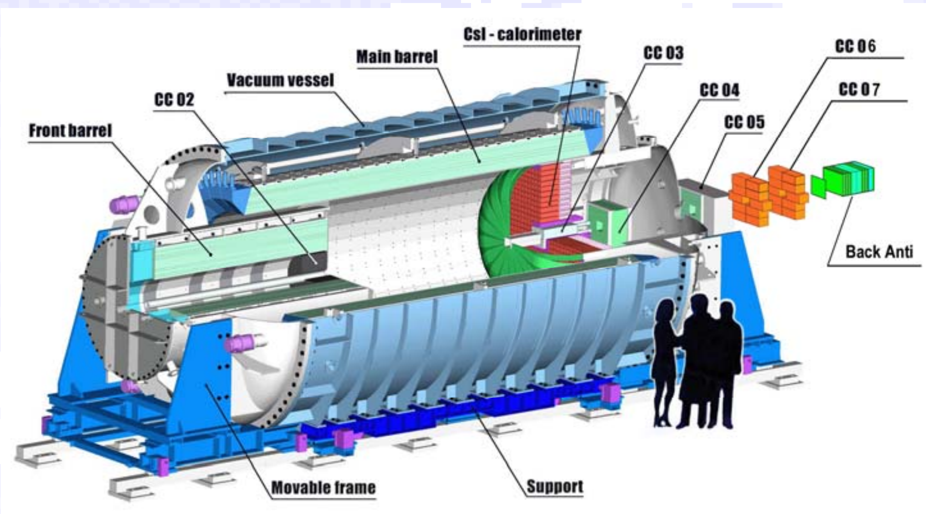


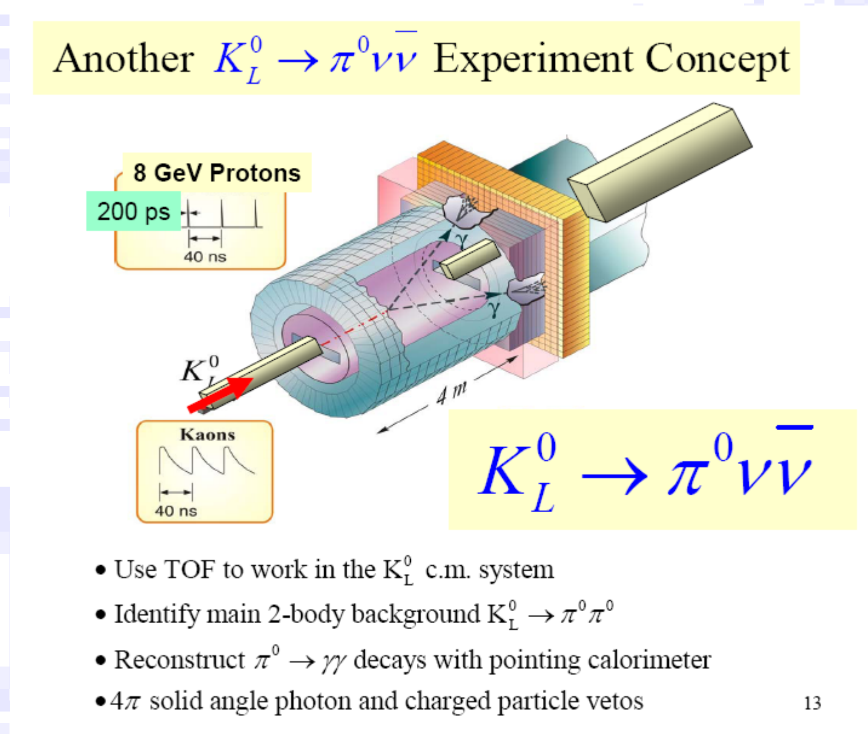
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

•KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

A hermetic "bottle" approach.

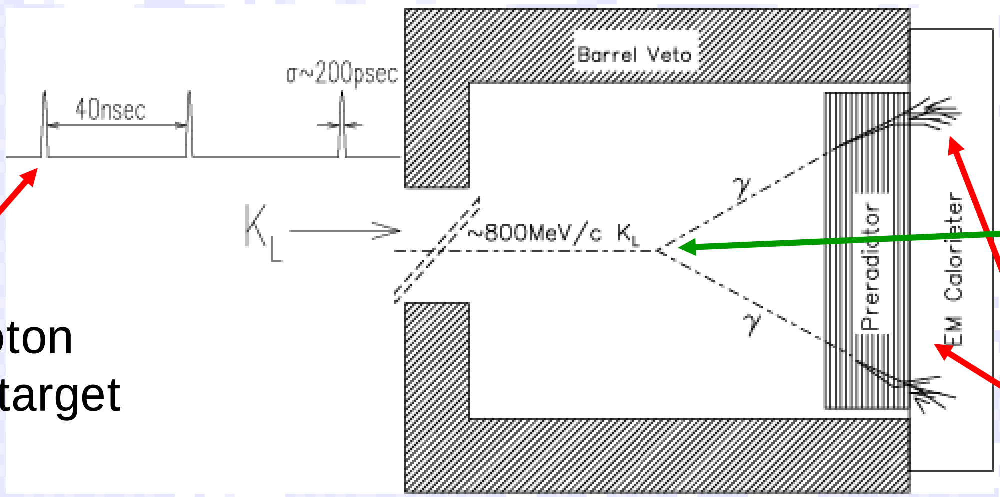
•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!





KOPIO inspired: Micro-bunch the beam, TOF determines K_L momentum.

Fully reconstruct the neutral Kaon in K_L □ ▲‡ ¯↔ ↔ measuring the Kaon momentum by time-of-flight.



Start when proton beam hits the target

End at the

decay time and decay point

reconstructed from the

two photons.

Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Neutrino Physics:

- Mass Hierarchy
- CP violation
- Precision measurement of the θ_{23} (atmospheric mixing). Maximal??
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Next generation precision cross section measurements

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Muon Physics:

- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- Next generation $(g\text{-}2)_{\mu}$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \rightarrow 3e$
- $\mu^{+}e^{-} \rightarrow \mu^{-}e^{+}$
- $\mu^{-}A \rightarrow \mu^{+}A'$; $\mu^{-}A \rightarrow e^{+}A'$; $\mu^{-}e^{-}(A) \rightarrow e^{-}\ e^{-}(A)$
- Systematic study of radiative muon capture on nuclei.

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

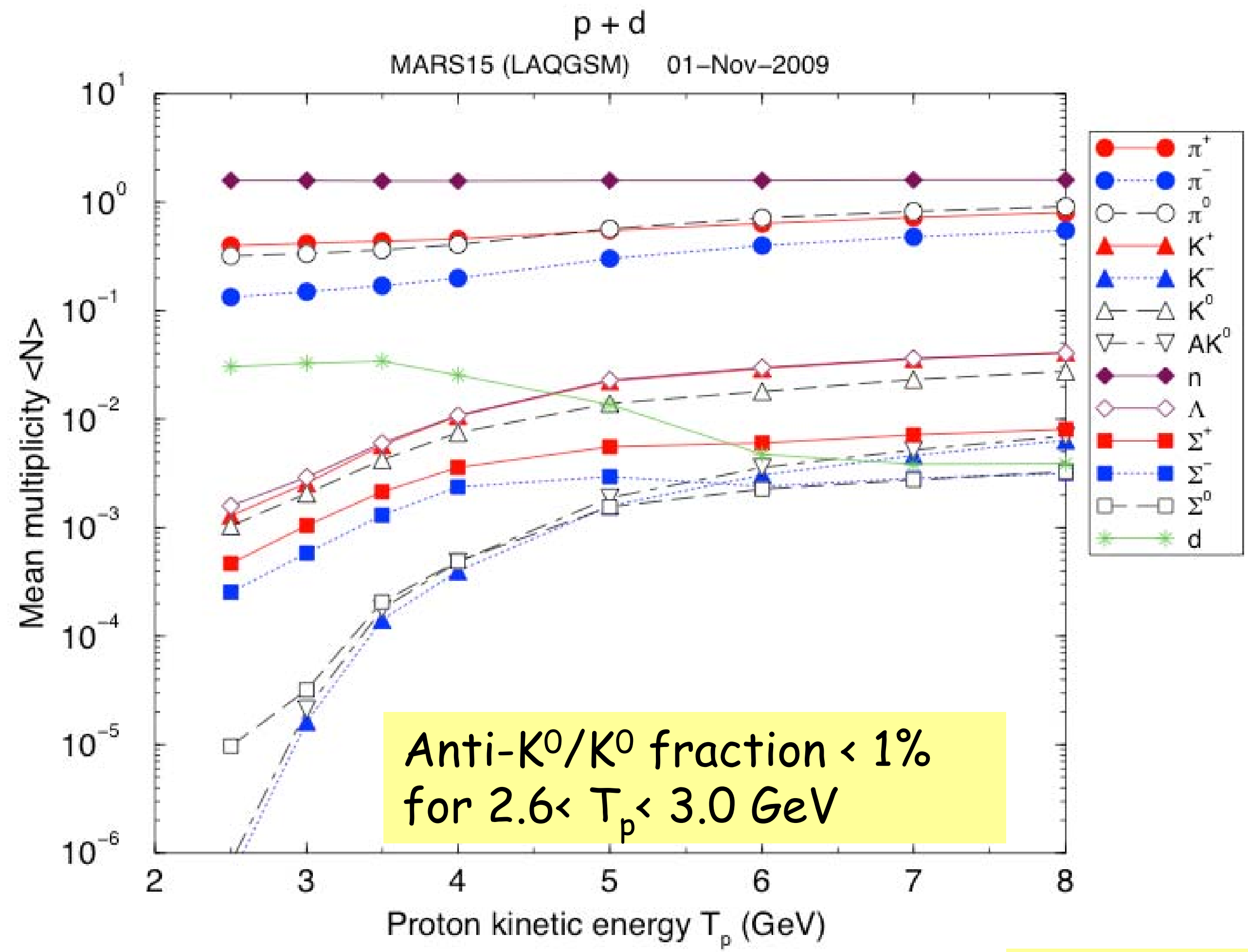
Baryons:

- pp $\rightarrow \Sigma^{+} K^{0} p^{+}$; $\Sigma^{+} \rightarrow p^{+} \mu^{+} \mu^{-}$ (HyperCP anomaly, and other rare Σ^{+} decays)
- pp $\rightarrow K^{+} \Lambda^{0} p^{+}$; Λ^{0} ultra rare decays
- $\Lambda^{0} \leftrightarrow \overline{\Lambda}^{0}$ oscillations (Project-X operates below anti-baryon threshold)
- neutron EDM

Nuclei:

- Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's.

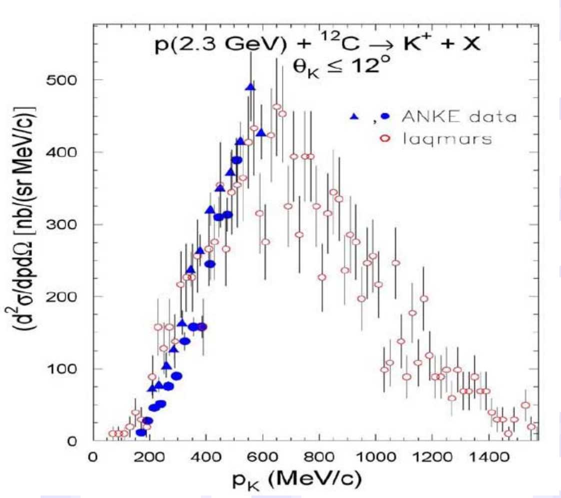
IC2 is high power, but what about kaon yields??

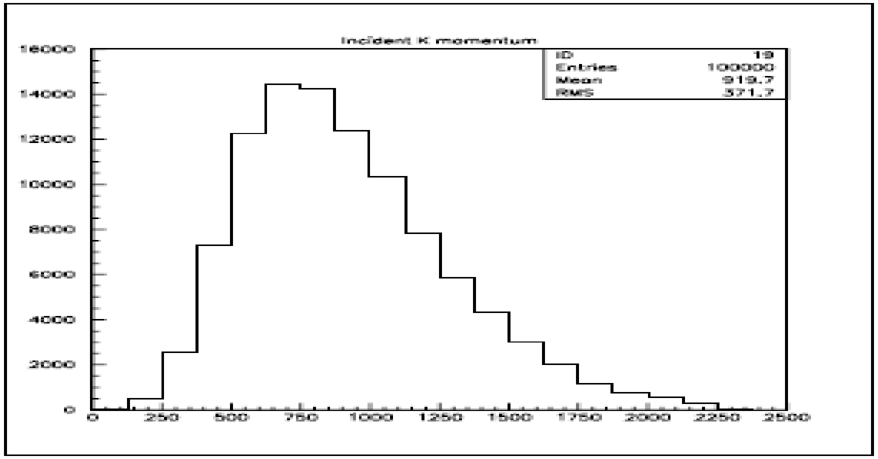


Anti-K^0/K^0 fraction < 1% for 2.6< T_p< 3.0 GeV

LAQGSM/MARS-15

KOPIO and ICD-2 kaon momentum spectra comparison





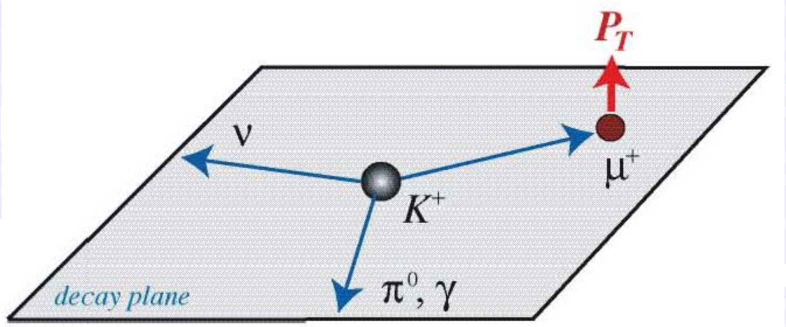
KOPIO Proposal

Figure 13: K_L^0 spectrum incident on KOPIO decay volume.

Transverse μ^+ polarization in $K_{\mu 3}$

$K^+ \rightarrow \pi^0 \mu^+ \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- P_T is T-odd, and spurious effects from final state interaction are small: $P_T(\mathrm{FSI}) < 10^{-5}$

  Non-zero P_T is a signature of T violation.

- Standard Model (SM) contribution to P_T : $P_T(\mathrm{SM}) < 10^{-7}$

  P_T in the region 10^{-3}~10^{-4} is a sensitive probe of CP violation beyond the SM.

- There are theoretical models of new physics which allow a sizable P_T without conflicting with other experimental constraints.

TREK experiment aims for a sensitivity of 10^{-4}

Direct CP violation

- Direct CP violation in K^0 system :

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.66 \pm 0.26)\times 10^{-3} \quad \Rightarrow$$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K^0} \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K^0} \to \pi^+\pi^-)} = (5.04 \pm 0.22) \times 10^{-6} \equiv R$$

- *If this effect is due to Higgs dynamics:*

Because there is no ΔI=1/2 suppression (~ 20) in the K^+ system

$$P_T \sim R \times 20 = 5 \times 10^{-6} \times 20 \sim 10^{-4}$$

-- *unless enhanced couplings to leptons!*

(I. Bigi, CERN Flavor WS, 2007)

General MSSM with R-parity

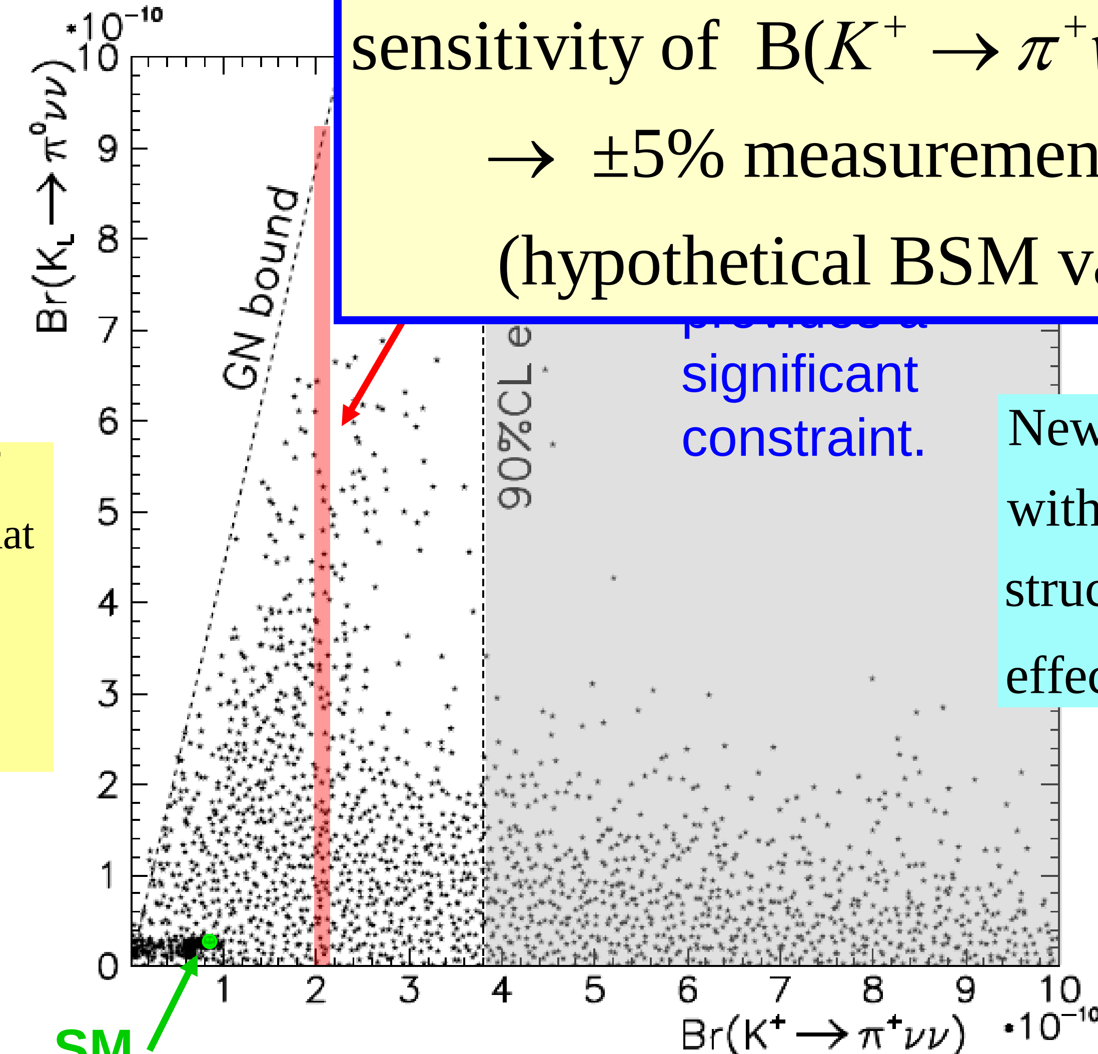
Fermilab P996 will improve the sensitivity of $B(K^+ \to \pi^+ \nu \bar{\nu})$ by >100 !

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

SM

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

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

New Physics found at LHC

↗ 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.

STANDARD MODEL

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

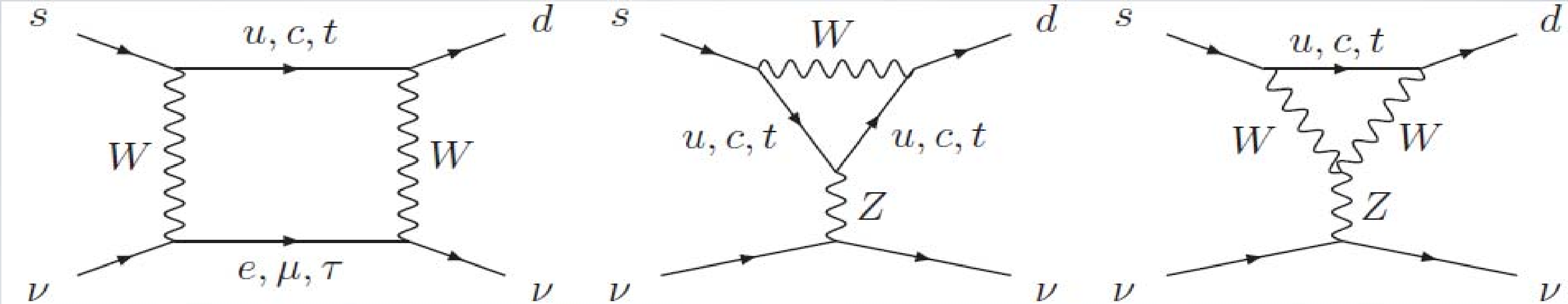
kinematics EM QCD weak

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

$$\frac{g^4}{16\pi^2 M_W^2}$$

K_S has ${\rm Re}Y$

Andreas Kronfeld, 4th PX Workshop



- Induced in SM at one (and higher) loop(s):

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

where $X(x_q) = \frac{1}{3}\sum_l X(x_q, x_l)$, $x_q = m_q^2/M_W^2$.

- GIM mechanism stems from CKM $V_{ud}^{*}V_{us} = -V_{td}^{*}V_{ts} - V_{cd}^{*}V_{cs}$.

- Last term is omnibus for higher dimension & long distance.

Andreas Kronfeld, 4th PX Workshop

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