基于第一性原理的粲重子衰变常数计算

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目录

一、动机

萨哈罗夫三条件：1、重子数不守恒； 2、C与CP破坏； 3、热平衡的偏离。

重味重子的研究中，两体非轻衰变过程可以用来寻找CP破坏[1]

$$\Lambda_b^0 \rightarrow \Lambda_c^+ + h \, ,(h = \pi, K) \quad (1)$$

半轻衰变过程[2]可以抽取CKM矩阵元Vcb：

$$\Lambda_b^0 \rightarrow \Lambda_c^+ l \bar{\nu} \quad (2)$$

形状因子是半轻衰变和非轻衰变的重要物理量：

$$\langle \Lambda_c | i\mathcal{A} | \Lambda_b \rangle \sim C \otimes T \otimes \underbrace{\langle \Lambda_c | O_{\Lambda_c} | 0 \rangle}_{f_{\Lambda_c} \phi_{\Lambda_c}} \otimes \langle 0 | O_{\Lambda_b} | \Lambda_b \rangle \quad (3)$$

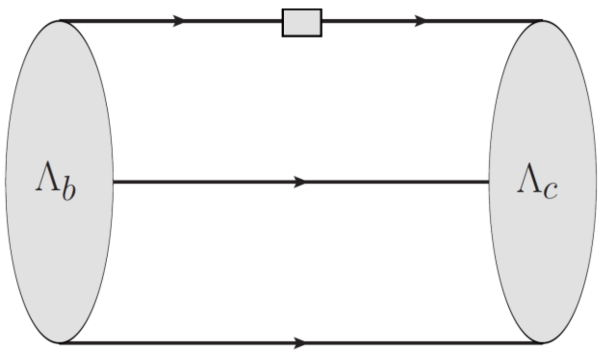


图1. $\Lambda_b^0 \rightarrow \Lambda_c^+$形状因子

形状因子正比于粲重子衰变常数：

$$\langle 0 | \epsilon_{ijk} (q_i^T C \Gamma_1 q_j) \Gamma_2 c_k | \mathcal{B}_c \rangle = f_{\mathcal{B}_c} m_{\mathcal{B}_c} u_{\mathcal{B}_c} \quad (4)$$

【1】R. Aaij et al. [LHCb], Phys. Rev. Lett. 133, [arXiv:2409.02759 [hep-ex]].
【2】R. Aaij et al. [LHCb], Phys. Rev. Lett. 128, no.19, 191803 (2022) [arXiv:2201.03497 [hep-ex]].

粲重子衰变常数主要由QCD求和规则计算[1-3]，精度在10%-20%

半轻衰变[4,5]：

$$\lambda^{P}_{\Lambda_c} = (1.19 \pm 0.19) \times 10^{-2}\ \mathrm{GeV}^2 \qquad Br(\Lambda_b \to \Lambda_c \ell \nu) = 6.2^{+1.4}_{-1.3}\%,$$
$$f_{\Omega_c} = (0.093 \pm 0.023)\ \mathrm{GeV}^3 \qquad Br(\Omega_c^0 \to \Xi^- l^+ \nu_l) = (3.06 \pm 0.15) \times 10^{-3}. \tag{5}$$

两体衰变 [6]：

TABLE IV: Various theoretical results on the bra
decays.

Mode	This work	[86]	[13][a]	[87, 88][a]
$\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$	$6.7^{+3.2+0.3+2.5}_{-2.2-2.8-1.3}$	$4.6^{+2.0}_{-3.1}$	4.5	5.6
$\mathcal{B}(\Lambda_b \to \Lambda_c K)$	$0.5^{+0.3+0.0+0.2}_{-0.2-0.2-0.1}$	...	...	...
$\alpha(\Lambda_b \to \Lambda_c \pi)$	-99.2	-100	-99	-99
$\alpha(\Lambda_b \to \Lambda_c K)$	-98.2	...	...	...

[a]We estimate the branching ratio by multiplying the

表1. 文献[2]中两体衰变分支比

影响分支比和CP破坏的精度，

新物理的间接寻找

格点计算优点：准确性，精确性，预期精度是5%左右。

【1】Z. G.Wang, Phys. Lett. B 685, 59-66 (2010) [arXiv:0912.1648 [hep-ph]].

【2】A. Khodjamirian, C.Klein, T.Mannel and Y.M.Wang, JHEP 09, 106 (2011) [arXiv:1108.2971 [hep-ph]].

【3】Y.J.Shi, W.Wang and Z. X.Zhao, Eur. Phys. J. C 80, no.6, 568 (2020) [arXiv:1902.01092 [hep-ph]].

【4】Y.Miao, H.Deng, K.S.Huang, J.Gao and Y.L.Shen, Chin. Phys. C 46, no.11, 113107 (2022) [arXiv:2206.12189 [hep-ph]].

【5】H. H.Duan, Y.L.Liu and M. Q.Huang, Eur. Phys. J. C 81, no.2, 168 (2021) [arXiv:2010.16176 [hep-ph]].

【6】C. Q. Zhang, J. M. Li, M. K. Jia and Z. Rui, Phys. Rev. D 105, no.7, 073005 (2022) [arXiv:2202.09181 [hep-ph]].

二、粲重子衰变矩阵元计算

格点中计算的两点关联函数：

$$C_{2pt}(t) = \int d^3x e^{-i\vec{x}\cdot\vec{p}} \langle 0|O(x), \bar{O}(0)|0\rangle \quad (6)$$

插入强子完备基：

$$1 = \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{|n(p)\rangle\langle n(p)|}{2E_n} \quad (7)$$

根据衰变常数的定义：

$$\langle 0|O(x)|\mathcal{B}_c(p)\rangle = e^{-ix\cdot p} f_{\mathcal{B}_c} m_{\mathcal{B}_c} u(p) \quad (8)$$

强子层次的关联函数进行参数化：

$$C_{2pt}(t)\mathrm{T} = 2m_{\mathcal{B}_c}^2 f_{\mathcal{B}_c}^2 e^{-m_{\mathcal{B}_c}\cdot t}(1+\Delta C e^{-\Delta m\cdot t}) \quad (9)$$

两态拟合抽取衰变常数。

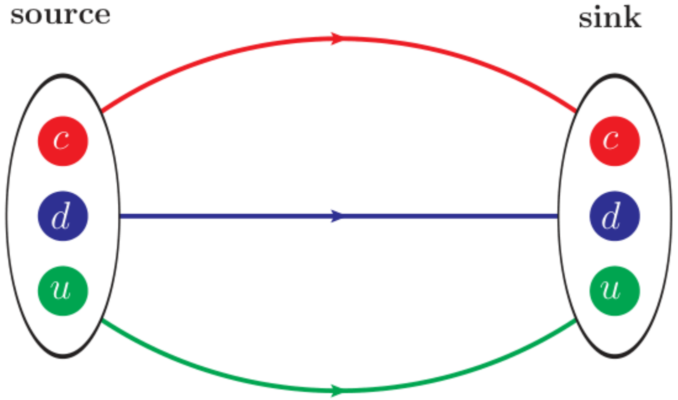


图2、夸克层次的两点关联函数

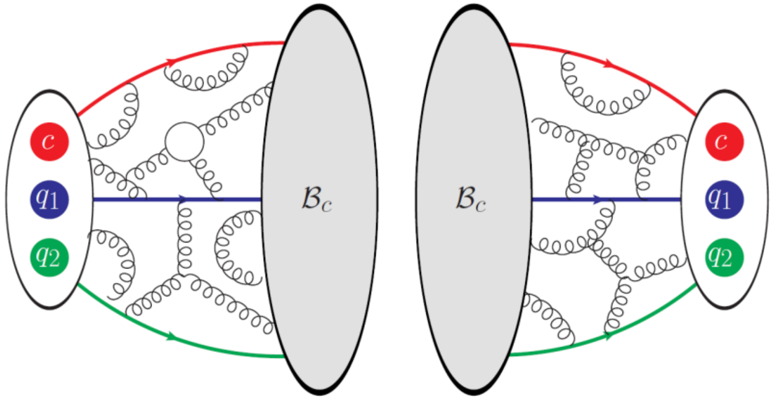


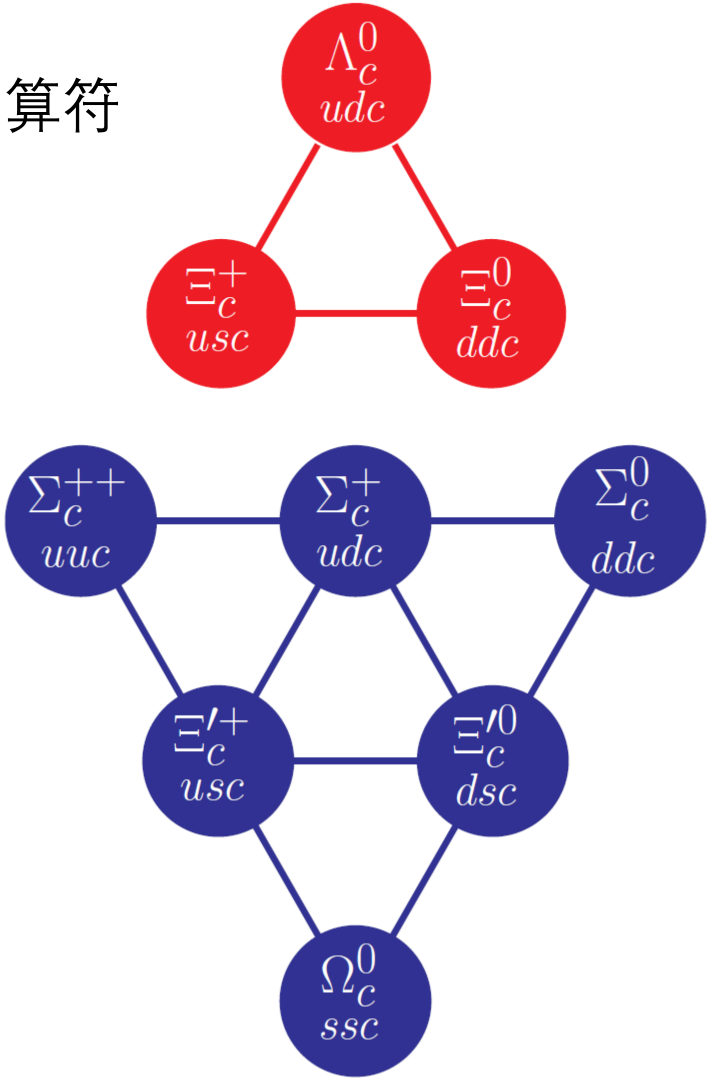
图3、强子层次的两点关联函数

1、粲重子算符构造

文献 [1] 通过di-quark的SU(2)对称性构造$\Lambda_c^+(udc)$和$\Sigma_c^+(udc)$算符

$$\bar{3}:\begin{cases} O_{\Lambda_c^+}=\epsilon_{ijk}(u_i^T C\gamma_5 d_j)P_+c_k \\ O_{\Xi_c^+}=\epsilon_{ijk}(u_i^T C\gamma_5 s_j)P_+c_k \\ O_{\Xi_c^0}=\epsilon_{ijk}(d_i^T C\gamma_5 s_j)P_+c_k \end{cases} \quad \text{反对称} \quad (10)$$

$$6:\begin{cases} O_{\Xi_c^{\prime +}}=\epsilon_{ijk}(u_i^T C\gamma_\mu s_j)P_+\gamma^\mu\gamma_5 c_k \\ O_{\Xi_c^{\prime 0}}=\epsilon_{ijk}(d_i^T C\gamma_\mu s_j)P_+\gamma^\mu\gamma_5 c_k \\ O_{\Sigma_c^+}=\epsilon_{ijk}(u_i^T C\gamma_\mu d_j)P_+\gamma^\mu\gamma_5 c_k \\ O_{\Sigma_c^0}=\epsilon_{ijk}(d_i^T C\gamma_\mu d_j)P_+\gamma^\mu\gamma_5 c_k \\ O_{\Sigma_c^{++}}=\epsilon_{ijk}(u_i^T C\gamma_\mu u_j)P_+\gamma^\mu\gamma_5 c_k \\ O_{\Omega_c^0}=\epsilon_{ijk}(s_i^T C\gamma_\mu s_j)P_+\gamma^\mu\gamma_5 c_k \end{cases} \quad \text{对称} \quad (11)$$



推广到SU(3) 对称性 $3\otimes 3=\bar{3}\oplus 6$

图4. 粲重子算符根据SU(3)对称性分类

【1】A. Khodjamirian, C.Klein, T.Mannel and Y.M.Wang, JHEP 09, 106 (2011) [arXiv:1108.2971 [hep-ph]].

Ξ_c 和 Ξ_c' 的差别在洛伦兹结构：

$$\begin{aligned} \Xi_c &= \epsilon_{ijk}(l_i^T C\gamma_5 s_j)P_+ c_k, \\ \Xi_c' &= \epsilon_{ijk}(l_i^T C\gamma_\mu\gamma_5 s_j)P_+\gamma^\mu\gamma_5 c_k. \end{aligned} \tag{12}$$

SU(3)对称性对算符的影响会体现在质量平台。

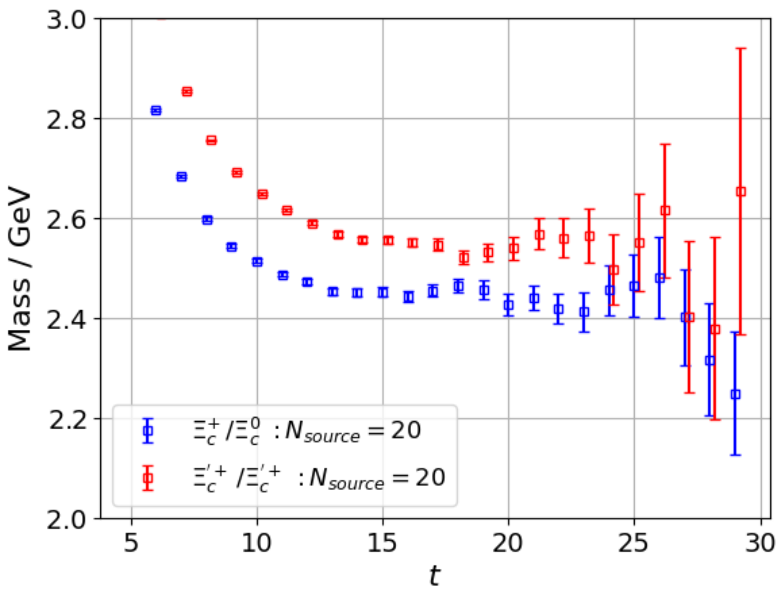


图5. Ξ_c和Ξ_c'的有效质量图

2、Source 测试

- 1、point to point ；
- 2、smear to point/ (smear to smear)$^{1/2}$ ，需要去掉体积效应；
- 3、wall to point/(wall to wall)$^{1/2}$，需要去掉gauge fixing和体积效应；
- 4、wall to point，不做gauge fixing，需要去掉体积效应。

重子	组态	Source	N conf	$L^3 \times T$
$\Lambda_c(udc)$	C24P29	All type	20	$24^3 \times 72$

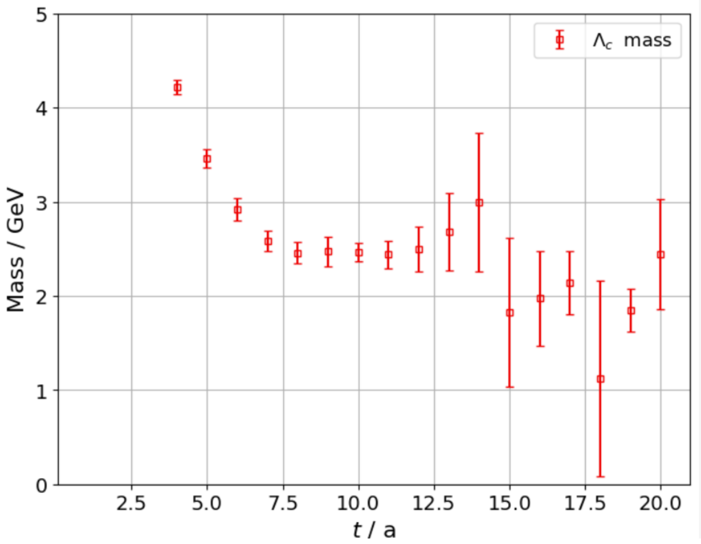


图6、point source to point sink

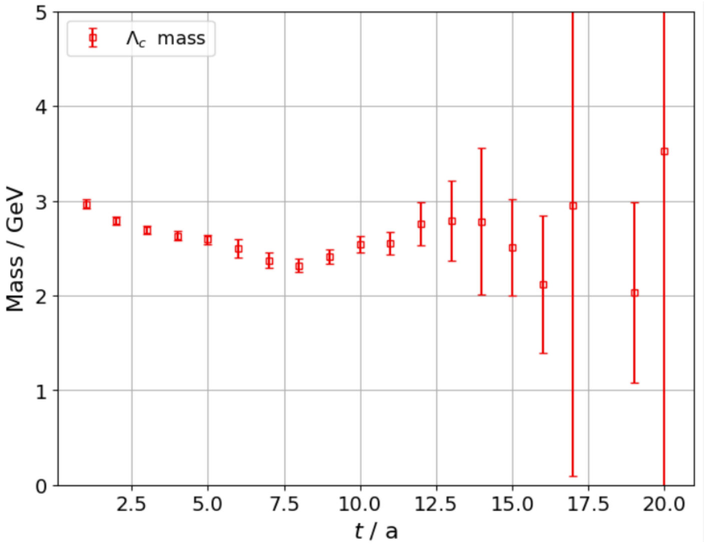


图7、smear source to point sink +

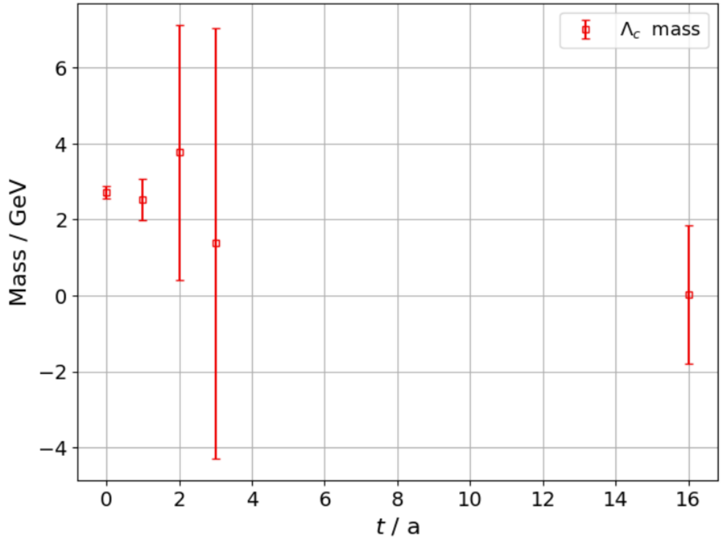


图8、smear source to smear sink

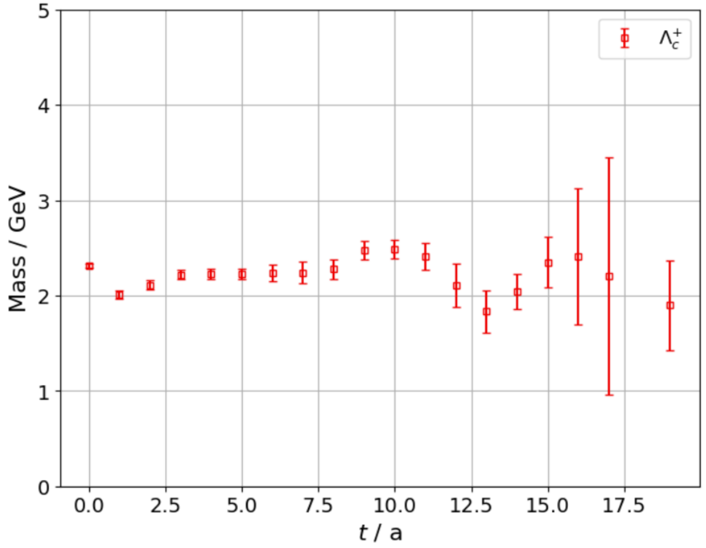


图9、wall source to point sink +

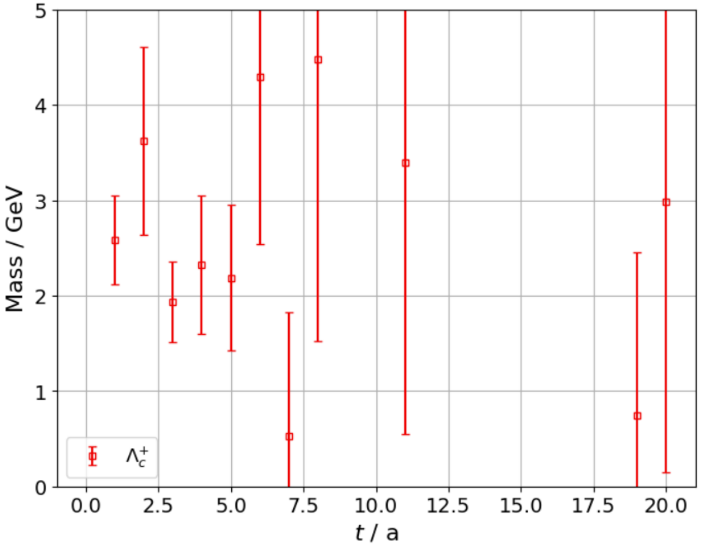


图10、wall source to wall sink

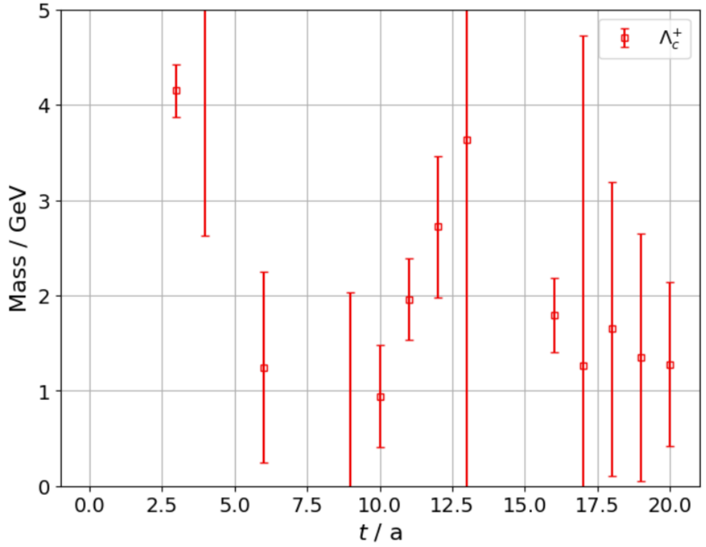


图11、wall source to point sink
不做gauge fixing

选用 point source 进行计算

2、格点QCD对矩阵元的计算

两点关联函数是两个时空点的计算

$$C_{2pt}(t) = \int d^3x e^{-i\vec{x}\cdot\vec{p}} \langle 0|O(x), \bar{O}(0)|0\rangle \tag{13}$$

与 point source 物理图像一致。

表2、CLQCD组态信息

Conf	$L^3 \times T$	a(fm)	Pion(MeV)	m_l	m_s	m_c	N_Conf	N_Src
C24P29	$24^3 \times 72$	0.105	290	-0.2770	-0.2357	0.4168	864	20
C32P29	$32^3 \times 64$	0.105	290	-0.2770	-0.2358	0.4158	984	16
C32P23	$32^3 \times 64$	0.105	230	-0.2790	-0.2338	0.4198	451	20
F32P30	$32^3 \times 96$	0.077	300	-0.2295	-0.2039	0.1968	777	20
H48P32	$48^3 \times 144$	0.052	320	-0.1850	-0.1703	0.0533	112	6

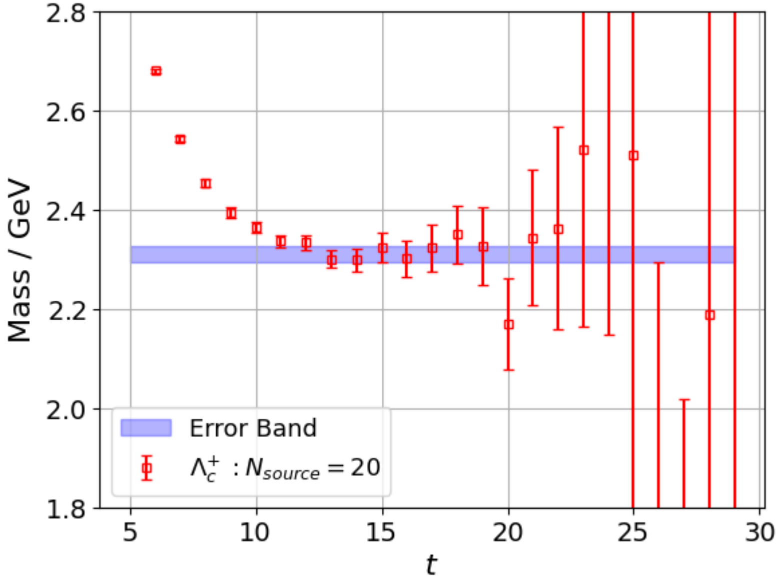


图12、 Λ_c^+重子有效质量

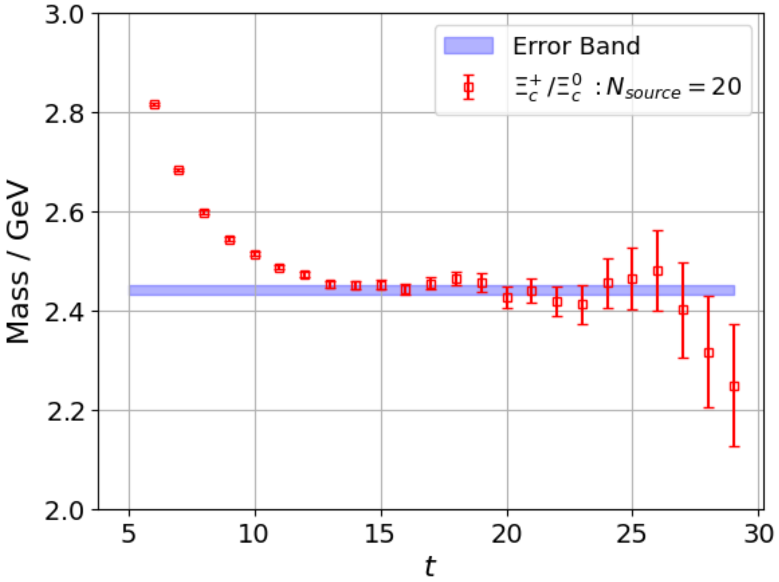


图13、Ξ_c^+/Ξ_c^0重子有效质量

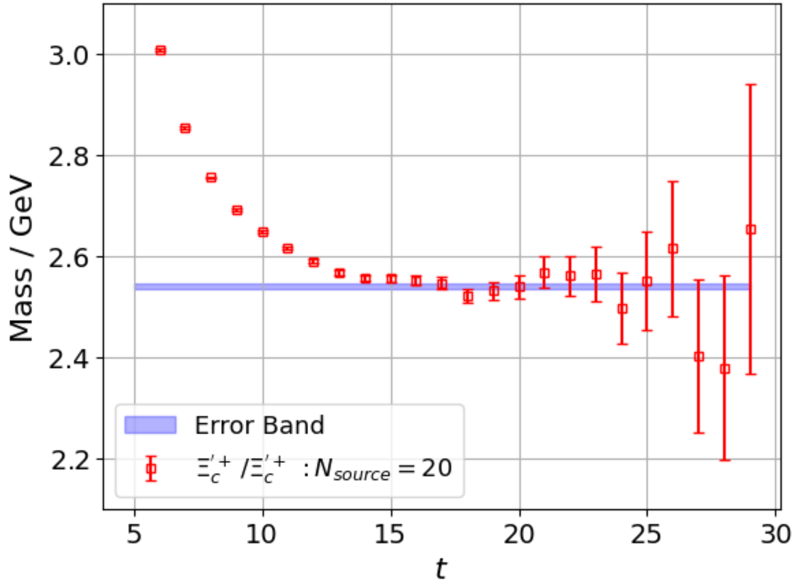


图14、Ξ'^+_c/Ξ'^0_c重子有效质量

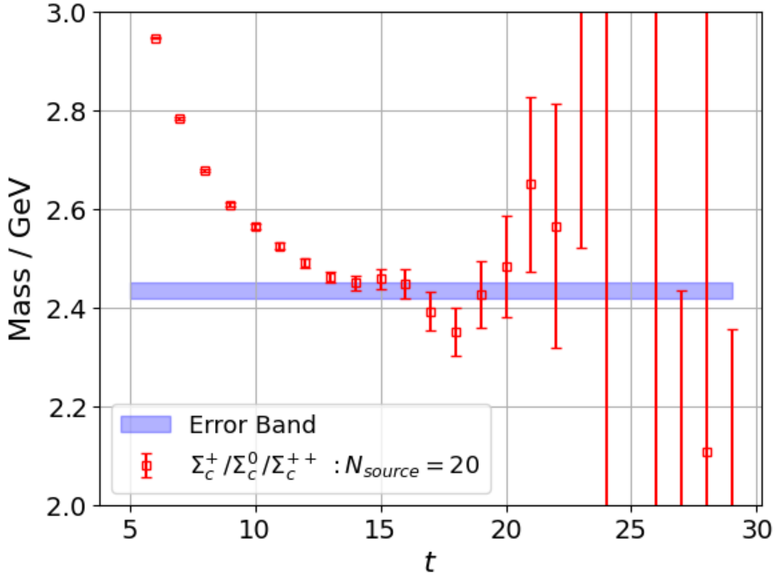


图15、$\Sigma_c^+/\Sigma_c^0/\Sigma_c^{++}$重子有效质量

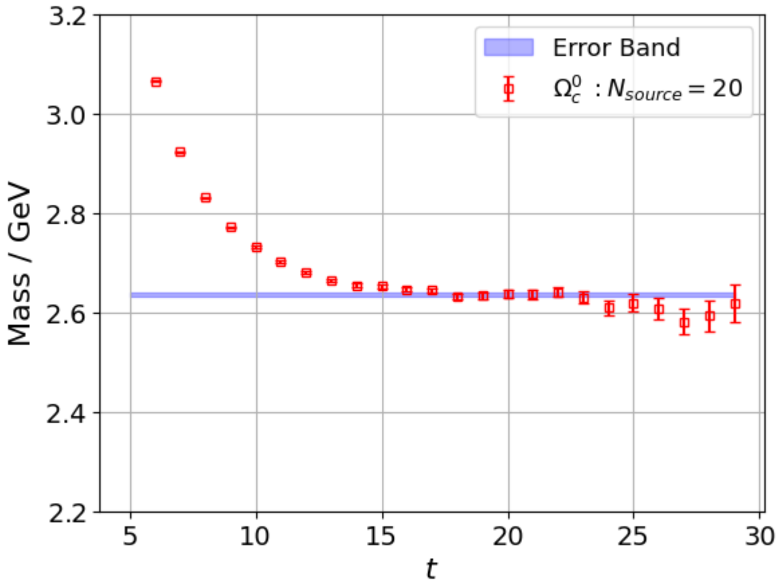


图16、Ω_c^0重子有效质量

C24P29
Ncfg=984
Nsrc=2×10

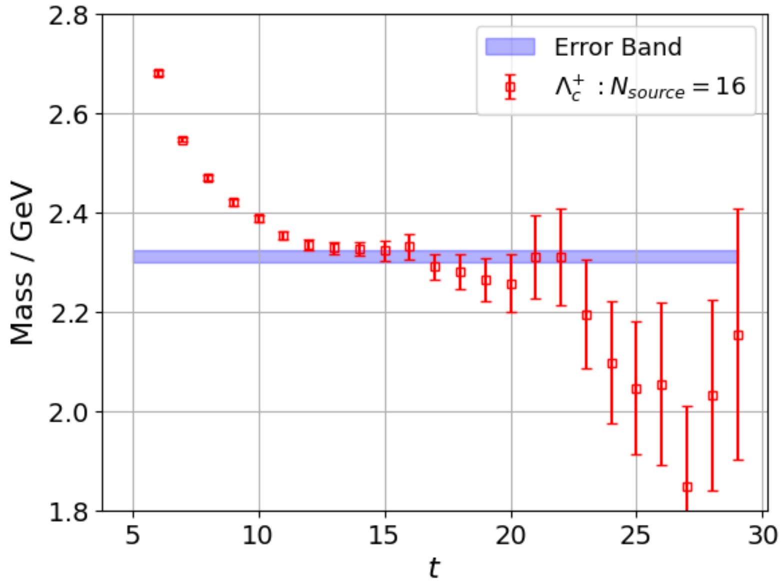


图17、 Λ_c^+重子有效质量

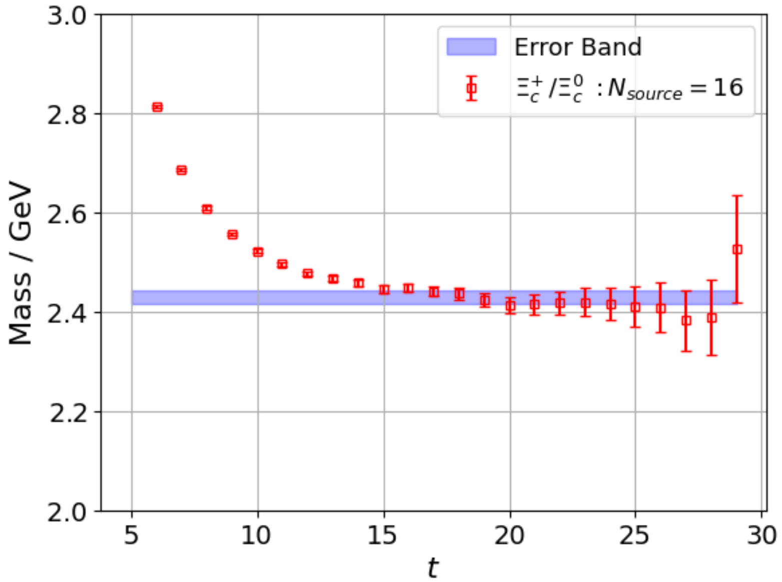


图18、Ξ_c^+/Ξ_c^0重子有效质量

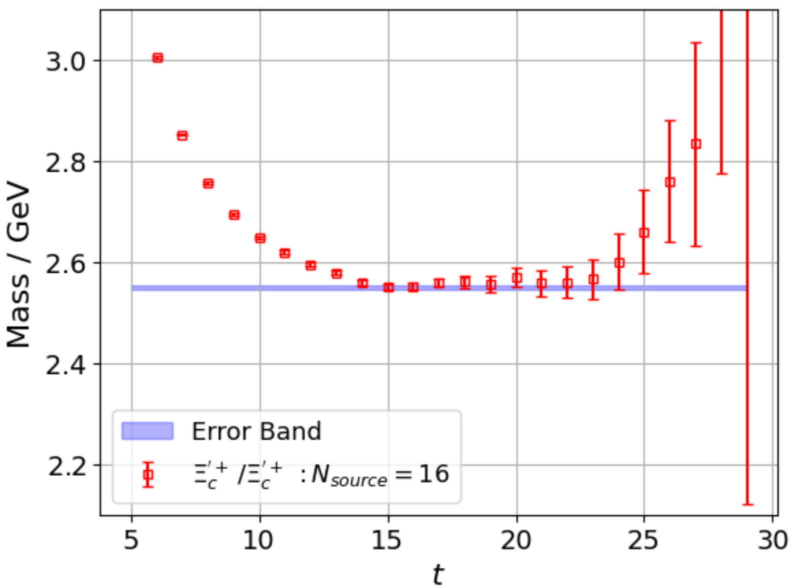


图19、Ξ'^+_c/Ξ'^0_c重子有效质量

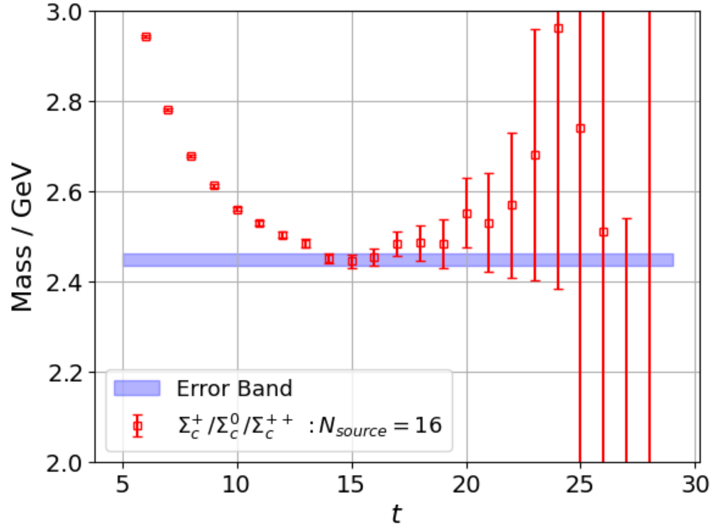


图20、$\Sigma_c^+/\Sigma_c^0/\Sigma_c^{++}$重子有效质量

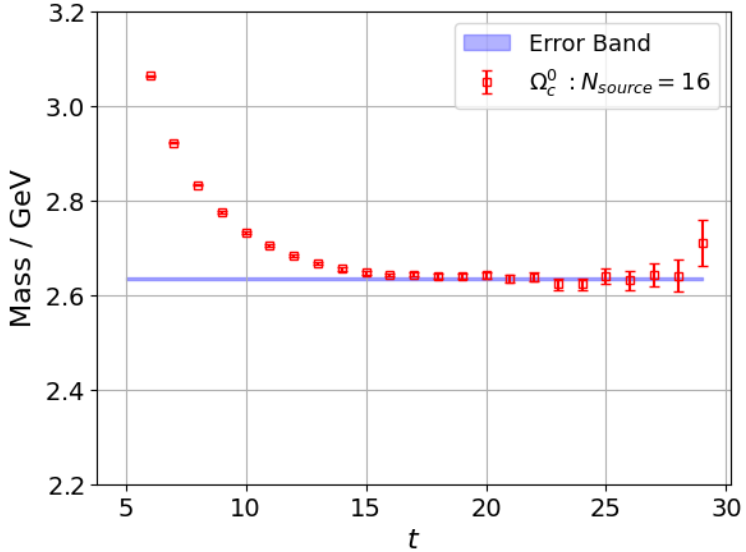


图21、Ω_c^0重子有效质量

C32P29
Ncfg=864
Nsrc=2×10

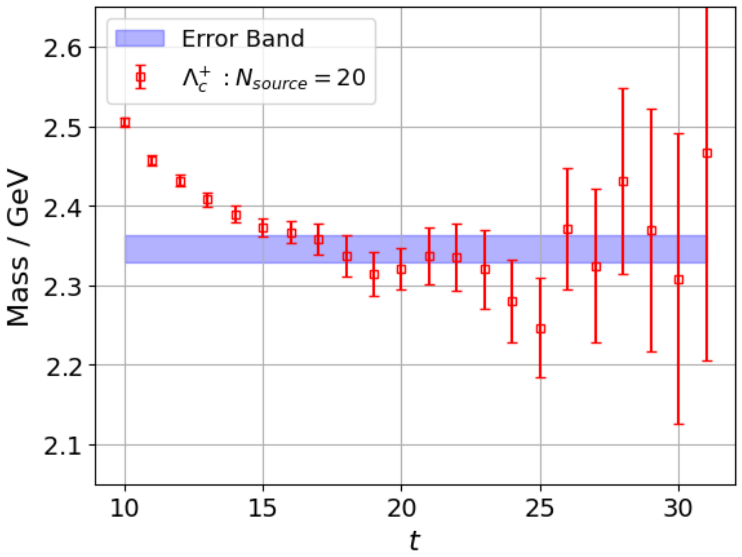


图22、 Λ_c^+重子有效质量

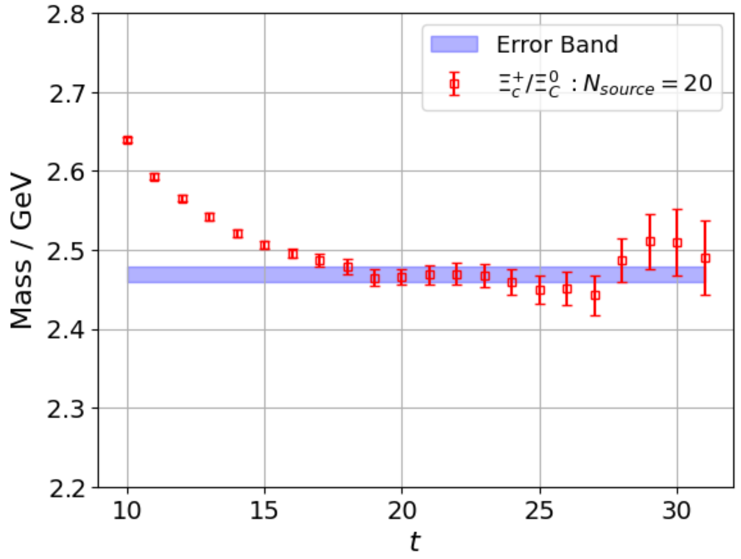


图23、Ξ_c^+/Ξ_c^0重子有效质量

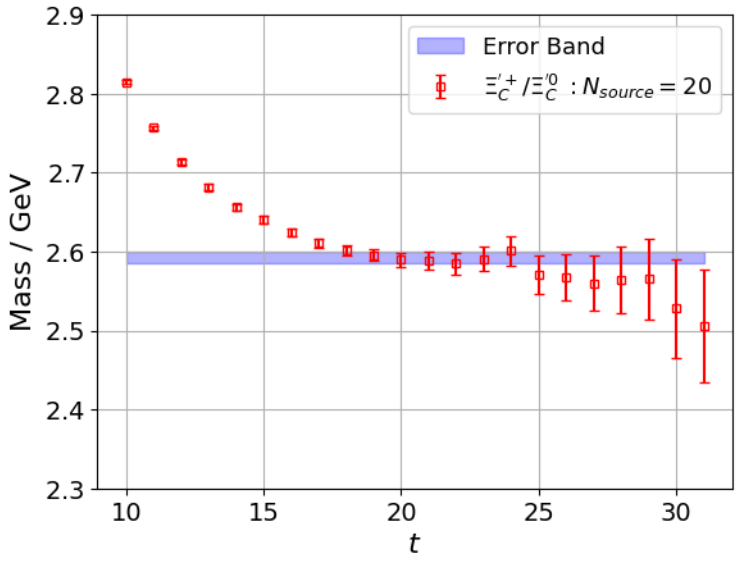


图24、Ξ'^+_c/Ξ'^0_c重子有效质量

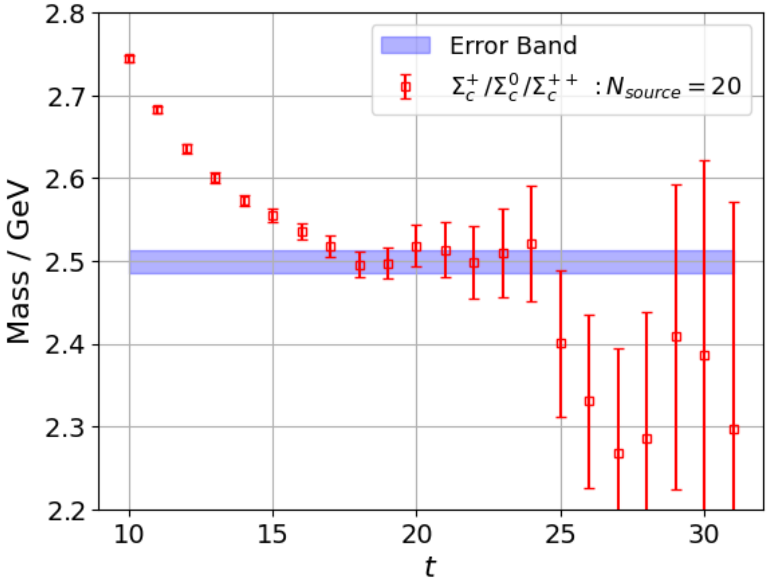


图25、$\Sigma_c^+/\Sigma_c^0/\Sigma_c^{++}$重子有效质量

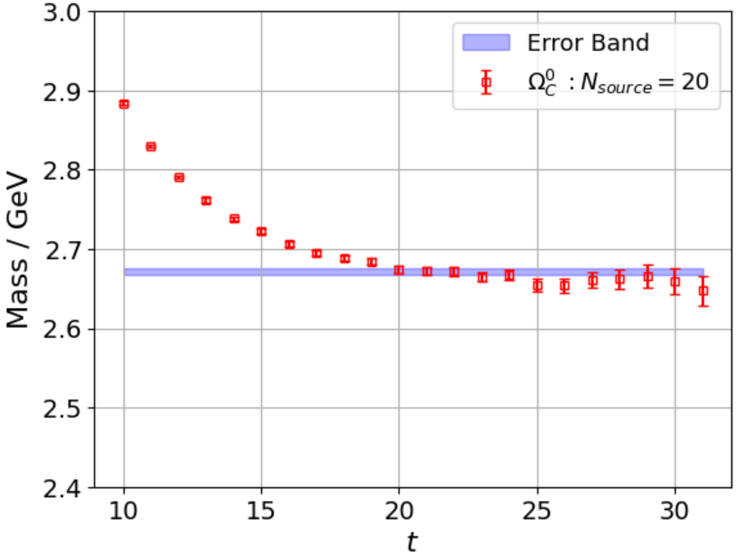


图26、Ω_c^0重子有效质量

F32P30
Ncfg=777
Nsrc=2×10

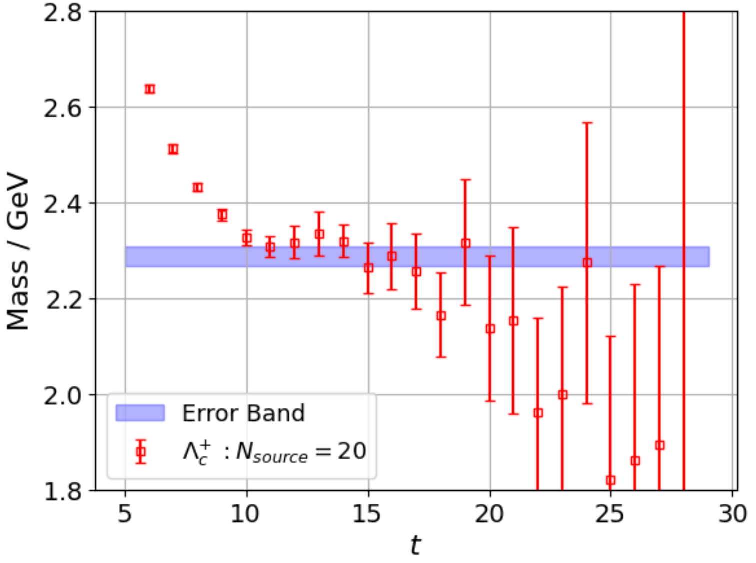


图27、Λ_c^+重子有效质量

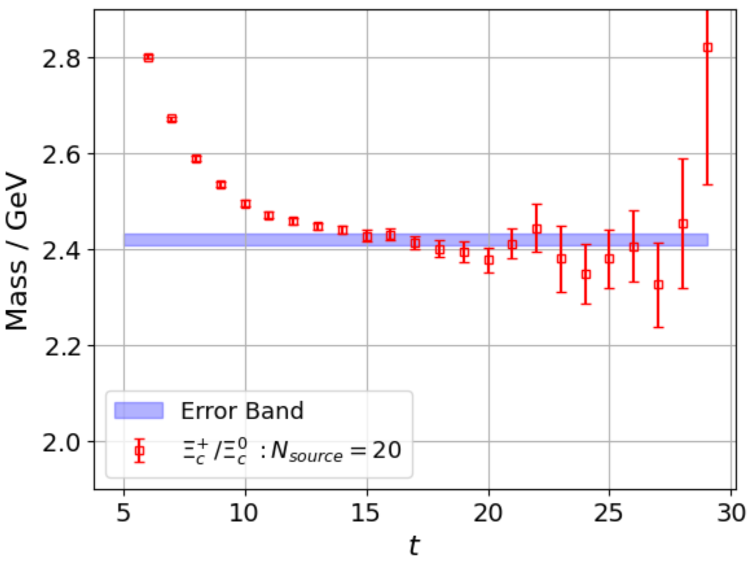


图28、Ξ_c^+/Ξ_c^0重子有效质量

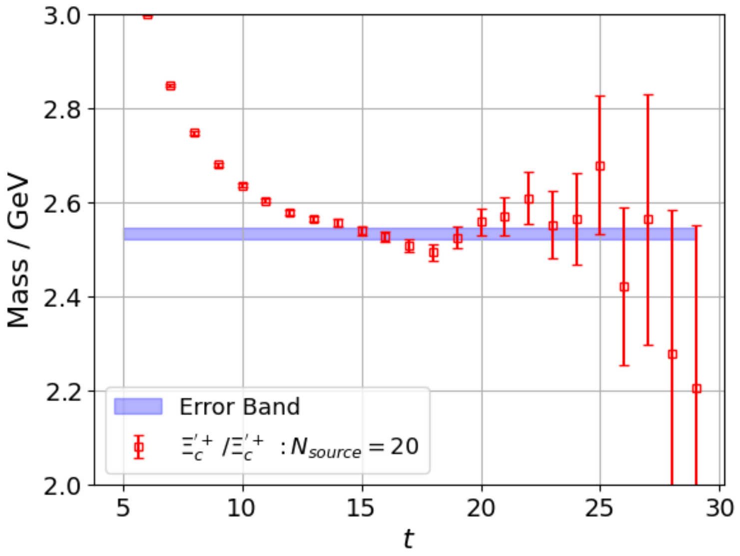


图29、Ξ'^+_c/Ξ'^0_c重子有效质量

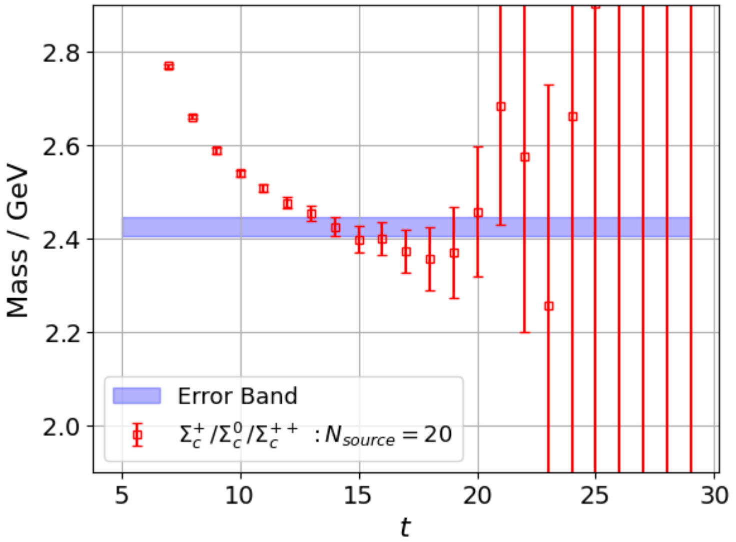


图30、$\Sigma_c^+/\Sigma_c^0/\Sigma_c^{++}$重子有效质量

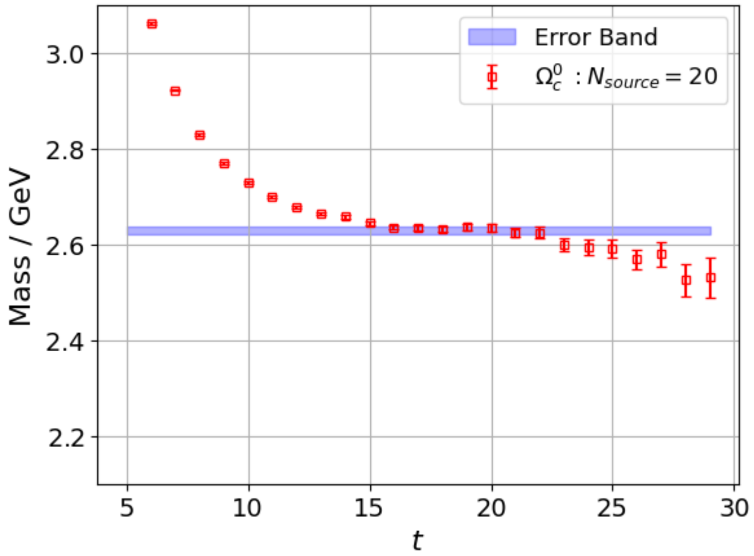


图31、Ω_c^0重子有效质量

C32P23
Ncfg=451
Nsrc=2×10

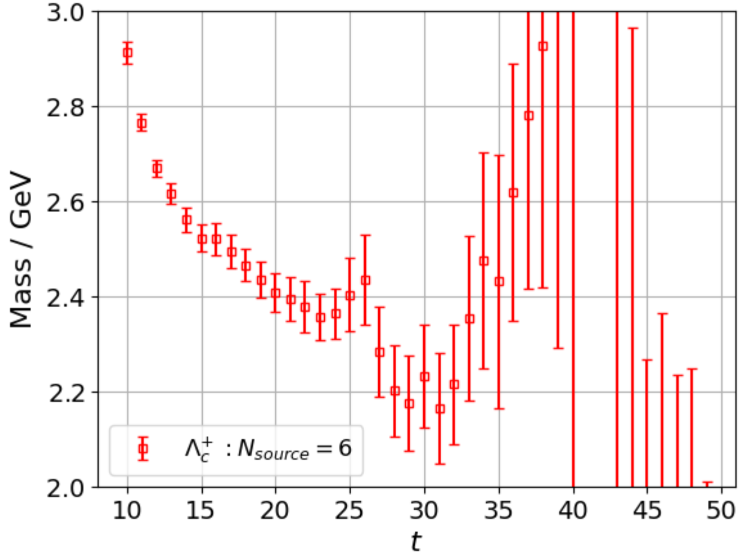


图32、 Λ_c^+重子有效质量

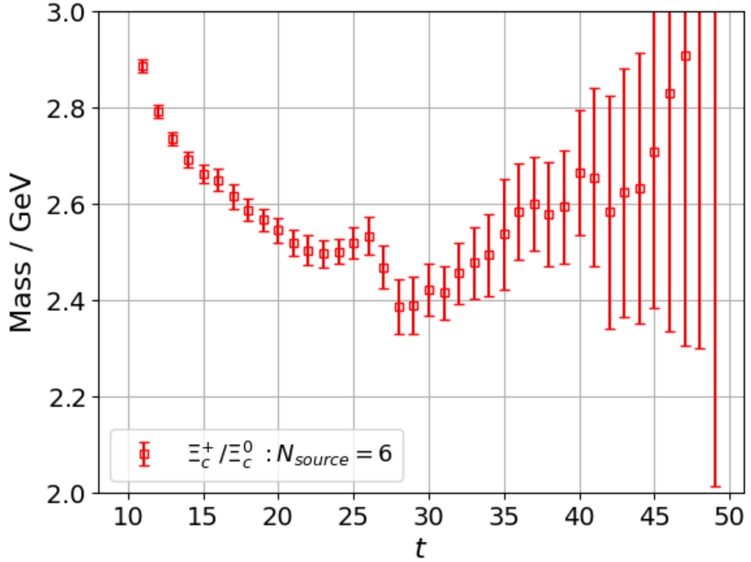


图33、Ξ_c^+/Ξ_c^0重子有效质量

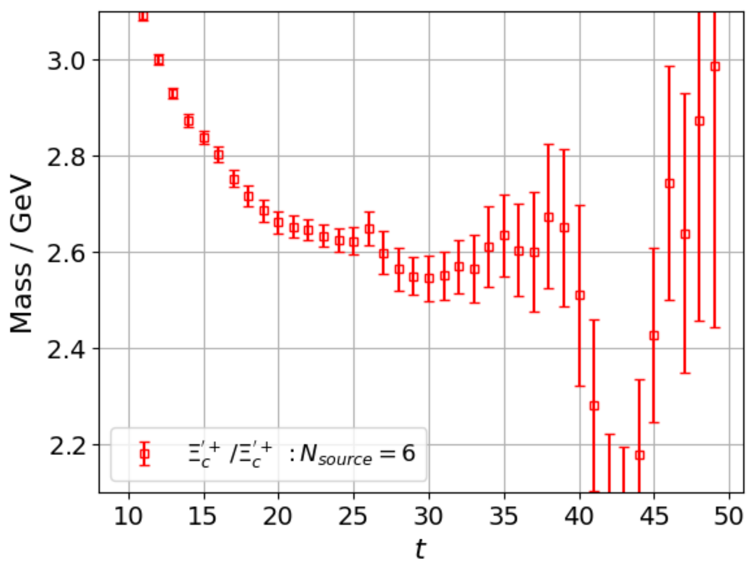


图34、$\Xi_c'^+/\Xi_c'^0$重子有效质量

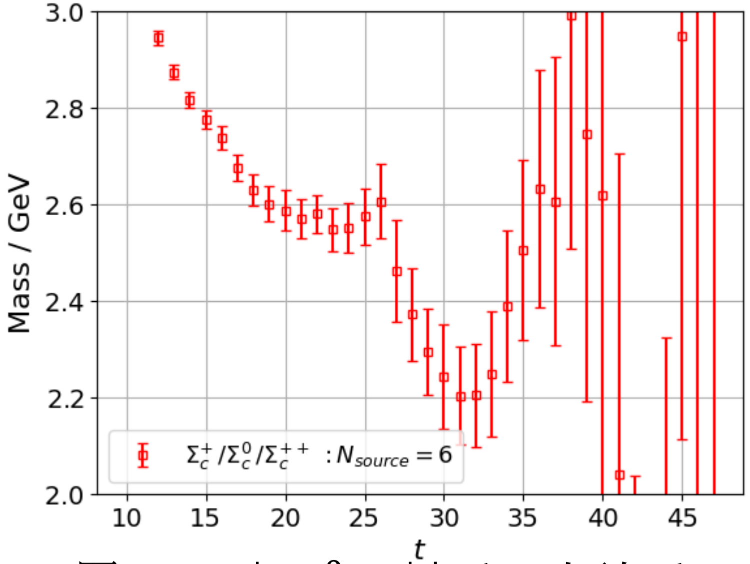


图35、$\Sigma_c^+/\Sigma_c^0/\Sigma_c^{++}$重子有效质量

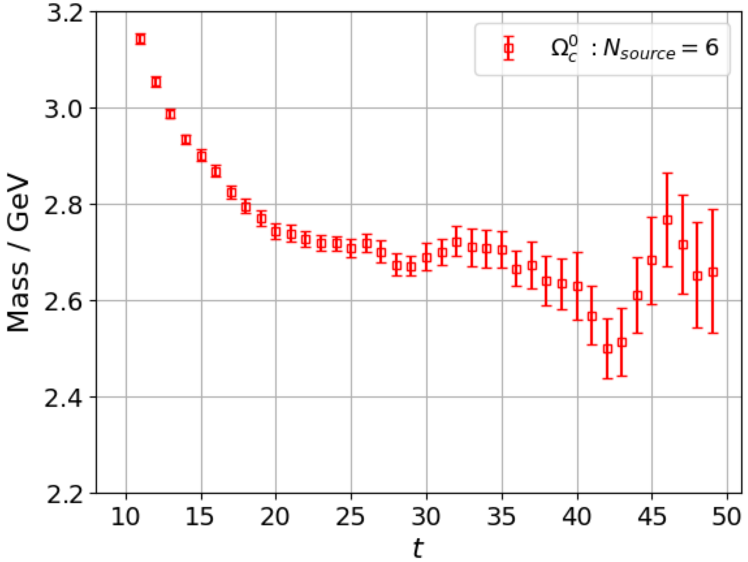


图36、Ω_c^0重子有效质量

H48P32
Ncfg=115
Nsrc=2×3

表3、裸的衰变常数汇总

	Decay constant (bare) $(10^{-2}\mathrm{GeV}^2)$							
Baryon	**C24P29**	**Chi2 / dof**	**C32P29**	**Chi2 / dof**	**F32P30**	**Chi2 / dof**	**H48P32**	**Chi2 / dof**
$\Lambda_c^+(udc)$	1.718 (86)	0.84 [12]	1.690 (63)	0.63 [12]	2.023 (97)	0.32 [8]	2.13 (29)	0.31 [16]
$\Xi_c^+(usc)$	1.753 (64)	1 [12]	1.65 (11)	0.54 [7]	1.978 (60)	0.75 [11]	2.20 (20)	0.33 [15]
$\Xi_c^0(dsc)$	1.753 (64)	1 [12]	1.65 (11)	0.54 [7]	1.978 (60)	0.75 [11]	2.20 (20)	0.33 [15]
$\Xi_c^{\prime +}(usc)$	2.465 (57)	1 [16]	2.544 (48)	1 [22]	2.973 (65)	0.42 [11]	3.39 (22)	0.68 [16]
$\Xi_c^{\prime 0}(dsc)$	2.465 (57)	1 [16]	2.544 (48)	1 [22]	2.973 (65)	0.42 [11]	3.39 (22)	0.68 [16]
$\Sigma_c^+(udc)$	2.16 (13)	1 [8]	2.252 (95)	0.98 [11]	2.68 (11)	0.41 [10]	3.24 (37)	0.46 [14]
$\Sigma_c^0(ddc)$	3.05 (18)	1 [8]	3.18 (13)	0.97 [11]	3.78 (16)	0.41 [10]	4.58 (53)	0.46 [14]
$\Sigma_c^{++}(uuc)$	3.05 (18)	1 [8]	3.18 (13)	0.97 [11]	3.78 (16)	0.41 [10]	4.58 (53)	0.46 [14]
$\Omega_c^0(ssc)$	3.901 (63)	1 [13]	3.896 (59)	0.97 [22]	4.514 (59)	1 [15]	5.31 (40)	0.25 [8]

C24P29：2~6%　　C32P29：2~6%　　F32P30：1~5%　　H48P32：6~16%

C32P23：3~7%

三、粲重子算符的重整化

格点中重子算符重整化的研究最早见于质子衰变[1-4]

$$\mathcal{O}_{RL} = \epsilon_{ijk}(\psi_1^{i\,T} C P_R \psi_2^j) P_L \psi_3^k,$$
$$\mathcal{O}_{LL} = \epsilon_{ijk}(\psi_1^{i\,T} C P_L \psi_2^j) P_L \psi_3^k, \quad (14)$$

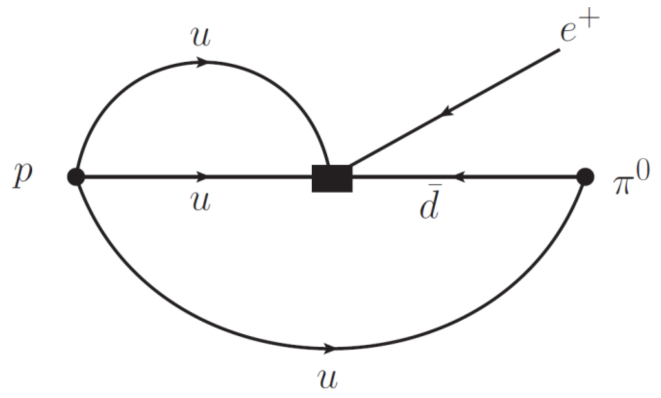


图37、质子衰变的三点关联函数

裸的粲重子算符定义为：

$$O^{(0)} = \epsilon_{ijk}(q_i^{(0)T} C\Gamma_1 q_j^{(0)})\Gamma_2 P_+ c_k^{(0)}, \quad (15)$$

粲重子算符重整化常数为：

$$O = Z_O O^{(0)} \quad (16)$$

【1】S. Aoki et al. [JLQCD], Phys. Rev. D 62, 014506 (2000) [arXiv:hep-lat/9911026 [hep-lat]].

【2】Y. Aoki, C. Dawson, J. Noaki and A. Soni, Phys. Rev. D 75, 014507 (2007) [arXiv:hep-lat/0607002 [hep-lat]].

【3】Y. Aoki, T. Izubuchi, E. Shintani and A. Soni, Phys. Rev. D 96, no.1, 014506 (2017) [arXiv:1705.01338 [hep-lat]].

【4】J. S. Yoo, Y. Aoki, P. Boyle, T. Izubuchi, A. Soni, and S. Syritsyn, Phys. Rev. D 105, 074501 (2022), arXiv:2111.01608 [hep-lat] .

裸的粲重子算符定义为：

$$O^{(0)} = \epsilon_{ijk}(q_i^{(0)T} C\Gamma_1 q_j^{(0)})\Gamma_2 P_+ c_k^{(0)}, \tag{17}$$

定义动量空间的四点格林函数：

$$G^{\alpha\beta\gamma}_{ef,cg}(x, y_1, y_2, y_3) = \langle O_c(x),\ \bar{u}_e^{\alpha}(y_1)\bar{d}_f^{\beta}(y_2)\bar{c}_g^{\gamma}(y_3)\rangle, \tag{18}$$

动量空间的格林函数：

$$G^{\alpha\beta\gamma}_{ef,cg}(p_1, p_2, p_3) = -\sum_{y_1 y_2 y_3}\sum_{x} e^{-ik\cdot x} e^{i(p_1\cdot y_1 + p_2\cdot y_2 + p_3\cdot y_3)} \times \epsilon_{\alpha'\beta'\gamma'} S^{(u),\alpha'\alpha}_{ae}(x, y_1)(C\gamma_5 S^{(d)})^{\beta'\beta}_{af}(x, y_2)(P_+ S^{(c)})^{\gamma'\gamma}_{cg}(x, y_3). \tag{19}$$

构建截断格林函数：

$$\Lambda^{\alpha'\beta'\gamma'}_{xy,cz}(p_1, p_2, p_3) = G^{\alpha\beta\gamma}_{ef,cg}(p_1, p_2, p_3) \times S^{(u),\alpha\alpha'-1}_{ex}(p_1) S^{(d),\beta\beta'-1}_{fy}(p_2) S^{(c),\gamma\gamma'-1}_{gz}(p_3), \tag{20}$$

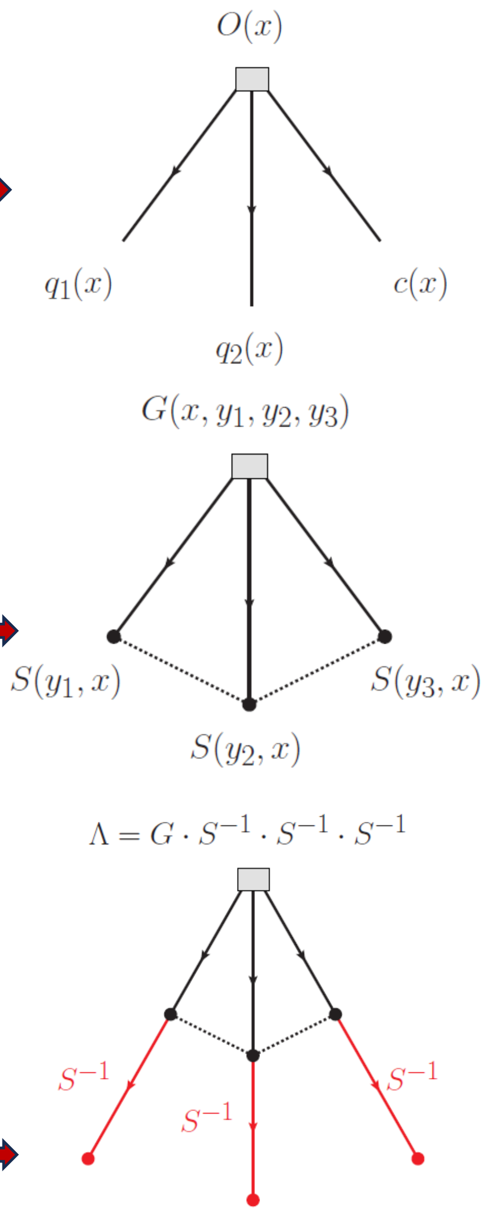


图38. 重整化流程

截断格林函数的投影矩阵定义为：

$$\text{赝标流：}\quad P^{\mu\nu\rho}_{yx,zc} = \frac{1}{48}\epsilon_{\mu\nu\rho}(\gamma_5 C^{-1})_{yx}(P_+)_{zc},$$
$$\text{矢量流：}\quad P^{\mu\nu\rho}_{yx,zc} = \frac{1}{192}\epsilon_{\mu\nu\rho}(\gamma_\mu C^{-1})_{yx}(\gamma_5\gamma_\mu P_+)_{zc}. \tag{21}$$

SMOM的重整化条件为：

$$Z_O Z_l^{-3/2}\Gamma(p_1,p_2,p_3)\Big|_{p_1^2=p_2^2=p_3^2=\mu^2} = 1. \tag{22}$$

动量满足：

$$p_1^2 = p_2^2 = p_3^2 = (p_1+p_2+p_3)^2 \tag{23}$$

测试结果：$Z_O|_{p_1^2=p_2^2=p_3^2=9} = 0.615661$

程序实现：国产软件 **Pyquda**

未来 benchmark：**Chroma**

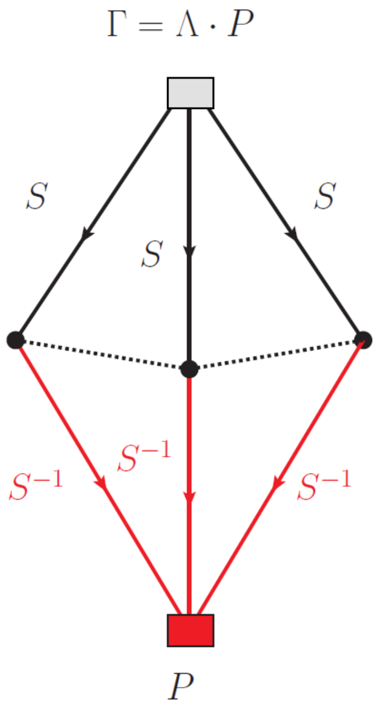


图39. 顶点函数 Γ

四、小结

- 构造粲重子算符
- 衰变常数计算精度大部分到达5%
- 粲重子算符的重整化测试

接下来：

- 计算不同pion介子质量的组态
- 做格距和手征极限外推
- 最终得到物理的衰变常数

谢谢

附录

粲重子内插流算符:

$$O_{\mathrm{B}}^{(\boldsymbol{\Gamma})} = \epsilon_{ijk}(q_i^T C\boldsymbol{\Gamma} q_j)\Gamma' q_k \quad (1)$$

其中，di-quark中的Γ矩阵为:

$$\begin{aligned}\boldsymbol{\Gamma} &= \{\,1,\ \gamma_5,\ \gamma_\mu,\ \gamma_5\gamma_\mu,\ \sigma_{\mu\nu}\,\} \\ &\Rightarrow \{\,S,\ P,\ V,\ A,\ T\,\}\end{aligned} \quad (2)$$

表1、QCD sum rule 中的粲重子内插流算符

	$\Lambda_c^+(udc)$	文献
赝标	$O_{\Lambda_c^+}^{(P)} = \epsilon_{ijk}(u_i^T C\gamma_5 d_j)c_k$	【1,2】
标量	$O_{\Lambda_c^+}^{(S)} = \epsilon_{ijk}(u_i^T Cd_j)\,\gamma_5 c_k$	【1,2】
轴矢	$O_{\Lambda_c^+}^{(A)} = \epsilon_{ijk}(u_i^T C\gamma_5\gamma_\mu d_j)\,\gamma^\mu c_k$	【1,2】

	$\Omega_c^0(ssc)$	文献
矢量	$O_{\Omega_c^0}^{(V)} = \epsilon_{ijk}(s_i^T C\gamma_\mu s_j)\,\gamma^\mu\gamma_5 c_k$	【5】

	$\Xi_c(usc/dsc)$	文献
矢量	$O_{\Xi_c}^{(V)} = \epsilon_{ijk}(s_i^T C\gamma_\mu c_j)\,\gamma^\mu\gamma_5 q_k$	【3】
混合	$O_{\Xi_c} = 2\beta O_{\Xi_c}^{(S)} + 2\beta O_{\Xi_c}^{(P)} + \cdots$	【4】

	$\Sigma_c^+(udc)$	文献
矢量	$O_{\Sigma_c^+}^{(V)} = \epsilon_{ijk}(u_i^T C\gamma_\mu d_j)\,\gamma^\mu\gamma_5 c_k$	【1】
张量	$O_{\Sigma_c^+}^{(T)} = \epsilon_{ijk}(u_i^T C\sigma_{\mu\nu} d_j)\sigma^{\mu\nu}\gamma_5 c_k$	【1】

根据P宇称和洛伦兹协变性，写下1/2⁺粲重子内插流算符：

$$
\begin{aligned}
O_{\mathcal{B}}^{(S)} &= \epsilon_{ijk}(q_i^T C q_j)\gamma_5 c_k \\
O_{\mathcal{B}}^{(P)} &= \epsilon_{ijk}(q_i^T C\gamma_5 q_j) c_k \\
O_{\mathcal{B}}^{(V)} &= \epsilon_{ijk}(q_i^T C\gamma_\mu q_j)\gamma^\mu\gamma_5 c_k \\
O_{\mathcal{B}}^{(A)} &= \epsilon_{ijk}(q_i^T C\gamma_5\gamma_\mu q_j)\gamma^\mu c_k \\
O_{\mathcal{B}}^{(T)} &= \epsilon_{ijk}(q_i^T C\sigma_{\mu\nu} q_j)\sigma^{\mu\nu}\gamma_5 c_k
\end{aligned}
\qquad (3)
$$

考虑[ud]夸克构成的di-quark结构，根据同位旋 SU(2) 对称性【1】：

单态：
(反对称)

$$
\left.\begin{aligned}
O_{\mathcal{B}}^{(P)} &= \frac{1}{2}\left[\epsilon_{ijk}(u_i^T C\gamma_5 d_j)c_k - \epsilon_{ijk}(d_i^T C\gamma_5 u_j)c_k\right] \\
O_{\mathcal{B}}^{(S)} &= \frac{1}{2}\left[\epsilon_{ijk}(u_i^T C d_j)\gamma_5 c_k - \epsilon_{ijk}(d_i^T C u_j)\gamma_5 c_k\right] \\
O_{\mathcal{B}}^{(A)} &= \frac{1}{2}\left[\epsilon_{ijk}(u_i^T C\gamma_5\gamma^\mu d_j)\gamma_\mu c_k - \epsilon_{ijk}(d_i^T C\gamma_5\gamma^\mu u_j)\gamma_\mu c_k\right]
\end{aligned}\right\} \Lambda_c
$$

三重态：
(对称)

$$
\left.\begin{aligned}
O_{\mathcal{B}}^{(V)} &= \frac{1}{2}\left[\epsilon_{ijk}(u_i^T C\gamma_\mu d_j)\gamma^\mu\gamma_5 c_k + \epsilon_{ijk}(d_i^T C\gamma_\mu u_j)\gamma^\mu\gamma_5 c_k\right] \\
O_{\mathcal{B}}^{(T)} &= \frac{1}{2}\left[\epsilon_{ijk}(u_i^T C\sigma_{\mu\nu} d_j)\sigma^{\mu\nu}\gamma_5 c_k + \epsilon_{ijk}(d_i^T C\sigma_{\mu\nu} u_j)\sigma^{\mu\nu}\gamma_5 c_k\right]
\end{aligned}\right\} \Sigma_c
$$

(4)

根据 SU(3) 对称性 $3 \otimes 3 = \bar{3} \oplus 6$：

$$
\bar{3}: \begin{cases}
O_{\Lambda_c^+} = \epsilon_{ijk}(u_i^T C\gamma_5 d_j)c_k \\
O_{\Xi_c^+} = \epsilon_{ijk}(u_i^T C\gamma_5 s_j)c_k \\
O_{\Xi_c^0} = \epsilon_{ijk}(d_i^T C\gamma_5 s_j)c_k
\end{cases} \qquad (5)
$$

$$
6: \begin{cases}
O_{\Xi_c'^+} = \epsilon_{ijk}(u_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k \\
O_{\Xi_c'^0} = \epsilon_{ijk}(d_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k \\
O_{\Sigma_c^0} = \epsilon_{ijk}(d_i^T C\gamma_\mu d_j)\gamma^\mu\gamma_5 c_k \\
O_{\Sigma_c^+} = \epsilon_{ijk}(u_i^T C\gamma_\mu d_j)\gamma^\mu\gamma_5 c_k \\
O_{\Sigma_c^{++}} = \epsilon_{ijk}(u_i^T C\gamma_\mu u_j)\gamma^\mu\gamma_5 c_k \\
O_{\Omega_c^0} = \epsilon_{ijk}(s_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k
\end{cases} \qquad (6)
$$

给出常用的粲重子算符

【1】 A. Khodjamirian, C.Klein, T.Mannel and Y.M.Wang, ``Form Factors and Strong Couplings of Heavy Baryons from QCD Light-Cone Sum Rules,‘’ JHEP 09, 106 (2011) doi:10.1007/JHEP09(2011)106 [arXiv:1108.2971 [hep-ph]].

【2】 Y. Miao, H. Deng, K. S. Huang, J. Gao and Y. L. Shen, ``Lambda_{b} \rightarrow \Lambda_{c} form factors from QCD light-cone sum rules," Chin. Phys. C 46, no.11, 113107 (2022) doi:10.1088/1674-1137/ac8652 [arXiv:2206.12189 [hep-ph]].

【3】 H.H.Duan, Y.L.Liu and M.Q.Huang, ``Semileptonic decay of $\Xi_c->\Xi \ell+\nu \ell$ from light-cone QCD sum rules," Phys. Rev. D 106, no.9, 096011 (2022) doi:10.1103/PhysRevD.106.096011 [arXiv:2201.03802 [hep-ph]].

【4】 T.M.Aliev, S. Bilmis and M.Savci, ``Semileptonic \Xic baryon decays in the light cone QCD sum rules," Phys. Rev. D 104, no.5, 054030 (2021) doi:10.1103/PhysRevD.104.054030 [arXiv:2108.01378 [hep-ph]].

【5】 H. H. Duan, Y. L. Liu and M.~Q. ~Huang, ``Semileptonic decay of $\Omega_c^0 \to \Xi^- l^+ \nu_l$ from light-cone sum rules," Eur. Phys. J. C 81, no.2, 168 (2021) doi:10.1140/epjc/s10052-021-08956-6 [arXiv:2010.16176 [hep-ph]].

测试投影算符$\boldsymbol{P_+}$对2pt的影响

Meinel:　1409.0497　粲重子谱，带P_+

　　　　2309.08107　$\Xi_c \to \Xi l\nu$，不带P_+

重子	组态	Source	N_conf	$L^3 \times T$
Λ_c^+	C24P29	Wall	10000	$24^3 \times 72$

Λ_c内插流算符：$O_{\Lambda_c} = \epsilon_{ijk}(u_i^T C\gamma_5 d_j)c_k$

$$O_{\Lambda_c}^{P+} = \epsilon_{ijk}(u_i^T C\gamma_5 d_j)P_+ c_k \qquad (7)$$

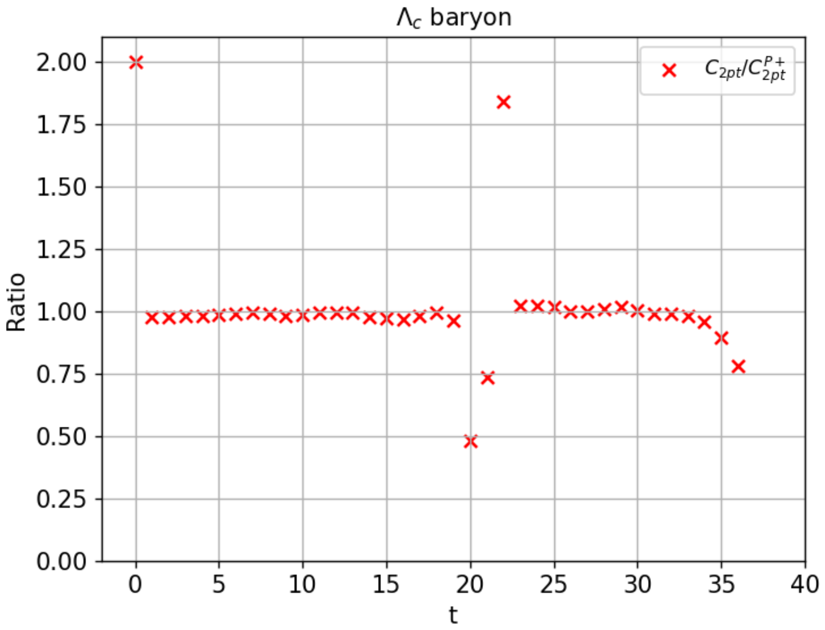


图1、第10000号组态比值C_{2pt}/C_{2pt}^{P+}

10000	0	0	3.18794e+05	-8270.03315
10000	0	1	8.54447e+04	-6884.05809
10000	0	2	2.58299e+04	-2000.06164
10000	0	3	7550.81071	-268.93099
10000	0	4	2217.98503	-19.91093
10000	0	5	707.30537	35.80540
10000	0	6	228.92450	19.20698
10000	0	7	66.67460	-1.00642
10000	0	8	17.98828	-2.64714
10000	0	9	4.88886	-1.32012
10000	0	10	1.30097	-0.44879
10000	0	11	0.31359	-0.13822
10000	0	12	0.07606	-0.04675
10000	0	13	0.02573	-0.01866
10000	0	14	0.01169	-0.00891
10000	0	15	0.00363	-0.00410
10000	0	16	0.00103	-0.00144
10000	0	17	3.30608e-04	-4.19329e-04
10000	0	18	8.34951e-05	-1.30992e-04
10000	0	19	1.79941e-05	-5.26028e-05
10000	0	20	1.66272e-06	-2.75526e-05

O_{Λ_c} 算符2pt

10000	1	0	6.37392e+05	-1.58875e+04
10000	1	1	8.33204e+04	-6558.06473
10000	1	2	2.52279e+04	-1904.83656
10000	1	3	7400.42151	-258.15850
10000	1	4	2178.60689	-23.29129
10000	1	5	697.76083	31.93488
10000	1	6	226.78921	17.97826
10000	1	7	66.33036	-1.08922
10000	1	8	17.84232	-2.69967
10000	1	9	4.80980	-1.34682
10000	1	10	1.28326	-0.46274
10000	1	11	0.31191	-0.14617
10000	1	12	0.07579	-0.04851
10000	1	13	0.02560	-0.01921
10000	1	14	0.01142	-0.00905
10000	1	15	0.00353	-0.00412
10000	1	16	9.99298e-04	-0.00144
10000	1	17	3.24858e-04	-4.21833e-04
10000	1	18	8.29435e-05	-1.35590e-04
10000	1	19	1.73715e-05	5.45837e-05
10000	1	20	7.97996e-07	-2.84549e-05

$O_{\Lambda_c}^{P+}$ 算符2pt

【6】Z.S. Brown, W.Detmold, S. Meinel and K.Orginos, ``Charmed bottom baryon spectroscopy from lattice QCD," Phys. Rev. D 90, no.9, 094507 (2014) doi:10.1103/PhysRevD.90.094507 [arXiv:1409.0497 [hep-lat]].

【7】C.Farrell and S.Meinel, ``Form factors for the charm-baryon semileptonic decay $\Xi_c\to \Xi \ell \nu$ from domain-wall lattice QCD," PoS LATTICE2023, 210 (2024) doi:10.22323/1.453.0210 [arXiv:2309.08107 [hep-lat]].

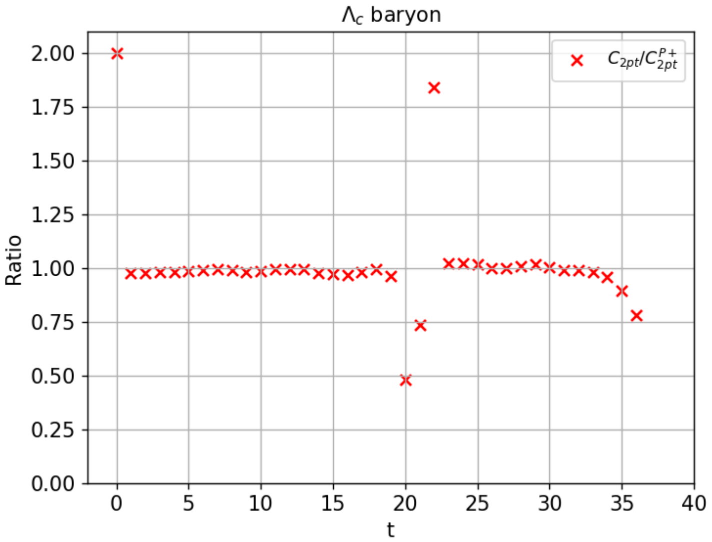


图2、第10000号组态2pt比值

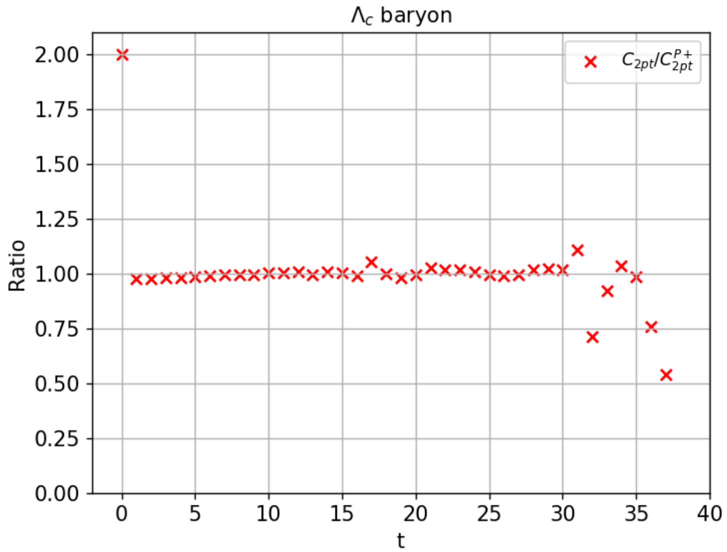


图3、第10100号组态2pt比值

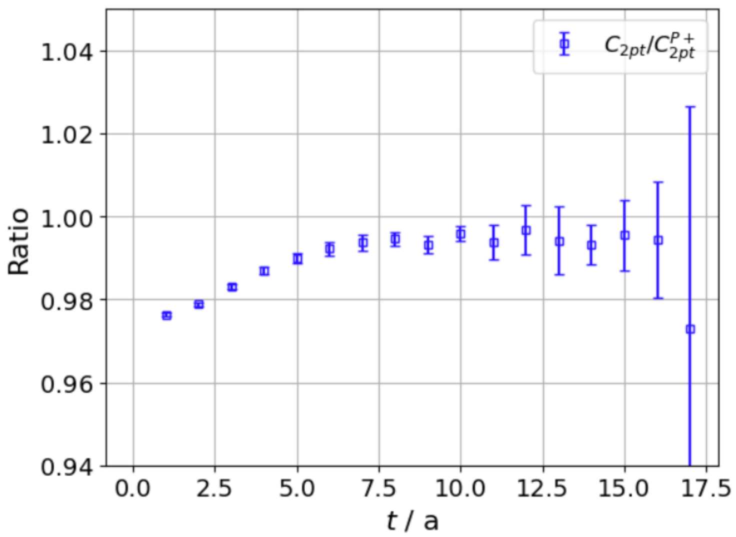


图4、 C_{2pt}/C_{2pt}^{P+}(20个组态)

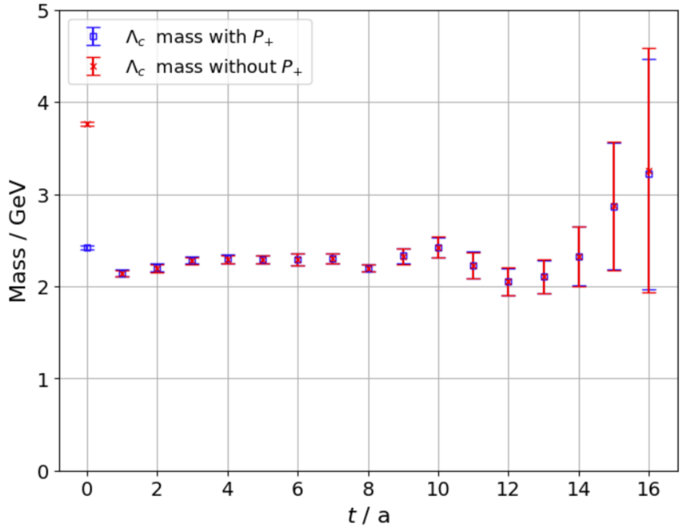


图5、两种不同算符的有效质量平台

P_+在t小的时候对C2pt数值存在影响；

t越大激发态贡献越小，趋近于基态；

对有效质量的影响很小。

表2、C32P29拟合结果

C32P29	Mass (GeV)		Decay constant (bare) ($10^{-2}\mathrm{GeV}^2$)	Chi2 / dof [dof]
Baryon	**This work**	**PDG**	**This work (bare)**	**This work**
$\Lambda_c^+(udc)$	2.311 (12)	2.286	1.690 (63)	0.63 [12]
$\Xi_c^+(usc)$	2.430 (14)	2.467	1.65 (11)	0.54 [7]
$\Xi_c^0(dsc)$	2.430 (14)	2.470	1.65 (11)	0.54 [7]
$\Xi_c^{\prime +}(usc)$	2.5497 (54)	2.578	2.544 (48)	1 [22]
$\Xi_c^{\prime 0}(dsc)$	2.5497 (54)	2.579	2.544 (48)	1 [22]
$\Sigma_c^+(udc)$	2.448 (12)	2.453	2.252 (95)	0.98 [11]
$\Sigma_c^0(ddc)$	2.448 (12)	2.454	3.18 (13)	0.97 [11]
$\Sigma_c^{++}(uuc)$	2.448 (12)	2.454	3.18 (13)	0.97 [11]
$\Omega_c^0(ssc)$	2.6351 (36)	2.695	3.896 (59)	0.97 [22]

表3、H48P32拟合结果

H48P32	**Mass (GeV)**		**Decay constant (bare) ($10^{-2}\mathrm{GeV}^2$)**	**Chi2 / dof [dof]**
Baryon	**This work**	**PDG**	**This work (bare)**	**This work**
$\Lambda_c^+(udc)$	2.357 (51)	2.286	2.13 (29)	0.31 [16]
$\Xi_c^+(usc)$	2.483 (31)	2.467	2.20 (20)	0.33 [15]
$\Xi_c^0(dsc)$	2.483 (31)	2.470	2.20 (20)	0.33 [15]
$\Xi_c'^+(usc)$	2.619 (25)	2.578	3.39 (22)	0.68 [16]
$\Xi_c'^0(dsc)$	2.619 (25)	2.579	3.39 (22)	0.68 [16]
$\Sigma_c^+(udc)$	2.552 (47)	2.453	3.24 (37)	0.46 [14]
$\Sigma_c^0(ddc)$	2.552 (47)	2.454	4.58 (53)	0.46 [14]
$\Sigma_c^{++}(uuc)$	2.552 (47)	2.454	4.58 (53)	0.46 [14]
$\Omega_c^0(ssc)$	2.705 (24)	2.695	5.31 (40)	0.25 [8]

表4、F32P30拟合结果

F32P30	Mass (GeV)		Decay constant (bare) ($10^{-2}\mathrm{GeV}^2$)	Chi2 / dof [dof]
Baryon	**This work**	**PDG**	**This work (bare)**	**This work**
$\Lambda_c^+(udc)$	2.360 (17)	2.286	2023 (97)	0.32 [8]
$\Xi_c^+(usc)$	2.4692 (94)	2.467	1.978 (60)	0.75 [11]
$\Xi_c^0(dsc)$	2.4692 (94)	2.470	1.978 (60)	0.75 [11]
$\Xi_c'^+(usc)$	2.5923 (69)	2.578	2.973 (65)	0.42 [11]
$\Xi_c'^0(dsc)$	2.5923 (69)	2.579	2.973 (65)	0.42 [11]
$\Sigma_c^+(udc)$	2.499 (14)	2.453	2.68 (11)	0.41 [10]
$\Sigma_c^0(ddc)$	2.499 (14)	2.454	3.78 (16)	0.41 [10]
$\Sigma_c^{++}(uuc)$	2.499 (14)	2.454	3.78 (16)	0.41 [10]
$\Omega_c^0(ssc)$	2.6711 (39)	2.695	4.514 (59)	1 [15]

表5、C32P23拟合结果

C32P23	Mass (GeV)		Decay constant (bare) $(10^{-2}\mathrm{GeV}^2)$	Chi2 / dof [dof]
Baryon	This work	PDG	This work (bare)	This work
$\Lambda_c^+(udc)$	2.286 (20)	2.286	1.710 (96)	0.21 [9]
$\Xi_c^+(usc)$	2.421 (12)	2.467	1.662 (76)	0.34 [11]
$\Xi_c^0(dsc)$	2.421 (12)	2.470	1.662 (76)	0.34 [11]
$\Xi_c'^+(usc)$	2.5431 (86)	2.578	2.534 (74)	0.36 [8]
$\Xi_c'^0(dsc)$	2.5431 (86)	2.579	2.534 (74)	0.36 [8]
$\Sigma_c^+(udc)$	2.426 (21)	2.453	2.17 (15)	0.45 [9]
$\Sigma_c^0(ddc)$	2.426 (21)	2.454	3.07 (22)	0.45 [9]
$\Sigma_c^{++}(uuc)$	2.426 (21)	2.454	3.07 (22)	0.45 [9]
$\Omega_c^0(ssc)$	2.6290 (79)	2.695	3.79 (14)	1 [9]