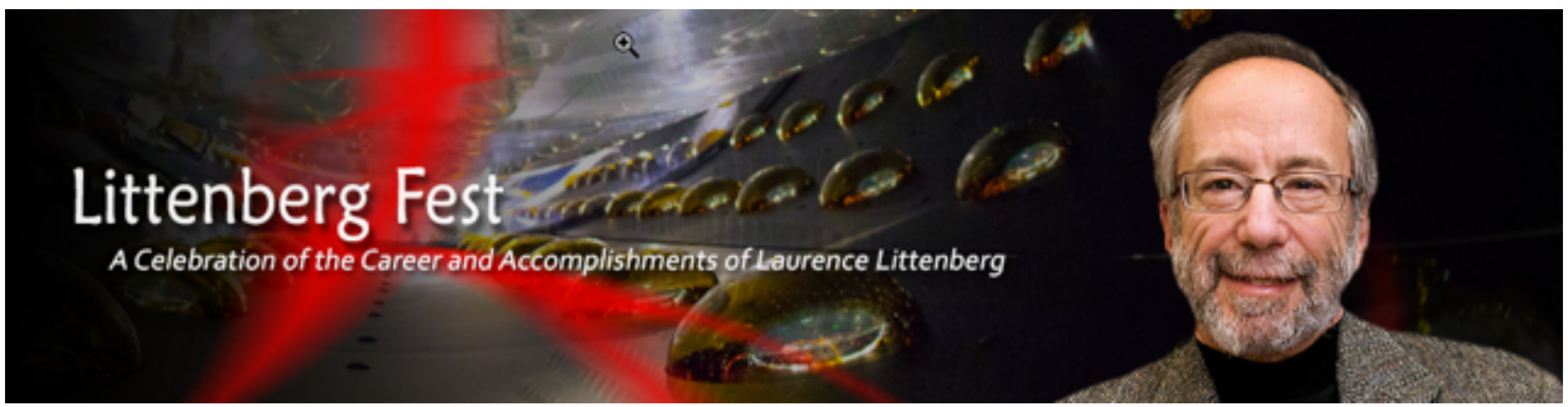
Rare Kaon Decays

German Valencia



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

- At the Littenberg fest we have to talk about the `Littenberg mode'.

- We have already heard about this in this FEST, but I will try to add a theory perspective

- precise determination of SM parameters

- or: ruling out new physics for over 25 years

G. Valencia, Monash University

reviews on rare kaon decays

- SUSY John Hagelin

Rare Kaon Decays Prog.Part.Nucl.Phys. 23 (1989) 1

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- ChPT, long distance

RARE AND RADIATIVE KAON DECAYS Ann.Rev.Nucl.Part.Sci. 43 (1993) 729-792

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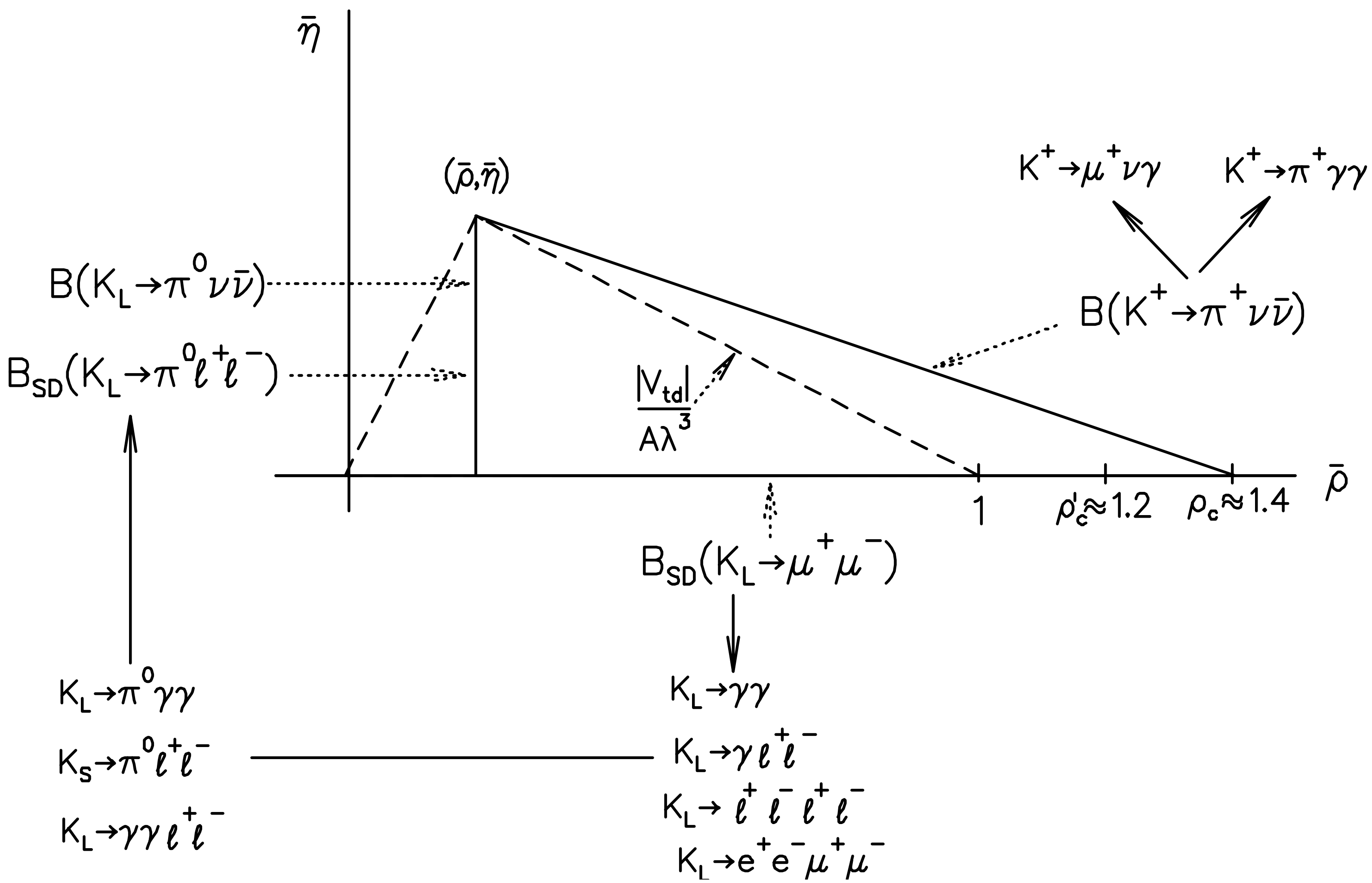
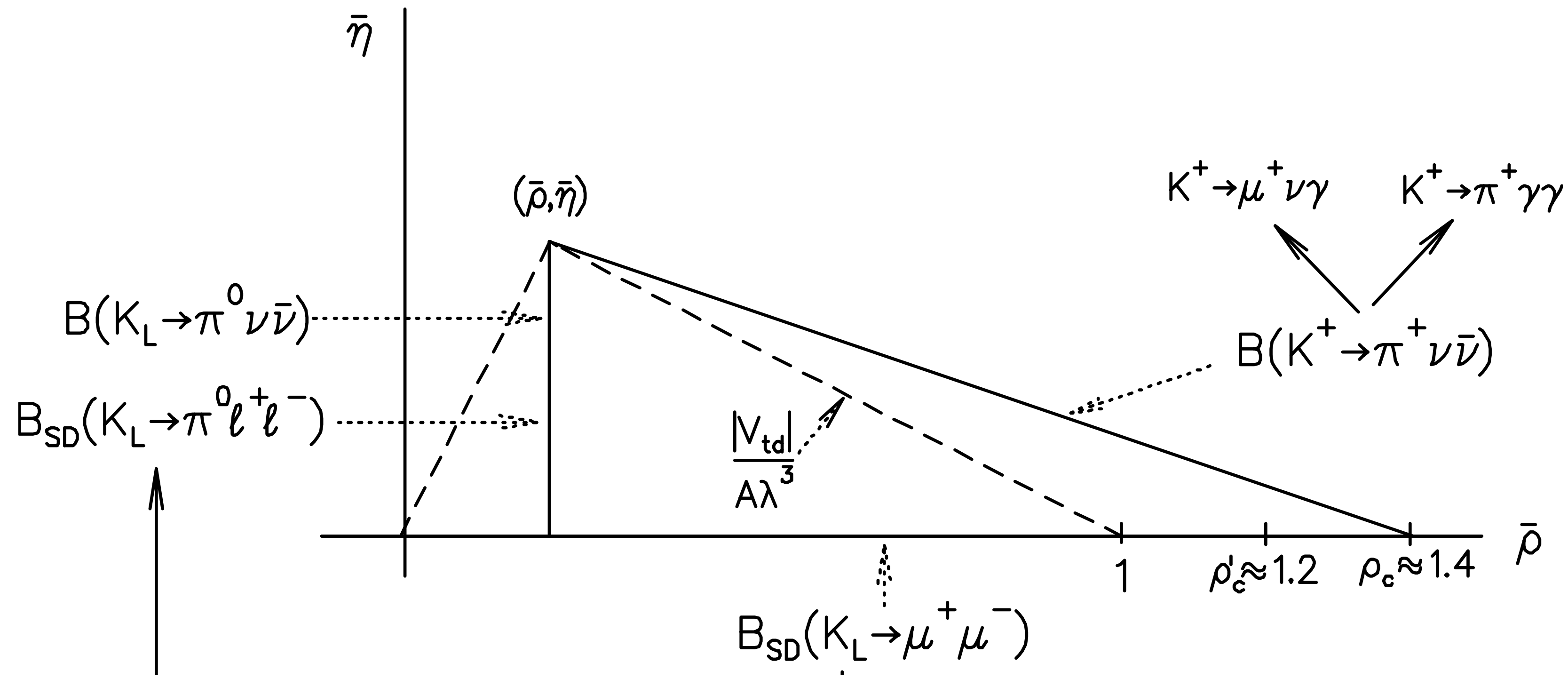
Rare Kaon Decays - PDB



Mode	90% CL upper limit	Exp't	Yr./Ref.
$K^+\to\pi^+e^-\mu^+$	1.2×10^{-11}	BNL-865	2005/Ref. 21
$K^+\to\pi^+e^+\mu^-$	5.2×10^{-10}	BNL-865	2000/Ref. 18
$K_L\to\mu e$	4.7×10^{-12}	BNL-871	1998/Ref. 22
$K_L\to\pi^0e\mu$	7.6×10^{-11}	KTeV	2008/Ref. 23
$K_L\to\pi^0\pi^0e\mu$	1.7×10^{-10}	KTeV	2008/Ref. 23

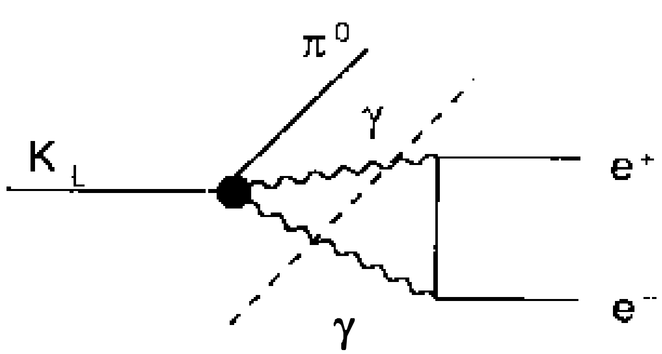
Λ_{NP} > 100 TeV

CMS $h\to\mu\ \tau$??



$$B_{\rm CPV} \approx 10^{-12}\left[15.7|a_S|^2 \pm 1.4\left(\frac{|V_{cb}|^2\overline{\eta}}{10^{-4}}\right)|a_S| + 0.12\left(\frac{|V_{cb}|^2\overline{\eta}}{10^{-4}}\right)^2\right] \approx (3.1 \pm 0.9)\times 10^{-11}$$

$K_S \to \pi^0 \ell^+ \ell^-$



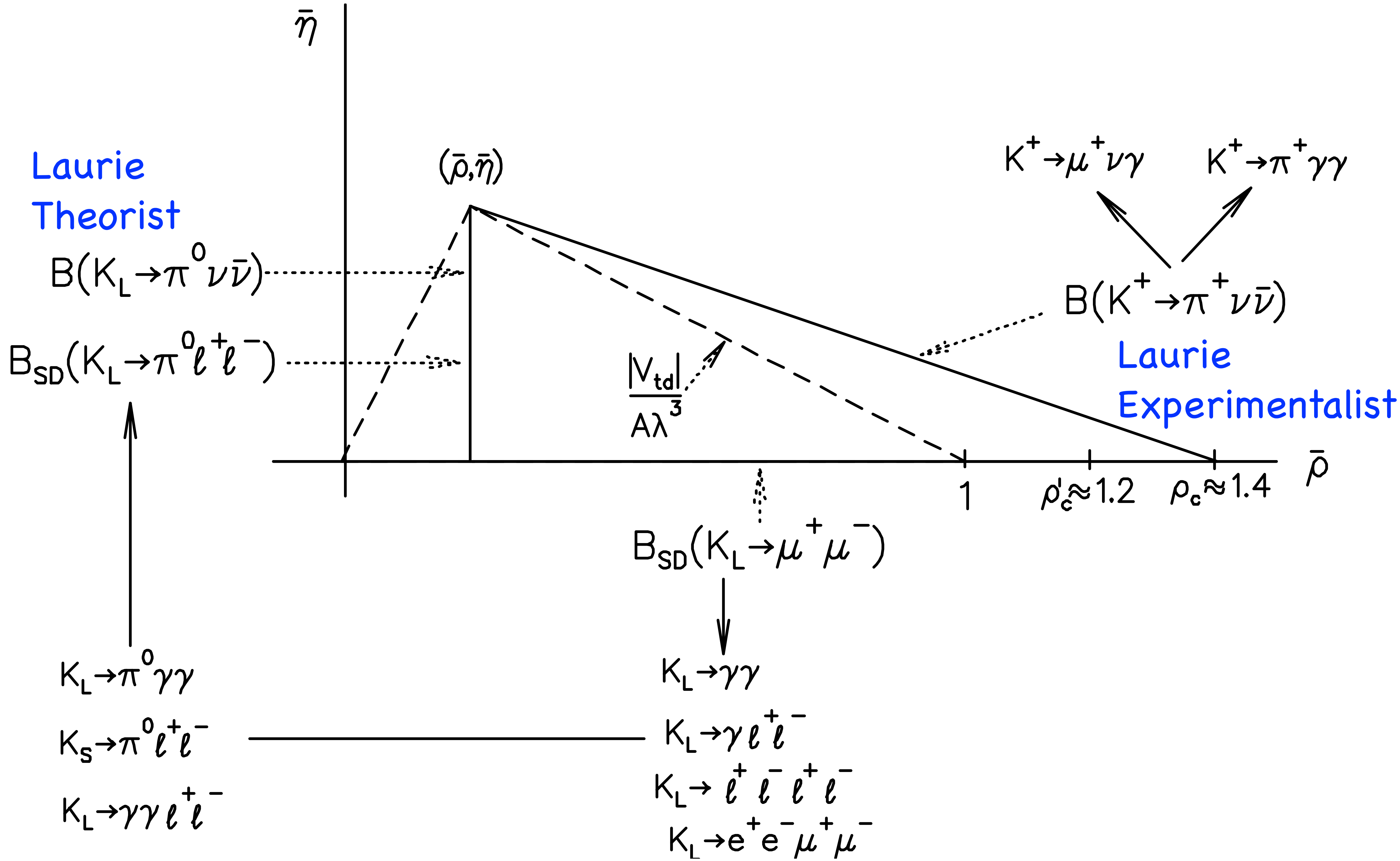
B_{CP} around 10^{-13}

background

$$K_L \to \pi^0 \gamma e^+ e^-$$

$$K_L \to \pi^0 \gamma\gamma e^+ e^- \sim \mathcal{O}(10^{-10})$$

Rare Kaon Decays



Laurie's paper

SICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE

CP-violating decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

Laurence S. Littenberg
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

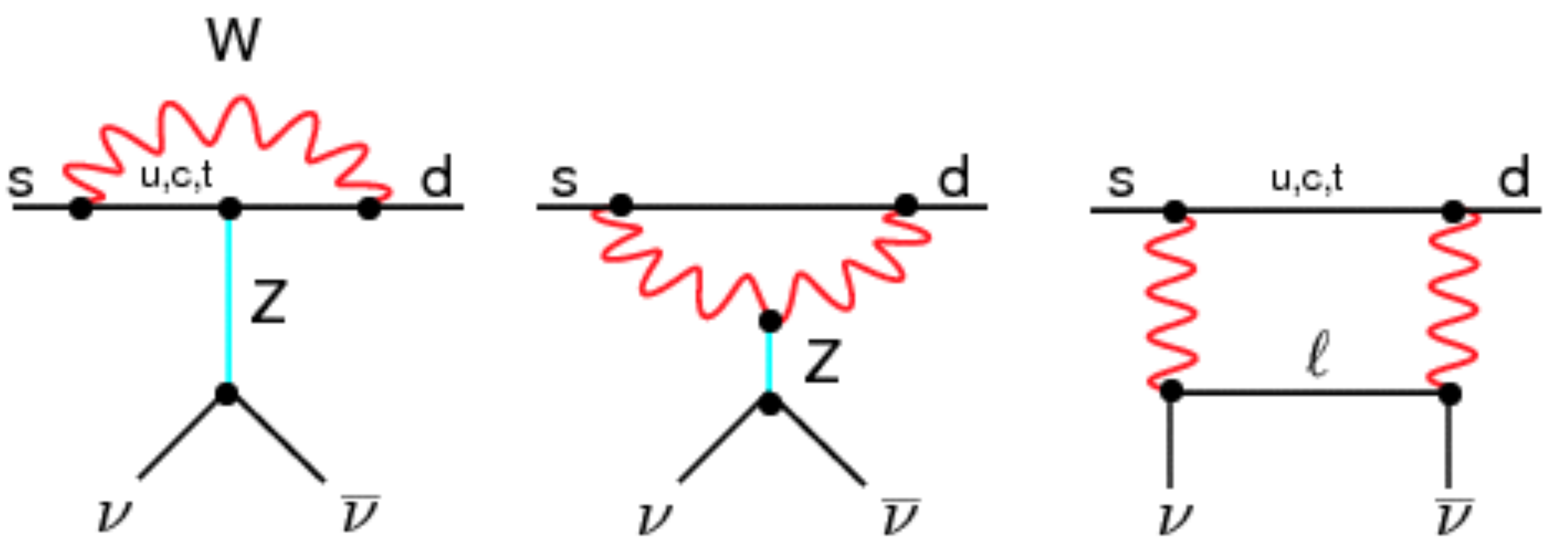
(Received 6 January 1989)

The process $K_L^0 \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of CP violation. The largest expected contribution to this decay is a direct CP-violating term at $\approx \text{few} \times 10^{-12}$. The indirect CP-violating contribution is some *3 orders of magnitude* smaller, and CP-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K_L^0 \to 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_\epsilon = 5.18 \times 10^{-6} \times 4.18 \times 3 \times 0.70 \times 10^{-6} (10.99 \times 10^{-3})^2 \approx 5.5 \times 10^{-15}$$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_{\text{direct}} = 4.18 \times 3 \times 0.70 \times 10^{-6} (1.07 \times 10^{-3})^2 \approx 10^{-11} .$$

Basics in SM

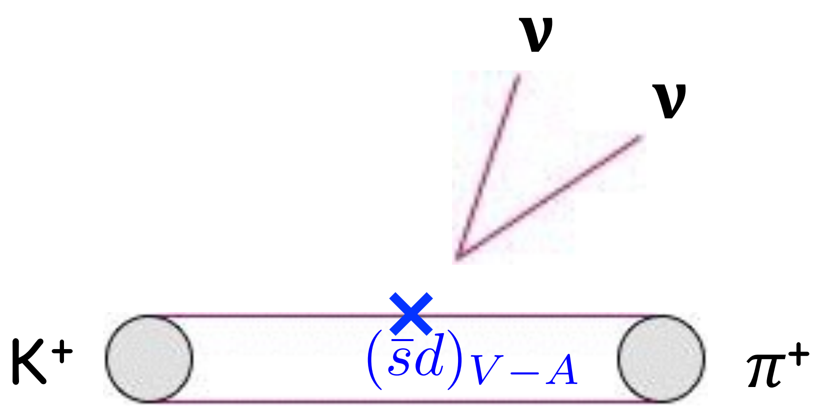


Inami-Lim

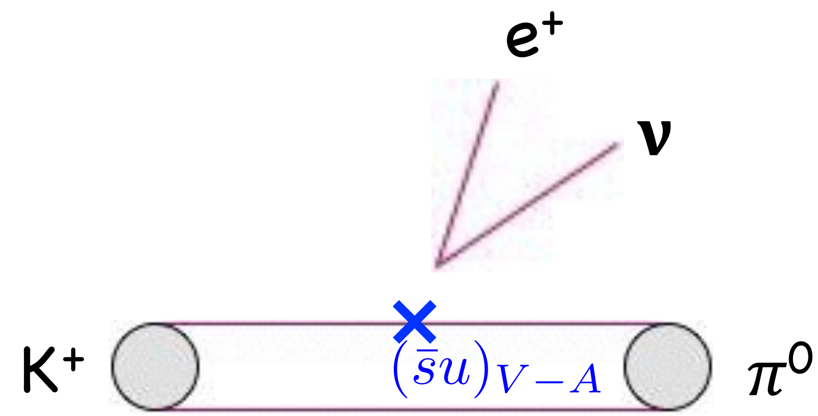
$$\mathcal{A}_q(s \to d\nu\bar{\nu}) \propto \lambda_q m_q^2 \propto \begin{cases} m_t^2(\lambda^5 + i\lambda^5)\,, & q = t\,, \\ m_c^2(\lambda + i\lambda^5)\,, & q = c\,, \\ \Lambda_{\rm QCD}^2 \lambda\,, & q = u\,, \end{cases}$$

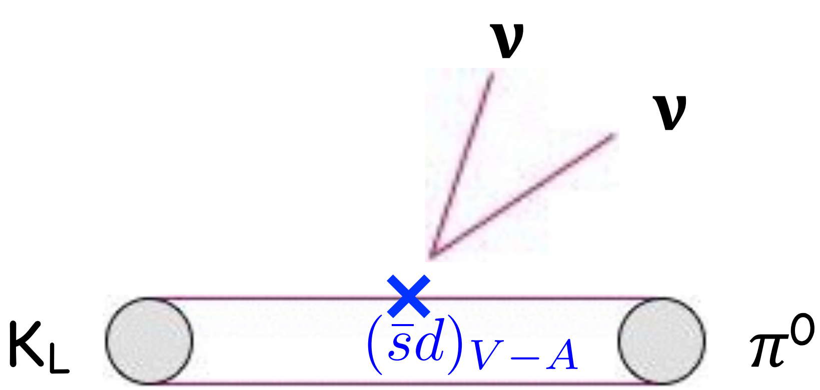
charm contributes to real part, K^+
but irrelevant for imaginary part K_L

Isospin and isospin breaking



$$\langle \pi^+|(\bar{s}d)_{V-A}|K^+\rangle = \sqrt{2}\langle \pi^0|(\bar{s}u)_{V-A}|K^+\rangle.$$





$$\langle \pi^0|(\bar{d}s)_{V-A}|\bar{K}^0\rangle = \langle \pi^0|(\bar{s}u)_{V-A}|K^+\rangle$$

- isospin breaking corrections: quark masses, electroweak radiative corrections
- reduce B ($K^+ \rightarrow \pi^+ \nu\nu$) and B($K_L \rightarrow \pi^0 \nu\nu$) relative to B($K^+ \rightarrow \pi^0 e^+ \nu$) by 10% and 5.6%, respectively

W.J. Marciano, Zohreh Parsa Phys.Rev. D53 (1996) 1-5

Latest (?) results

$$B\left(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)\right) = \kappa_+ (1+\Delta_{\rm EM}) \left[\left(\frac{{\rm Im}(V_{ts}^\star V_{td})}{\lambda^5} X_t\right)^2 + \left(\frac{{\rm Re}(V_{cs}^\star V_{cd})}{\lambda}(P_c + \delta P_{c,u}) + \frac{{\rm Re}(V_{ts}^\star V_{td})}{\lambda^5} X_t\right)^2\right].$$

long distance

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \Theta_{\rm W}} \lambda^8$$

NNLO QCD, 2 loop EW

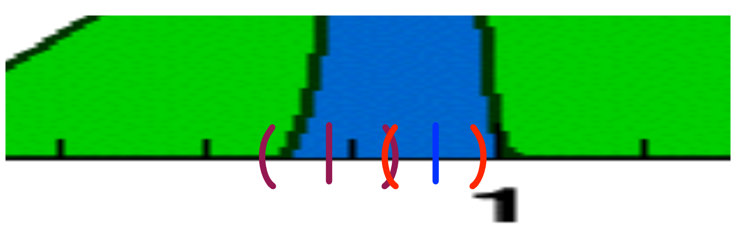
NLO QCD and 2 loop EW

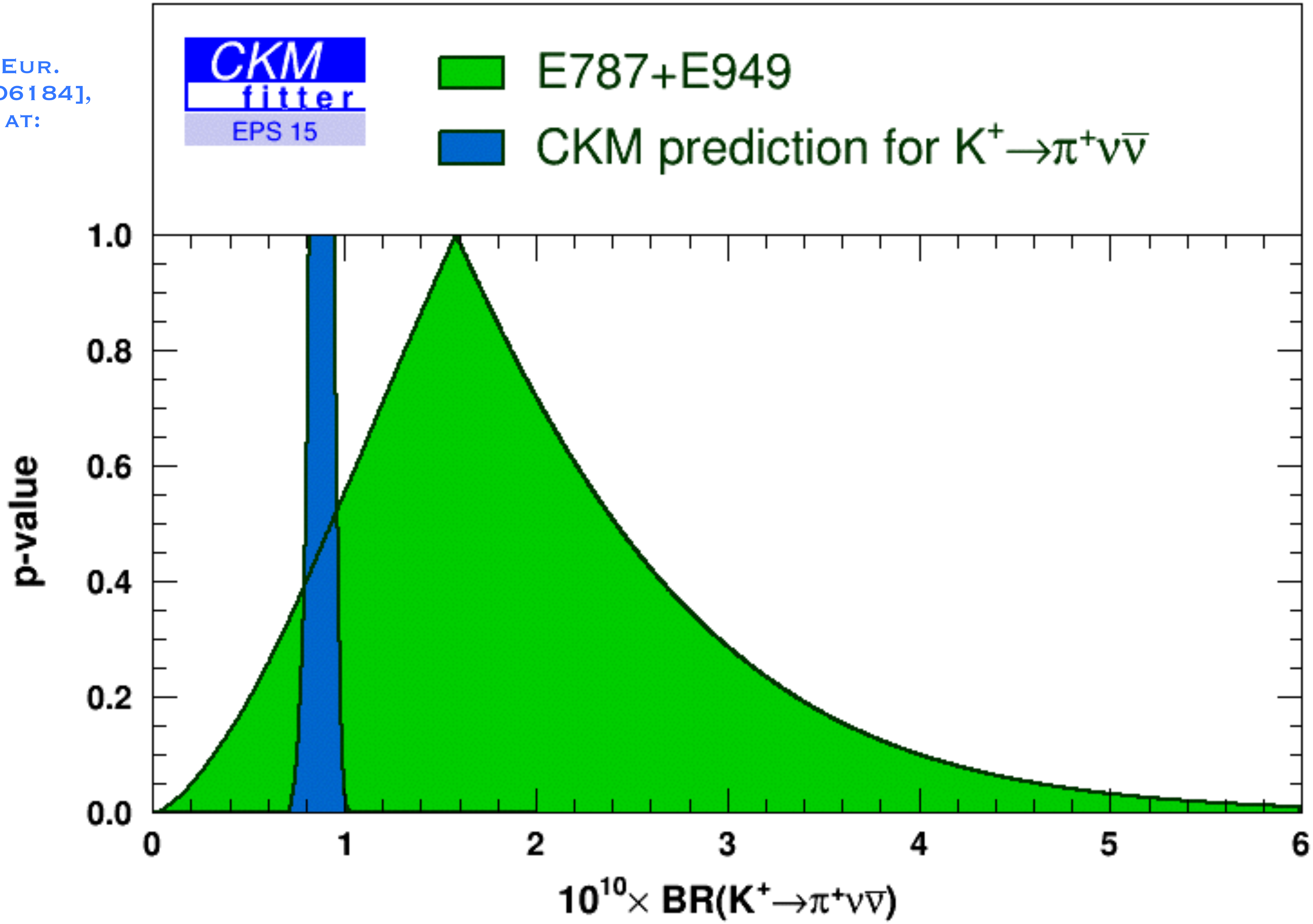
$$B(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{{\rm Im}(V_{ts}^\star V_{td})}{\lambda^5} X_t\right)^2$$

$$\kappa_{\rm L} = \frac{r_{K_{\rm L}}}{r_{K^+}} \frac{\tau(K_{\rm L})}{\tau(K^+)} \kappa_+ = 1.80 \cdot 10^{-10}$$

latest numerical results K^+

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

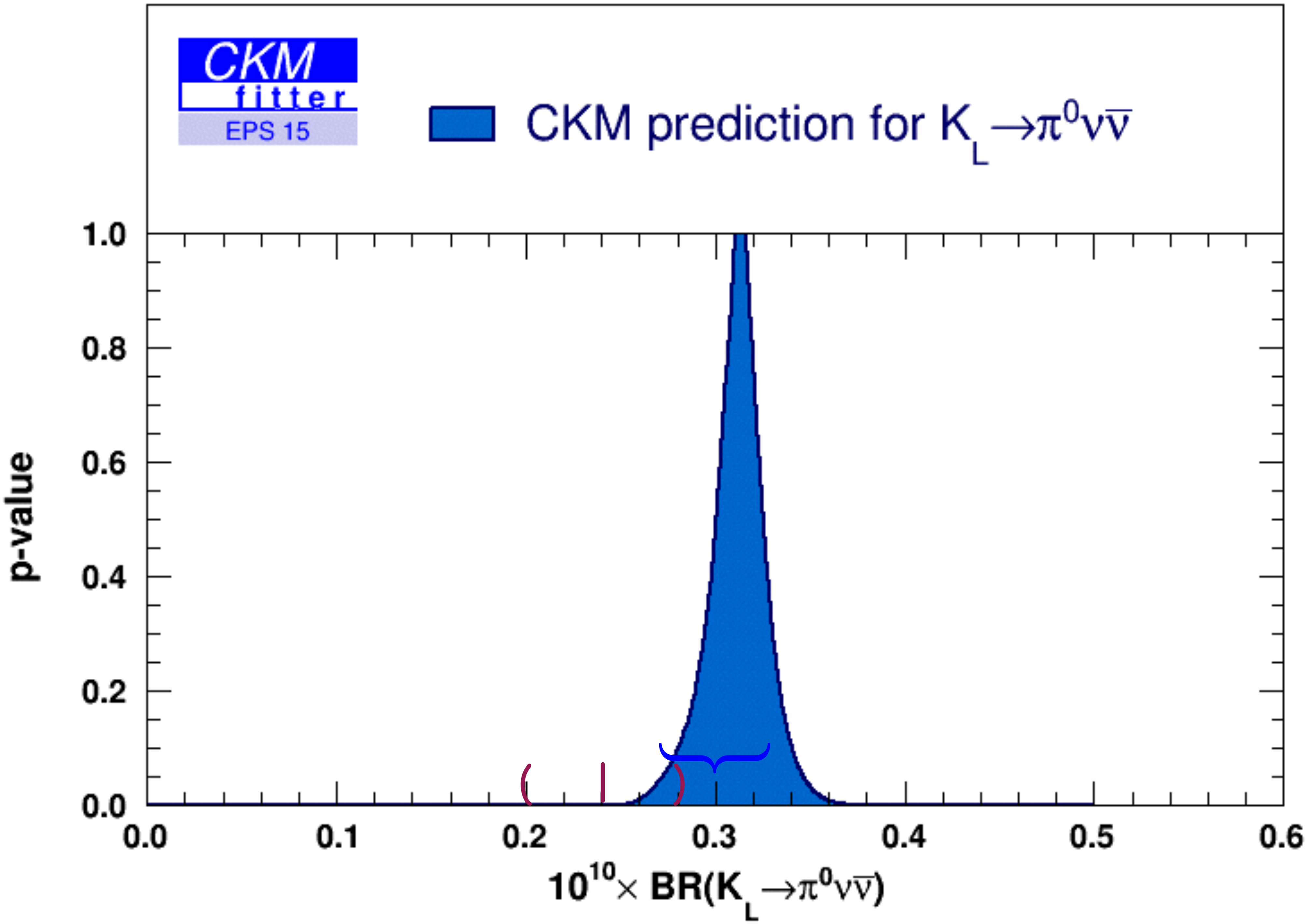




Brod, Gorbahn, Stamou 2011: $(7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$

Buras, Buttazzo, Girrbach-Noe, Knegjens 2015: $(9.11 \pm 0.72) \times 10^{-11}$

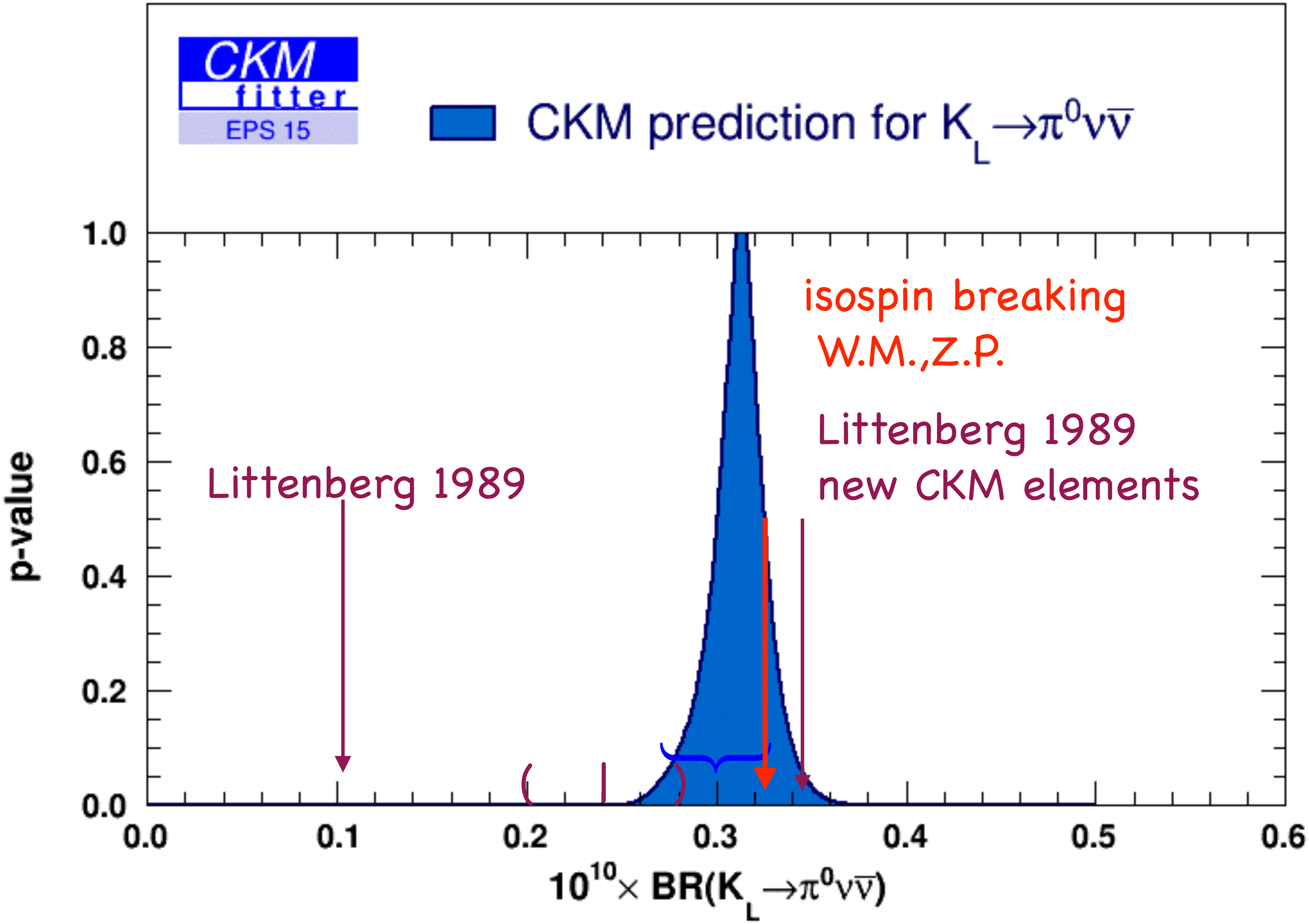
latest numerical results K_L



Brod, Gorbahn, Stamou 2011: $(2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$

Buras, Buttazzo, Girrbach-Noe, Knegjens 2015: $(3.00 \pm 0.30) \times 10^{-11}$

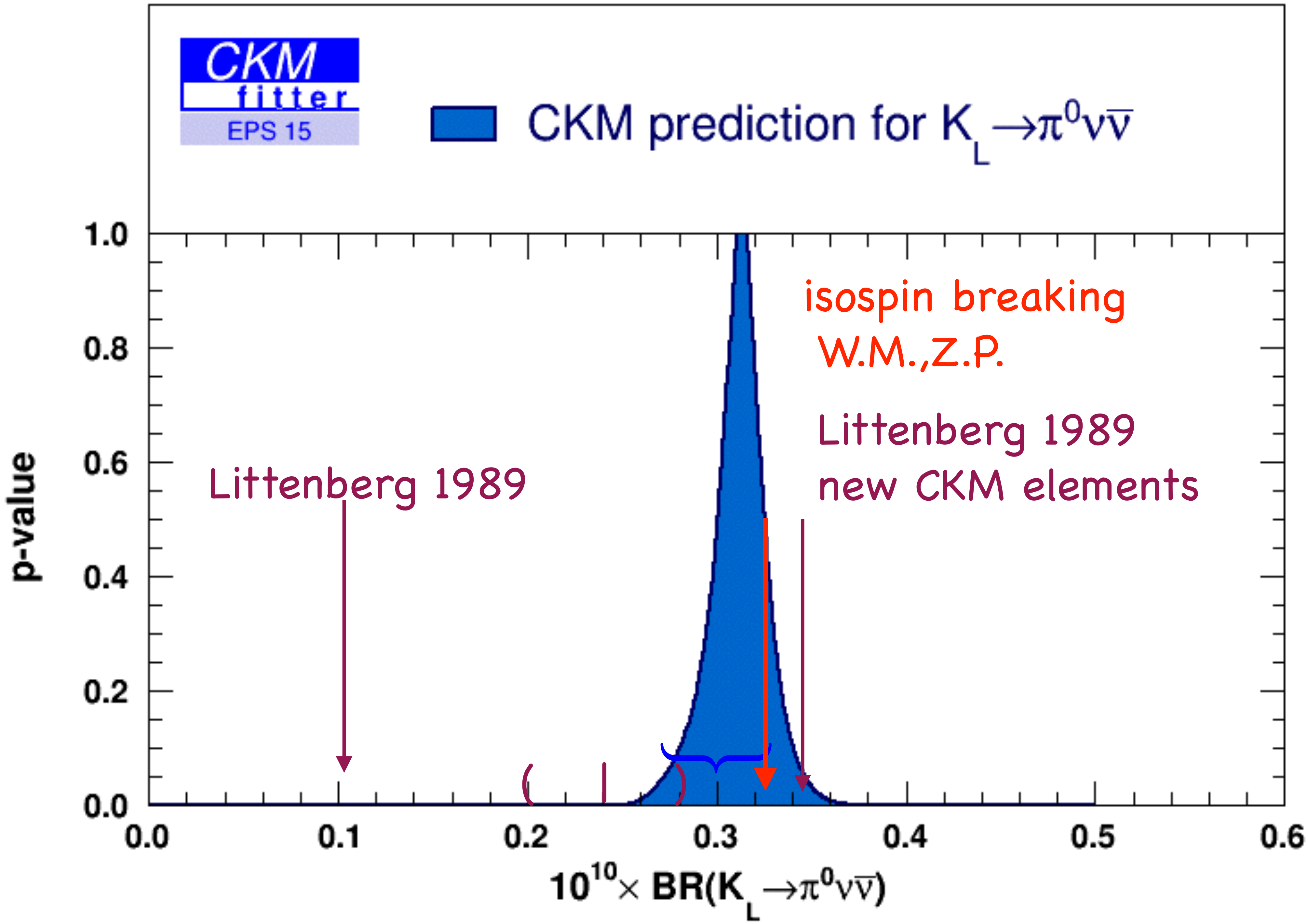
add Laurie's result



Brod, Gorbahn, Stamou 2011: $(2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$

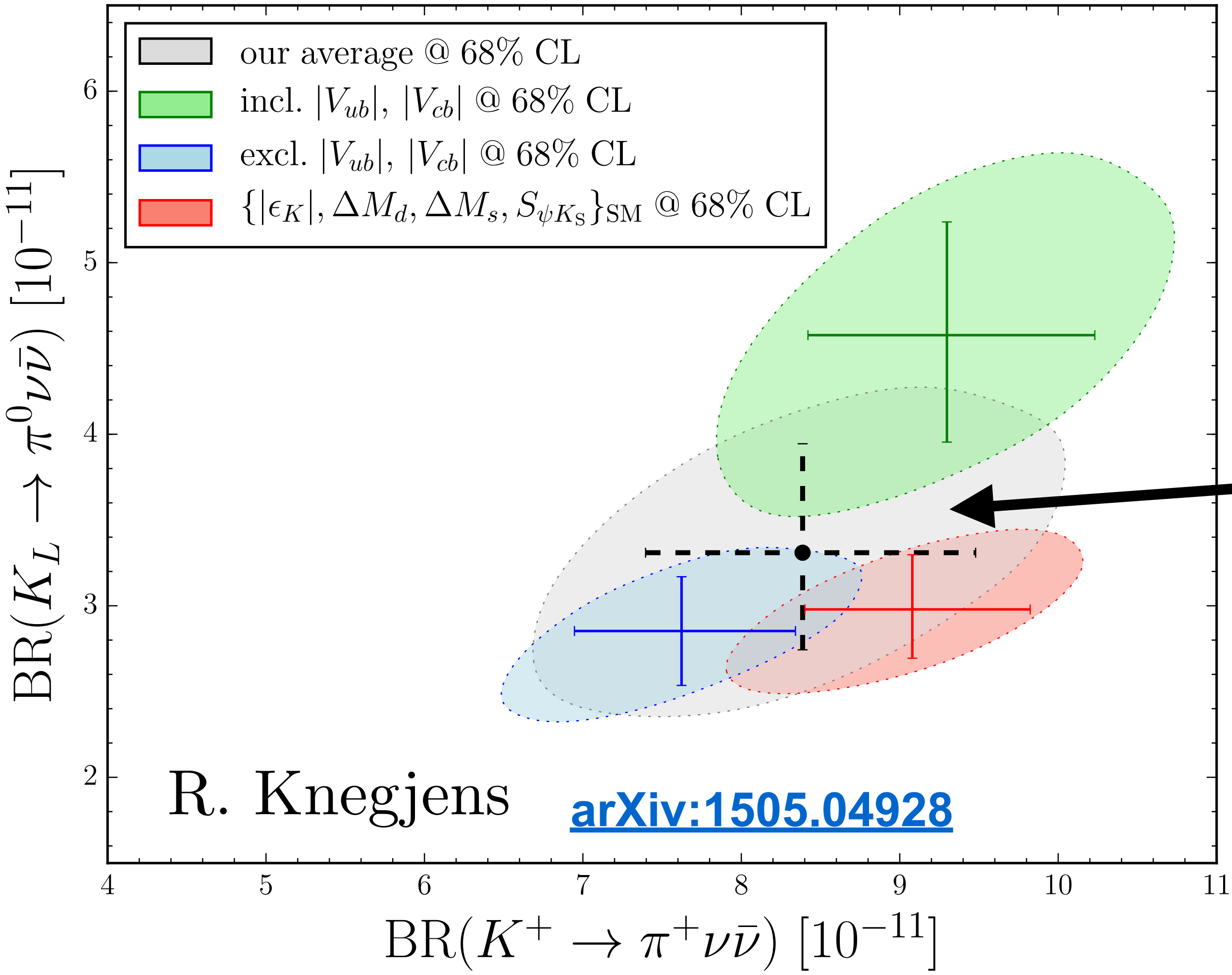
Buras, Buttazzo, Girrbach-Noe, Knegjens 2015: $(3.00 \pm 0.30) \times 10^{-11}$

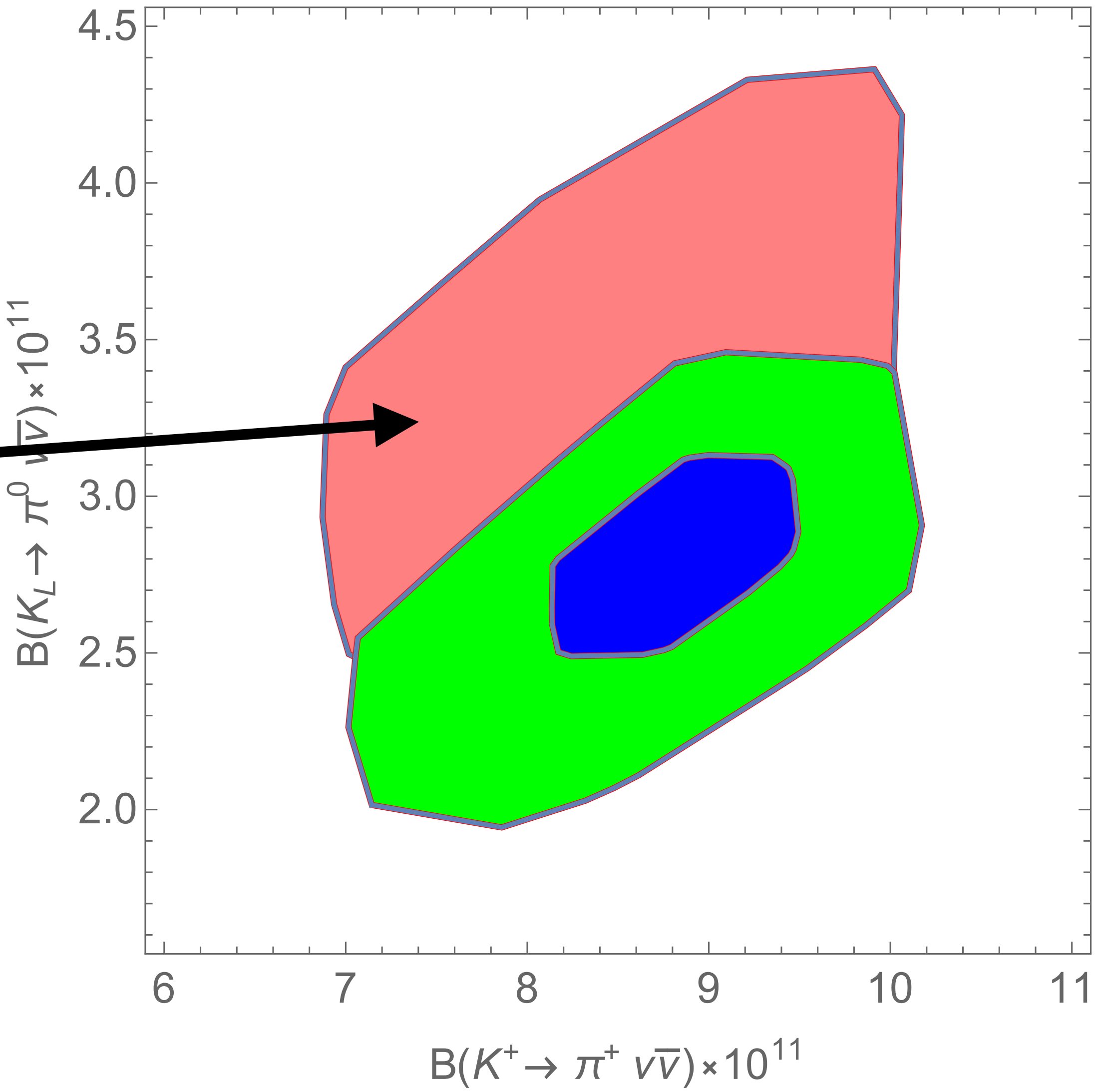
paraphrase Milind Diwan according to Laurie



(calculation) so clean, theorists are not really needed!

SM parametric error





Buras group

$$|V_{ub}| = \begin{cases} (3.72 \pm 0.14) \times 10^{-3} & \text{excl} \\ (4.40 \pm 0.25) \times 10^{-3} & \text{incl} \\ (3.88 \pm 0.29) \times 10^{-3} & \text{avg} \end{cases},$$

$$|V_{cb}| = \begin{cases} (39.36 \pm 0.75) \times 10^{-3} & \text{excl} \\ (42.21 \pm 0.78) \times 10^{-3} & \text{incl} \\ (40.7 \pm 1.4) \times 10^{-3} & \text{avg} \end{cases}$$

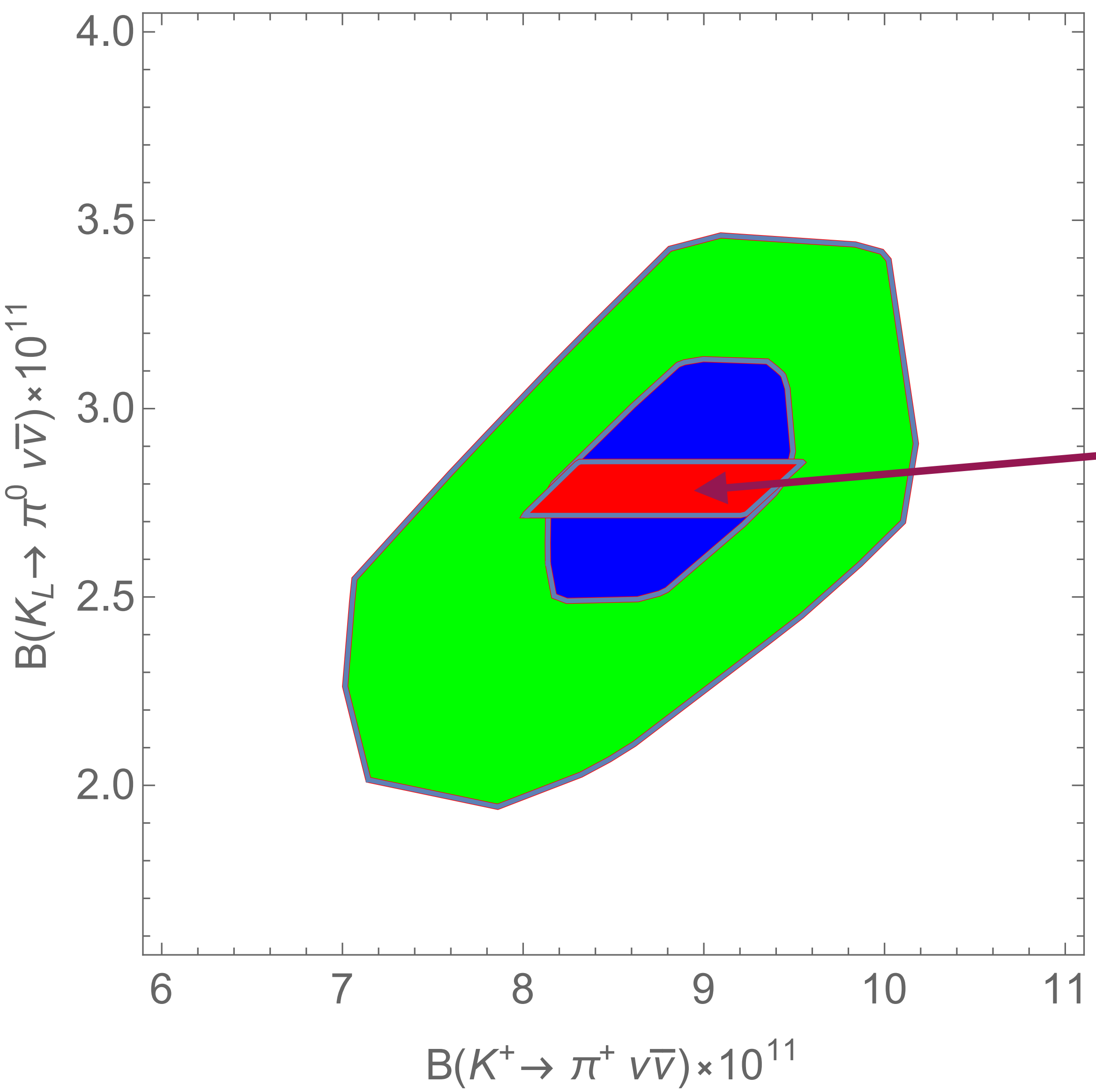
$$\gamma = (73.2^{+6.3}_{-7.0})^\circ.$$

Wolfenstein parameters and Jarlskog invariant:

Observable	Central ± 1 σ	± 2 σ
A	0.810 [+0.018 -0.024]	0.810 [+0.025 -0.030]
λ	0.22548 [+0.00068 -0.00034]	0.22548 [+0.00096 -0.00068]
ϱbar	0.1453 [+0.0133 -0.0073]	0.145 [+0.032 -0.015]
ηbar	0.343 [+0.011 -0.012]	0.343 [+0.022 -0.025]
J $[10^{-5}]$	2.96 [+0.19 -0.18]	2.96 [+0.30 -0.22]

CKMfitter

SM P_c and $X(x_t)$ error



Buras group

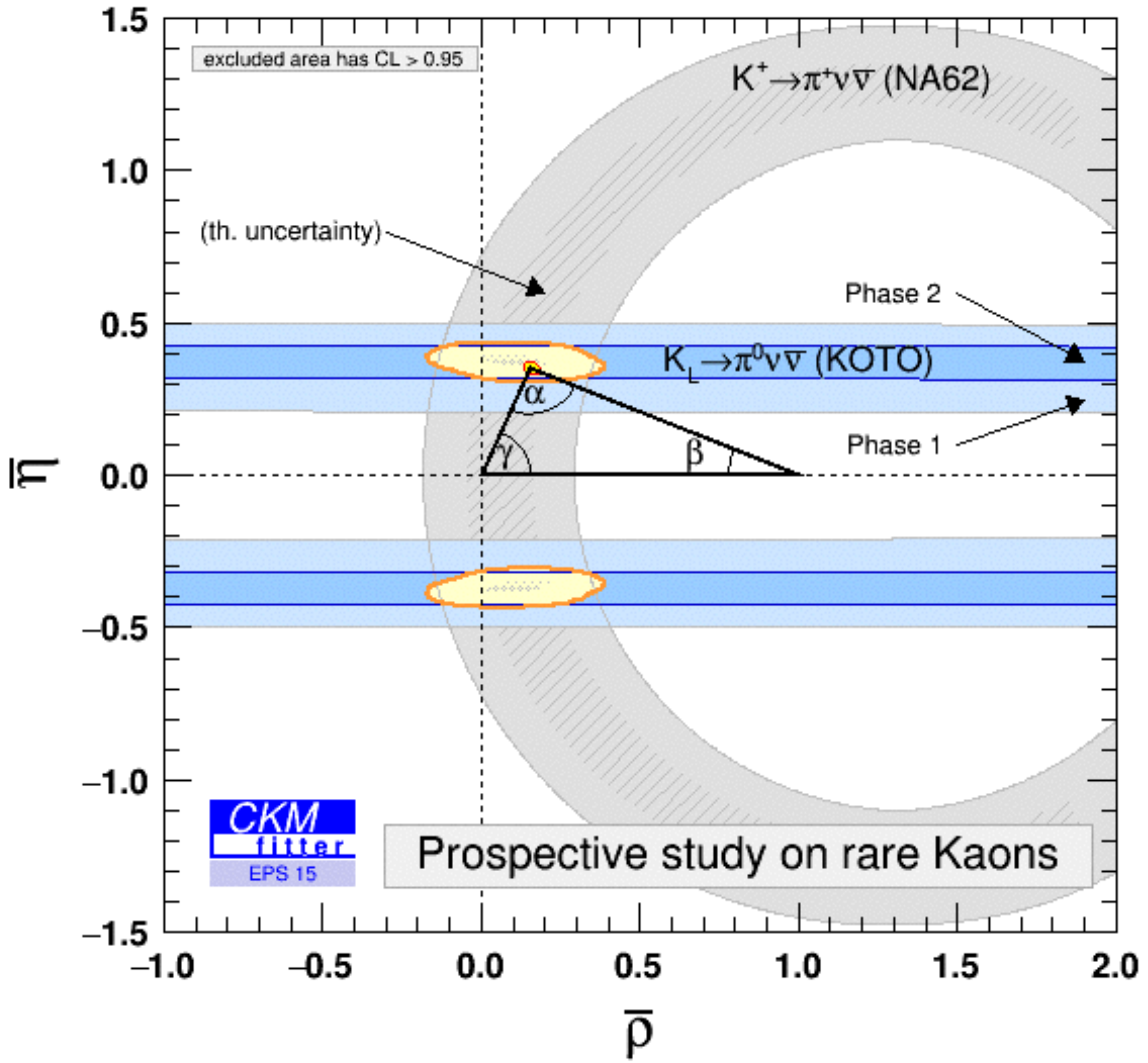
$$X(x_t) = 1.481 \pm 0.005|_{\rm th} \pm 0.008|_{\rm exp}.$$

- NLO QCD corrections
- two-loop electroweak contributions

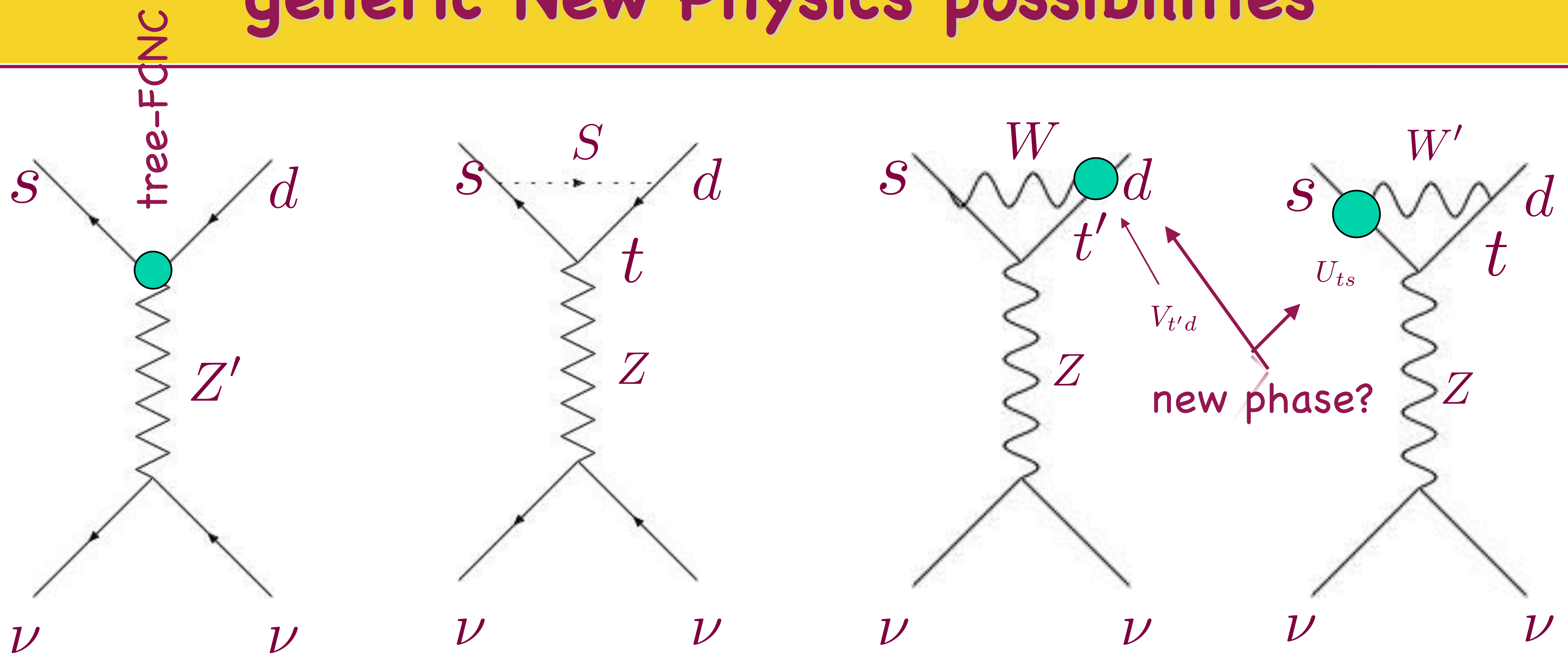
$$P_c(X) = 0.404 \pm 0.024,$$

- NLO and NNLO QCD corrections
- two-loop electroweak contributions
- long distance contribution $0.04 \pm 0.02,$

future projections



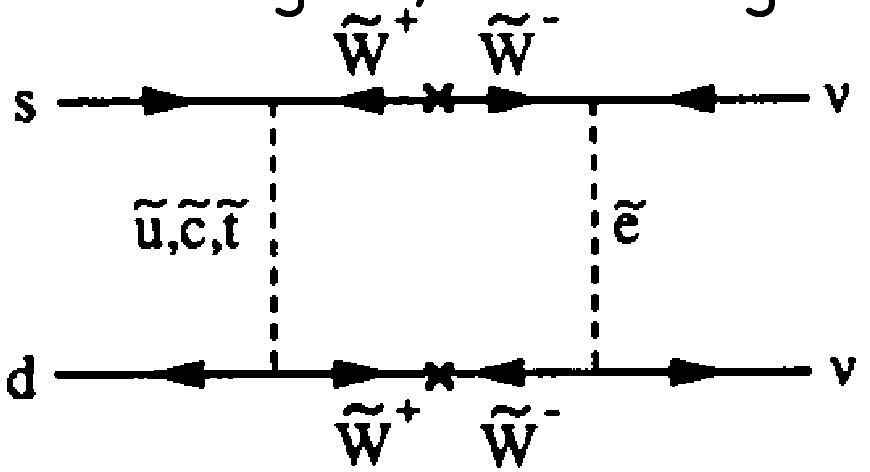
generic New Physics possibilities



- tree-level FCNC in new neutral bosons
- new charged scalars or vectors
- new heavy fermions

specific New Physics models

Hagelin, Littenberg



'Trivial' SUSY

Prog.Part.Nucl.Phys. 23 (1989) 1

Grossman, Isidori, Murayama LFV

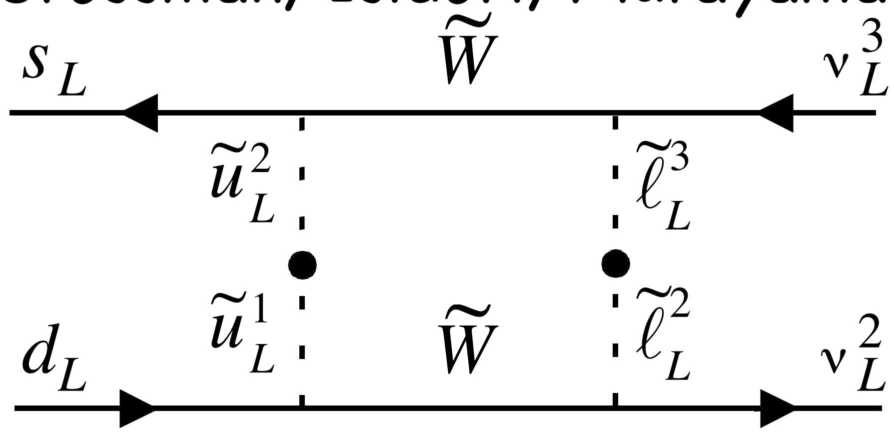
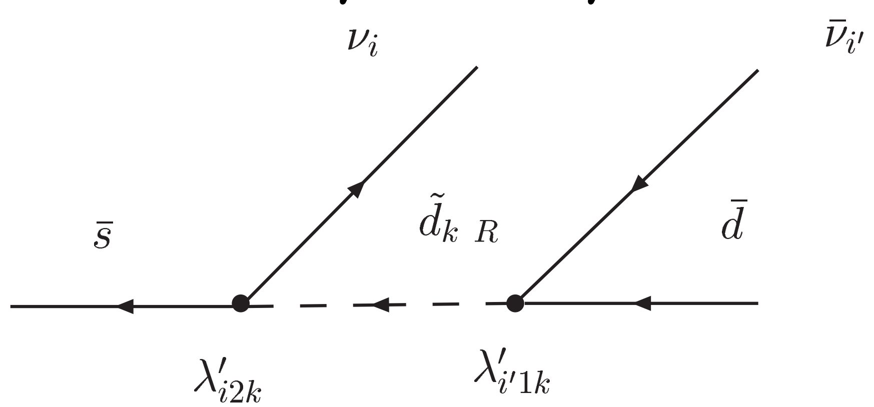


Figure 1: Wino-Wino box diagram.

Phys.Lett. B588 (2004) 74-80

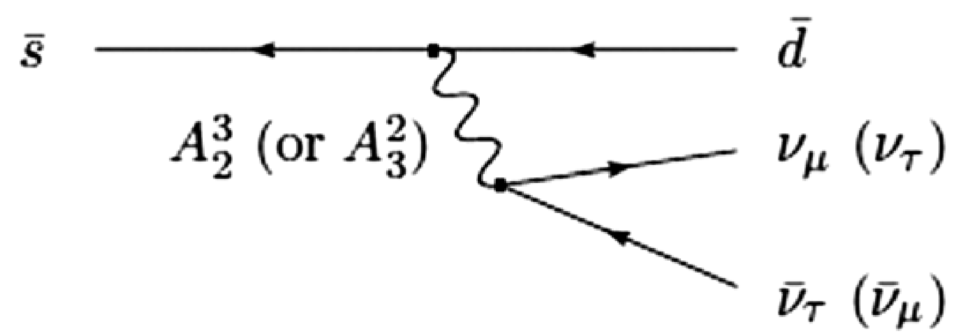
Deandrea, Welzel, Oertel



R parity violation

JHEP 0410:038,2004

Koide



Family gauge boson

PHYSICAL REVIEW D 92, 036009 (2015)

... (not as many as for the 750 GeV diphoton)

Grossman and Nir

10 April 1997

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 398 (1997) 163–168

$K_L \to \pi^0 \nu \bar{\nu}$ beyond the Standard Model ⋆

Yuval Grossman[a], Yosef Nir[b]

[a] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

[b] Department of Particle Physics, Weizmann Institute of Science, Rehovot 76100, Israel

Received 29 January 1997

Editor: M. Dine

Abstract

We analyze the decay $K_L \to \pi^0 \nu \bar{\nu}$ in a model independent way. If lepton flavor is conserved the final state is (to a good approximation) purely CP even. In that case this decay mode goes mainly through CP violating interference between mixing and decay. Consequently, a theoretically clean relation between the measured rate and electroweak parameters holds in any given model. Specifically, $\Gamma(K_L \to \pi^0 \nu \bar{\nu})/\Gamma(K^+ \to \pi^+ \nu \bar{\nu}) = \sin^2\theta$ (up to known isospin corrections), where θ is the relative CP violating phase between the $K - \bar{K}$ mixing amplitude and the $s \to d \nu \bar{\nu}$ decay amplitude. The experimental bound on $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ provides a model independent upper bound: $\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 1.1 \times 10^{-8}$. In models with lepton flavor violation, the final state is not necessarily a CP eigenstate. Then CP conserving contributions can dominate the decay rate.

- simplified notation

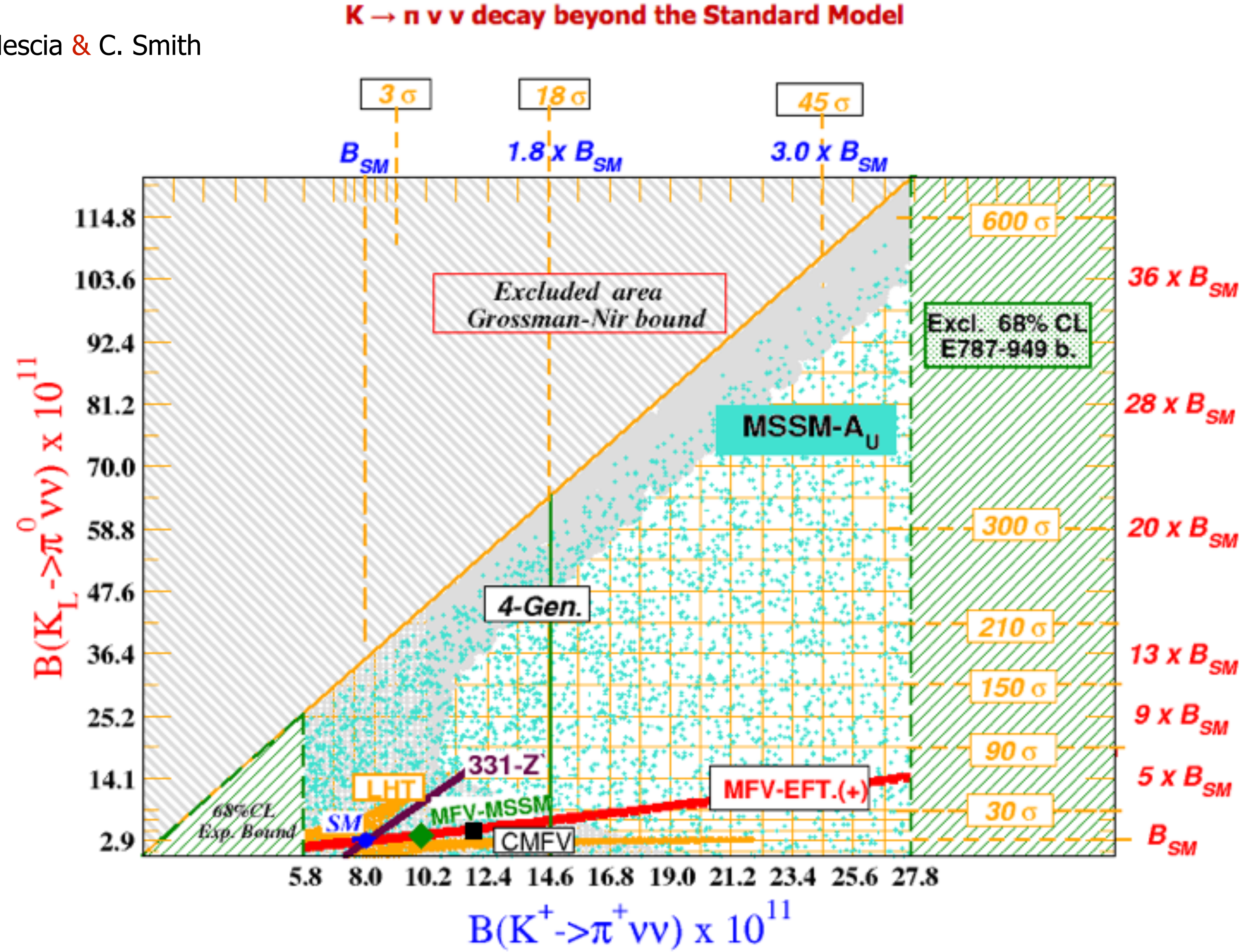
$$\mathrm{BR}(K^+ \to \pi^+ \nu \overline{\nu}) = \kappa_+ \left| \xi X - P_{(u,c)} \right|^2 , \quad \mathrm{BR}(K_L \to \pi^0 \nu \overline{\nu}) = \kappa_L \, \mathrm{Im}(\xi X)^2 ,$$

- beyond SM modifies the complex quantity X
- Im(X) ≤ |X| combined with known isospin corrections

$$\begin{aligned} \mathscr{B}(K_L \to \pi^0 \nu \bar{\nu}) \quad & \lesssim 4.3 \times \mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) \\ & < 1.4 \times 10^{-9}. \quad \text{(GN bound)} \end{aligned}$$

sample of recent models

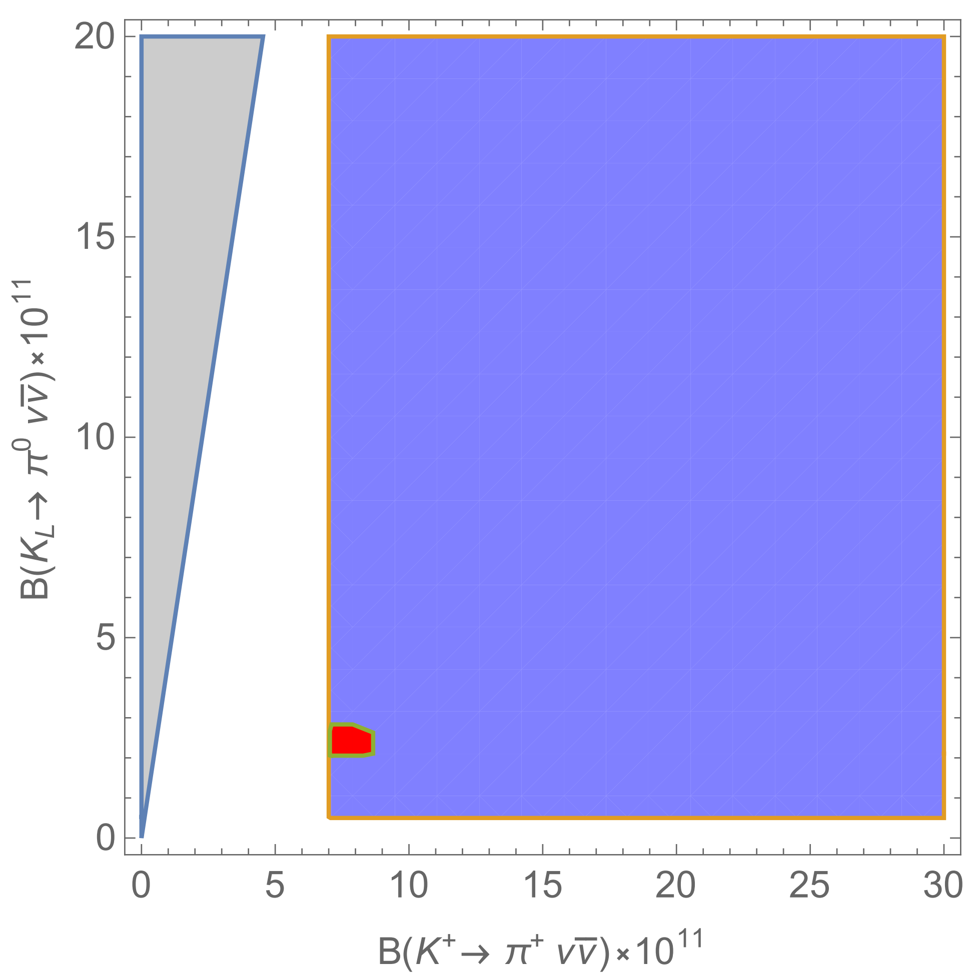
June 2010 by F. Mescia & C. Smith



the fourth generation

- perfect example of complementarity between flavour physics and LHC
- kaons constraining 4th generation parameters until 2012
- Higgs found in 2012: 4th generation ruled out

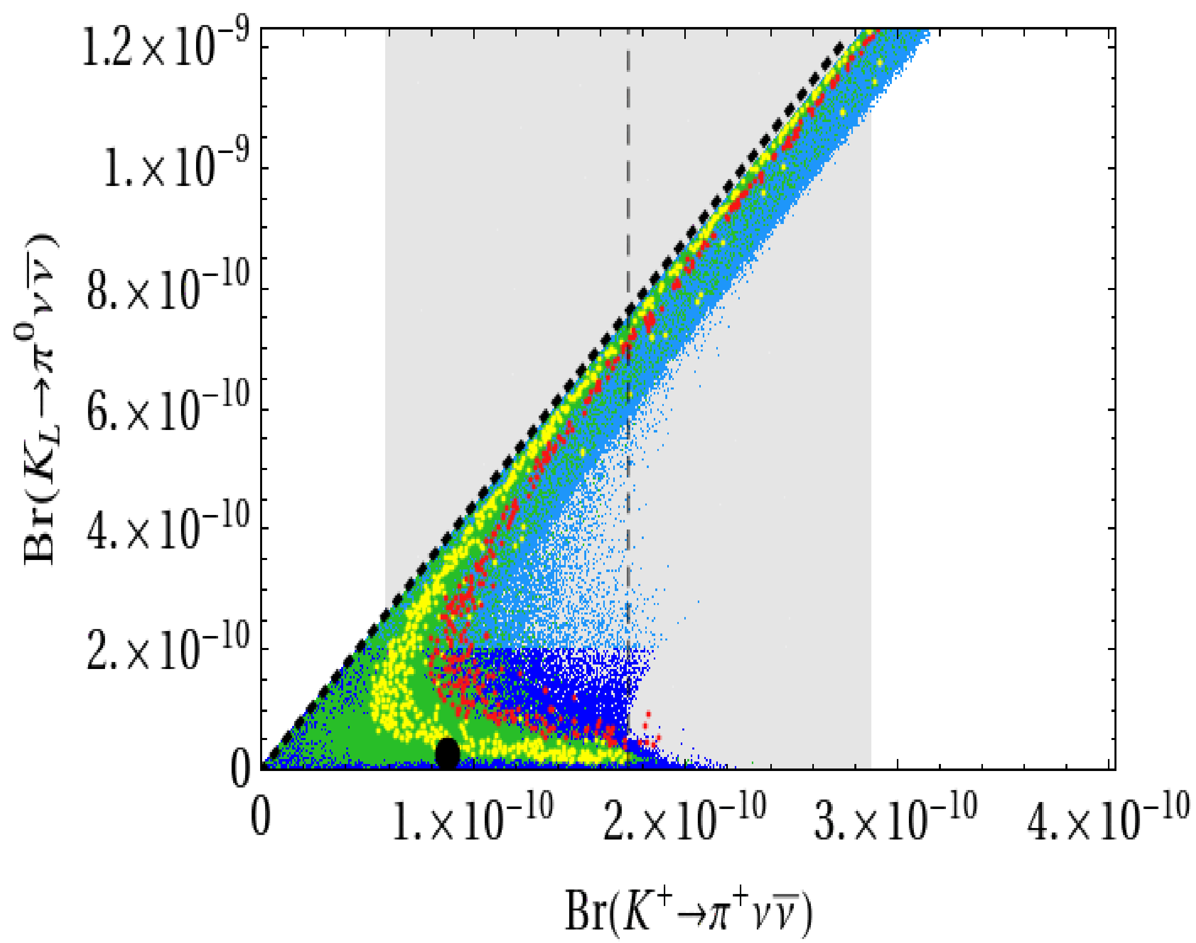
-ph/9804412
Toshihiko Hattori, Tsutom Hasuike , Seichi Wakaizumi



TILLMANN HEIDSIECK[1]

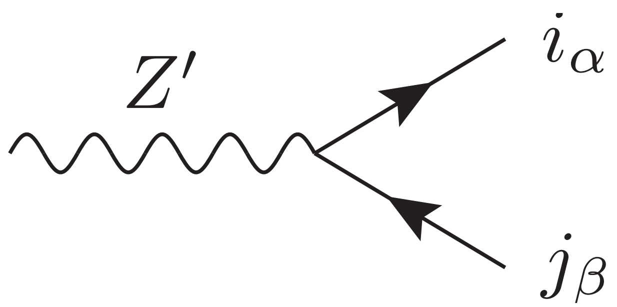
SM4 with 2010 global fit

$B(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$



Buras-MFV

- start with a Z′:



$$i\gamma_\mu \delta_{\alpha\beta}\left[\Delta_L^{ij}(Z')P_L + \Delta_R^{ij}(Z')P_R\right]$$

- write NP in terms of SM:

$$X(x_t) \to X(x_t)_{\rm SM} + \frac{\pi^2}{2M_W^2 G_{\rm F}^2}\frac{\Delta_L^{\nu\nu}(Z^{(\prime)})}{V_{ts}^* V_{td} M_Z^{(\prime)2}}\left[\Delta_L^{sd}(Z^{(\prime)}) + \Delta_R^{sd}(Z^{(\prime)})\right]$$

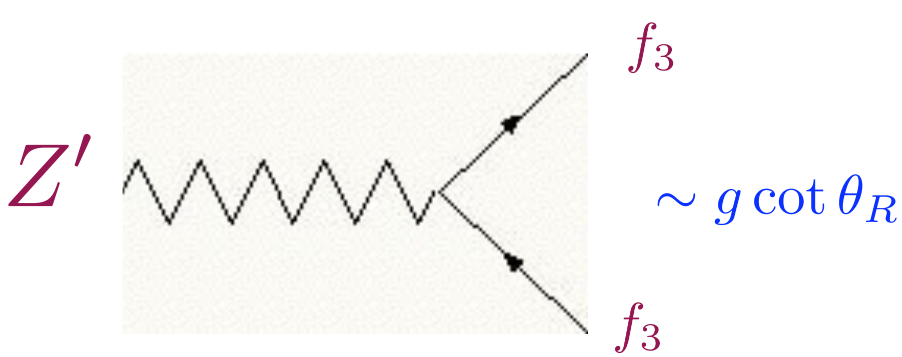
- define MFV as $\Delta_R^{sd}(Z') = 0, \;\; \Delta_L^{sd}(Z') = \left|\Delta_L^{sd}(Z')\right| e^{\phi_{\lambda_t}}$

- scan `reasonable' parameters

Non-universal Z´

- based on SU(3)xSU(2)$_L$xSU(2)$_R$xU(1)$_{B-L}$
- Single out the third generation
- generically this produces a pattern of couplings:

$$\tan\theta_R = \frac{g}{g_R}$$

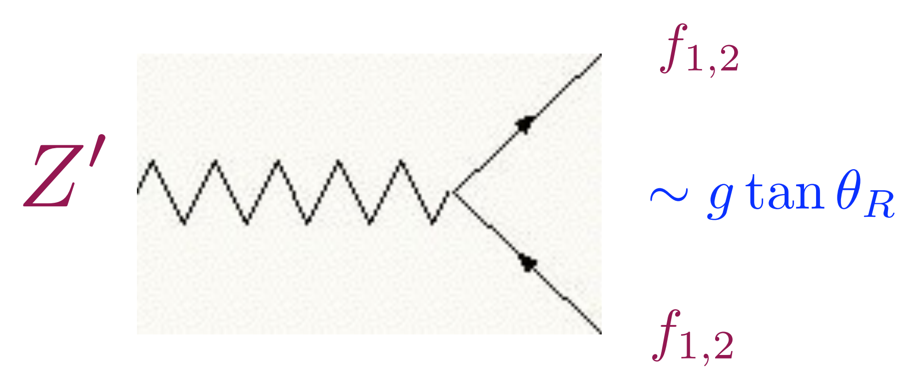


- From LEP and LEPII using R_b, A^b_{FB}, and $\sigma(e^+e^-\to\tau^+\tau^-)$:

$$\cot\theta_R\ \tan\theta_W\ \left(\frac{M_W}{M_{Z'}}\right) \leq 1$$

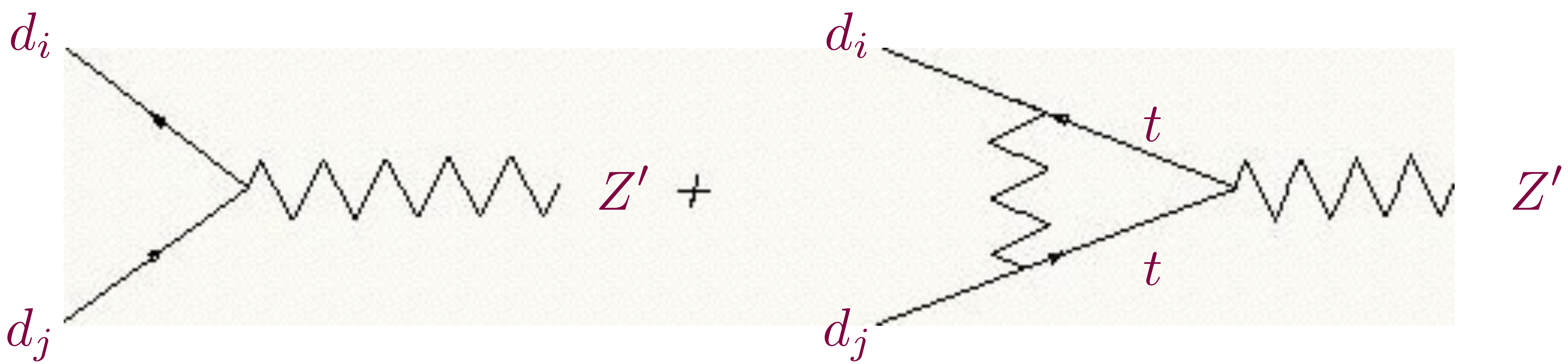
- For $\cot\theta_R \sim 10 \implies M_{Z'} > 450\ \text{GeV}$
- Perturbative unitarity

$$\cot\theta_R\ \leq 20$$



Z′ couplings and FCNC operators

Couplings enhanced by $\cot\theta_R$ $\quad \dfrac{g}{2\cos\theta_W}\bar{q}_i\gamma^\mu\left(a_{ij}P_L + b_{ij}P_R\right)q_j Z'_\mu$



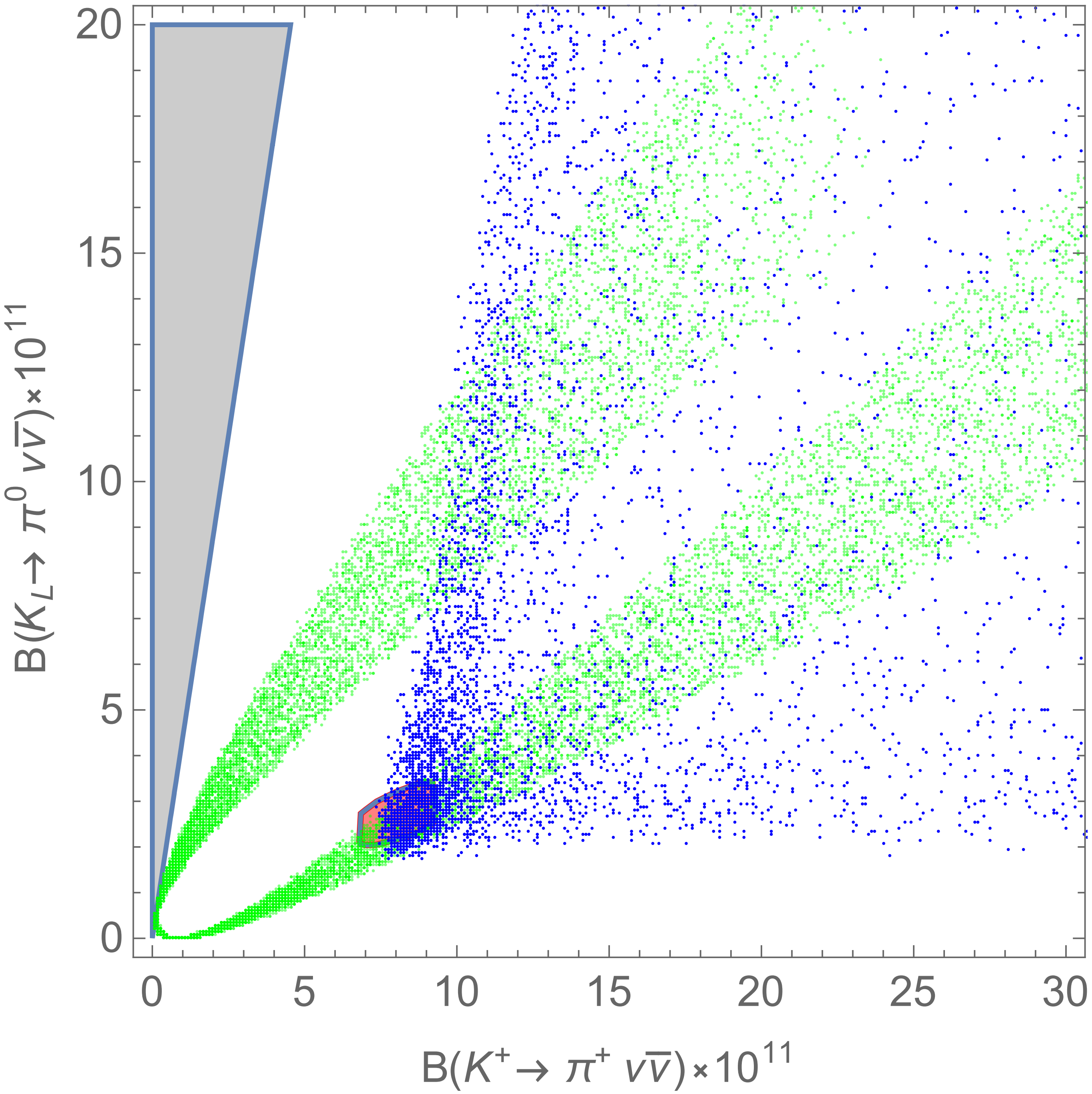
$$b_{ij} = \sin\theta_W \cot\theta_R \cos\xi_Z V^{D\star}_{Rbi} V^{D}_{Rbj} \qquad a_{ij} = \frac{\alpha}{2\pi\sin\theta_W} I(\lambda_t,\lambda_H)\cot\theta_R V^\star_{ti}V_{tj}$$

$$\xi_Z = 0 \qquad (\text{ no mixing}) \qquad 5.5 \le I(\lambda_t,\lambda_H)\left|\frac{V^\star_{tb}V_{ts}}{0.04}\right| \le 6.5 \qquad (\Delta M_{B_s})$$

- W-W′ and Z-Z′ mixing near zero from b $\rightarrow$ s γ and Z $\rightarrow \tau^+\tau^-$

Z′ coupling to tau-neutrino is enhanced, and it is right-handed

An example Z′



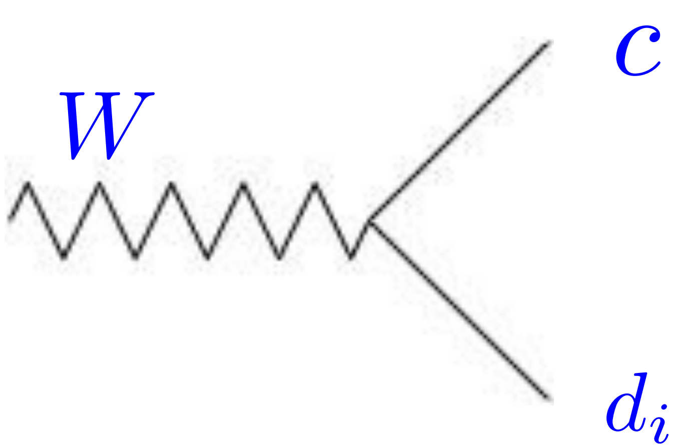
SM : 2 sigma parameter scan

Z′ MFV Buras group

Z′ Non-universal (RH): He, GV

$$B\left(K^+ \to \pi^+\nu\bar{\nu}(\gamma)\right) = \kappa_+(1+\Delta_{\rm EM})\left[\left(\frac{{\rm Im}(V_{ts}^\star V_{td})}{\lambda^5}X_t\right)^2 + \left(\frac{{\rm Re}(V_{cs}^\star V_{cd})}{\lambda}(P_c+\delta P_{c,u}) + \frac{{\rm Re}(V_{ts}^\star V_{td})}{\lambda^5}X_t\right)^2\right].$$

New Physics in charm?



$$-\frac{g}{\sqrt{2}} V_{ci}\gamma^{\mu}\left((1+\kappa_{ci}^{L})P_L + \kappa_{ci}^{R} P_R\right)$$

$$+ \frac{\mathrm{Re}(V_{cs}^{\star}V_{cd})}{\lambda} X'(x_c)\mathrm{Im}(\kappa_{cd}^{L} + \kappa_{cs}^{\star L})$$

$$\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu}(\gamma)) = \kappa_+ (1+\Delta_{\mathrm{EM}}) \left[\left(\frac{\mathrm{Im}\,(V_{ts}^{\star}V_{td})}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}(V_{cs}^{\star}V_{cd})}{\lambda} X'(x_c)|\kappa_{cd}^{R}\kappa_{cs}^{\star R}| \right)^2 \right.$$

$$\left. + \left(\frac{\mathrm{Re}\,(V_{cs}^{\star}V_{cd})}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\,(V_{ts}^{\star}V_{td})}{\lambda^5} X_t \right)^2 \right]. \quad (1)$$

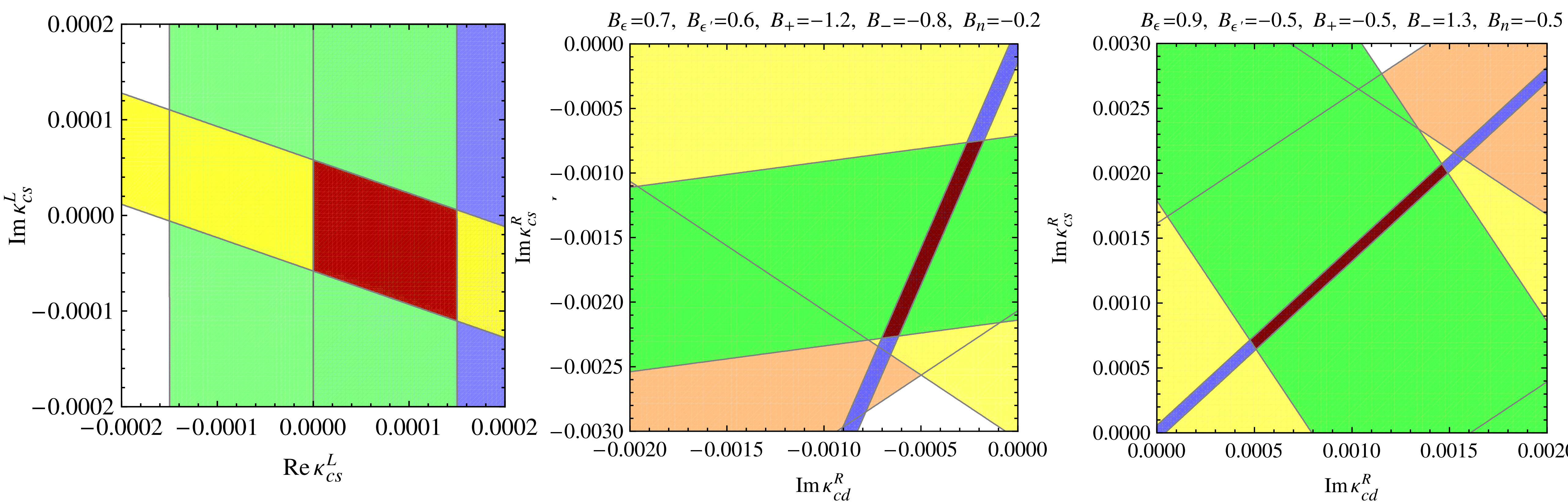
$$P_c \to P_c + (\kappa_{cd}^{L} + \kappa_{cs}^{\star L}) X'(x_c)$$

$$\mathrm{B}\,(K_L \to \pi^0\nu\overline{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,(V_{ts}^{\star}V_{td})}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}(V_{cs}^{\star}V_{cd})}{\lambda} X'(x_c)\mathrm{Im}(\kappa_{cd}^{R}\kappa_{cs}^{\star R}) \right)^2$$

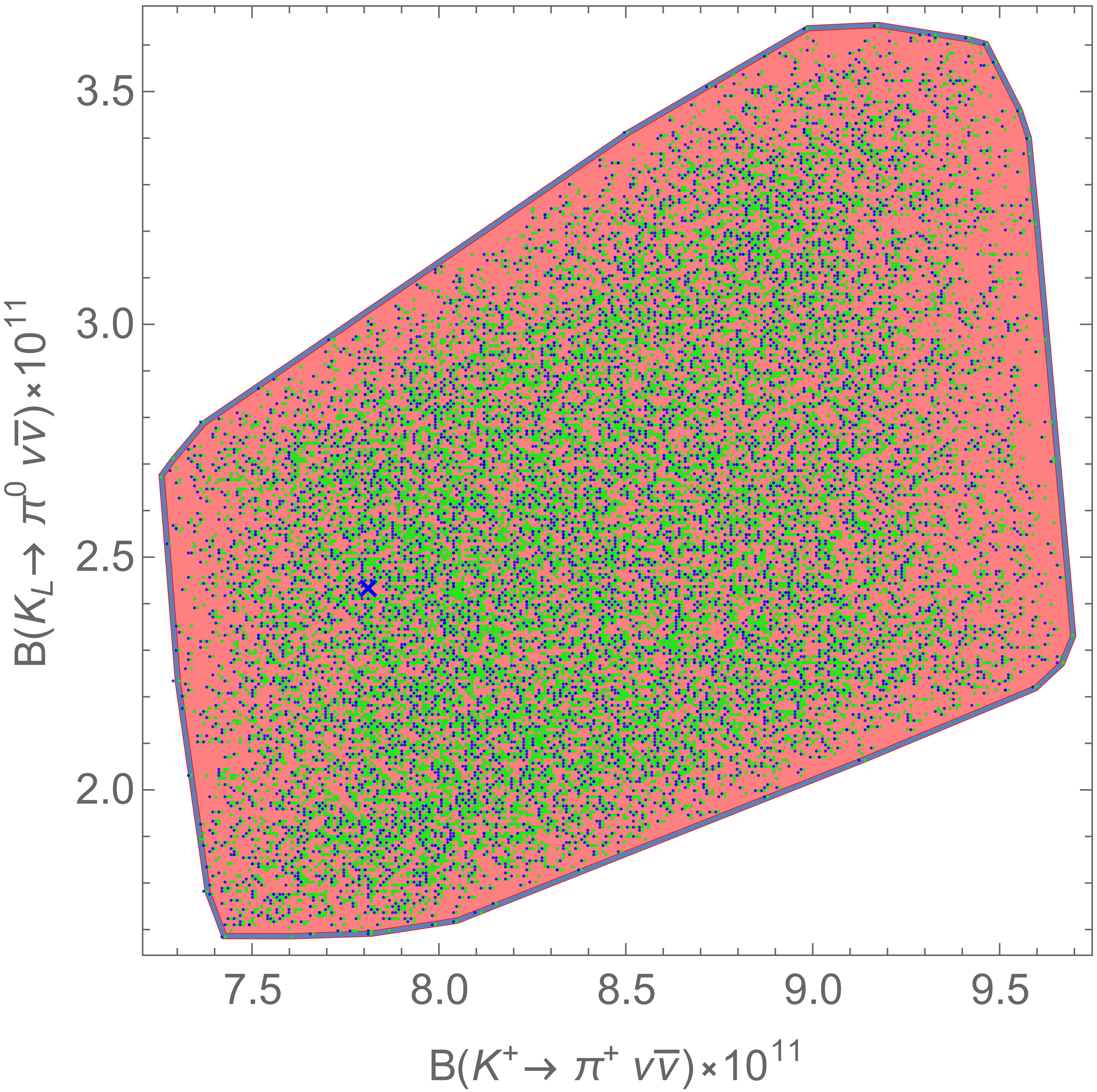
$$+ \frac{\mathrm{Re}(V_{cs}^{\star}V_{cd})}{\lambda} X'(x_c)\mathrm{Im}(\kappa_{cd}^{L} + \kappa_{cs}^{\star L})$$

menu of constraints

Process	Eq.	Constraint	#
$D \to \ell\nu$	(14)	$\lvert\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} - \kappa^{\mathrm{R}}_{cd})\rvert \le 0.04$	1
$D_s \to \ell\nu$	(15)	$0 \le \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{R}}_{cs}) \le 0.1$	2
$b \to c\ell\bar{\nu}$	(22)	$-0.13 \le \mathrm{Re}\,\kappa^{\mathrm{R}}_{cb} \le 0$	3
$B \to J/\psi K,\ \eta_c K$	(31)	$-5 \times 10^{-4} \le \mathrm{Im}(\kappa^{\mathrm{R}}_{cb} + \kappa^{\mathrm{R}}_{cs}) \le 0.04$	4
$K^+ \to \pi^+ \nu\bar{\nu}$	(58)	$-1.3 \times 10^{-3} \le \mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) + 0.42\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \le 2.5 \times 10^{-4}$	5
$K_L \to \mu^+\mu^-$	(63)	$\lvert\mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 6 \times 10^{-4}\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs}\rvert \le 1.5 \times 10^{-4}$	6
ΔM_K	(67)	$\lvert 0.043\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) - 0.015\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} - \mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) + 0.28\,\mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs})\rvert \le 8.5 \times 10^{-4}$	7
ϵ (mixing)	(69)	$\lvert 0.015\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 0.043\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} - 0.28\,\mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) - \mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs})\rvert \le 2.5 \times 10^{-6}$	8
ΔM_d	(73)	$-0.031 \le \mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) + 0.4\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cb} \le 0.003$	9
$\sin(2\beta)$ (mixing)	(77)	$-1.5 \times 10^{-3} \le 0.4\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) - 0.69\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cb} - 0.31\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \le 0.012$	10
ΔM_s	(81)	$-0.014 \le \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cb}) + 0.018\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{L}}_{cb}) \le 0.015$	11
$\sin(2\beta_s)$ (mixing)	(85)	$-0.09 \le 0.026\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cs}) + \mathrm{Im}(\kappa^{\mathrm{L}}_{cb} - \kappa^{\mathrm{L}}_{cs}) \le 7 \times 10^{-4}$	12



New physics in charm?



× SM central values from Brod et.al

SM : 2 sigma parameter scan

modified charm RH couplings

modified charm LH couplings

at the moment overlaps with SM within uncertainty

a loophole in GN?- George Hou

Kaori Fuyuto, Wei-Shu Hou, Masaya Kohda.
Phys.Rev.Lett. 114 (2015) 171802

- the PDB mini-review is `more or less the same' every 2 years…
- simple enough to a theorist: the K^+ experiments cut a section of the kinematic region that the K_L experiments do not. If NP falls in that gap, the GN bound doesn't apply…
- Laurie not satisfied… very long discussion on different acceptance for 2 body mode vs 3 body mode in the two experiments (that's where I can contribute 😉 to the collaboration… 😀)
- short story: it took a month to produce the sentence:

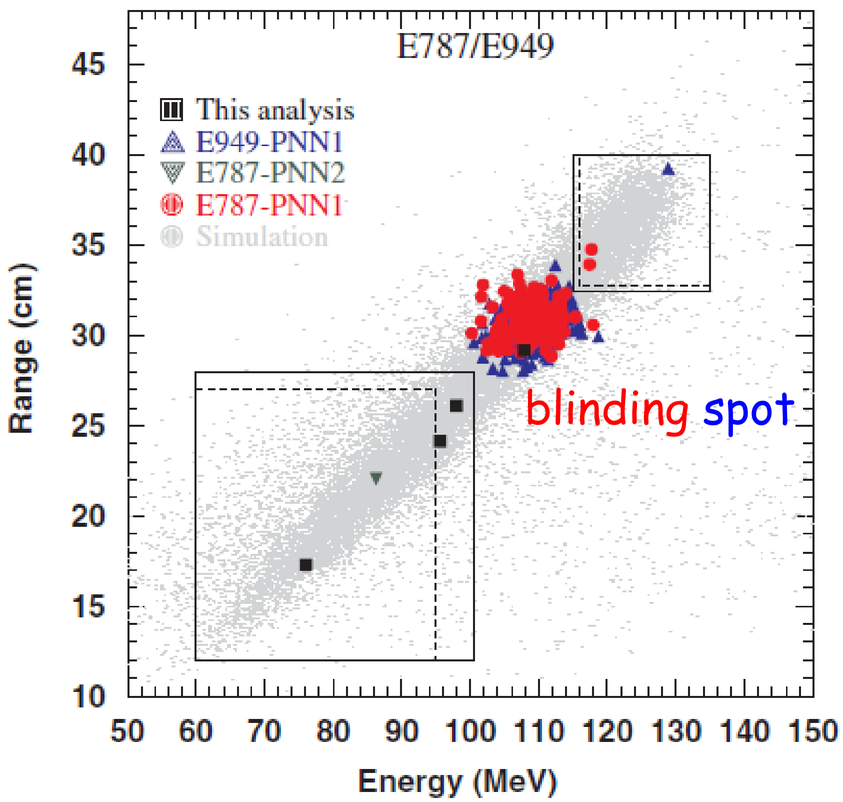
It was pointed out in a recent paper that there is a kinematic gap in the Grossman-Nir bound that makes the $K_L \to \pi^0 \nu \overline{\nu}$ mode interesting for new physics searches at the current sensitivity level

a loophole in GN?– George Hou

Bound on $K \to \pi X^0$

BV. The E949 limit of $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 2.7 \times 10^{-7}$ at 90% C.L. [60] can be combined with the world average value of $\mathcal{B}(K^+ \to \pi^+\pi^0)$ [24] to set a 90% C.L. limit of $\mathcal{B}(K^+ \to \pi^+ X) < 5.6 \times 10^{-8}$ for $M_X = M_{\pi^0}$ with X stable

PHYSICAL REVIEW D **79**, 092004 (2009)



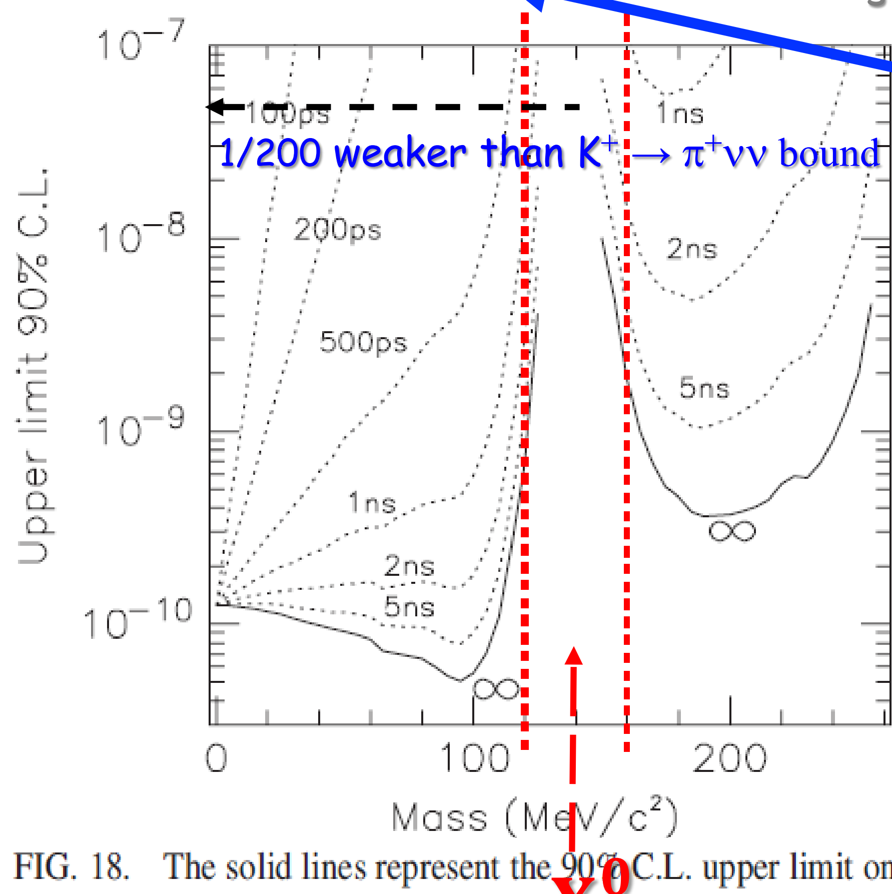


FIG. 18. The solid lines represent the 90% C.L. upper limit on $\mathcal{B}(K^+ \to \pi^+ X)$ as a function of the mass of X assuming X is

very useful too!
now dark γ or Z

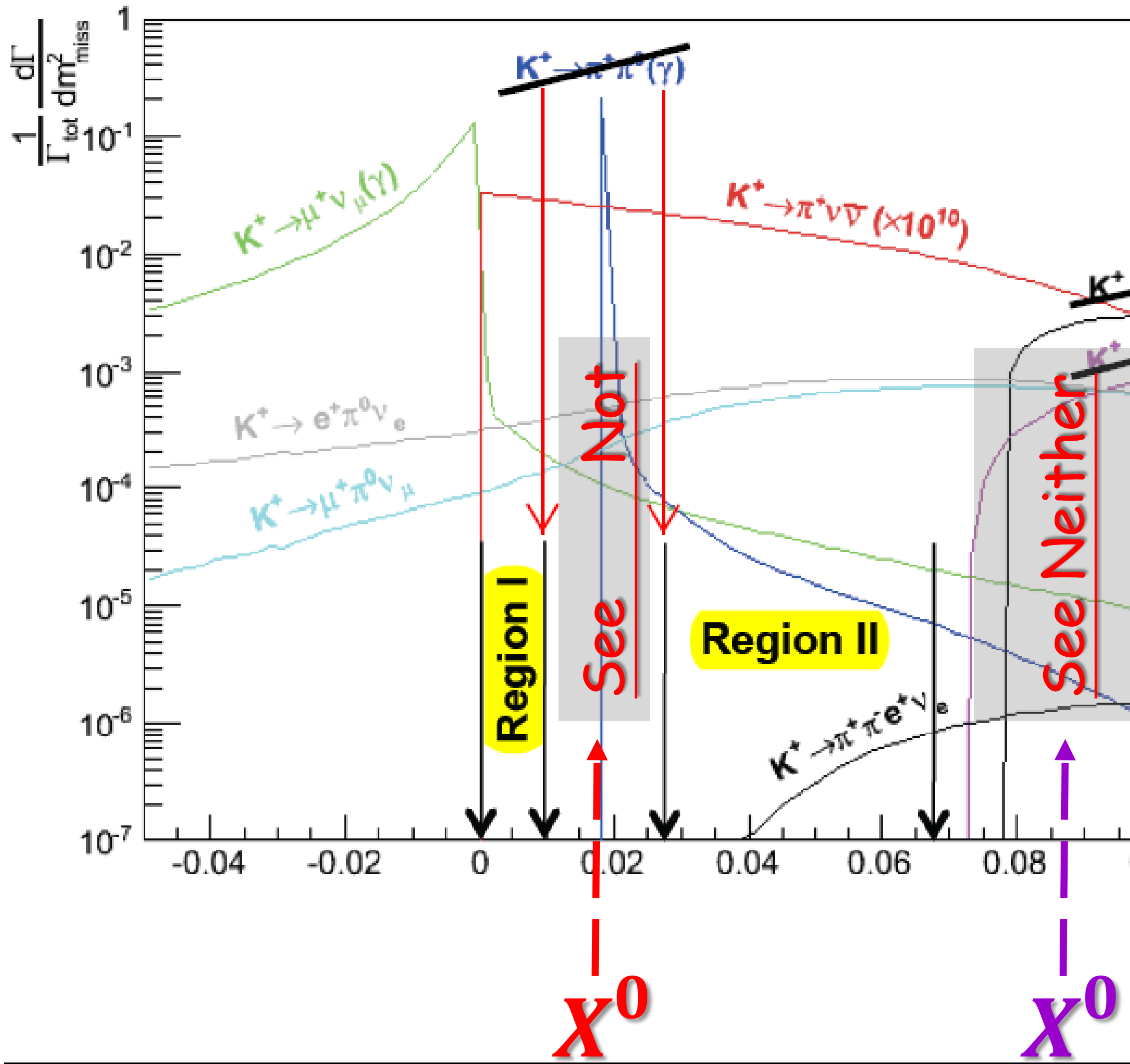
more on the loophole– George Hou

$K^+ \to \pi^+$ "π^0" Loophole vs $K_L \to \pi^0 X^0$

NA62 @ CERN

Window basically Same as E787/949 @ BNL

Kinematic exclusion:
exclude 0.01 - 0.025 GeV^2 [(100)^2 - (160)^2 MeV^2]



The KOTO Expt at J-PARC can discover $K_L \to \pi^0 X^0$ above the Grossman-Nir Bound !

$$\mathcal{B}(K_L \to \pi^0 \nu\bar\nu) \lesssim 4.3 \times \mathcal{B}(K^+ \to \pi^+ \nu\bar\nu)$$
$$\lesssim 1.4 \times 10^{-9}, \quad \text{(GN bound)}$$

"Blind man Blessed by Senses."

A Surprise! "Trivial"

A $K_L \to \pi^0\nu\bar\nu$ experiment, however, cannot do kinematic reconstruction: besides detecting two photons (assumed as π^0), it measures "nothing to nothing". The K_L and "π^0" momenta are not known. The approach is thus to veto everything and to learn while pushing down the sensitivity. However, the $\nu\bar\nu$ being the target, one cannot veto weakly interacting light particles (WILP). Thus, for $K \to \pi X^0$ where X^0 is *any* WILP that falls into the missing mass window, the K^+ experiment would be oblivious, *but the K_L experiment can have a blunt feel!* Although the GN relation of Eq. (4) is in no way violated, ~~the perceived GN bound of Eq. (2)~~ does not apply. This is the main and rather simple point of this Letter, independent of model discussion. The X^0 need not be the leptonic force, as it simply goes undetected. Fuyoto, WSH, Kohda

Our other collaboration

- a piggyback on Laurie's mode (add a pion)

Phys.Lett. B385 (1996) 379-384

Abstract

We study the reactions $K \to \pi\pi\nu\overline{\nu}$ within the minimal standard model. We use isospin symmetry to relate the matrix elements to the form factors measured in $K_{\ell 4}$. We argue that these modes are short distance dominated and can be used for precise determinations of the CKM parameters ρ and η. Depending on the value of the CKM angles we find branching ratios in the following ranges: $B(K_L \to \pi^+\pi^-\nu\overline{\nu}) = [2\text{–}5] \times 10^{-13}$; $B(K_L \to \pi^0\pi^0\nu\overline{\nu}) = [1\text{–}3] \times 10^{-13}$; $B(K^+ \to \pi^+\pi^0\nu\overline{\nu}) = [1\text{–}2] \times 10^{-14}$. We also discuss a possible CP-odd observable.

Phys.Rev. D84 (2011) 052009

The rare decay $K_L^0 \to \pi^0\pi^0\nu\bar{\nu}$ was studied with the E391a detector at the KEK 12-GeV proton synchrotron. Based on 9.4×10^9 K_L^0 decays, an upper limit of 8.1×10^{-7} was obtained for the branching fraction at 90% confidence level. We also set a limit on the $K_L^0 \to \pi^0\pi^0 X$ ($X \to$ invisible particles) process; the limit on the branching fraction varied from 7.0×10^{-7} to 4.0×10^{-5} for the mass of X ranging from 50 MeV/c^2 to 200 MeV/c^2.

conclusion

- Laurie's contributions to rare kaon decays have been improving our knowledge of SM parameters and `ruling out' new physics for more than 25 years
  - really, pushing them into smaller and smaller regions of allowed parameter space
- We expect them to continue doing so for many years to come