# Kaon Phenomenology

Lattice Meets Phenomenology
IPPP, University of Durham
17.9.2010

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# Kaons and Fundamental Physics

- ➡ Determination of fundamental parameters
  - lepton universality
  - CKM unitarity
  - mass determination
- ➡ Test suppression of top-dominated FCNCs
  - rare decays
  - CP violation
- ➡ Interplay between SD & LD is essential

# Leptonic and Semileptonic

Observables: $K(\pi) \to l\bar{\nu}_l \quad \& \quad K \to \pi\, l\bar{\nu}_l$

$$\frac{\Gamma(K^{\pm}_{\ell 2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2}\right)^2 \times (1 + \delta_{\rm em})$$

Lattice

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{\rm ew} |V_{us}|^2 f_+(0)^2\, I_K^\ell(\lambda_{+,0}) \left(1 + \delta^K_{SU(2)} + \delta^{K\ell}_{\rm em}\right)^2$$

# CKM Unitarity

$$\Gamma(K_{l3}) \qquad |V_{us}|f_+(0) = 0.21661(47)$$

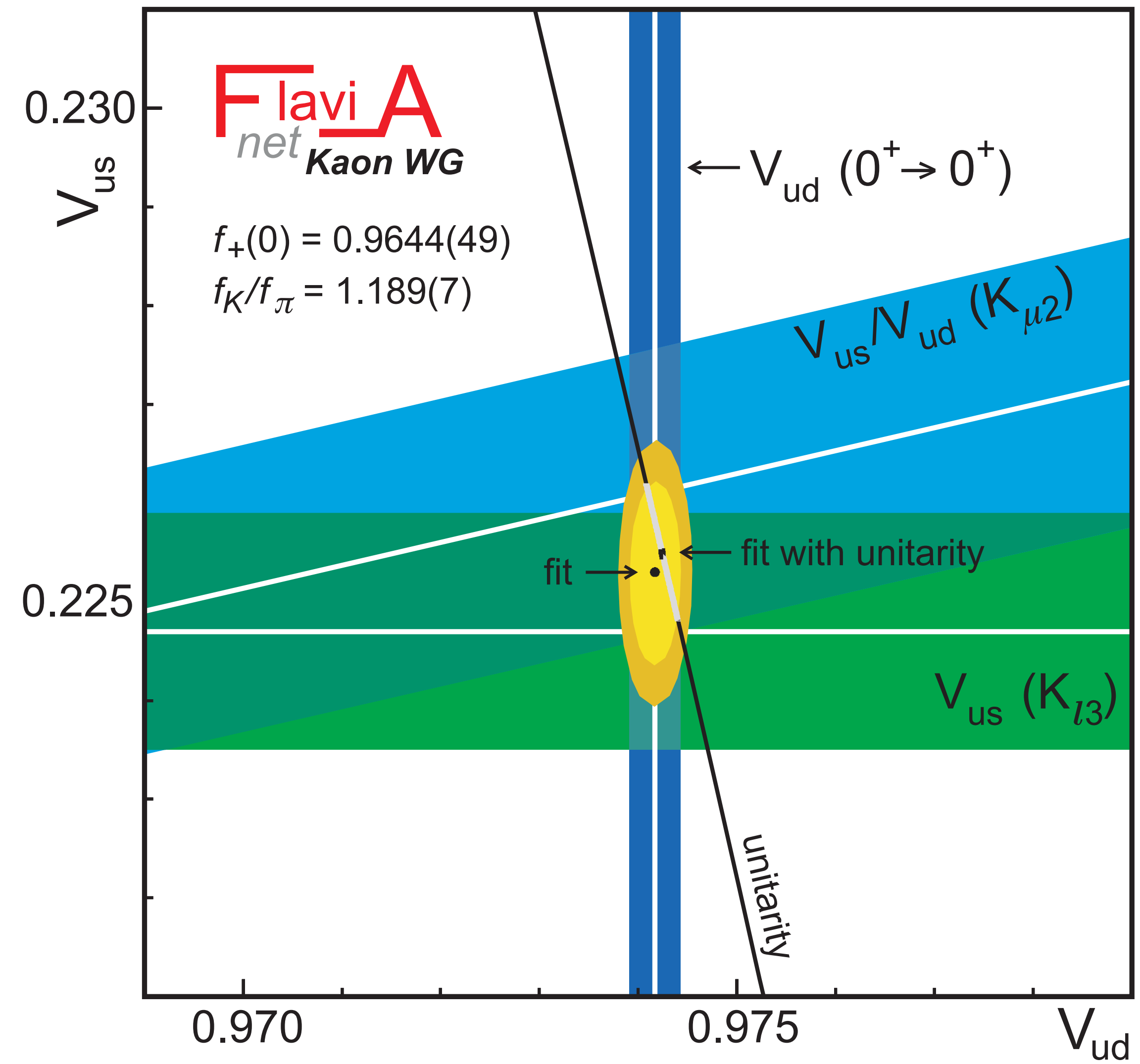
[Flavianet]

$$\frac{\Gamma(K_{l2})}{\Gamma(\pi_{l2})} \qquad \frac{|V_{us}|f_K}{|V_{ud}|f_\pi} = 0.27599(59)$$

and nuclear β decay

$$V_{ud} = 0.97425(22)$$

[Hardy, Towner `08]




$$\Delta_{CKM} = |V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| - 1$$
$$= (0.1 \pm 0.6) \times 10^{-3}$$

# CKM Unitarity (Model Independent)

[Cirigliano et. al. `09]

$\Lambda_{NP} \gg M_W$ Neglect $\mathcal{O}\left(\frac{M_W}{\Lambda_{NP}}\right)$ corrections

Use SU(2)⊗U(1) invariant operators [Buchmüller-Wyler `06]

(plus $U(3)^5$ flavour symmetry)

$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q) \qquad O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{l}\gamma_{\mu}\sigma^{a}l)$$

Constrained from EW precision data [Han, Skiba `05]

Redefine

$$G_F(\mu \to e\nu\bar{\nu}) \to G_F(1 - 2\bar{\alpha}_{ll}^{(3)}) \longrightarrow G_F^{\mu}$$

$$G_F(d \to u e\bar{\nu}) \to G_F(1 - 2\bar{\alpha}_{lq}^{(3)}) \longrightarrow G_F^{SL}$$

# CKM Unitarity (Model Independent)

$$V_{ud_i}^{PDG} = \frac{G_F^{SL}}{G_F^{\mu}} V_{ud_i} \longrightarrow \Delta_{CKM} = 4\left(\bar{\alpha}_{ll}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \dots\right)$$

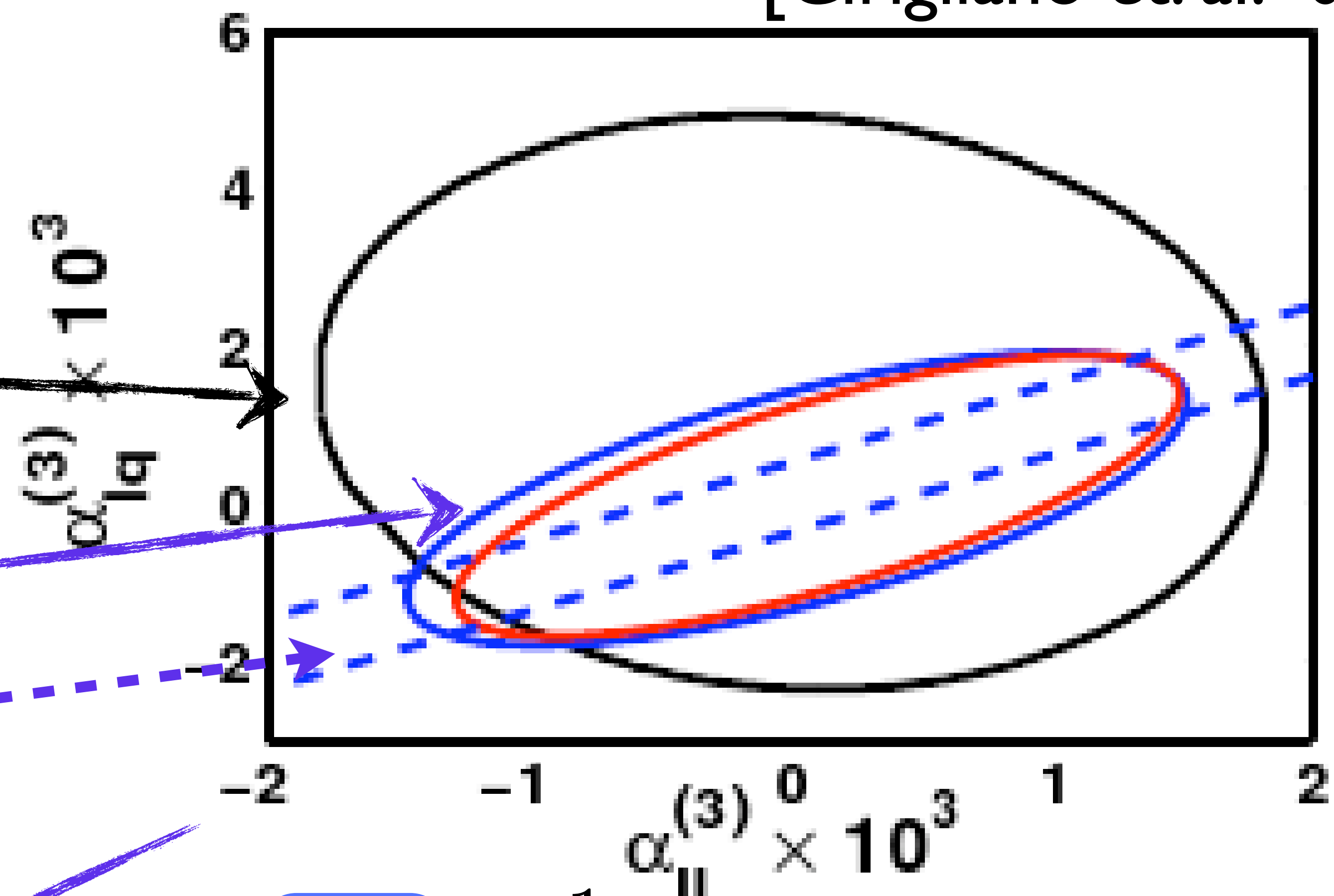
[Cirigliano et. al. `09]

$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a} l)(\bar{q}\gamma_{\mu}\sigma^{a} q)$$

from HEP

HEP + CKM

CKM




$$\Lambda_{NP} > 10\text{TeV}$$

$$O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^{\mu}\sigma^{a} l)(\bar{l}\gamma_{\mu}\sigma^{a} l)$$

# Leptonic and Semileptonic

$$K(\pi) \to l\bar{\nu}_l \quad \& \quad K \to \pi\, l\bar{\nu}_l$$

## Observables

$$R_K = \frac{\Gamma(K \to e\bar{\nu})}{\Gamma(K \to \mu\bar{\nu})} \qquad R_K^{SM} = 2.477(1) \times 10^{-5}$$

[Cirigliano, Rosell `07]

See also[Marciano, Sirlin `93]

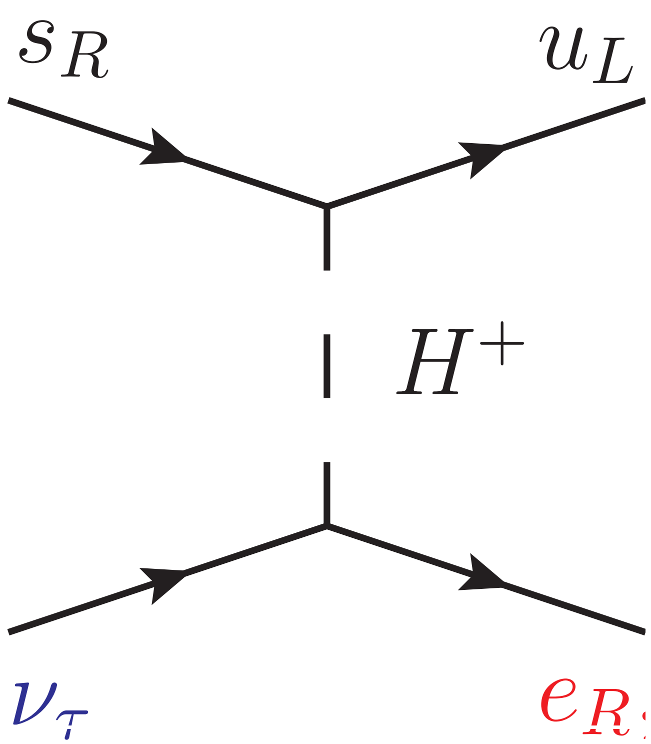
$$R_K^{NA62} = 2.500(16) \times 10^{-5}$$ [numbers from KAON09]

$$R_K^{KLOE} = 2.493(25)(19) \times 10^{-5}$$

New numbers from NA62 in agreement with SM

Test of lepton universality violation driven by experimental precision

# Lepton Universality in the MSSM




LF Conserving: ~ lepton mass

Lepton Flavour Violation: $\Delta_R^{31} \sim \frac{g_2^2}{16\pi^2}\delta_{RR}^{31}$
[Masiero, Paradisi, Petronzio `08]

$$R_K^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{SM}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

$$\Delta r_K \sim \frac{m_K^4}{m_{H^+}^4}\frac{m_\tau}{m_e}|\Delta_R^{31}|^2 \tan_\beta^6 \longrightarrow \text{can reach } 10^{-2}$$

But: finetuning of $m_e$ necessary [Girrbach et. al. `09]

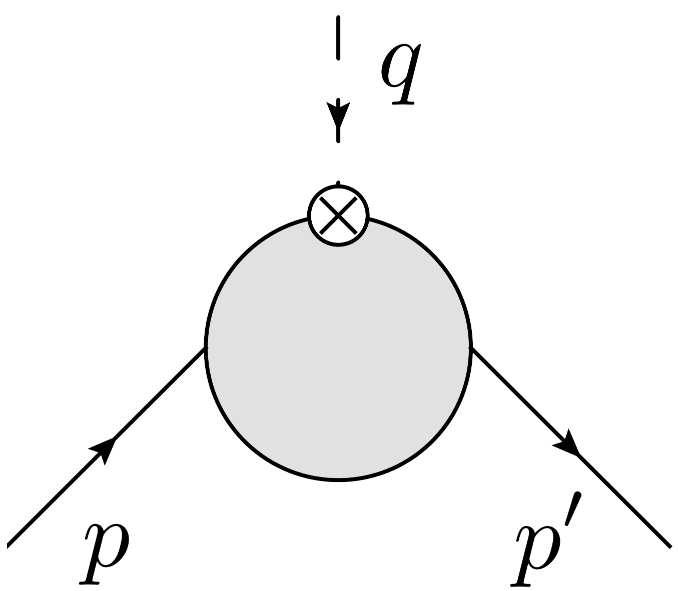
Model independent MLFV and GUT analysis [Isidori et. al. `09]

# Lattice & Continuum: Masses

How do lattice results correspond to the continuum?

- Lattice perturbation theory
- Non-perturbative renormalisation

Transform to $\overline{\text{MS}}$ scheme using perturbation theory

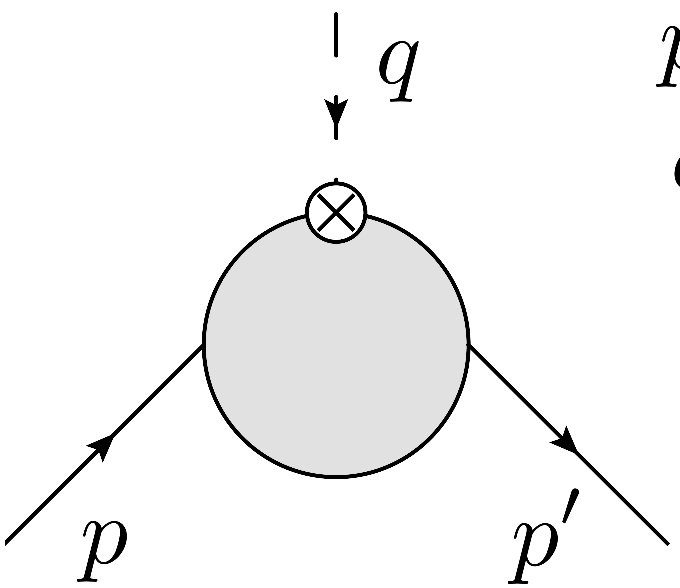



$$S_B(p')\Lambda_{P,B}(p,p')S_B(p) = \int d^4x\, d^4y\, e^{ip'x} e^{-ipy} \langle T([i\bar{u}_B\gamma_5 s_B](0)\, u_B(x)\, \bar{s}_B(y))$$

condition: $$Z_q^{-1} Z_m^{-1}\, \mathrm{tr}[\Lambda_{P,B}(p,p')\gamma_5] = 12$$

momentum configuration plus 2 point function:
fix mass and field renormalisation

# Conversion RI/SMOM → $\overline{\text{MS}}$




$$p^2 = p'^2 = -\mu^2$$
$$q^2 = 0$$

[Martinelli et. al. `93-`95]

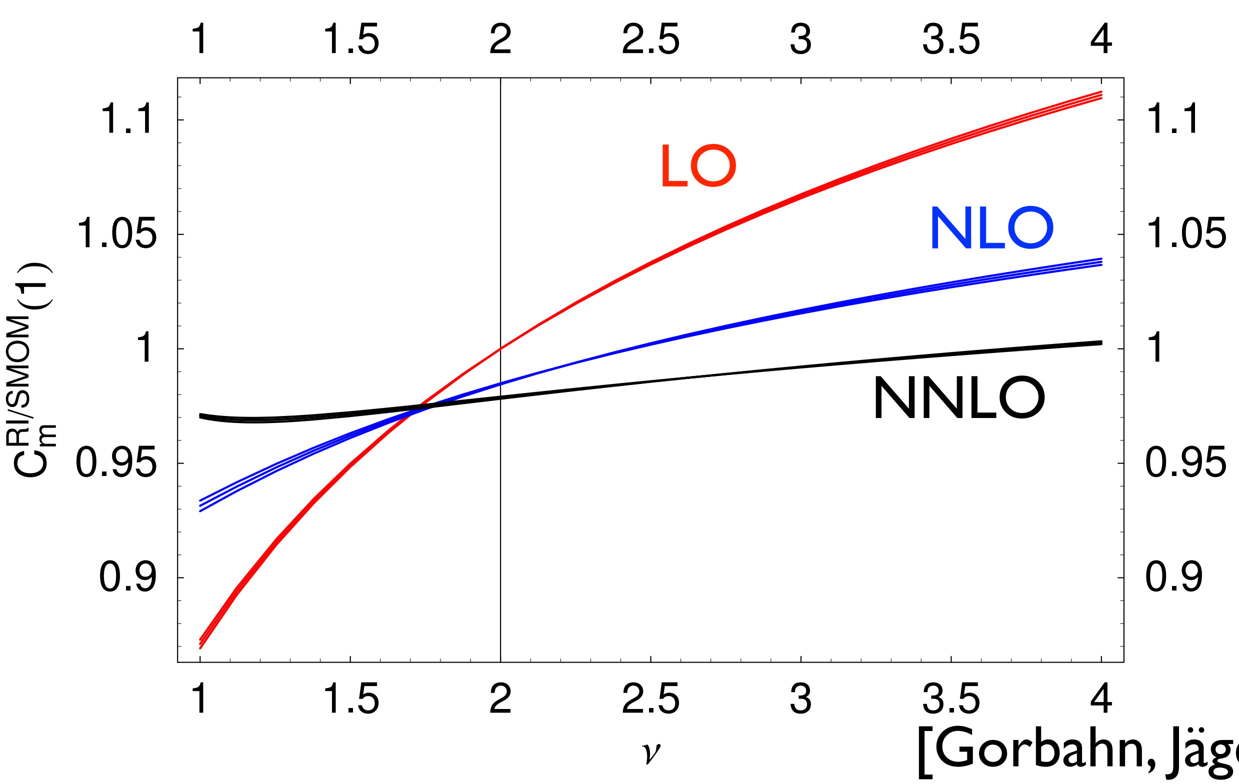
corresponds to: RI/MOM scheme

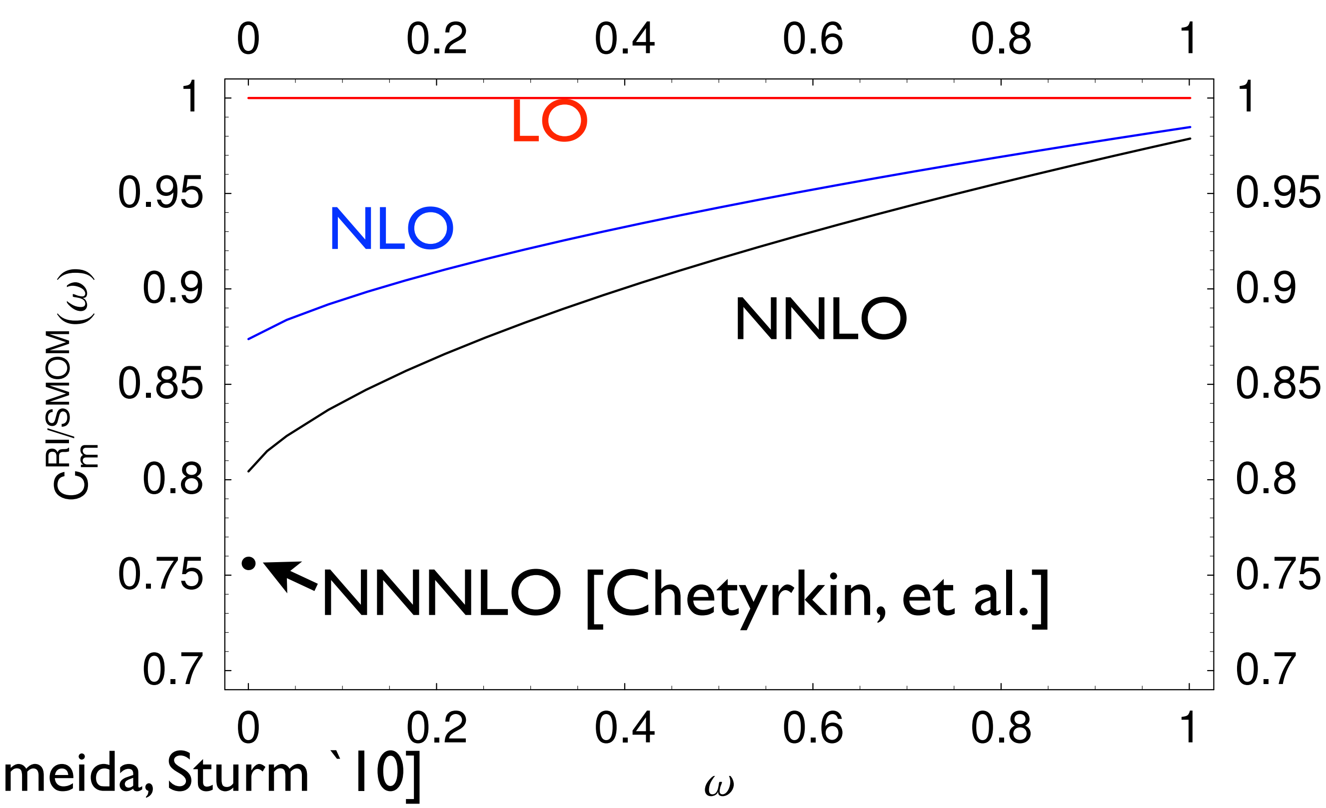
matching@NNLO: poor convergence

find a scheme good for lattice & loops

$p^2 = p'^2 = q^2 = -\mu^2$ RI/SMOM [Sturm et. al. `09]

off shell: $\Lambda^2/q^2$ suppression and good convergence




[Gorbahn, Jäger; Almeida, Sturm `10]

# Rare Kaon Decays

FCNCs which are dominated by top-quark loops:

$\mathrm{b} \to \mathrm{s}:$ $|V_{tb}^* V_{ts}| \propto \lambda^2$

$\mathrm{b} \to \mathrm{d}:$ $|V_{tb}^* V_{td}| \propto \lambda^3$

$\mathrm{s} \to \mathrm{d}:$ $|V_{ts}^* V_{td}| \propto \lambda^5$

CKM suppression: enhanced sensitivity to NP

$$\underbrace{V_{ts}^* V_{td}}_{\lambda^5} + \underbrace{V_{cs}^* V_{cd}}_{\lambda} = -\underbrace{V_{us}^* V_{ud}}_{\lambda}$$

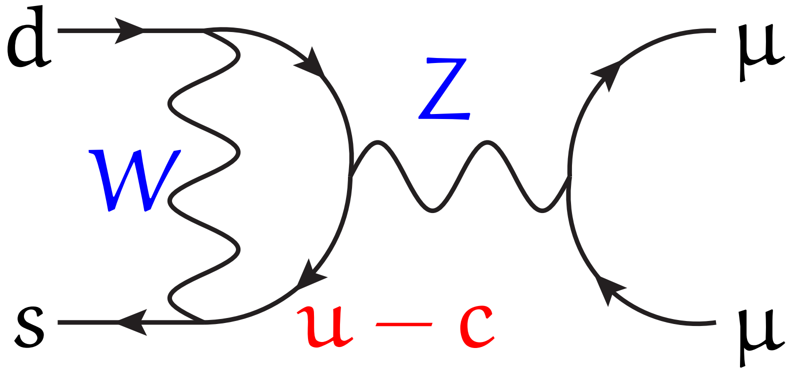
how can we suppress the light quark contribution?

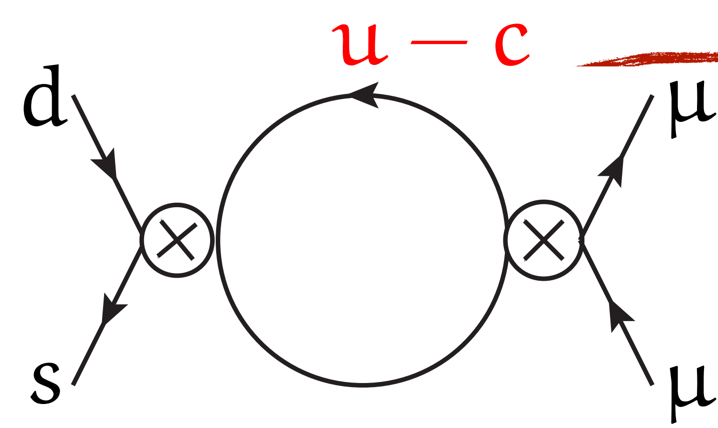
Quadratic GIM: $\lambda \frac{m_c^2}{M_W^2}$

CP violation: $\mathrm{Im}(V_{cs}^* V_{cd})$

# GIMnastics

## Quadratic GIM suppresses light quark contribution



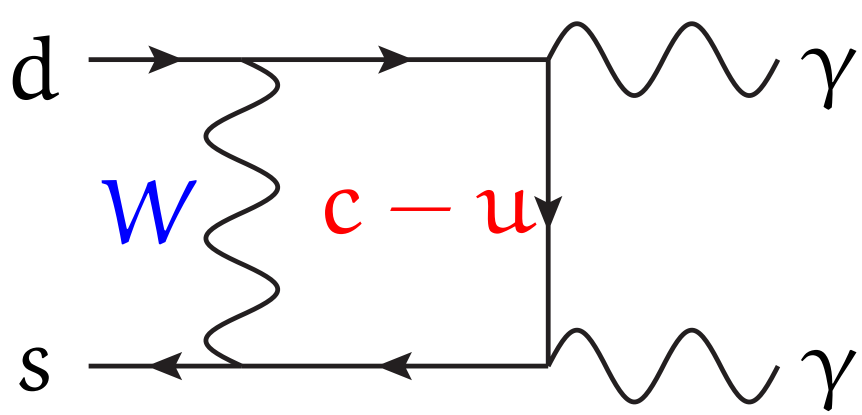

$m_c^2 - m_u^2$

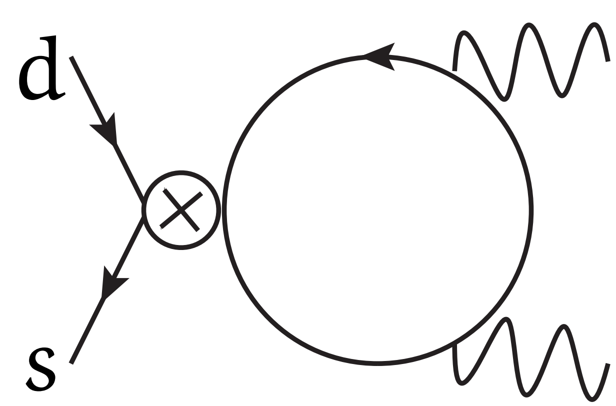
$m_c^2 G_F^2 \log \frac{m_c}{M_W}$

NNLO

[MG, Haisch `07]

## No quadratic suppression for $K_L \to \gamma\gamma$

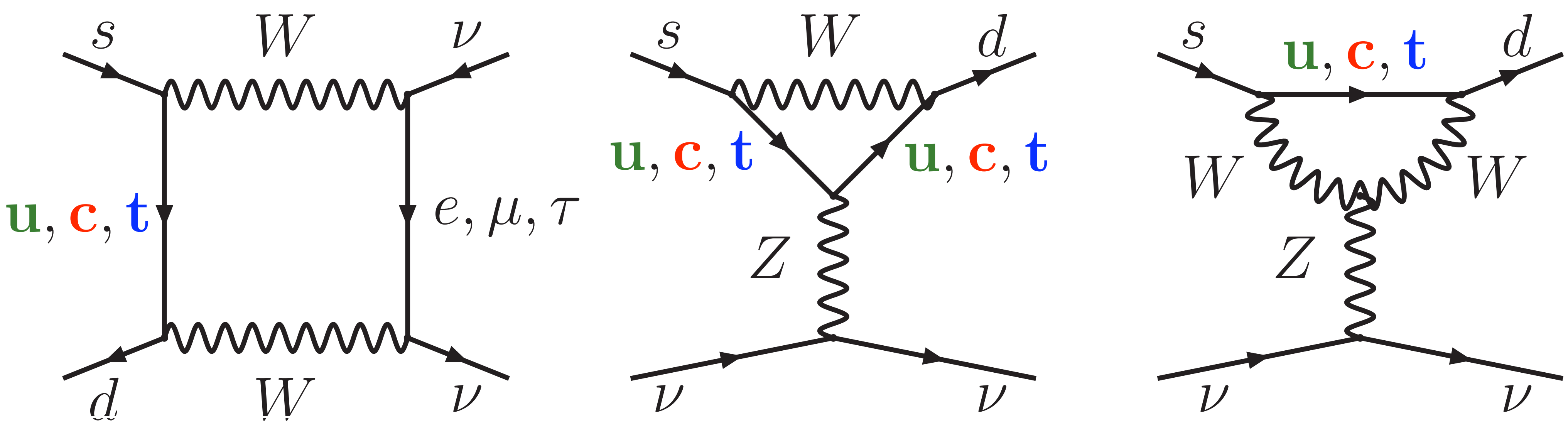



$G_F \log \frac{\Lambda_{QCD}}{m_c}$

$\frac{\alpha}{4\pi} \times K_L \to \gamma\gamma$ also contributes to: $K_L \to \mu^+\mu^-$

# No couplings to $\gamma$ s: $K \to \pi \nu \bar{\nu}$

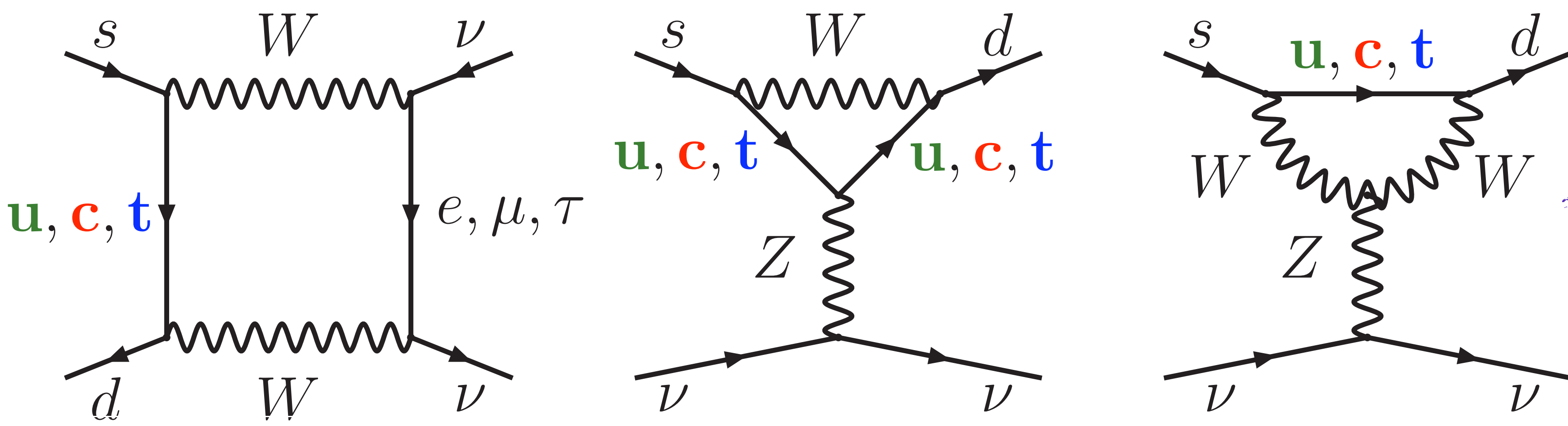



- Dominant Operator: $Q_\nu = (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_L \gamma^\mu \nu_L)$

$$\sum_i V_{is}^* V_{id} F(x_i) = V_{ts}^* V_{td} (F(x_t) - F(x_u)) + V_{cs}^* V_{cd} (F(x_c) - F(x_u))$$

Quadratic GIM: $\lambda^5 \frac{m_t^2}{M_W^2}$ $\quad \lambda \frac{m_c^2}{M_W^2} \ln \frac{M_W}{m_c}$ $\quad \lambda \frac{\Lambda^2}{M_W^2}$

# $K_L \to \pi^0 \bar{\nu} \nu$: Effective Hamiltonian




including NLO EW

[Bord, Gorbahn, Stamou `10]

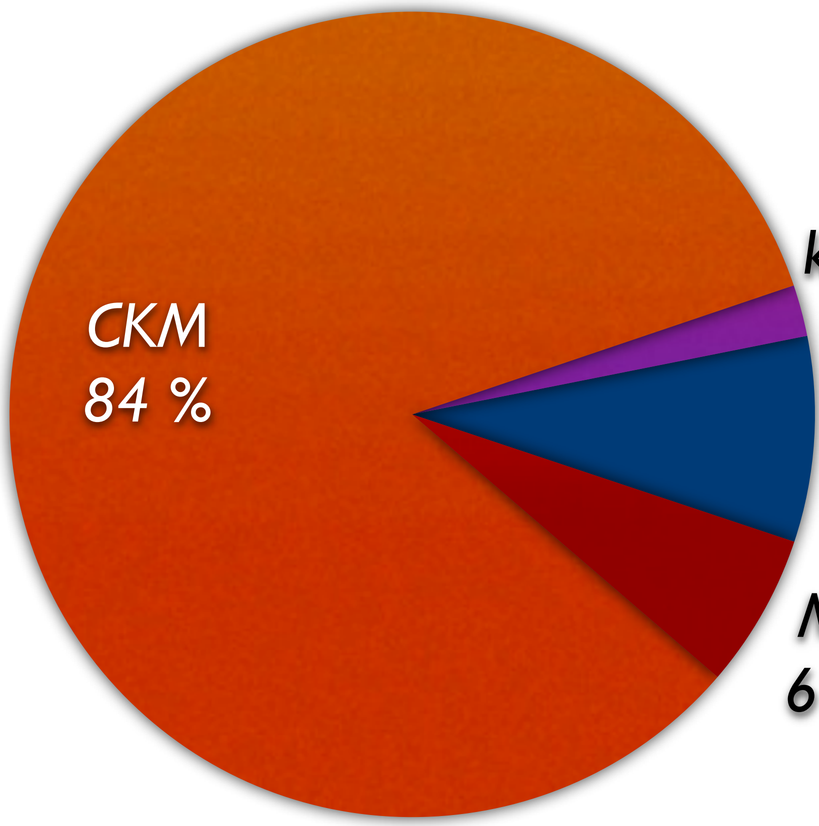
CP violating

Only top quark contributes: $H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha V_{ts}^* V_{td}}{2\pi \sin^2 \Theta_W} X(x_t) Q_\nu$

Use isospin symmetry and normalise to: $K^+ \to \pi^0 e^+ \nu$

$$\mathcal{B}r(K_L \to \pi^0 \bar{\nu} \nu) = \kappa_L \left( \frac{\text{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

# $K_L \to \pi^0 \nu\bar{\nu}$: Theoretical Status




Matrix element extracted from $\mathrm{K}_{l3}$ decays. $\mathrm{N}^{\frac{3}{2}}\mathrm{LO}\ \chi\mathrm{PT}$
[Mescia, Smith ´07; Bijnens, Ghorbani ´07]

$\mathrm{X}(x_t)$: Full NLO electroweak corrections
[Brod, Gorbahn, Stamou ´10]
Reduce theory uncertainty by factor of 2

$$\mathcal{B}r_{K_L} = 2.57(37)(4) \times 10^{-11}$$

Experiment: $< 6.7 \times 10^{-8}$ [E391a ´08]

=> K0T0

# $K^+ \to \pi^+ \bar{\nu}\nu$ and $K_L \to \pi^0 \bar{\nu}\nu$

Different from $K_L \to \pi^0 \bar{\nu}\nu$

- CP conserving: Top & charm contribute

$$\mathcal{B}r\left(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)\right) = \kappa_+ (1 + \Delta_{EM})$$

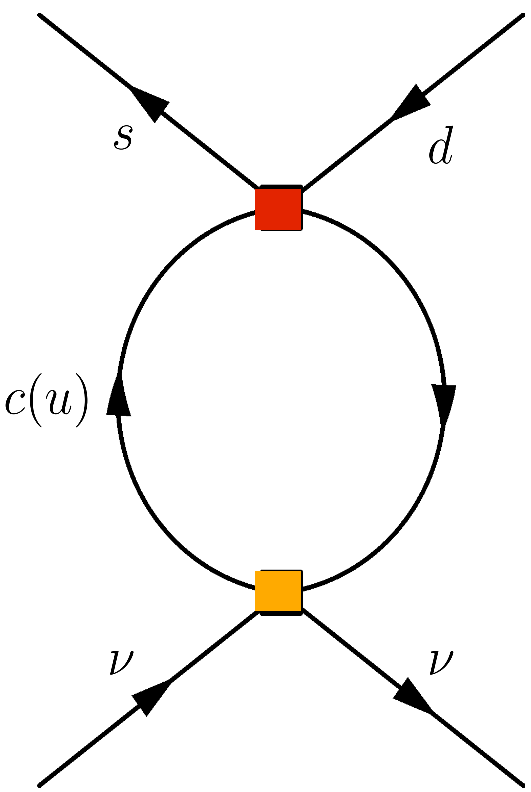
$$\times \left| \frac{V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \mathrm{Re} V_{cs}^* V_{cd} \left(P_c(m_c^2) + \delta P_{c,u}\right)}{\lambda^5} \right|^2 .$$

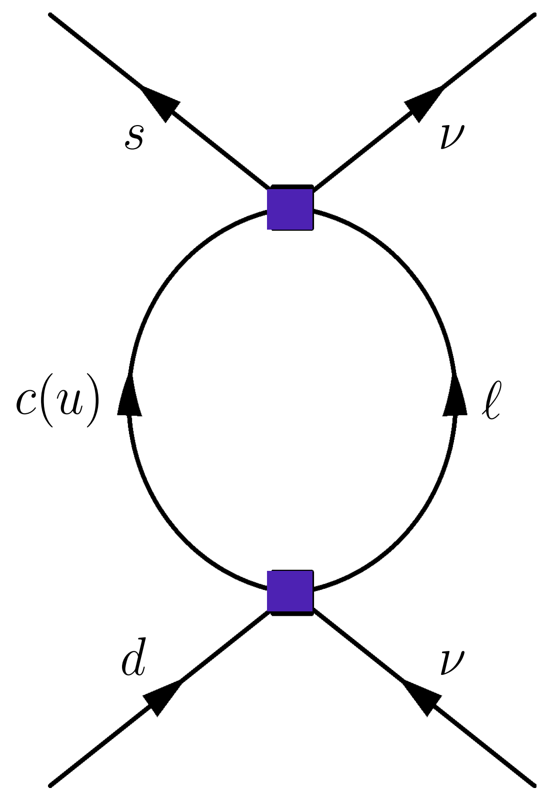
$\frac{m_c^2}{M_W^2}$ suppression lifted by $\log\left(\frac{m_c}{M_W}\right)\frac{1}{\lambda^4}$

Like in $K_L \to \pi^0 \bar{\nu}\nu$

- Only $Q_\nu$: Quadratic GIM & Isospin symmetry
- Top quark contribution like in $K_L \to \pi^0 \bar{\nu}\nu$

# $K^+ \to \pi^+ \bar{\nu}\nu$ charm contribution

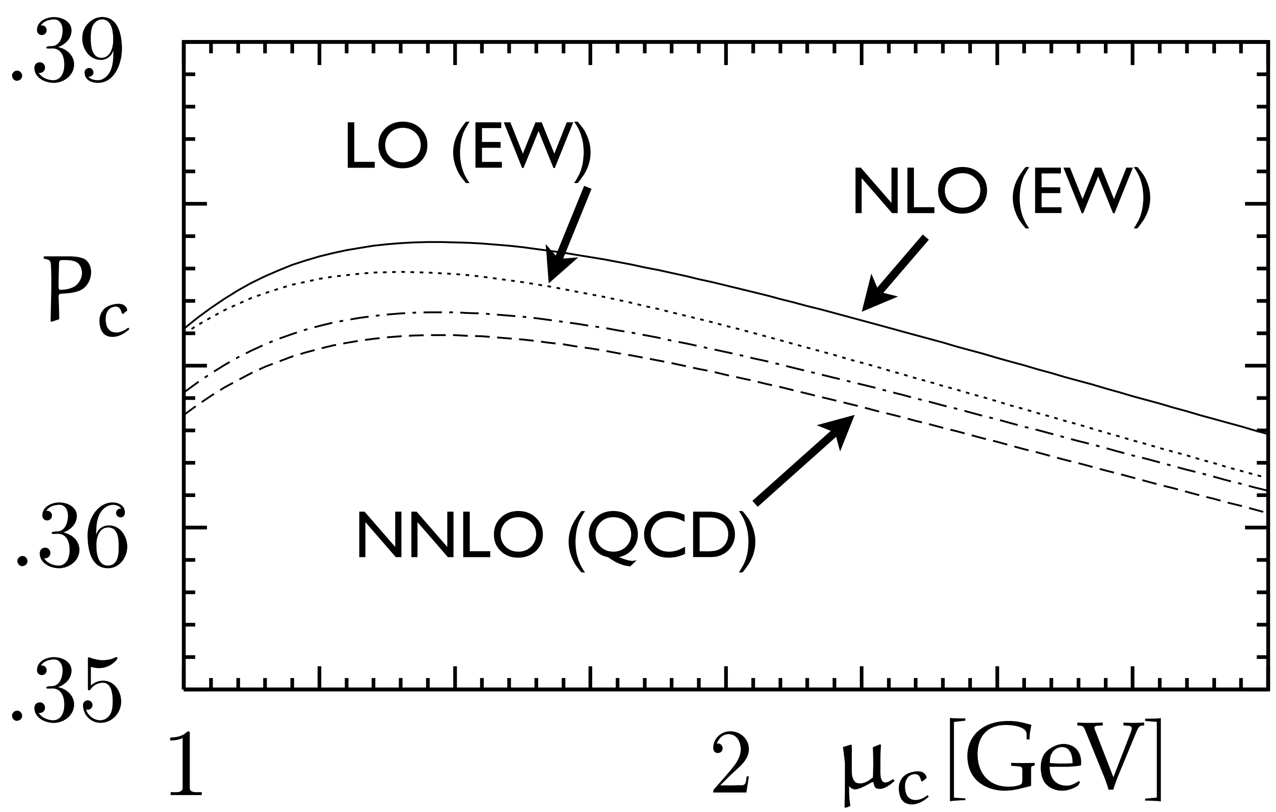



$$\bar{s}_i\gamma^\mu(1-\gamma_5)q_j \;\bar{q}_j\gamma_\mu(1-\gamma_5)d_i$$
$$\bar{s}_i\gamma^\mu(1-\gamma_5)q_i \;\bar{q}_j\gamma_\mu(1-\gamma_5)d_j$$

$$\bar{c}\gamma^\mu\gamma_5 c \;\; \bar{\nu}\gamma^\mu(1-\gamma_5)\nu$$

$$\bar{s}\gamma^\mu(1-\gamma_5)q \;\bar{\nu}_l\gamma_\mu(1-\gamma_5)l$$
$$\bar{l}\gamma^\mu(1-\gamma_5)\nu_l \;\bar{q}\gamma_\mu(1-\gamma_5)d$$

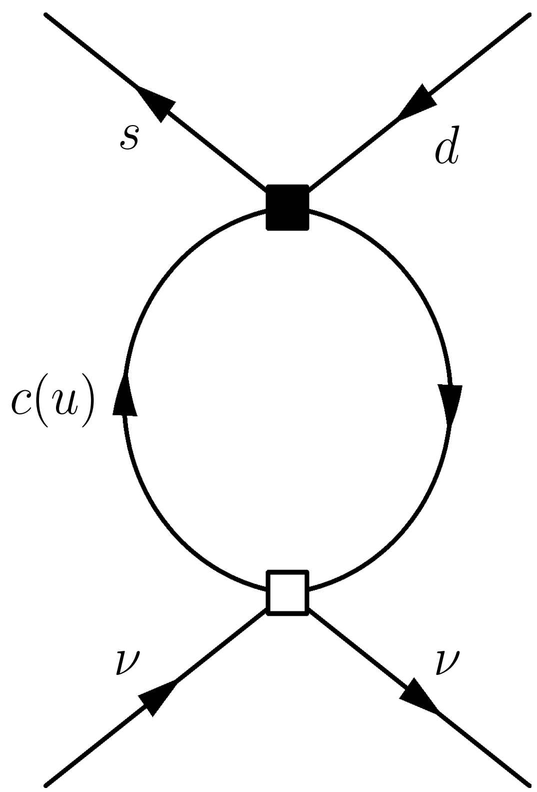



- Resum $\log \frac{m_c}{M_W}$ in $P_c$

$P_c$ at NNLO: ±2.5% (theory)
[Buras, Gorbahn, Haisch, Nierste ´06]

NLO EW [Brod, Gorbahn`08]

# Long Distance Contribution




No GIM below the charm quark mass scale

$q^2/m_c^2$ higher dimensional operators
UV scale dependent

One loop CHPT calculation approximately cancels this scale dependence [Isidori, Mescia, Smith `05]

Also: box-type diagrams considered
(from two semileptonic operator insertions)
cancelation is more complicated

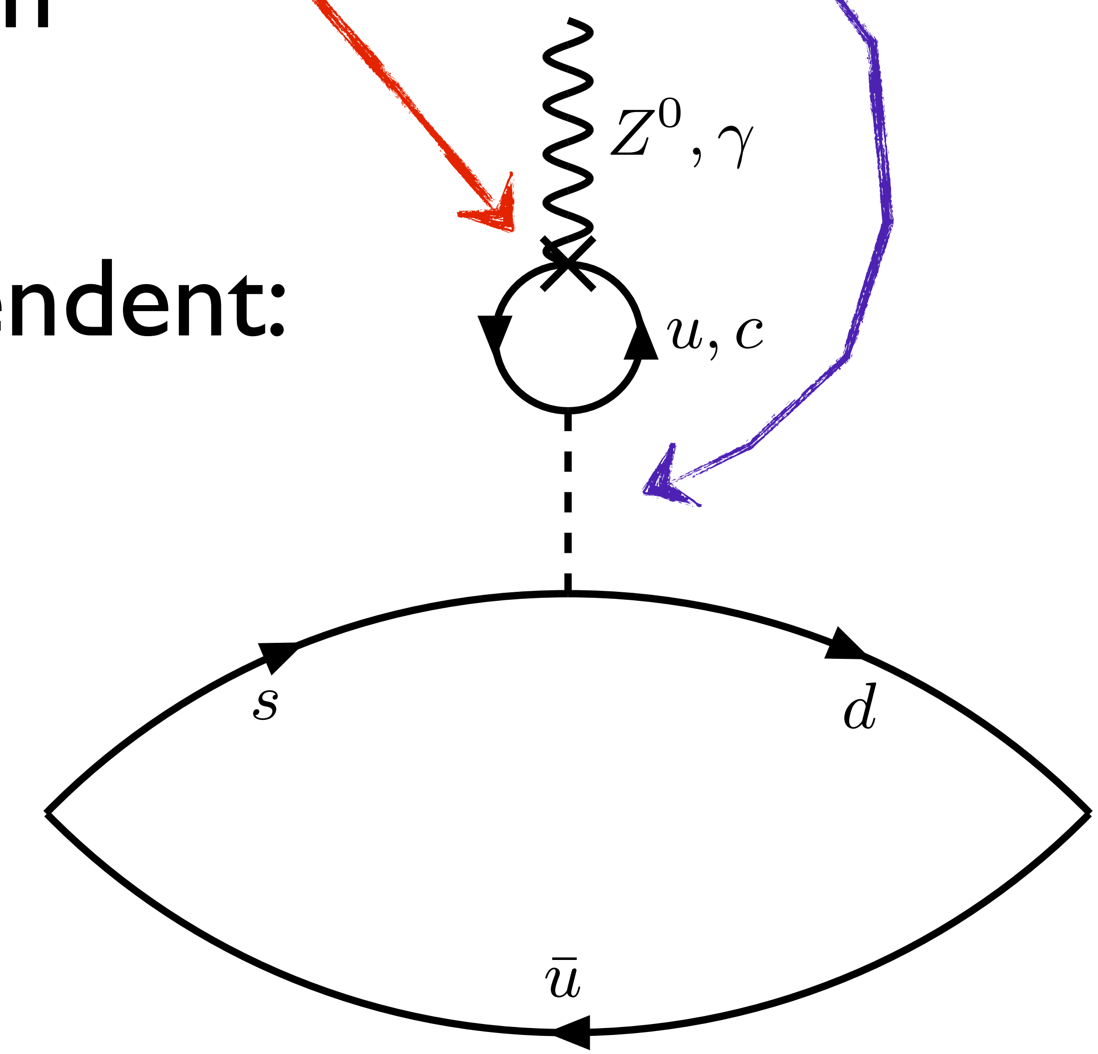
$$\delta P_{c,u} = 0.04 \pm 0.02$$ [Isidori, Mescia, Smith `05]

# One Current & One Operator

$$\left(\mathcal{T}_i^j\right)^\mu_{\rm em}(q^2) = -i\int d^4x\, e^{-i\,q\cdot x}\,\langle\pi^j(p)|T\left\{J^\mu_{\rm em}(x)\left[Q_i^u(0)-Q_i^c(0)\right]\right\}|K^j(k)\rangle$$

Current and operator insertion

[Isidori, Martinelli, Turchetti `06]




$\mathcal{O}\left(\frac{1}{a^2}\right)$ divergence mass independent: cancelled by GIM

$\mathcal{O}\left(\frac{1}{a}\right)$ appear → maximally twisted fermions

also: no semileptonic operators discussed

# $K^+ \to \pi^+ \bar{\nu} \nu$ Long distance

- Matrix element extracted from $K_{l3}$ decays
  [Mescia, Smith ´07]
- $K^+ \to \pi^+ \nu \bar{\nu}$ is $K^+ \to \pi^+ \nu \bar{\nu}(\gamma)$
  QED radiative corrections included:

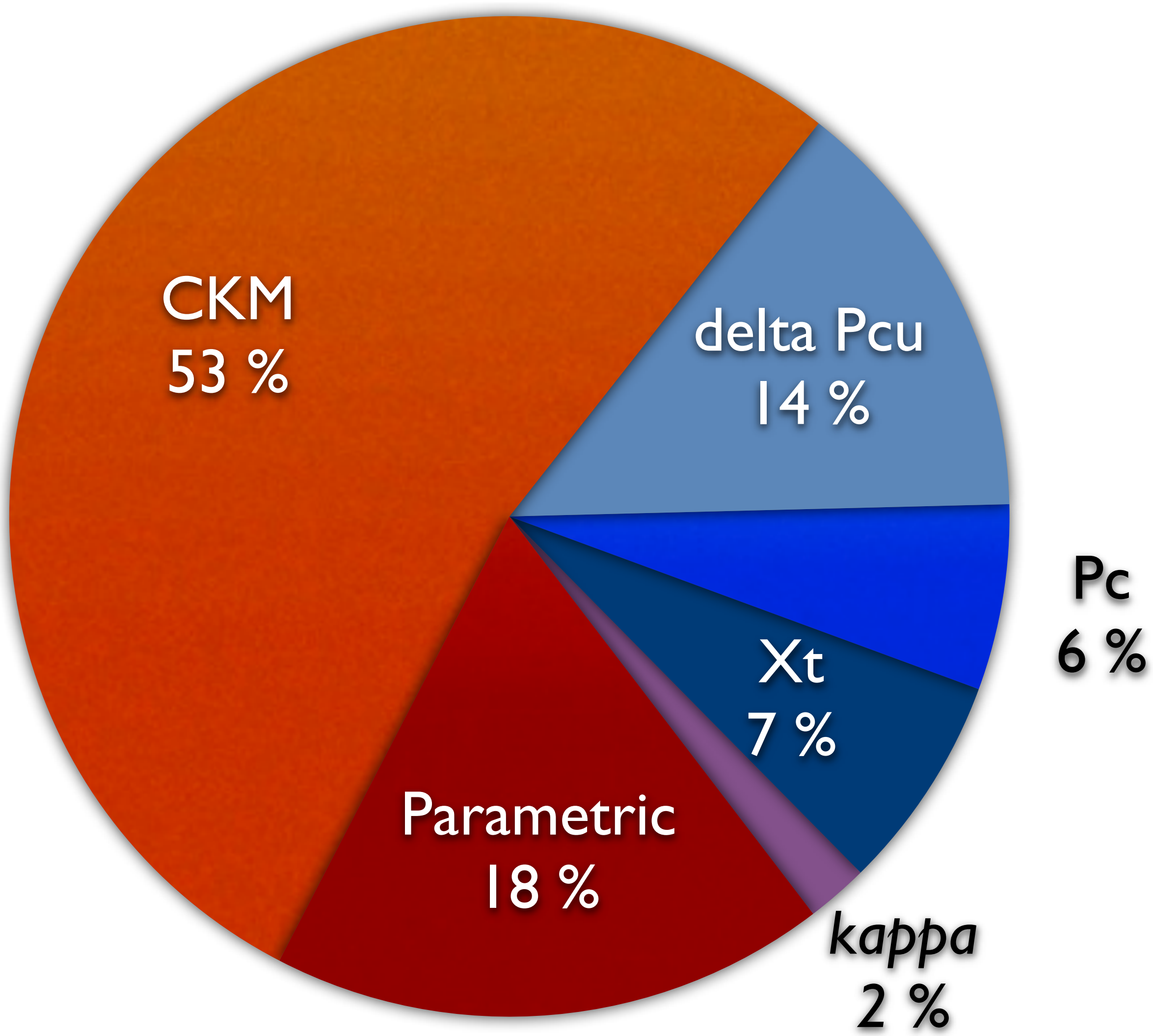
$$\Delta_{\text{EM}}(E_\gamma < 20\text{MeV}) = -0.003$$

- Uncertainty in $\kappa_+(1 - \Delta_{\text{EM}})$ reduced by $\frac{1}{7}$

- Below charm scale: Dimension 8 operators
  [Falk et. al. ´01]
- Together with light quarks: $\delta P_{c,u} = 0.04 \pm 0.02$
  [Isidori, Mescia, Smith ´05]

# $K^+ \to \pi^+ \bar{\nu}\nu$ Error Budget

Theory error budget $\mathcal{B}_{K^+} = 0.822(69)(29) \times 10^{-10}$

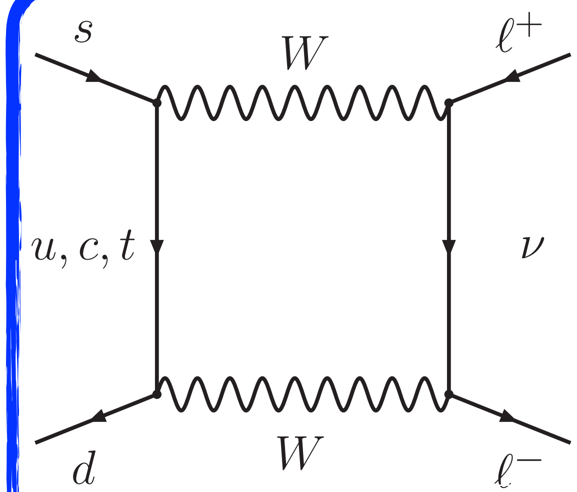


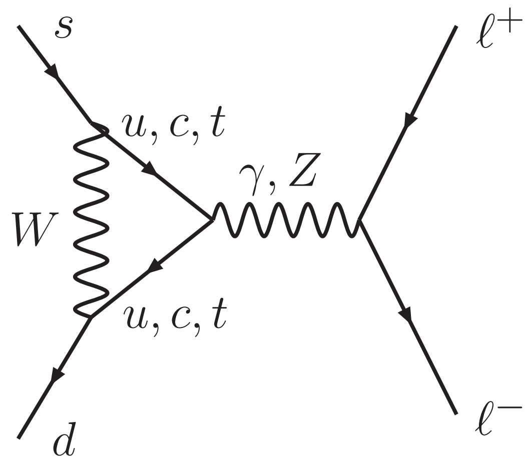

**Experiment** [E787, E949 ´08]

$$\mathcal{B}r_{K^+} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Talk by Goadzovski on NA62 => 10%

# $K_L \to \pi^0 l^+ l^-$: Three Contributions



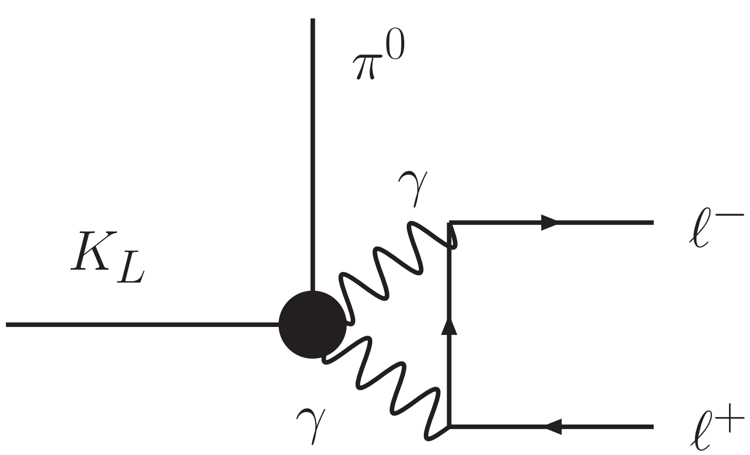




$$Q_{7V} = (\bar{s}_L \gamma_\mu d_L)(\bar{l}\gamma^\mu l) \to 1^{--}$$

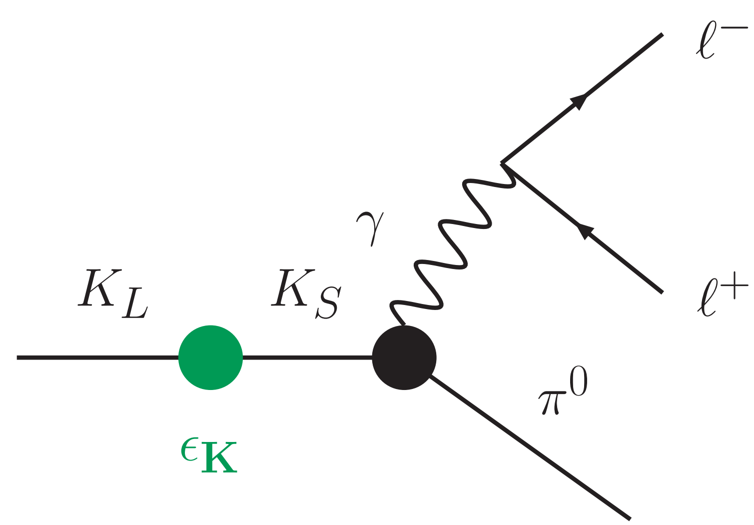
$$Q_{7A} = (\bar{s}_L \gamma_\mu d_L)(\bar{l}\gamma^\mu \gamma_5 l)$$
$$\to 1^{++},\ 0^{-+}$$

Direct CP Violating

Wilson Coefficients: $y_{7V}$, $y_{7A}$ at NLO [Buchalla et al. ´96]

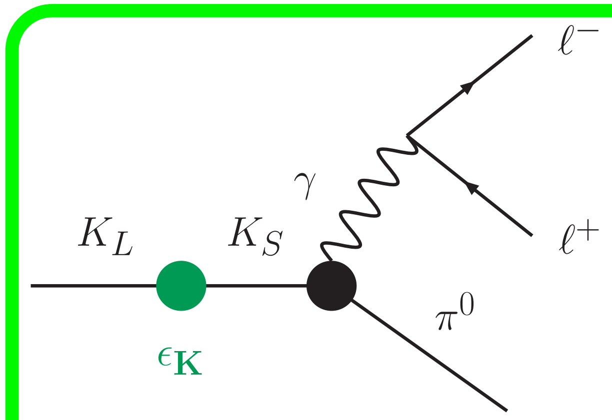



CP Conserving




Indirect CP Violating

# $K_L \to \pi^0 l^+ l^-$: Three Contributions

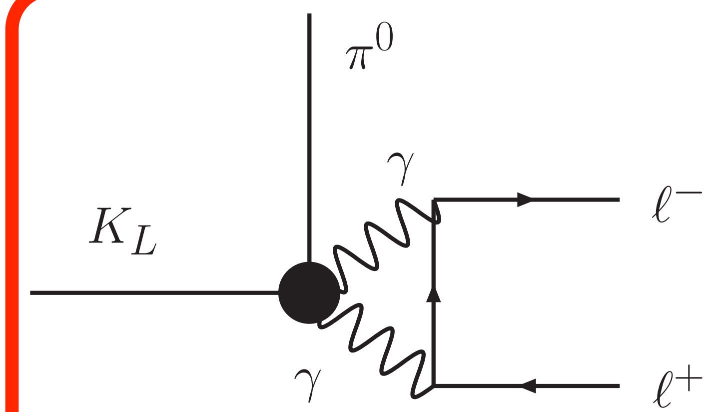



**Counterterm** $|a_S| = 1.2 \pm 0.2$ **from** $K_S \to \pi^0 l^+ l^-$

[D´Ambrosio et. al. ´98, Mescia et. al. ´06]

**For** $1^{--}$ **interference with** $Q_{7V}$

[Buchalla et. al. ´03, Friot et al. ´04]




**Estimate from** $K_L \to \pi^0 \gamma\gamma$

[Isidori et. al. ´04]

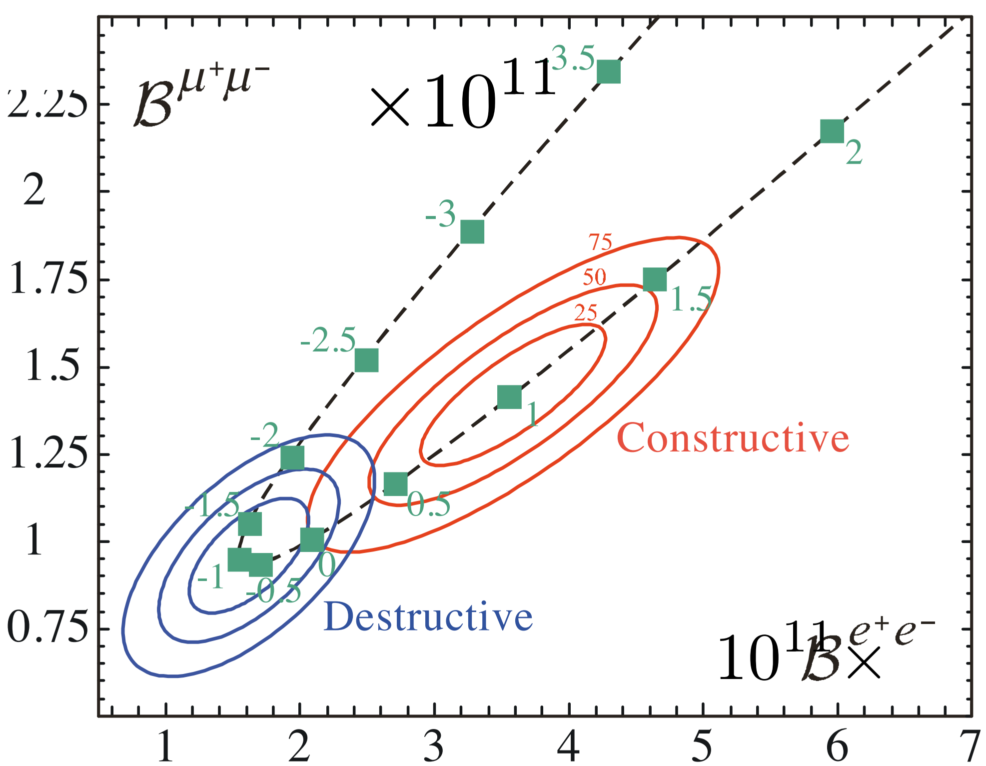
$$\mathcal{B}r(K_L \to \pi^0 \ell^+ \ell^-) = \left(C^\ell_{dir} \pm C^\ell_{int}|a_S| + C^\ell_{mix}|a_S|^2 + C^\ell_{\gamma\gamma}\right) \times 10^{-12}$$

| $\ell$ | $C^\ell_{dir}$ | $C^\ell_{int}$ | $C^\ell_{mix}$ | $C^\ell_{\gamma\gamma}$ |
|---|---|---|---|---|
| $e$ | $(4.62 \pm 0.24)(y_V^2 + y_A^2)$ | $(11.3 \pm 0.3)y_V$ | $14.5 \pm 0.5$ | $\approx 0$ |
| $\mu$ | $(1.09 \pm 0.05)(y_V^2 + 2.32 y_A^2)$ | $(2.63 \pm 0.06)y_V$ | $3.36 \pm 0.20$ | $5.2 \pm 1.6$ |

# $K_L \to \pi^0 l^+ l^-$ : Improvements

- Measure both $\mathcal{B}r_{e^+e^-}$ and $\mathcal{B}r_{\mu^+\mu^-}$ : [Mescia et. al. ´06]
  Disentangle short distance contribution $(y_{7V},\ y_{7A})$

- Dominant theory error in $a_s$:
  Forward backward asymmetry. [Mescia, Smith, Trine ´06]
  Better measurement of $K_S \to \pi^0 l^+ l^-$ . [Smith ´07]




[Mescia et. al. ´06]

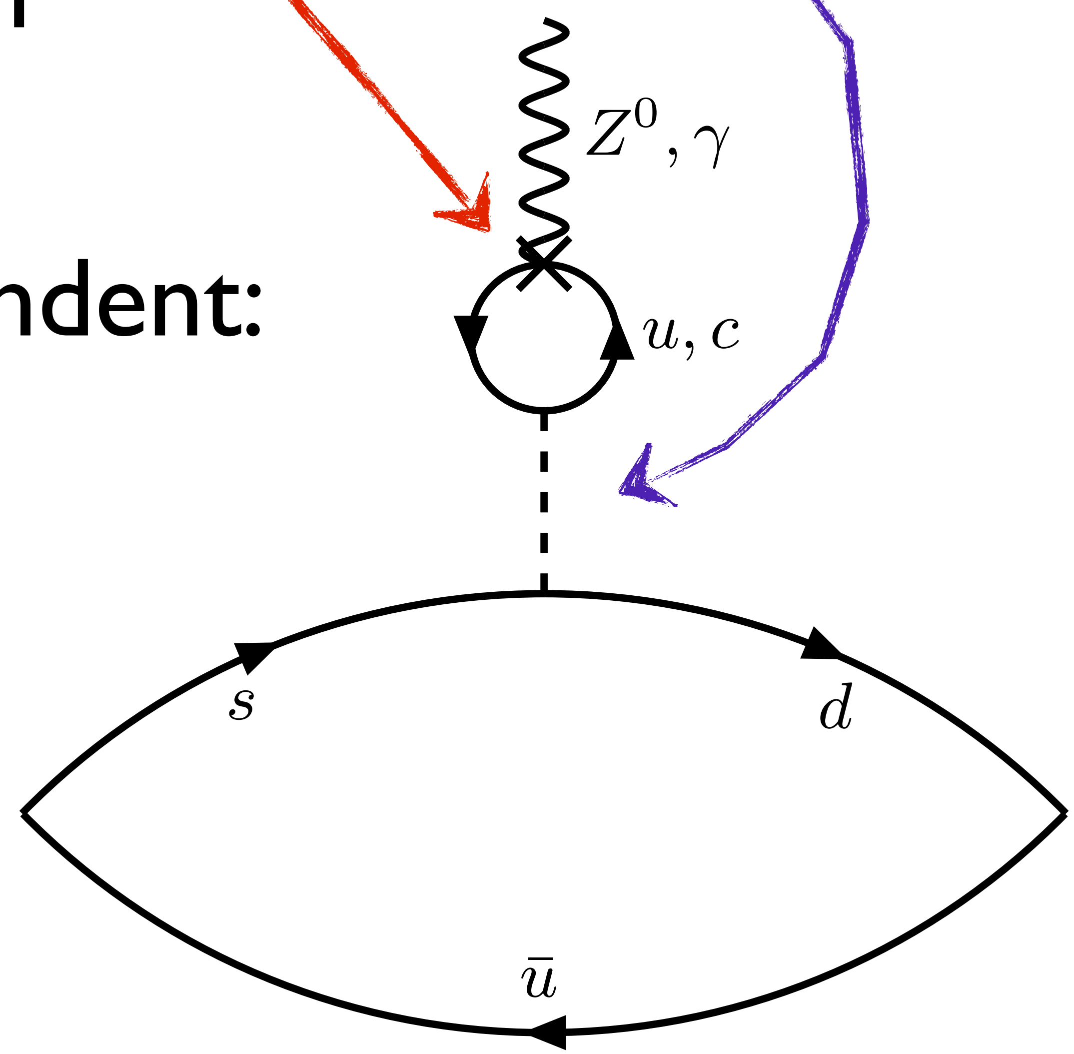
| [KTEV ´04] | [KTEV ´00] |
|---|---|
| $\mathrm{Br}_{e^+e^-}$ | $\mathrm{Br}_{\mu^+\mu^-}$ |
| $< 28 \times 10^{-11}$ | $< 38 \times 10^{-11}$ |

# One Current & One Operator

$$\left(\mathcal{T}_i^j\right)^\mu_{\rm em}(q^2) \;=\; -i\int d^4x\, e^{-i\,q\cdot x}\,\langle\pi^j(p)|T\left\{J^\mu_{\rm em}(x)\,[Q_i^u(0)-Q_i^c(0)]\right\}|K^j(k)\rangle$$

Current and operator insertion

[Isidori, Martinelli, Turchetti `06]

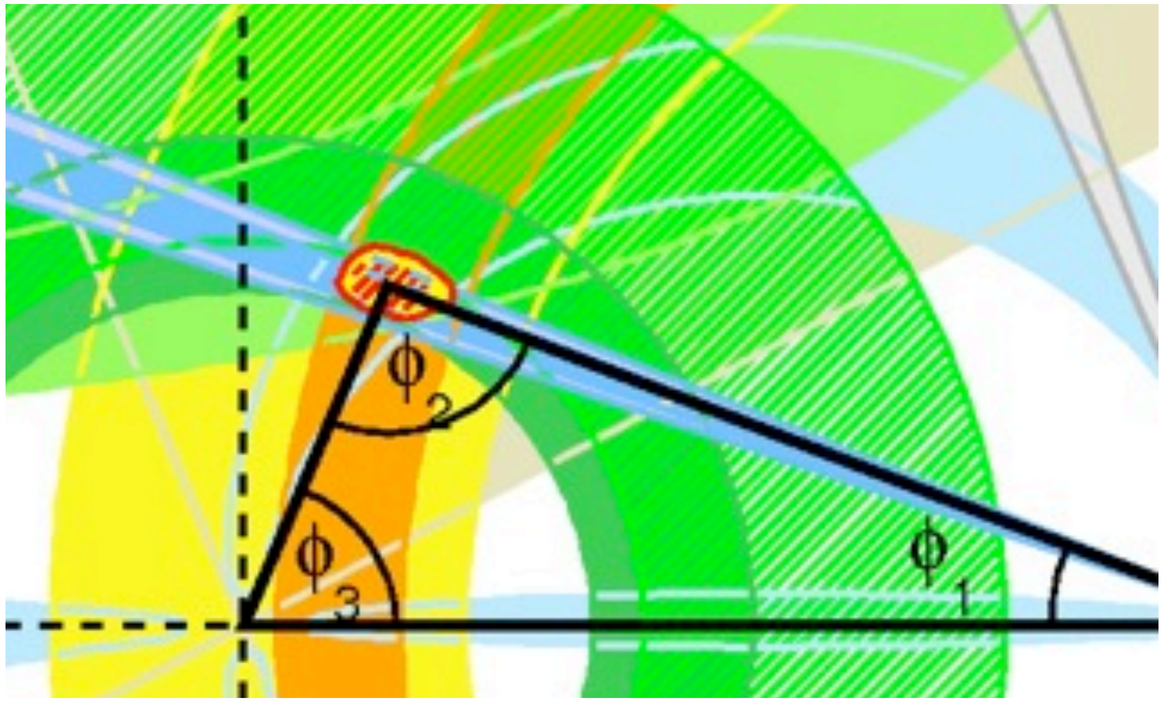



$\mathcal{O}\left(\frac{1}{a^2}\right)$ divergence mass independent: cancelled by GIM

$\mathcal{O}\left(\frac{1}{a}\right)$ vector current→ define conserved current

What about the two photon contribution?

# $\epsilon_K$ :Indirect CP Violation




$$\epsilon_K \simeq \frac{\langle(\pi\pi)_{I=0}|K_L\rangle}{\langle(\pi\pi)_{I=0}|K_S\rangle}$$

$$\frac{\Im A_0}{\Re A_0}$$

$$\epsilon_K = e^{i\phi_\epsilon}\sin\phi_\epsilon\left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi\right)$$

- In almost all old analysis: $\phi_\epsilon = 45^\circ$ and $\xi = 0$
- In reality: $\xi \neq 0$ $\phi_\epsilon \neq 45^\circ$ [Andriyash et. al.'04]

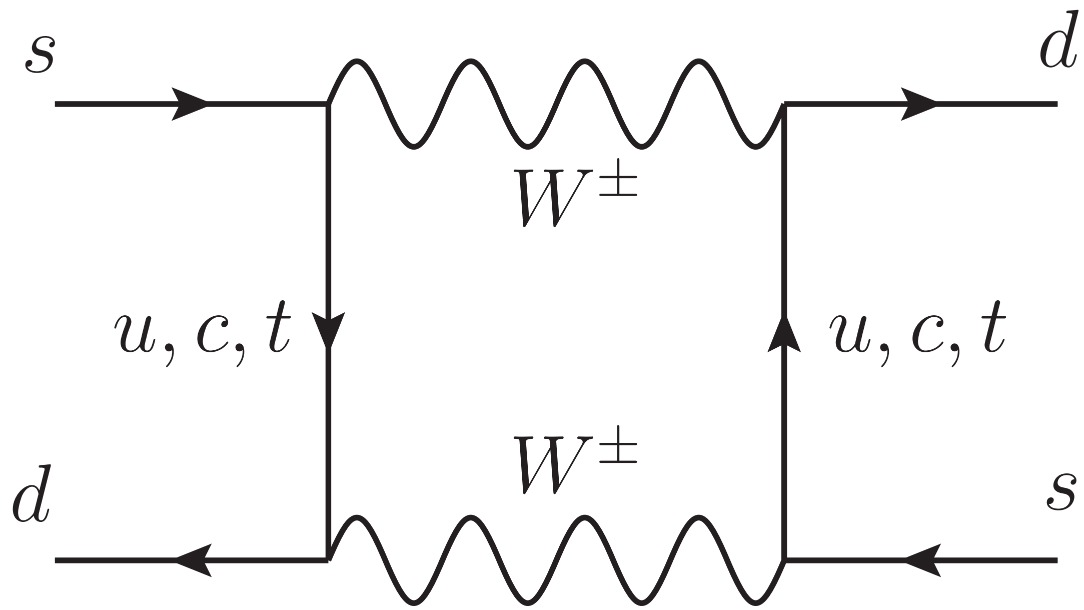
$$|\epsilon_K^{SM}| = \kappa_\epsilon|\epsilon_K|(\phi_\epsilon = 45^\circ, \xi = 0)$$

+ similar contribution as $\delta P_{c,u}$ in $\epsilon_K$

$$\kappa_\epsilon = 0.94 \pm 0.02$$ [Buras, Guadagnoli, Isidori `10]

# Calculation of $M_{12}^K = \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle$

Box diagram
with internal u,c,t




$$\lambda_i \lambda_j A(x_i, x_j)$$

$$\lambda_i = V_{is}^* V_{id}$$

plus GIM:

$$\lambda_c + \lambda_t = -\lambda_u$$

Gives three different contributions for

$$M_{12}^K = \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle$$

Caveat: first only SD

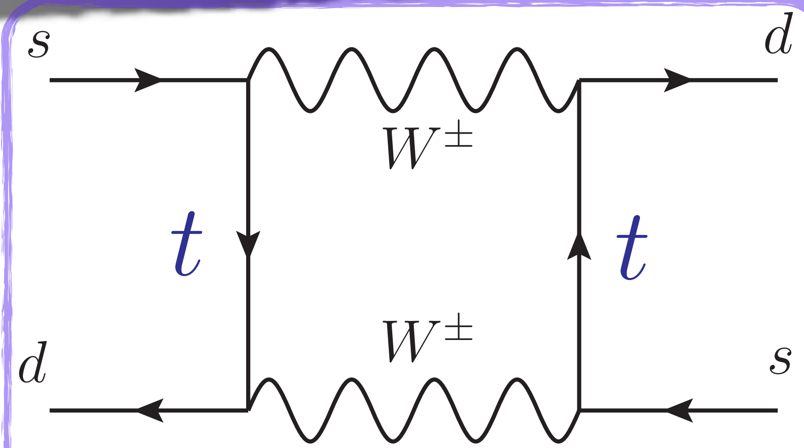
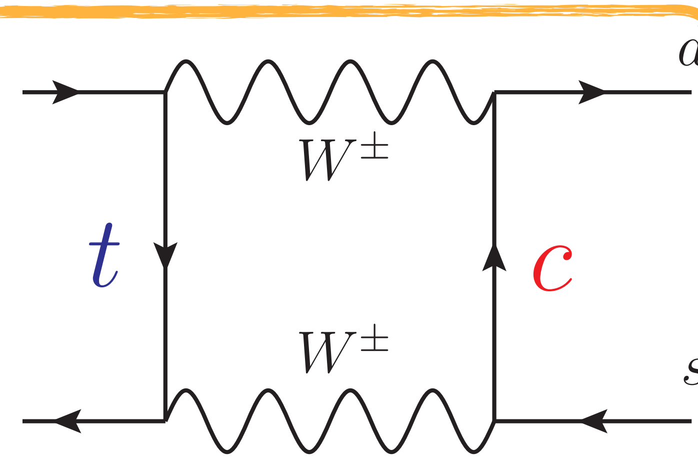
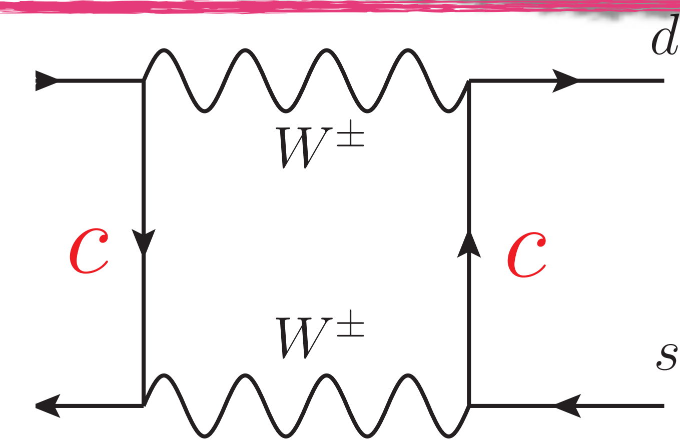
$$\mathcal{H} \propto \Big[\lambda_t^2 \eta_t S(x_t)$$ top

$$+2\lambda_c \lambda_t \eta_{ct} S(x_c, x_t)$$ charm top

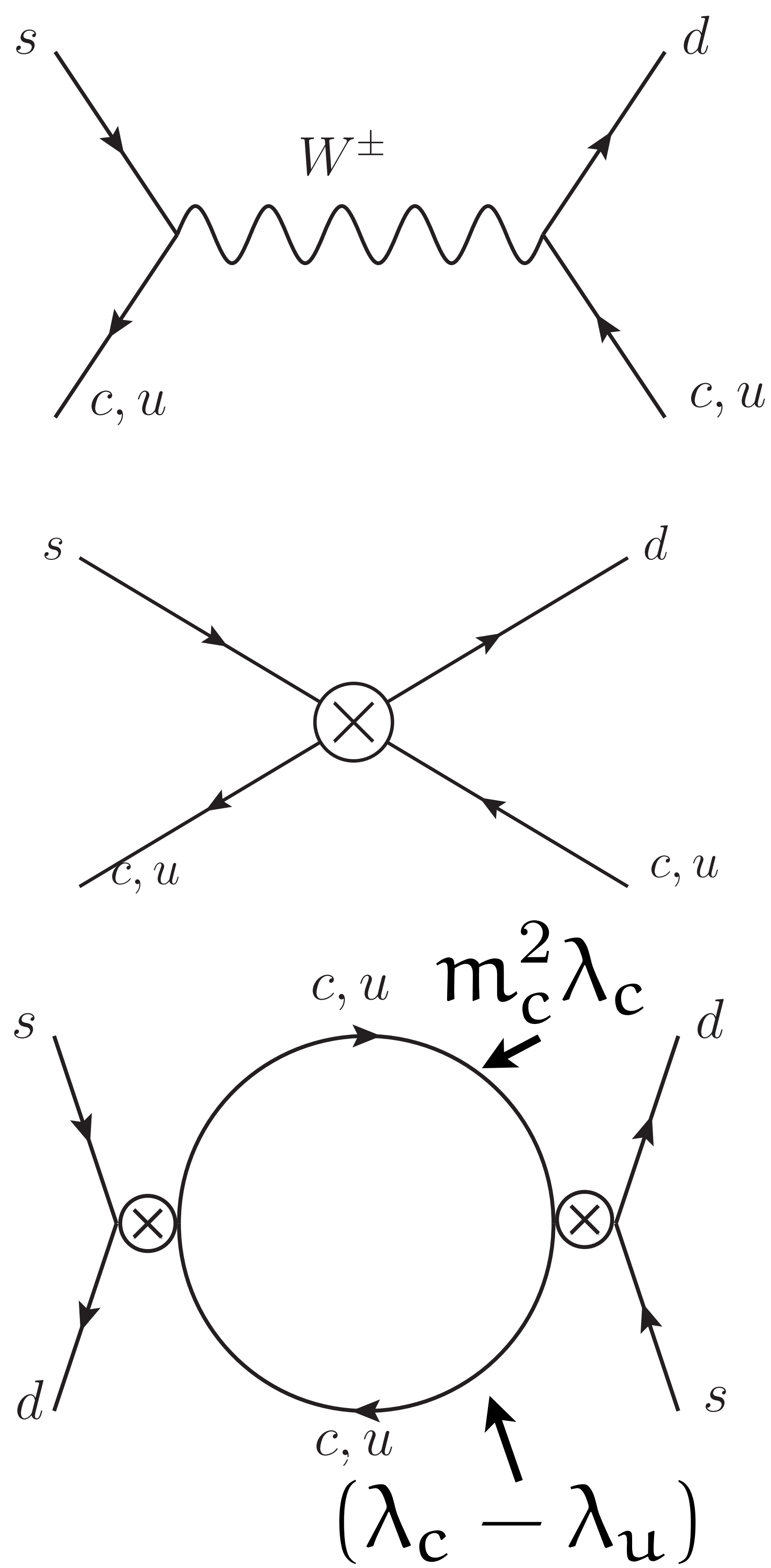
$$+\lambda_c^2 \eta_c S(x_c)\Big] b(\mu) \tilde{Q}$$ charm

$$\tilde{Q} = (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$$

# Calculation of $M_{12}^K = \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle$

| |  |  |  |
|---|---|---|---|
| | **top** | **charm top** | **charm** |
| | $\log x_t$ | $\log x_c$ | $(\log x_c)^0$ ← **hard GIM** |
| LO | $(\alpha_s \log x_c)^n$ | $(\alpha_s \log x_c)^n \log x_c$ | $(\alpha_s \log x_c)^n$ |
| NLO | $\alpha_s(\alpha_s \log x_c)^n$ | $(\alpha_s \log x_c)^n$ | $\alpha_s(\alpha_s \log x_c)^n$ |
| $\epsilon_K$ | 75% | 37% | -12% |
| scale | 1.8% | 16% | 17.7% |

# $\eta_{ct}$ :Charm Top at LO




- The Leading Order result

  $$(\alpha_s \log x_c)^n \log x_c$$

  starts with a $\log x_c$

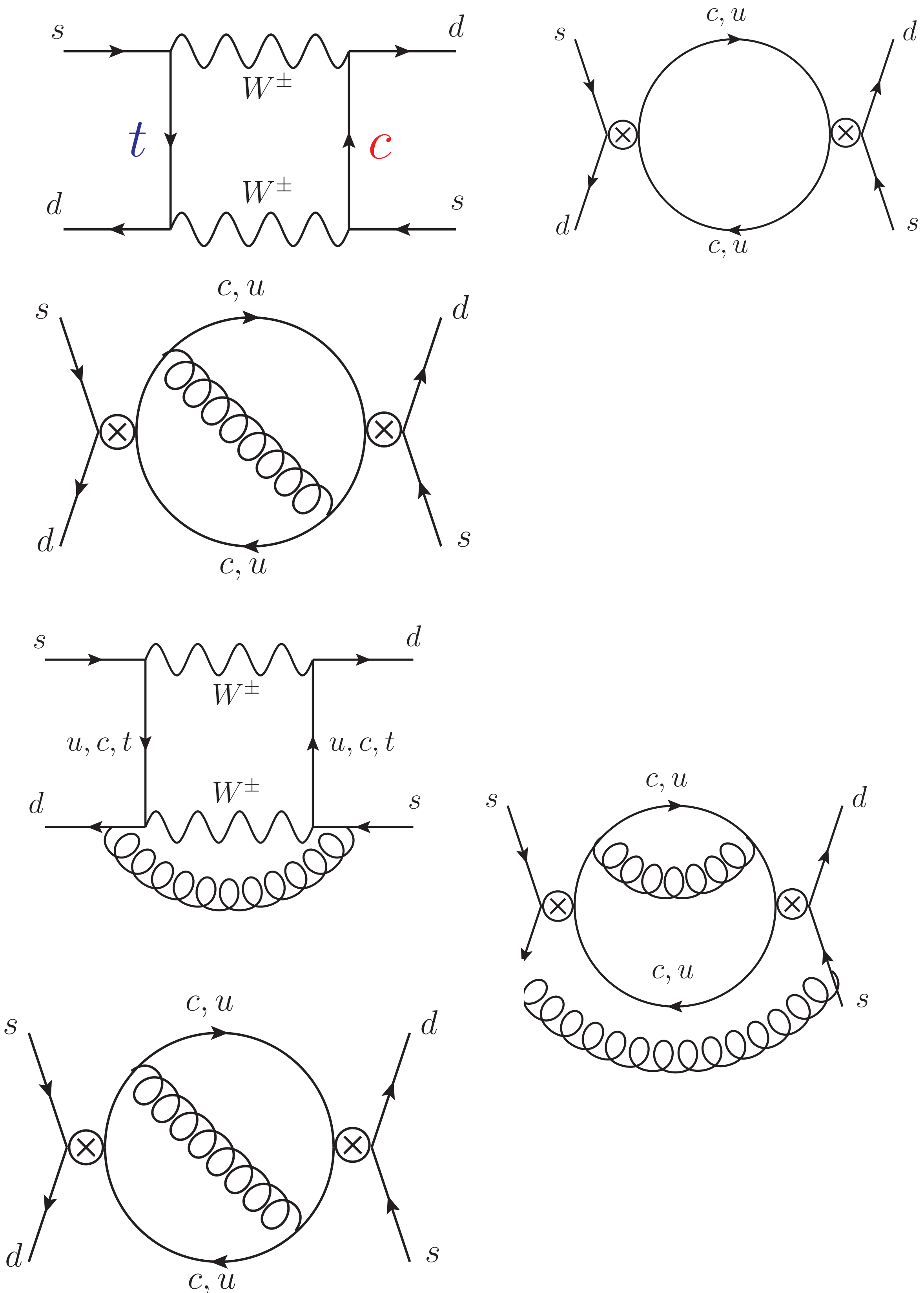
- Tree level matching

- One-loop Renormalistion Group Equation

  $$m_c^2 \lambda_c (\lambda_c - \lambda_u) \log \frac{m_c}{M_W}$$

  $$\rightarrow m_c^2 \lambda_c \lambda_t \tilde{Q} \log x_c$$

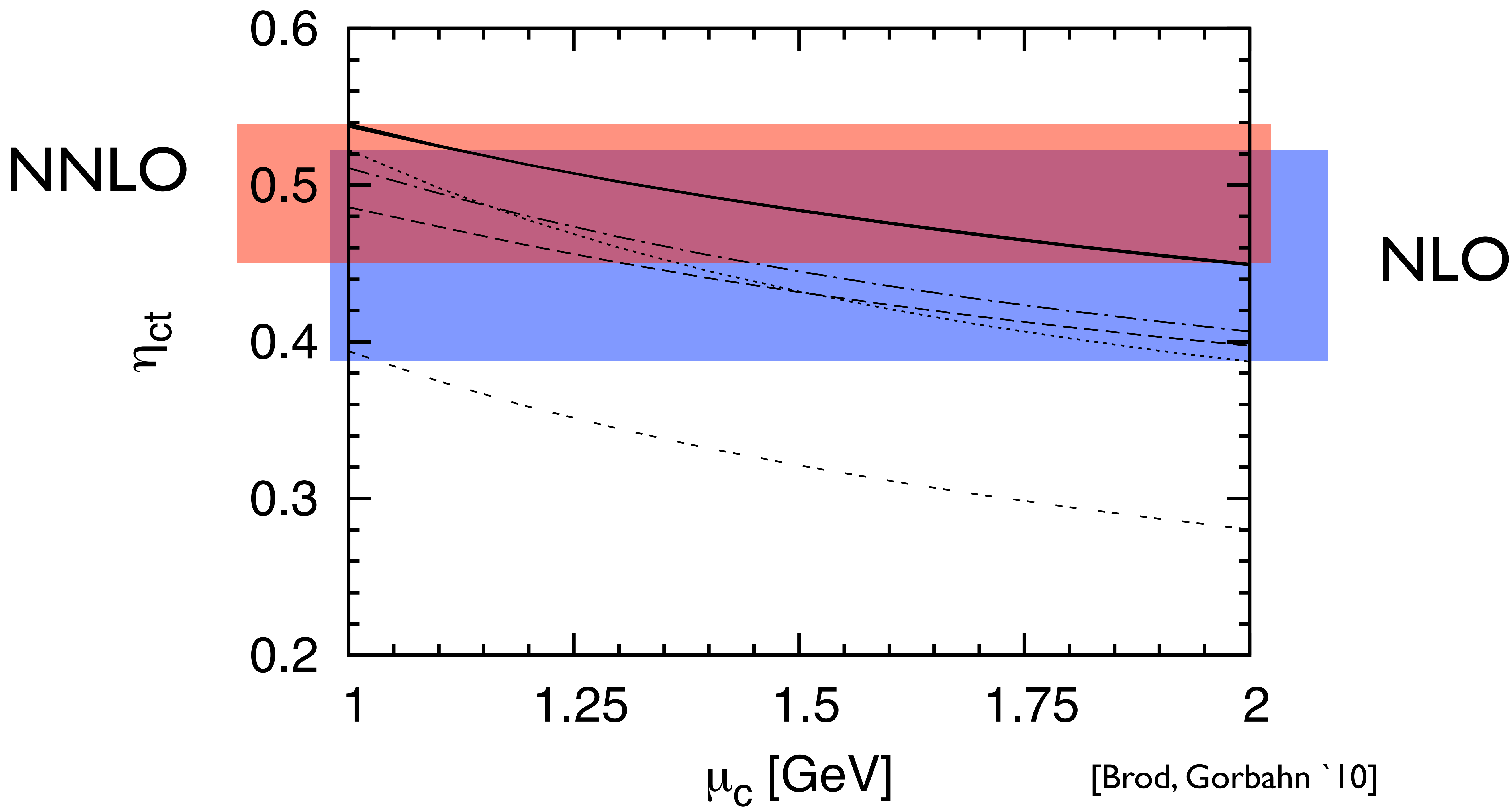
# $\eta_{ct}$ :Charm Top beyond LO




- One-loop matching at $\mu_t$
- One-loop matching at $\mu_c$
- Two-loop RG running
- Plus d=6 operators NLO [Herrlich, Nierste]

- NNLO: RGE and matching for d=6 operators RGE: [MG, Haisch `04], Matching: [Bobeth, et. al. `00]
- O(10000) diagrams were calculated [Brod, Gorbahn `10]

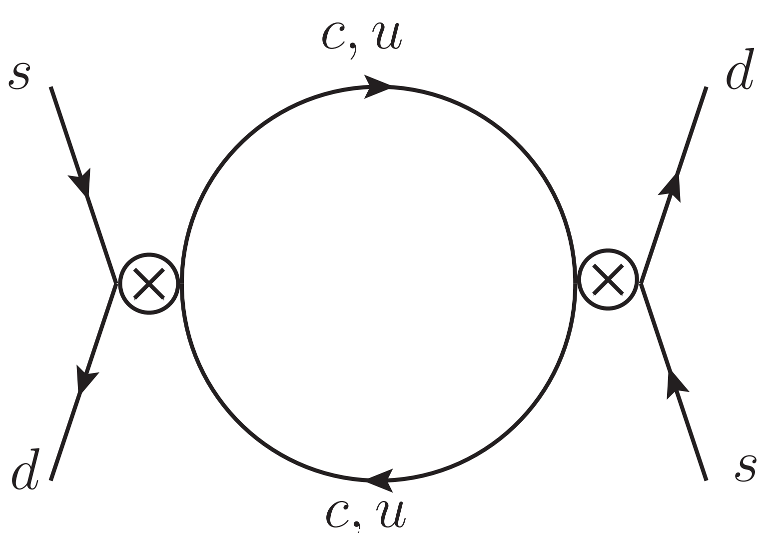
# $\eta_{ct}$ at NNLO




[Brod, Gorbahn `10]

# Long Distance Contribution

$\varepsilon_K$ LD of the matrix element is known precisely




$$\int d^4x \, \langle K^0 | \, H^{|\Delta S|=1}(x) \, H^{|\Delta S|=1}(0) \, | \bar{K}^0 \rangle$$

dispersive part

absorptive part

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left( \frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right)$$

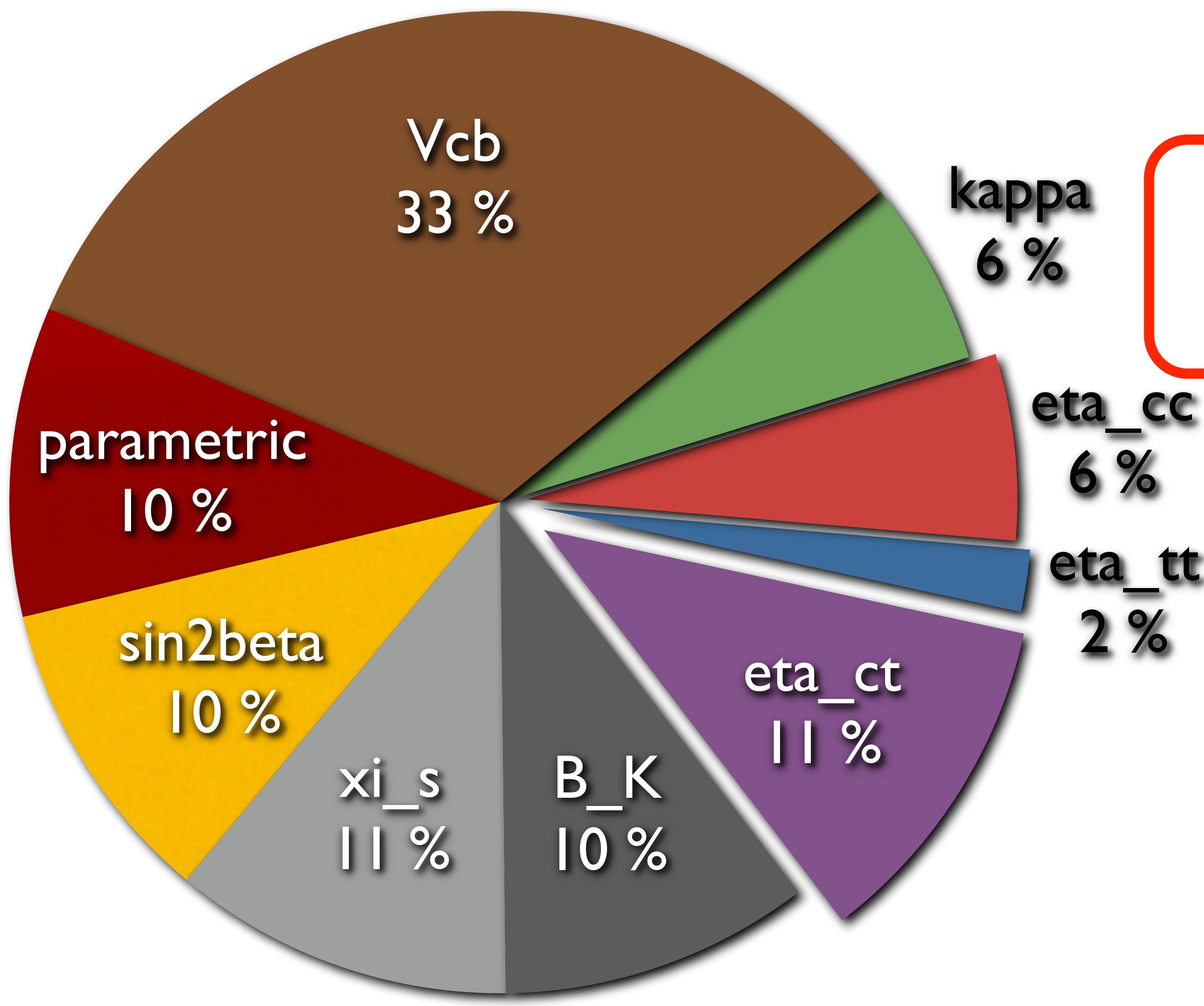
estimated form $\epsilon'$

dispersive part estimated in CHPT

no higher dimensional operators and scale cancellation

put everything in: $\kappa_\epsilon = 0.94 \pm 0.02$ [Buras, Isidori, Guadgnoli `10]

# $|\varepsilon_K|$ and Error Budget




New input [PDG `10]

$$|\epsilon_K| = 1.89(27) \times 10^{-3}$$

using

$$\eta_{ct} = 0.494 \pm 0.046$$

$$|V_{cb}| = 406(13) \times 10^{-4}$$

Experiment [PDG `10]:

$$|\epsilon_K| \stackrel{\text{exp.}}{=} 2.229(12) \times 10^{-3}$$

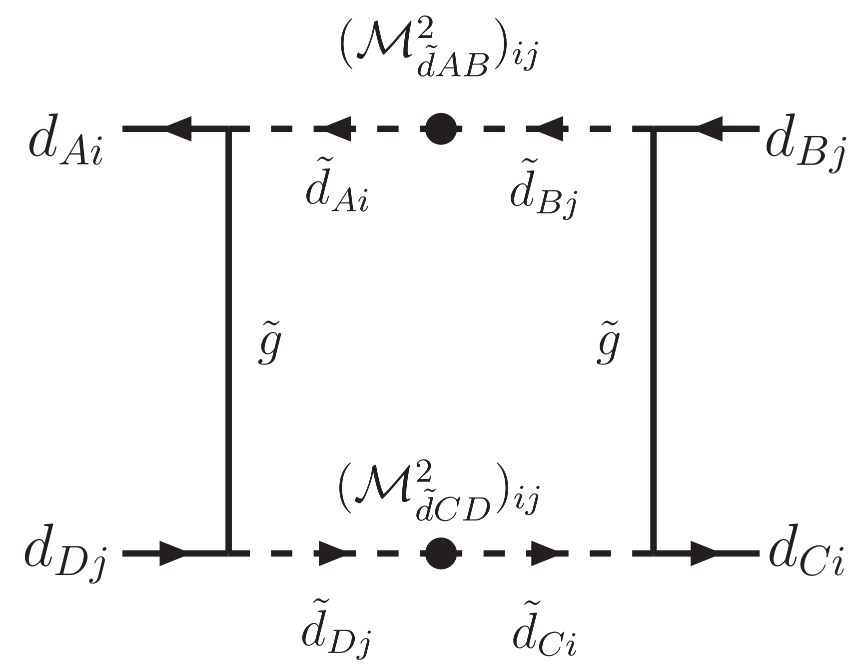
# New Physics & New Operators

So far we mostly discussed the SM background

New operators are generated by your favourite NP model

Talks by Petrov and Jäger

4 more operators




$$Q_1^{\mathrm{VLL}} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{s}^\beta \gamma^\mu P_L d^\beta),$$

$$Q_1^{\mathrm{LR}} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{s}^\beta \gamma^\mu P_R d^\beta),$$

$$Q_2^{\mathrm{LR}} = (\bar{s}^\alpha P_L d^\alpha)(\bar{s}^\beta P_R d^\beta),$$

$$Q_1^{\mathrm{SLL}} = (\bar{s}^\alpha P_L d^\alpha)(\bar{s}^\beta P_L d^\beta),$$

$$Q_2^{\mathrm{SLL}} = (\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\alpha)(\bar{s}^\beta \sigma^{\mu\nu} P_L d^\beta)$$

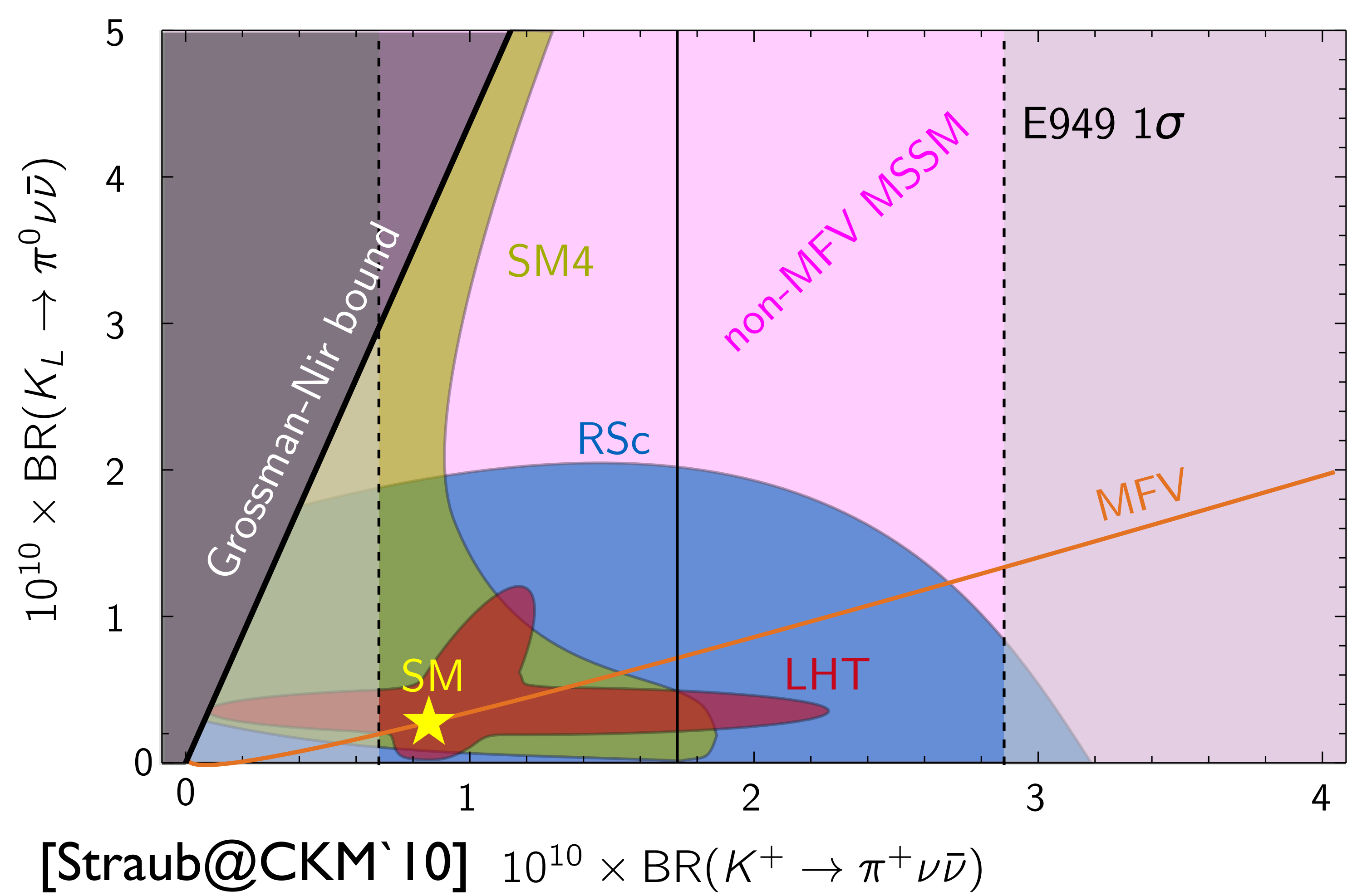
# Conclusions

$K \to \pi \nu \bar{\nu}$ : very clean and sensitive to short distances
Lattice could clarify the long distance contribution to $K^+$

the same for $\varepsilon_K$ (thanks to the improvement by Lattice)
Matrix elements for NP?

Closer contact of the perturbative and lattice community could be beneficial (quark masses)

Many more exciting things in kaon physics:
$\epsilon'$, unitarity, lepton univ.




[Straub@CKM`10]