Theoretical Progress on Charm Weak Decays

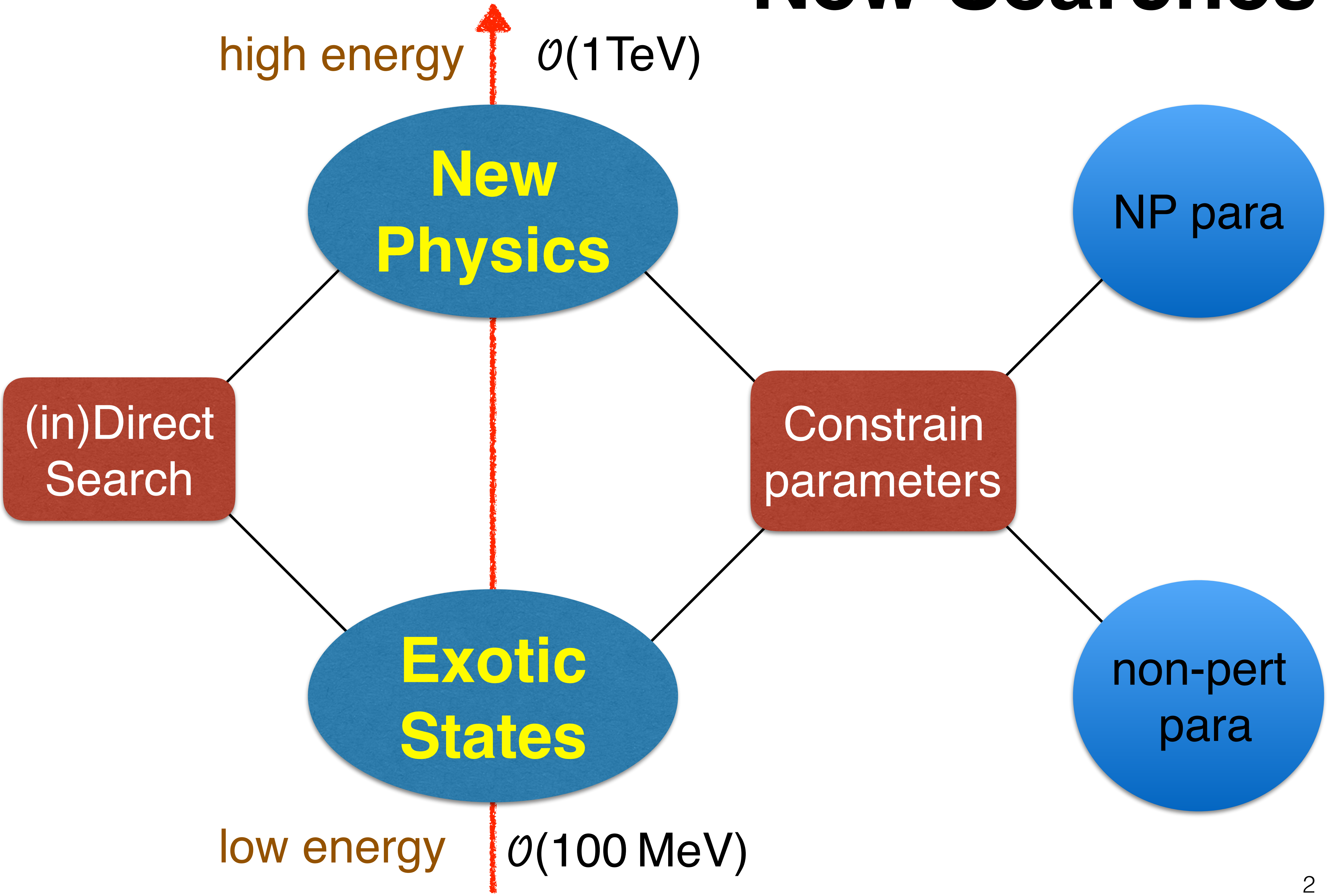
Fu-Sheng Yu

Lanzhou University

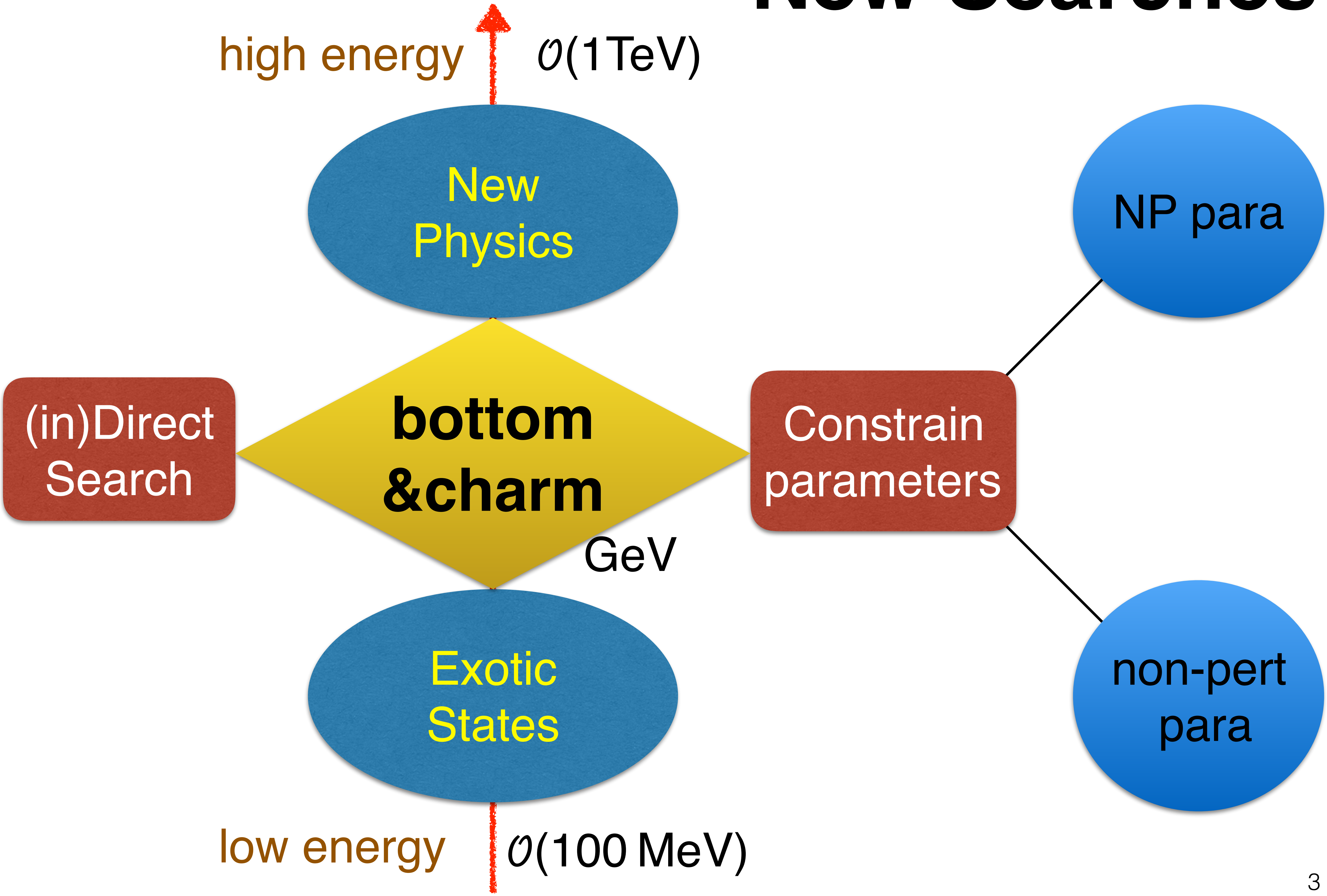
2017.09.23 @ NankaiU

Joint workshop on charmed hadron decays @ BESIII, Belle, LHCb

New Searches



New Searches



Outline

1. **Theories in charm decays**

2. **To search for new physics — CP violation**

3. **To search for exotic states — weak decay is a new tool**

Many recent works cannot be included

See Prof. Cai-Dian Lu's and Prof. Wei Wang's talks

粲物理的一个特点：

理论与实验紧密结合

Theories of heavy flavor decays

- Amplitudes are described by effective Hamiltonian based on OPE in the **heavy-quark limit**
- **QCD-inspired methods at the leading $1/m_Q$**
  - PQCD, QCDF, SCET
  - **NLO, NNLO effects by α_s**
  - perturbative, successful in B decays
- **Big Problem in charm : $1/m_c$ power corrections**
  - **Non-perturbative**
  - **Long-distance contributions** are important around 1GeV and below, final-state interaction or resonance.

- **In phenomenology**
  - some data to be explained
  - some important observables to be predicted
- **Basic ideas:**
  - Calculate what we can — HQET and factorization
  - Parametrize what we cannot — $1/m_Q$ corrections
  - Include important information — SU(3) breaking
  - Non-perturbations/corrections — extracted from data
  - Predict some observables to be tested

Theoretical Methods for Charm decays

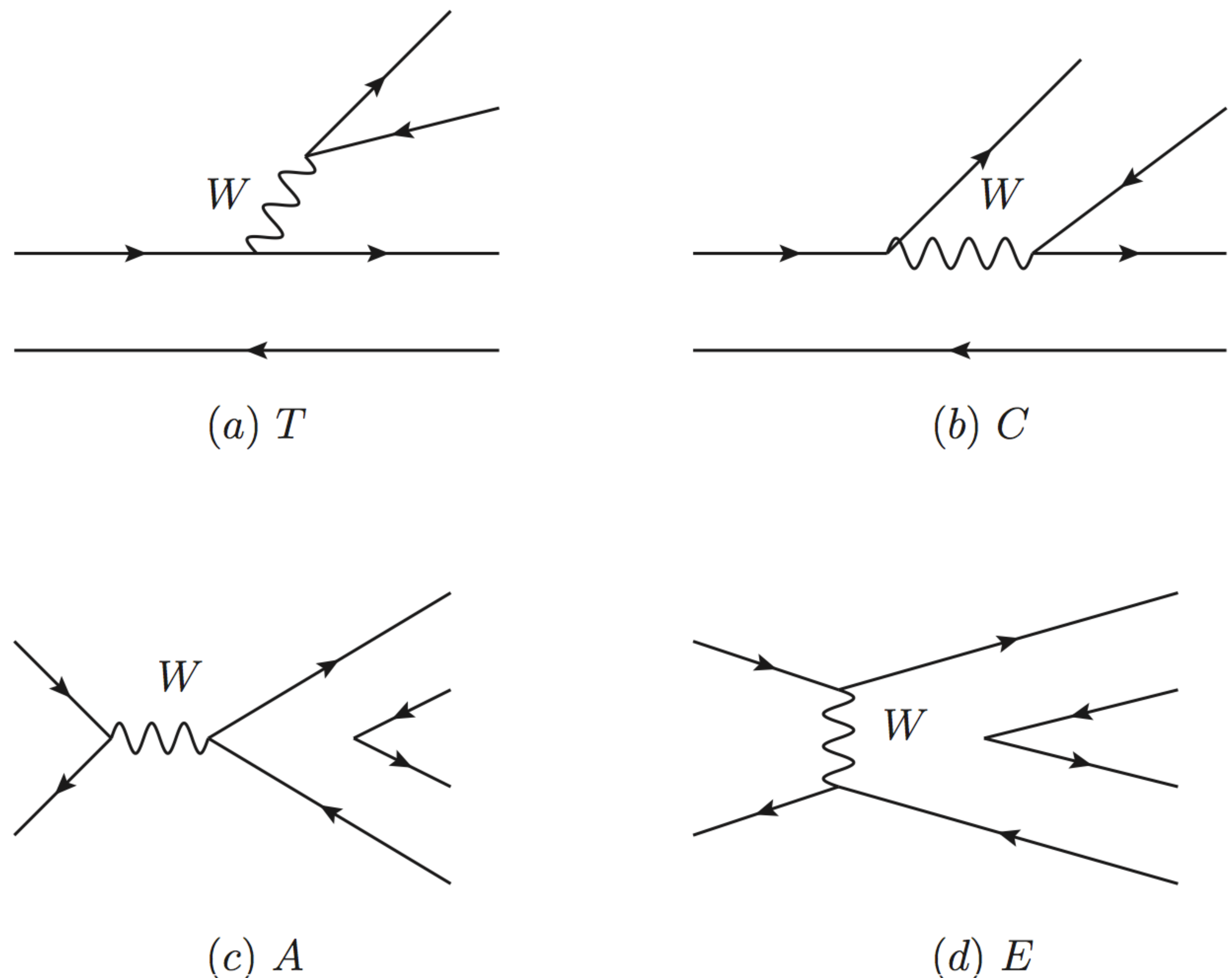
- Factorization-Assisted Topological-amplitude approach [Li, Lü, **FSY**, 12’][Qin, Li, Lü, **FSY**, 13’]
- Topologies with SU(3) symmetry [Cheng, Chiang, 10’][Cheng, Chiang, Kuo, 16’]
- Topologies with SU(3) breaking [Muller, Nierste, Schacht, 15’]
- Final state interaction [Biswas, Sinha, Abbas, 15’]

All are **fitting by data** of branching fractions

Measurements with higher precision
are important to improve the understanding

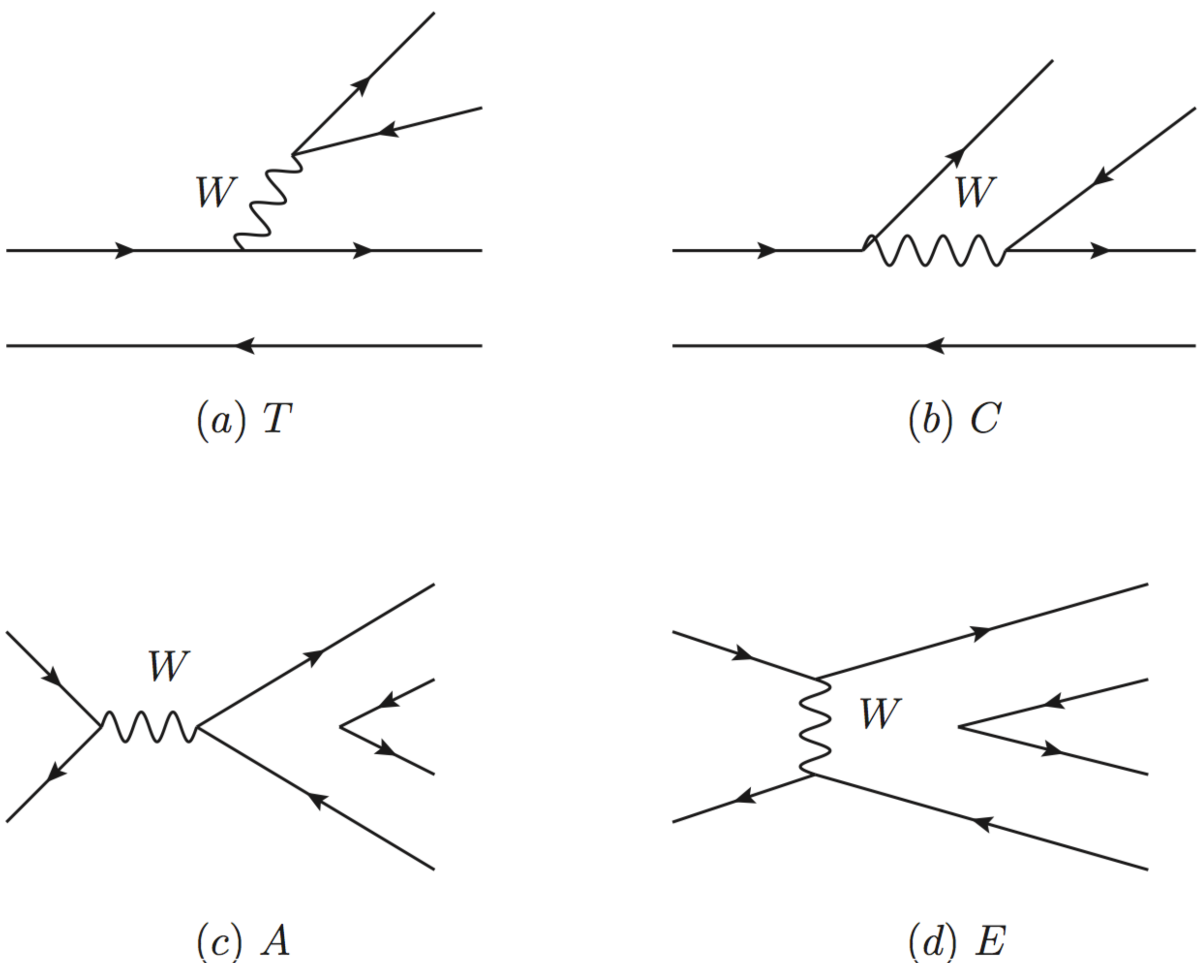
Basic Picture: topological diagrams

- According to the **weak flavor flows**
- **including all strong interaction effects, so all the corrections…**
- **Amplitudes <u>extracted from data</u>**



- Lose predictive power
  - either in the SU(3) flavour symmetry limit, [Bhattacharya, Rosner, 08',10'; Cheng, Chiang,10']
  - or beyond the SU(3) symmetry [Muller, Nierste, Schacht, 15']

Factorization-Assisted Topological-amplitude approach (FAT)



Dynamics In **factorization**:

- **Short-distance**: Wilson coefficients
- **Long-distance**: hadronic matrix elements

Non-perturbative quantities

↓

Extracted from data

↓

Predictions

[H.n.Li, C.D.Lü, **FSY**, PRD12]
[Q.Qin, H.n.Li, C.D.Lü, **FSY**, PRD14]

Measurements of ΔA_{CP}

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

Measurements	ΔA_{CP}	Publication	World Average
2011LHCb (D*)	(-0.82±0.24)%	PRL108,111602	ICHEP2012: (-0.74±0.15)% HFAG2012: (-0.68±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	HFAG2013: (-0.33±0.12)%
2013LHCb (B)	(+0.49±0.33)%	PLB723(2013)33	
2014LHCb (B)	(+0.14±0.18)%	JHEP07(2014)041	HFAG2014: (-0.25±0.10)%
2016LHCb (D*)	(-0.10±0.09)%	1602.03160	(-0.14±0.07)%

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Prediction in 2012

[H.n.Li,C.D.Lü,**FSY**,PRD12']

ΔA$_{CP}$=(-0.06 ~ -0.19)%

New CP-Violation Effect in charm decays

[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

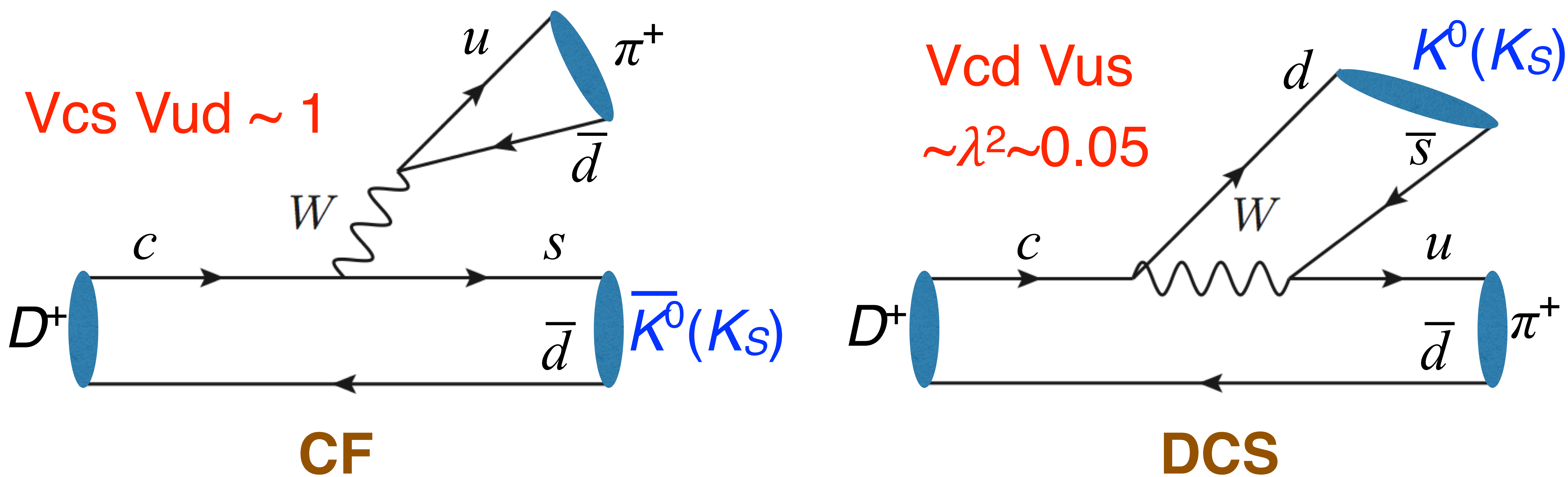
CPV can occur in $D \to f\, K_S\ (K_L)$

- ⋆ Interference between Cabibbo-favored (**CF**) and doubly Cabibbo-suppressed (**DCS**) amplitudes

$$|K_S^0\rangle = (1+\bar{\varepsilon})|K^0\rangle - (1-\bar{\varepsilon})|\overline{K}^0\rangle$$

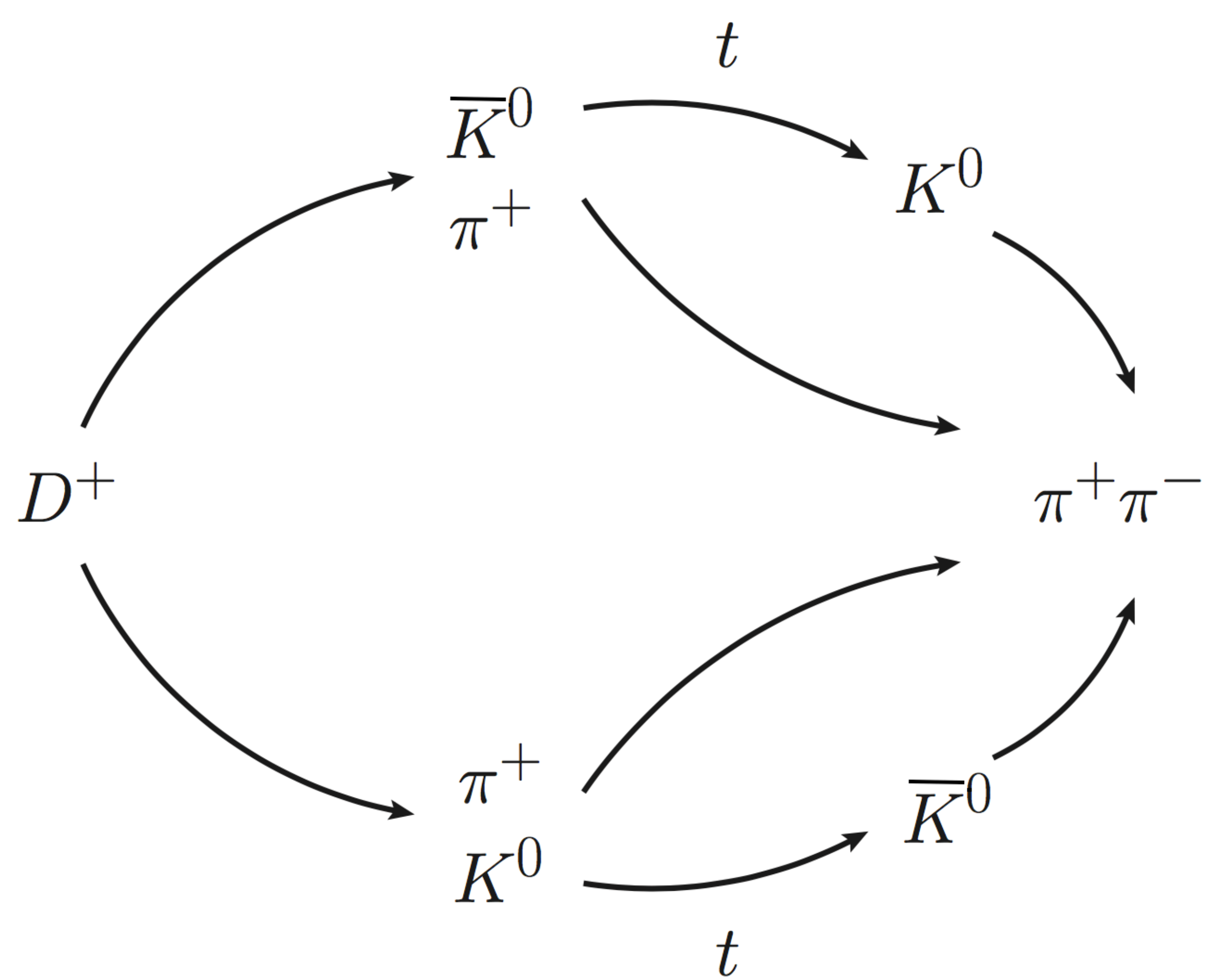
$$|K_L^0\rangle = (1+\bar{\varepsilon})|K^0\rangle + (1-\bar{\varepsilon})|\overline{K}^0\rangle$$

$D^+ \to K_S \pi^+$



$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) + A\lambda^5(\bar\rho - i\bar\eta)/2 \\ -\lambda + A^2\lambda^5[1-2(\bar\rho + i\bar\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 + A\lambda^4[1-2(\bar\rho+i\bar\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix}$$

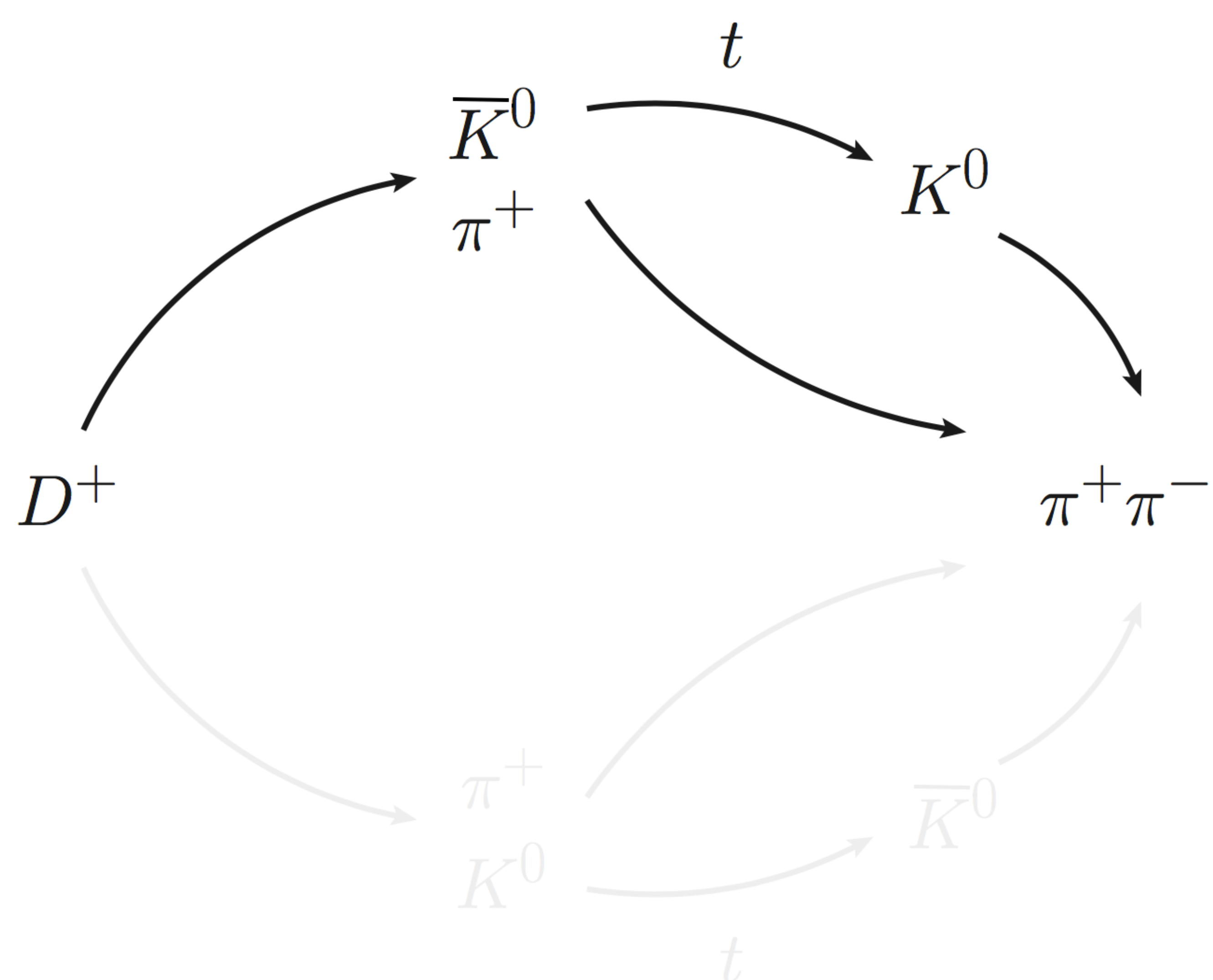
$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t)\right] / D(t)$$



Indirect CPV in kaon mixing

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t)\right] / D(t)$$

$$A_{CP}^{\overline{K}^0}(t) = 2e^{-t/\tau_S}\left[\mathcal{R}e(\epsilon) - e^{\Delta\Gamma t/2}\left(\mathcal{R}e(\epsilon)\cos(\Delta m t) + \mathcal{I}m(\epsilon)\sin(\Delta m t)\right)\right]$$ **(10^{-3})**



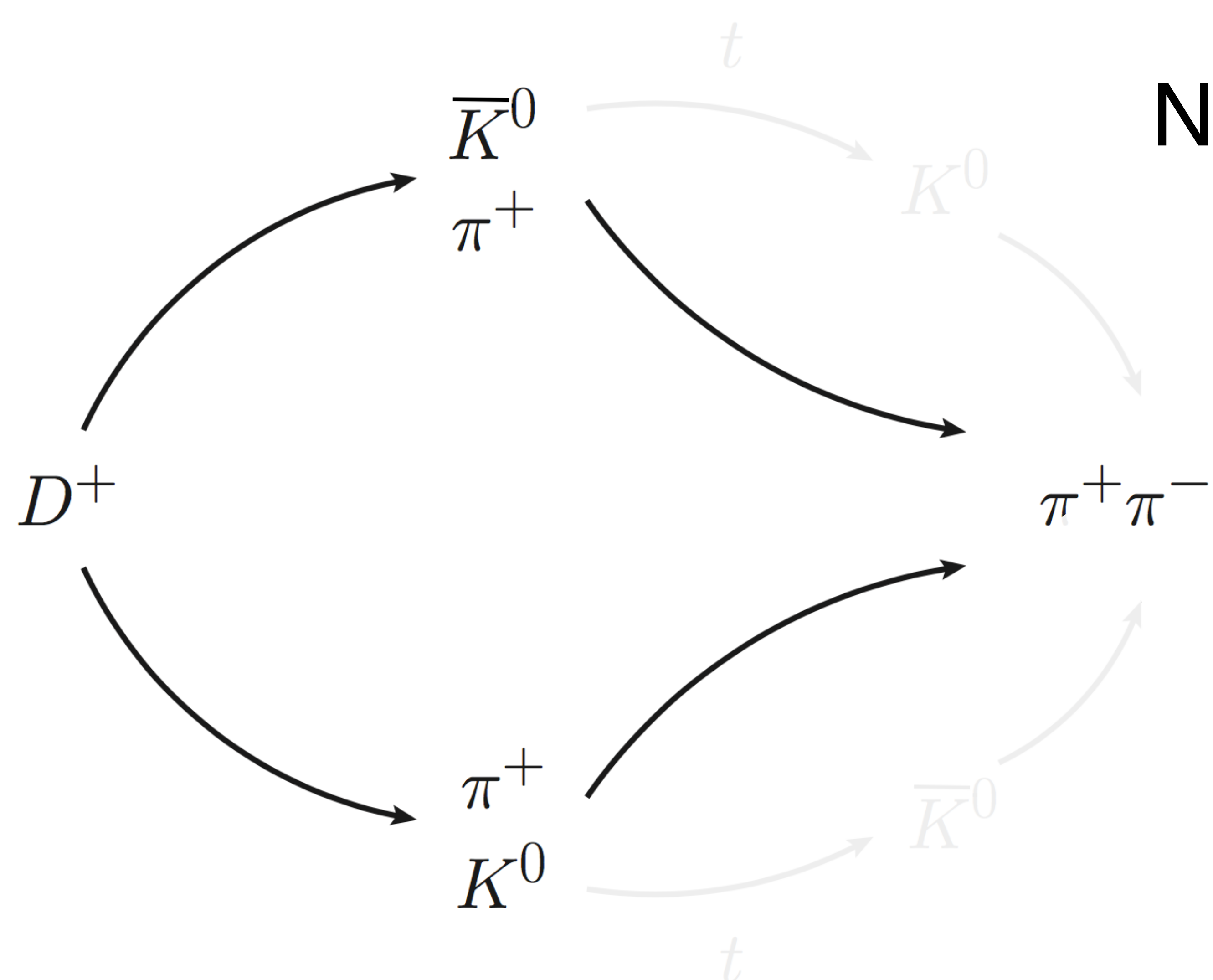
Dominant

[Zhi-Zhong Xing,PLB 353,313(1995), arXiv:hep-ph/9505272]

Direct CPV in charm decays

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t)\right] / D(t)$$

$$A_{CP}^{dir}(t) = e^{-t/\tau_S}\, 2r_f \sin\delta_f \sin\phi = \mathcal{O}(\lambda^6) = (10^{-5})$$



Negligible in SM

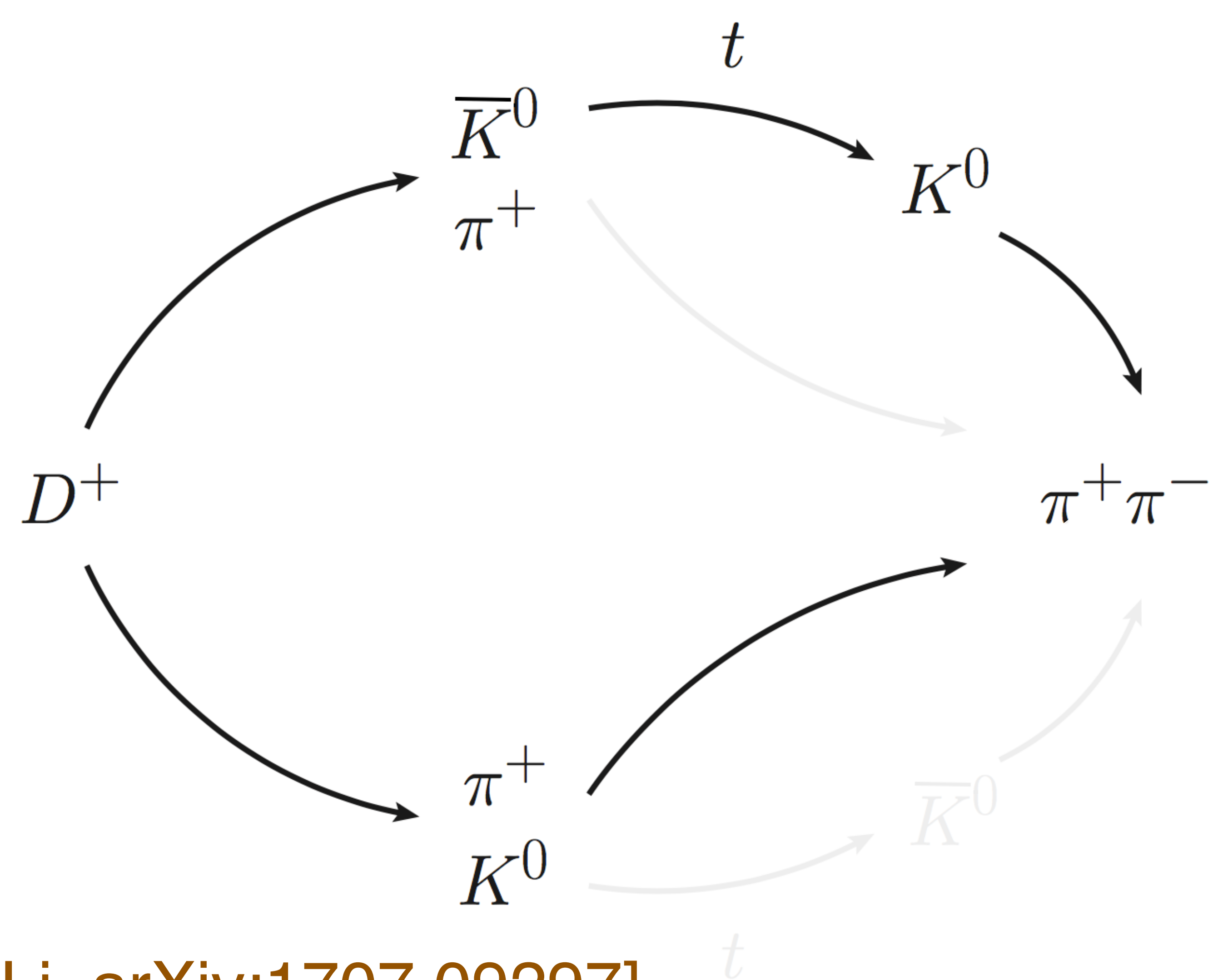
[Bigi, Yamamoto,PLB 349,363(1995), arXiv:hep-ph/9502238]

CPV in interference between kaon mixing and charm decays

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t)\right] / D(t)$$

$$A_{CP}^{int}(t) = e^{-t/\tau_S} 4r_f \cos\phi \sin\delta_f \left[-\mathcal{I}m(\epsilon) + e^{\Delta\Gamma t/2}\Big(\mathcal{I}m(\epsilon)\cos(\Delta m t) - \mathcal{R}e(\epsilon)\sin(\Delta m t)\Big)\right]$$

($10^{-4\sim-3}$)



Non-negligible

and

important

New findings

[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

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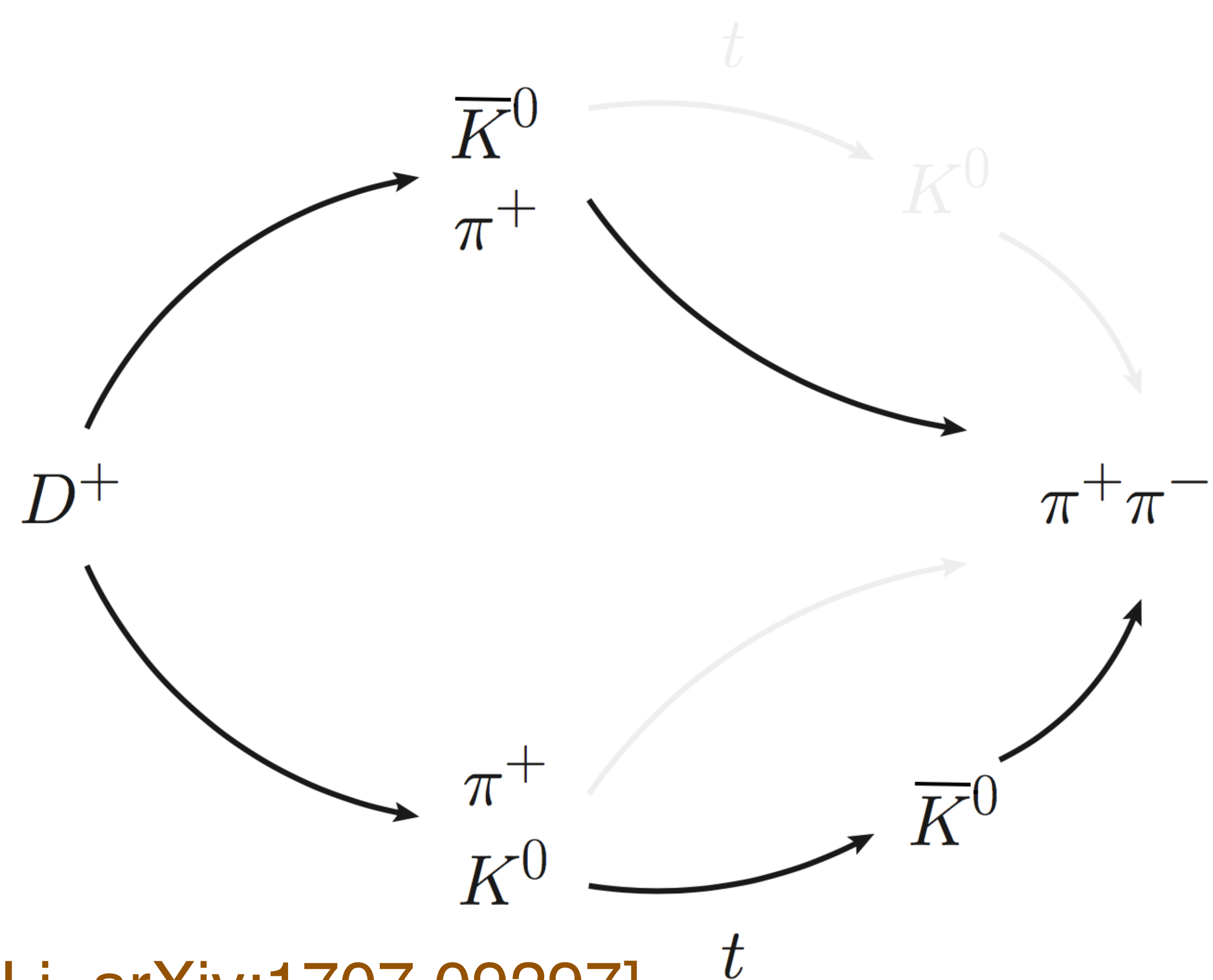
($10^{-4\sim-3}$)



Non-negligible

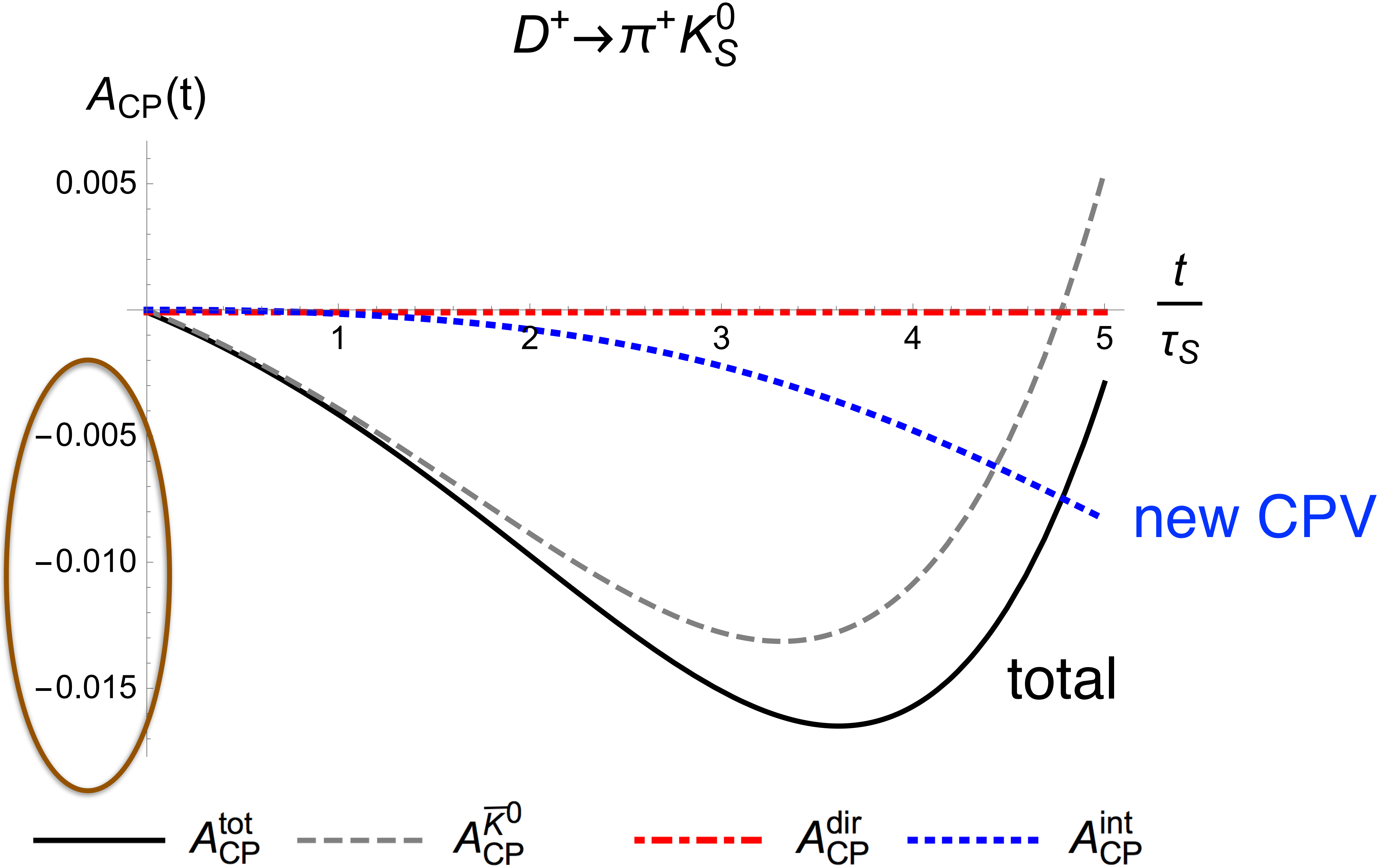
and

important

New findings

[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

Time-dependent CPV



[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

Precision in exp

- **Precision of measurement** of CPV can reach $\mathcal{O}(10^{-4})$

LHCb: $\Delta a_{CP}^{\mathrm{dir}} = (-0.061 \pm 0.076)\%$ @ 3 fb^{-1}

→ 0.12×10^{-3} @ 50 fb^{-1}

	Br	LHCb	Belle	theory
$\Delta A_{cp}(K_S, K^+, \pi^+)$	$\mathcal{O}(\%)$	K_S efficiency	prefer	clear $\mathcal{O}(10^{-3})$
$\Delta A_{cp}(K^+K^-, \pi^+\pi^-)$	$\mathcal{O}(10^{-3})$	prefer	prefer	unclear. If too tiny?

LHCb @ 3 fb^{-1}

CF mode	Yield
$D^+ \to K_S \pi^+$	4.8×10^6
$D_s^+ \to K_S K^+$	1.5×10^6

[1406.2624]

SCS mode	Yield
$D^0 \to K^+K^-$	7.7×10^6
$D^0 \to \pi^+\pi^-$	2.5×10^6

[1602.03160]

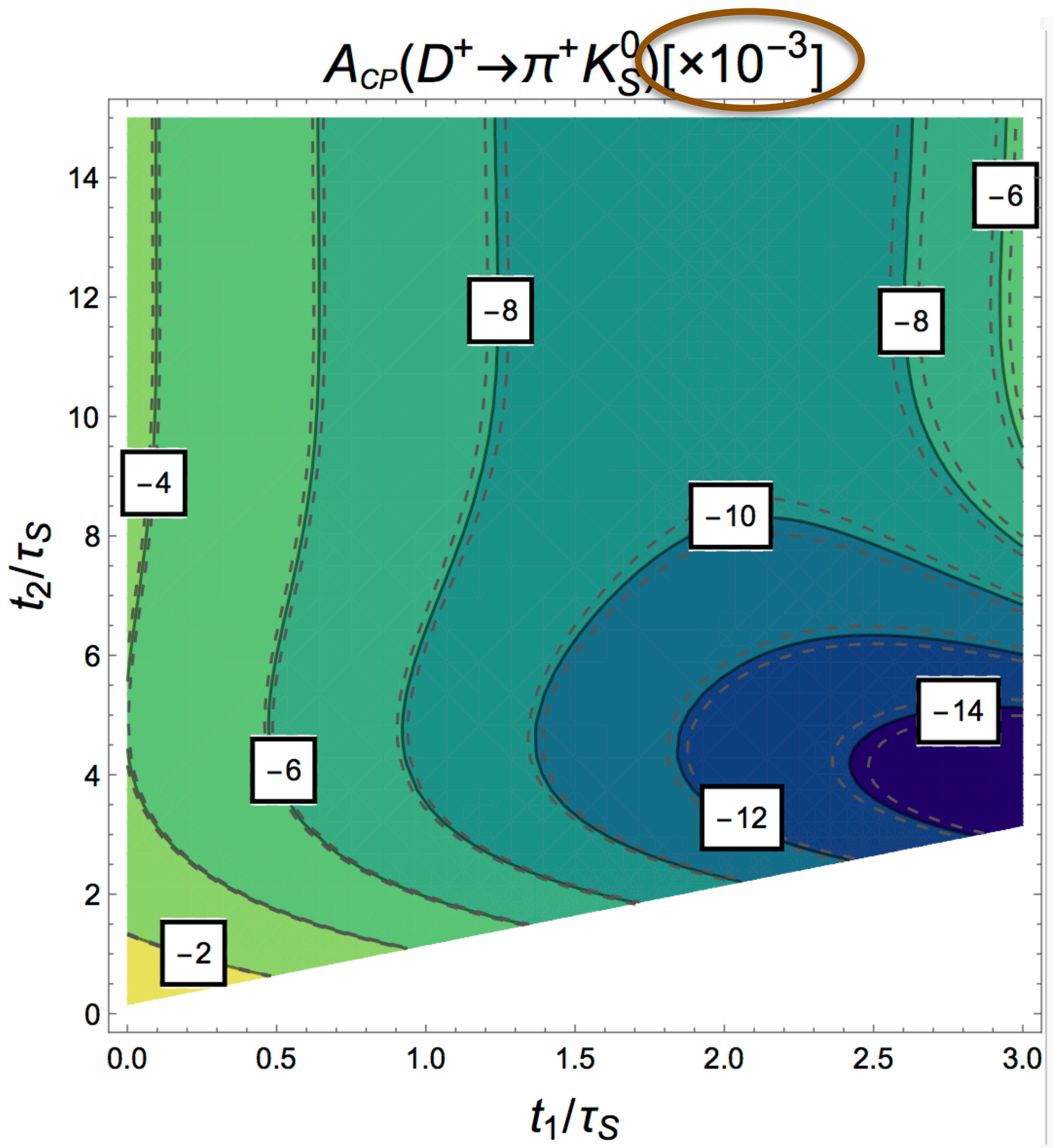
Sensitivity of Acp at Belle II

	mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}	BR(%)
SCS	$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03	0.4%
	$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05	0.14%
	$D^0 \to \pi^0\pi^0$	976	$\sim \pm 0.60$	± 0.08	
	$D^0 \to K_s^0\pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.03	
	$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07	
	$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09	
	$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13	
	$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40	
	$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33	
	$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04	
	$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14	
	$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14	
CF	$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03	1.5%
	$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05	
	$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29	
CF	$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05	1.5%

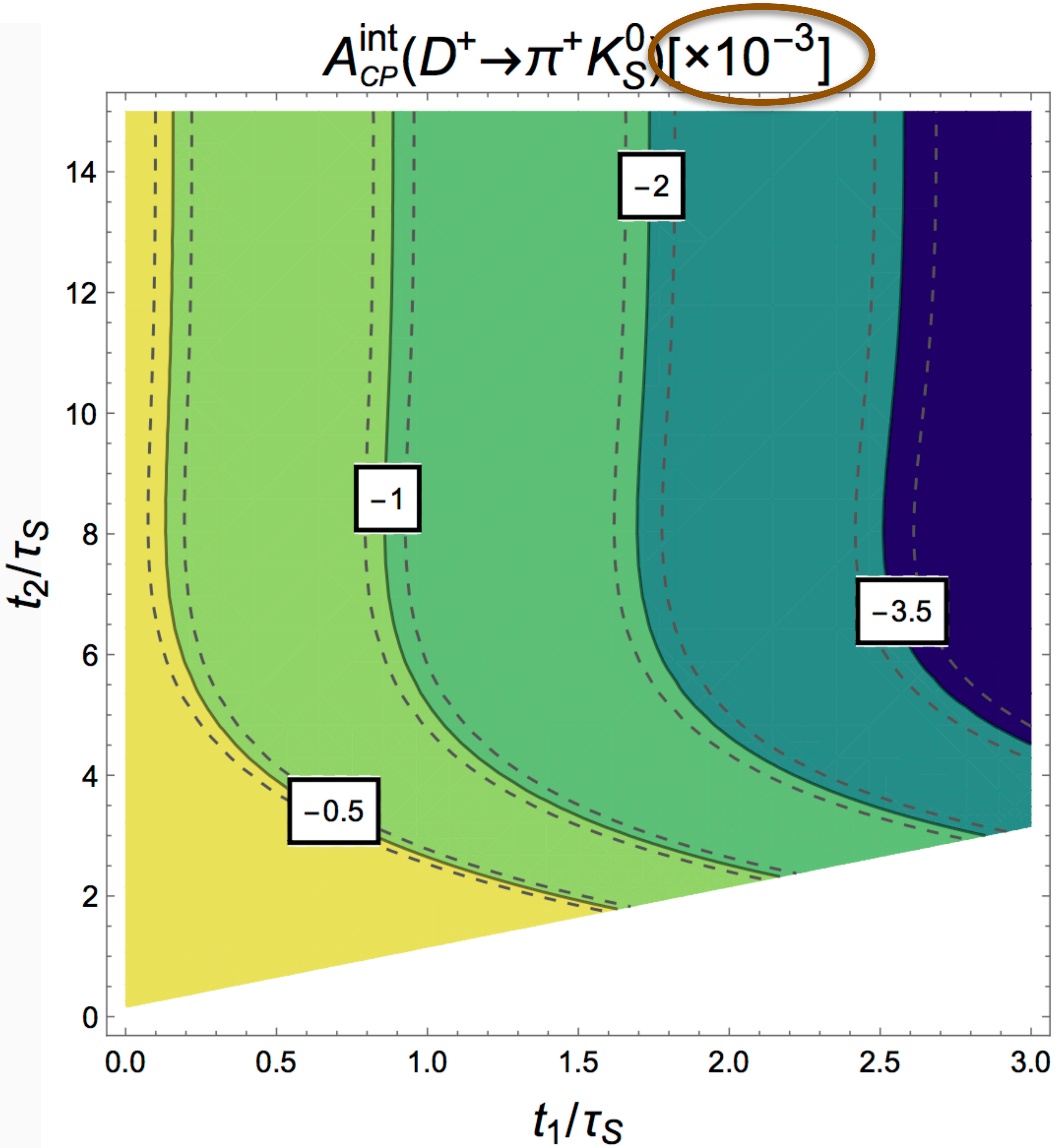
$\mathcal{O}(10^{-4})$

Time-Integrated CPV

total



new CPV effect



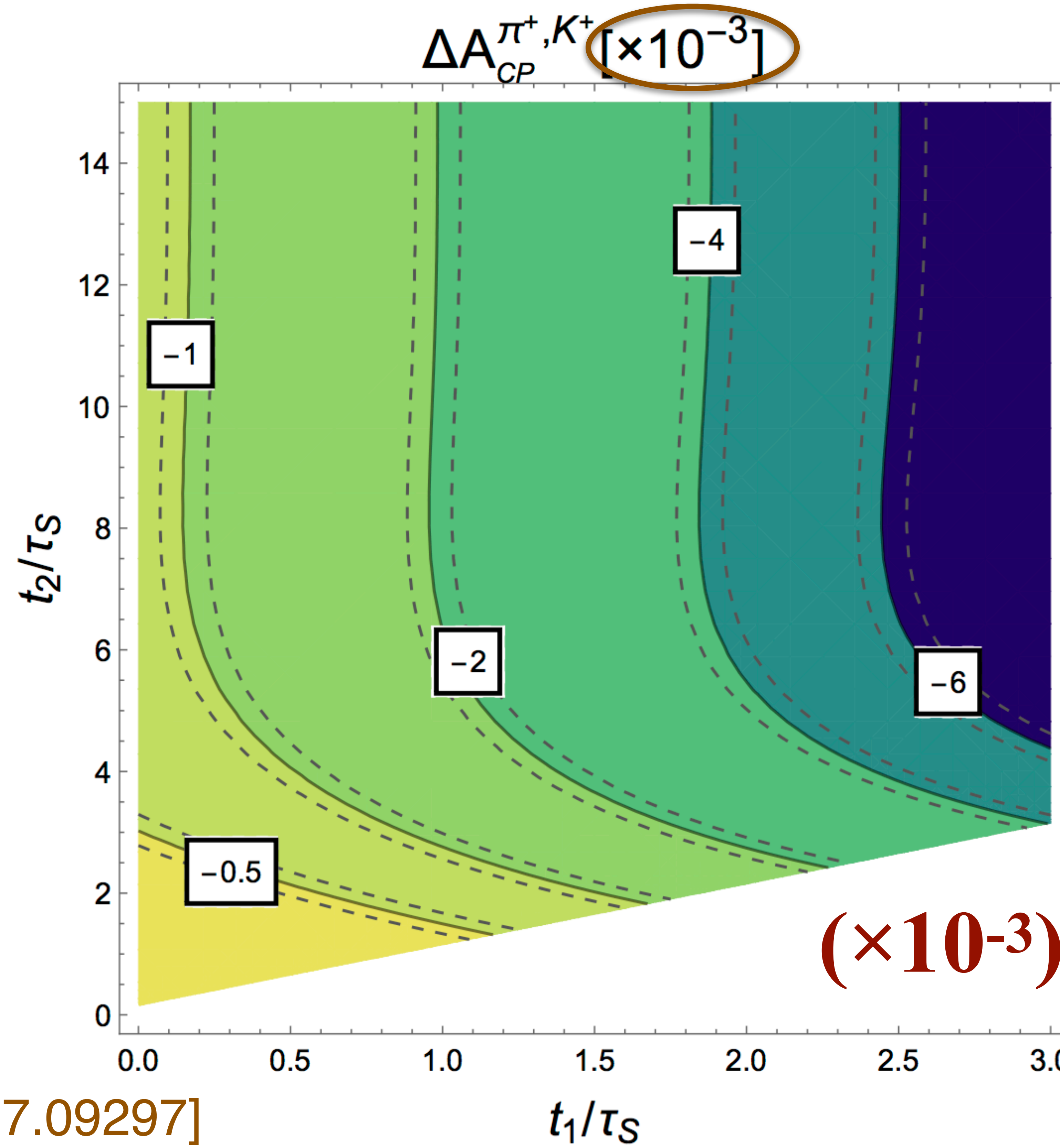
[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

$$\Delta A_{CP}^{\pi^+,K^+} \equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2)$$

New Observable

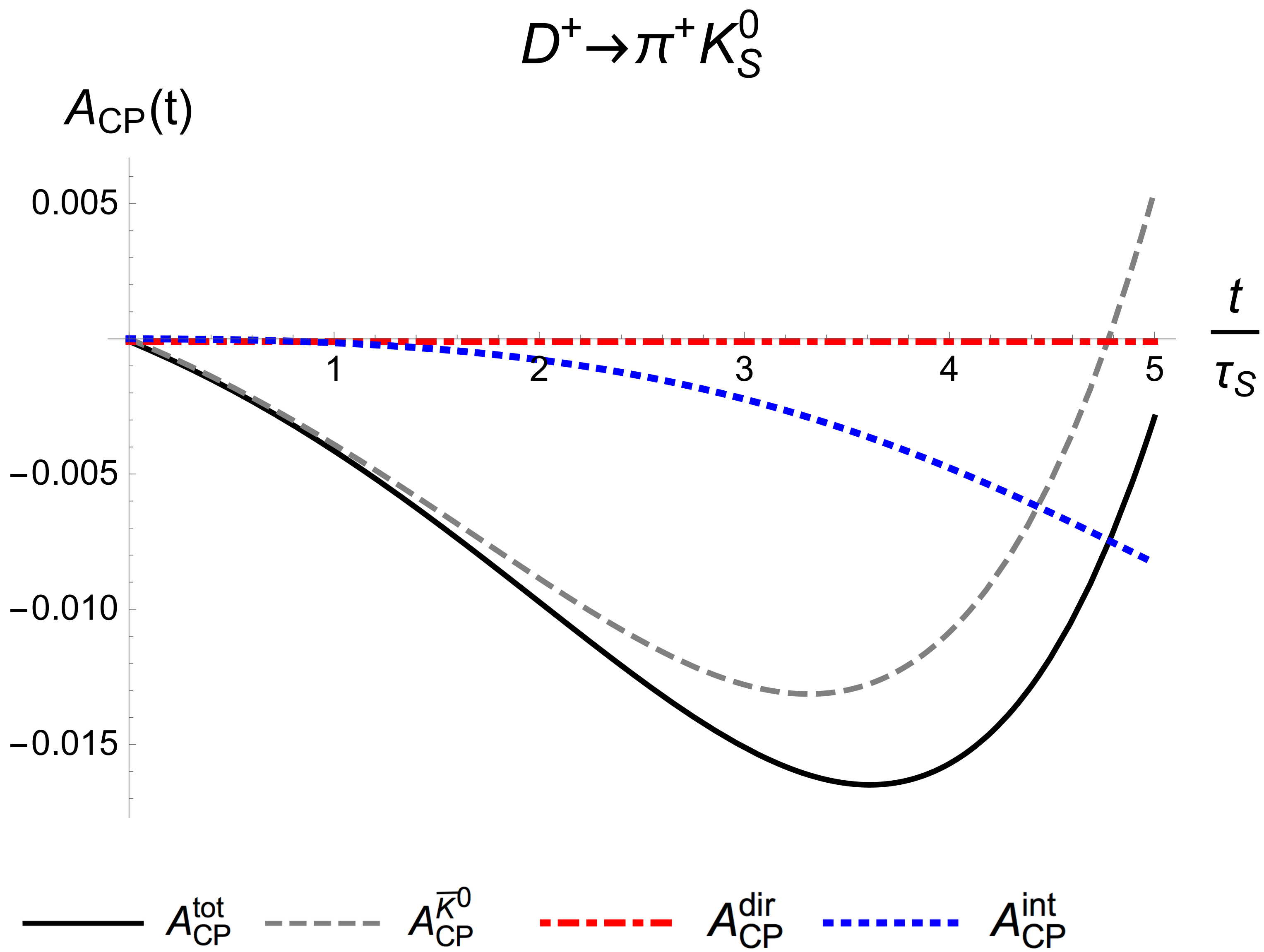
revealing
new CPV effect

$A_{CP}^{\overline{K}^0}$
is mode-independent
and cancelled



[**FSY**, D.Wang, H.n.Li, arXiv:1707.09297]

$A_{CP}(t=0)$: Smoking gun for new physics

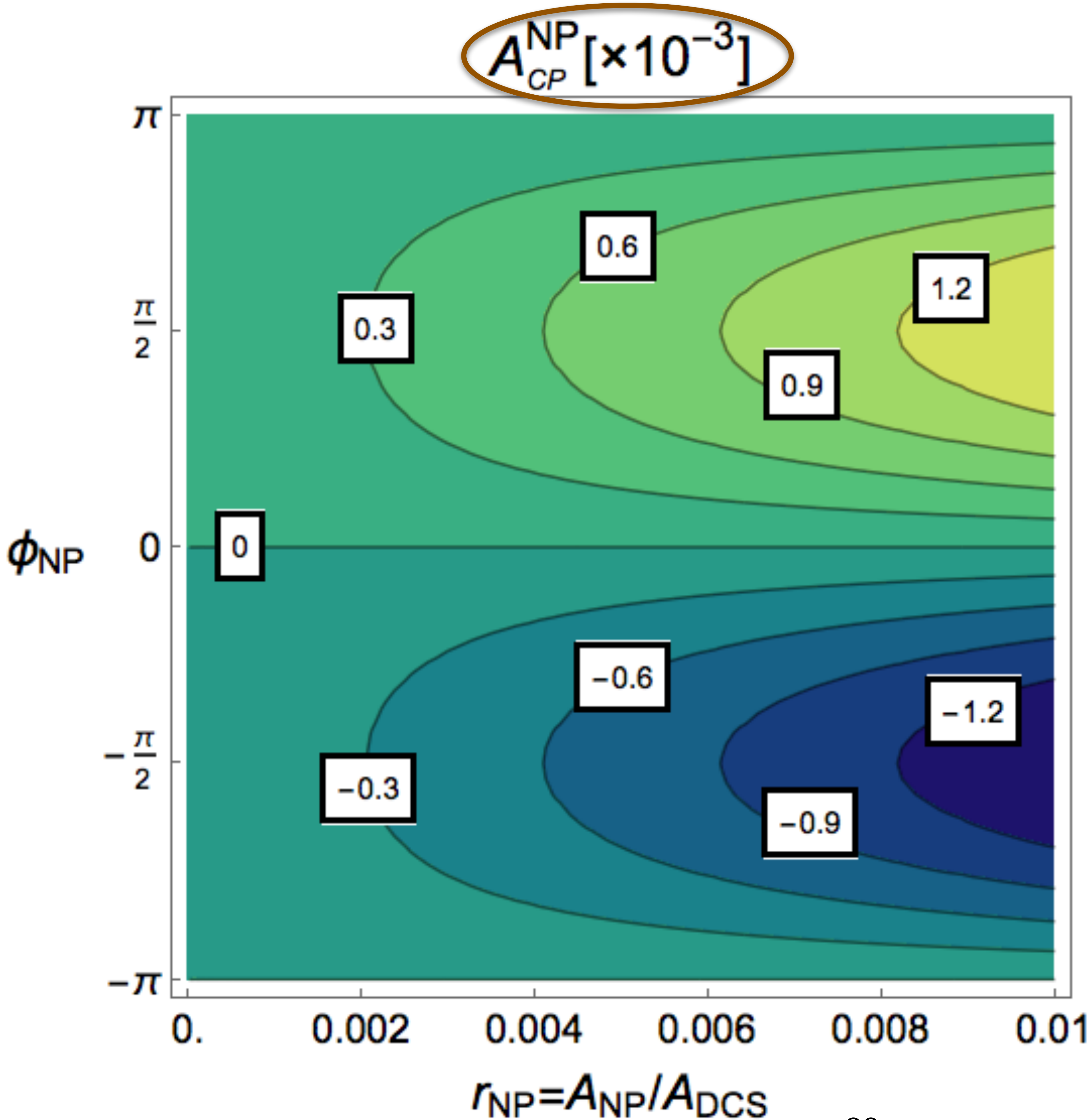


Measurements on time evolution

$A_{CP}(t=0) = A_{CP}^{dir}$
$= O(10^{-5})$

If non-vanishing in the forthcoming exps, signal of new physics!

$$A(D \to f K_S^0) = A_{CF} + A_{DCS}(1 + r_{NP} e^{i\phi_{NP}} e^{i\delta_{NP}})$$



$$A_{SM}^{dir} = \mathcal{O}(10^{-5})$$

Even if $r_{NP} = 0.001 \sim 0.01$, the direct CPV of $A_{CP}^{NP}/A_{CP}^{SM} = \mathcal{O}(10)$

Promising for NP!

A_{SM} are tree-level

Precisions at LHCb upgrade and Belle II is $\mathcal{O}(0.1\times 10^{-3})$

Ambiguities in penguins

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

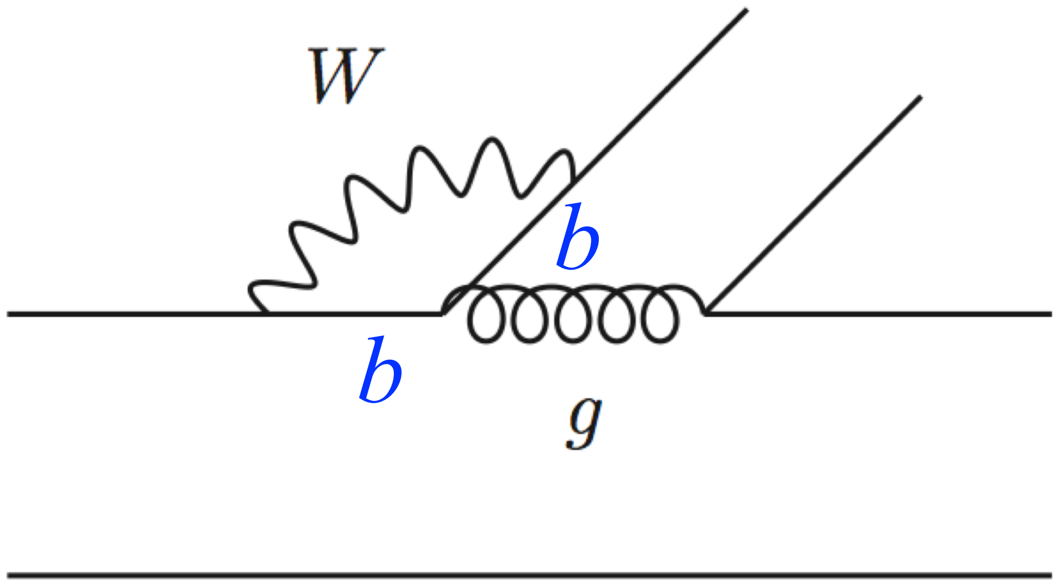
range from 10^{-5} to 10^{-2} in literature

[many papers…]

- $@m_c \sim 1.5$GeV, perturbation theories do not work
- Penguin neglected in Br's

$\Delta A_{cp}(KK,\pi\pi)_{exp} <\sim \mathcal{O}(10^{-3})$

uncertainties of Br's ~ $\mathcal{O}(\%)$



Even if CPV observed, it cannot tell SM or NP

Experimental data of branching fractions

↓

Theoretical understanding of decay amplitudes

↓

Find new CPV effects and predictions

↓

Measurements?

Charmed baryon physics was a desert

During last decades, no data and no theories

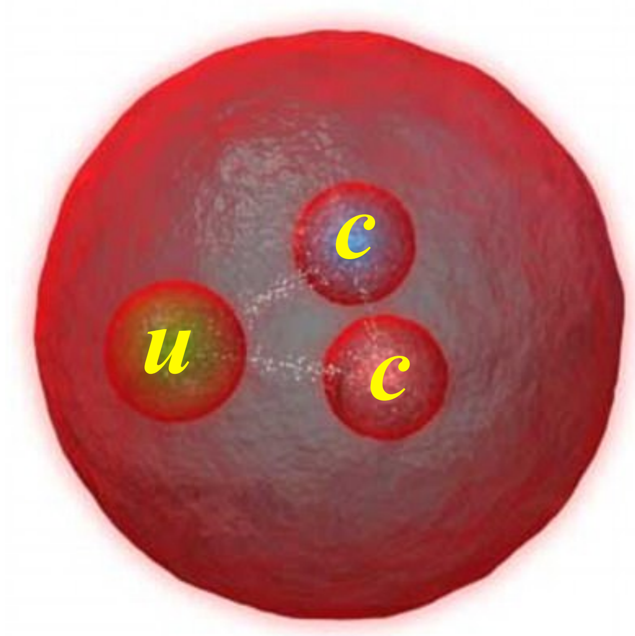
Now we see some plants by BESIII, Belle and LHCb

See Z.W.Yang’s, P.R.Li’s and X.Y.Zhou’s talks

More discoveries are expected

Weak Decays of Ξ_{cc}

See Prof. Lü's talk



Theoretical Framework

1. Short-distance contributions

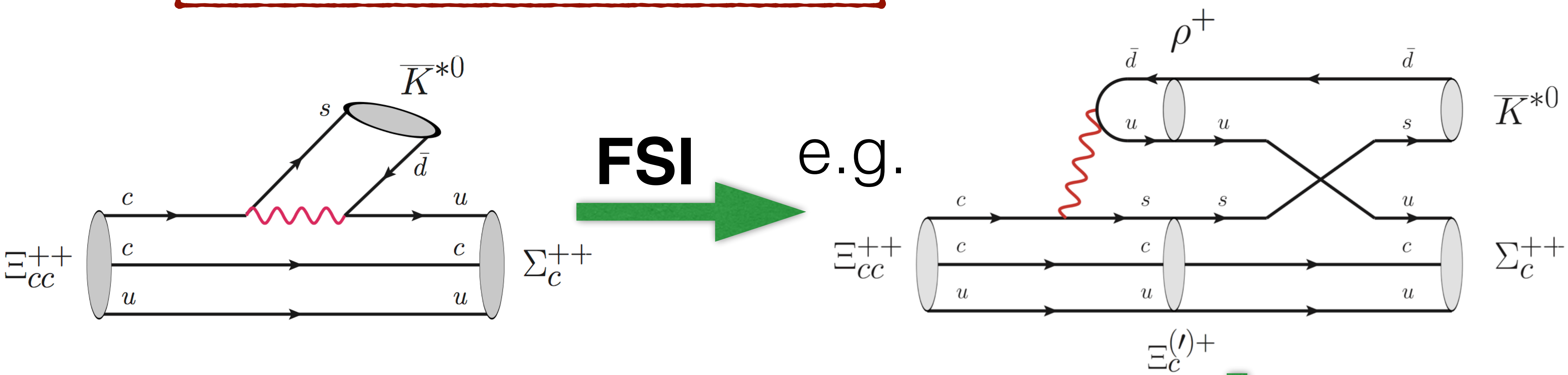
   — under factorization hypothesis

2. Long-distance contributions

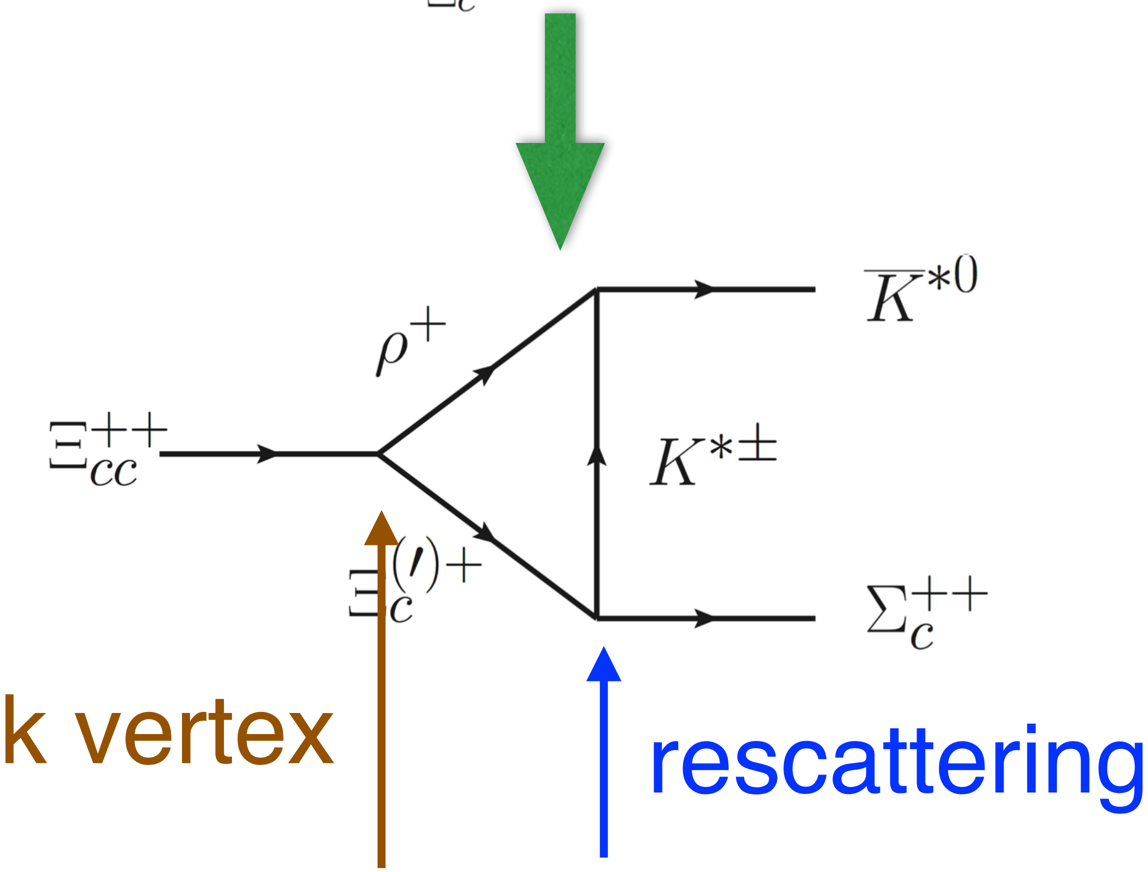
   — final-state interacting (FSI) effects, rescattering

[**FSY**, Jiang, Li, Lü, Wang, Zhao, arXiv:1703.09086]

$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}$



Rescattering mechanism of the final-state interacting effects



Absorptive part:

$$\mathrm{Abs}\mathcal{M}(p_i \to p_f q) =$$

$$\frac{1}{2}\sum_j \left(\prod_{k=1}^{j} \int \frac{d^3 p_k}{(2\pi)^3 2E_k}\right)(2\pi)^4 \quad \times \delta^4\Big(p_f + q - \sum_{k=1}^{j} p_k\Big) M(p \to \{p_k\}) T^*(p_f q \to \{p_k\})$$

Relative Branching Fractions with long-distance contributions

Baryons	Modes	$\mathcal{B}_{\rm LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
	pD^{*+}	0.04
	pD^{+}	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^{+}\overline{K}^{*0}$	$(\mathcal{R}_\tau/0.3)\times 0.22$
	$\Sigma_c^{++}(2455)K^{-}$	$(\mathcal{R}_\tau/0.3)\times 0.008$
	$\Xi_c^{+}\rho^{0}$	$(\mathcal{R}_\tau/0.3)\times 0.04$
	ΛD^{+}	$(\mathcal{R}_\tau/0.3)\times 0.004$
	pD^{0}	$(\mathcal{R}_\tau/0.3)\times 0.002$

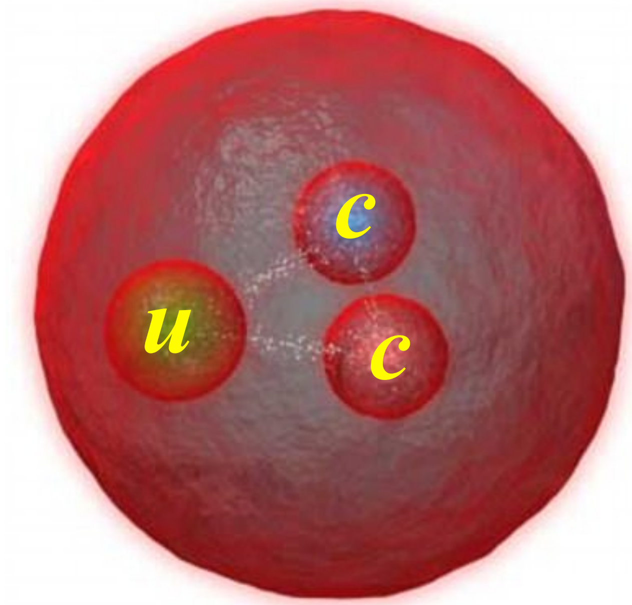
$\Lambda_c^+K^-\pi^+\pi^+$

Largest

Uncertainties of the relative branching fractions induced by the parameter of η are less than 10%

LHCb observed Xi_cc^++

[LHCb, 1707.01621]



Understanding of long-distance contributions

↓

Predictions on charmed baryon decays

↓

LHCb successfully discovered Xi_cc^++

↓

Understanding is correct.

To study singly charmed baryons

and tetraquarks…

Search for tetraquarks via weak decays

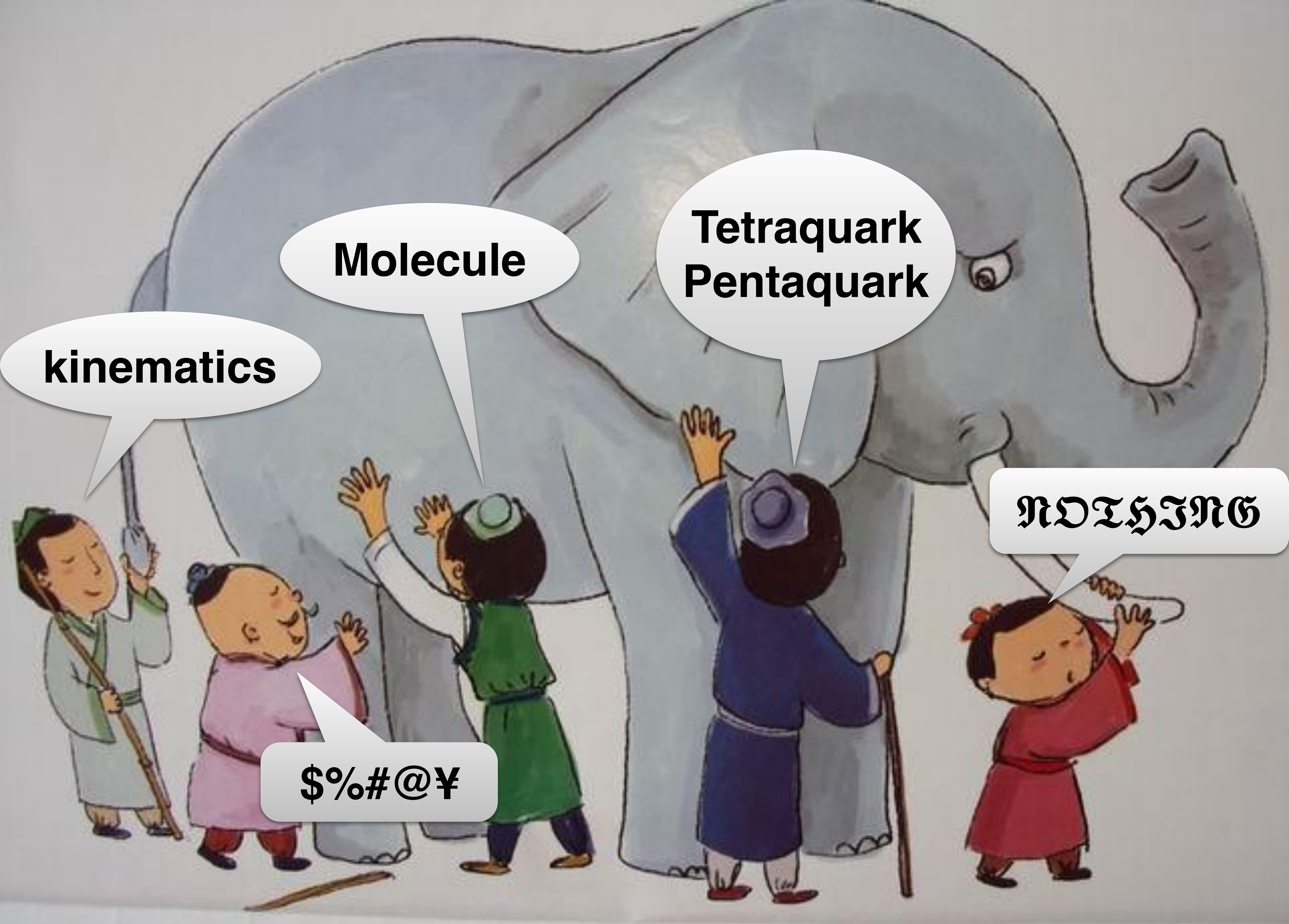
$bs\bar{u}\bar{d}$: **A Promising Detectable Tetraquark**

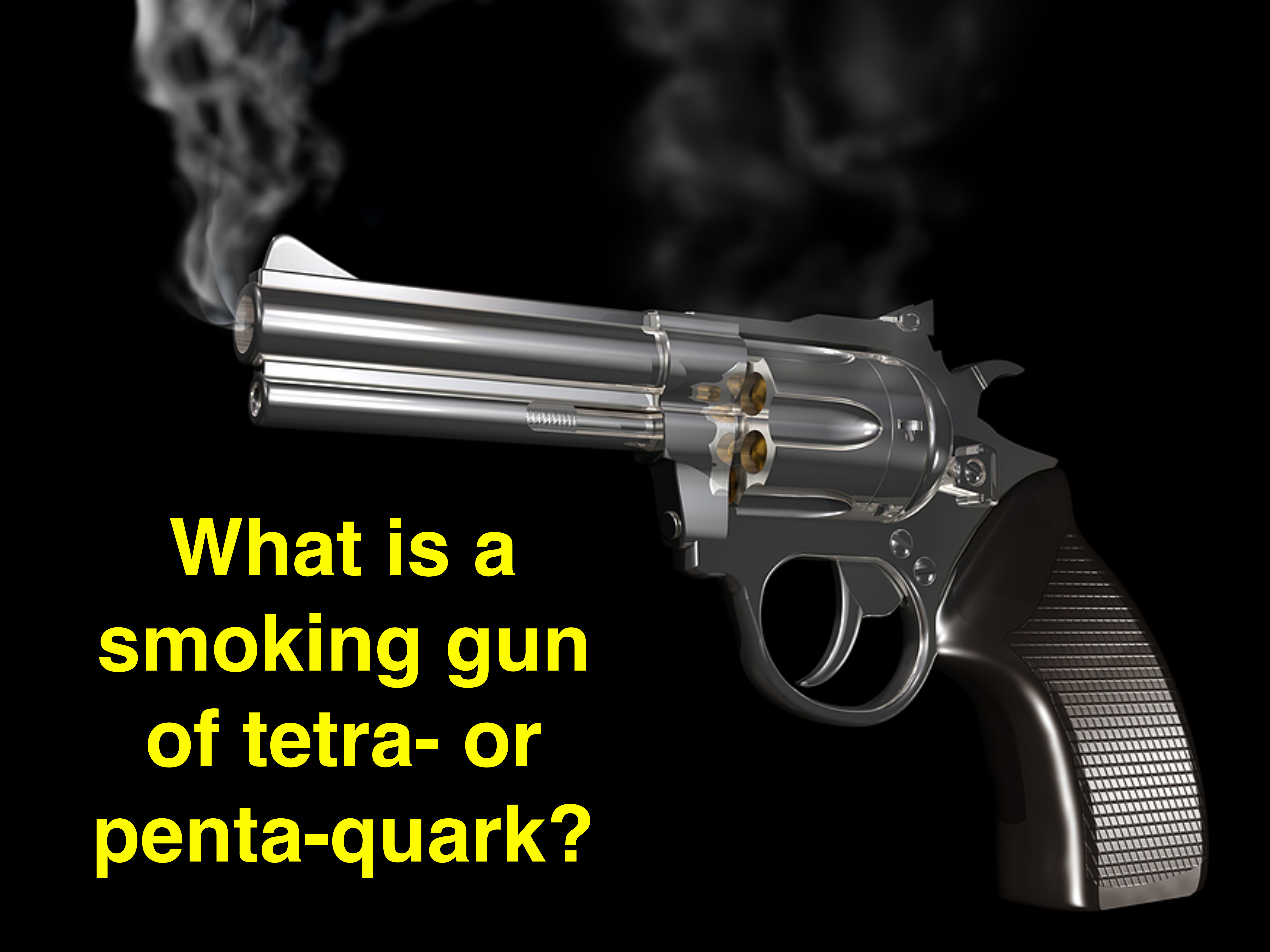
Fu-Sheng Yu

Sep 8, 2017 - 5 pages

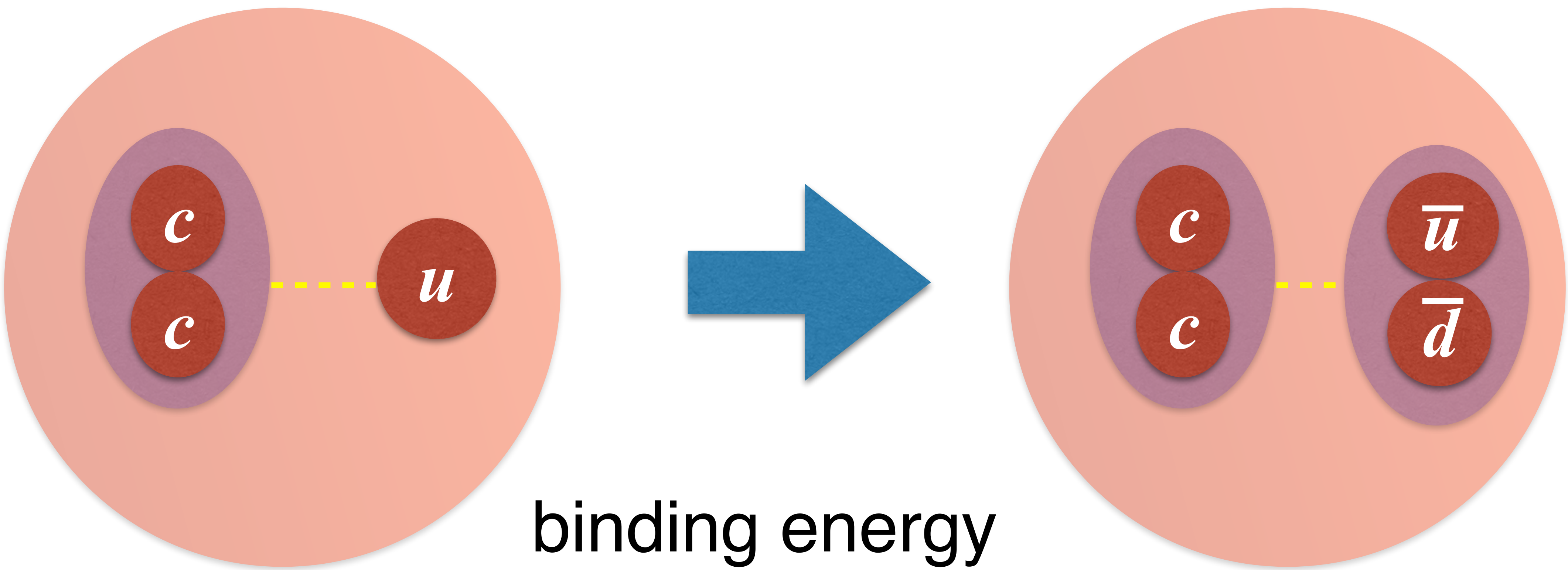
e-Print: arXiv:1709.02571 [hep-ph] | PDF

What are the Exotic Hadrons?


kinematics
Molecule
Tetraquark
Pentaquark
NOTHING
$%#@¥


What is a
smoking gun
of tetra- or
penta-quark?

If observe weak decays, signal tetraquarks



binding energy of cc-diquark

But lower production

Ξ_{cc}^{++}

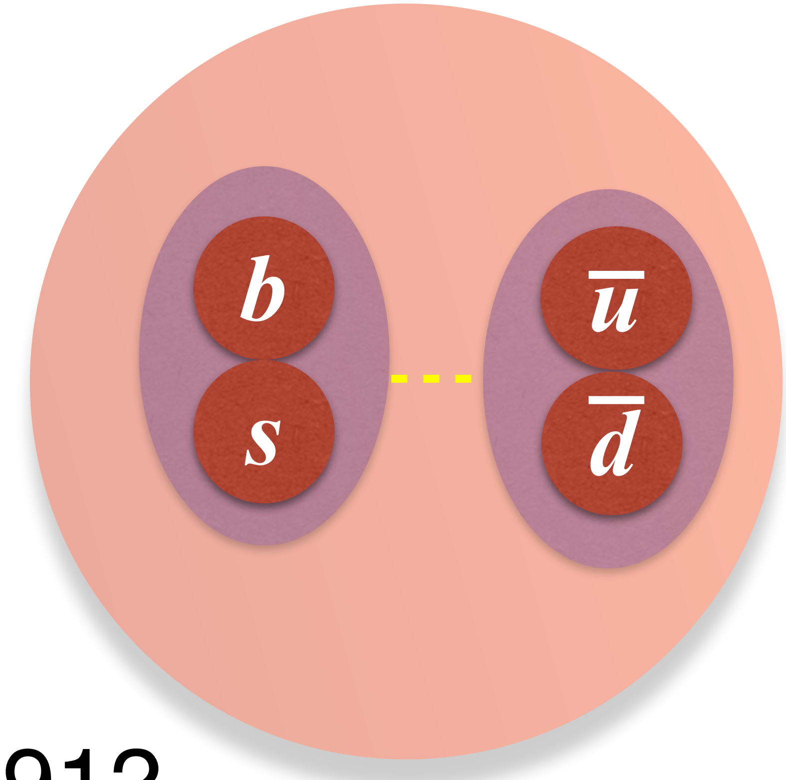
cc-Tetraquark

[LHCb, 1707.01621]

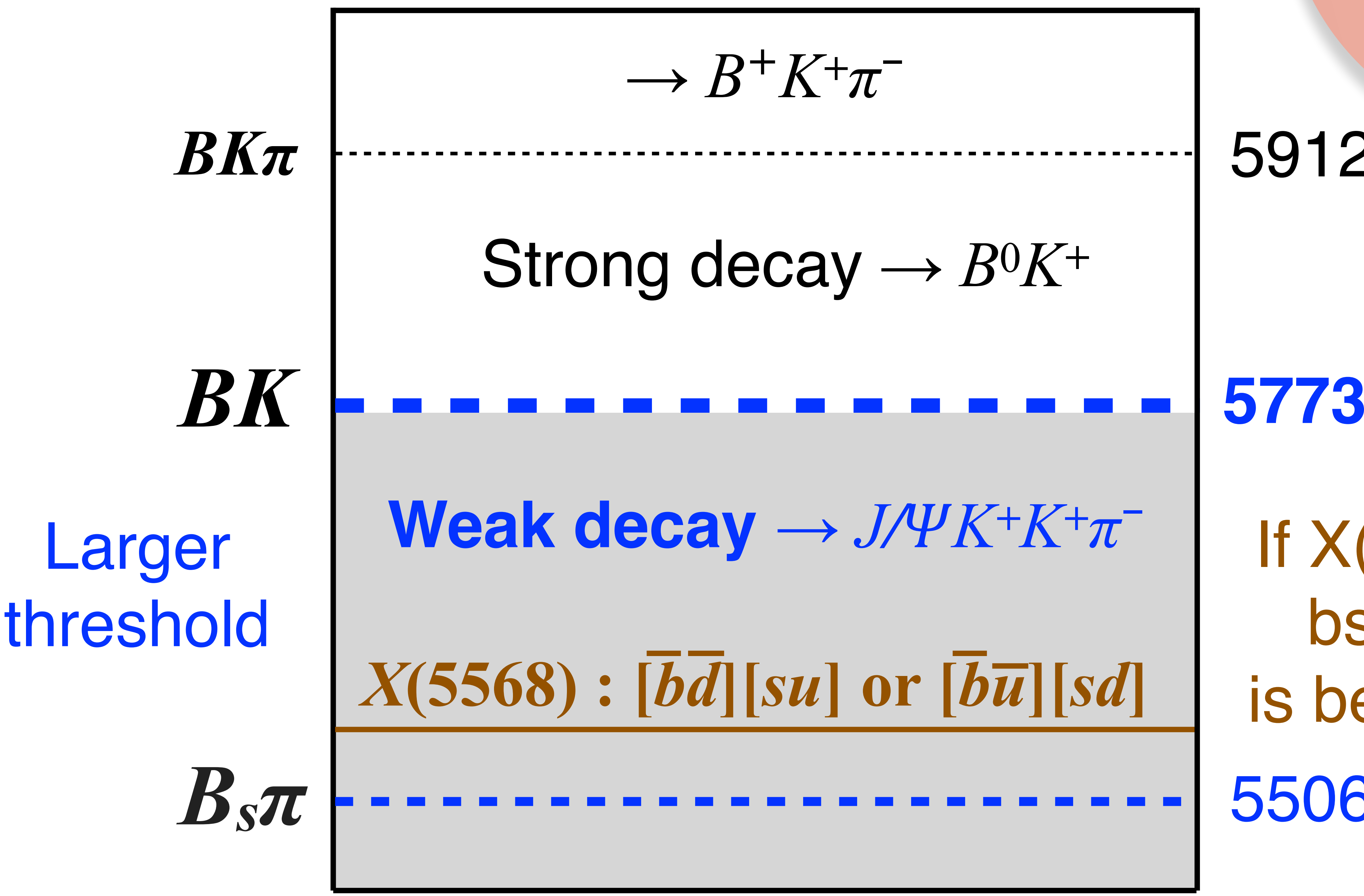
[Karliner, Rosner, 1707.07666]

[Eichten, Quigg, 1707.09575]

$[\bar{b}\bar{s}][ud]$ Tetraquarks



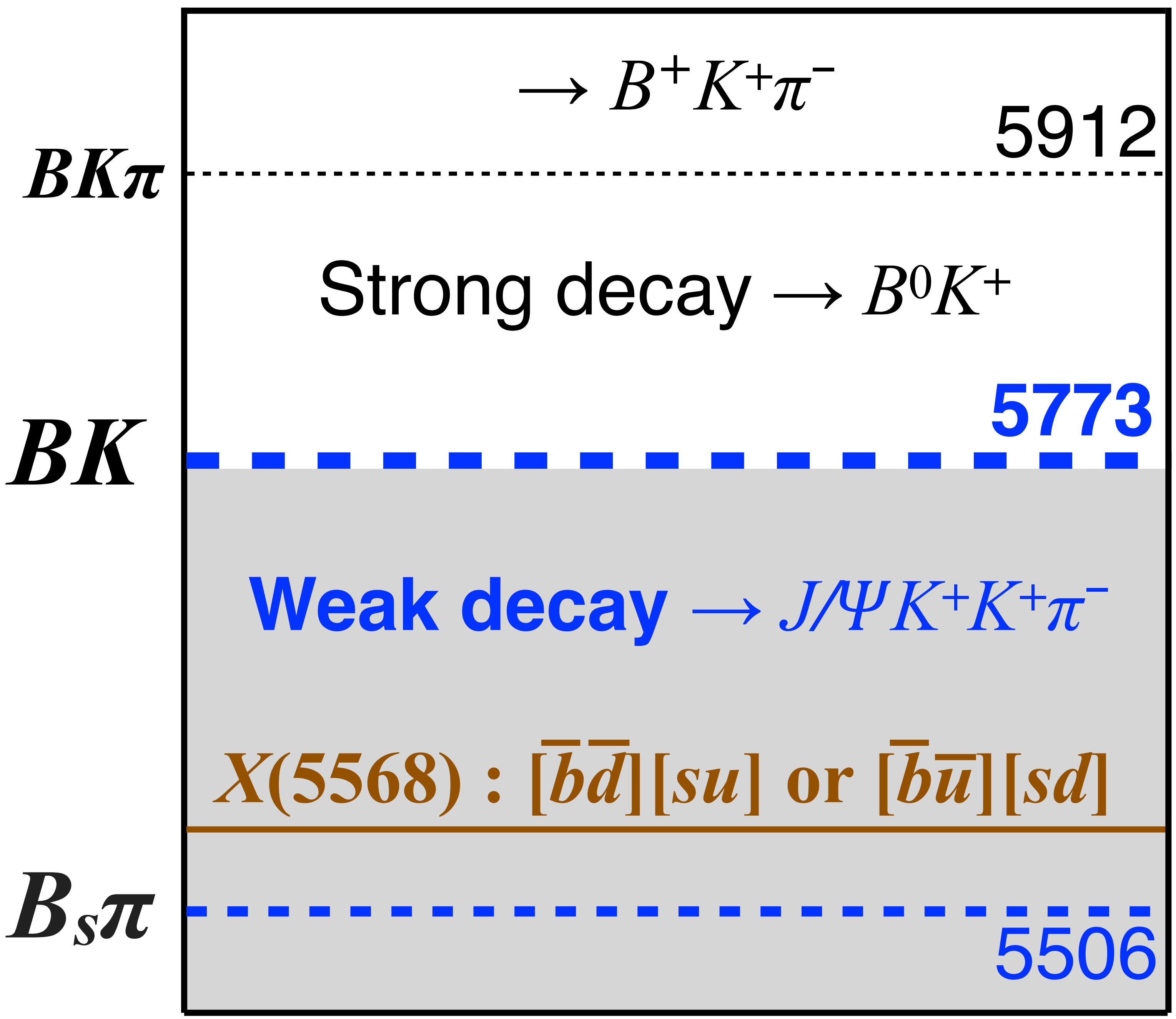
Lowest-lying state, 0^+



If X(5568) exists, bs-tetraquark is below threshold

$[\bar{b}\bar{s}][ud]$ Tetraquarks

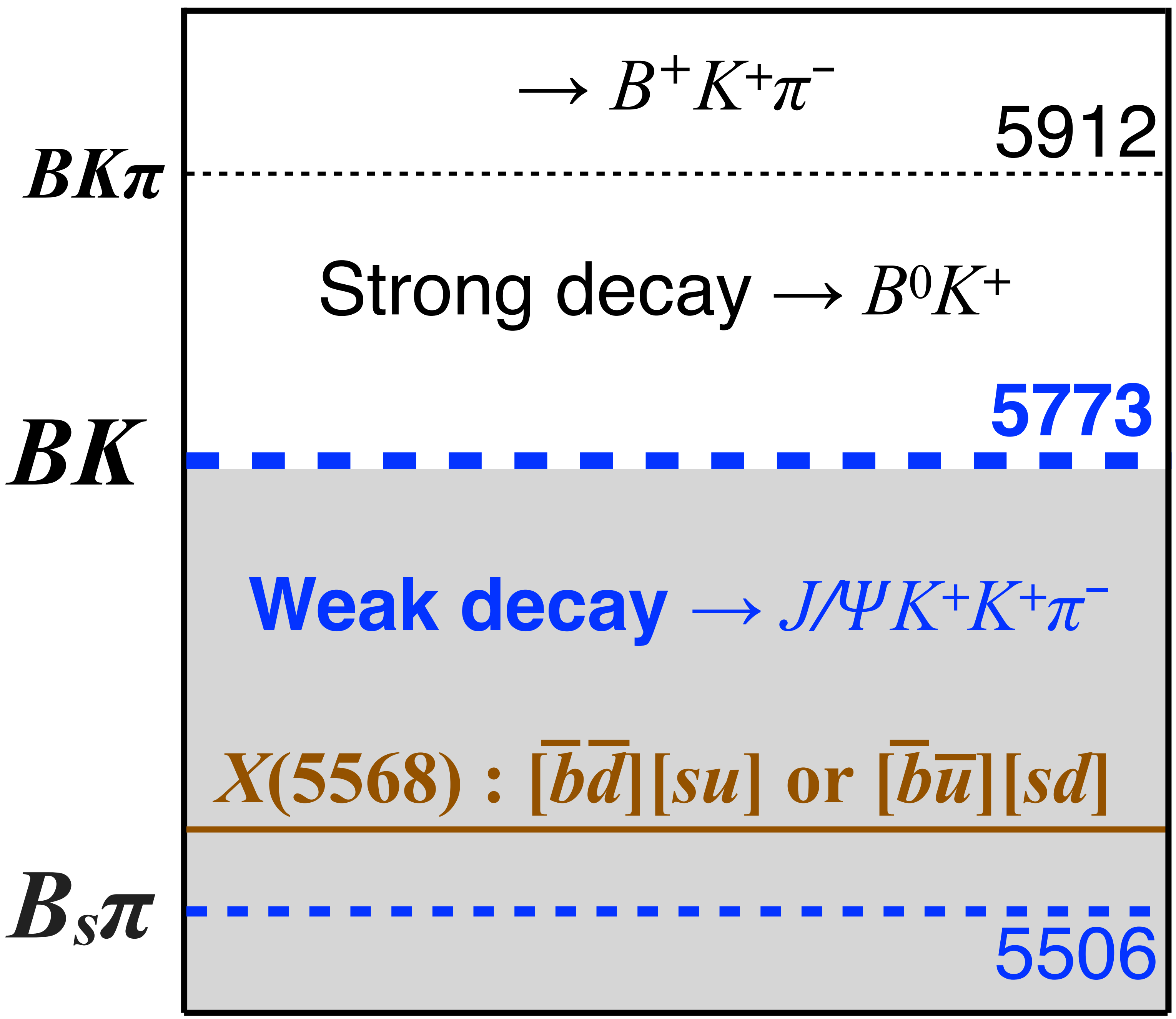
Lowest-lying state, 0^+



1. Higher threshold, BK is 270MeV over $B_s\pi$
2. If X(5568) exists, in SU(3) symmetry bs-tetraquark is below threshold, and weakly decay.
3. If above threshold, *Kaon* suppresses background. better than $B_s\pi$

$[\bar{b}\bar{s}][ud]$ Tetraquarks

Lowest-lying state, 0^+



@ LHCb

1. Large production
2. If below threshold, easy to measure:
   - $\tau \sim \tau_B$ in heavy quark symmetry
   - J/Ψ involving.
3. If above threshold, *Kaon* reduce bkg. better than $B_s\pi$

Production @ LHCb

3×10^5 yields of $B^-\to J/\Psi K^-$ @ 3 fb^{-1} [LHCb, arXiv:1612.06116]

$$B^+ : B^0 : B_s^0 : \Lambda_b = 1 : 1 : \lambda : \frac{\lambda}{2} \qquad \lambda \sim 0.2 - 0.3$$

[Y.Jin, S.Y.Li, S.Q.Li, PRD16']

- Production Ratio $$\frac{P_{T_{bs}^-}}{P_{B^-}} = \lambda \times \frac{\lambda}{2} \times \frac{\lambda}{2} \sim (0.2 - 0.7)\% = \mathcal{O}(10^{-3})$$

- Decaying branching fractions:

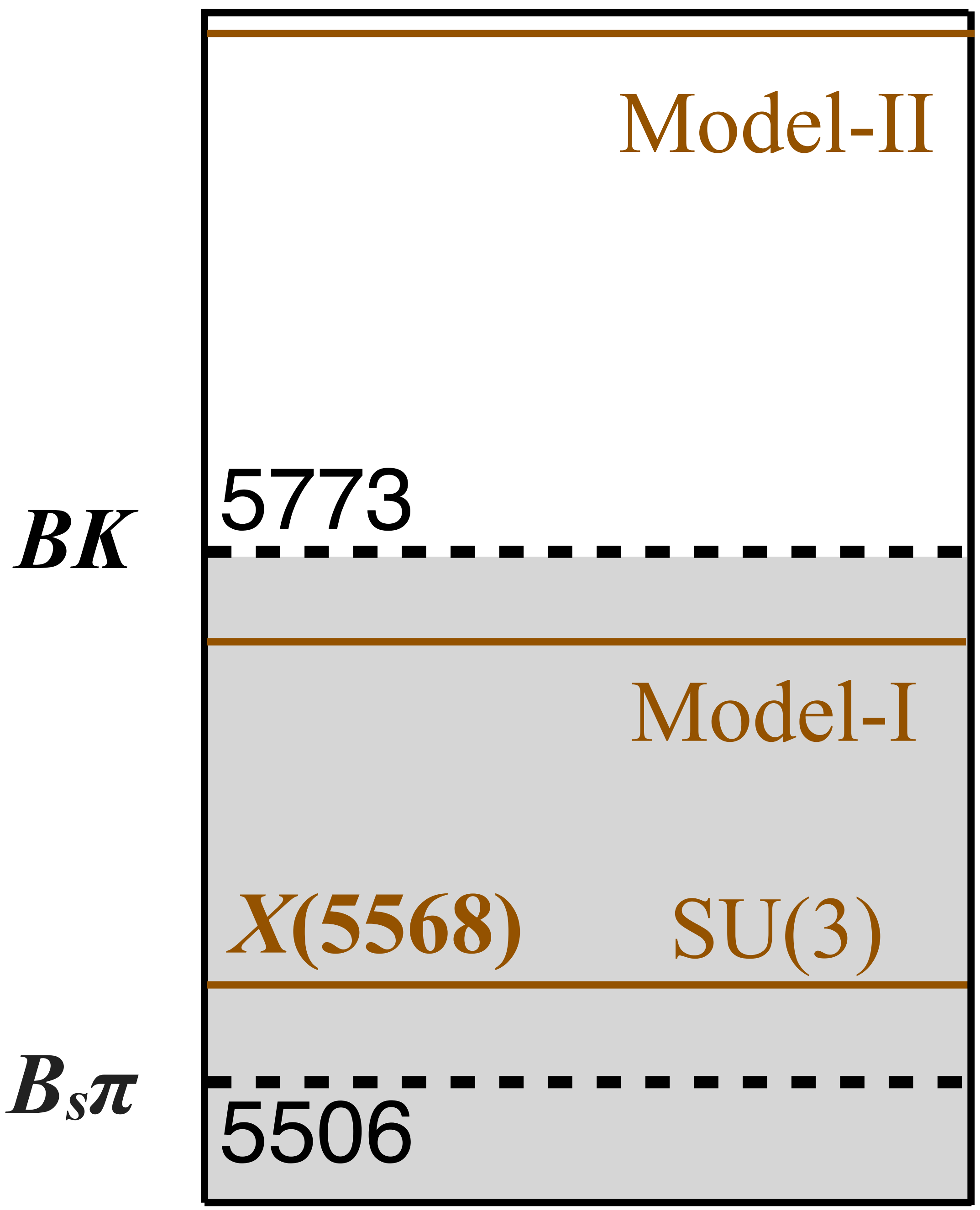
$$\mathrm{Br}(T_{bs}\to J/\Psi K^+K^+\pi^-) \sim \mathrm{Br}(b\to s\, J/\Psi) \sim \mathrm{Br}(B^+\to J/\Psi K^+)$$

Expected to have hundreds of signal yields

If exists below threshold,
it must be discovered @ LHCb RUN II

$[bs][\bar{u}\bar{d}]$ Tetraquarks

Lowest-lying state, 0^+



Model-II: simple quark model

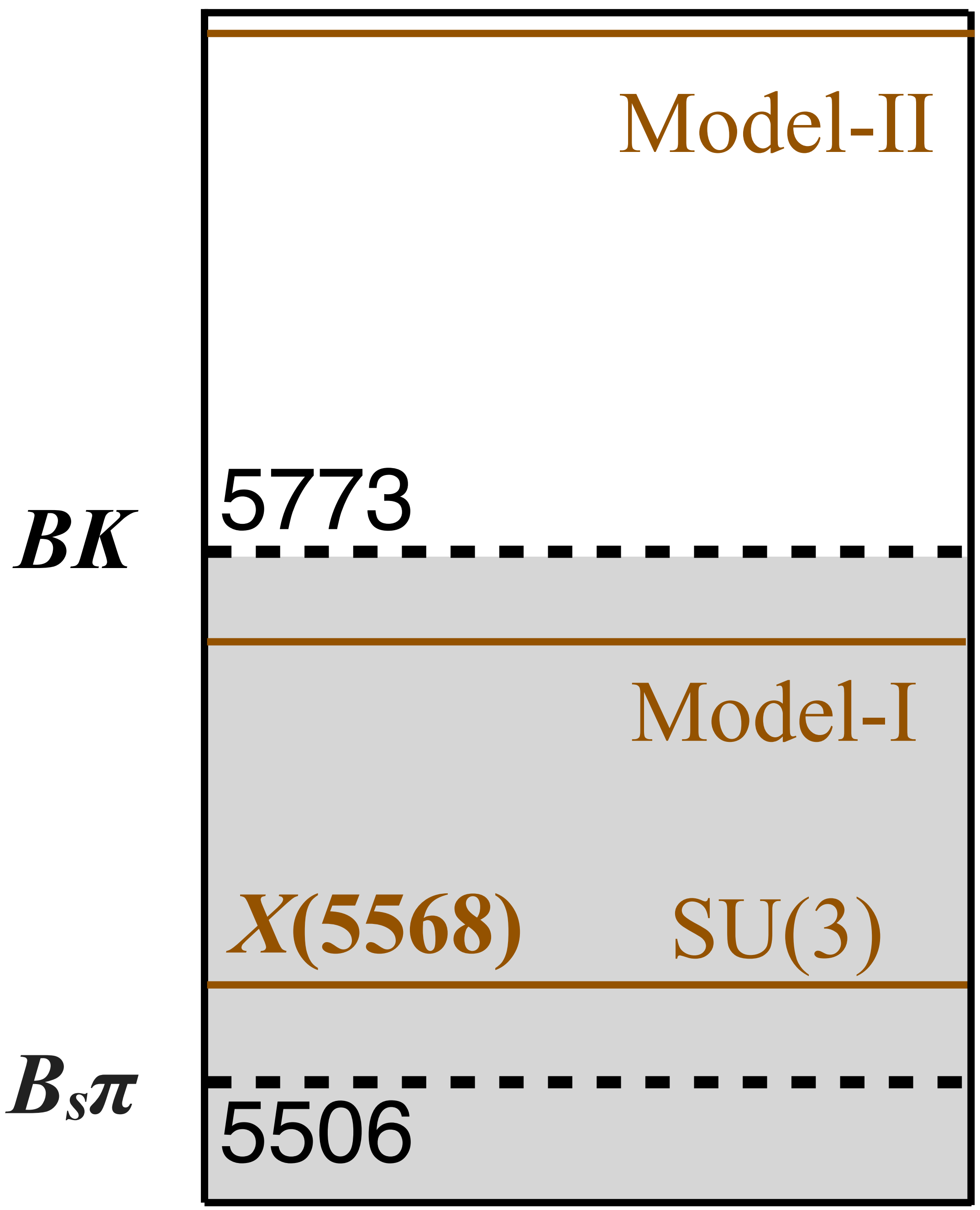
$$= m_b^b + m_s^b + 2m_q^b + a_{bs}/(m_b^b m_s^b) - 3a/(m_q^b)^2 + B(bs)$$

Model-I: diquark-antidiquark

$$H = m_{[bs]} + m_{[ud]} + \sum_{i<j} 2\kappa_{ij}(\mathbf{S}_i \cdot \mathbf{S}_j)$$

$[bs][\bar{u}\bar{d}]$ Tetraquarks

Lowest-lying state, 0^+



Above threshold: Strong decay

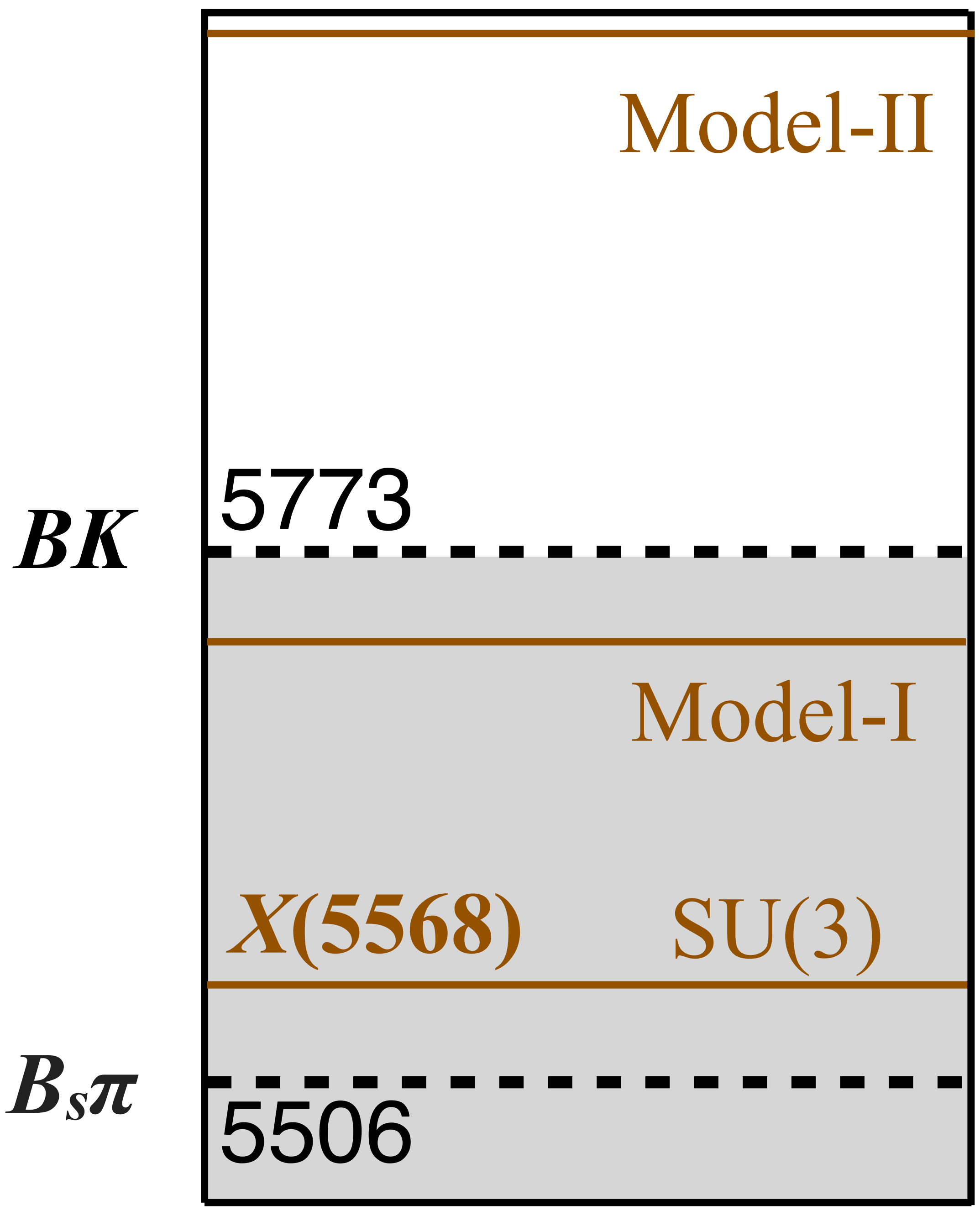
$\rightarrow \overline{B}^0 K^- \text{ or } B^- \overline{K}^0$

Below threshold: Weak decay

$\rightarrow J/\Psi K^- K^- \pi^+$

$[bs][\bar{u}\bar{d}]$ Tetraquarks

Lowest-lying state, 0^+



If nothing observed

below threshold,

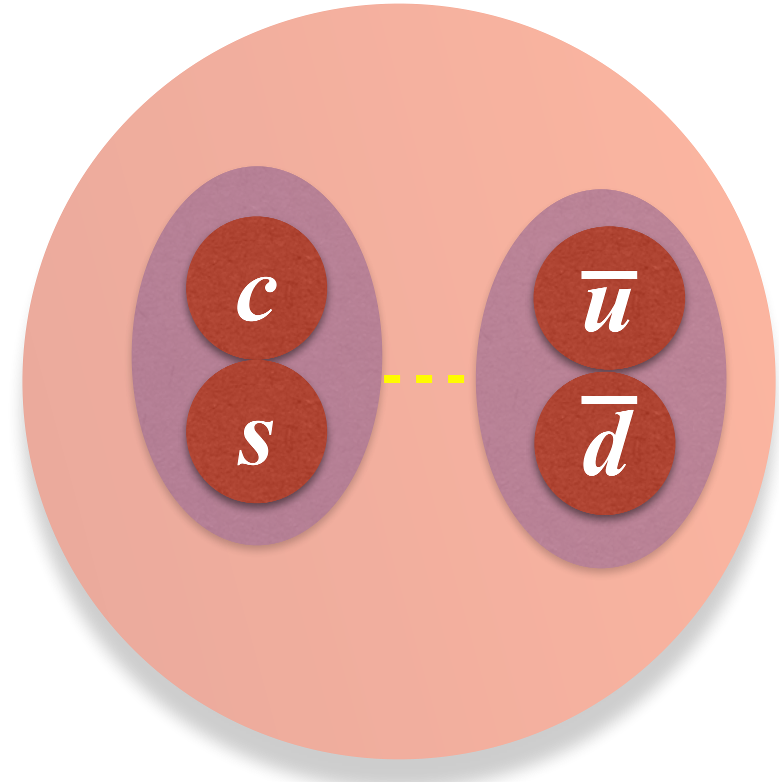
constrain

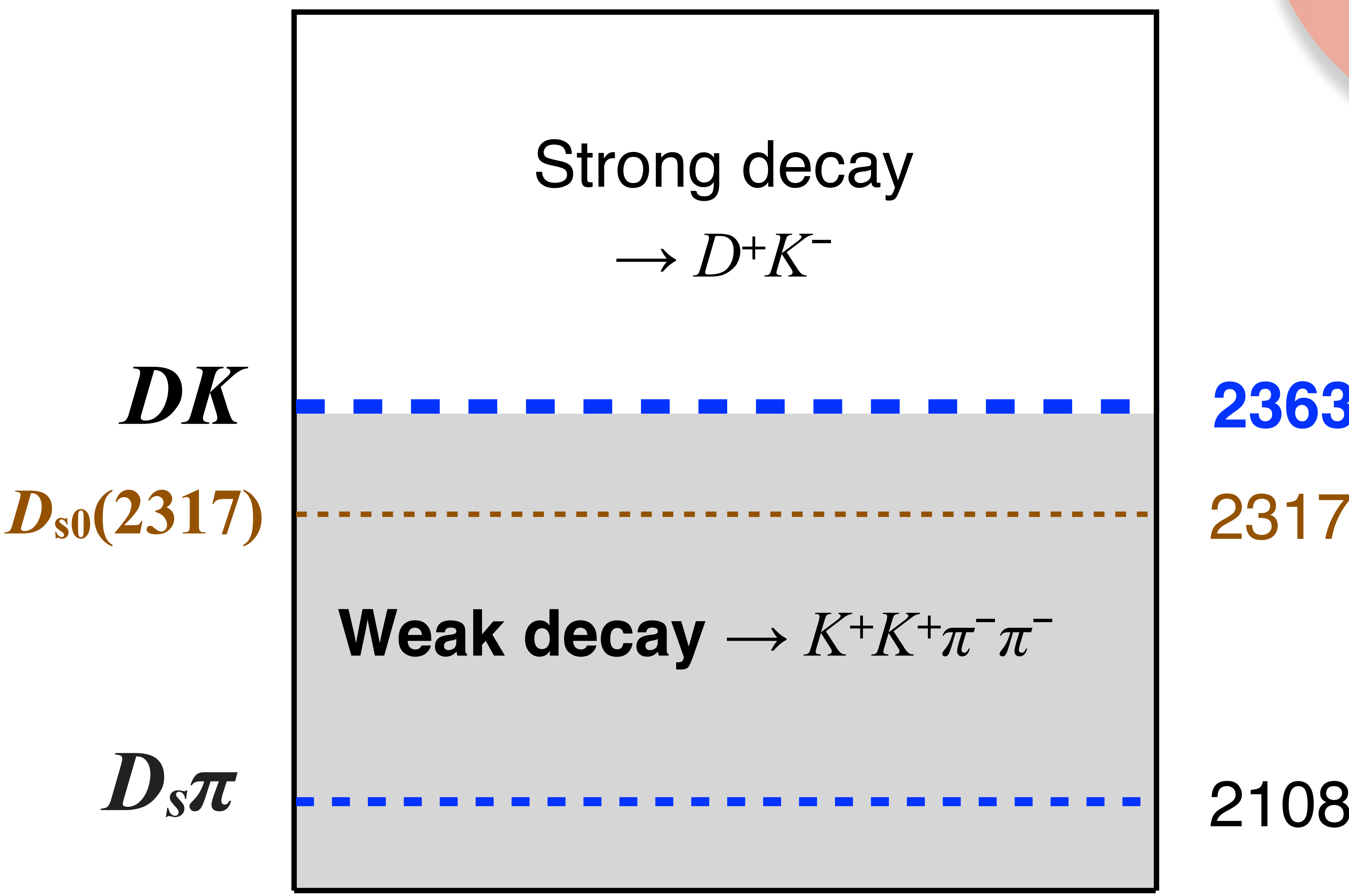
the lower mass of

the ground state of

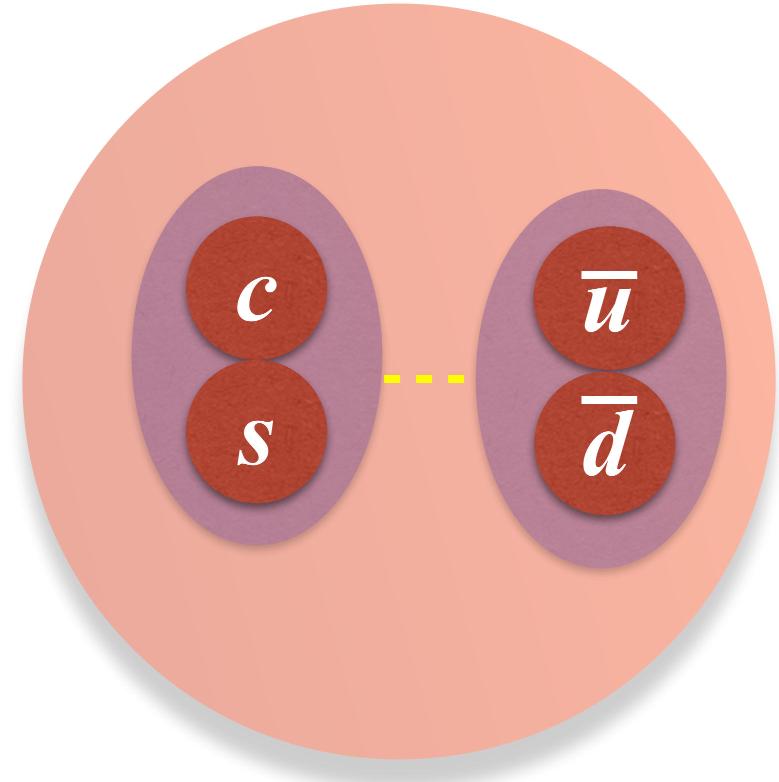
tetraquarks

$[cs][\bar{u}\bar{d}]$ Tetraquarks

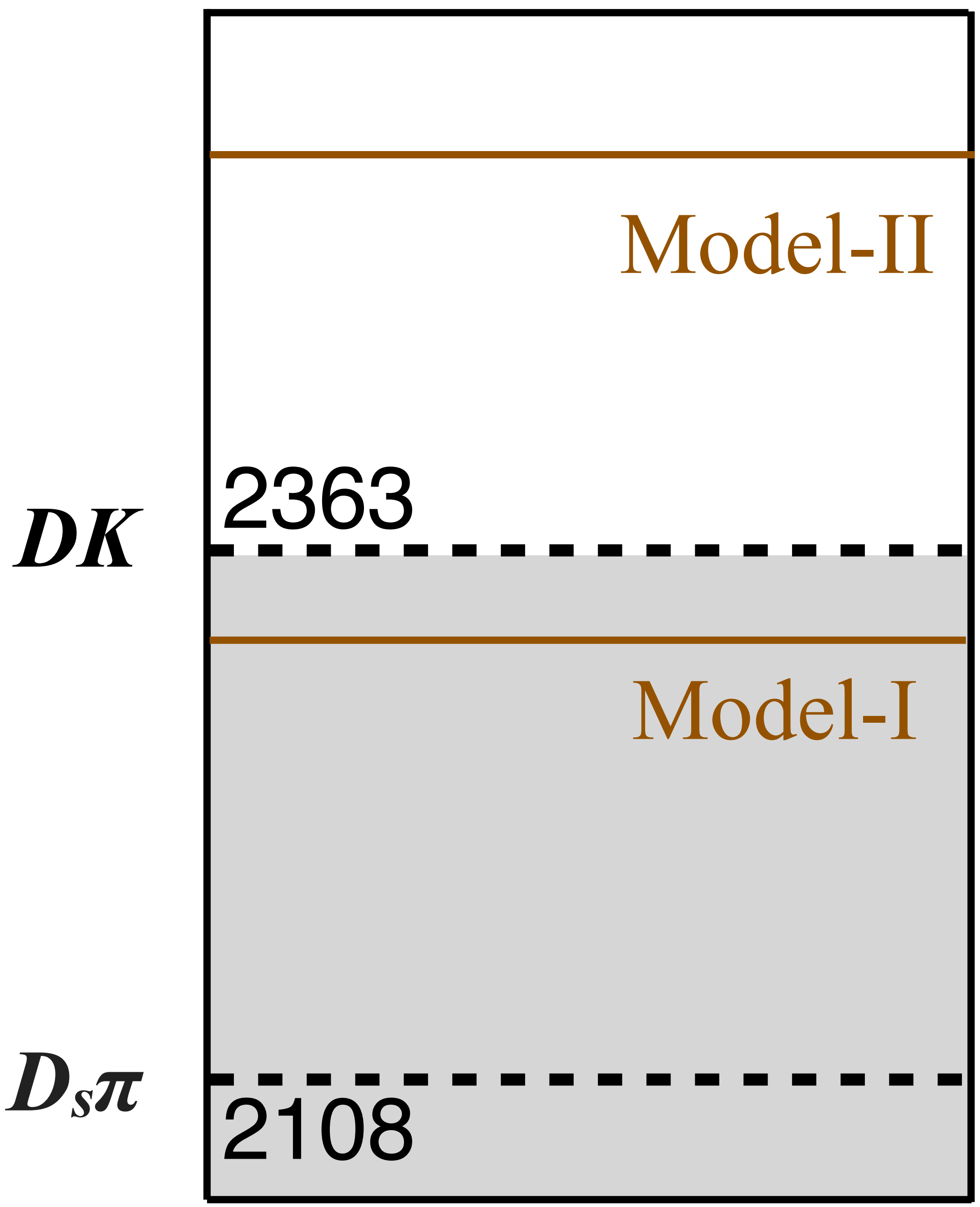




$[cs][\bar{u}\bar{d}]$ Tetraquarks



Lowest-lying state, 0^+



Strong decay

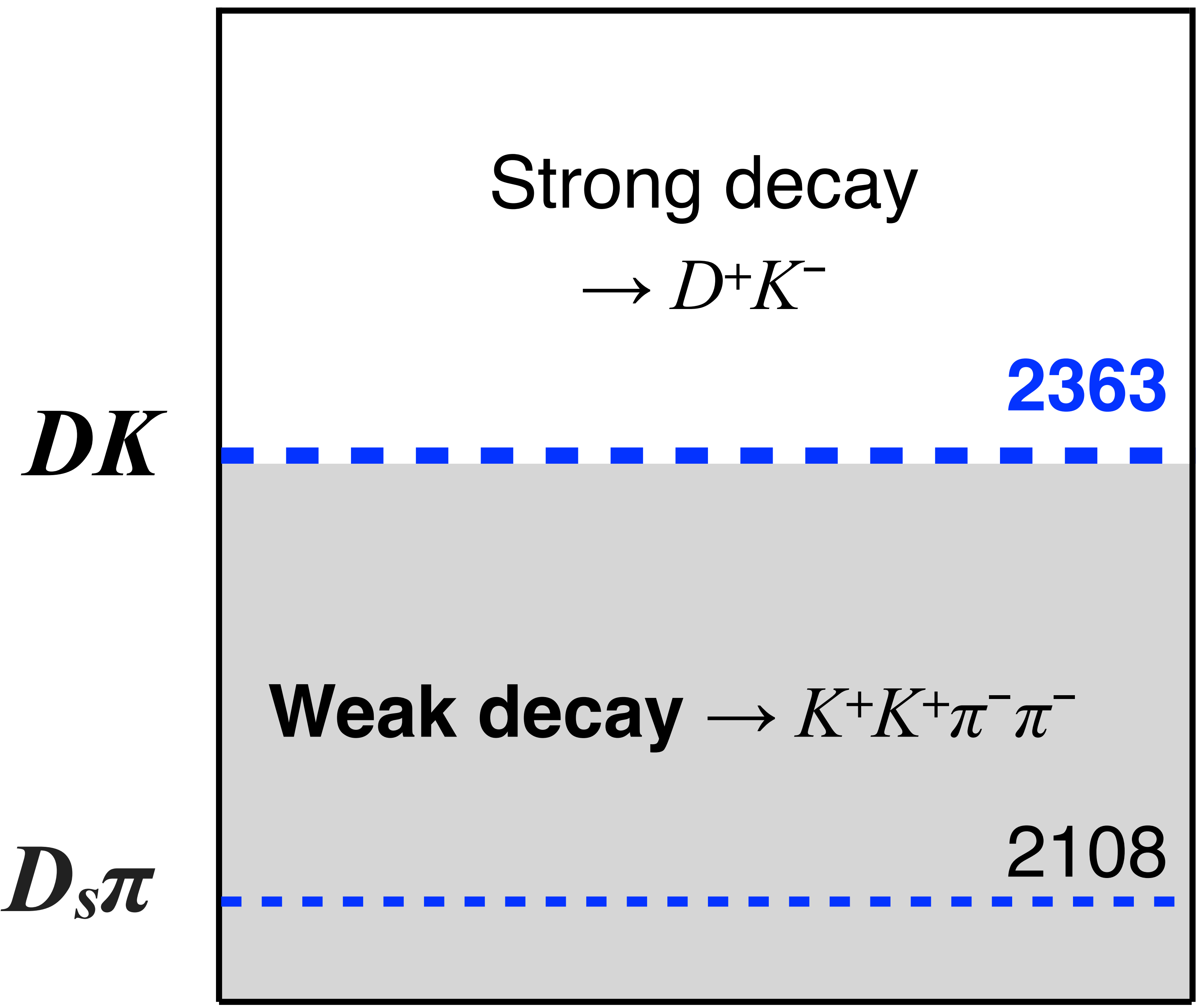
$\rightarrow D^+K^-$

Weak decay

$\rightarrow K^+K^+\pi^-\pi^-$

$[cs][\bar{u}\bar{d}]$ Tetraquarks

- Largest production with four flavors.



@ LHCb

- three orders larger than bs-tetraquark

@ Belle (II)

- lower background

@ BESIII

- try?

$[bs][\bar{u}\bar{d}]$ and $[cs][\bar{u}\bar{d}]$ **Tetraquarks**

are the most promising

stable open heavy flavor

tetraquark states

accessible in experiments

Summary

- **Charm physics is becoming more charming**
- **Charm physics requires collaborations between theorists and experimentalists.**
  - In theory, non-pert para's to be obtained by data
  - In experiment, any effort is helpful
- **To search for new physics**
  - **New CPV** is found in charm decays into neutral K.
  - Direct CPV is promising to search for new physics
- **To search for exotic states**
  - **Weak decays** is a new tool for searches and constraints
  - **$cs\bar{u}\bar{d}$** tetraquark is to be measured

谢谢大家！

祝身体健康！顺心快乐！

祝国庆中秋快乐！