

重味重子物理研究的机遇



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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

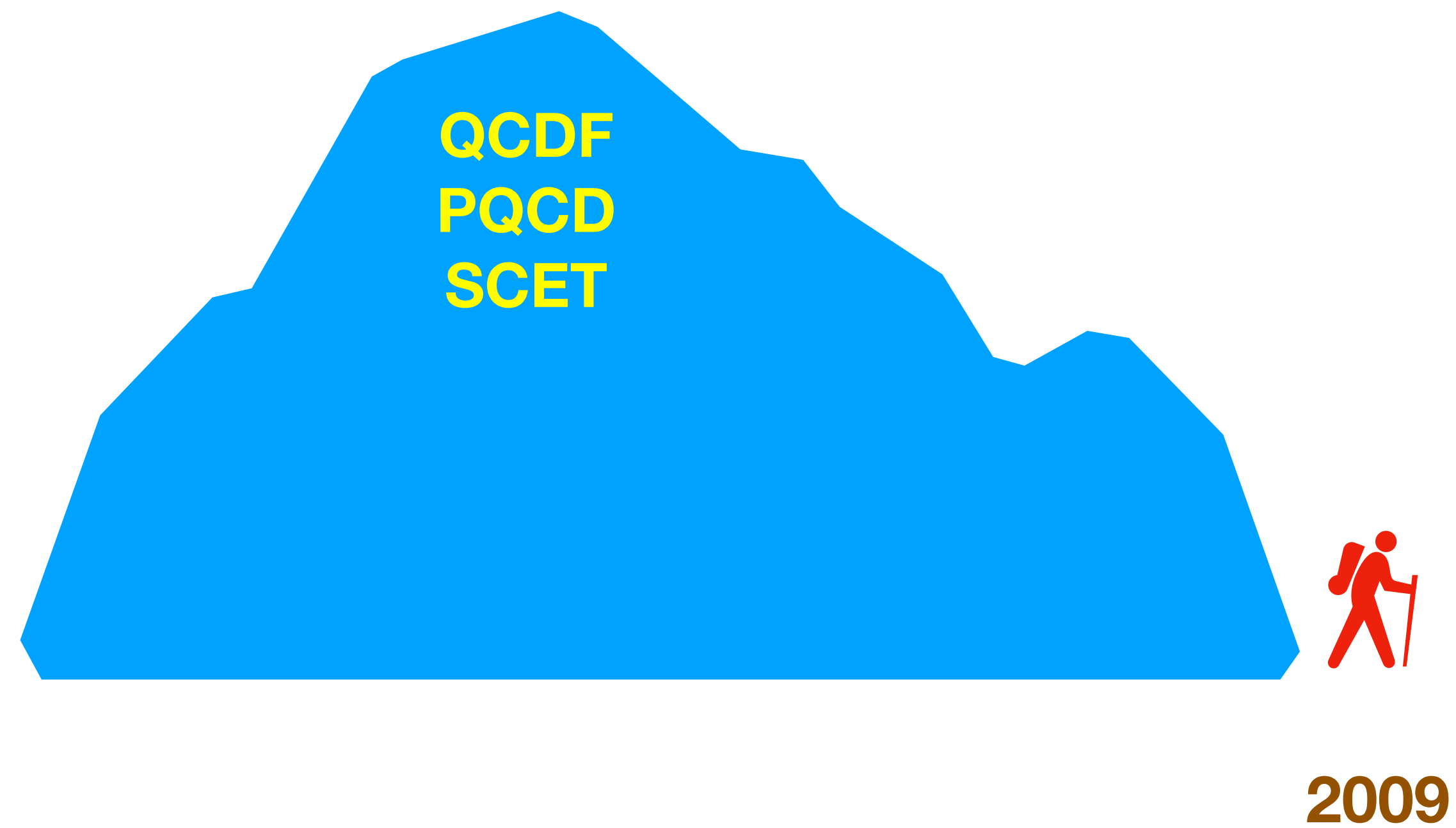


QCDF
PQCD
SCET

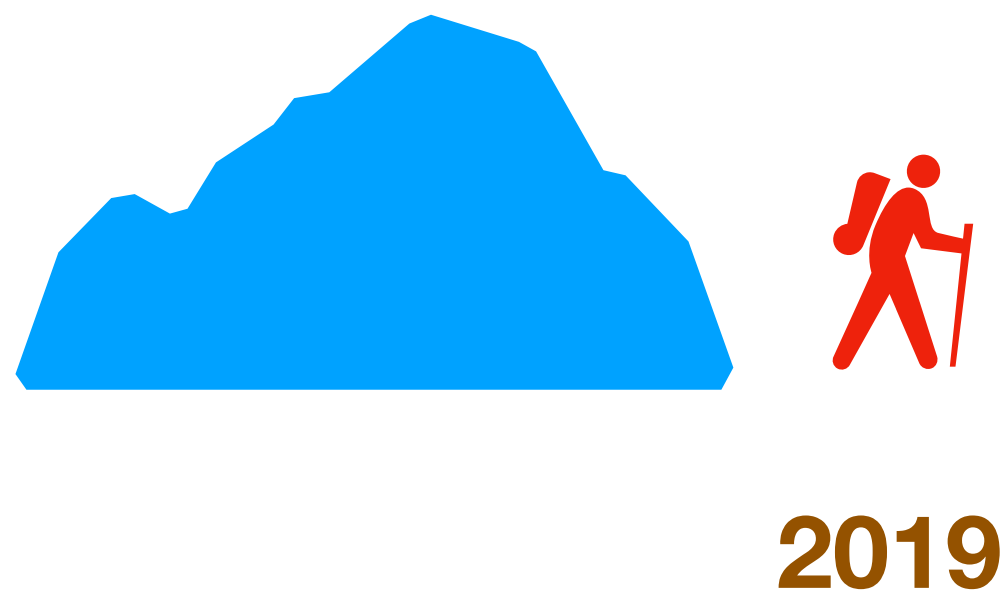
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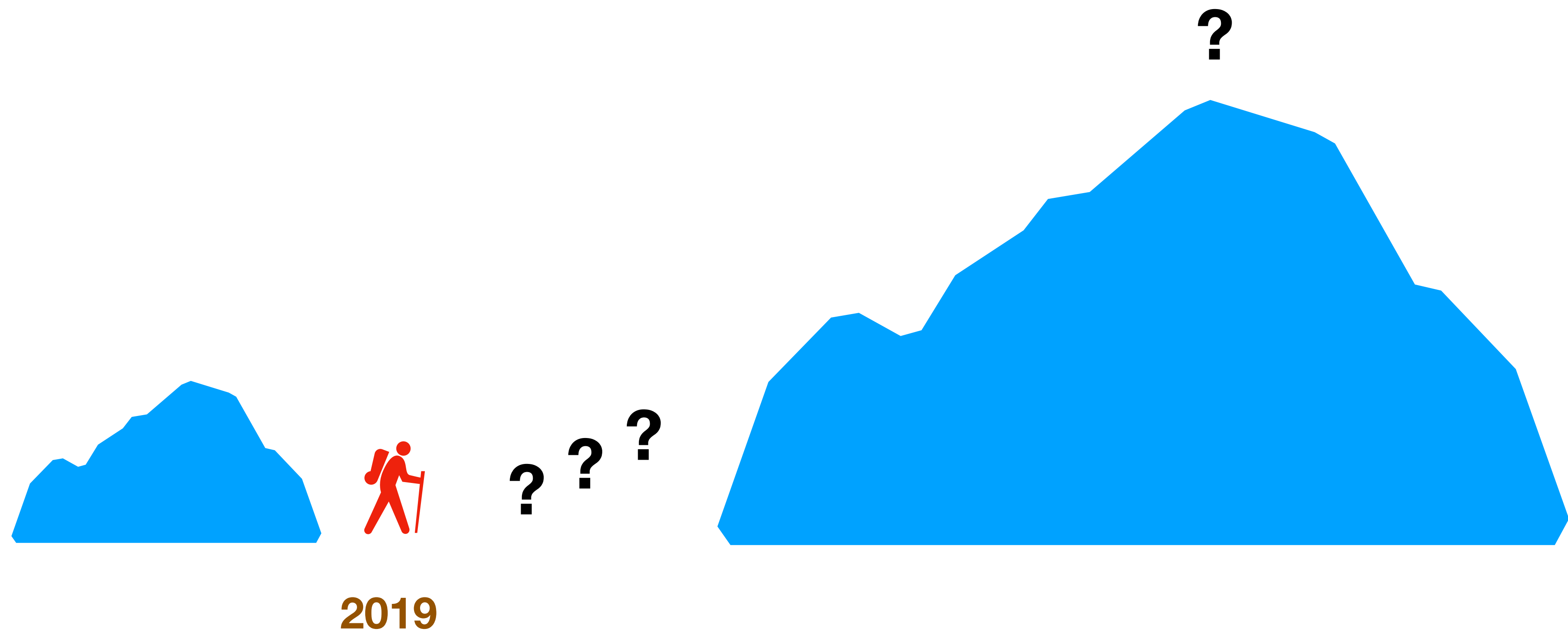
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Baryon physics ?

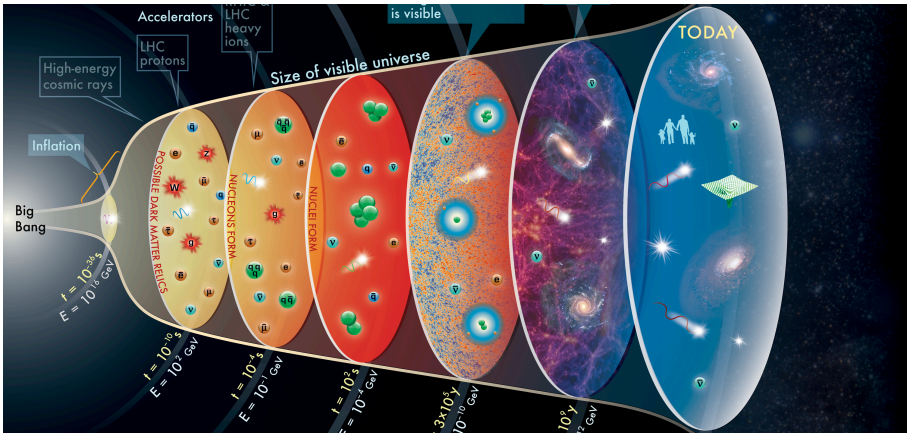


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Baryon physics



元素周期表																		原子序数 Z
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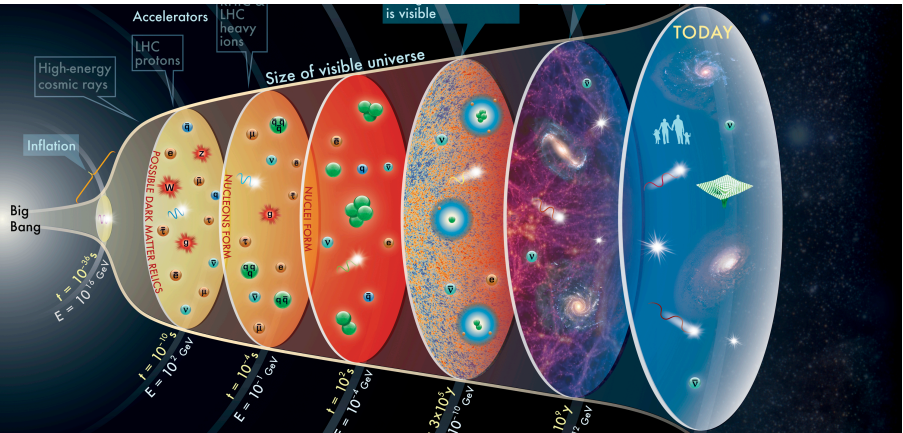


Baryon physics



- 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 nucleosynthesis.

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6	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
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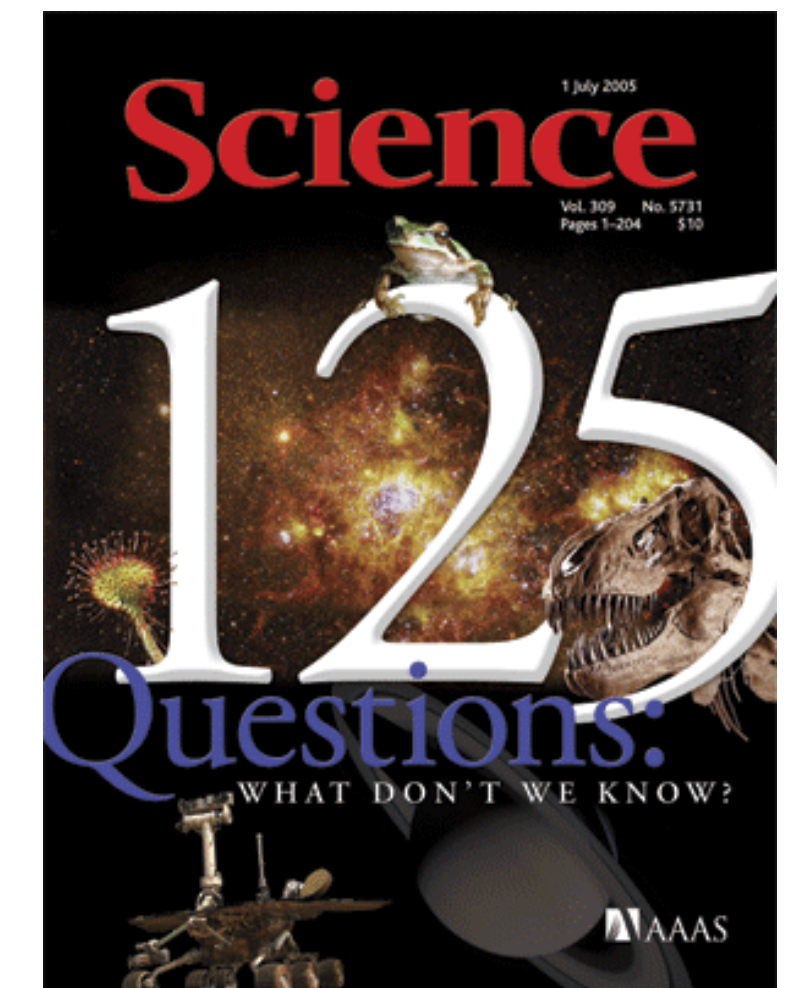
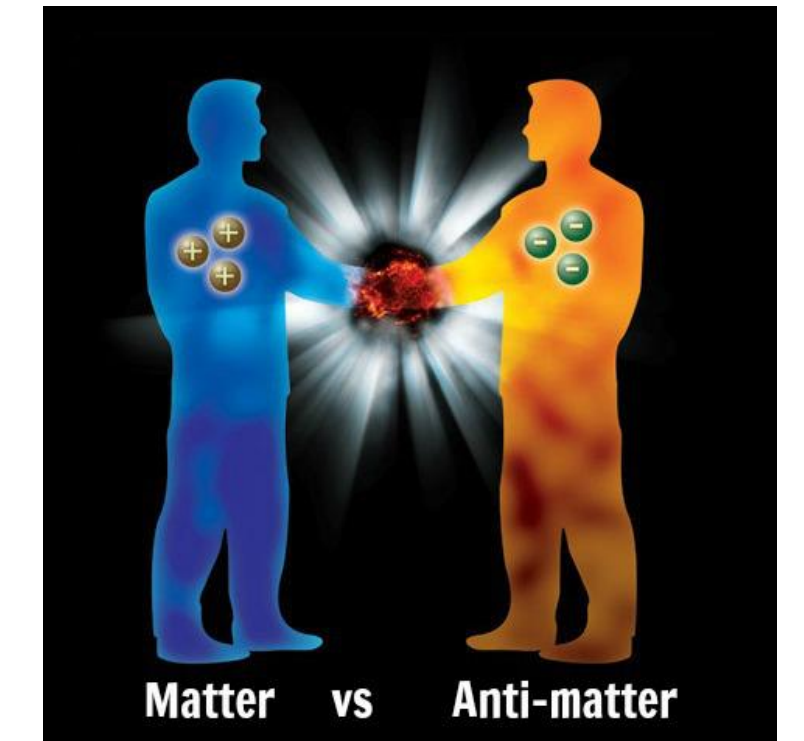
Baryon physics

- 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 nucleosynthesis.
- 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.



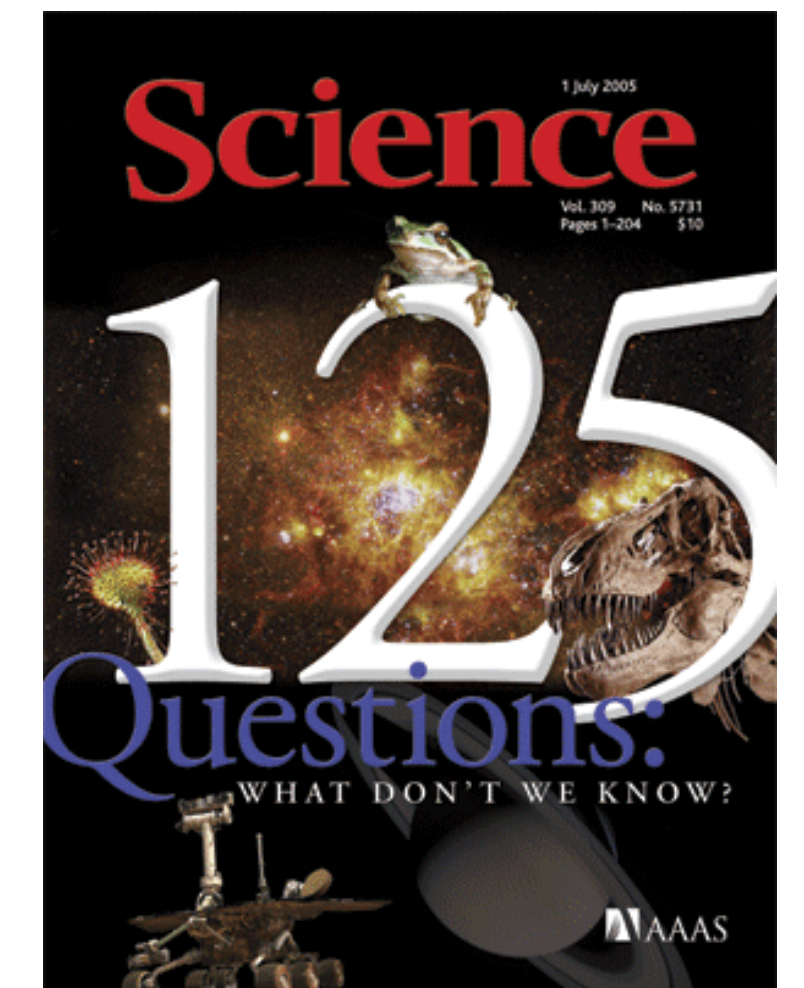
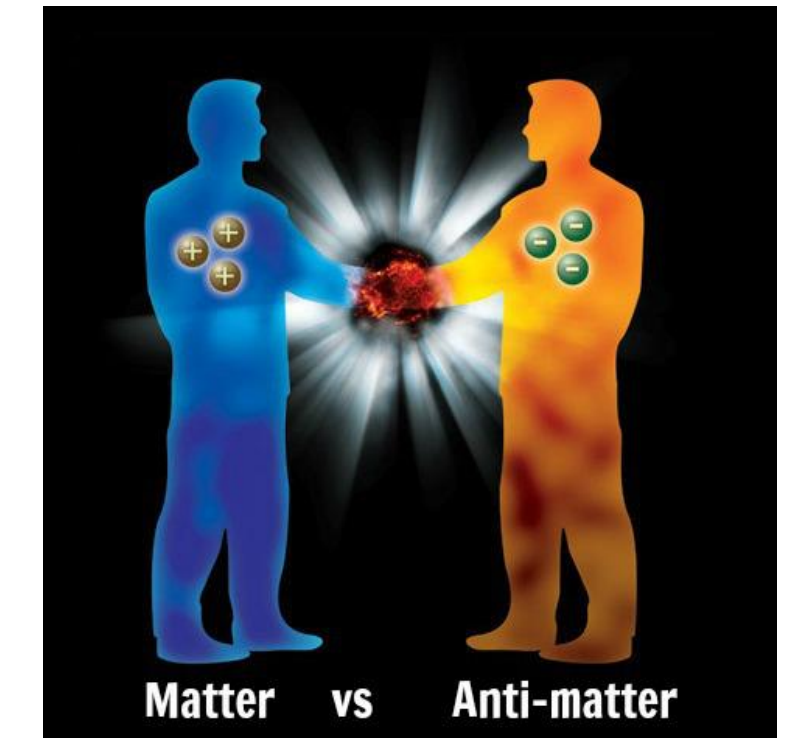
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CP violation in baryons



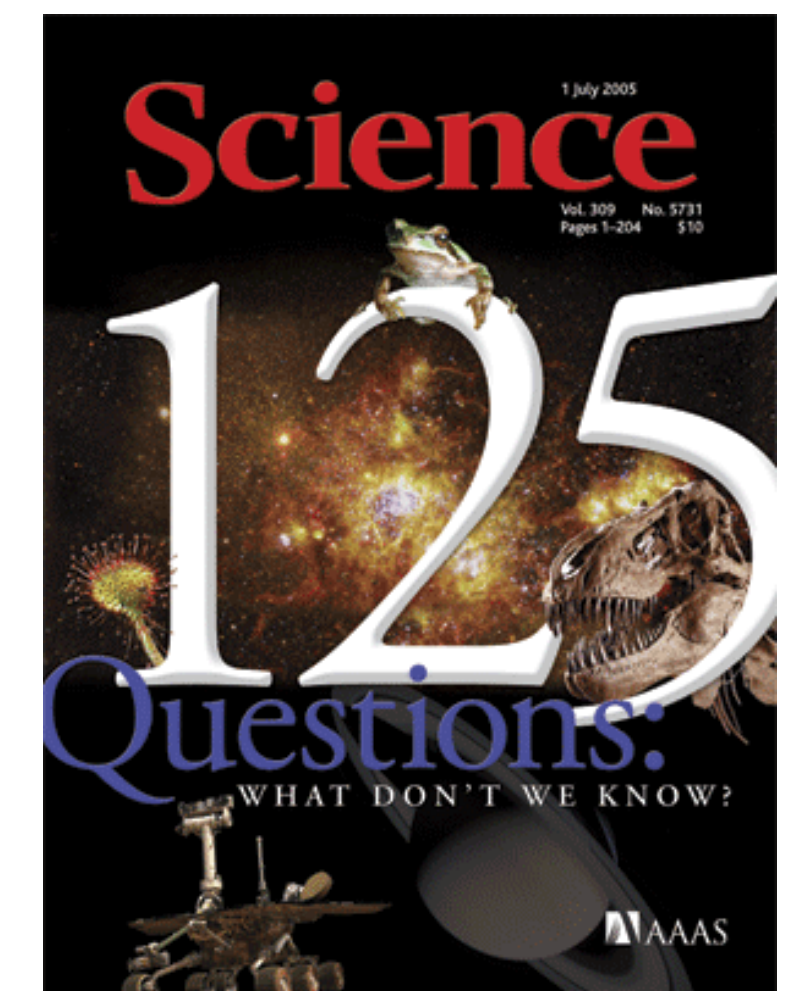
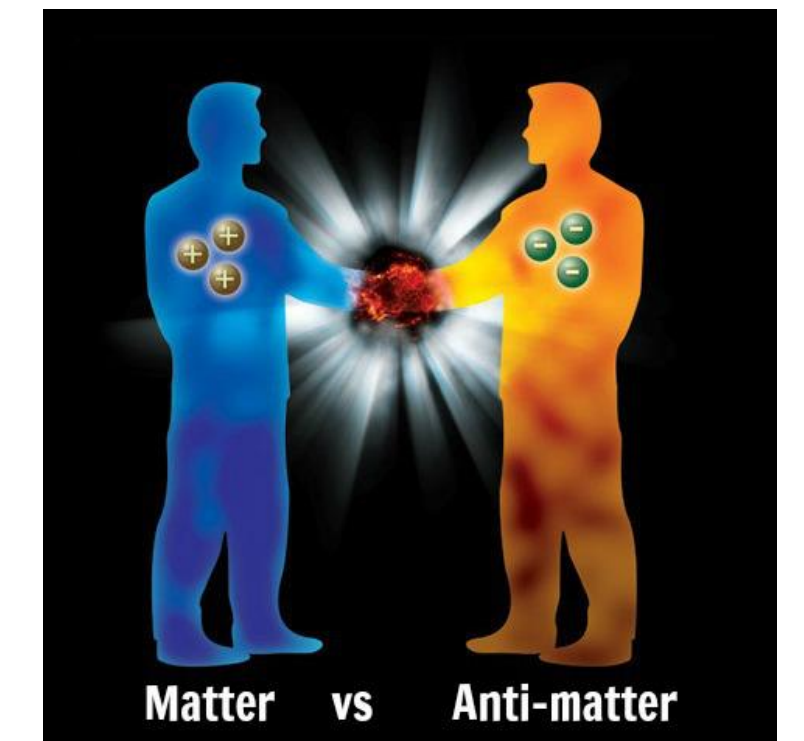
CP violation in baryons

- Sakharov conditions for **Baryogenesis**:
 - 1) **baryon** number violation
 - 2) C and **CP violation**
 - 3) out of thermal equilibrium



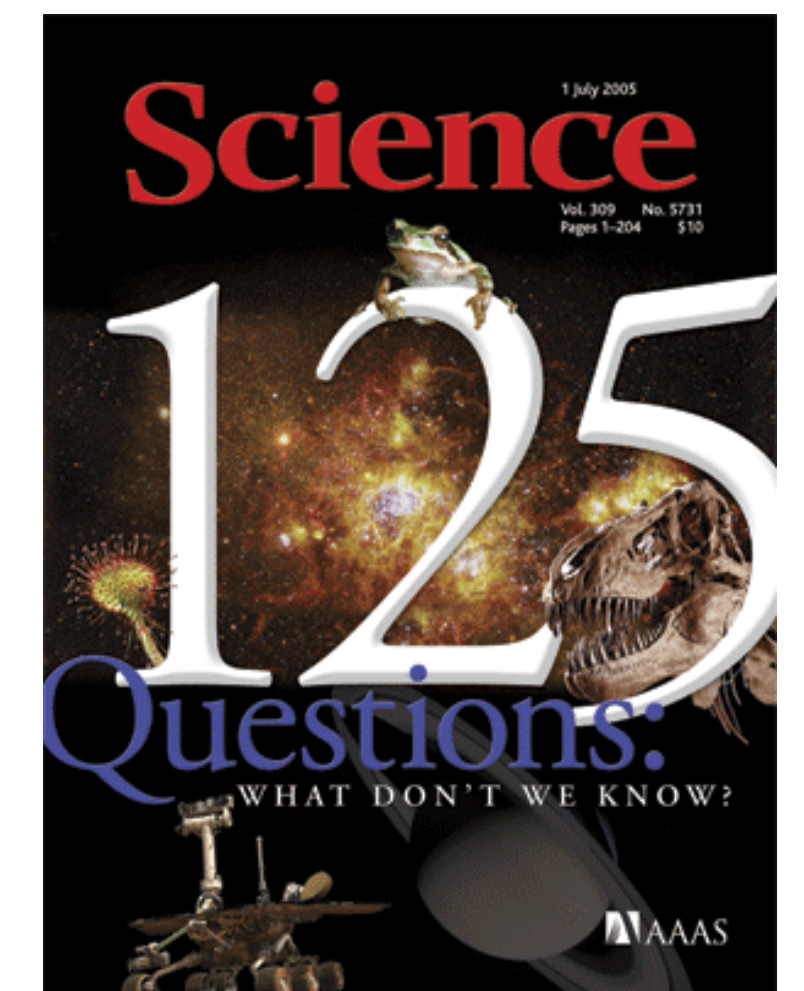
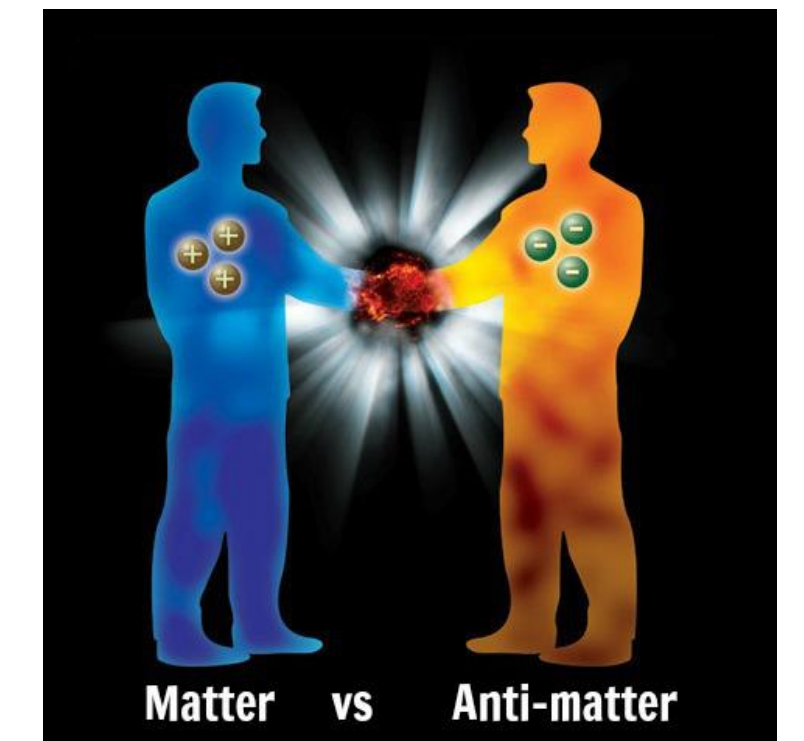
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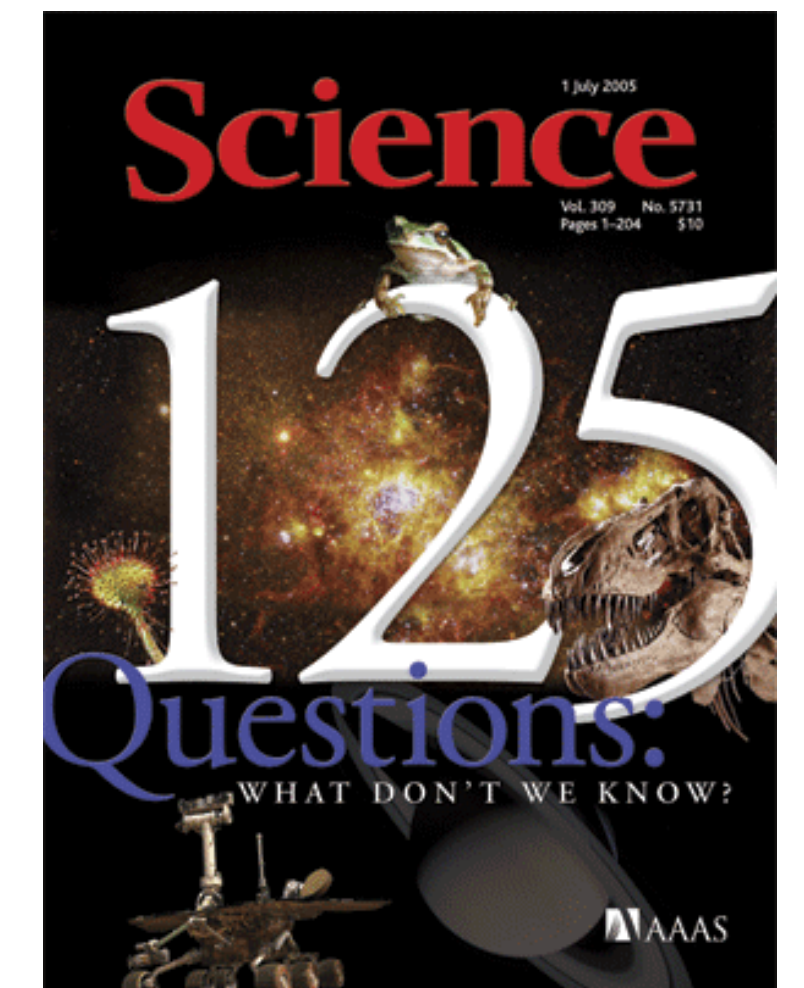
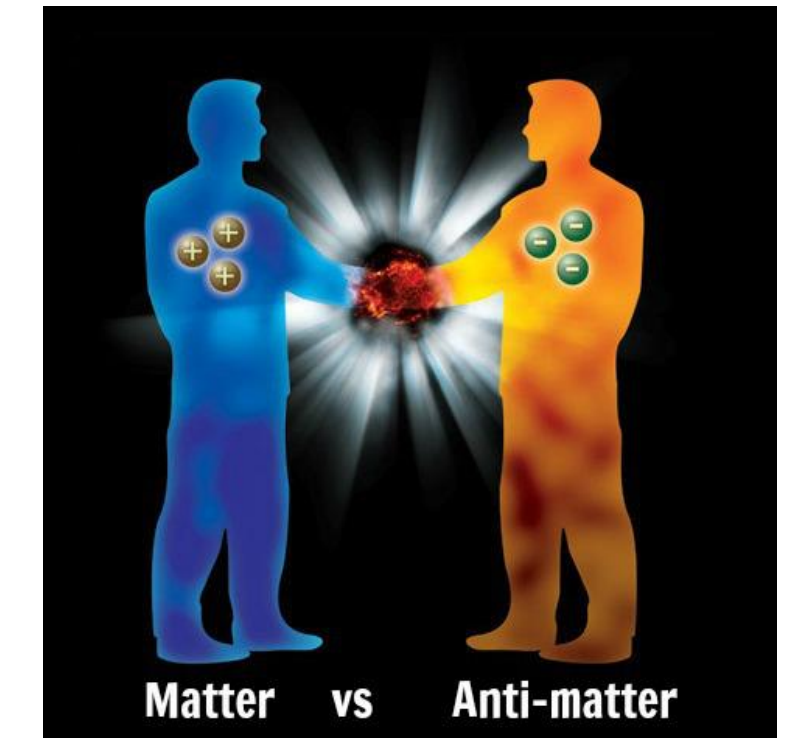
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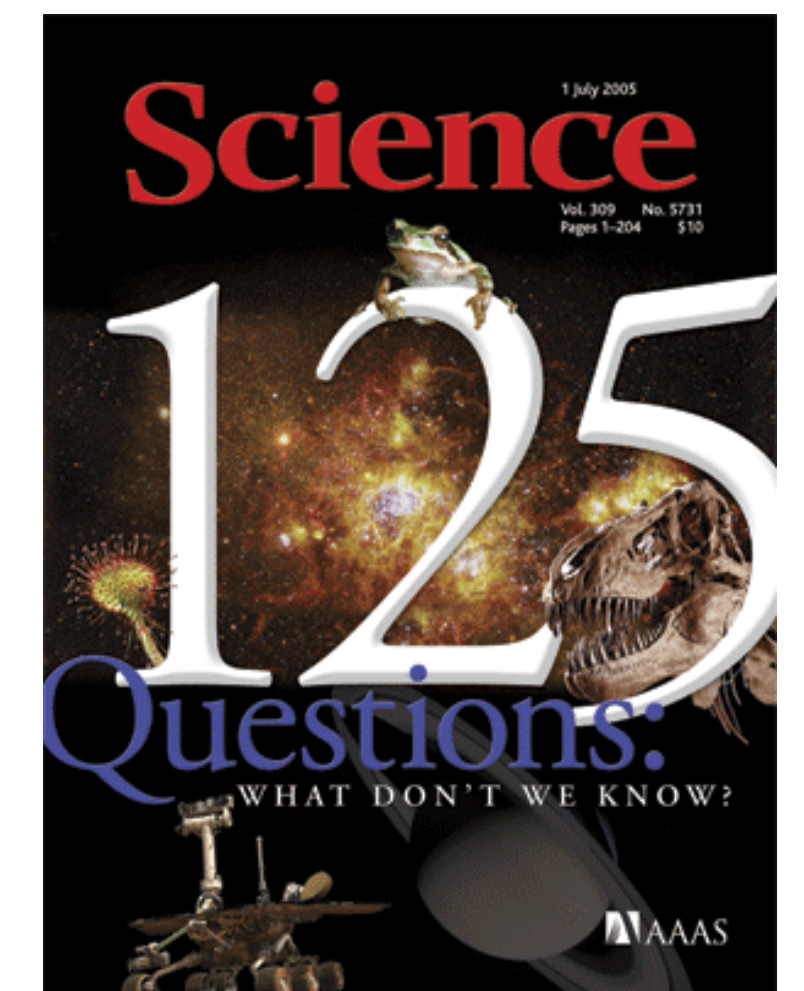
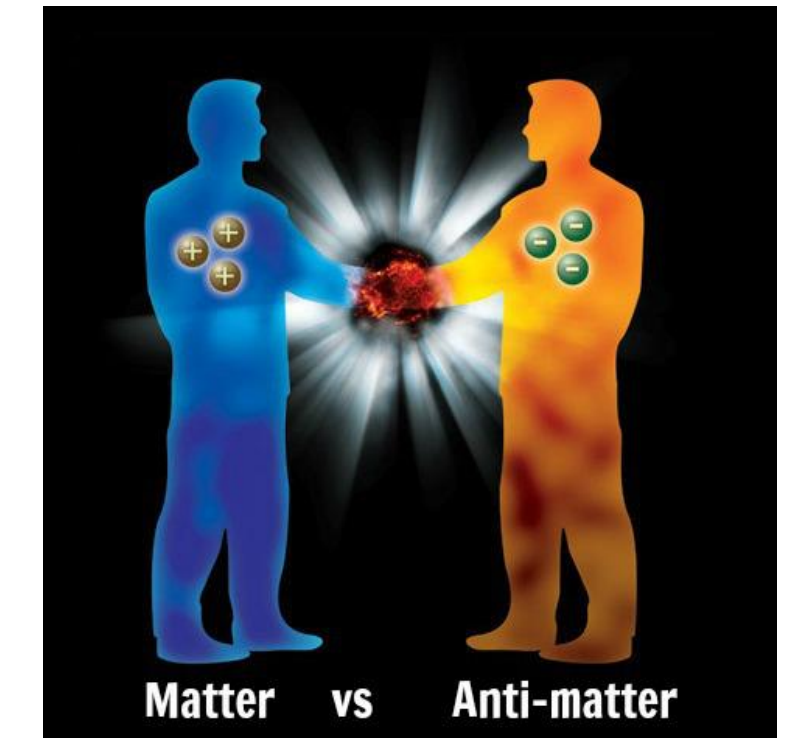
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- CPV is the most important issue in heavy flavor physics
- CPV well established in K, B and D mesons,
but CPV never established in any baryon
- **Key goal is to predict and search for baryon CPV**



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}
b baryons	10^{10}	—	10^{13}

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	$\rightarrow 2025$	$\rightarrow 2030$
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	2011	2012	2018	2023	2029	2035
LHCb	Run I		Run II	Run III	Run IV	Run V
Integrated luminosity	1 fb ⁻¹	3 fb ⁻¹	9 fb ⁻¹	23 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹

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- BESIII and Belle II have fruitful results on charmed baryons and hyperons

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

Theoretical opportunities

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- **Baryons are very different from mesons!!**
- **Helicities** of baryons provide fruitful phenomenological observables.
 More information can be obtained from the angular distributions and polarizations.
 Few body for more observables.
- 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 $\Lambda_b \rightarrow \Lambda_c$ than $B \rightarrow D^{(*)}$ transitions [Bernlochner, Ligeti, Robinson, Sutcliffe, 2019]

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

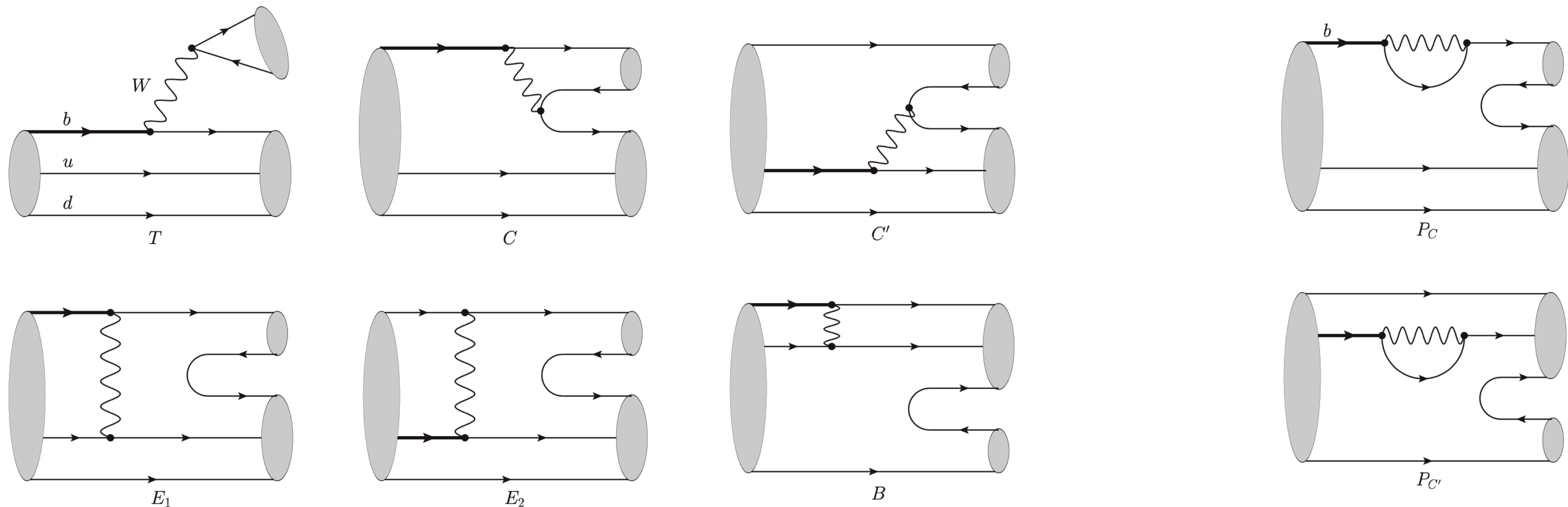
- **QCD studies on baryons are limited**
- **Generalized factorization** [Hsiao, Geng, 2015; Liu, Geng, 2021]:
lost of non-factorizable contributions, such as W-exchange diagrams.
- **QCDF** [Zhu, Ke, Wei, 2016, 2018]: based on diquark picture.
- **PQCD** [Lu, Wang, Zou, Ali, Kramer, 2009]: only consider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

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

大有可为!

Theoretical challenges

- Topological diagrams: more diagrams than mesons.



- **More non-factorizable diagrams: C' , E_1 , E_2 , B . They are non-negligible.**

$$\frac{|C|}{|T|} \sim \frac{|C'|}{|C|} \sim \frac{|E_1|}{|C|} \sim \frac{|E_2|}{|C|} \sim O\left(\frac{\Lambda_{\text{QCD}}^h}{m_Q}\right)$$

Leibovich, Ligeti, Stewart, 2004

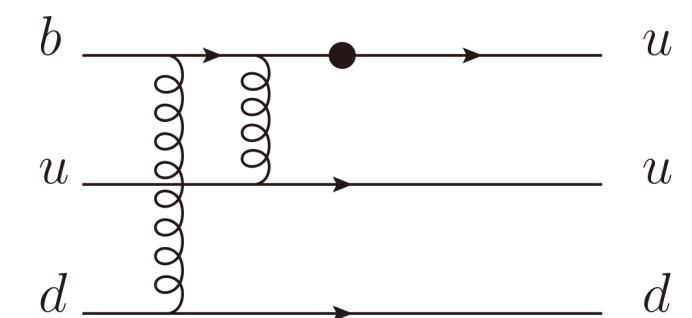
Theoretical progresses: PQCD

- 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]	$2.2_{-0.5}^{+0.8} \times 10^{-3}$	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 $\Lambda_b \rightarrow p\pi, pK$,” Phys. Rev. D **80**, 034011 (2009) [arXiv:0906.1479 [hep-ph]].

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[76] R. Mohanta, A. K. Giri and M. P. Khanna, “Charmless two-body hadronic decays of Λ_b baryon,” Phys. Rev. D **63**, 074001 (2001) [arXiv:hep-ph/0006109 [hep-ph]].

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[78] M. q. Huang and D. W. Wang, “Light cone QCD sum rules for the semileptonic decay $\Lambda_b \rightarrow p\ell\bar{\nu}$,” 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						
		twist-3	twist-4	twist-5	twist-6	total
Λ_b	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 ± 0.09 ± 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 ± 0.07 ± 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

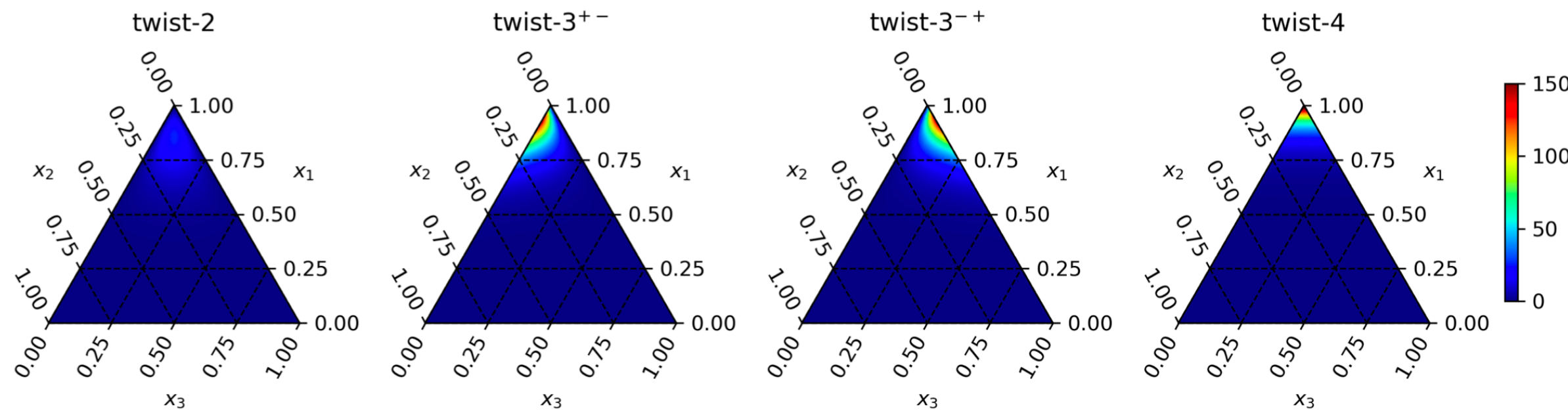
Theoretical progresses: PQCD

- 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

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



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

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

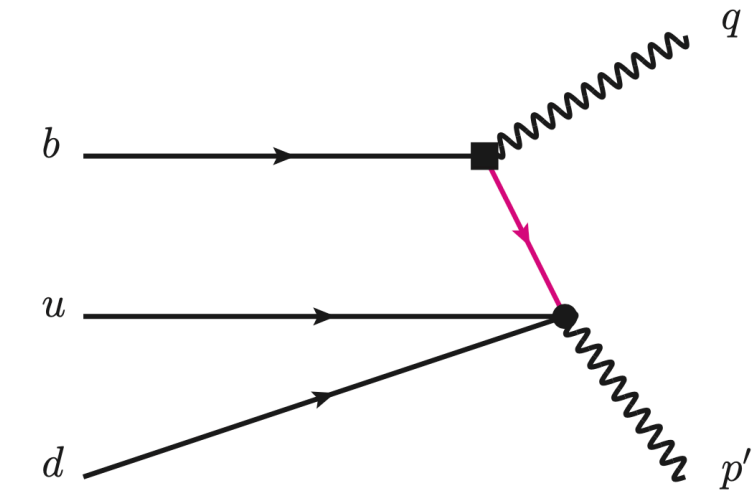
- Heavy-to-light form factors have been systematically studied in the light-cone sum rules (LCSR)

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

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

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

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



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

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

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

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

Theoretical progresses: LCSR

$\Lambda_b \rightarrow p$

	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]	$0.023^{+0.006}_{-0.005}$	$-0.039^{+0.009}_{-0.009}$	$0.023^{+0.006}_{-0.005}$	$-0.039^{+0.009}_{-0.009}$
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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

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

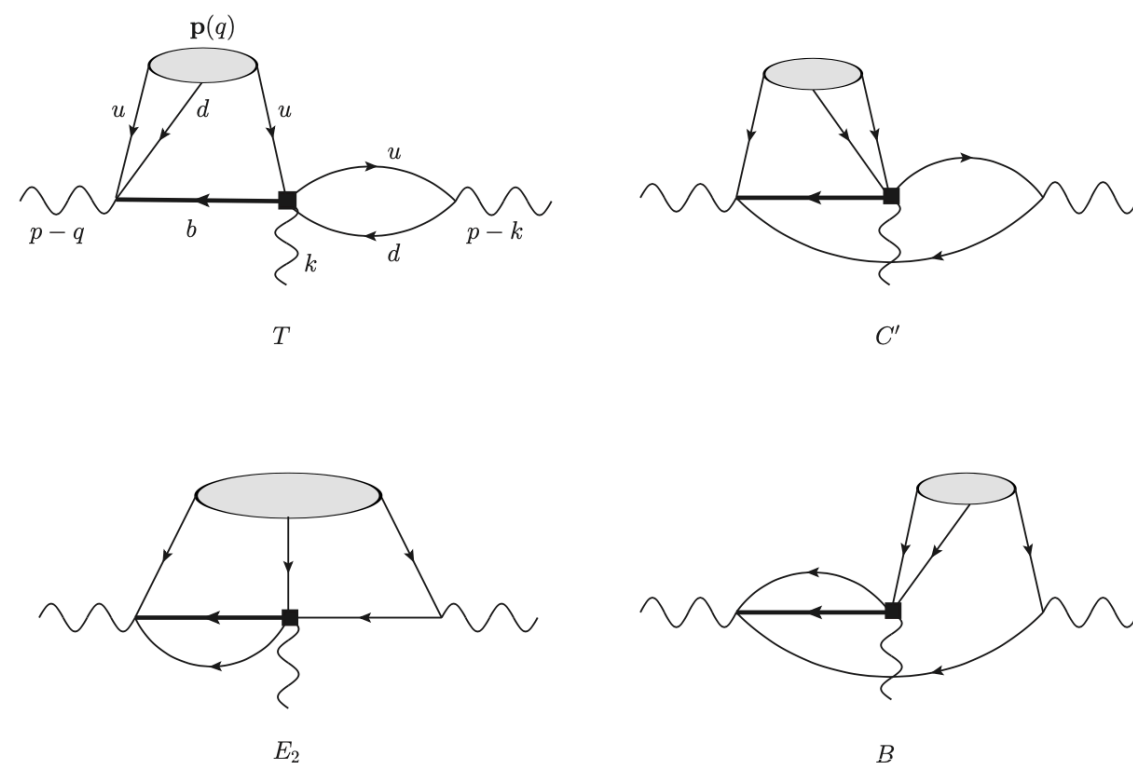
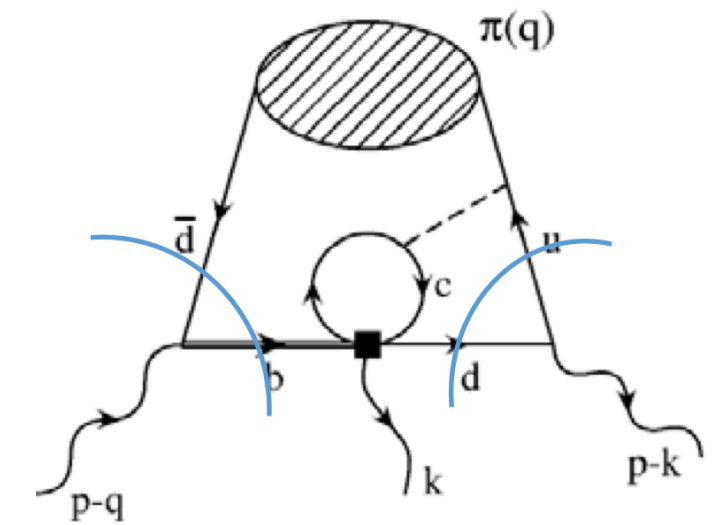
[K.S.Huang, W.Liu, Y.L.Shen, FSY, 2205.xxxxx]

$\Lambda_b \rightarrow N^*$

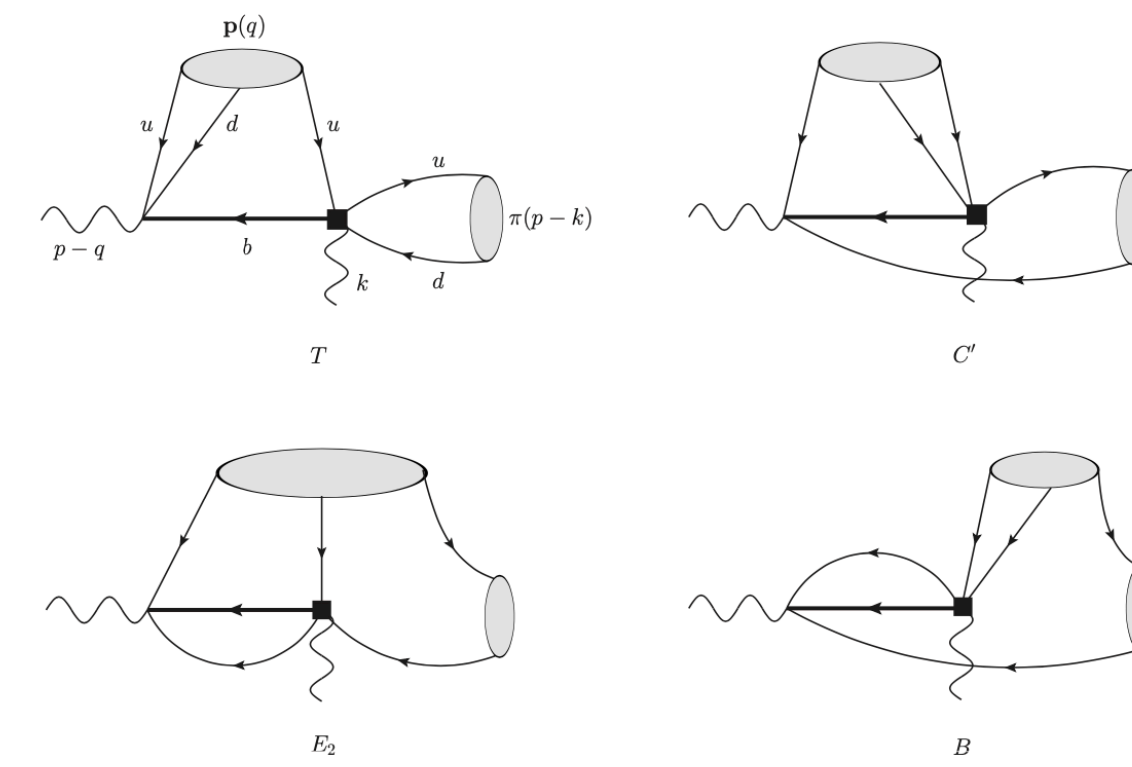
	F_1	F_2	G_1	G_2
Ioffe Current				
Gegenbauer-1	0.23 ± 0.57	0.002 ± 0.12	0.23 ± 0.57	0.002 ± 0.12
Gegenbauer-2	0.20 ± 0.15	0.009 ± 0.029	0.20 ± 0.15	0.009 ± 0.029
QCDSR	0.015 ± 0.021	0.019 ± 0.005	0.015 ± 0.021	0.019 ± 0.005
Exponential	0.029 ± 0.031	0.017 ± 0.008	0.029 ± 0.031	0.017 ± 0.008
Free-parton	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 $\Lambda_b \rightarrow p\pi, pK$ are studied firstly in LCSRs**
[H.Y.Jiang, Khodjamirian, FSY, S.Cheng, in preparation]
- LCSR has been studied in $B \rightarrow \pi\pi$ [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	$\Lambda_b \rightarrow p\pi$	$\Lambda_b \rightarrow pK$
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

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

$$M_1(x_2, x_3) = \frac{\not{x}_2 \not{x}_3}{4} \psi_3^{+-}(x_2, x_3) + \frac{\not{x}_3 \not{x}_2}{4} \psi_3^{-+}(x_2, x_3),$$

$$M_2(x_2, x_3) = \frac{\not{x}_2}{\sqrt{2}} \psi_2(x_2, x_3) + \frac{\not{x}_3}{\sqrt{2}} \psi_4(x_2, x_3),$$

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

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

Light-Cone Distribution Amplitudes: Λ_b

Model-I: Gegenbauer-1

$$\begin{aligned}\psi_2(x_2, x_3) &= m_{\Lambda_b}^4 x_2 x_3 \left[\frac{1}{\epsilon_0^4} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_0} + a_2 C_2^{3/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) \frac{1}{\epsilon_1^4} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_1} \right] \\ \psi_3^{+-}(x_2, x_3) &= \frac{2m_{\Lambda_b}^3 x_2}{\epsilon_3^3} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_3}, \\ \psi_3^{-+}(x_2, x_3) &= \frac{2m_{\Lambda_b}^3 x_3}{\epsilon_3^3} e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_3}, \\ \psi_4(x_2, x_3) &= \frac{5}{\mathcal{N}} m_{\Lambda_b}^2 \int_{m_{\Lambda_b}(x_2+x_3)/2}^{s_0} ds e^{-s/\tau} (s - m_{\Lambda_b}(x_2 + x_3)/2)^3,\end{aligned}$$

Ball, Braun, Gardi, 0804.2424, PLB 2008

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

Model-II: Gegenbauer-2

$$\begin{aligned}\psi_2(x_2, x_3) &= m_{\Lambda_b}^4 x_2 x_3 \frac{a_2^{(2)}}{\epsilon_2^{(2)4}} C_2^{3/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(2)}}, \\ \psi_3^{+-}(x_2, x_3) &= m_{\Lambda_b}^3 (x_2 + x_3) \left[\frac{a_2^{(3)}}{\epsilon_2^{(3)3}} C_2^{1/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(3)}} + \frac{b_3^{(3)}}{\eta_3^{(3)3}} C_2^{1/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\eta_3^{(3)}} \right] \\ \psi_3^{-+}(x_2, x_3) &= m_{\Lambda_b}^3 (x_2 + x_3) \left[\frac{a_2^{(3)}}{\epsilon_2^{(3)3}} C_2^{1/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(3)}} - \frac{b_3^{(3)}}{\eta_3^{(3)3}} C_2^{1/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\eta_3^{(3)}} \right] \\ \psi_4(x_2, x_3) &= m_{\Lambda_b}^2 \frac{a_2^{(4)}}{\epsilon_2^{(4)2}} C_2^{1/2} \left(\frac{x_2 - x_3}{x_2 + x_3} \right) e^{-m_{\Lambda_b}(x_2+x_3)/\epsilon_2^{(4)}},\end{aligned}$$

Ali, Hambrock, Parkhomenko, 2012

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

Light-Cone Distribution Amplitudes: Λ_b

Model-III: Exponential

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

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

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

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

$$\omega_0 = 0.4 \text{ GeV}$$

Model-IV: Free Parton

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

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

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

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

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

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

Light-Cone Distribution Amplitudes: **proton**

$$\begin{aligned}
 (\bar{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}{2P_z} (C \not{z})_{\beta\alpha} (\bar{N}^+ \gamma_5)_{\gamma} \\
 & + V_6 \frac{m_p^2}{2P_z} (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}{2P_z} (C \gamma_5 \not{z})_{\beta\alpha} (\bar{N}^+)_{\gamma} \\
 & - A_6 \frac{m_p^2}{2P_z} (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}{P_z} (iC \sigma_{Pz})_{\beta\alpha} (\bar{N}^+ \gamma_5)_{\gamma} - T_4 \frac{m_p}{P_z} (iC \sigma_{zP})_{\beta\alpha} (\bar{N}^- \gamma_5)_{\gamma} - T_5 \frac{m_p^2}{2P_z} (iC \sigma_{\perp z})_{\beta\alpha} (\bar{N}^+ \gamma_5 \gamma^{\perp})_{\gamma} \\
 & - T_6 \frac{m_p^2}{2P_z} (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

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

- Twist-5 LCDAs

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

- 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

