Kaon Physics

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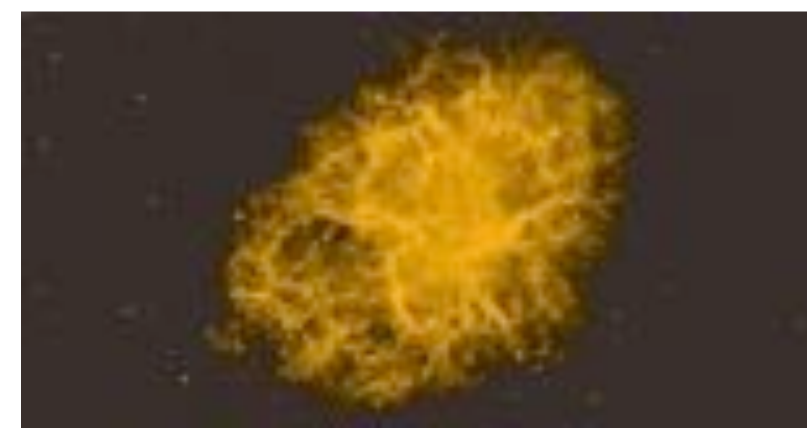


Indirect searches for new physics

Search of remnants of new physics:
In decays induced by
higher-dimensional operators ← new particles

Yet the standard model will also induce
higher-dimensional operators ← W, Z & top

NP competes with SM $\frac{M_{SM}}{M_{NP}}$ need high statistics

If SM contribution is suppressed: NP sensitivity enhanced

Interesting Topics (incomplete)

very clean

- (Semi-)leptonic Kaon Decays — Lepton Universality & CKM Unitarity

clean and suppressed by $V^*_{ts} V_{td}$

- Rare Kaon Decays — SM Prediction; MSSM & new light particles
- CP violation in ϵ_K — new NNLO results

Leptonic and Semileptonic

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

Observables

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

[FlavianetKaon `08]

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

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)

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

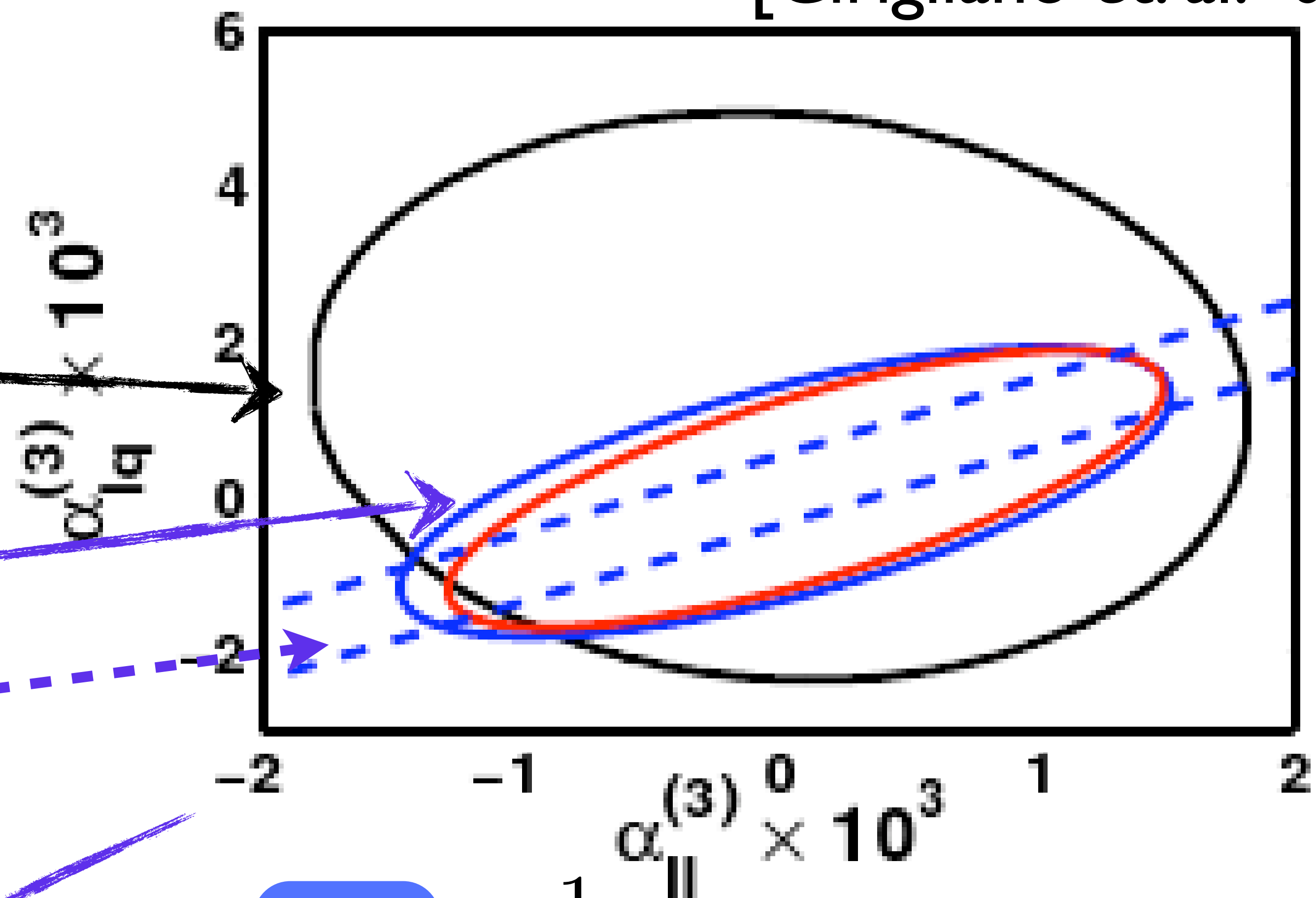
[Cirigliano et. al. `09]

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

from HEP

HEP + CKM

CKM



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

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

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]

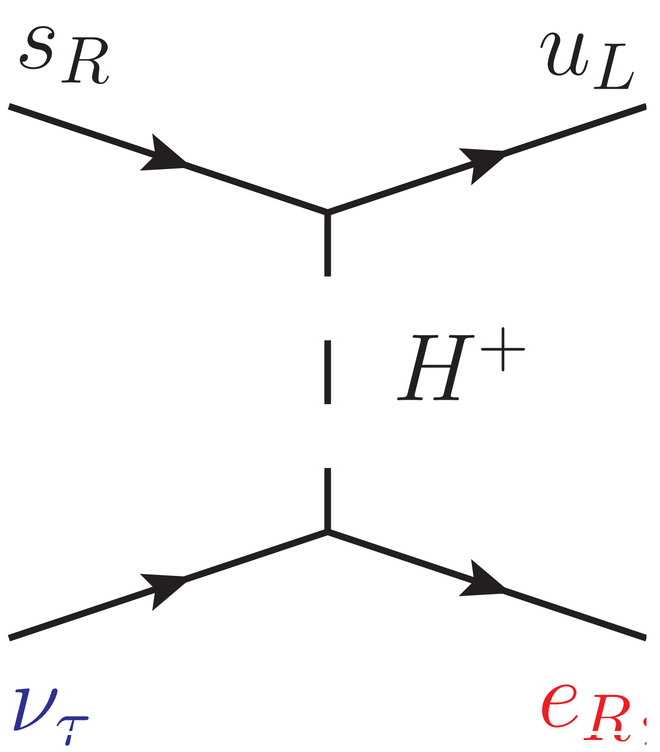
$$R_K^{NA62} = 2.500(16) \times 10^{-5}$$

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

[numbers from KAON09]

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]

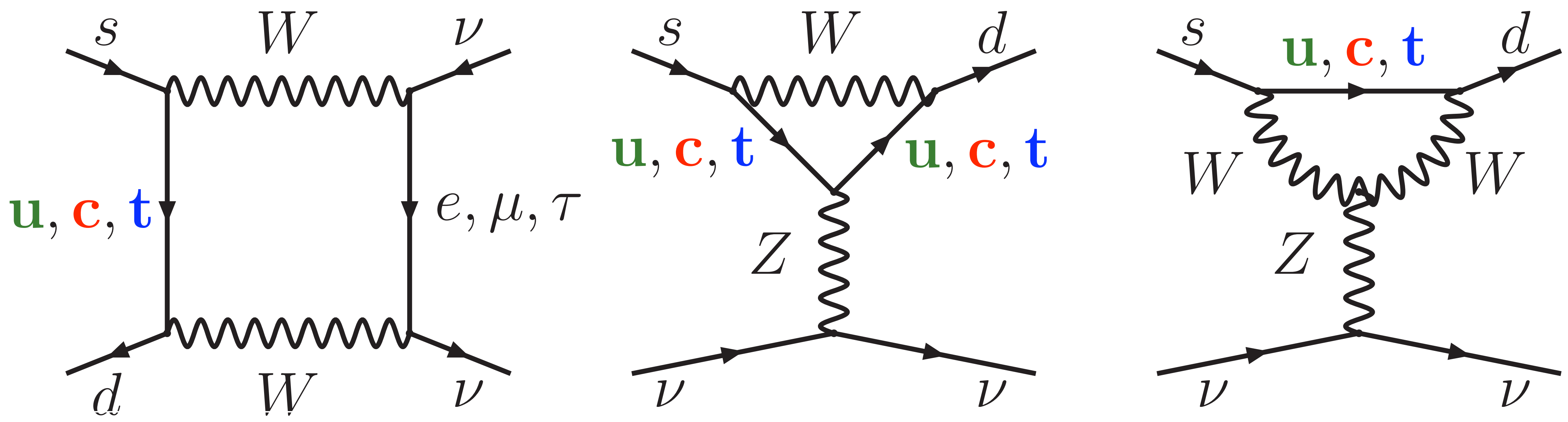
$$R_K^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{SM}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

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

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

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

Introduction: $K \to \pi \nu \bar{\nu}$



- 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: $\lambda^5 \frac{m_t^2}{M_W^2}$ $\lambda \frac{m_c^2}{M_W^2} \ln \frac{M_W}{m_c}$ $\lambda \frac{\Lambda^2}{M_W^2}$

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

$s \longrightarrow d$ and New Physics (NP)

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

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

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

Rare K Decays: Additional Cabbibo suppression λ^5

$$\mathcal{L}_{\text{eff}} = \frac{C(b \rightarrow s)}{\Lambda_{\text{NP}}^2}(\bar{b}\Gamma s)(\bar{\nu}\Gamma\nu) + \frac{C(b \rightarrow d)}{\Lambda_{\text{NP}}^2}(\bar{b}\Gamma d)(\bar{\nu}\Gamma\nu) + \frac{C(s \rightarrow d)}{\Lambda_{\text{NP}}^2}(\bar{s}\Gamma d)(\bar{\nu}\Gamma\nu)$$

Low NP scale $\Lambda_{\text{NP}} \simeq 1\,\text{TeV}$

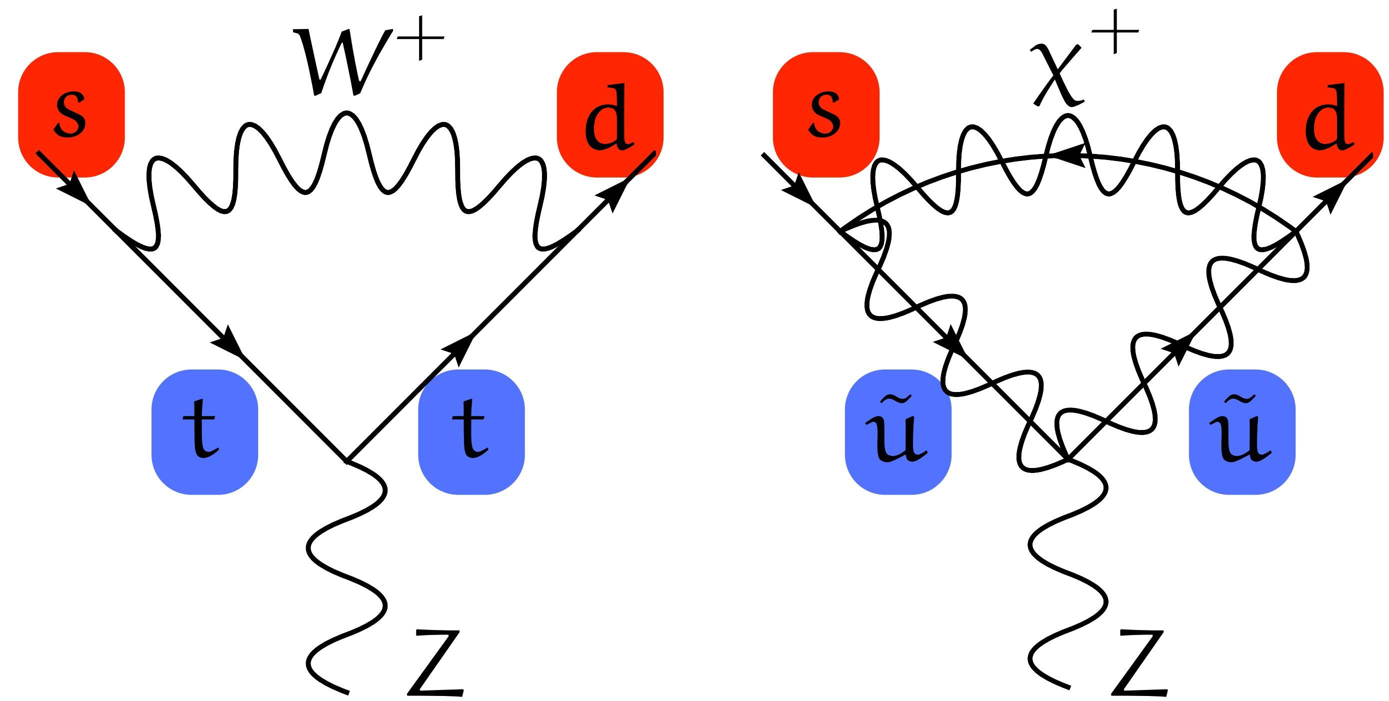
NP Flavour Sector $C(s \rightarrow d) < \lambda^5$

For Generic NP $C(s \rightarrow d) \simeq 1$

New Physics scale $\Lambda_{\text{NP}} > 75\,\text{TeV}$

Rare K decays and New Physics:

- Test deviation of flavour alignment (Minimal Flavour Violation MFV)



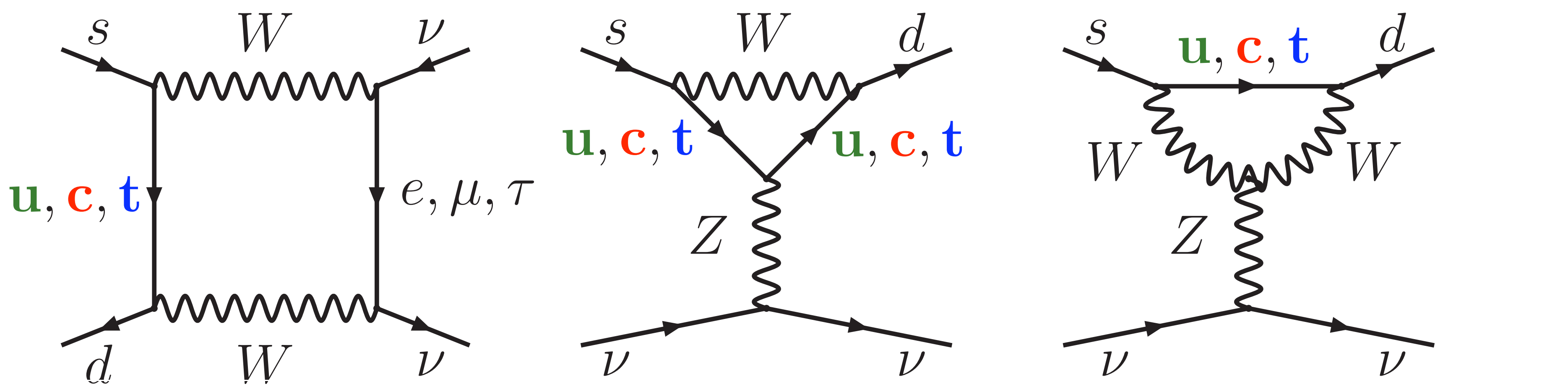
- Precise theory prediction
- Sensitive to small deviations from MFV

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

also:

$$K_L \to \pi^0 \mu^+ \mu^-$$
$$K_L \to \pi^0 e^+ e^-$$

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



CP violating

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

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

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

$K_L \to \pi^0 \bar{\nu} \nu$: short distance

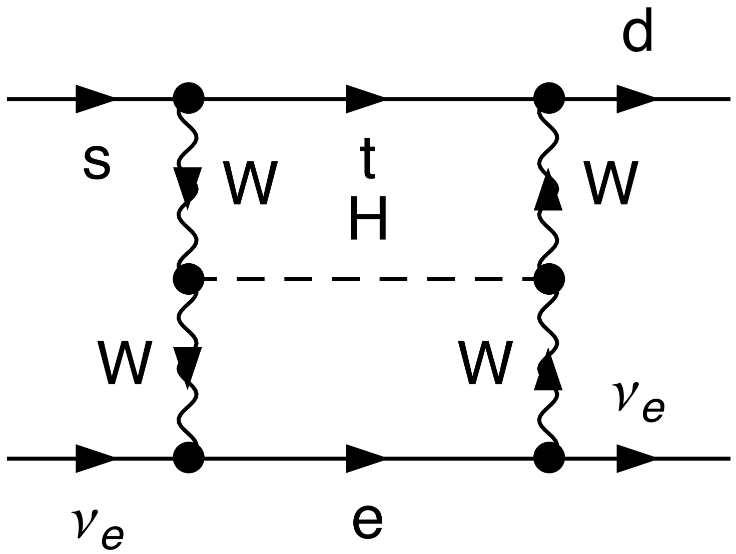
X_t Is purely short distance

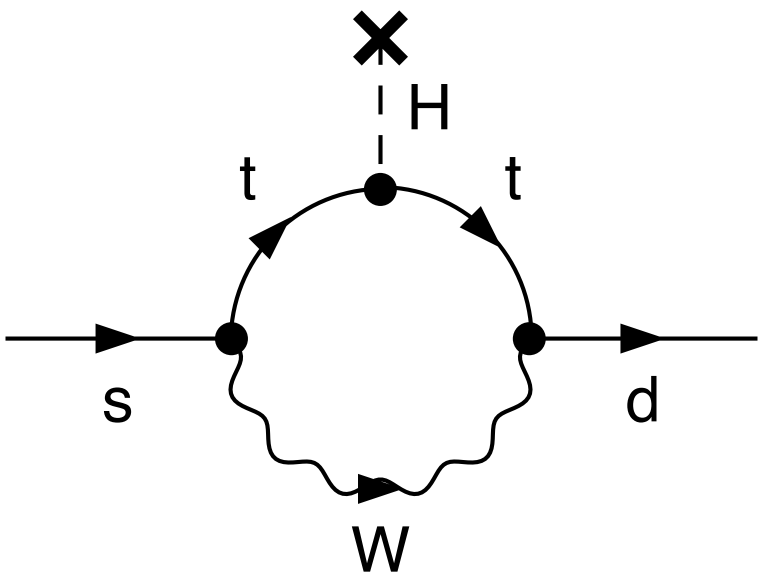
- NLO QCD: ±1% (theory)[Misiak et.al., Buchalla et. al. ´99]
- EW corrections large m_t:
  ±2% uncertainty [Buchalla, Buras ´99]
- $X(x_t)$: Dominant theory uncertainty for $K_L \to \pi^0 \bar{\nu} \nu$
- For example a change $\sin^{OS} \theta_W \leftrightarrow \sin^{\overline{MS}} \theta_W$
  results in 5% uncertainty

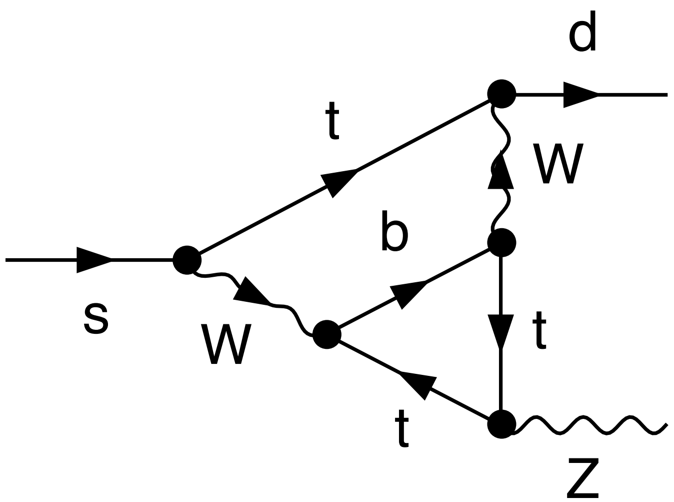
$$H_{eff} = \frac{4 G_F}{\sqrt{2}} \frac{\alpha V^*_{ts} V_{td}}{2\pi \sin^2 \Theta_W} X(x_t) Q_\nu$$

$X(x_t)$: Electroweak Corrections

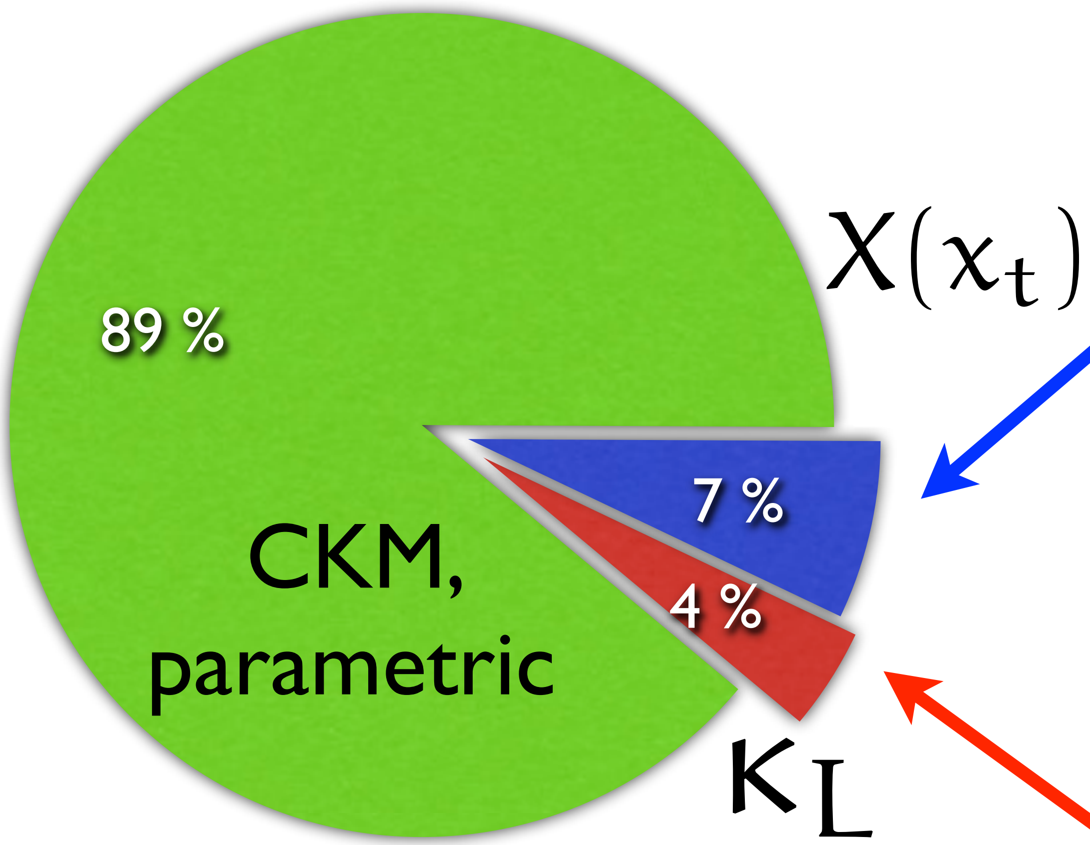
- Use the $\overline{\text{MS}}$ scheme
- Normalise to G_F
- VEV minimises renormalised potential: include tadpoles
- Traces with γ_5: use HV scheme
- NLO EW: +0.5% shift
  [Brod, Gorbahn, Stamou ´10]







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



$X(x_t)$: Full NLO electroweak corrections
[Brod, MG, Stamou ´10]

Reduce theory uncertainty by factor of 2

Matrix element extracted from K_{l3} decays. $N^{\frac{3}{2}}LO$ χPT
[Mescia, Smith ´07; Bijnens, Ghorbani ´07]

No further long distance uncertainty

$$\mathcal{B}r_{K_L} = (2.6 \pm 0.4) \times 10^{-11}$$

$$< 6.7 \times 10^{-8}$$ [E391a ´08]

$K^+ \to \pi^+ \bar{\nu}\nu$ 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 $\log(\frac{m_c}{M_W})\frac{1}{\lambda^4}$

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

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

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

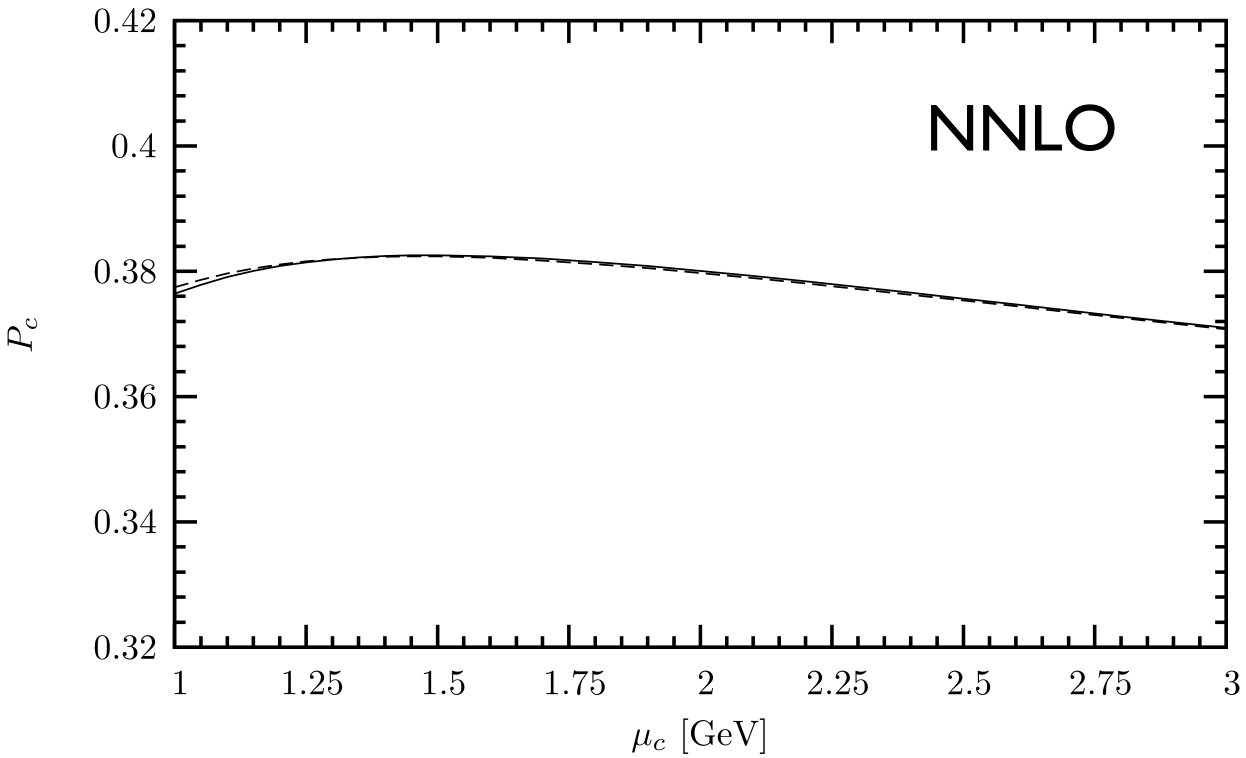
- Matrix element extracted from K_{l3} decays
  [Mescia, Smith ´07]
- $K^+ \to \pi^+ \nu \bar{\nu}$ is $K^+ \to \pi^+ \nu \bar{\nu}(\gamma)$
  QED radiative corrections included:

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

- Uncertainty in $\kappa_+(1 - \Delta_{EM})$ 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]
- Could be Improved by Lattice [Isidori et. al. ´05]

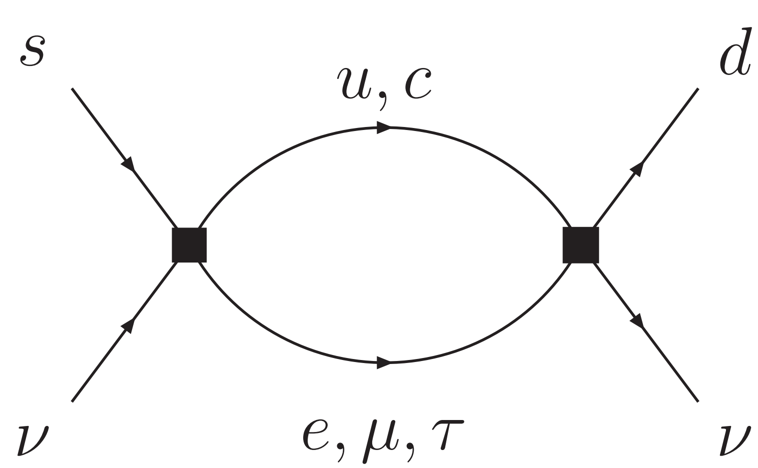
$K^+ \to \pi^+ \bar{\nu} \nu$ charm contribution



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

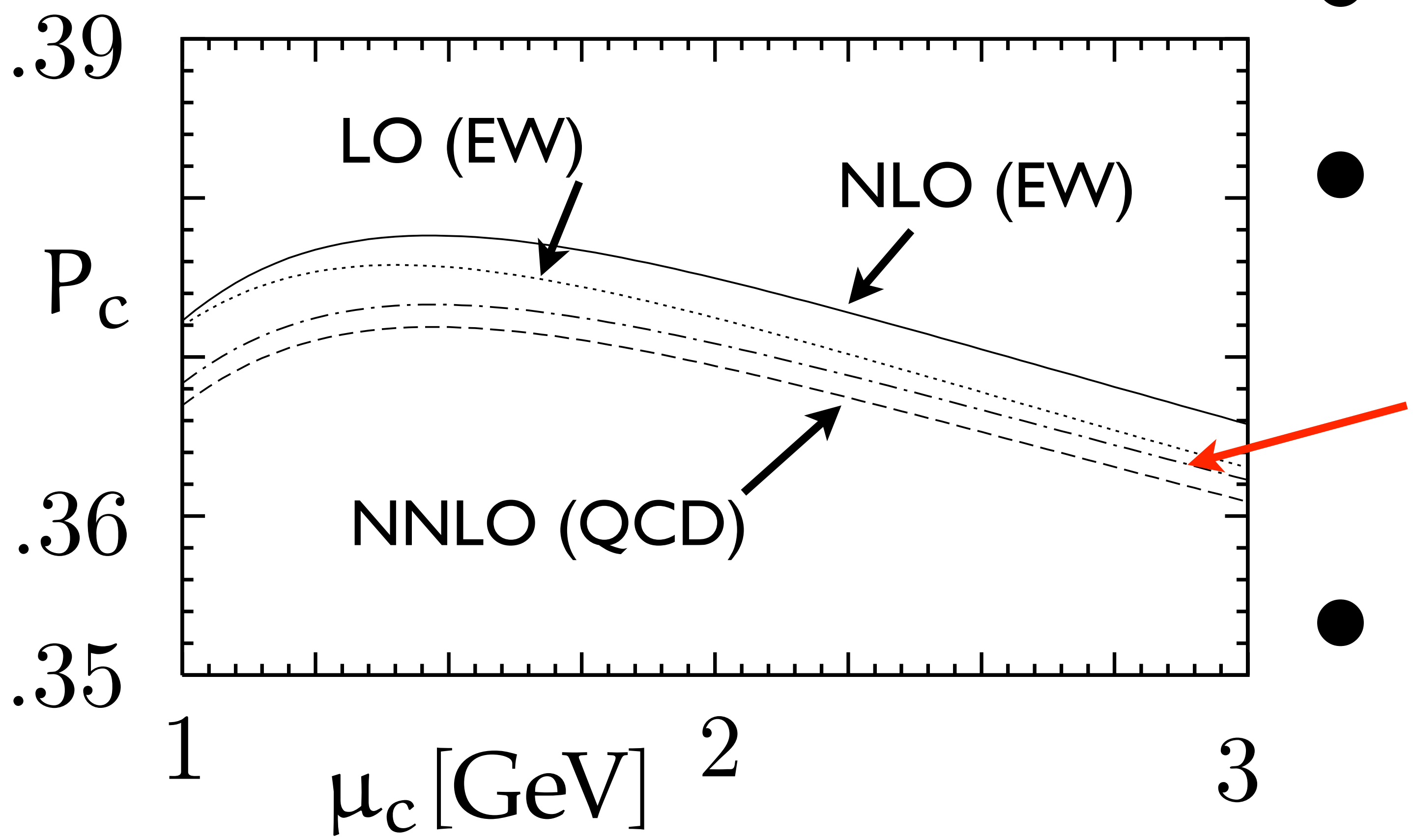
P_c at NNLO: ±2.5% (theory)

[Buras, MG, Haisch, Nierste ´06]



- Bilocal mixing is $\mathcal{O}(G_F^2)$
- What is the parameter $x_c = \frac{m_c^2}{M_W^2}$
- EW corrections define M_W

$K^+ \to \pi^+ \bar{\nu} \nu$ charm contr. (EW)



[Brod, MG ´08]

- Use $\overline{MS}$ scheme
- Normalise to G_F
- use

$$x_c = \sqrt{2} \frac{\sin^2 \theta_W}{\pi \alpha} G_F m_c^2(\mu_c)$$

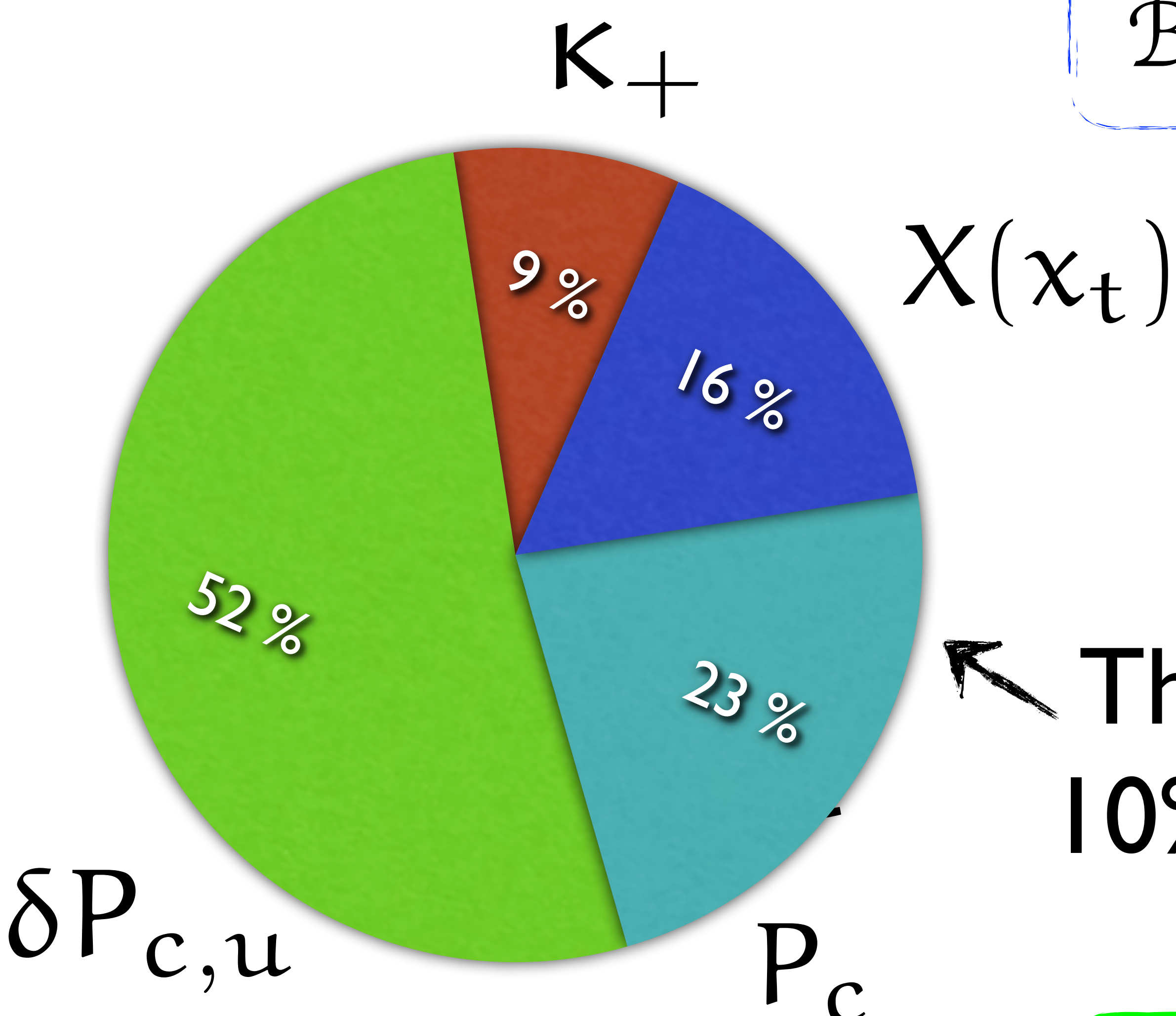
- instead of

$$x_c = \frac{m_c(\mu)^2}{M_W^2}$$

- P_c enhanced by up to 2% for all EW

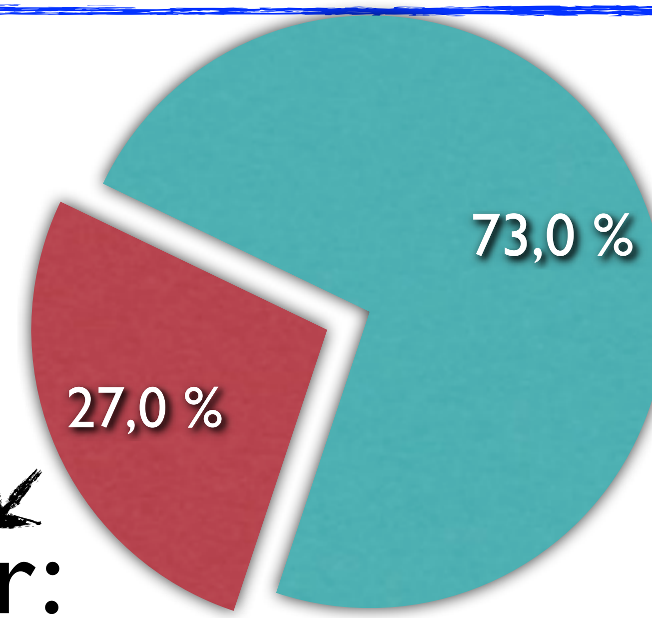
$K^+ \to \pi^+ \bar{\nu} \nu$ Error budget

Theory error budget



for $m_c(m_c) = (1286 \pm 13)\mathrm{MeV}$
[Kühn et. al. ´07]

$$\mathcal{B}r_{K^+} = (0.85 \pm 0.07) \times 10^{-10}$$



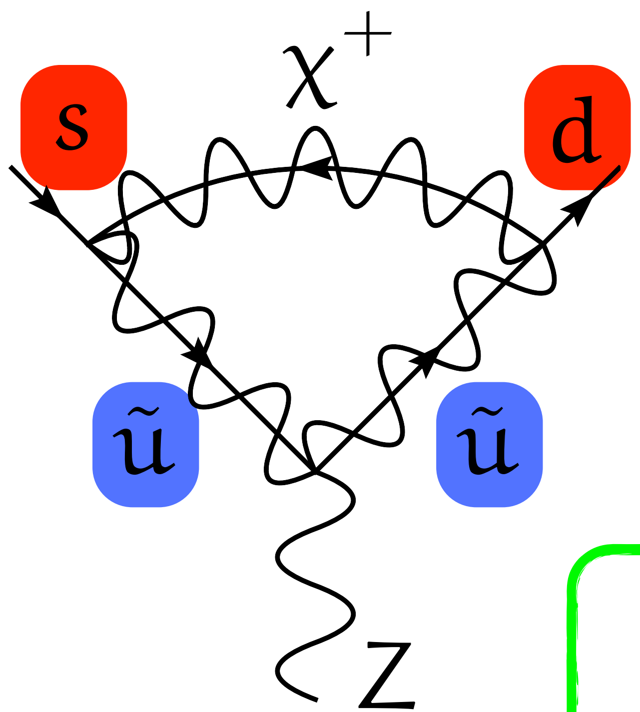
Theory error:
10%x30% = 3%

Parametric uncertainty

Experiment [E787, E949 ´08]

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

$K \to \pi \bar{\nu} \nu$ in the MSSM



New physics in: $X(x_t) \to X(x_t, \tilde{m}, \tilde{M})$

MSSM is a 2HDM of Type II:

$$\mathcal{L} = -Y^d_{ij} H_d \bar{d}^i_R q^j - Y^u_{ij} H_u \bar{u}^i_R q^j + \text{h.c.}$$

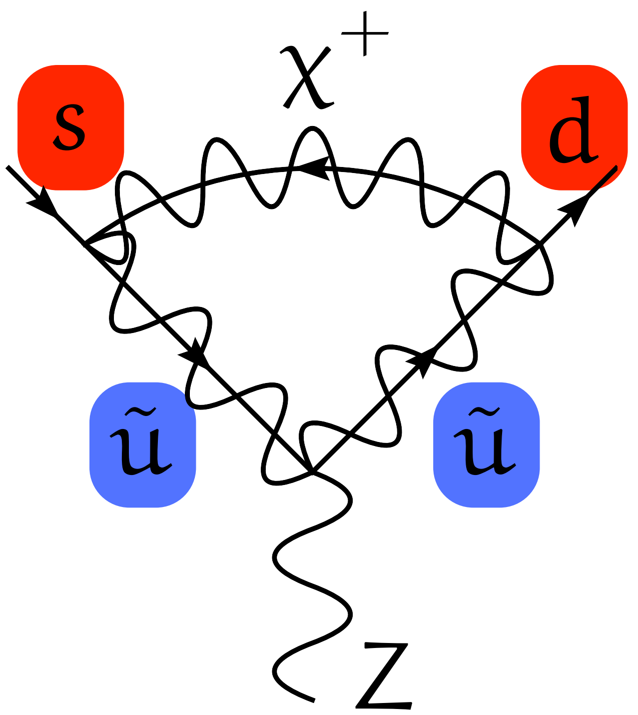
for small $\tan\beta = v_u / v_d = \mathcal{O}(1)$

Yukawa and mass-matrix aligned

Flavour Violation in squark mass matrix

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

$K \to \pi\bar{\nu}\nu$ in the MSSM: MFV



Minimal Flavour Violation: Aligned squarks and quarks

No strong enhancement possible. Interesting correlations with other observable

[Buras, Gambino, MG, Jäger, Silvestrini `00; Isidori, Mescia, Paradisi, Smith, Trine `06]

Diagonal

Flavour Violation in squark mass matrix

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

$K \to \pi \bar{\nu} \nu$ and non MFV

Offdiagonal squark mass-matrix: Extra Flavour Violation

Diagonalisation: Mass insertions

$$\delta^{u}_{LR_{ij}} = \frac{\hat{\mathcal{M}}^2_{\tilde{u}_{i_R j_L}}}{\hat{\mathcal{M}}^2_{\tilde{u}}}$$

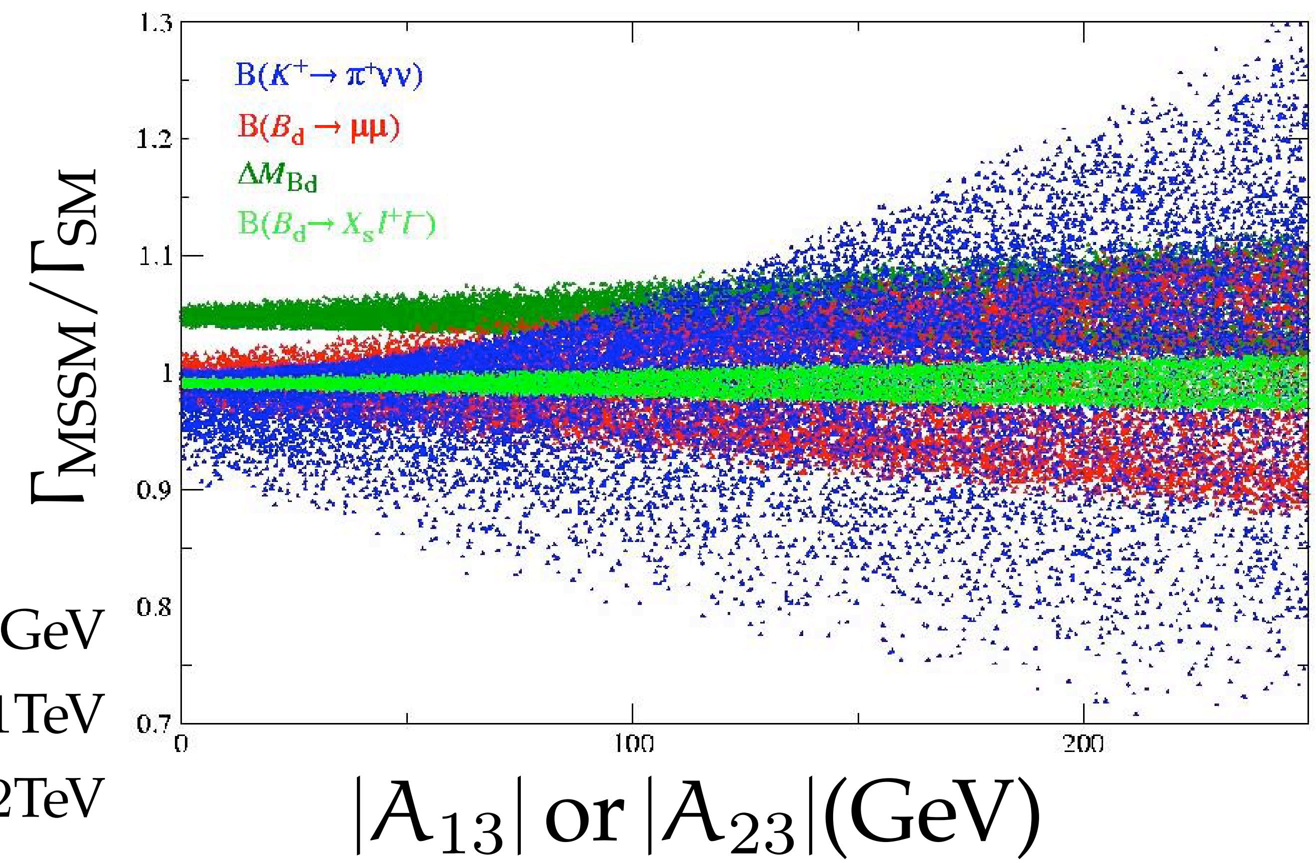
sensitive to A_u [Isidori, Mescia, Paradisi, Smith, Trine `06]

2 LR insertions dominant

[Colangelo, Isidori ´98]

$$X^2_{LL} \propto \delta^{u*}_{LR_{ts}} \delta^{u}_{LR_{td}}$$

No CKM suppression



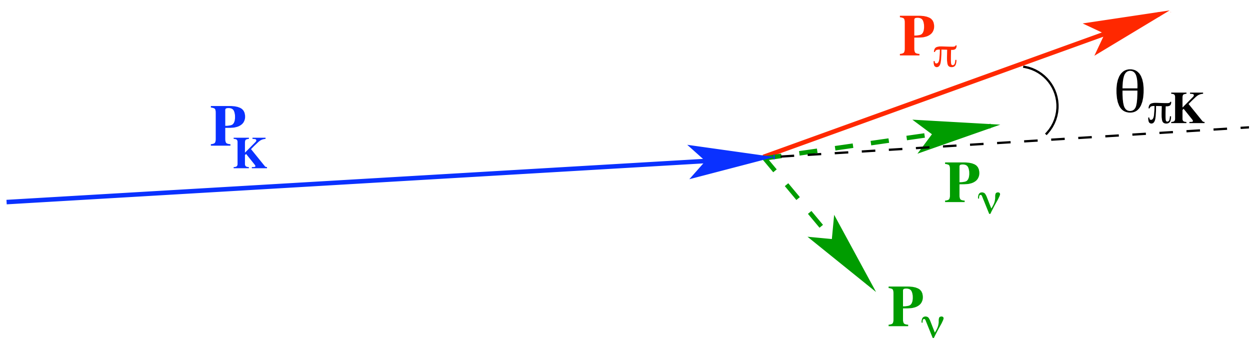
$\tan\beta = 2-4 \quad \mu = 500 \pm 10\text{GeV} \quad M_2 = 300 \pm 10\text{GeV}$

$M_{\tilde{u}_R} = 600 \pm 20\text{GeV} \quad M_{\tilde{q}_L} = 800 \pm 20\text{GeV} \quad A_0 = 1\text{TeV}$

$M_1 = 500\text{GeV} \quad M_{\tilde{d}_R} = M_{\tilde{l}} = M_3 = M_{\tilde{H}^+} = 2\text{TeV}$

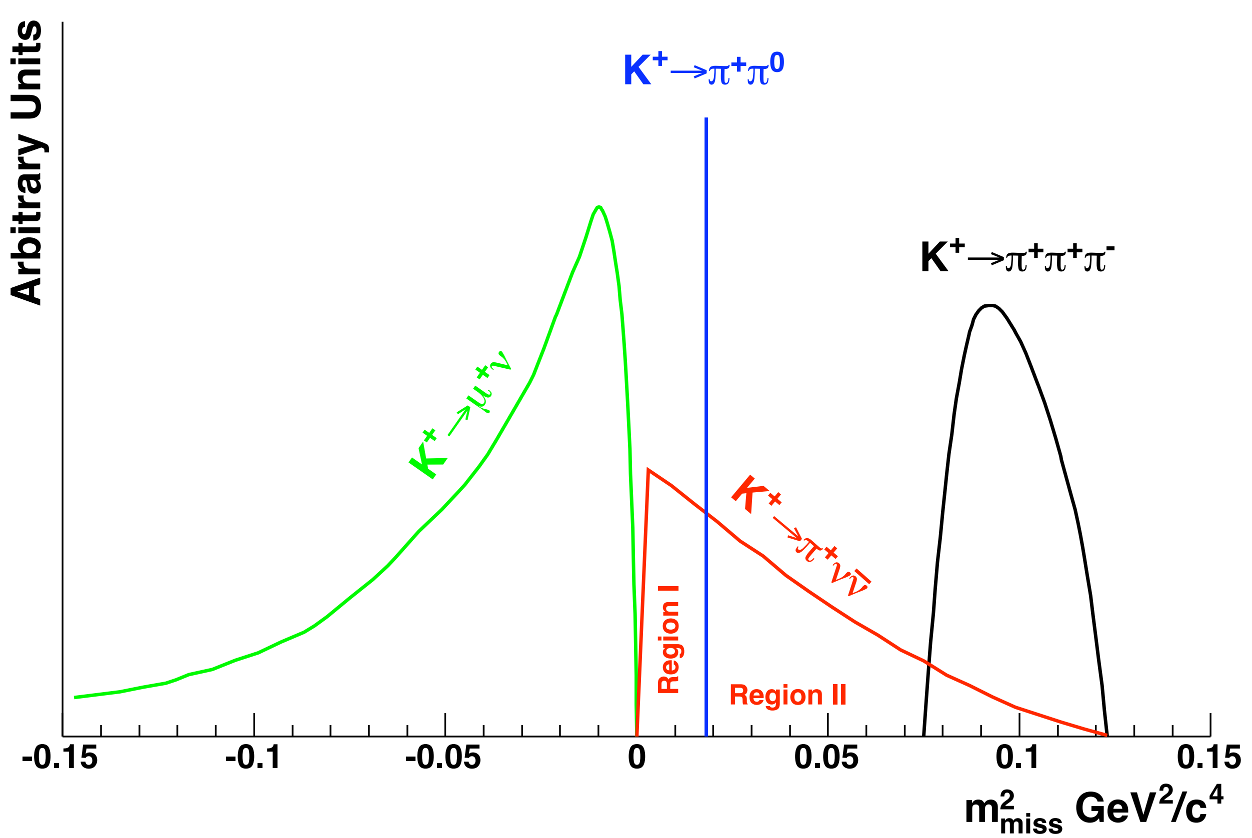
Beyond the Z-Penguin

Experiment: Background from frequent K^+-Decays



Measure p_π & $\theta_{\pi K}$

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



- Can new physics change the shape?
- In all models there is only one operator for $K \to \pi \bar{\nu} \nu$

Missing Mass Distribution (NP)

Can new physics change the missing mass distribution?

$K^+ \to \pi^+ +$ and new light particles:

Sensitivity to the mass

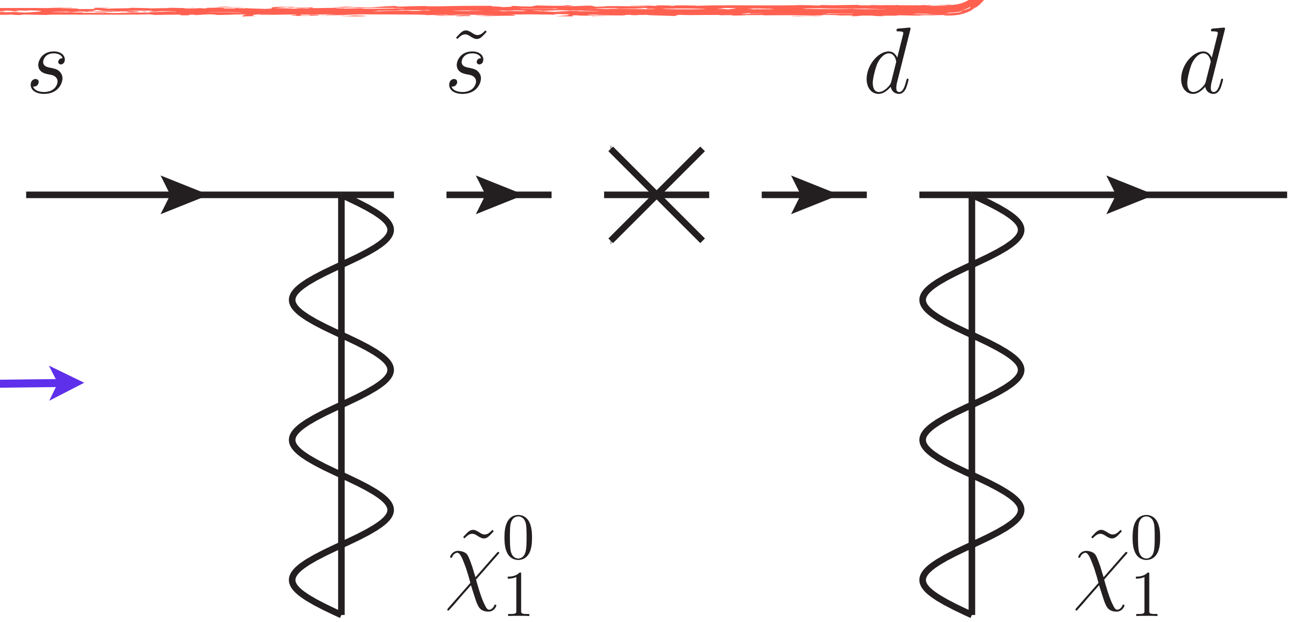
New Operators

Toy example recently studied [Dreiner et. al. '09]:
light neutralinos:

$$K^+ \to \pi^+ \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

MFV: one loop

Non-MFV: tree level



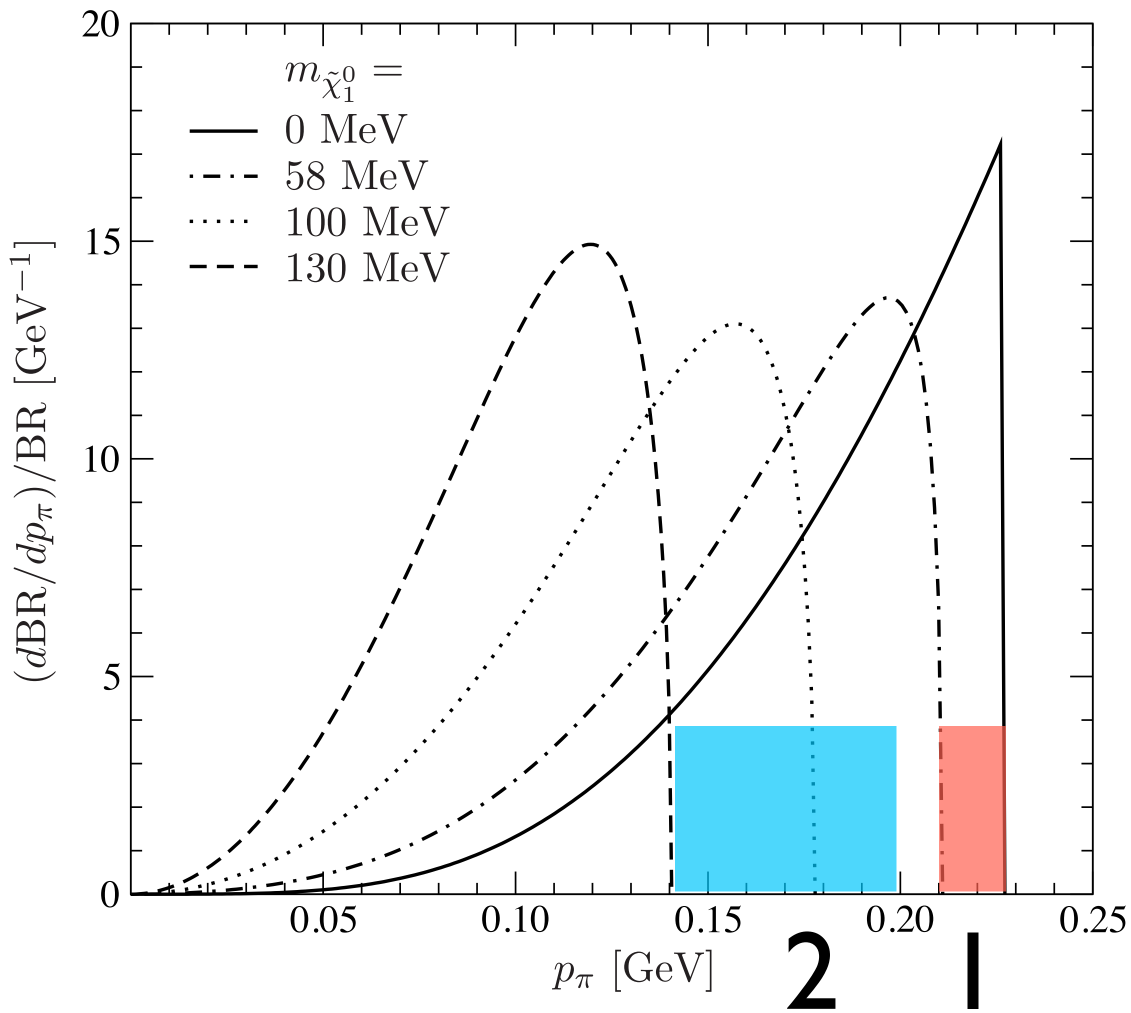
Light Neutralinos

Decay in very light neutralinos: $K^+ \to \pi^+ \tilde{\chi}_1^0 \tilde{\chi}_1^0$ [Dreiner et. al. '09]

in Non-MFV scenarios:

$m_{\tilde{\chi}_1^0} = 0 : \propto$ to $K^+ \to \pi^+ \bar{\nu}\nu$

$m_{\tilde{\chi}_1^0} \neq 0 : \not\propto$ to $K^+ \to \pi^+ \bar{\nu}\nu$



in MFV scenarios:

effects are smaller but new operators like

$(\bar{s}d)(\tilde{\chi}_1^0 P_L \chi_1^0)$

appear, yet the SM like

$(\bar{s}\gamma_\mu d)(\tilde{\chi}_1^0 \gamma^\mu \gamma_5 \tilde{\chi}_1^0)$

Operator dominates

- Estimate the missing mass distribution for new Ops

Decay in One Light Boson $\mathcal{P}$

- Peak in the missing mass distribution
- Already constrained by Experiment: $\mathcal{B}_{K\to\pi^+\mathcal{P}} \lesssim \mathcal{B}_{K\to\pi^+\bar{\nu}\nu}$
- e.g.: Meta-stable SUSY Violation [Banks, Haber `09]

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_2^3 m_t^2}{\Lambda_{\text{ISS}}^3} V_{td}V_{ts}^* \, \bar{d}(1-\gamma_5)\gamma^\mu s\, \partial_\mu \mathcal{P}$$

coupling to light pseudo-Nambu Goldstone boson

SM like Flavour suppression

$$\mathcal{B}_{K^+\to\pi^+\mathcal{P}} \sim 5\cdot 10^{-15}\left(\frac{2\text{TeV}}{\Lambda_{ISS}}\right)^6$$

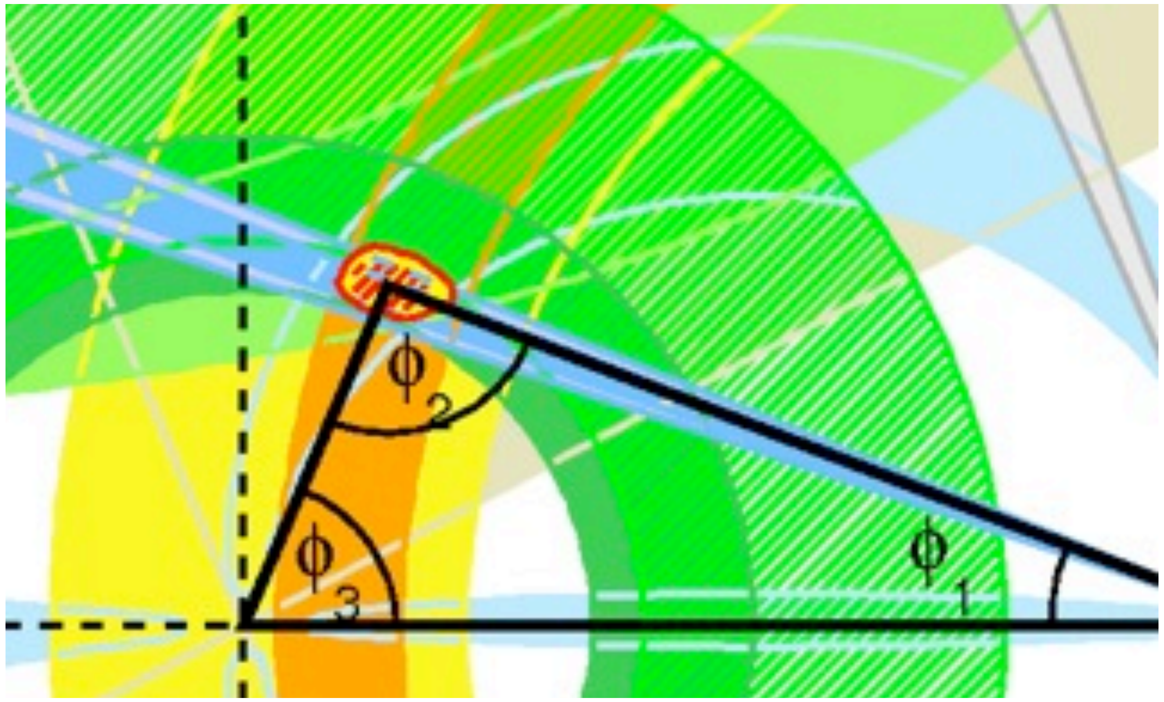
contributes only for small scale Λ_{ISS}

In this model there is also a coupling to electrons:

For light $m_{\mathcal{P}}$ red star cooling gives a much stronger bound

MFV like & electron coupling: Model dependent

ϵ_K :Indirect CP violation



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

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

- 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]

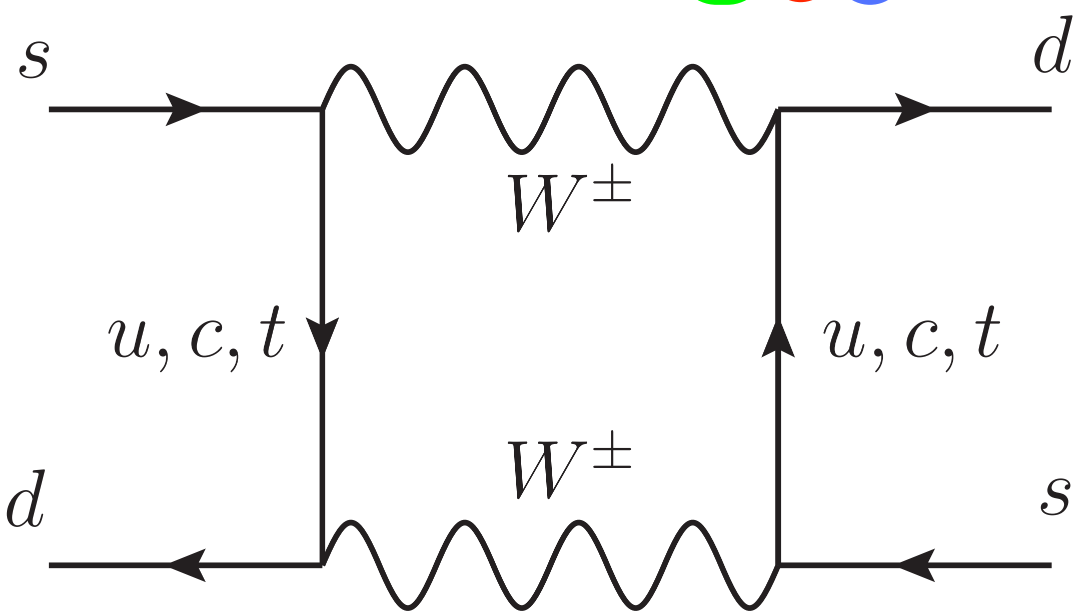
$$|\epsilon_K^{SM}| = \kappa_\epsilon |\epsilon_K| (\phi_\epsilon = 45^\circ, \xi = 0)$$

also similar effect as $\delta P_{c,u}$ in ϵ_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

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

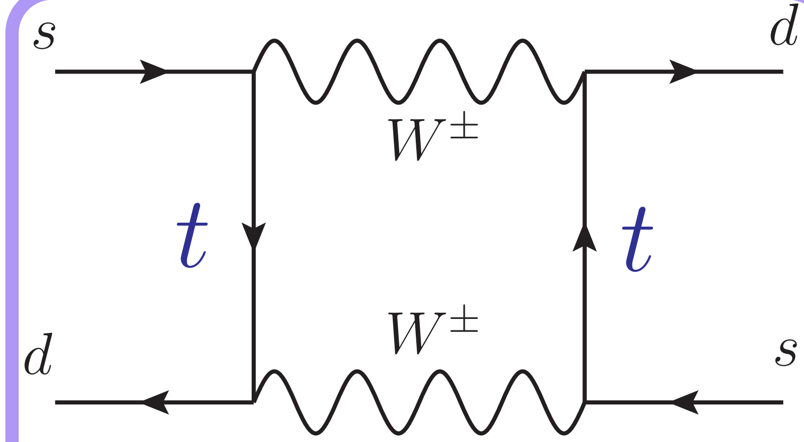
$$\mathcal{H} \propto \Big[\lambda_t^2 \eta_t S(x_t)$$ top

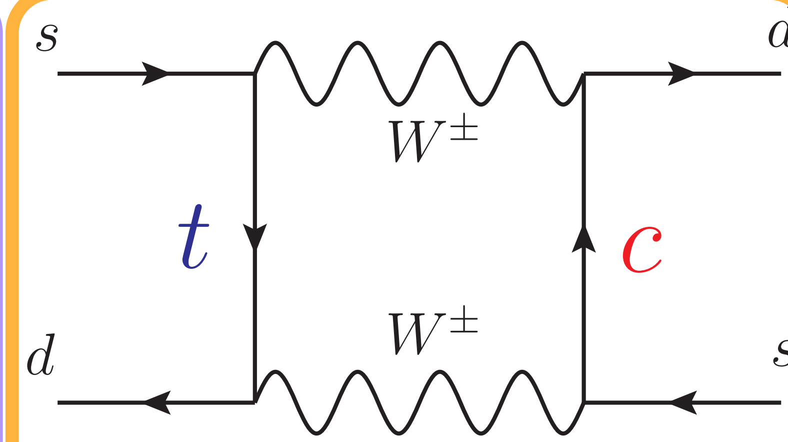
$$+2\lambda_c \lambda_t \eta_{ct} S(x_c, x_t)$$ charm top

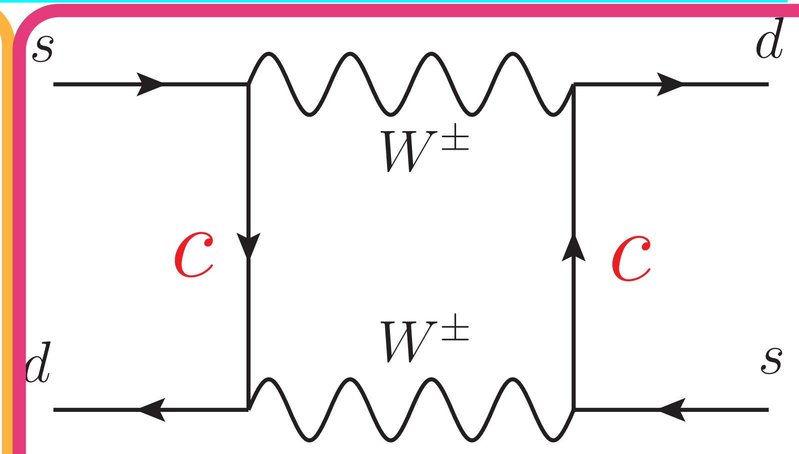
$$+\lambda_c^2 \eta_c S(x_c)\Big] b(\mu) \tilde{Q}$$ charm

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

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	$\alpha_s (\alpha_s \log x_c)^n$	$(\alpha_s \log x_c)^n$	$\alpha_s (\alpha_s \log x_c)^n$
ϵ_K	75%	37%	-12%
scale	1.8%	7.5%	17.7%

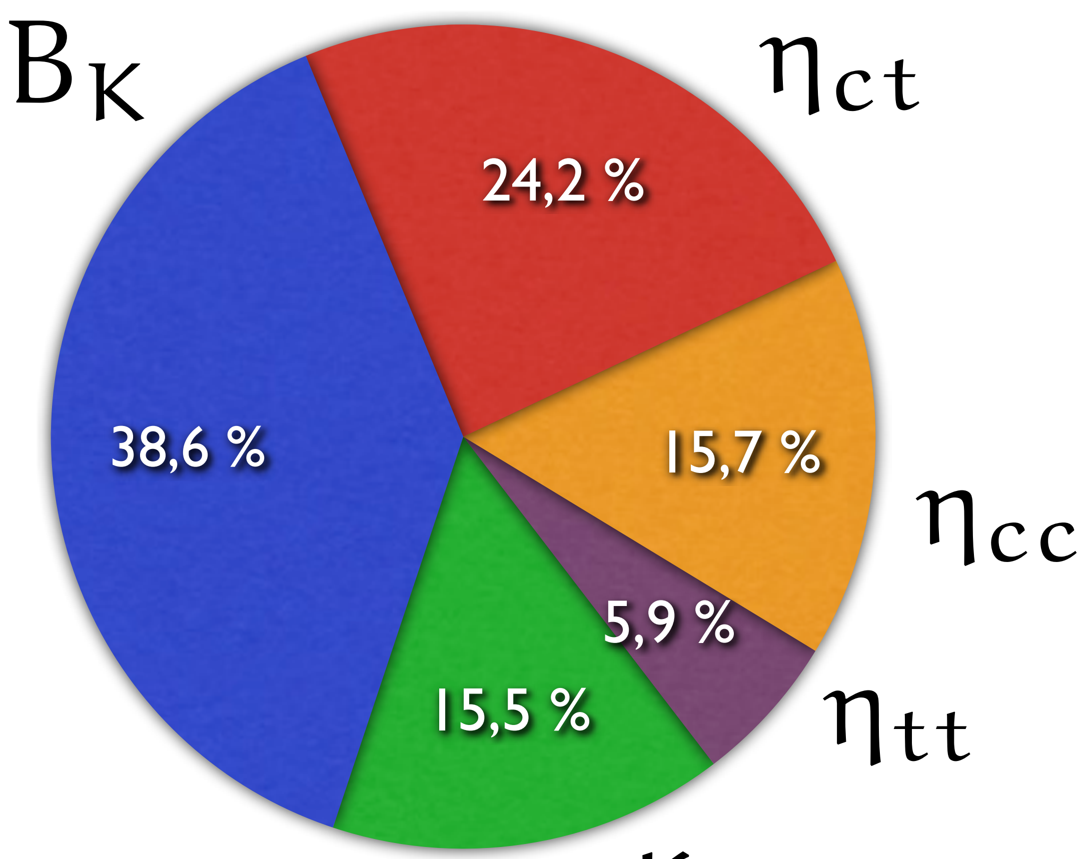
Error Budget for ϵ_K @ NLO

$$\epsilon_K = \kappa_\epsilon C_\epsilon B_K |V_{cb}|^2 \lambda^2 \bar{\eta} \left(|V_{cb}|^2 (1-\bar{\rho}) \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \right)$$

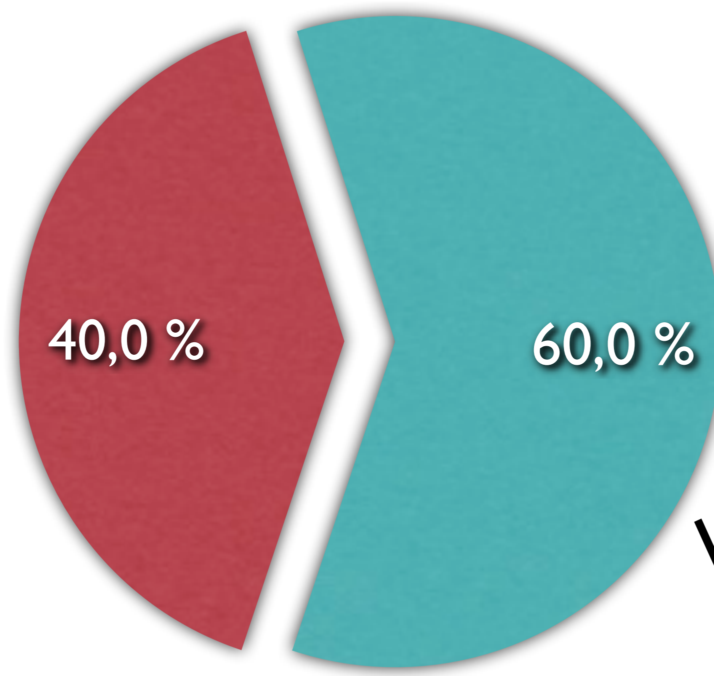
$$\epsilon_K = (1.78 \pm 0.25) \cdot 10^{-3}$$

[Buras, Guadagnoli'09]

Theory uncertainty



$B_K = 0.72(4)$



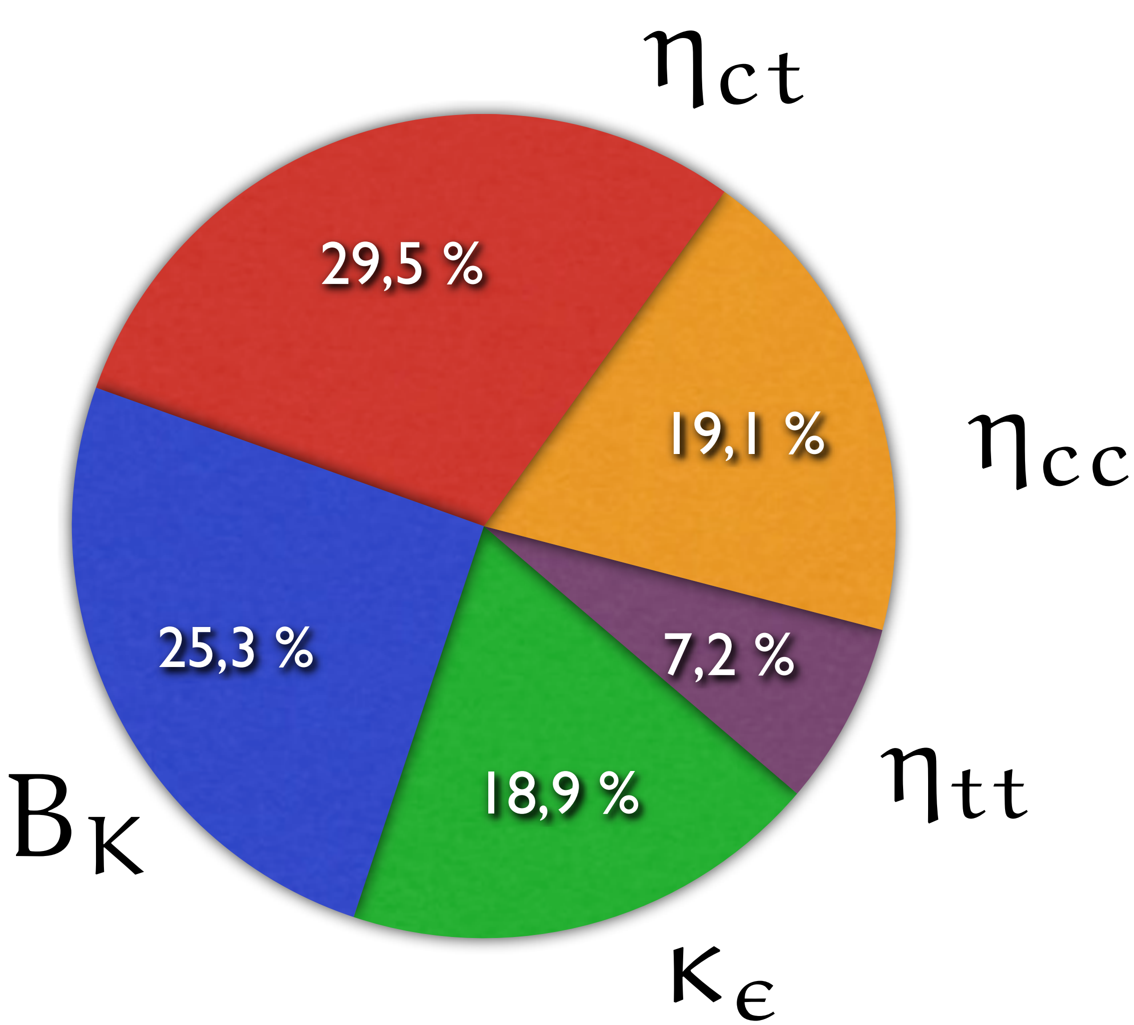
Parametric uncertainty

$|V_{cb}| = 41.2(1.1) \cdot 10^{-3}$

$\bar{\eta}, \bar{\rho}, \ldots$

Error Budget for ϵ_K @ NLO

For a 3% uncertainty in B_K the perturbative uncertainties become dominant

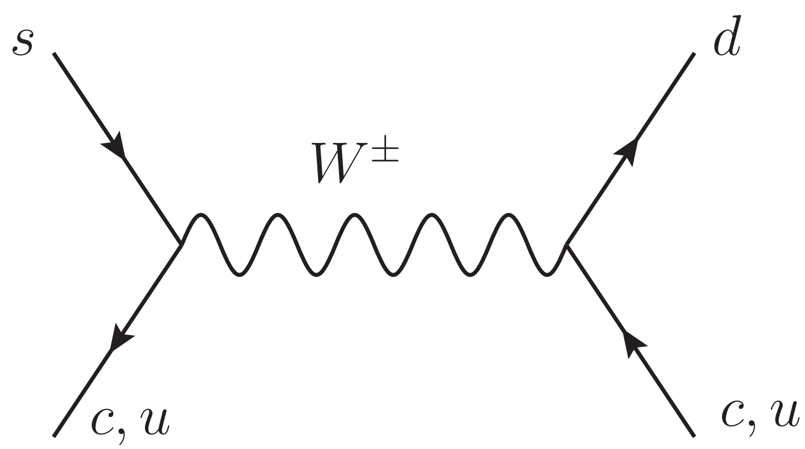


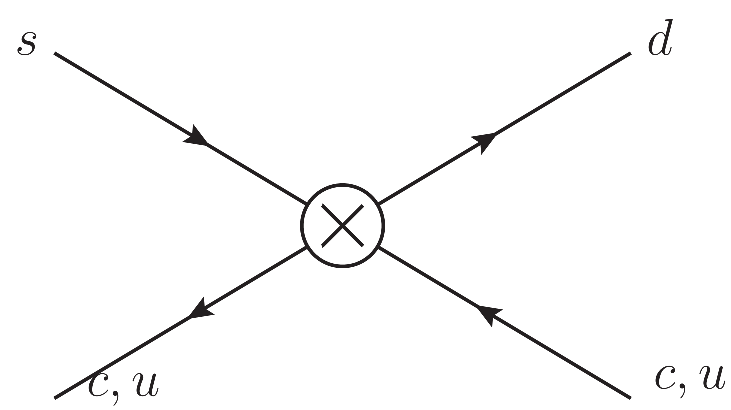
η_{ct} : largest uncertainty needs a 3 loop RGE analysis

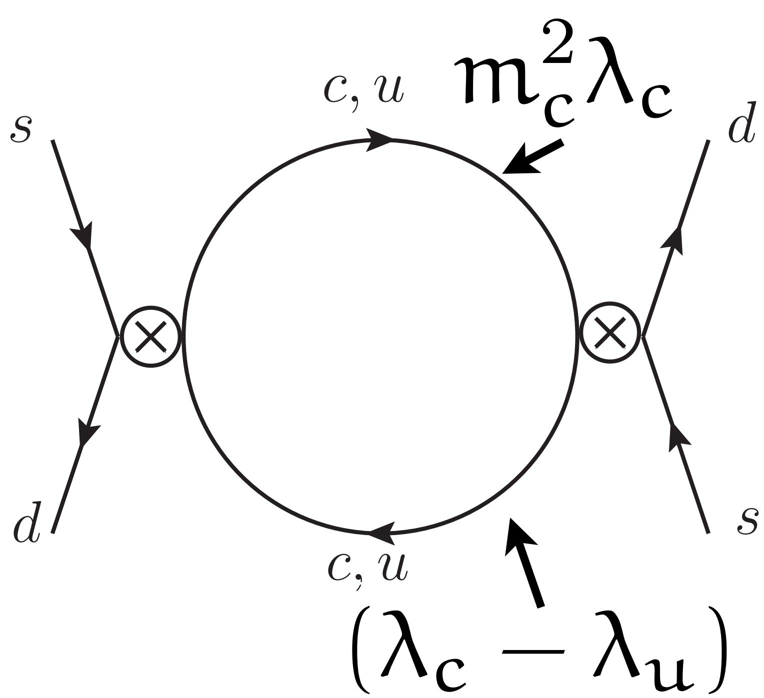
η_{cc} : second largest perturbative uncertainty needs a 3 loop matching calculation

[Brod, MG in progress]

η_{ct} :Charm Top at LO







- The Leading Order result

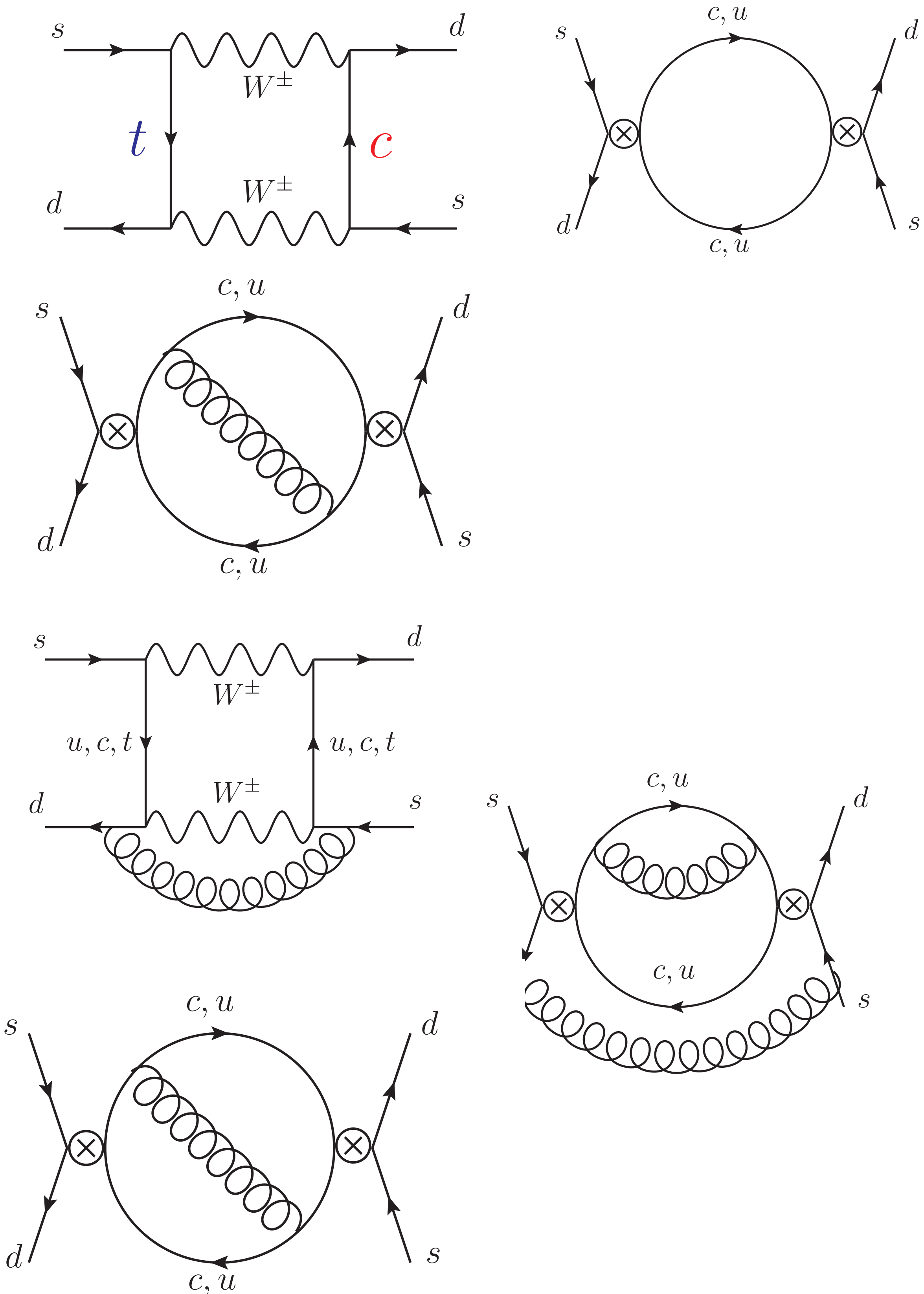
  $$(\alpha_s \log x_c)^n \log x_c$$

  starts with a $\log x_c$
- Tree level matching
- One-loop Renormalistion Group Equation

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

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

η_{ct} :Charm Top beyond LO

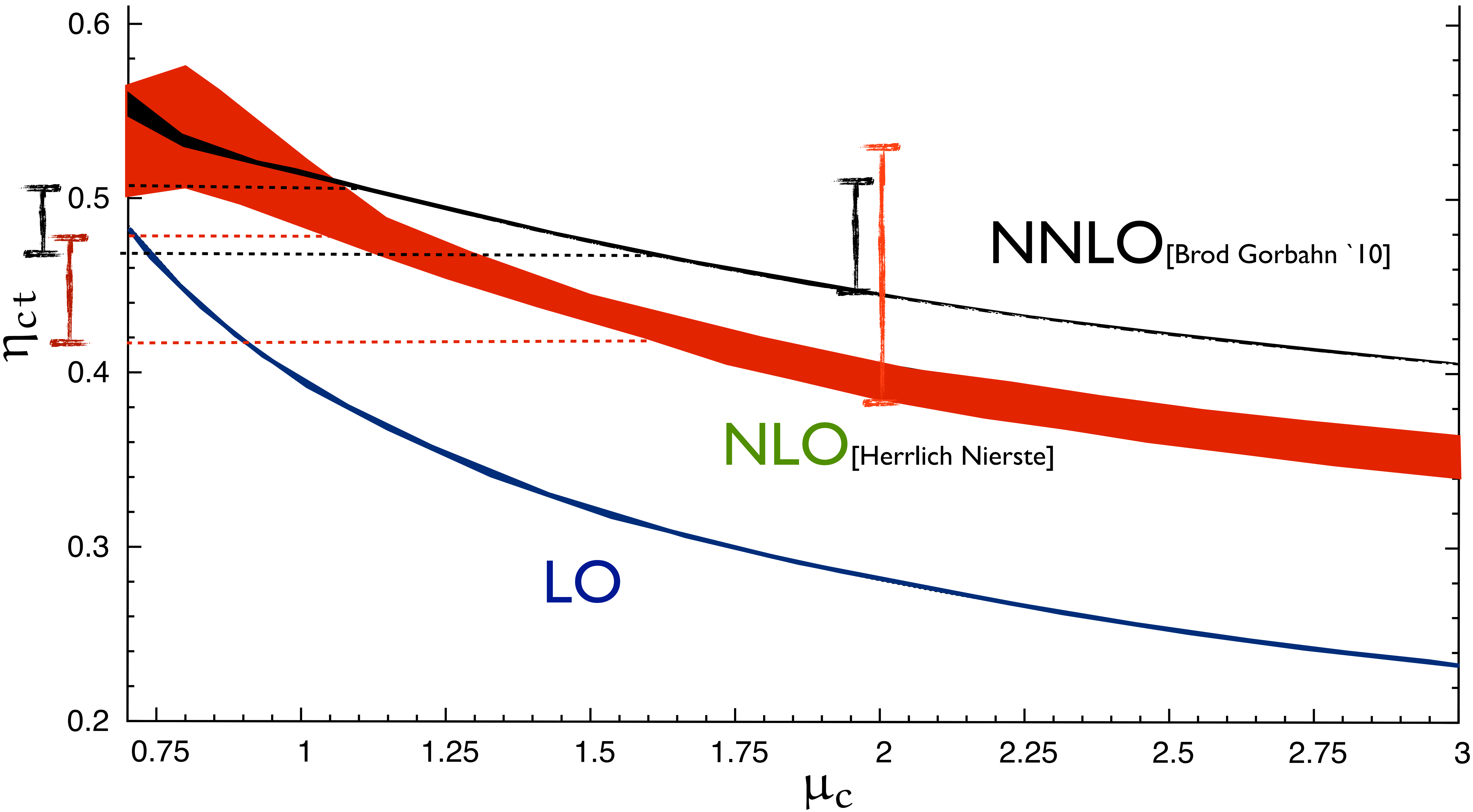


- One-loop matching at μ_t
- One-loop matching at μ_c
- Two-loop RG running
- Plus d=6 operators NLO [Herrlich, Nierste]

$$\eta_{ct} = 0.47 \pm 0.04$$

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

η_{ct} at NNLO



Conclusions

$K \to \pi \bar{\nu} \nu$ very clean and suppressed

probe of the new physics flavour structure

ϵ_K Improvements B_K → NNLO calculation

Strong NP sensitivity: Talks by Blanke & Haisch

very clean semileptonic and leptonic modes
are also interesting