Implications on Observation of charm CPV

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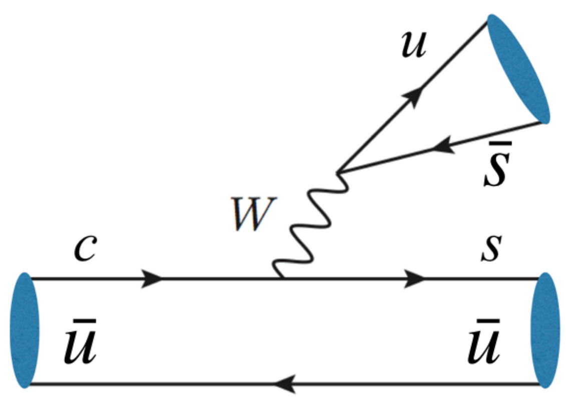
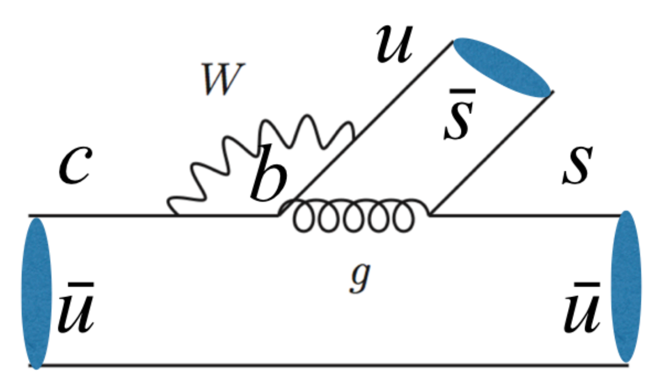
LHCb observes charm CPV

1903.08726

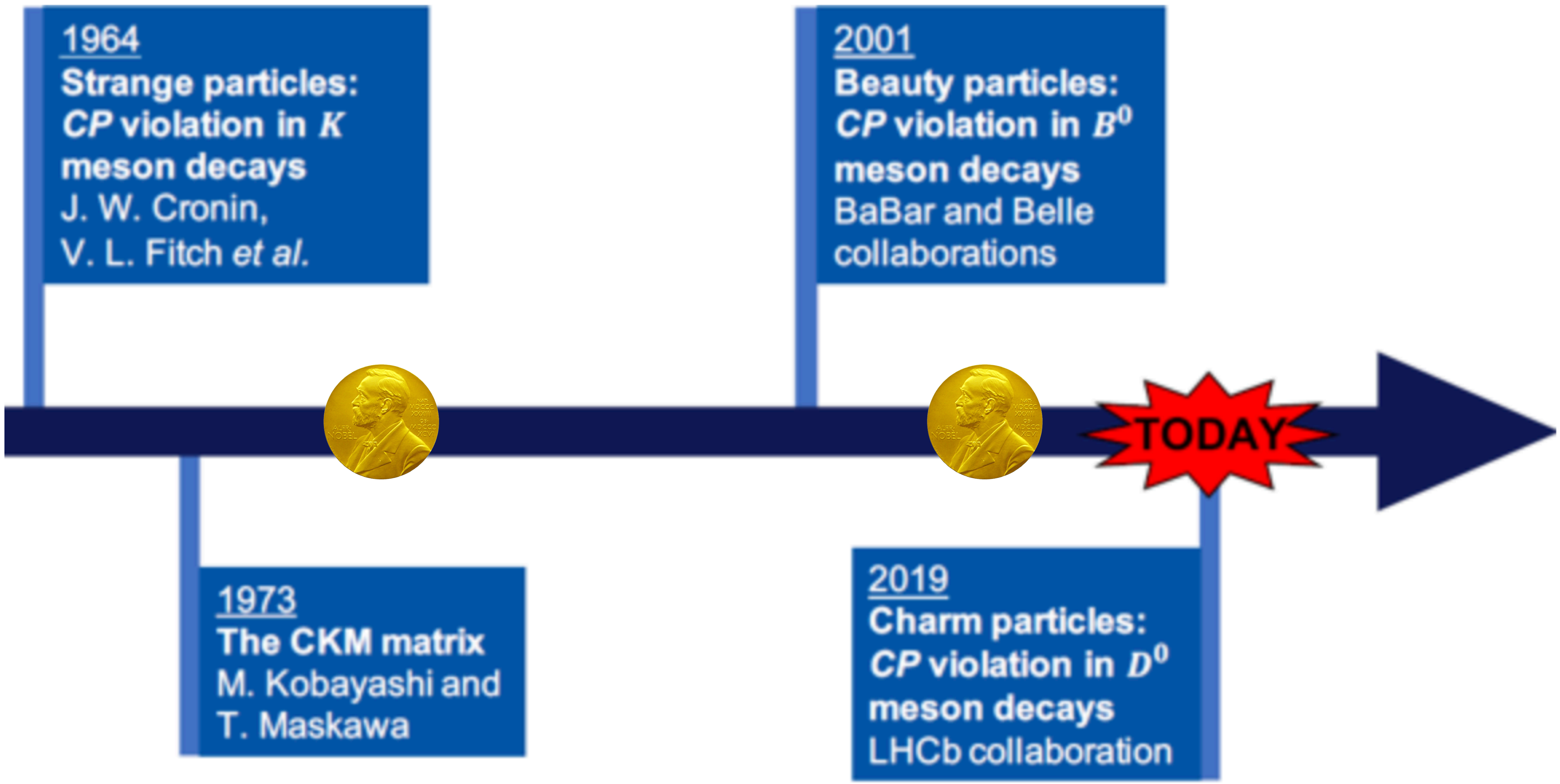
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

- $> 5\sigma$ **, first observation of CPV in charm**





LHCb observes charm CPV

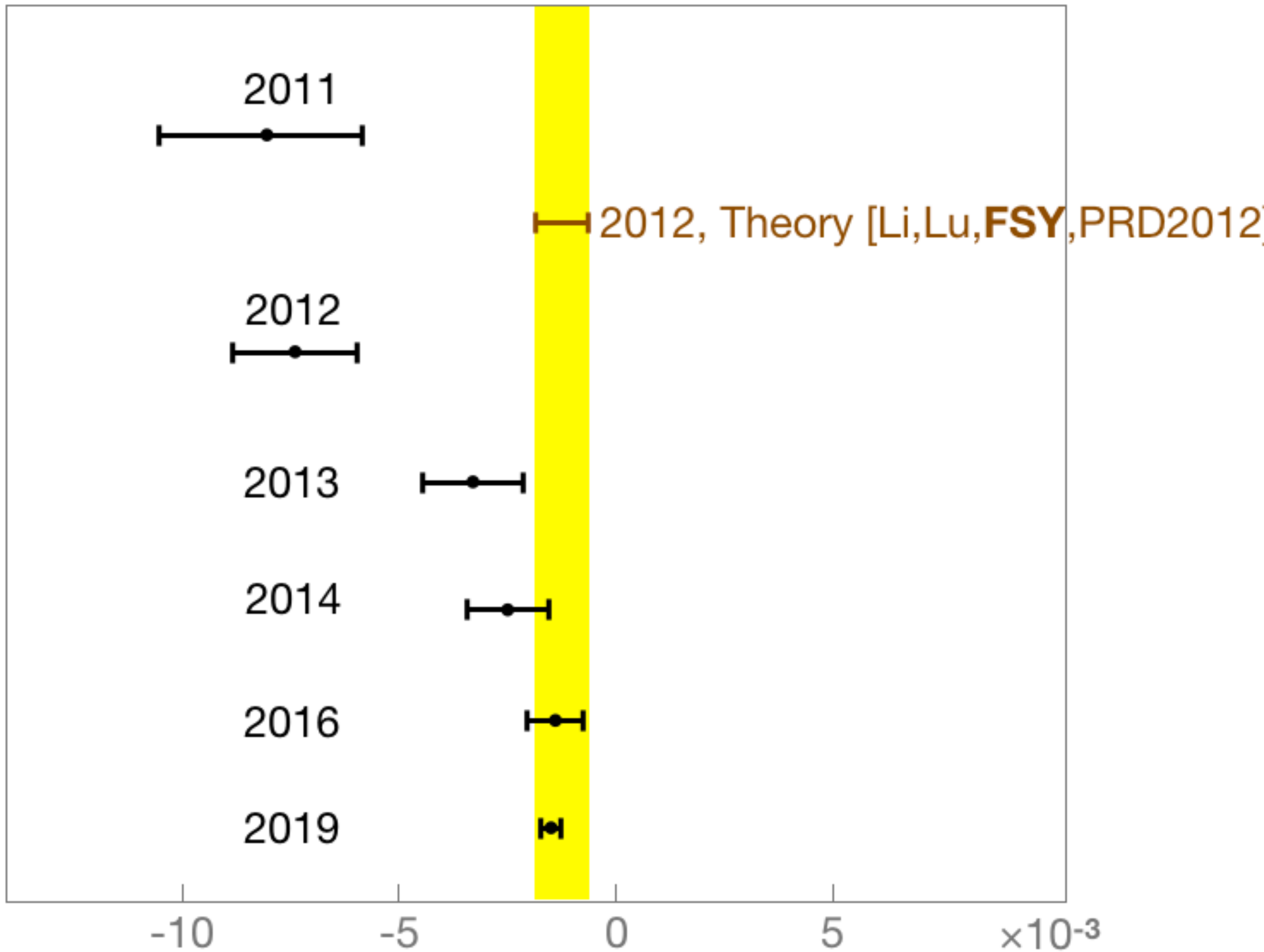


An important milestone in particle physics

Measurements of ΔA_{CP}

Measurements	ΔA_{CP}	Publication	World Average
2011LHCb (D*)	(-0.82±0.24)%	PRL108,111602	(-0.74±0.15)%
2012 CDF	(-0.62±0.23)%	PRL109,111801	
2012 Belle	(-0.87±0.41)%	1212.1975	
2013LHCb (D*)	(-0.34±0.18)%	LHCb-CONF-2013-03	(-0.33±0.12)%
2013LHCb (B)	(+0.49±0.33)%	PLB723(2013)33	
2014LHCb (B)	(+0.14±0.18)%	JHEP07(2014)041	(-0.25±0.10)%
2016LHCb (D*)	(-0.10±0.09)%	PRL116,191601	(-0.14±0.07)%
2019LHCb(all)	(-0.15±0.03)%	1903.08726	(-0.16±0.03)%

Exp Averages



Understanding charm CPV

$$\mathcal{A}(D^0 \to K^+K^-) = \lambda_s \mathcal{T}^{KK} + \lambda_b \mathcal{P}^{KK},$$

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \lambda_d \mathcal{T}^{\pi\pi} + \lambda_b \mathcal{P}^{\pi\pi},$$

$$\lambda_i = V_{ci}^* V_{ui}$$

$$\Delta A_{CP} = -2r \sin\gamma \left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|} \sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|} \sin\delta^{\pi\pi} \right)$$

$$r = |\lambda_b / \lambda_{d,s}|$$

$$2r \sin\gamma = 1.5 \times 10^{-3}$$

$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

→

$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|} \sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|} \sin\delta^{\pi\pi} \right) \approx 1$$

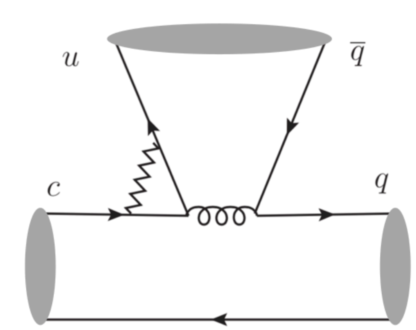
Li, Lu, **FSY**, PRD86,036012(2012); 1903.10638

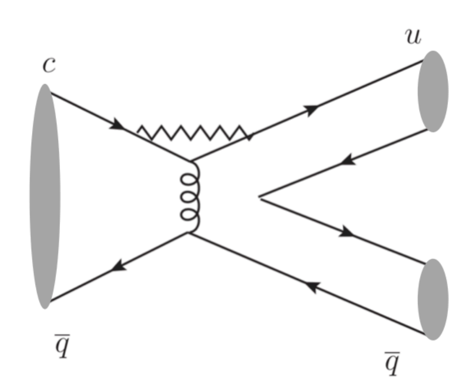
$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK}+\frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right)\approx 1 \quad \xrightarrow{\text{SU(3)}} \quad \boxed{\frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta\sim 1/2}$$

factorization-assisted topological-amplitude approach Li, Lu, **FSY**, '12

$$\frac{\mathcal{P}^{\pi\pi}}{\mathcal{T}^{\pi\pi}}=0.66e^{i134^\circ}, \quad \text{and} \quad \frac{\mathcal{P}^{KK}}{\mathcal{T}^{KK}}=0.45e^{i131^\circ}$$

Key: **Long-distance dynamics**

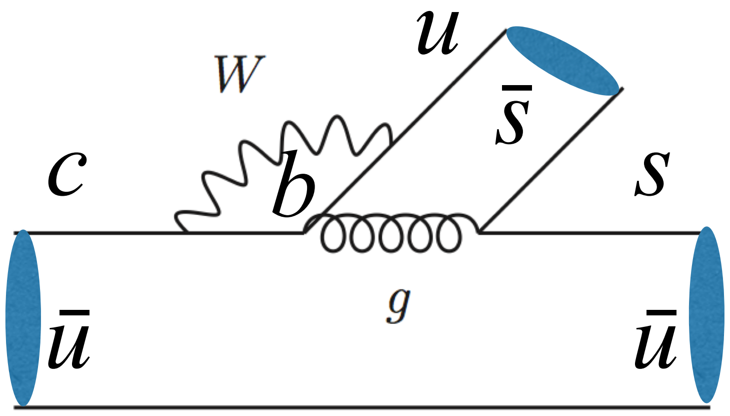




Understand: tree —> penguin; Branching ratio —> CPV

Charm CPV in theory

- **Ambiguity in perturbative theory**
  - **heavy quark expansion $1/m_c$,** m_c=1.3GeV, **converges slowly** in exclusive decays



★ **ΔA$_{CP}$(K^+K^-, $\pi^+\pi^-$) predicted from 10^{-4} to 10^{-2}**

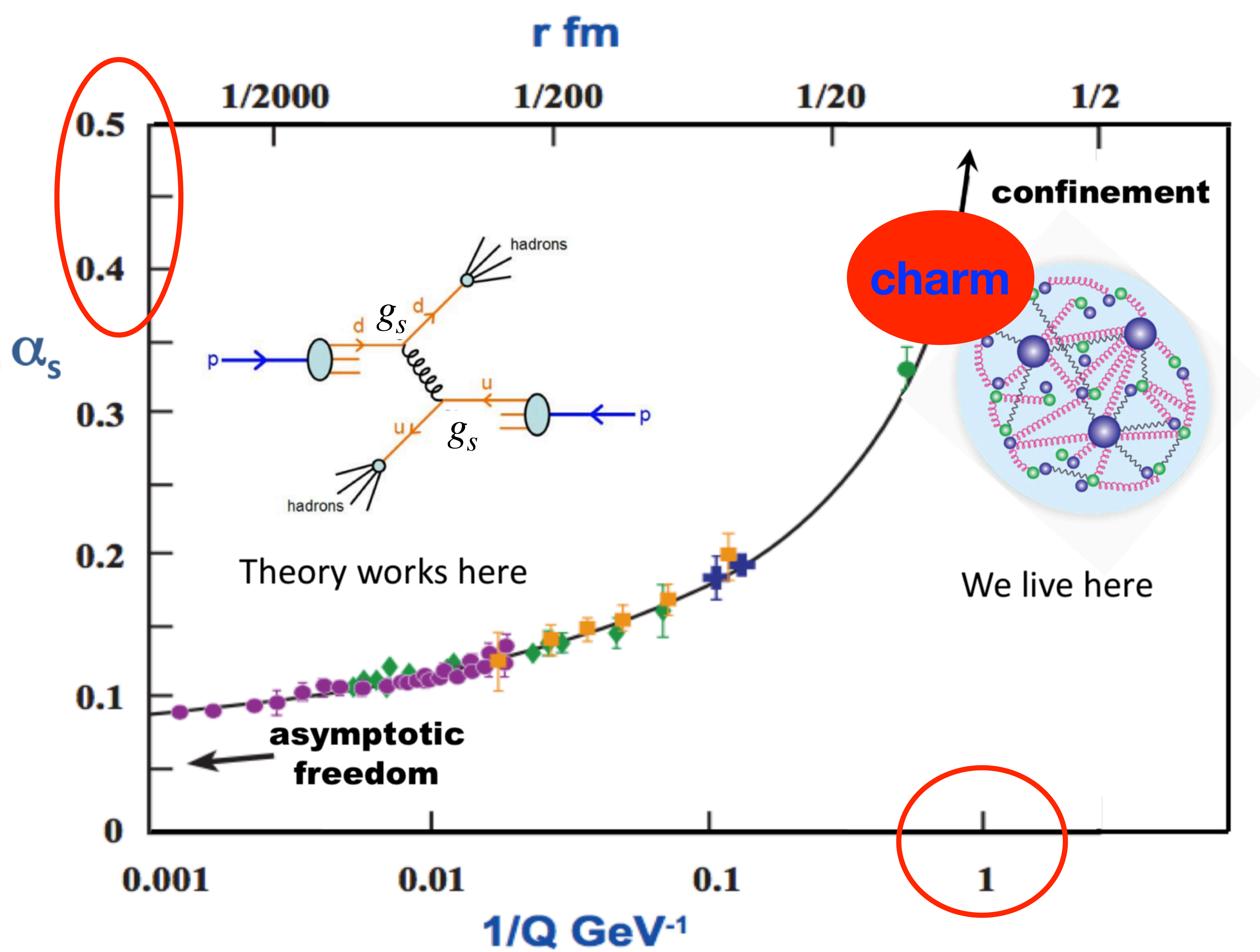
Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11; Brod, Grossmann, Kagan, Zupan, '11, '12; Feldmann, Nandi, Soni, '12; Bhattarcharya, Gronau, Rosner, '12; Cheng, Chiang, '12; Li, Lu, **FSY**, '12; Franco, Mishima, Silvestrini, '12; Hiller, Jung, Schacht, '12. Khodjamirian, Petrov, 17.

in the SM:

Cheng,Chiang,'12 : $(-1.51 \pm 0.04) \times 10^{-3}$

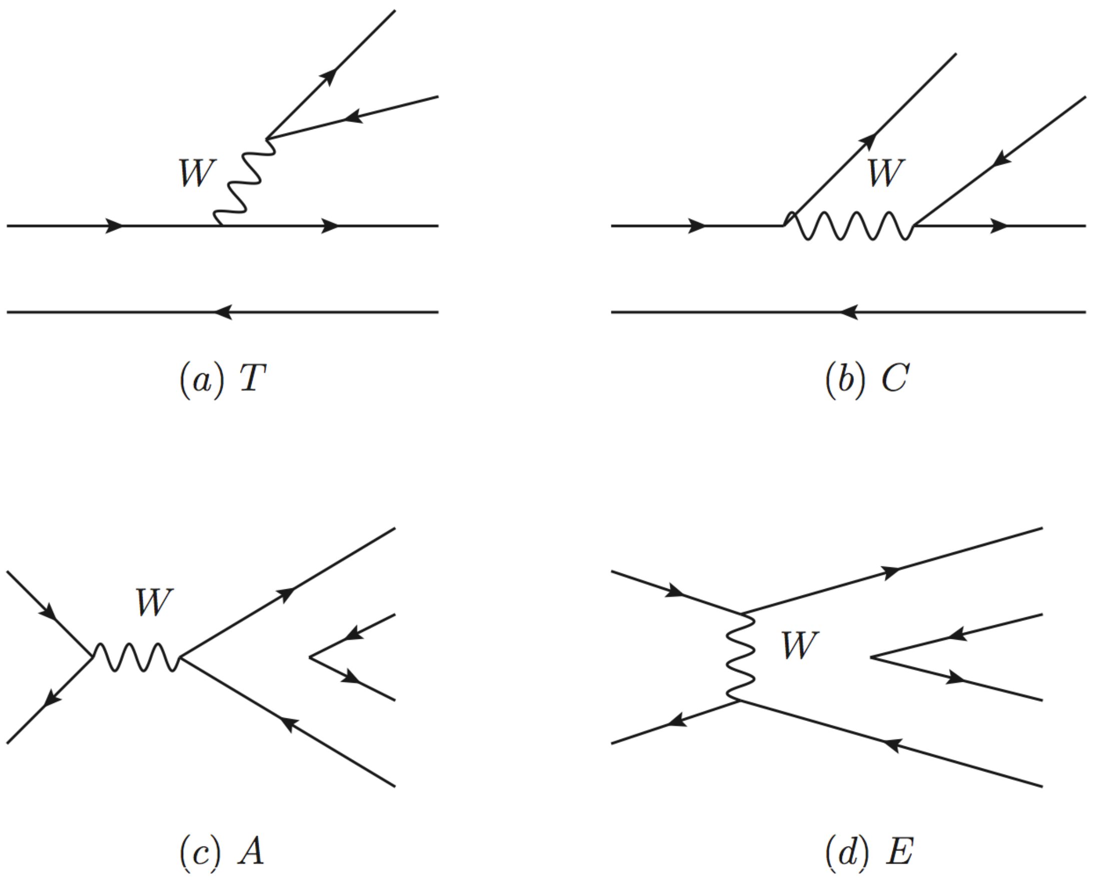
Li, Lu, **FSY**,'12 : $(-0.6 \sim -1.9) \times 10^{-3}$

Long-distance dynamics in charm



Topological Amplitudes

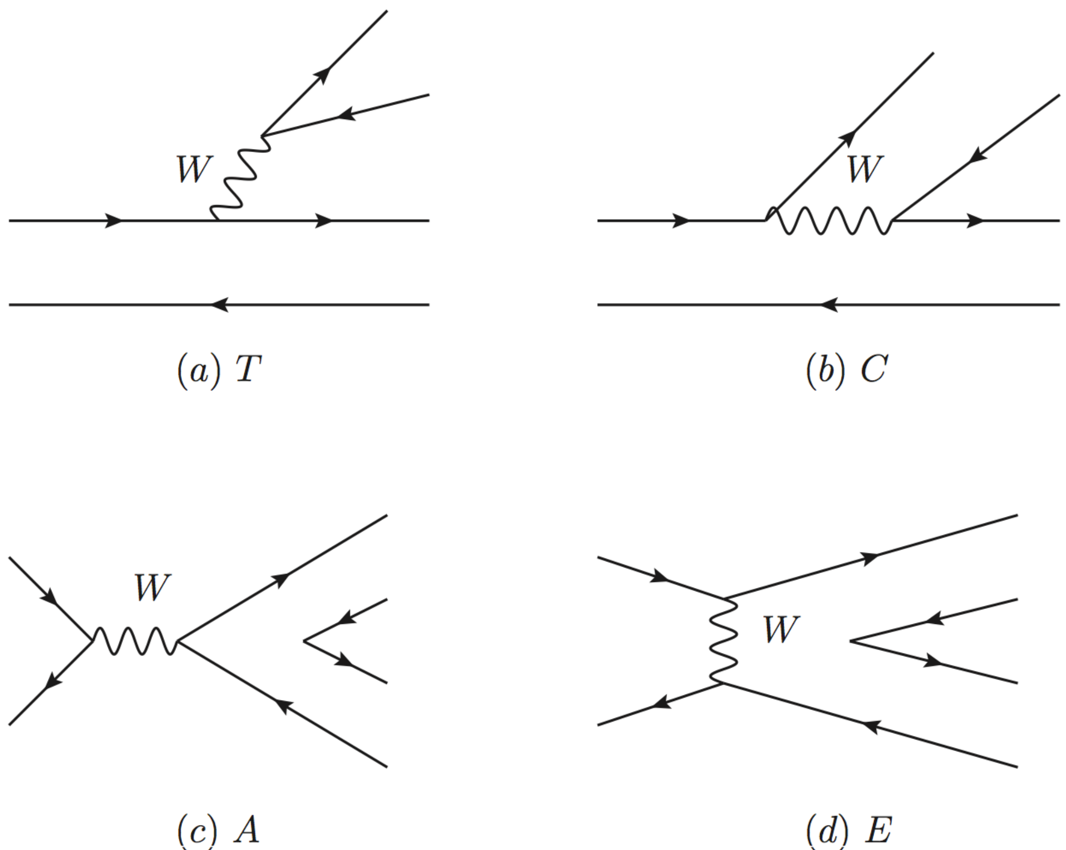
- According to the **weak flavour flows**
- **Including all strong interaction effects**
- **Amplitudes extracted from data**



Chau,86'; Chau,Cheng,87'; Bhattacharya, Rosner, 08'; Cheng, Chiang,10'

- Always in the flavour **SU(3) symmetry** limit, but **losing predictive power**

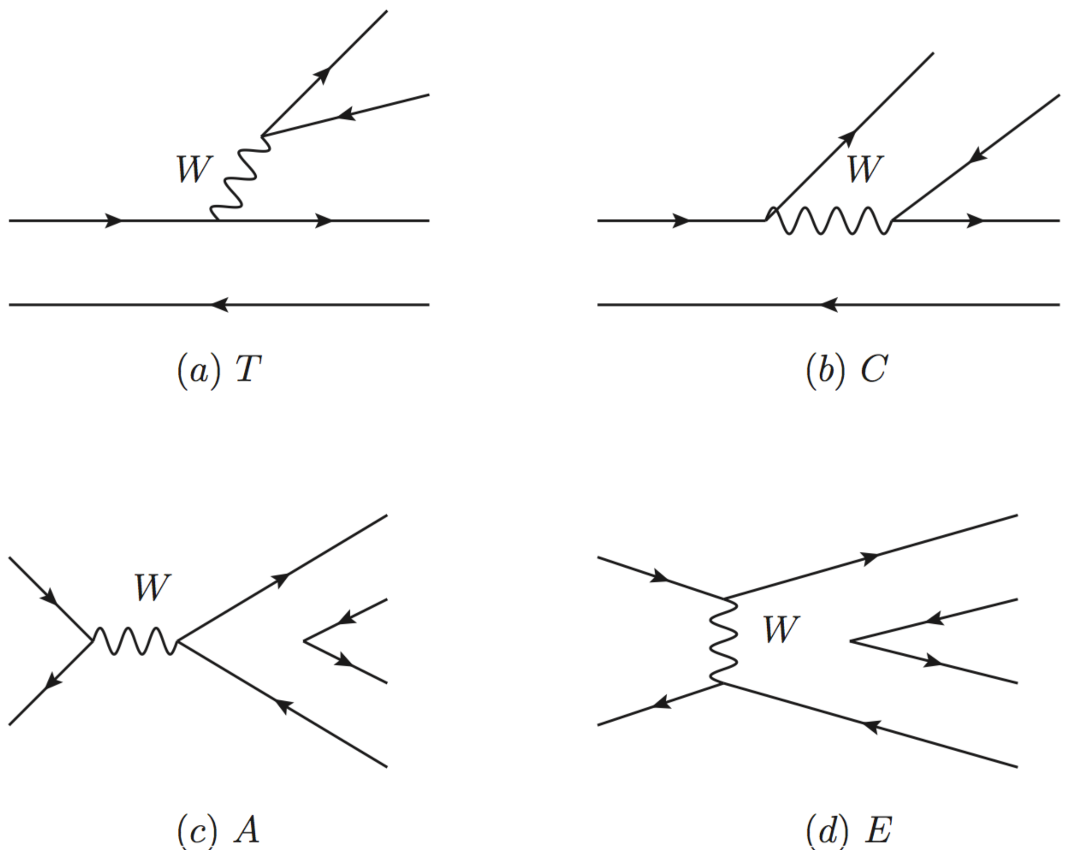
Factorization-Assisted Topological-Amplitude Approach (FAT)



- Dynamics In **factorization**:
  - **Short-distance**: Wilson coefficients
  - **Long-distance**: hadronic matrix elements

Li, Lu, **FSY**, '12

Factorization-Assisted Topological-Amplitude Approach (FAT)



- Dynamics In **factorization**:
  - **Short-distance**: Wilson coefficients
  - **Long-distance**: hadronic matrix elements

↓

Non-perturbative quantities

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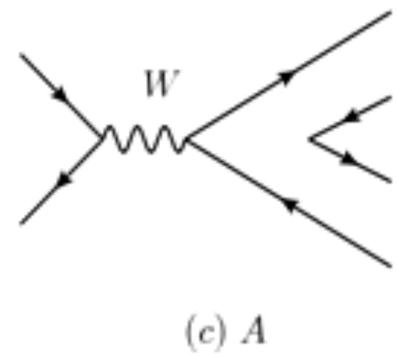
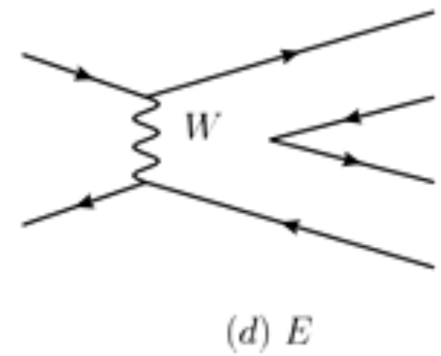
Extracted from data

Li, Lu, **FSY**, '12

W-annihilation (A) W-exchange (E)





$$\langle P_1 P_2 | \mathcal{H}_{\text{eff}} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} b_{q,s}^{E,A}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)$$

Li, Lu, **FSY**, '12

A: $b_{q,s}^A(\mu) = C_1(\mu) \chi_{q,s}^A e^{i\phi_{q,s}^A}$

E: $b_{q,s}^E(\mu) = C_2(\mu) \chi_{q,s}^E e^{i\phi_{q,s}^E}$

SU(3) breaking effects

nonperturbative contributions

Long-distance dynamics in charm

Understand branching ratio first

Modes	Br(exp)	Br(this work)	A_{CP}^{tot}
$D^0 \to \pi^+\pi^-$	1.45 ± 0.05	1.43	0.58
$D^0 \to K^+K^-$	4.07 ± 0.10	4.19	−0.42
$D^0 \to K^0\bar{K}^0$	0.320 ± 0.038	0.36	0.05
$D^0 \to \pi^0\pi^0$	0.81 ± 0.05	0.57	1.38
$D^0 \to \pi^0\eta$	0.68 ± 0.07	0.94	−0.29
$D^0 \to \pi^0\eta'$	0.91 ± 0.13	0.65	1.53
$D^0 \to \eta\eta$	1.67 ± 0.18	1.48	0.18
$D^0 \to \eta\eta'$	1.05 ± 0.26	1.54	−0.94
$D^+ \to \pi^+\pi^0$	1.18 ± 0.07	0.89	0
$D^+ \to K^+\bar{K}^0$	6.12 ± 0.22	5.95	−0.93
$D^+ \to \pi^+\eta$	3.54 ± 0.21	3.39	−0.26
$D^+ \to \pi^+\eta'$	4.68 ± 0.29	4.58	1.18
$D_S^+ \to \pi^0K^+$	0.62 ± 0.23	0.67	0.39
$D_S^+ \to \pi^+K^0$	2.52 ± 0.27	2.21	0.84
$D_S^+ \to K^+\eta$	1.76 ± 0.36	1.00	0.70
$D_S^+ \to K^+\eta'$	1.8 ± 0.5	1.92	−1.60

$\times 10^{-3}$

and then predict CPV

Factorization-Assisted Topological approach

Li, Lu, **FSY**, '12

Implications of LHCb2019

1903.08726

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$$= (-1.54 \pm 0.29) \times 10^{-3}$$

1. Charm CPV of order 10^{-3}

2. Precision of order 10^{-4}

Implication: What next potential to observe charm CPV?

1. Charm CPV of order 10^{-3}	2. Precision of order 10^{-4}

1) Large branching fractions
2) Fully charged final particles @LHCb
3) Large production

$$Br(D^+ \to K^+K^-\pi^+) = 9.5 \times 10^{-3}$$

Compared to $Br(D^0 \to \pi^+\pi^-) = 1.4 \times 10^{-3}$

which dominates error of

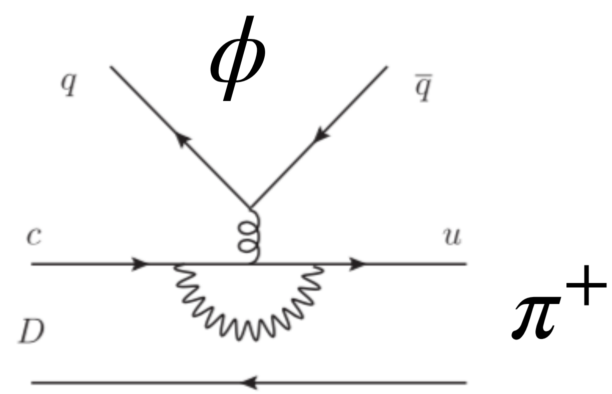
$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

Li, Lu, **FSY**, 1903.10638

What is the next potential mode to observe charm CPV?

$$Br(D^+ \to K^+K^-\pi^+) = 9.5 \times 10^{-3}$$

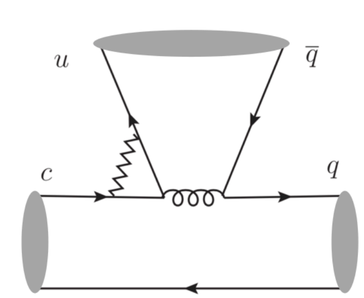
$$A_{CP}(D^+ \to \pi^+\phi) = 10^{-7}$$

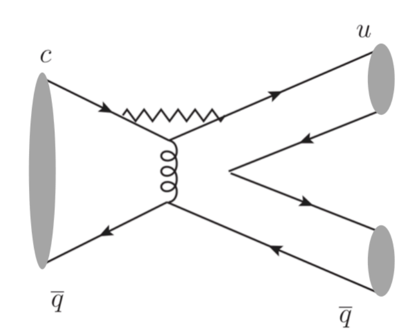


Qin, Li, Lu, **FSY**, ‘14

$$A_{CP}(D^+ \to K^+\overline{K}^{*0}) = 0.2 \times 10^{-3}$$

$$A_{CP}(D^+ \to K^+\overline{K}_0^{*0}(1430)) = -0.88 \times 10^{-3}$$

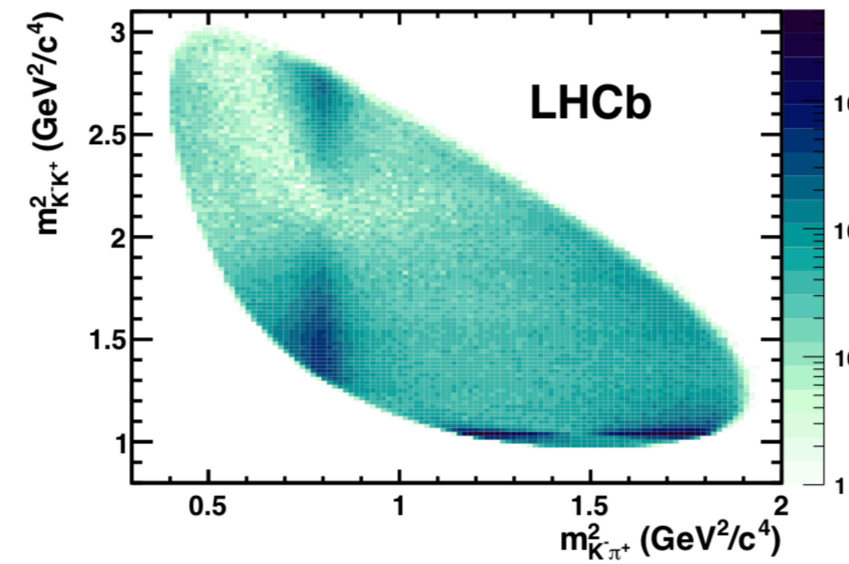




Li, Lu, **FSY**, 1903.10638

Searching Strategies

1. Binned $D^+ \to K^+K^-\pi^+$



$$Br(D^+ \to K^+K^-\pi^+) = 9.5 \times 10^{-3}$$

LHCb, '11, '19

$$D^+ \to \pi^+\phi, \quad Br = 2.6 \times 10^{-3}; \quad A_{CP} = 10^{-7}$$

Benchmark

$$D^+ \to K^+\overline{K}^{*0}, \quad Br = 2.4 \times 10^{-3}; \quad A_{CP} = 0.2 \times 10^{-3}$$

$$D^+ \to K^+\overline{K}_0^{*0}(1430), \quad Br = 1.8 \times 10^{-3}; \quad A_{CP} = -0.88 \times 10^{-3}$$

Precision —> 10^{-4}

Li, Lu, **FSY**, 1903.10638

Searching Strategies

2. Phase Space Integrated

Li, Lu, **FSY**, 1903.10638

(1) $A_{CP}(D^+ \to K^+K^-\pi^+) - A_{CP}(D^+ \to \pi^+\pi^-\pi^+)$

$$= A_{CP}^{\rm raw}(D^+ \to K^+K^-\pi^+) - A_{CP}^{\rm raw}(D^+ \to \pi^+\pi^-\pi^+)$$

Br=0.95% Br=0.3%

(2) $A_{CP}(D^+ \to K^+K^-\pi^+) - A_{CP}(D_s^+ \to K^+\pi^+\pi^-)$

$$= \left[A_{CP}^{\rm raw}(D^+ \to K^+K^-\pi^+) - A_{CP}^{\rm raw}(D^+ \to K^-\pi^+\pi^+)\right]$$

Br=0.95% Br=9%

$$-\left[A_{CP}^{\rm raw}(D_s^+ \to K^+\pi^+\pi^-) - A_{CP}^{\rm raw}(D_s^+ \to K^+K^-\pi^+)\right]$$

Br=0.66% Br=5.5%

Summary & Outlook

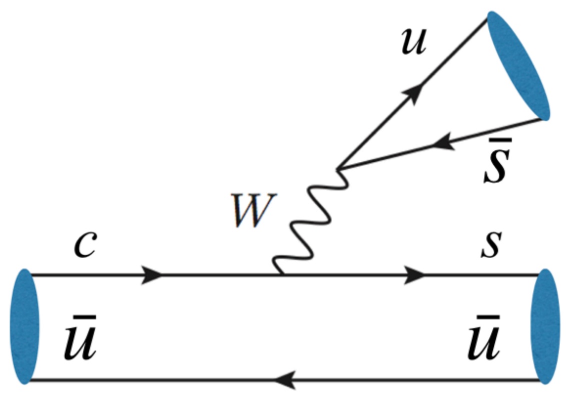
- CPV in D0->K+K- and pi+pi-
  - Understandable in the Standard Model
  - factorization-assisted topological approach works well in charm decays
  - Next potential is D+ ->K+K-pi+
- Charm CPV is becoming more charming with precision at order of 10^{-4}
- Impacts on new physics to be studied

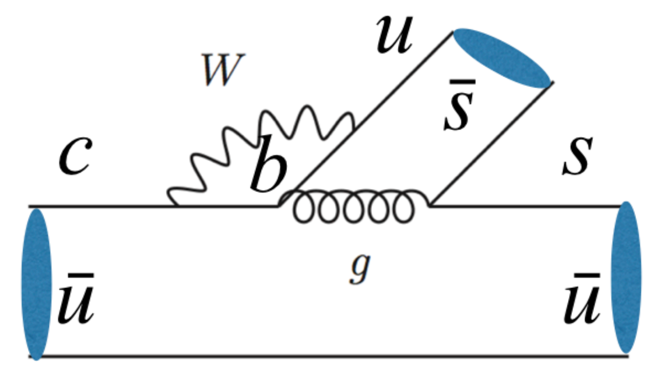
Thank you for your attention!

Backups

Direct CPV in charm

tree **v.s.** **penguin**





$V_{cd}V_{ud}/V_{cs}V_{us}$ $V_{cb}V_{ub}$

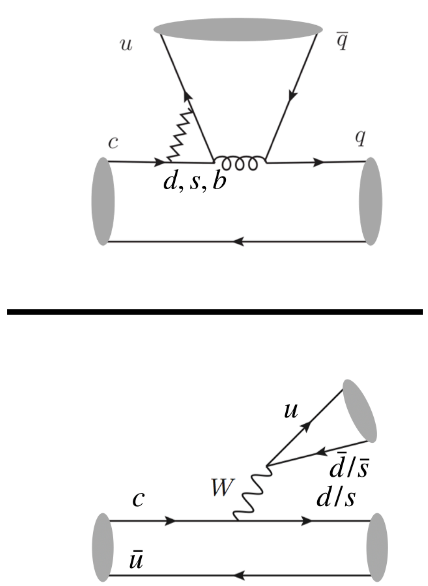
λ $\lambda^5 + i\lambda^5$

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

$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right) \approx 1$$

$$\rightarrow \quad \frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta \sim 1/2 \quad \text{or } \mathrm{Im}[\mathcal{P}/\mathcal{T}] \sim 1/2$$

FAT2012 $$\frac{\mathcal{P}^{\pi\pi}}{\mathcal{T}^{\pi\pi}} = 0.66e^{i134^\circ}, \quad \text{and} \quad \frac{\mathcal{P}^{KK}}{\mathcal{T}^{KK}} = 0.45e^{i131^\circ}$$



$$= \quad \frac{P}{T} = \frac{a_4 + a_6 r_\chi}{a_1} = 0.36e^{-i108^\circ}$$

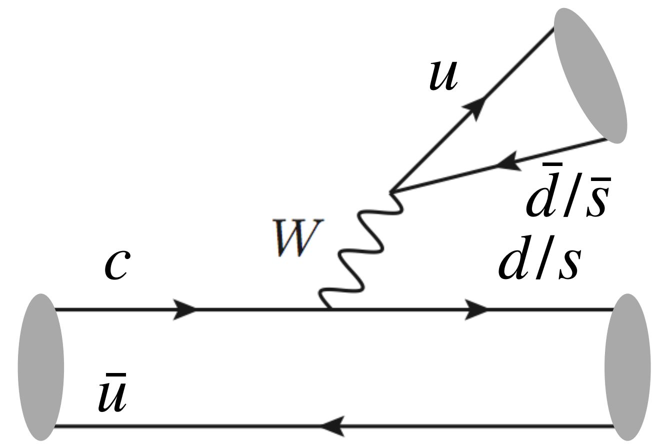
$$r_\chi = 2m_0^2/m_c = 2.8, \text{ where } m_0^\pi = m_\pi^2/(m_u + m_d)$$

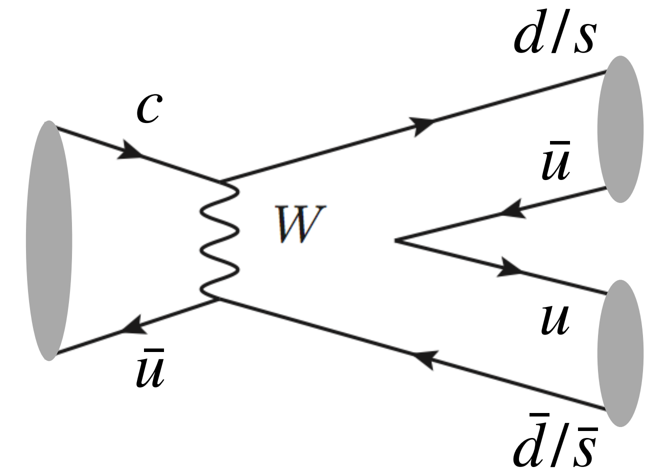
$$a_4 = -0.036 - i0.098, \ a_6 = -0.031 - i0.098$$

$$C_{3,5}(\mu) \rightarrow C_{3,5} - \frac{\alpha_s(\mu)}{8\pi N_c}\sum_{q=d,s}\frac{\lambda_q}{\lambda_b}C^q(\mu,\langle l^2\rangle) + \frac{1}{N_c}\frac{\alpha_s(\mu)}{4\pi}\frac{m_c^2}{\langle l^2\rangle}[C_{8g}(\mu) + C_5(\mu)],$$

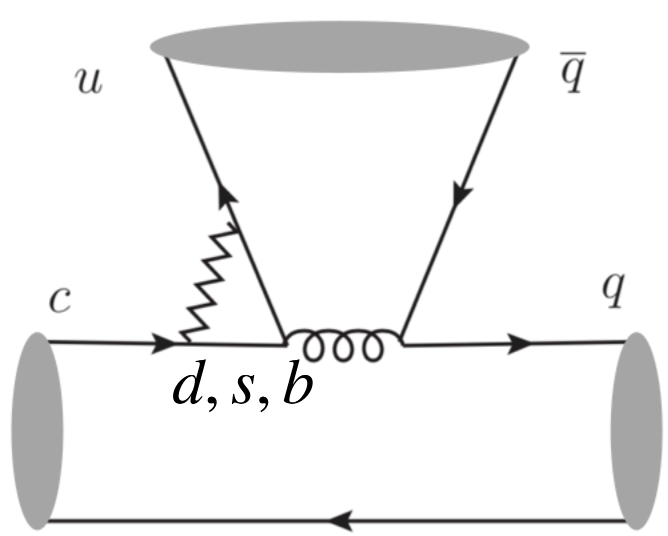
$$C_{4,6}(\mu) \rightarrow C_{4,6} + \frac{\alpha_s(\mu)}{8\pi}\sum_{q=d,s}\frac{\lambda_q}{\lambda_b}C^q(\mu,\langle l^2\rangle) - \frac{\alpha_s(\mu)}{4\pi}\frac{m_c^2}{\langle l^2\rangle}[C_{8g}(\mu) + C_5(\mu)],$$

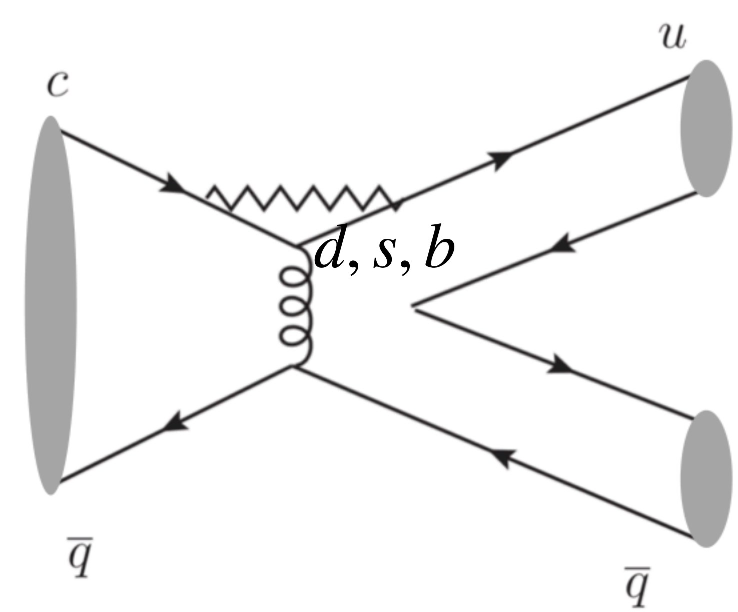
Tree



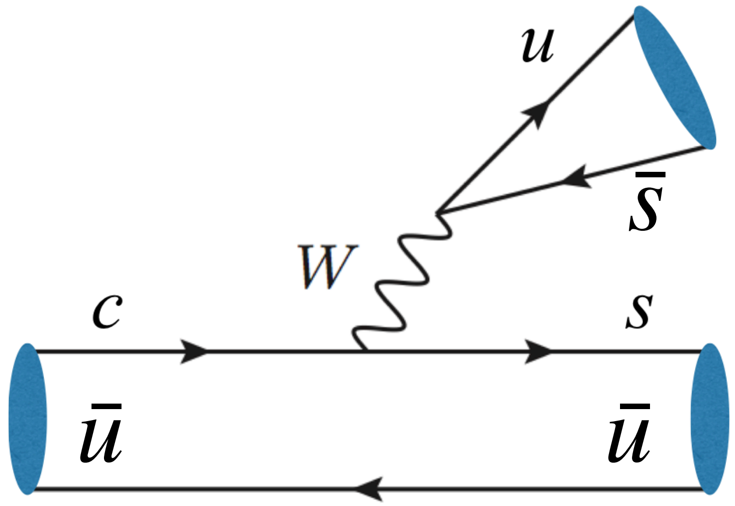


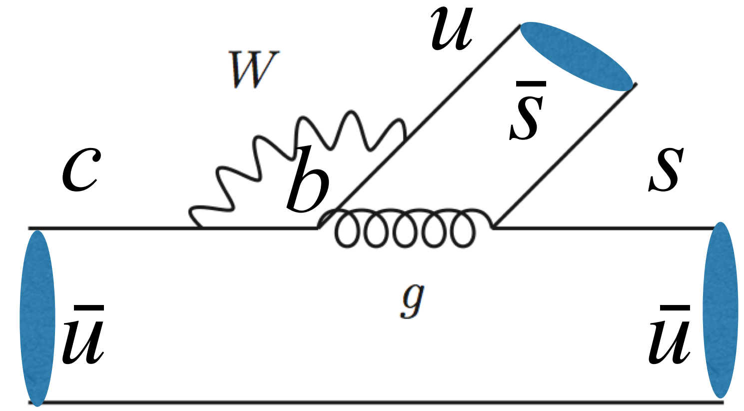
Penguin





Before 2011…





$$A_{CP} \sim \frac{|V_{cb}^{*} V_{ub}|}{|V_{cs}^{*} V_{us}|} \frac{\alpha_s}{\pi} \sim 10^{-4}$$

CPV in charm is expected to be $\leq 10^{-3}$

Grossman, Kagan, Nir, ’07; Bigi, Paul, Recksiegel, ’11