Direct *CP* violation in $K^0 \to \mu^+\mu^-$

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Karlsruhe Institute of Technology

Kaon physics

- Kaon decays can probe both of short-distance and long-distance physics
- Discrepancies in $s \to dqq$ (CP-violating FCNC)
  - First lattice result and theory calculations indicated $\boldsymbol{\varepsilon'_K}$ discrepancy in $\boldsymbol{K^0 \to \pi\pi}$ (**2.8-2.9σ**) recall: Mishima-san talk
  - Indirect CPV $\boldsymbol{\varepsilon_K}$ suffers for 4.0σ tension in exclusive $|V_{cb}|$ case [$\boldsymbol{\varepsilon_K} \propto |V_{cb}|^4$]

  [LANL-SWME, 1710.06614]
- There are many promising on-going experiments for kaon precisions; LHCb / NA62 / KOTO / KLOE-2 / TREK
- One can test our understanding of the SM, unitarity of CKM and ChPT, and also probe physics beyond the SM

collider search

could give stronger constraints

Lattice
perturbative calculations
meson effective theory (ChPT)

ε'_K and ε_K discrepancies?

$$K_L \to \pi\pi$$

CP-violating FCNC

correlations

B

$$K_S \to \mu^+\mu^-$$

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

Understanding of ChPT

$$K_S \to \pi^0\mu^+\mu^-$$

$$K_S \to \pi^+\pi^- e^+e^-$$

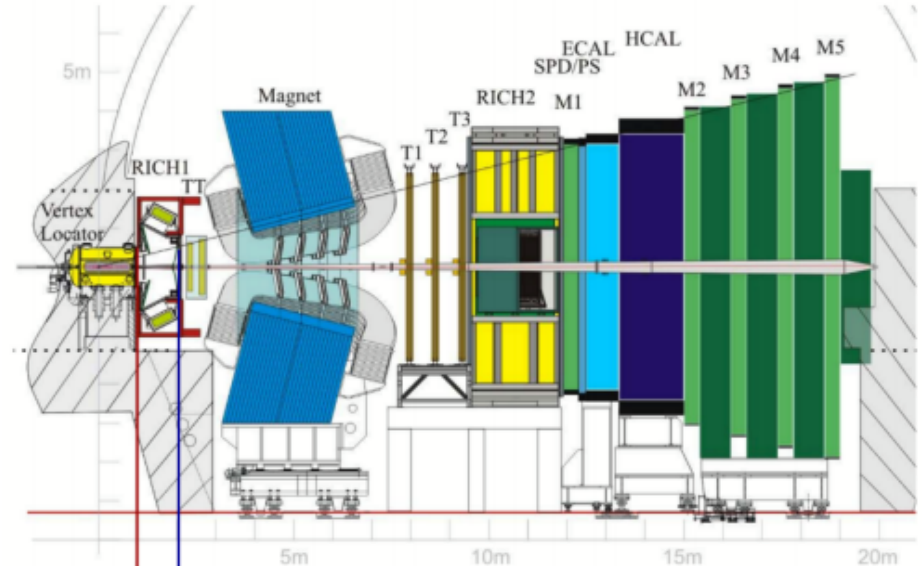
$$K_S \to 4l$$

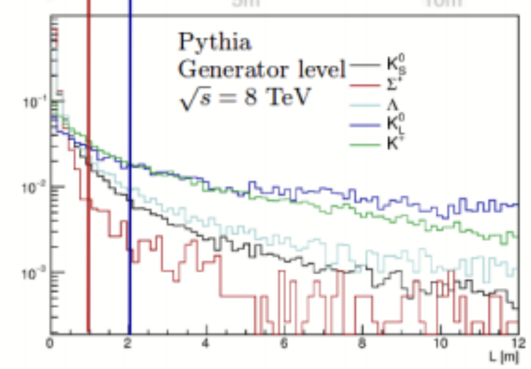
reduce th. error →

$$K_L \to \pi^0 l^+ l^-$$

less sensitive because of LD contributions

Kaon in LHCb

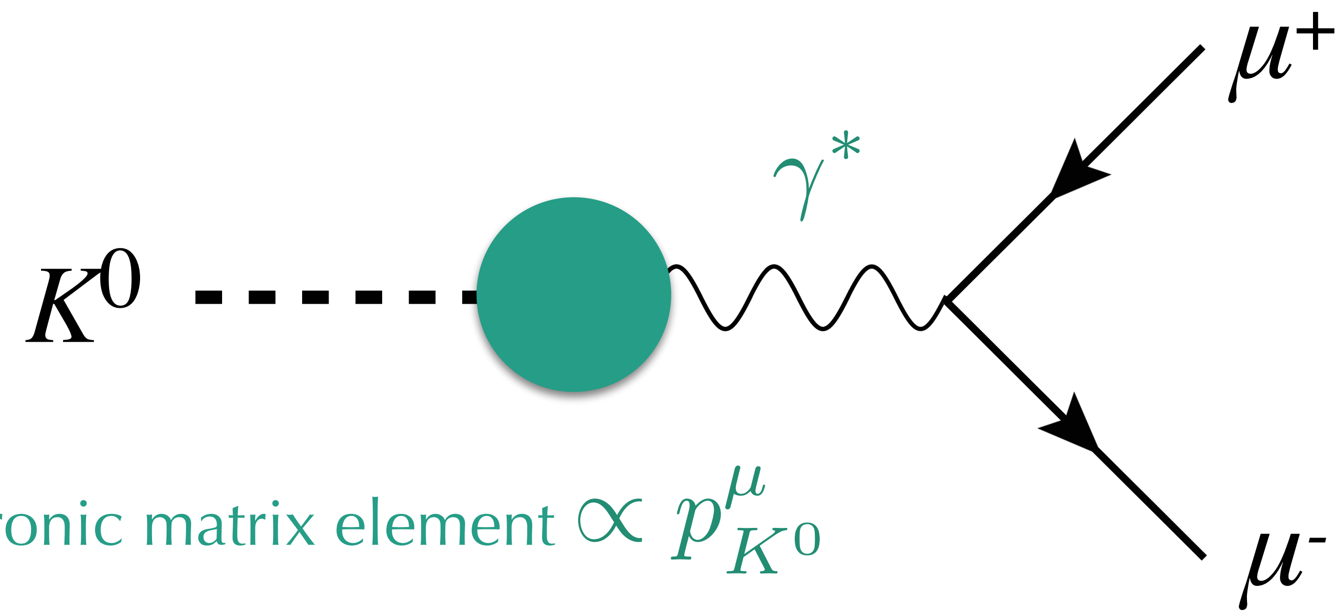




- LHCb experiment has been designed for efficient reconstructions of ***b*** and ***c***
- Huge production of strangeness [$O(10^{13})/\mathrm{fb}^{-1}$ K^0_S] is suppressed by its trigger efficiency [ε~1-2%@LHC Run-I, ε~18%@LHC Run-II]
- LHCb Upgrade (LS2=Phase I upgrade, LS4=Phase II upgrade) could realize high efficiency for K^0_S [ε~90%@LHC Run-III] [M. R. Pernas, HL/HE LHC meeting, FNAL, 2018]
- In LHC Run-III and HL-LHC, we could probe the *ultra* rare decay Br~$O(10^{-11\sim12})$

$K^0 \to \mu^+\mu^-$

- There is no single photon exchange in $P \to l^+l^-$



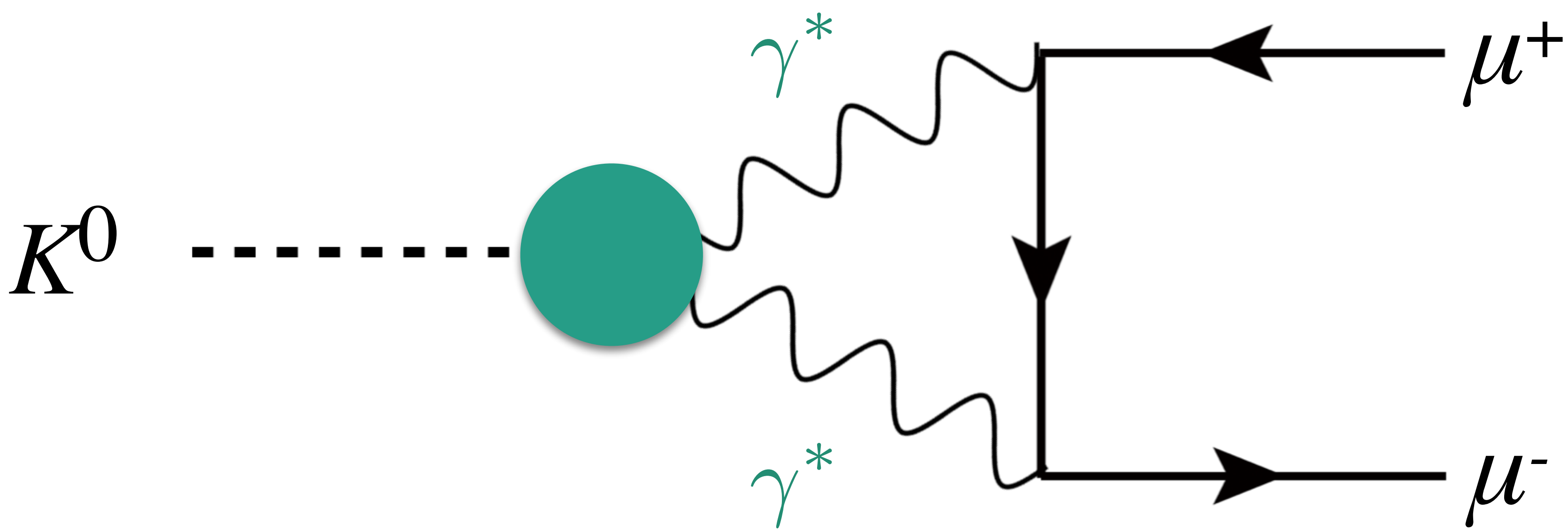
Hadronic matrix element $\propto p^\mu_{K^0}$

$$\propto p^\mu_{K^0} \left(\bar{\ell}\gamma_\mu \ell\right)$$
$$= (p+q)^\mu \left(\overline{u}(p)\gamma_\mu v(q)\right) = 0$$

No contribution from single photon diagrams

$K^0 \to \mu^+\mu^-$

- There is no single photon exchange in $P \to l^+l^-$
- Two photons exchange give dominant contributions in $K^0 \to \mu^+\mu^-$



K_L ~ CP-odd $\longrightarrow$ $\bar{\ell}\gamma_5\ell$ = CP-odd

$CP|K_L\rangle \sim CP|K_2^0\rangle = -|K_2^0\rangle$ S-wave (L=0, S=0, J=0) $CP|\bar{\ell}\gamma_5\ell\rangle \to -|\bar{\ell}\gamma_5\ell\rangle$

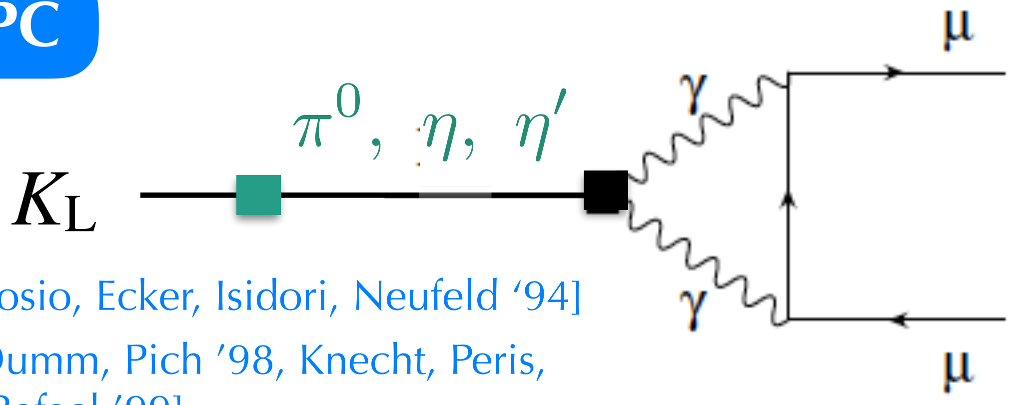
K_S ~ CP-even $\longrightarrow$ $\bar{\ell}\ell$ = CP-even

$CP|K_S\rangle \sim CP|K_1^0\rangle = |K_1^0\rangle$ P-wave (L=1, S=1, J=0) $CP|\bar{\ell}\ell\rangle \to |\bar{\ell}\ell\rangle$

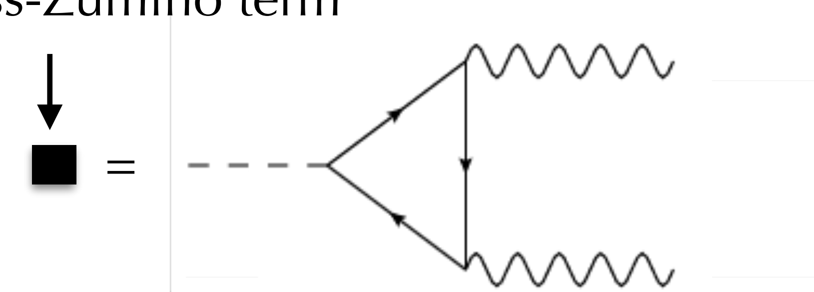
$K_L \to \mu^+\mu^-$

- $K_L \to \mu^+\mu^- = |\text{S-wave}|^2 + |\text{P-wave}|^2$ P-wave is significantly suppressed in the SM

LD CPC



Wess-Zumino term



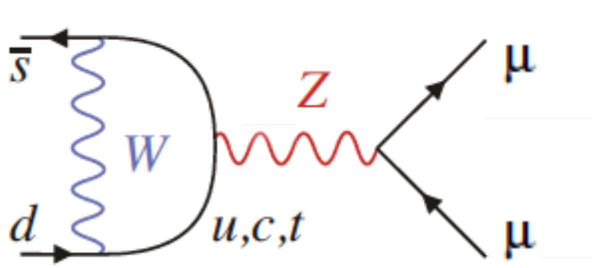
chiral anomaly

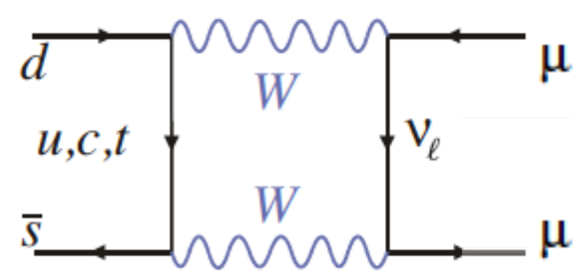
[D'Amborosio, Ecker, Isidori, Neufeld '94]
[Gomez Dumm, Pich '98, Knecht, Peris, Perrottet, Rafael '99]

- $[K_L \to \pi \to \gamma\gamma] + [K_L \to \eta \to \gamma\gamma] = 0$ (by Gell-Mann—Okubo formula)
- Higher chiral orders spoil this cancellation. exact mass relation in SU(3)F with its breaking $\frac{\left(\frac{K^-+\bar{K}^0}{2}\right)^2 + \left(\frac{K^++K^0}{2}\right)^2}{2} = \frac{3\eta^2+\pi^2}{4}$
- Only abs. of the amplitude can be determined from $B(K_L \to \gamma\gamma)_{exp}$

→ **sign ambiguity of $A(K_L \to \gamma\gamma)$**

SD CPC





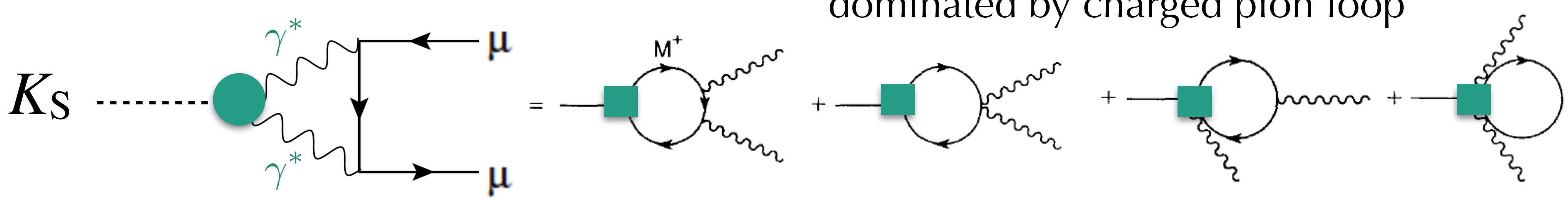
$\propto \mathrm{Re}\,[V_{ts}^* V_{td}]$

$K_S \to \mu^+\mu^-$

- $K_S \to \mu^+\mu^-$ = |S-wave|^2 + |P-wave|^2 ←no interference if μ polarizations are not measured

LD CPC [Ecker, Pich '91]

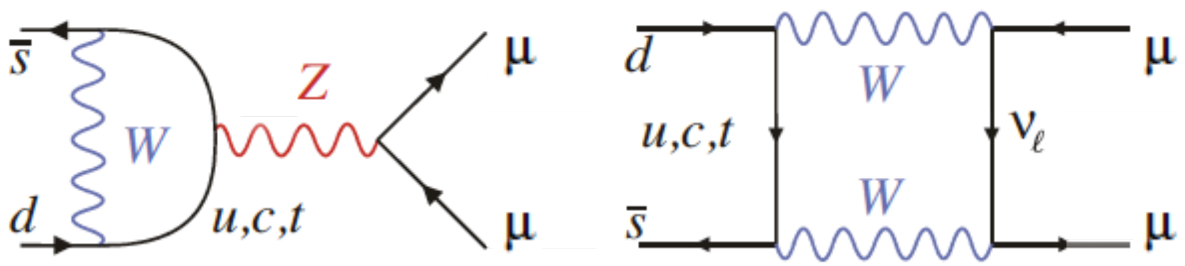
dominated by charged pion loop



- Abs. of the amplitude can be determined from $B(K_S \to \gamma\gamma)_{exp}$, which includes 17% enhancement from a final state interaction (FSI) of pions
- Since two photons are off-shell states, the FSI is debatable and large uncertainty is considered (which will be sharpened by a dispersive treatment of $K_S \to \gamma\gamma$, $K_S \to \gamma\mu\mu$, $K_S \to \mu\mu\mu\mu$ and $K_S \to \mu\mu ee$ measured by KLOE-2, LHCb Upgrade)

[Colangelo, Stucki, Tunstall '16]

SD CPV



$\propto \mathrm{Im}\,[V_{ts}^* V_{td}]$

$K^0 \to \mu^+\mu^-$ systems

- SM predictions: [Ecker, Pich '91, Isidori, Unterdorfer '04, TK, D'Ambrosio '17]

$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm SM} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} (+) \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9} (-) \end{cases}$$

LD other

An unknown sign ambiguity

$$\pm = \mathrm{sgn}\left[\frac{\mathcal{A}(K_L \to \gamma\gamma)}{\mathcal{A}(K_L \to (\pi^0)^* \to \gamma\gamma)}\right]$$

changes the relative sign between LD and SD

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm SM} = [4.99(\mathrm{LD}) + 0.19(\mathrm{SD})] \times 10^{-12}$$
$$= (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$$

LD other

- Both of $K_L \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-$ are dominated **by the *CP*-conserving long-distance contributions (two photon exchanges)**

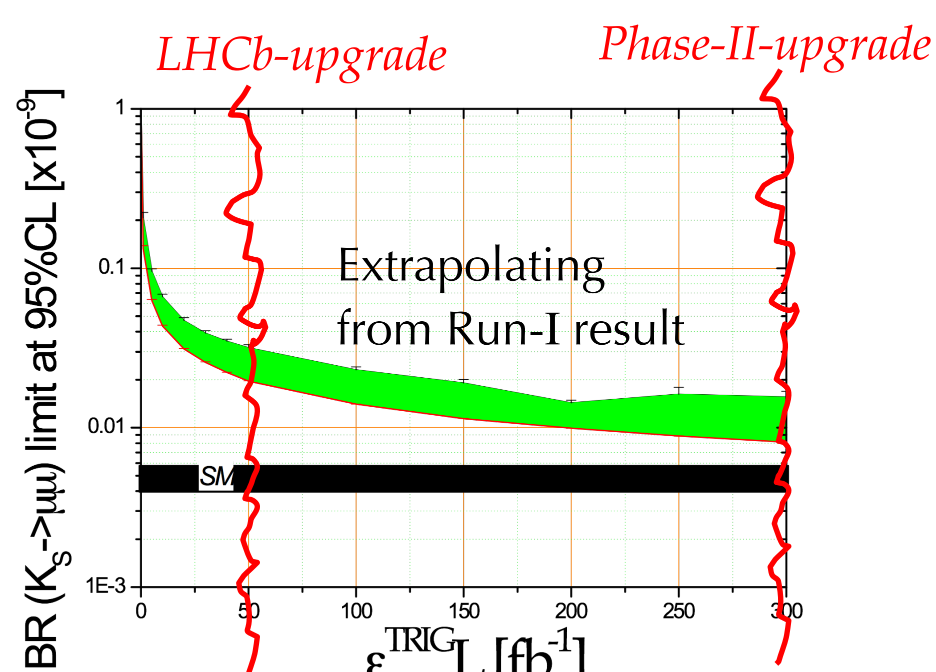
- Current bounds:

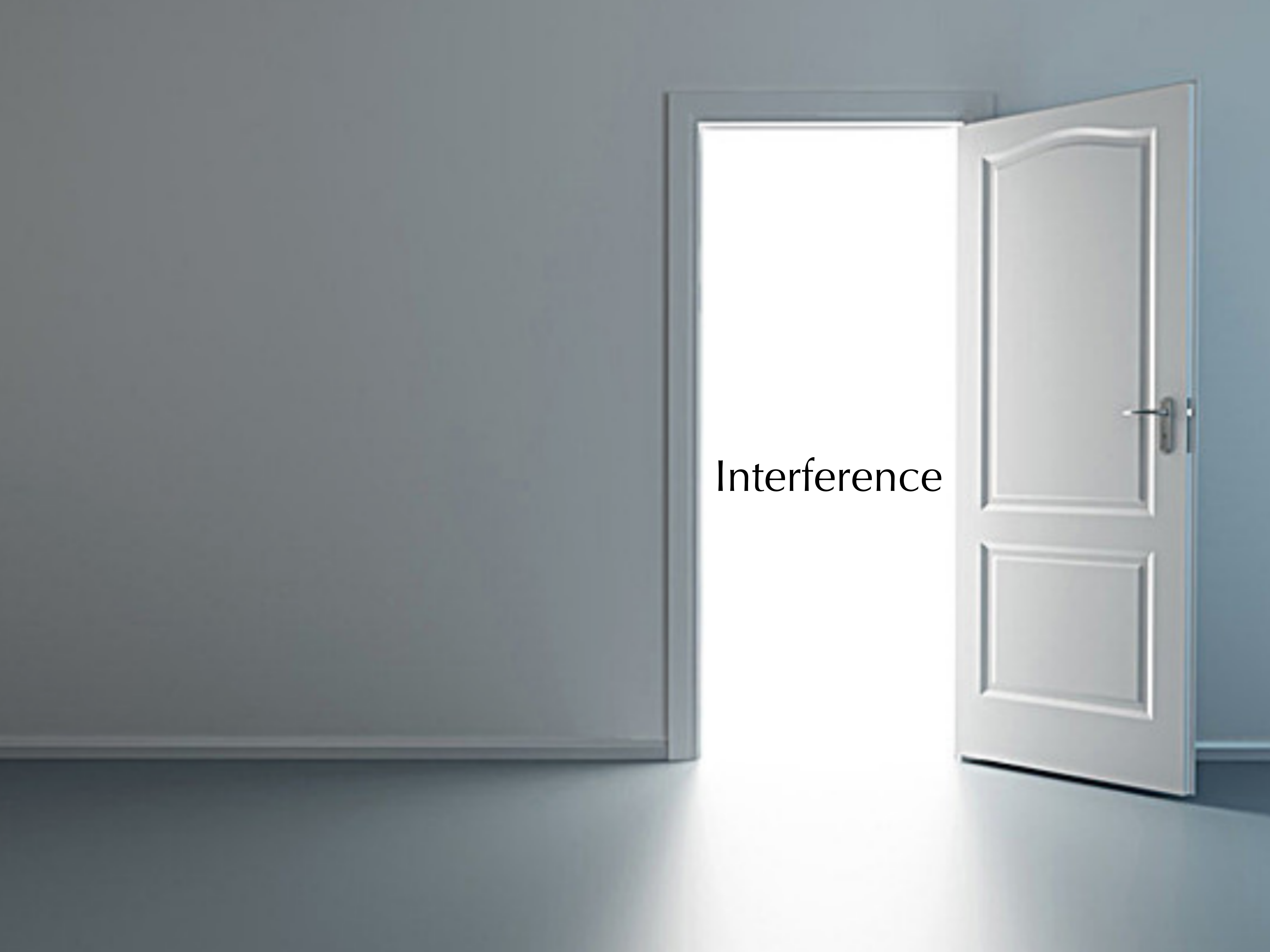
$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm exp} = (6.84 \pm 0.11) \times 10^{-9}$$ [BNL E871 '00]

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm exp} < 0.8 \times 10^{-9}$$ [LHCb Run-I full data '17]

- LHCb Upgrade is aiming to reach the SM sensitivity of $K_S \to \mu\mu$

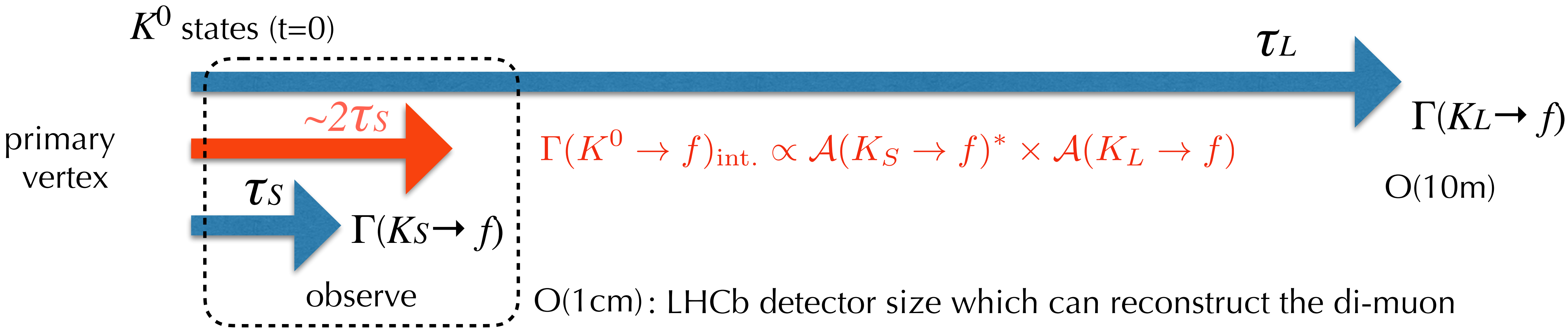
[D. M. Santos,HQL2018]




Interference

Interference between K_L and K_S

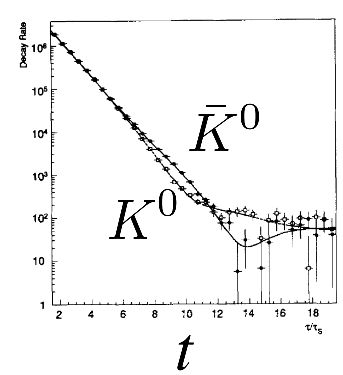
- When the same final states exist in K_L and K_S decays, the interference between K_L and K_S initial states gives a contribution



- Such an interference is discussed from ’67 (Sehgal and Wolfenstein), and has been observed and utilized in many processes:
  e.g., $K^0 \to \pi\pi$, $K^0 \to 3\pi^0$, $K^0 \to \pi^+\pi^-\pi^0$, and $K^0 \to \pi^0 e^+ e^-$

cf. CPLEAR experiment
(1990-99@CERN)

$$p\bar{p} \to \left[\begin{array}{l} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{array} \right.$$



$\{K_S, K_L\} \to \pi^+\pi^-$
measured the interference between K_L and K_S
[CPLEAR collaboration ’95]

Interference between K_L and K_S

$K_S \to \mu^+\mu^-$

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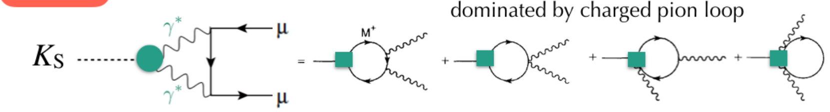

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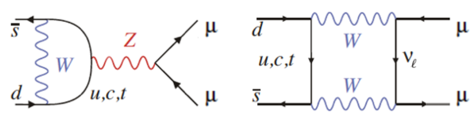
SD CPV



$\propto \mathrm{Im}\,[V_{ts}^* V_{td}]$

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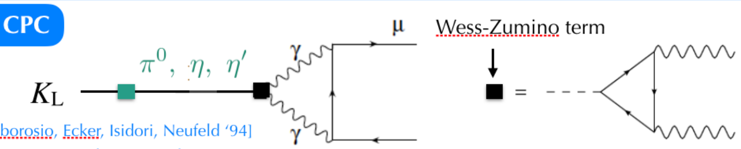
LD CPC



[D'Ambrosio, Ecker, Isidori, Neufeld '94] [Gomez Dumm, Pich '98, Knecht, Peris, Perrottet, Rafael '99]

Wess-Zumino term; chiral anomaly

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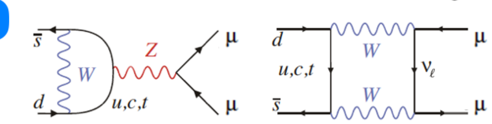


$\propto \mathrm{Re}\,[V_{ts}^* V_{td}]$

Interference

- Dominant interference term [TK, D'Ambrosio, PRL '17]

$$\mathcal{H}_{\rm eff}^{|\Delta S|=1} = \frac{G_F \alpha}{\sqrt{2}} \lambda_t y'_{7A} (\bar{s}\gamma_\mu\gamma_5 d)(\bar{\mu}\gamma^\mu\gamma_5\mu) + \mathrm{H.c.}$$

$$\sum_{\rm spin} \mathcal{A}(K_1 \to \mu^+\mu^-)^* \mathcal{A}(K_2 \to \mu^+\mu^-)$$

$$= \frac{16 i G_F^4 M_W^4 F_K^2 M_K^2 m_\mu^2 \sin^2\theta_W}{\pi^3} \mathrm{Im}[\lambda_t] y'_{7A} \{A_{L\gamma\gamma}^\mu - 2\pi \sin^2\theta_W (\mathrm{Re}[\lambda_t] y'_{7A} + \mathrm{Re}[\lambda_c] y_c)\}$$

- Interference comes from $K_S \to \mu\mu$ S-wave SD times $K_L \to \mu\mu$ S-wave CPC LD; $K_S \to \mu\mu$ P-wave LD is dropped
- **Proportional to direct CPV**
- Insensitive to indirect CPV $\bar{\epsilon}$

$$y'_{7A} = -0.654(34), \quad A_{L\gamma\gamma}^\mu = \pm 2.01(1) \cdot 10^{-4} \cdot [0.71(101) - i5.21]$$

top loop; $\gamma\gamma$ loop; sign ambiguity

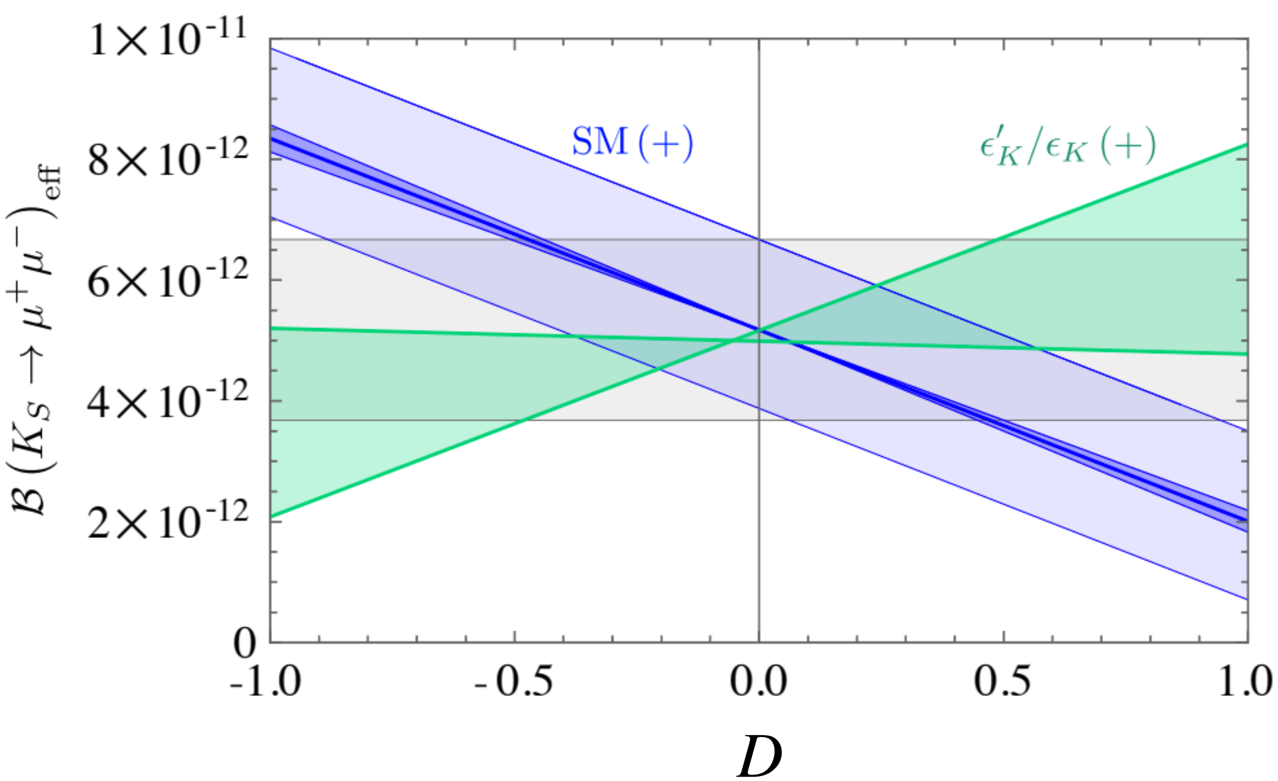
Direct *CP* asymmetry in $K_S \to \mu\mu$

[TK, D'Ambrosio, PRL '17] [Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18]
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

- Interference contribution is comparable size to CPC of $K_S \to \mu\mu$ thanks to the large absorptive part of long-distance contributions to $K_L \to \mu\mu$
- The unknown sign of $\mathcal{A}(K_L \to \gamma\gamma)$ can be probed, which reduces theoretical uncertainty of $K_L \to \mu\mu$
- Nonzero dilution factor (D) can be achieved by an accompanying charged kaon tagging and a charged pion tagging

$$pp \to K^0 K^- X$$
$$pp \to K^{*+} X \to K^0 \pi^+ X$$
$$\text{with } K^0 \to \{K_S, K_L\} \to \mu^+\mu^-$$

Dilution factor: $D = \dfrac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$



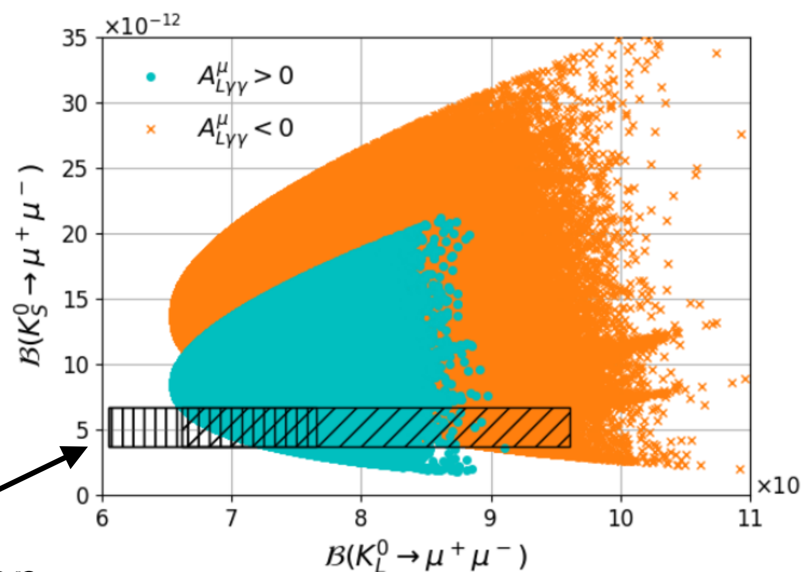
gray: $K_S \to \mu\mu$ (CPC) in the SM
Blue: $K_S \to \mu\mu$ with the interference in the SM
Green: Z scenario (LH) with ε'_K anomaly

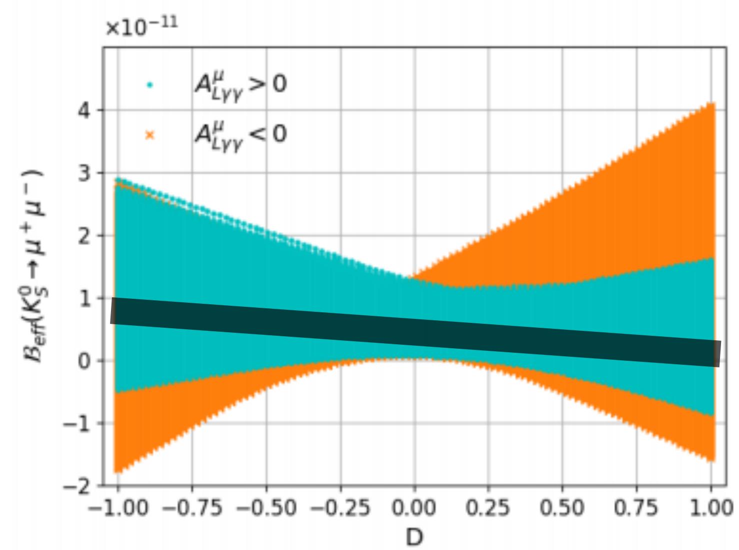
SUSY contributions to $K^0 \to \mu^+\mu^-$

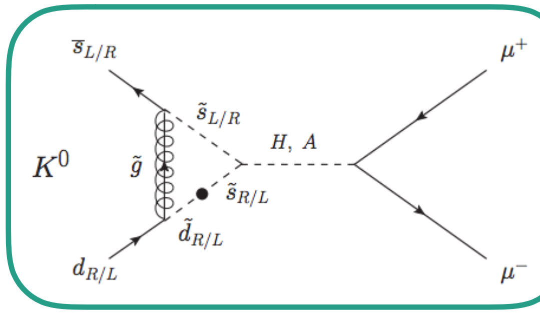
One of the MSSM scenario from Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18

mass difference between right-handed squarks, large tanβ, light M_A~TeV

No inter-ference plot (D=0)





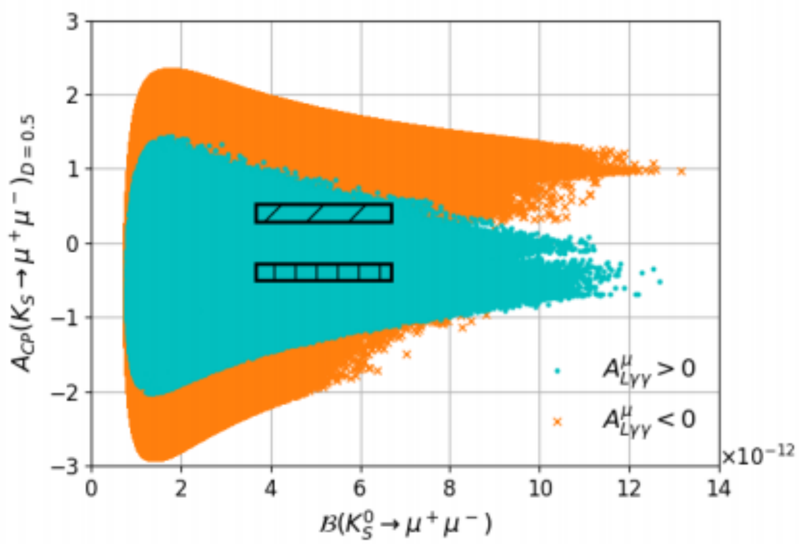


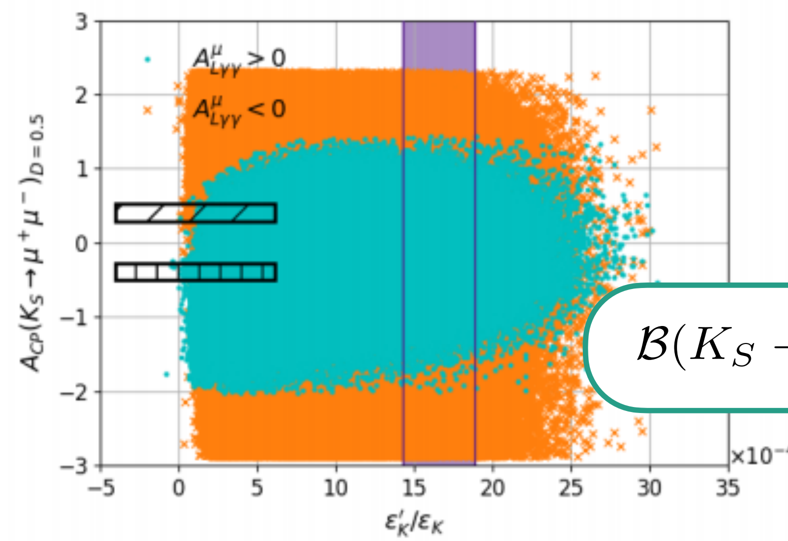
SM prediction [$\mathrm{sgn}(A^{\mu}_{L\gamma\gamma}) > 0$]

SM prediction

measured $\varepsilon'_K/\varepsilon_K$

D=0.5





Large deviations from SM predictions are possible in the MSSM

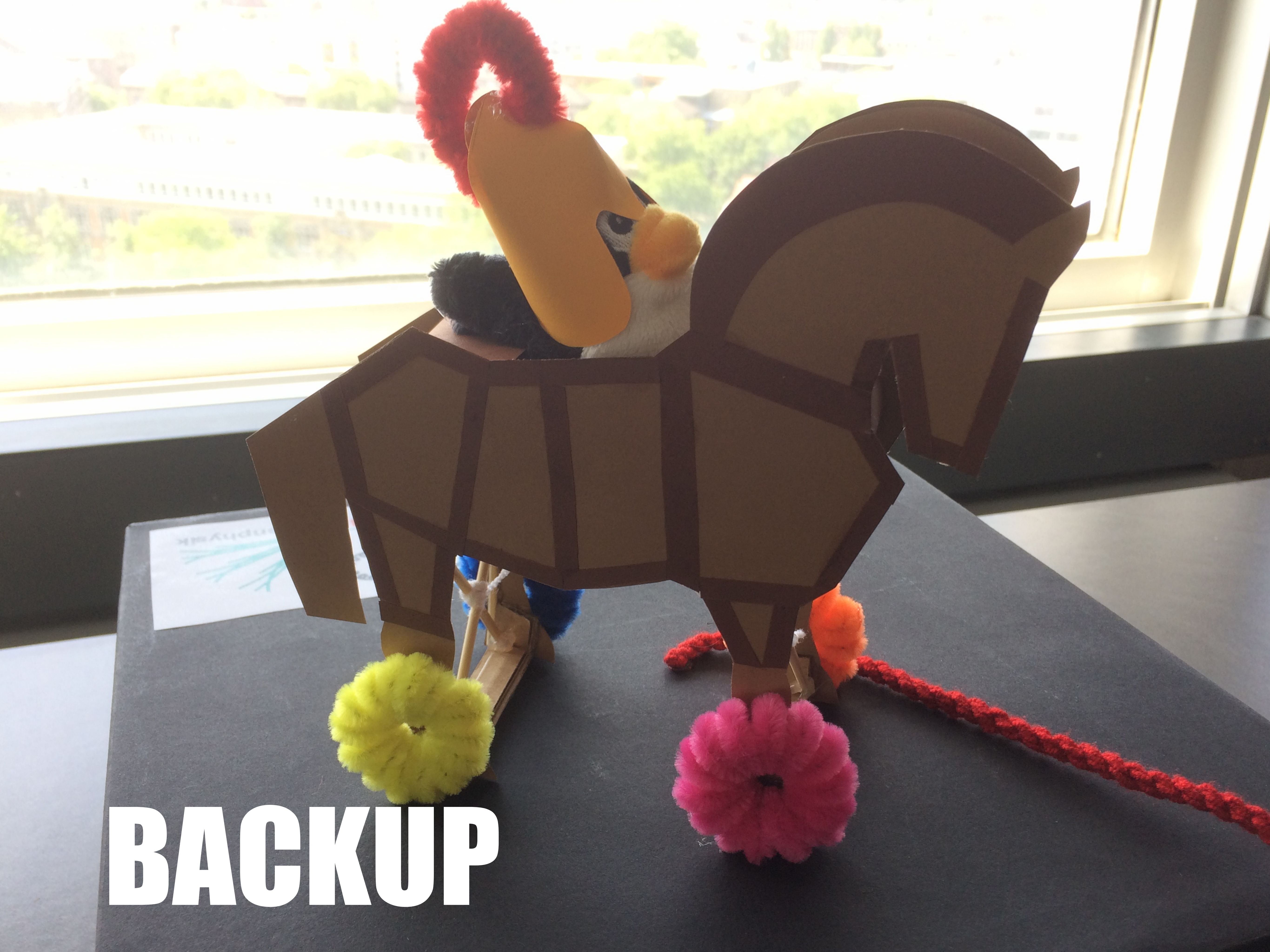
$$\mathcal{B}(K_S \to \mu^+\mu^-)|_{\rm MSSM} \sim \mathcal{O}(1) \times 10^{-11}$$

See also Leptoquark study: $B(K_S \to \mu\mu)$~O(10^{-10}) is possible [Bobeth, Buras '18]

Conclusions

- Kaon physics can probe *CP*-violating FCNC from various ways

- **LHCb Upgrade can probe $K_S \to \mu^+ \mu^-$ around SM sensitivity and could open a short distance window by the interference effect in $K^0 \to \mu^+ \mu^-$**
- **The interference contribution in $K^0 \to \mu^+ \mu^-$ emerges from a genuine direct CP violation**
- The interference contribution can change the $K_S \to \mu^+ \mu^-$ LD-CPC prediction at **O(60%)**
- Crosscheck of KOTO [$K_L \to \pi^0 \nu\nu$] is possible

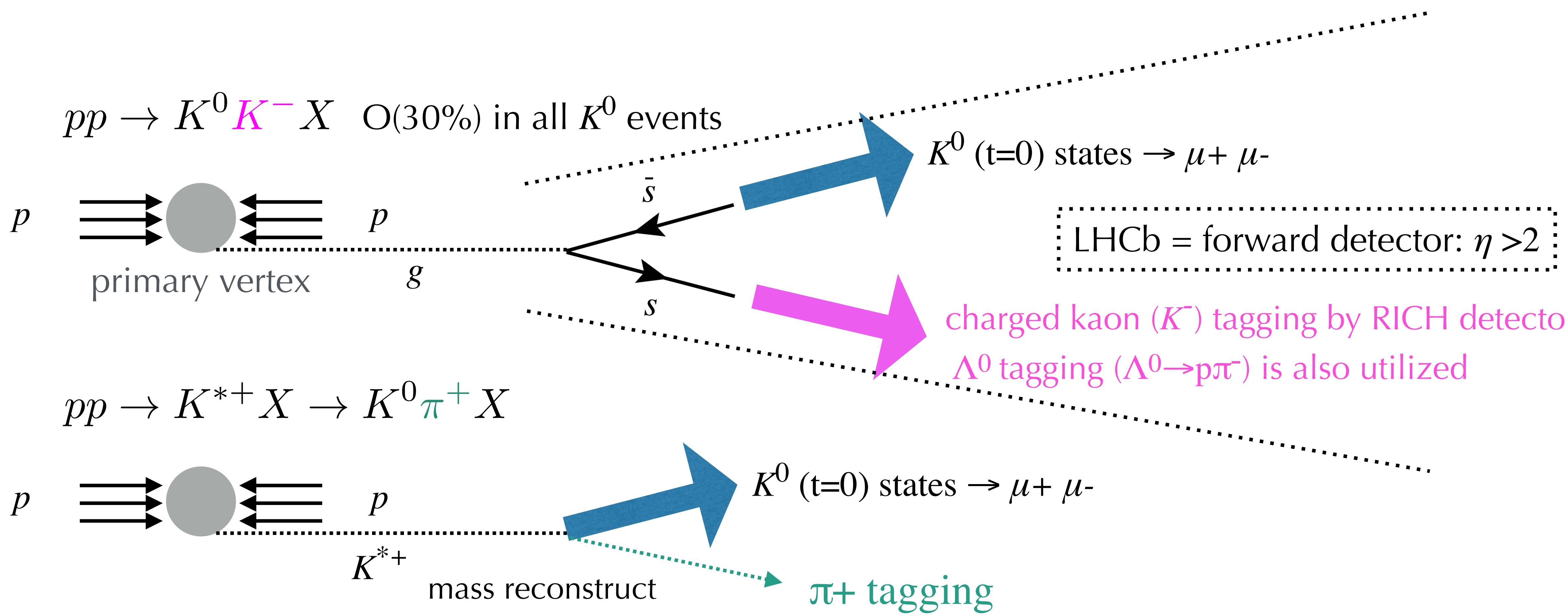

BACKUP

Dilution factor D

[D'Amborosio, TK '17]

- Since $f_s(\mu^2) = f_{\bar{s}}(\mu^2)$ (PDF in p), $\sigma(pp \to K^0 X) \simeq \sigma(pp \to \overline{K}^0 X)$ and then $D = 0$ in LHC

- Nonzero dilution factor D could be obtained by an accompanying charged kaon tagging and a charged pion tagging



A similar charged pion tagging for D^0 through $D^{*+} \to D^0\,\pi$+(slow) has been achieved in the LHCb