HL/HE questions in strangeness+tau

Giancarlo D'Ambrosio
INFN Sezione di Napoli

taus: Lusiani Pich Passemar

Rare n Strange 2017: strange physics at LHCb

GD, Lewis Tunstall, Diego Martinez Santos,Veronika Chobanova, Xabier Cid Vidal, Francesco Dettori, Marc-Olivier Bettler

Collaboration with Teppei Kitahara arXiv: 1707.06999 PRL

hyperons: Jorge is the master

Collaboration with Teppei Kitahara, Isabel Fernández Suárez, Miriam Lucio Martínez, Diego Martínez Santos, Veronika Georgieva Chobanova

Collaboration with Crivellin,A., Kitahara, T and Nierste, U. e-Print: arXiv:1703.05786

Collaboration with Cappiello,L. E. Greynat,D. EPJC

Collaboration with Abhishek Iyer

Outline

- $K^0 \to \mu\mu$ Golden mode
- $K_S \to \pi\mu\mu$
- $K_S \to \pi\pi ee$
- $K_S \to \mu\mu\mu\mu$
- Questions on hyperons and taus

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST 1974

Rare decay modes of the K mesons in gauge theories

M. K. Gaillard* and Benjamin W. Lee†
National Accelerator Laboratory, Batavia, Illinois 60510‡
(Received 4 March 1974)

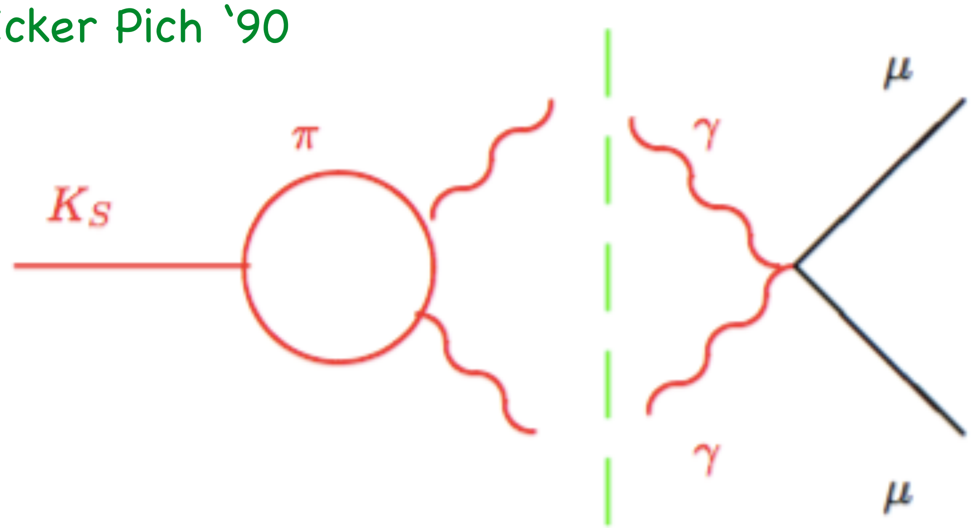
Rare decay modes of the kaons such as $K\to\mu\bar{\mu}$, $K\to\pi\nu\bar{\nu}$, $K\to\gamma\gamma$, $K\to\pi\gamma\gamma$, and $K\to\pi e\bar{e}$ are of theoretical interest since here we are observing higher-order weak and electromagnetic interactions. Recent advances in unified gauge theories of weak and electromagnetic interactions allow in principle unambiguous and finite predictions for these processes. The above processes, which are "induced" $|\Delta S|=1$ transitions, are a good testing ground for the cancellation mechanism first invented by Glashow, Iliopoulos, and Maiani (GIM) in order to banish $|\Delta S|=1$ neutral currents. The experimental suppression of $K_L\to\mu\bar{\mu}$ and nonsuppression of $K_L\to\gamma\gamma$ must find a natural explanation in the GIM mechanism which makes use of extra quark(s). The procedure we follow is the following: We deduce the effective interaction Lagrangian for $\lambda+\mathfrak{N}\to l+\bar{l}$ and $\lambda+\bar{\mathfrak{N}}\to\gamma+\gamma$ in the free-quark model; then the appropriate matrix elements of these operators between hadronic states are evaluated with the aid of the principles of conserved vector current and partially conserved axial-vector current. We focus our attention on the Weinberg-Salam model. In this model, $K\to\mu\bar{\mu}$ is suppressed due to a fortuitous cancellation. To explain the small K_L-K_S mass difference and nonsuppression of $K_L\to\gamma\gamma$, it is found necessary to assume $m_{\mathcal{P}}/m_{\mathcal{P}'}\ll 1$, where $m_{\mathcal{P}}$ is the mass of the proton quark and $m_{\mathcal{P}'}$ the mass of the charmed quark, and $m_{\mathcal{P}'}<5$ GeV. We present a phenomenological argument which indicates that the average mass of charmed pseudoscalar states lies below 10 GeV. The effective interactions so constructed are then used to estimate the rates of other processes. Some of the results are the following: $K_S\to\gamma\gamma$ is suppressed; $K_S\to\pi\gamma\gamma$ proceeds at a normal rate, but $K_L\to\pi\gamma\gamma$ is suppressed; $K_L\to\pi\nu\bar{\nu}$ is very much forbidden, and $K^+\to\pi^+\nu\bar{\nu}$ occurs with the branching ratio of $\sim 10^{-10}$; $K^+\to\pi^+e\bar{e}$ has the branching ratio of $\sim 10^{-6}$, which is comparable to the presently available experimental upper bound. The predictions of other models are briefly discussed. Relevant renormalization

VALUE (10^{-9})	*CL%*		*DOCUMENT ID*		*TECN*
< 9	90	[1]	AAIJ	2013G	LHCB
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.032\times 10^4$	90		GJESDAL	1973	ASPK
$< 0.7\times 10^4$	90		HYAMS	1969B	OSPK

[1] AAIJ 2013G uses 1.0 fb^{-1} of pp collisions at $\sqrt{s}=7$ TeV. They obtained B($K^0_S\to\mu^+\mu^-$) $< 11\times 10^{-9}$ at 95% C.L.

$K_S \to \mu\mu$

Ecker Pich '90



No CP conserving Short Distance due to Furry Theorem

Gaillard Lee

LD 5×10^{-12} 30% TH err

Short Distance

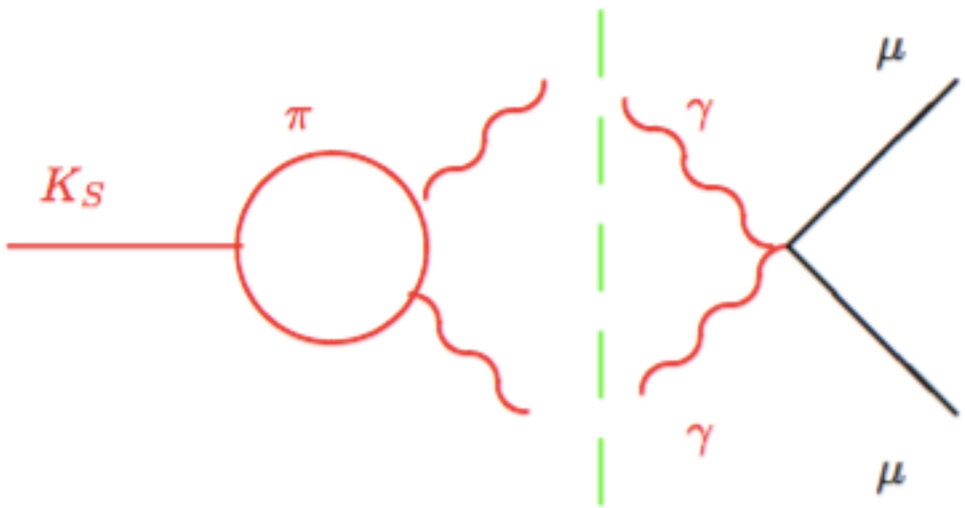
SM $10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$

NP few 10^{-11} allowed

LHCB

$< 8 \times 10^{-10}$ 90%CL

$K_S \to \mu\mu$: how to improve the THEORY error



Dispersive treatment of $K_S \to \gamma\gamma$ and $K_S \to \gamma l^+ l^-$

Gilberto Colangelo, Ramon Stucki, and Lewis C. Tunstall

LD $\quad 5 \times 10^{-12}$ **20% TH err**

$$K_S \to \gamma\mu\mu$$
$$K_S \to \mu\mu\mu\mu$$
$$K_S \to ee\mu\mu$$
$$K_S \to \gamma\gamma$$

$K_L \to \mu\mu$

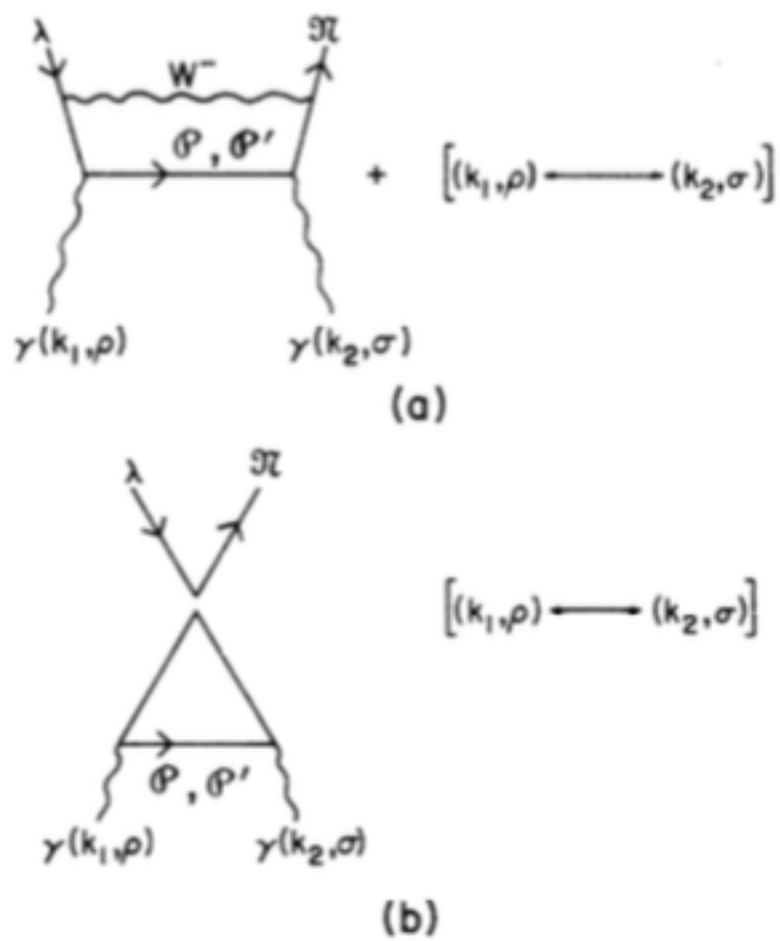


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

$\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-)$

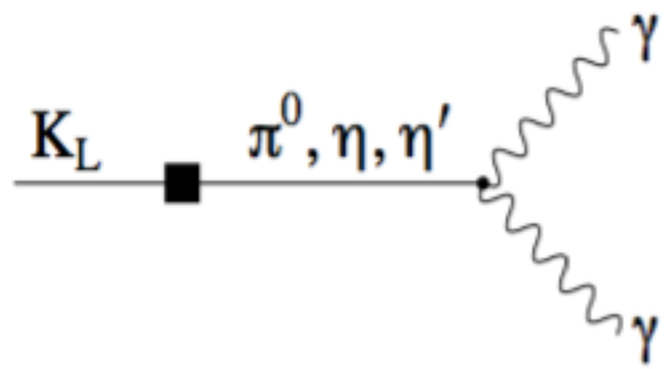
VALUE (10^{-6})	EVTS	DOCUMENT ID		TECN	C
3.48 ± 0.05	**OUR AVERAGE**				
3.474 ±0.057	6210	AMBROSE	2000	B871	
3.87 ±0.30	179	[1] AKAGI	1995	SPEC	
3.38 ±0.17	707	HEINSON	1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	1991B	SPEC	In

$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm exp} = (6.84 \pm 0.11) \times 10^{-9}$$

$K_L \to \gamma\gamma\,|_{\rm exp}$ known

Dispersive calculation: Re A, Im A

We do not know the sign of $A(K_L \to \gamma\gamma)$

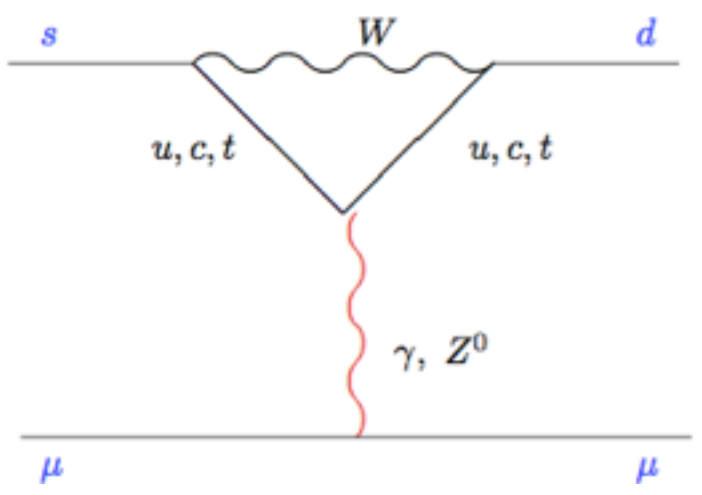


$$A(K_L \to 2\gamma_\perp)_{O(p^4)} = A(K_L \to \pi^0 \to 2\gamma_\perp) + A(K_L \to \eta_8 \to 2\gamma_\perp)$$

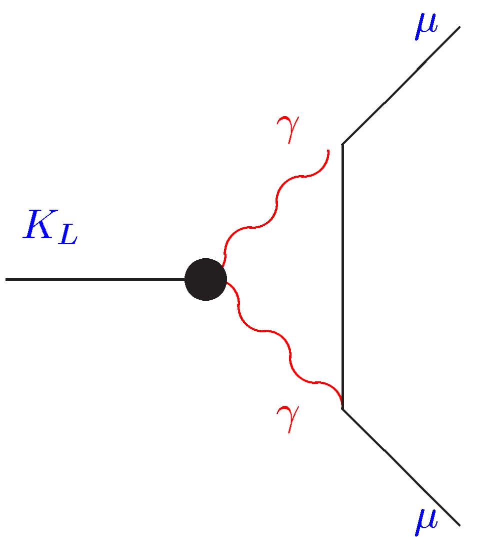
$$= A(K_L \to \pi^0)A(\pi^0 \to 2\gamma_\perp)\left[\frac{1}{M_K^2 - M_\pi^2} + \frac{1}{3}\cdot\frac{1}{M_K^2 - M_8^2}\right] \simeq 0$$

Kaon Decays in the Standard Model
Vincenzo Cirigliano (Los Alamos), Gerhard Ecker, Helmut Neufeld (Vienna U.), Antonio Pich, Jorge Portoles, refs therein

$K_L \to \mu\mu$



$<<$



$$\frac{\Gamma(K_L \to \mu\overline{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim \quad |ReA|^2 + |ImA|^2$$

Absorptive calculation model independent

27.14

Subtracting from expt. the Absorptive contribution

$$0.98 \pm 0.55 = |ReA|^2 = (\chi_{\gamma\gamma}(M_\rho) + \chi_{\text{short}} - 5.12)^2$$

$$|\chi_{\text{short}}^{\text{SM}}| = 1.96(1.11 - 0.92\bar{\rho})$$

RBC-UK QCD

Buras K->2π

$$\varepsilon'/\varepsilon = (1.4 \pm 7.0) \cdot 10^{-4}$$

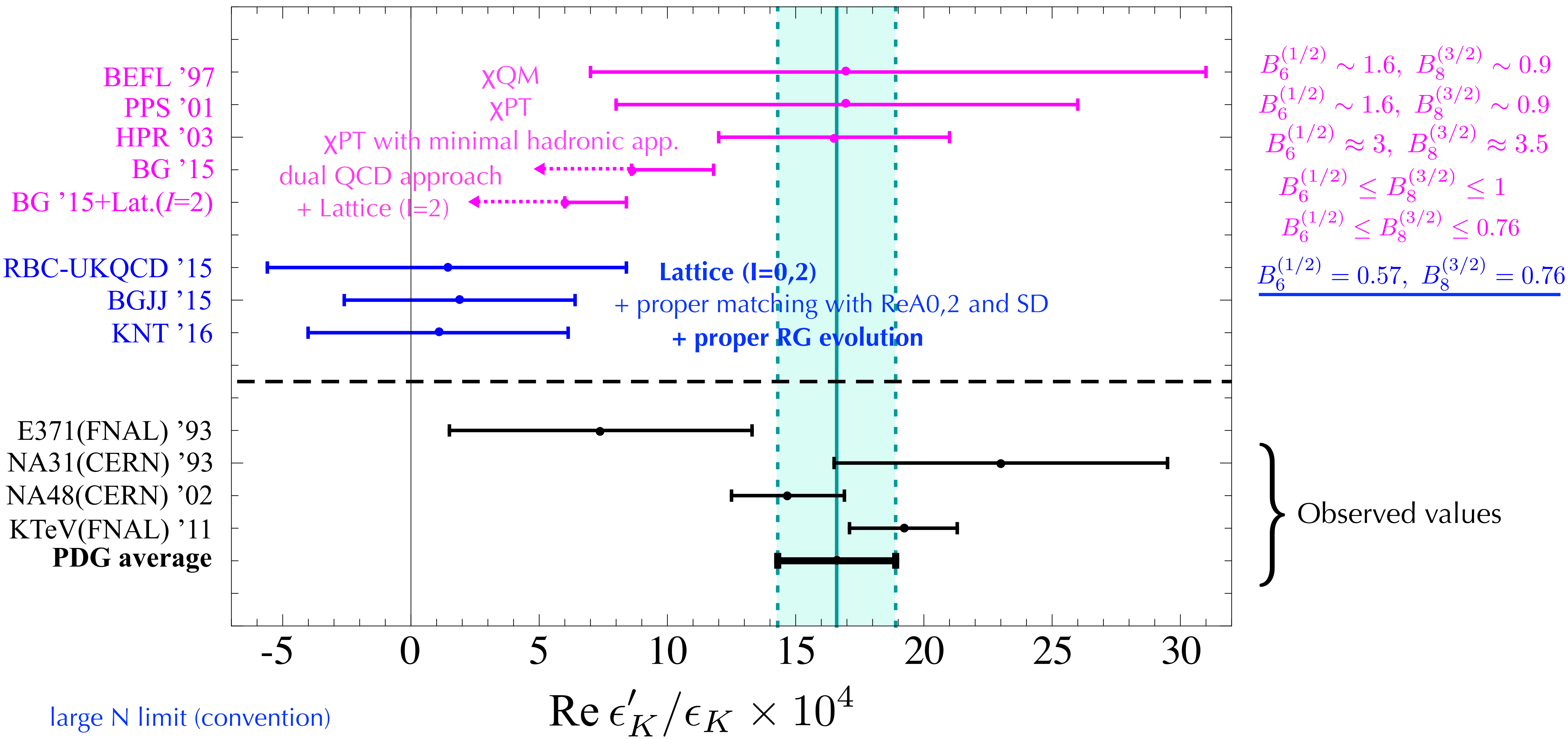
$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right) = 31.0 \pm 6.6$$

$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{exp}} = 22.4$$

Buras, Mainz

Current situation of $\epsilon'_K/\epsilon_K \propto \mathrm{Im}A_0 - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)\mathrm{Im}A_2$



large N limit (convention)

$B_6^{(1/2)} = B_8^{(3/2)} = 1$

dual QCD prediction

$B_6^{(1/2)} \leq B_8^{(3/2)} < 1,\ B_8^{(3/2)} = 0.8$

	Exp.	χPT	dual QCD	**Lattice (I=0,2)**
$\left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)$	22.45 ± 0.05	~ 14	16.0 ± 1.5	31.0 ± 11.1

Models solving ε'/ε anomaly

- Several new physics models have been studied to explain ε'/ε anomaly

MSSM -- chargino Z penguin	*[M. Endo, S. Mishima, D. Ueda and KY, PLB762(2016)493]*
-- gluino Z penguin	*[M. Tanimoto and KY, PTEP(2016)no.12,123B02]*
-- gluino box	*[T.Kitahara, U.Nierste and P.Tremper, PRL117(2016)no.9, 091802 A.Crivellin, G.D'Ambrosio, T.Kitahara and U.Nierste, 1703.05786]*
Vector-like quarks	*[C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]*
Little Higgs Model with T-parity	*[M.Blanke, A.J.Buras and S.Recksiegel, EPJ.C76 (2016)no.4,182]*
331 model	*[A.J.Buras and F.De Fazio, JHEP1603(2016)010 & JHEP1608 (2016) 115]*
Right handed current	*[V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB 767 (2017) 1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]*

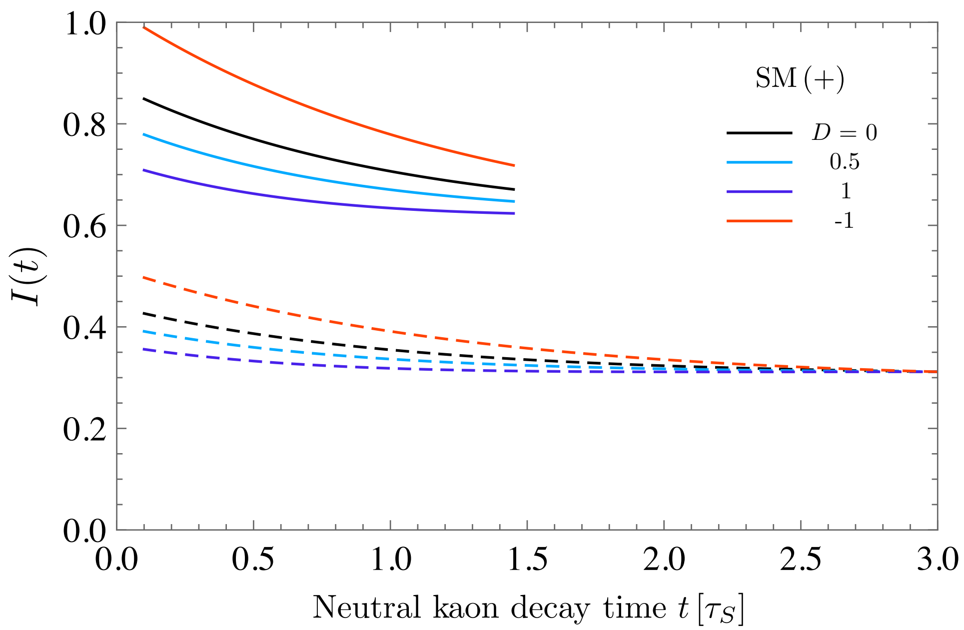
- Different implications (correlations & predictions) for other observables appear depending on models $\Rightarrow$ Possibility of model discriminations

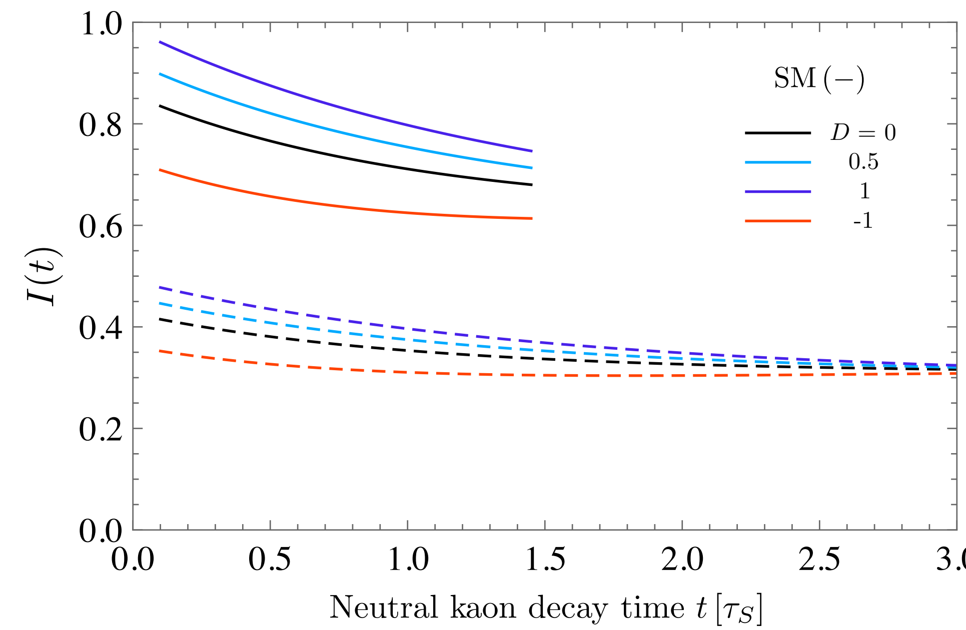
Can we study $K^0(t)$?

GD , Kitahara
1707.06999 PRL

$$pp \to K^0 K^- X$$

$$pp \to K^{*+} X \to K^0 \pi^+ X$$





$$|\overset{(-)}{K}{}^0(t)\rangle = \frac{1}{\sqrt{2}(1 \pm \bar{\epsilon})} \left[e^{-iH_S t} \left(|K_1\rangle + \bar{\epsilon}|K_2\rangle \right) \pm e^{-iH_L t} \left(|K_2\rangle + \bar{\epsilon}|K_1\rangle \right) \right]$$

$$D = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

- Short distance interfering with Large CP conserving LD contribution !

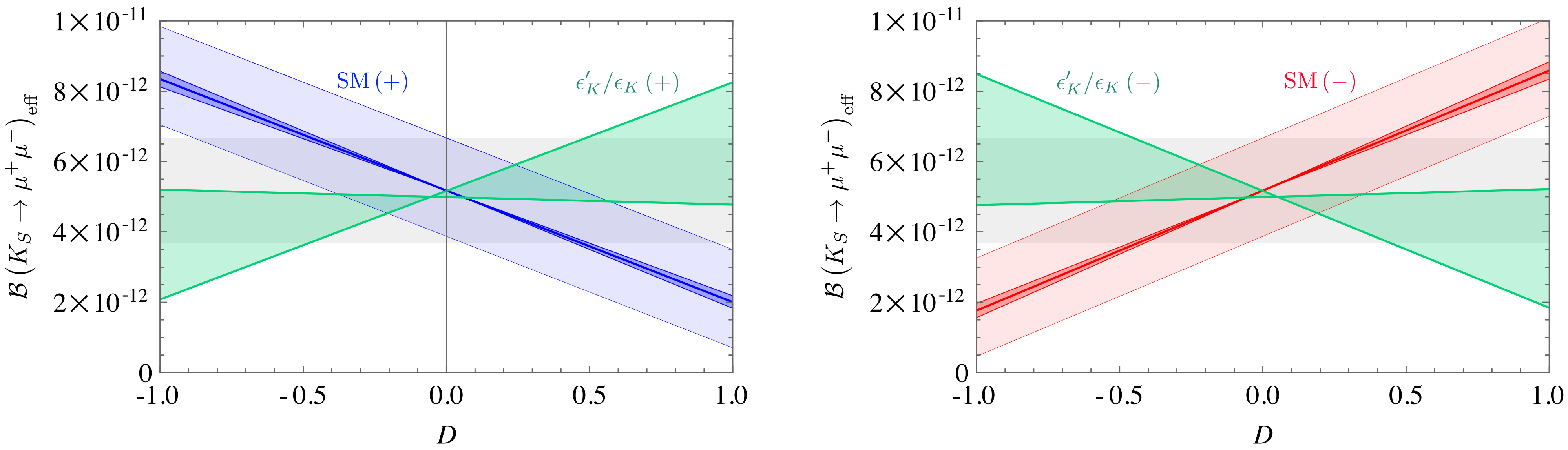
- We may be able to study the time evolution of K^0 by tracking the associated particles (K^-)

$$\sum_{\text{spin}} \mathcal{A}(K_1 \to \mu^+\mu^-)^* \mathcal{A}(K_2 \to \mu^+\mu^-)$$

$$\underline{\sim \mathrm{Im}[\lambda_t] y'_{7A}} \left\{ A^{\mu}_{L\gamma\gamma} - 2\pi \sin^2\theta_W \left(\mathrm{Re}[\lambda_t] y'_{7A} + \mathrm{Re}[\lambda_c] y_c \right) \right\}$$

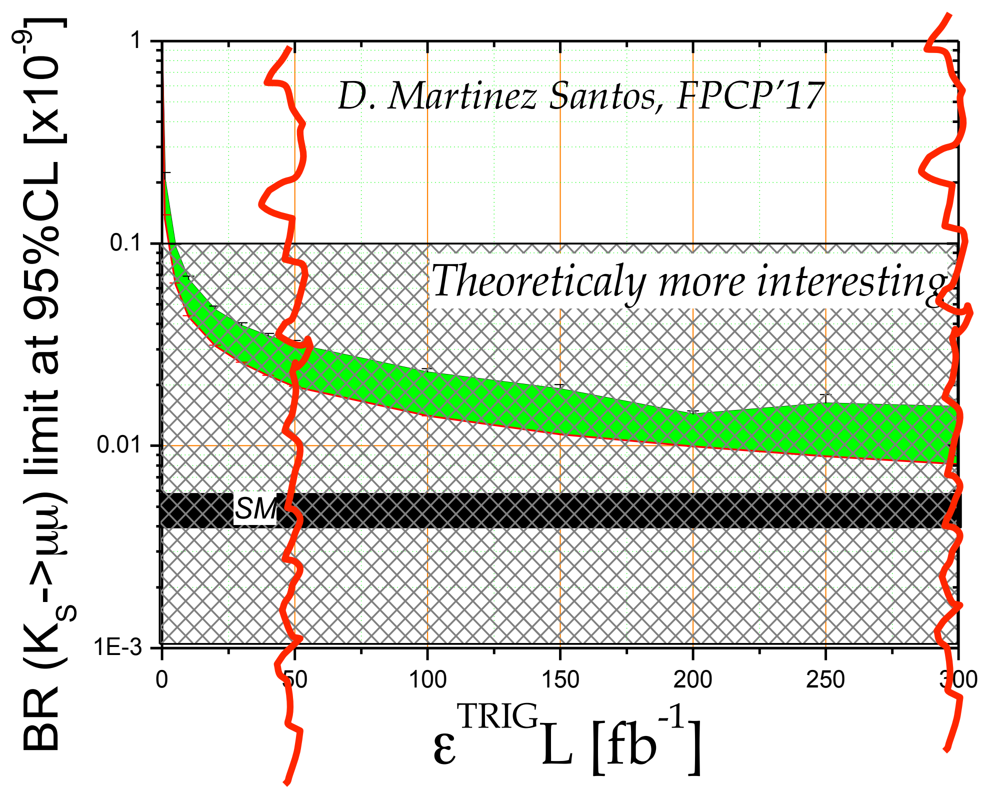
GD , Kitahara
1707.06999 PRL

Short distance window



$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm eff}$$
$$= \tau_S \left[\int_{t_{min}}^{t_{max}} dt \left(\Gamma(K_1) e^{-\Gamma_S t} + \frac{D}{8\pi M_K} \sqrt{1 - \frac{4m_\mu^2}{M_K^2}} \sum_{\rm spin} {\rm Re}\left[e^{-i\Delta M_K t} \mathcal{A}(K_1)^* \mathcal{A}(K_2) \right] e^{-\frac{\Gamma_S+\Gamma_L}{2} t} \right) \varepsilon(t) \right]$$
$$\times \left(\int_{t_{min}}^{t_{max}} dt\, e^{-\Gamma_S t}\, \varepsilon(t) \right)^{-1},$$

$K_S \rightarrow \mu\ \mu$ prospects



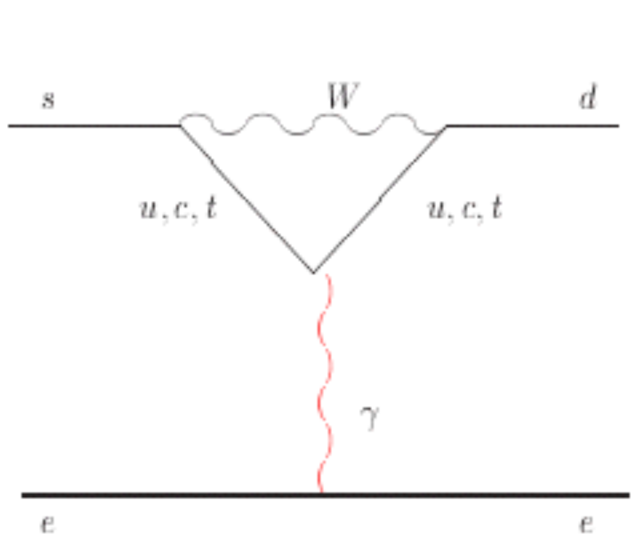
LHCb-upgrade *Phase-II-upgrade?*

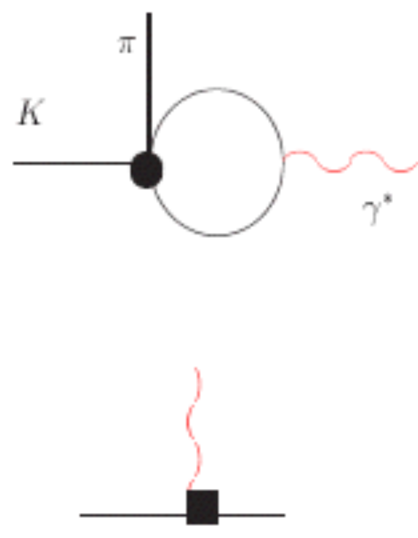
- Extrapolating from Run-I result
- The most interesting region can be achieved by LHCb upgrade with trigger improvements
- Starting to investigate tagged decays, which would allow to access NP in the K_S-K_L interference [D'Ambrosio&Kitahara https://arxiv.org/abs/1707.06999]

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

- 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 $a_S,\ b_S$

$$a_+^{\text{exp.}} = -0.578 \pm 0.016$$

averaging flavour

$$b_+^{\text{exp.}} = -0.779 \pm 0.066 \,.$$

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

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

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

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

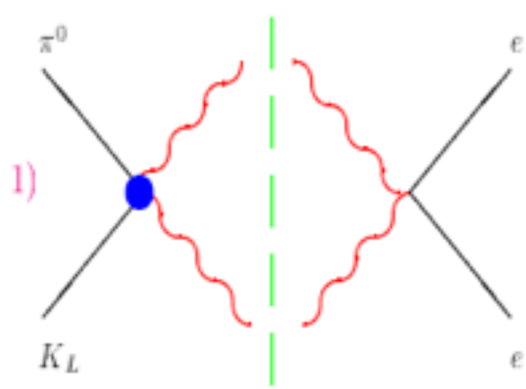
- $K_S \to \pi^0 \mu^+ \mu^-$ 6 events observed

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

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

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

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

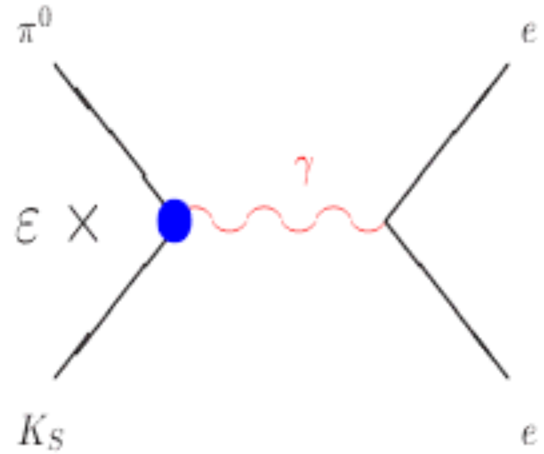


CP conserving NA48

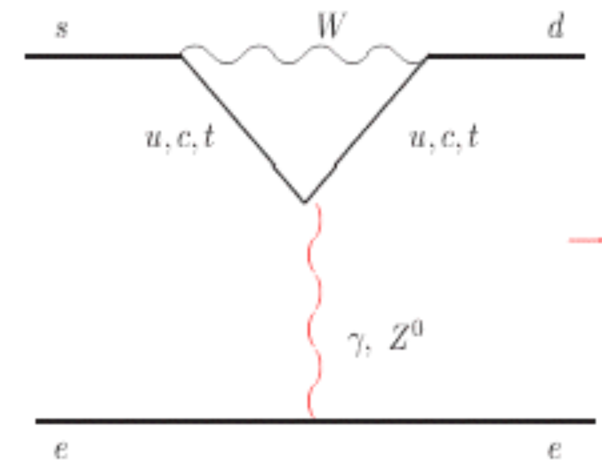
$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$

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) $\varepsilon \times$



$+$ 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

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

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

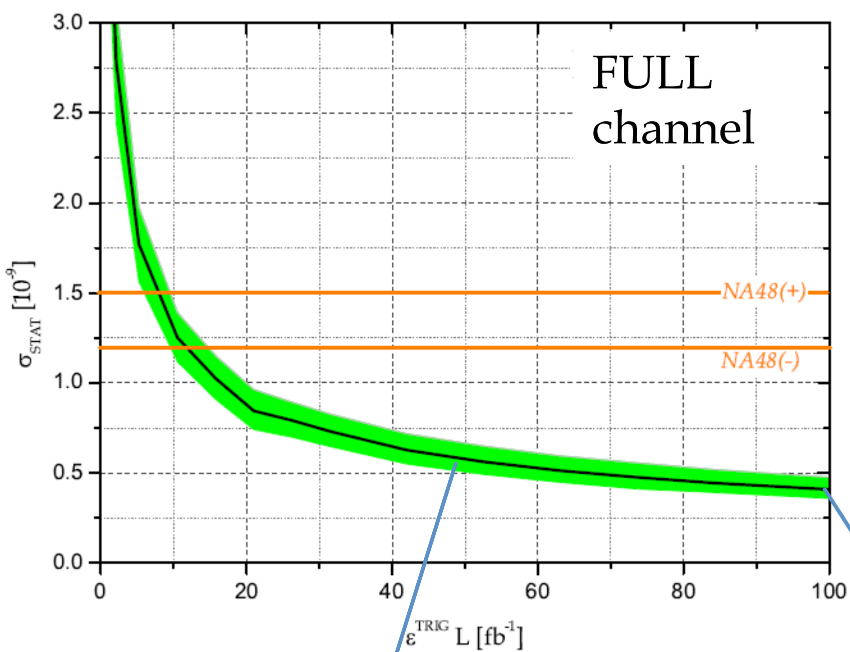
$K_S \rightarrow \pi^0 \mu\mu$ sensitivity study

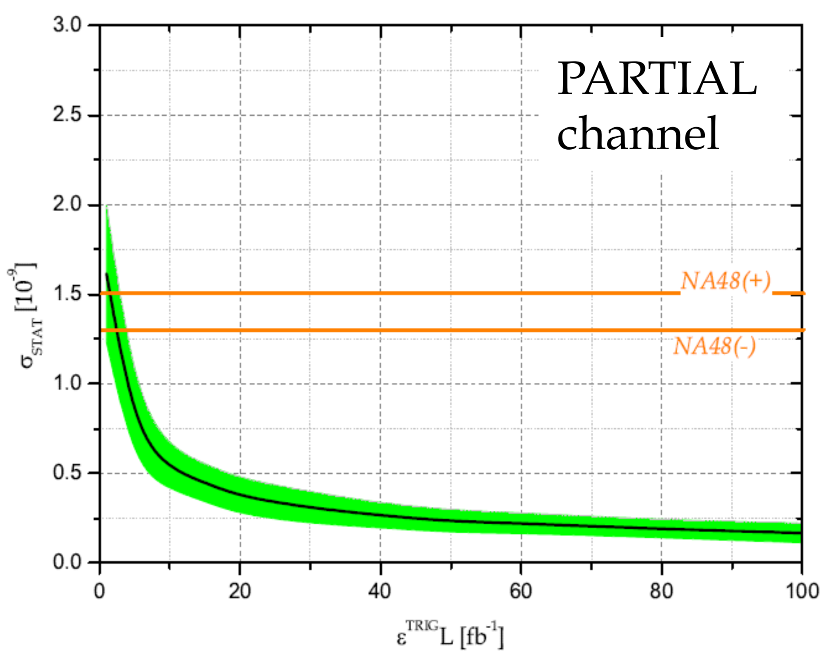
CERN-LHCb-PUB-2016-017

$K_S \rightarrow \pi^0 \mu\ \mu$ sensitivity study

V. Chobanova et al,
CERN-LHCb-PUB-2016-017

Normalize yields to $K_S \rightarrow \pi\ \pi$ → sensitivity to BR





LHCb Upgrade, 100 % eff

LHCb HL-LHC
100 fb $^{-1}$ 100 % eff
or 300 fb $^{-1}$ 33 % eff

$K_S \to \pi^0 \mu\mu$ short distance?

$$A_{FB}^{K_S^{\pi^0 \mu\mu}}(z) = \frac{\Gamma(\cos\theta_{K\mu} > 0) - \Gamma(\cos\theta_{K\mu} < 0)}{\Gamma(\cos\theta_{K\mu} > 0) + \Gamma(\cos\theta_{K\mu} < 0)}$$

- sensitive to short distance physics
- several background to control $\quad (\quad \epsilon_K \quad |a_S|^2 \quad)$

$$K_S \to \pi^+\pi^-\mu\mu \sim 10^{-14}$$

$$K_S \to \pi^+\pi^- ee \sim 10^{-5}$$

$\Gamma(K_S^0 \to \pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$

VALUE (10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.79 ± 0.15	**OUR AVERAGE**				
4.83 ±0.11 ±0.14	23k	[1] BATLEY	2011	NA48	2002 data
4.69 ±0.30	676	[2] LAI	2003C	NA48	1998+1999 data

• • • We do not use the following data for averages, fits, limits, etc. • • •

$$K(p_K) \to \pi(p_1)\pi(p_2)\gamma(q)$$

- Lorentz + gauge invariance $\Rightarrow$ Electric (E) and Magnetic(M) amplitude

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K\partial_\nu\pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K\partial^\sigma\pi\right]$$

- Unpolarizated photons

$$\frac{d^2\Gamma}{dz_1 dz_2} \sim |E|^2 + |M|^2$$

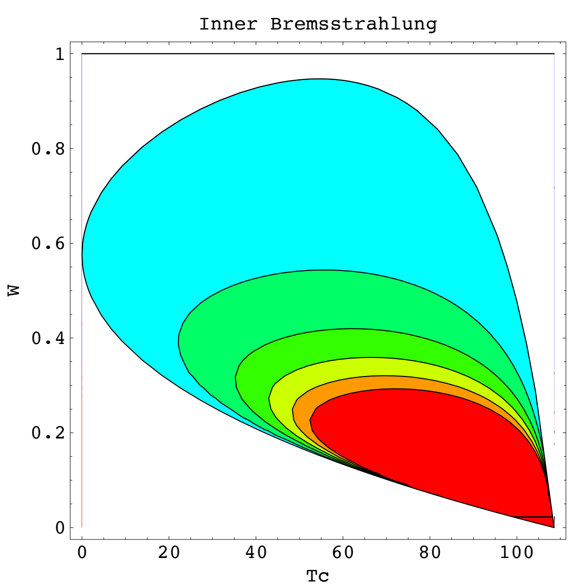
$$|E^2| = |E_{IB}|^2 + 2Re(E^*_{IB}E_D) + |E_D|^2$$

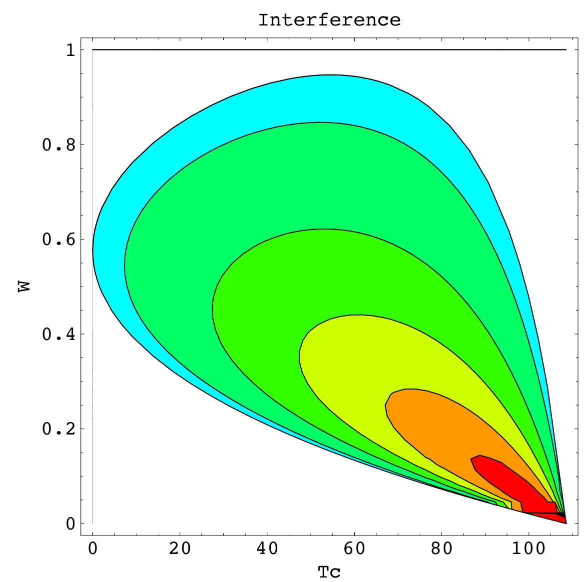
$$\downarrow$$

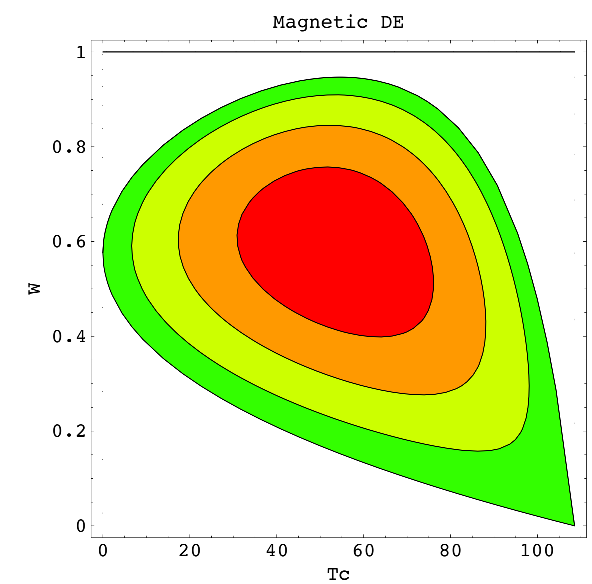
Low Theorem $\Rightarrow E_{IB} \sim \frac{1}{E^*_\gamma} +$ c $\qquad$ E_D, M chiral tests

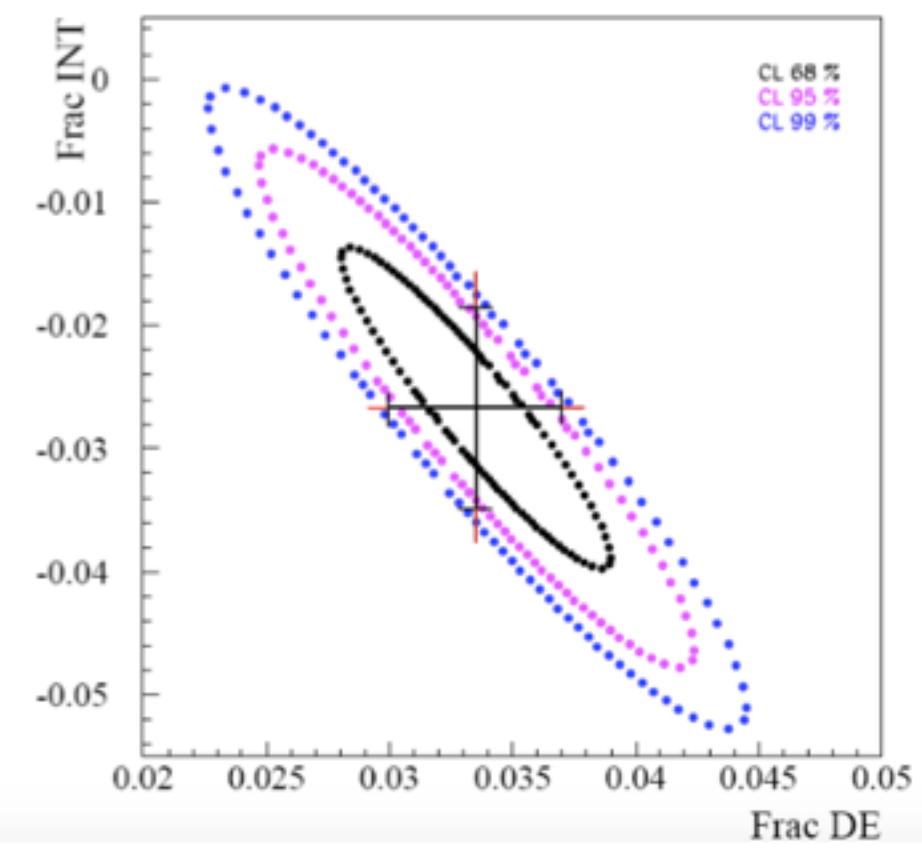
$$K^+ \to \pi^+\pi^0\gamma$$

Dalitz plot NA48/2







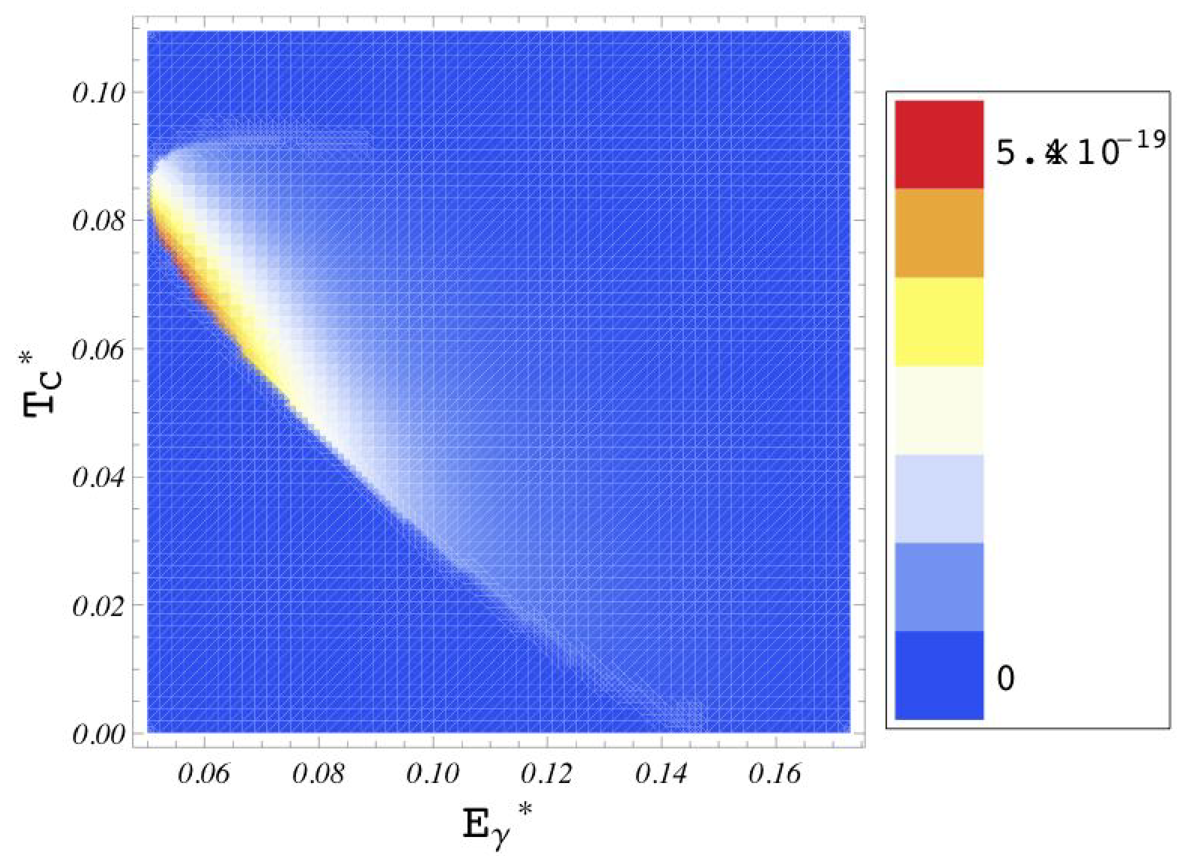


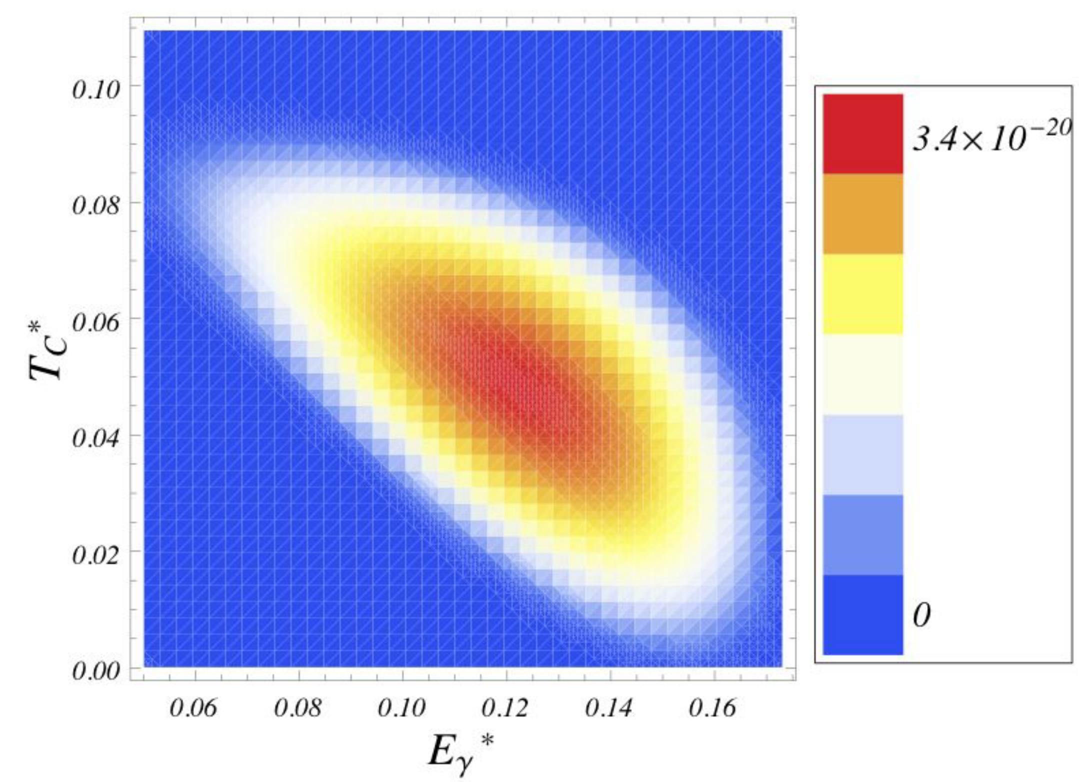
$K^+ \to \pi^+\pi^0 ee$

Cappiello Cata GD Gao

Starting from CP conserving IB, DE

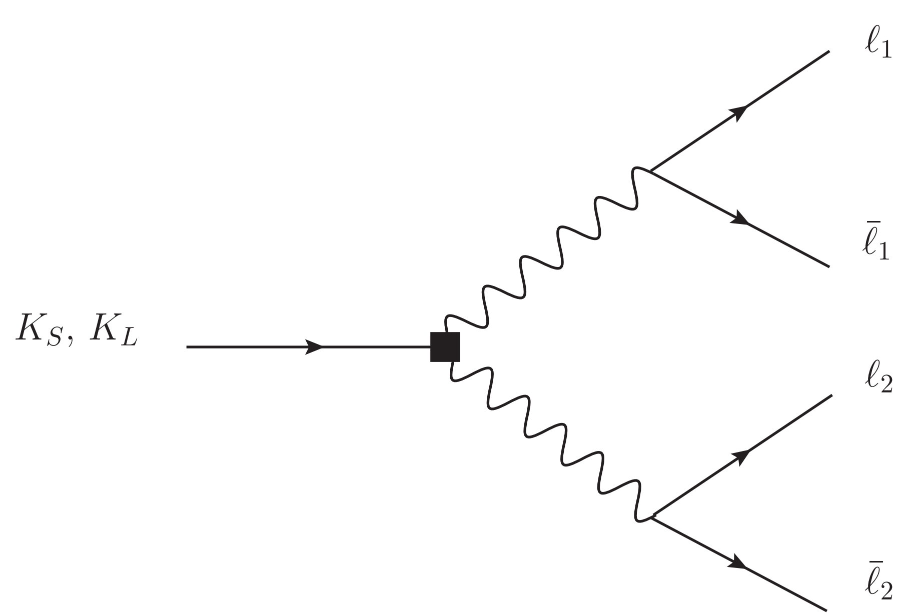
q_c (MeV)	B $[10^{-8}]$	B/M	B/E	B/BE	B/BM
$2m_l$	418.27	71	4405	128	208
55	5.62	12	118	38	44
100	0.67	8	30	71	36
180	0.003	12	5	-19	44





Interesting channels

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



GD,Greynat, Vulvert

Hyperons

- Hyperon semileptonic decays/Vus determination
- Search for resonance (Hypercp) $\Sigma \to p\mu\mu$

PDG Live — particle data group — Send Feedback

Home | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

$\Xi^- \to \Lambda \mu^- \overline{\nu}_\mu$

$\Gamma(\Xi^- \to \Lambda \mu^- \overline{\nu}_\mu)/\Gamma(\Xi^- \to \Lambda \pi^-)$

VALUE (10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.35^{+0.35}_{-0.22}$	**OUR FIT**					
0.35 ± 0.35		1	YEH	1974	HBC	Effective denom.=2859
*** We do not use the following data for averages, fits, limits, etc ***						
<2.3	90	0	THOMPSON	1980	ASPK	Effective denom.=1017
<1.3			DAUBER	1969	HBC	
<12			BERGE	1966	HBC	

References

THOMPSON	1980	PR D21 25	Studies in the BNL 21 GeV/c Negative Hyperon Beam.
YEH	1974	PR D10 3545	Observation of Rare Decay Modes of the Ξ Hyperons
DAUBER	1969	PR 179 1262	Production and Decay of Cascade Hyperons
BERGE	1966	PR 147 945	Some Properties of Ξ^- and Ξ^0 Hyperons Produced in 1.7 GeV/c

see fit info

$\Lambda \to p \mu^- \overline{\nu}_\mu$

$\Gamma(\Lambda \to p \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda \to N\pi)$

VALUE (10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.57 ± 0.35	**OUR FIT**				
1.57 ± 0.35	**OUR AVERAGE**				
1.4 ± 0.5	14	BAGGETT	1972B	HBC	$K^- p$ at rest
2.4 ± 0.8	9	CANTER	1971B	HBC	$K^- p$ at rest
1.3 ± 0.7	3	LIND	1964	RVUE	
1.5 ± 1.2	2	RONNE	1964	FBC	

References

BAGGETT	1972B	ZPHY 252 362	Measurement of the $\Lambda \to p\mu^-\overline{\nu}_\mu$ Branching Ratio
CANTER	1971B	PRL 27 59	Branching Ratio for $\Lambda \to p\mu\overline{\nu}_\mu$
LIND	1964	PR 135 B1483	Experimental Investigation of $V - A$ in Leptonic Λ Decay
RONNE	1964	PL 11 357	Branching Ratio for the Muonic Decay Mode of the Λ Hyperon

see fit info

- Most data in the μ-channel is very old (60's and 70's)! $\delta\text{Br}/\text{Br} \sim 10\% - 100\%$

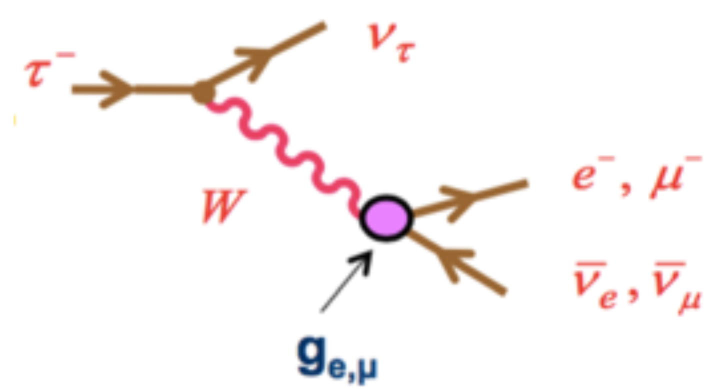
	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
Expt.	0.189(41)	0.442(39)	0.0092(14)	0.6(5)
SM-NLO	0.153(8)	0.444(22)	0.0084(4)	0.275(14)

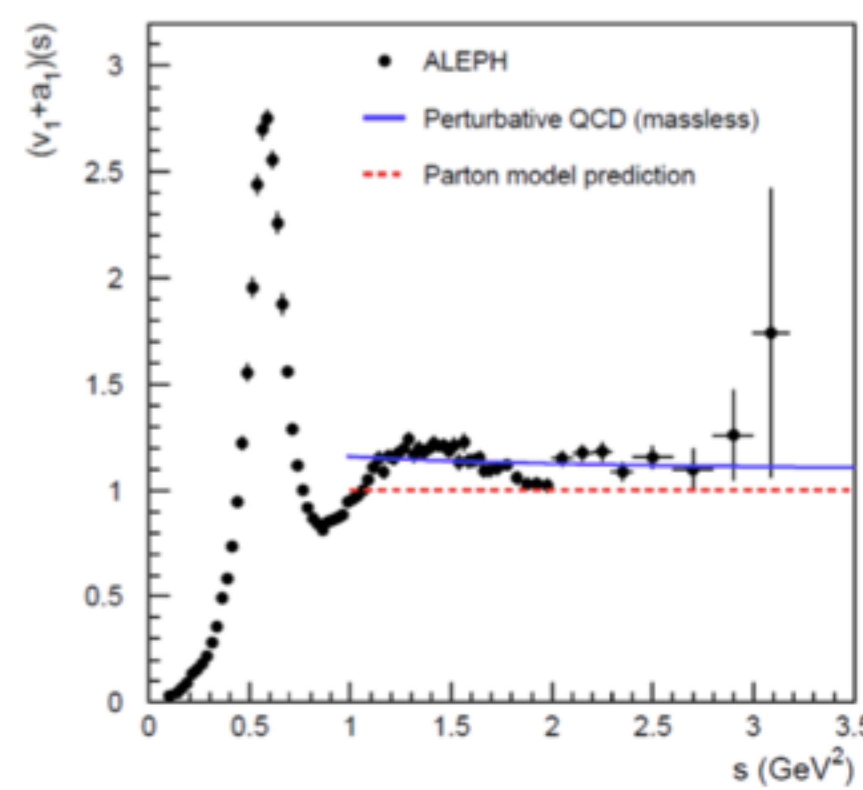
- Good agreement between SM and data $\Rightarrow$ Bounds on $\epsilon_S^{s\ell}$ and $\epsilon_T^{s\ell}$

Possible tau issues

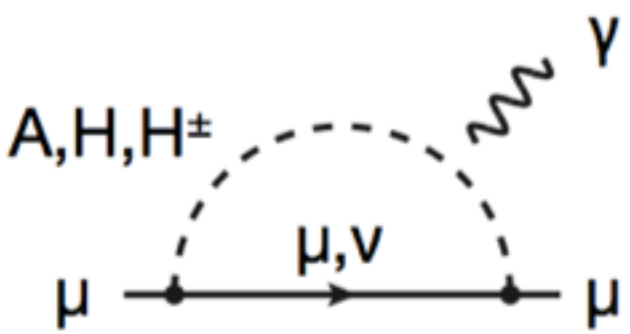
Experiment	Number of τ pairs
LEP	~3x10^5
CLEO	~1x10^7
BaBar	~5x10^8
Belle	~9x10^8
Belle II	~10^{12}

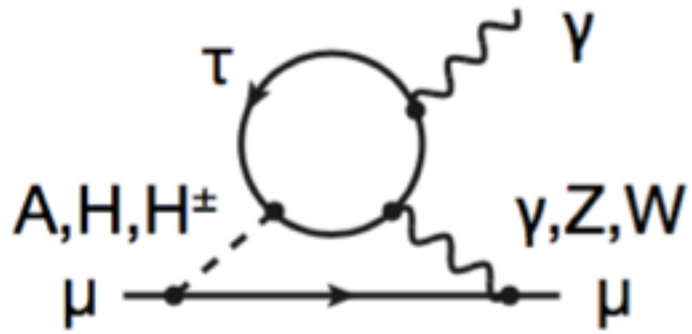
- Leptonic universality
- QCD tests
- Vus
- Lepton flavour universality





- The lepton universality tests give strong constraints on type-X (lepton-specific) 2HDMs ⇨ Model favoured to explain the g-2 discrepancy





M. Endo@b2tip'15

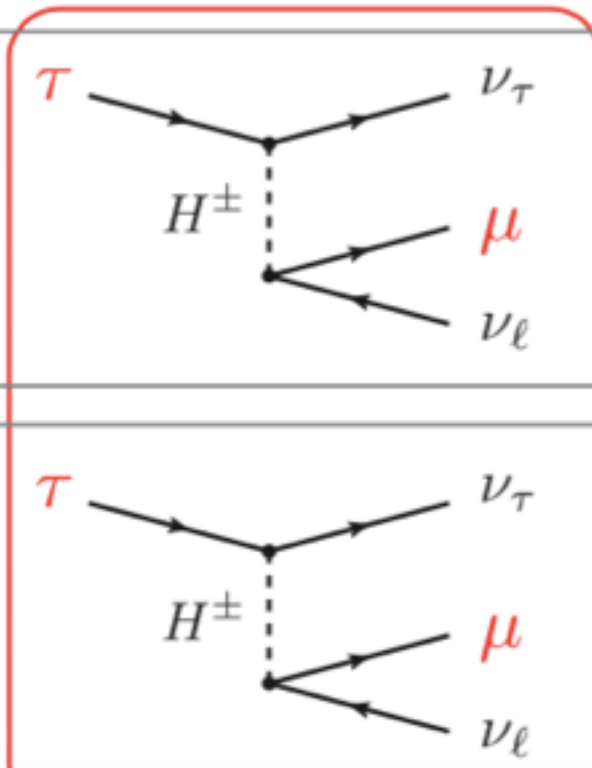
Barr-Zee contribution with A enhances muon g-2

⇨ Contribution to LU :

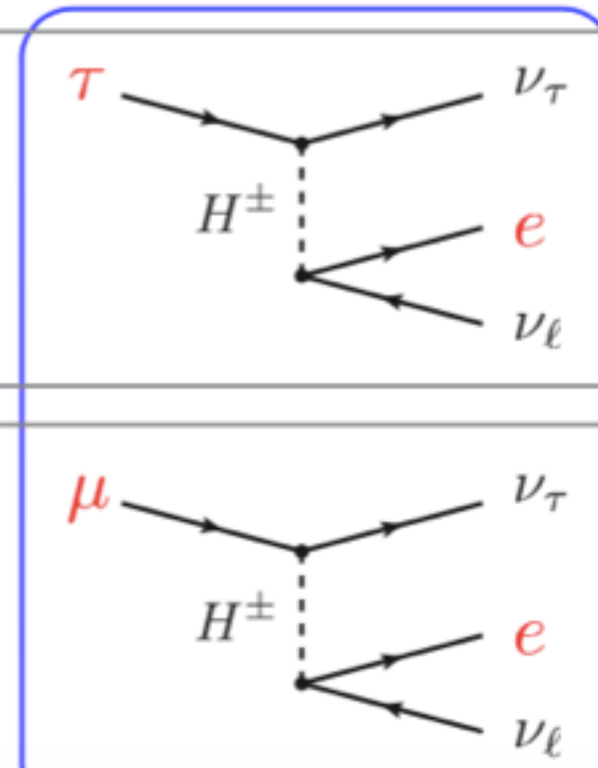
$$\frac{g_\mu}{g_e} = \frac{1+\Delta_{\tau\to\mu}}{1+\Delta_{\tau\to e}} = 1.0018 \pm 0.0014$$

$$\frac{g_\tau}{g_e} = \frac{1+\Delta_{\tau\to\mu}}{1+\Delta_{\mu\to e}} = 1.0029 \pm 0.0015$$

Large



Negligible



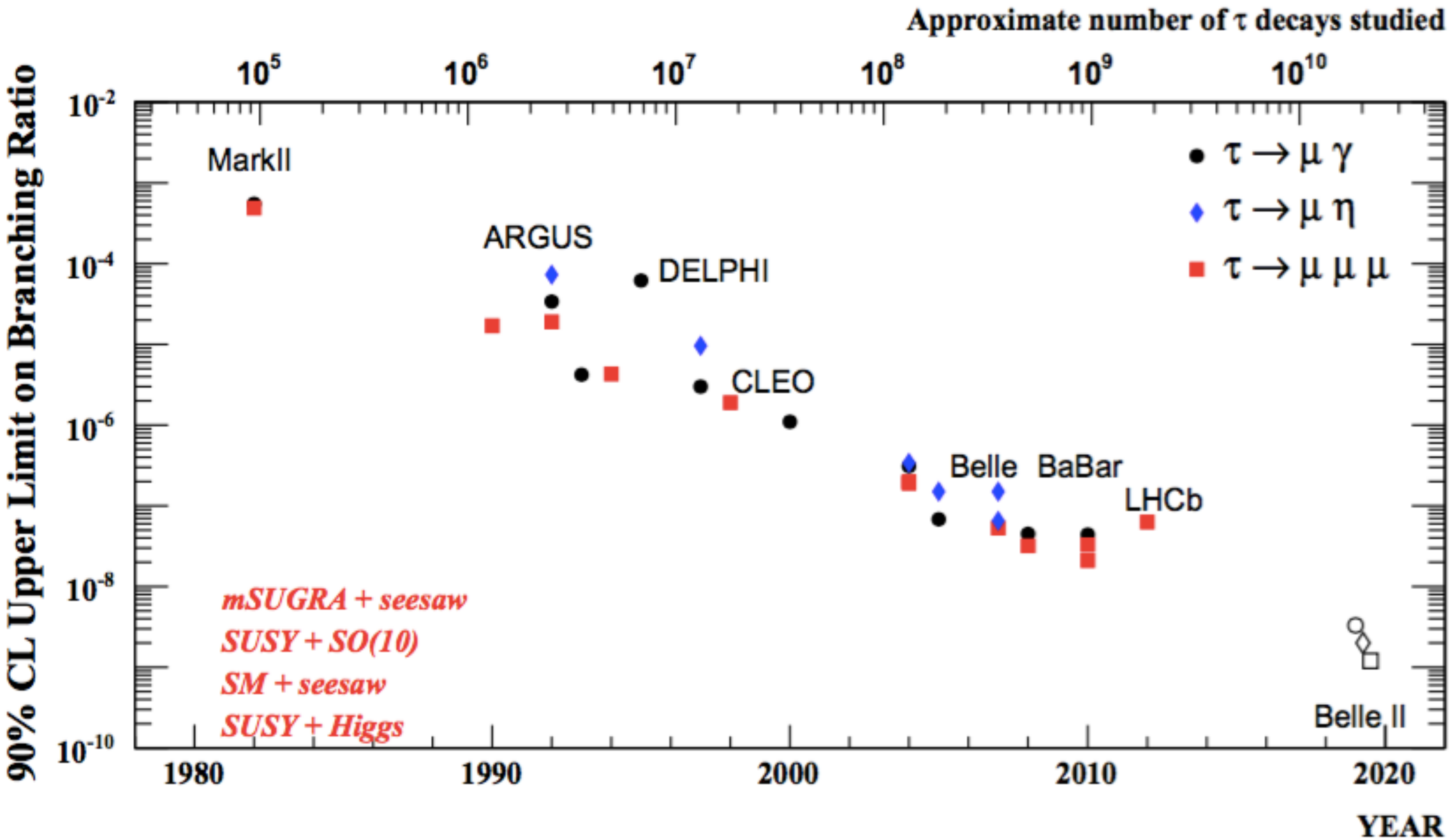
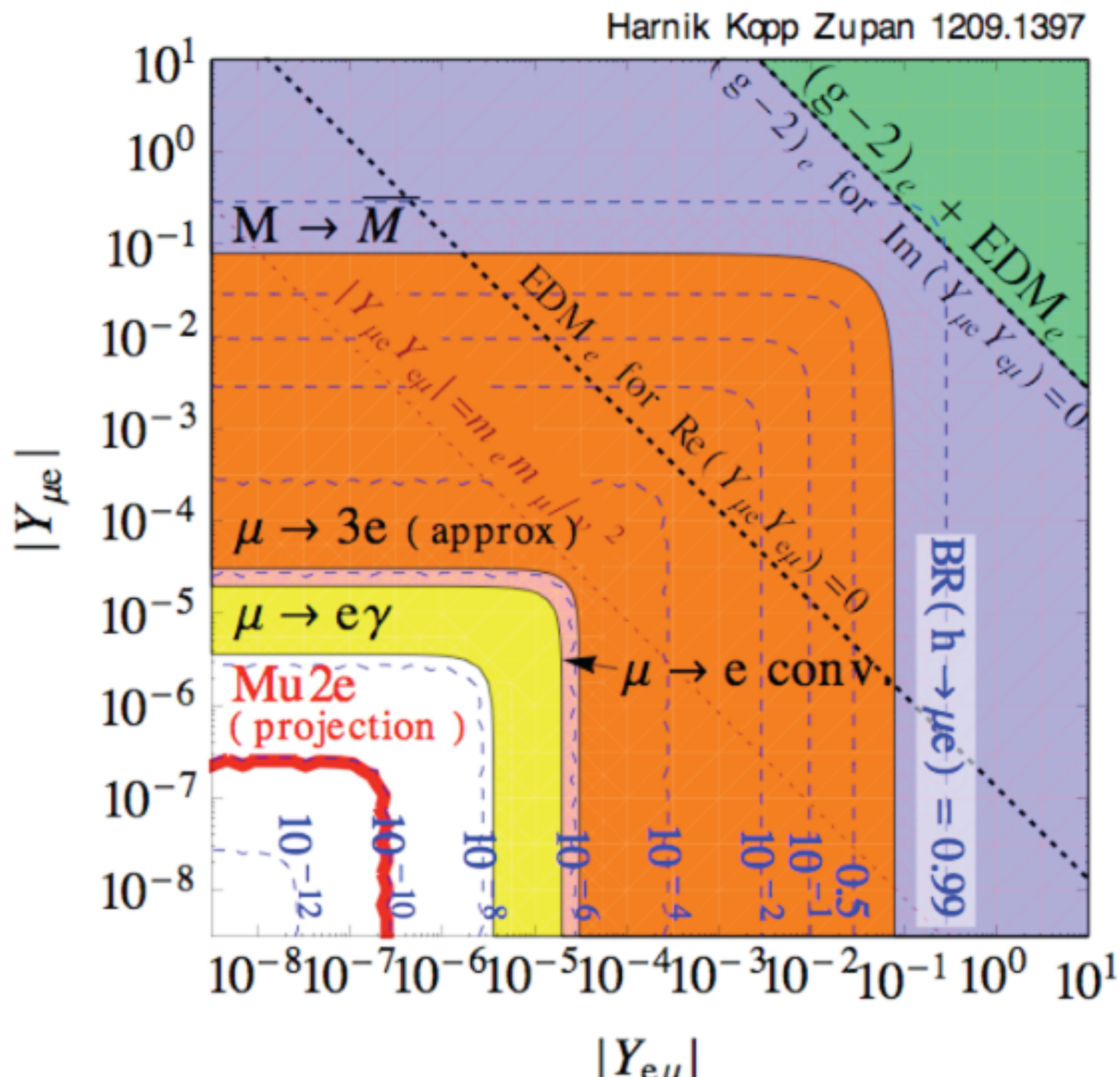


Figure 5: Evolution of 90% CL upper limit on LFV in τ decays vs. approximate number of τ decays studied.

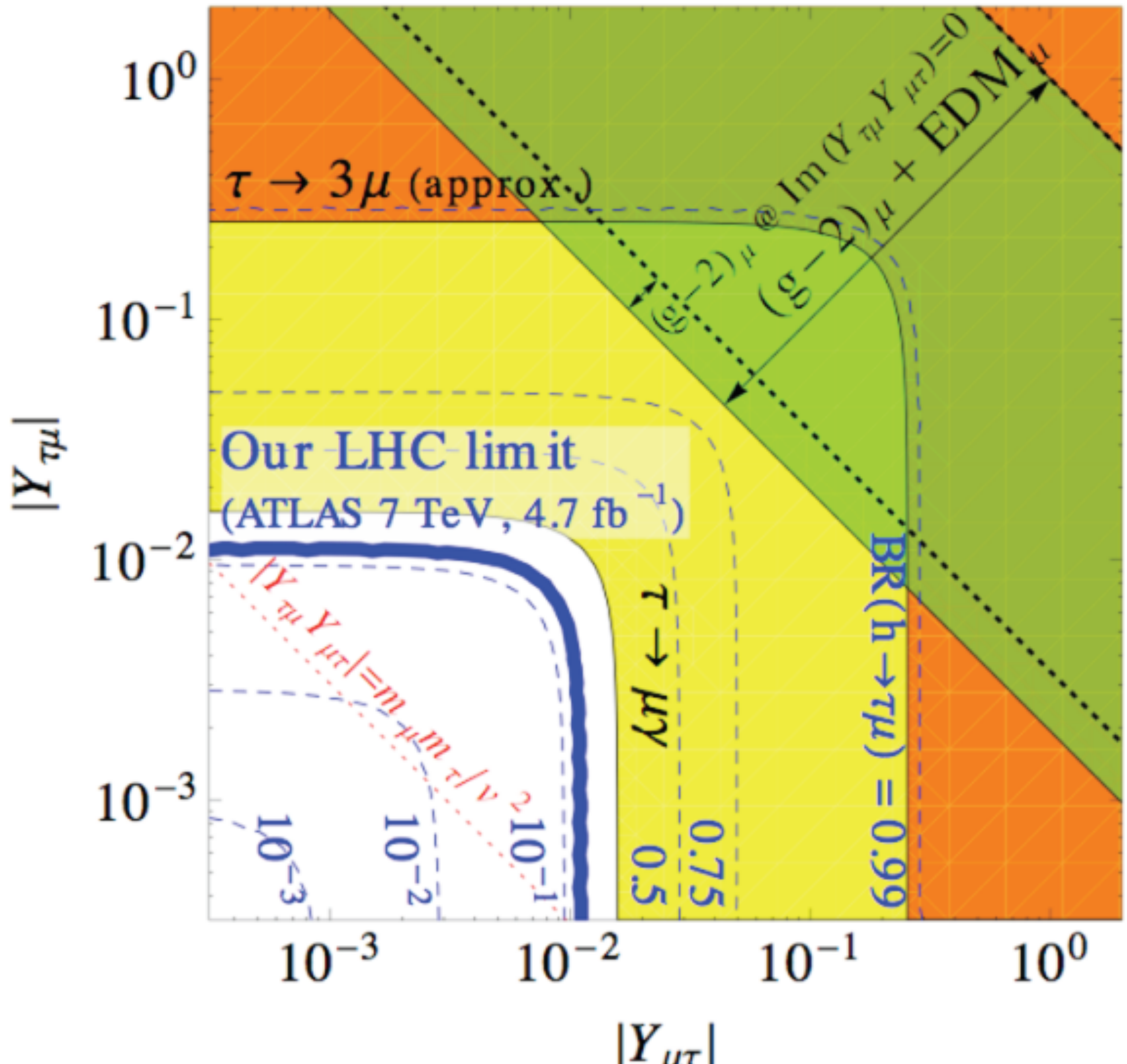
Higgs couplings to μe



Outside of LHC reach.

Probing "natural" models.

Higgs couplings to $\tau\mu$



LHC $h \to \tau\mu$ gives dominant bound.

(currently just a theorist's re-interpretation)

"natural models" are within reach.

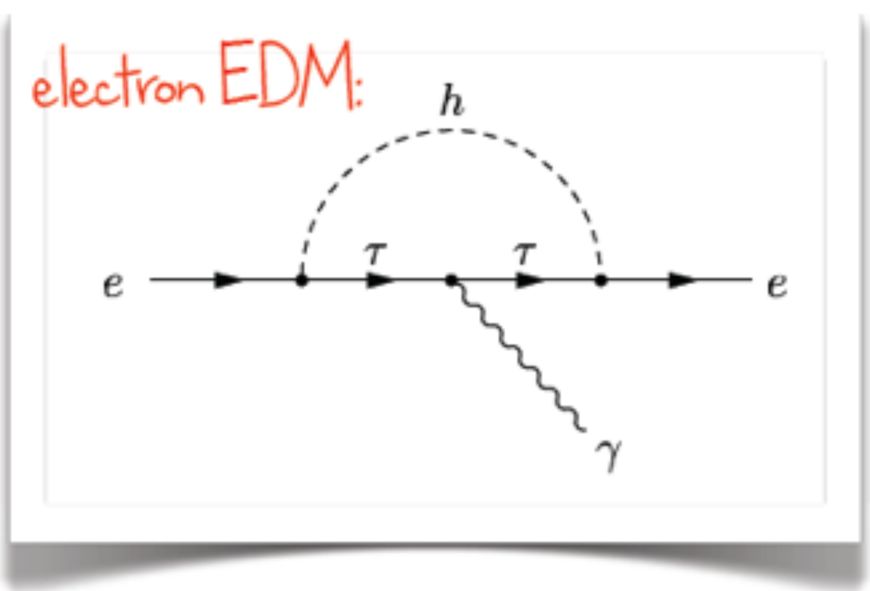
RH, Kopp, Zupan 1209.1397

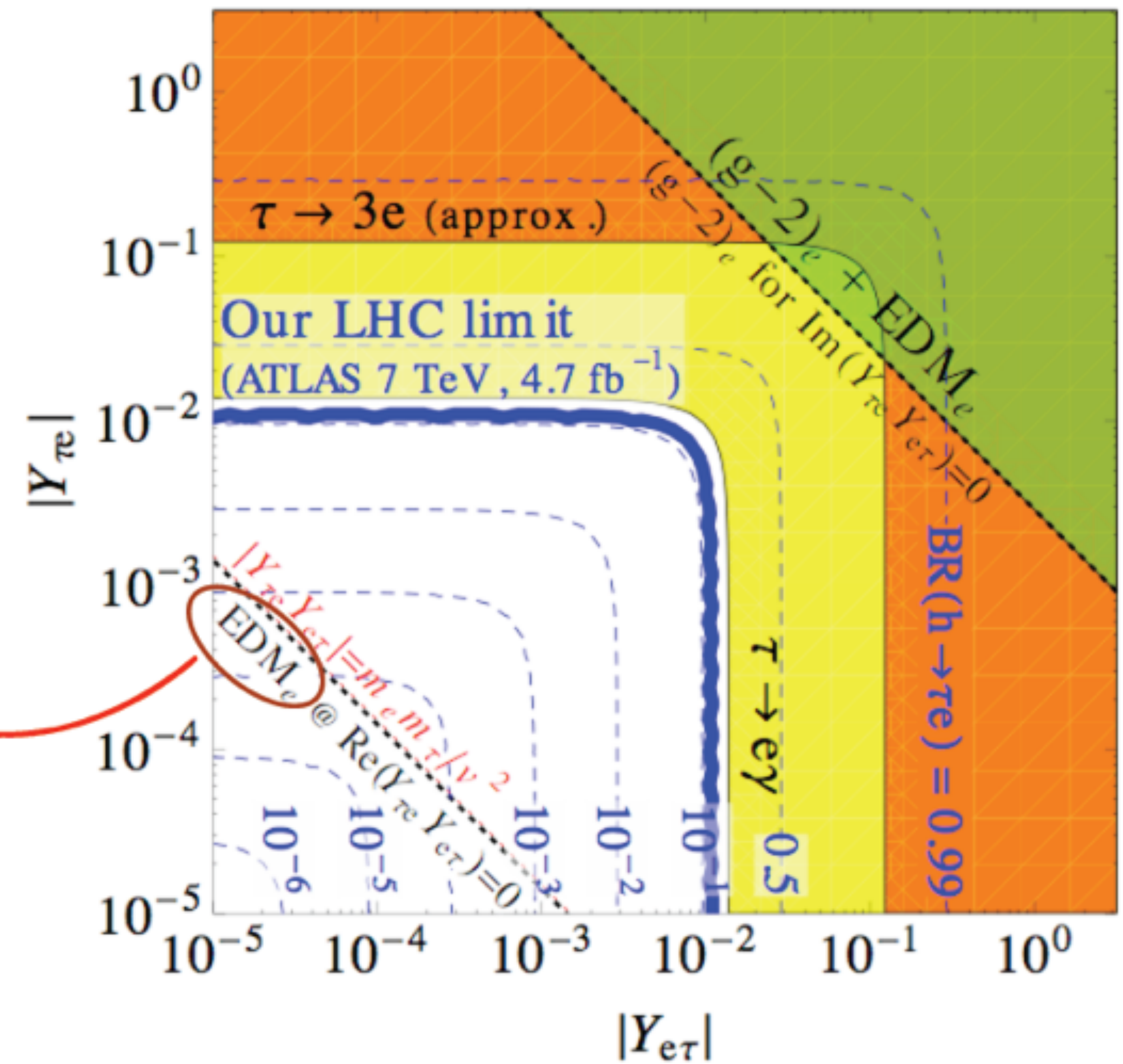
Higgs couplings to τe

* τe is similar to $\tau\mu$.... but:

Harnik, Kopp Zupan 1209.1397

Electron EDM is interesting here!



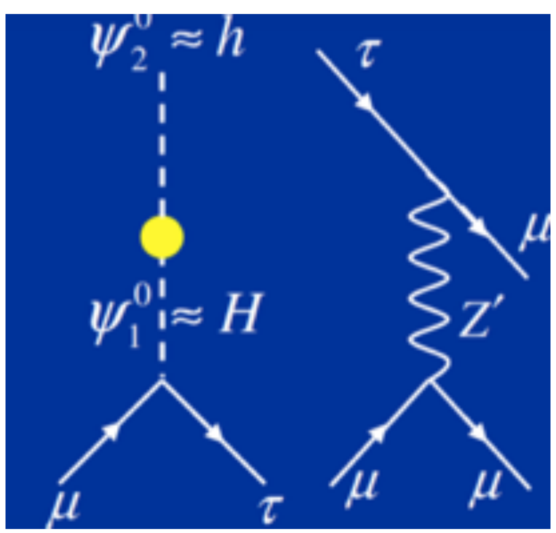


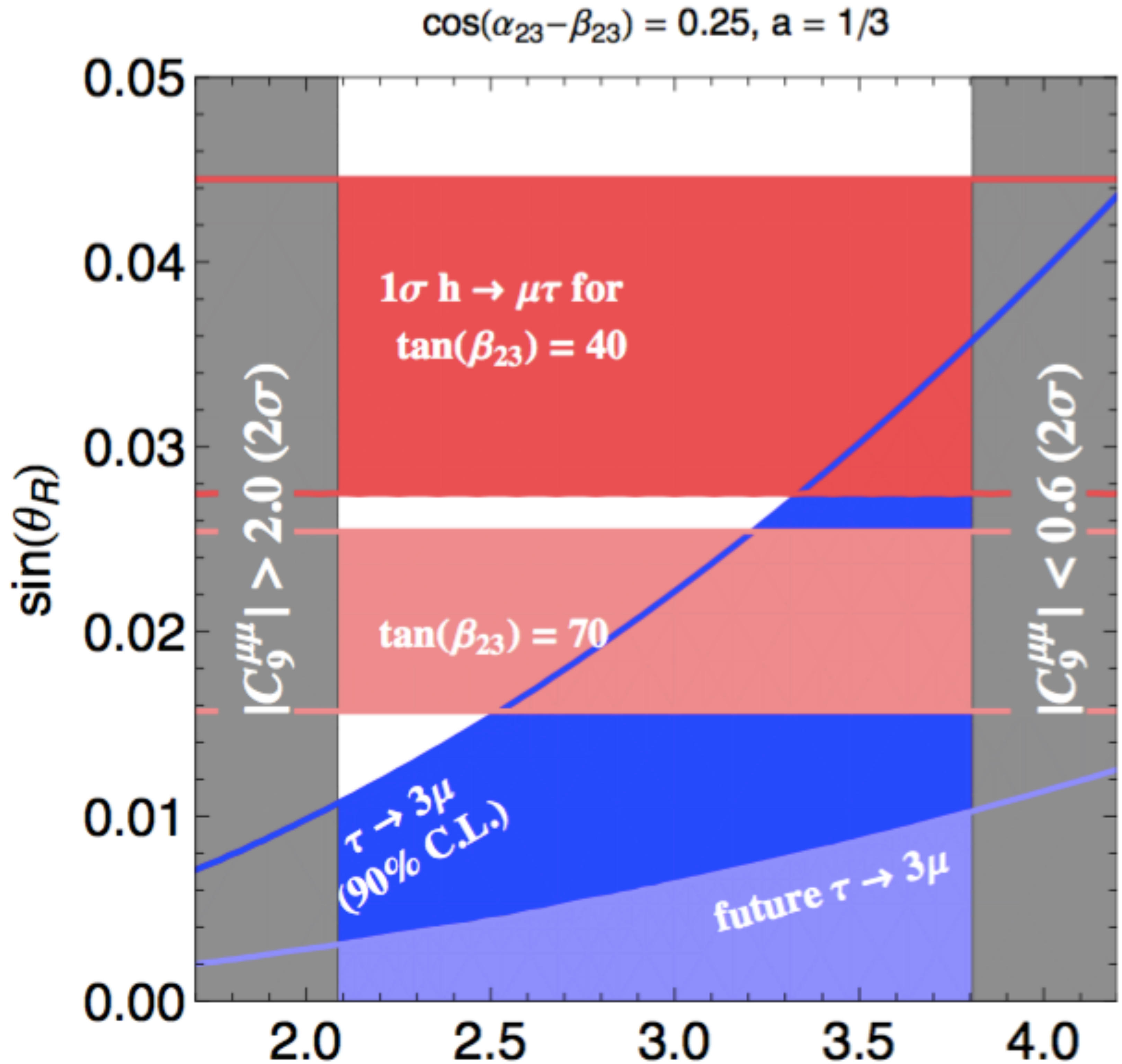
Altmannshofer & Straub'14,
Crivellin,GD, Heeck 15

Interplay

$H \to \mu\tau \qquad \tau \to 3\mu$

Motivated by B-anomalies
Z'-model with 2 higgs in
Lmu-Ltau model





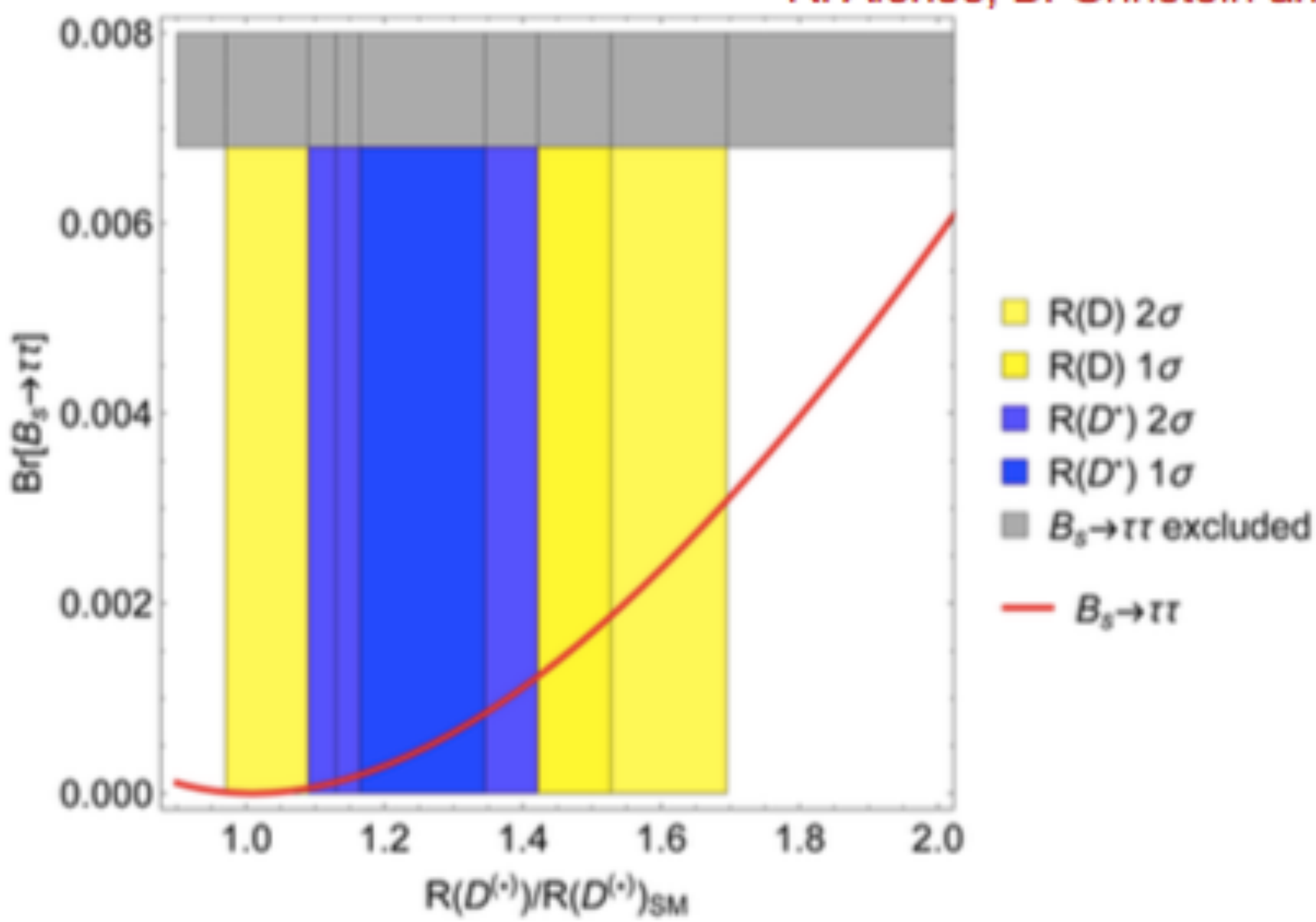
Conclusions

- My personal view: we are just at the beginning in exploring the potentiality: See KS->$\mu\mu$, also the improvement for Ecal (I did not discuss much ee in the final state)
- New ideas in this sector came out recently

R(D$^{(*)}$) and b→sττ with Leptoquarks

- Large couplings to the 2nd generation needed in order avoid collider bounds.
- Cancelation in b→sνν needed: C$^{(1)}$=-C$^{(3)}$

R. Alonso, B. Grinstein and J. Camalich, 1505.05164



B_s→ττ very strongly enhanced

Kaon physics

Tests of CPV already among most stringent (ε_K, ε')

Near future improvements mostly due to theory (Lattice)

More progress foreseen in rare decays

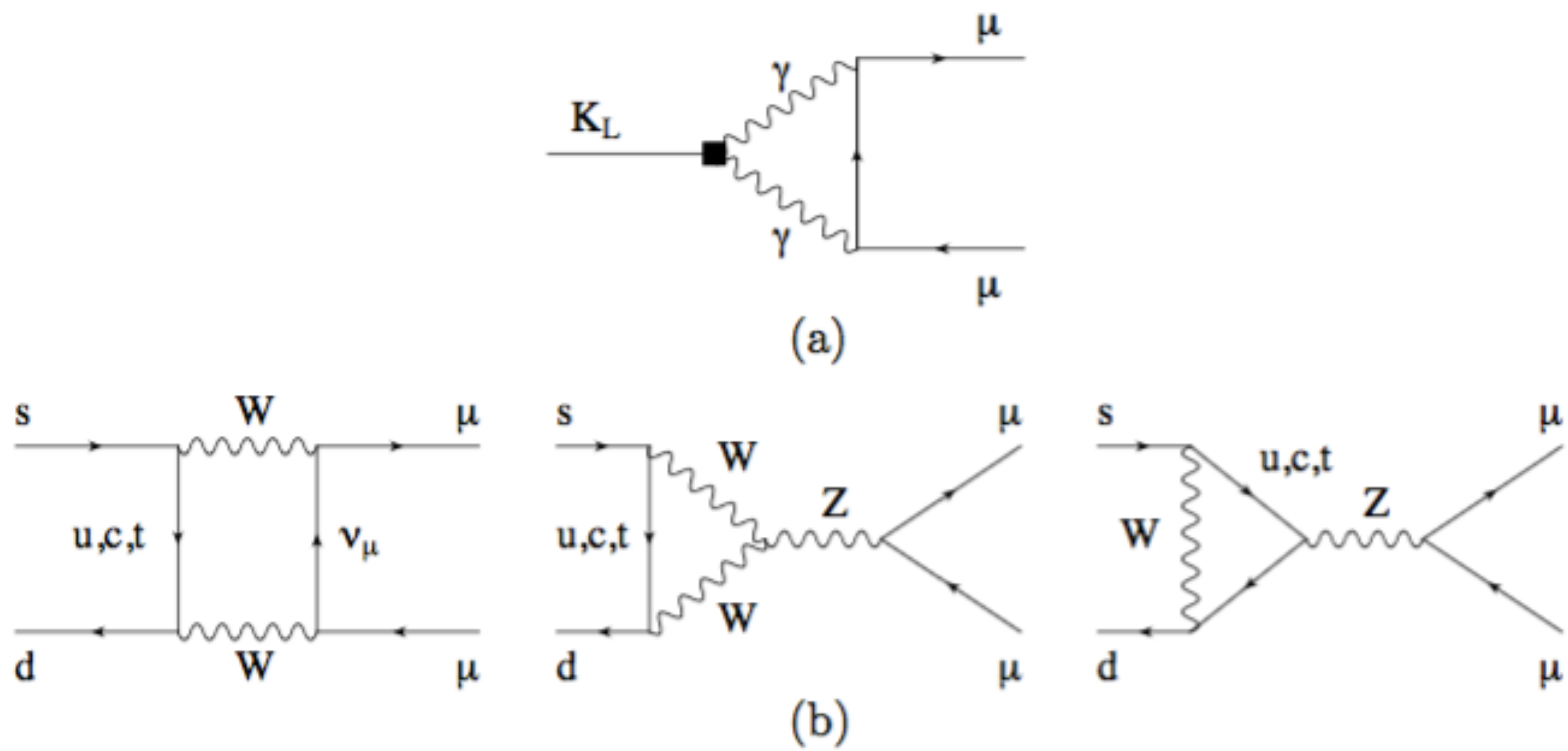
$\Rightarrow$ $K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}$

$\Rightarrow$ rare K decays at HL-LHCb?

d'Ambrosio, PoS(FPCP2015)018

	PDG	Prospects	
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	$(\mathrm{LD})(5.0 \pm 1.5) \cdot 10^{-12}$ $\quad \mathrm{NP} < 10^{-11}$	
$K_L \to \mu\mu$	$(6.84 \pm 0.11) \times 10^{-9}$	difficult : SD << LD	
$K_S \to \mu\mu\mu\mu$	–	SM LD $\sim 2 \times 10^{-14}$	
$K_S \to ee\mu\mu$	–	$\sim 10^{-11}$	NP?
$K_S \to eeee$	–	$\sim 10^{-10}$	
$K_S \to \pi^+\pi^-\mu^+\mu^-$	–	SM LD $\sim 10^{-14}$	

SD depends from a crucial sign



$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm SM} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} (+), \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9} (-), \end{cases}$$

$$\begin{aligned} \mathcal{B}(K_S \to \mu^+\mu^-)_{\rm SM} &= (4.99\,(\mathrm{LD}) + 0.19\,(\mathrm{SD})) \times 10^{-12} \\ &= (5.18 \pm 1.50 \pm 0.02) \times 10^{-12} \end{aligned}$$

We need FIGHT DE/IB$\sim 10^{-3}$

	IB	DE_{exp}	
$K_S \to \pi^+\pi^-\gamma$	10^{-3}	$< 9 \cdot 10^{-5}$	$E1$
$K^+ \to \pi^+\pi^0\gamma$	10^{-4} $(\Delta I = \frac{3}{2})$	$(0.44 \pm 0.07)10^{-5}$ PDG	$M1$,$E1$
$K_L \to \pi^+\pi^-\gamma$	10^{-5} (CPV)	$(2.92 \pm 0.07)10^{-5}$ KTeVnew	$M1$, VMD

CPV is only from IB K_L (also measured in $K_L \to \pi^+\pi^-e^+e^-$)

BUT IB suppressed in K^+ and K_L.

$$K^+ \to \pi^+\pi^0\gamma$$

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K \partial_\nu \pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K \partial^\sigma \pi\right]$$

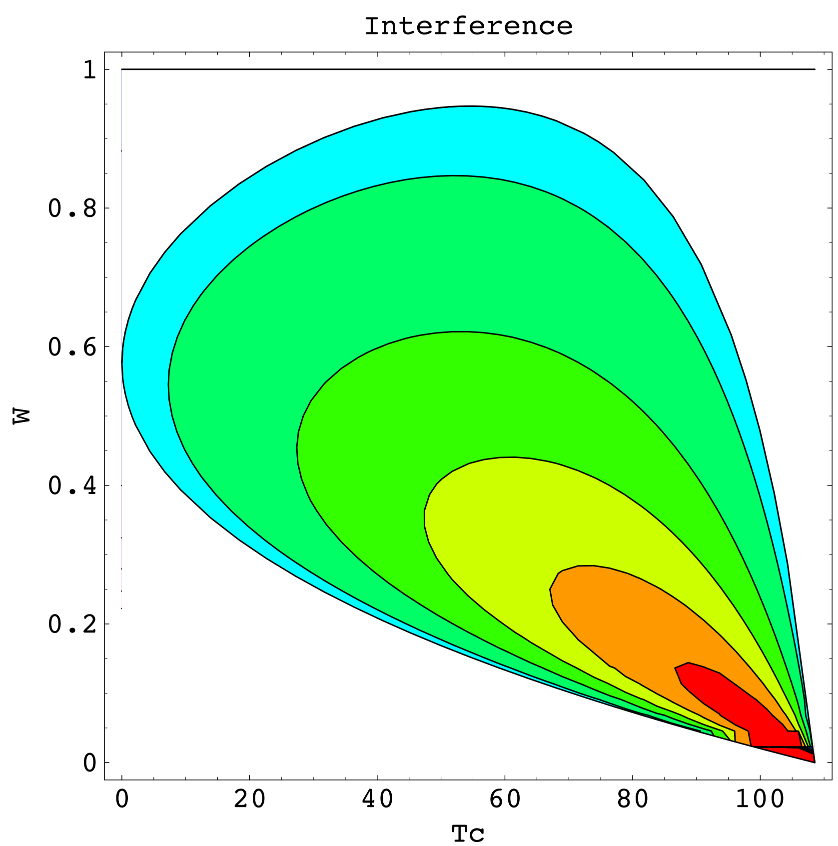
$E1$ and $M1$ are measured with Dalitz plot

$$\frac{\partial^2\Gamma}{\partial T_c^* \partial W^2} = \frac{\partial^2\Gamma_{IB}}{\partial T_c^* \partial W^2}\left[1 + \frac{m_{\pi^+}^2}{m_K} 2Re\left(\frac{E1}{eA}\right) W^2 + \frac{m_{\pi^+}^4}{m_K^2}\left(\left|\frac{E1}{eA}\right|^2 + \left|\frac{M1}{eA}\right|^2\right) W^4\right]$$

$$W^2 = (q \cdot p_K)(q \cdot p_+)/(m_\pi^2 m_K^2)$$

$$A = A(K^+ \to \pi^+\pi^0)$$

NA48/2 CP violation



Dalitz plot analysis crucial

SM $\leq \mathcal{O}(10^{-5})$ Paver et al.

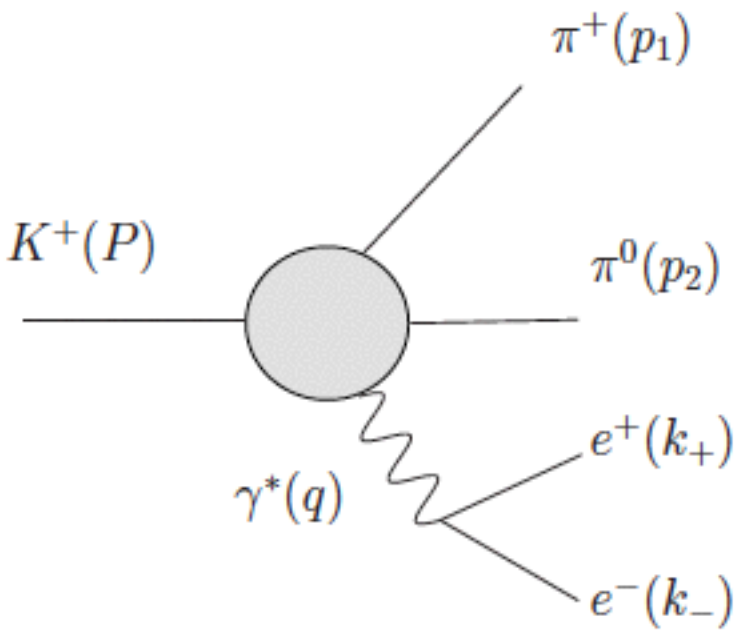
NP $\leq \mathcal{O}(10^{-4})$ Colangelo et al.

NA48/2 $< 1.5 \cdot 10^{-3}$ at 90% CL

BUT NOT in the interesting interf. kin. region (statistics)

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

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