重味重子物理研究的机遇

于福升

兰州大学

感谢常老师、孙老师、陈老师邀请！

河南师范大学，2022.05.27

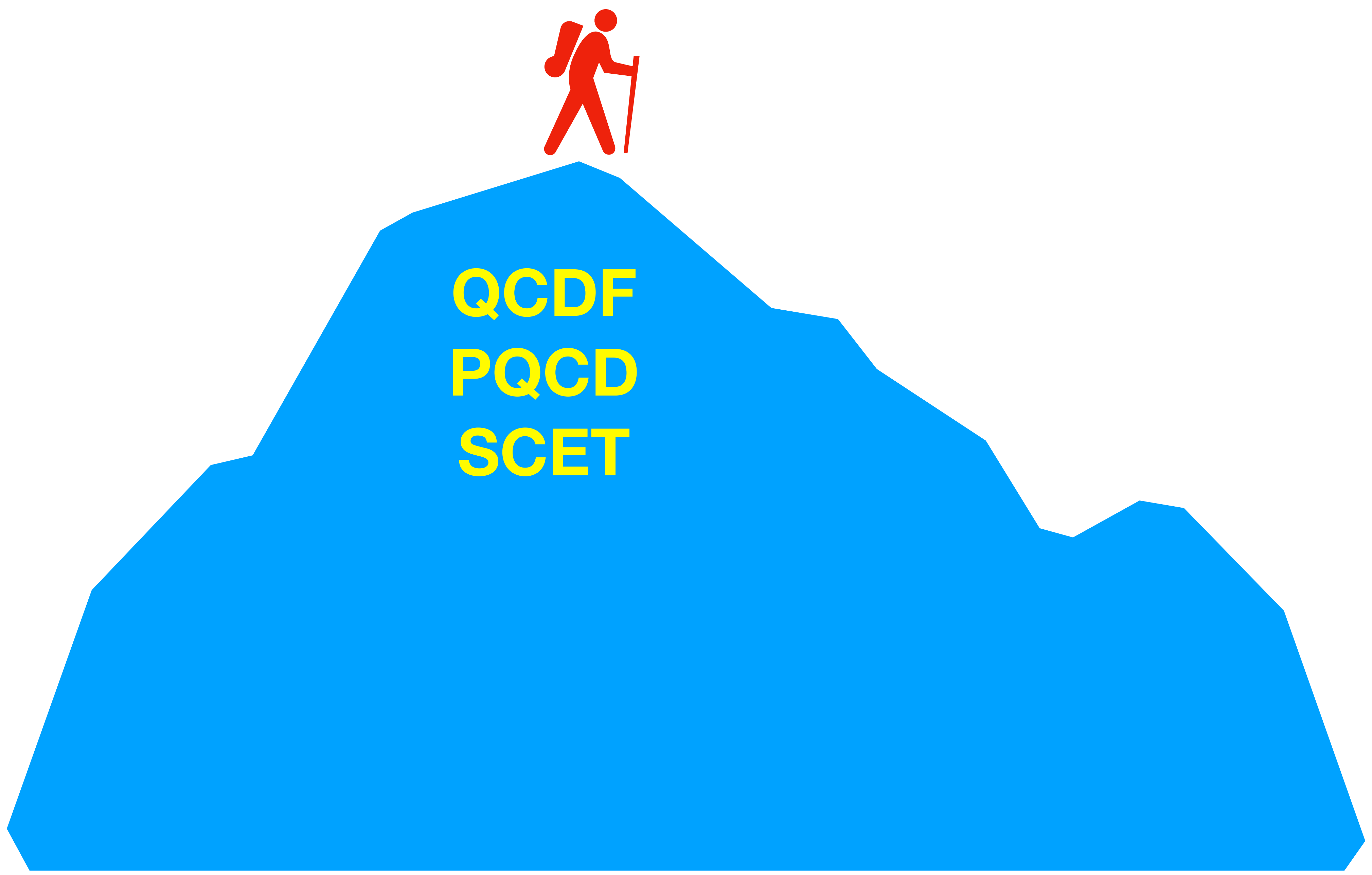
Outline

- Why baryon physics?
- Opportunities of baryon physics
- Recent progresses: PQCD, LCSR
- Outlooks: LCDA
- Summary

1999

my talk @ PQCD meeting, Guangzhou, 2019

B physics



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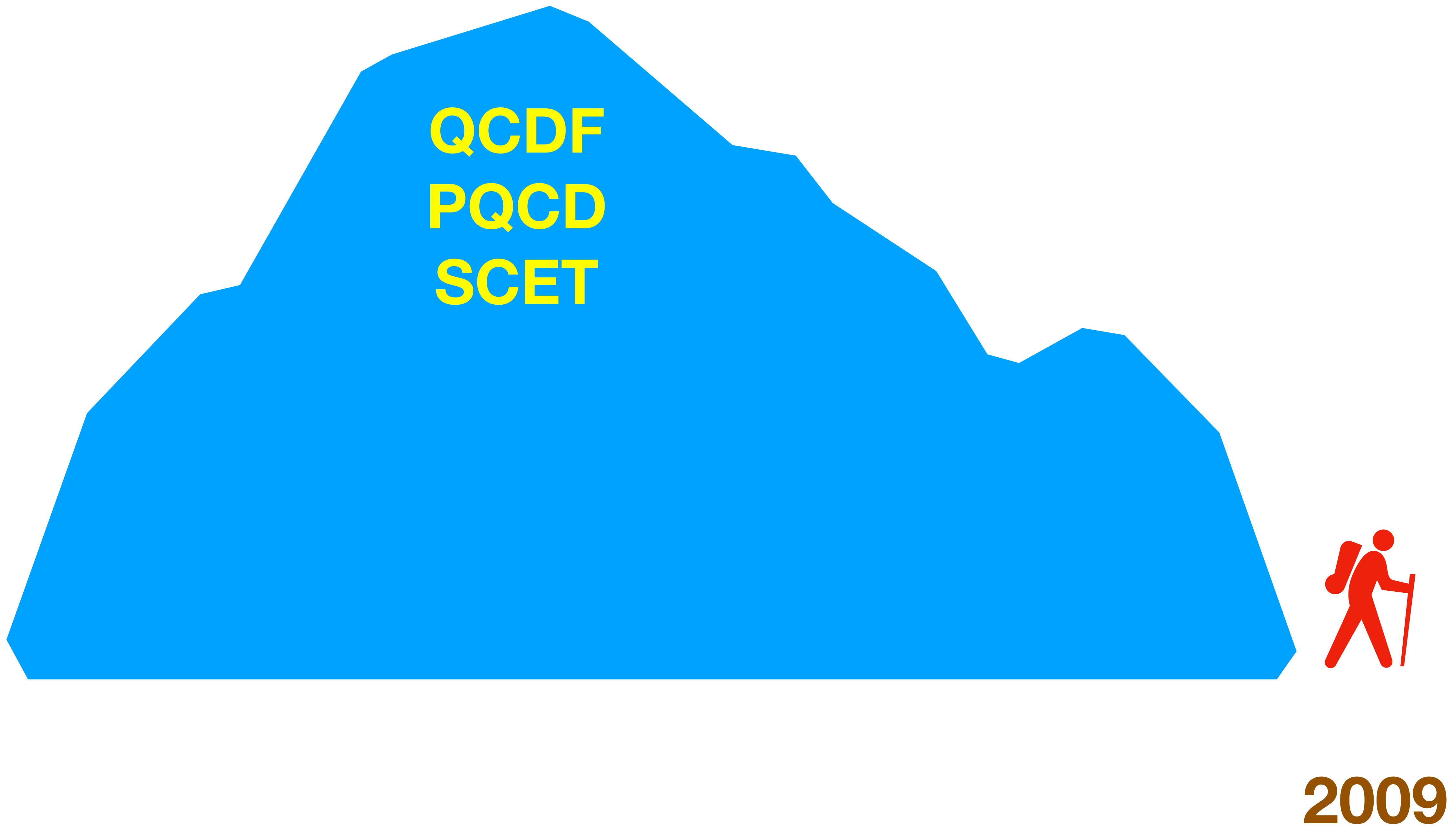

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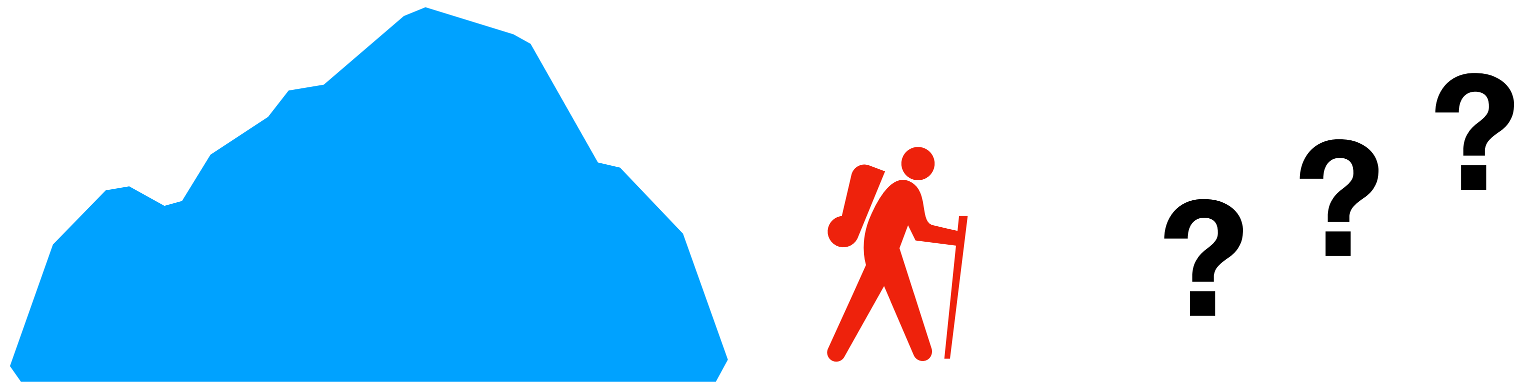

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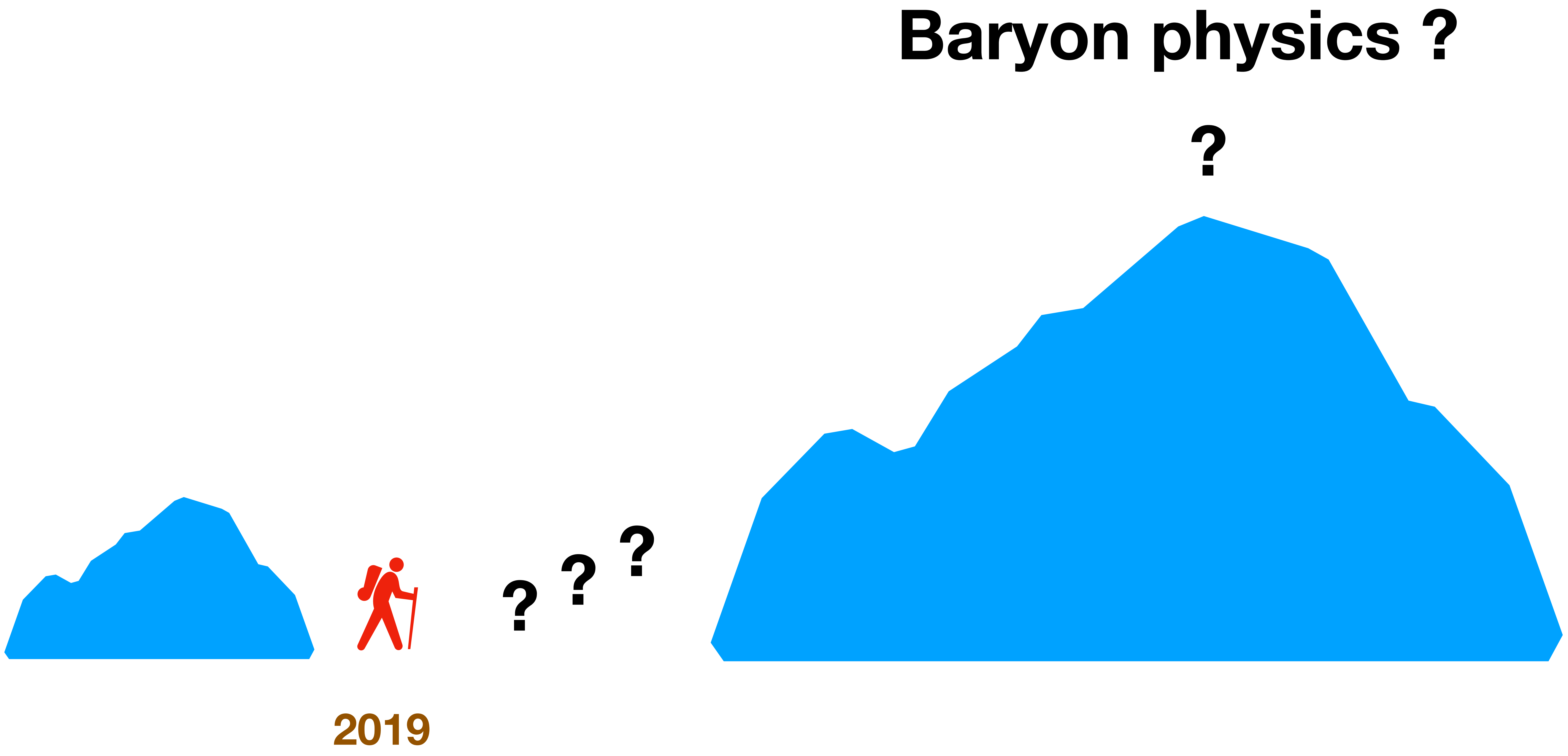

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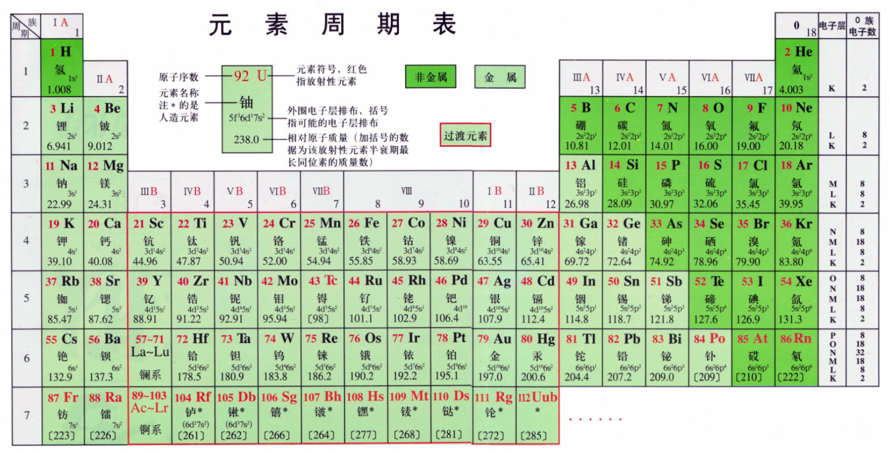
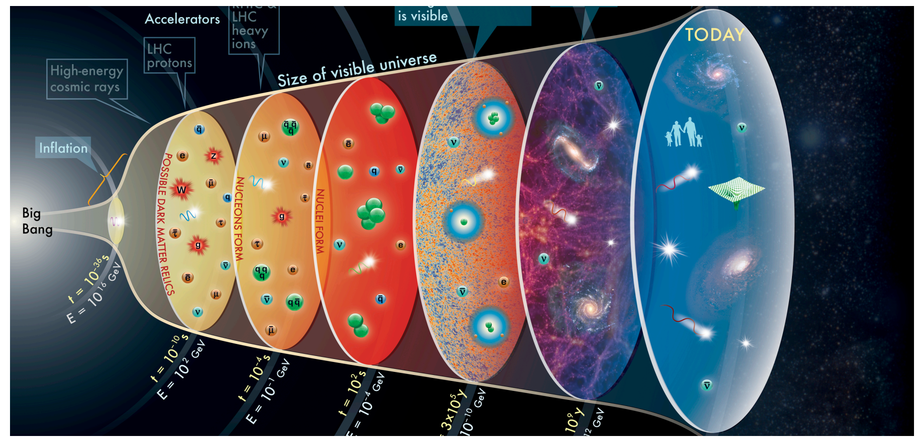
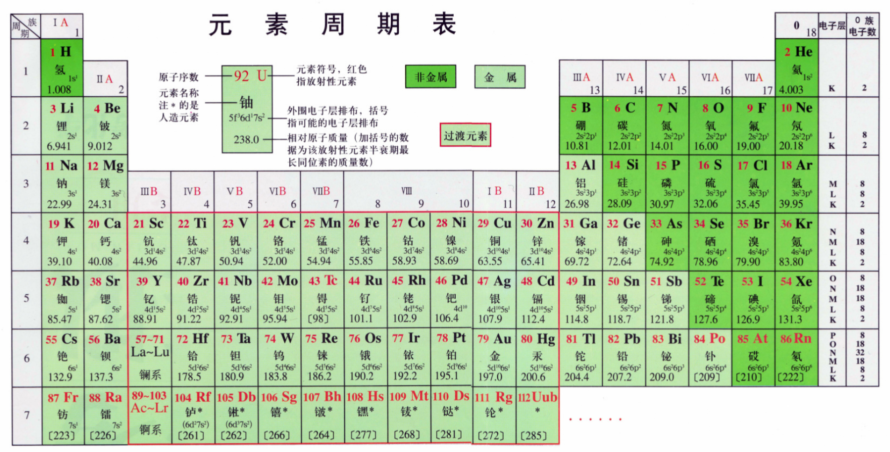
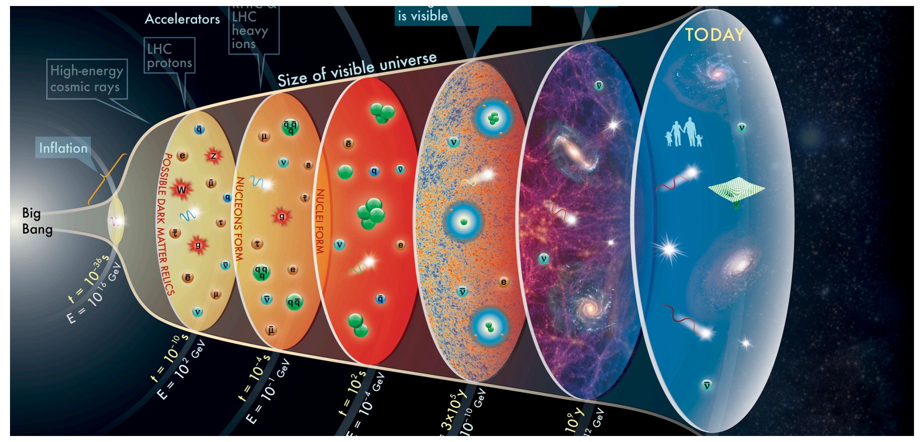




Baryon physics

- The visible matter of the Universe is mainly made of baryons.
- Baryons play an important role in the evolution of the Universe, such as baryogenesis and big-bang nucleosythesis.





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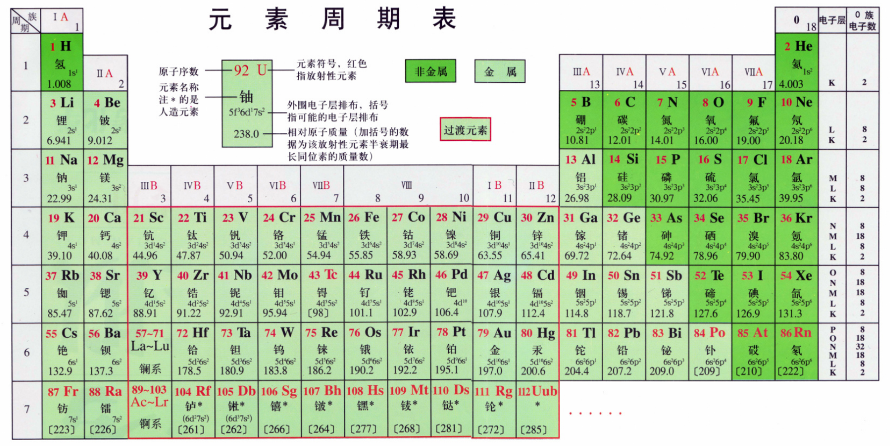
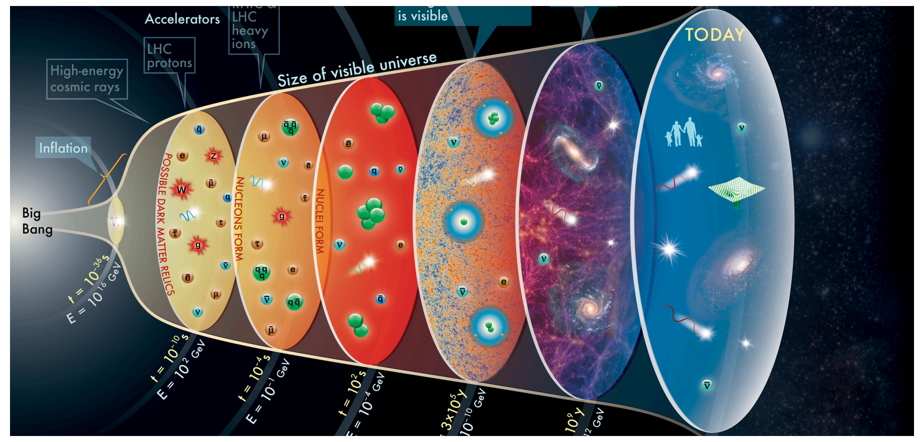
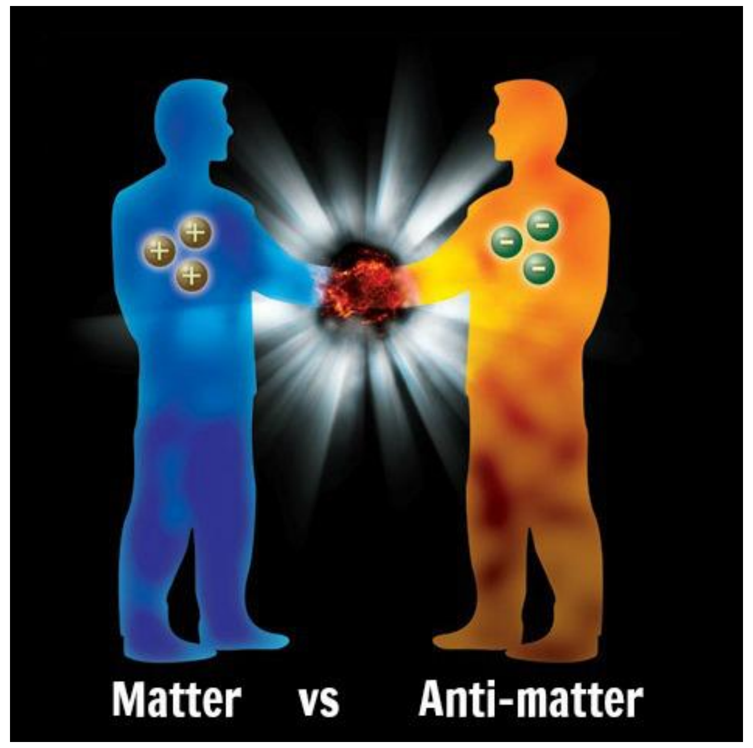
- The visible matter of the Universe is mainly made of baryons.
- Baryons play an important role in the evolution of the Universe, such as baryogenesis and big-bang nucleosythesis.
- However, our knowledge on the basic nucleon are even limited.
- The mass and spin puzzles of proton are among the most important problems in physics.
- Related to the inner structures and perturbative and non-perturbative QCD dynamics.





CP violation in baryons



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- Sakharov conditions for **Baryogenesis**:

  1) **baryon** number violation
  2) C and **CP violation**
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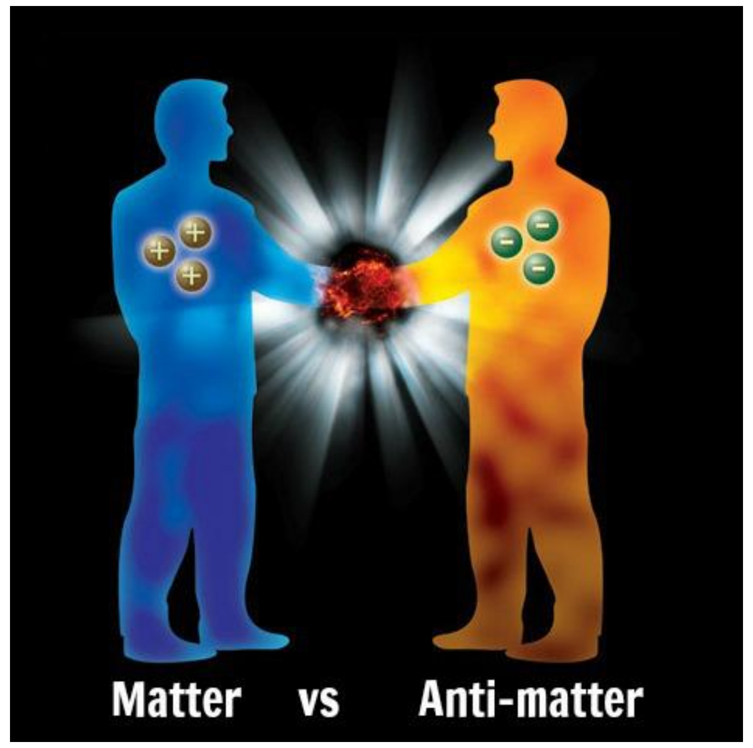

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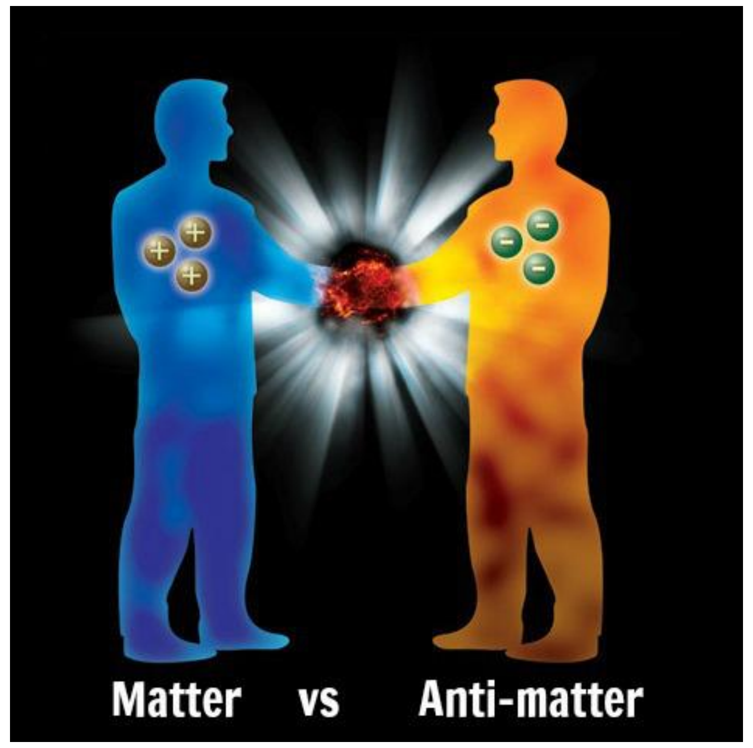

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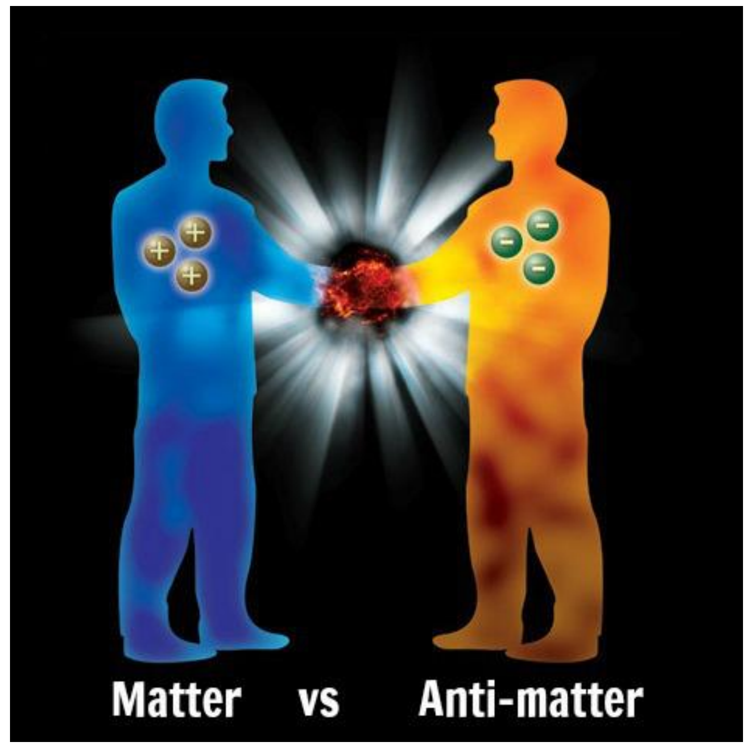

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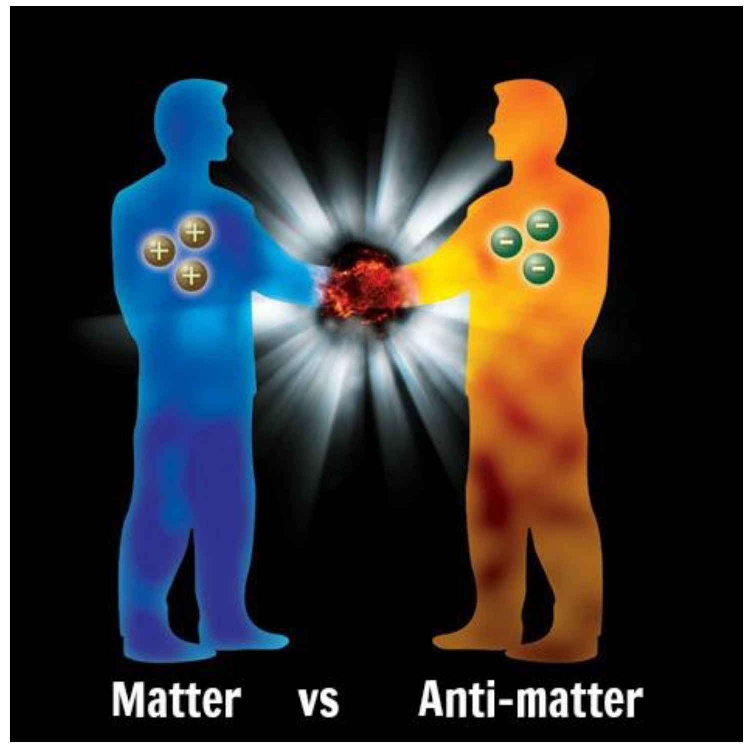

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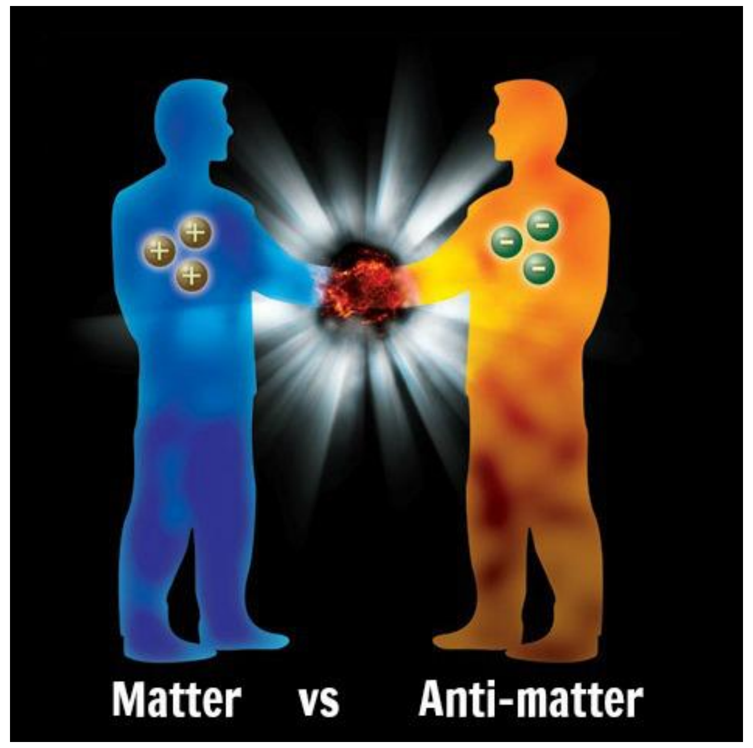
- **Key goal is to predict and search for baryon CPV**



Experimental opportunities

- LHCb is a **baryon factory** !!

Large Production: $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \rightarrow \frac{N_{\Lambda_b}}{N_{B^{0(-)}}} \sim 0.5$

Machine	CEPC (10^{12} Z)	Belle II (50 ab^{-1} + 5 ab^{-1} at $\Upsilon(5S)$)	LHCb (50 fb^{-1})
Data taking	2030-2040	$\rightarrow$ 2025	$\rightarrow$ 2030
B^+	6×10^{10}	3×10^{10}	3×10^{13}
B^0	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	6×10^{7}	–	6×10^{10}
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	2011	2012	2018	2023	2029	2035
LHCb	Run I		Run II	Run III	Run IV	Run V
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- BESIII and Belle II have fruitful results on charmed baryons and hyperons

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- CPV in some B-meson decays are as large as **10%**:

$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = -0.32 \pm 0.04, \quad A_{CP}(\overline{B}^0 \to K^-\pi^+) = -0.084 \pm 0.004, \quad A_{CP}(\overline{B}_s^0 \to K^+\pi^-) = +0.213 \pm 0.017$$

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- **It can be expected that CPV in b-baryons might be observed soon !!**

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  Few body for more observables.

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- Scalar diquark in $\Lambda_{b(c)}$ is simpler than spin 1/2 quark in B mesons in the heavy quark limit.

  Much less free parameters in $\Lambda_b \to \Lambda_c$ than $B \to D^{(*)}$ transitions [Bernlochner, Ligeti, Robinson, Sutcliffe, 2019]

Decay	$N_{\rm IW}$ at $\mathcal{O}(1)$	$N_{\rm SIW}$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$	$N_{\rm SIW}$ at $\mathcal{O}(\Lambda^2_{\rm QCD}/m_c^2)$
$\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$	1	0	2
$B \to D^* l \nu$	1	3	6

Theoretical opportunities

- **Baryons are very different from mesons!!**

- **Factorization:** Heavy-to-light form factor is factorizable at leading power in SCET.
  No end-point singularity! [Wei Wang, 1112.0237] Taking $\Lambda_b \to \Lambda$ as an example,

$$\xi_\Lambda = f_{\Lambda_b}\Phi_{\Lambda_b}(x_i) \otimes J(x_i, y_i) \otimes f_\Lambda \Phi_\Lambda(y_i)$$

- However, the **leading-power result is one order of magnitude smaller** than the total one

Leading power:	$\xi_\Lambda(q^2 = 0) = -0.012^{+0.009}_{-0.023}$
Sum Rules [Feldman, Yip, 2011]:	$\xi_\Lambda(q^2 = 0) = 0.38$

- Two hard gluons suppressed by α_s^2 at the leading power.
  Compared to the soft contributions in the power corrections.

- **More is different!!**

Theoretical opportunities

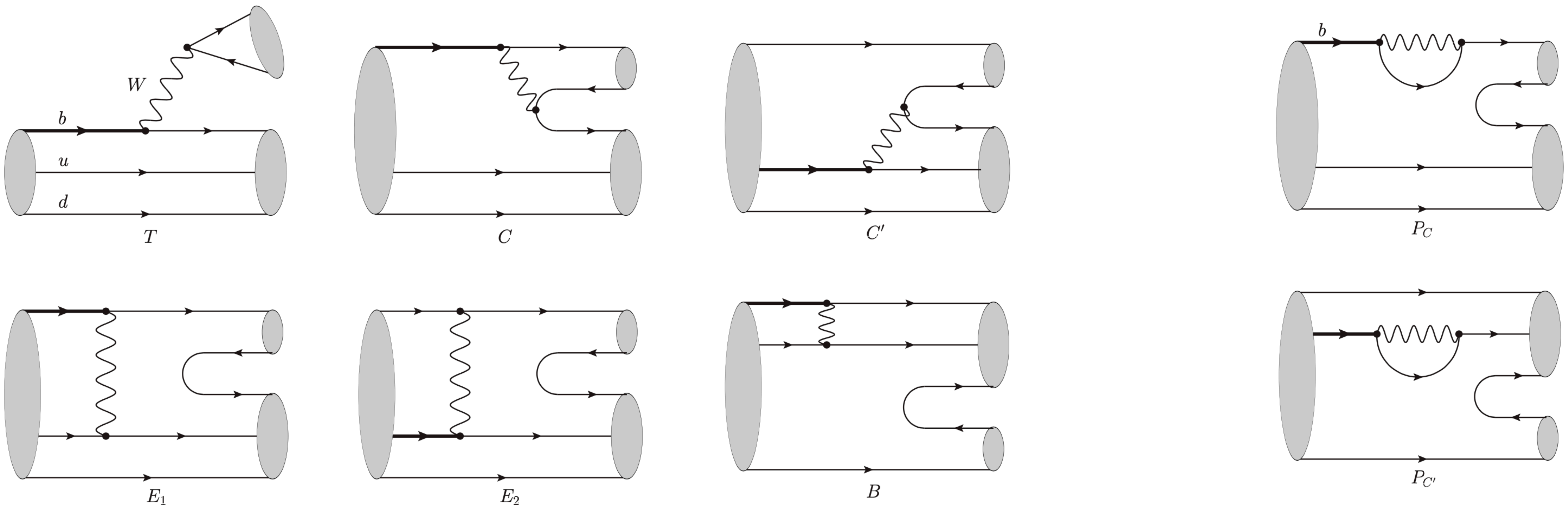
- **QCD studies on baryons are limited**
- Generalized factorization [Hsiao, Geng, 2015; Liu, Geng, 2021]:
  lost of non-factorizable contributions, such as W-exchange diagrams.
- QCDF [Zhu, Ke, Wei, 2016, 2018]: based on diquark picture.
- PQCD [Lu, Wang, Zou, Ali, Kramer, 2009]: only consider the leading twists of LCDAs.
- **Currently, no complete QCD-inspired method for non-leptonic b-baryon decays**

	EXP	GF	PQCD	QCDF
$Br(\Lambda_b \to p\pi)[\times 10^{-6}]$	4.3 ± 0.8	4.2+-0.7	$4.66^{+2.22}_{-1.81}$	4.11~4.57
$Br(\Lambda_b \to pK)[\times 10^{-6}]$	5.1 ± 0.9	4.8+-0.7	$1.82^{+0.97}_{-1.07}$	1.70~3.15
$A_{CP}(\Lambda_b \to p\pi)[\%]$	-2.5 ± 2.9	-3.9+-0.2	-32^{+49}_{-1}	-3.74~-3.08
$A_{CP}(\Lambda_b \to pK)[\%]$	-2.5 ± 2.2	5.8+-0.2	-3^{+25}_{-4}	8.1~11.4

大有可为！

Theoretical challenges

- Topological diagrams: more diagrams than mesons.



- **More non-factorizable diagrams: C’, E1, E2, B. They are non-negligible.**

$$\frac{|C|}{|T|} \sim \frac{|C'|}{|C|} \sim \frac{|E_1|}{|C|} \sim \frac{|E_2|}{|C|} \sim O\left(\frac{\Lambda^h_{\mathrm{QCD}}}{m_Q}\right)$$

Leibovich, Ligeti, Stewart, 2004

Theoretical progresses: PQCD

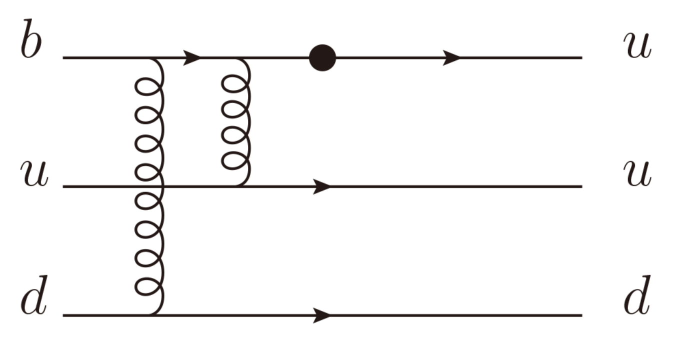
- PQCD successfully predicted correct CPV in B meson decays [Keum, Li, Sanda, 2000; Lu, Ukai, Yang, 2000].
- It is hopeful to predict correct CPV of b-baryons. W-exchange diagrams included.
- The only prediction of b-baryon CPV by PQCD is given in [Lu, Wang, Zou, Ali, Kramer, 2009]
- However, the form factors are two orders of magnitude smaller than Lattice or sum rules

Lattice [35]	0.22 ± 0.08
PQCD [67]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$

H.n.Li, 1999; Lu, Wang, Zou, Ali, Kramer, 2009

- Only the leading twist of light-cone distribution amplitudes (LCDAs) were considered.
- Recall that leading power is suppressed, so sub-leading power would be dominated.
- Consider higher twist LCDAs!!

$$\mathcal{A} = \Psi_{\Lambda_b}(x_i, b_i, \mu) \otimes H(x_i, b_i, x'_i, b'_i, \mu) \otimes \Psi_P(x'_i, b'_i, \mu)$$



Form Factors

	$f_1(0)$	$f_2(0)$	$g_1(0)$	$g_2(0)$
NRQM [76]	0.043			
heavy-LCSR [50]	$0.023^{+0.006}_{-0.005}$		$0.023^{+0.006}_{-0.005}$	
light-LCSR-$\mathcal{A}$ [77]	$0.14^{+0.03}_{-0.03}$	$-0.054^{+0.016}_{-0.013}$	$0.14^{+0.03}_{-0.03}$	$-0.028^{+0.012}_{-0.009}$
light-LCSR-$\mathcal{P}$ [77]	$0.12^{+0.03}_{-0.04}$	$-0.047^{+0.015}_{-0.013}$	$0.12^{+0.03}_{-0.03}$	$-0.016^{+0.007}_{-0.005}$
QCD-light-LCSR [78]	0.018	-0.028	0.018	-0.028
HQET-light-LCSR [78]	-0.002	-0.015		
3-point QSR [49]	0.22	0.0071		
lattice [47]	0.22 ± 0.08	0.04 ± 0.12	0.12 ± 0.14	0.04 ± 0.31
PQCD [32]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$			

[32] C. D. Lu, Y. M. Wang, H. Zou, A. Ali and G. Kramer, "Anatomy of the pQCD approach to the baryonic decays $\Lambda_b \to p\pi, pK$," Phys. Rev. D **80**, 034011 (2009) [arXiv:0906.1479 [hep-ph]].

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[49] C. S. Huang, C. F. Qiao and H. G. Yan, "Decay $\Lambda_b \to p$ lepton anti-neutrino in QCD sum rules," Phys. Lett. B **437**, 403 (1998) [arXiv:hep-ph/9805452 [hep-ph]].

[50] Y. M. Wang, Y. L. Shen and C. D. Lu, "$\Lambda_b \to p, \Lambda$ transition form factors from QCD light-cone sum rules," Phys. Rev. D **80**, 074012 (2009) [arXiv:0907.4008 [hep-ph]].

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[78] M. q. Huang and D. W. Wang, "Light cone QCD sum rules for the semileptonic decay $\Lambda_b \to pl\bar{\nu}$," Phys. Rev. D **69**, 094003 (2004) [arXiv:hep-ph/0401094 [hep-ph]].

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PQCD [32]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$			
this work (exponential)	0.27 ± 0.12	0.008 ± 0.005	0.31 ± 0.16	0.014 ± 0.008
this work (free parton)	0.24 ± 0.10	0.007 ± 0.004	0.27 ± 0.13	0.014 ± 0.010

- Higher twist LCDAs contribute to the correct order of form factors.

J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, FSY, 2202.04804

Theoretical progresses: PQCD

proton

Λ_b

	twist-3	twist-4	twist-5	twist-6	total
exponential					
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3^{+-}	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3^{-+}	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$
free parton					
twist-2	0.0006	-0.00007	-0.0005	-0.000002	0.0001
twist-3^{+-}	-0.0001	0.002	0.0003	-0.00001	0.002
twist-3^{-+}	-0.0002	0.006	0.00003	0.00005	0.005
twist-4	0.009	0.0005	0.22	~ 0	0.23
total	0.009	0.008	0.22	0.00004	$0.24 \pm 0.07 \pm 0.06$

- High-twist LCDA dominant: twist-5 of proton + twist-4 of Λ_b
- Consistent with the power analysis by SCET.

J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, FSY, 2202.04804

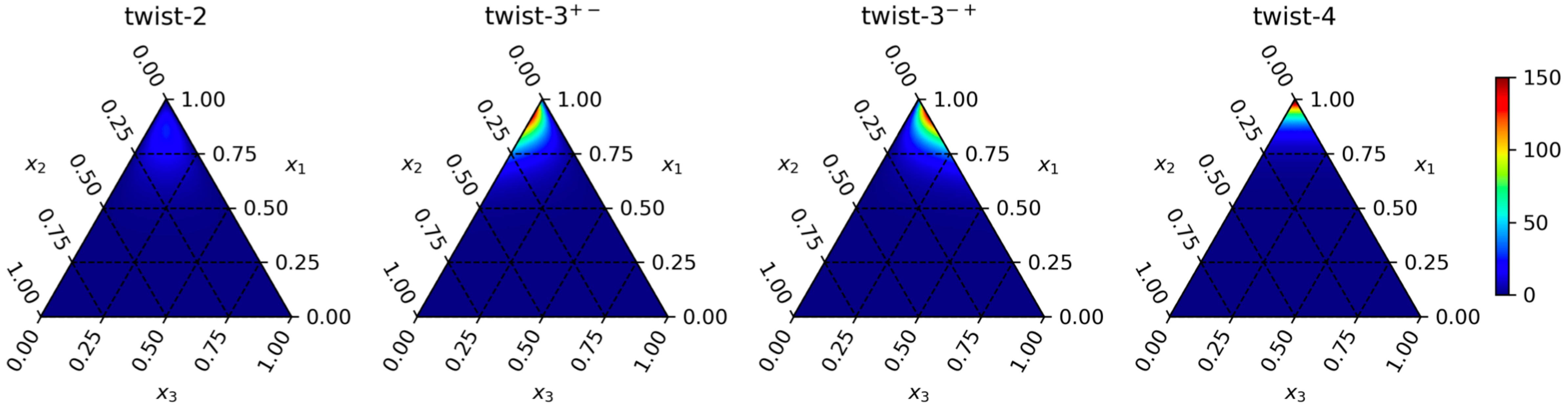
Theoretical progresses: PQCD

- Power-suppressed contribution incredibly surpasses the leading-power one

h_{ij}	twist-3	twist-4
twist-2	0	$r\psi_2 4(x_1-1)x_3(-V_2+V_3+A_2+A_3+T_3+T_7+S_1-P_1)$
twist-3^{+-}	$\psi_3^{+-}2x_3(-x_1)(V_1+A_1)$	$r\psi_3^{+-}2x_3(V_3-A_3)$
twist-3^{-+}	0	$r\psi_3^{-+}2x_3(2T_2+T_3-T_7+S_1+P_1)$
twist-4	$\psi_4 8x_3(-T_1)$	$r\psi_4 4(x_1-1)(1-x_2')(V_2-V_3-A_2-A_3)$

h_{ij}	twist-5	twist-6
twist-2	$r^2\psi_2 4x_3(-V_4+V_5-A_4-A-5)$	$r^3\psi_2 8(1-x_1)(1-x_2')T_6$
twist-3^{+-}	$r^2\psi_3^{+-}2(x_1-1)(1-x_2')(T_4+2T_5-T_8+S_2+P_2)$	0
twist-3^{-+}	$r^2\psi_3^{-+}2(x_1-1)(1-x_2')(V_4-A_4-T_8)$	$r^3\psi_3^{-+}2(1-x_2')(-V_6-A_6)$
twist-4	$r^2\psi_4 4(1-x_2')(V_4-V_5+A_4+A_5+T_4+T_8+S_2-P_2)$	0

$$r = m_p/m_{\Lambda_b}$$



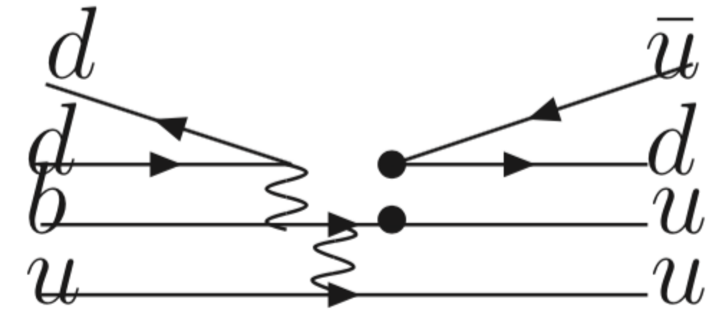
$$x_1 \to 1,\ x_{2,3} \to 0$$

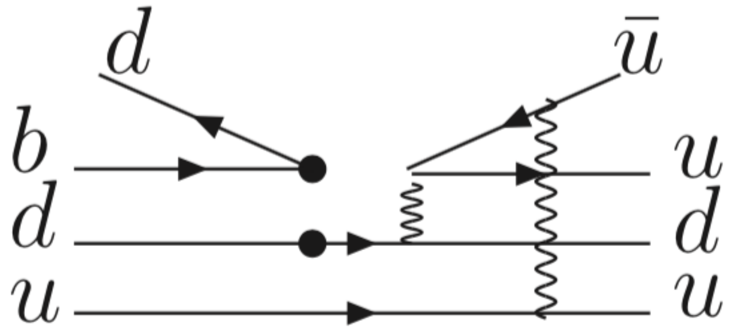
J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, FSY, 2202.04804

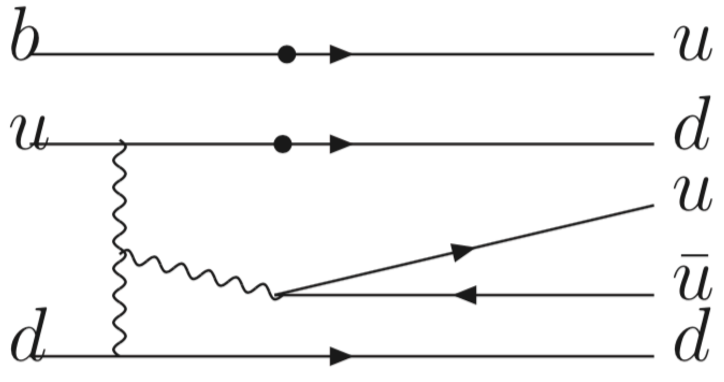
Theoretical progresses: PQCD

- It can be expected that PQCD can predict CPV of b-baryons

J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, FSY, 2205.xxxxx







Lu, Wang, Zou, Ali, Kramer, 2009

Theoretical progresses: LCSR

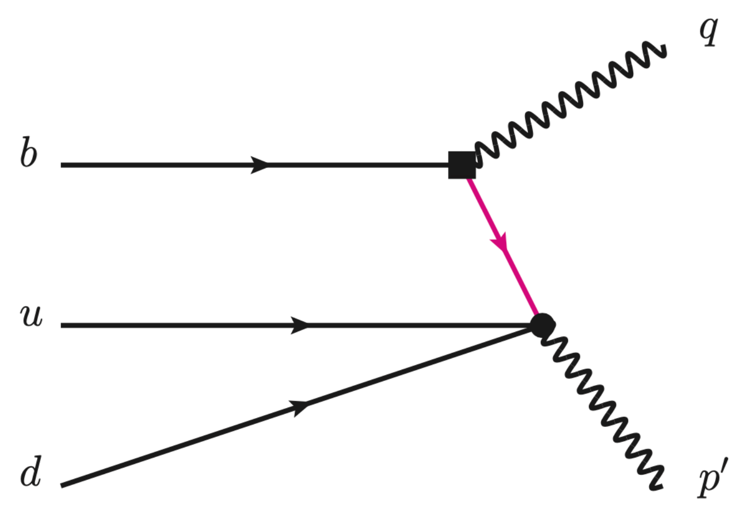
- Heavy-to-light form factors have been systematically studied in the light-cone sum rules (LCSR)

✓Next-to-leading order corrections [Y.M.Wang, Y.L.Shen, 2016]

✓LCDAs of heavy baryons [Bell, Feldman, Y.M.Wang, Yip, 2013]

✓$\Lambda_b \to p, N^*$ transitions [K.S.Huang, W.Liu, Y.L.Shen, FSY, 2205.xxxxx]

$$\Pi_{\mu,a}(p,q) = \frac{1}{m_p^2 - p^2} \sum_{s'} \langle 0 | \eta_i(0) | p(p,s') \rangle \langle p(p,s') | j_{\mu,a}(0) | \Lambda_b(p+q) \rangle + \frac{1}{m_{N^*}^2 - p^2} \sum_{s'} \langle 0 | \eta_i(0) | N^*(p,s') \rangle \langle N^*(p,s') | j_{\mu,a}(0) | \Lambda_b(p+q) \rangle + \ldots$$



- Test three interpolating currents
- Test five models of Λ_b LCDAs

$$\eta_{\rm IO}(x) = \varepsilon^{abc}\left[u^{aT}(x) C \gamma^\rho u^b(x)\right] \gamma_5 \gamma_\rho d^c(x)$$

$$\eta_{\rm TE}(x) = \varepsilon^{abc}\left[u^{aT}(x) C \sigma^{\rho\sigma} u^b(x)\right] \gamma_5 \sigma_{\rho\sigma} d^c(x)$$

$$\eta_{\rm LP}(x) = \varepsilon^{abc}\left[u^{aT}(x) C \not{n} u^b(x)\right] \gamma_5 \not{n} d^c(x)$$

Theoretical progresses: LCSR

- Ioffe and tensor currents are preferred for proton
- Λ_b LCDA models of QCDSR, exponential, and free-parton are preferred.
- $\Lambda_b \to N^*$ are helpful to distinguish them.

[K.S.Huang, W.Liu, Y.L.Shen, FSY, 2205.xxxxx]

$\Lambda_b \to p$

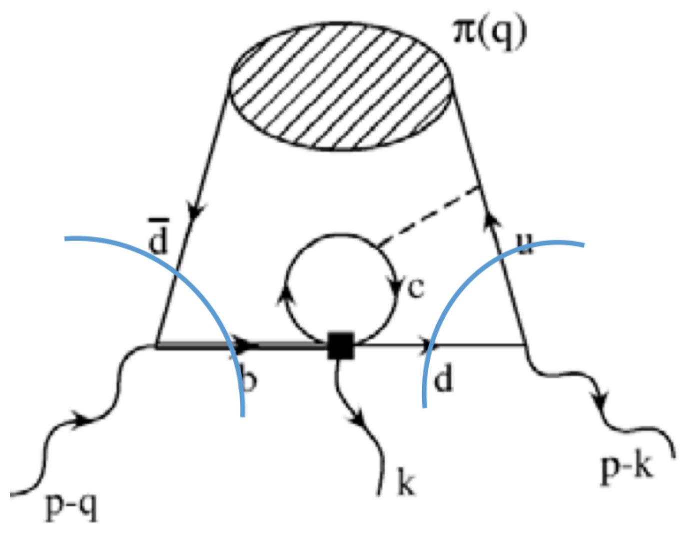
	f_1	f_2	g_1	g_2
Ioffe current				
Gegenbauer-1	0.53 ± 0.39	-0.12 ± 0.099	0.53 ± 0.39	-0.12 ± 0.099
Gegenbauer-2	0.50 ± 0.077	-0.11 ± 0.021	0.50 ± 0.077	-0.11 ± 0.021
QCDSR	0.13 ± 0.023	-0.023 ± 0.004	0.13 ± 0.023	-0.023 ± 0.004
Exponential	0.14 ± 0.087	-0.026 ± 0.017	0.14 ± 0.087	-0.026 ± 0.017
Free-parton	0.17 ± 0.11	-0.031 ± 0.022	0.17 ± 0.11	-0.031 ± 0.022
Tensor current				
Gegenbauer-1	0.37 ± 0.34	-0.070 ± 0.058	0.37 ± 0.34	-0.070 ± 0.058
Gegenbauer-2	0.36 ± 0.079	-0.068 ± 0.015	0.36 ± 0.079	-0.068 ± 0.015
QCDSR	0.11 ± 0.023	-0.023 ± 0.005	0.11 ± 0.023	-0.023 ± 0.005
Exponential	0.12 ± 0.071	-0.024 ± 0.014	0.12 ± 0.071	-0.024 ± 0.014
Free-parton	0.16 ± 0.10	-0.033 ± 0.021	0.16 ± 0.10	-0.033 ± 0.021
LP current				
Gegenbauer-1	0.29 ± 0.062	-0.050 ± 0.011	0.29 ± 0.062	-0.050 ± 0.011
Gegenbauer-2	0.31 ± 0.071	-0.050 ± 0.013	0.31 ± 0.071	-0.050 ± 0.013
QCDSR	0.29 ± 0.061	-0.050 ± 0.010	0.29 ± 0.061	-0.050 ± 0.010
Exponential	0.27 ± 0.11	-0.045 ± 0.017	0.27 ± 0.11	-0.045 ± 0.017
Free-parton	0.38 ± 0.15	-0.063 ± 0.024	0.38 ± 0.15	-0.063 ± 0.024
heavy-LCSR[13]	$0.023^{+0.006}_{-0.005}$	$-0.039^{+0.009}_{-0.009}$	$0.023^{+0.006}_{-0.005}$	$-0.039^{+0.009}_{-0.009}$
light-LCSR- $\mathcal{A}$[14]	$0.14^{+0.03}_{-0.03}$	$-0.054^{+0.016}_{-0.013}$	$0.14^{+0.03}_{-0.03}$	$-0.028^{+0.012}_{-0.009}$
light-LCSR- $\mathcal{P}$[14]	$0.12^{+0.03}_{-0.04}$	$-0.047^{+0.015}_{-0.013}$	$0.12^{+0.03}_{-0.03}$	$-0.016^{+0.007}_{-0.005}$
QCD-light-LCSR[16]	0.018	-0.028	0.018	-0.028
HQET-light-LCSR[16]	-0.002	-0.015	-0.002	-0.015
PQCD-Exponential[32]	0.27 ± 0.12	0.008 ± 0.005	0.31 ± 0.13	0.014 ± 0.010
PQCD-Free-parton[32]	0.24 ± 0.10	0.007 ± 0.004	0.27 ± 0.16	0.014 ± 0.008
CCQM[26]	0.080	-0.036	0.007	-0.001
RQM[27]	0.169	-0.050	0.196	-0.0002
LFQM[28]	0.1131	-0.0356	0.1112	-0.0097
LQCD[29]	0.22 ± 0.08	0.04 ± 0.12	0.12 ± 0.14	0.04 ± 0.31

$\Lambda_b \to N^*$

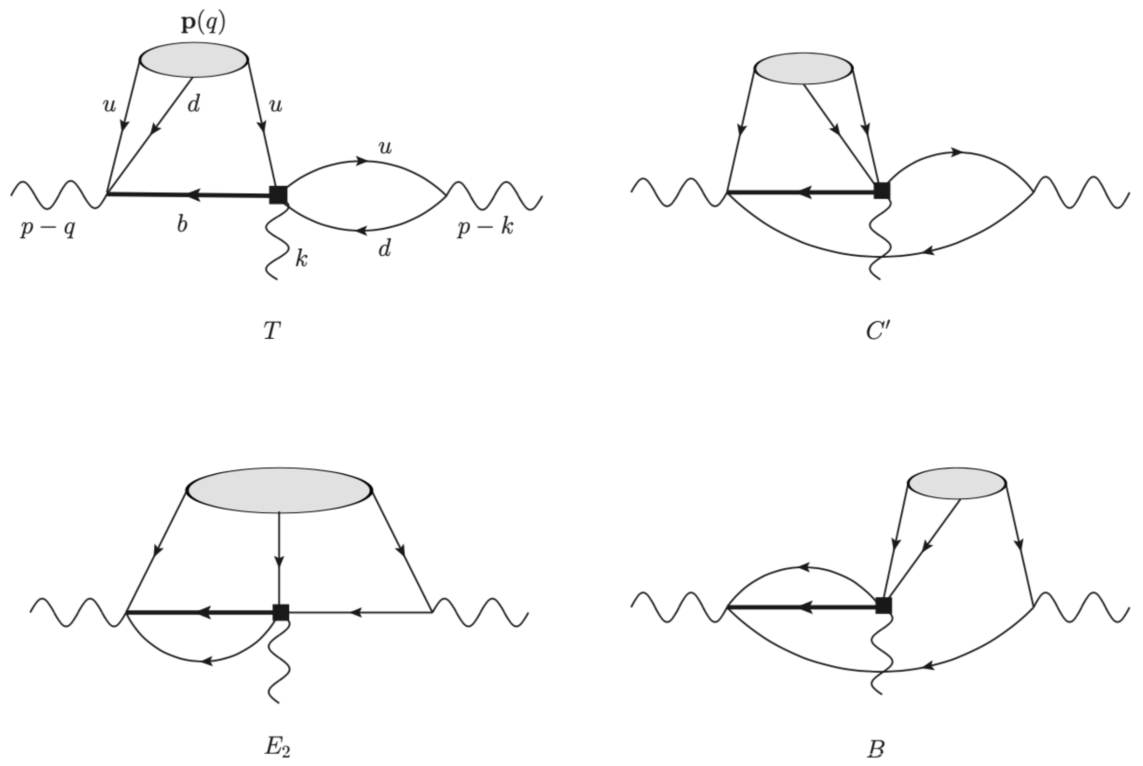
	F_1	F_2	G_1	G_2
Ioffe Current				
Gegenbauer-1	0.23 ± 0.57	0.002 ± 0.12	0.23 ± 0.57	0.002 ± 0.12
Gegenbauer-2	0.20 ± 0.15	0.009 ± 0.029	0.20 ± 0.15	0.009 ± 0.029
QCDSR	0.015 ± 0.021	0.019 ± 0.005	0.015 ± 0.021	0.019 ± 0.005
Exponential	0.029 ± 0.031	0.017 ± 0.008	0.029 ± 0.031	0.017 ± 0.008
Free-parton	0.006 ± 0.026	0.028 ± 0.015	0.006 ± 0.026	0.028 ± 0.015
Tensor Current				
Gegenbauer-1	0.32 ± 0.29	-0.11 ± 0.087	0.32 ± 0.29	-0.11 ± 0.087
Gegenbauer-2	0.32 ± 0.069	-0.10 ± 0.023	0.32 ± 0.069	-0.10 ± 0.023
QCDSR	0.10 ± 0.019	-0.035 ± 0.007	0.10 ± 0.019	-0.035 ± 0.007
Exponential	0.10 ± 0.062	-0.036 ± 0.021	0.10 ± 0.062	-0.036 ± 0.021
Free-parton	0.14 ± 0.089	-0.050 ± 0.032	0.14 ± 0.089	-0.050 ± 0.032
LP Current				
Gegenbauer-1	1.16 ± 0.22	-0.34 ± 0.065	1.16 ± 0.22	-0.34 ± 0.065
Gegenbauer-2	1.22 ± 0.24	-0.34 ± 0.075	1.22 ± 0.24	-0.34 ± 0.075
QCDSR	1.16 ± 0.22	-0.34 ± 0.064	1.16 ± 0.22	-0.34 ± 0.064
Exponential	1.07 ± 0.42	-0.30 ± 0.11	1.07 ± 0.42	-0.30 ± 0.11
Free-parton	1.48 ± 0.60	-0.43 ± 0.16	1.48 ± 0.60	-0.43 ± 0.16
LCSR(1)[30]	-0.562 ± 0.015	0.451 ± 0.0133	0.523 ± 0.014	-0.454 ± 0.013
LCSR(2)[30]	-0.185 ± 0.005	0.184 ± 0.006	0.143 ± 0.004	-0.093 ± 0.003
LCSR-1[31]	-0.297 ± 0.080	-0.213 ± 0.064	-0.028 ± 0.084	0.106 ± 0.031
LCSR-2[31]	-0.202 ± 0.060	-0.0640 ± 0.0018	-0.144 ± 0.043	0.062 ± 0.002

Theoretical progresses: LCSR

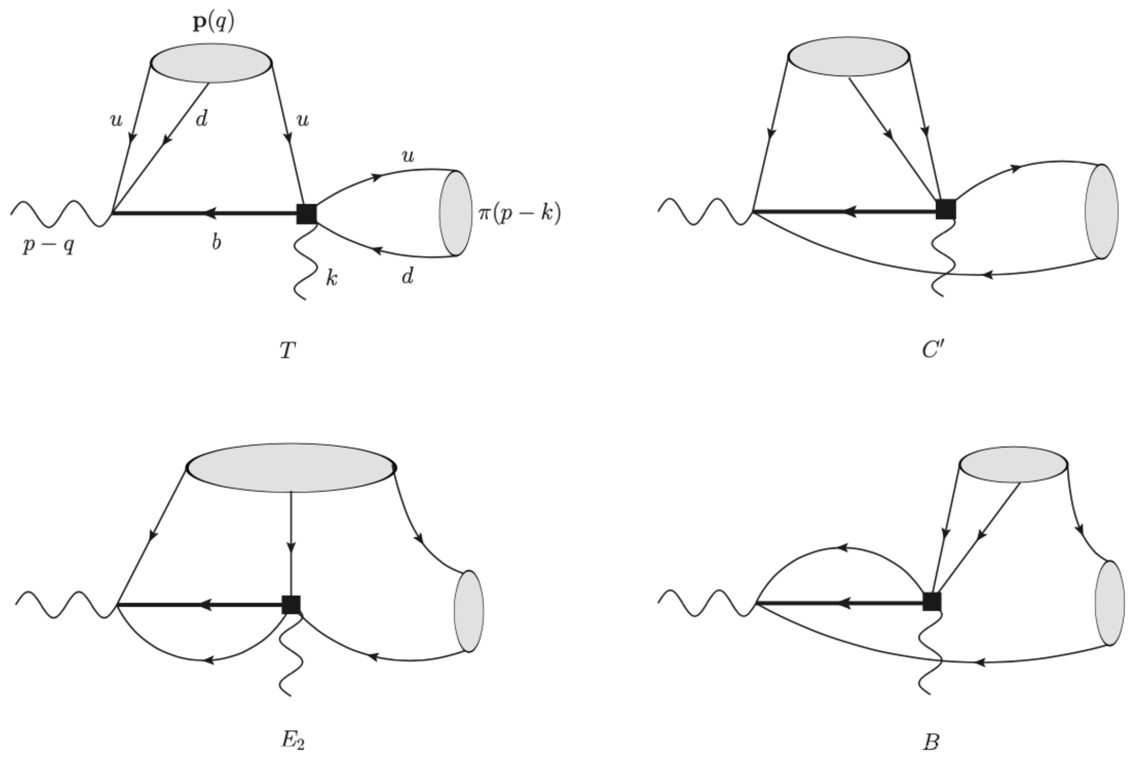
- **Two-body hadronic decays of $\Lambda_b \to p\pi,\ pK$ are studied firstly in LCSRs**
  [H.Y.Jiang, Khodjamirian, FSY, S.Cheng, in preparation]



- LCSR has been studied in $B \to \pi\pi$ [Khodjamirian, 2001, 2003, 2005] and applied to predict CPV of D meson decays [Khodjamirian, 2017]
- It overcomes the difficulty of calculation on W-exchange diagrams in QCDF.



Three-point correlator scheme



Two-point correlator scheme

Theoretical progresses: LCSR

- **Two-body hadronic decays of b-baryons are studied firstly in LCSRs** [H.Y.Jiang, Khodjamirian, FSY, S.Cheng, in preparation]
- The full framework has been well established.
- Two-point correlators can be easily calculated, to cross check the 3-point results, and to be extended to NLO corrections.
- The preliminary numerical results are consistent with data.

Topology	3pt scheme	2pt scheme
$T(10^{-9})$	$(-1.57i, -1.51i)$	$(-1.79i, -1.80i)$
$C'(10^{-9})$	$(0.20i, 0.20i)$	$(0.26i, 0.25i)$

channel	$\Lambda_b \to p\pi$	$\Lambda_b \to pK$
topology	T,C', E_2, B P_C, $P_{C'}$	T,E_2 P_C
BR (10^{-6})	5.94	6.50
BR (PDG) (10^{-6})	4.5 ± 0.8	5.4 ± 1.0
A_{CP}	-0.018	-0.001
A_{CP} (PDG)	-0.025 ± 0.029	-0.025 ± 0.022

Outlooks: LCDAs

- Light-cone distribution amplitudes are fundamental structures of hadrons.
- LCDAs are non-perturbative quantities, thus difficult for predictions.
- LCDAs of b-baryons and light baryons are much less known
- They are however important inputs in the calculations.
- So they dominate the theoretical uncertainties.
- The errors in each method are large.
- The differences between different methods are large.
- Theoretical efforts are urgently required.

Light-Cone Distribution Amplitudes: Λ_b

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) = \frac{1}{8\sqrt{2}N_c}\Big\{f^{(1)}_{\Lambda_b}(\mu)[M_1(x_2,x_3)\gamma_5 C^T]_{\gamma\beta} + f^{(2)}_{\Lambda_b}(\mu)[M_2(x_2,x_3)\gamma_5 C^T]_{\gamma\beta}\Big\}[\Lambda_b(p)]_\alpha$$

$$M_1(x_2,x_3) = \frac{\not{\bar{n}}\not{n}}{4}\psi_3^{+-}(x_2,x_3) + \frac{\not{n}\not{\bar{n}}}{4}\psi_3^{-+}(x_2,x_3),$$

$$M_2(x_2,x_3) = \frac{\not{n}}{\sqrt{2}}\psi_2(x_2,x_3) + \frac{\not{\bar{n}}}{\sqrt{2}}\psi_4(x_2,x_3),$$

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) = \frac{f'_{\Lambda_b}}{8\sqrt{2}N_c}[(\not{p} + m_{\Lambda_b})\gamma_5 C]_{\beta\gamma}[\Lambda_b(p)]_\alpha \psi(x_i,\mu),$$

$$\psi(x_i) = N x_1 x_2 x_3 \; exp\left(-\frac{m^2_{\Lambda_b}}{2\beta^2 x_1} - \frac{m_l^2}{2\beta^2 x_2} - \frac{m_l^2}{2\beta^2 x_3}\right),$$

Light-Cone Distribution Amplitudes: Λ_b

Model-I: Gegenbauer-1

$$\psi_2(x_2,x_3) = m_{\Lambda_b}^4 x_2 x_3 \left[\frac{1}{\epsilon_0^4} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_0} + a_2 C_2^{3/2}\left(\frac{x_2-x_3}{x_2+x_3}\right)\frac{1}{\epsilon_1^4} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_1}\right]$$

$$\psi_3^{+-}(x_2,x_3) = \frac{2m_{\Lambda_b}^3 x_2}{\epsilon_3^3} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_3},$$

$$\psi_3^{-+}(x_2,x_3) = \frac{2m_{\Lambda_b}^3 x_3}{\epsilon_3^3} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_3},$$

$$\psi_4(x_2,x_3) = \frac{5}{\mathcal{N}} m_{\Lambda_b}^2 \int_{m_{\Lambda_b}(x_2+x_3)/2}^{s_0} ds e^{-s/\tau}(s - m_{\Lambda_b}(x_2+x_3)/2)^3,$$

Ball, Braun, Gardi, 0804.2424, PLB 2008

with the Gegenbauer moment $a_2 = 0.333^{0.250}_{-0.333}$, the Gegenbauer polynomial $C_2^{3/2}(x) = 3(5x^2-1)/2$, the parameters $\epsilon_0 = 200^{+130}_{-60}$ MeV, $\epsilon_1 = 650^{+650}_{-300}$ MeV and $\epsilon_3 = 230 \pm 60$

Model-II: Gegenbauer-2

$$\psi_2(x_2,x_3) = m_{\Lambda_b}^4 x_2 x_3 \frac{a_2^{(2)}}{{\epsilon_2^{(2)}}^4} C_2^{3/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}/(x_2+x_3)/\epsilon_2^{(2)}},$$

$$\psi_3^{+-}(x_2,x_3) = m_{\Lambda_b}^3 (x_2+x_3)\left[\frac{a_2^{(3)}}{{\epsilon_2^{(3)}}^3} C_2^{1/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(3)}} + \frac{b_3^{(3)}}{{\eta_3^{(3)}}^3} C_2^{1/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}(x_2+x_3)/\eta_3^{(3)}}\right]$$

$$\psi_3^{-+}(x_2,x_3) = m_{\Lambda_b}^3 (x_2+x_3)\left[\frac{a_2^{(3)}}{{\epsilon_2^{(3)}}^3} C_2^{1/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(3)}} - \frac{b_3^{(3)}}{{\eta_3^{(3)}}^3} C_2^{1/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}(x_2+x_3)/\eta_3^{(3)}}\right]$$

$$\psi_4(x2,x3) = m_{\Lambda_b}^2 \frac{a_2^{(4)}}{{\epsilon_2^{(4)}}^2} C_2^{1/2}\left(\frac{x_2-x_3}{x_2+x_3}\right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(4)}}, \quad (10)$$

$a_2^{(2)} = 0.391 \pm 0.279$, $a_2^{(3)} = -0.161^{+0.108}_{-0.207}$, $a_2^{(4)} = -0.541^{+0.173}_{-0.09}$, $b_3^{(3)} = -0.24^{+0.24}_{-0.147}$, $\epsilon_2^{(2)} = 0.551^{+\infty}_{-0.356}$ GeV, $\epsilon_2^{(3)} = 0.055^{+0.01}_{-0.02}$ GeV, $\epsilon_2^{(4)} = 0.262^{+0.116}_{-0.132}$ GeV and $\eta_3^{(3)} = 0.633 \pm 0.099$ GeV.

Ali, Hambrock, Parkhomenko, 2012

Light-Cone Distribution Amplitudes: Λ_b

Model-III: Exponential

$$\psi_2(x_2,x_3) = \frac{x_2 x_3}{\omega_0^4} m_{\Lambda_b}^4 e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$
$$\psi_3^{+-}(x_2,x_3) = \frac{2x_2}{\omega_0^3} m_{\Lambda_b}^3 e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$
$$\psi_3^{-+}(x_2,x_3) = \frac{2x_3}{\omega_0^3} m_{\Lambda_b}^3 e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$
$$\psi_4(x_2,x_3) = \frac{1}{\omega_0^2} m_{\Lambda_b}^2 e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

$\omega_0 = 0.4$ GeV

Model-IV: Free Parton

$$\psi_2(x_2,x_3) = \frac{15x_2x_3m_{\Lambda_b}^4(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b})}{4\bar\Lambda^5}\Theta(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b})$$
$$\psi_3^{+-}(x_2,x_3) = \frac{15x_2m_{\Lambda_b}^3(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b})^2}{4\bar\Lambda^5}\Theta(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b}),$$
$$\psi_3^{-+}(x_2,x_3) = \frac{15x_3m_{\Lambda_b}^3(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b})^2}{4\bar\Lambda^5}\Theta(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b}),$$
$$\psi_4(x_2,x_3) = \frac{5m_{\Lambda_b}^2(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b})^3}{8\bar\Lambda^5}\Theta(2\bar\Lambda - x_2m_{\Lambda_b} - x_3m_{\Lambda_b}),$$

$\bar\Lambda \equiv (m_{\Lambda_b} - m_b)/2 \approx 0.8$ GeV

Bell, Feldmann, Y.M.Wang, Yip, 1308.6114, JHEP2013

Light-Cone Distribution Amplitudes: proton

$$
\begin{aligned}
(\overline{Y}_P)_{\alpha\beta\gamma}(x_i', \mu) = \frac{1}{8\sqrt{2}N_c}\Big\{ &- S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma \\
&- P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1 (C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + V_2 (C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma \\
&+ V_3 \frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4 \frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5 \frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma \\
&+ V_6 \frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - A_1 (C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma - A_2 (C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma \\
&- A_3 \frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma + A_4 \frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma - A_5 \frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma \\
&- A_6 \frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1 (iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma - T_2 (iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma \\
&- T_3 \frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4 \frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5 \frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma \\
&- T_6 \frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7 \frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma \\
&+ T_8 \frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma \Big\},
\end{aligned}
$$

	twist-3	twist-4	twist-5	twist-6
Vector	V_1	V_2, V_3	V_4, V_5	V_6
Pseudo-Vector	A_1	A_2, A_3	A_4, A_5	A_6
Tensor	T_1	T_2, T_3, T_7	T_4, T_5, T_8	T_6
Scalar		S_1	S_2	
Pesudoscalar		P_1	P_2	

Braun, Fries, Mahnke, Stein,
hep-ph/0007279, NPB 2000

Light-Cone Distribution Amplitudes: proton

- Twist-3 LCDAs

$$
\begin{aligned}
V_1(x_i) =&120x_1x_2x_3[\phi_3^0 + \phi_3^+(1-3x_3)],\\
A_1(x_i) =&120x_1x_2x_3(x_2-x_1)\phi_3^-,\\
T_1(x_i) =&120x_1x_2x_3[\phi_3^0 + \frac{1}{2}(\phi_3^- - \phi_3^+)(1-3x_3)].
\end{aligned}
$$

- Twist-4 LCDAs

$$
\begin{aligned}
V_2(x_i) =&24x_1x_2[\phi_4^0 + \phi_4^+(1-5x_3)],\\
V_3(x_i) =&12x_3[\psi_4^0(1-x_3) + \psi_4^-(x_1^2+x_2^2-x_3(1-x_3)) + \psi_4^+(1-x_3-10x_1x_2)],\\
A_2(x_i) =&24x_1x_2(x_2-x_1)\phi_4^-,\\
A_3(x_i) =&12x_3(x_2-x_1)[(psi_4^0 + \psi_4^+) + \psi_4^-(1-2x_3)],\\
T_2(x_i) =&24x_1x_2[\xi_4^0 + \xi_4^+(1-5x_3)],\\
T_3(x_i) =&6x_3[(\xi_4^0+\phi_4^0+\psi_4^0)(1-x_3) + (\xi_4^- + \phi_4^- - \psi_4^-)(x_1^2+x_2^2-x_3(1-x_3))\\
&+ (\xi_4^+ + \phi_4^+ + \psi_4^+)(1-x_3-10x_1x_2)],\\
T_7(x_i) =&6x_3[(-\xi_4^0+\phi_4^0+\psi_4^0)(1-x_3) + (-\xi_4^- + \phi_4^- - \psi_4^-)(x_1^2+x_2^2-x_3(1-x_3))\\
&+ (-\xi_4^+ + \phi_4^+ + \psi_4^+)(1-x_3-10x_1x_2)],\\
S_1(x_i) =&6x_3(x_2-x_1)[(\xi_4^0+\phi_4^0+\psi_4^0+\xi_4^++\phi_4^++\psi_4^+) + (\xi_4^-+\phi_4^--\psi_4^-)(1-2x_3)],\\
P_1(x_i) =&6x_3(x_2-x_1)[(\xi_4^0-\phi_4^0-\psi_4^0+\xi_4^+-\phi_4^+-\psi_4^+) + (\xi_4^--\phi_4^-+\psi_4^-)(1-2x_3)].
\end{aligned}
$$

- Twist-5 LCDAs

$$
\begin{aligned}
V_4(x_i) =&3[\psi_5^0(1-x_3) + \psi_5^-(2x_1x_2 - x_3(1-x_3)) + \psi_5^+(1-x_3-2(x_1^2+x_2^2))],\\
V_5(x_i) =&6x_3[\phi_5^0 + \phi_5^+(1-2x_3)],\\
A_4(x_i) =&3(x_2-x_1)[-\psi_5^0 + \psi_5^- x_3 + \psi_5^+(1-2x_3)],\\
A_5(x_i) =&6x_3(x_2-x_1)\phi_5^-,\\
T_4(x_i) =&\frac{3}{2}[(\xi_5^0+\psi_5^0+\phi_5^0)(1-x_3) + (\xi_5^-+\phi_5^--\psi_5^-)(2x_1x_2-x_3(1-x_3))\\
&+ (\xi_5^++\phi_5^++\psi_5^+)(1-x_3-2(x_1^2+x_2^2))],\\
T_5(x_i) =&6x_3[\xi_5^0 + \xi_5^+(1-2x_3)],\\
T_8(x_i) =&\frac{3}{2}[(\psi_5^0+\phi_5^0-\xi_5^0)(1-x_3) + (\phi_5^- - \phi_5^- - \xi_5^-)(2x_1x_2-x_3(1-x_3))\\
&+ (\phi_5^++\phi_5^+-\xi_5^+)(\mu)(1-x_3-2(x_1^2+x_2^2))],\\
S_2(x_i) =&\frac{3}{2}(x_2-x_1)[-(\psi_5^0+\phi_5^0+\xi_5^0) + (\xi_5^-+\phi_5^--\psi_5^0)x_3 + (\xi_5^++\phi_5^++\psi_5^0)(1-2x_3)],\\
P_2(x_i) =&\frac{3}{2}(x_2-x_1)[(\psi_5^0+\phi_5^0-\xi_5^0) + (\xi_5^--\phi_5^-+\psi_5^0)x_3 + (\xi_5^+-\phi_5^+-\psi_5^0)(1-2x_3)].
\end{aligned}
$$

- Twist-6 LCDAs

$$
\begin{aligned}
V_6(x_i) =&2[\phi_6^0 + \phi_6^+(1-3x_3)],\\
A_6(x_i) =&2(x_2-x_1)\phi_6^-,\\
T_6(x_i) =&2[\phi_6^0 + \frac{1}{2}(\phi_6^- - \phi_6^+)(1-3x_3)],
\end{aligned}
$$

Light-Cone Distribution Amplitudes: proton

Table 2: Parameters in the proton LCDAs in units of 10^{-2} GeV^2 [73]. The accuracy of those parameters without uncertainties is of order of 50%.

	ϕ_i^0	ϕ_i^-	ϕ_i^+	ψ_i^0	ψ_i^-	ψ_i^+	ξ_i^0	ξ_i^-	ξ_i^+
twist-3 $(i=3)$	0.53 ± 0.05	2.11	0.57						
twist-4 $(i=4)$	-1.08 ± 0.47	3.22	2.12	1.61 ± 0.47	-6.13	0.99	0.85 ± 0.31	2.79	0.56
twist-5 $(i=5)$	-1.08 ± 0.47	-2.01	1.42	$1.61 \pm .047$	-0.98	-0.99	0.85 ± 0.31	-0.95	0.46
twist-6 $(i=6)$	0.53 ± 0.05	3.09	-0.25						

Parameters of LCDAs of proton

Model	Method	$f_N \cdot 10^3$ Gev^2	$\lambda_1 \cdot 10^3$ Gev^2	$\lambda_2 \cdot 10^3$ Gev^2	A_1^u	V_1^d	f_1^u	f_1^d	f_2^d	Ref.
	QCDSR	5.0(5)	-27(9)	54(19)						
ASY		-	-	-	0	1/3	1/10	3/10	4/15	
CZ	QCDSR	5.3(5)	-	-	0.47	0.22	-	-	-	[1]
KS	QCDSR	5.1(3)	-	-	0.34	0.24	-	-	-	[2]
COZ	QCDSR	5.0(3)	-	-	0.39	0.23	-	-	-	[3]
SB	QCDSR	-	-	-	0.38	0.24	-	-	-	[4]
BK	PQCD	6.64	-	-	0.08	0.31	-	-	-	[5]
BLW	QCDSR	-	-	-	0.38(15)	0.23(3)	0.07(5)	0.40(20)	0.22(5)	[6]
BLW	LCSR (LO)	-	-	-	0.13	0.30	0.09	0.33	0.25	[6]
ABO1	LCSR (NLO)	-	-	-	0.11	0.30	0.11	0.27	-	[7]
ABO2	LCSR (NLO)				0.11	0.30	0.11	0.29	-	[7]
LAT09	LATTICE	3.23 (63)	-35.57 (65)	70.02 (13)	0.19 (2)	0.20 (1)	-	-	-	[8]
LAT14	LATTICE	3.07 (36)	-38.77 (18)	77.64 (37)	0.07 (4)	0.31 (2)	-	-	-	[9]
LAT19	LATTICE	3.54 (6)	-44.9 (42)	93.4 (48)	0.30 (32)	0.192 (22)	-	-	-	[10]

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Outlooks: others

- **Non-leptonic decays**:
  - other approaches except for PQCD and LCSR.
- **Form factors**:
  - more models, higher excited states.
- **FCNC processes**:
  - higher excited states.
- **CPV observables, polarizations and angular distributions.**

Summary

- Baryon physics is an opportunity of heavy flavor physics at the current stage.

My dream on baryon physics