New directions in Kaon Physics

— Interference in $K^0 \to \mu^+\mu^-$ as a new golden mode —

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Rencontres de Moriond since 1966

CPP Chiba Particle Physics

Based on Marchevski, Martinez Santos + D'Ambrosio, Dery, Grossman, TK, Schacht, JHEP (2025)

$|V_{us}|$ vs unitarity (CAA)

$K \to \pi \ell \bar{\nu}$
$K^- \to \mu \bar{\nu}$
tree-level CPC

ε_K and ε'

$K_L \to \pi\pi$

Correlation

B anomalies

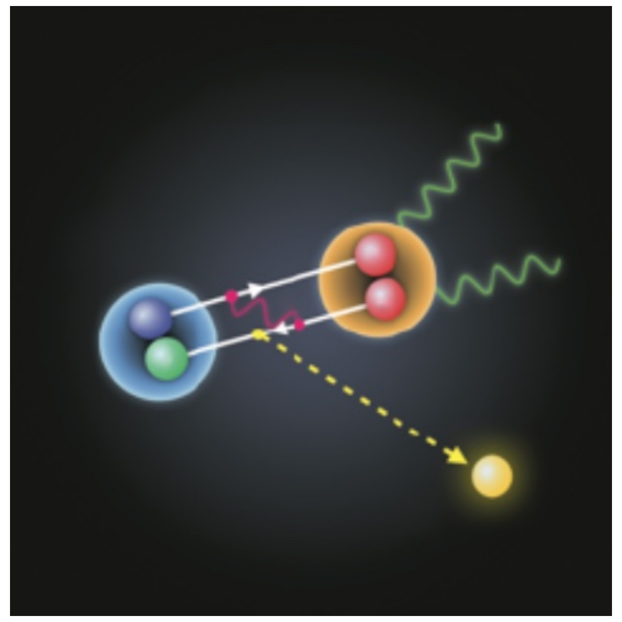
FCNC and CPV

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

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

loop-level CPC
Long-distance dominant
just ultra-tare kaon decay….

$K \to \pi X?$



New theoretical ideas

$|V_{us}|$ vs unitarity (CAA)

$K \to \pi \ell \bar{\nu}$ tree-level CPC
$K^- \to \mu \bar{\nu}$

ε_K and ε'

$K_L \to \pi\pi$

Correlation

B anomalies

FCNC and CPV

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

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

Sensitive to CPV when $K_L^0 - K_S^0$ interference considered!

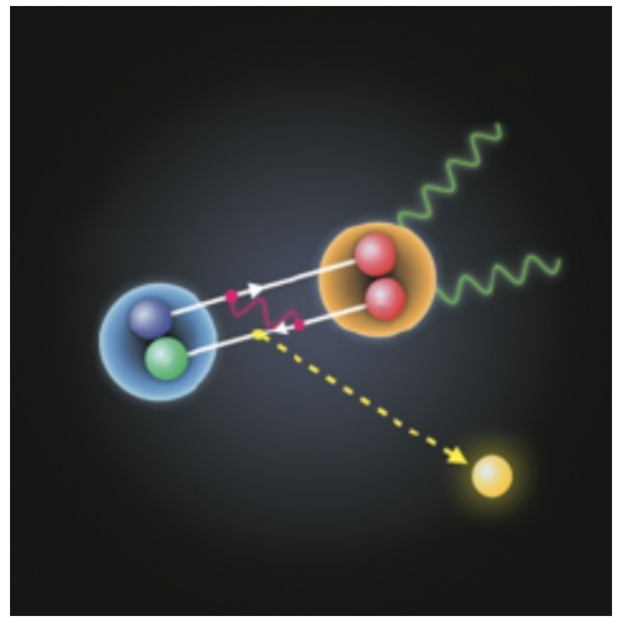
New idea in 2017

[D'Ambrosio, TK, PRL, 1707.06999]

kaon unitarity triangle

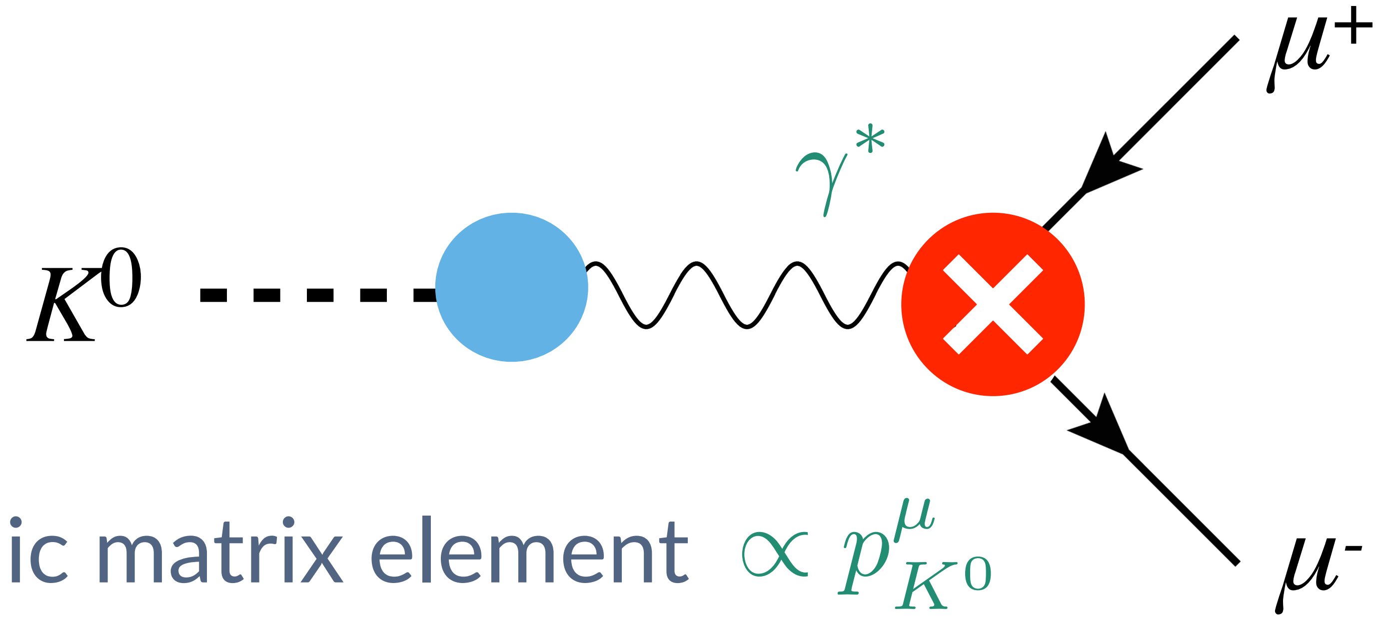
[Dery, 2504.12386]

$K \to \pi X?$

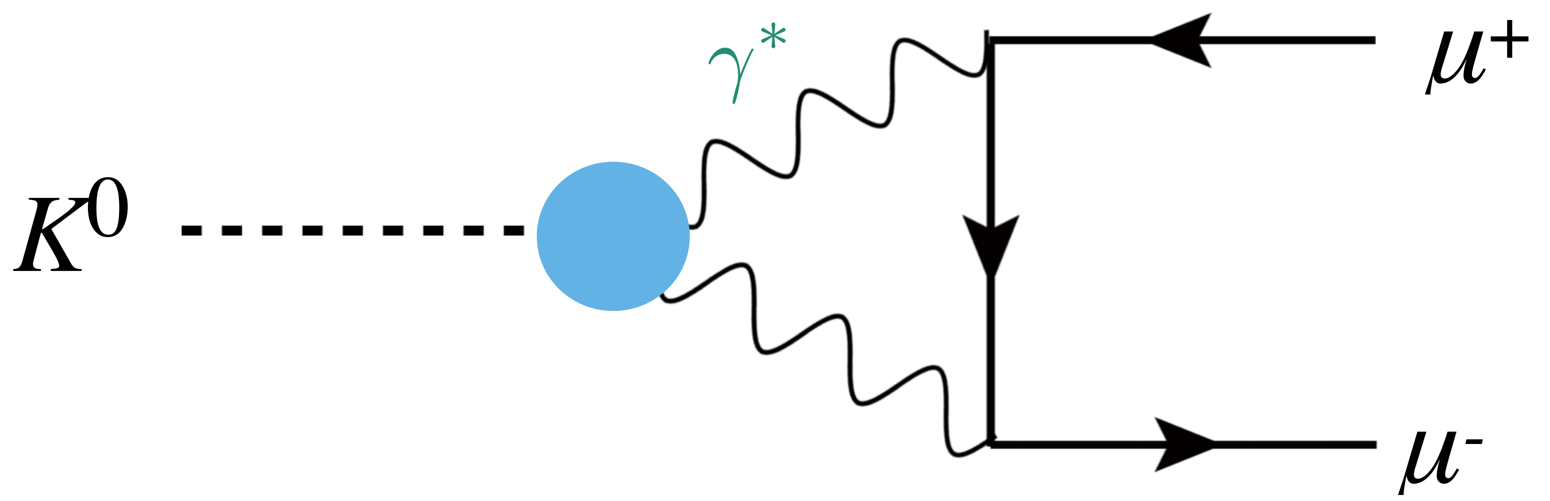


Introduction to $K^0_{L/S} \to \mu^+\mu^-$

- Double-photon exchange is the leading contribution in $K^0 \to \mu^+\mu^-$



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



Leading

- Both CP-conserving and CP-violating contributions exist

S-wave $(L=0, S=0)$

$J = 0$ { K^0_L almost *CP*-odd; K^0_S almost *CP*-even }

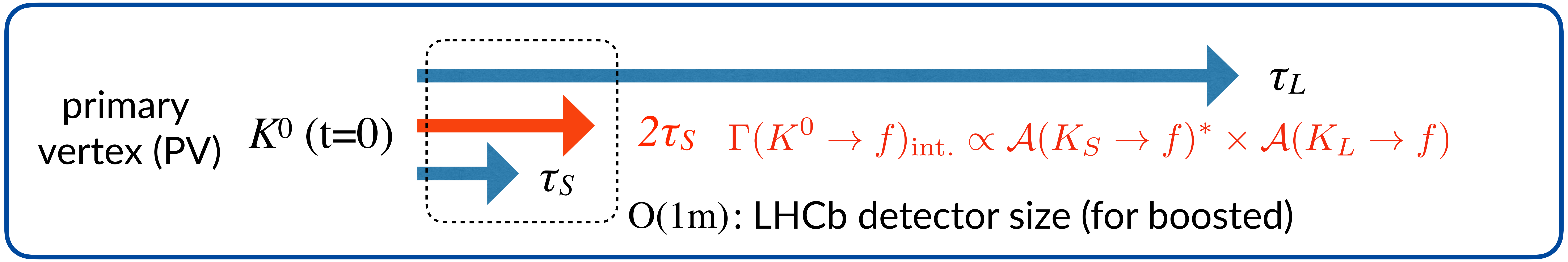
$\bar{\ell}\gamma_5\ell$ (spin singlet) = *CP*-odd

$\bar{\ell}\ell$ (spin triplet) = *CP*-even

P-wave $(L=1, S=1)$

Interference between K_L^0 and K_S^0

- When the same final states exist in both K_L^0 and K_S^0 decays, the interference provides nonzero contributions:



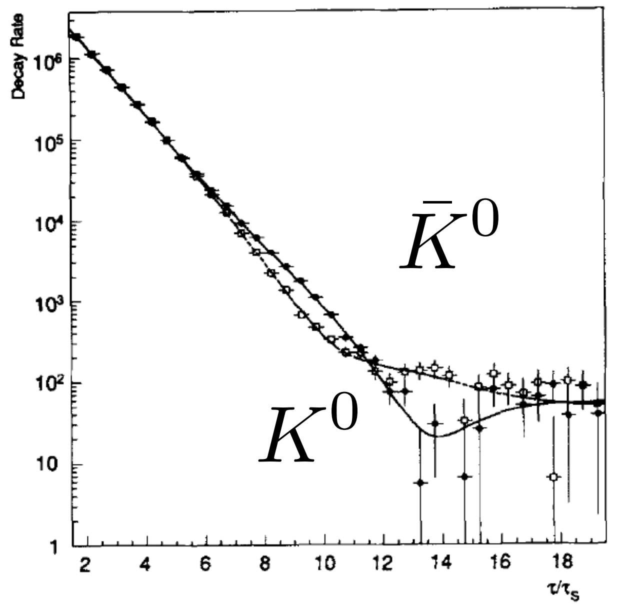
- Such an interference has been observed/utilized in many processes: e.g.,

$K^0 \to \pi\pi, K^0 \to 3\pi$ and $K^0 \to \pi^0 e^+ e^-$

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

cf. CPLEAR experiment@CERN) $\{K_S, K_L\} \to \pi^+\pi^-$

[CPLEAR collaboration '95] measured the interference between K_L and K_S

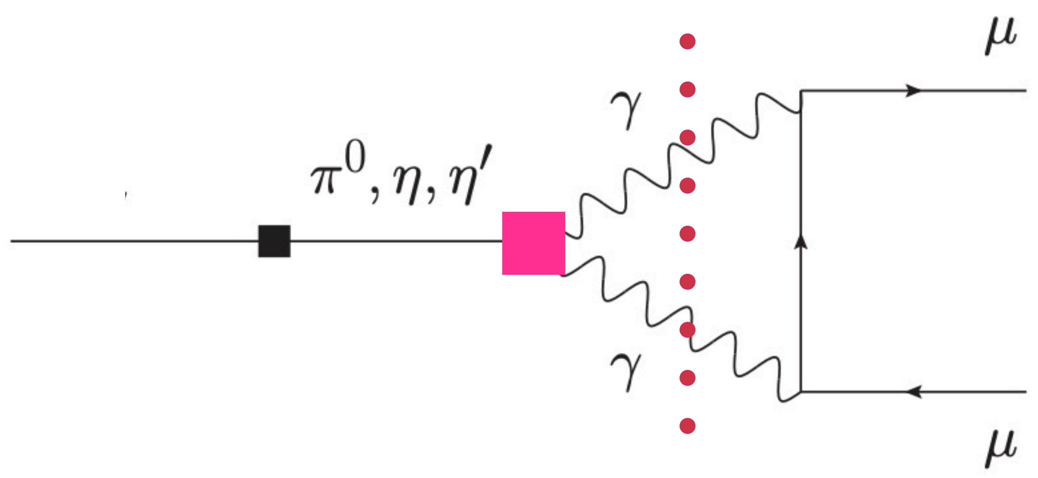


Direct *CP* violation in $K^0_{L/S} \to \mu^+\mu^-$

- Important idea: interference corresponds to **genuine direct CP violation**

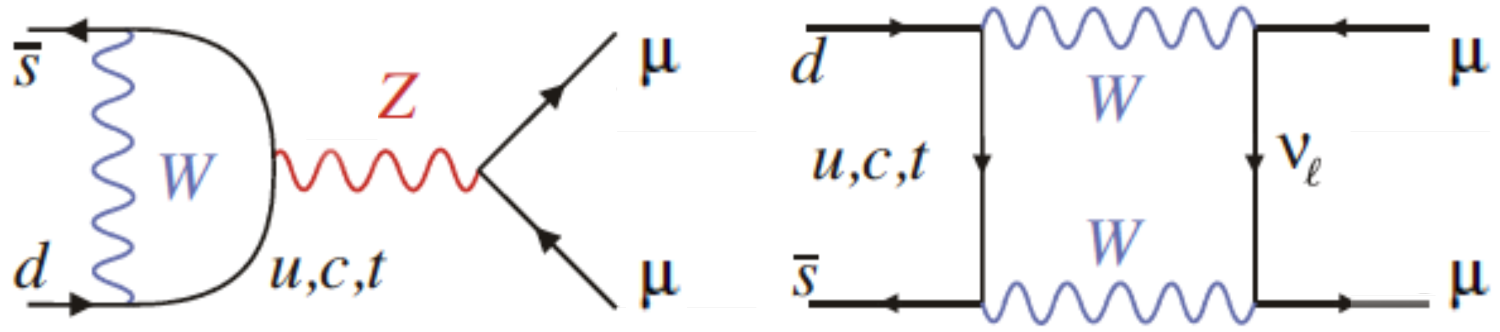
[D'Ambrosio, TK, 1707.06999; Dery, Ghosh, Grossman, Schacht, 2104.06427]

K_L



Interference

K_S



weak phase = 0;
strong phase = photon loop:
$K_L \to \gamma\gamma \,|\, \gamma\gamma \to \mu\mu$

weak phase = arg $[V^*_{ts} V_{td}]$;
strong phase = 0

Both weak and strong phase differences exist

Two advantages:

1. **Numerically enhanced** by the anomaly-driven (■) $K^0_L \to \gamma\gamma$, $\mathcal{O}(1/f_\pi)$
2. **Theoretically clean** due to the optical theorem in K^0_L amplitude

Four-fold ambiguity

- There are four-fold ambiguity of the strong phase in light of the experimental determination [Dery, Ghosh, Grossman, TK, Schacht, 2211.03804]

Optical theorem

$$\cos^2\varphi_0 = \frac{\alpha_{em}^2 m_\mu^2}{2\beta_\mu m_K^2}\log^2\left(\frac{1-\beta_\mu}{1+\beta_\mu}\right)\times\frac{\mathcal{B}\left(K_L^0\to\gamma\gamma\right)}{\mathcal{B}\left(K_L^0\to\mu^+\mu^-\right)}$$

$$= 0.96\pm 0.02_{\rm exp}\pm 0.02_{\rm th}$$

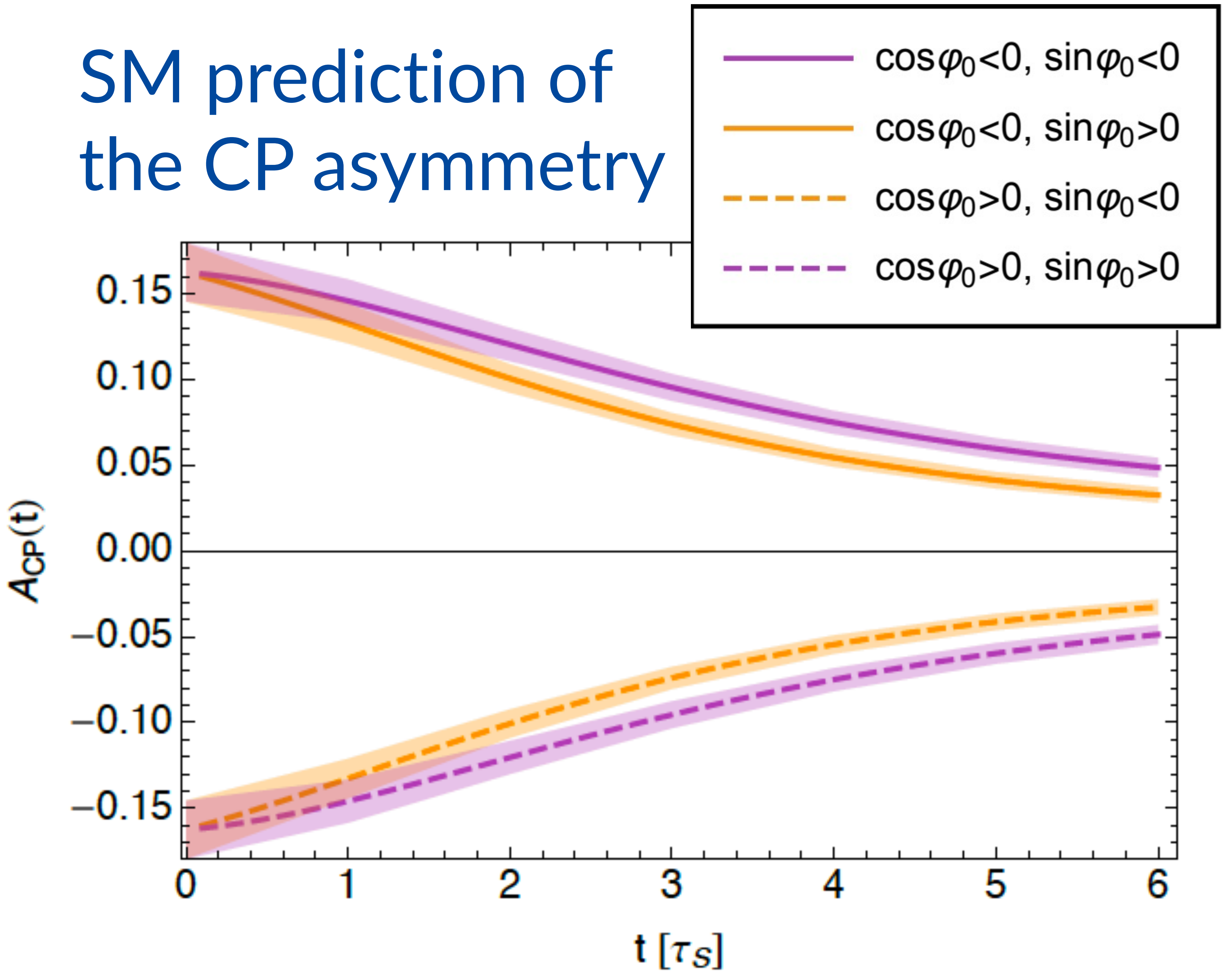
$$\varphi_0 \simeq 12^\circ, 168^\circ, 192^\circ, 348^\circ$$

- This provides two SM predictions in $K_L^0\to\mu^+\mu^-$

$$\mathcal{B}\left(K_L^0\to\mu^+\mu^-\right)_{\rm SM} = \begin{cases} 7.44^{+0.41}_{-0.34}\times 10^{-9} & \text{for} \quad \tilde{A}_{\rm CP}>0 \quad (\cos\varphi_0<0) \\ 6.83^{+0.24}_{-0.17}\times 10^{-9} & \text{for} \quad \tilde{A}_{\rm CP}<0 \quad (\cos\varphi_0>0)\end{cases}$$

[Hoferichter, Hoid, de Elvira, 2310.17689]

SM prediction of the CP asymmetry



[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]

New physics for $K_S^0 \to \mu^+\mu^-$ including interference

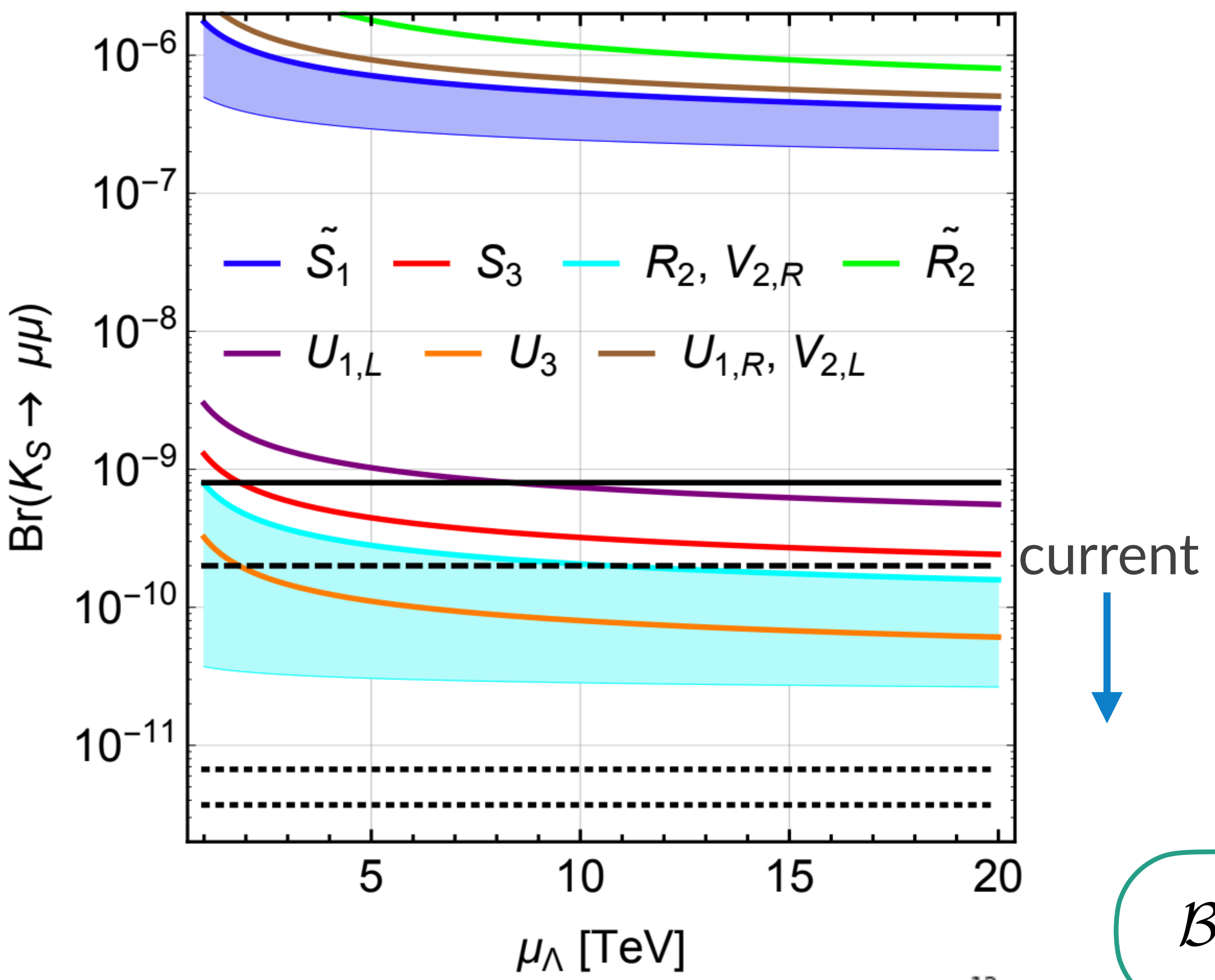
Leptoquark

can be $\mathcal{O}(10^{-10})$

R_2, or $U_{1,\mathrm{L}}$
(the others are excluded by $K^+ \to \pi^+\nu\bar{\nu}$)

[Bobeth, Buras '18]

D=0 Upper bound



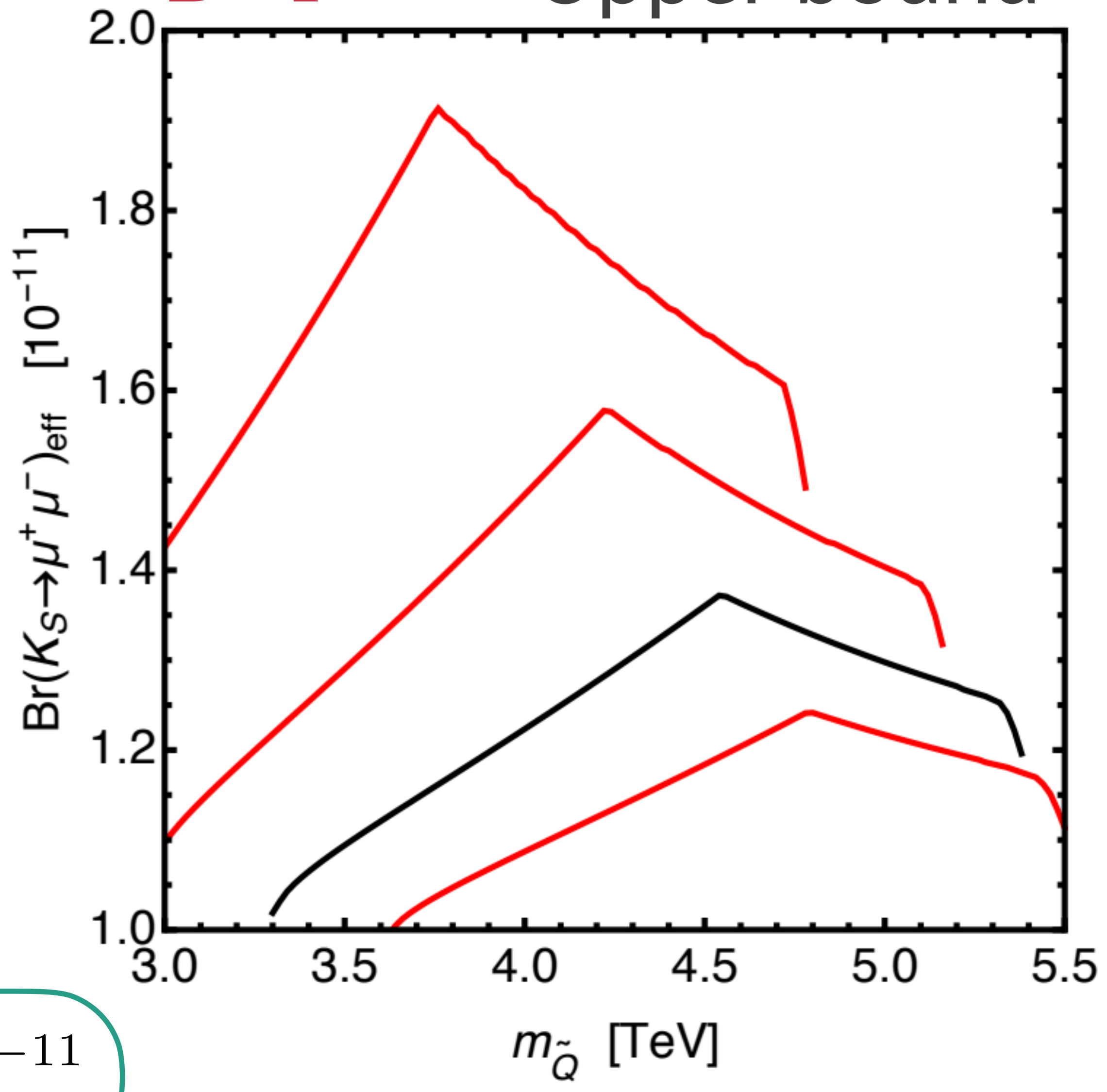
MSSM with large A_{LR}

$\lesssim 2 \times 10^{-11}$

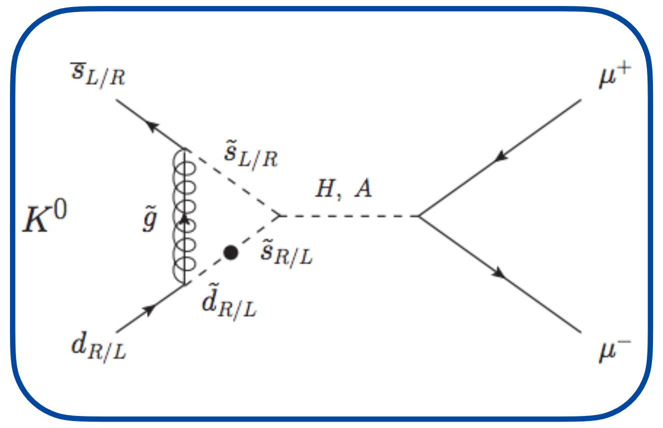
Only large $|D|$

[Endo, Goto, TK, Mishima, Ueda, Yamamoto '18]

D=1 Upper bound



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

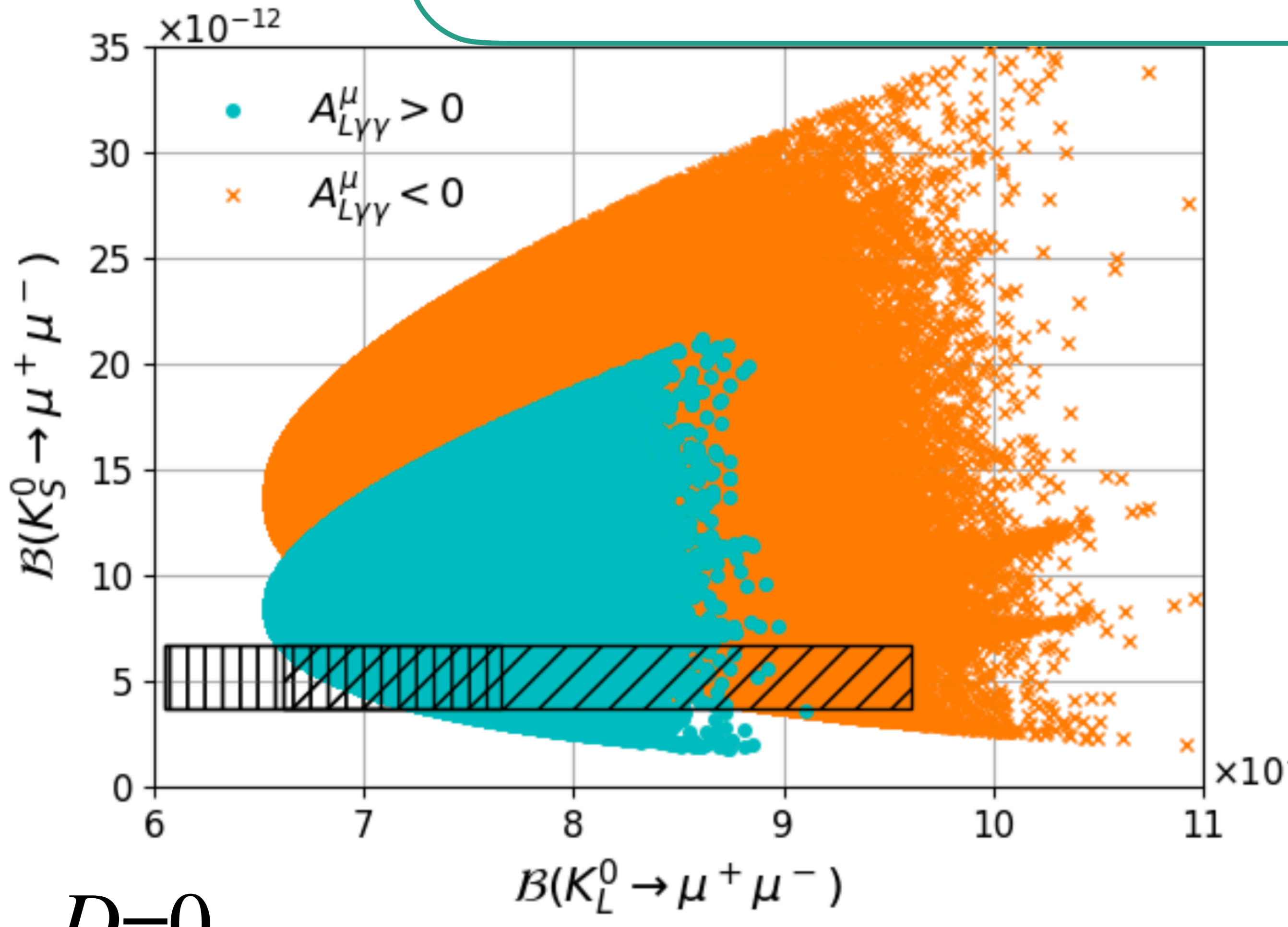


MSSM with large $\tan\beta$

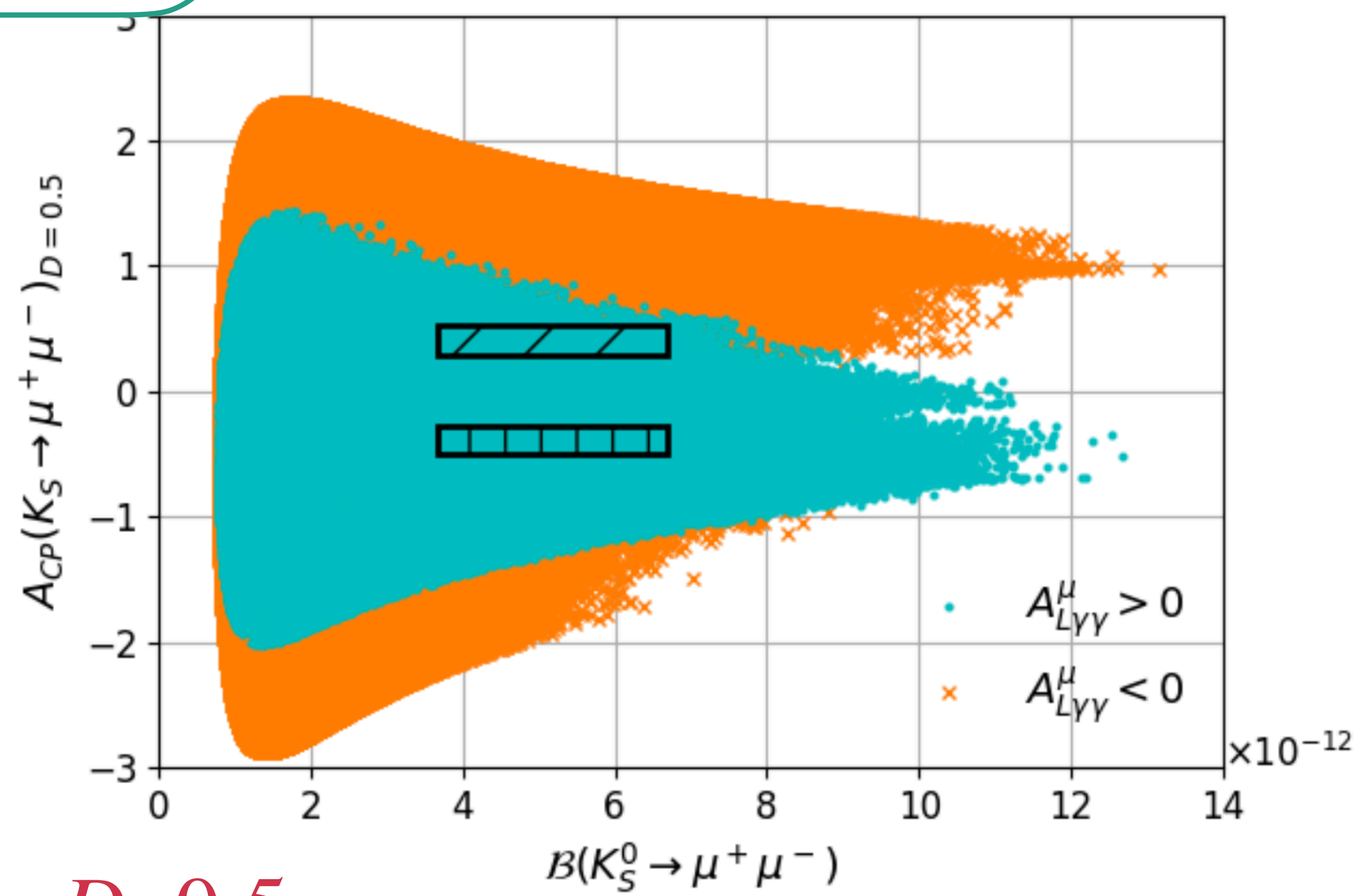
$\lesssim 3 \times 10^{-11}$

Even *D*=0

[Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18]



D=0



D=0.5

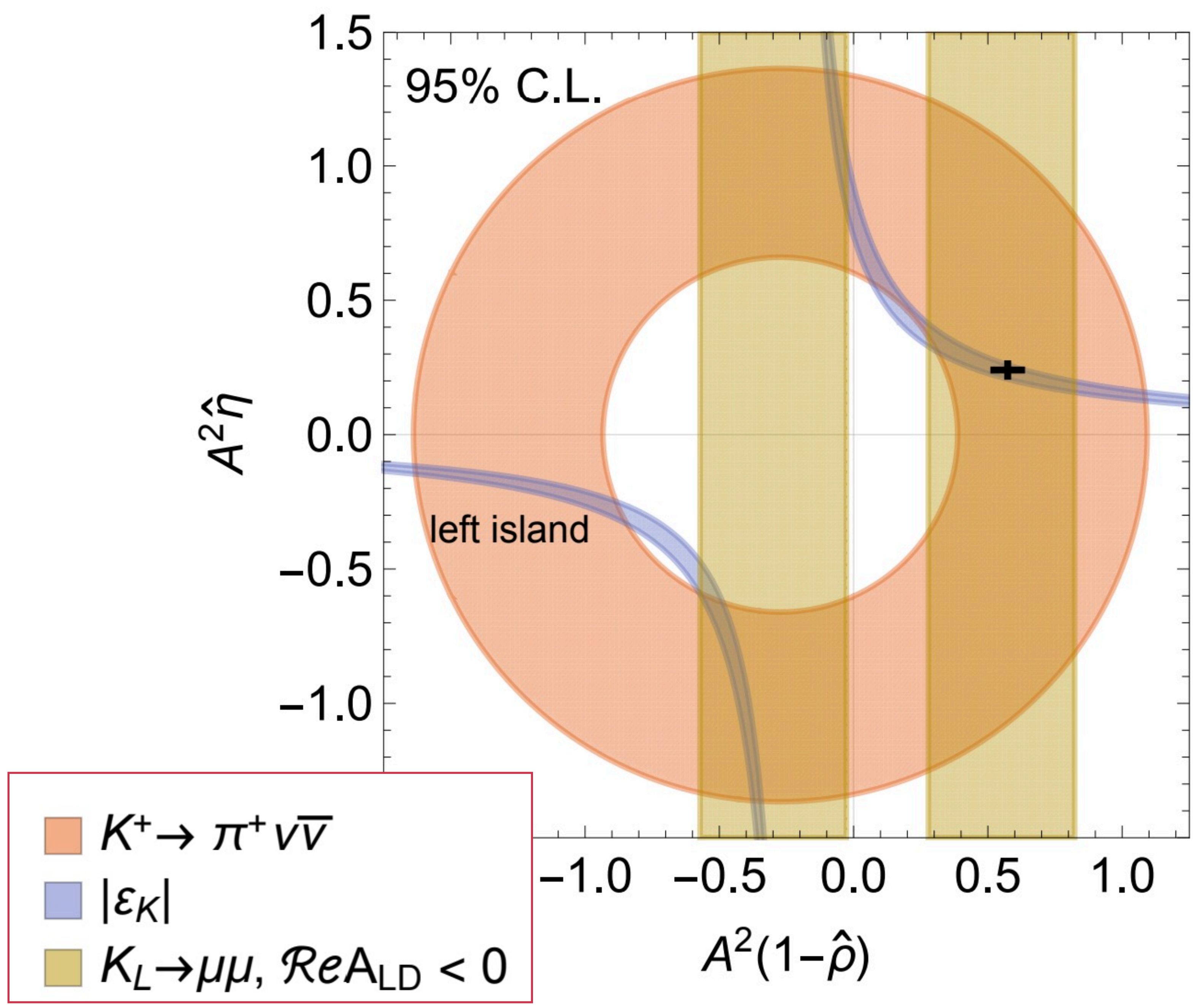
Kaon unitarity triangle

[Buras, Venturini, 2109.11032;
Lunghi, Soni, 2408.11190;
Dery, 2504.12386]

- New idea: large uncertainty from $|V_{cb}|$ can be dropped, when one considers the unitarity triangle in not $(\bar\rho, \bar\eta)$, but in $(A^2(1-\hat\rho), A^2\hat\eta)$ plane

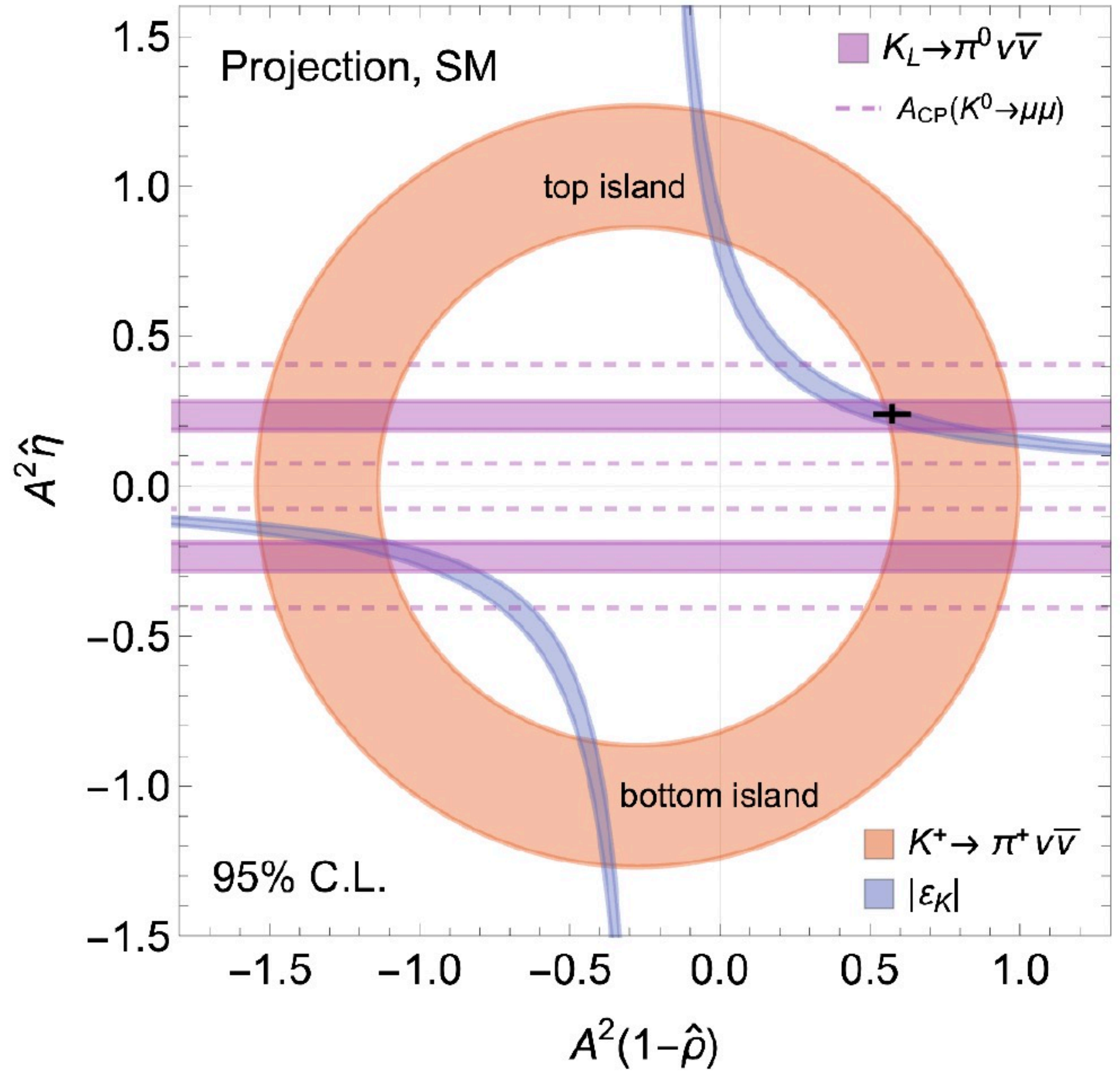
with $A^2\lambda^4(1-\hat\rho+i\hat\eta) \equiv -\frac{V_{td}V_{ts}^*}{V_{cd}V_{cs}^*}$

[Dery, 2504.12386]



current best-fit point

near future
≈ 2040



$K_L\to\pi^0\nu\bar\nu$
$A_{CP}(K^0\to\mu\mu)$

[Dery, KAON2025]

Beautiful in theory side — but can LHCb really do it?

K^0 and $\overline{K}^0$ yields are almost the same in the LHC (momentum-dependent asymmetry is about a few-percent)

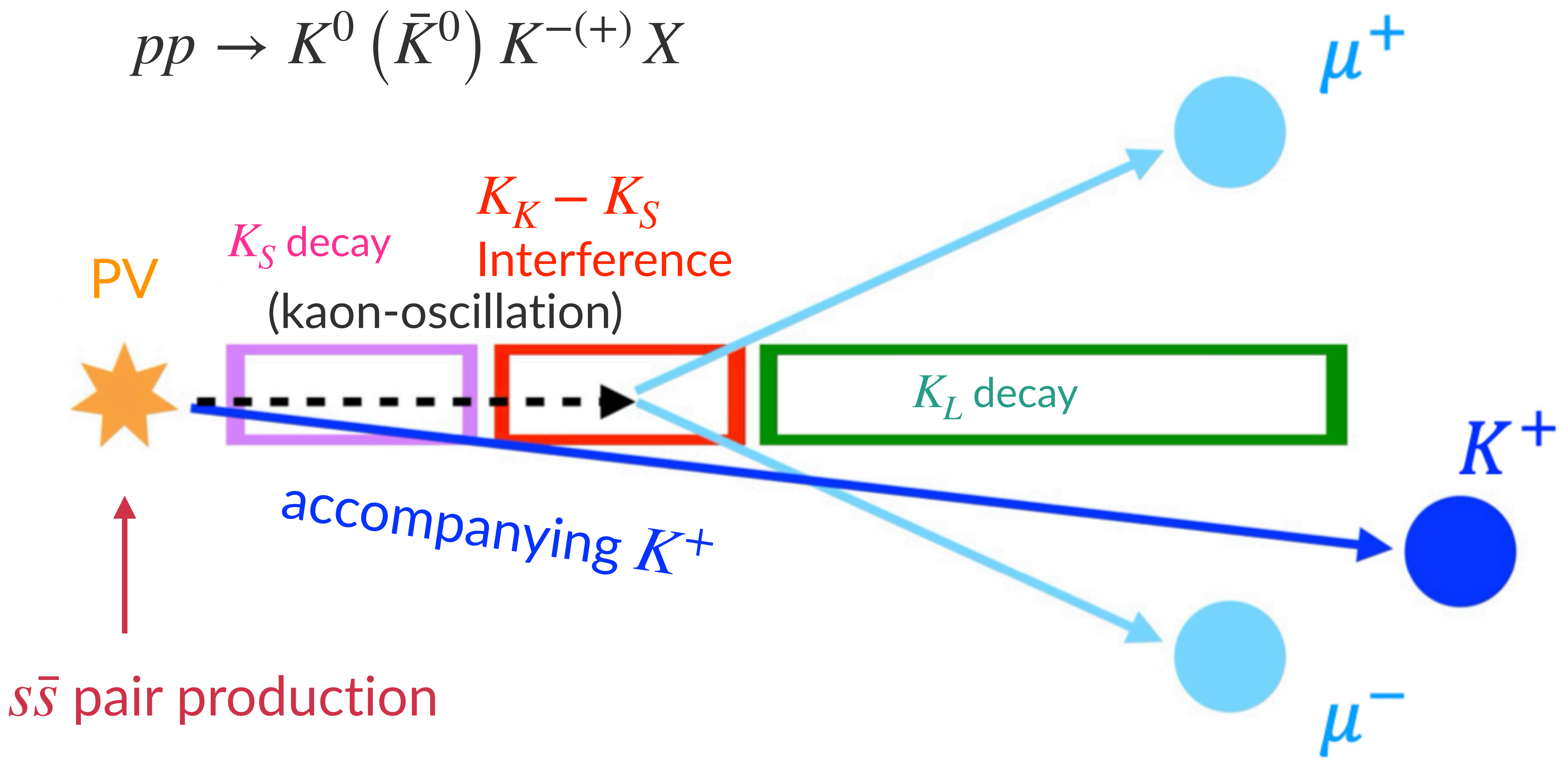
→ **Additional flavor tag** is needed

Flavor tagging method

- We simulates the following events within an LHCb-like setup:

[D'Ambrosio, TK, 1707.06999]

$$pp \to K^0\left(\bar{K}^0\right) K^{-(+)} X$$



- Forward $s\bar{s}$ productions
- Two opposite sign muon generated from the interference region
- Single accompanying charged kaon to distinguish $K^0(t=0)$ or $\overline{K}^0(t=0)$

Comparison with B_s^0 tagging

- Similar tagging can be possible for B_s^0 decays: **same-side-kaon (SSK) tag** $pp \to B_s^0 \left(\overline{B_s^0}\right) K^{+(-)}X$

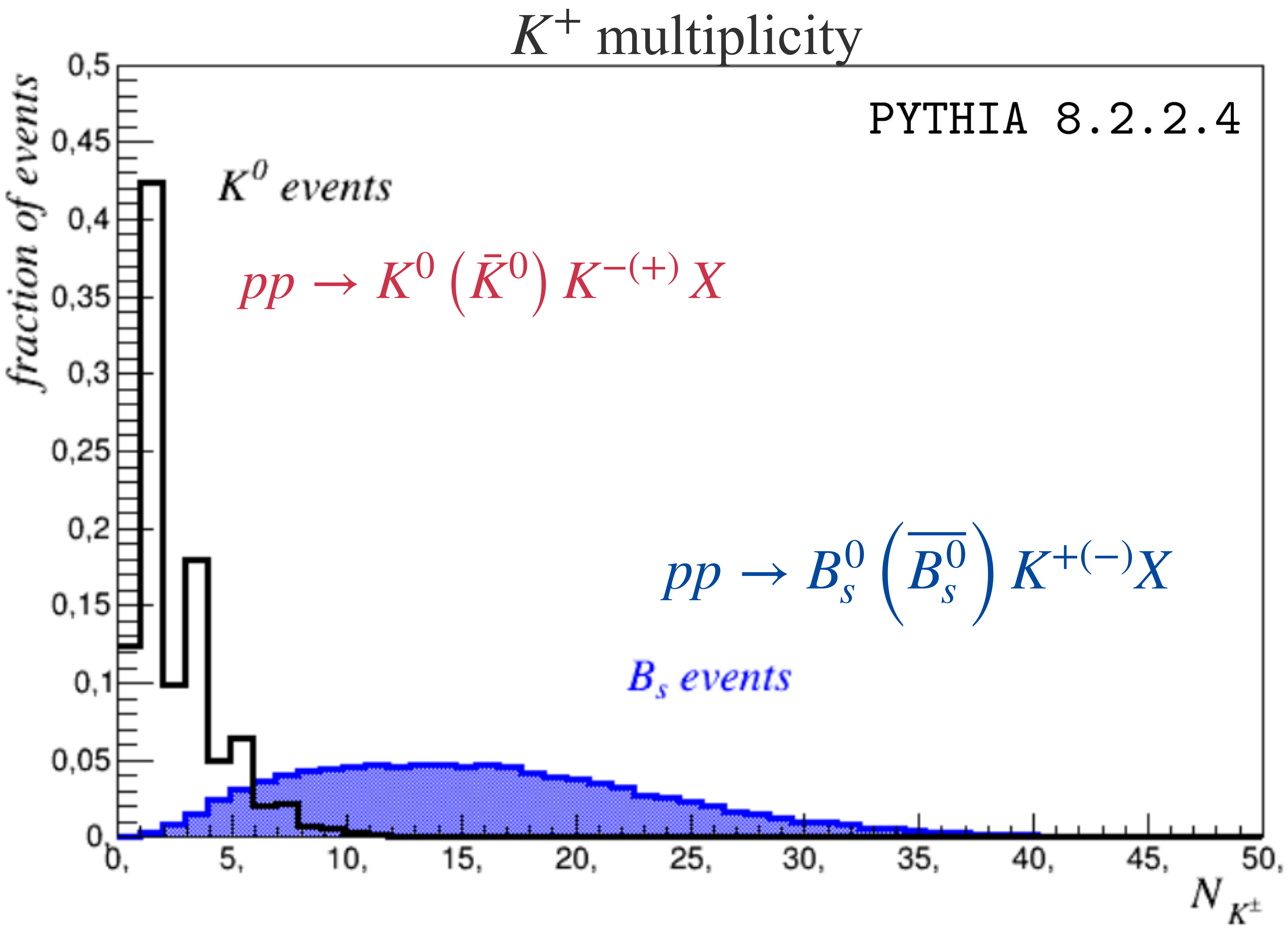
[LHCb, LHCb-CONF-2012-033]

- Our fast simulation result:

Tagging power: $T_P = \varepsilon_T D^2 \approx 22\%$

tagging efficiency of K^0 $\varepsilon_T \approx 62\%$

Dilution factor $D \approx 60\%$



cf. $T_P(B_s^0) \approx 3\%$ much better than the B_s^0 tagging power, thanks to the lower K^+ multiplicity

Background reduction

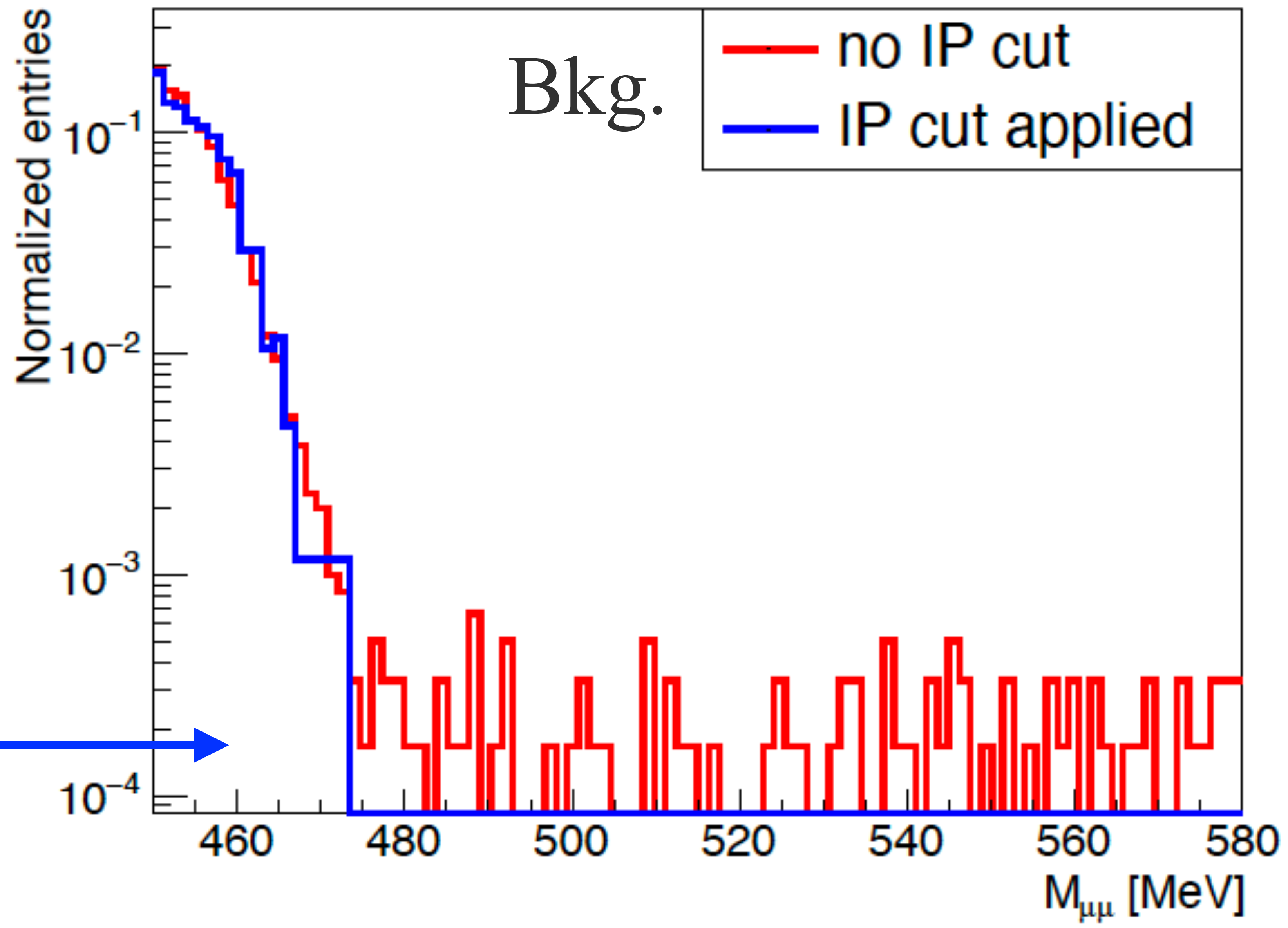
- Background is currently dominated by $K_S^0 \to \pi^+(\to \mu^+\nu)\,\pi^-(\to \mu^-\bar{\nu})$

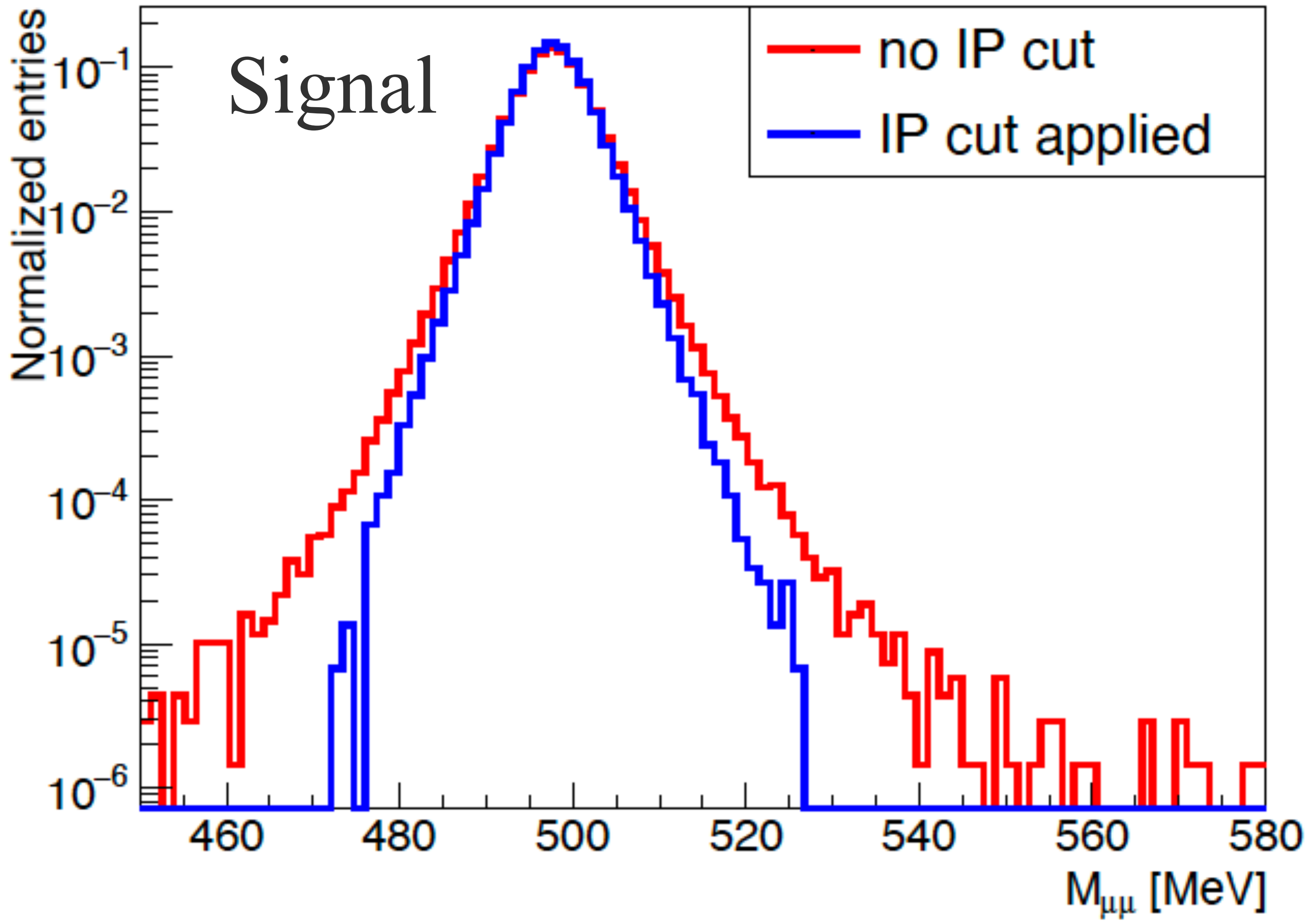
  muon from pion decays in flight

- This Bkg. can be separated by an impact parameter cut of K^0 from the PV

  reconstructed invisible K^0 line

Out of the kaon invariant mass cut



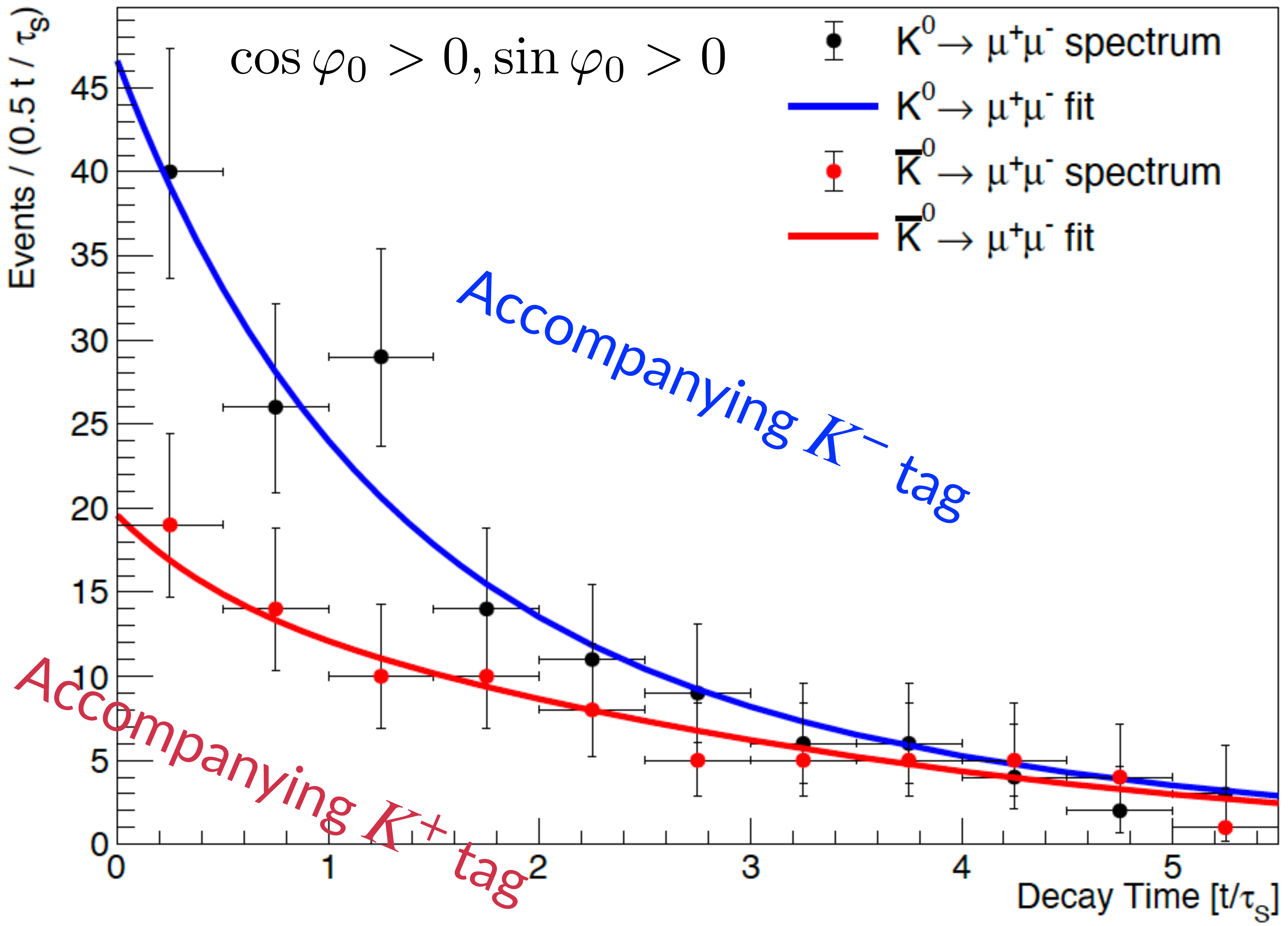


- The IP cut will **improve** the signal sensitivity **by a factor of** ≈ 9 for 300 fb-1

Decay-time analysis

[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]

- We simulate the decay-time distribution for the **LHCb Upgrade II setup**
- It is clearly shown that the CP violation between $K^0 \to \mu^+\mu^-$ and $\overline{K}^0 \to \mu^+\mu^-$ can be measured for small decay time region

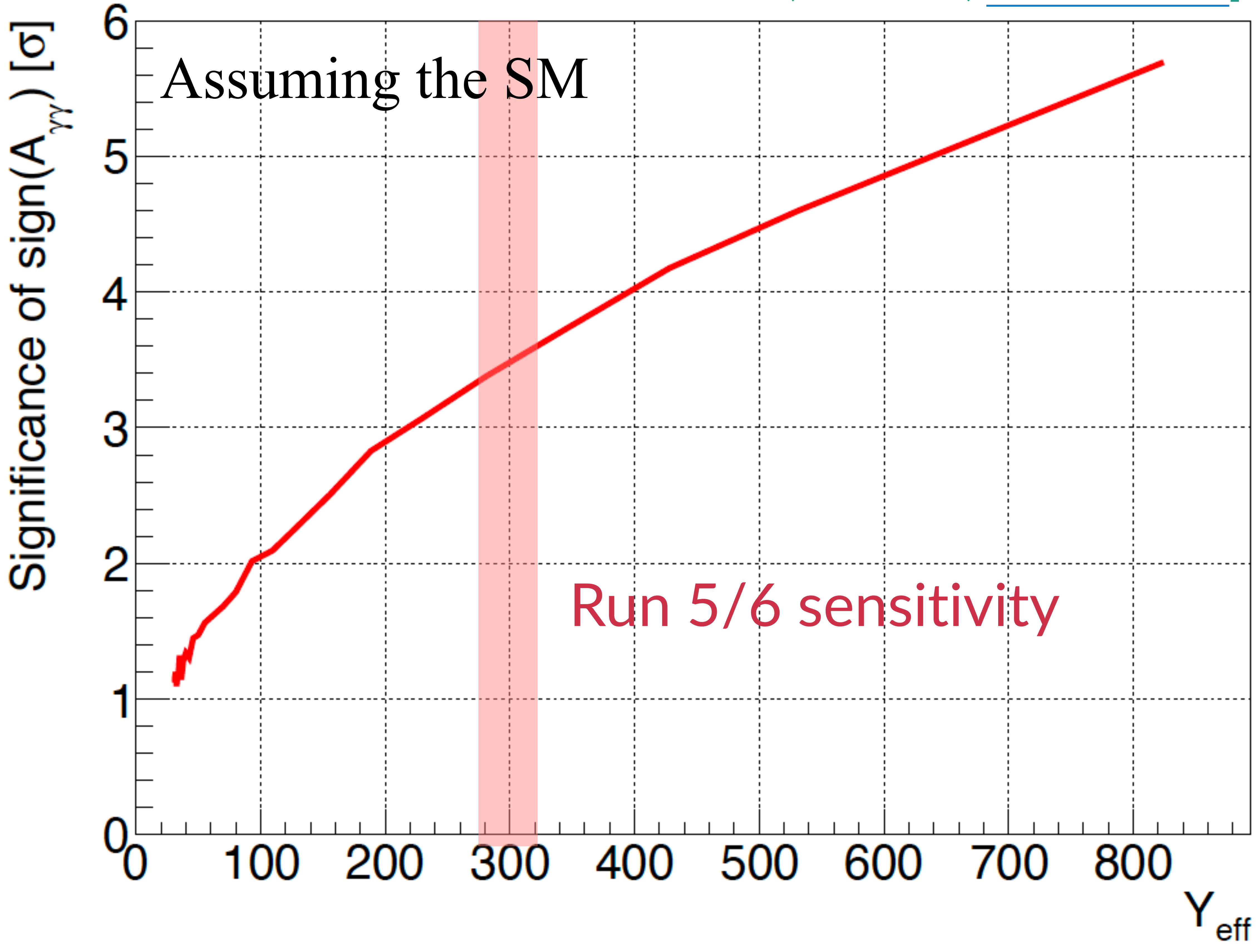


Sensitivity to the sign of $A(K_L^0 \to \gamma\gamma)$

- A simultaneous fit to the K^0 and $\overline{K}^0 \to \mu^+\mu^-$ decay-time distributions can probe the unknown sign of $A(K_L^0 \to \gamma\gamma)$
- LHCb Upgrade II can distinguish discrete ambiguity in the SM prediction of $\mathcal{B}(K_L^0 \to \mu^+\mu^-)$

→ reduce theoretical uncertainty

[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]



Sensitivity to the CP-violating parameter

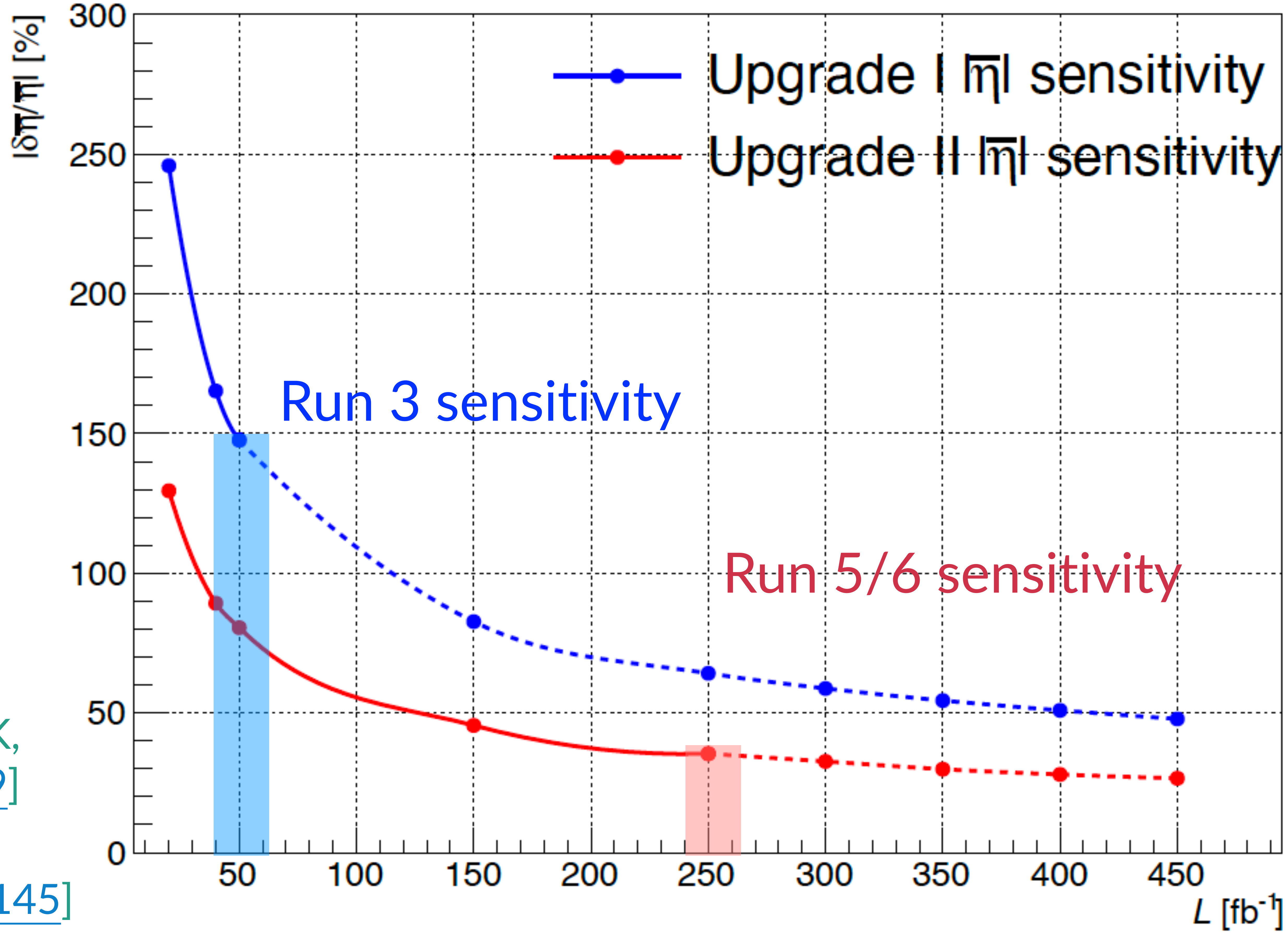
- In Upgrade II, a **factor 3 improvement** is expected using events by downstream track
- LHCb Upgrade I and II can measure $A^2\lambda^5|\bar{\eta}|$ with 150% and 35% accuracy, respectively
- Further improvements for flavor tagging are possible via

$$pp \to K^{*+}X \to K^0\pi^+X$$
$$pp \to K^0\Lambda(\to p\pi^-)X$$

[D'Ambrosio, TK, 1707.06999]

deep-learning method [Prouve, et al, 2404.14145]

[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]

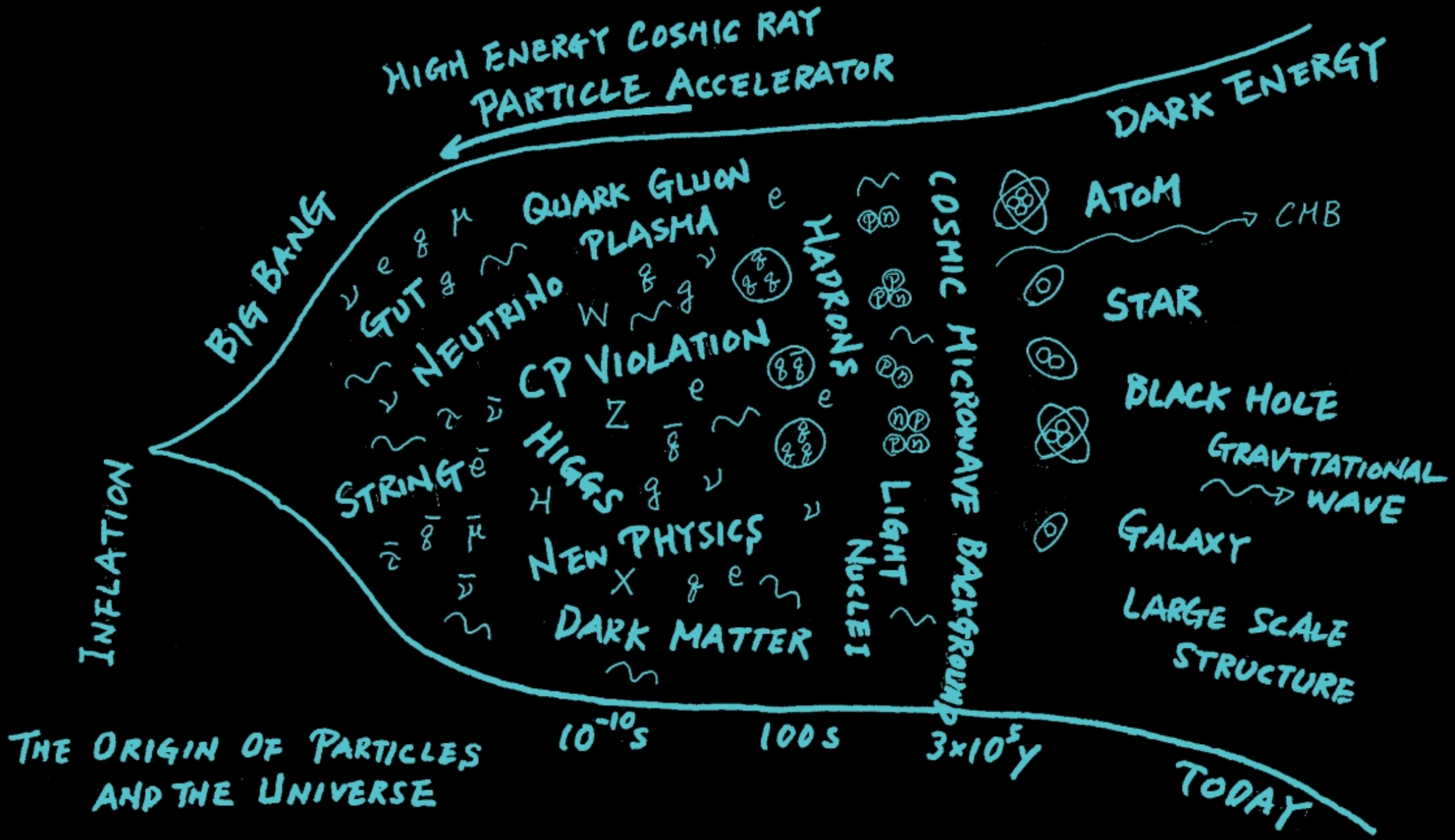


Conclusions

- New direction ⇨ $K_L^0 - K_S^0$ interference in $K^0 \to \mu^+\mu^-$ provides a powerful probe of **CP-violating short-distance physics**
- Excellent flavor tagging via $pp \to K^0\left(\bar{K}^0\right) K^{-(+)} X$ is essential, and simulation shows that it is **much better than** the SSK tag in B_s^0 decays
- LHCb Upgrade II will offer a unique opportunity to directly measure the **CP-violating parameter** $A^2\lambda^5|\bar{\eta}|$ **with 35%** uncertainty **via** $K^0 \to \mu^+\mu^-$
- Run 5 (after the Upgrade II) starts from 2036; **complementary to KOTO II (**$K_L^0 \to \pi^0\nu\bar{\nu}$**) ?**

Thank you!

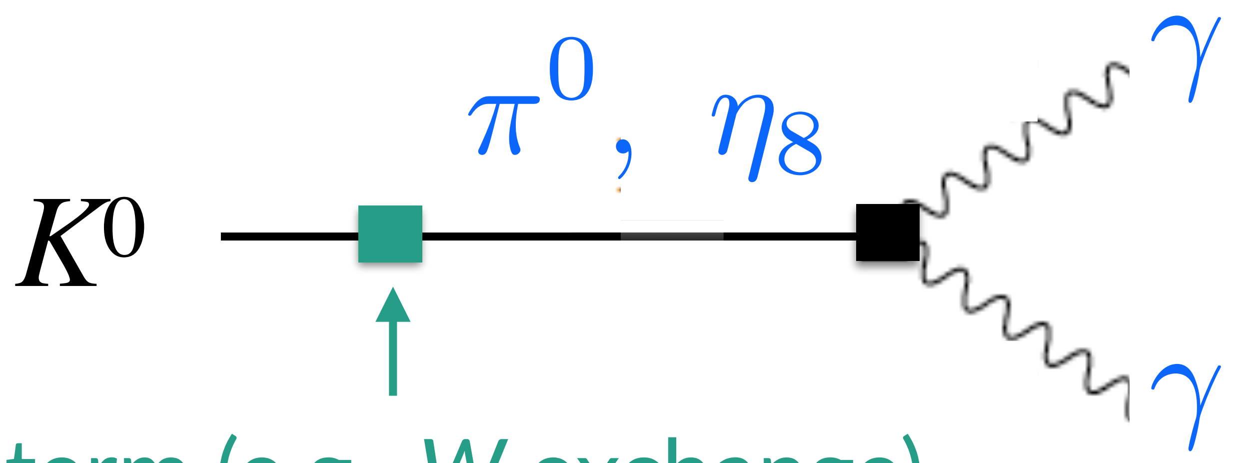
Backup slides

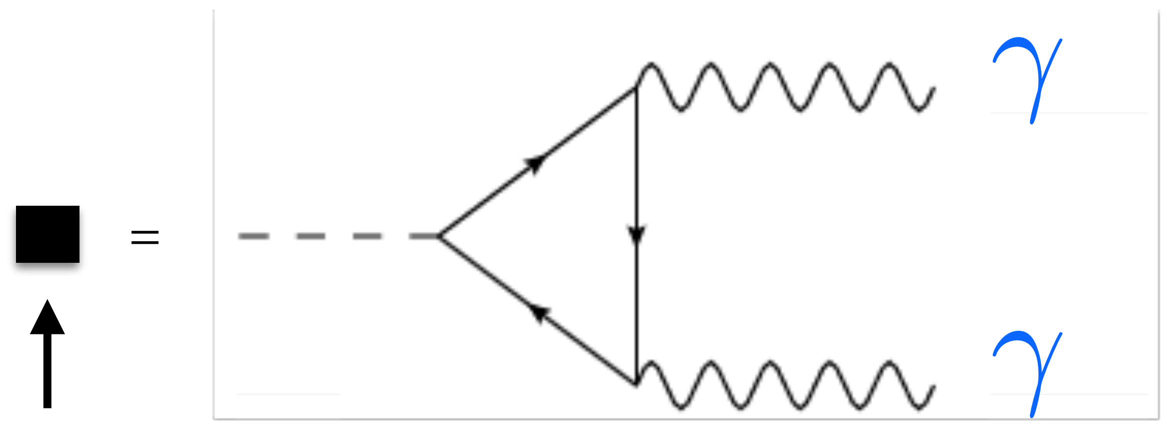


(c) KMI/Nagoya-U

Interesting cancellation in $K^0 \to \gamma\gamma$

- Leading contribution in $K^0 \to \gamma\gamma$ comes from the following diagram:





- The amplitude @O(p^4) [e.g., D'Ambrosio, Ecker, Isidori, Neufeld '94]

$$Amp. \propto \frac{1}{m_K^2 - m_\pi^2} + \frac{1}{3}\frac{1}{m_K^2 - m_{\eta_8}^2} = \frac{4m_K^2 - 3m_{\eta_8}^2 - m_\pi^2}{3(m_K^2 - m_\pi^2)(m_K^2 - m_{\eta_8}^2)} \quad = 0$$

- Gell-Mann—Okubo formula ($SU(3)_F$ with massive strange) [Gell-Mann '61; Okubo '62]

$$4m_K^2 = 3m_{\eta_8}^2 + m_\pi^2$$

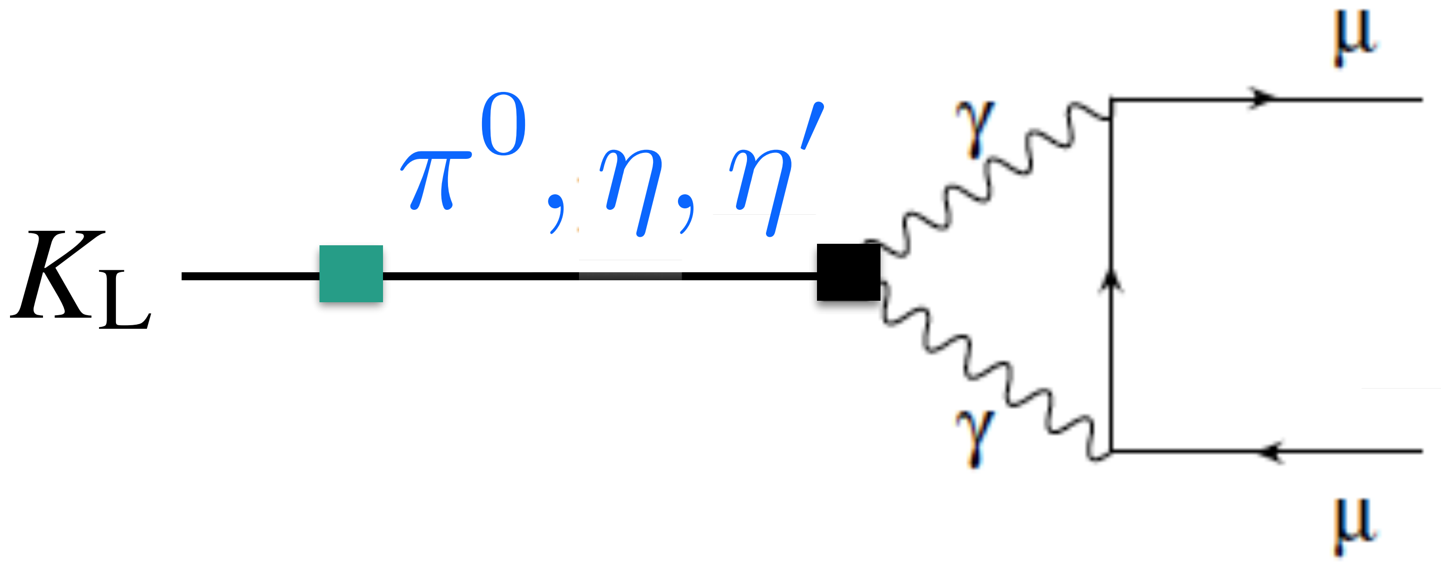
Leading pieces are canceled out

Details of $K_L^0 \to \mu^+\mu^-$

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

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

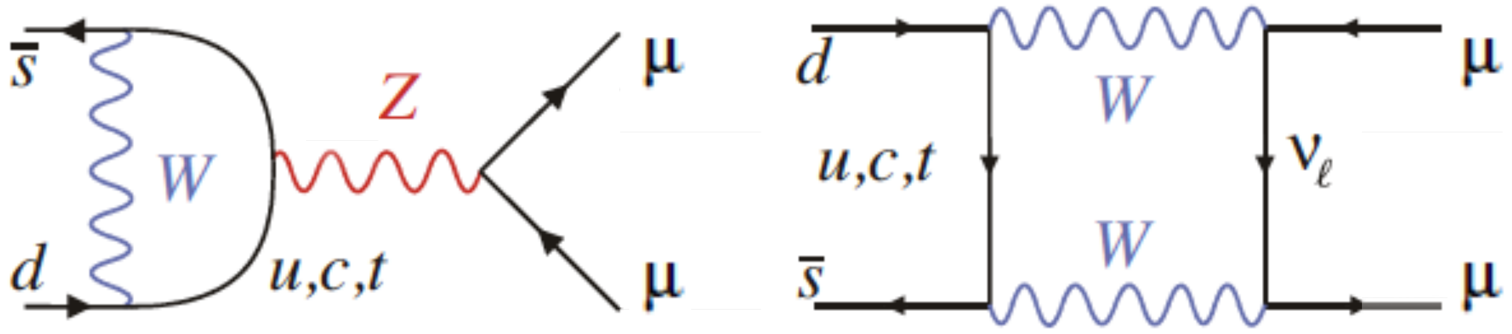
Long distance CPC



Interference

- π^0 and η contributions are cancelled out @O(p^4) by the Gell-Mann—Okubo formula. The higher order corrections are unknown.
- Absolute value of the amplitude can be extracted from BR($K_L \to \gamma\gamma)_{exp}$ → **sign ambiguity of** $A(K_L \to \gamma\gamma)$

Short distance CPC



$\propto \mathrm{Re}\left[V_{ts}^* V_{td}\right] = \mathrm{Re}\left[\lambda_t\right]$

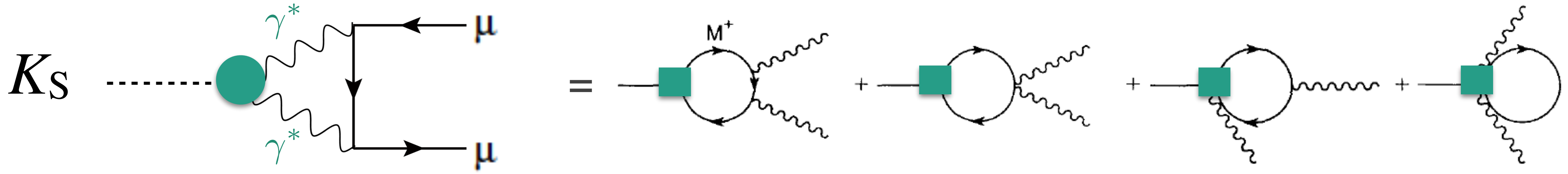
Details of $K_S^0 \to \mu^+\mu^-$

[Ecker, Pich '91;
Colangelo, Stucki, Tunstall '16]

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

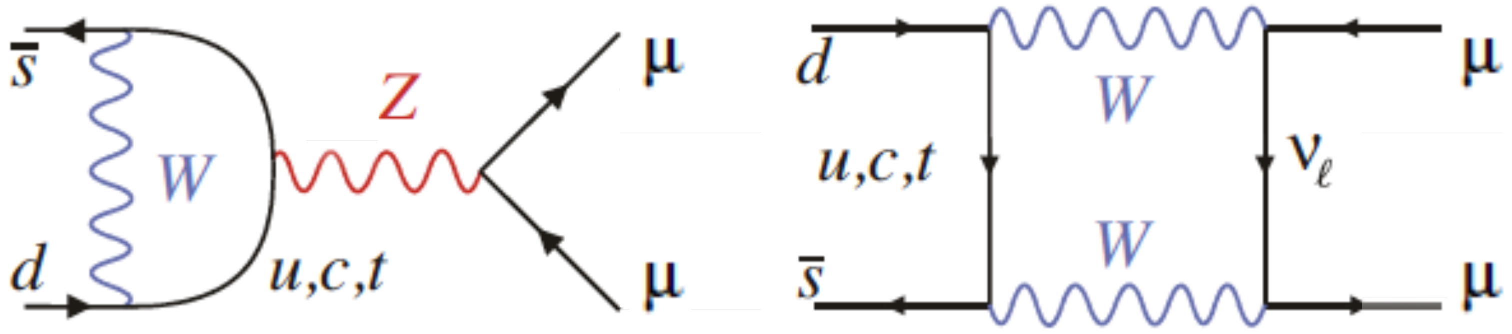
Long distance CPC

charged pion loop = leading



- BR$(K_S \to \gamma\gamma)_{exp}$ determines A$(K_S \to \gamma\gamma)$, which includes 17% (FSI) enhancement from pion loop
- Since two photons are off-shell states, the 17% enhancement is debatable and large uncertainty appears (reducible via $K_S \to \gamma\mu\mu$, $K_S \to \mu\mu\mu\mu$ and $K_S \to \mu\mu ee$ by LHCb, KLOE-2)

Short distance CPV



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