QCD corrections to Kaon Mixing

Khodjamirian Fest
Colour meets Flavour: QCD and Quark Flavour Physics
Siegen 13.10.2011

Based on work done in collaboration with Joachim Brod

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Excellence Cluster `Universe´

IAS TUM Institute for Advanced Study

TUM

TUM LMU Excellence Cluster Universe

QCD meets Flavour

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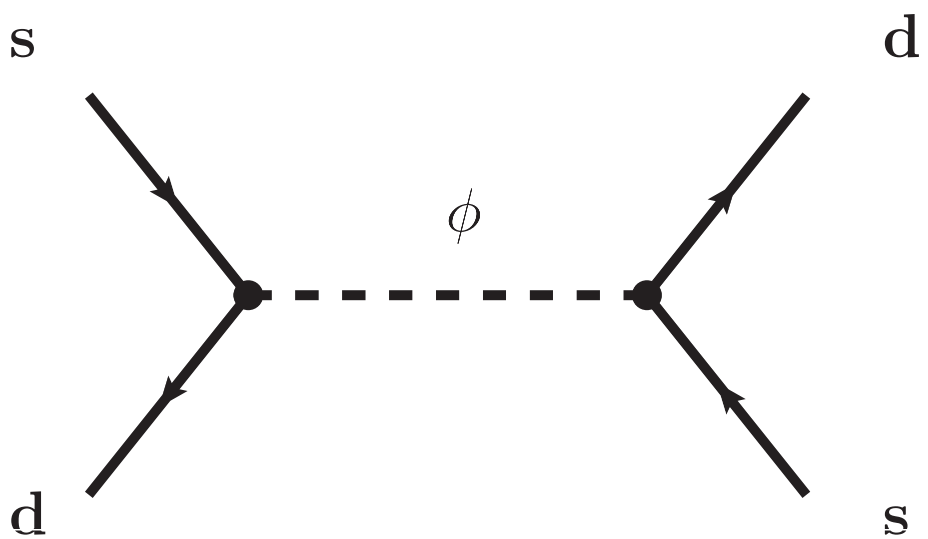
In Flavour Physics:

Find (or build) a path, which connects low and high energies:

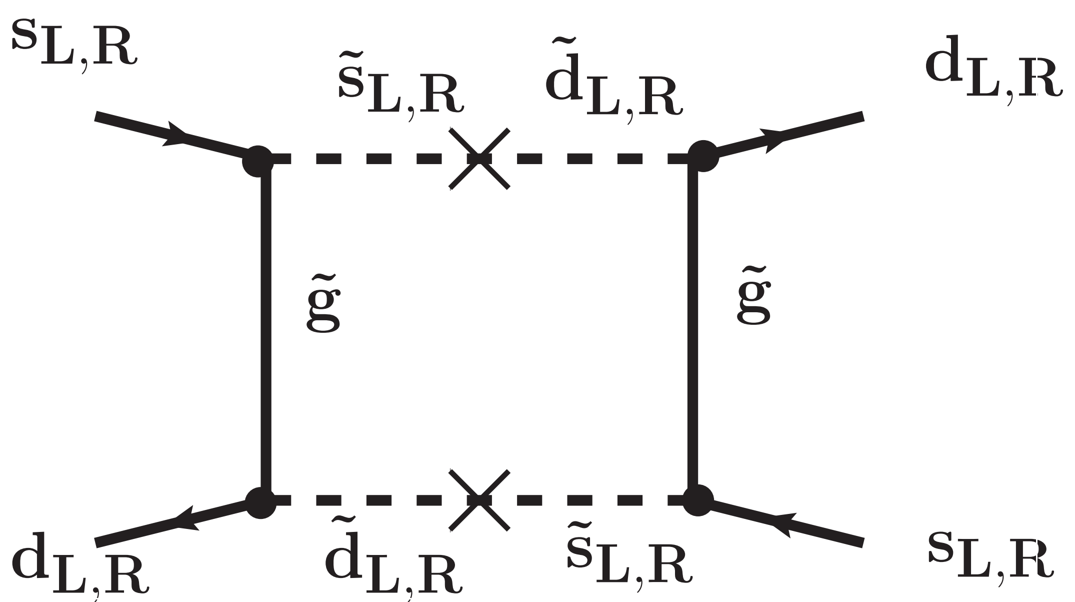
QCD meets Flavour

Kaon Mixing & New Physics

Many more sources of CP & flavour violation:



2HDM Type III



SUSY models

+Technicolour, extra dimensions, ...

Strong constraints from ε_K & ΔM_K!

But we have to understand the standard model background

Kaon Mixing

$$i\frac{d}{dt}\begin{pmatrix}|K^0(t)\rangle\\|\overline{K}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{11}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{11}\end{pmatrix}\right]\begin{pmatrix}|K^0(t)\rangle\\|\overline{K}^0(t)\rangle\end{pmatrix}$$

M_{12} is related to important observables

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M_{12} is related to important observables

CP violation in mixing Re(ϵ_K) and interference Im(ϵ_K)

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

$$A_I = \langle(\pi\pi)_I|K^0\rangle$$

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CP violation in mixing $\mathrm{Re}(\epsilon_K)$ and interference $\mathrm{Im}(\epsilon_K)$

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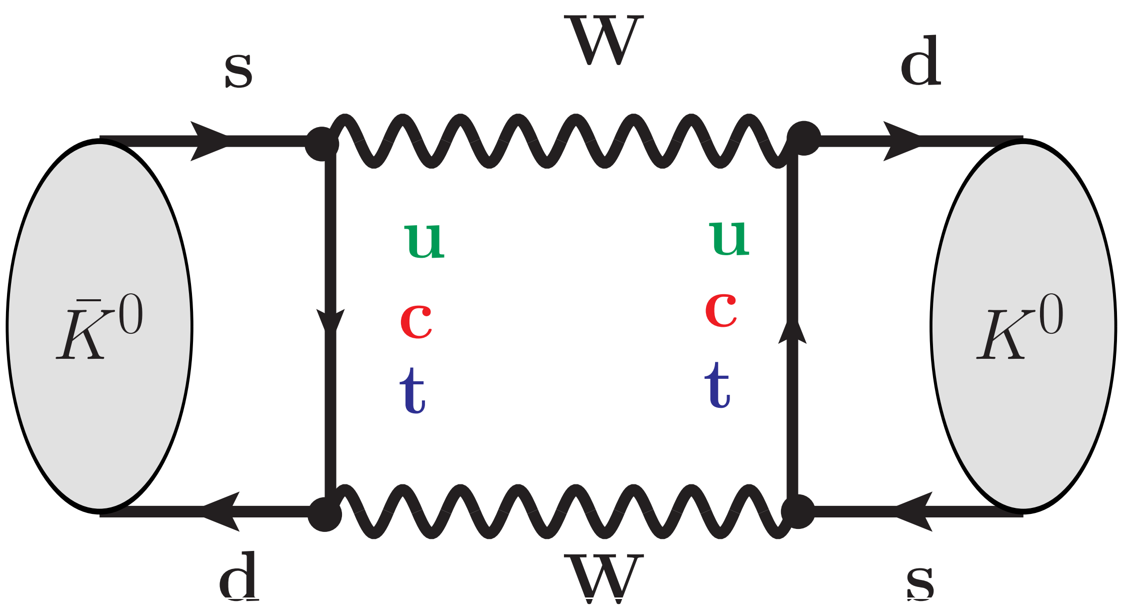
and K_L–K_S mass difference: $\Delta M_K = 2\,\mathrm{Re}\,M_{12}$

$$2M_K M_{12} = \langle K^0|\,H^{|\Delta S|=2}\,|\bar{K}^0\rangle - \frac{i}{2}\int d^4x\,\langle K^0|\,H^{|\Delta S|=1}(x)\,H^{|\Delta S|=1}(0)\,|\bar{K}^0\rangle$$

dispersive part

Standard Model Box Diagram



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$x_i = \frac{m_i^2}{M_W^2} \qquad \lambda_i = V_{id}^* V_{is}$$

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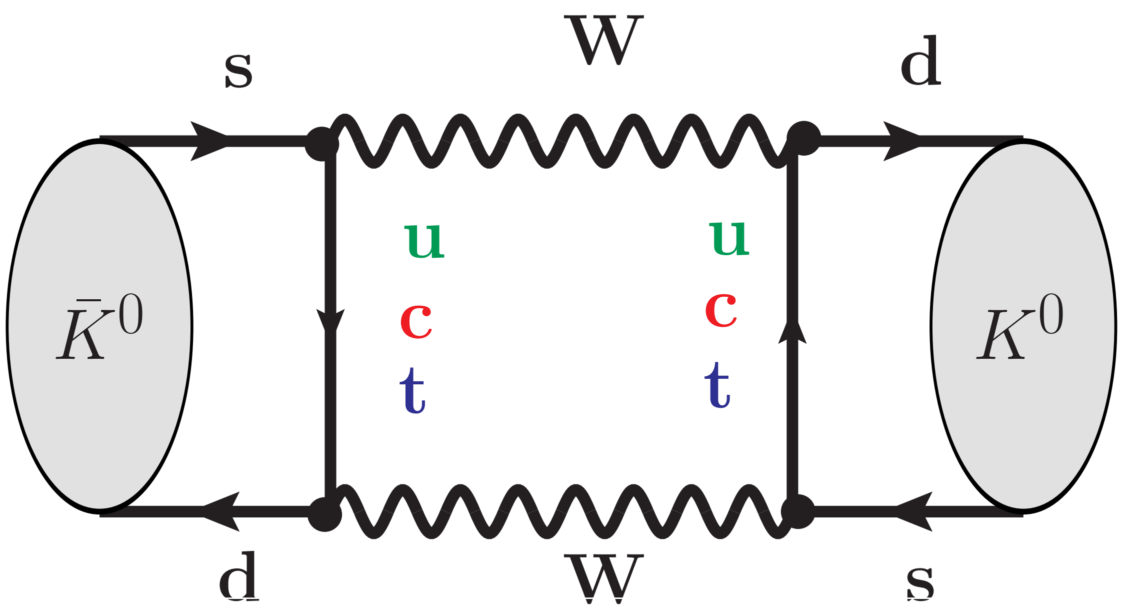

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Three CKM factors: $\lambda_t = O(\lambda^5 e^{i\delta})$, $\lambda_c = O(\lambda + i\lambda^5)$ and $\lambda_u = O(\lambda)$

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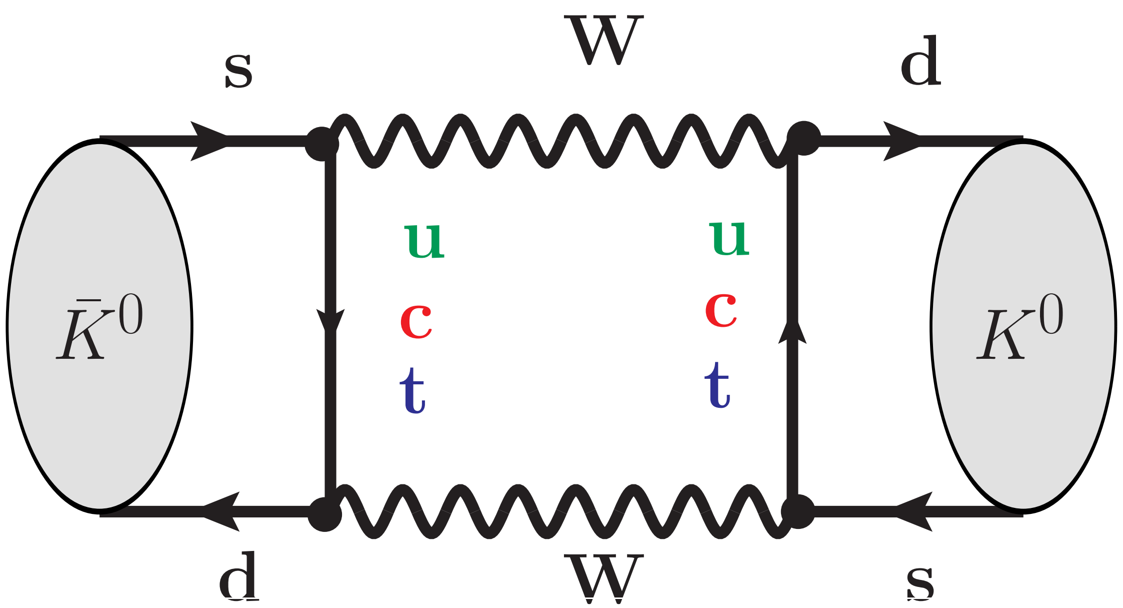

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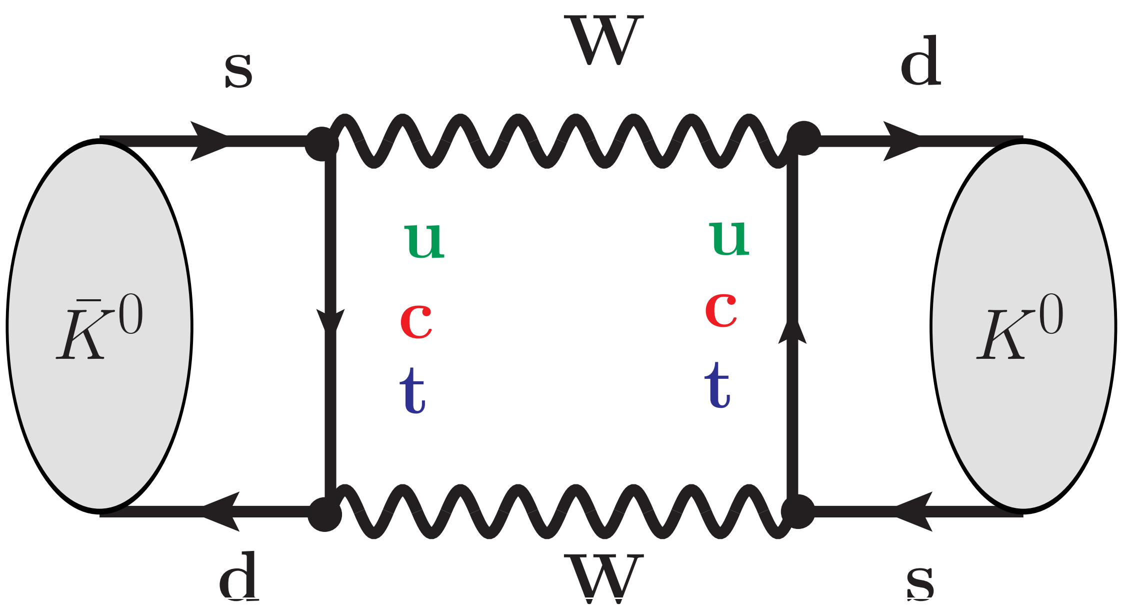
Eliminate $-\lambda_u = \lambda_t + \lambda_c$: For CP violation

$$x_t \lambda_t \lambda_t + x_c \log(x_c) \lambda_c \lambda_t + x_c \lambda_c \lambda_c + \frac{\Lambda_{QCD}^2}{M_W^2} \lambda_c \lambda_{t/c}$$

Standard Model Box Diagram



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For CP conserving

$$x_c\, \lambda_c \lambda_c + \frac{\Lambda_{QCD}^2}{5 M_W^2}\, \lambda_c \lambda_c$$

Formula for ϵ_K

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

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Δm_K, ϕ_ε: Directly from experiment:

$\mathrm{Im}(A_0)/\mathrm{Re}(A_0)$: from ϵ'/ϵ

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Factorize short and long distance: $H^{|\Delta S|=2} = C(\mu)\tilde{Q}$

From lattice: $\hat{B}_K = \frac{3b(\mu)}{2f_K^2 M_K^2} \langle K^0|\tilde{Q}|\bar{K}^0\rangle$ ($\tilde{Q} = (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$)

Experiment & Theory

Experiment:

ε_K is measured precisely:

$|\varepsilon_K| = 2.228(11)\times 10^{-3}$.

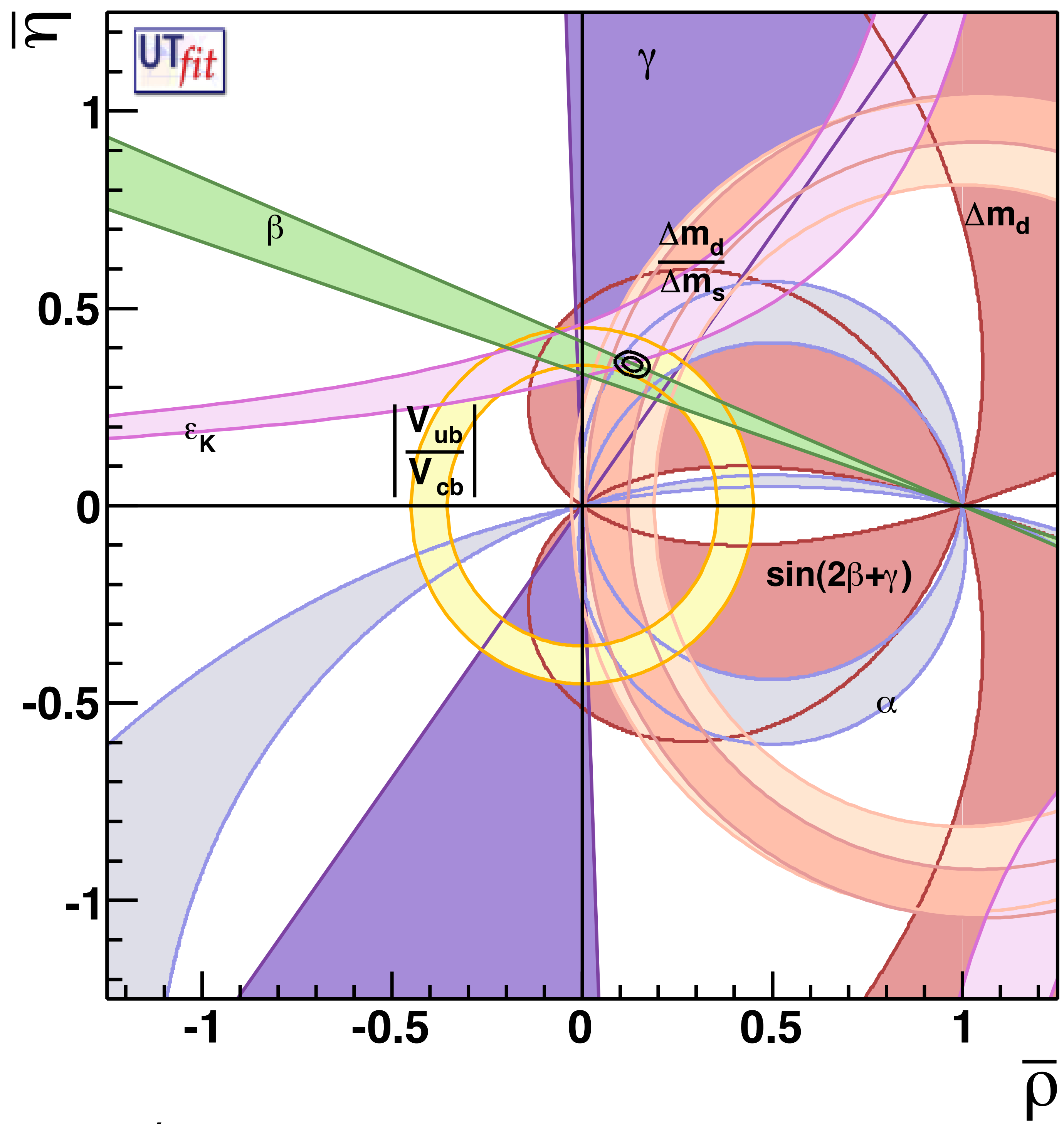
[PDG2010]

Theory:

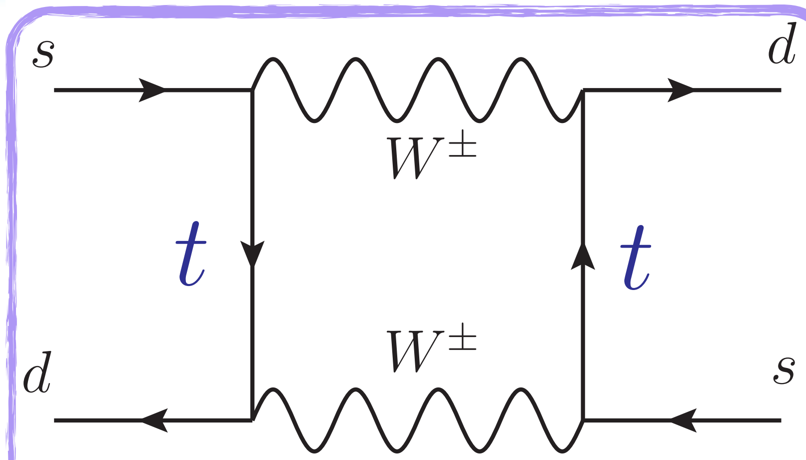
how well can we calculate ε_K ?

$|\varepsilon_K| = 1.83(27)\times 10^{-3}$.

[NLO SM prediction]



Perturbative Calculation

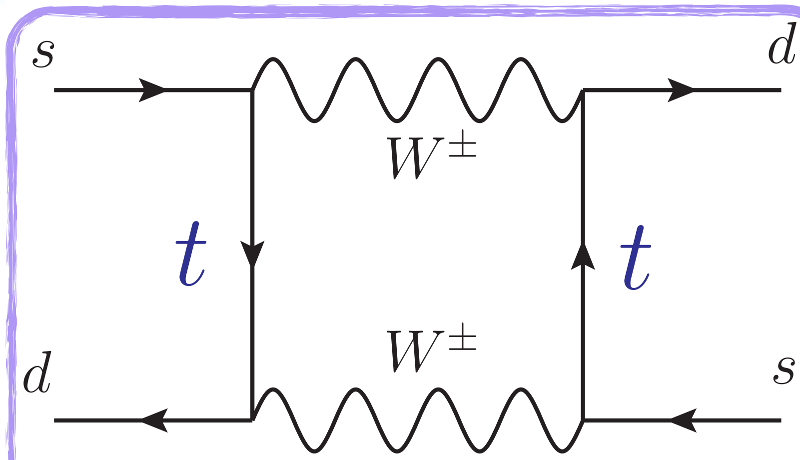


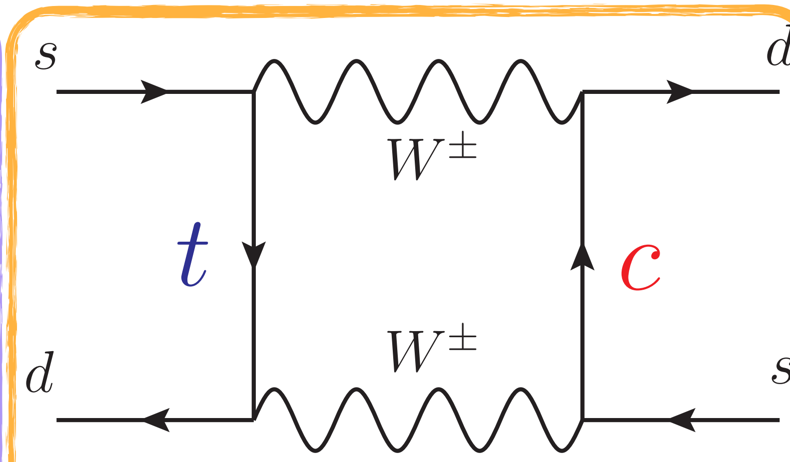
top: η_{tt}

$\log x_t$

LO	$(\alpha_s \log x_c)^n$
NLO	$\alpha_s(\alpha_s \log x_c)^n$
ϵ_K	75%
scale	1.8%

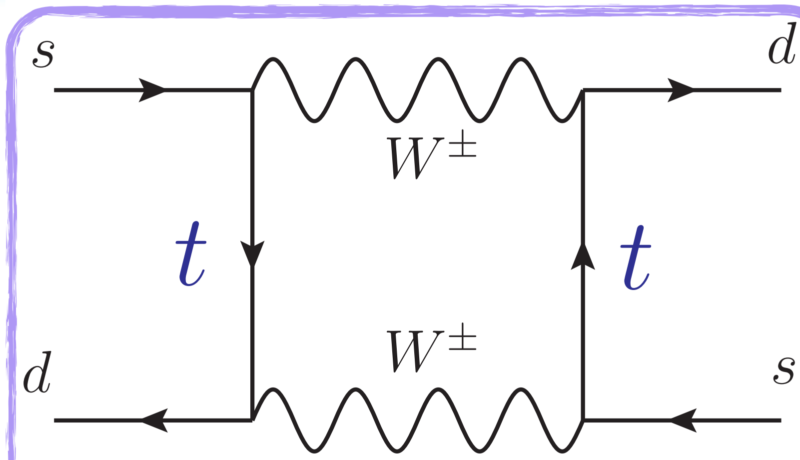
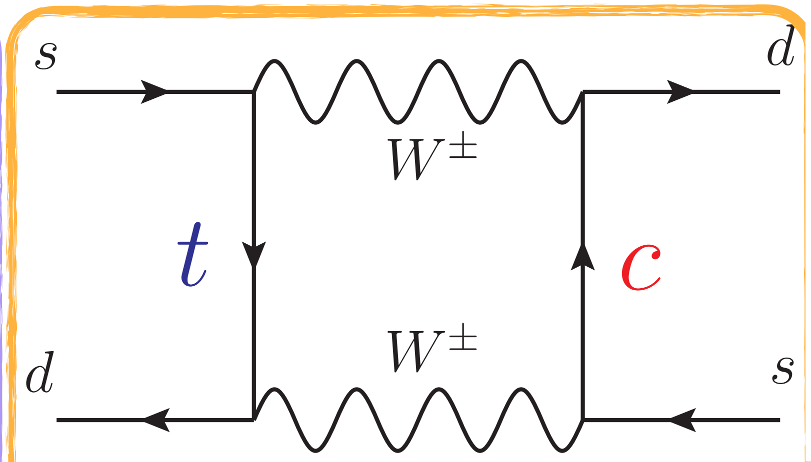
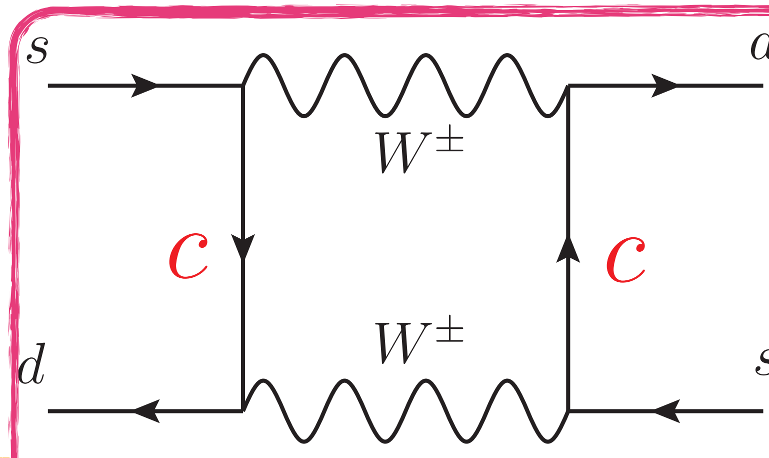
Perturbative Calculation





	top: η_{tt} $\log x_t$	charm top: η_{tt} $\log x_c$
LO	$(\alpha_s \log x_c)^n$	$(\alpha_s \log x_c)^n \log x_c$
NLO	$\alpha_s(\alpha_s \log x_c)^n$	$(\alpha_s \log x_c)^n$
ϵ_K	75%	40%
scale	1.8%	25%

Perturbative Calculation

	top: η_{tt}	charm top: η_{tt}	charm: η_{cc}
	$\log x_t$	$\log x_c$	$(\log x_c)^0$ ↖ 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	$\alpha_s(\alpha_s \log x_c)^n$	$(\alpha_s \log x_c)^n$	$\alpha_s(\alpha_s \log x_c)^n$
ϵ_K	75%	40%	-15%
scale	1.8%	25%	38%

Charm & Top Quark

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$

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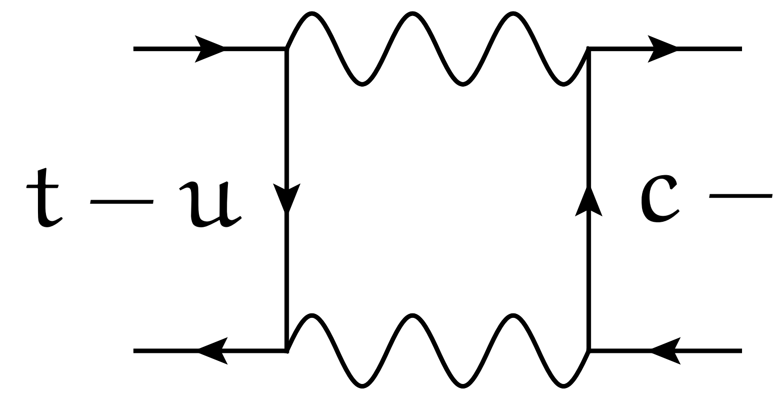
1-loop diagram: infrared divergent

$$\approx \lambda_{\text{Cabibbo}}^6 \times \frac{m_c^2}{M_W^2} \log\left(\frac{m_c^2}{M_W^2}\right) \tilde{Q}$$



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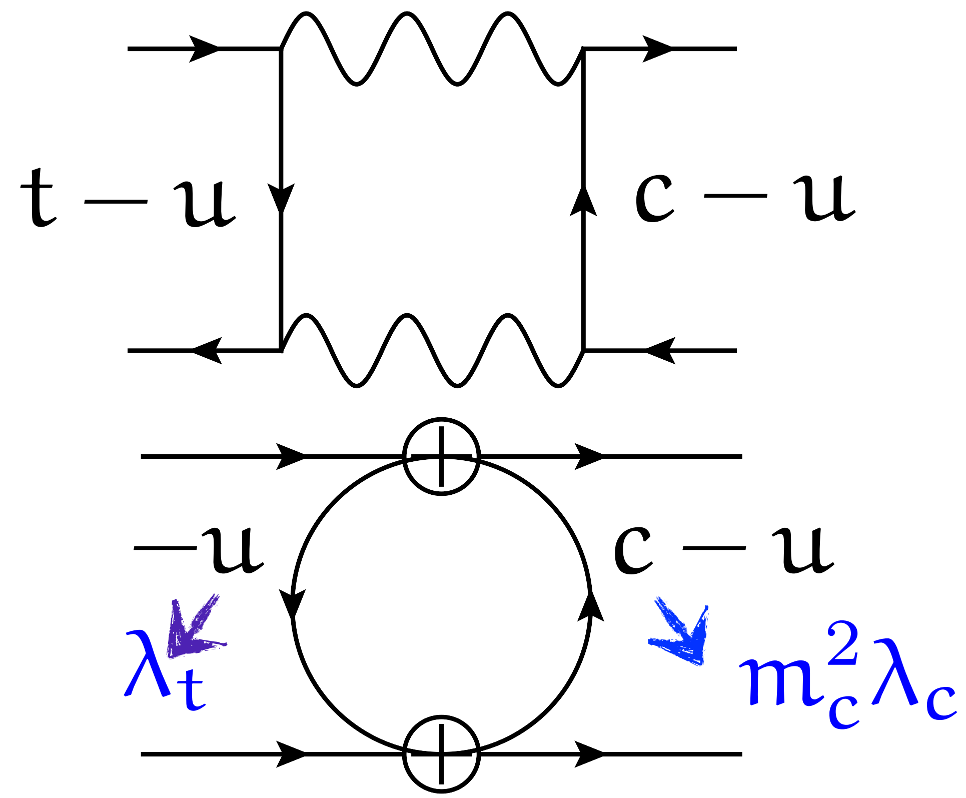
Leading Log: 1-loop RGE

$$\approx \lambda_{\text{Cabibbo}}^6 \frac{m_t^2}{M_W^2} \tilde{Q} \sum_{i=1}^{\infty} \left(\frac{\alpha_s}{4\pi}\right)^{(i-1)} \ln^i \left(\frac{m_c^2}{M_W^2}\right)$$



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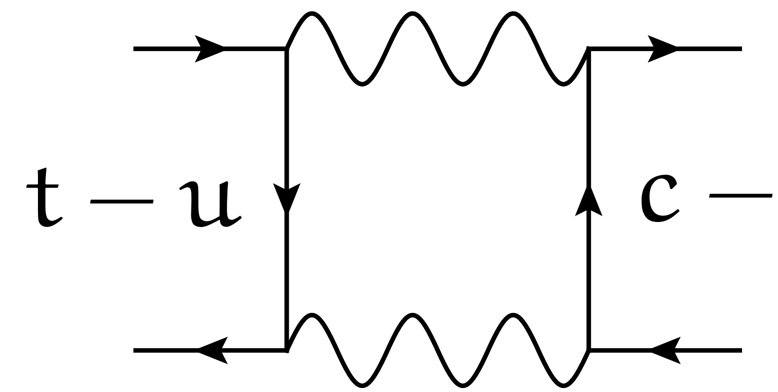

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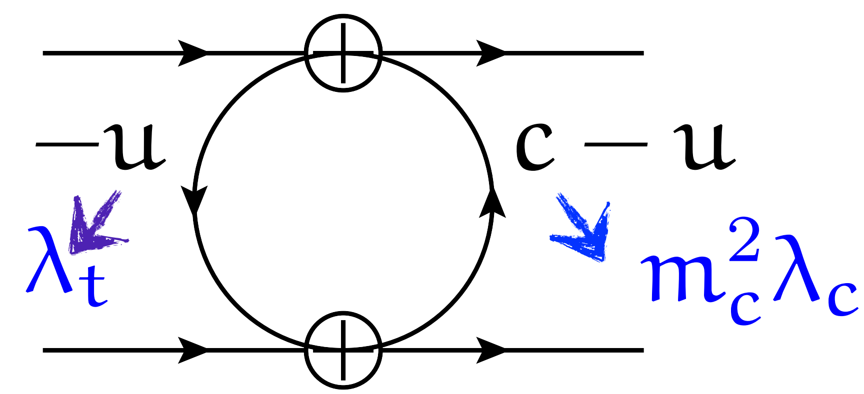


Leading order:
Tree-level matching &
1-loop RGE and 1-loop RGI

NLO: $\eta_{ct} = 0.457(73)$
+40% Contribution to ϵ_K
(Uncertainty 6%)

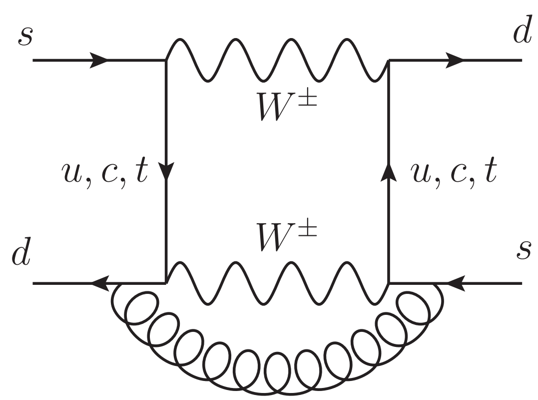
η_{ct}: NNLO Order

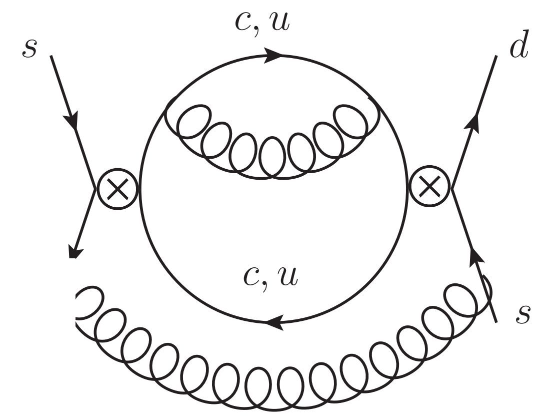
$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$

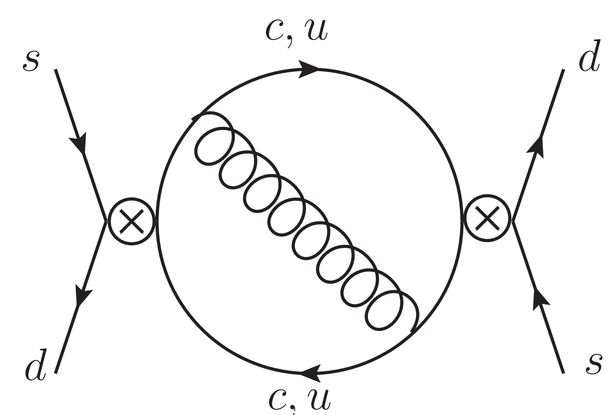
2-loop Matching at the high scale ($\mu = \mu_{t/W}$):

3-loop renormalisation group equations

2-loop Matching at ($\mu = \mu_b$) and ($\mu = \mu_c$)

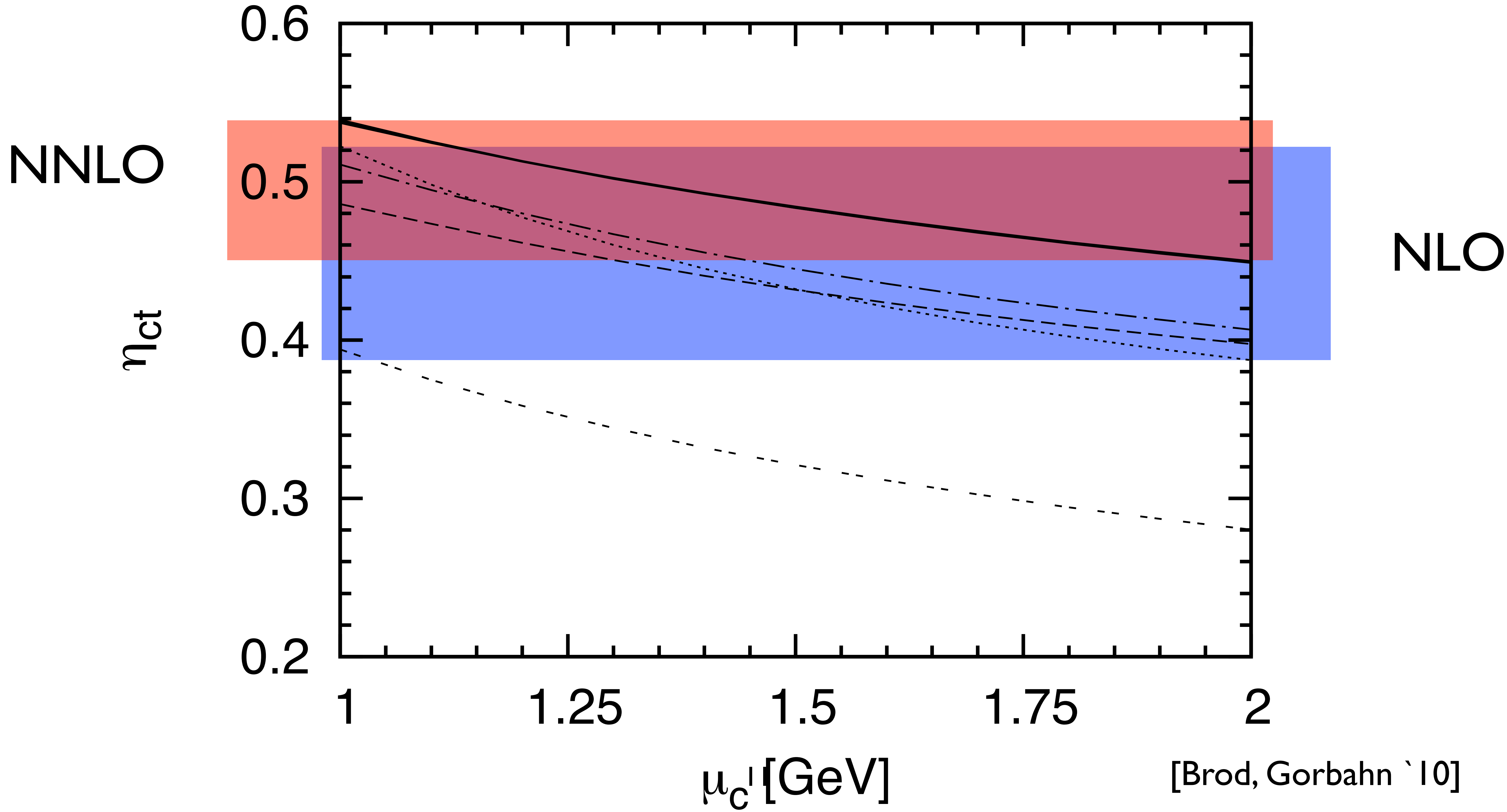






Scale Dependence of η_{ct}

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \boxed{\lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right)} + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$



[Brod, Gorbahn `10]

Charm Quark Contribution

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$

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Matching box diagrams at ($\mu=\mu_t$) and expand in m_c^2:

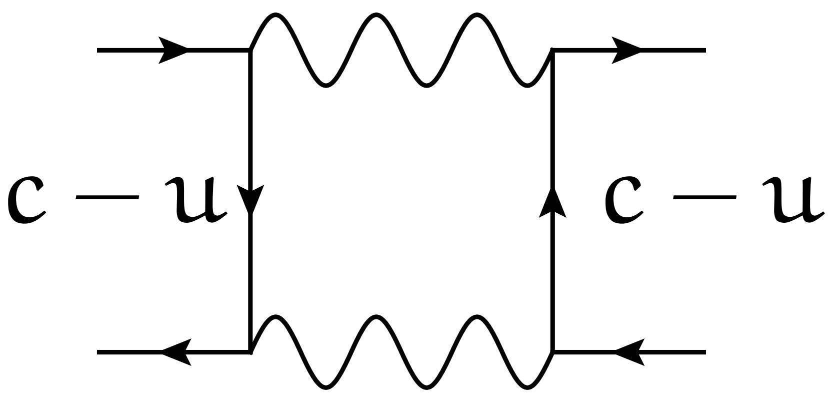

Diagram with 2 charm quarks cancels with 1 charm 1 up quark diagrams

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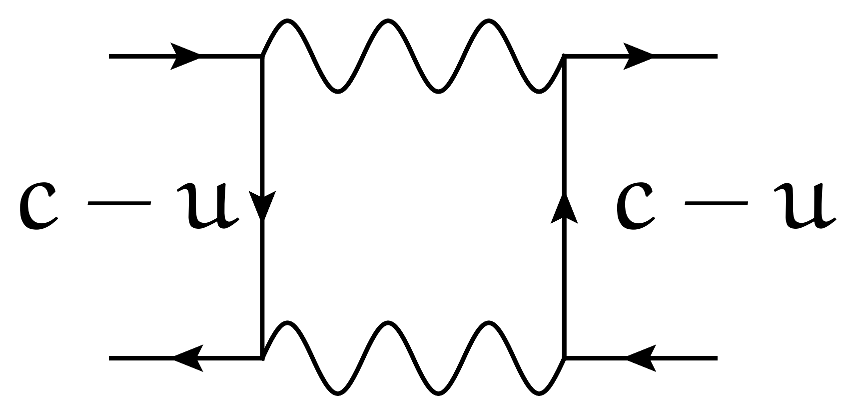
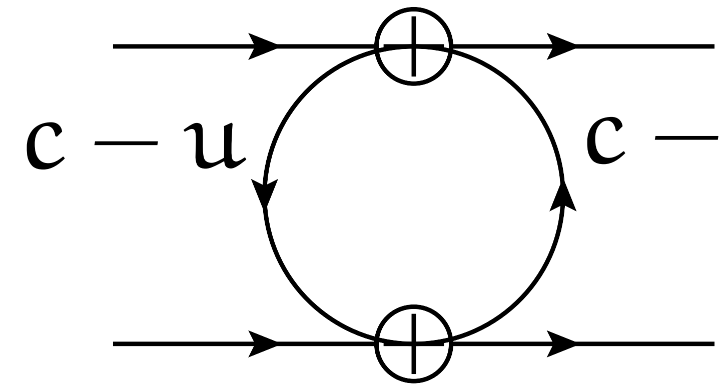


Diagram with 2 charm quarks cancels with 1 charm 1 up quark diagrams

→RGE & matching ($\mu=\mu_{t/W}$) only for: current-current operators



Leading order ($\mu=\mu_c$): 1-loop matching

$$\approx \lambda_{\text{Cabibbo}}^6 \eta_{cc} \frac{m_c^2}{M_W^2} \tilde{Q}$$

η_{cc} at NNLO

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$

η_{cc} = 1.40(37) at NLO QCD [Herrlich, Nierste '94]

– Using there new estimation of the uncertainty

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– Using there new estimation of the uncertainty

A few weeks of 3-loop matching:

η_{cc} at NNLO

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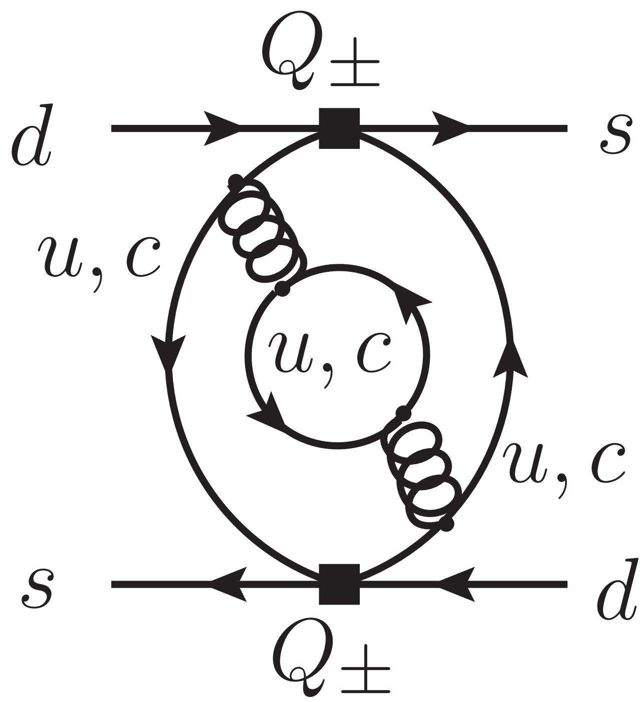

η_{cc} = 1.40(37) at NLO QCD [Herrlich, Nierste '94]

– Using there new estimation of the uncertainty

A few weeks of 3-loop matching:

We find a sizable NNLO correction

[Brod, Gorbahn `11]

η_{cc} at NNLO

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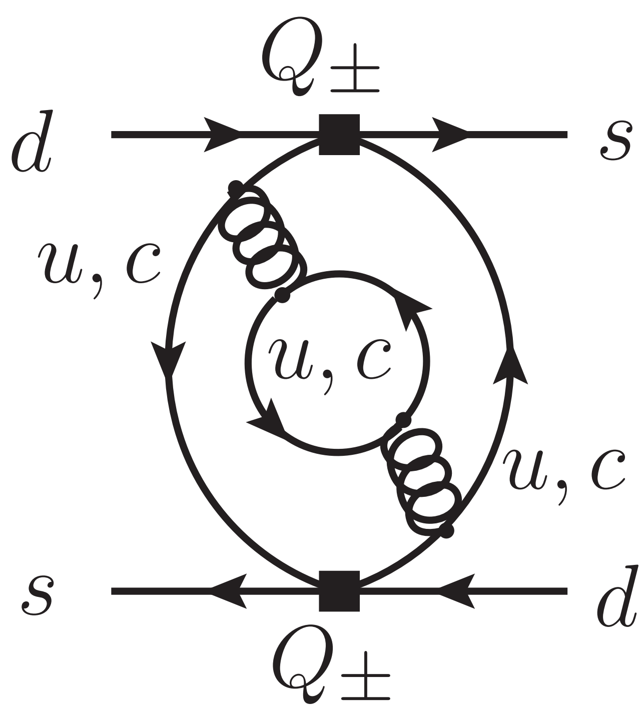
– Using there new estimation of the uncertainty



A few weeks of 3-loop matching:

We find a sizable NNLO correction
[Brod, Gorbahn `11]

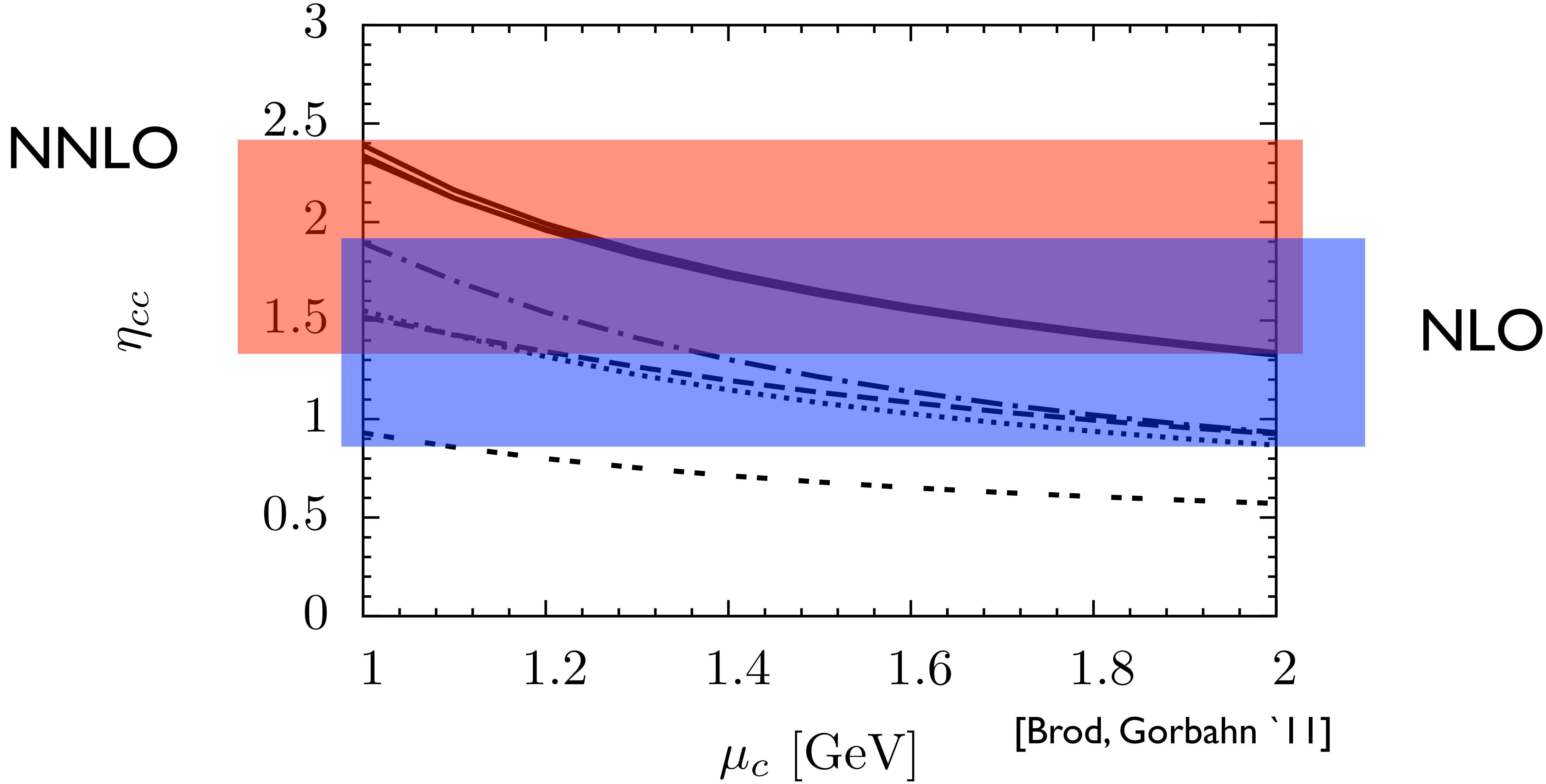
Expanding in an ordinary perturbation theory at $\mu = m_c$

$$\eta_{cc}/\alpha_s^{2/9} = 1 + \alpha_s(0.25 + 0.32 L_c) + \alpha_s^2(1.20 + 0.03 L_b + 0.22 L_c + 0.27 L_c^2)$$

$$\alpha_s = \alpha_s(m_c)\,, \quad L_i = \log(m_i^2/M_W^2)$$

Scale Dependence of η_{cc}

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$



η_{ct} & η_{cc}: Numbers

$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} S\left(\frac{m_t^2}{M_W^2}\right) + \lambda_c \lambda_t \eta_{ct} S\left(\frac{m_c^2}{M_W^2}\right) + \lambda_c^2 \eta_{cc} S\left(\frac{m_c^2}{M_W^2}\right)\right] \tilde{Q}$$

η_{ct}: Uncertainty dominated by μ_c scale dependence [1–2 GeV]

$$\eta_{ct}^{NLO} = 0.456(73) \rightarrow \eta_{ct}^{NNLO} = 0.496(46)$$

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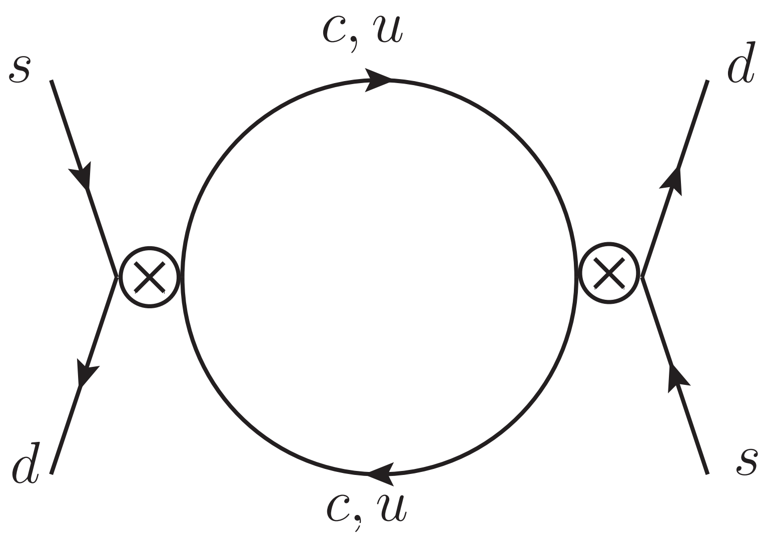
η_{ct}: Uncertainty dominated by μ_c scale dependence [1–2 GeV]

$$\eta_{ct}^{NLO} = 0.456(73) \rightarrow \eta_{ct}^{NNLO} = 0.496(46)$$

η_{cc}: Finite shift and scale uncertainty of same size – added in squares

$$\eta_{cc}^{NLO} = 1.38(53) \xrightarrow{\text{scale}} \eta_{cc}^{NNLO} = 1.86(54) \xrightarrow{\text{scale+finite}} \eta_{cc}^{NNLO} = 1.87(76)$$

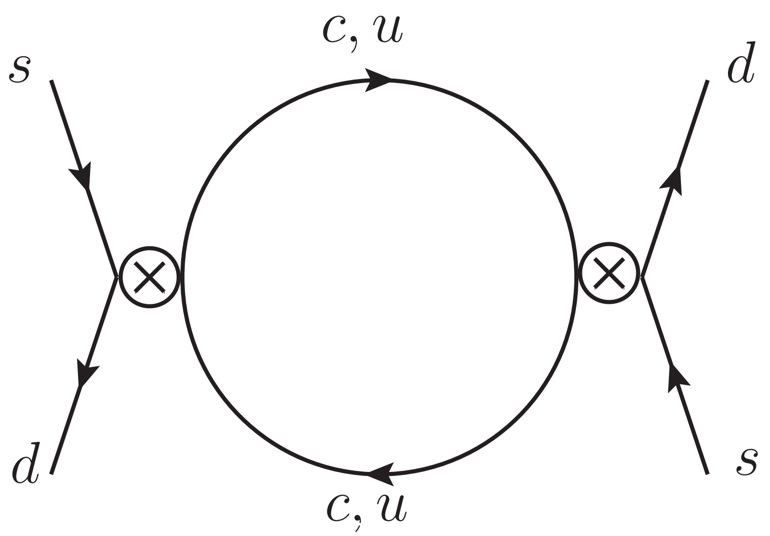
Long Distance Contribution



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

Higher dimensional operator [Cata Peris`04]

Long Distance Contribution



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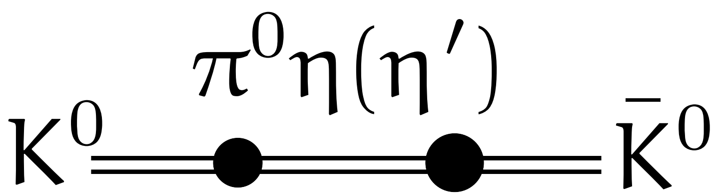
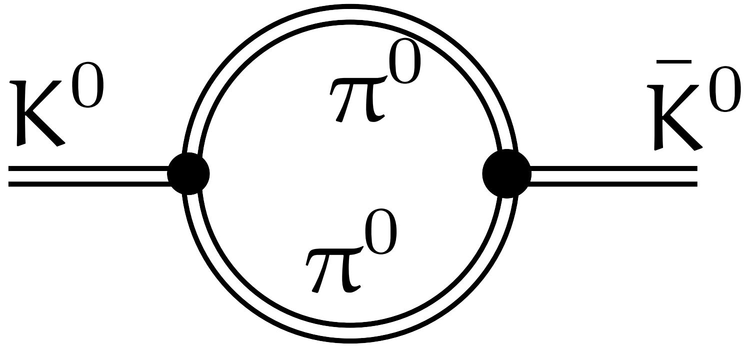
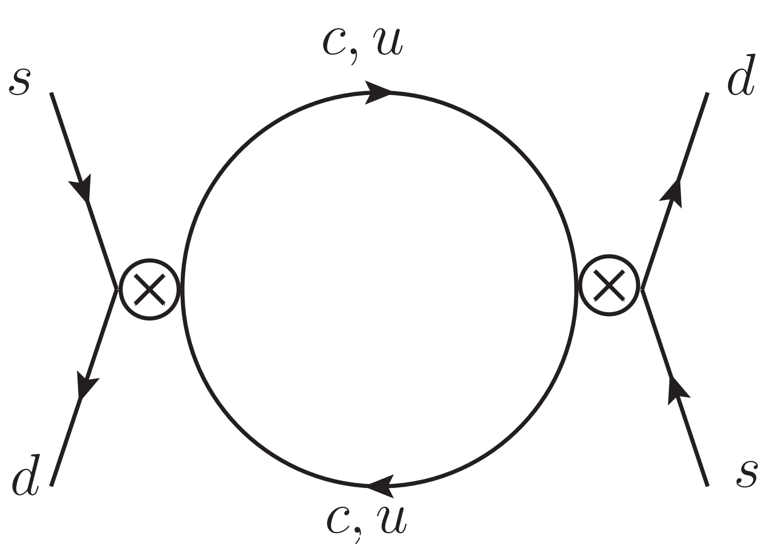


Light quark loops in CHPT:
π^0,η tree level vanishes (Gell-Mann-Okuba)
η´comes with zero phase [Gerard et.al. `05]



1-loop diagram divergent:
estimate from $\ln(m_\pi/m_\rho)$ [Buras et.al. `10]

Long Distance Contribution



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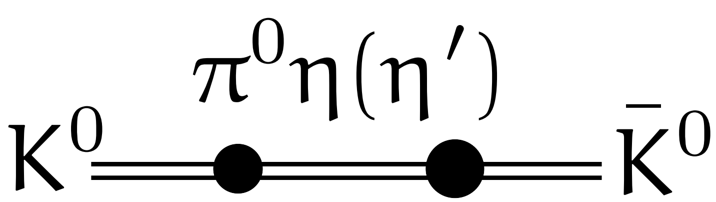
Higher dimensional operator [Cata Peris`04]



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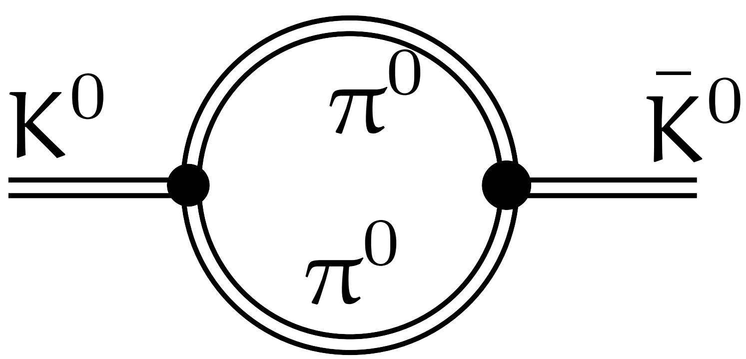

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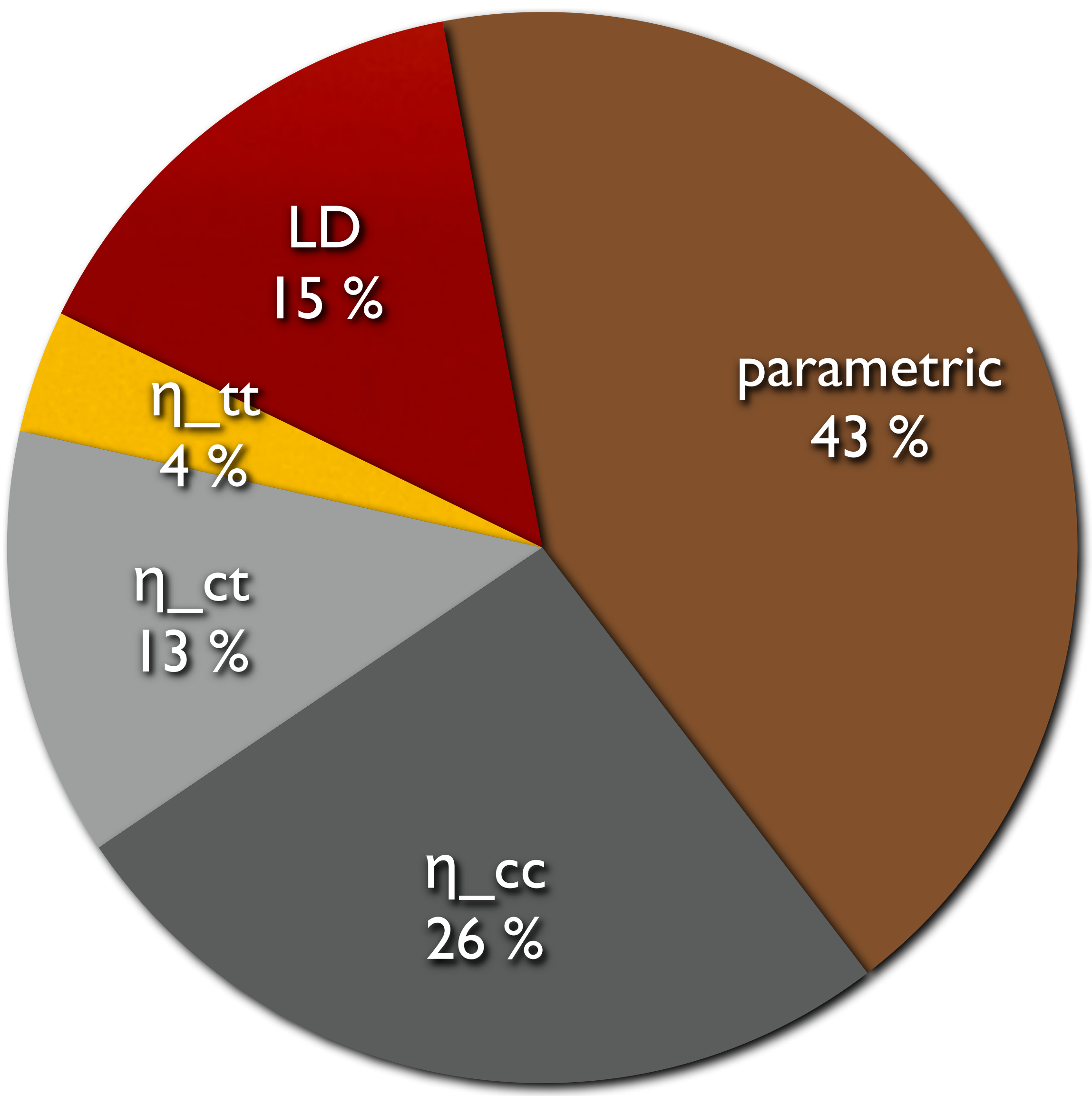
estimate from $\ln(m_\pi/m_\rho)$ [Buras et.al. `10]

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

absorptive part
estimated form ϵ´

Results and Error Budget



input [PDG `10]

$$|\epsilon_K| = 1.81(28) \times 10^{-3}$$
$$|V_{cb}| = 406(13) \times 10^{-4}$$

Experiment [PDG `10]:

$$|\epsilon_K| \stackrel{\text{exp.}}{=} 2.228(11) \times 10^{-3}$$

B_K precisely known [Aubin, UKQCD, ETM]
we use 0.725 (26)

The short distance part of ΔM_K saturates 86% of ΔM_K experimental

$$\Delta M_K^{SD} = (3.0 \pm 1.2) \times 10^{-15} \text{GeV}$$

Conclusions

Perturbative QCD corretions to Kaon mixing at NNLO

+ Improvements from lattice and experimental input:

Slight tension between the standard model prediction and the experimental value for ϵ_K

Hint for new physics? or rather theory uncertainty still to large