北京航空航天大學
BEIHANG UNIVERSITY

粲重子谱学研究

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1409.3133

1603.05388

1805.08330

2012.01135

……

……

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Selected physics cases for upgraded BEPCII

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1409.3133 → 1603.05388 → 1805.08330 → 2012.01135 → …… → ……

Contents

- Exotic hadrons
  - ✓ Singly charmed baryons—$\Lambda_c(2595)$: 1409.3133, 1603.05388
  - ✓ Excited kaons above 4 GeV ($KD\overline{D^{(*)}}$)—Kc(4180): 1805.08330, 2012.01134
- Rare processes & new physics
  - ✓ Searching for NP in hyperon decays
  - ✓ Weak radiative hyperon decays
- Summary & outlook

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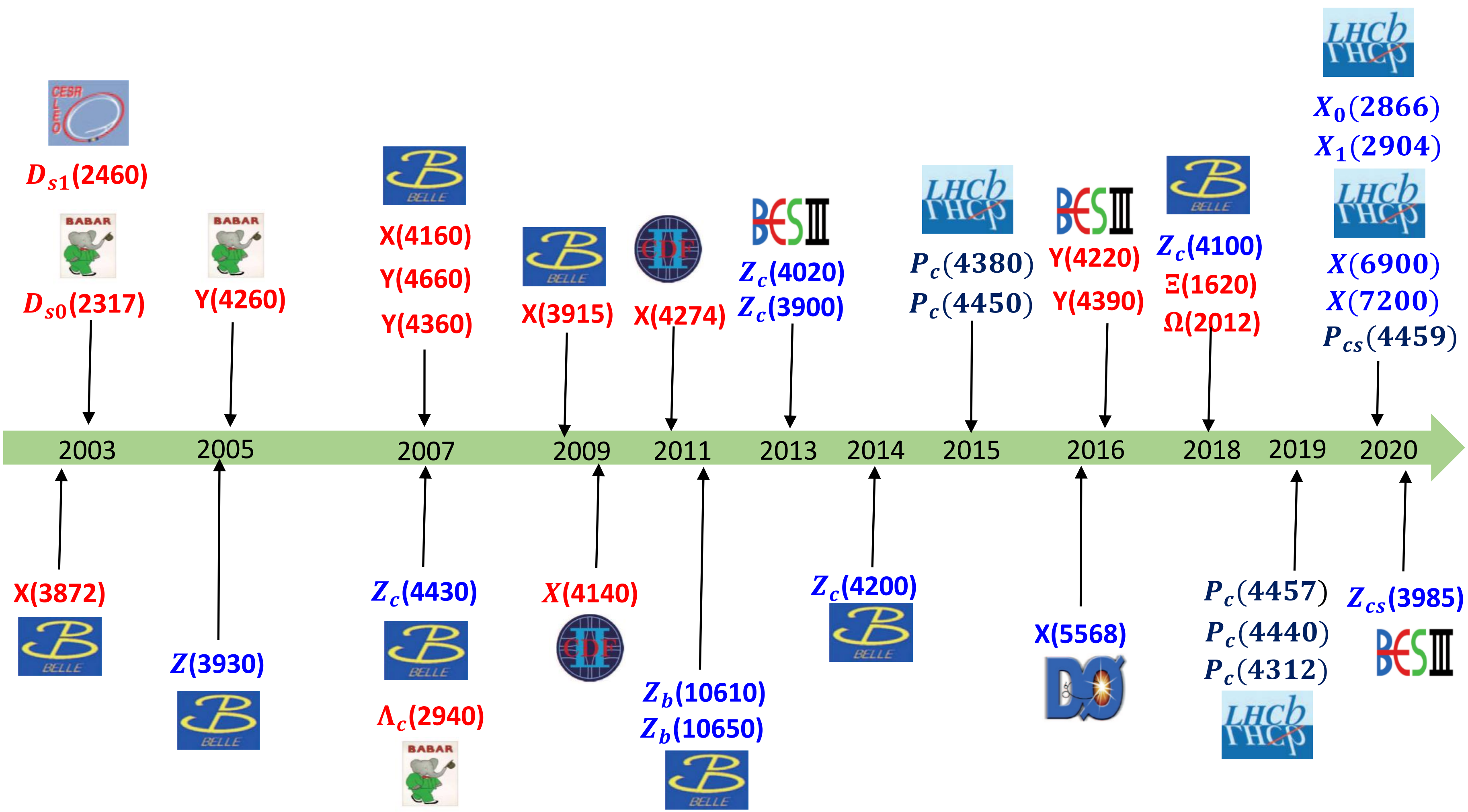
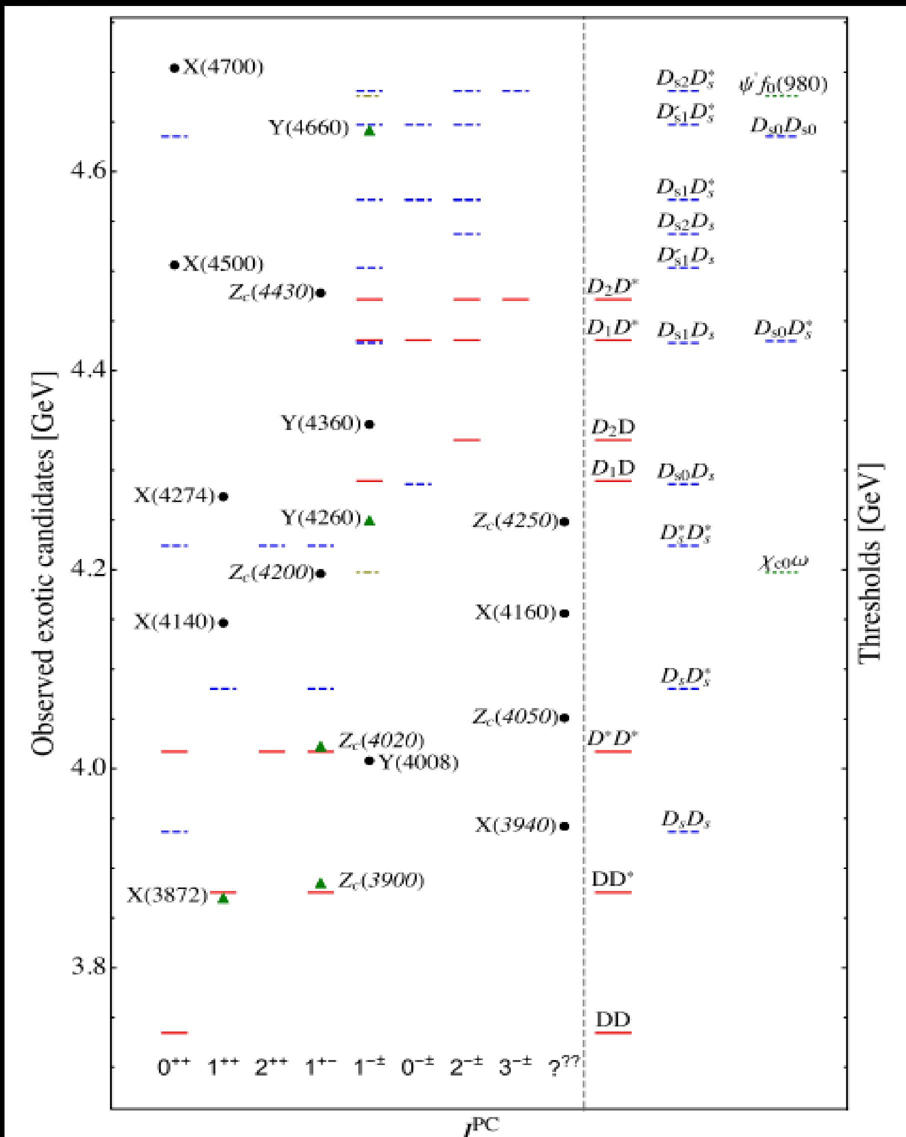
  - ✓ **Weak radiative hyperon decays**
- **Summary & outlook**

Exotic mesons or baryons Tetraquark states Pentaquark states



Many (if not all) of them close to thresholds



Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004.

Theoretical methods for molecules

- **Model dependent approaches**
  - ✓ One boson exchange modes
  - ✓ Local Hidden gauge approaches
  - ✓ Unquenched quark models
  - ✓ ……

Unitary Chiral Approach (Effective Field Theory)

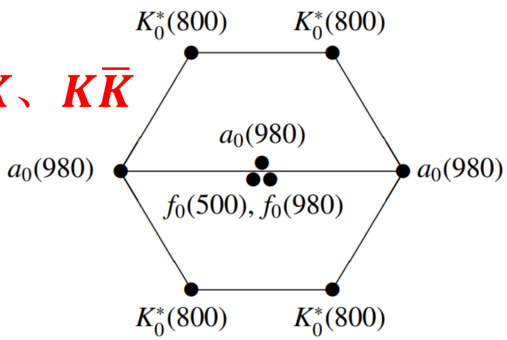
- **Model independent approaches**
  - ✓ **Chiral field theory theory**
  - ✓ **Effective field theories**
  - ✓ **……**

Unitary Chiral Approach

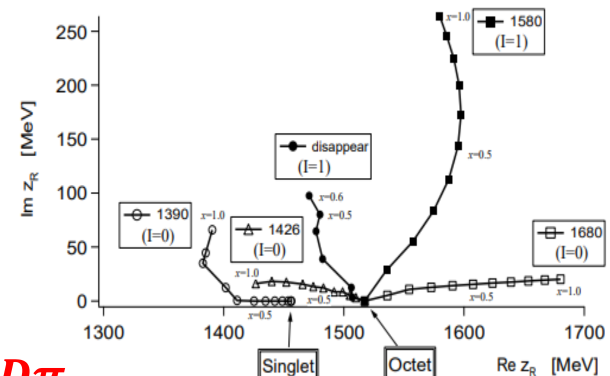
❑ Very successful:

- ✓ Low-lying scalar nonet — J. A. Oller et al. NPA 620, 438
- ✓ Double pole structure of $\Lambda(1405)$ — D. Jido et al. NPA725,181
- ✓ Molecular picture of $D^*_{s0}(2317)$ — M. Altenbuchinger et al. PRD89,014021

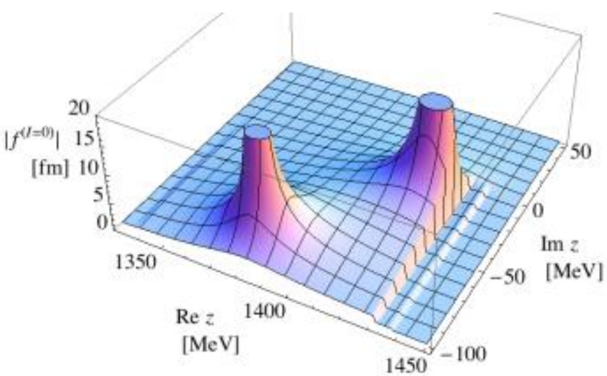
$\pi\pi$、πK、$K\bar{K}$



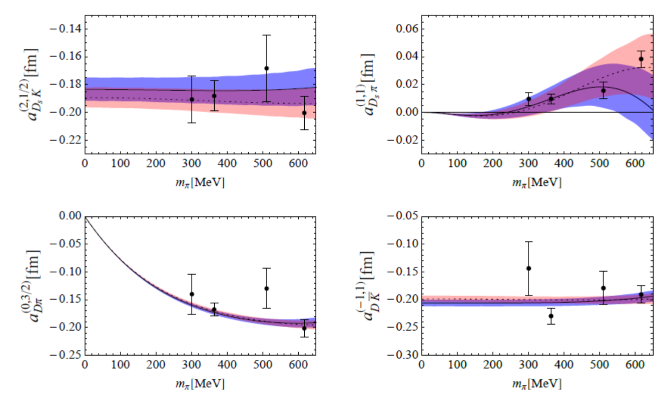
$\bar{K}N$



$\bar{K}N$



$DK/D\pi$



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Motivation: $\Lambda_c(2595)$

- **Very few excited charmed baryons have been well established**

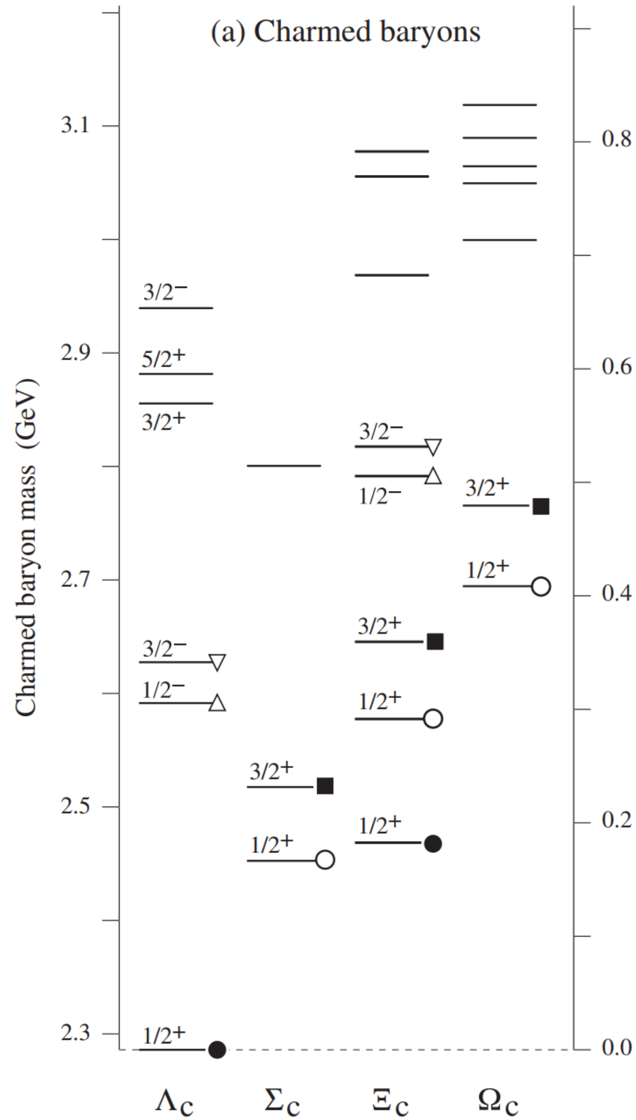
  $\Lambda_c(2595)$, $\Xi_c(2790)$ with $J^P = 1/2^-$

  $\Lambda_c(2625)$, $\Xi_c(2815)$with $J^P = 3/2^-$

  $\Xi_c(3055), \Omega_c(3000), \Omega_c(3050)$, … with unknown J^P

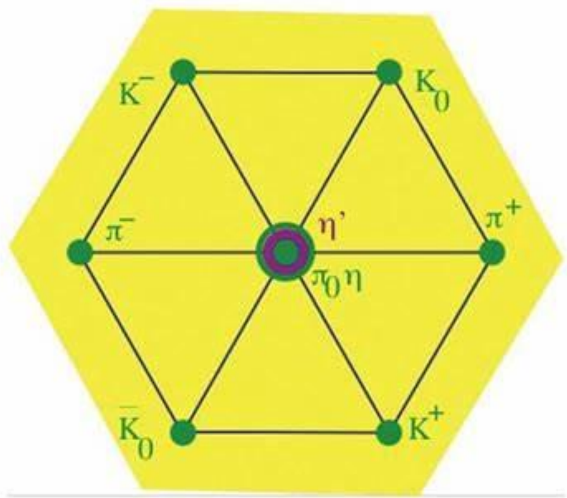
- **More theoretical studies needed**

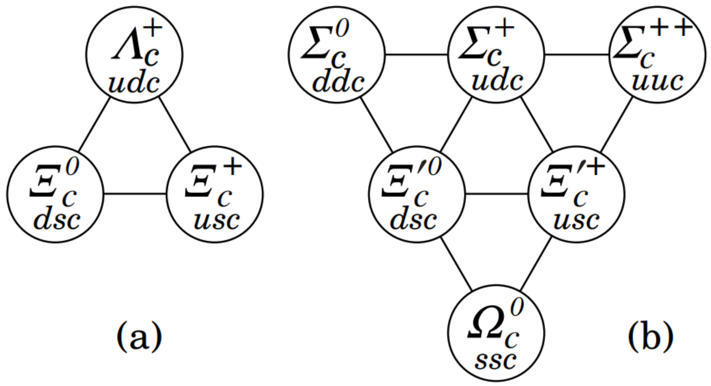
  Possible resonances: mass? width? J^P?
  main components?



36 established

Can the interactions between a pseudoscalar meson and a singly charmed baryons generate molecules



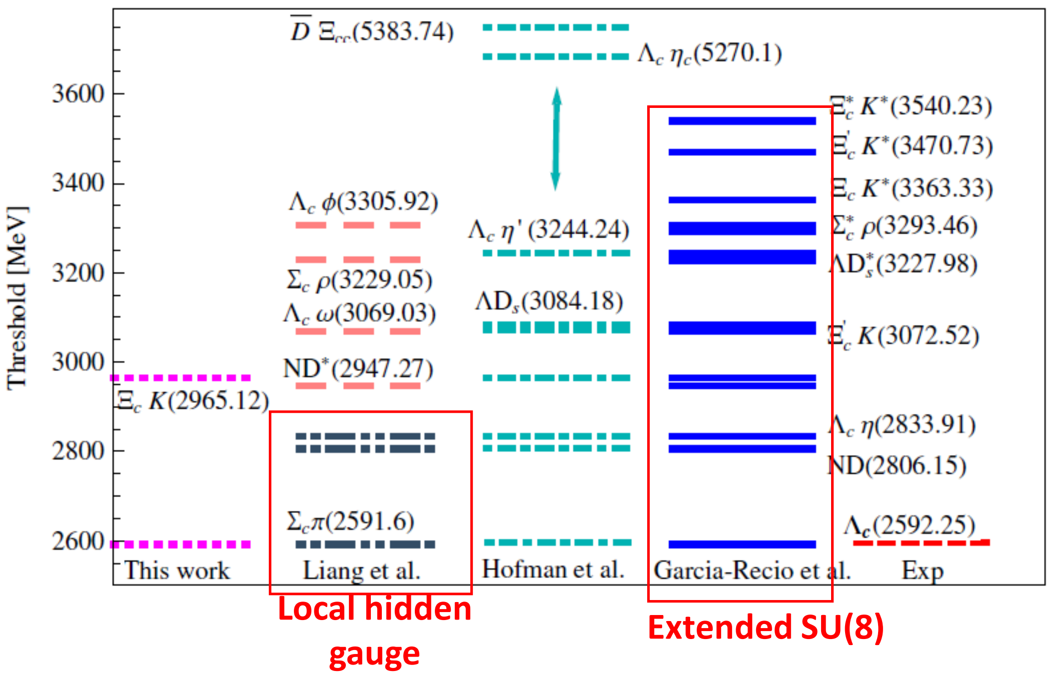


$\Lambda_c(2595)$

❑ Effective Lagrangian

Lutz et al. **NPA**730,110

$$\mathcal{L} = \frac{i}{16 f_0^2}\mathrm{Tr}(\bar{H}_{[\bar{3}]}(x)\gamma^\mu[H_{[\bar{3}]}(x),[\phi(x),(\partial_\mu\phi(x))]_-]_+) + \frac{i}{16 f_0^2}\mathrm{Tr}(\bar{H}_{[6]}(x)\gamma^\mu[H_{[6]}(x),[\phi(x),(\partial_\mu\phi(x))]_-]_+)$$



❑ BS equation

T=V+VGT

Kernel potential V

- Only Goldstone bosons and singly charmed baryons
- The $[\bar{3}]$ and $[6]$ are not mixed

Different number of coupled channels!

Regularization: heavy quark symmery

- BS equation

T*=*V*+*VGT G loop function: UV divergent

✓ Cutoff method(**CUT**)

$$G_{CUT}(s) = \int_0^{q_{max}} \frac{d^3q}{(2\pi)^3} \frac{1}{4E_M E_m} \frac{1}{\sqrt{s} - E_M - E_m + i\epsilon}$$

✓ Dimensional regularization method(DRM, $\overline{MS}$ **scheme**)

$$G_{\overline{MS}}(s) = \frac{1}{16\pi^2}\left[\frac{m^2 - M^2 + s}{2s}\log\left(\frac{m^2}{M^2}\right)\right.$$
$$- \frac{q}{\sqrt{s}}(\log[2q\sqrt{s} + m^2 - M^2 - s] + \log[2q\sqrt{s} - m^2 + M^2 - s]$$
$$- \log[2q\sqrt{s} + m^2 - M^2 + s] - \log[2q\sqrt{s} - m^2 + M^2 + s])$$
$$\left. + \left(\log\left(\frac{M^2}{\mu^2}\right) + a\right)\right]$$

violate power counting rules and HQS

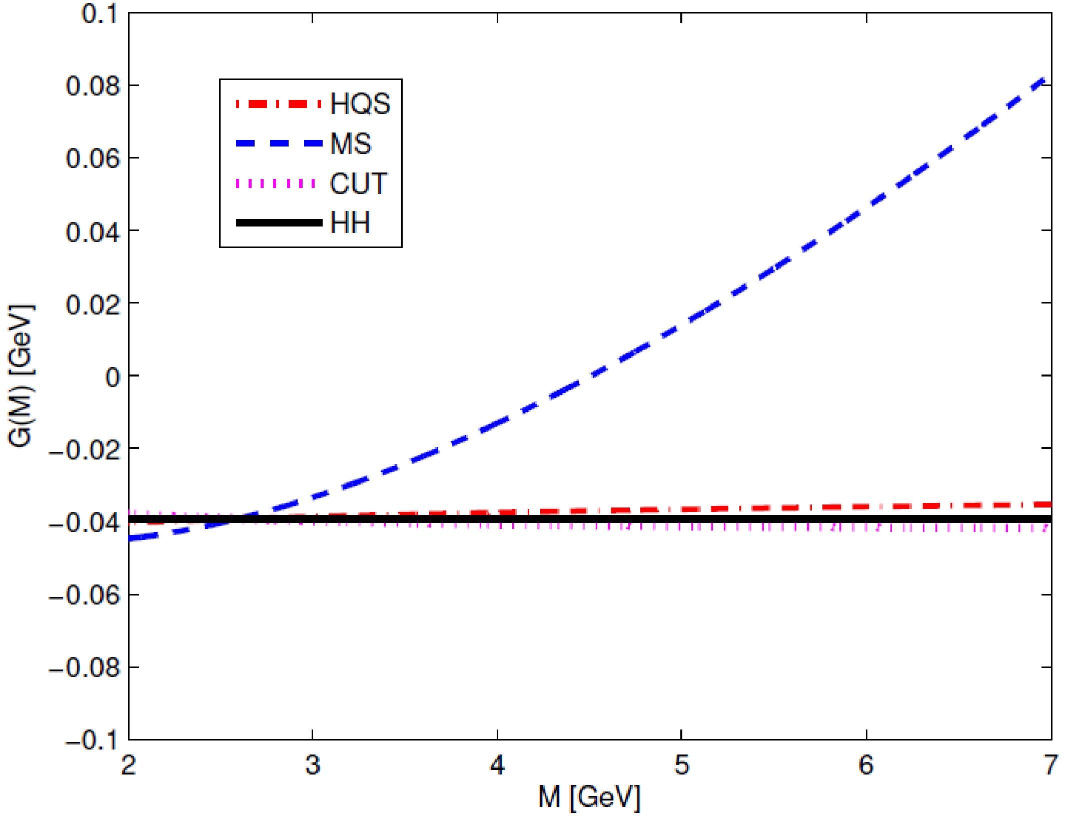
Cleven et al. EPJA47,19 Altenbuchinger et al. PRD89,014021

✓ Heavy quark symmetry inspired scheme(**HQS**)

$$G_{HQS} = G_{\overline{MS}} - \frac{2\mathring{M}}{16\pi^2}\left(\log\left(\frac{\mathring{M}^2}{\mu^2}\right) - 2\right) + \frac{2m_{\text{sub}}}{16\pi^2}\left(\log\left(\frac{\mathring{M}^2}{\mu^2}\right) + a\right)$$

Regularization: heavy quark symmery

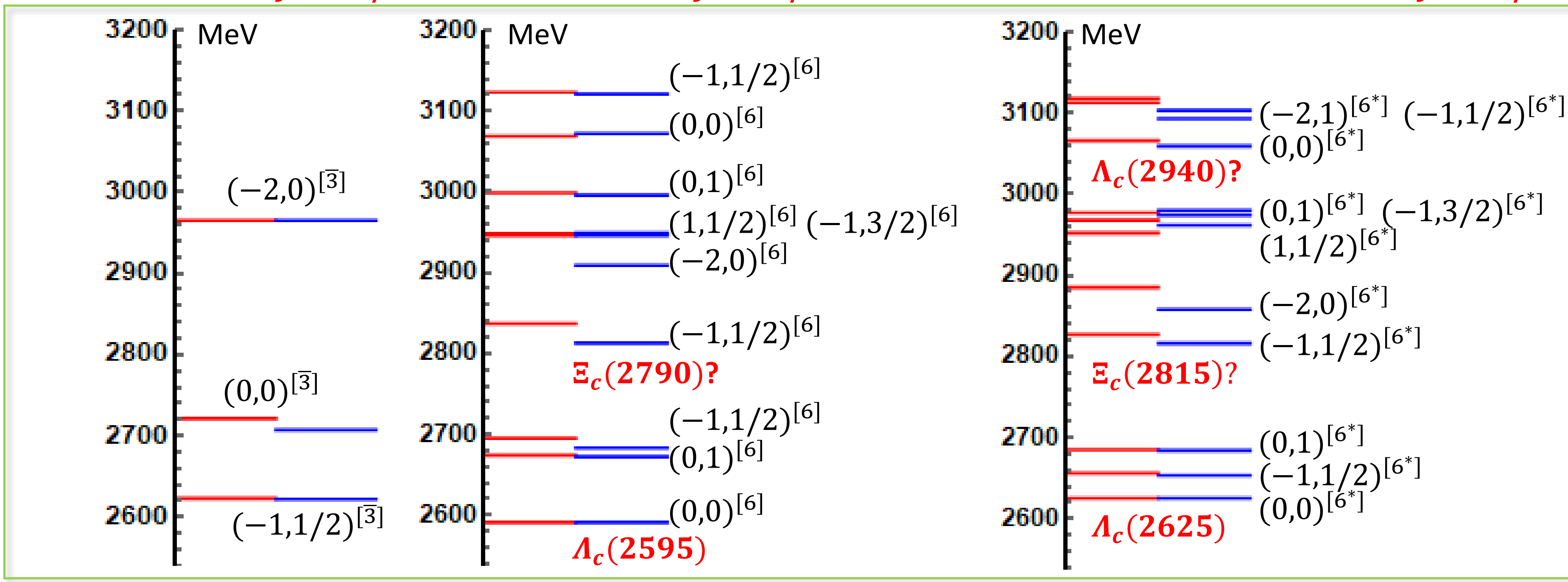
- ✓ **Cutoff method**
- x Dimensional regularization method(DRM, $\overline{MS}$ scheme)
- ✓ **Heavy quark symmetry inspired scheme**



Dynamically generated states

- ❑ q_{max} or a determined by $\Lambda_c(2595)$ for $1/2$ or $\Lambda_c(2625)$ for $3/2$

$\bar{3}\times 8$ $J=1/2$ 6×8 $J=1/2$ $6^*\times 8$ $J=3/2$



- Red: HQS
- Blue: CUT
- $(S,I)^M$

- Consistent results from **HQS** and **CUT** $\pi\Sigma_c$(UChPT) vs $D^{(*)}N$(SU(8)/LHG)

Molecular picture for $\Lambda_c(2595)$!

To further explore the nature of $\Lambda_c(2595)$

- Compositeness rule

- N_c dependence

Compositeness of $\Lambda_c(2595)$

- The relevance of hadronic components in a molecular state
  - **Deuteron** as neutron-proton bound state by Weinberg **Model independent**
- For a separable potential Aceti,EPJA50,57

$$\sum_i X_i = 1 - Z, \quad X_i = -\mathrm{Re}\left[g_i^2 \left[\frac{\partial G_i^{II}(s)}{\partial\sqrt{s}}\right]_{\sqrt{s}=\sqrt{s_0}}\right] \quad Z = -\sum_{ij}\left[g_i G_i^{II}(\sqrt{s})\frac{\partial V_{ij}(\sqrt{s})}{\partial\sqrt{s}} G_j^{II}(\sqrt{s}) g_j\right]_{\sqrt{s}=\sqrt{s_0}}$$

Sum rule

- X_i the compositeness for channel i
- g_i the coupling of the resonances to channel i
- s_0 the position of resonances
- Z the field renormalization constant
- G^{II} the loop function in second Riemann sheet
- V the potential

Compositeness X_i

0 — No i-th hadronic component

1 — Complete i-th hadronic component

The larger the compositeness is, the larger the molecular components is!

Compositeness of $\Lambda_c(2595)$

Kernel potential

- Chiral unitary approach (**2 channel**)
- Local hidden gauge (**3 channel**)
- Extended SU(8) scheme (**16 channel**)

$\otimes$

Loop function

- Cutoff
- HQS
- DR-naturalness $G[\mu(\alpha)] = 0$

Garcia-Recio et al. PRD92,034011

$\sum_i X_i$	DR-naturalness	CUT	DR-HQS
UChPT(2 channels)	$0.218 + i0.725$	$0.196 + i0.768$	$0.228 + i0.713$
HLG(3 channels)	$0.772 + i0.085$	$0.195 + i0.641$	$0.214 + i0.727$
Extended SU(8)(16 channels)	$0.843 + i0.012$	$0.521 + i0.602$	$0.607 + i0.219$

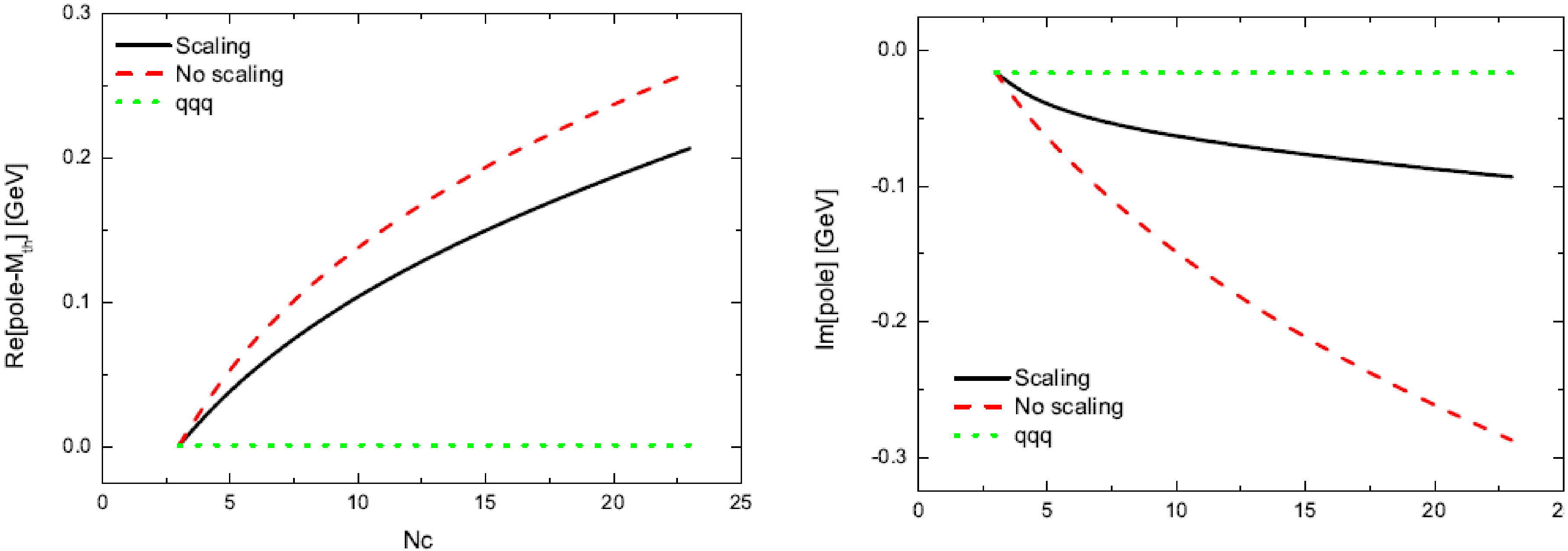
Differs in different models and regularization scheme

The compositeness is model dependent!

N_c dependence of $\Lambda_c(2595)$

- The N_c dependence of the resonances
  - Reveal $q\bar{q}$ nature of vector mesons Pelaez,PRL92,102001 Xiao,MPLA22,55

Ordinary qqq state: $M_R - M_B - m \sim \mathcal{O}(1)$, $\Gamma_R \sim \mathcal{O}(1)$
Deviation: dominant molecular component



The pole position of $\Lambda_c(2593)$ as a function of N_c

Summary

- ❑ Goldstone bosons and charmed baryons

UChPT

↓

Appreciable molecular component for $\Lambda_c(2595)$!

↑ ↑

Compositeness N_c dependence

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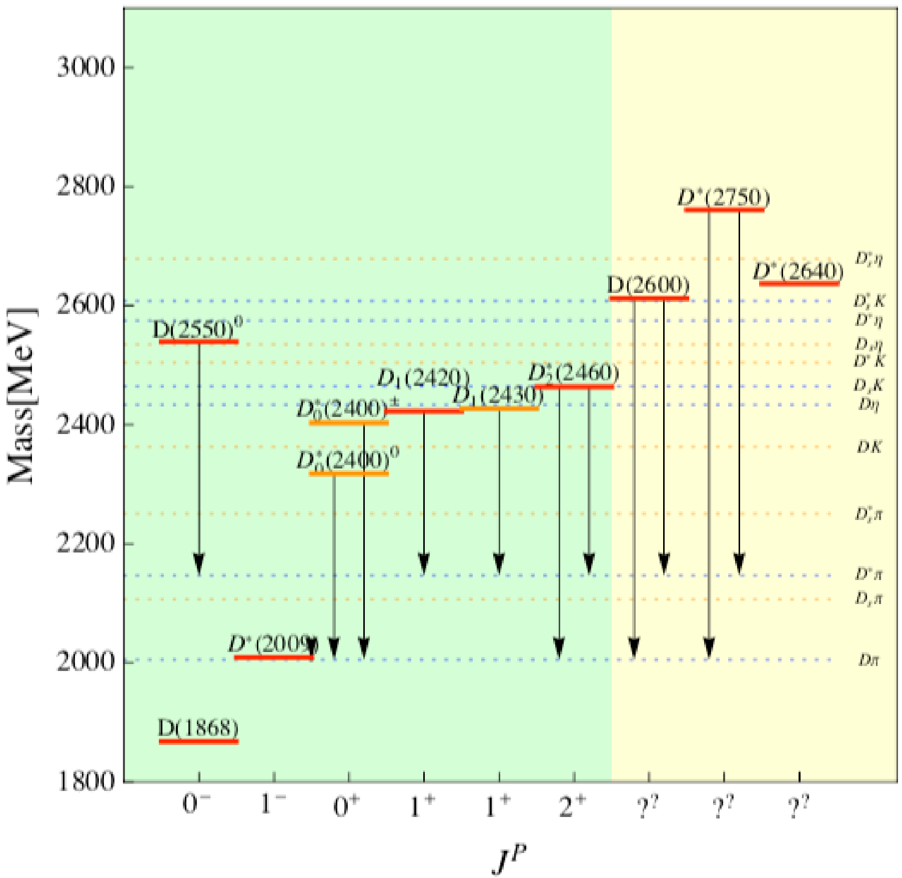
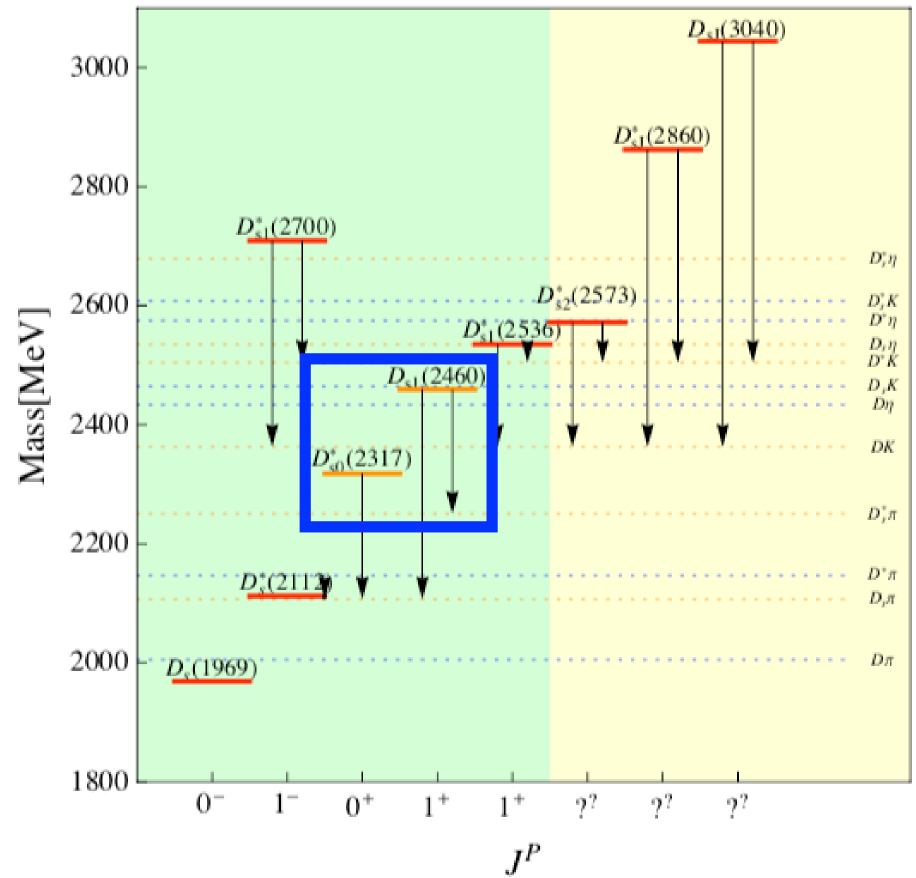
Ds0*(2317)/Ds1(2460) unconventional hadrons

adding charm

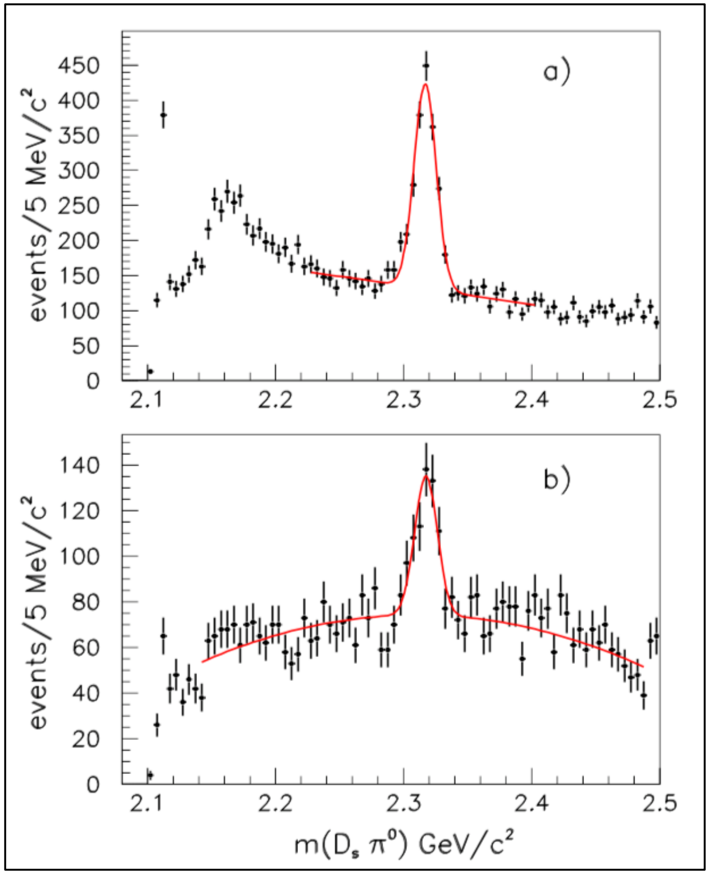




Ds0*(2317) **Ds1(2460)**

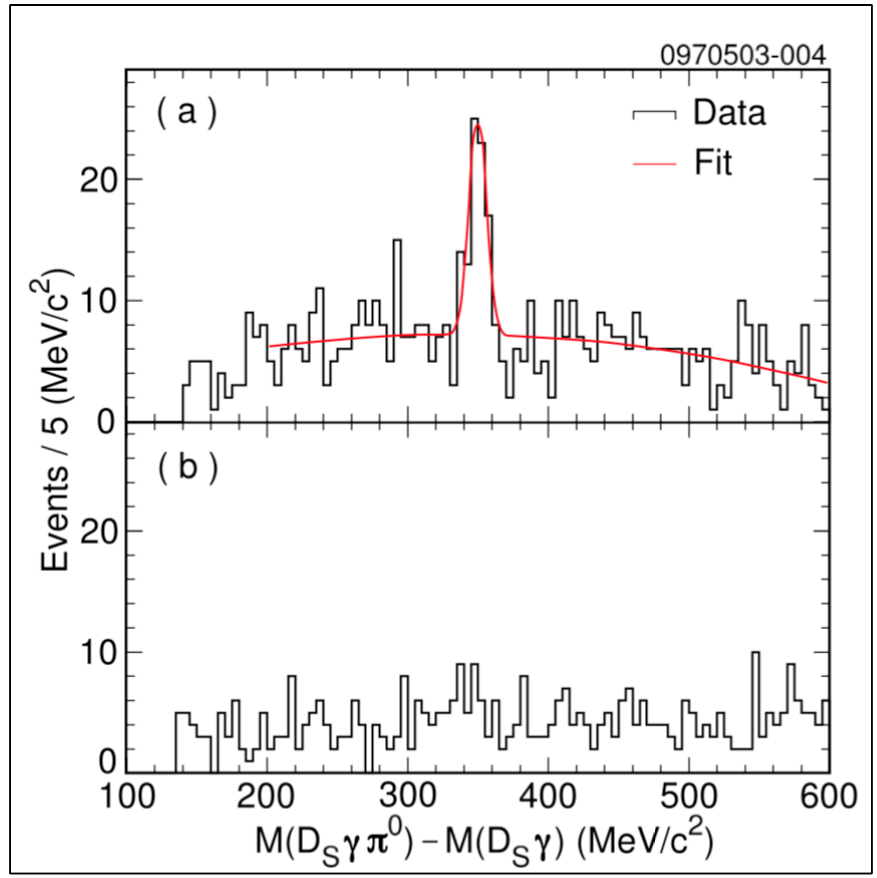
Discovery channels

Ds0*(2317)



BaBar PRL90,242001(2003)

Ds1(2460)



CLEO PRD68,032002(2003)

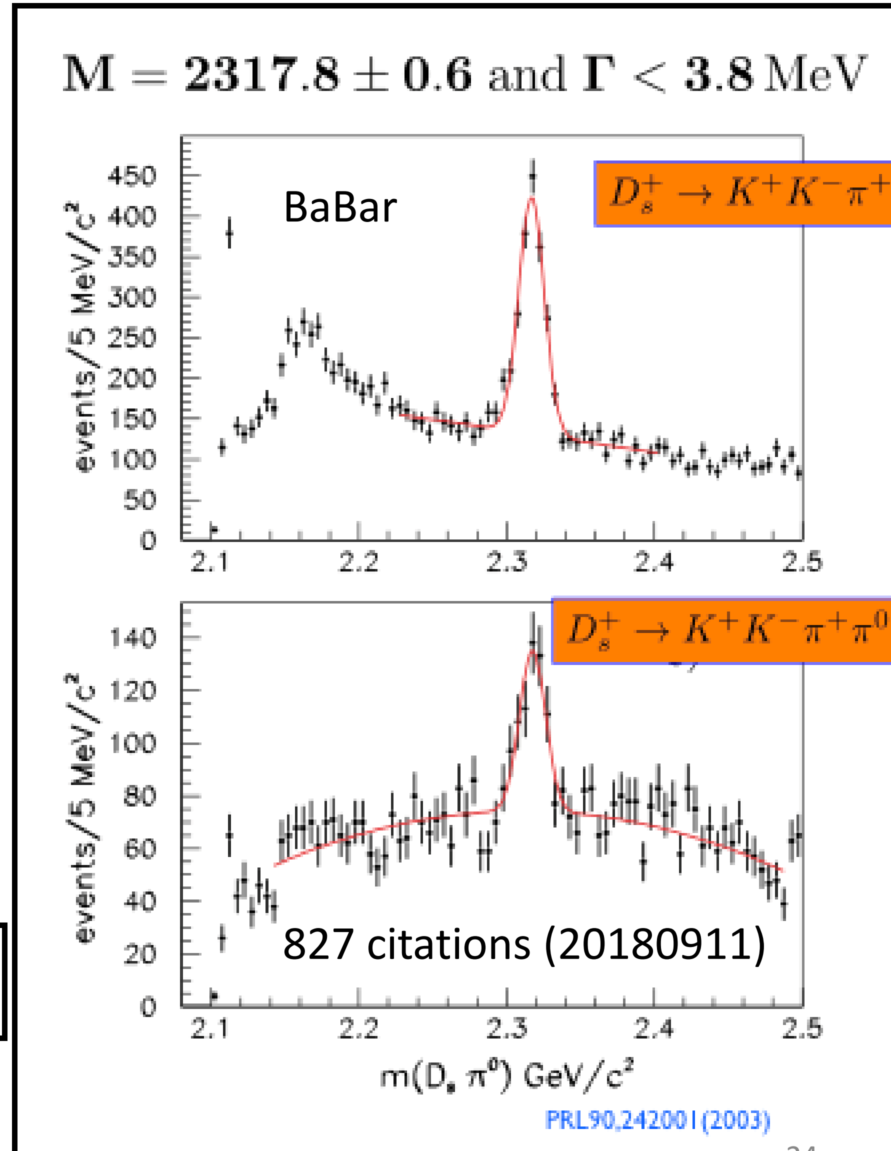
What are special about these two states

- $\mathbf{D}_{s0}^{*}(2317)$, $\mathbf{D}_{s1}(2460)$

- 160/70 MeV lower than the GI quark model predictions--difficult to be understood as conventional csbar states.

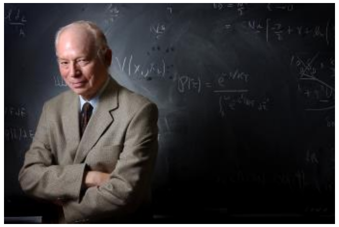
- "Dynamically generated" from strong DK interaction
  - ✓ E. E. Kolomeitsev 2004,
  - ✓ F. K. Guo 2006,
  - ✓ D. Gamermann 2007

$$m_{D_{s1}(2460)} - m_{D_{s0}^{*}(2317)} \approx m_{D^*} - m_D$$



Feng-Kun Guo, EPJ Web of Conferences **202**, 02001 (2019)

UChPT in Bethe-Salpeter equation



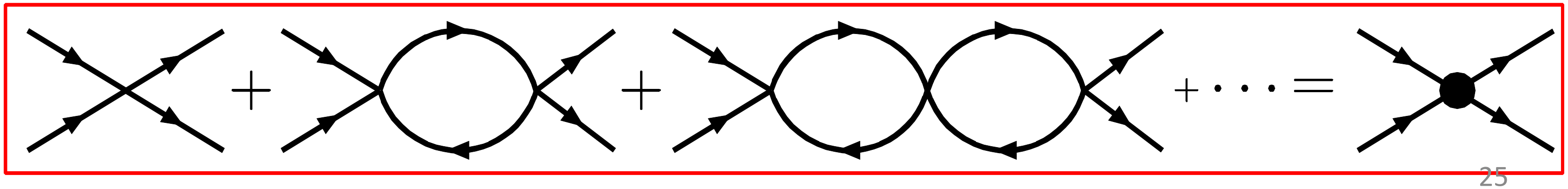
- **Model independent DK interaction from ChPT**

$$\mathcal{V}_{\rm WT}(P(p_1)\phi(p_2)\to P(p_3)\phi(p_4)) = \frac{1}{4f_0^2}\mathcal{C}_{\rm LO}\,(s-u)$$

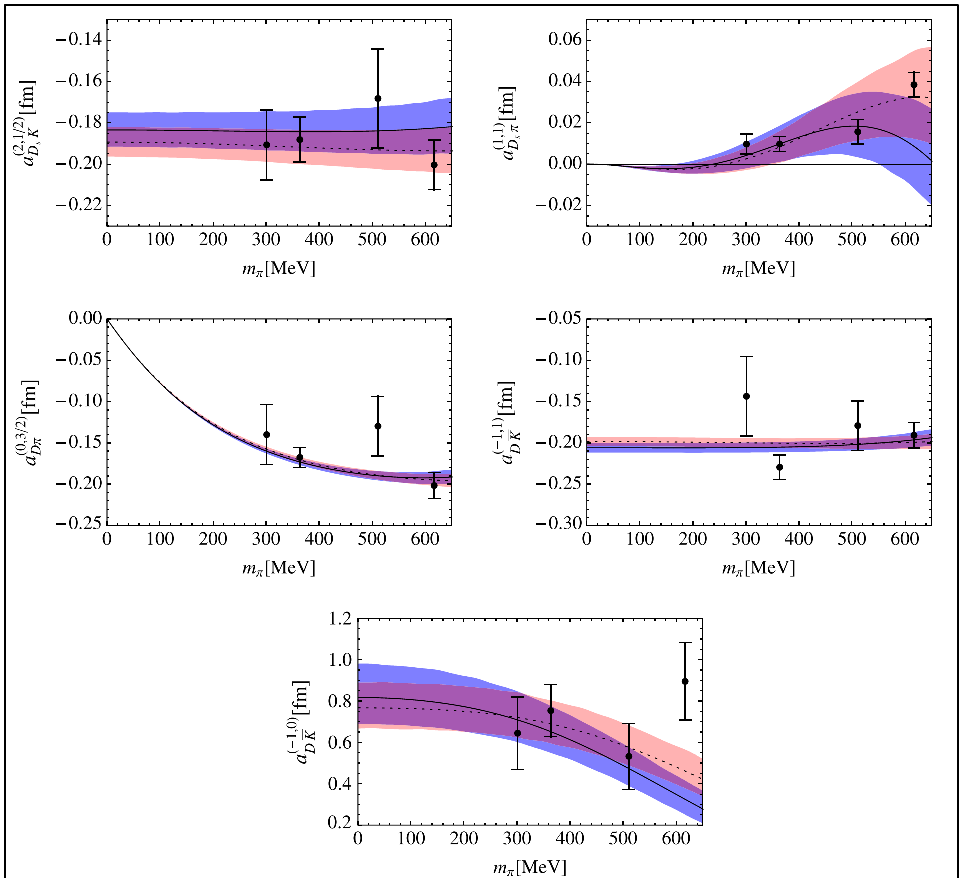
Weinberg-Tomazawa

$$\begin{aligned}\mathcal{V}_{\rm NLO}(P(p_1)\phi(p_2)\to P(p_3)\phi(p_4)) = &-\frac{8}{f_0^2}C_{24}\left(c_2\,p_2\cdot p_4-\frac{c_4}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3+p_1\cdot p_2\;p_3\cdot p_4\right)\right)\\ &-\frac{4}{f_0^2}\mathcal{C}_{35}\left(c_3\,p_2\cdot p_4-\frac{c_5}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3+p_1\cdot p_2\;p_3\cdot p_4\right)\right)\\ &-\frac{4}{f_0^2}\mathcal{C}_6\,\frac{c_6}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3-p_1\cdot p_2\;p_3\cdot p_4\right)\\ &-\frac{8}{f_0^2}\mathcal{C}_0\,c_0+\frac{4}{f_0^2}\mathcal{C}_1\,c_1\,,\end{aligned}\qquad(11)$$

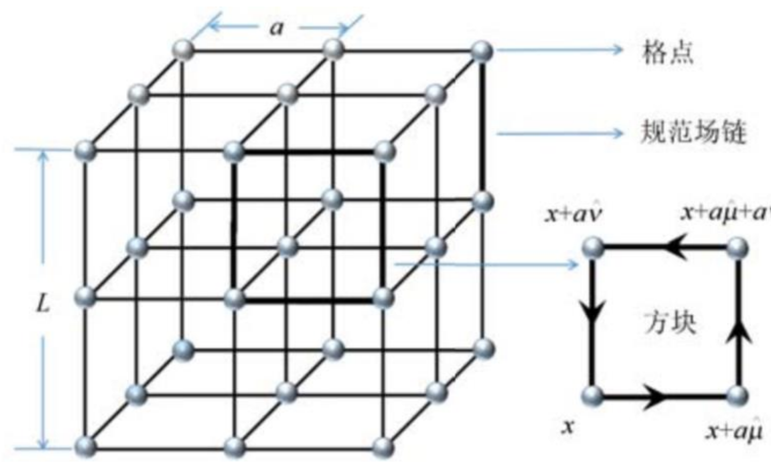
- **Resumed in the Bethe-Salpeter equation (two-body elastic unitarity)**



Fixing the LECs using latest LQCD* data



- NLO ChPT kernel: 5 LECs
- A quite good description of the 20 Lattice **scattering lengths of pseudoscalar mesons and D mesons （I=0 DK excluded）** can be achieved.



Ds0 and Ds1 dynamically generated

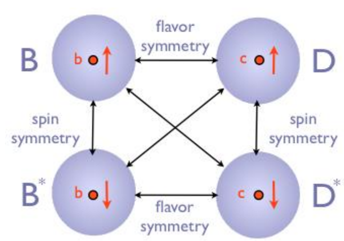
- **Charm sector**

"Post-diction"

$\mathbf{D^*_{s0}(2317),\ D_{s1}(2460)}$

TABLE V. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of charm mesons dynamically generated in the HQS UChPT.

(S, I)	$J^P = 0^+$	$J^P = 1^+$
(1, 0)	2317 ± 10	2457 ± 17
(0, 1/2)	$(2105 \pm 4) - i(103 \pm 7)$	$(2248 \pm 6) - i(106 \pm 13)$



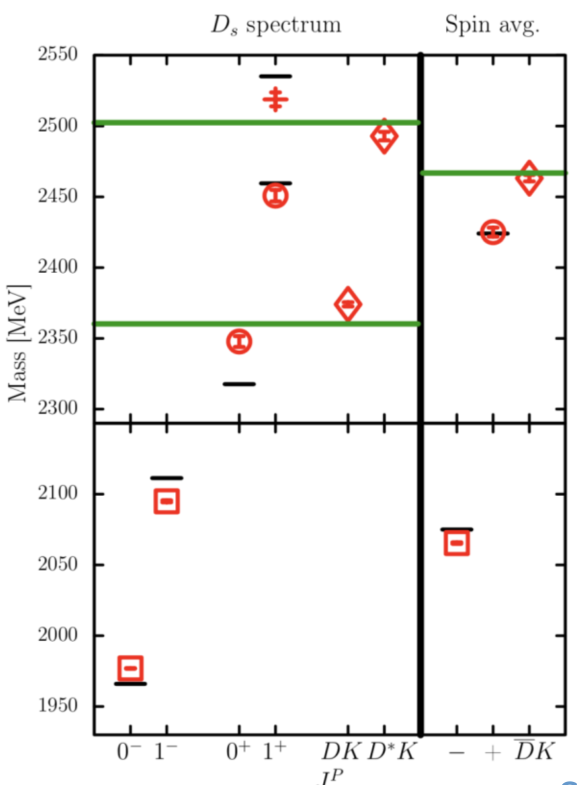
- **Bottom Sector**

TABLE VI. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of bottom mesons dynamically generated in the HQS UChPT.

(S, I)	$J^P = 0^+$	$J^P = 1^+$
(1, 0)	5726 ± 28	5778 ± 26
(0, 1/2)	$(5537 \pm 14) - i(118 \pm 22)$	$(5586 \pm 16) - i(124 \pm 25)$

More support from recent lQCD studies

- G.K.C. Cheung et al., arXiv:2008.06432[hep-lat].
- G. S. Bali et al., arXiv:1706.01247 [hep-lat].
- C. B. Lang et al., arXiv:1403.8103 [hep-lat].
- D. Mohler et al., arXiv:1308.3175 [hep-lat].



"DK components substantial"

FIG. 12. On the left, our final results for the lower lying D_s spectrum as detailed in Table VII. The short horizontal black lines indicate the corrected experimental values (see Section II) while the green horizontal lines give the positions of the DK and D^*K non-interacting thresholds. Our lattice results for the finite volume thresholds are labelled DK and D^*K, respectively. The errors indicated are statistical only. On the right, the negative parity spin-averaged $1S$ mass $m_- = \frac{1}{4}(m_{0^-} + 3m_{1^-})$ is shown and denoted $-$, while the same spin-average of the positive parity 0^+ and 1^+ states is labelled with $+$ and the weighted average of the threshold is labelled as $\overline{DK}$.

See as well Miguel Albaladejo et al. **arXiv:1805.07104**

What about adding a $\overline{D^*}$ to the DK pair

- **Fixed center approximation (FCA):**

$$K(D\overline{D^*}+\bar{D}D^*)\sim KX(3872)/Zc(3900)$$

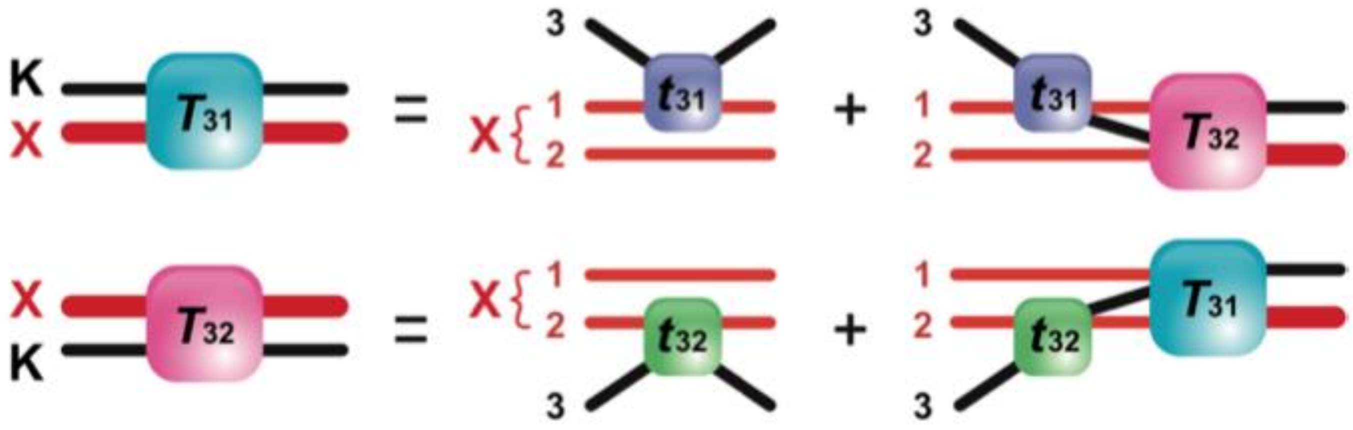
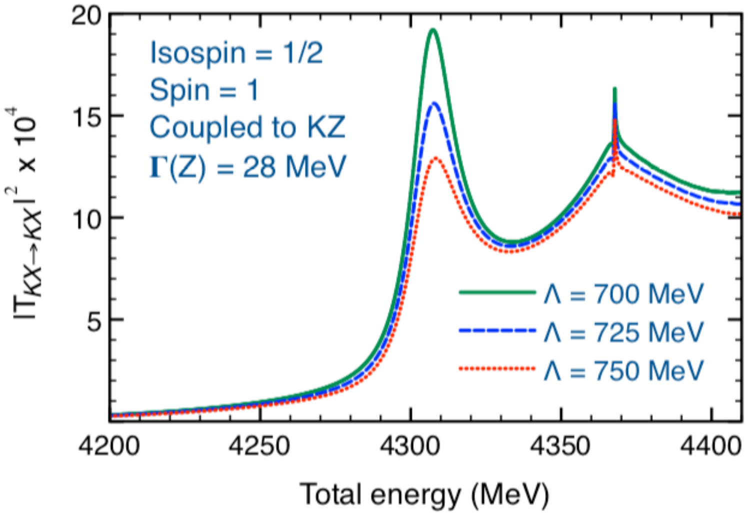
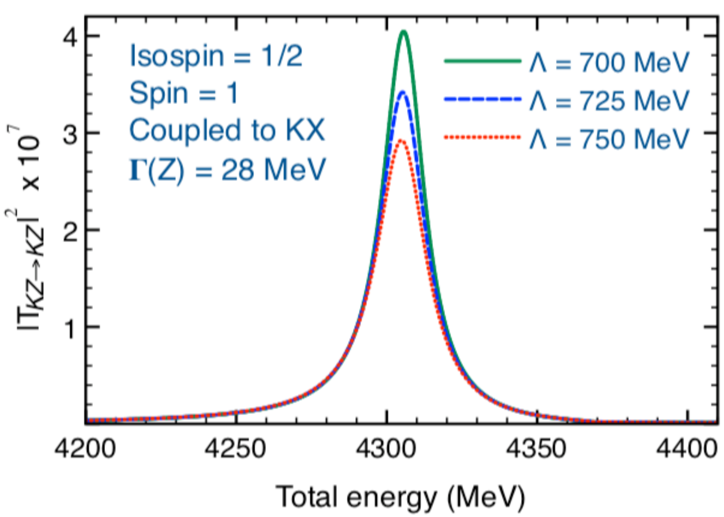


Figure 2: Diagrams showing the scattering of the particle labeled "3" (K) on a cluster (X) made of particles 1 (D) and 2 ($\bar{D}^*$).

1805.08330

K*(4307) as an exicted K* with large ccbar





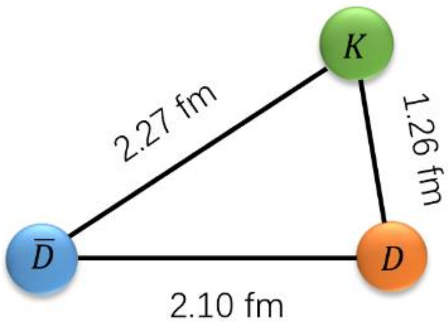
- **Treating KX and KZ as coupled channel systems**
- **A resonance with M=(4307 ± 2) – i(9 ± 2) MeV with $I(J^P) = 1/2(1^-)$**

In agreement with Li Ma, Qian Wang, Ulf-G. Meißner, 1711.06143, but with completely different dynamics

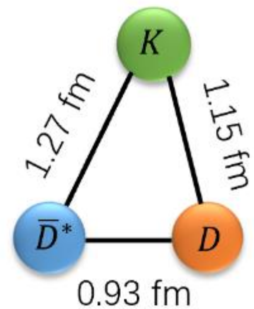
Instead of a D, adding a $\bar{D}$ to the DK pair

[2012.01134](2012.01134)

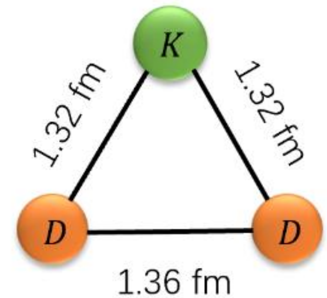
The Three Musketeers



Kc(4180)



K*(4307)

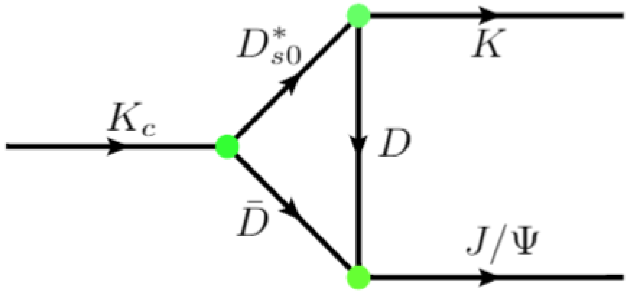


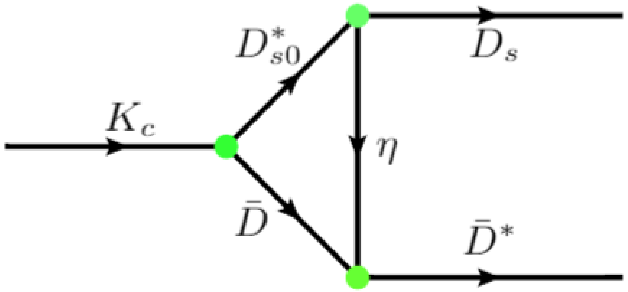
R(4140)

	This work	Ref [28]	Ref [29]
Method	GEM(SE)	BOA(SE)	FCA(FE)
Interaction Models	χEFT+OBE	delocalized π bond	χEFT+OBE
$\frac{1}{2}(0^-)\ D\bar{D}K$	$4181.2^{+2.4}_{-1.4}(B_3 \simeq 48.9^{+1.4}_{-2.4})$	-	-
$\frac{1}{2}(1^-)\ D\bar{D}^*K$	$4294.1^{+6.6}_{-3.1}(B_3 \simeq 77.3^{+3.1}_{-6.6})$	$4317.92^{+6.13}_{-6.55}(B_3 \simeq 53.52^{+6.55}_{-6.13})$	$4307 \pm 2(B_3 \simeq 64 \pm 2)$

$K_c(4180)$ decay

2012.01134



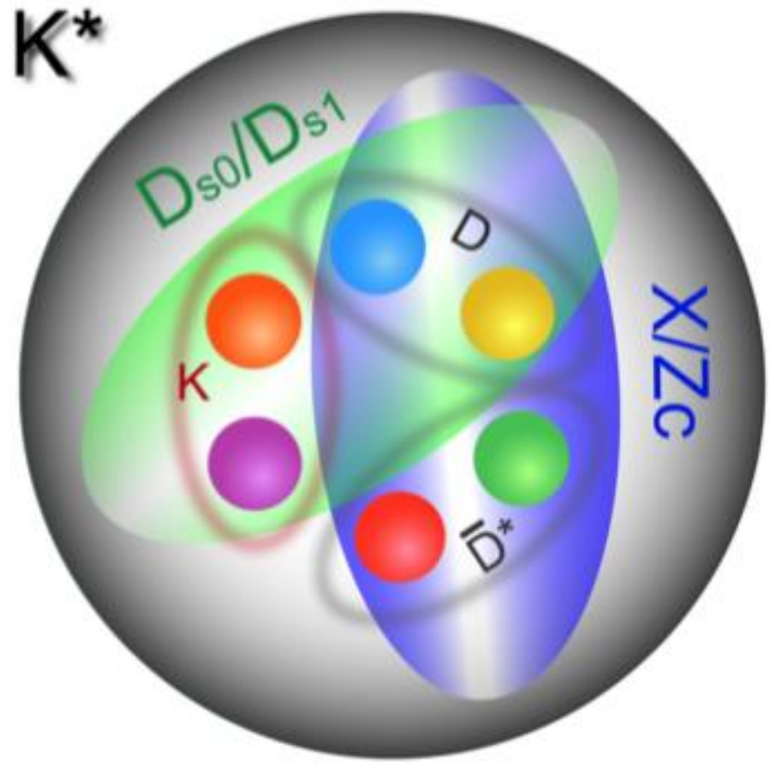


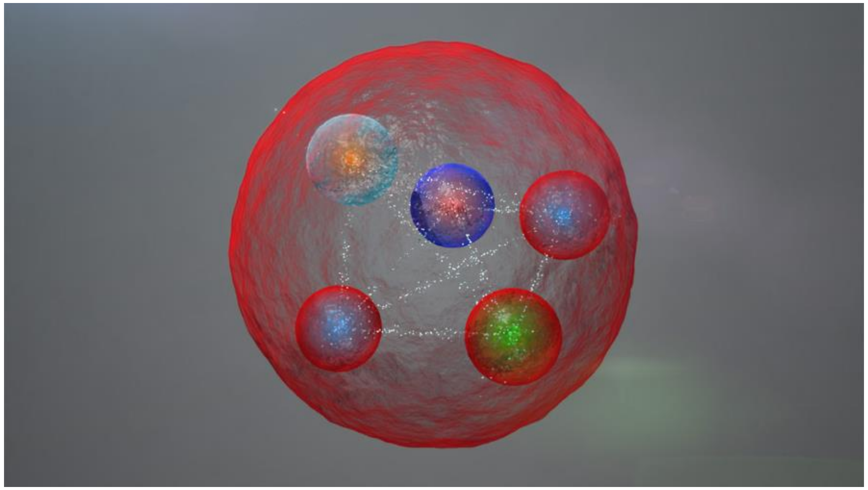
~1 MeV

~1 MeV

K*(4307)/Kc(4180)—bosonic counterpart of Pc

but with 3 constituents





Pentaquark (N*) by LHCb

Phys.Rev.Lett. 115 (2015) 072001

Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV,
Jia-Jun Wu, R. Molina, E. Oset, B.S. Zou, 1007.0573

Kc(4180) can be searched for at BESIII

$e^+e^- \to K D^* \bar{D}_s$

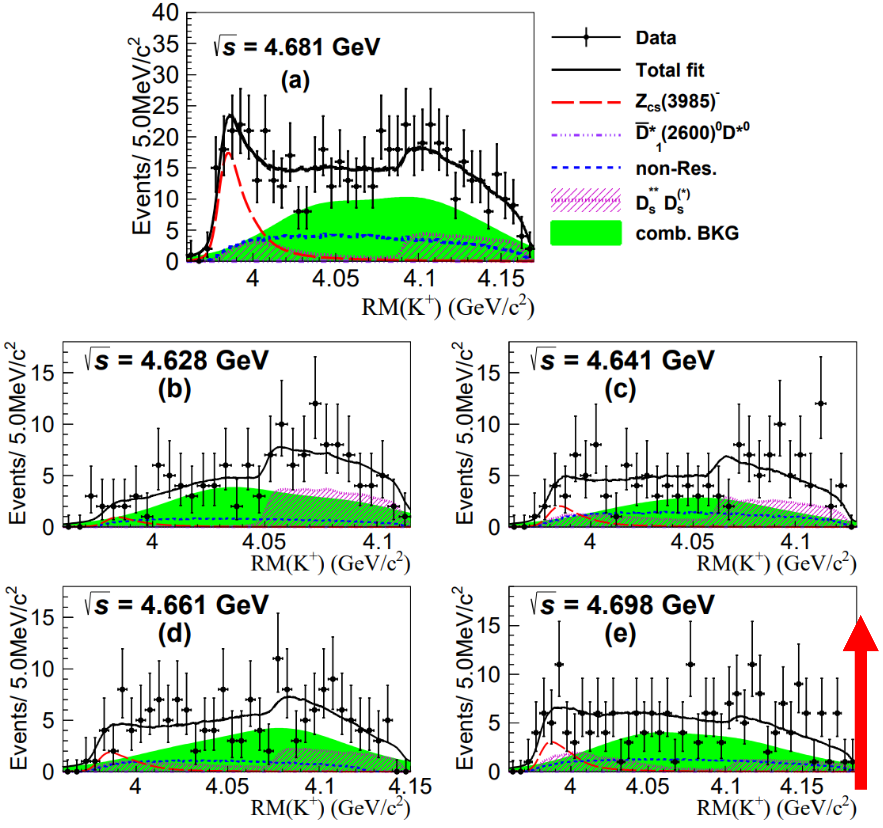


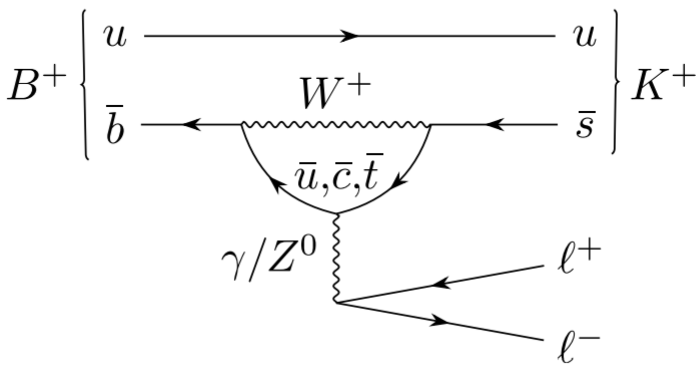
FIG. 3. Simultaneous unbinned maximum likelihood fit to the K^+ recoil-mass spectra in data at $\sqrt{s}$=4.628, 4.641, 4.661, 4.681 and 4.698 GeV. Note that the size of the $D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ component is consistent with zero.

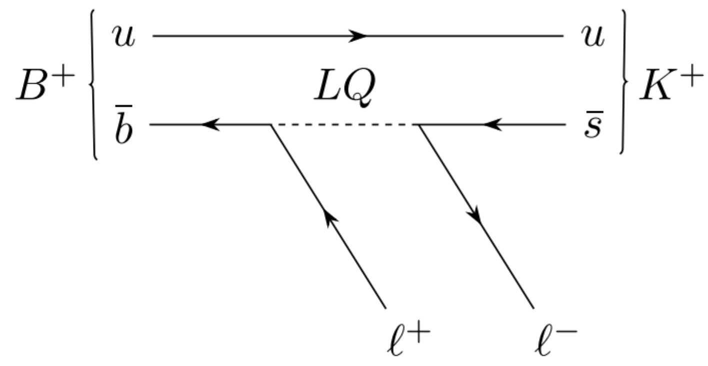
BESIII: 2011.07855: an integrated luminosity of 3.7 $\mathbf{fb^{-1}}$

Contents

- Exotic hadrons
  - ✓ Singly charmed baryons—$\Lambda_c(2595)$: 1409.3133, 1603.05388
  - ✓ Excited kaons above 4 GeV ($KD\overline{D^{(*)}}$)—Kc(4180): 1805.08330, 2012.01134
- Rare processes & new physics
  - ✓ Searching for NP in hyperon decays
  - ✓ Weak radiative hyperon decays
- Summary & outlook

• 2103.12738





Implications of new evidence for lepton-universality violation in $b \to s\ell^+\ell^-$ decays

Li-Sheng Geng,[1,2] Benjamín Grinstein,[3] Sebastian Jäger,[4] Shuang-Yi Li,[5] Jorge Martin Camalich,[6,7] and Rui-Xiang Shi[5]

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[2]*School of Physics and Microelectronics, Zhengzhou University, Zhengzhou, Henan 450001, China*
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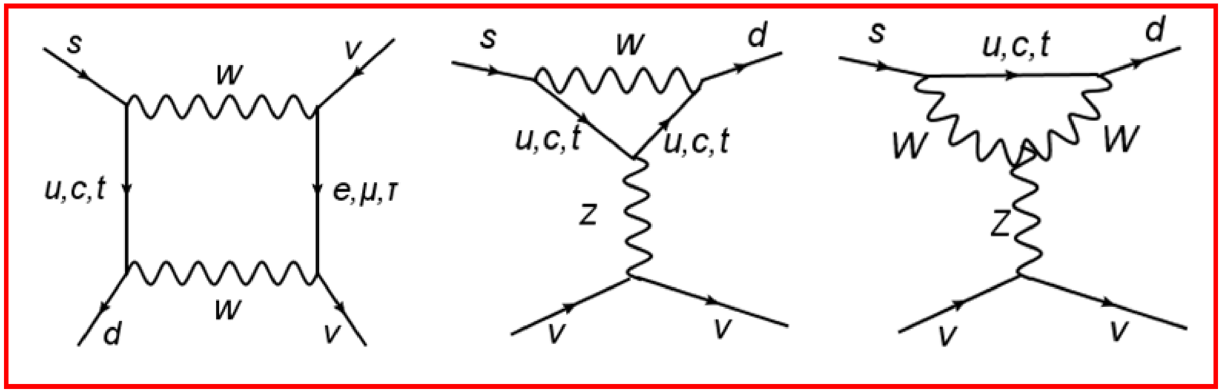
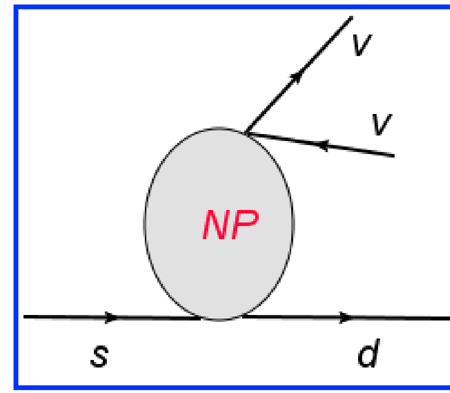
[7]*Universidad de La Laguna, Departamento de Astrofisica, La Laguna, Tenerife, Spain*

Motivated by renewed evidence for New Physics in $b \to s\ell\ell$ transitions in the form of LHCb's new measurements of theoretically clean lepton-universality ratios and the purely leptonic $B_s \to \mu^+\mu^-$ decay, we quantify the combined level of discrepancy with the Standard Model and fit values of short-distance Wilson coefficients. A combination of the clean observables R_K, R_{K^*}, and $B_s \to \mu\mu$ alone results in a discrepancy with the Standard Model at 4.0σ, up from 3.5σ in 2017. One-parameter scenarios with purely left-handed or with purely axial coupling to muons fit the data well and exclude the Standard Model at $\sim 5\sigma$ level. In a two-parameter fit to new-physics contributions with both vector and axial-vector couplings to muons the allowed region is much more defined than in 2017, principally due to the much more precise result on $B_s \to \mu^+\mu^-$, which probes the axial coupling to muons. Including angular observables data narrows the allowed region further. A by-product of our analysis is an updated average of $\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.8 \pm 0.3) \times 10^{-9}$.

□ $s \rightarrow d$ transitions are highly suppressed in the SM



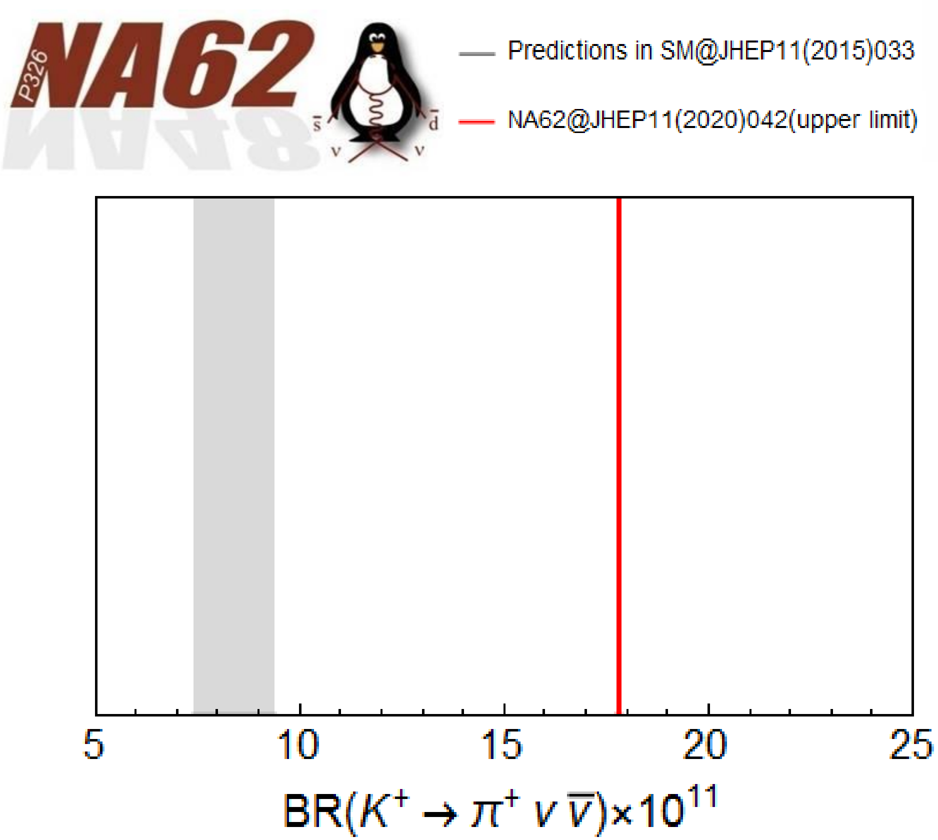


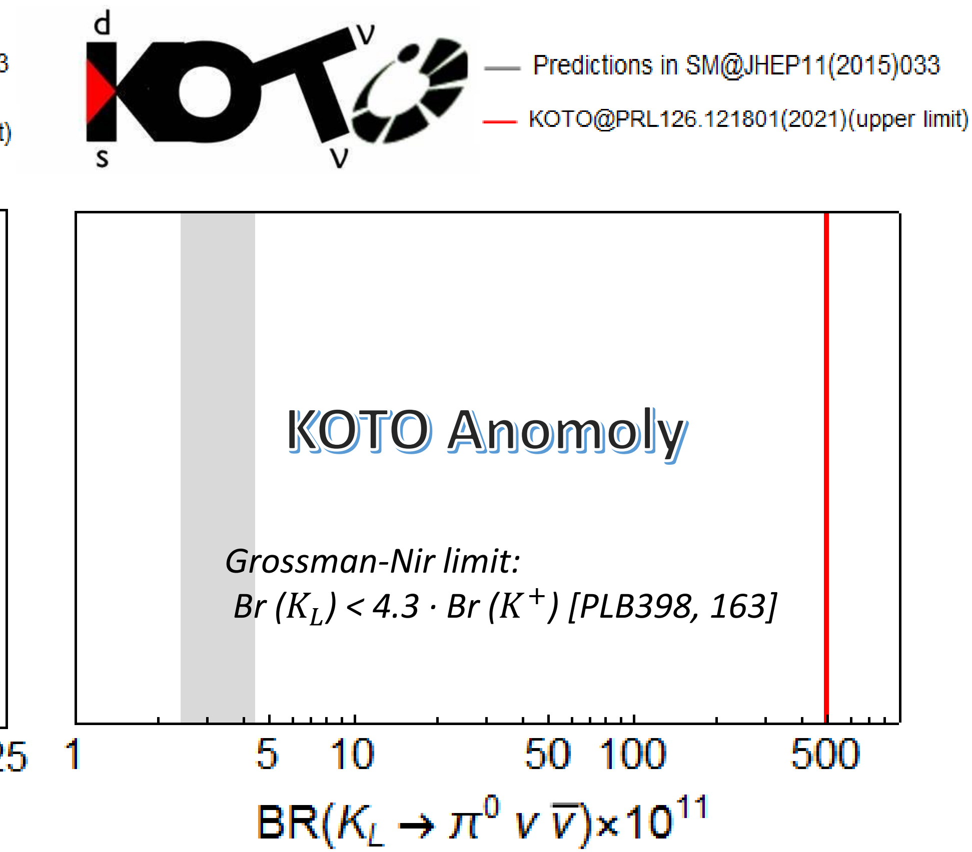
□ As such, they are ideal for tests of the SM and searches for BSM

- *G. Buchalla and A. J. Buras, hep-ph/9901288*
- *V. Cirigliano et al., 1107.6001*
- ***Hai-Bo Li, 1612.01775***
- *A. A. Alves Junior et al., 1808.03477*

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

- **Latest experimental results**

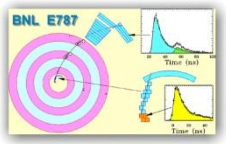




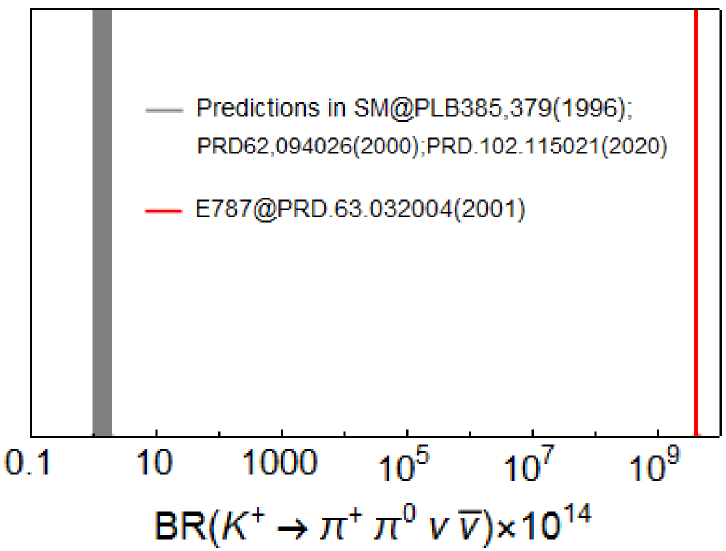
- **The K → π ν ν̄ results imply that there is still room for new physics (NP), but maybe not so much. However, they are only sensitive to the vectorial (parity even) couplings of the s → d currents.**

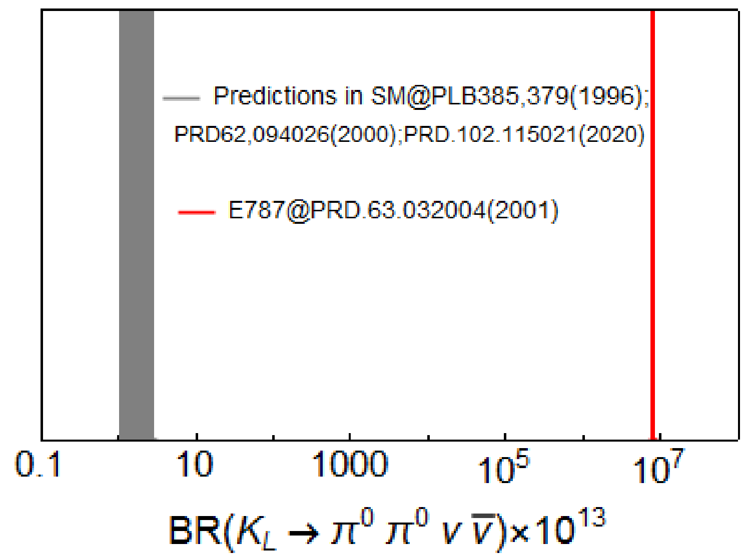
$K \to \pi\pi\nu\bar{\nu}$

- Latest experimental results



KEK-PS E391a





- Although the $K \to \pi\, \pi\, \nu\, \bar{\nu}$ modes receive contributions from the axial-vectorial type of NP, the current results provide little constraints on them

$K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$

- The branching ratio of the $K_L \to \mu^+\mu^-$ decay and the leptonic forward-backward asymmetry (AFB) of the $K^+ \to \pi^+\mu^+\mu^-$ decay have been measured

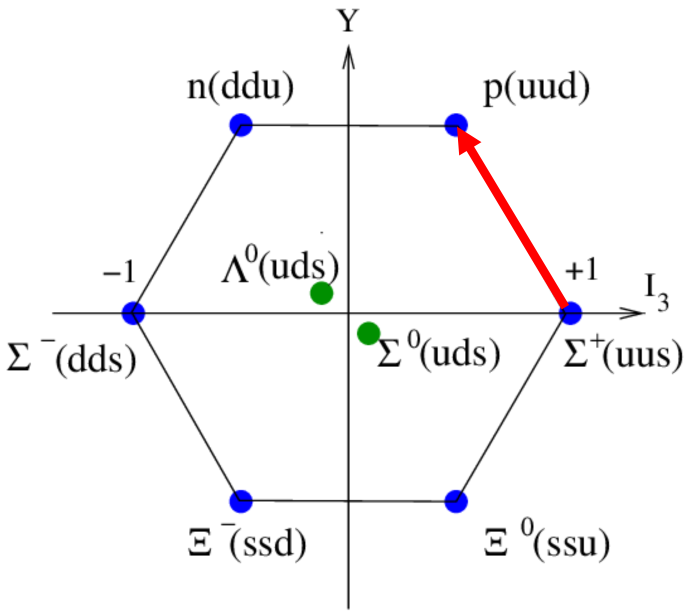
$$\mathrm{BR}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$$ PTEP 2020, 083C01 (2020)

$$|A_{FB}| < 2.3 \times 10^{-2}, \qquad \text{at } 90\% \text{ CL}$$ PLB 697, 107 (2011)

- They not only are dominated by long-range contributions , but also cannot probe all the interesting axial-vectorial, scalar operators, and their spin flip structures

Hyperons might be a game changer

- Having spin ½ (instead of spin 0), they lead to different decay modes, observables, as well as sensitivities to the underlying structure of the $s \to d$ currents



- Experimentally and theoretically more challenging, compared to their kaon siblings
  - No direct data for $B_1 \to B_2 \nu\bar{\nu}$; first theoretical studies only appeared recently
  - Latest measurement of $\Sigma^+ \to p\mu^+\mu^-$ only with a significance of 4.1 sigma

$B_1 \to B_2 \nu\bar{\nu}$

Different from their kaonic counterparts, they are sensitive to both vectorial and axial-vectorial couplings of the $s \to d$ currents

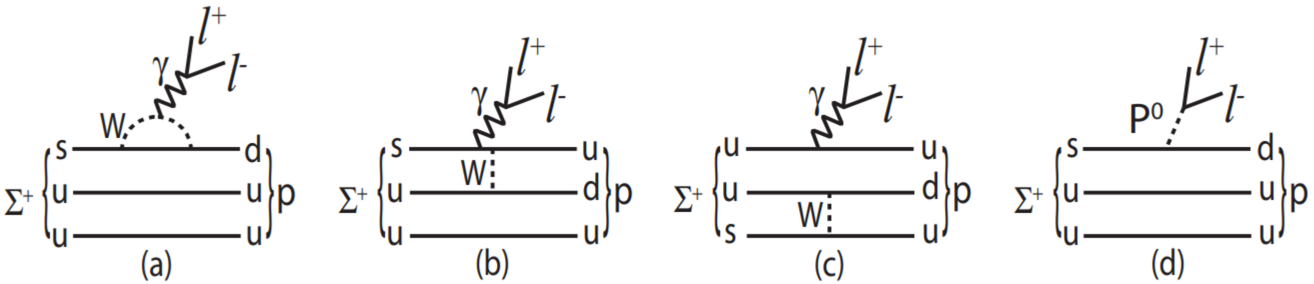
- **No direct data yet, but promising data from BESIII & LHCb**
  - BESIII/LHCb experiments in the near future — *Front. Phys. 12, 121301 (2017)*; *JHEP05(2019)048*
  - Upper limits derived from Hyperon lifetime — *PRD 102,015023 (2020)*
- **On the theory side, the first studies just appeared**

  Xiao-Hui Hu et al., CPC43(2019)093104; Jusak Tandean, JHEP04(2019)104
- **More theoretical studies are needed**
  - Constraints from/compare with more kaon modes: 2, 3, 4 final states
  - The state of the art results from **covariant baryon chiral perturbation theory for the relevant form factors**

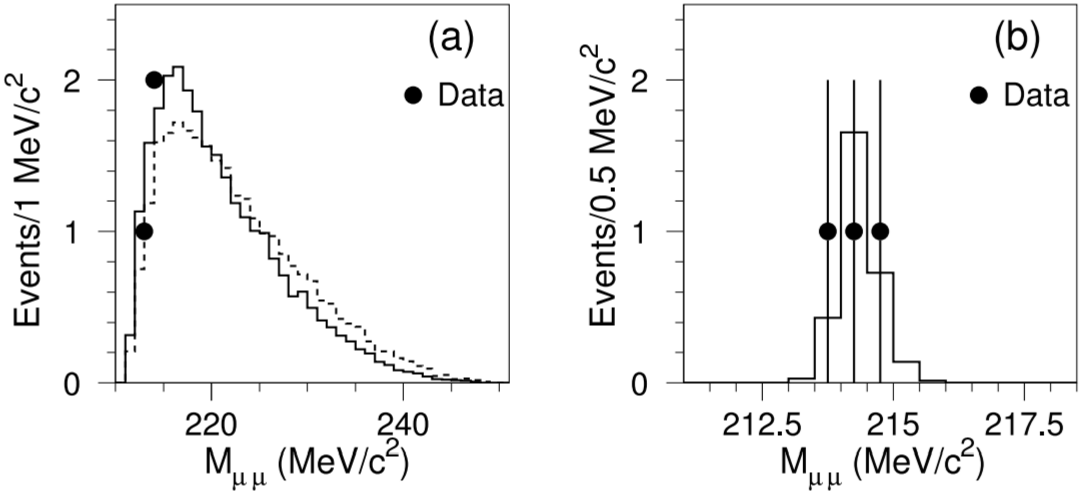
L. S. Geng et al., Phys. Rev. D 79, 094022 (2009)
T. Ledwig et al., Phys. Rev. D 90, 054502 (2014)

$\Sigma^+ \rightarrow p\mu^+\mu^-$

- **Experimental results from HyperCP@**PRL 94, 021801 (2004)



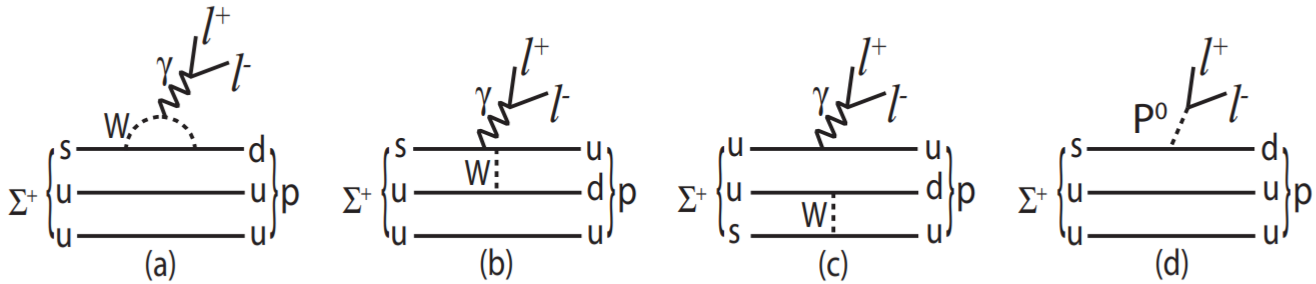
$$[8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$$



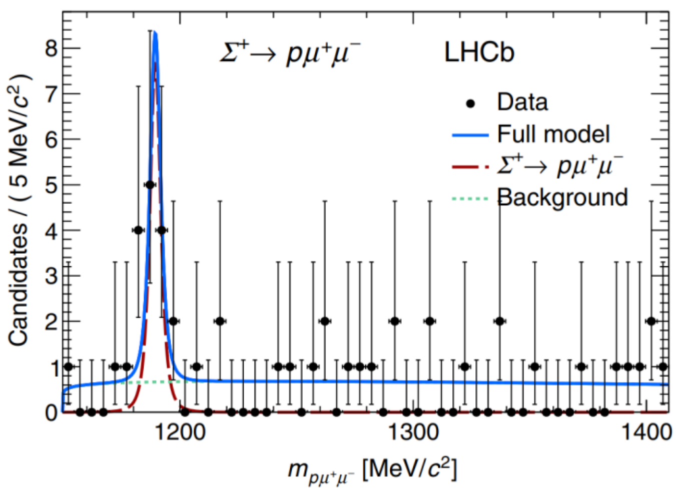
Di-muon meson
214.3 ± 0.5 MeV

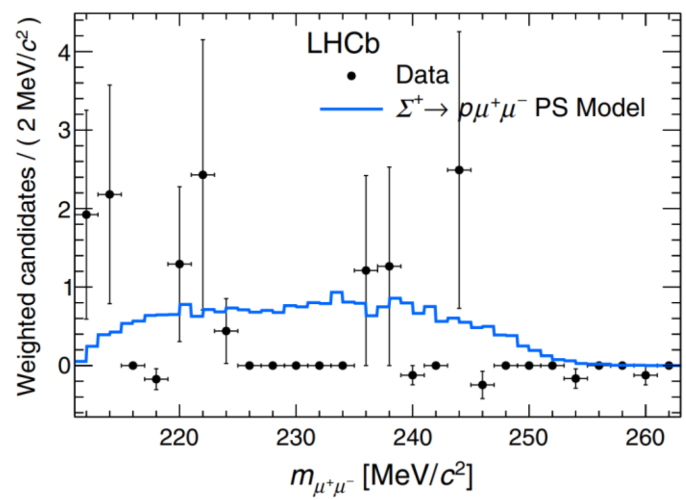
$\Sigma^+ \to p\mu^+\mu^-$

- **Experimental results from LHCb @PRL120, 221803(2018)**



$$(2.2^{+1.8}_{-1.3}) \times 10^{-8}$$





Our purpose

Study the hyperon rare decays and compare with their kaon counterparts and investigate their sensitivities to different structures of new physics.

- **$s \to d\,\nu\,\bar{\nu}$ transitions dominated by short−distance contributions**

$\Lambda \to n\nu\bar{\nu}$
$\Sigma^+ \to p\nu\bar{\nu}$
$\Xi^0 \to \Sigma^0\nu\bar{\nu}$
$\Xi^0 \to \Lambda\nu\bar{\nu}$

V.S

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

Channels	$\delta C^L_{\nu_\ell} + C^R_{\nu_\ell}$	$\delta C^L_{\nu_\ell} - C^R_{\nu_\ell}$
$\Lambda \to n\nu\bar{\nu}$	✔	✔
$\Sigma^+ \to p\nu\bar{\nu}$	✔	✔
$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	✔	✔
$\Xi^0 \to \Lambda\nu\bar{\nu}$	✔	✔

Channels	$\delta C^L_{\nu_\ell} + C^R_{\nu_\ell}$	$\delta C^L_{\nu_\ell} - C^R_{\nu_\ell}$
$K^+ \to \pi^+\nu\bar{\nu}$	✔	✗
$K_L \to \pi^0\nu\bar{\nu}$	✔	✗
$K^+ \to \pi^+\pi^0\nu\bar{\nu}$	✔	✔
$K_L \to \pi^0\pi^0\nu\bar{\nu}$	✗	✔

Our purpose

Study the hyperon rare decays and compare with their kaon counterparts and investigate their sensitivities to different structures of new physics.

- $s \to d\mu^+\mu^-$ transitions dominated by long-distance contributions

$\Sigma^+ \to p\mu^+\mu^-$

V.S

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

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

Channels	$\delta C_{10} + C'_{10}$	$\delta C_{10} - C'_{10}$	$C_S + C'_S$	$C_S - C'_S$
$A_{FB}(\Sigma^+ \to p\mu^+\mu^-)$	✔	✔	✔	✔
$\mathrm{BR}(K_L \to \mu^+\mu^-)$	✗	✔	✗	✔
$A_{FB}(K^+ \to \pi^+\mu^+\mu^-)$	✗	✗	✔	✗

The leptonic forward backward asymmetry can be useful to constrain new physics

The LE effective Hamiltonian $s \to d$ *transitions*

- **In SM** $\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}}\lambda_t\left(\sum_{i=1}^{10} C_i O_i + \sum_{\ell=e,\mu,\tau} C^L_{\nu_\ell} O^L_{\nu_\ell}\right)$ $\lambda_q = V_{qs}V^*_{qd}$ Nucl. Phys. B548, 309 (1999)

  - $s \to d\,\nu\bar{\nu}$ *transitions*

$$C^L_{\nu_\ell} = \frac{1}{2\pi\sin^2\theta_W}\left(\frac{\lambda_c}{\lambda_t}X^\ell_c + X_t\right) \qquad O^L_{\nu_\ell} = \alpha\left(\bar{d}\gamma_\mu(1-\gamma_5)s\right)\left(\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right)$$

  - $s \to d\ell^+\ell^-$ *transitions*

Short-distance

$$O_7 = \frac{e}{4\pi}m_s\bar{d}\sigma_{\mu\nu}(1+\gamma_5)sF^{\mu\nu}$$

$$O_9 = \alpha\left(\bar{d}\gamma_\mu(1-\gamma_5)s\right)\left(\bar{\ell}^-\gamma^\mu\ell^+\right)$$

$$O_{10} = \alpha\left(\bar{d}\gamma_\mu(1-\gamma_5)s\right)\left(\bar{\ell}^-\gamma^\mu\gamma_5\ell^+\right)$$

Long-distance

$$\mathcal{M}_{\text{LD}} = -\frac{e^2G_F}{q^2}\bar{B}_2\sigma_{\mu\nu}q^\nu(a+b\gamma_5)B_1\bar{\ell}^-\gamma^\mu\ell^+ - e^2G_F\bar{B}_2\gamma_\mu(c+d\gamma_5)B_1\bar{\ell}^-\gamma^\mu\ell^+$$

$WRHDs$: $\Sigma^+ \to p\gamma^*$

- **In BSM (NP)**

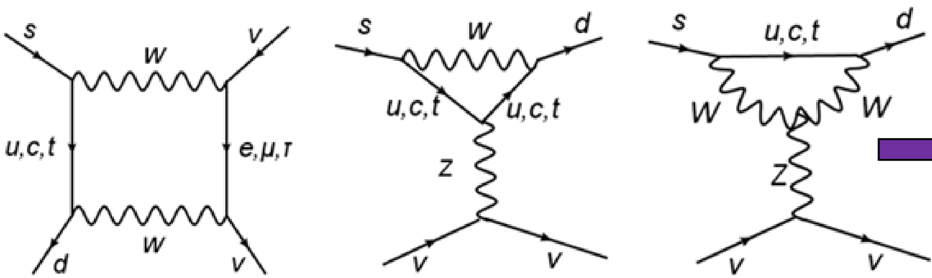
  - The NP operators can be obtained by a **chiral flip** in the quark current, and one also has scalar, pseudoscalar and their primed operators.

$$O_S = \alpha\left(\bar{d}(1+\gamma_5)s\right)\left(\bar{\ell}^-\ell^+\right), \qquad O'_S = \alpha\left(\bar{d}(1-\gamma_5)s\right)\left(\bar{\ell}^-\ell^+\right),$$

$$O_P = \alpha\left(\bar{d}(1+\gamma_5)s\right)\left(\bar{\ell}^-\gamma_5\ell^+\right), \qquad O'_P = \alpha\left(\bar{d}(1-\gamma_5)s\right)\left(\bar{\ell}^-\gamma_5\ell^+\right).$$

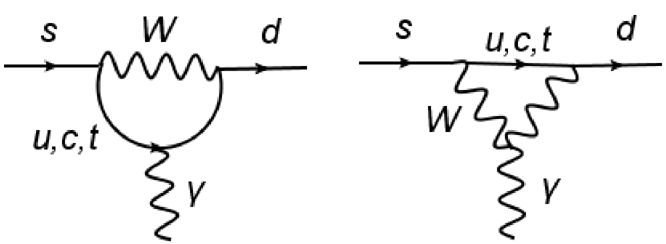
SM operators and Feynman diagrams for $s \to d\nu\bar{\nu}$ and $s \to d\mu^+\mu^-$ decays

$s \to d\nu\bar{\nu}$ transitions:

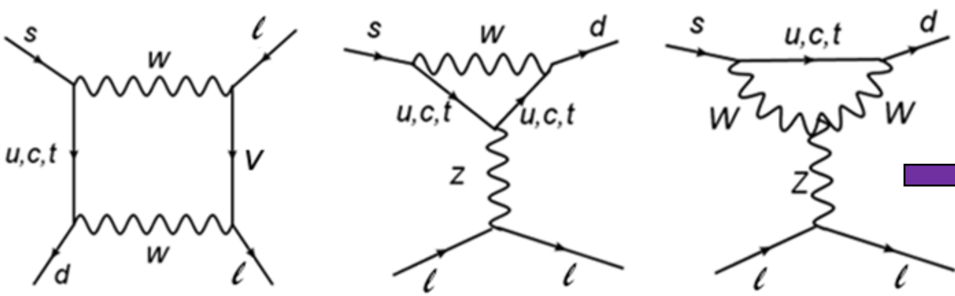


$$\frac{G_F\lambda_t\alpha}{\sqrt{2}} C^L_{\nu_\ell} \left(\bar{d}\gamma_\mu(1-\gamma_5)s\right)\left(\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right)$$

$s \to d\mu^+\mu^-$ transitions:



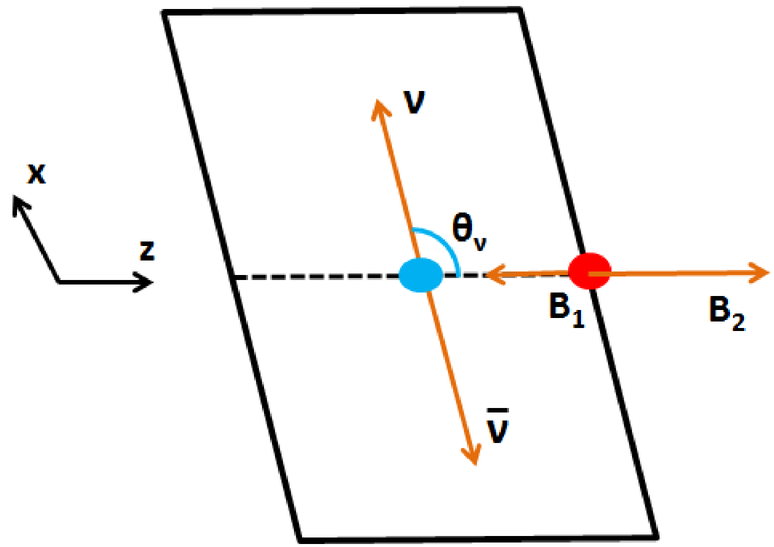
$$\frac{G_F\lambda_t}{\sqrt{2}} C_7 \frac{e}{4\pi} m_s \bar{d}\sigma_{\mu\nu}(1+\gamma_5)sF^{\mu\nu}$$



$$\frac{G_F\lambda_t\alpha}{\sqrt{2}} C_{9(10)} \left(\bar{d}\gamma_\mu(1-\gamma_5)s\right)\left(\bar{\ell}^-\gamma^\mu(\gamma_5)\ell^+\right)$$

- ☐ **Wilson coefficient $C_i(\mu)$ are calculated in PT at $\mu=m_W$ and rescaled to $\mu=1$ GeV.**
- ☐ **O_T does not contribute to $s \to d\mu^+\mu^-$ transitions PRL.113.241802.**

Decay mode 1: $B_1 \to B_2 \nu\bar{\nu}$



$$\Delta = M_1 - M_2$$

$$\delta = \Delta / M_1$$

- The total decay width in the presence of NP, expanded up to NLO in δ, can be written as

$$\Gamma = \sum_{\ell=e,\mu,\tau} \frac{\alpha^2 G_F^2 |\lambda_t|^2 f_1(0)^2 \Delta^5}{60\pi^3} \cdot \left[\left(1 - \frac{3}{2}\delta\right) \left|C^L_{\nu_\ell} + C^R_{\nu_\ell}\right|^2 + 3\left(1 - \frac{3}{2}\delta\right) \frac{g_1(0)^2}{f_1(0)^2} \left|C^L_{\nu_\ell} - C^R_{\nu_\ell}\right|^2 + \mathcal{O}\left(\delta^2\right) \right]$$

- These decay channels are sensitive to vectorial (parity even) and axial-vectorial (parity odd) couplings of the $s \to d$ currents
- A reliable determination of the form factors is necessary to better control uncertainties

Form factors relevant to $B_1 \to B_2 \nu\bar{\nu}$

- **Following** *PRL114 (2015) 161802*, **the form factors are obtained from covariant baryon chiral perturbation theory up to one loop order and isospin symmetry, and thus providing model independent inputs**

$$f_1(0)^{\Lambda n} = f_1(0)^{\Lambda p}, \qquad g_1(0)^{\Lambda n} = g_1(0)^{\Lambda p},$$
$$f_1(0)^{\Sigma^+ p} = f_1(0)^{\Sigma^- n}, \qquad g_1(0)^{\Sigma^+ p} = g_1(0)^{\Sigma^- n},$$
$$f_1(0)^{\Xi^0 \Sigma^0} = -f_1(0)^{\Xi^- \Sigma^0}, \qquad g_1(0)^{\Xi^0 \Sigma^0} = -g_1(0)^{\Xi^- \Sigma^0},$$
$$f_1(0)^{\Xi^0 \Lambda} = f_1(0)^{\Xi^- \Lambda}, \qquad g_1(0)^{\Xi^0 \Lambda} = g_1(0)^{\Xi^- \Lambda},$$

	Λn	$\Sigma^+ p$	$\Xi^0 \Sigma^0$	$\Xi^0 \Lambda$
$f_1(0)$	$-\sqrt{\frac{3}{2}}$	-1	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{3}{2}}$
$g_1(0)$	$-0.89(2)$	$0.33(2)$	$-0.86(3)$	$0.24(4)$

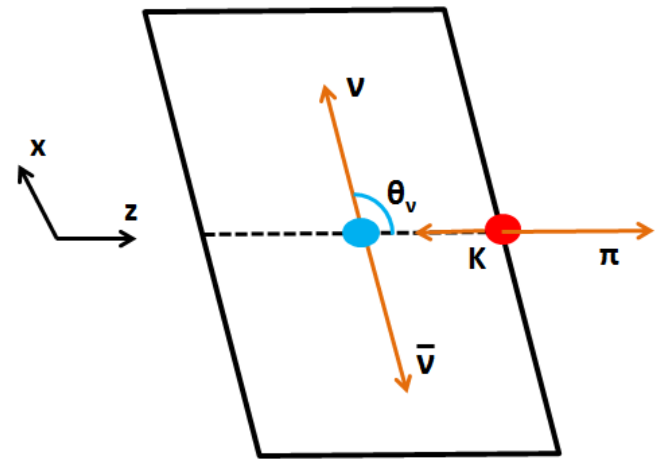
L. S. Geng et al., Phys. Rev. D 79, 094022 (2009)
T. Ledwig et al., Phys. Rev. D 90, 054502 (2014)

Decay mode 2: $K \to \pi\nu\bar{\nu}$

- **Isospin symmetry relate the form factors in the FCNC processes to those of the well-known charge-current decays**

$$\langle\pi^+|(\bar{s}d)_{V-A}|K^+\rangle = \sqrt{2}\langle\pi^0|(\bar{s}u)_{V-A}|K^+\rangle,$$

$$\langle\pi^0|(\bar{s}d)_{V-A}|K^0\rangle = \langle\pi^0|(\bar{s}u)_{V-A}|K^+\rangle,$$



- **Branching ratios of two K → π ν ν̄ processes in the presence of NP are**

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{2\alpha^2|\lambda_t|^2\mathrm{BR}(K^+ \to \pi^0 e^+\nu_e)}{|V_{us}|^2}\sum_{\ell=e,\mu,\tau}|C^L_{\nu_\ell} + C^R_{\nu_\ell}|^2,$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \frac{2\alpha^2\tau_{K_L}\mathrm{BR}(K^+ \to \pi^0 e^+\nu_e)}{\tau_{K^+}|V_{us}|^2}\sum_{\ell=e,\mu,\tau}\left(\mathrm{Im}[(C^L_{\nu_\ell} + C^R_{\nu_\ell})\lambda_t^*]\right)^2,$$

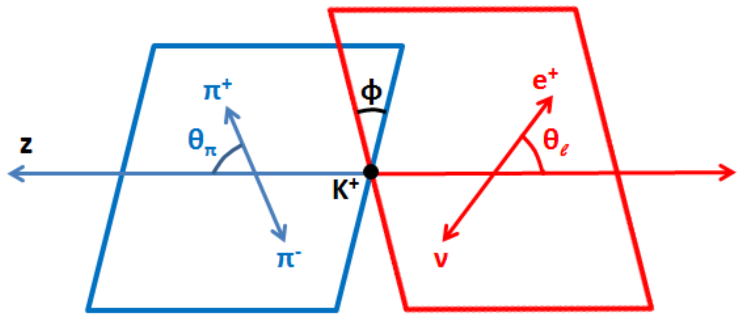
- The 3-body decay channels are only sensitive to **vectorial couplings** of the $s \to d$ currents
- Uncertainties are mainly from the measurements of the charged current $K^+ \to \pi^0 e^+ \upsilon$ decay.

Decay mode 3: $K \to \pi\pi\nu\bar{\nu}$ (I)

- Isospin symmetry relate the form factors in the FCNC processes to those of the well-known charged-current decay

$$\langle\pi^+\pi^0|(\bar{s}d)_{V-A}|K^+\rangle = -\sqrt{2}\langle(\pi^+\pi^-)_{I=1}|(\bar{s}u)_{V-A}|K^+\rangle,$$

$$\langle\pi^0\pi^0|(\bar{s}d)_{V-A}|K^0\rangle = \langle(\pi^+\pi^-)_{I=0}|(\bar{s}u)_{V-A}|K^+\rangle.$$



- Four-body differential decay rate in terms of 9 angular coefficients

$$\frac{d^5\Gamma}{ds_\pi ds_\ell d(\cos\theta_\pi)d(\cos\theta_\ell)d\phi} = \alpha^2 G_F^2|\lambda_t|^2 N(s_\pi, s_\ell) J_5(s_\pi, s_\ell, \theta_\pi, \theta_\ell, \phi)$$

$$J_5 = I_1 + I_2\cos 2\theta_\ell + I_3\sin^2\theta_\ell\cos 2\phi + I_4\sin 2\theta_\ell\cos\phi + I_5\sin\theta_\ell\cos\phi$$

$$+I_6\cos\theta_\ell + I_7\sin\theta_\ell\sin\phi + I_8\sin 2\theta_\ell\sin\phi + I_9\sin^2\theta_\ell\sin 2\phi,$$

- After integrating out the angle θ_ℓ and ϕ, only I_1 and I_2 contribute to the **total decay width**, i.e.,

$$\Gamma = \int_{4m_\pi^2}^{m_K^2}\int_0^{(m_K-\sqrt{s_\pi})^2}\int_{-1}^{1} \alpha^2 G_F^2|\lambda_t|^2 N(s_\pi, s_\ell)\cdot 4\pi(I_1 - \frac{1}{3}I_2)\cdot ds_\pi ds_\ell d(\cos\theta_\pi).$$

Decay mode 3: $K \to \pi\pi\nu\bar{\nu}$ (II)

- I_1 and I_2 in terms of helicity amplitudes

$$I_1 = \frac{s_\ell}{2}\left(3|H_+^V|^2 + 3|H_-^V|^2 + 2|H_0^V|^2 + 3|H_+^A|^2 + 3|H_-^A|^2 + 2|H_0^A|^2\right),$$

$$I_2 = \frac{s_\ell}{2}\left(|H_+^V|^2 + |H_-^V|^2 - 2|H_0^V|^2 + |H_+^A|^2 + |H_-^A|^2 - 2|H_0^A|^2\right).$$

- Helicity amplitudes for $K^+ \to \pi^+\pi^0\upsilon\bar{\upsilon}$

$$H_0^{V(A)} = \frac{i(C_{\nu_\ell}^L - C_{\nu_\ell}^R)\left(4F \cdot m_K^2 X + G \cdot \sigma_\pi \cos\theta_\pi \left(-(s_l - s_\pi)^2 + m_K^4 + 4X^2\right)\right)}{4m_K^3\sqrt{s_l}},$$

$$H_+^{V(A)} = -\frac{i\sqrt{s_\pi}\sigma_\pi \sin\theta_\pi \left(G \cdot m_K^2(C_{\nu_\ell}^L - C_{\nu_\ell}^R) + H \cdot X(C_{\nu_\ell}^L + C_{\nu_\ell}^R)\right)}{\sqrt{2}m_K^3},$$

$$H_-^{V(A)} = \frac{i\sqrt{s_\pi}\sigma_\pi \sin\theta_\pi \left(G \cdot m_K^2(C_{\nu_\ell}^L - C_{\nu_\ell}^R) - H \cdot X(C_{\nu_\ell}^L + C_{\nu_\ell}^R)\right)}{\sqrt{2}m_K^3},$$

- Helicity amplitudes for $K_L \to \pi^0\pi^0\upsilon\bar{\upsilon}$

$$H_0^{V(A)} = \frac{i\sqrt{2}X \cdot F \cdot \mathrm{Re}\left[(C_{\nu_\ell}^L - C_{\nu_\ell}^R)\lambda_t^*\right]}{m_K\sqrt{s_l}},$$

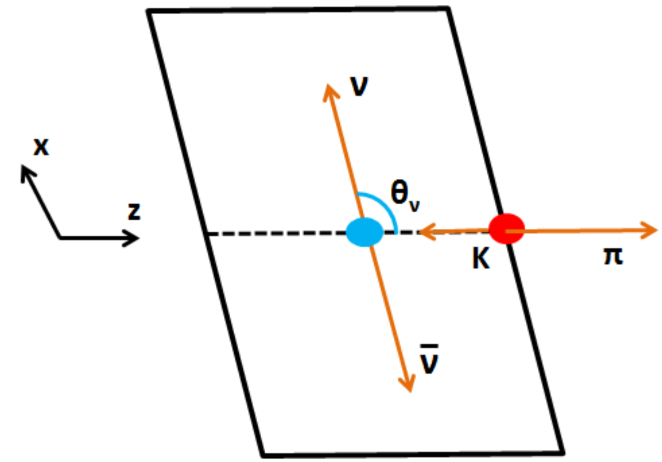
$$H_+^{V(A)} = 0,$$

$$H_-^{V(A)} = 0,$$

Decay modes 4&5: $K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$ (I)

- Branching ratio of $K_L \to \mu^+\mu^-$ JHEP 08, 088 (2006)

$$\mathrm{BR}(K_L \to \mu^+\mu^-) = \left[6.7 + \left(\frac{0.08\alpha\pi^2}{\sqrt{2}G_F m_s m_\mu}\mathrm{Im}\left[\lambda_t^*(C_S - C_S')\right]\right)^2 + \left(1.1(C_{10}' - C_{10}) + \frac{0.10\alpha\pi^2}{\sqrt{2}G_F m_s m_\mu}\mathrm{Re}\left[\lambda_t^*(C_P - C_P')\right] - 0.2 \pm 0.4^{+0.5}_{-0.5}\right)^2\right] 10^{-9},$$



- For the $K^+ \to \pi^+\mu^+\mu^-$ decay

$$\frac{d\Gamma}{dq^2 d\cos\theta_\mu} = \Gamma_0 \beta_\mu \sqrt{\lambda(q^2)}\left[a(q^2) + b(q^2)\cos\theta_\mu + c(q^2)\cos^2\theta_\mu\right]$$

$$a(q^2) = q^2\left(\beta_\mu^2 \left|F_S(q^2)\right|^2 + \left|F_P(q^2)\right|^2\right) + \frac{\lambda(q^2)}{4}\left(\left|F_A(q^2)\right|^2 + \left|F_V(q^2)\right|^2\right) + 4m_\mu^2 m_{K^+}^2 \left|F_A(q^2)\right|^2 + 2m_\mu\left(m_{K^+}^2 - m_{\pi^+}^2 + q^2\right)\mathrm{Re}\left[F_P(q^2)F_A(q^2)^*\right],$$

$$b(q^2) = 2m_\mu \beta_\mu \sqrt{\lambda(q^2)}\mathrm{Re}\left[F_S(q^2)F_V(q^2)^*\right],$$

$$c(q^2) = -\frac{\beta_\mu^2 \lambda(q^2)}{4}\left(\left|F_A(q^2)\right|^2 + \left|F_V(q^2)\right|^2\right),$$

Decay modes 4&5: $K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$ (II)

$$F_V(q^2) = \left(C_9 + C_9'\right) f_+(q^2) + \frac{2m_s}{m_{K^+} + m_{\pi^+}} f_T(q^2) C_7 + F_{V\gamma}(q^2),$$

$$F_A(q^2) = \left(C_{10} + C_{10}'\right) f_+(q^2),$$

$$F_S(q^2) = \frac{m_{K^+}^2 - m_{\pi^+}^2}{2(m_s - m_d)} f_0(q^2) \left(C_S + C_S'\right),$$

$$F_P(q^2) = \frac{m_{K^+}^2 - m_{\pi^+}^2}{2(m_s - m_d)} f_0(q^2) \left(C_P + C_P'\right) - m_\mu \left(C_{10} + C_{10}'\right) \left[f_+(q^2) - \frac{m_{K^+}^2 - m_{\pi^+}^2}{q^2} \left(f_0(q^2) - f_+(q^2)\right)\right]$$

where $\Gamma_0 = \frac{G_F^2 \alpha^2 |\lambda_t|^2}{512\pi^3 m_{K^+}^3}$, $\beta_\mu = \sqrt{1 - \frac{4m_\mu^2}{q^2}}$ and $\lambda(q^2) = q^4 + m_{K^+}^4 + m_{\pi^+}^4 - 2(m_{K^+}^2 m_{\pi^+}^2 + m_{K^+}^2 q^2 + m_{\pi^+}^2 q^2)$

Long-distance contribution $F_{V\gamma}(q^2) = -\left[\left(\alpha_+ + \beta_+ \frac{q^2}{m_{K^+}^2}\right) + \frac{1}{m_{K^+}^2 G_F} W_+^{\pi\pi}(q^2)\right] \frac{\sqrt{2}}{2\pi\lambda_t^*},$ JHEP 08, 004 (1998)

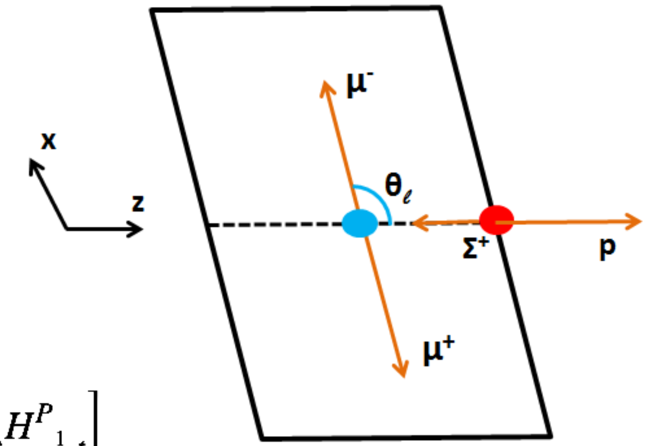
The branching ratio and forward-backward asymmetry are defined as

$$\mathrm{BR} = 2\Gamma_0 \int_{q^2_{\min}}^{q^2_{\max}} \beta_\mu \sqrt{\lambda(q^2)} \left(a(q^2) + \frac{1}{3} c(q^3)\right),$$

$$A_{FB} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \beta_\mu \sqrt{\lambda(q^2)}\, b(q^2)}{2 \int_{q^2_{\min}}^{q^2_{\max}} \beta_\mu \sqrt{\lambda(q^2)} \left(a(q^2) + \frac{1}{3} c(q^3)\right)},$$

Decay mode 6: of $\Sigma^+ \to p\mu^+\mu^-$ (I)

Helicity basis allows for an explicit separation of long and short range contributions



$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \mathcal{N}(q^2)\left[I_1(q^2) + I_2(q^2)\cos\theta_\ell + I_3(q^2)\cos^2\theta_\ell\right]$$

$$\begin{aligned}
I_1(q^2) =& \left(|H^A_{\frac12,t}|^2 + |H^A_{-\frac12,t}|^2\right)\cdot 8m_\ell^2 + \left(|H^S_{\frac12,t}|^2 + |H^S_{-\frac12,t}|^2\right)\cdot\left(2q^2 - 5m_\ell^2\right) \\
&+ \left(|H^P_{\frac12,t}|^2 + |H^P_{-\frac12,t}|^2\right)\cdot\left(2q^2 - 3m_\ell^2\right) - 8m_\ell\sqrt{q^2}\cdot \mathrm{Re}\left[H^{A*}_{\frac12,t}H^P_{\frac12,t} + H^{A*}_{-\frac12,t}H^P_{-\frac12,t}\right] \\
&+ \left(|H^V_{\frac12,0}|^2 + |H^V_{-\frac12,0}|^2\right)\cdot\left(8m_\ell^2 + 2q^2\beta^2\right) + \left(|H^A_{\frac12,0}|^2 + |H^A_{-\frac12,0}|^2\right)\cdot 2q^2\beta^2 \\
&+ \left(|H^V_{\frac12,+}|^2 + |H^V_{-\frac12,-}|^2\right)\cdot\left(8m_\ell^2 + q^2\beta^2\right) + \left(|H^A_{\frac12,+}|^2 + |H^A_{-\frac12,-}|^2\right)\cdot q^2\beta^2,
\end{aligned}$$

$$I_2(q^2) = -8m_\ell\sqrt{q^2}\beta\cdot\mathrm{Re}\left[H^S_{\frac12,t}H^{V*}_{\frac12,0} + H^S_{-\frac12,t}H^{V*}_{-\frac12,0}\right] - 4q^2\beta\cdot\mathrm{Re}\left[H^A_{\frac12,+}H^{V*}_{\frac12,+} - H^A_{-\frac12,-}H^{V*}_{-\frac12,-}\right]$$

Short-distance

$$\begin{aligned}
I_3(q^2) =& \left(|H^V_{\frac12,0}|^2 + |H^V_{-\frac12,0}|^2 + |H^A_{\frac12,0}|^2 + |H^A_{-\frac12,0}|^2\right)\cdot\left(-2q^2\beta^2\right) \\
&+ \left(|H^V_{\frac12,+}|^2 + |H^V_{-\frac12,-}|^2 + |H^A_{\frac12,+}|^2 + |H^A_{-\frac12,-}|^2\right)\cdot q^2\beta^2,
\end{aligned}$$

H^V includes long-distance contributions, and $H^{A,S,P}$ only contain short-distance contributions

$$\begin{aligned}
H^V_{\frac12,0} =& -\frac{iC_7 m_s\left[\sqrt{Q_-}\left(g_T(q^2) - g_T^{(1)}(q^2)\frac{M_1+M_2}{M_1} - g_T^{(2)}(q^2)\frac{Q_+}{M_1^2}\right) + \sqrt{Q_+}\left(g_{T5}(q^2) + g_{T5}^{(1)}(q^2)\frac{M_1-M_2}{M_1} - g_T^{(2)}(q^2)\frac{Q_-}{M_1^2}\right)\right]}{2\pi\sqrt{q^2}} \\
&+ \frac{\sqrt{Q_-}\left(C_9 + C_9'\right)\left[f_1(q^2)(M_1+M_2) + f_2(q^2)\frac{q^2}{M_1}\right]}{\sqrt{q^2}} + \frac{\sqrt{Q_+}\left(C_9 - C_9'\right)\left[g_1(q^2)(M_1-M_2) - g_2(q^2)\frac{q^2}{M_1}\right]}{\sqrt{q^2}} \\
&+ \frac{4\sqrt{2}\pi\left[-a\sqrt{Q_-} - b\sqrt{Q_+} - c\sqrt{Q_-}(M_1+M_2) + d\sqrt{Q_+}(M_1-M_2)\right]}{\sqrt{q^2}\lambda_t},
\end{aligned}$$

→ **Long-distance**

Decay mode 6: $\Sigma^+ \to p\mu^+\mu^-$ (II)

Decay width expanded in δ reads

$$\frac{d\Gamma}{d\cos\theta_\ell} = \mathcal{N}\left[k_1 + k_2\cos\theta_\ell + k_3\cos^2\theta_\ell\right],$$

$$k_1 = \left(\frac{137.06}{\Delta^2 f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{a}{\lambda_t}\right|^2 + \left(\frac{58.50}{f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{c}{\lambda_t}\right|^2 + \left(\frac{1221.67}{\Delta^2 f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{b}{\lambda_t}\right|^2 + \left(\frac{974.60}{f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{d}{\lambda_t}\right|^2 + \left(\frac{168.52}{\Delta f_1(0)^2}\delta\right)\mathrm{Re}\left[\frac{ac^*}{\lambda_t\lambda_t^*}\right] - \left(\frac{2199.79}{\Delta f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\mathrm{Re}\left[\frac{bd^*}{\lambda_t\lambda_t^*}\right],$$

$$k_3 = \left(\frac{8.30}{\Delta^2 f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{a}{\lambda_t}\right|^2 - \left(\frac{6.99}{f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{c}{\lambda_t}\right|^2 + \left(\frac{9.00}{\Delta^2 f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{b}{\lambda_t}\right|^2 - \left(\frac{7.00}{f_1(0)^2}\right)\left(1-\frac{3}{2}\delta\right)\left|\frac{d}{\lambda_t}\right|^2,$$

$$k_2 = (C_S + C_S')\,\mathrm{Re}\left[\left(\frac{2.32}{\Delta f_1(0)}\delta\right)\frac{f_S(0)}{f_1(0)}\left(\frac{a}{\lambda_t}\right)^* + \left(\frac{4.64}{f_1(0)}\right)\left(1-\frac{3}{2}\delta\right)\frac{f_S(0)}{f_1(0)}\left(\frac{c}{\lambda_t}\right)^*\right] + (C_S - C_S')\,\mathrm{Re}\left[\left(\frac{2.32}{\Delta f_1(0)}\delta\right)\frac{g_P(0)}{f_1(0)}\left(\frac{b}{\lambda_t}\right)^* - \left(\frac{2.32}{f_1(0)}\delta\right)\frac{g_P(0)}{f_1(0)}\left(\frac{d}{\lambda_t}\right)^*\right] + (C_{10} + C_{10}')\,\mathrm{Re}\left[\left(\frac{5.51}{\Delta f_1(0)}\delta\right)\left(\frac{b}{\lambda_t}\right)^* - \left(\frac{4.68}{f_1(0)}\delta\right)\left(\frac{d}{\lambda_t}\right)^* + \left(\frac{11.02}{\Delta f_1(0)}\delta\right)\frac{f_2(0)}{f_1(0)}\left(\frac{b}{\lambda_t}\right)^* - \left(\frac{9.36}{f_1(0)}\delta\right)\frac{f_2(0)}{f_1(0)}\left(\frac{d}{\lambda_t}\right)^*\right] + (C_{10} - C_{10}')\,\mathrm{Re}\left[\left(\frac{11.02}{\Delta f_1(0)}\right)\frac{g_1(0)}{f_1(0)}\left(1-\frac{3}{2}\delta\right)\left(\frac{a}{\lambda_t}\right)^* + \left(\frac{4.68}{f_1(0)}\delta\right)\frac{g_1(0)}{f_1(0)}\left(\frac{c}{\lambda_t}\right)^*\right],$$

where $\Delta = M_1 - M_2$ and $\mathcal{N} = \frac{G_F^2\alpha^2|\lambda_t|^2\Delta^5 f_1(0)^2}{2048\pi^3}$.

$$\mathrm{BR} = 2\tau_{B_1}\mathcal{N}\left(I_1 + \frac{1}{3}I_3\right),$$

$$A_{FB} = \frac{I_2}{I_1 + \frac{1}{3}I_3}.$$

$f_2(0)$ is relevant for A_{FB}.

Five $s \to d\nu\bar{\nu}$ processes

Kaon	$K^+\pi^+$	$K_L\pi^0$	$K^+\pi^+\pi^0$	$K_L\pi^0\pi^0$
SM	$8.17(7)\ 10^{-11}$	$2.60(2) \times 10^{-11}$	$7.90(34) \times 10^{-15}$	$3.11(6) \times 10^{-13}$
Expt.	$< 1.78 \times 10^{-10}$	$< 4.9 \times 10^{-9}$	$< 4.3 \times 10^{-5}$	$< 8.1 \times 10^{-7}$
$\delta C^L_{\nu_\ell} + C^R_{\nu_\ell}$	$(-3.4, 0.7)$	$(-15.0, 13.0)$	$(-2.3, 2.3) \times 10^4$	✗
$\delta C^L_{\nu_\ell} - C^R_{\nu_\ell}$	✗	✗	$(-1.1, 1.1) \times 10^5$	$(-3.0, 3.0) \times 10^3$

Hyperon		Λn	$\Sigma^+ p$	$\Xi^0\Sigma^0$	$\Xi^0\Lambda$
	SM-NLO	$6.0(1) \times 10^{-13}$	$3.3(1) \times 10^{-13}$	$8.4(5) \times 10^{-14}$	$5.4(2) \times 10^{-13}$
BESIII	Projection	$< 0.3\ 10^{-6}$	$< 0.4\ 10^{-6}$	$< 0.9\ 10^{-6}$	$< 0.8\ 10^{-6}$
	$\delta C^L_{\nu_\ell} + C^R_{\nu_\ell}$	$(-1.6, 1.6) \times 10^3$	$(-1.8, 1.8) \times 10^3$	$(-1.1, 1.1) \times 10^4$	$(-1.8, 1.8) \times 10^3$
	$\delta C^L_{\nu_\ell} - C^R_{\nu_\ell}$	$(-1.3, 1.3) \times 10^3$	$(-3.4, 3.4) \times 10^3$	$(-5.3, 5.3) \times 10^3$	$(-7.4, 7.4) \times 10^3$
Hyperon lifetime	Data	$< 8.5\ 10^{-3}$	$< 4.9\ 10^{-3}$	$< 2.3\ 10^{-4}$	$< 2.3\ 10^{-4}$
	$\delta C^L_{\nu_\ell} + C^R_{\nu_\ell}$	$(-2.7, 2.7) \times 10^5$	$(-1.9, 1.9) \times 10^5$	$(-1.7, 1.7) \times 10^5$	$(-3.0, 3.0) \times 10^4$
	$\delta C^L_{\nu_\ell} - C^R_{\nu_\ell}$	$(-2.2, 2.2) \times 10^5$	$(-3.7, 3.7)\ 10^5$	$(-8.5, 8.5) \times 10^4$	$(-1.3, 1.3) \times 10^5$

- $\delta C^L_{\nu l} + C^R_{\nu l}$ is constrained more stringently by the kaon modes
- $B_1 \to B_2 \nu\bar{\nu}$ are better than their kaon siblings to constrain $\delta C^L_{\nu l} - C^R_{\nu l}$

Comparison of the SM predictions for $B_1 \to B_2 \nu\bar{\nu}$

	Λn	$\Sigma^+ p$	$\Xi^0\Sigma^0$	$\Xi^0\Lambda$
SM-NLO	$6.0(1) \times 10^{-13}$	$3.3(1) \times 10^{-13}$	$8.4(5) \times 10^{-14}$	$5.4(2) \times 10^{-13}$
In Ref. [2]	7.1×10^{-13}	4.3×10^{-13}	1.0×10^{-14}	6.3×10^{-13}
In Ref. [3]	1.98×10^{-12}	5.01×10^{-13}	1.24×10^{-14}	7.35×10^{-13}

[2] Jusak Tandean, JHEP 04, 104 (2019)

[3] Xiao-Hui Hu et al., Chin. Phys. C 43, 093104 (2019)

$s \to d\mu^+\mu^-$

$\Sigma^+ \to p\mu^+\mu^-$

	$a\,(\mathrm{GeV}^2)\times 10^{-3}$	$b\,(\mathrm{GeV}^2)\times 10^{-3}$	$\mathrm{BR}\times 10^8$	$A_{FB}\times 10^5$	$\mathrm{BR}\times 10^8$ [19, 20]	$A_{FB}\times 10^5$ [19, 20]
Case 1	$13.3+2.84i$	$-6.0-1.83i$	1.7	$-1.7(2)$	1.6	3.7
Case 2	$-13.3+2.84i$	$6.0-1.83i$	3.5	0.3(1)	3.5	-1.4
Case 3	$6.0+2.84i$	$-13.3-1.83i$	5.5	0.4(0)	5.1	0.9
Case 4	$-6.0+2.84i$	$13.3-1.83i$	9.3	$-0.4(0)$	9.1	-0.3

	$\mathrm{BR}(K_L\to\mu^+\mu^-)$	$\lvert A_{FB}\rvert(K^+\to\pi^+\mu^+\mu^-)$	$\lvert A_{FB}\rvert(\Sigma^+\to p\mu^+\mu^-)$
SM	$(7.64\pm1.22)\,10^{-9}$	0	$(-1.7\sim0.4)\,10^{-5}$
Expt.	$(6.84\pm0.11)\,10^{-9}$	$<2.3\,10^{-2}$ (90% C.L.)	$<2.3\,10^{-2}$ (90% C.L.)
C_S+C_S'	✗	$(-3.05, 3.05)$	$(-5.3, 5.3)\times10^3$
C_S-C_S'	$(-0.12, 0.12)$	✗	$(-1.7, 1.7)\times10^3$
$\delta C_{10}+C_{10}'$	✗	✗	$(-2.2, 2.2)\times10^3$
$\delta C_{10}-C_{10}'$	$(-2.35, 0.59)$	✗	$(-1.4, 1.4)\times10^3$

- The contribution of the form factor $f_2(0)$ can be relevant for AFB.
- Current kaon bounds except for the $\delta C_{10}+C_{10}'$ scenario are a few orders of magnitude better than those of $\Sigma^+\to p\mu^+\mu^-$ if measured up to the same precision.

[19] X.G. He et al., PRD72, 074003 (2005)
[20] X.G. He et al., JHEP 10, 040 (2018)

Contents

- ☐ **Exotic hadrons**
  - ✓ **Singly charmed baryons—$\Lambda_c(2595)$: 1409.3133, 1603.05388**
  - ✓ **Excited kaons above 4 GeV ($KD\overline{D^{(*)}}$)—Kc(4180): 1805.08330, 2012.01134**
- ☐ **Rare processes & new physics**
  - ✓ **Searching for NP in hyperon decays**
  - ✓ **Weak radiative hyperon decays**
- ☐ **Summary & outlook**

$B_i \rightarrow B_f \gamma$

☐ *Asymmetry parameters*

The effective Lagrangian for the weak radiative hyperon decay $B_i \rightarrow B_f \gamma$ is written as

$$\mathcal{L} = \frac{eG_F}{2} \bar{B}_f (a + b\gamma_5) \sigma^{\mu\nu} B_i F_{\mu\nu}.$$

One can easily calculate the following decay width in helicity basis from Lagrangian above

$$\frac{d\Gamma}{d\cos\theta} = \frac{e^2 G_F^2}{\pi} (|a|^2 + |b|^2)[1 + \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2} \cos\theta] \cdot |\vec{k}|^3,$$

$$\alpha = \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2}, \qquad \Gamma = \frac{e^2 G_F^2}{\pi} (|a|^2 + |b|^2) \cdot |\vec{k}|^3,$$

where **α is the asymmetry parameter**, G_F is the Fermi constant, and α is the angle between the spin of the initial hyperon B_i and the 3-momentum $\vec{k}$ of the final baryon B_f.

Latest experimental results

Decay modes	Branch ratios	α
$\Lambda \to n\gamma$	$(1.75 \pm 0.15) \times 10^{-3}$	–
$\Sigma^+ \to p\gamma$	$(1.23 \pm 0.05) \times 10^{-3}$	-0.76 ± 0.08
$\Sigma^0 \to n\gamma$	–	–
$\Xi^0 \to \Lambda\gamma$	$(1.17 \pm 0.07) \times 10^{-3}$	-0.70 ± 0.07
$\Xi^0 \to \Sigma^0\gamma$	$(3.33 \pm 0.10) \times 10^{-3}$	-0.69 ± 0.06
$\Xi^- \to \Sigma^-\gamma$	$(1.27 \pm 0.23) \times 10^{-4}$	1.0 ± 1.3

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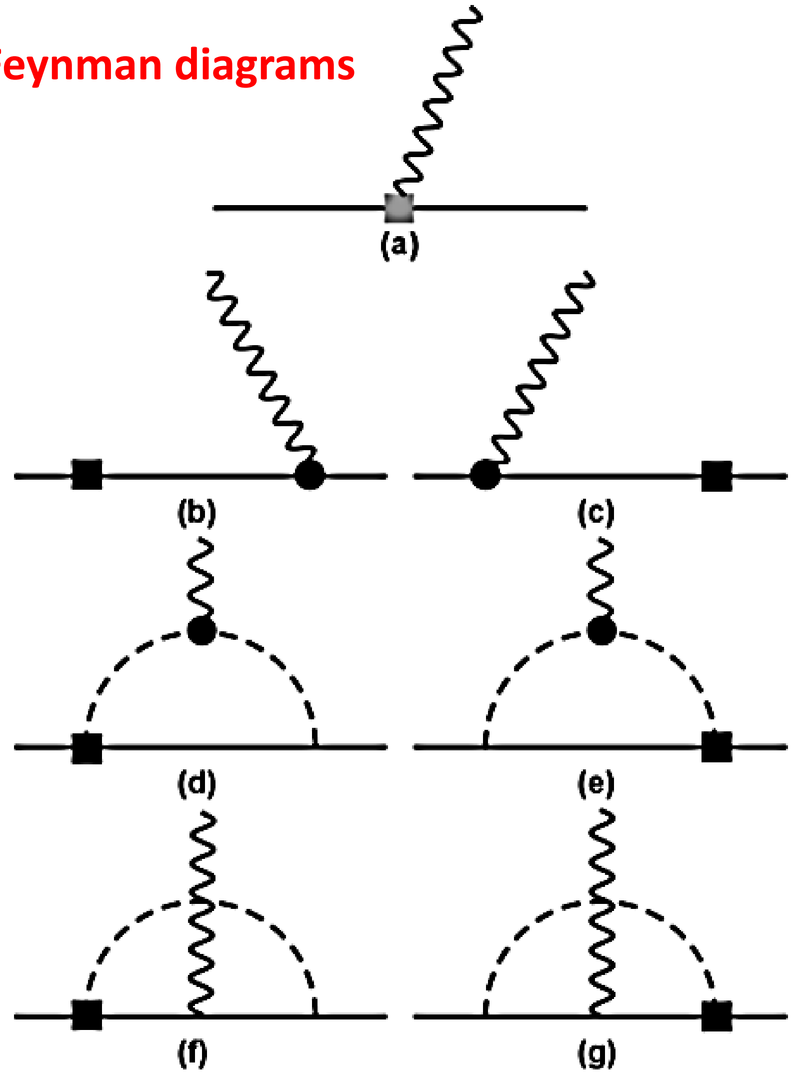
On the theory side

Up to now, none of the theories or approaches can explain simultaneously the asymmetry parameters data.

Therefore, we studied the weak radiative hyperon decays in covariant baryon chiral perturbation theory (BChPT) together with the extended-on-mass shell renormalization scheme (EOMS).

Theoretical framework: EOMS Baryon ChPT

Feynman diagrams



Lagrangians

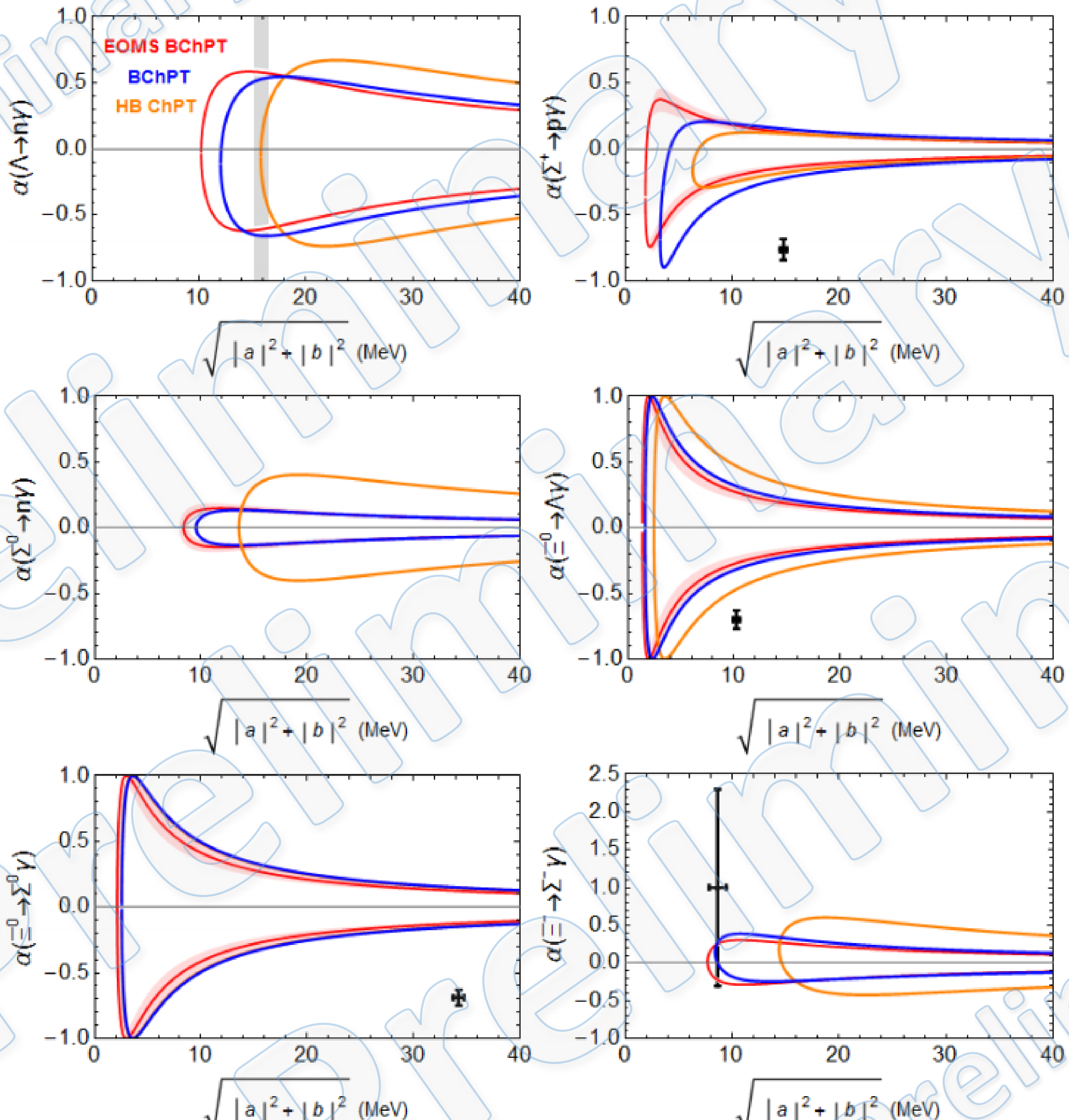
$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2} G_F m^2_{\pi^+} F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle + h.c,$$

$$\mathcal{L}^{(2)}_{MB} = \frac{b_6^D}{8m_B}\langle \bar{B}\sigma^{\mu\nu}\{F^+_{\mu\nu}, B\}\rangle + \frac{b_6^F}{8m_B}\langle \bar{B}\sigma^{\mu\nu}[F^+_{\mu\nu}, B]\rangle,$$

$$\mathcal{L}^{(1)}_B = \langle \bar{B} i\gamma^\mu D_\mu B - m_0 \bar{B}B\rangle,$$

$$\mathcal{L}^{(2)}_M = \frac{F_\phi^2}{4}\langle u_\mu u^\mu + \chi^+\rangle,$$

$$\mathcal{L}^{(1)}_{MB} = \frac{D}{2}\langle \bar{B}\gamma^\mu \gamma_5 \{u_\mu, B\}\rangle + \frac{F}{2}\langle \bar{B}\gamma^\mu \gamma_5 [u_\mu, B]\rangle,$$



The EOMS BChPT can still not explain the present asymmetry parameters data.

PartII—summary

- For the $s \to d\nu\overline{\nu}$ transitions, $\delta C_{\nu l}^{L} + C_{\nu l}^{R}$ can be determined well by the kaon modes but the $B_1 \to B_2 \nu\overline{\nu}$ modes are better than their kaon counterparts for the constraint on $\delta C_{\nu l}^{L} - C_{\nu l}^{R}$.

- For the $s \to d\mu^+\mu^-$ transitions, current kaon bounds are a few orders of magnitude better than those of $\Sigma^+ \to p\mu^+\mu^-$ if they are measured up to the same precision, except for the $\delta C_{10} + C_{10}^{'}$ scenario. In addition, the contribution of the form factor $f_2(0)$ is relevant for A_{FB}.

- The EOMS BChPT can still not explain the present asymmetry parameters data in weak radiative hyperon decays.

PartII—outlook

- For the $s \to d\nu\bar{\nu}$ transitions, measurements of $B_1 \to B_2\nu\bar{\nu}$ decays can help better constrain the axial-vectorial coupling $\delta C_{\nu l}^{L} - C_{\nu l}^{R}$.

- For the $\Sigma^+ \to p\mu^+\mu^-$ decay, a measurement of leptonic forward-backward asymmetry A_{FB} can help constrain $\delta C_{10} + C_{10}^{'}$.

- For the weak radiative hyperon decays, the re-measurement of asymmetry parameters can provide some guidance for future theory studies.

Contents

- ☐ **Exotic hadrons**
  - ✓ **Singly charmed baryons—$\Lambda_c(2595)$: 1409.3133, 1603.05388**
  - ✓ **Excited kaons above 4 GeV ($KD\overline{D^{(*)}}$)—Kc(4180): 1805.08330, 2012.01134**
- ☐ **Rare processes & new physics**
  - ✓ **Searching for NP in hyperon decays**
  - ✓ **Weak radiative hyperon decays**
- ☐ **Summary & outlook**

Summary and outlook

- Updated BESIII could make important and unique contributions to studies of exotic (non-conventional) hadrons and new physics
- We showcased a few examples in this talk.
- We look forward to more collaborations between theory and experiment