NARODOWA AGENCJA
WYMIANY AKADEMICKIEJ

Hyperon non-leptonic decays in χPT, revisited

Joint collaboration between NCBJ, UU, IFIC

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UPPSALA UNIVERSITET
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Nora Salone | Stefan Leupold | Fernando Alvarado Àlvarez

What are the hyperons?

- They are qqq systems with at least one strange quark.

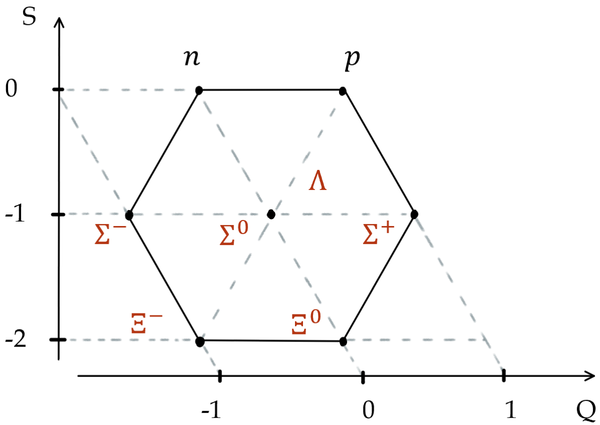

Figure: Baryon octet (spin = $\frac{1}{2}$).

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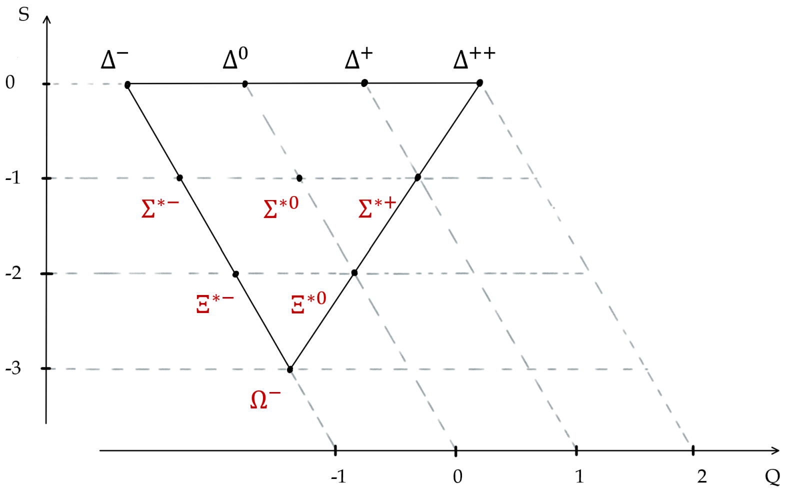

Figure: Baryon decuplet (spin = $\frac{3}{2}$).

What are the hyperons? (cont.)

- 1961 - Gell-Mann and Ne'eman, "The Eightfold Way".
- These multiplets arise from possible combinations of the three lightest quark flavors u, d, s.
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$$\begin{pmatrix} \frac{2u\overline{u}-d\overline{d}-s\overline{s}}{3} & u\overline{d} & u\overline{s} \\ d\overline{u} & \frac{-u\overline{u}+2d\overline{d}-s\overline{s}}{3} & d\overline{s} \\ s\overline{u} & s\overline{d} & \frac{-u\overline{u}-d\overline{d}+2s\overline{s}}{3} \end{pmatrix}$$

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- For $q\overline{q}$ systems:

$$\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

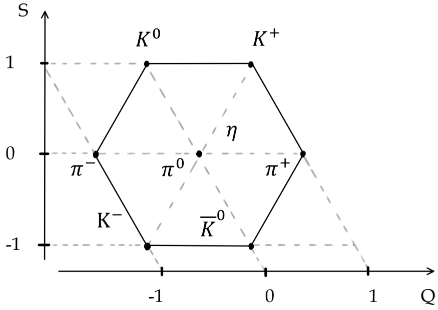
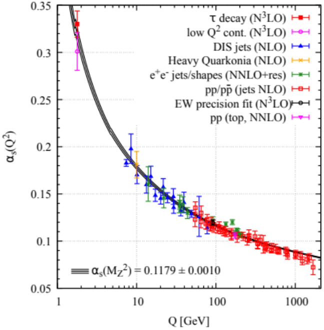


Figure: Meson octet (spin = 0).

Why the hyperon sector?

- Most of the observed mass in our Universe is composed of stable nuclei containing protons and neutrons.
- How do the quarks interact inside the hadrons? Different energy range implies different behavior.

Zyla et al. (PDG), (2020)



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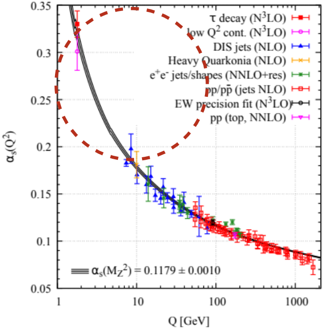

- α_s is the "running" coupling of the strong interaction (QCD).
- The lower the energy, the larger α_s is: *confinement* regime.

Perturbation theory

- The interaction between the DFs of our theory is written as a **Taylor series** in the expansion parameter, i.e. the strong coupling α_s.
- The validity of the approximation depends on whether $\alpha_s << 1$:

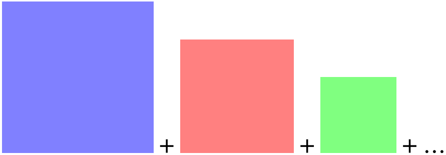

Figure: Credit Astrid Blin

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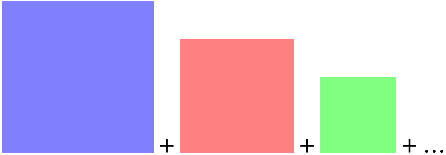

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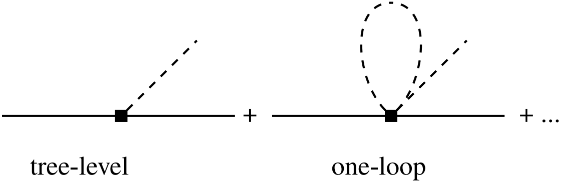

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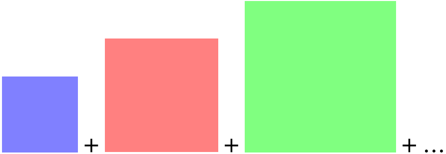

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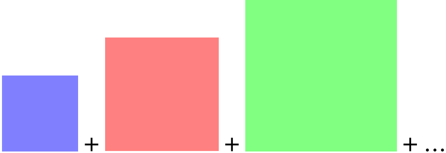

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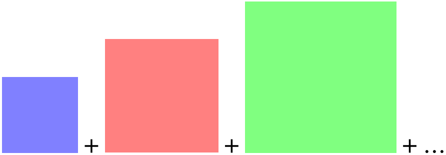

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But in the meantime...

Spontaneous symmetry breaking

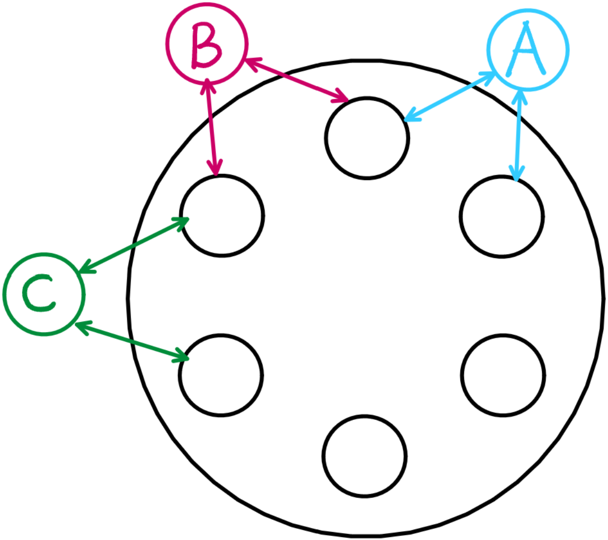

Figure: Example from A. Salam, adapted by S. Leupold in "QCD and EFT" course, UU.

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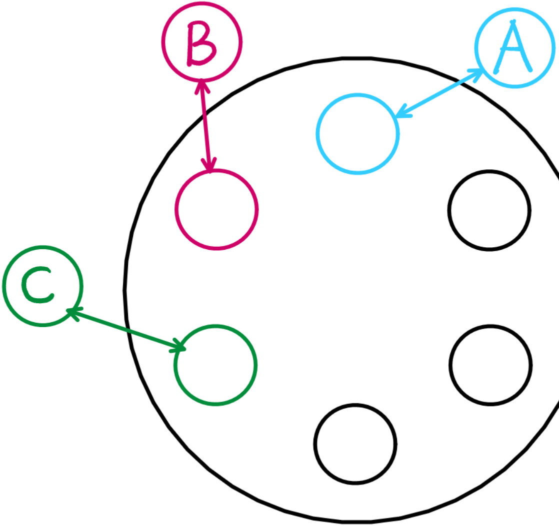

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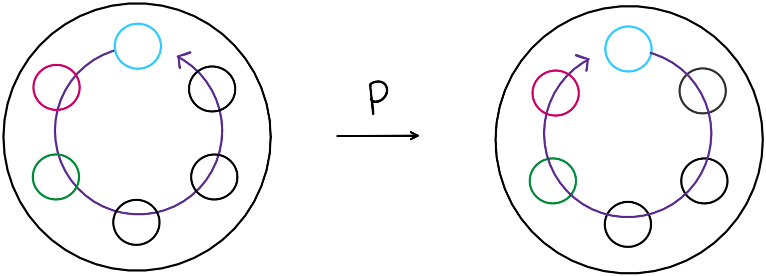

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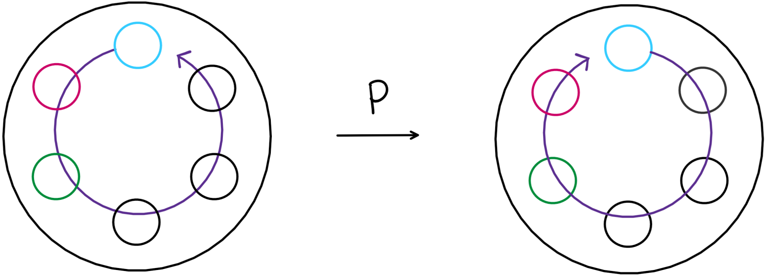

The ground state (the dinner) does not possess the same symmetry of the initial Lagrangian (the dinner table).

SSB (cont.)

Feature A

A physical theory may have a symmetry group = it is left **unchanged** by transformations that belong to that group.

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Feature B

For every broken symmetry, **massless DF's** arise: **Goldstone bosons**.

Some particle properties

- **Helicity**: projection of spin vector on momentum direction.

$$\xrightarrow[s_Y\ \longrightarrow]{\quad\vec{p}_Y\quad} \qquad \text{right-handed}$$

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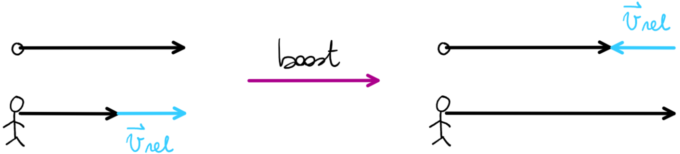

Figure: Massive particle under Lorentz boost, picture from this video.

Chiral perturbation theory

- Vacuum expectation value (VEV), or **ground state**

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Treatment idea: $m_{u,d,s} << \Lambda_{\rm QCD} \sim 1$ GeV.

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  $$\langle 0|\overline{q}q|0\rangle \neq 0 \quad \textbf{NOT invariant!}$$

  This is caused by **spontaneous breaking** of chiral symmetry.

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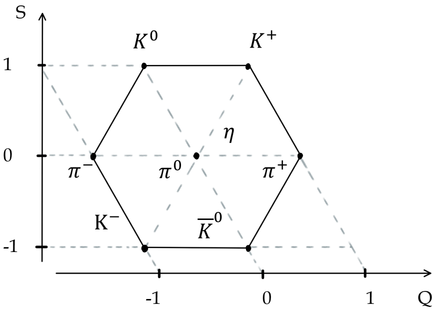
The "massless" Goldstone bosons are the pseudoscalar **octet** mesons!



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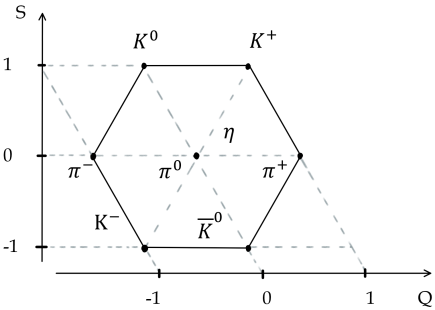
Approximate symmetry: in reality $m_q \neq 0$, but at these energies the approximation is **quite good**.



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Motivation

- Polarization parameter α_Λ at BESIII ($B\overline{B}$ production) was found 17% higher than world average [Nature Physics 15 (2019)], [PRL 129, 131801 (2022)]

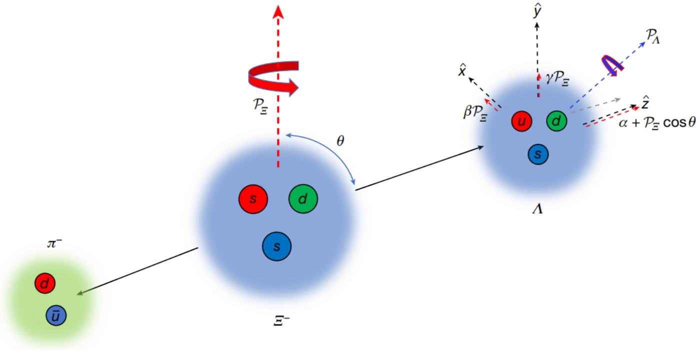

Figure: Sequential decay of produced baryon at BESIII [Nature Physics 606 (2022)].

Decay angular distribution $$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_i \vec{P}_i \cdot \hat{p}_i, \quad i = \Lambda, \Xi$$

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Updated α implies updated amplitude value, **updated parameters** of our theory!

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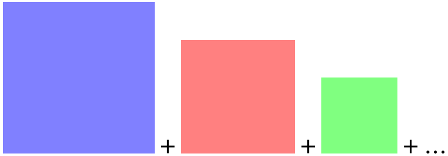

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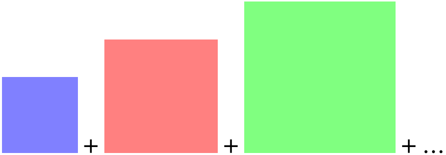

Procedure

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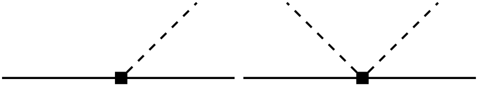

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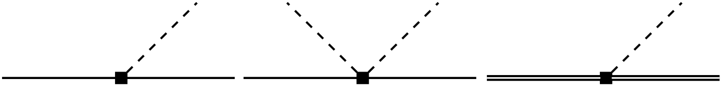

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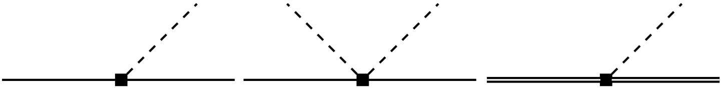

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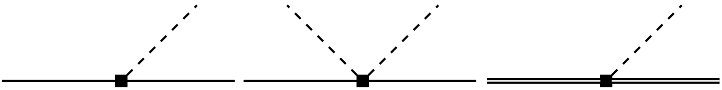

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From experimental data:

$$S_{\text{expt}}, \; P_{\text{expt}} = f(\alpha, \Gamma)$$

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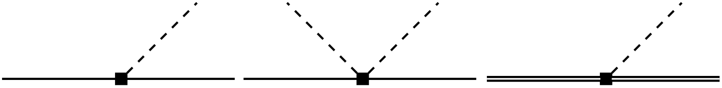

The resulting amplitudes:

$$S_{\rm theory},\ P_{\rm theory} = a\ h_D + b\ h_F + c\ h_C$$

From experimental data:

$$S_{\rm expt},\ P_{\rm expt} = f(\alpha, \Gamma)$$

Goal

To fit $S_{\rm theory}$ to $S_{\rm expt}$ using least squares method to obtain values of $h_{D,F,C}$.

S-wave diagrams

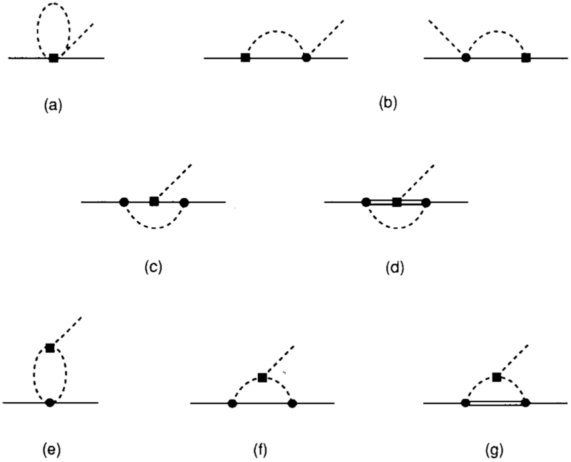

Figure: S-wave 1-loop corrections, Jenkins, [Nucl. Phys. B 375 (1992)]

P-wave diagrams

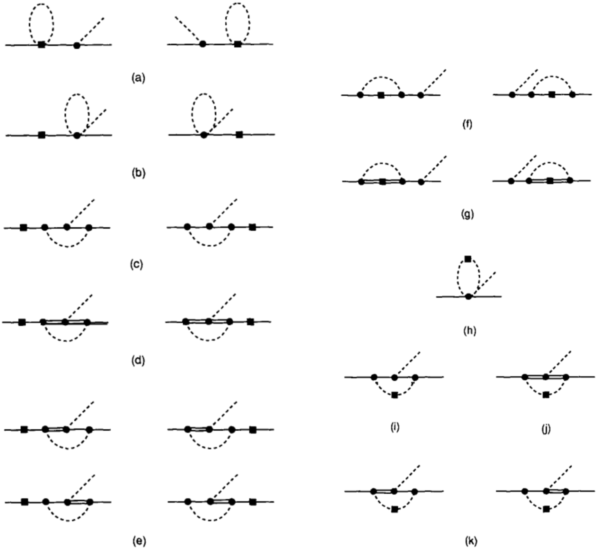

Figure: P-wave 1-loop corrections, Jenkins, [Nucl. Phys. B 375 (1992)]

Subject of study

- $\Delta S = 1$ transitions:
  - $\Sigma^+ \to n\pi^+$
  - $\Sigma^- \to n\pi^-$
  - $\Lambda \to p\pi^-$
  - $\Xi^- \to \Lambda\pi^-$

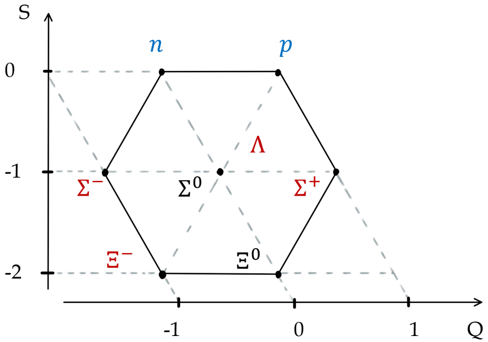

Figure: Baryon octet (spin = $\frac{1}{2}$).

- **Old works**: [Nucl. Phys. B 375 (1992)], [PRD 61, 114014 (2000)], [EPJC 6 (1999)]: *heavy-baryon approximation*, non-relativistic.

Preliminary results

Directly from the updated measurements of the decay asymmetry parameter α, decay width Γ, the new values of S_{expt}, P_{expt} are

Decay	S	S_{old}	P	P_{old}
$\Sigma^+ \to n\pi^+$	0.06 ± 0.01	0.06 ± 0.01	1.81 ± 0.01	1.81 ± 0.01
$\Sigma^+ \to p\pi^0$	-1.39 ± 0.02	-1.43 ± 0.05	1.25 ± 0.03	1.17 ± 0.07
$\Sigma^- \to n\pi^-$	1.91 ± 0.01	1.88 ± 0.01	-0.07 ± 0.01	-0.06 ± 0.01
$\Lambda \to p\pi^-$	1.38 ± 0.01	1.42 ± 0.01	0.63 ± 0.01	0.52 ± 0.02
$\Lambda \to n\pi^0$	-1.05 ± 0.01	-1.04 ± 0.01	-0.42 ± 0.01	-0.39 ± 0.04
$\Xi^- \to \Lambda\pi^-$	-2.00 ± 0.01	-1.98 ± 0.01	0.39 ± 0.01	0.48 ± 0.02
$\Xi^0 \to \Lambda\pi^0$	1.51 ± 0.01	1.52 ± 0.02	0.27 ± 0.01	-0.33 ± 0.02

Table: Comparison between amplitude values [NPB 375 (1992)].

These are the new reference values for these amplitudes.

Preliminary results (cont.)

Next step:

- We take the full amplitude:

$$S_{\text{theory}} = S_{\text{tree}} + S_{\text{loop}}$$

and fit it to the new reference values S_{expt} to obtain new $h_{D,F,C}$ values.

Preliminary results (cont.)

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- **Current issue**: in general, S, P may be complex, but the reference values are all real! Ideally,

$$\Im[\mathcal{M}] << \Re[\mathcal{M}]$$

  This might have to do with the renormalization procedure, probably missing counterterms: <u>currently under discussion</u>.

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Thank you for your attention!