Rare and CP violating Kaon decays: a probe of TeV scale physics

BEACH 2012
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TUM-IAS &
Excellence Cluster `Universe´

This Talk

Wichita: Cowtown

Past:
Why are rare Kaon decays so rare?

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Present:
Precision theory prediction for $K_L \to \pi \bar{\nu} \nu$ and ε_K

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Wichita: Cowtown


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Why are rare Kaon decays so rare?

Present:
Precision theory prediction for $K_L \to \pi\, \bar{\upsilon}\, \upsilon$ and ε_K

Future:
What can we learn about New Physics from Kaons?

Why are Kaon Decays so rare?

Before the charm quark: why are the two Branching ratios

$$\mathcal{B}r(K_L \to \mu^+\mu^-) \simeq 6.84(11)\cdot 10^{-9} \qquad \mathcal{B}r(K_L \to \gamma\gamma) \simeq 5.47(4)\cdot 10^{-4}$$

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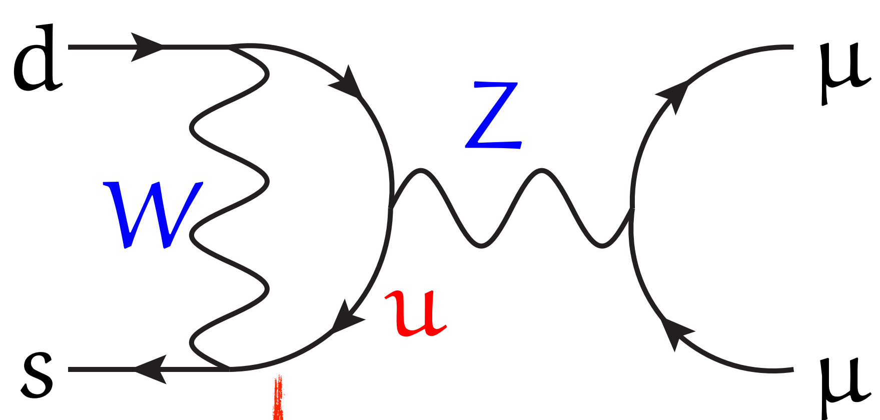
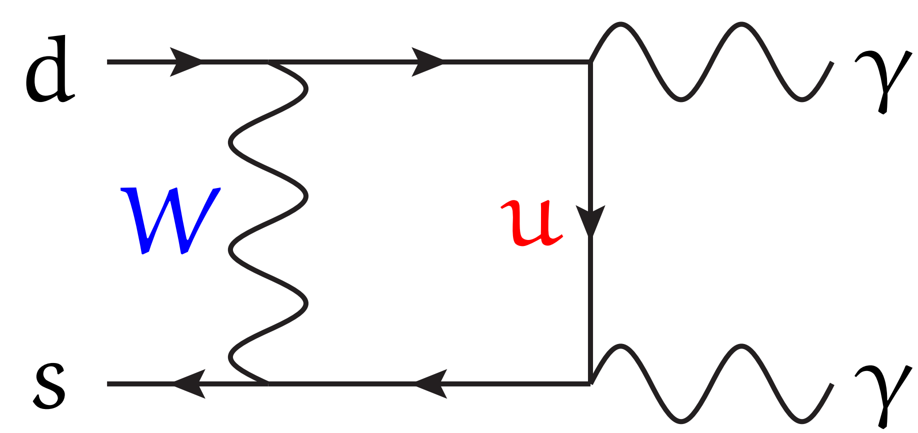
$K_L \to \mu^+ \mu^-$: The 2 μs are in J=0 state → no 1 γ coupling



$\mathcal{O}(G_F^2 \Lambda_{\text{Fermi}}) = \mathcal{O}(G_F \alpha)$



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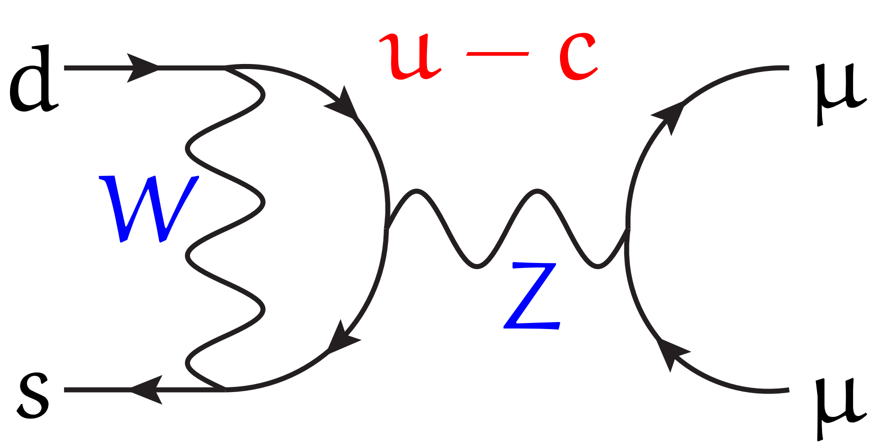
The GIM Mechanism

GIM: charm quark to suppress neutral currents



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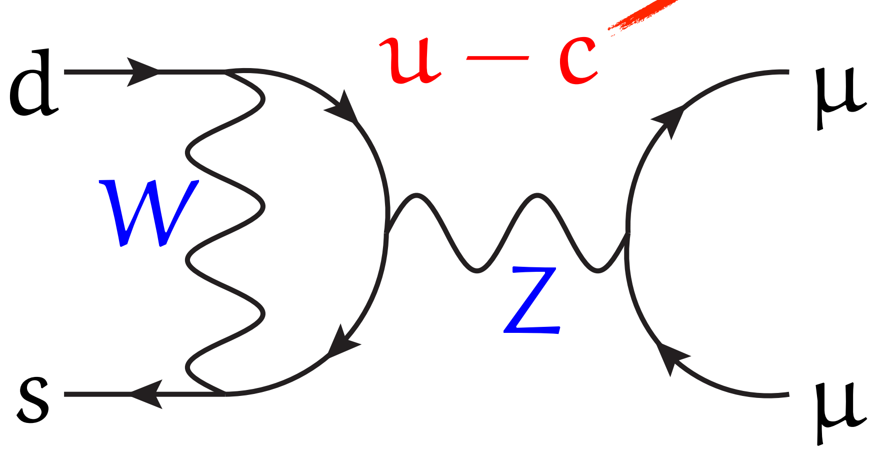

$$\frac{1}{\not{q} - m_u} \to \frac{1}{\not{q} - m_u} - \frac{1}{\not{q} - m_c}$$

Cutoff is then m_c^2

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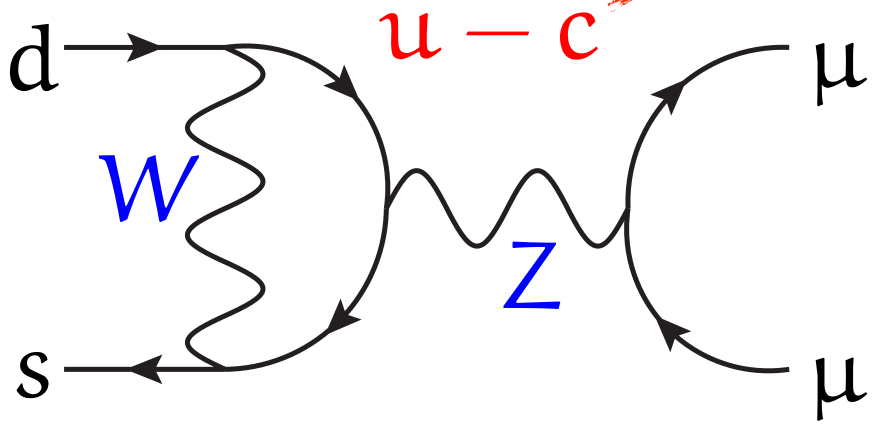

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Quadratic GIM explains the smallness of $\mathcal{B}r(K_L \rightarrow \mu^+\mu^-)$

$\frac{m_c^2}{M_W^2}$ dependence: predict charm quark

Charm Quark Mass

Quadratic GIM suppresses light quark contribution

Sensitive to short distances (SD)

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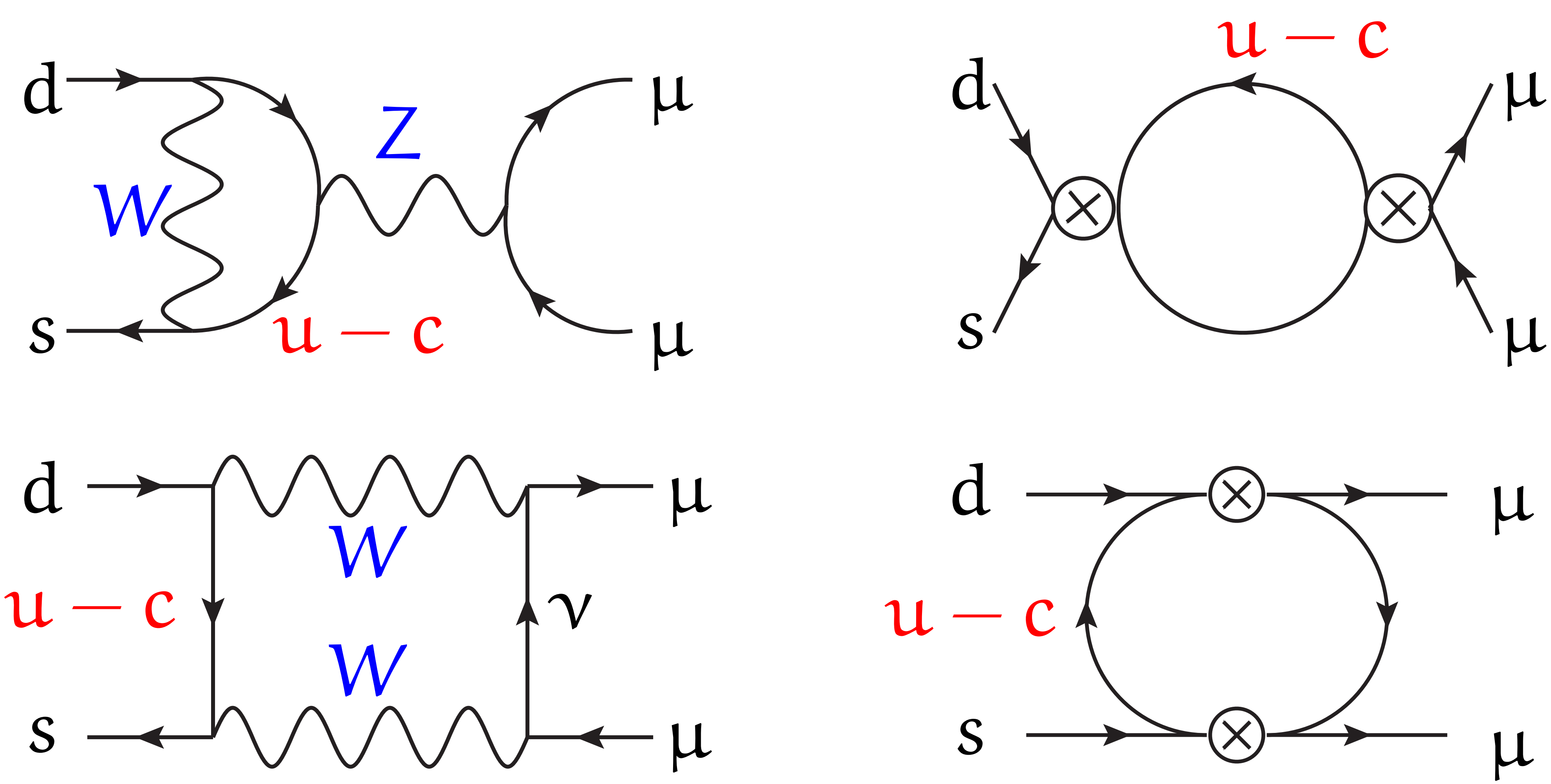
Effective theory language:



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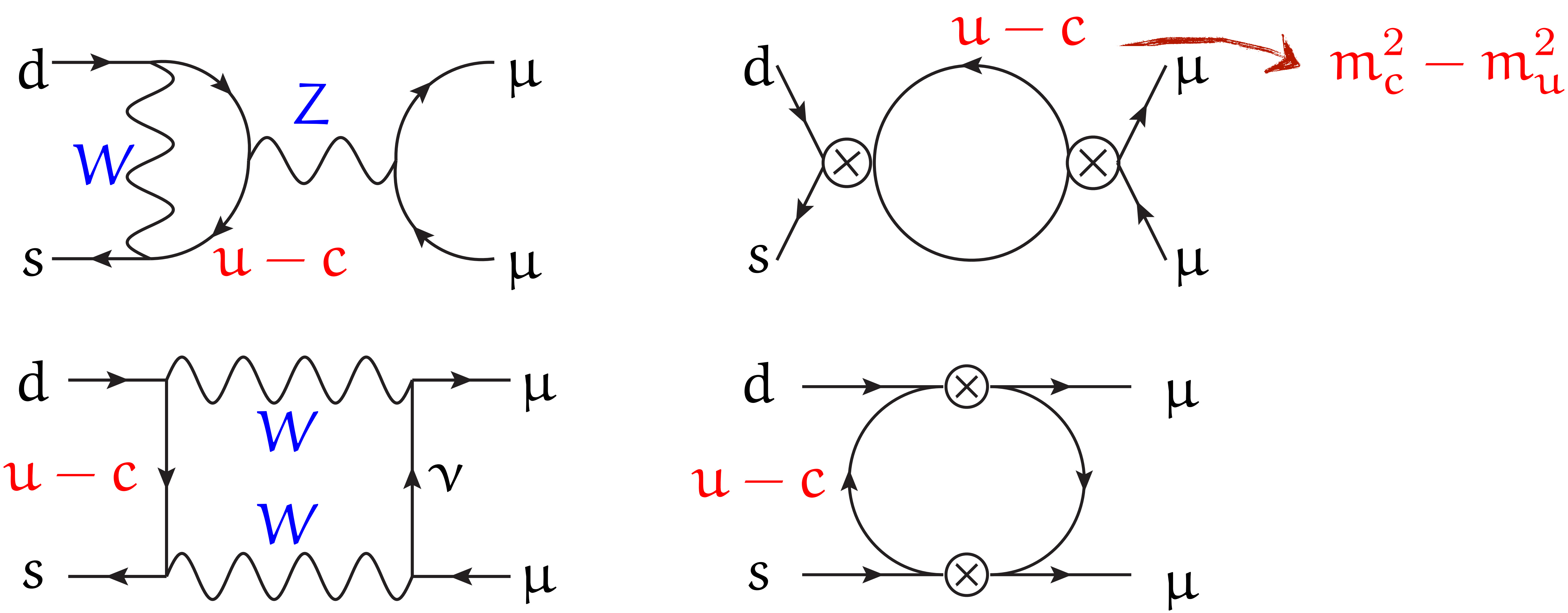

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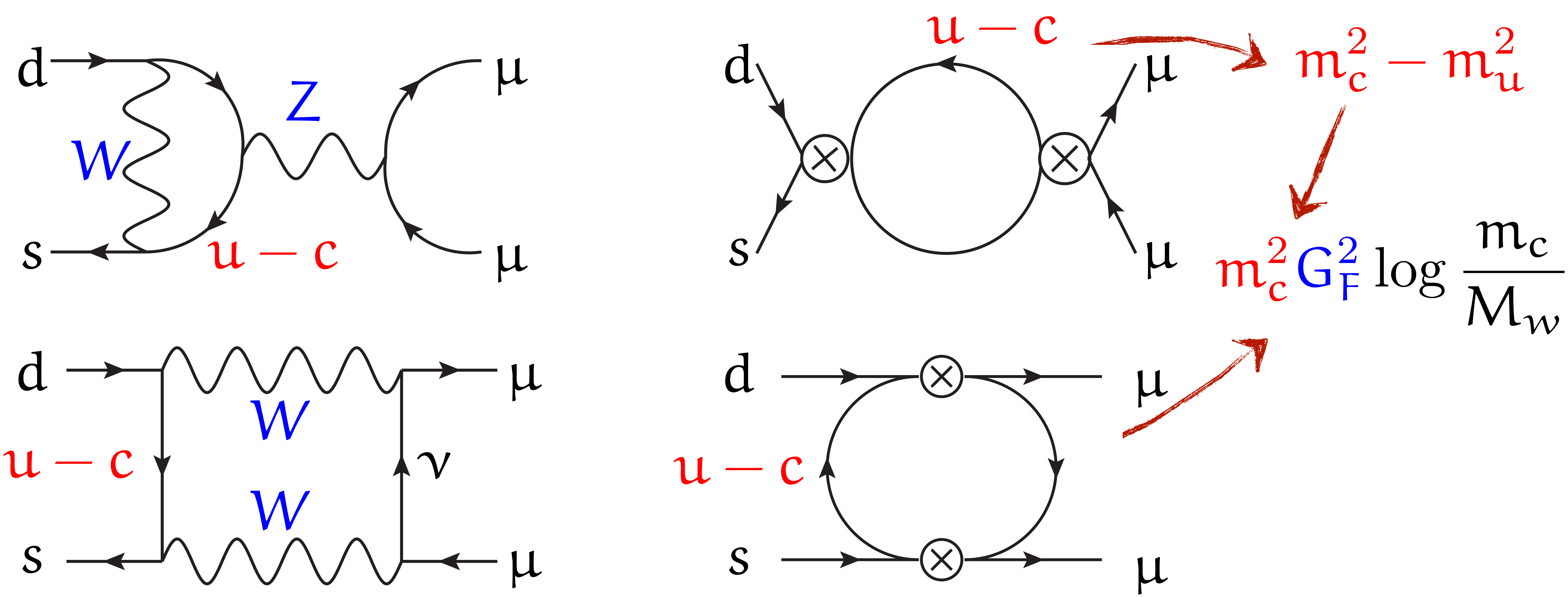

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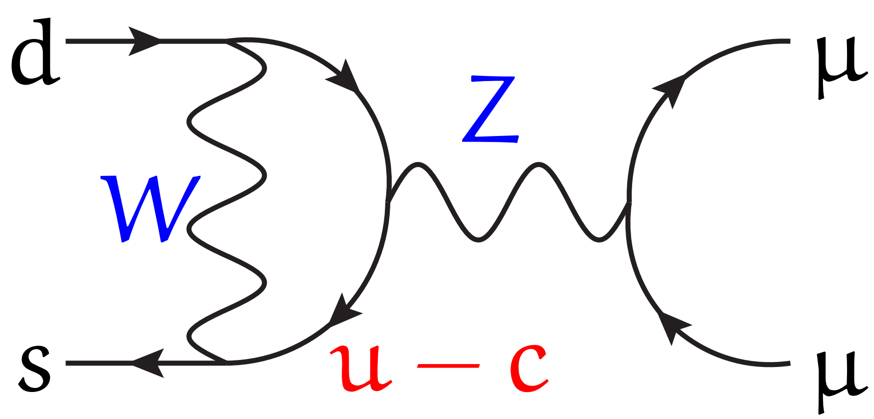
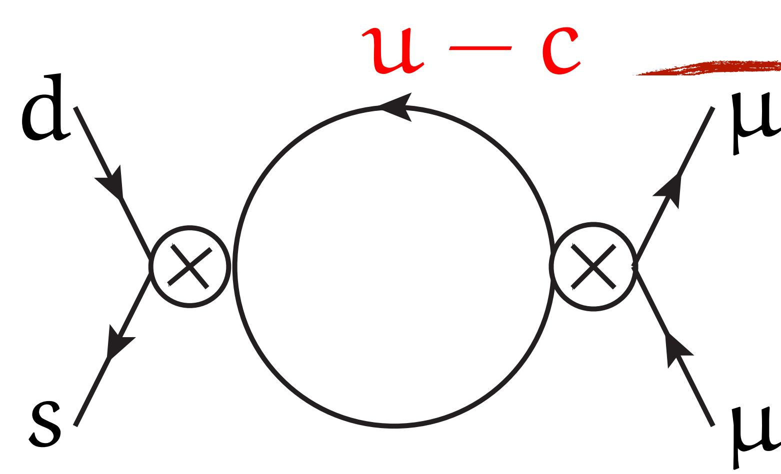
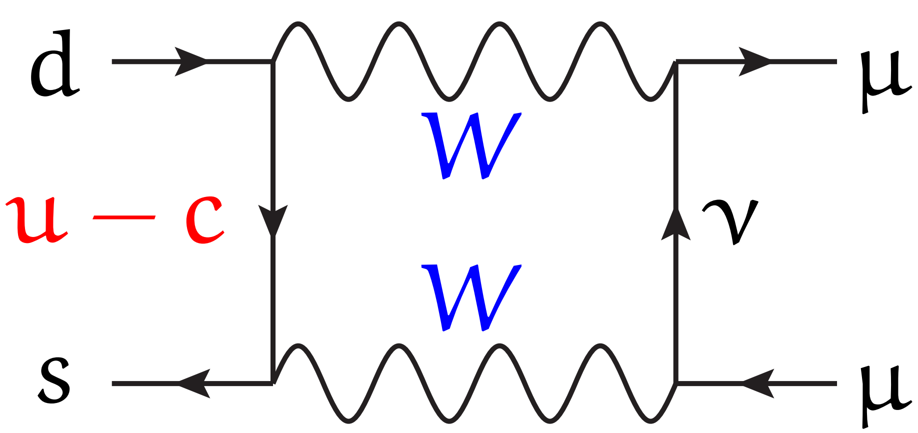
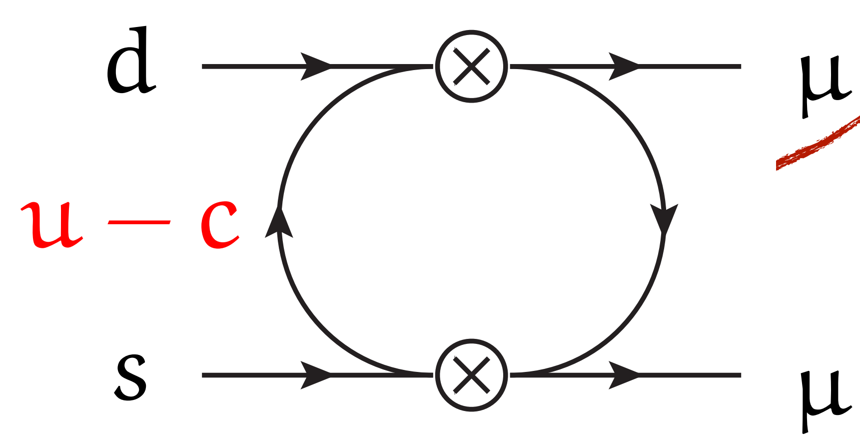




$$m_c^2 - m_u^2$$

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



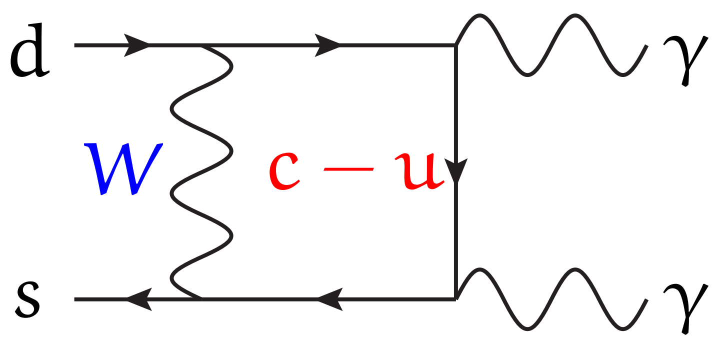


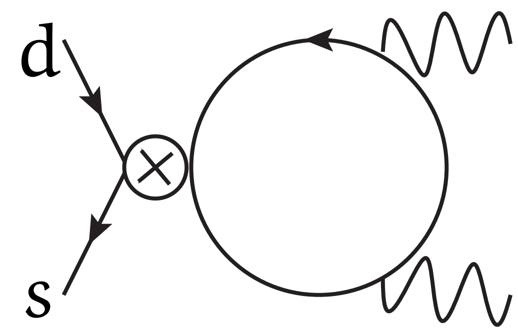
NNLO

[MG, Haisch `07]

Contributions to $K_L \to \mu^+\mu^-$

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





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

(same for photon penguin)

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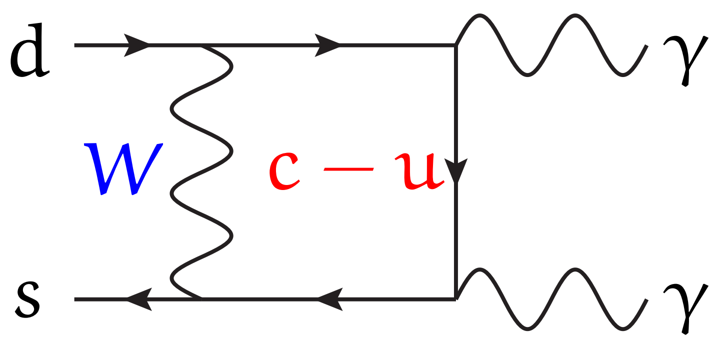

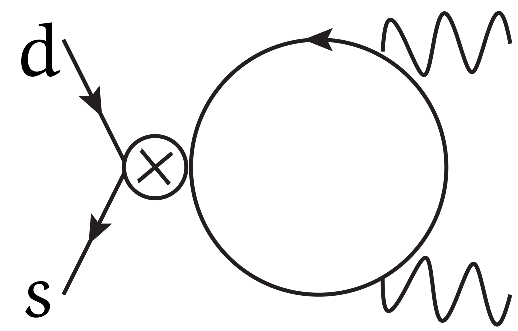

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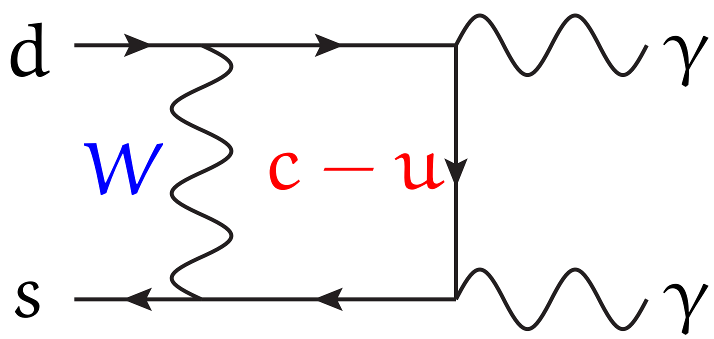

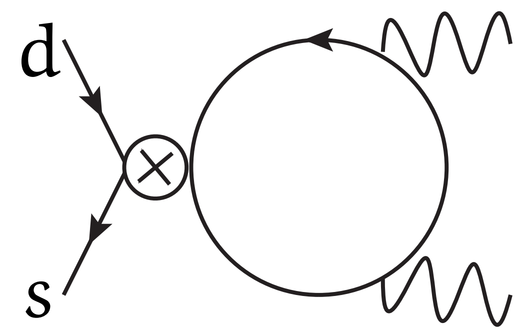

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including top

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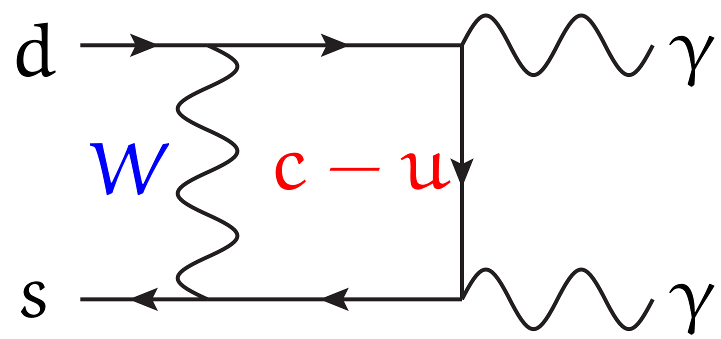

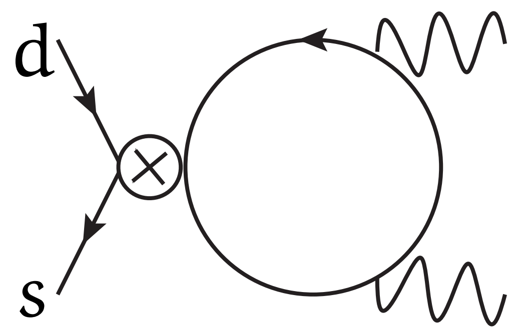

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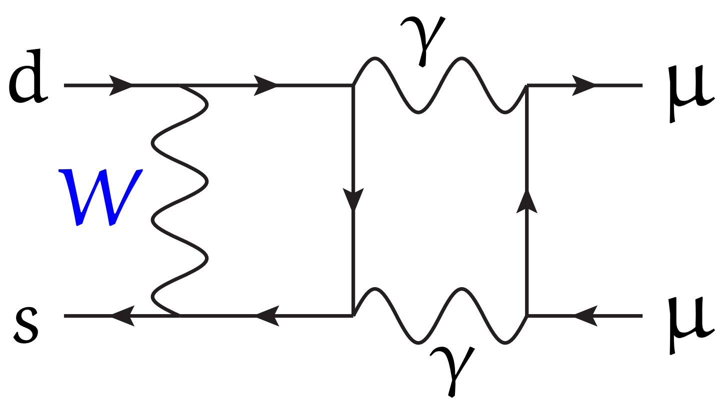

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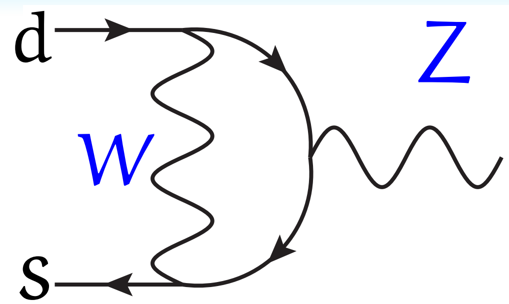
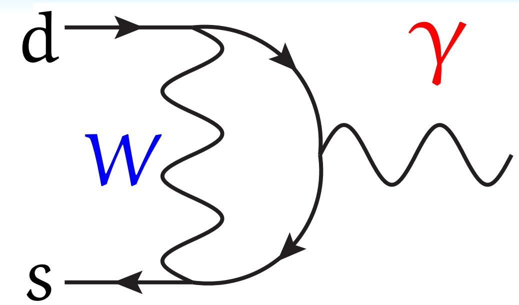
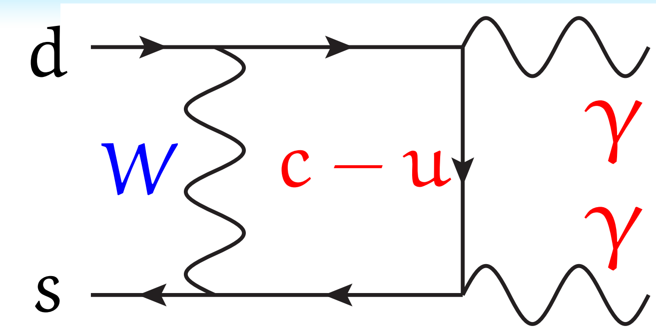
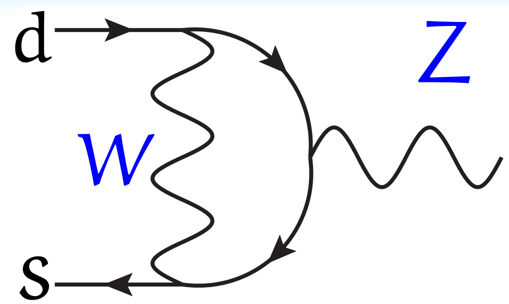
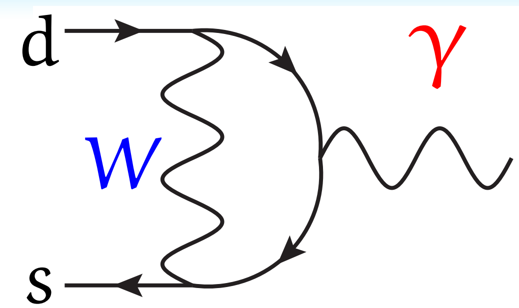
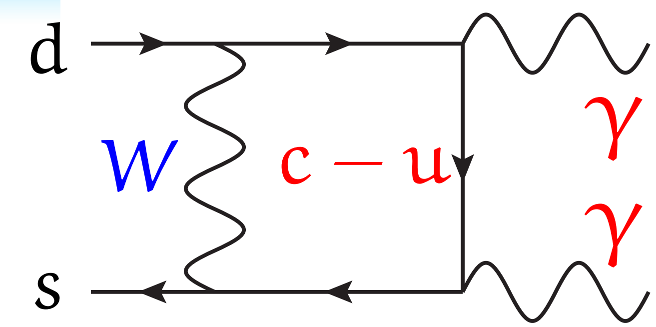
Dispersive Absorptive

Rare Kaon Decays

			
$K_L \to \mu^+\mu^-$	SD	–	α_e LD

Rare Kaon Decays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	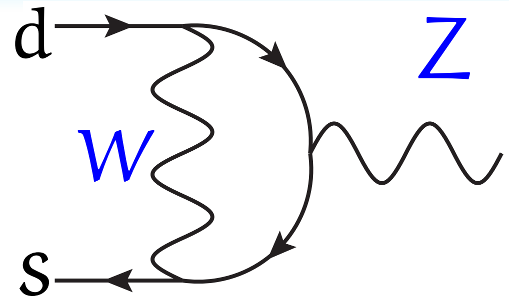	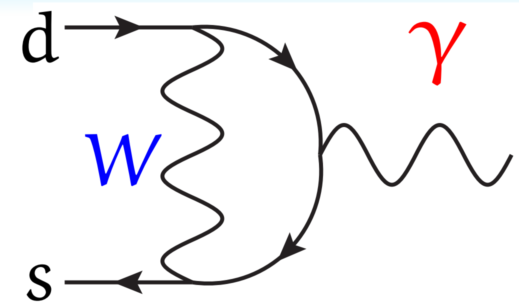	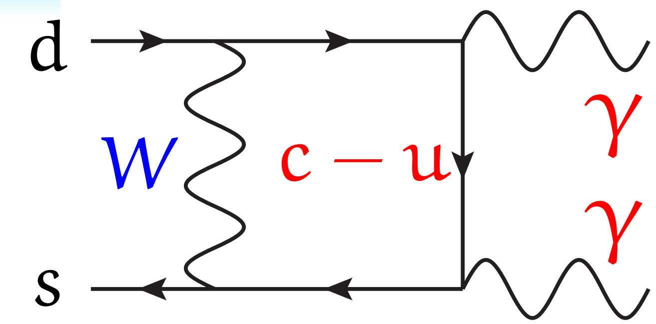
$K_L \to \mu^+ \mu^-$	SD	–	α_e LD
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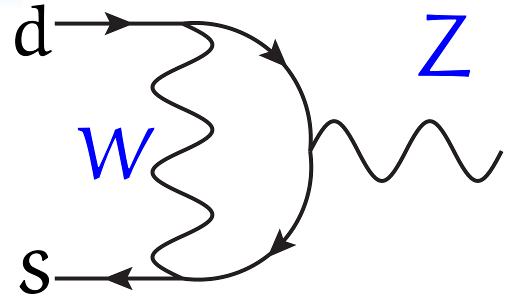
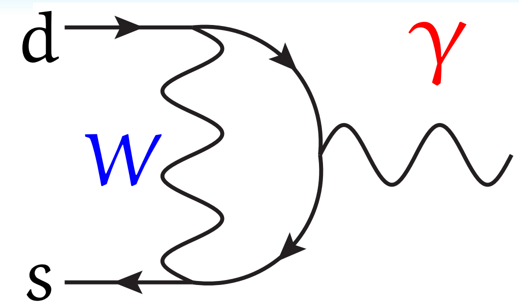
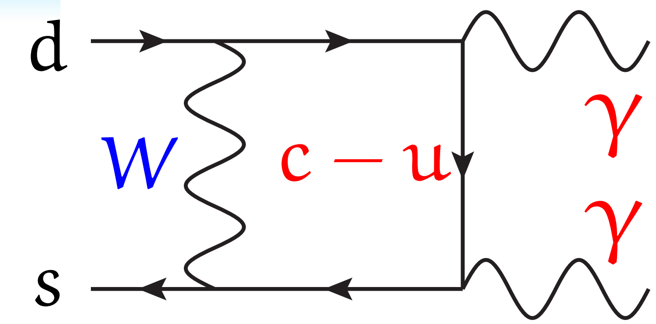
$K_S \to \pi l^+ l^-$	–	LD	–

Rare Kaon Decays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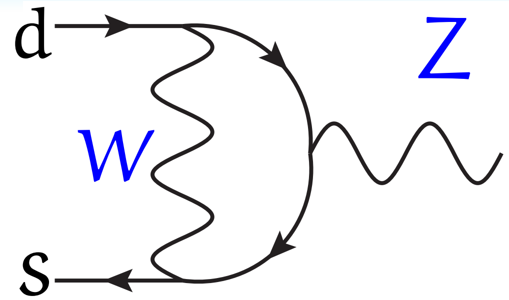
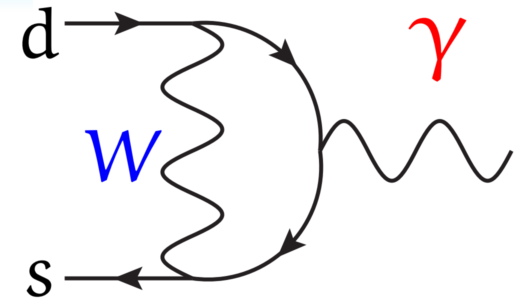
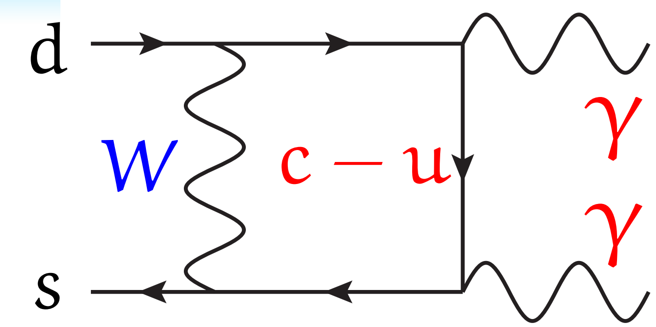
Rare Kaon Decays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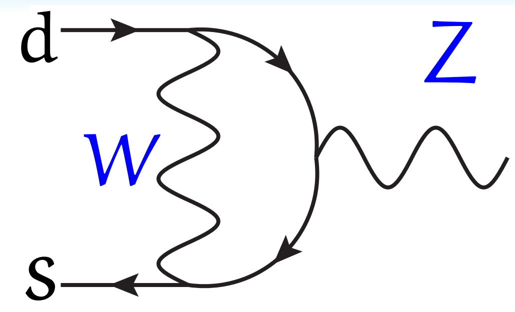
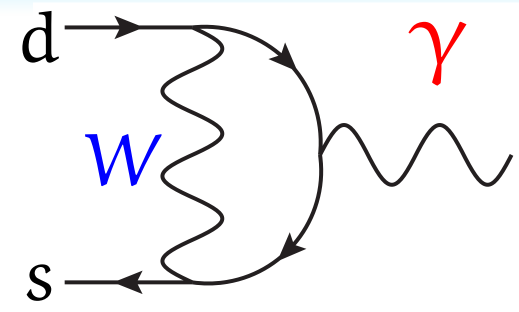
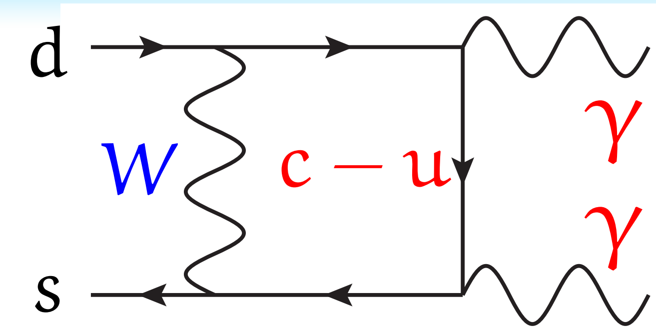
$K_L \to \pi l^+ l^-$	SD	SD $+\epsilon_K$ LD	α_e LD

CP violating

Rare Kaon Decays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CP violating	NLO QCD [Buchalla et. al. `95]	$K_L \to K_S$ & $K_S \to \pi^0 l^+ l^-$ [Mescia et. al. `06]	Estimate from $K_L \to \pi^0 \gamma\gamma$ [Isidori et. al. `04]

Top quark

m_c^2 / M_W^2 suppression

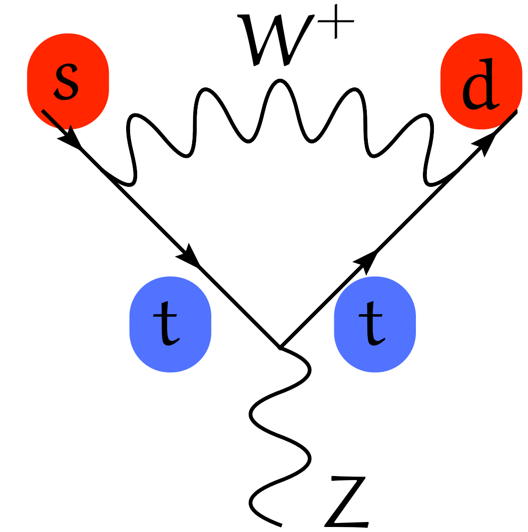
$\rightarrow$ top-quark dominates

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

$$\frac{m_c^2}{M_W^2} \log\left(\frac{m_c^2}{M_W^2}\right) \lambda = 0.3 \cdot \frac{m_t^2}{M_W^2} \lambda^5$$

$$V_{ij} = \mathcal{O}\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \mathcal{O}(0.2)$$



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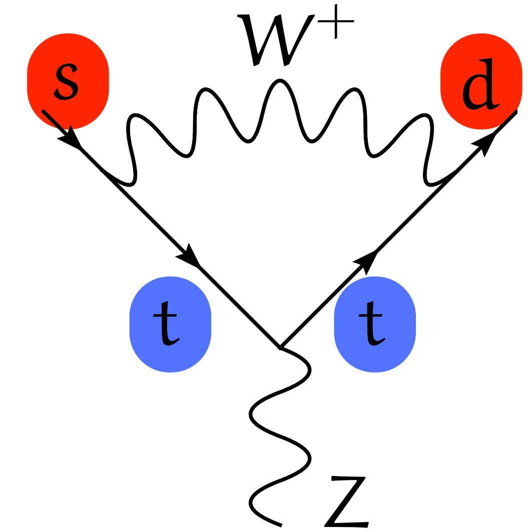

FCNCs which are dominated by top-quark loops:

$b \to s:$	$b \to d:$	$s \to d:$
$\lvert V_{tb}^* V_{ts} \rvert \propto \lambda^2$	$\lvert V_{tb}^* V_{td} \rvert \propto \lambda^3$	$\lvert V_{ts}^* V_{td} \rvert \propto \lambda^5$

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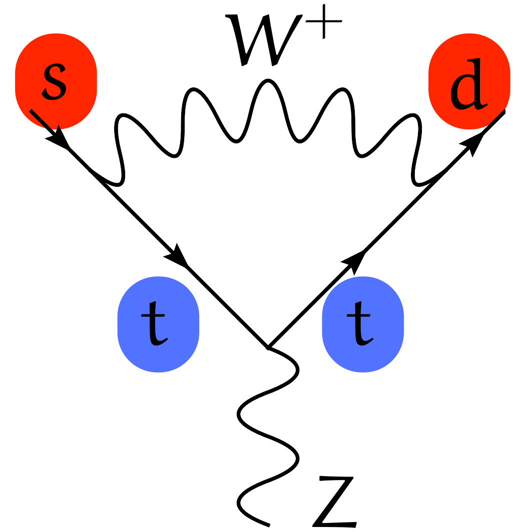

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Kaons test new physics up to 100 TeV

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– Z-Penguin & Boxes 1 γ-Penguin and scalar can contribute

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$K \to \pi\, \bar{\upsilon}\, \upsilon$: cleanest modes – Only Z-Penguin & Boxes

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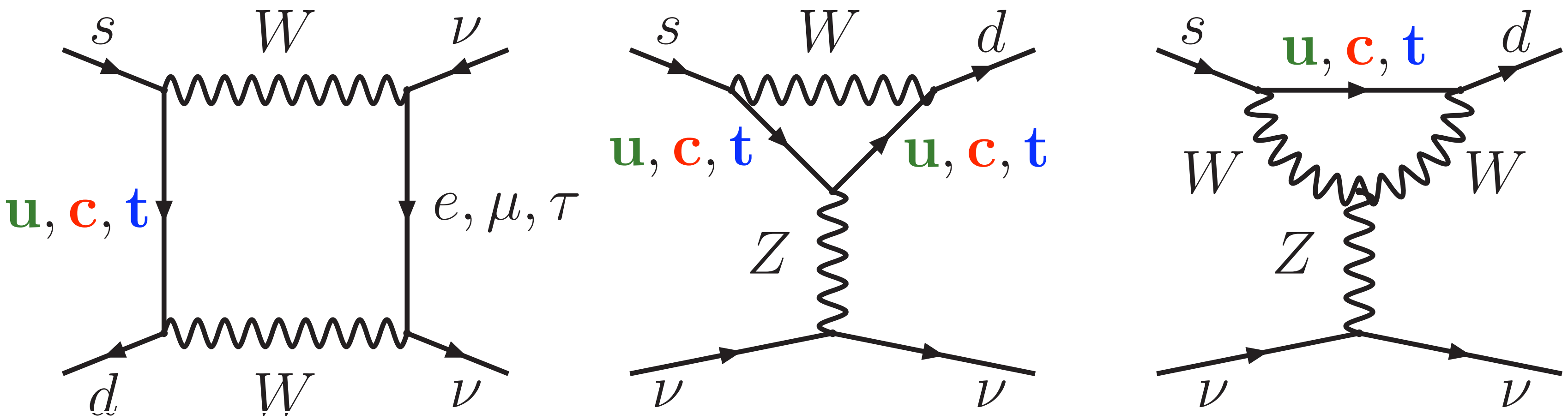
Hadronic decays: CP violation in mixing ε_K
Light quark contributions suppressed by
quadratic GIM and small 2nd generation complex phase

$K^+ \to \pi^+ \bar{\upsilon}\, \upsilon$ at M_W



$$x_i = \frac{m_i^2}{M_W^2}$$

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

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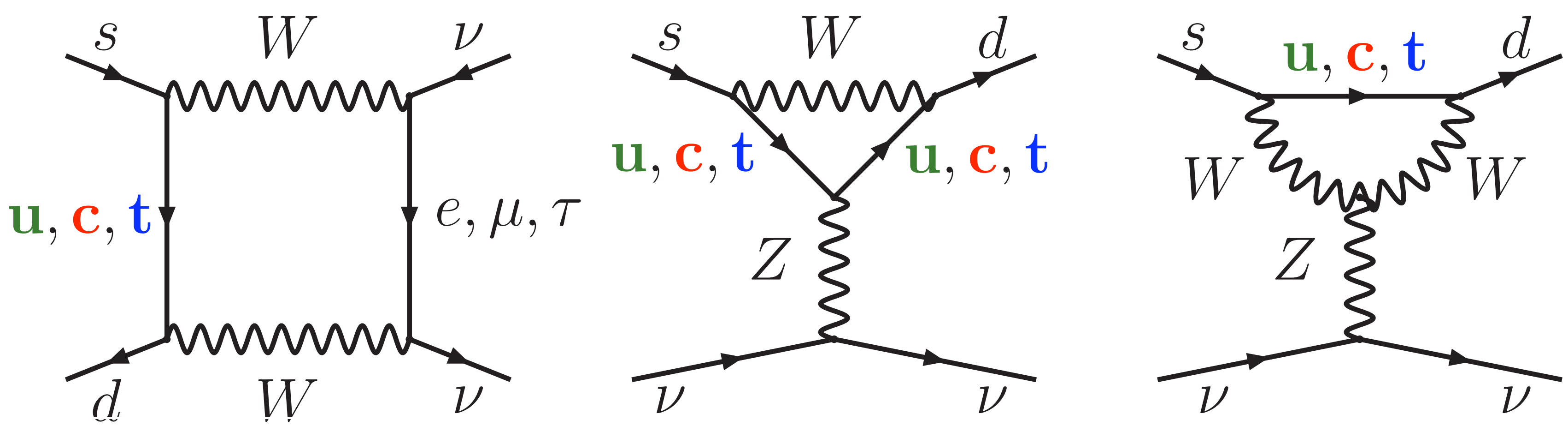

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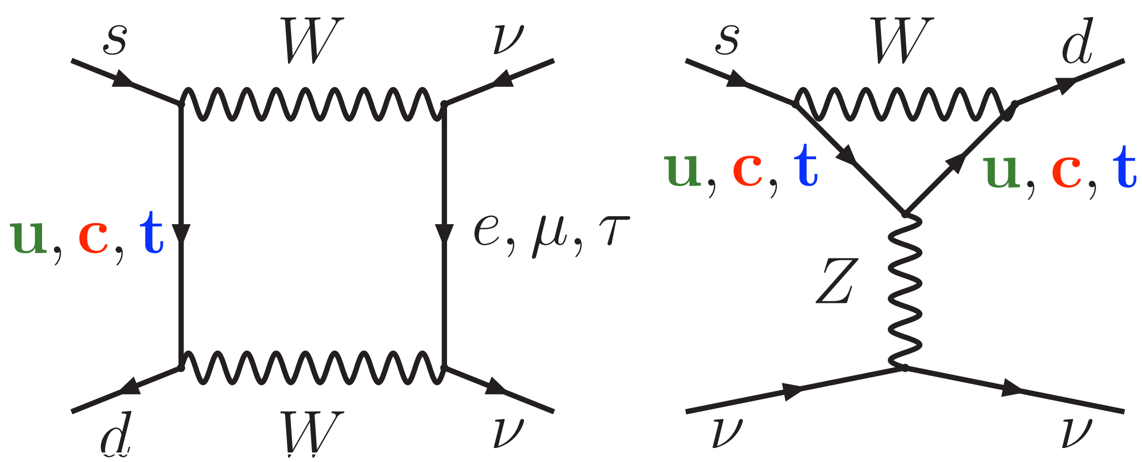
Quadratic GIM: $\boxed{\lambda^5 \frac{m_t^2}{M_W^2}}$

Matching (NLO +EW):

[Misiak, Urban; Buras, Buchalla;
Brod, MG, Stamou`11]

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

$K^+ \to \pi^+ \bar{\nu} \nu$ at M_W



$$x_i = \frac{m_i^2}{M_W^2}$$

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

Quadratic GIM: $\boxed{\lambda^5 \frac{m_t^2}{M_W^2}}$

Matching (NLO +EW):

[Misiak, Urban; Buras, Buchalla; Brod, MG, Stamou`11]

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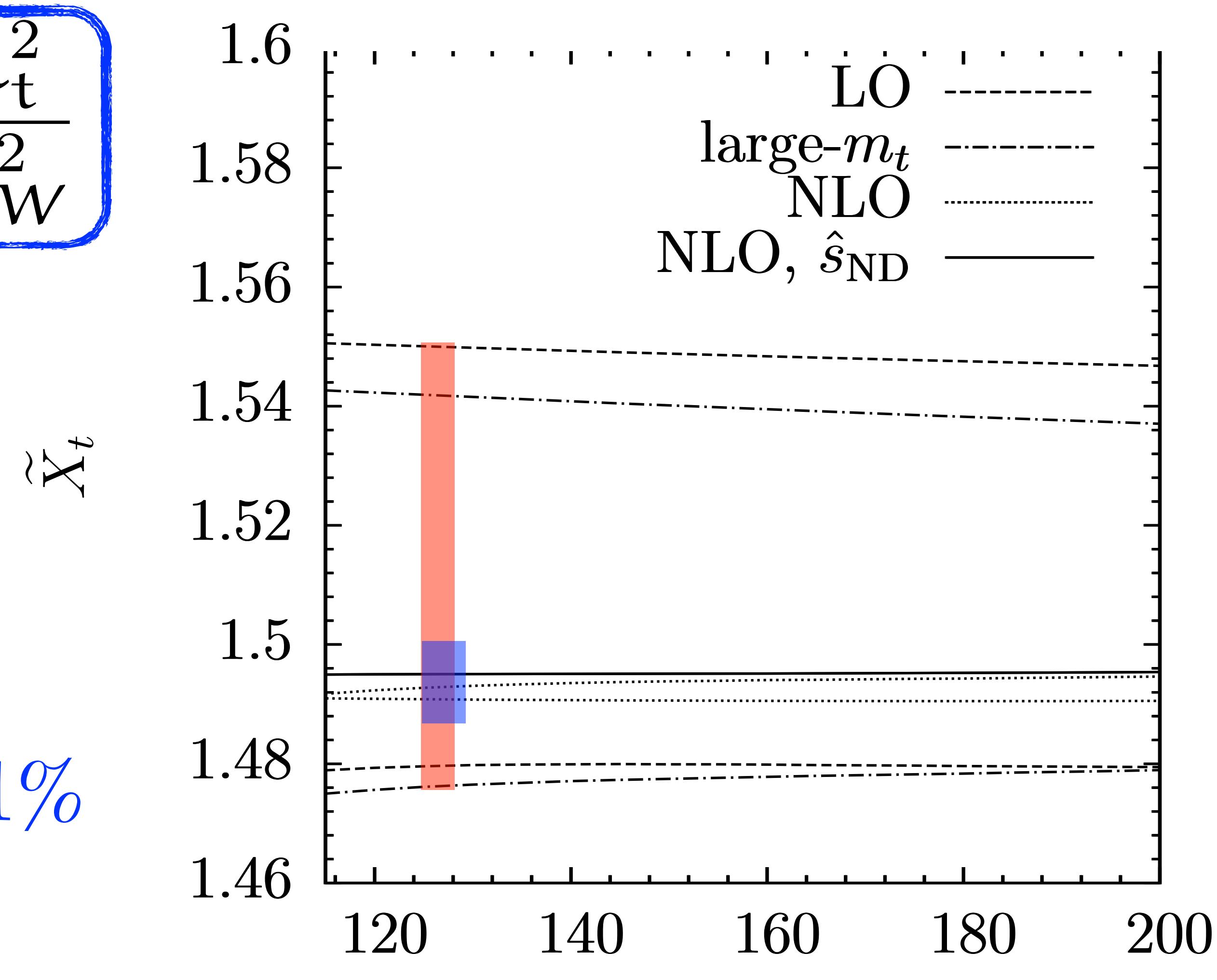
After 2011 uncertainty below 1%



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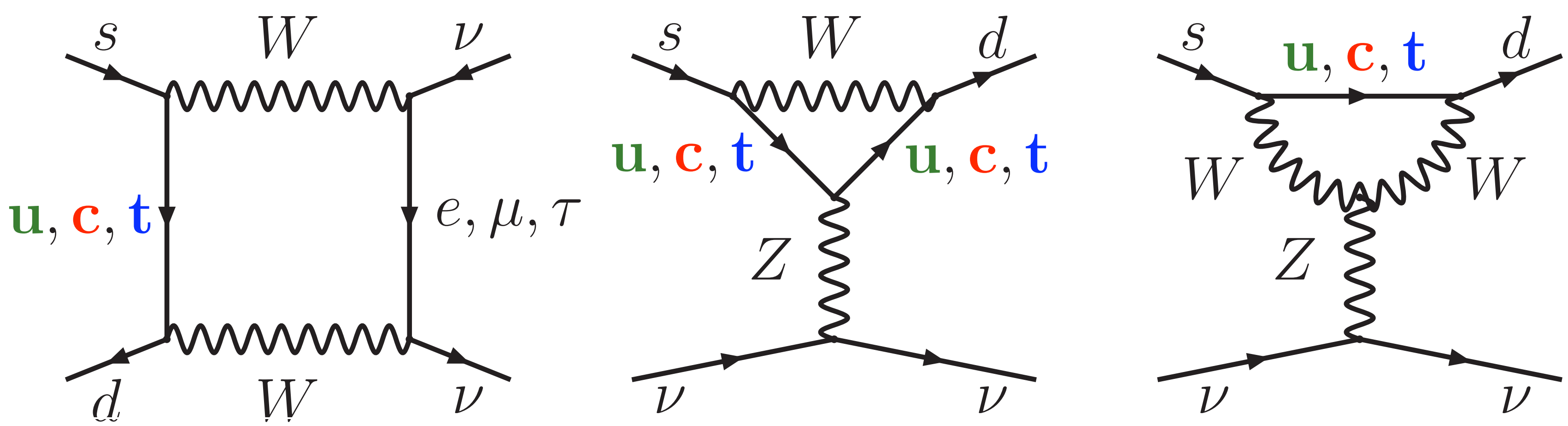

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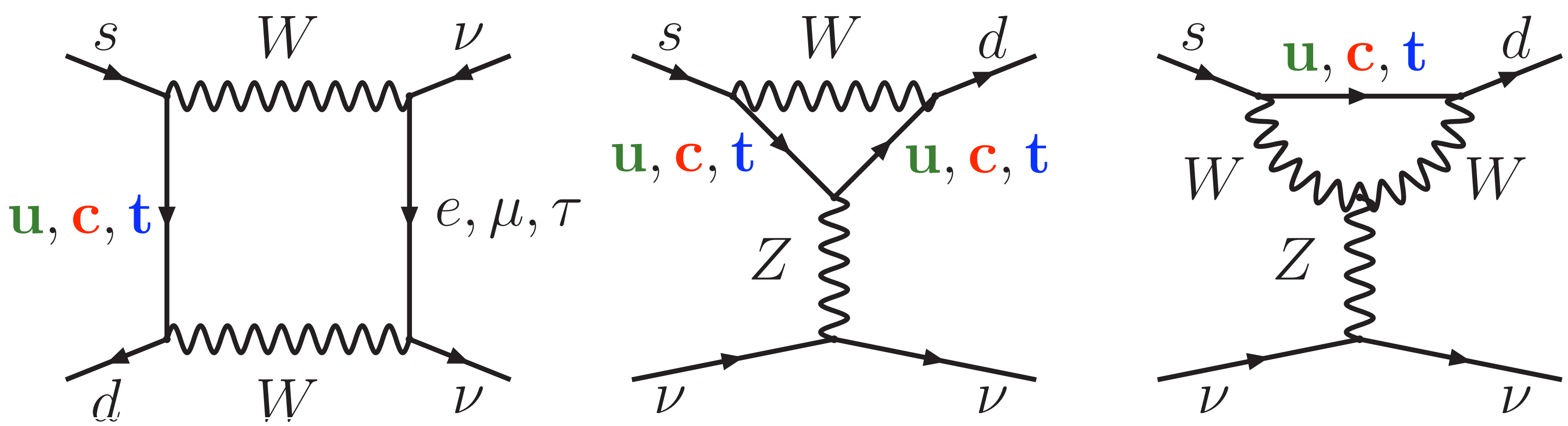

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Matrix element from K_{l3} decays

(Isospin symmetry: $K^+ \to \pi^0 e^+ \nu$)

[Mescia, Smith]

$K^+ \to \pi^+ \bar{\nu}\, \nu$ from M_W to m_c

P_c: charm quark contribution to $K^+ \to \pi^+ \bar{\nu}\, \nu$ (30% to BR)

Series converges very well (NNLO:10%→2.5% uncertainty)

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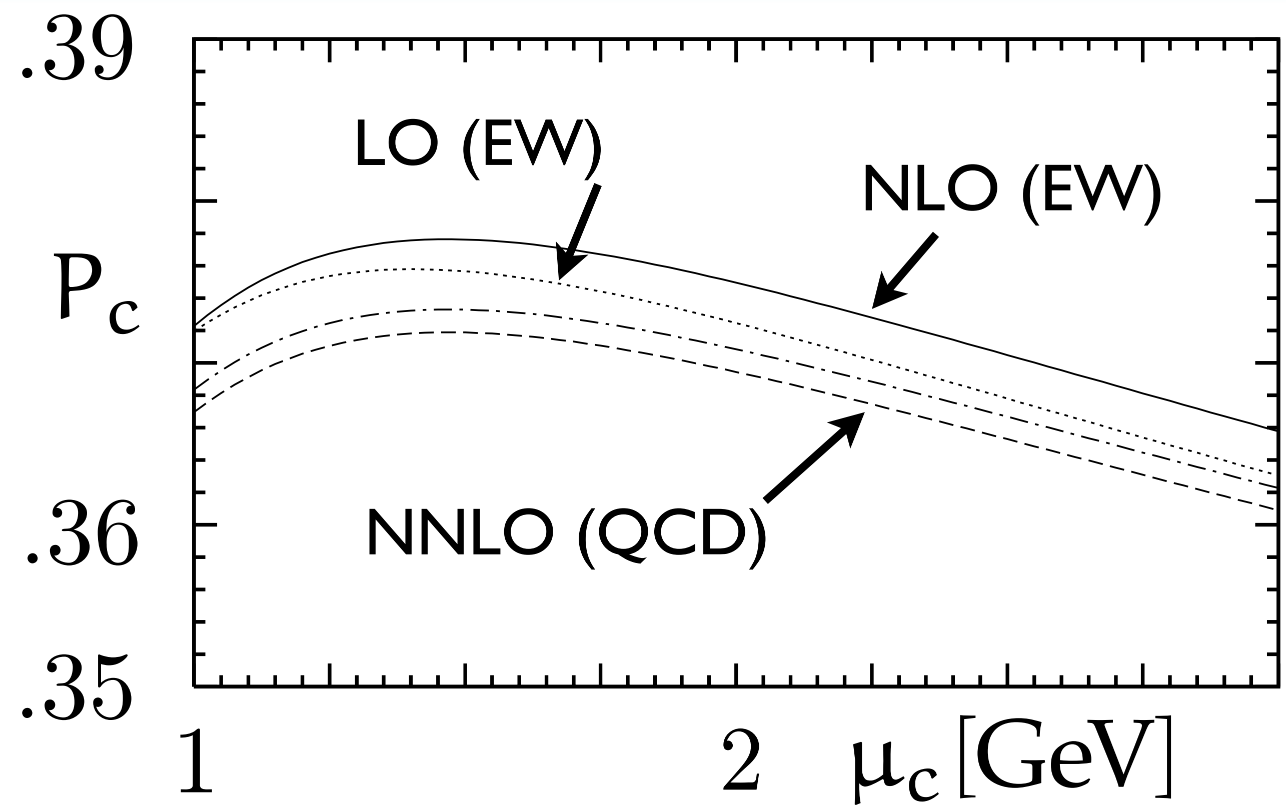

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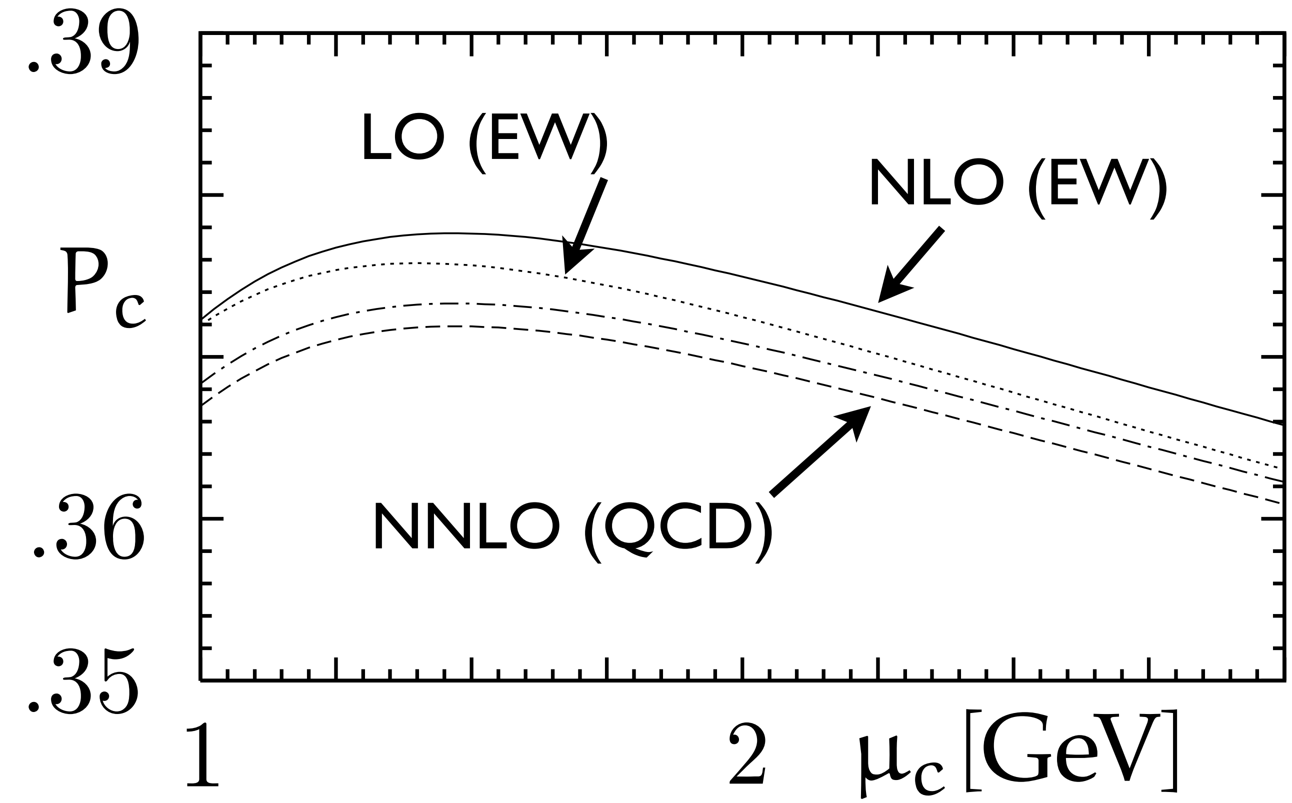

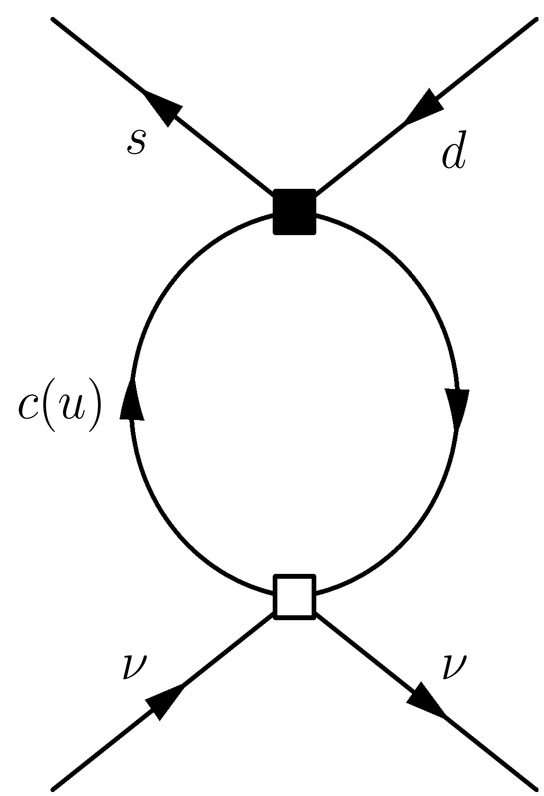

No GIM below the charm quark mass scale

higher dimensional operators UV scale dependent

One loop ChiPT calculation approximately cancels this scale dependence $\quad \delta P_{c,u} = 0.04 \pm 0.02$

[Isidori, Mescia, Smith `05]

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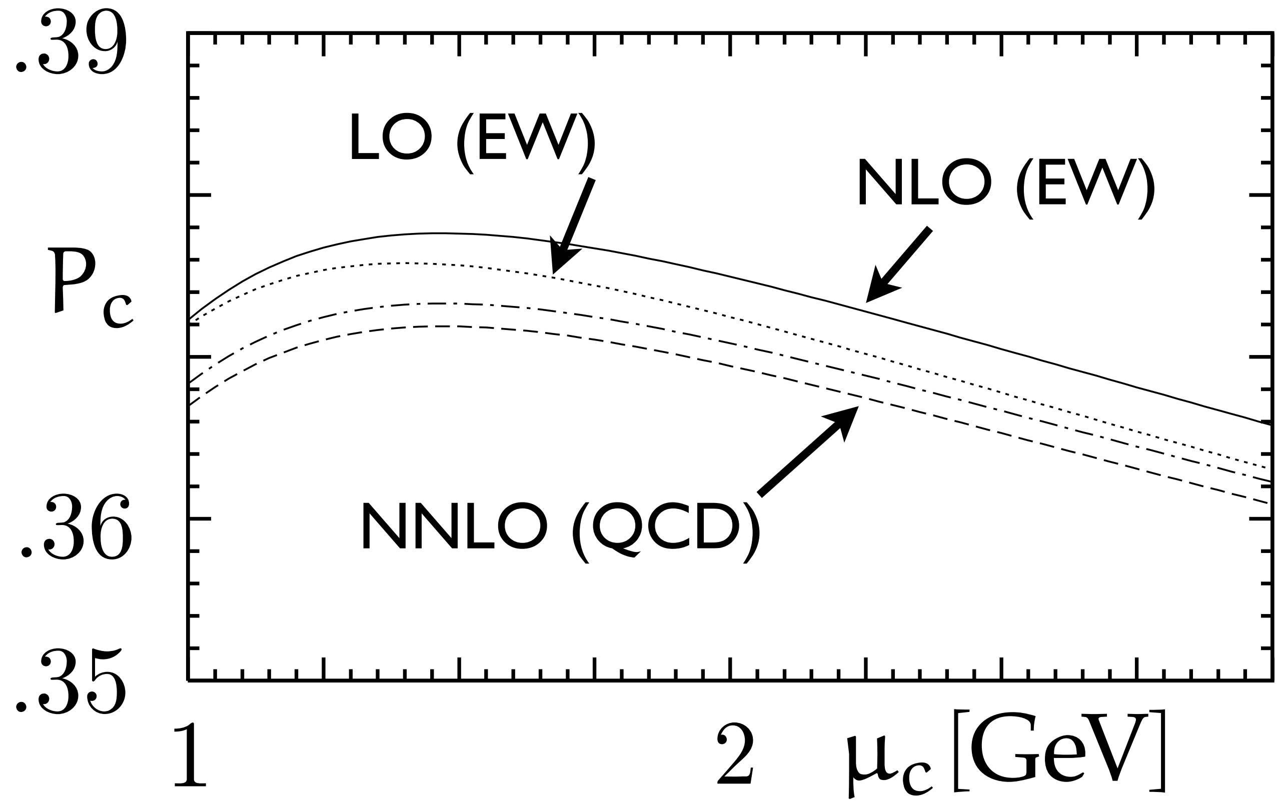

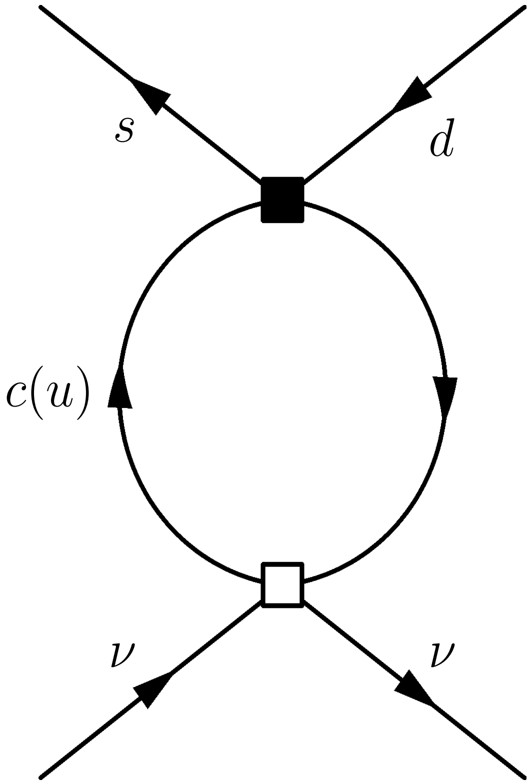

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Could be calculated on the lattice

[Isidori, Martinelli, Turchetti `06]

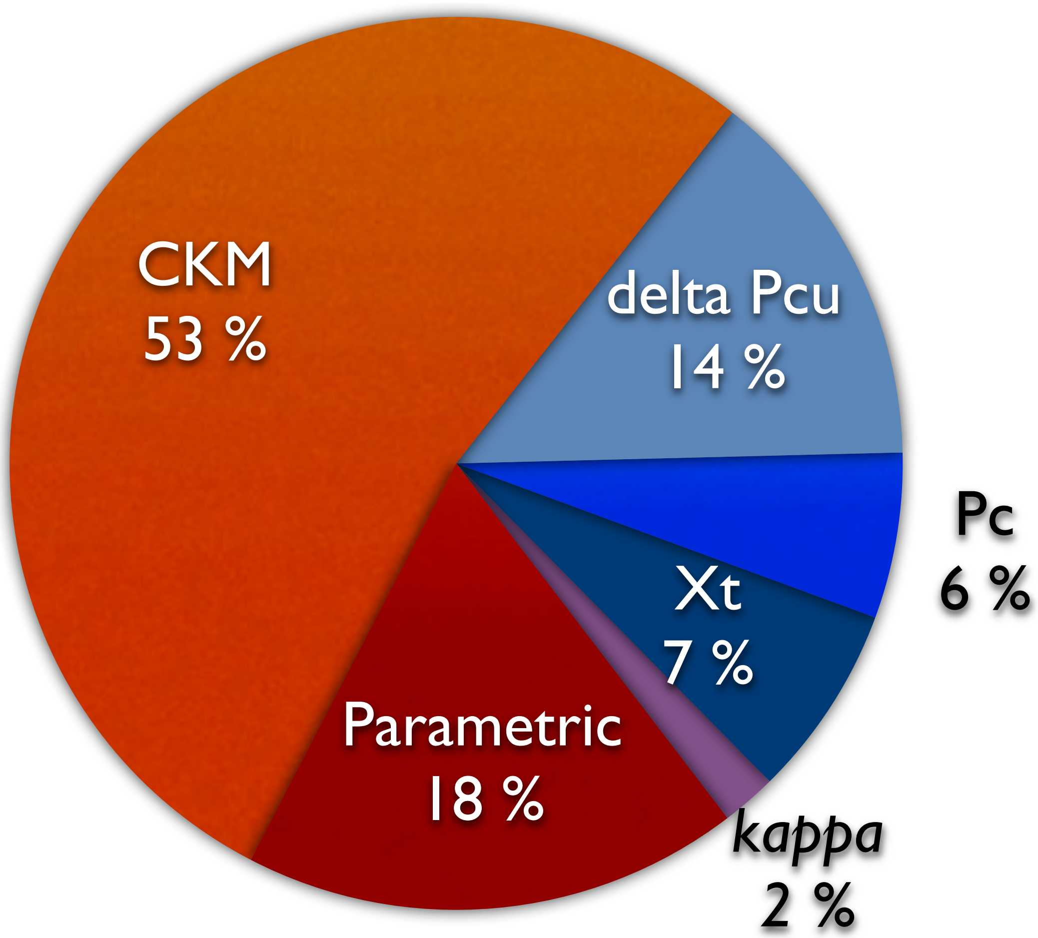
$K \to \pi \bar{\nu} \nu$: Error Budget

$$BR^{th}(K^+ \to \pi^+ \bar{\nu} \nu) = 8.2(3)(7) \cdot 10^{-11}$$

$$BR^{exp}(K^+ \to \pi^+ \bar{\nu} \nu) = 17(11) \cdot 10^{-11}$$

[E787, E949 ´08]

NA62 aims at 10% accuracy



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[E787, E949 ´08]

$BR^{exp}(K^+ \to \pi^+ \bar{\upsilon} \upsilon) < 6.7 \cdot 10^{-8}$

[E391a ´08]

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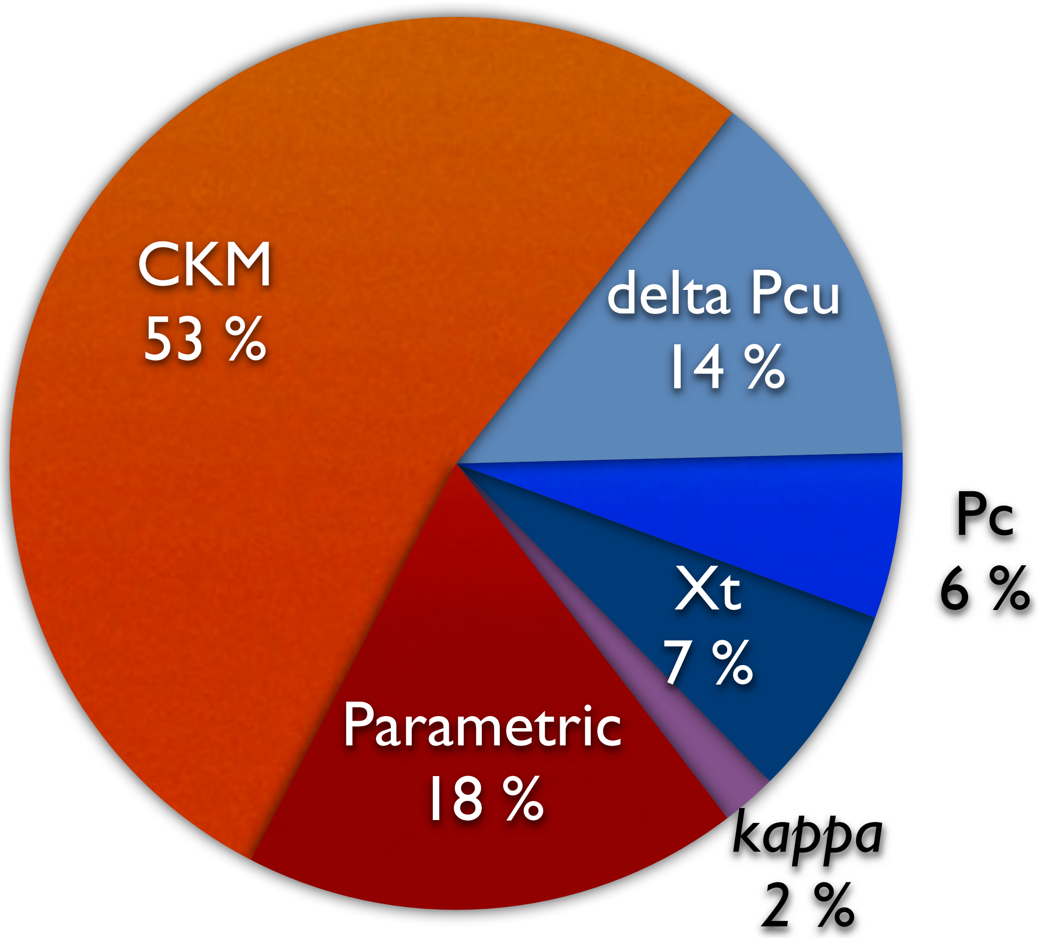

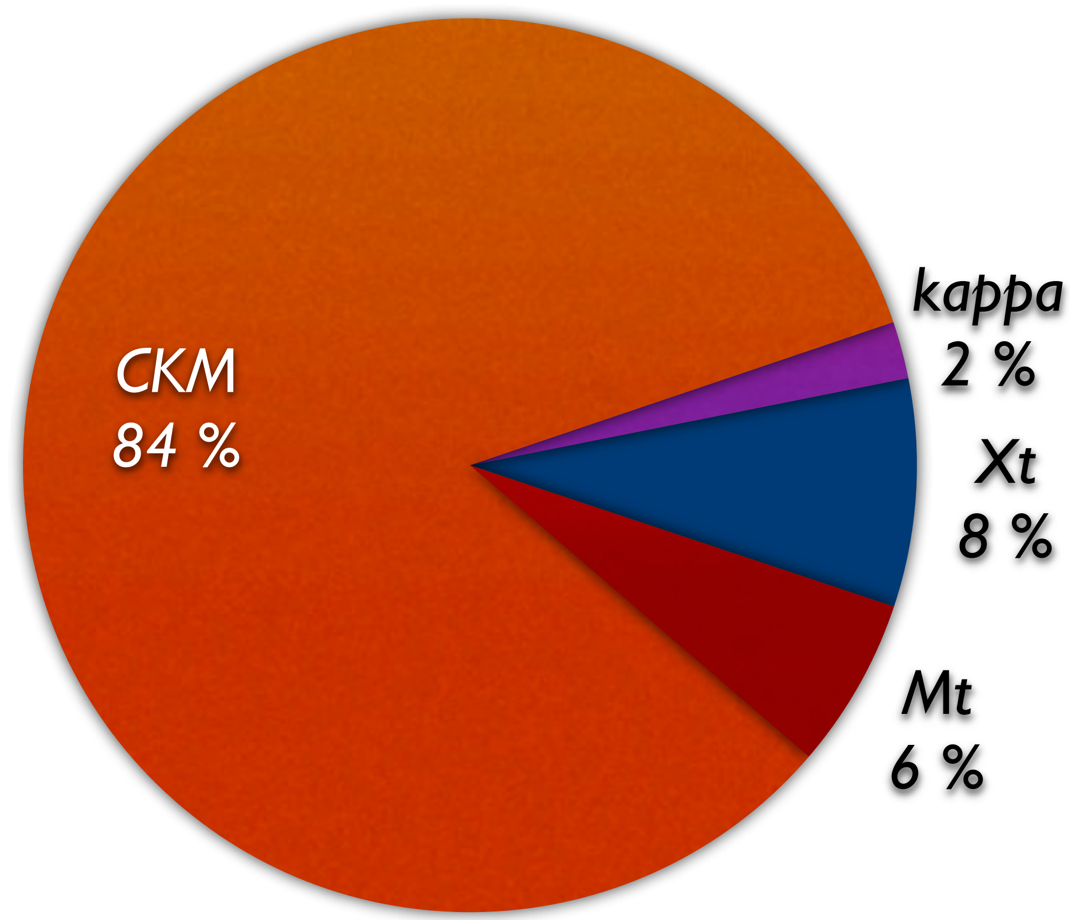

ε_K: CP violation in Kaon Mixing

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

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

from experiment

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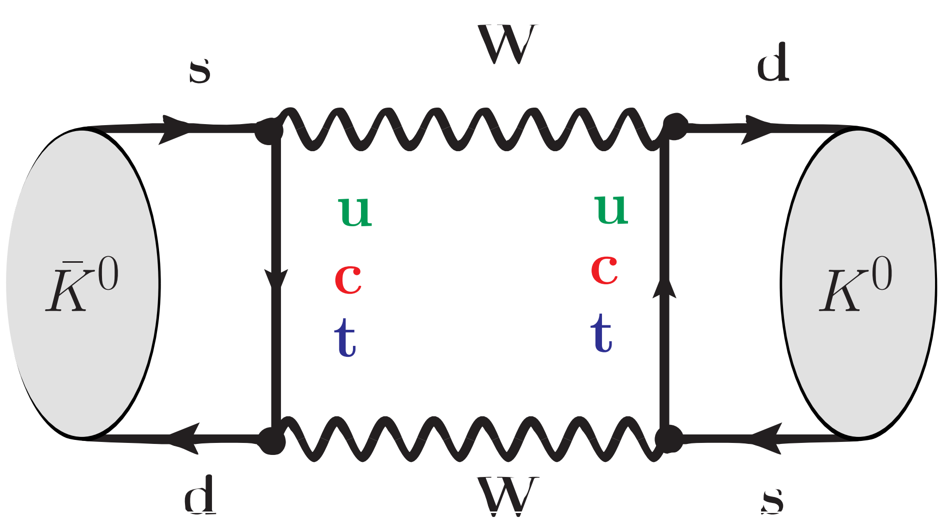
dispersive part



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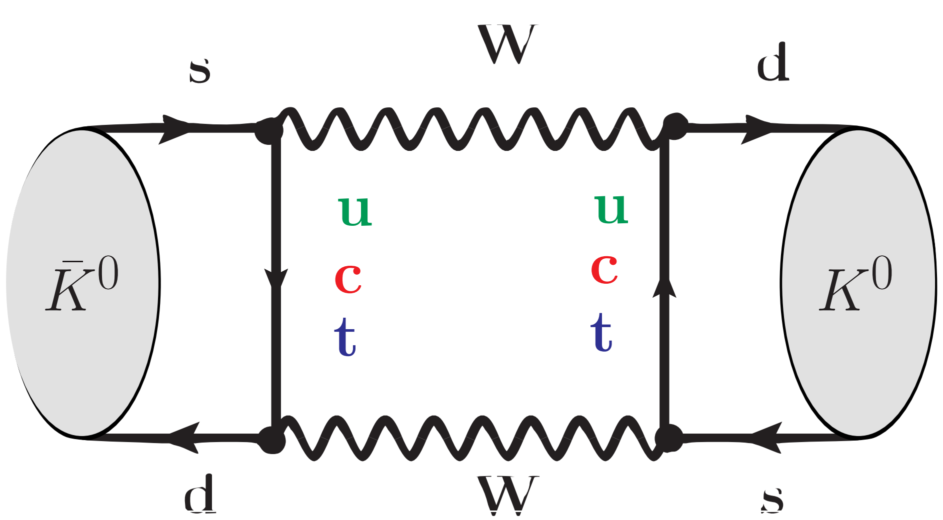

Local Interaction:

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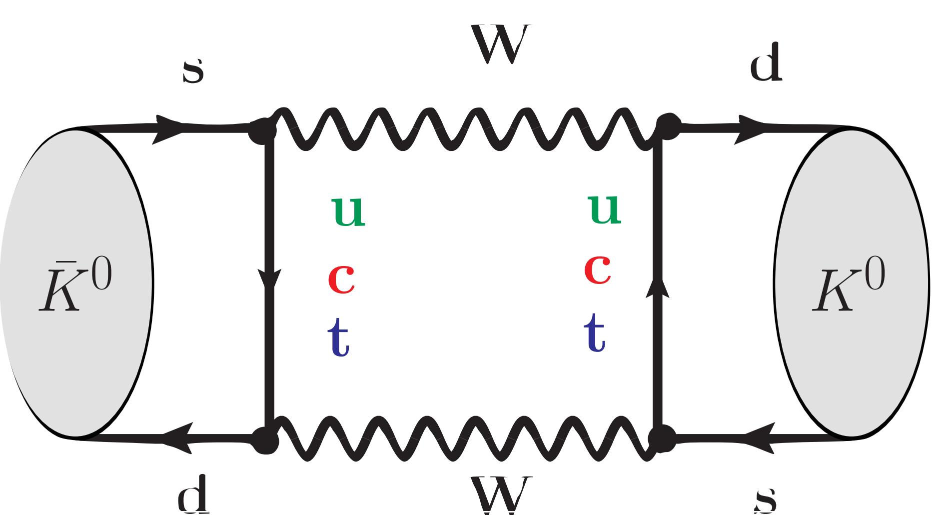

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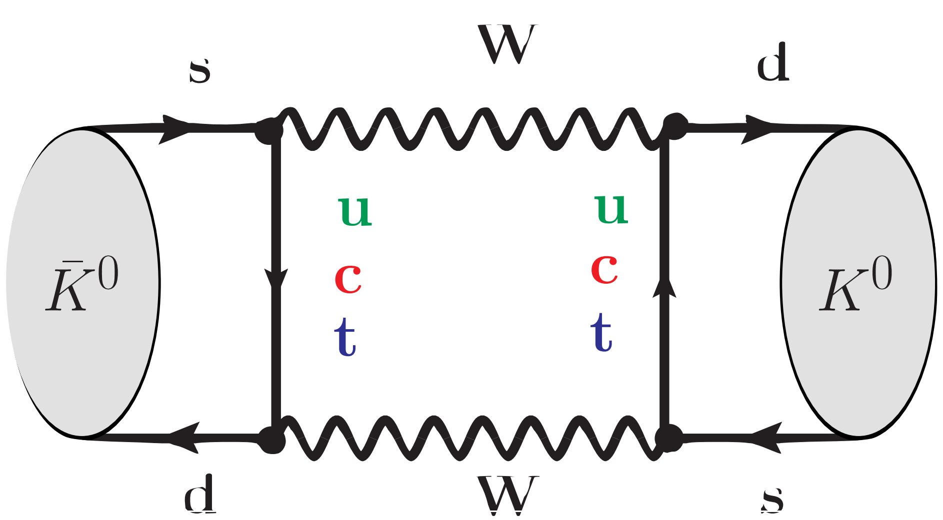

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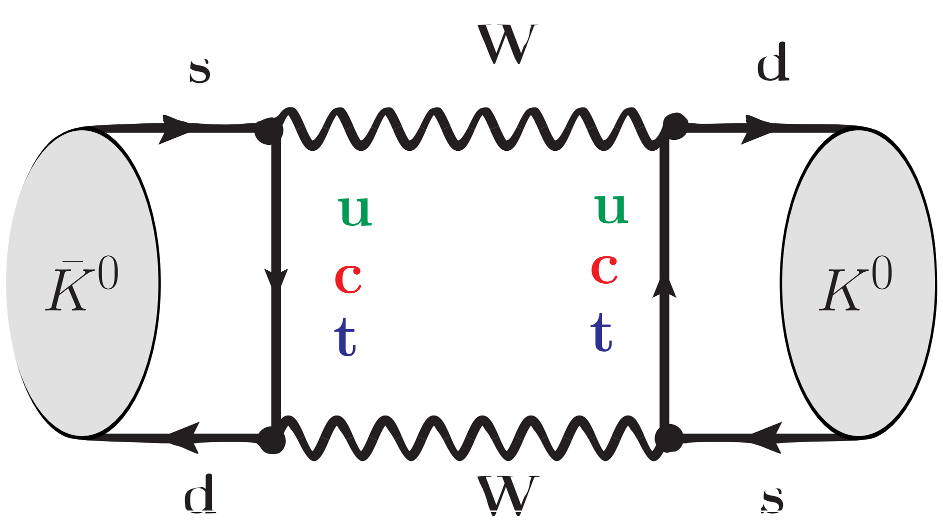

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η_{ct}: 3-loop RGE, 2-loop Matching [Brod, MG \`10]

η_{cc}: 3-loop RGE, 3-loop Matching [Brod, MG \`12]

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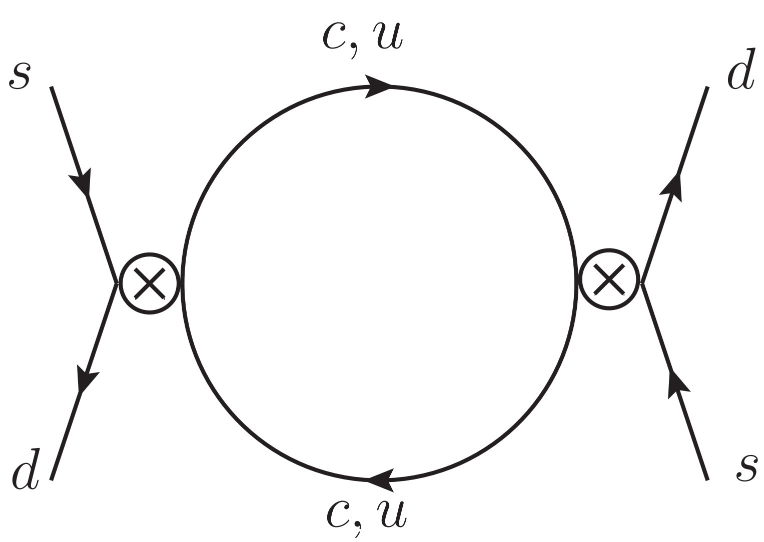
Long Distance ϵ_K



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

Higher dimensional operator [Cata Peris`04]

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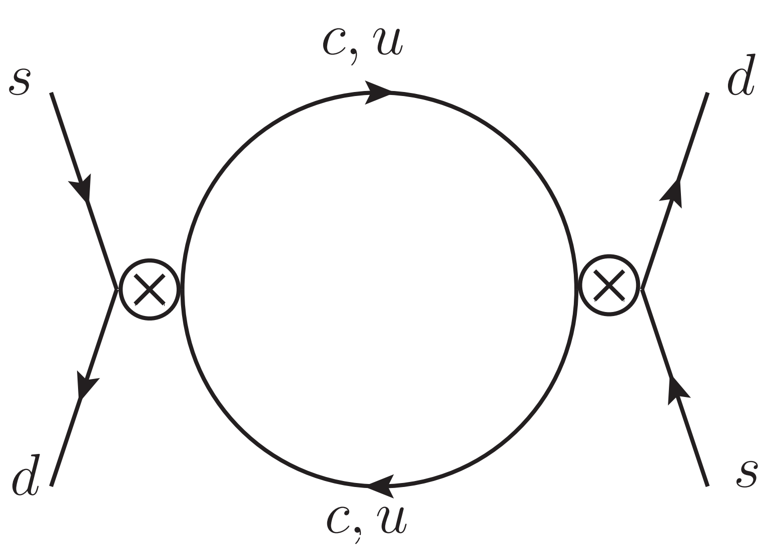

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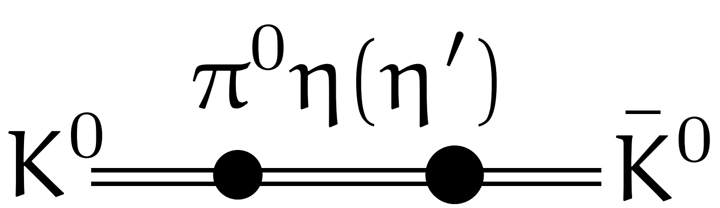
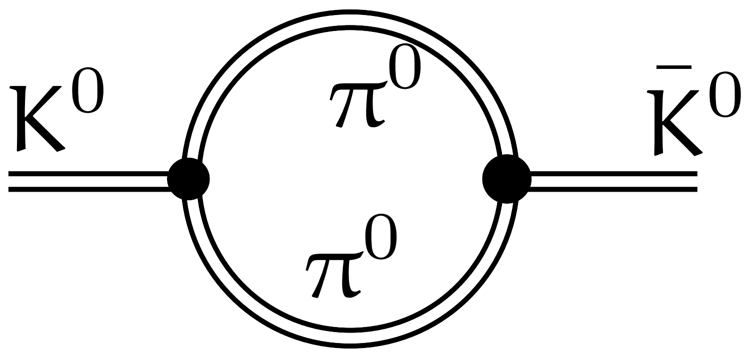


Light quark loops in CHPT:
π^0,η tree level vanishes (Gell-Mann-Okuba)
η' comes with zero phase [Gerard et.al. `05]



1-loop diagram divergent:
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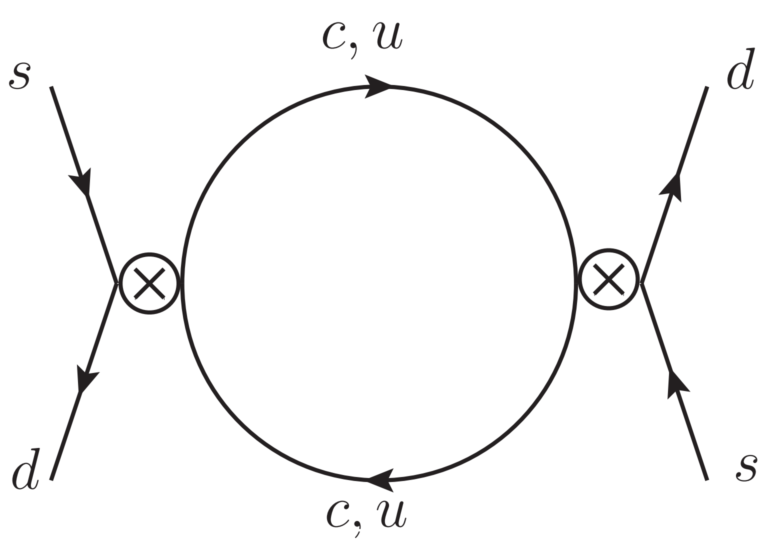

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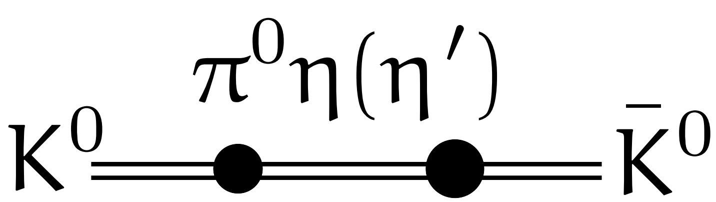

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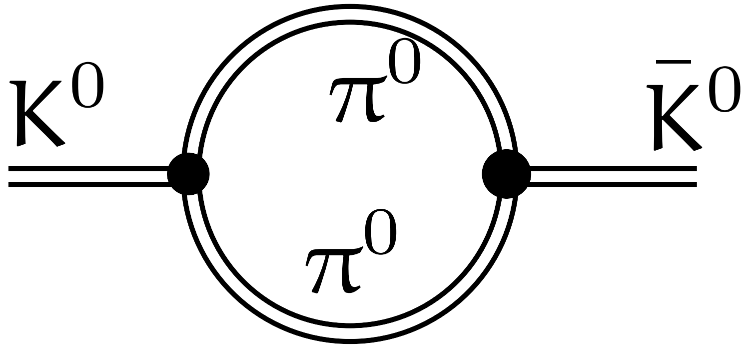

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$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)} \right)$$

absorptive part

estimated form ϵ´

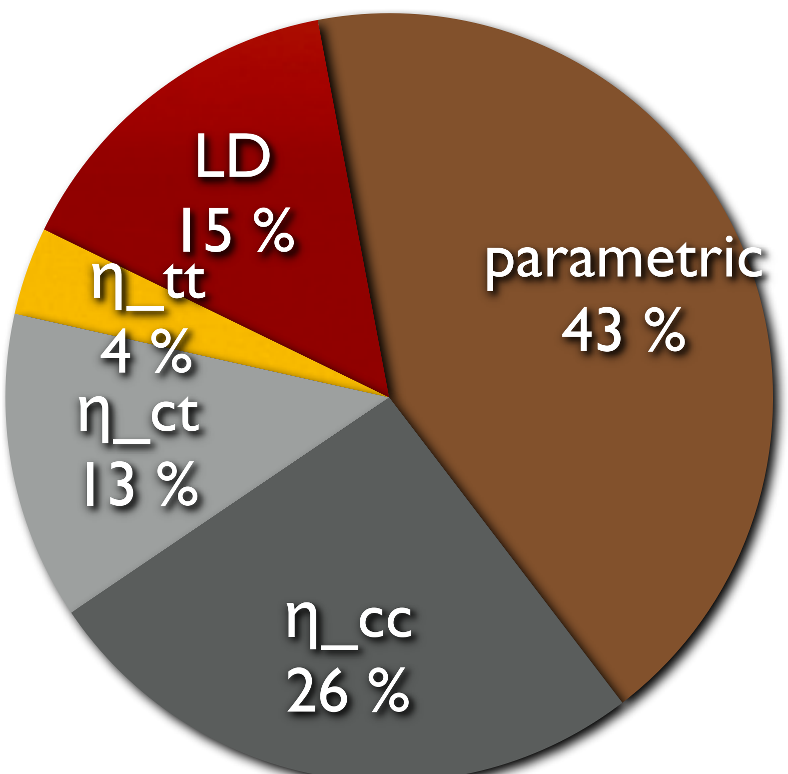
Future: Lattice

[N. Christ]

Residual Theory Uncertainty

After Lattice QCD & NNLO progress: η_{cc} dominant uncertainty

$$|\epsilon_K| = 1.81(28) \cdot 10^{-3}$$
$$\overset{\text{exp.}}{=} 2.23(1) \cdot 10^{-3}$$



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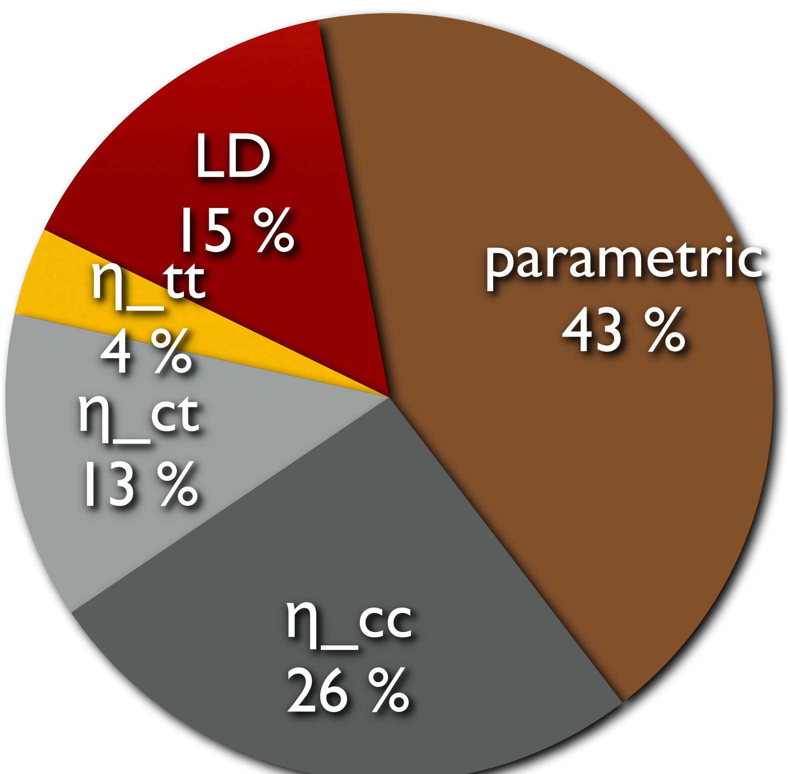

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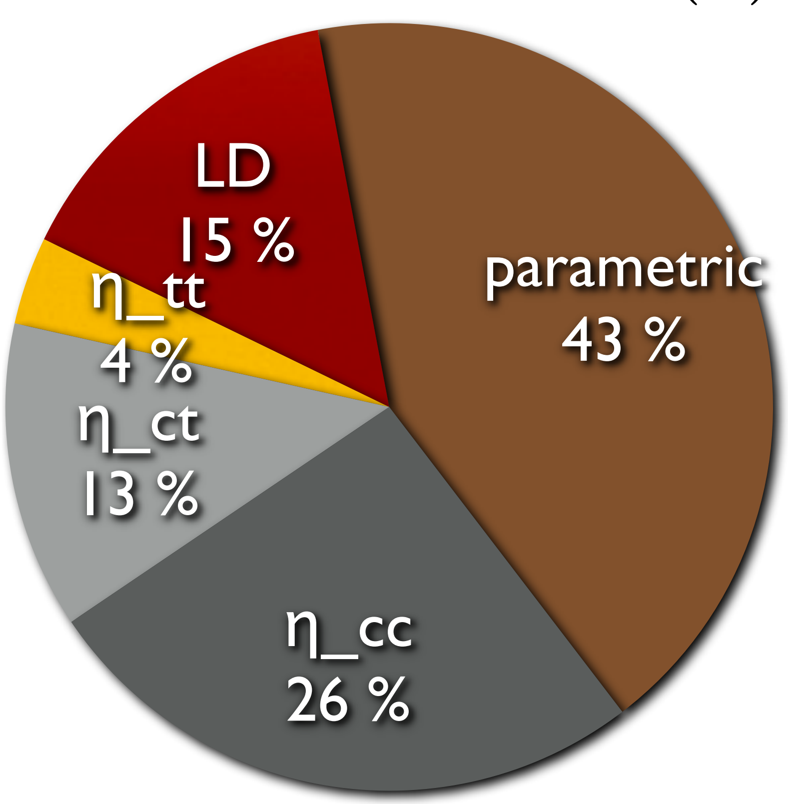

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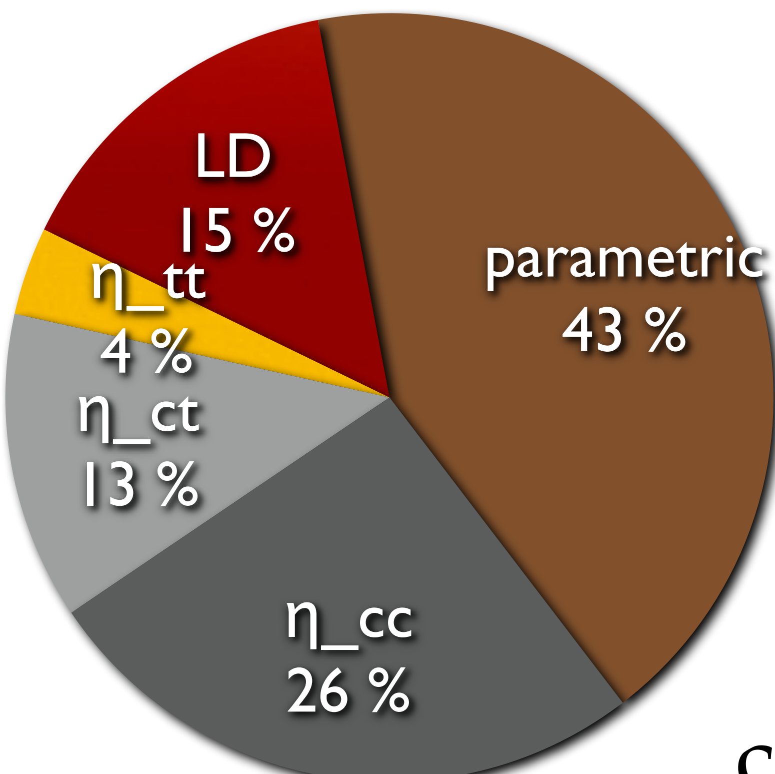
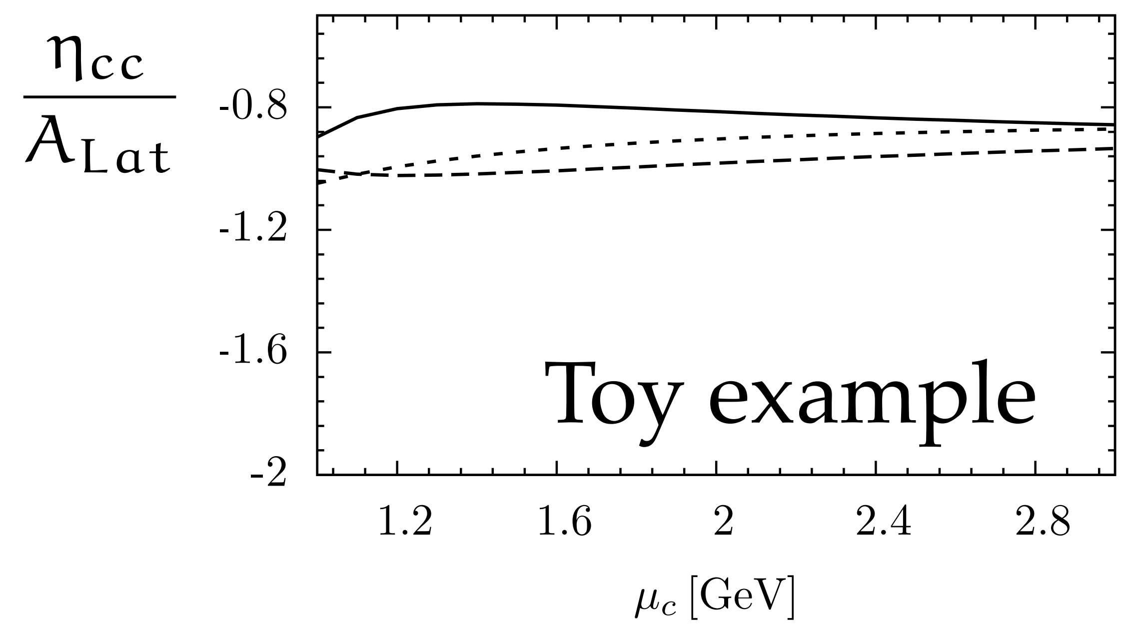


ε_K & charm possible for next generation Lattice QCD[Christ `11]



Requires matching of Lattice and continuum QCD – toy numerics converge well

3, Constrain and Interpret NP

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Operator based Approach:

Write down all $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ invariant Operators

[Buchmüller, Wyler]

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[Buchmüller, Wyler]

Top-down approach:

Supersymmetry, LHT-Model, RS-Model …

Model (in)dependent

Heavy new physics: $(\bar{D}_L \gamma^\mu S_L)(H^\dagger D_\mu H) \to \bar{d}_L \gamma^\mu s_L Z^\mu + \bar{u}_L \gamma^\mu c_L Z^\mu$

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study this in a model independent way

and classify models

	Observable	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L \to \pi^0\nu\bar{\nu}$	$K_L \to \pi^0\ell^+\ell^-$	$K_L \to \ell^+\ell^-$	$K^+ \to \ell^+\nu$	$P_T(K^+ \to \pi^0\mu^+\nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ
$O_{\varphi q}^{(1)}$	$(\bar{D}_L\gamma^\mu S_L)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓
$O_{\varphi q}^{(3)}$	$(\bar{D}_L\gamma^\mu\sigma^i S_L)(H^\dagger D_\mu\sigma^i H)$	✓	✓	✓	hs	hs	✓	✓	✓
$O_{\varphi d}$	$(\bar{d}_R\gamma^\mu s_R)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓

[Jäger@NA62 ´09 workshop]

Correlations in RS and LHT

The axial vector (Z_L-Z_R) contribution dominates
the $K_L \rightarrow \pi^0 l^+ l^-$ decay modes in many models of new physics

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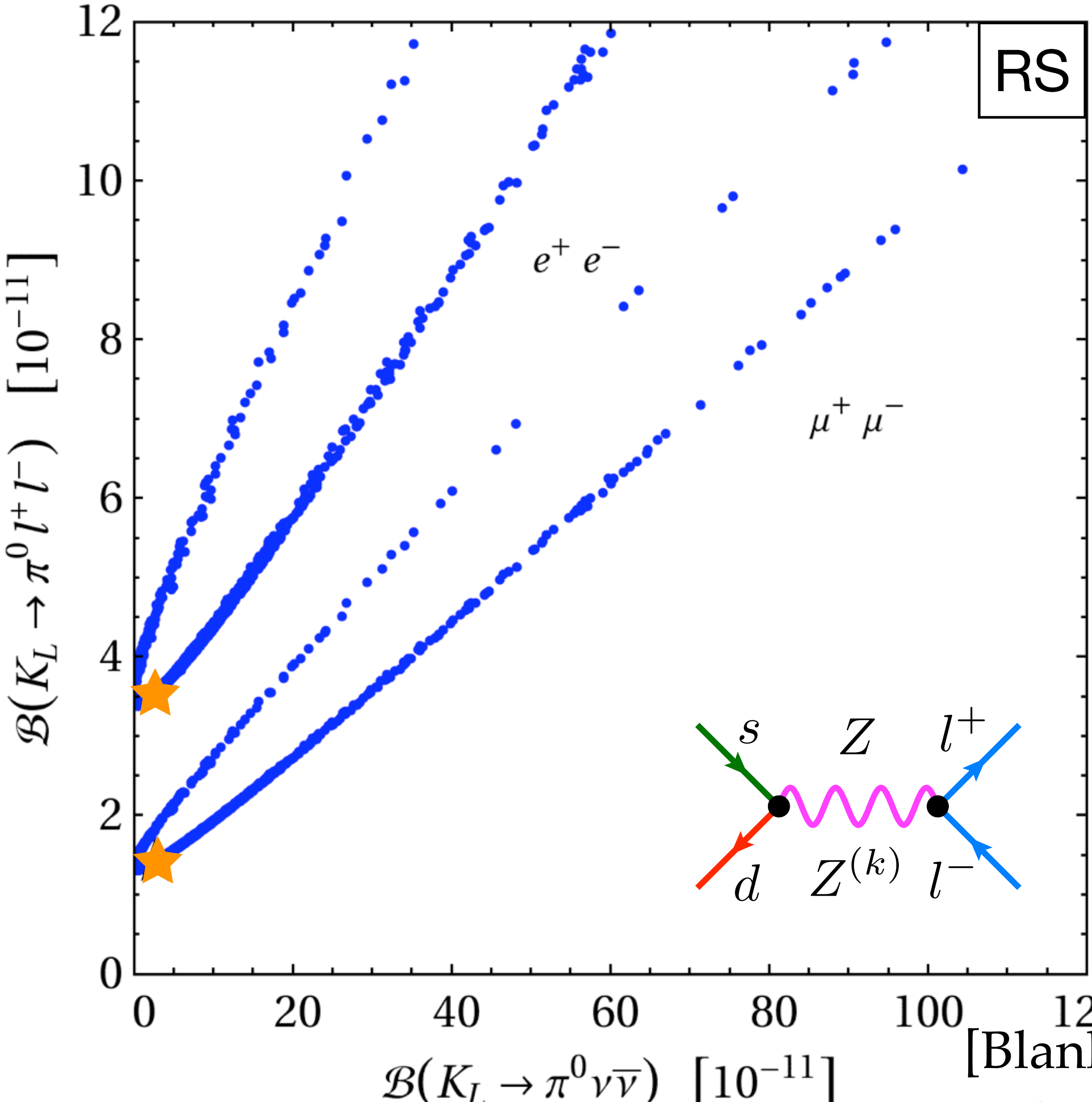
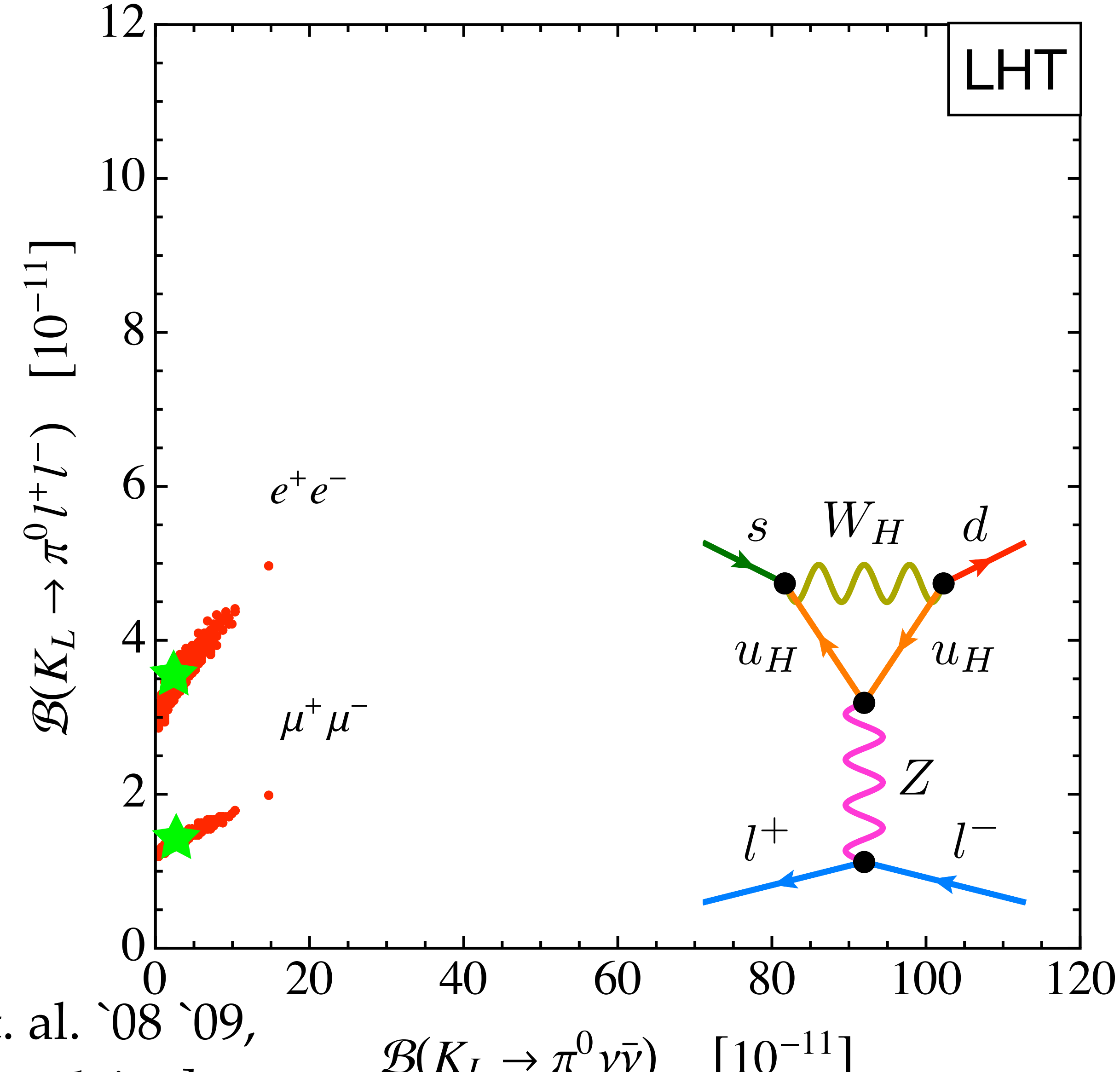
Correlations in Randall Sundrum and Little Higgs Models



[Blanke et. al. `08 `09,
Bauer et. al. `09]



Correlations with ε_K

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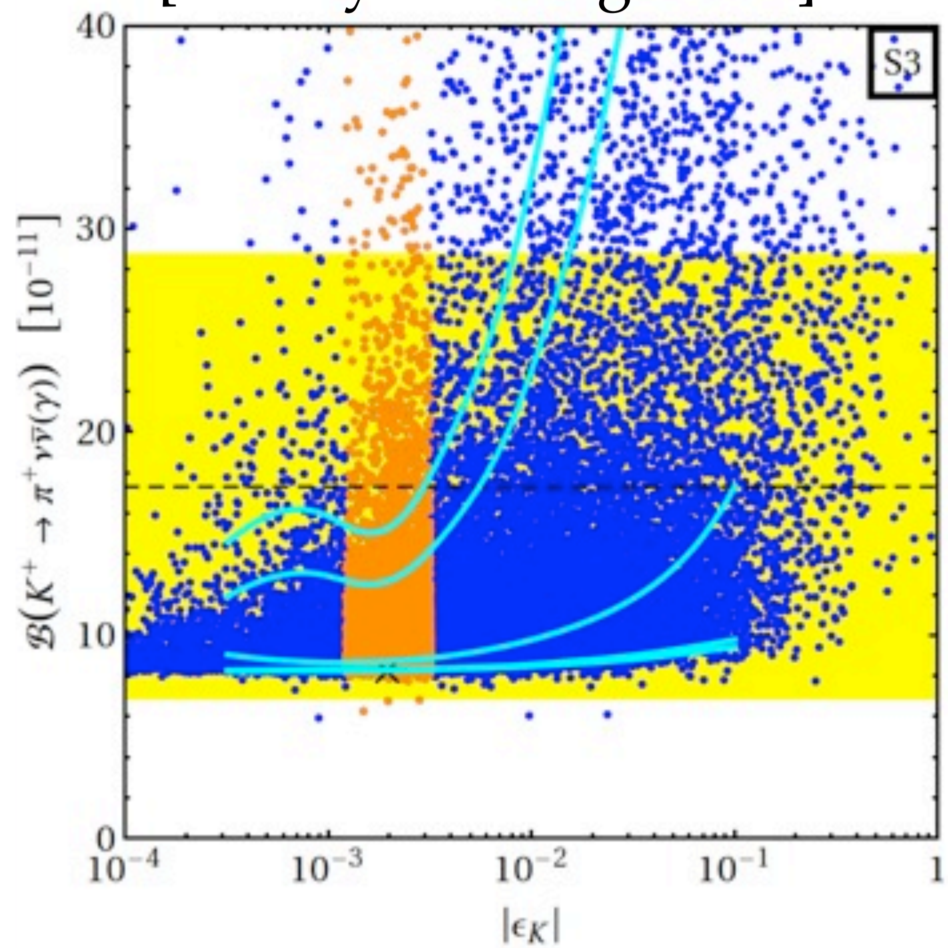
Can still lead to interesting restrictions of the model parameter space

RS with common down-type bulk mass
[Plot by S. Casagrande]



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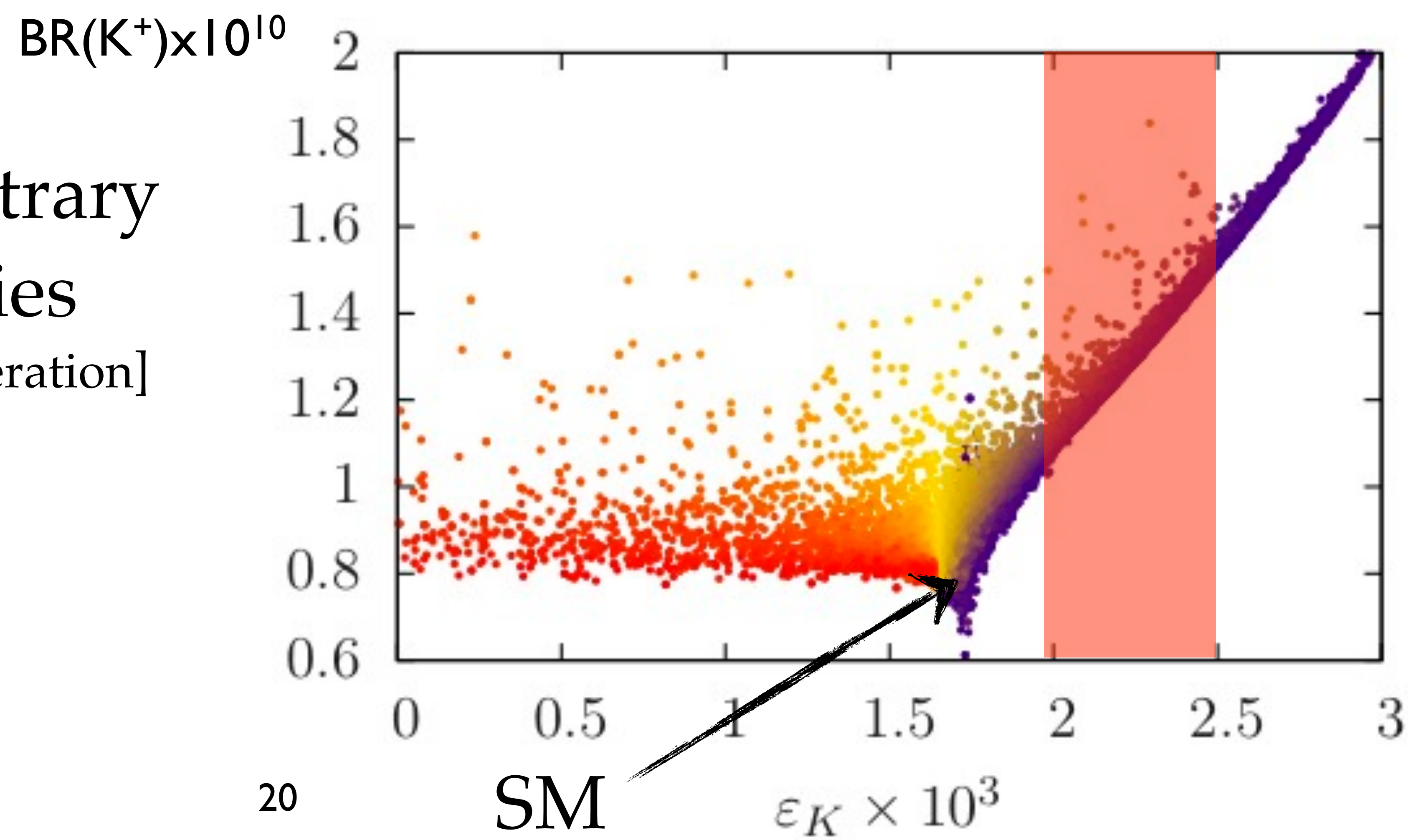

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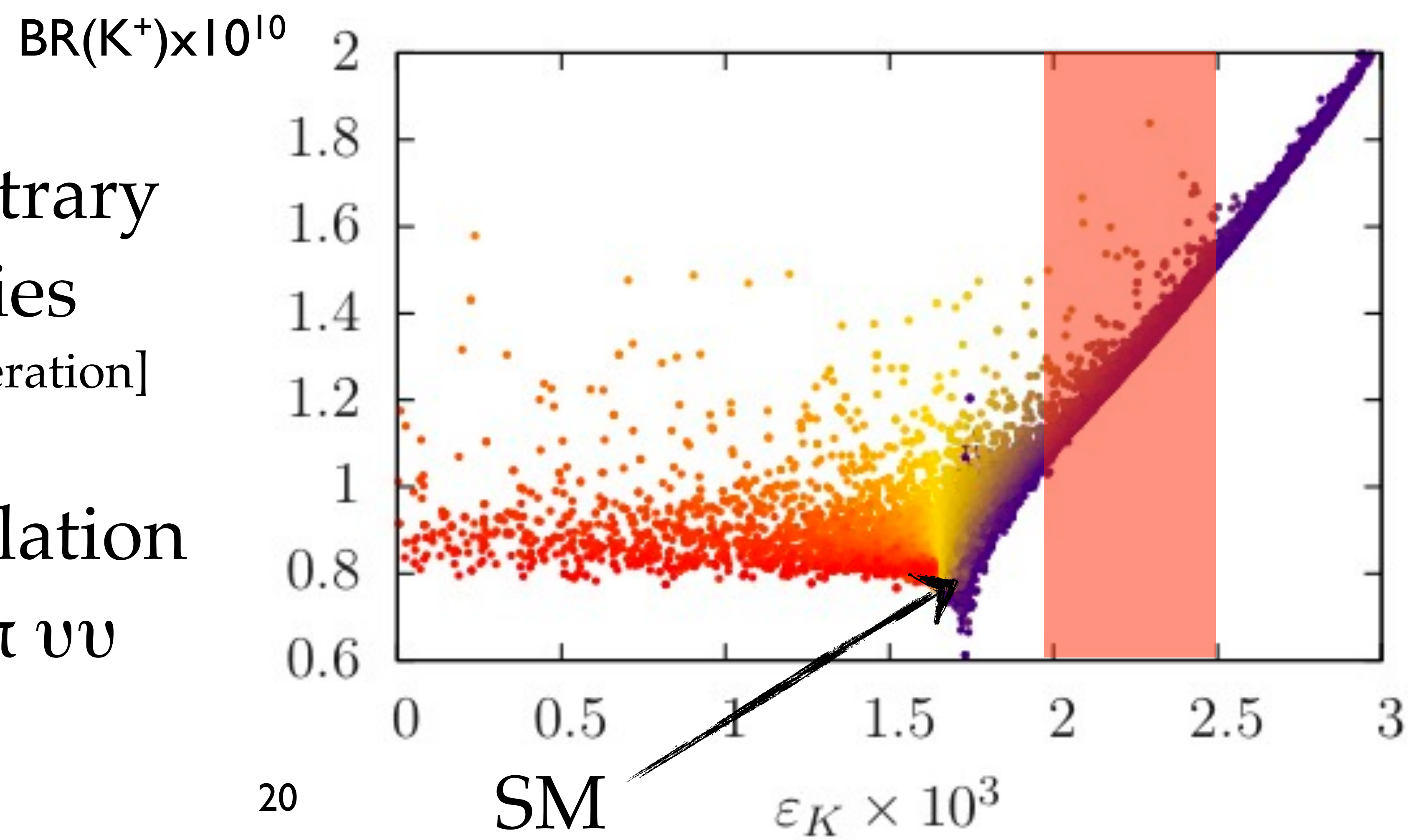
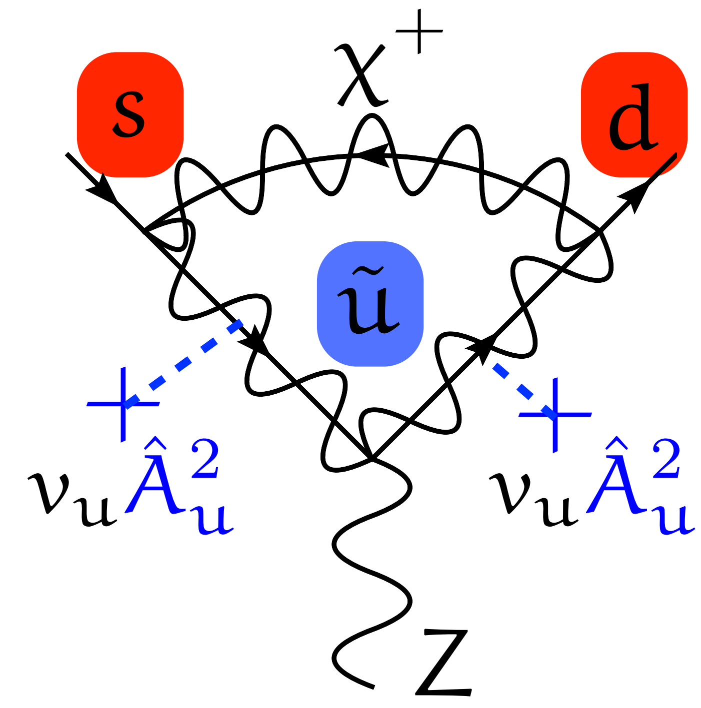


No correlations in the MSSM

The MSSM has many sources of flavour violation – Z Penguin sensitive to up-type A-terms [Collangelo, Isidori `98]

$$\hat{\mathcal{M}}^2_{\tilde{u}} = \begin{pmatrix} \hat{M}^2_{\tilde{u}_L} & v_u \hat{A}^\dagger_u - v_d \mu \hat{Y}^\dagger_u \\ v_u \hat{A}_u - v_d \mu^* \hat{Y}_u & \hat{M}^2_{\tilde{u}_R} \end{pmatrix}$$



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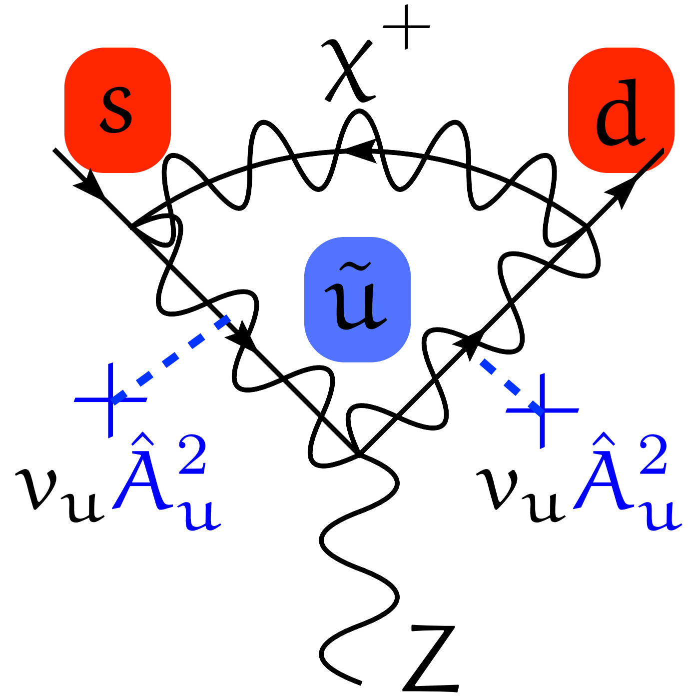
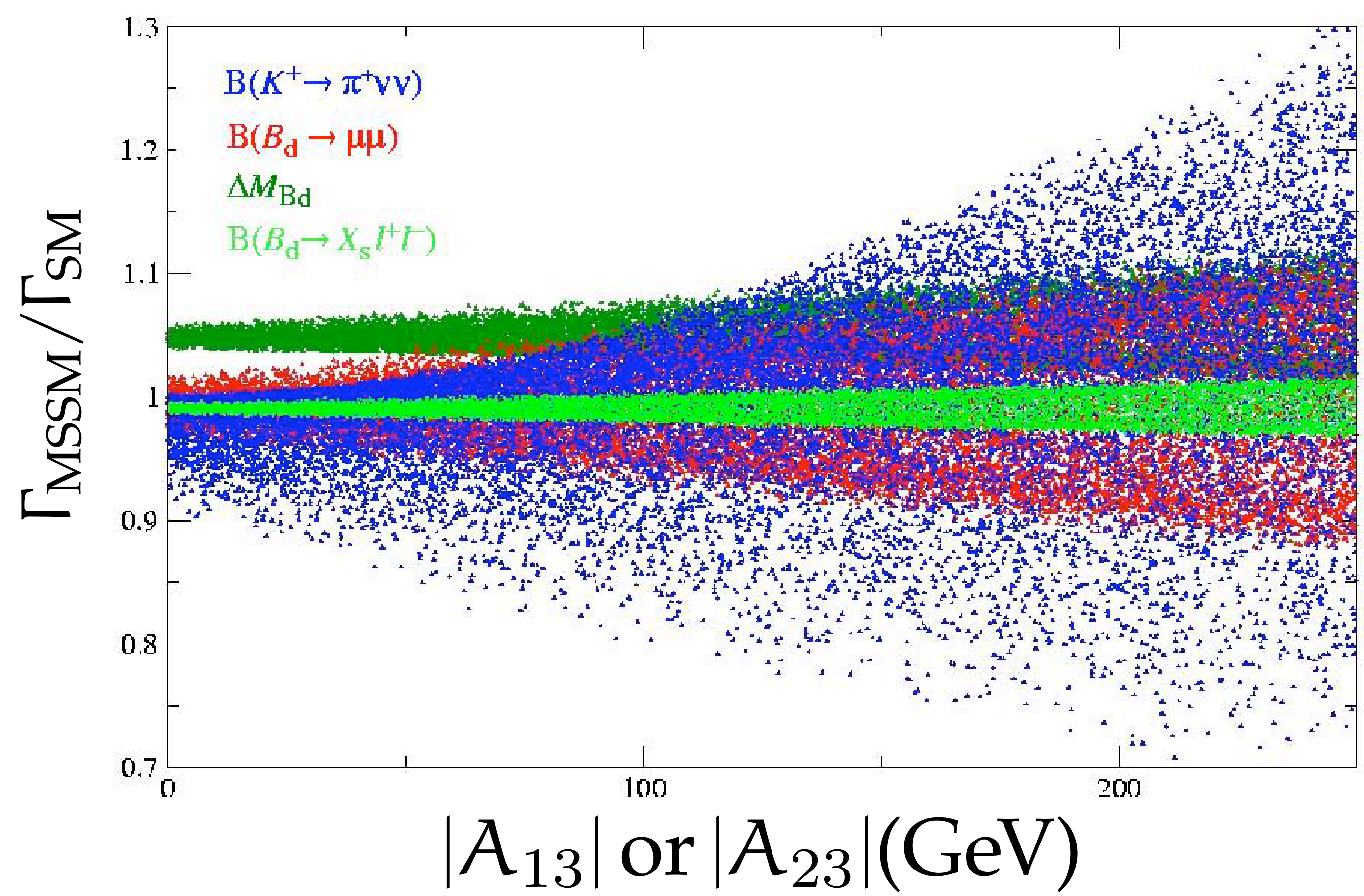


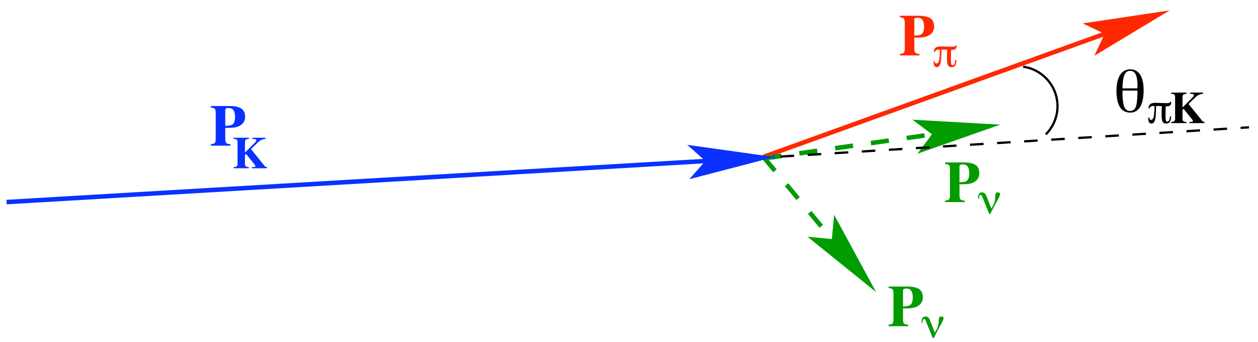
MSSM parameter scan shows sensitivity to A_{13} & A_{23}

[Isidori et. al. `06]



Beyond the Z Penguin

Experiment: Background from frequent K^+-Decays



Measure p_π & $\theta_{\pi K}$

cut on: $m^2_{miss} \simeq m_K^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$

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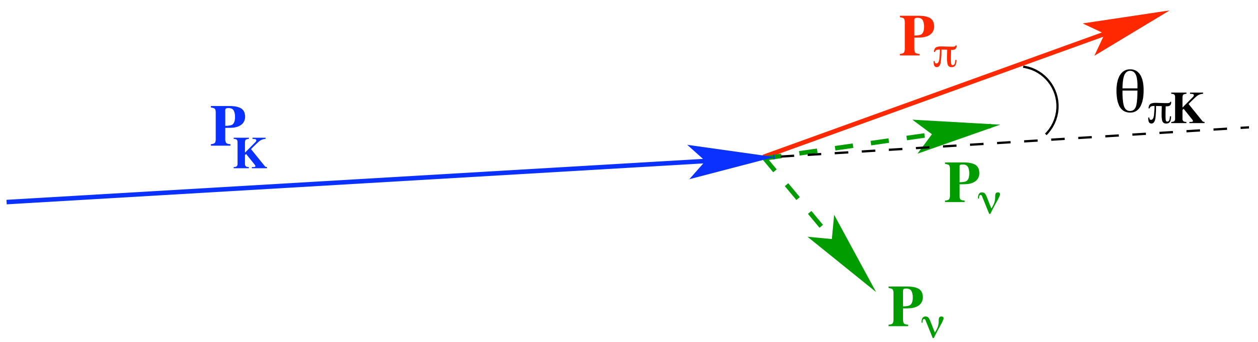

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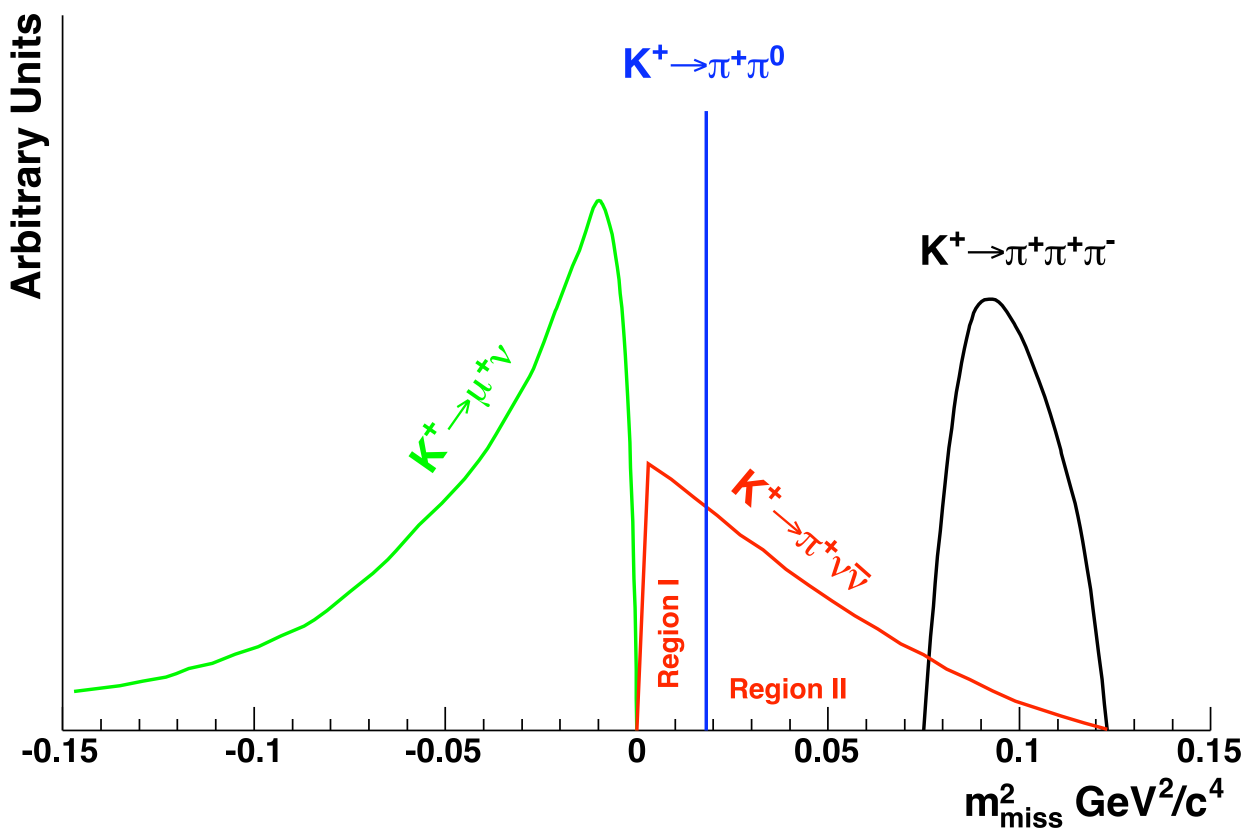

Couplings to weakly interacting light new particles strongly constrained by

$K^+ \to \pi^+ +$ invisible

[Kamenik, Smith `11]

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Improvements from theory side possible using Lattice QCD and interplay with perturbative QCD