Future of CP violation in a_{sl}

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IP3

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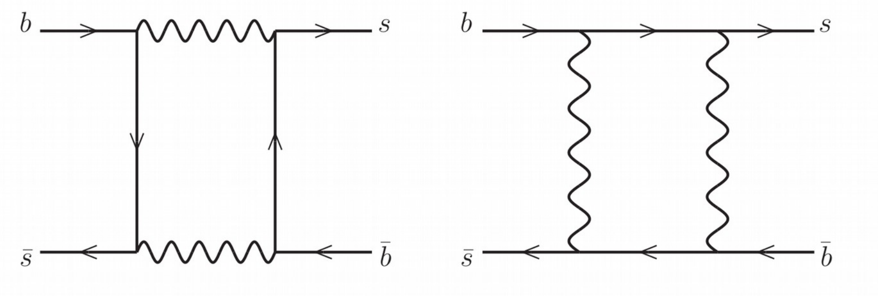
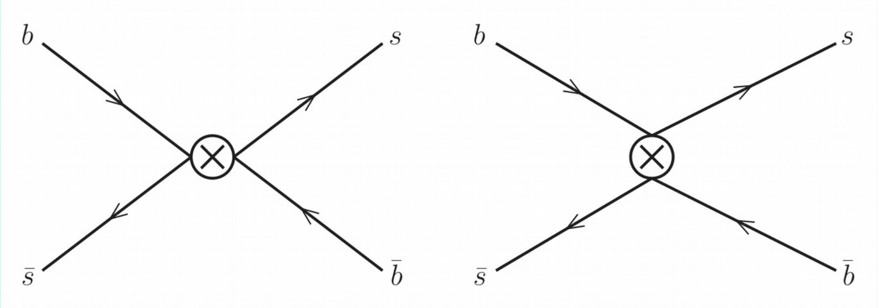
a_{sl}

- $a_{sl} \equiv \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\bar{B} \to f) + \Gamma(B \to \bar{f})}$
- $a_{sl} \approx \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$
  Ratio is nice for calculation – major uncertainty in both (f_B) cancels out
- Theory: $a_{sl}^s = 2.22 \pm 0.27 \times 10^{-5}$ $a_{sl}^d = (-47 \pm 6) \times 10^{-5}$
- Exp: $a_{sl}^s = (170 \pm 300) \times 10^{-5}$ $a_{sl}^d = (-150 \pm 170) \times 10^{-5}$

B_s Mixing

$$\frac{\partial}{\partial t}\begin{pmatrix} B_s \\ \overline{B}_s \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} B_s \\ \overline{B}_s \end{pmatrix}$$





$$M_{12}^q = \frac{G_F^2}{16\pi^2}\lambda_t^2 M_W^2 S_0(x_t)\hat{\eta}_B \frac{\langle \overline{B}_q|Q_1|B_q\rangle}{2M_{B_q}}$$

$$\Gamma_{12}^q = -\frac{G_F^2 m_b^2}{24\pi M_{B_q}} \sum_{x=u,c}\sum_{y=u,c}\left[G_1^{q,xy}\langle \overline{B}_q|Q_1|B_q\rangle - G_2^{q,xy}\langle \overline{B}_q|Q_2|B_q\rangle\right] + \mathcal{O}(1/m_b)$$

What are the limits on a_{sl}?

- Unknown matrix elements of dimension 7 operators
  - Being done by lattice (e.g. HPQCD soon)
  - Also calculable via sum rules (Kirk, Lenz, Rauh 1711.02100)
- NNLO QCD
  - In 1709.02160, some $O(\alpha_s^2)$ corrections calculated

Duality Violation?

- a_{sl} theory calculation depends on assumption of quark-hadron duality
- How can we test this?
- Calculation of Γ_{12} – sum over intermediate shared decay states of B and $\overline{B}$ mesons
- Is quark level sum same?

Phenomenological study

- On the ultimate precision of meson mixing observables (1603.07770)
- Phenomenological study of duality violation in mixing
  - By quark-hadron duality *we* mean validity of HQE
  - So e.g. $\exp\left(-m_b/\Lambda\right)$ term goes to zero in HQE – could be source of daulity violation in some "full" solution of QCD.

Possible source of duality violation

- Expansion parameter is really $\frac{\Lambda}{\sqrt{M_i^2 - M_f^2}}$
- Different in different decay channels

Channel	Expansion parameter x	Numerical value	$\exp[-1/x]$
$b \to c\bar{c}s$	$\frac{\Lambda}{\sqrt{m_b^2 - 4m_c^2}} \approx \frac{\Lambda}{m_b}\left(1 + 2\frac{m_c^2}{m_b^2}\right)$	$0.054 - 0.58$	$9.4 \cdot 10^{-9} - 0.18$
$b \to c\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2 - m_c^2}} \approx \frac{\Lambda}{m_b}\left(1 + \frac{1}{2}\frac{m_c^2}{m_b^2}\right)$	$0.045 - 0.49$	$1.9 \cdot 10^{-10} - 0.13$
$b \to u\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2 - 4m_u^2}} = \frac{\Lambda}{m_b}$	$0.042 - 0.48$	$4.2 \cdot 10^{-11} - 0.12$

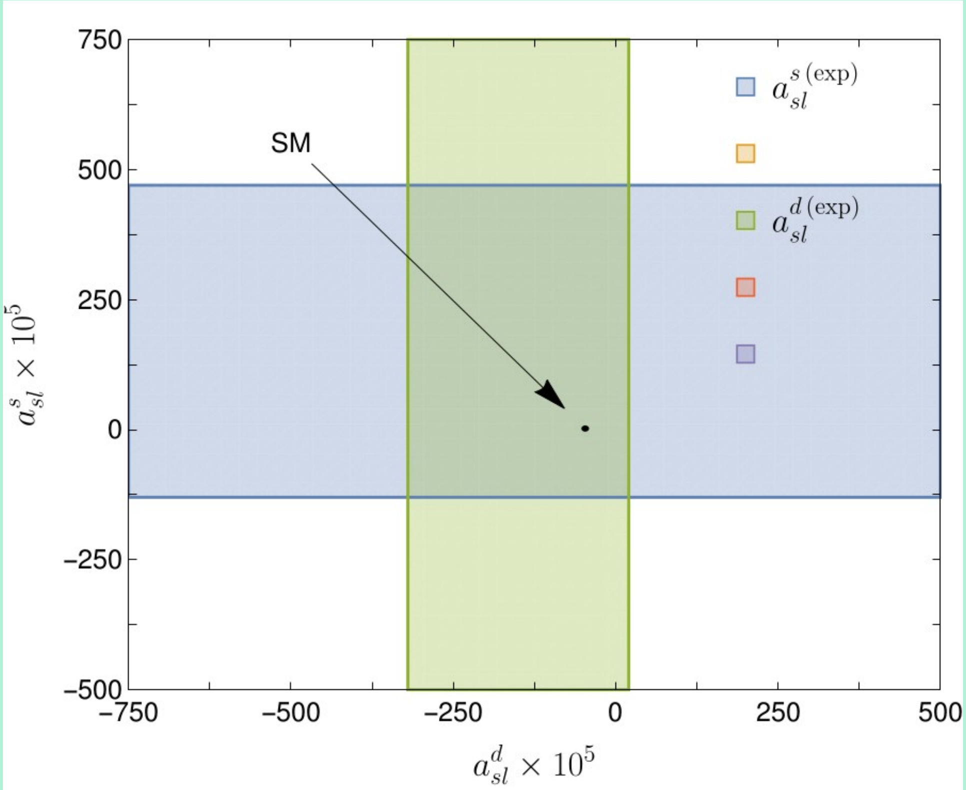
GIM suppression broken with duality violation

- Break up Γ_{12} using CKM unitarity

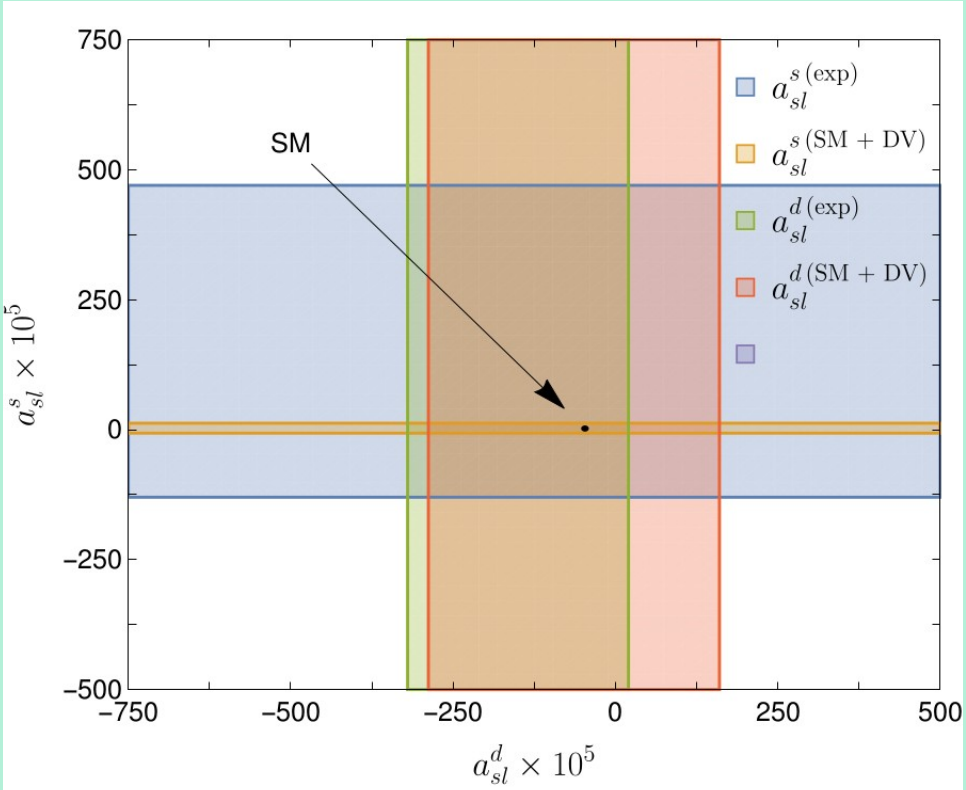
$$\frac{\Gamma_{12}}{M_{12}} = -\frac{\Gamma_{12}^{cc}}{\tilde{M}_{12}} - 2\frac{\lambda_u}{\lambda_t}\frac{\Gamma_{12}^{cc} - \Gamma_{12}^{uc}}{\tilde{M}_{12}} - \frac{\lambda_u^2}{\lambda_t^2}\frac{\Gamma_{12}^{cc} - 2\Gamma_{12}^{uc} + \Gamma_{12}^{uu}}{\tilde{M}_{12}}$$

- See GIM suppression in action
- Break duality differently in each channel → large effects

Limits on a_{sl} from duality violation



Limits on a_{sl} from duality violation



Limits on a_{sl} from duality violation

- These limits come from bounds on $\frac{\Delta \Gamma_s}{\Delta M_s} = \mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)$
- Currently ~ 15-20% precision from theory
- Main uncertainties in this calculation come from matrix elements of dimension 7 operators, scale variation

Limits on a_{sl} from duality violation

- In 1603.07770 we did a forward looking / "aggressive" calculation – what if the dimension 7 matrix elements were known to 20% accuracy?
- Reduce the theory error by almost 1/3
- Is this a plausible scenario?

Sum rules for a_{sl}

- In 1711.02100 we used sum rules to calculate bag parameters
- For dimension 6 operators, errors of ~ 10-15% achieved
  - Comparable with latest lattice

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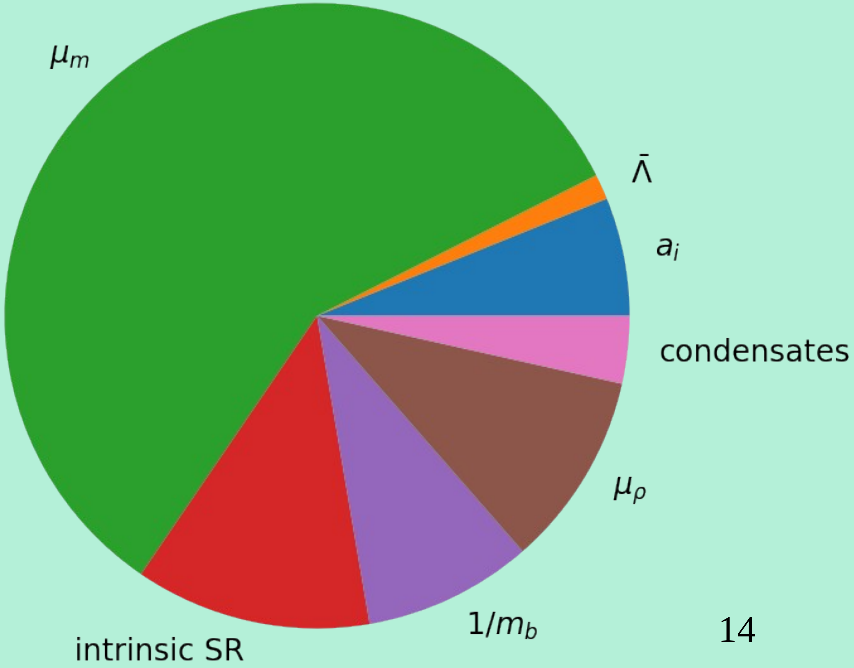
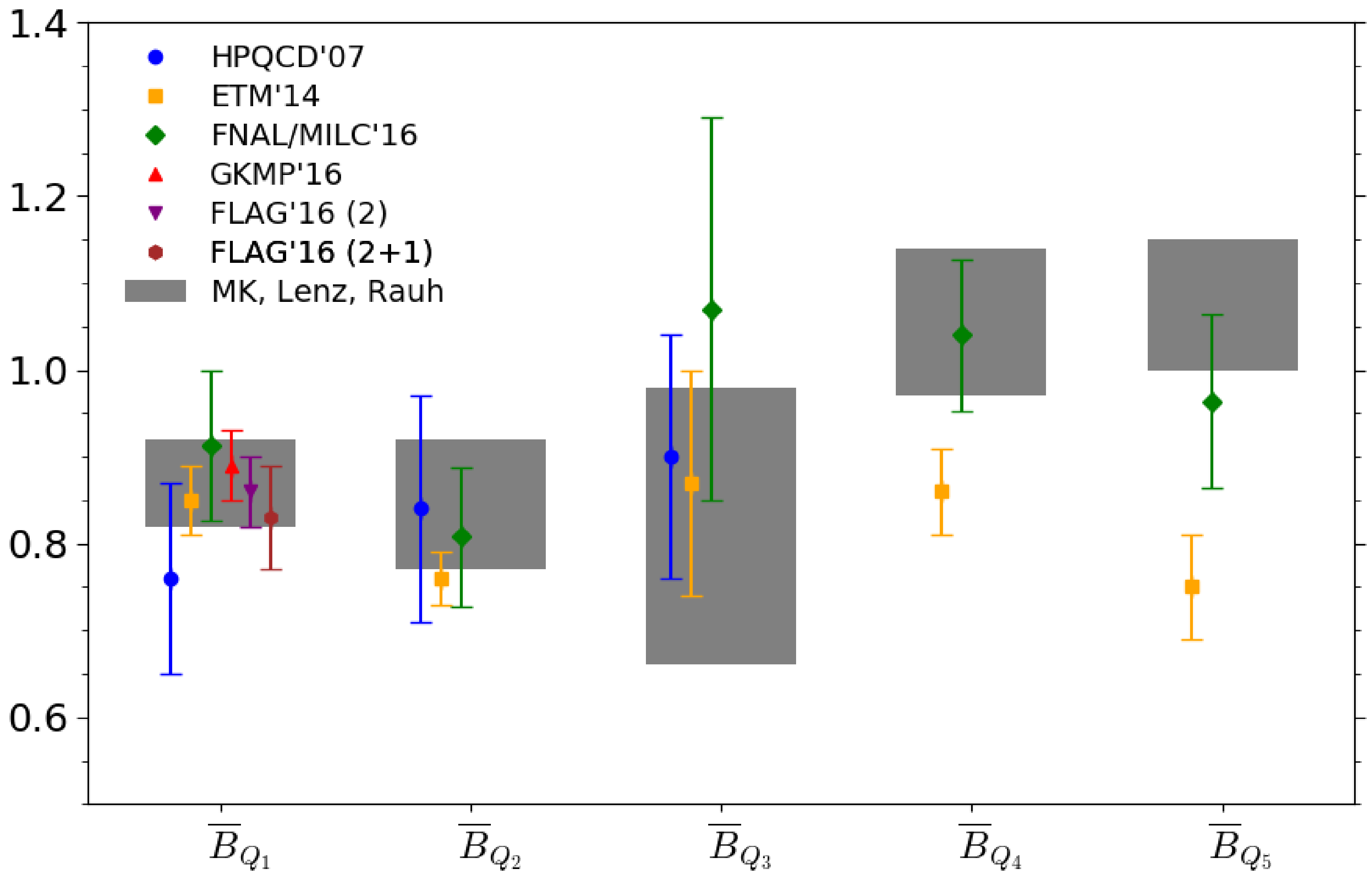



1.4
1.2
1.0
0.8
0.6
HPQCD'07
ETM'14
FNAL/MILC'16
GKMP'16
FLAG'16 (2)
FLAG'16 (2+1)
MK, Lenz, Rauh
$\overline{B}_{Q_1}$
$\overline{B}_{Q_2}$
$\overline{B}_{Q_3}$
$\overline{B}_{Q_4}$
$\overline{B}_{Q_5}$

Sum rules for a_{sl}

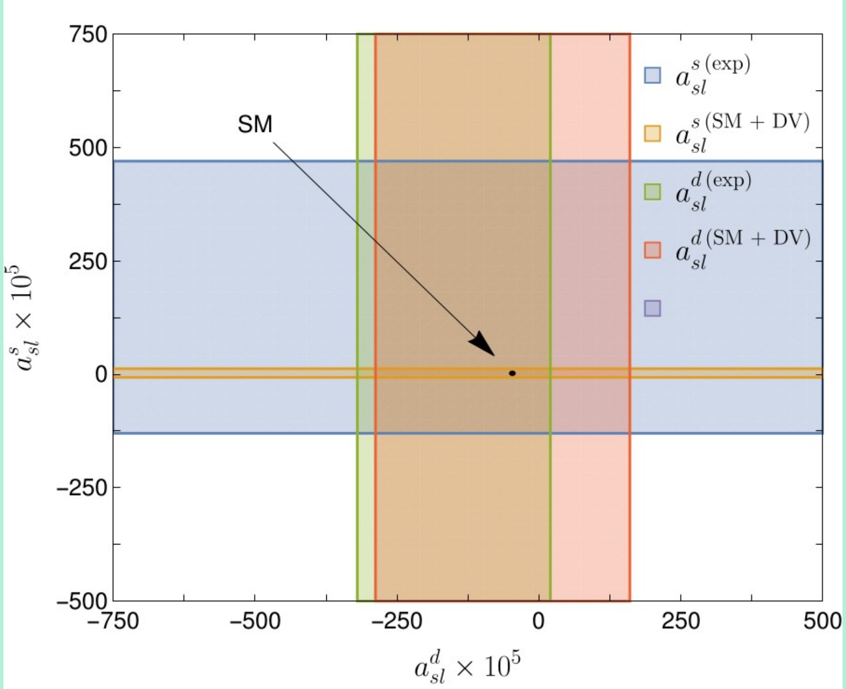
- Calculation for dimension 7 operators should be doable in the same way
- Hopefully provide a timely comparison with upcoming lattice results
- But issues with calculation (pole cancellation)

NNLO QCD Corrections

- In 1709.02160, $O\left(\alpha_s^2 N_f\right)$ corrections calculated
- Steps towards full NNLO calculation
  - Expected to take ~ 5-10 years
- Also NLO QCD for dimension 7 operators has been studied – but issues with uncancelled divergences

Future knowledge of a_{sl}

- **If** similar accuracy as dimension 6 possible, **and** higher order corrections calculated, can achieve high precision



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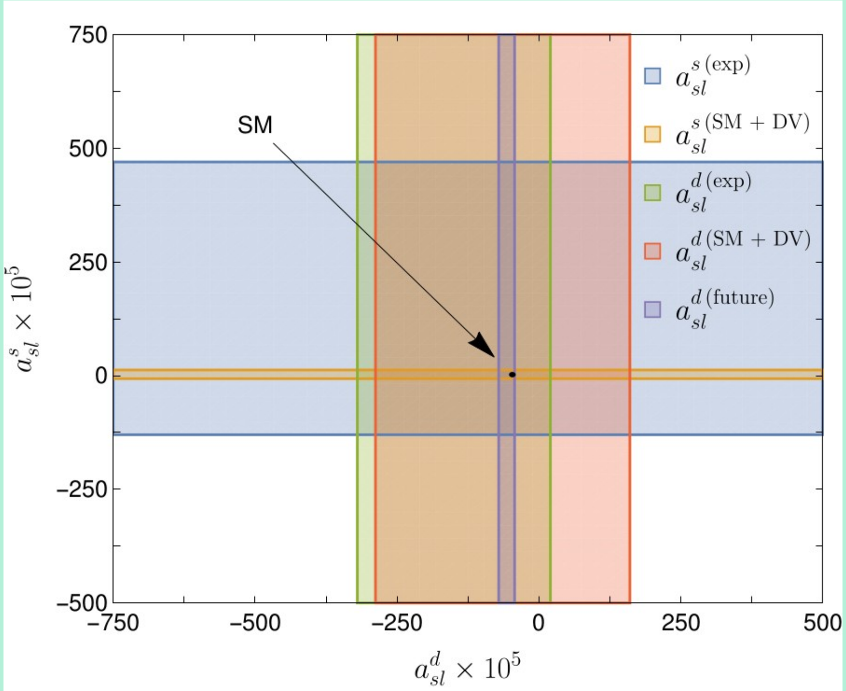

Summary

- $a_{sl}^{s,d}$ is well known from theory
- But if we question an underlying assumption (quark-hadron duality violation) then uncertainty is much larger
- Lattice / sum rule calculation of dimension 7 matrix elements will improve SM prediction **and** allow to test quark-hadron duality
- NP might then be much more clearly seen