Novel Firmware VII

I do charm job

CONNECTIVITY
FUN IS IN AIR

Mushy Pion Poems 2020, May 4-6

Flavor Mini Review

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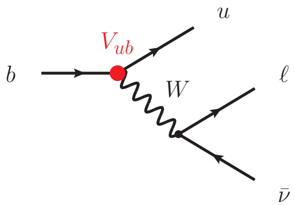
PHENO Symposium 2020, May 4

Plan

- Flavor Theory
- B physics
- D physics
- K physics

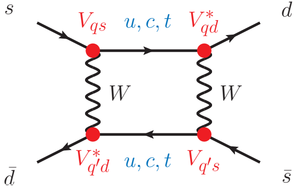
Flavor Theory

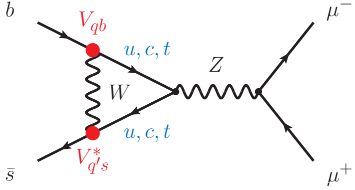
Flavor in the SM



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}, \quad \lambda \approx 0.23$$

Flavor-changing Neutral Currents





- Box $= V_{qd} V^*_{qd'} V_{q'd} V^*_{q'd'} \times f\left(\frac{m_q^2}{M_W^2}, \frac{m_{q'}^2}{M_W^2}\right)$
- Unitarity of CKM matrix ➻ GIM mechanism
- $f = f(m_c^2, m_t^2)$

Effective Field Theory

- Physics at different energy scales necessitates EFT approach
  - E.g. SM kaon mixing at low energies:

$$\mathcal{A} = C \times \langle (sd)_{V-A}(sd)_{V-A} \rangle$$

- In general, effective Lagrangian of the form

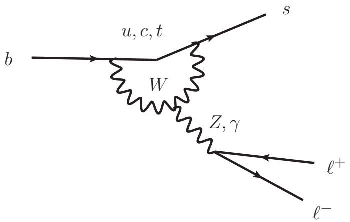
$$\mathcal{L} = \sum_k C_k \mathcal{O}_k$$

- BSM physics might change C or induce new operators $\mathcal{O}$
- This might lead to new kinematics!

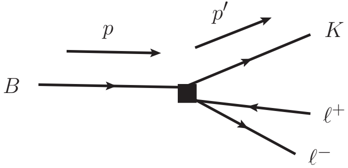
Bottom Physics

$R_{K^{(*)}}$

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$



- In general, $d\Gamma(B \to K\ell\ell) \propto |\langle K\ell\ell|H_{\text{eff}}|B\rangle|^2$ ... complicated function involving nonperturbative QCD
- For small $q^2 = (p - p')^2$, form factors simplify – "color transparency"



SM Expectation

$$R_K^{\rm SM} \equiv \frac{\Gamma_\mu^{\rm SM}}{\Gamma_e^{\rm SM}}$$

- SM prediction is very clean: [hep-ph/0310219, 0709.4174]

$$\Gamma_\ell^{\rm SM} =\propto \int_{q^2_{\rm min}=1.1\,{\rm GeV}^2}^{q^2_{\rm max}=6.0\,{\rm GeV}^2} dq^2 \xi(q^2)\left(|F_A|^2+|F_V|^2\right)$$
$$\times\left[1+\mathcal{O}\left(\frac{m_\ell^4}{q^4}\right)+\frac{m_\ell^2}{M_B^2}\mathcal{O}\left(\alpha_s, \frac{m_\ell^2}{M_B^2}\sqrt{\frac{\Lambda_{\rm QCD}}{E}}\right)\right]$$

- with a single form factor $\xi(q^2)$ [hep-ph/9812358, hep-ph/0008255]

- Numerically, including QED effects [1605.07633] we have

$$R_K^{\rm SM} = 1 + ‰ + \text{cut-dep. QED of } \mathcal{O}(\text{few } \%)\,.$$

New LHCb results for R_K

- Most systematics cancels in double ratio

$$R_K^{\text{LHCb}} \equiv \frac{\text{BR}(B^+ \to K^+ \mu\mu)}{\text{BR}(B^+ \to K^+ ee)} \Big/ \frac{\text{BR}(B^+ \to K^+ J/\psi(\mu\mu))}{\text{BR}(B^+ \to K^+ J/\psi(ee))}$$

- New LHCb [1903.09252]:

$$R_K^{\text{LHCb 2019}} = 0.846^{+0.060}_{-0.054}\ (\text{stat.})\ ^{+0.016}_{-0.014}\ (\text{syst.})$$

- Compare to old LHCb [1406.6482]:

$$R_K^{\text{LHCb 2011/12}} = 0.745^{+0.090}_{-0.074}\ (\text{stat.})\ \pm 0.036\ (\text{syst.})$$

New Belle results for R_{K^*}

- Most systematics cancels in ratio

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu\mu)}{\mathrm{BR}(B \to K^* ee)}$$

- New Belle result [1904.02440]:

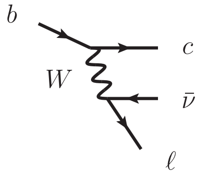
$$R_K^{\text{Belle 2019}} = \begin{cases} 0.52^{+0.36}_{-0.26} \pm 0.05 & q^2 \in [0.045, 1.1]\,\mathrm{GeV}^2 \\ 0.96^{+0.45}_{-0.29} \pm 0.11 & q^2 \in [1.1, 6]\,\mathrm{GeV}^2 \end{cases}$$

- Compare to LHCb result [1705.05802]:

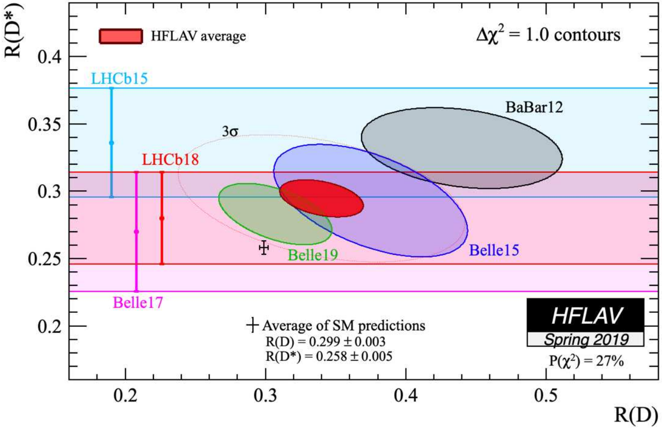
$$R_K^{\text{LHCb 2017}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & q^2 \in [0.045, 1.1]\,\mathrm{GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & q^2 \in [1.1, 6]\,\mathrm{GeV}^2 \end{cases}$$

R_D and R_{D^*}

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$



- Precisely known in SM [1203.2654, 1606.08030, 1707.09977]
- . . . and beyond: [1703.05330, 2002.00020, Der HAMMER]
- $R_D^{\mathrm{SM}} = 0.299 \pm 0.003$, $R_{D^*}^{\mathrm{SM}} = 0.258 \pm 0.005$ [1612.07233]
- $R_D = 0.307(37)(16)$, $R_{D^*} = 0.283(18)(14)$ [1904.08794]



HFLAV average
$\Delta\chi^2 = 1.0$ contours
LHCb15
BaBar12
3σ
LHCb18
Belle15
Belle19
Belle17
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
P(χ²) = 27%
R(D*)
R(D)

New Physics?

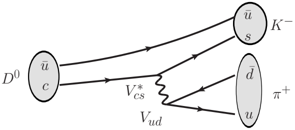
- 2HDM [Phys. Lett. B 283 (1992) 427]
  - Strong constraints from $B_c \to \tau\nu$ [1611.06676, but also 1811.09603]
  - $\Gamma(B_c \to \tau\bar{\nu}) = \Gamma_{\text{tot}}(B_c)\text{BR}(B_c \to \tau\bar{\nu})$
- Leptoquarks [1511.06024 etc.]
- A sum rule implies $R_{\Lambda_c} = 0.38 \pm 0.01_{\text{exp}} \pm 0.01_{\text{th}}$ for any NP [1811.09603, 1905.08253]

$$R_{\Lambda_c} \equiv \frac{\text{BR}(\Lambda_b \to \Lambda_c\tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c\ell\nu)}$$

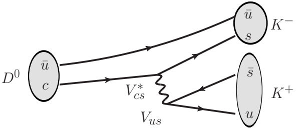
Charm physics

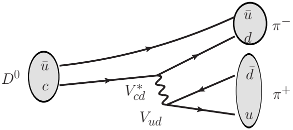
ΔA_{CP}

Hadronic Two-body D Decays

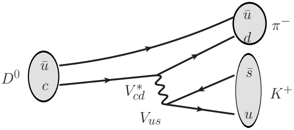


CF

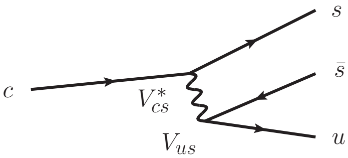


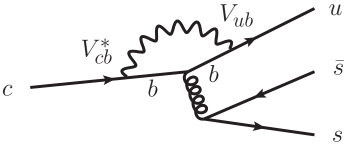


SCS



DCS





What is measured?

- Time-dependent asymmetry (decays into CP-eigenstate f)

$$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_f^d + a_f^m + a_f^i$$

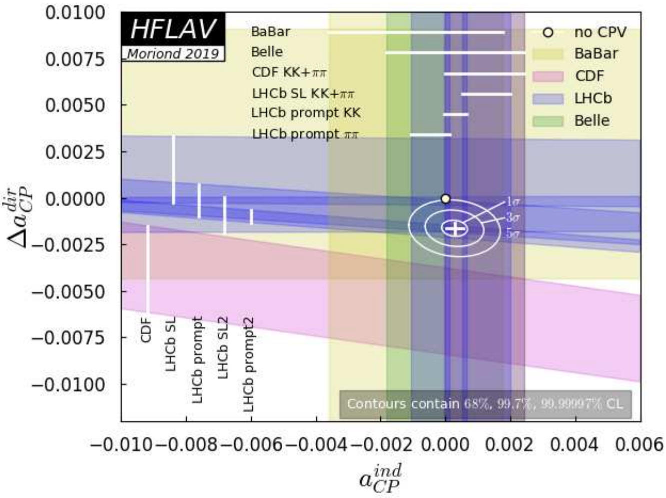
- Flavor at $t = 0$ determined by tagging:
  - *Prompt* charm: $D^{*+} \to D^0\pi^+$, $D^{*-} \to \bar{D}^0\pi^-$
  - *Semileptonic* charm: $B^- \to D^0\mu^-X$, $B^+ \to \bar{D}^0\mu^+X$
- Flavor at t determined by time evolution:

$$i\frac{d}{dt}\begin{pmatrix} D(t) \\ \bar{D}(t) \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} D(t) \\ \bar{D}(t) \end{pmatrix}$$

ΔA_{CP}

$$\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-}$$

- Most systematics cancel in difference
- Mixing and interference CPV also "cancel"
- Fortunately, direct CP asymmetry does *not* cancel:
  - $V_{us}V_{cs}^* = -V_{ud}V_{cd}^* \Rightarrow A_{K^+K^-} = -A_{\pi^+\pi^-}$ in U-spin limit ($s \leftrightarrow d$)
- LHCb 2019 combi: $\Delta A_{CP} = (-0.154 \pm 0.029)\%$


HFLAV
Moriond 2019
BaBar
Belle
CDF KK+$\pi\pi$
LHCb SL KK+$\pi\pi$
LHCb prompt KK
LHCb prompt $\pi\pi$
no CPV
BaBar
CDF
LHCb
Belle
1σ
3σ
5σ
CDF
LHCb SL
LHCb prompt
LHCb SL2
LHCb prompt2
Contours contain 68%, 99.7%, 99.99997% CL
0.0100
0.0075
0.0050
0.0025
0.0000
−0.0025
−0.0050
−0.0075
−0.0100
Δa_{CP}^{dir}
−0.010 −0.008 −0.006 −0.004 −0.002 0.000 0.002 0.004 0.006
a_{CP}^{ind}

Is it the SM?

$$\Delta A_{CP} = 4\text{Im}\left(\frac{\lambda_b}{\Sigma}\right)\left|\frac{p_0}{t_0}\right| \sin\delta_{\text{strong}}$$

- $\lambda_b = V_{ub}V_{cb}^*$, $\Sigma = (V_{us}V_{cs}^* - V_{ud} - V_{cd}^*)/2$
- $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [1903.08726]

  gives $|p_0/t_0| = 0.65(12)$ [1903.10952]
- Consistent picture [1203.6659]
  - Assume nominal U-spin breaking $\epsilon_U \approx 20\%$
  - Expansion in ϵ_U gives additional testable relations

A consistent picture emerges. . .

$$\Delta A_{CP} \approx -0.15\%$$

$$\frac{|A(D^0 \to K^+ K^-)|}{|A(D^0 \to \pi^+ \pi^-)|} - 1 = (82 \pm 2)\%$$

$$\frac{|A(D^0 \to K^- \pi^+)|}{|A(D^0 \to K^+ \pi^-)|} - 1 = (15 \pm 3)\%$$

$$\frac{|A(D^0 \to K^+ K^-)| + |A(D^0 \to \pi^+ \pi^-)|}{|A(D^0 \to K^+ \pi^-)| + |A(D^0 \to K^- \pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

. . . but is it the SM? Power Corrections

- In B decays, expansion in powers of $\Lambda_{\rm QCD}/m_b$ is reasonable [hep-ph/0104110]
- In D decays, expansion in powers of $\Lambda_{\rm QCD}/m_c$ is questionable
  - Branching ratios show that power corrections are large!
- Rough estimate of power corrections (SM Wilson coefficients, color counting, etc.) leads to [1111.5000]
  - $\text{Im}(\lambda_b/\Sigma)|p_0/t_0| \approx 0.03 \ldots 0.04\%$
  - $\Rightarrow \Delta A_{CP} \lesssim 0.2\%$

...but is it the SM? QCD Sum Rules

- Estimate penguin $\langle P^+P^-|Q_2|D^0\rangle$ using QCD sum rules [1706.07780]
  - OPE of correlation function
  - Factorization of hard scattering kernel and pion DA
  - Use BR as input for tree amplitude
- $|p_0/t_0|_{\pi\pi} = 0.093 \pm 0.011$, $|p_0/t_0|_{KK} = 0.075 \pm 0.015$
- $\Rightarrow |\Delta A_{CP}| < (0.020 \pm 0.003)\%$
- Duality violation $\lesssim$ factor 2-3 (nearby f_0 resonance?)
- Estimate branching ratios?

Baryons

- LHCb has also measured [1712.07051]

$$A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$$

- Also here, many systematics cancel
- However, the modes are not related by U-spin symmetry
- Other sum rules exist, e.g. [1811.11188]

$$A_{CP}(\Lambda_c^+ \to pK^+K^-) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-) = 0$$

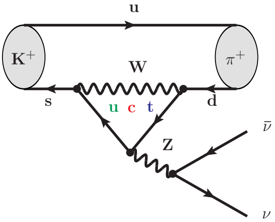
$$A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) + A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) = 0$$

$$A_{CP}(\Lambda_c^+ \to \Sigma^+K^+\pi^-) + A_{CP}(\Xi_c^+ \to p\pi^+K^-) = 0$$

Kaon Physics

Rare Kaon Decays

Rare K decays



- Theoretically extremely clean:
  - SM $\mathcal{H}_{\text{eff}}$ known to NNLO QCD [hep-ph/9901278, hep-ph/9901288; hep-ph/0603079]
    NLO EW [0805.4119, 1009.0947]
  - $\mathcal{O}$(few %) theory uncertainty

$$\mathcal{H}_{\text{eff}} \propto \left[V_{cs}^* V_{cd} P_c \left(\frac{m_c^2}{M_W^2} \right) + V_{ts}^* V_{td} X_t \left(\frac{m_t^2}{M_W^2} \right) \right] \times \left(\bar{s}_L \gamma^\mu d_L \right) \left(\bar{\nu}_L \gamma_\mu \nu_L \right)$$

Matrix Elements – Isospin

$$A(K^+ \to \pi^+ \nu\bar{\nu}) \quad \propto \quad \langle \pi^+ | (\bar{s}d)_{V-A} | K^+ \rangle (\bar{\nu}\nu)_{V-A}$$

$K \to \pi\nu\nu$		$K \to \pi\ell\nu$
$\langle \pi^+ \| (\bar{s}d)_{V-A} \| K^+ \rangle$	$=$	$\sqrt{2} \times \langle \pi^0 \| (\bar{s}u)_{V-A} \| K^+ \rangle$
Unknown		Well measured

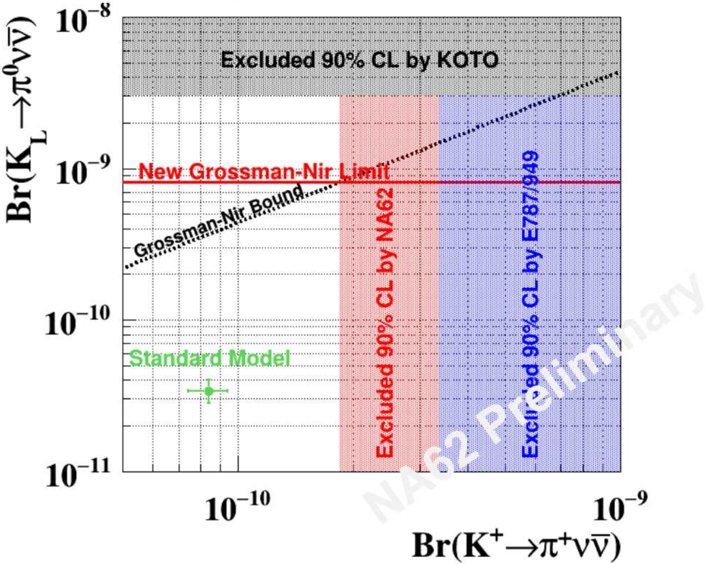
- Isospin-breaking corrections [0705.2025]

Grossman-Nir Bound

- $K^+ \to \pi^+ \nu\bar{\nu}$ is CP-conserving $\Rightarrow$ $\mathrm{A} \propto |X_t|$
- $K_L \to \pi^0 \nu\bar{\nu}$ is CP-violating $\Rightarrow$ $\mathrm{A} \propto \mathrm{Im}\, X_t$
- Correlation between two modes allows to disentangle NP scenarios

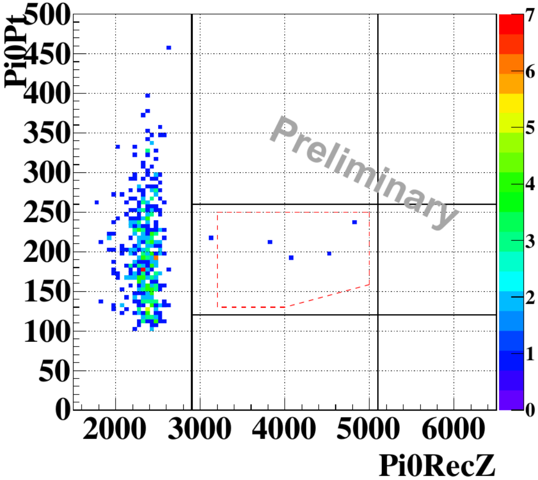
- From $\mathrm{Im}\, X_t \leq |X_t|$ follows the Grossman-Nir bound
- $\mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) \leq 4.3\ \mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu)$

NA62 2019

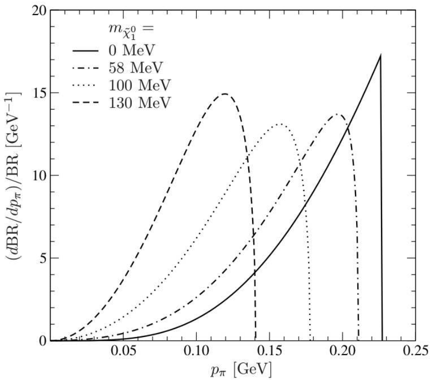


Excluded 90% CL by KOTO
New Grossman-Nir Limit
Grossman-Nir Bound
Excluded 90% CL by NA62
Excluded 90% CL by E787/949
Standard Model
NA62 Preliminary
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$Br(K_L \to \pi^0 \nu \bar{\nu})$
10^{-10}
10^{-9}
$Br(K^+ \to \pi^+ \nu \bar{\nu})$

KOTO result 2019



- "BR" $(K_L \to \pi^0 \bar{\nu} \nu) = 21^{+20}_{-11} \times 10^{-10}$ [1909.11111]



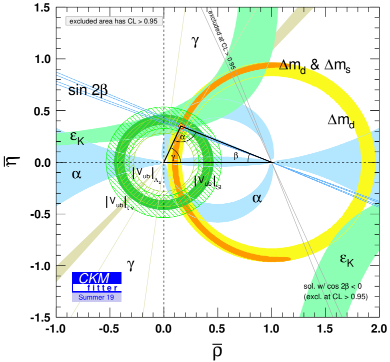
- Exotic final states (neutralinos in the RPV MSSM, DM, ...) can change final state distribution [0905.2051]
- See also [1111.6402, 1909.11111]

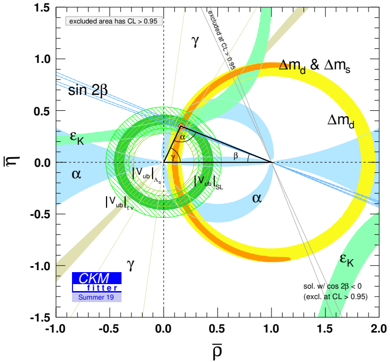
ϵ_K

Definition

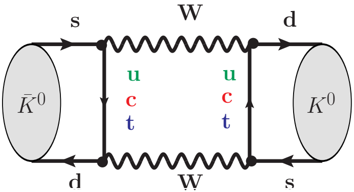
$$\epsilon_K \equiv \frac{\eta_{00} + 2\eta_{+-}}{3} = \frac{\langle (\pi\pi)_{I=0} | K_L \rangle}{\langle (\pi\pi)_{I=0} | K_S \rangle}$$

- $\eta_{00} = \langle \pi^0 \pi^0 | K_L \rangle / \langle \pi^+ \pi^- | K_S \rangle$
- $\eta_{+-} = \langle \pi^+ \pi^- | K_L \rangle / \langle \pi^+ \pi^- | K_S \rangle$


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
$|V_{ub}|_{\Lambda_b}$
$|V_{ub}|_{SL}$
$|V_{ub}|_{\tau\nu}$
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar\eta$
$\bar\rho$


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
$|V_{ub}|_{\Lambda_b}$
$|V_{ub}|_{SL}$
$|V_{ub}|_{\tau\nu}$
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar\eta$
$\bar\rho$

c-t vs. u-t Unitarity



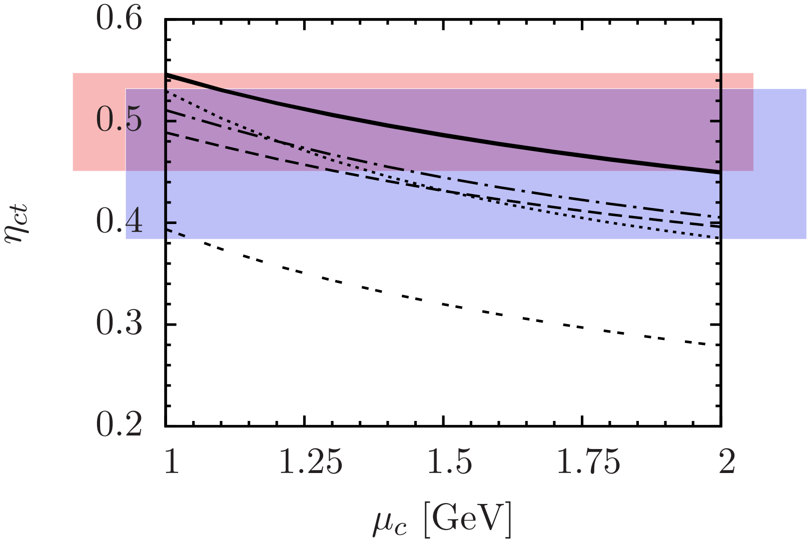
c-t unitarity	Im	Re
λ_t^2	$\sim \lambda^{10}$	$\sim \lambda^{10}$
$\lambda_c \lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$
λ_c^2	$\sim \lambda^6$	$\sim \lambda^2$

u-t unitarity	Im	Re
λ_t^2	$\sim \lambda^{10}$	$\sim \lambda^{10}$
$\lambda_u \lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$
λ_u^2	0	$\sim \lambda^2$

$\lambda_q \equiv V_{qs} V_{qd}^*$ $\quad$ $\text{Im}(M_{12}) \to \epsilon_K$ $\quad$ $\text{Re}(M_{12}) \to \Delta M_K$

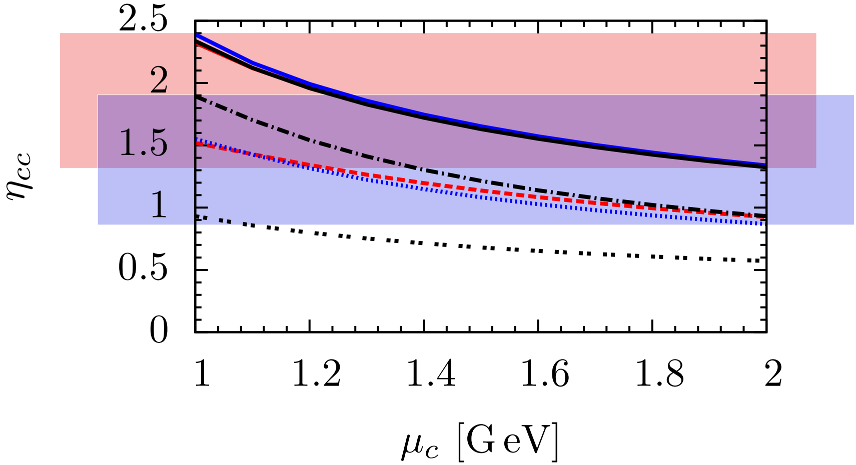
Traditional $|\Delta S| = 2$ Hamiltonian

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


0.6
0.5
0.4
0.3
0.2
η_{ct}
1
1.25
1.5
1.75
2
μ_c [GeV]

η_{ct} @ NNLO – Result

$$\eta_{ct} = 0.496 \pm 0.047$$



2.5
2
1.5
1
0.5
0
η_{cc}
1
1.2
1.4
1.6
1.8
2
μ_c [GeV]

η_{cc} @ NNLO – Result

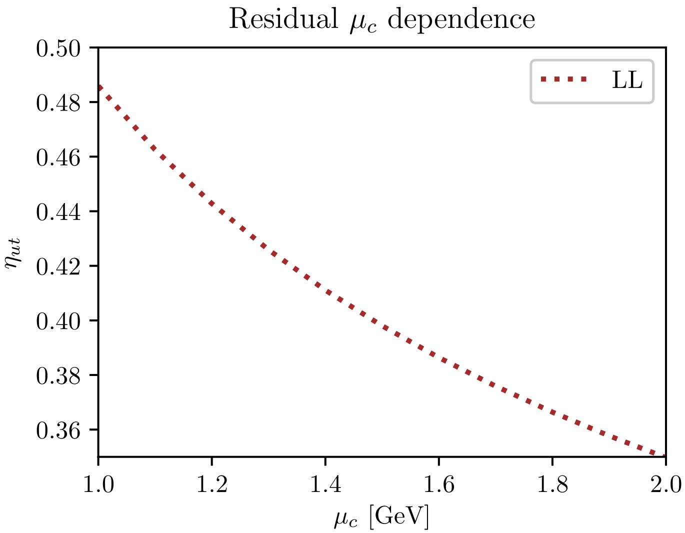
$$\eta_{cc} = 1.87 \pm 0.76$$

New $|\Delta S| = 2$ Hamiltonian

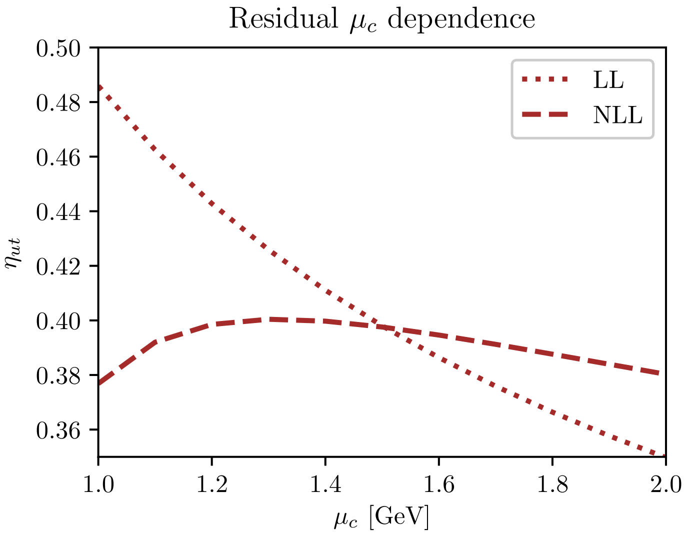
$$H^{|\Delta S|=2} \propto \left[\lambda_t^2 \eta_{tt} \mathscr{S}\left(\frac{m_t^2}{M_W^2}\right) + \lambda_u^2 \eta_{uu} \mathscr{S}\left(\frac{m_c^2}{M_W^2}\right) + 2\lambda_u \lambda_t \eta_{ut} \mathscr{S}\left(\frac{m_c^2}{M_W^2}, \frac{m_t^2}{M_W^2}\right)\right] Q^{|\Delta S|=2}$$

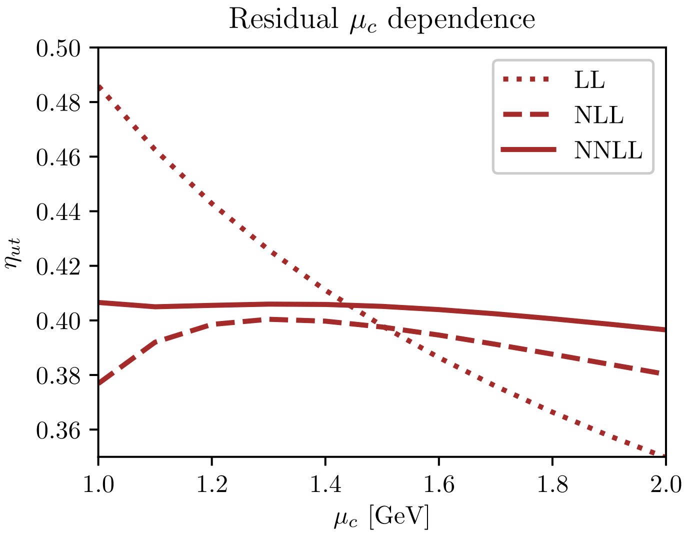
Suggested in [1212.5931]

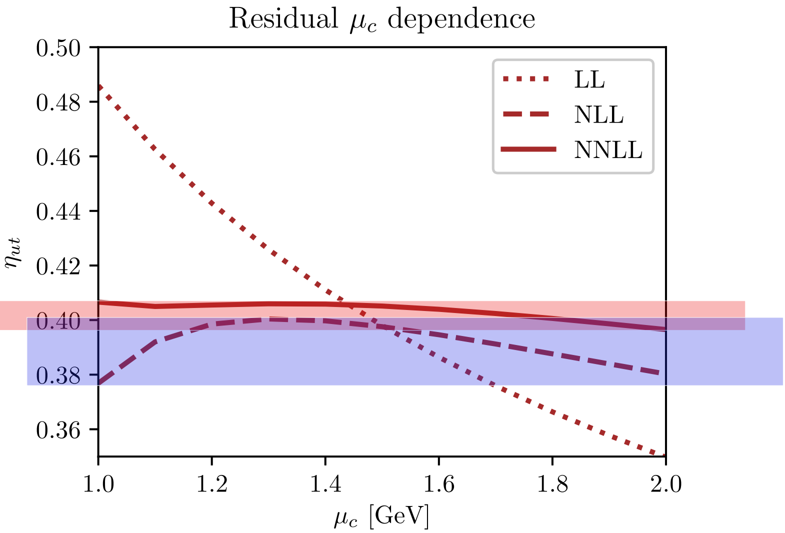
η_{ut} @ NNLO – Scale Dependence



η_{ut} @ NNLO – Scale Dependence




Residual μ_c dependence
0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
η_{ut}
LL
NLL
NNLL
1.0
1.2
1.4
1.6
1.8
2.0
μ_c [GeV]


Residual μ_c dependence
0.50
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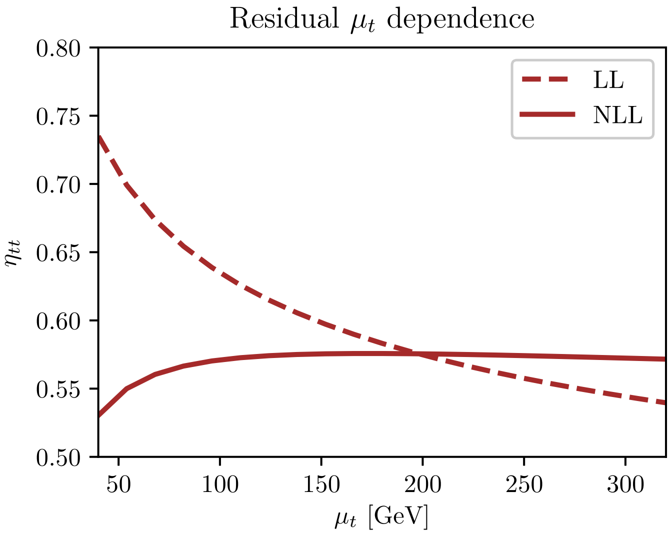
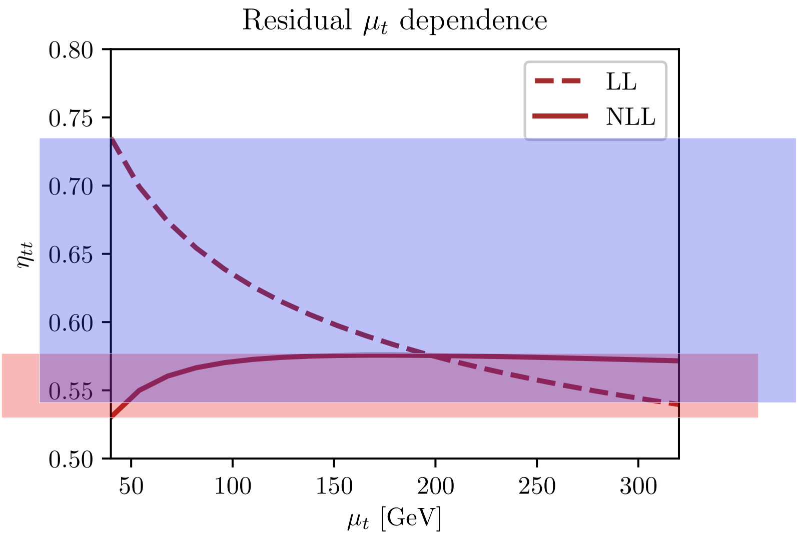
0.38
0.36
η_{ut}
1.0
1.2
1.4
1.6
1.8
2.0
μ_c [GeV]
LL
NLL
NNLL

η_{ct} @ NNLO – Result

$$\eta_{ut} = 0.402 \pm 0.005$$

[arxiv:1911.06822]


Residual μ_t dependence
0.80
0.75
0.70
0.65
0.60
0.55
0.50
η_{tt}
LL
NLL
50
100
150
200
250
300
μ_t [GeV]


Residual μ_t dependence
LL
NLL
η_{tt}
0.80
0.75
0.70
0.65
0.60
0.55
0.50
50
100
150
200
250
300
μ_t [GeV]

η_{tt} @ NLO – Result

$$\eta_{tt} = 0.55 \pm 0.02$$

[Nucl.Phys. B347 (1990) 491-536; our error estimate]

$$\epsilon'$$

Recent Lattice Result

$$\epsilon_K \equiv \frac{\eta_{+-} - \eta_{00}}{3} \propto \frac{1}{2\sqrt{2}} \frac{\langle(\pi\pi)_{I=2}|K^0\rangle}{\langle(\pi\pi)_{I=0}|K^0\rangle}$$

- $\mathrm{Re}(\epsilon'/\epsilon) = 16.6(2.3) \times 10^{-4}$ (exp.)
- $\mathrm{Re}(\epsilon'/\epsilon) = 21.7(2.6)(6.2)(5.0) \times 10^{-4}$ [2004.09440]

Summary

- Flavor physics remains exciting
- Many topics not discussed
  - Lepton flavor
  - Spectroscopy
  - Higgs and flavor
  - ...
- Looking forward to more detailed talks!

Backup

More ΔA_{CP}

Three Types of CP Violation

- Solving the D.E. gives

$$\Gamma(D^0(t) \to f) = e^{-\Gamma t}|A_f|^2 \times f(x, y, \lambda_f, t)\,,$$
$$\Gamma(\bar{D}^0(t) \to f) = e^{-\Gamma t}|\bar{A}_f|^2 \times \bar{f}(x, y, \lambda_f, t)\,.$$

- We defined
  - decay amplitudes $A_f \equiv \langle f|D\rangle$, $\bar{A}_f \equiv \langle f|\bar{D}\rangle$
  - $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$, with $|p|^2 + |q^2| = 1$
  - $x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$
  - $y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$
  - $\lambda_f \equiv (q\bar{A}_f)/(pA_f)$

Three Types of CP Violation

- Since D mixing is slow, we can approximate the decay rate with a single exponential $\Gamma(D^0(t) \to f) = \exp(-\hat{\Gamma} t)$, where

$$\hat{\Gamma}(D^0(t) \to f) = \Gamma\left[1 + \eta^{CP}\left|\frac{q}{p}\right|(y\cos\phi - x\sin\phi)\right],$$

$$\hat{\Gamma}(\bar{D}^0(t) \to f) = \Gamma\left[1 + \eta^{CP}\left|\frac{p}{q}\right|(y\cos\phi + x\sin\phi)\right].$$

- Expanding to linear order in t, the time-dependent CP asymmetry becomes

$$A_{CP}(f;t) = a_f^{\text{dir}} + \frac{t}{\tau(D_0)} a^{\text{ind}}$$

$$a_f^{\text{dir}} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

$$a_f^{\text{ind}} = \eta^{CP}\left[y\left(\left|\frac{p}{q}\right| - \left|\frac{q}{p}\right|\right)\cos\phi + x\left(\left|\frac{p}{q}\right| + \left|\frac{q}{p}\right|\right)\sin\phi\right]$$

What is measured

- Including subleading terms, can write the time-integrated asymmetry as

$$A_{CP}(f) \approx a_f^{\text{dir}}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau} y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau} a^{\text{ind}}$$

- Here, $y_{CP} = (\hat{\Gamma} - \hat{\bar{\Gamma}})/2\Gamma - 1$; $\tau = 1/\Gamma$ is the D^0 lifetime.
- The difference between the $D \to K^+K^-$ and $D \to \pi^+\pi^-$ asymmetries is

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &\approx \Delta a^{\text{dir}}(f)\left(1 + \frac{\overline{\langle t(f)\rangle}}{\tau} y_{CP}\right) + \frac{\Delta\langle t(f)\rangle}{\tau} a^{\text{ind}} .\end{aligned}$$

Raw asymmetries and ΔA_{CP}

- Obtain raw asymmetries by “counting”

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) = \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \bar{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \bar{D}^0(f)\pi^-)}$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) = \frac{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) - N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)}{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) + N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)}$$

- They can be approximated as

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \approx A_{CP}(f) + A_{\text{Detection}}(\pi) + A_{\text{Production}}(D^*)$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \approx A_{CP}(f) + A_{\text{Detection}}(\mu) + A_{\text{Production}}(B)$$

- Most systematics cancel in the difference

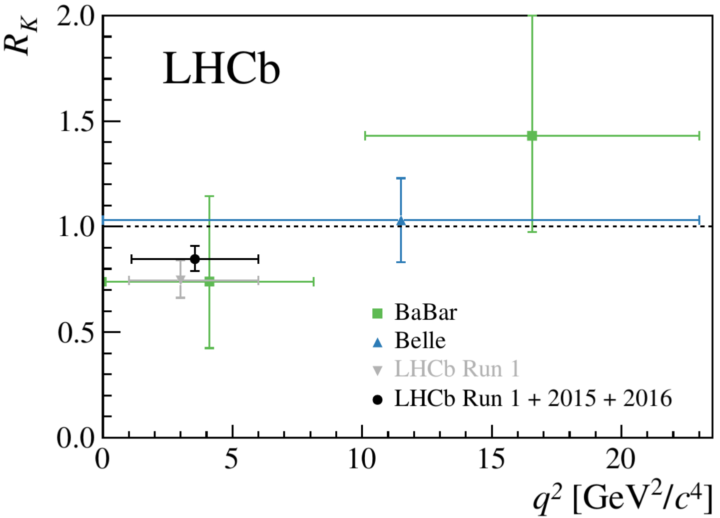
$$\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)\,.$$

Contribution of Direct CPV

- To extract the contribution of direct CP violation, we need [1903.08726]
  - $\Delta\langle t\rangle/\tau = 0.115 \pm 0.002$
  - $\overline{\langle t\rangle}/\tau = 1.71 \pm 0.10$
  - $y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$
  - $A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4} \simeq -a_{CP}^{\text{ind}}$
- This gives

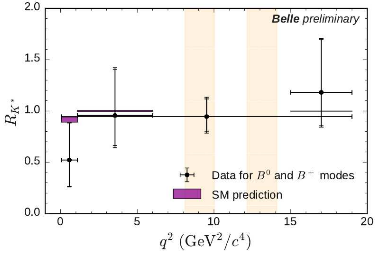
$$\Delta A_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \times 10^{-4}\,.$$

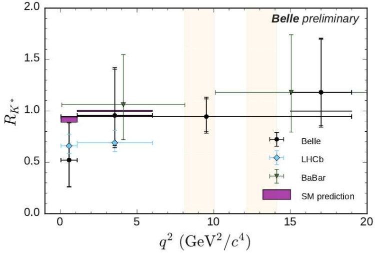
Moriond slides



[Th. Humair, talk at Moriond 2019]

$R(K^*)$: (Preliminary) Result





q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

- All measured values are in accordance with the SM and other recent measurements.
- First measurement of $R(K^{*+})$.

[M. Prim, talk at Moriond 2019; see also 1904.02440]