, Nagoya 26th May 201

Rare kaon decay : challenges and perspectives

Giancarlo D'Ambrosio

(CERN and INFN-Napoli)

Thanks

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Plan of the talk

- K->pi nu nu
- K->pi ll
- K-> pi gamma gamma
- Ks-> mu mu
- K->pi pi ll

Calculation of Wilson coefficient in OPE expansion (QCD corrections)

Progress of Theoretical Physics, Vol. 65, No. 1, January 1981

Effects of Superheavy Quarks and Leptons in Low-Energy Weak Processes $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^0 \leftrightarrow \bar{K}^0$

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(Received October 13, 1980)

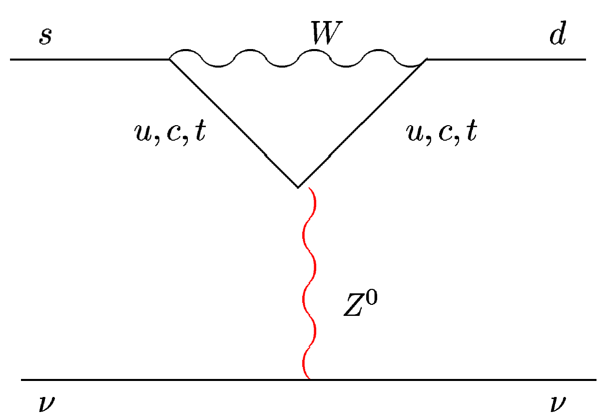
We investigate potentially important effects due to the existence of superheavy quarks and leptons of the sequential type in higher-order weak processes at low energies. The second-order $\Delta S \neq 0$ neutral-current processes $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^+ \nu\bar{\nu}$ and K_L-K_S mass difference are analysed allowing for fermions of masses comparable to or larger than the weak-boson mass in the Kobayashi-Maskawa scheme and in the general sequential scheme with an arbitrary number of generations. Possible connection between heavy-quark masses and light-heavy quark mixing are also examined. The requirement that the rare decay processes such as $K_L \to \mu\bar{\mu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ be absent up to order αG_F yields a rather stringent bound on the magnitude of light-heavy quark mixing: Such mixing has to be less than m_W/m_{Quark} times a factor much smaller than unity.

Buchalla Buras, Buras et al , Fleisher

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

Why we need to the experiments KOTO and NA62

$$A(s \to d\nu\overline{\nu})_{\text{SM}} \sim \overline{s}_L\gamma_\mu d_L \quad \overline{\nu}_L\gamma^\mu\nu_L \times \left[\sum_{q=c,t} V^*_{qs}V_{qd}\, m_q^2\right]$$



$$\sim \quad \left[A^2\lambda^5\ (1-\rho-i\eta)m_t^2 + \lambda m_c^2\right]$$

SM $\underbrace{V-A \otimes V-A}$ Littenberg

$\Downarrow$

$$\Gamma(K_L \to \pi^0\nu\overline{\nu}) \quad \begin{cases} \text{CP violating} \\ \Rightarrow\ J = A^2\lambda^6\eta \\ \text{Only } top \end{cases}$$

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

Brod,CKM2010, Straub, Gorbhan

Buras et al
1503.02693

$$B(K^+) \sim \kappa_+ \left[\left(\frac{\mathrm{Im}\lambda_\mathrm{t}}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_\mathrm{c}}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\lambda_\mathrm{t}}{\lambda^5} X_t \right)^2 \right]$$

- κ_+ from K_{l3}
- P_c: SD charm quark contribution (30%±2.5% to BR)
  LD $\delta P_{c,u} \sim 4 \pm 2\%$
- $B(K^\pm) = (8.22 \pm 0.27 \pm 0.29) \times 10^{-11}$ first error parametric (V_{cb}), second non-pert. QCD
- E949 $B(K^\pm) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

K_L

$B(K_L) = (2.43 \pm 0.25 \pm 0.06) \times 10^{-11}$ vs

E391a $B(K_L) < 2.6 \times 10^{-8}$ at 90% C.L.

K_L Model-independent bound, based on $SU(2)$ properties dim-6 operators for $\bar{s}d\bar{\nu}\nu$ Grossman-Nir

$$B(K_L) \leq \frac{\tau_L}{\tau_+} \times B(K^{\pm})_{\rm E949} \leq 1.4 \times 10^{-9} \quad \text{at } 90\% C.L.$$

Loophole Fuyuto et al

Generic Flavor structures strongly constrained

Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert_D$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d \to \psi K$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s \to \psi \phi$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

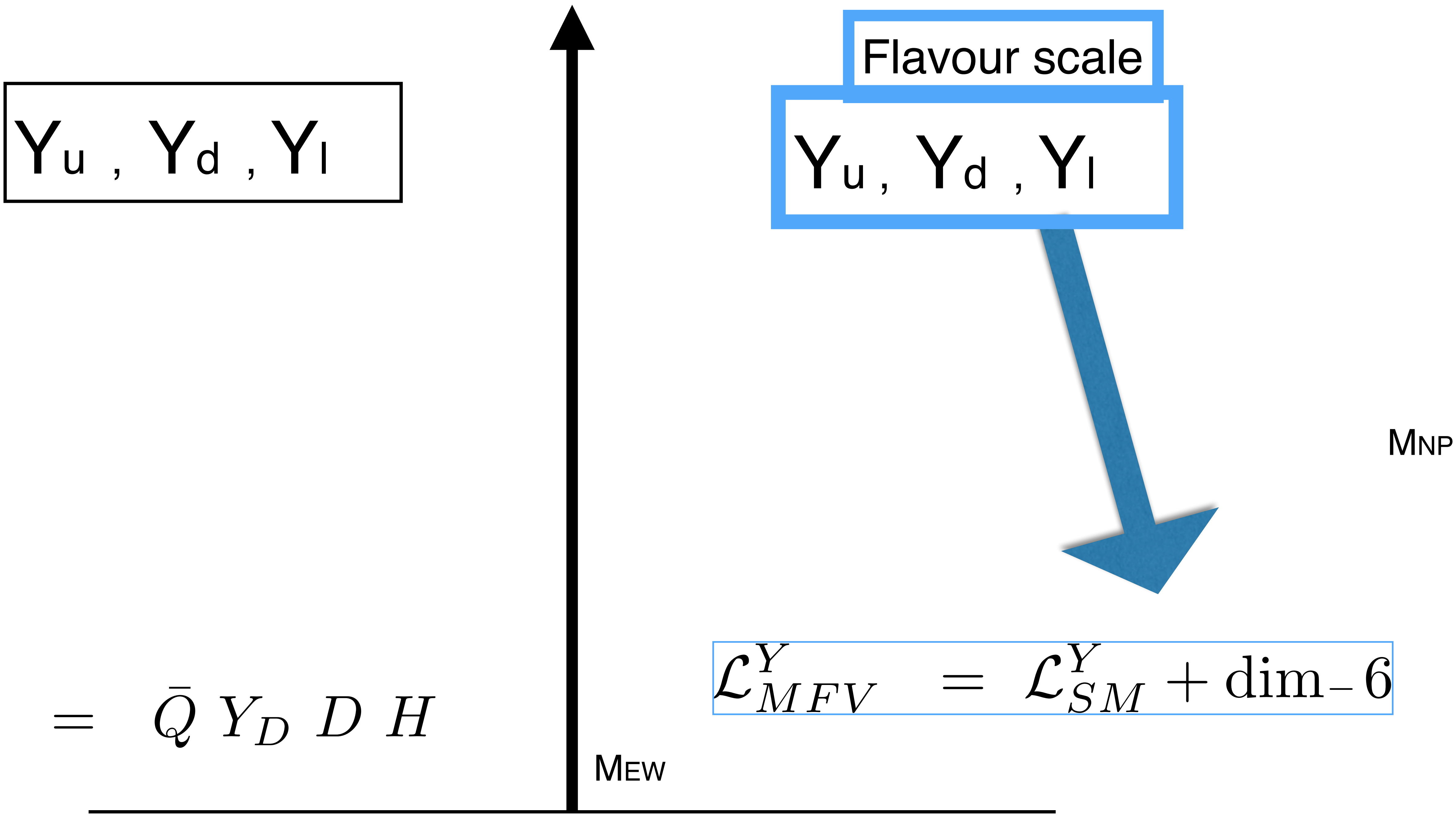
Isidori Nir Perez 10

Problem already known since ’86 technicolour (Chivukula Georgi) susy (Hall Randall) extra dimensions (Rattazzi Zafferoni)

Maybe there is an energy gap between the theory of flavor and the EW scale , ameliorating also a clash from the scale of the bounds in the table above and the requirement of solving the hierarchy problem

SM

MFV



$$\mathcal{L}^{Y}_{SM} \;=\; \bar{Q}\; Y_D\; D\; H$$

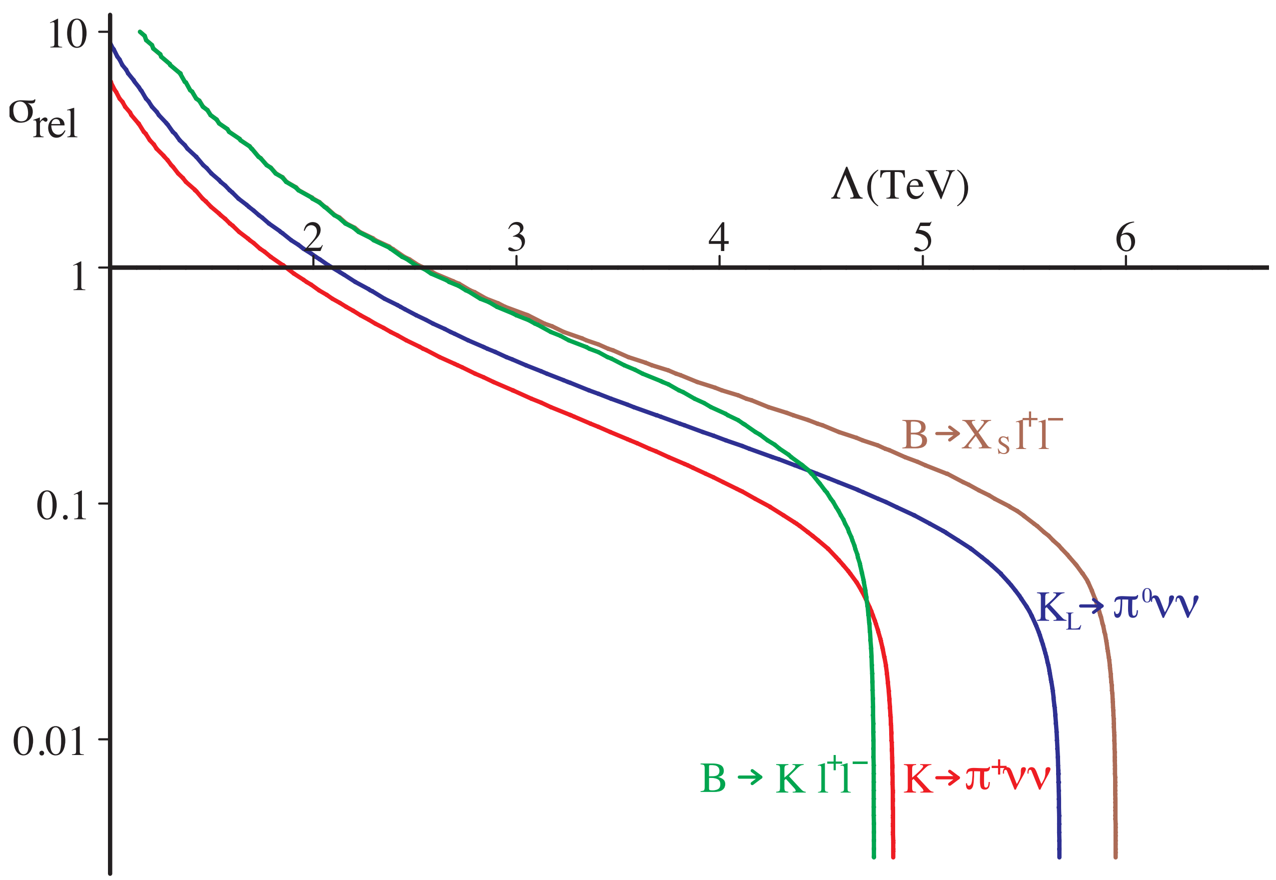
$$\mathcal{L}^{Y}_{MFV} \;=\; \mathcal{L}^{Y}_{SM} + \mathrm{dim}_{-}6$$

$$G_F = \overbrace{\mathrm{U}(3)_Q \otimes \mathrm{U}(3)_U \otimes \mathrm{U}(3)_D \otimes \mathrm{U}(3)_L \otimes \mathrm{U}(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

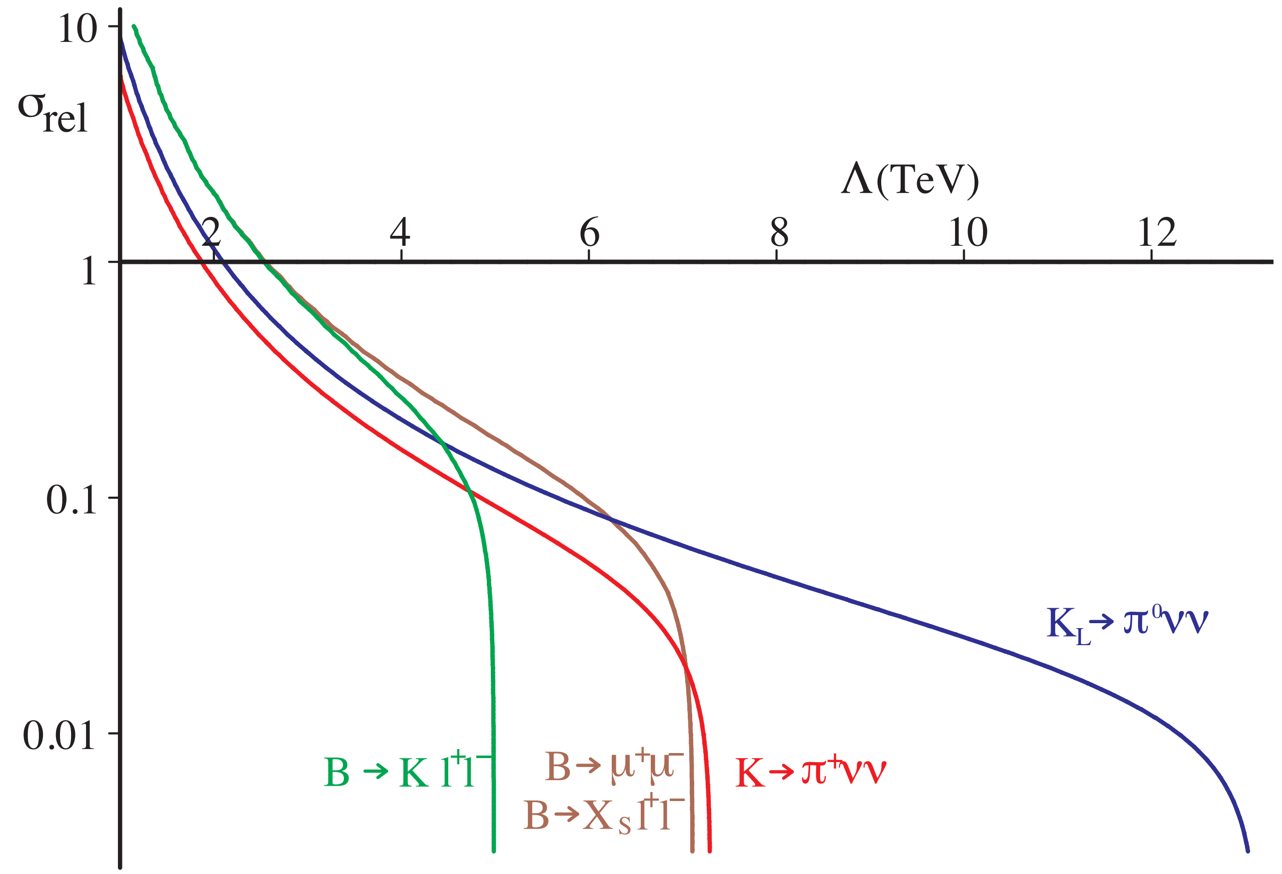
Bounds ameliorated

Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	+	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	8.3	13.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.3	3.8	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1		

GD,Giudice,Isidori,Strumia

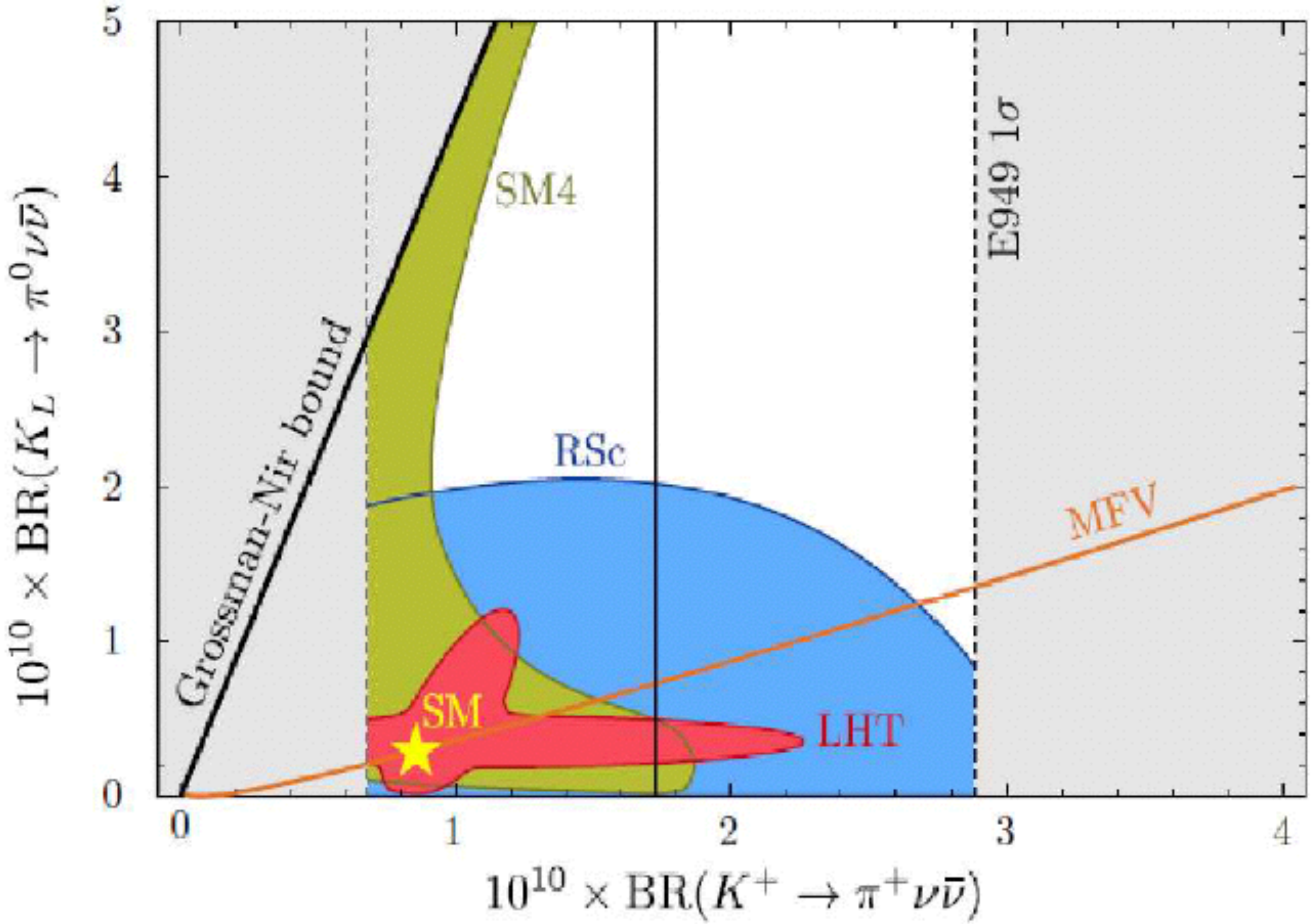


10% Overall CKM error



1% Overall CKM error

NA62 , KOTO



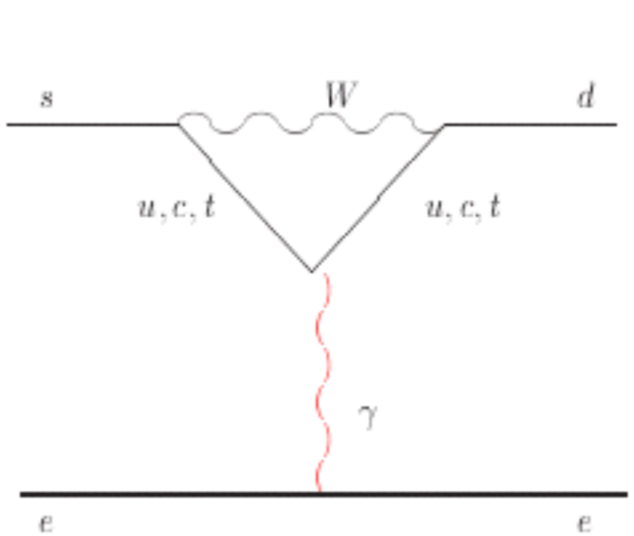
Also Z' Buras et al,
Kneeglens Moriond 2015
Yamamoto et al 2015
and M.Blanke rev

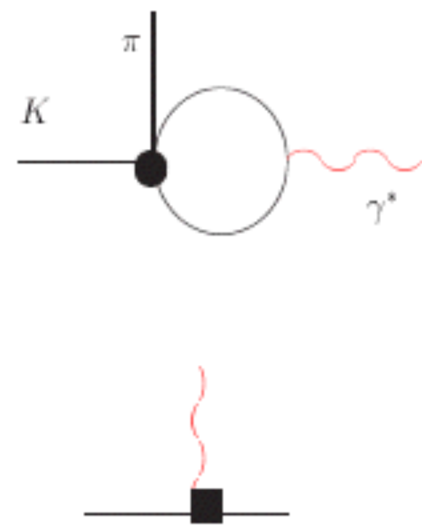
Straub, CKM 2010 workshop (arXiv:1012.3893v2)

$K^{\pm}(K_S) \to \pi^{\pm}(\pi^0)\ell^+\ell^-$

- short distance $<<$ long distance

LD described by form factor W





$$W^i = G_F m_K^2 (a_i + b_i z) + W^i_{\pi\pi}(z)$$

$$i = \pm, S$$

$$a_i, b_i \sim O(1), \qquad z = \frac{q^2}{m_K^2}$$

- Observables $\Gamma(K^+ \to \pi^+ e^+ e^-)$, $\Gamma(K^+ \to \pi^+ \mu\overline{\mu})$, slopes
- $a_i \quad O(p^4) \qquad a_+ \sim N_{14} - N_{15}, \qquad a_S \sim 2N_{14} + N_{15}$ Ecker, Pich, de Rafael
- $b_i \quad O(p^6)$ G.D., Ecker, Isidori, Portoles
- $a_+,\ b_+$ in general not related to $a_S,\ b_S$

- Expt. E865
  $K^+ \to \pi^+ e^+ e^- : \quad a_+ = -0.586 \pm 0.010 \quad b_+ = -0.655 \pm 0.044$

  confirmed by NA48/2 (1.4 σ's away) also in $K^+ \to \pi^+ \mu\overline{\mu}$

- HyperCP has confirmed E865 (02) ($K^+ \to \pi^+ \mu\overline{\mu}$) and put a bound on the CP asymmetry (≤ 0.1)

Problems: $\begin{array}{ccc} a_i & b_i & \text{same phenomenological size} \\ p^4 & p^6 & \text{different theoretical order} \end{array}$

Probably explained by large VMD. Then we can just parameterize

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-) = 4.6 \times 10^{-9} a_S^2$$

$K_S \to \pi^0 l^+ l^-$ at NA48/1 Collaboration at CERN

- $K_S \to \pi^0 e^+ e^-$ 7 evts observed (with 0.15 expected bkg evts)

$$B(K_S \to \pi^0 e^+ e^-)_{m_{ee}>165 \text{ MeV}} = \left(3.0^{+1.5}_{-1.2} \pm 0.2\right) \times 10^{-9}$$

$$|a_S| = 1.08^{+0.26}_{-0.21}$$

- $K_S \to \pi^0 \mu^+ \mu^-$ 6 events observed

$$B(K_S \to \pi^0 \mu^+ \mu^-) = \left(2.9^{+1.5}_{-1.2} \pm 0.2\right) \times 10^{-9}$$

$$|a_S|_{\mu\mu} = 1.54^{+0.40}_{-0.32} \pm 0.06$$

$$K_L(p) \to \pi^0(p_3)\gamma(q_1)\gamma(q_2)$$

Lorentz + gauge invariance $\Rightarrow$ $M \sim$ $A(y,z)$ $B(y,z)$

	$A(y,z)$	$B(y,z)$
	$\gamma\gamma$	$\gamma\gamma$
	$J=0$	D − wave too
	$F^{\mu\nu}F_{\mu\nu}$	$F^{\mu\nu}F_{\mu\lambda}\partial_\nu K_L \partial^\lambda \pi^0$

$y = p\cdot(q_1-q_2)/m_K^2$, $z = (q_1+q_2)^2/m_K^2$

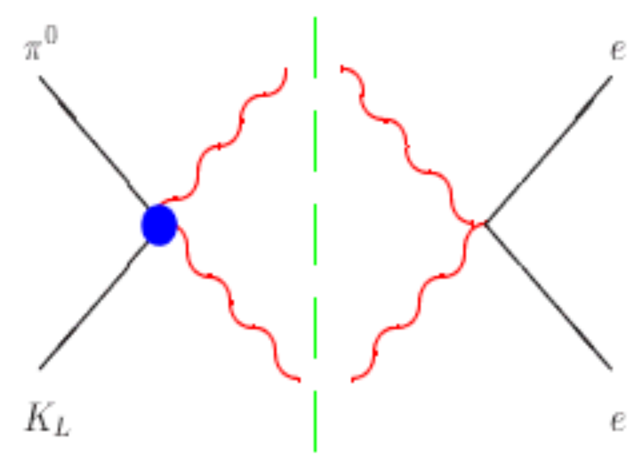
$r_\pi = m_\pi/m_K$

- $\frac{d^2\Gamma}{dydz} \sim z^2|A+B|^2 + \left(y^2 - \left(\frac{(1+r_\pi^2-z)^2}{4} - r_\pi^2\right)\right)^2 |B|^2$ S, B
- Different gauge structure $\Rightarrow$ B≠0 at $z \to 0$ (collinear photons).

Crucial role in $K_L \to \pi^0 e^+ e^-$

A suppressed by m_e/m_K

B is not



Morozumi et al, Flynn Randall

Sehgal Heiliger, Ecker et al., Donoghue et al.

KTeV and NA48 not only ϵ'

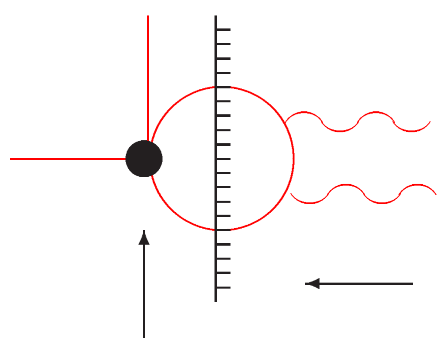
Actually the study of unit. cut was crucial to i) to bring agreement expt vs Theory in $K_L \to \pi^0\gamma\gamma$ and ii) show that $K_L \to \pi^0 ee$ CP conserving was negligible

3 CT's

$F_{\mu\nu}F^{\mu\alpha}\partial_\alpha K_L \partial^\nu \pi^0$

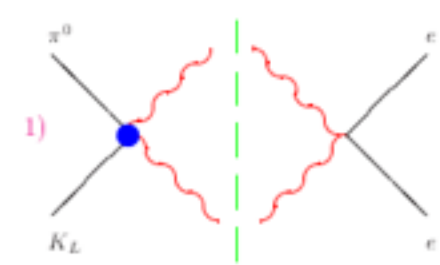
$F^2 \; \partial K_L \partial \pi^0$

$F^2 \; m_K^2 K_L \pi^0$



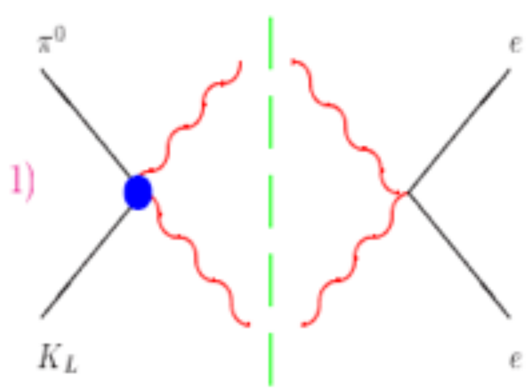
Full description of unitarity cut

$A(K \to 3\pi) = a + b\,Y + c\,Y^2 + d\,X^2$



$K_L \to \pi^0 e^+ e^-$: summary

$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10}$ at 90% CL KTeV

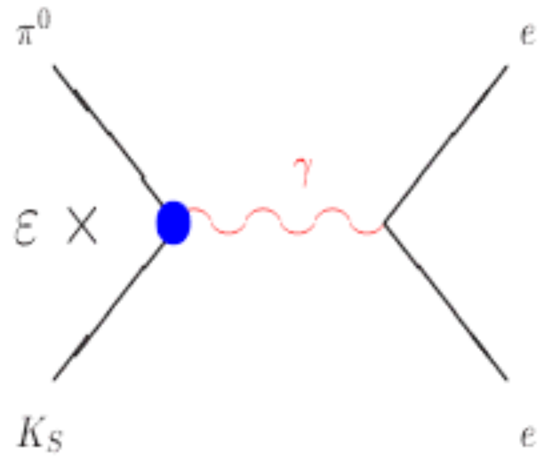


CP conserving NA48

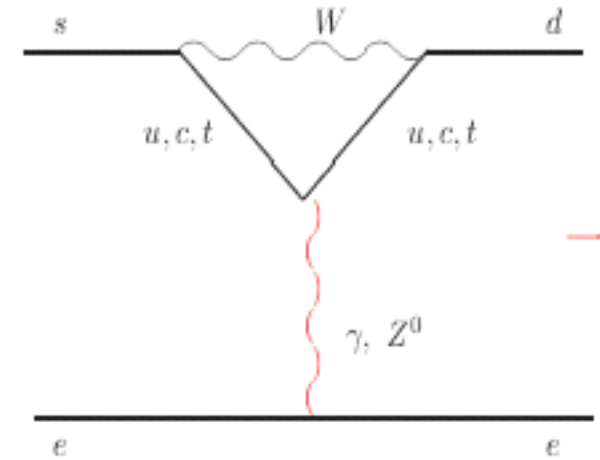
$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$

V-A$\otimes$ V-A $\Rightarrow \langle \pi^0 e^+ e^- | (\bar{s} d)_{V-A} (\bar{e} e)_{V-A} | K_L \rangle$ violates CP

2) ε ×



+ 3)



$\longrightarrow$ Im λ_t

$\lambda_t = V_{td}V_{ts}^*$

$\uparrow$ $\mathrm{B}(K_s \to \pi^0 e^+ e^-) = 4.6 a_S^2 \times 10^{-9}$

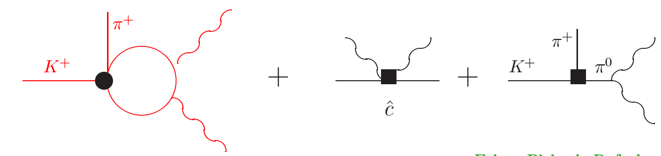
Possible large interference: $a_S < -0.5$ or $a_S > 1$; short distance probe even for a_S large

$$|2) + 3)|^2 = \left[15.3\ a_S^2 - 6.8 \frac{Im\lambda_t}{10^{-4}}\ a_S + 2.8 \left(\frac{Im\lambda_t}{10^{-4}}\right)^2\right] \cdot 10^{-12}$$

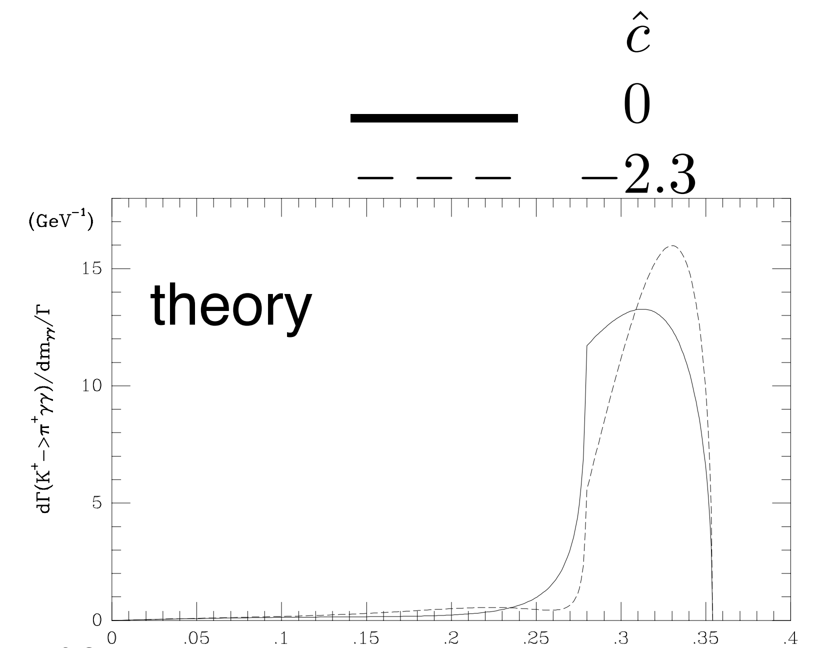
$$[17.7 \pm \qquad 9.5 + \qquad 4.7] \quad \cdot 10^{-12}$$

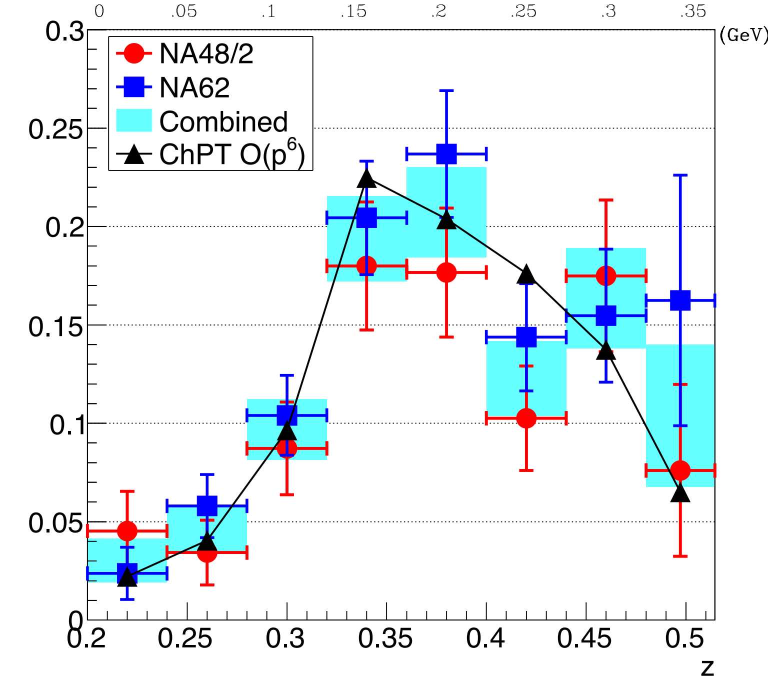
$K^+ \to \pi^+\gamma\gamma$ NA48/2 + NA62 ('14)

Auxiliary channel useful to assess the CP conserving contribution to $K_L \to \pi^0 ee$



Final 381 evts NA48/2 + NA62 during a 3-day special NA48/2 run in 2004 and a 3-month NA62 run in 2007





$$B = (1.003 \pm 0.051_{\text{stat}} \pm 0.024_{\text{syst}}) \cdot 10^{-6}$$

$$\hat{c} = 1.86 \pm 0.26$$

$K^+ \to \pi^+\gamma\gamma$ NA62 sensitivity

$$A(K \to 3\pi) = a + b\,Y + c\,Y^2 + d\,X^2$$

This decay $K^+ \to \pi^+\gamma\gamma$: The error obtained in the form factor ($\hat{c}$) is dominated by the expt K-> 3pi error in the quadratic slope !

$K_S \to \mu\bar{\mu}$ LHCB

After 40 years improvement by 3 orders of magnitudes from LHCB

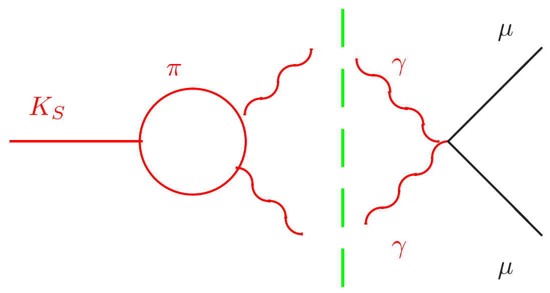
$$B(K_S \to \mu\bar{\mu}) < 11 \times 10^{-9}$$

95% CL

Isidori Underdorfer

SM

$\sim 5 \times 10^{-12}$



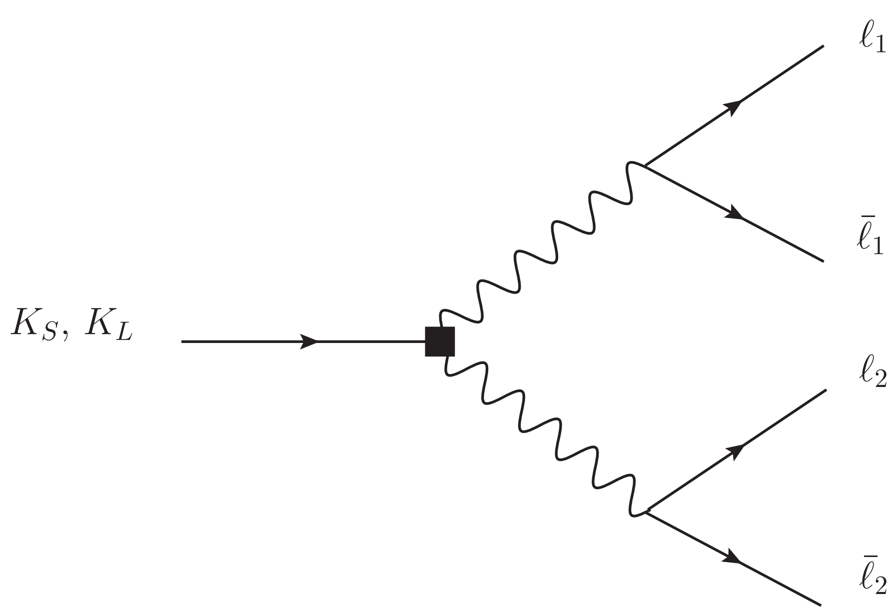
SD 1.5 10^-12

NP 1.5 10^-11
Allowed

NP Limits from CPviol in $K_L \to \mu\mu$

Other interesting channels

$$K_S \to \mu\mu\mu\mu \quad - \quad \text{SM LD} \ \sim 2 \times 10^{-14}$$
$$K_S \to ee\mu\mu \quad - \quad \sim 10^{-11}$$
$$K_S \to eeee \quad - \quad \sim 10^{-10}$$



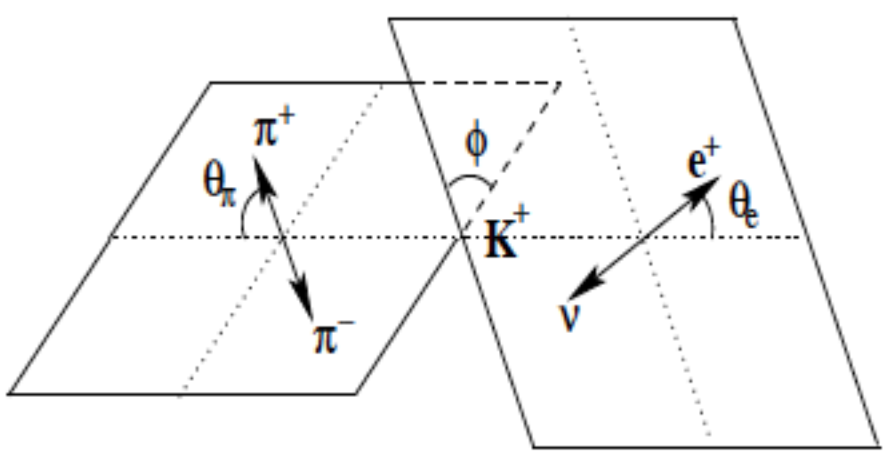
GD,Greynat, Vulvert

K_{l4} and $\pi\pi$ strong phases $\delta_I^l(s)$

Cabibbo Maksymowicz

$$\frac{G_F}{\sqrt{2}} V_{us}\ \bar{e}\gamma^\mu(1-\gamma^5)\nu\ H_\mu(p_1,p_2,q)$$

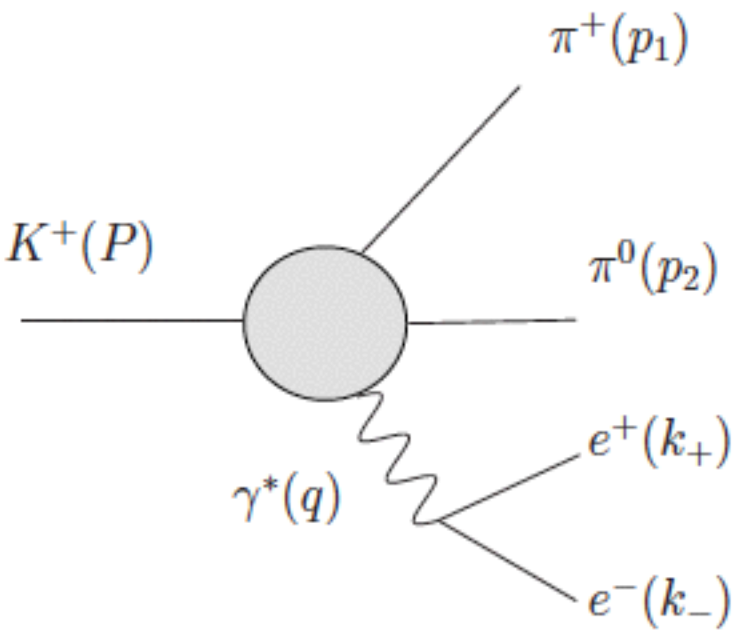
$$H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3\ \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta. \qquad F_i(s) = f_i(s) e^{i\delta_0^0(s)} + ..$$



- crucial to measure $\sin\delta \Longrightarrow$ interf F_3
- Look angular plane asymmetry

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

Sehgal et al; Savage,Wise et al



- $\mathcal{M}_{LD} = \frac{e}{q^2}\, \bar{e}\gamma^\mu(1-\gamma^5)\ e\ H_\mu$
- $H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3\ \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta$
- $F_{1,2} \sim E \quad F_3 \sim M$

- Interference $E \quad M$ novel compared to $K_L \to \pi^+\pi^-\gamma$
- $E \quad M$ known from $K_L \to \pi^+\pi^-\gamma$ (IB and DE)

$K^+ \to \pi^+\pi^0\gamma^* \to \pi^+\pi^0 e^+ e^-$ Cappiello, Cata,G.D. and Gao,

- the asymm. , $\frac{\Re(E_B\ M^*)}{|E_B|^2 + |M|^2}$, not as lucky $E_B >> M$:

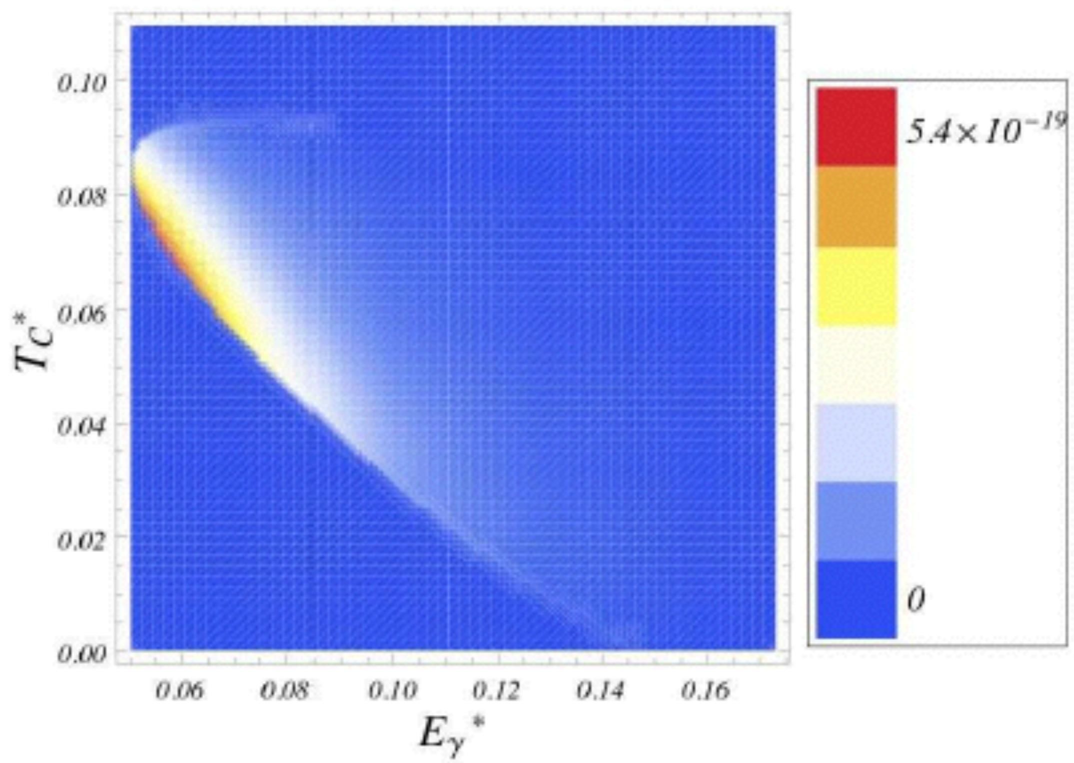
- $B(K^+)_{IB} \sim 3.3 \times 10^{-6}\ \sim\ 50\ B(K^+)_M$

- Short distance info without having simultaneously K^+ and K^-, asymm. in phase space, (P-violation) interesting! No ϵ-contamination

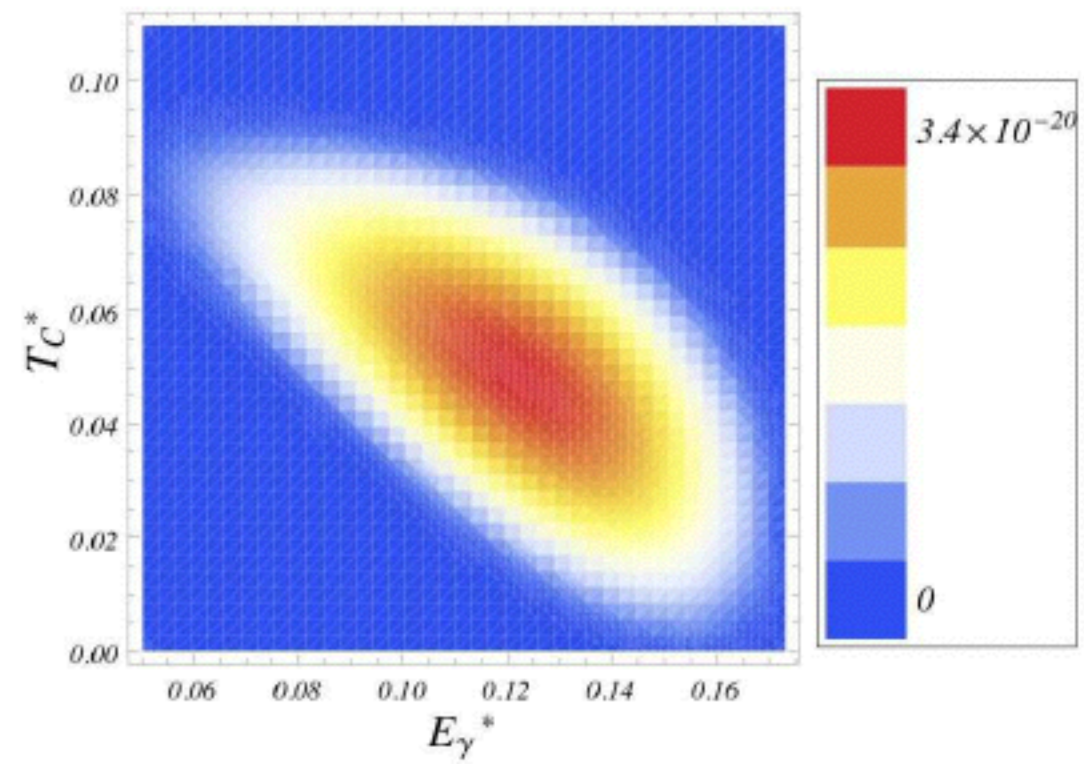
- interesting Dalitz plots (at fixed q^2) to disentangle M from E_B

- at $q^2 = 50\mathrm{MeV}$ IB only 10 times larger than DE

q_c (MeV)	B $[10^{-8}]$	B/M	B/E	B/BE	B/BM
$2m_l$	418.27	71	4405	128	208
55	5.62	12	118	38	44
100	0.67	8	30	71	36
180	0.003	12	5	-19	44



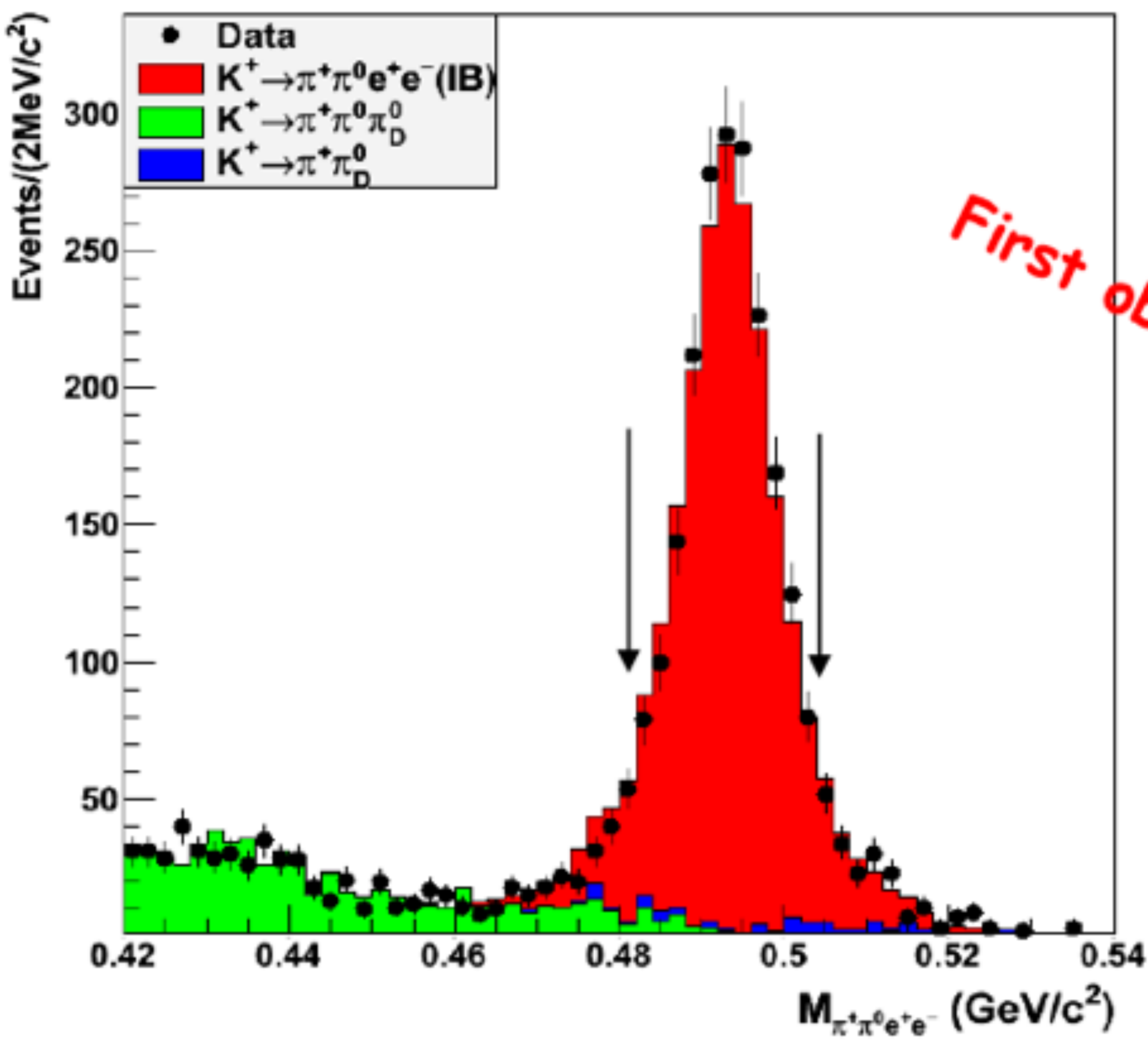
IB



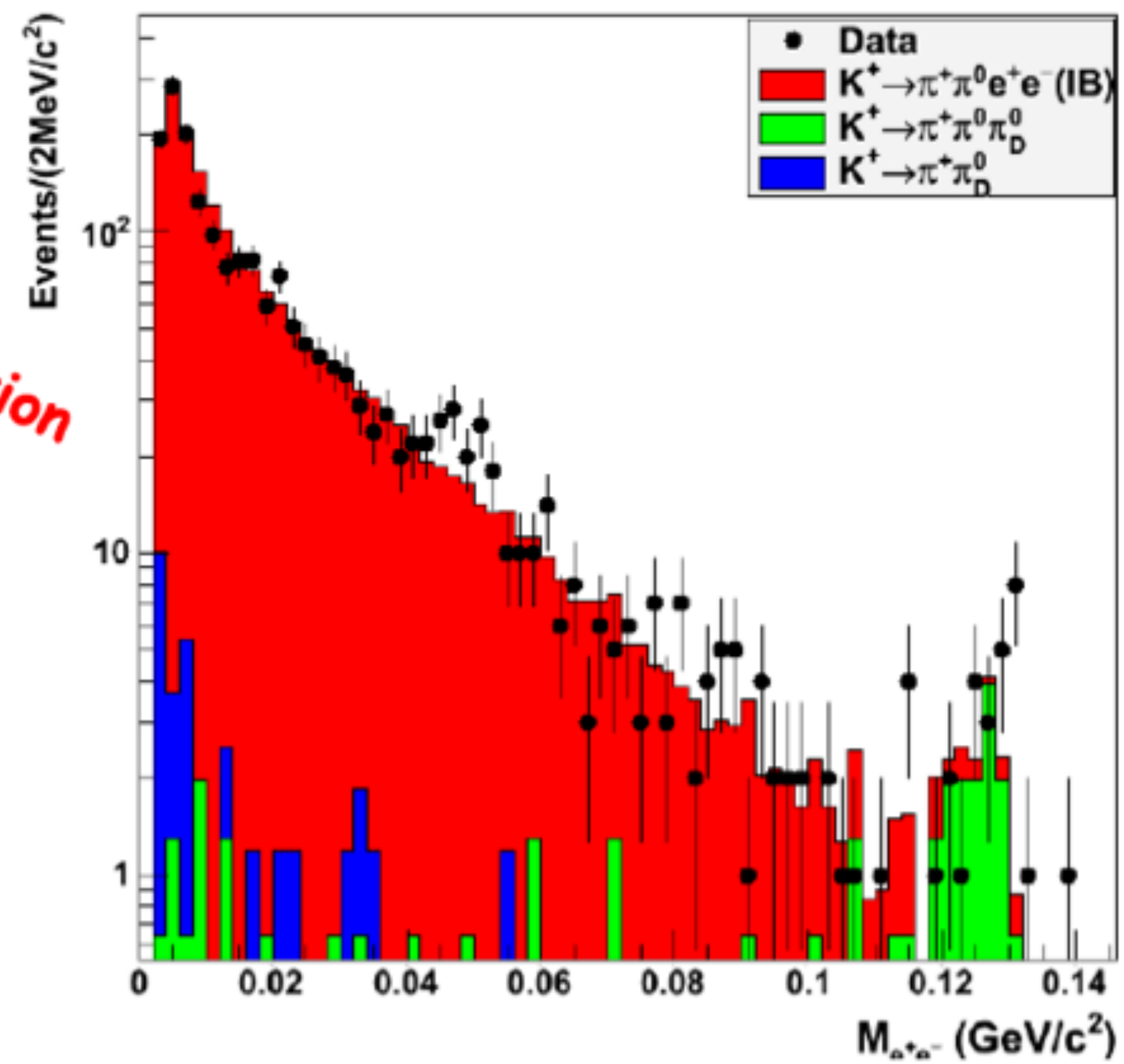
DE

$K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ Data samples and background estimates

Moriond 2015
NA62 Misheva



First observation



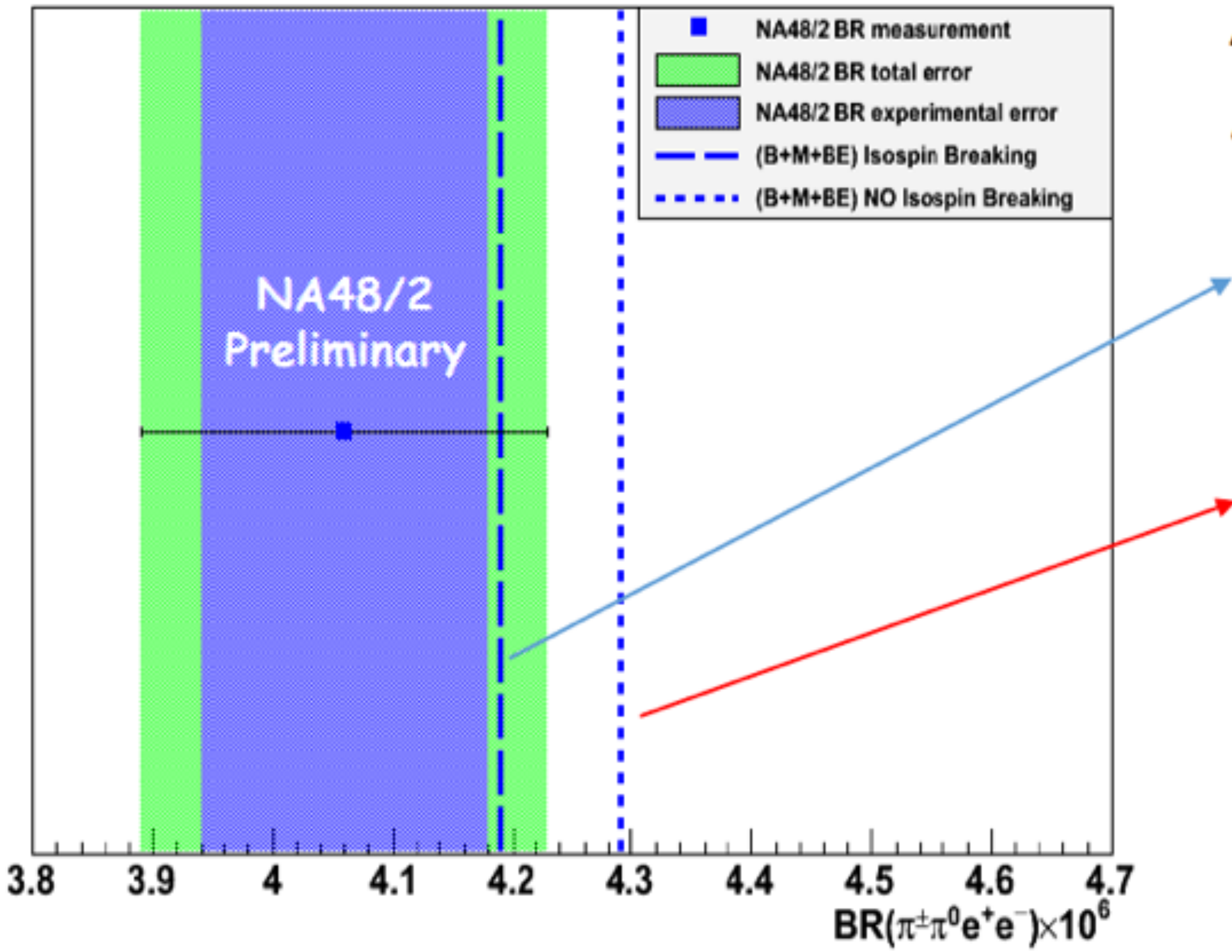
- 1916 -total number of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ candidates
- Total background (~3%)

  $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{e-e+\gamma}$ (30 ± 5.5)events

  $K^{\pm} \to \pi^{\pm}\pi^{0}_{e-e+\gamma}(\gamma)$ (26 ± 5.1)events

- Background suppression
  - $K^{\pm} \to \pi^{\pm}\pi^{0}\ e^{-}e^{+}\gamma$ ($M^{2}_{\pi\pi} > 0.120\ (GeV/c^{2})^{2}$)
  - $K^{\pm} \to \pi^{\pm}\ e^{-}e^{+}\gamma\ (\gamma)$ ($|M_{ee\gamma} - M_{\pi 0}\ PDG| > 7$ MeV)
- 1860 genuine $K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ events

Preliminary result of BR($K^\pm \to \pi^\pm \pi^0 e^- e^+$)



L. Cappiello, O. Cata, G. D'Ambrosio, Dao Neng-Gao, Eur. Phys. J. C 72:1872 (2012) :

Isospin breaking (private communication)

$BR(K^\pm \to \pi^\pm \pi^0 e^- e^+)^{Theory} = 4.19 \cdot 10^{-6}$

No isospin breaking (published)

$BR(K^\pm \to \pi^\pm \pi^0 e^- e^+)^{Theory} = 4.29 \cdot 10^{-6}$

No radiative corrections in the theoretical predictions!

Rad. corr. is taken into account in the experimental result via Photos implementation in the MC simulaton.

NA48/2
2003 data

$BR(K^\pm \to \pi^\pm \pi^0 e^- e^+)_{total} = (4.06 \pm 0.12_{exp} \pm 0.13_{ext}) \times 10^{-6}$

Conclusion

NP maybe HIDDEN but still present (see GIM)

Next FPCP round table on Kaon anomalies?

CPT Invariance Tests in Neutral Kaon Decay

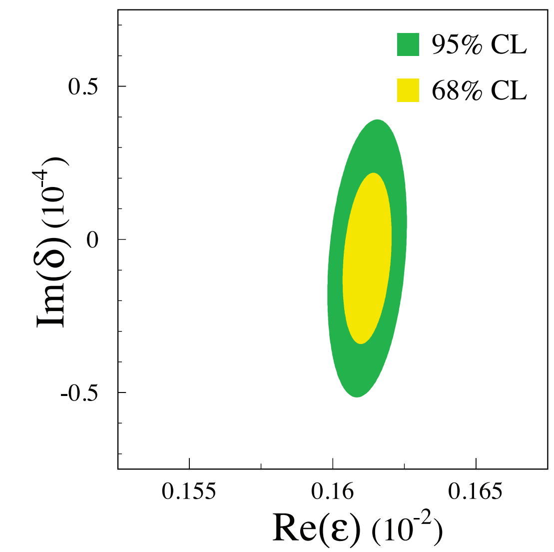
Antonelli, G.D.

$\Re(\epsilon)$ $\Im(\delta)$

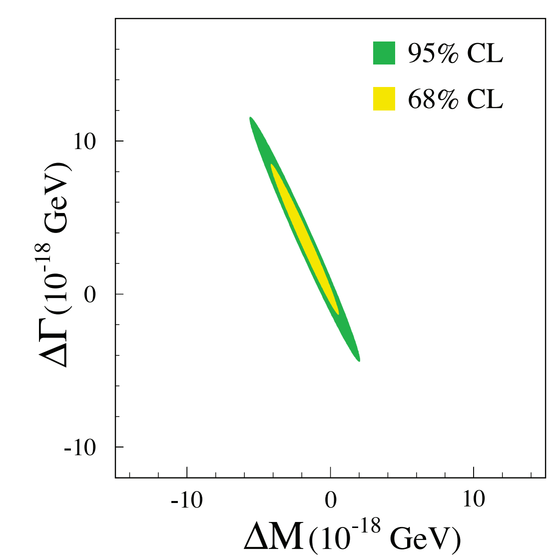
Review Bell-Steinberger relations: unitarity determines CP and CPT violating in terms of $A_L(f)A_S^*(f)$

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right]\left[\frac{\Re(\epsilon)}{1+|\epsilon|^2}-i\Im(\delta)\right]=\frac{1}{\Gamma_S-\Gamma_L}\sum_f A_L(f)A_S^*(f)$$

CPLEAR, NA48, KLOE, PDGfit, KTEV



$$|m_{K^0}-m_{\overline{K}^0}|<4.0\times10^{-19}\text{ GeV}\quad\text{at 95 \% C.L.}$$



PRIN studies: $K_L \to \pi^0 \ell^+ \ell^-$

$K_L \to \pi^0 \ell^+ \ell^-$ vs $K \to \pi \nu \bar{\nu}$:

- Measurements are complementary and can help to discriminate among NP models

  Different operators contribute to $K_L \to \pi^0 \ell^+ \ell^-$ and $K \to \pi \nu \bar{\nu}$
- Nominally easier experimental signatures for $\pi^0 \ell^+ \ell^-$, but some irreducible backgrounds (esp. for $\pi^0 e^+ e^-$)
- Larger theoretical uncertainties, need progress on ancillary measurements such as BR($K_S \to \pi^0 \ell^+ \ell^-$)

Modifications to NA62 needed for $K_L \to \pi^0 \ell^+ \ell^-$ are straightforward

- Removal of CEDAR, Gigatracker
- Realignment of straws, RICH; new IRC
- Possibly new SAC to handle higher rates

Potential for $K_L \to \pi^0 \ell^+ \ell^-$ experiment was studied by NA48

$K_L \to \pi^0 \ell^+ \ell^-$ with NA62 setup?

Extrapolated from studies for NA48

Assuming 1 sly at 2.4 × 10^{13} → 3 × 10^{12} K_L decays in FV

	$K_L \to \pi^0 e^+ e^-$	$K_L \to \pi^0 \mu^+ \mu^-$
SM BR	3.5 × 10^{-11}	1.4 × 10^{-11}
Acceptance	3%	18%
SM signal events	~3	~8
S/B	~1/10	~1/6

$K_L \to \pi^0 e^+ e^-$ channel is plagued by $K_L \to e^+ e^- \gamma\gamma$ background

- Like $K_L \to \gamma\gamma$ with internal conversion + bremsstrahlung
- 3% acceptance for $K_L \to \pi^0 e^+ e^-$ reflects tight cuts on Dalitz plot to reject
- Need to explore other strategies: statistical separation, kinematic fitting
- NA62 has better 2-3× better mass resolution on $\ell\ell$ vertex than NA48

Continuing to study in context of PRIN project

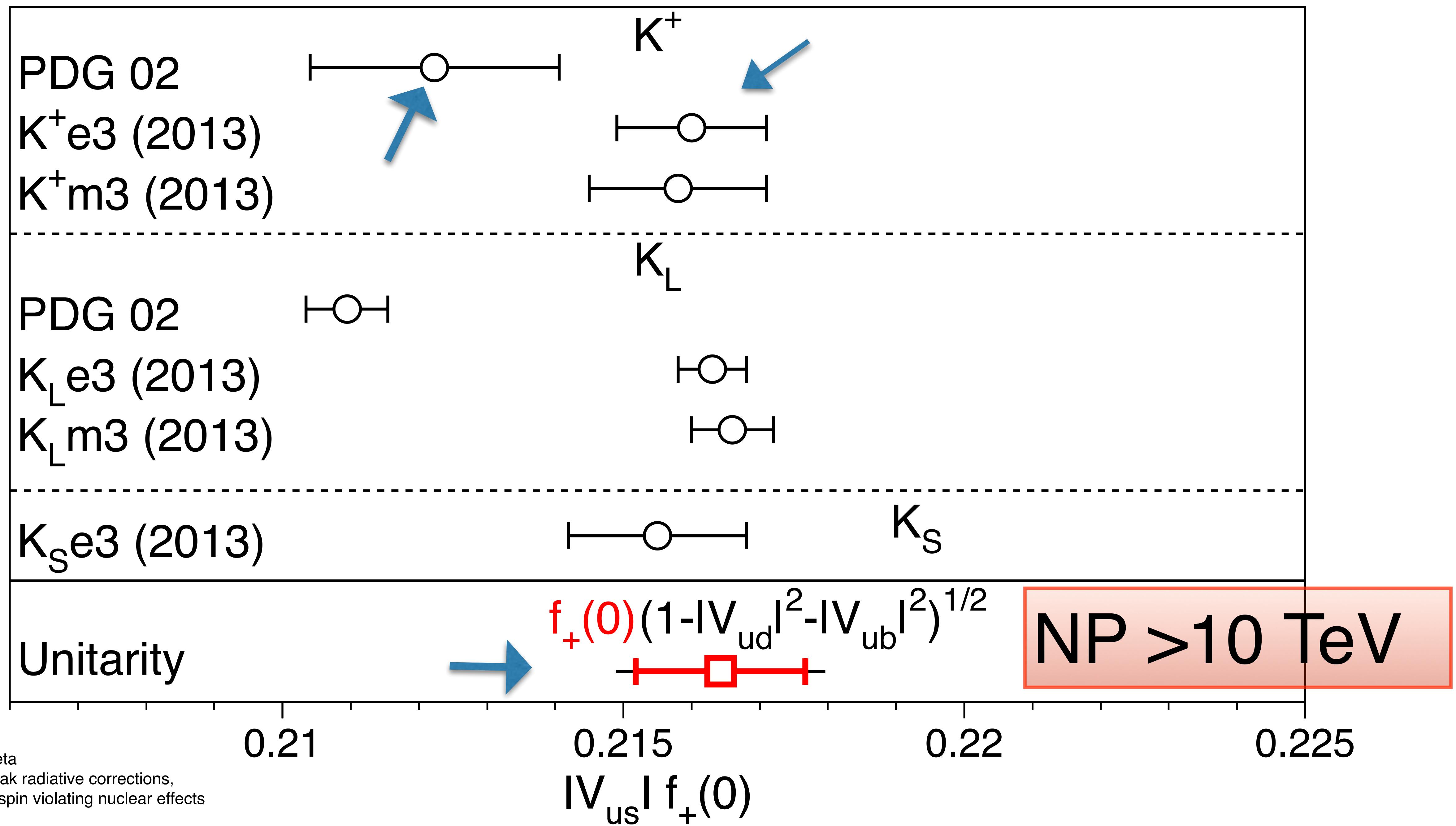
Vus from semileptonic decays

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\mathrm{EW}} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\mathrm{EM}}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

S_{EW} Universal SD EW correction (1.0232)



superallowed +neutron beta
error: Rad corr electroweak radiative corrections, nuclear structure, and isospin violating nuclear effects

High Statistics Measurement of the $K^+ \to \pi^0 e^+ \nu$ (K^+_{e3}) Branching Ratio

A. Sher,[3,*] R. Appel,[6,3] G. S. Atoyan,[4] B. Bassalleck,[2] D. R. Bergman,[6,†] N. Cheung,[3] S. Dhawan,[6] H. Do,[6] J. Egger,[5] S. Eilerts,[2,‡] H. Fischer,[2,§] W. Herold,[5] V.V. Issakov,[4] H. Kaspar,[5] D. E. Kraus,[3] D. M. Lazarus,[1] P. Lichard,[3] J. Lowe,[2] J. Lozano,[6,‖] H. Ma,[1] W. Majid,[6,¶] S. Pislak,[7,6] A. A. Poblaguev,[4] P. Rehak,[1] Aleksey Sher,[7] J. A. Thompson,[3] P. Truöl,[7,6] and M. E. Zeller[6]

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Role of KTeV,   KLOE, Istra

Chiral Perturbation theory

χPT effective field theory approach based on two assumptions

- π's Golstone bosons of $SU(3)_L \times SU(3)_R \to SU(3)_V$ $SU(3)_L \times SU(3)_R$ symm. $\mathcal{L}_{QCD}$ $m_q = 0$
- (chiral) power counting There is a small expansion parameter $p^2/\Lambda^2_{\chi SB}$

$\Lambda_{\chi SB} \simeq 4\pi F_\pi \sim 1.2$ GeV

$$\mathcal{L}_{\Delta S=0} = \mathcal{L}^2_{\Delta S=0} + \mathcal{L}^4_{\Delta S=0} + \cdots = \frac{F_\pi{}^2}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U \chi^\dagger \rangle}^{\pi\to l\nu,\ \pi\pi\to\pi\pi,\ K\to\pi..} + \overbrace{\sum_i L_i O_i}^{K\to\pi..} + \cdots$$

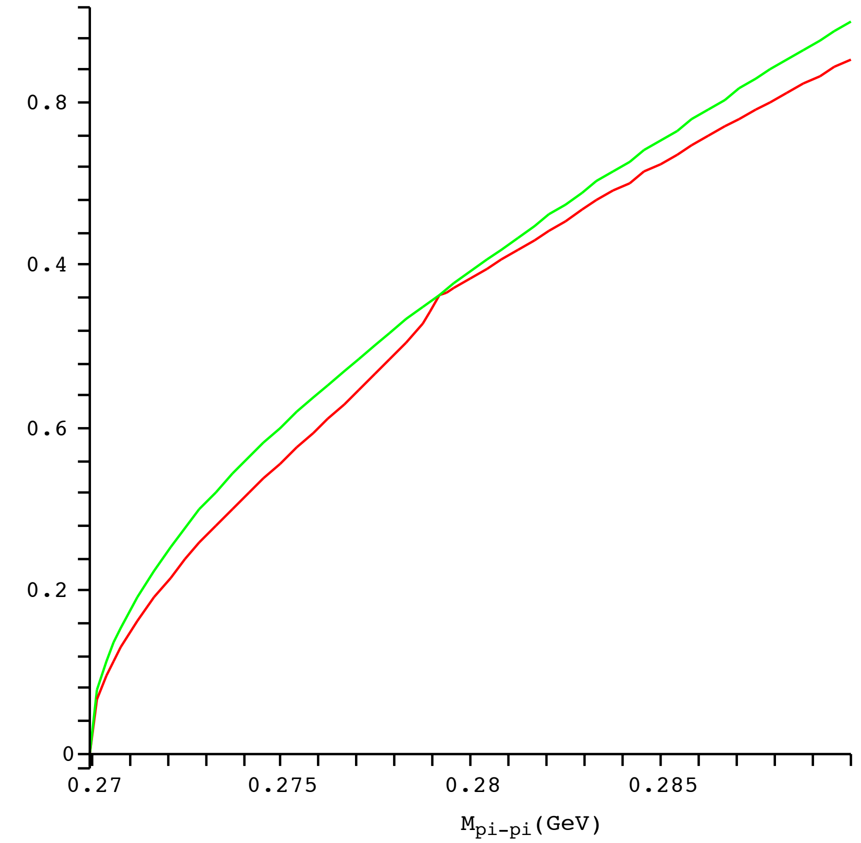
L$_i$ Gasser Leutwyler coeff
expts. O$_i$ p^4

Fantastic chiral prediction

$A_{\pi\pi} \sim (s - m_\pi{}^2)/F_\pi{}^2$

Cusp effect in K->3pi

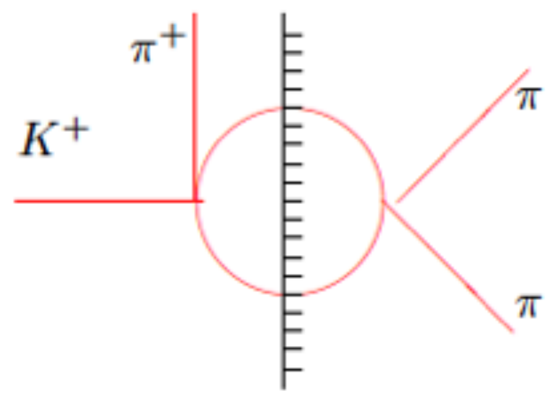
- in 2002 Mannelli at CERN discusses that their incredible energy resolution may lead to pionium discovery in K+ ->pi+ pi0 pi0
- But the plot (expt red curve) on the right was not yet understood



a_0, a_2 from $K \to 3\pi$ rescattering; Cabibbo,Cabibbo-Isidori

- rescattering generates an absorptive contribution proportional to the scattering lenghts a_0, a_2

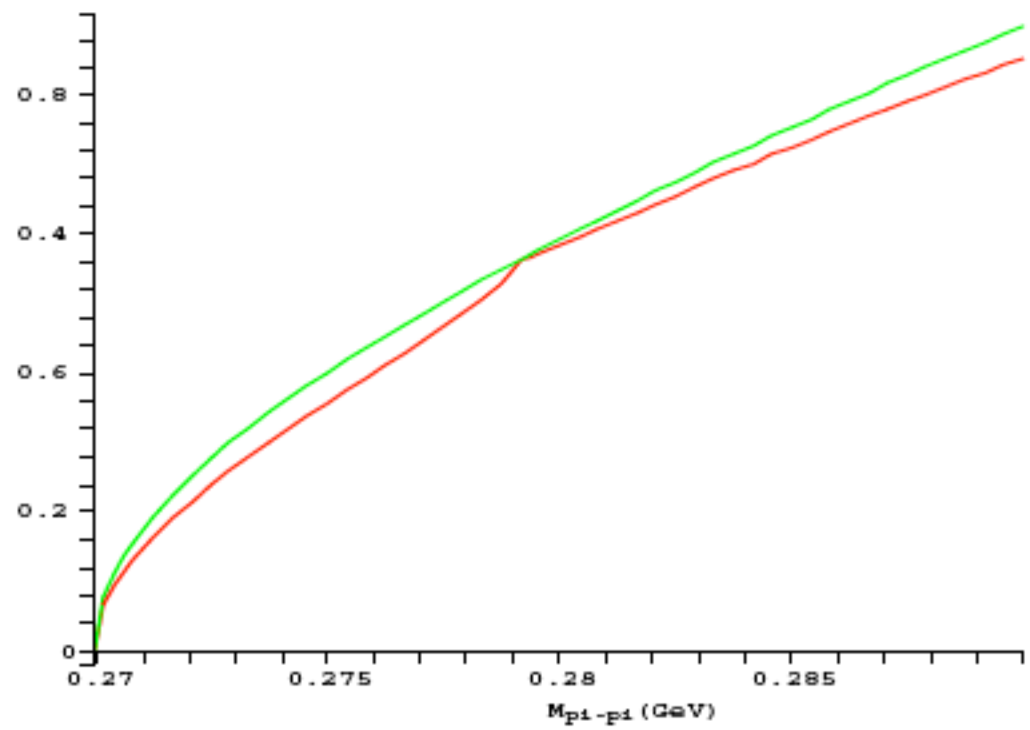
Final State Interaction



Zeldovich,Grinstein et al
Isidori,Maiani,Pugliese

The amplitude T(s) has a critical behaviour near $\pi\pi$ threshold: NA48 good energy resolution$\Longrightarrow a_0, a_2$

a_0, a_2 Cabibbo,Cabibbo-Isidori



- No cusp with cusp
- cusp: opening of the $\pi^+\pi^-$-thresho
- Rescattering $\pi^+\pi^- \rightarrow \pi$ proportional to $a_0 - a_2 \Longrightarrow$

$$\left.\frac{d\Gamma(K^+ \rightarrow \pi^+\pi^0\pi^0)}{dM_{\pi^0\pi^0}}\right|_{\mathrm{NA48}} \Rightarrow \mathrm{cusp\,for} M_{\pi^0\pi^0} = M_{\pi^+\pi^-}$$

$$\overset{\mathrm{cusp}}{\Rightarrow} a_0 - a_2.$$

Ke4, K->3pi, Dirac, CHPT

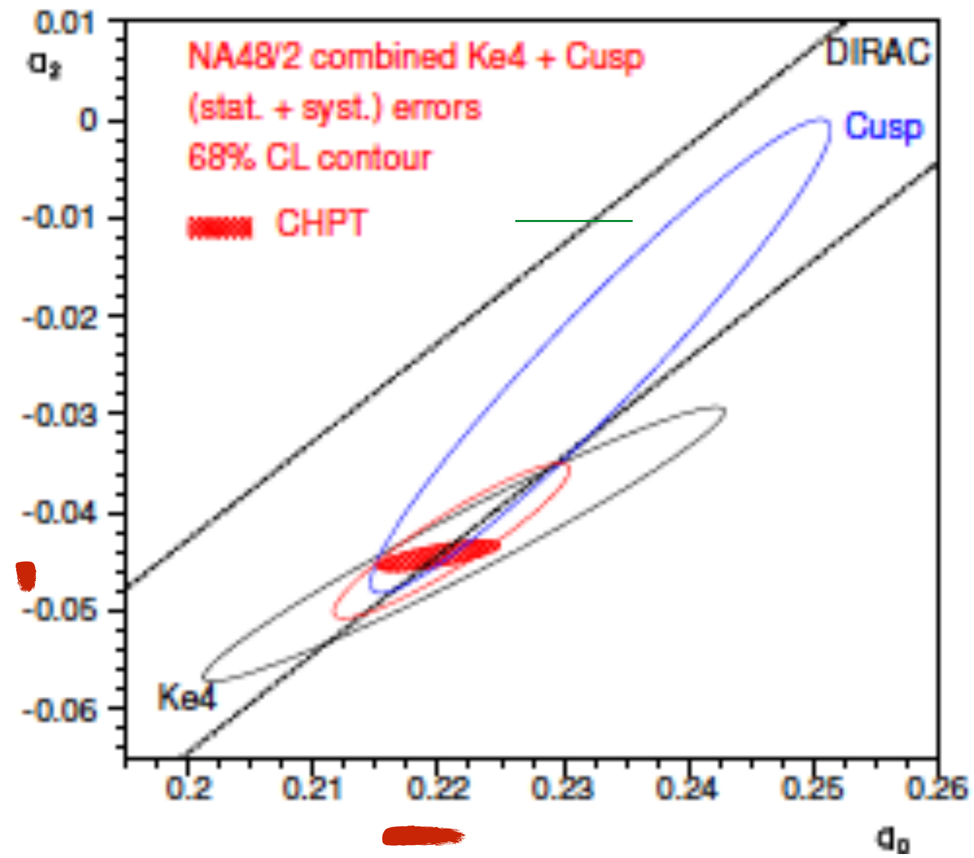
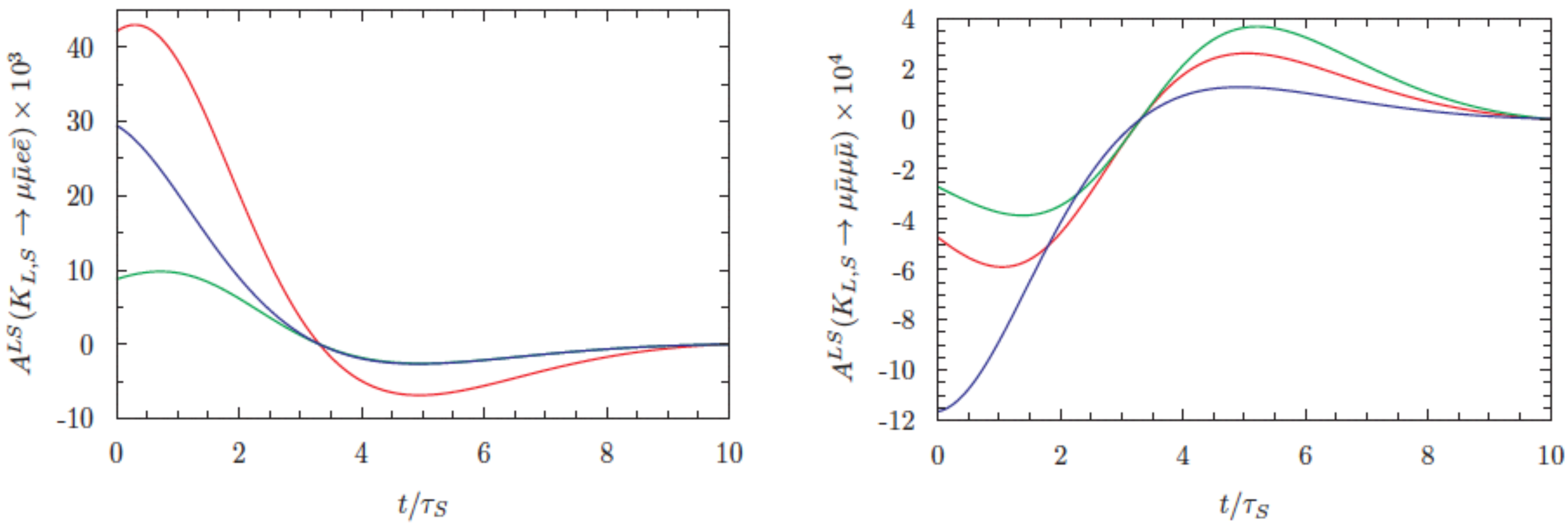


FIG. 8 NA48/2 K_{e4} and cusp results from two-parameter fits in the (a_0, a_2) plane. The smallest contour corresponds to the combination of NA48/2 results. The cross-hatched ellipse is the CHPT prediction (4.92) of Colangelo *et al.* (2001a,b). The dash-dotted lines correspond to the recent result from DIRAC (Adeva *et al.*, 2011). We thank Brigitte Bloch-Devaux for updating the original figure from Batley *et al.* (2010c).

Time interference effects



Interferences between K_L and $K_S \to \ell_1\bar{\ell}_1\ell_2\bar{\ell}_2$. The red line corresponds to the case $\alpha_S = 0$, the green line is $\alpha_S = -3$ while the blue line is $\alpha_S = 3$. As explained in the text we assume the sign $K_L \to \gamma\gamma$. For 4μ's 10^{14} K_S needed , $ee\mu\mu$ 10^{12}

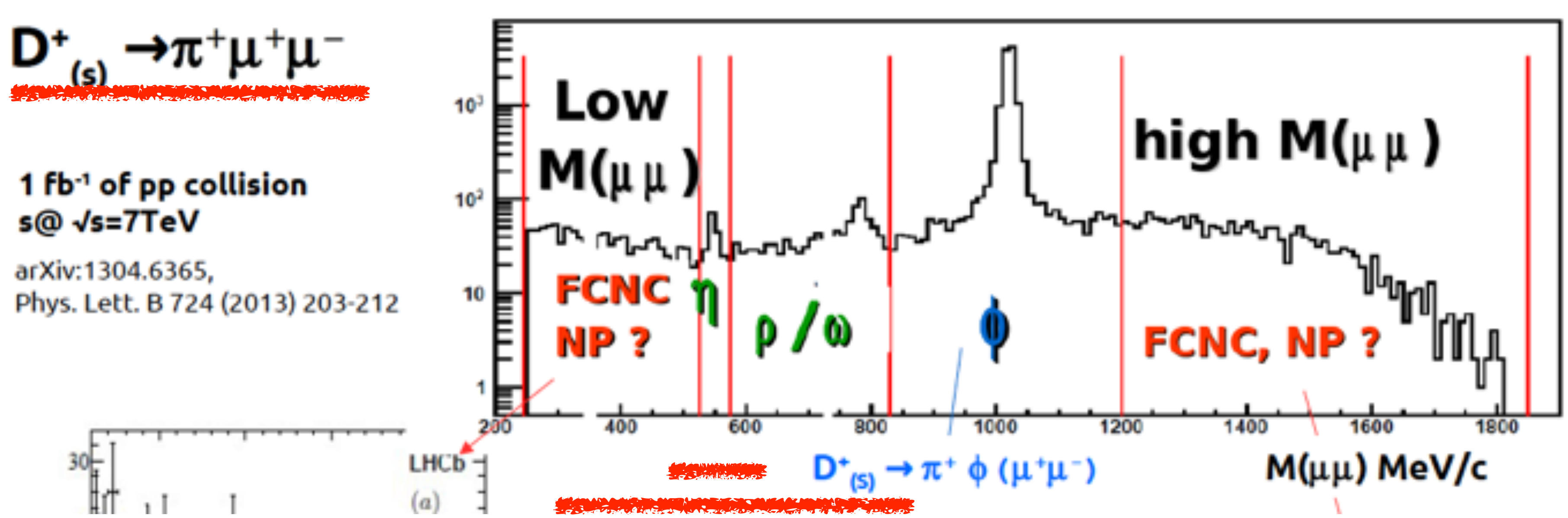
Conclusion I

Theorists had a good idea: $B_s \to \mu\mu$

Experimentalists did better

SM $B_s \to \mu\mu$

$K_S \to \mu\mu$ bound



Conclusion II

Theorists had a good idea: ϵ'

Experimentalists did better KTeV and NA48!

see Rare Kaon decays

Weak interaction

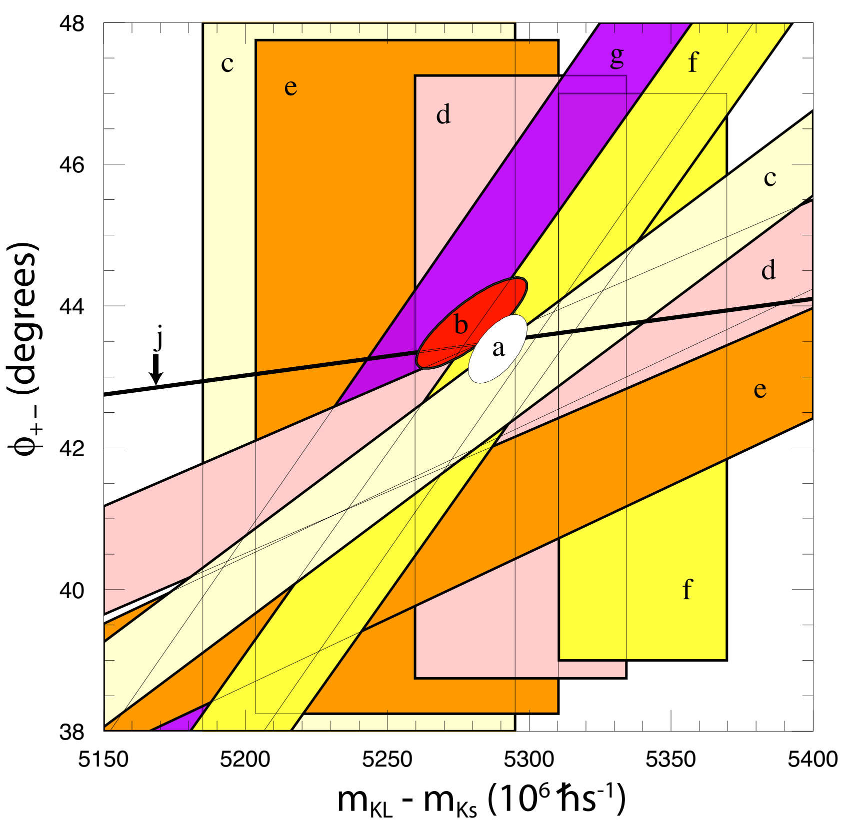
The symmetry of the short distance hamiltonian $-\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^{*} C_{-} (\overline{s}_L \gamma^{\mu} u_L)(\overline{u}_L \gamma_{\mu} d_L)$

described in CHPT

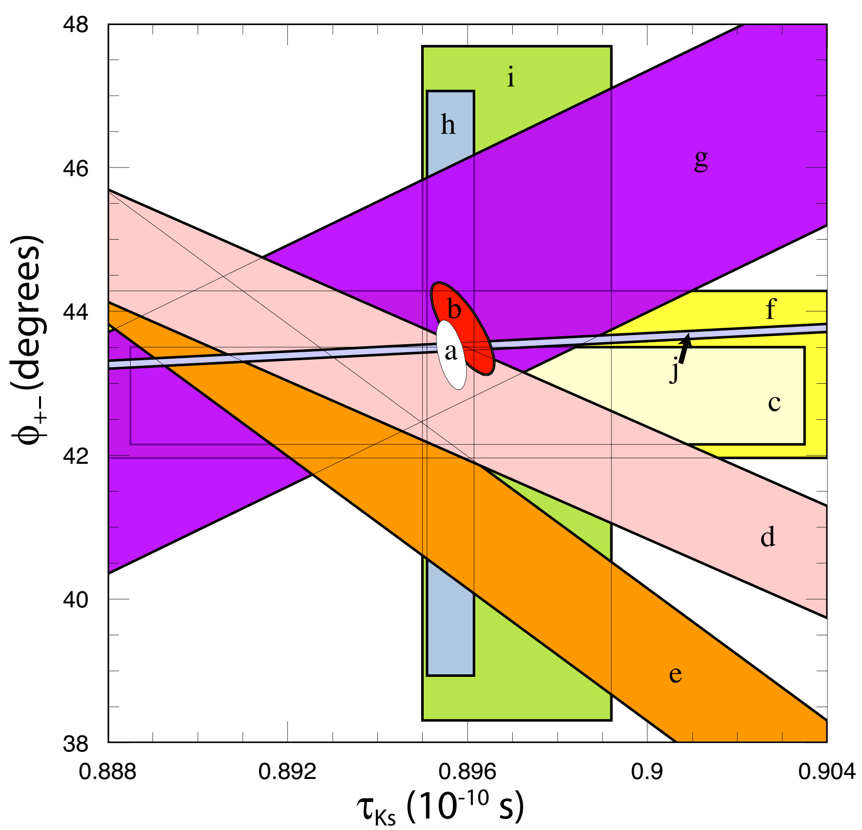
$$\mathcal{L}_{\Delta S=1} = \mathcal{L}^2_{\Delta S=1} + \mathcal{L}^4_{\Delta S=1} + \cdots = G_8 F^4 \underbrace{\langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K \to 2\pi/3\pi} + \underbrace{G_8 F^2 \sum_i N_i W_i}_{K^+ \to \pi^+ \gamma\gamma, K \to \pi l^+ l^-} + \cdots$$

VMD not as successful, in particular for K->3pi, where in principle large VMD important

CP-Violation in KL Decays Wolfenstein, Lin Trippe



do not assume CPT invariance



assume CPT invariance

$$\phi_{+-} - \phi_{00} \sim 0.006^{o} \pm 0.008^{o} \quad \tau_{K_S} = 0.8954 \pm 0.0004 \cdot 10^{-10} s$$

Issues

- Still to improve: maybe some form factors can be removed
- Do we need a mini review for CHPT?

$$\mathcal{L}_{SM}^{Y} \quad = \quad \bar{Q} Y_D D H + \bar{Q} Y_U U H_c + \bar{L} Y_E E H$$

$$\mathcal{H}_{\Delta F=2}^{SM} \sim \frac{G_F^2 M_W^2}{16\pi^2} \left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right] + \text{charm}$$

$$\mathcal{L}_{soft} = \tilde{Q}^\dagger m_Q^2 \tilde{Q} + \tilde{L}^\dagger m_L^2 \tilde{L} + \bar{\tilde{\bar{U}}} a_u \tilde{Q} \ H_u$$

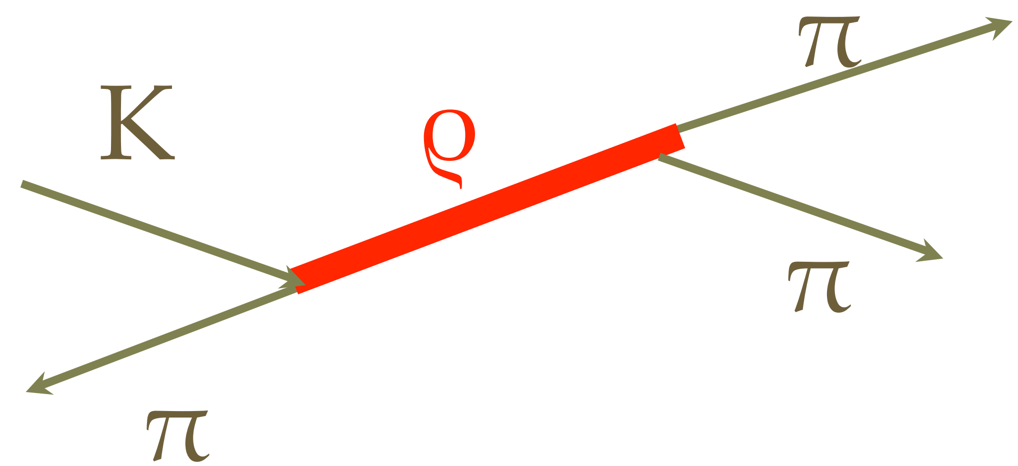
$$\mathcal{L}_{\rm soft} = \tilde{Q}^\dagger m^2_{\tilde{Q}} \tilde{Q} + \tilde{L}^\dagger m_{\tilde{L}}{}^2 \tilde{L} + \tilde{\bar{\bar{U}}} a_u \tilde{Q} \ H_u$$

$$G_F = \overbrace{\mathrm{U}(3)_Q \otimes \mathrm{U}(3)_U \otimes \mathrm{U}(3)_D \otimes \mathrm{U}(3)_L \otimes \mathrm{U}(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

Hard Wall weak interactions: K->3pi

Luigi Cappiello, Oscar Cata and G.D.

In this channel there is a large VMD in the phenomenological slope

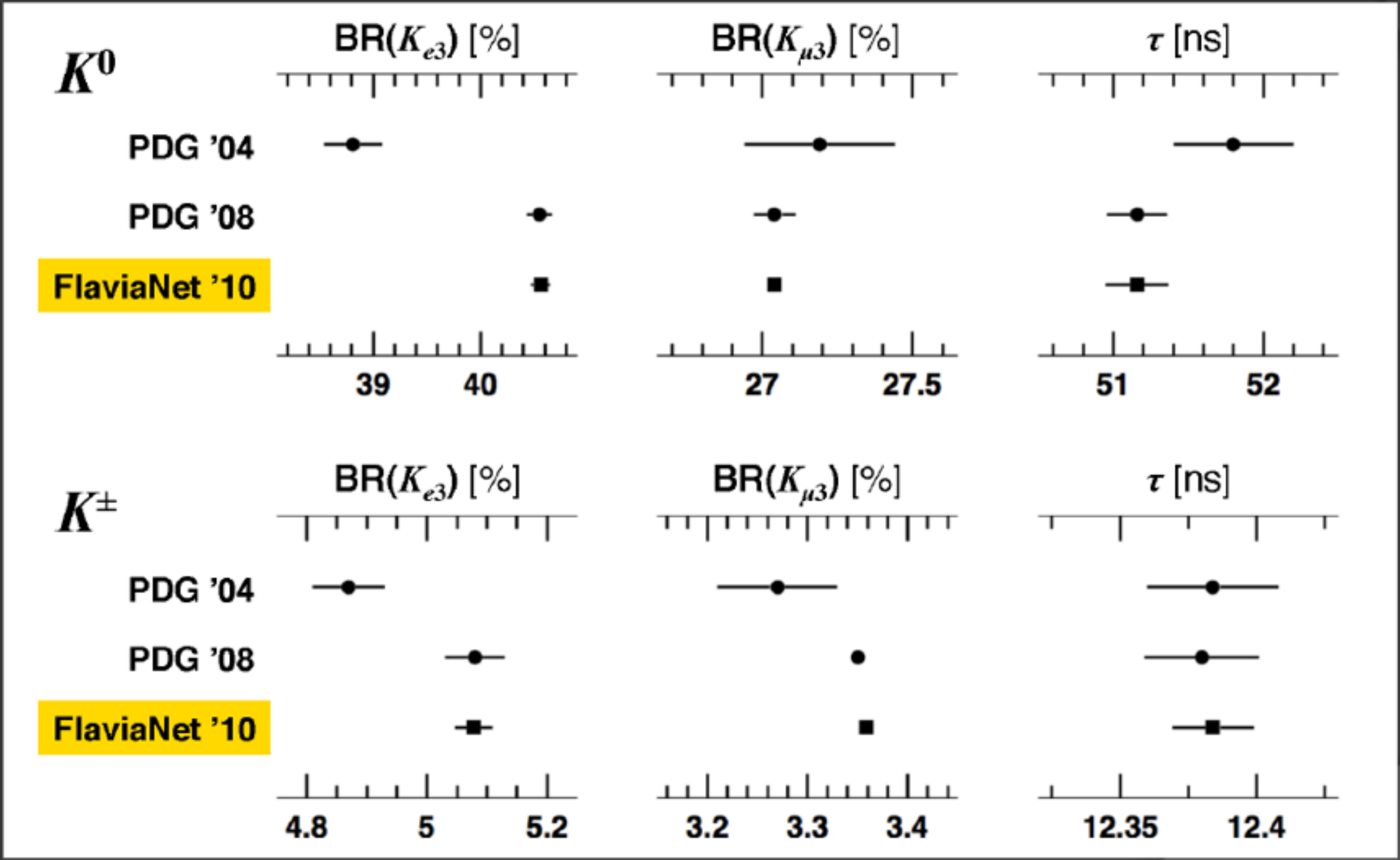


However this is proportional to $L_3 + 3/4\, L_9$

4D $L_3 + 3/4\, L_9 = 0$

5D $L_3 + 3/4\, L_9 \neq 0$ and in agreement with phenomenology

Evolution of Experimental Input…



"V_{us} Revolution" with experimental input changing ~ 5% in some cases…..

Input from many experiments: **BNL865, KTeV, ISTRA+, KLOE, NA48, NA48/2**

Vector Meson Dominance in the strong sector

Ecker, Gasser, de Rafael, Pich

L	L	V	A	Total (Scalar incl.)	Total QCD rel. incl.
L	0.4 ± 0.3	0,6	0	0,6	0,9
L	1.4 ± 0.3	1,2	0	1,2	1,8
L	-3.5 ± 1.1	-3,6	0	-3,0	-4,9
L	-0.3 ± 0.5	0	0	0	0
L	1.4 ± 0.5	0	0	1,4	1,4
L	-0.2 ± 0.3	0	0	0	0
L	-0.4 ± 0.2	0	0	-0,3	-0,3
L	0.9 ± 0.3	0	0	0,9	0,9
L	6.9 ± 0.7	6,9	0	6,9	7,3
L	-5.5 ± 0.7	-10	4	-6,0	-5,5

QCD inspired relations relations

$$F_V = 2G_V = \sqrt{2} f_\pi$$

$$F_A = f_\pi$$

$$M_A = \sqrt{2} M_V$$

KSFR: $G_V = \sqrt{2}\ F_\pi$ determined by dominance of pion, V,A to recover QCD short distance constraints

$$L_1^V = \frac{L_2^V}{2} = -\frac{L_3^V}{6} = \frac{G_V^2}{8M_V^2}, \qquad L_9^V = \frac{F_V G_V}{2M_V^2}, \qquad L_{10}^{V+A} = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2}$$

QCD inspired relations relations

$$L_1^V = L_2^V/2 = -L_3^V/6 = L_9^V/8 = -L_{10}^{V+A}/6 = f_\pi^2/(16M_V^2)$$