TOWARDS A DESCRIPTION OF DIBARYONS FROM FUNCTIONAL METHODS

Joshua Hoffer

9. September 2026
NSTAR 2026, Seville, Spain

HADRONS

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Conventional

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Exotic

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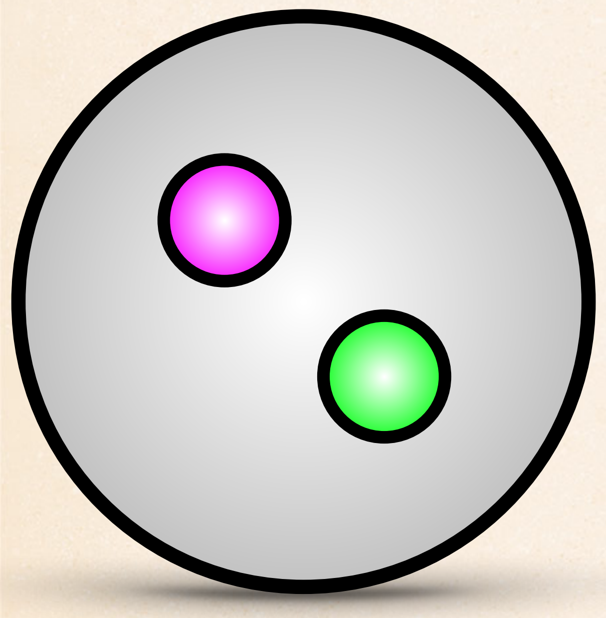
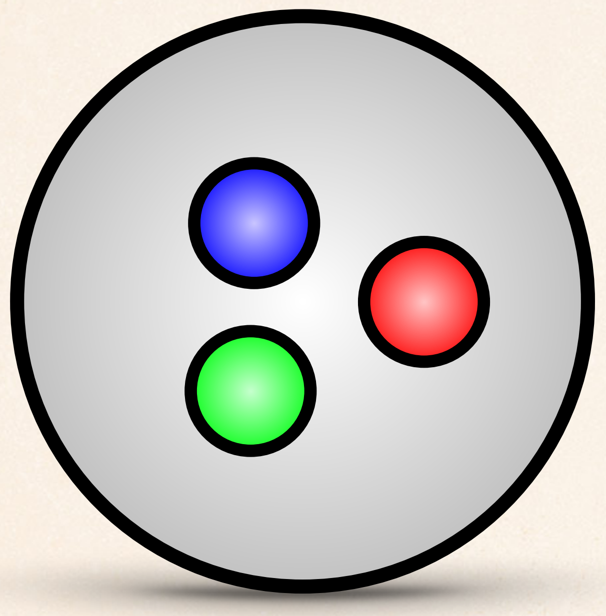
Conventional



Meson



Baryon

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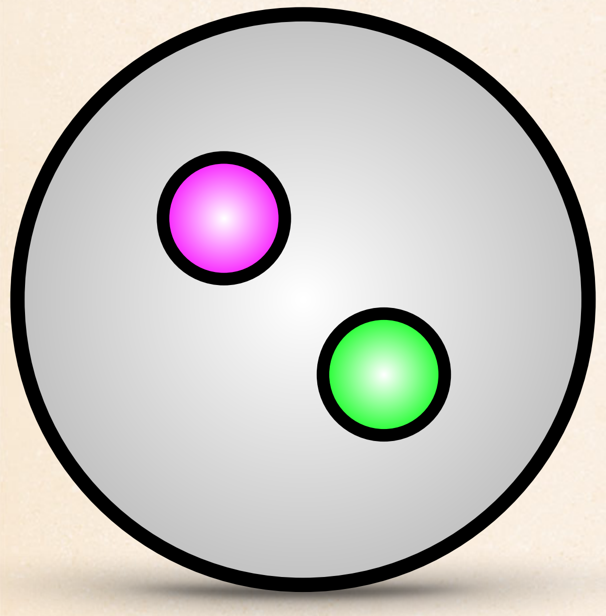

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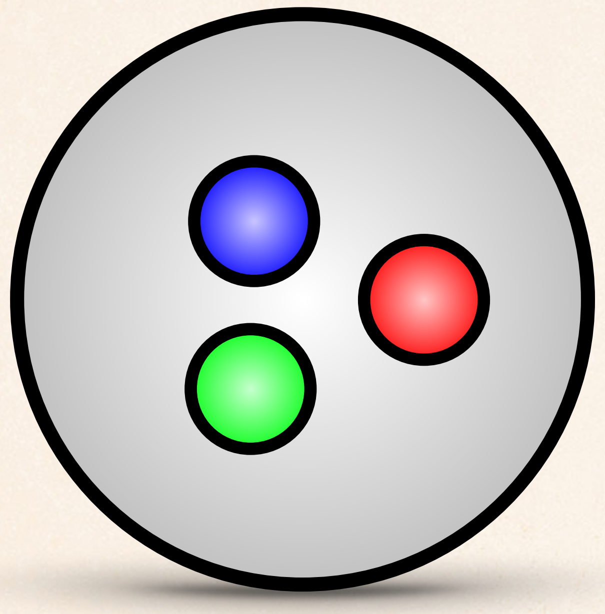
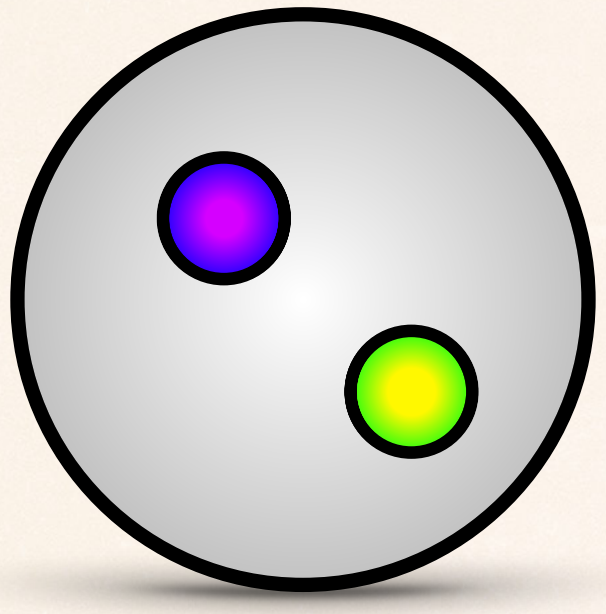


Baryon



Glueball

Exotic

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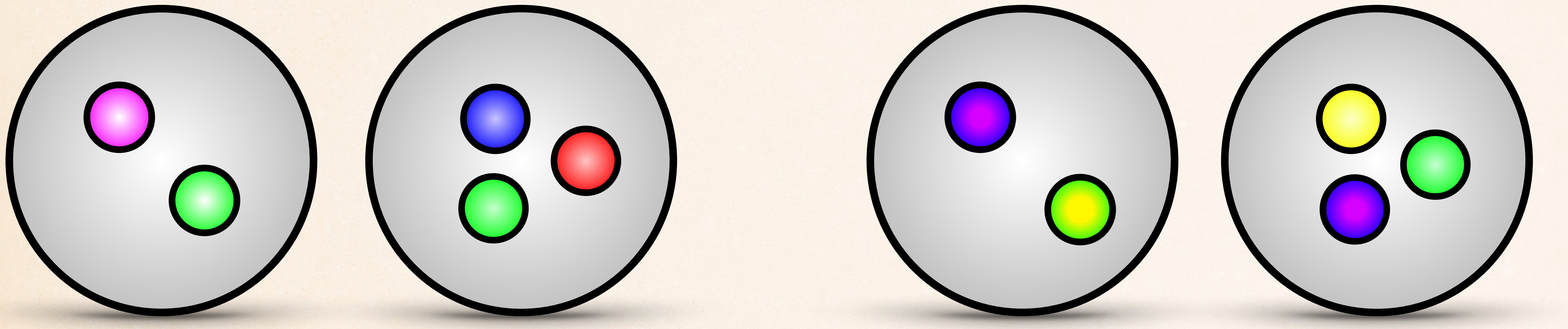

Meson Baryon Glueball Hybrid

HADRONS

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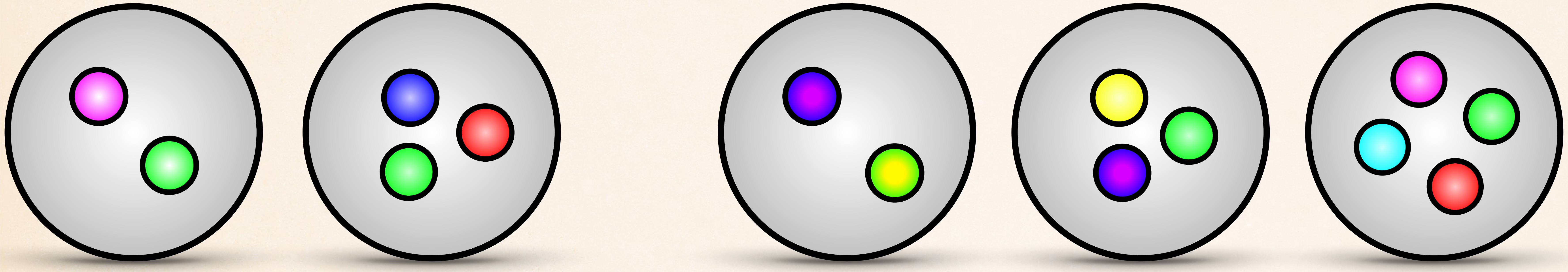

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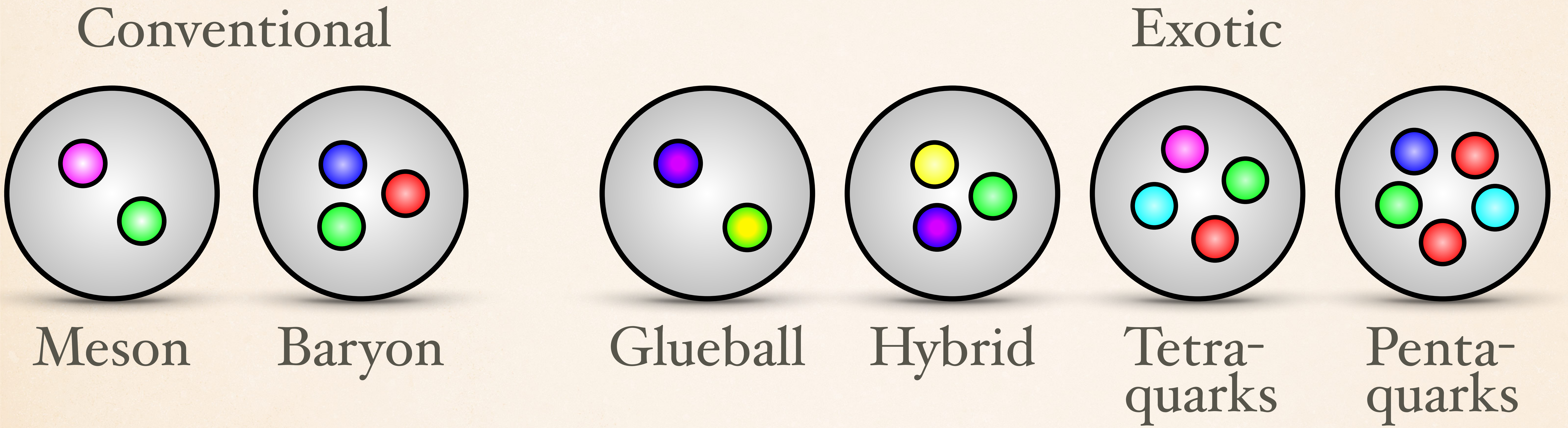
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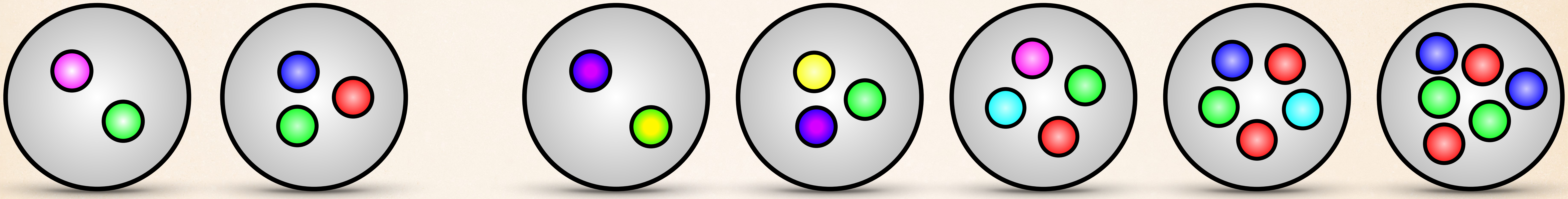

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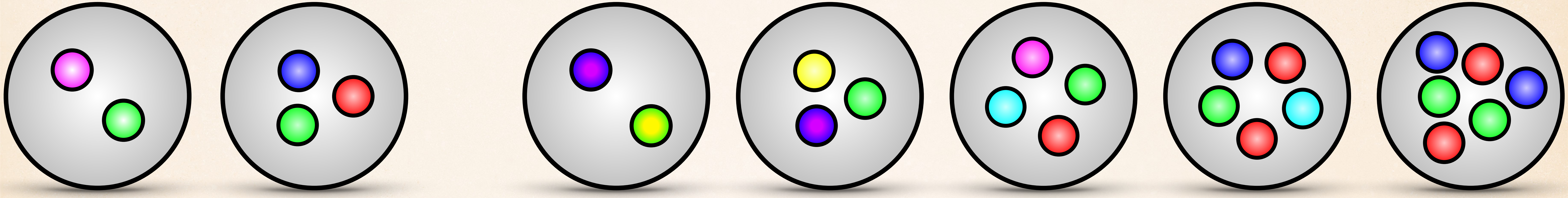

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Overview see talk Gernot Eichmann

HADRONS

see talk Angel Miramontes

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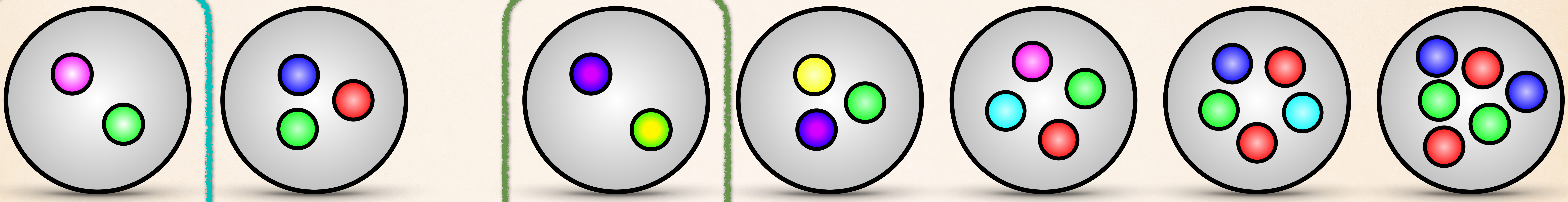

see talk Markus Huber

see talk Angel Miramontes

Overview see talk Gernot Eichmann

HADRONS

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Overview see talk Gernot Eichmann

HADRONS


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Hexaquark
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Overview see talk Gernot Eichmann

HEXAQUARKS

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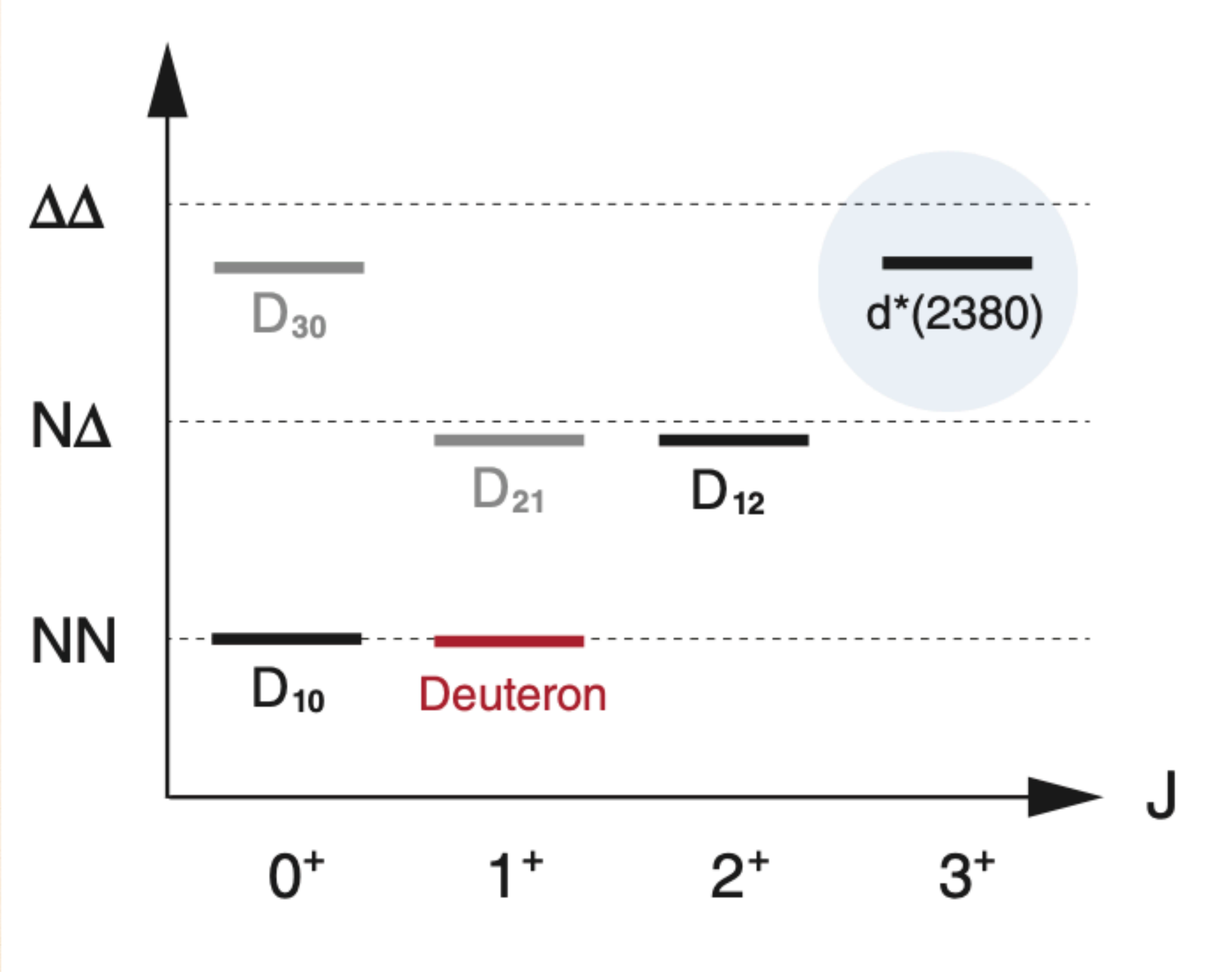
- Many interesting particles:
  - Deuteron and its cousins, Diproton (Helium 2), Neutronium
  - H-dibaryon, all-charm dibaryons



Dyson, Xuong, PRL 13 (1964)
Adlarson et al., PRL 106 (2011), PRL 112 (2014),
Bashkanov, Brodsky, Clement, PLB 727 (2013),
Gal, Garcilazo, PRL 111(2013), . . .

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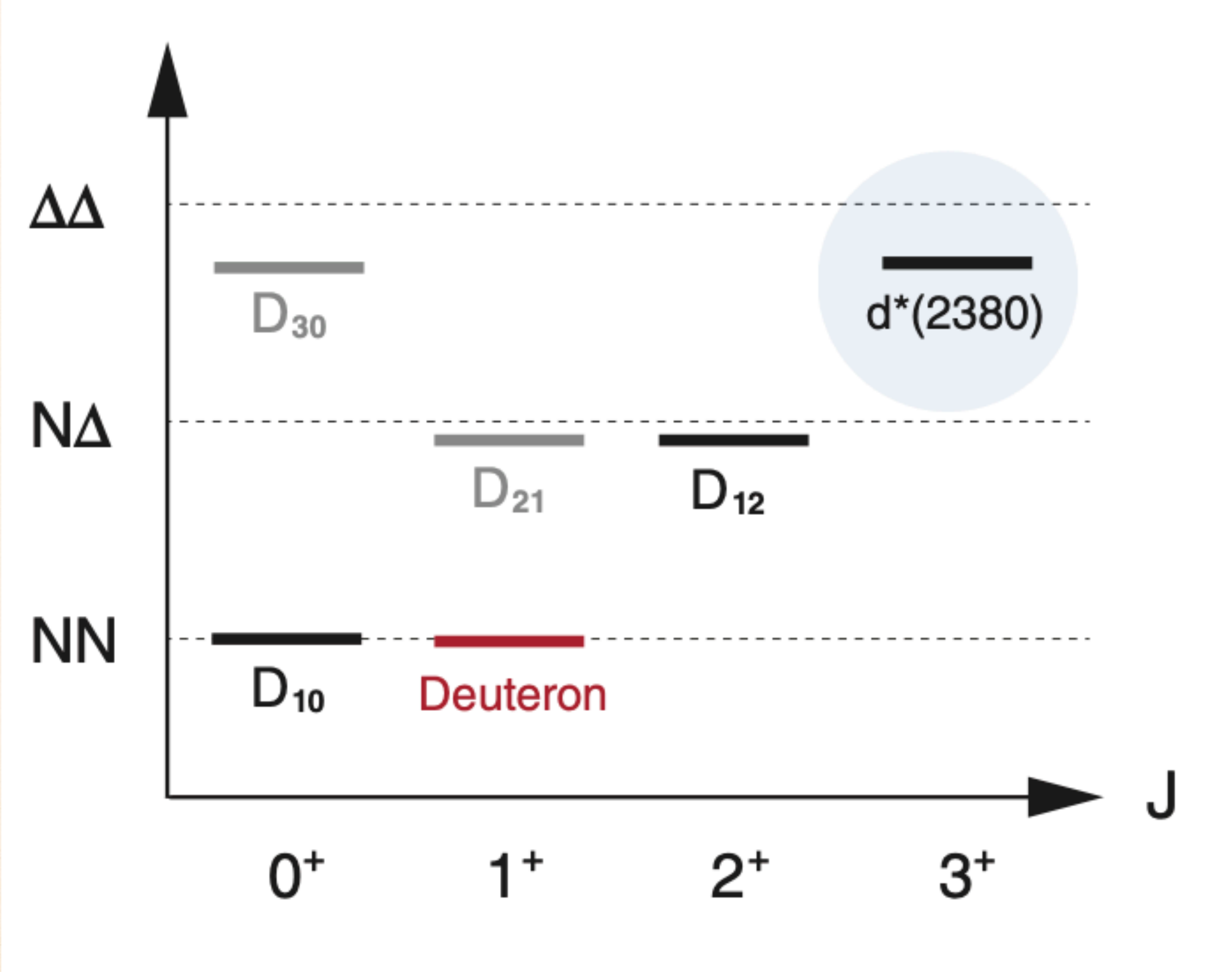

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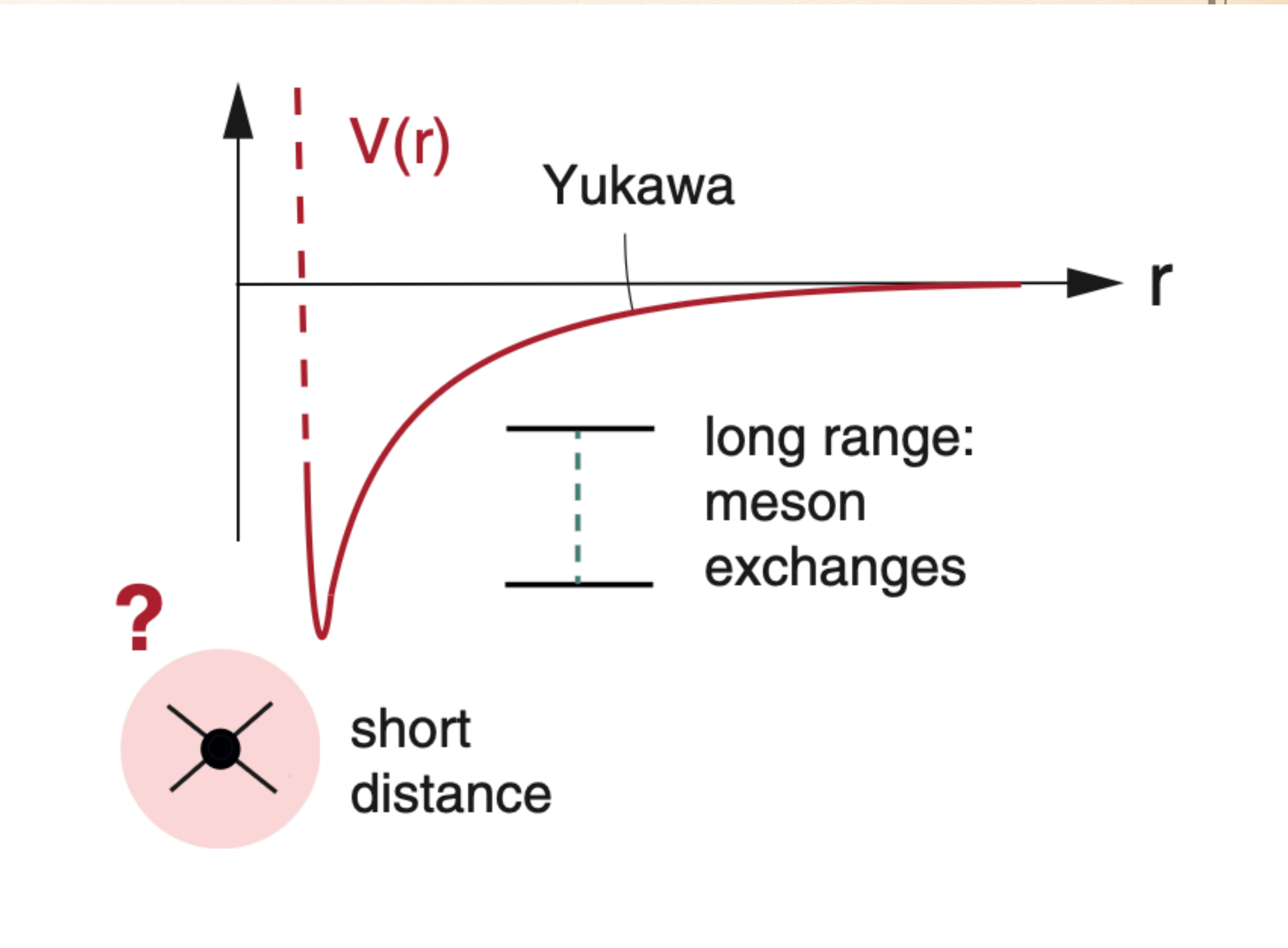
- Many interesting particles:
  - Deuteron and its cousins, Diproton (Helium 2), Neutronium
  - H-dibaryon, all-charm dibaryons
- Study spectrum from quark and gluon level
- Investigate Microscopic origins of short-range nuclear force

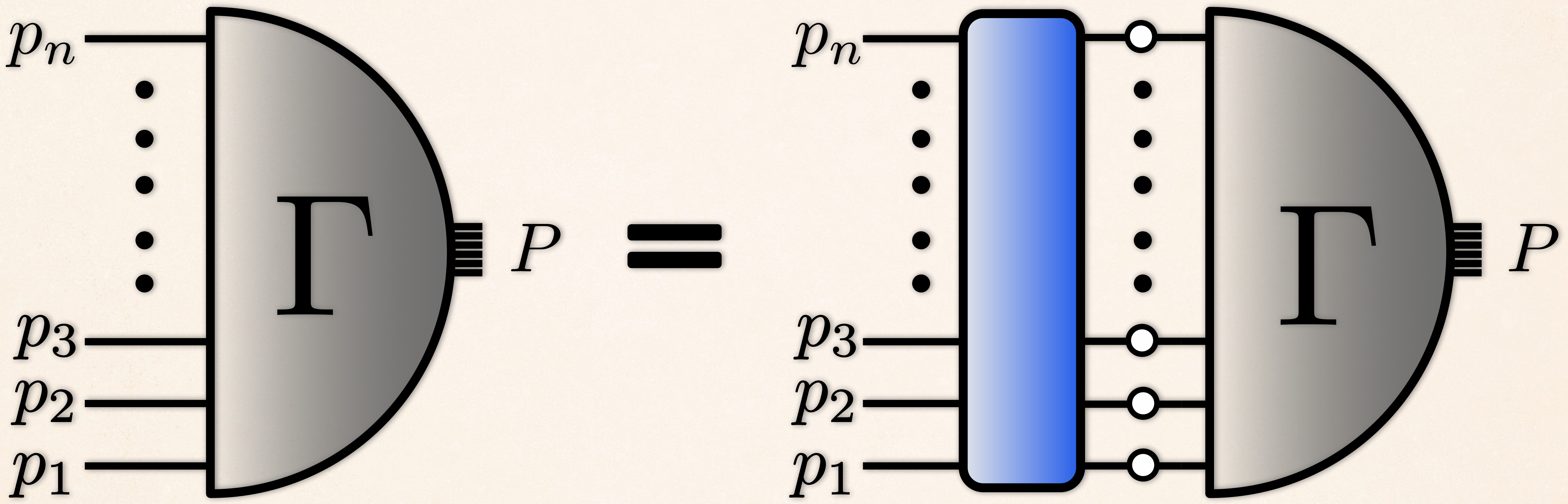


FUNCTIONAL FRAMEWORK

- Fully relativistic
- Non-perturbative
- Exact QCD n-point functions (need to be truncated later)
- Flexible framework
  - Easily adjustable regarding different quark flavours and tensors
  - Evaluate importance of different diagrams for the equation

FUNCTIONAL FRAMEWORK

- Properties of Hadrons from Hadronic bound state equations



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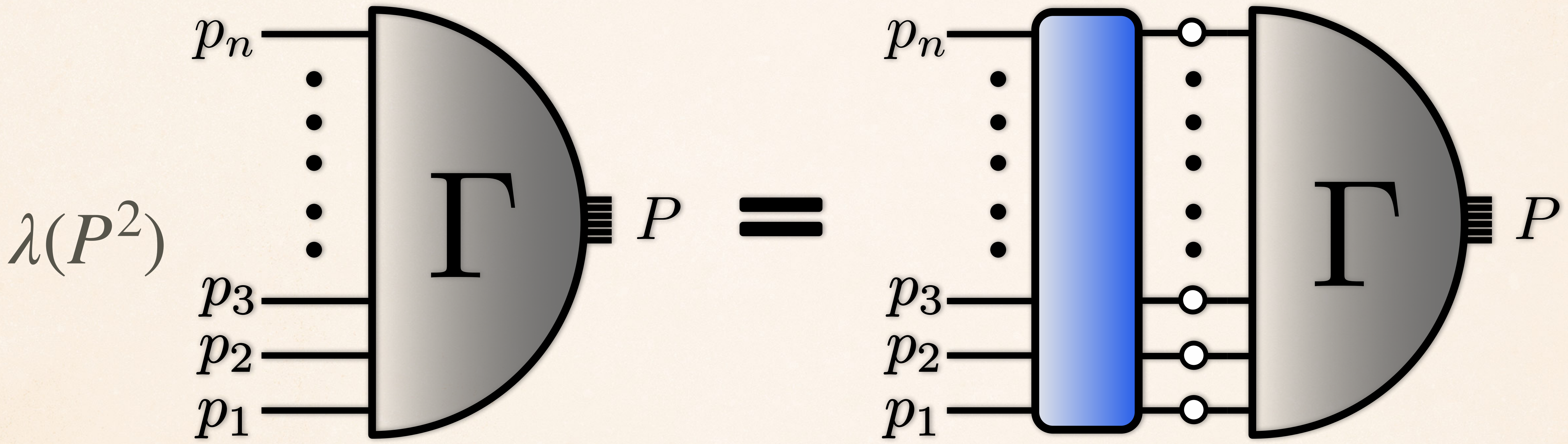

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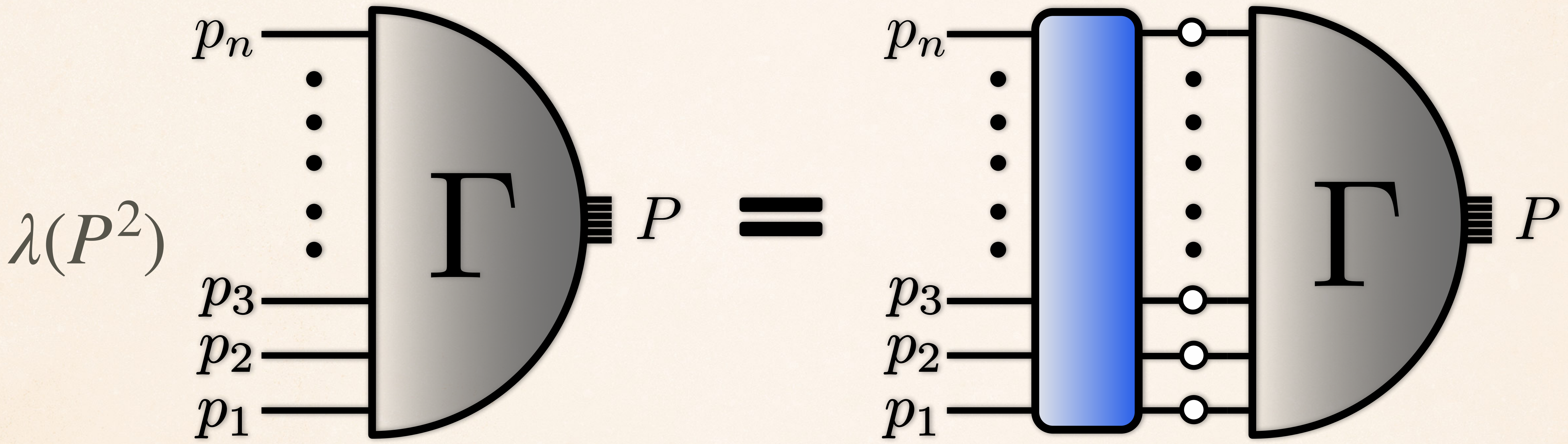

$$\boxed{\lambda(P^2)\,\Gamma = KG\,\Gamma}$$

FUNCTIONAL FRAMEWORK

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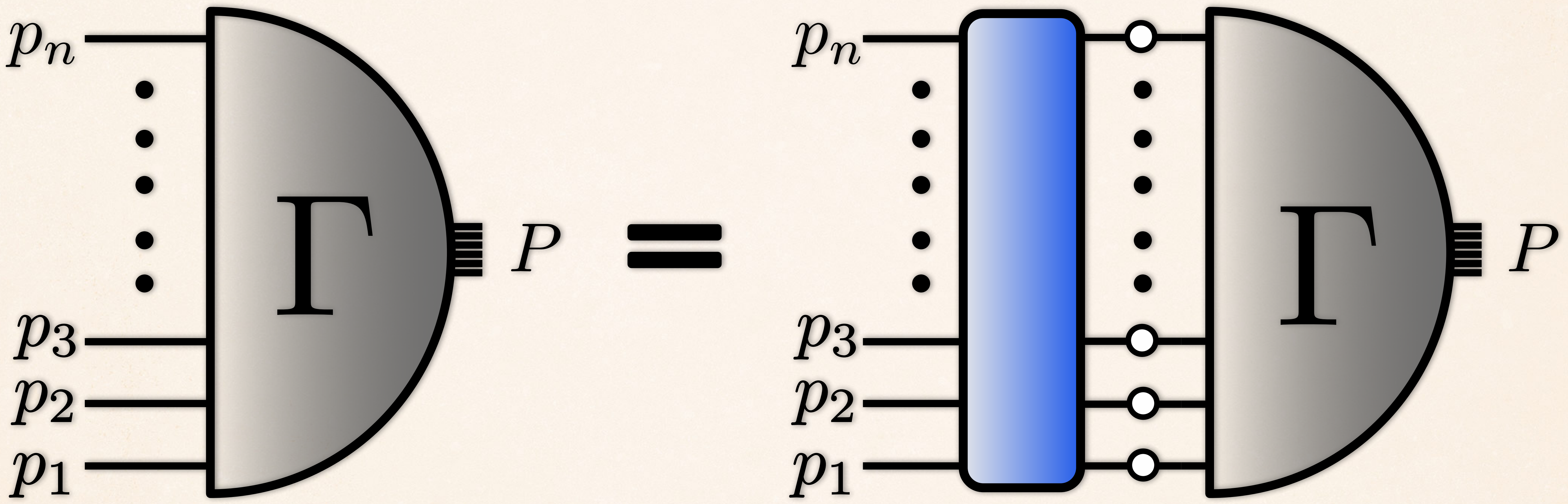
$\lambda(P^2)$



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with $\lambda(P^2 = -M^2) = 1$

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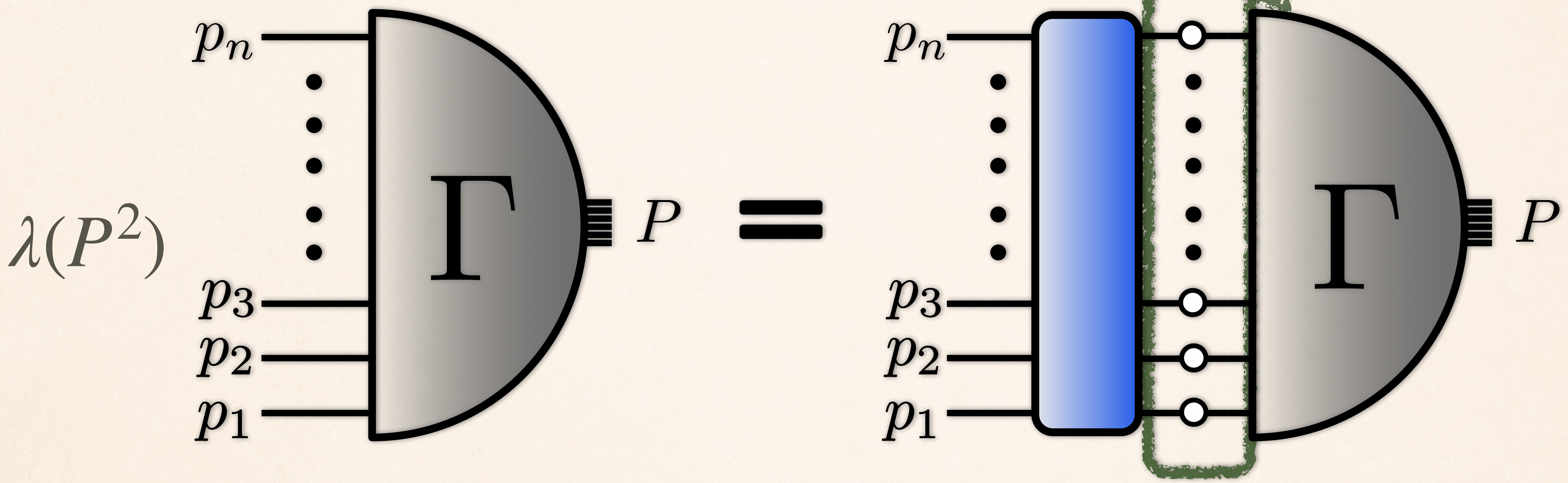

Full quark propagators as input

$$\lambda(P^2)\,\Gamma = KG\,\Gamma$$

with $\lambda(P^2 = -M^2) = 1$

FUNCTIONAL FRAMEWORK

- As an input: quantum equations of motion → Dyson-Schwinger equations

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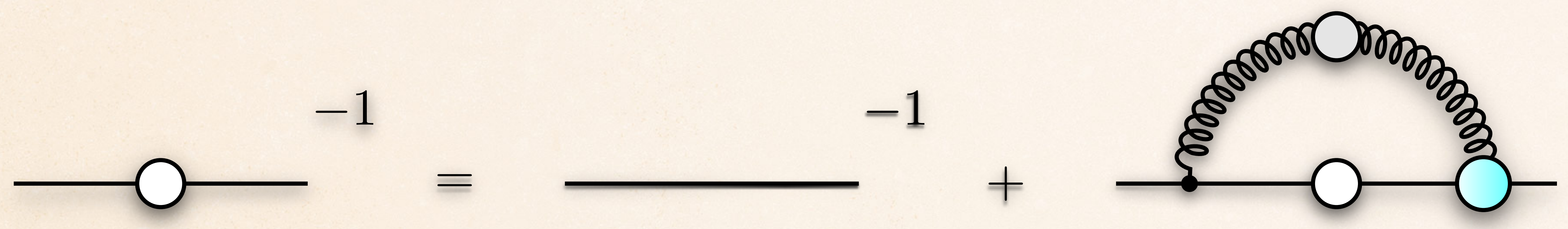

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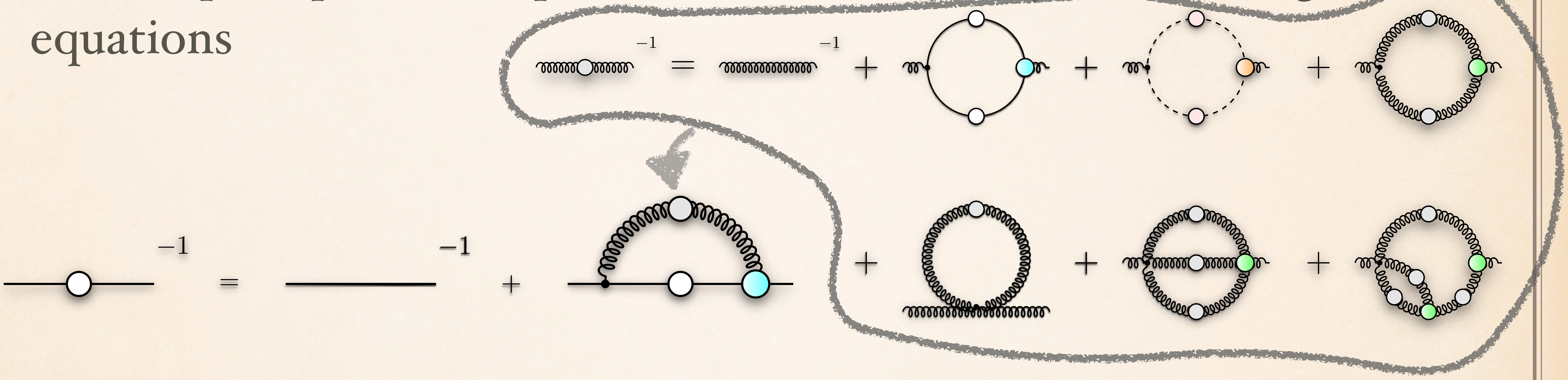

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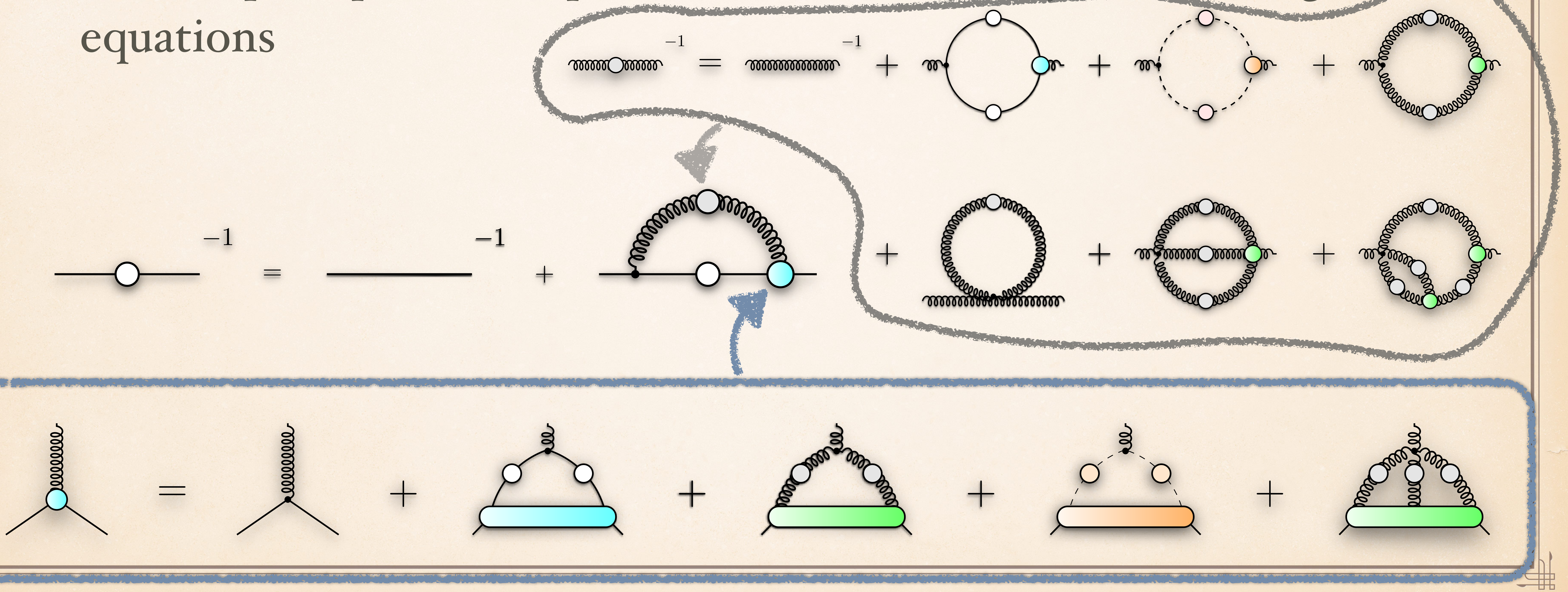
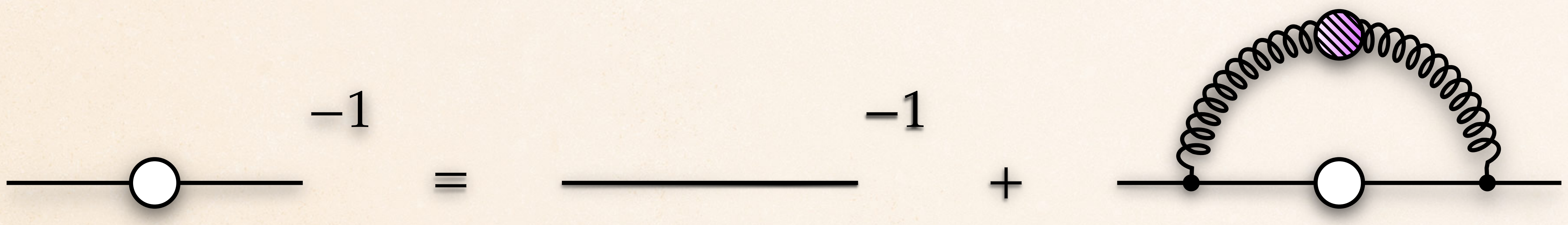


FUNCTIONAL FRAMEWORK

- As an input: quantum equations of motion → Dyson-Schwinger equations
  - Quark-Gluon vertex + Gluon DSE → effective gluon exchange



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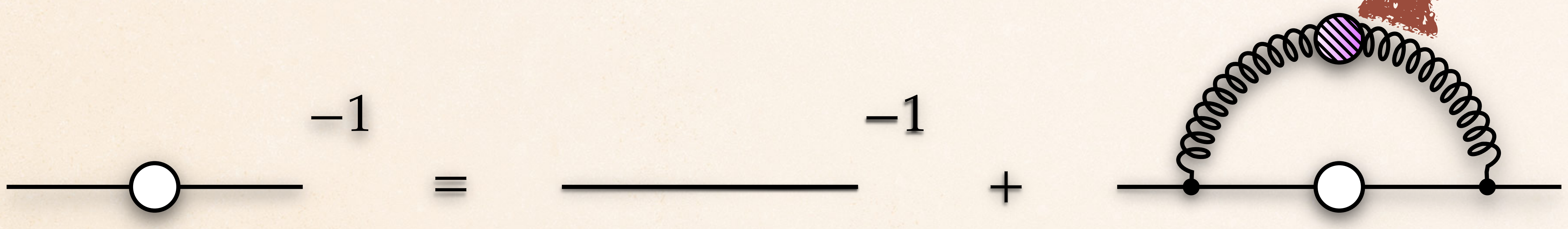
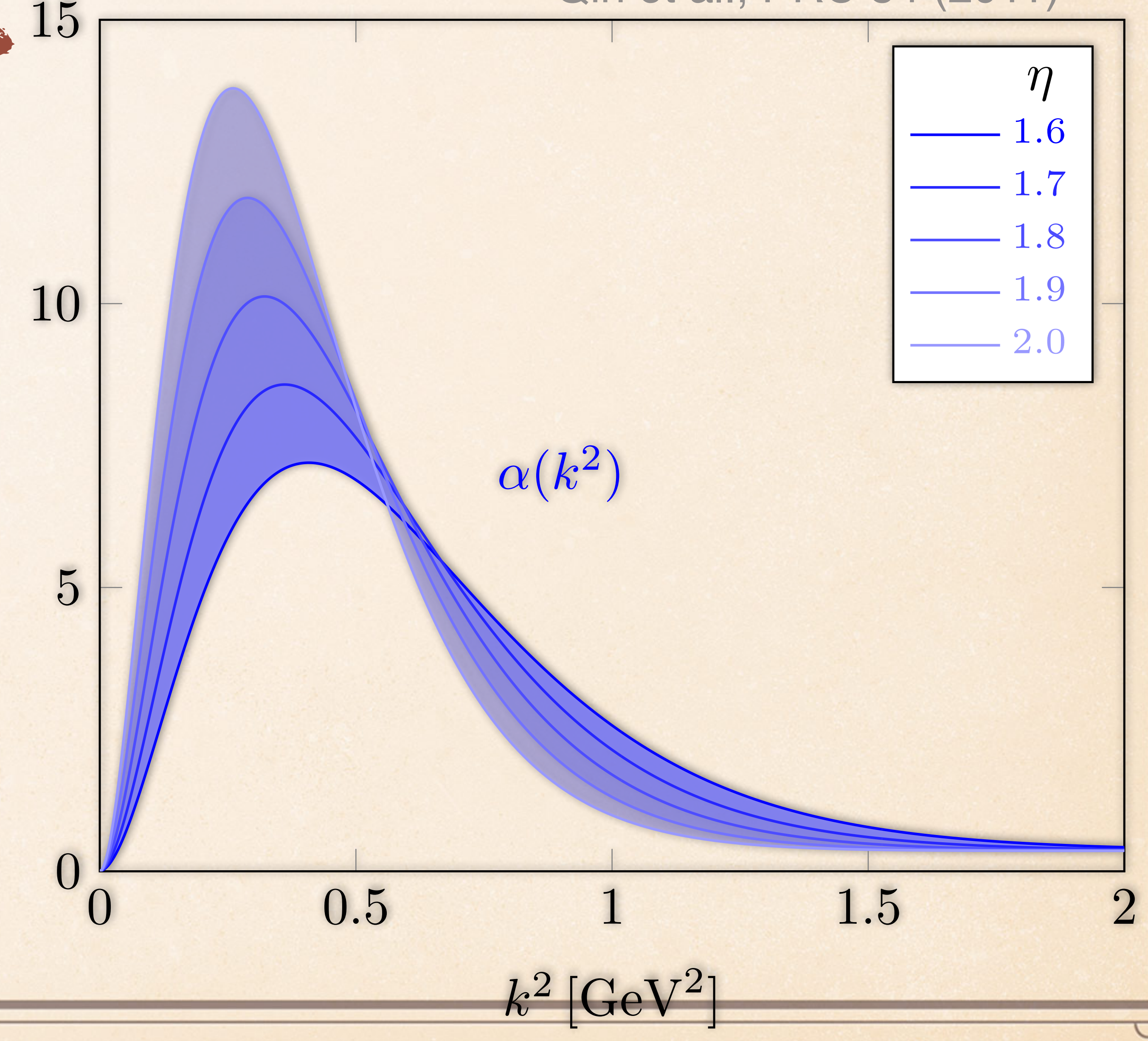


Maris, Tandy, PRC 60 (1999)
Qin et al., PRC 84 (2011)



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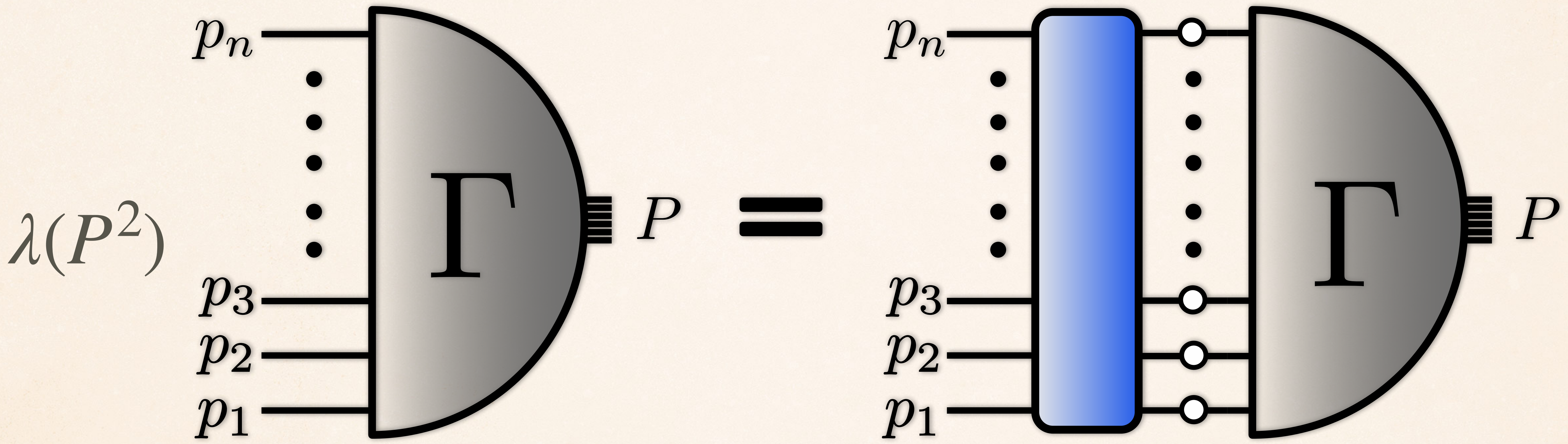

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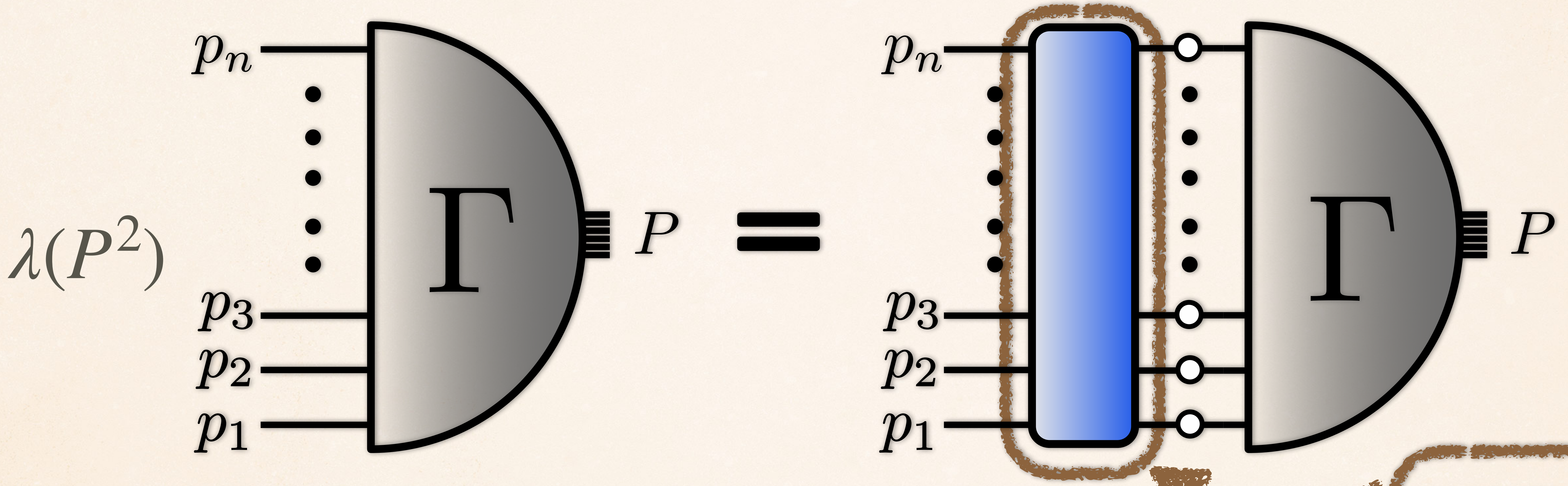
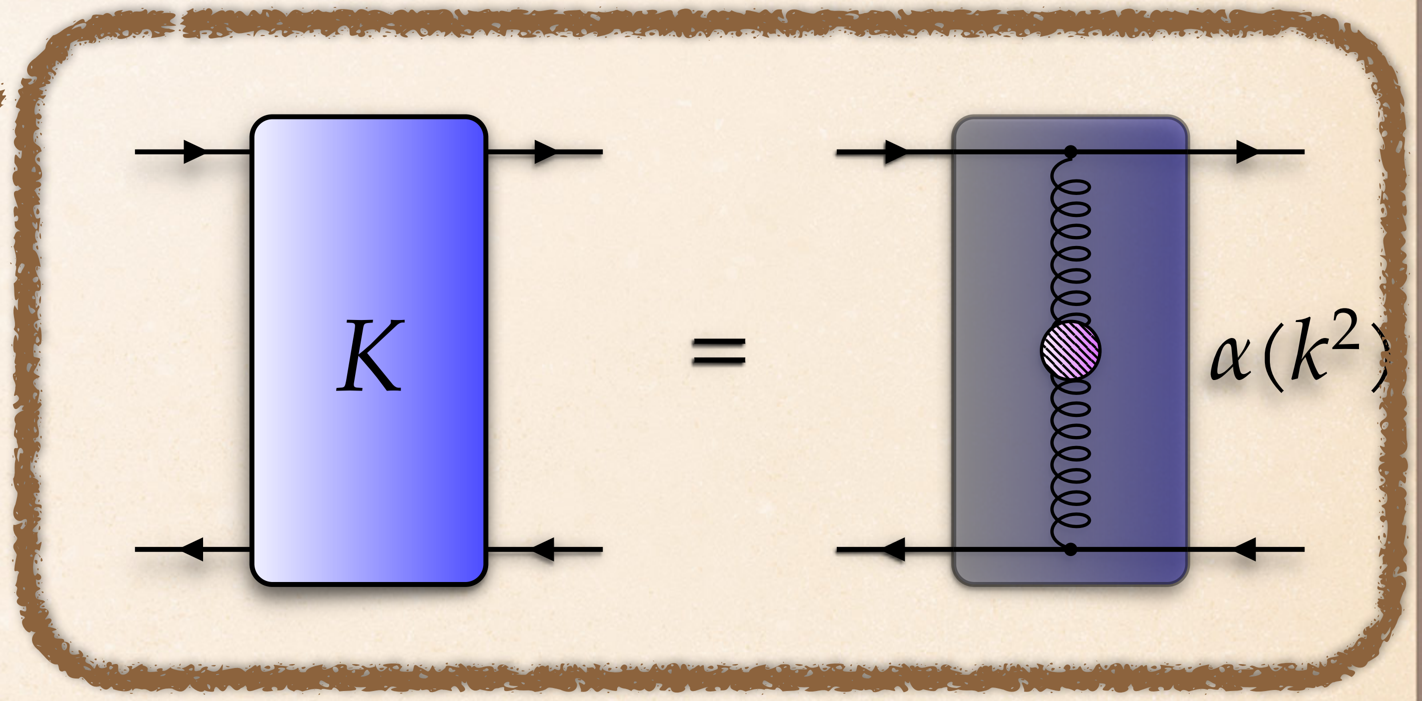


Two-body interactions



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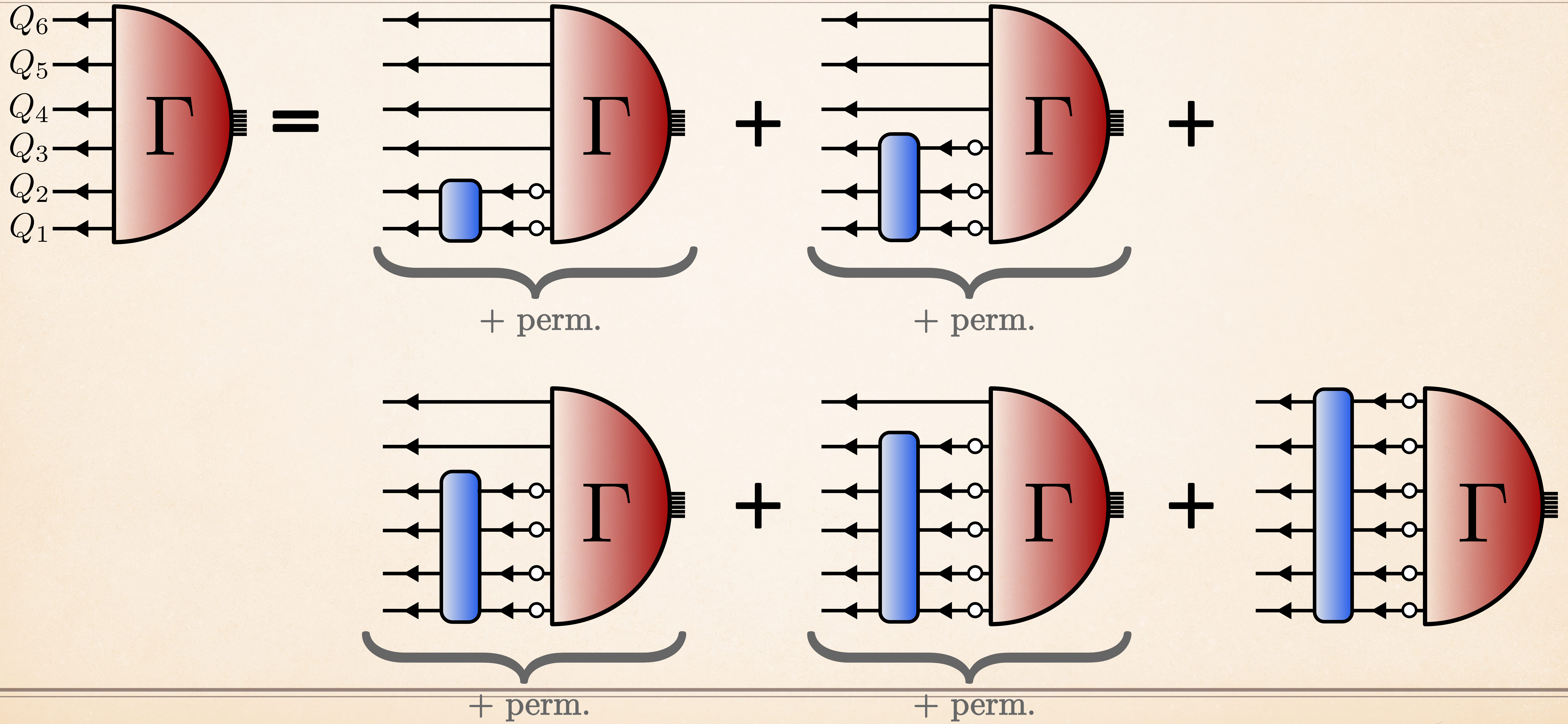
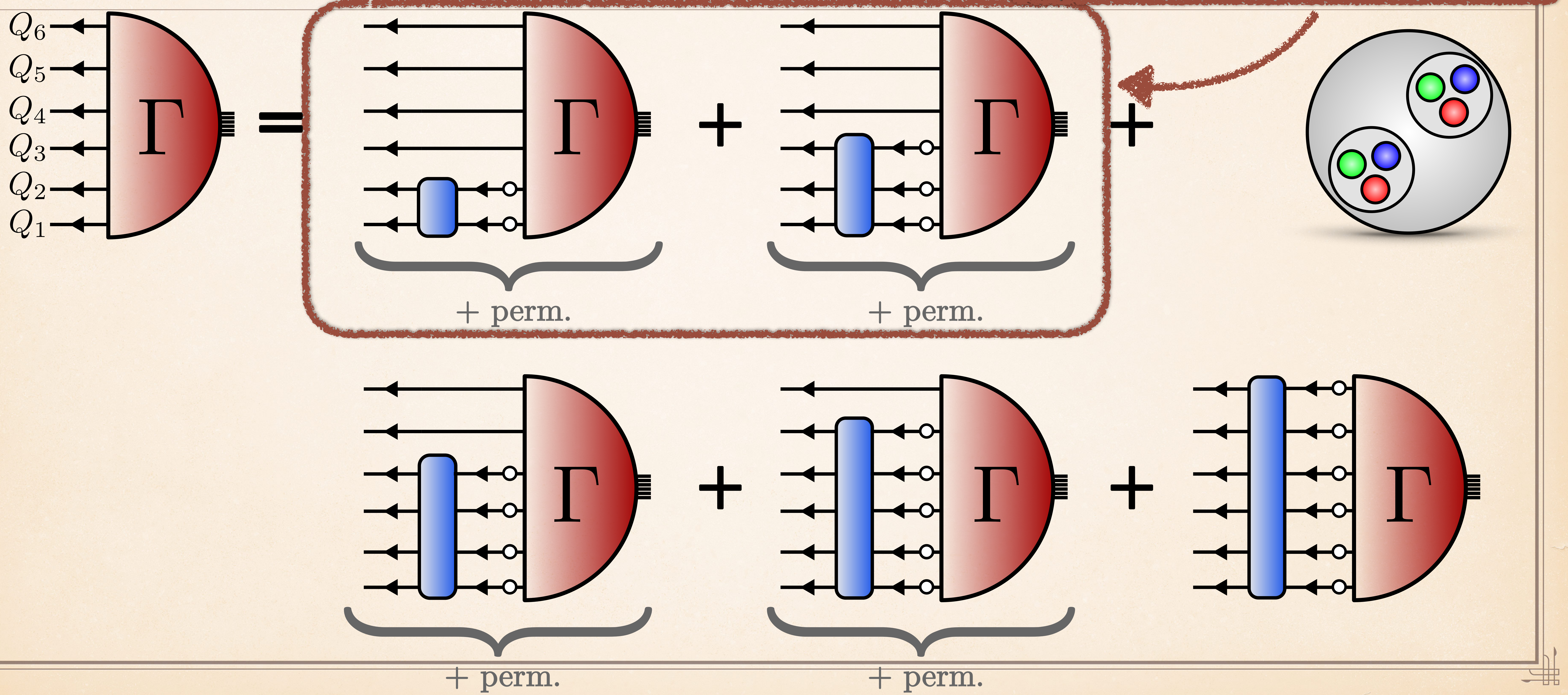
HEXAQUARK BSE



HEXAQUARK BSE

Baryon-Baryon dynamics



HEXAQUARK BSE

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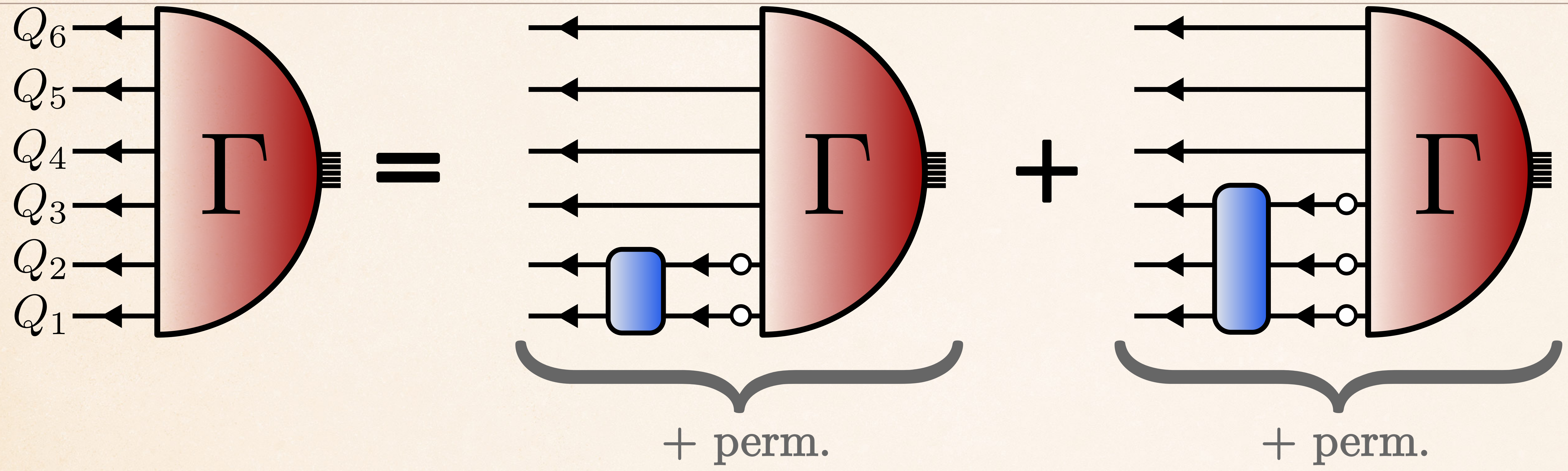

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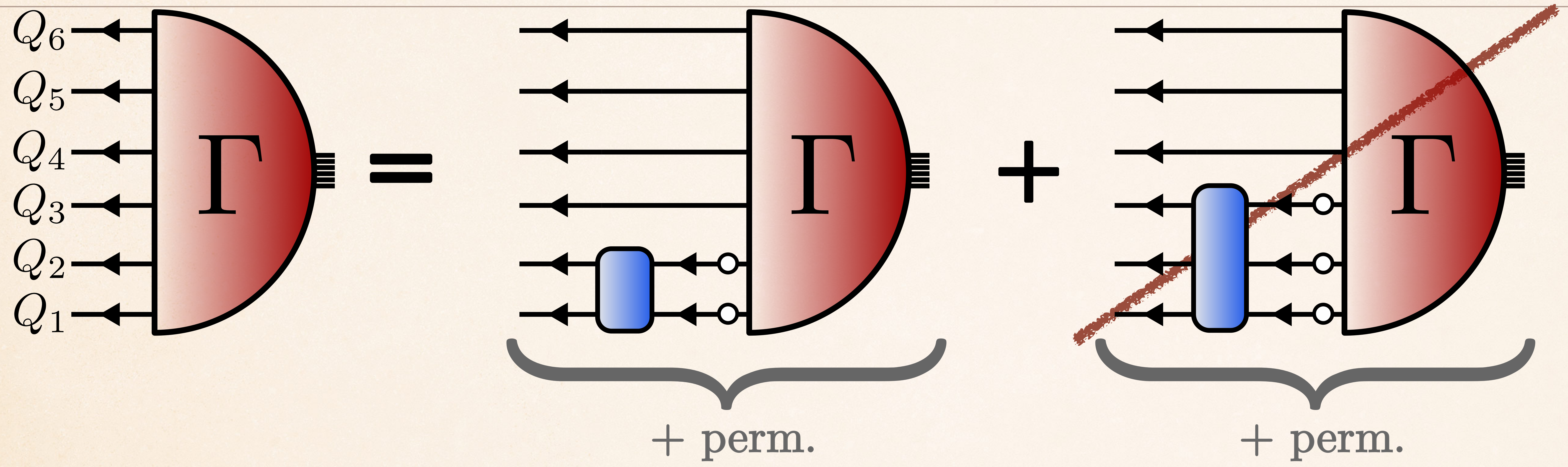

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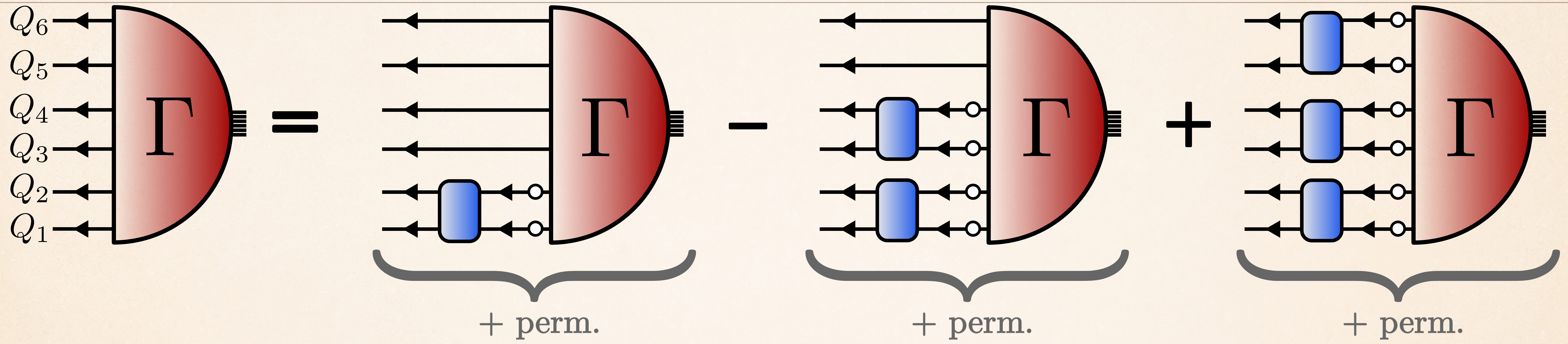

Huang, Weldon, PRD 11 (1975)
Kvinikhidze, Khvedelidze, Theor.Math.Phys. 90 (1992)

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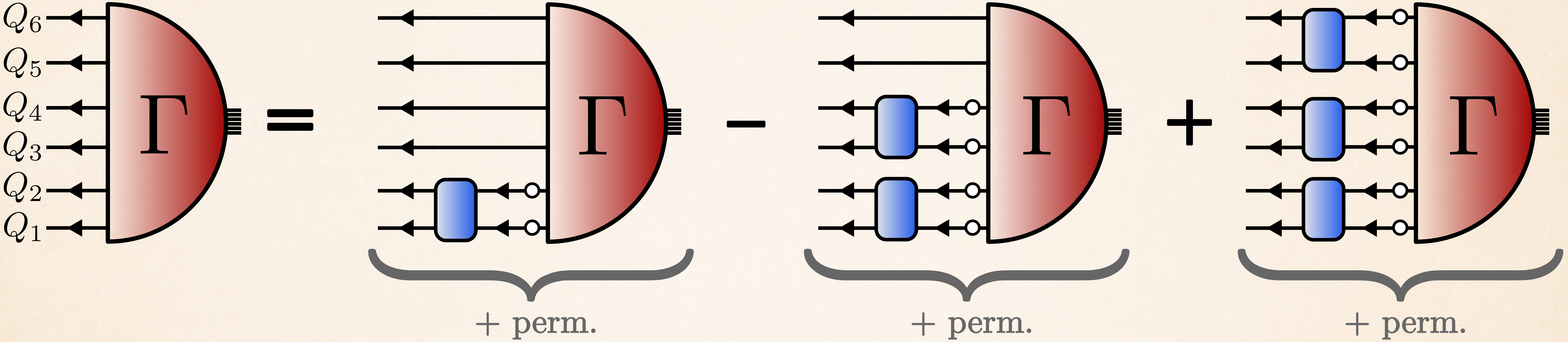

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Kvinikhidze, Khvedelidze, Theor.Math.Phys. 90 (1992)

10 Baryon-Baryon combinations:

(123)(456)	(125)(346)	(134)(256)	(136)(245)	(146)(235)
(124)(356)	(126)(345)	(135)(246)	(145)(236)	(156)(234)

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \Gamma_{\mathrm{C}} \otimes \Gamma_{\mathrm{F}}$$

SIX-QUARK BSA

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- Overall BSA needs to be antisymmetric under quark exchange $\rightarrow$ Express in terms of irreducible representations of S_6 $\rightarrow$ antisinglet $\bar{\mathbf{1}}$

PERMUTATION GROUP S_6

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- 720 elements: f_{123456} , ...

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  $1 \rightarrow 2 \rightarrow \ldots \rightarrow 6 \rightarrow 1$

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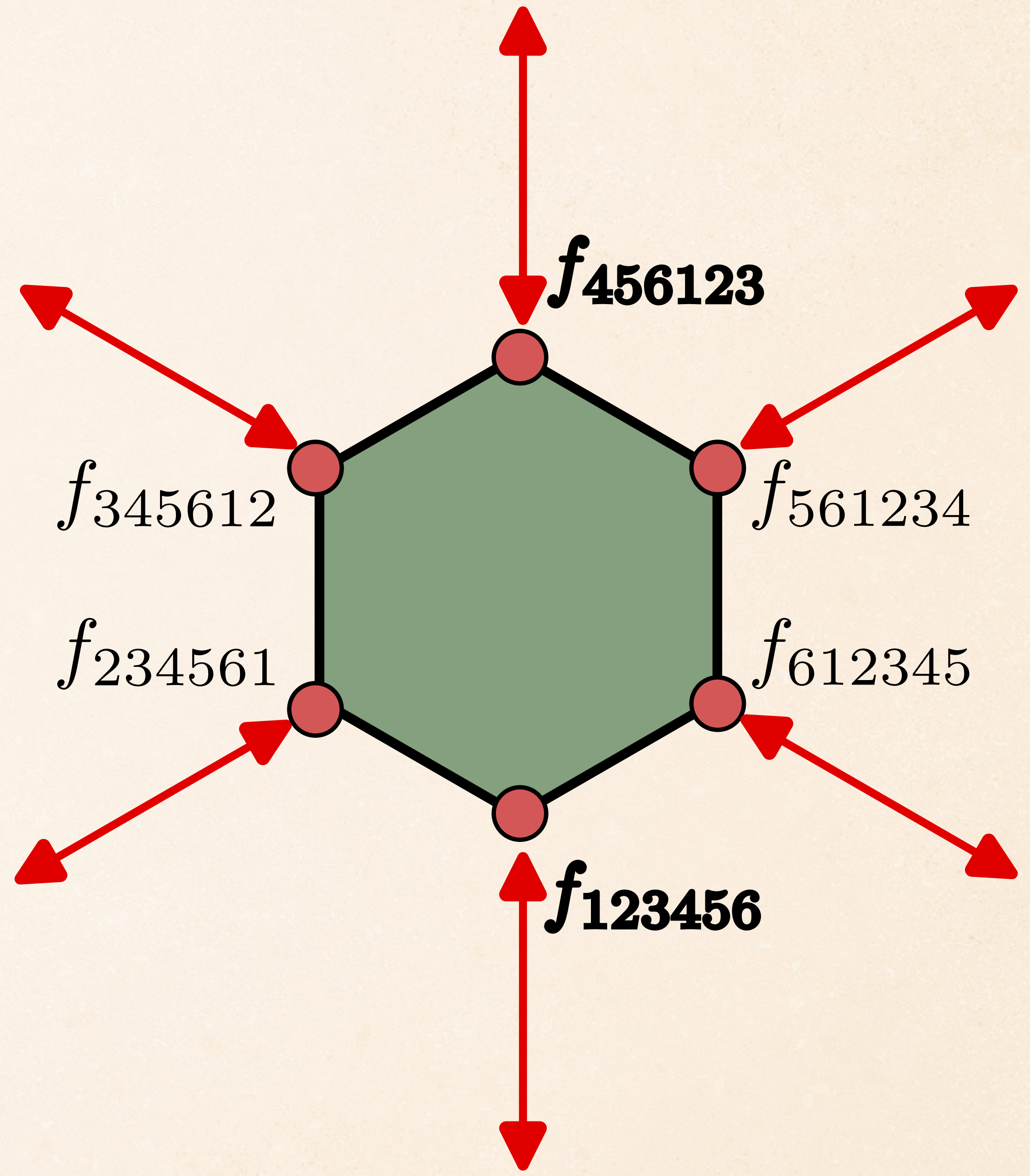
- Use C^6 →**120 Hexagons** connected by T



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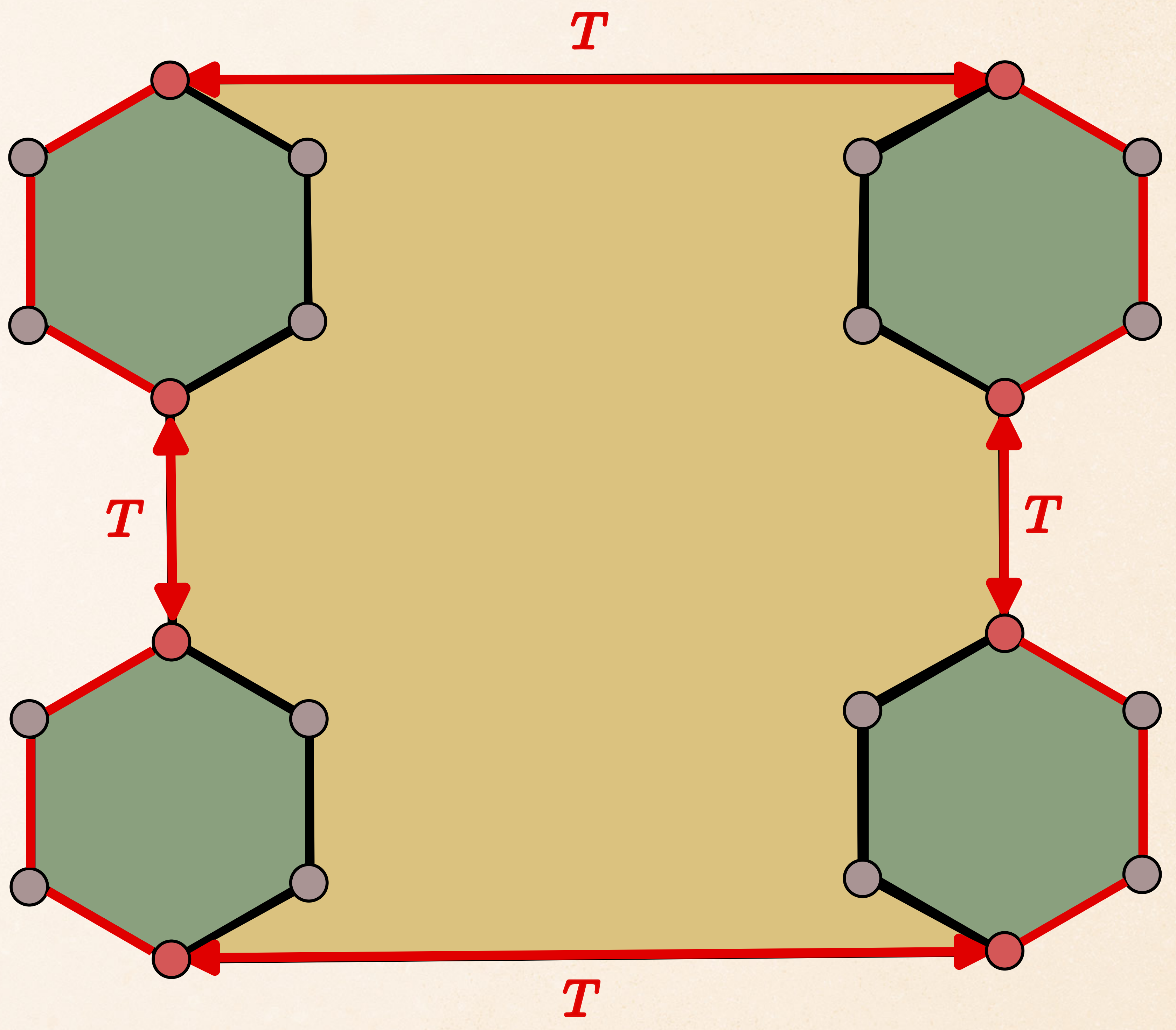
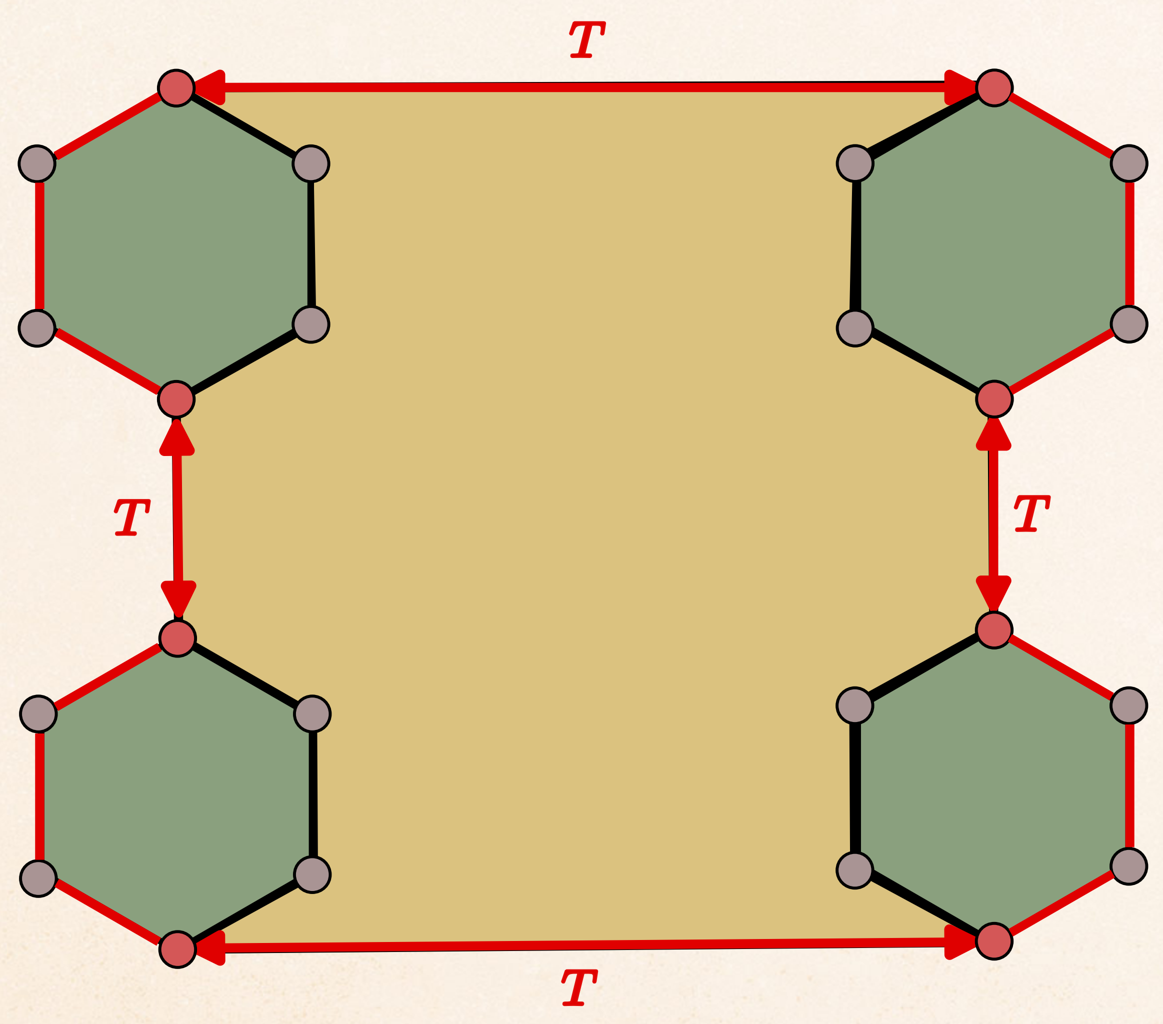
- Transposition T: $1 \leftrightarrow 2$
- Cyclic permutation C:
  $1 \to 2 \to \dots \to 6 \to 1$
- Generate group $S_6 = \langle T, C \rangle$
- 120 Hexagons connected by T
- Repeat $C^3\,T$
  → **90 “plaquettes” with 8 elements**



Eichmann, JH, in preparation

CHESSBOARD PLANES FOR S_6



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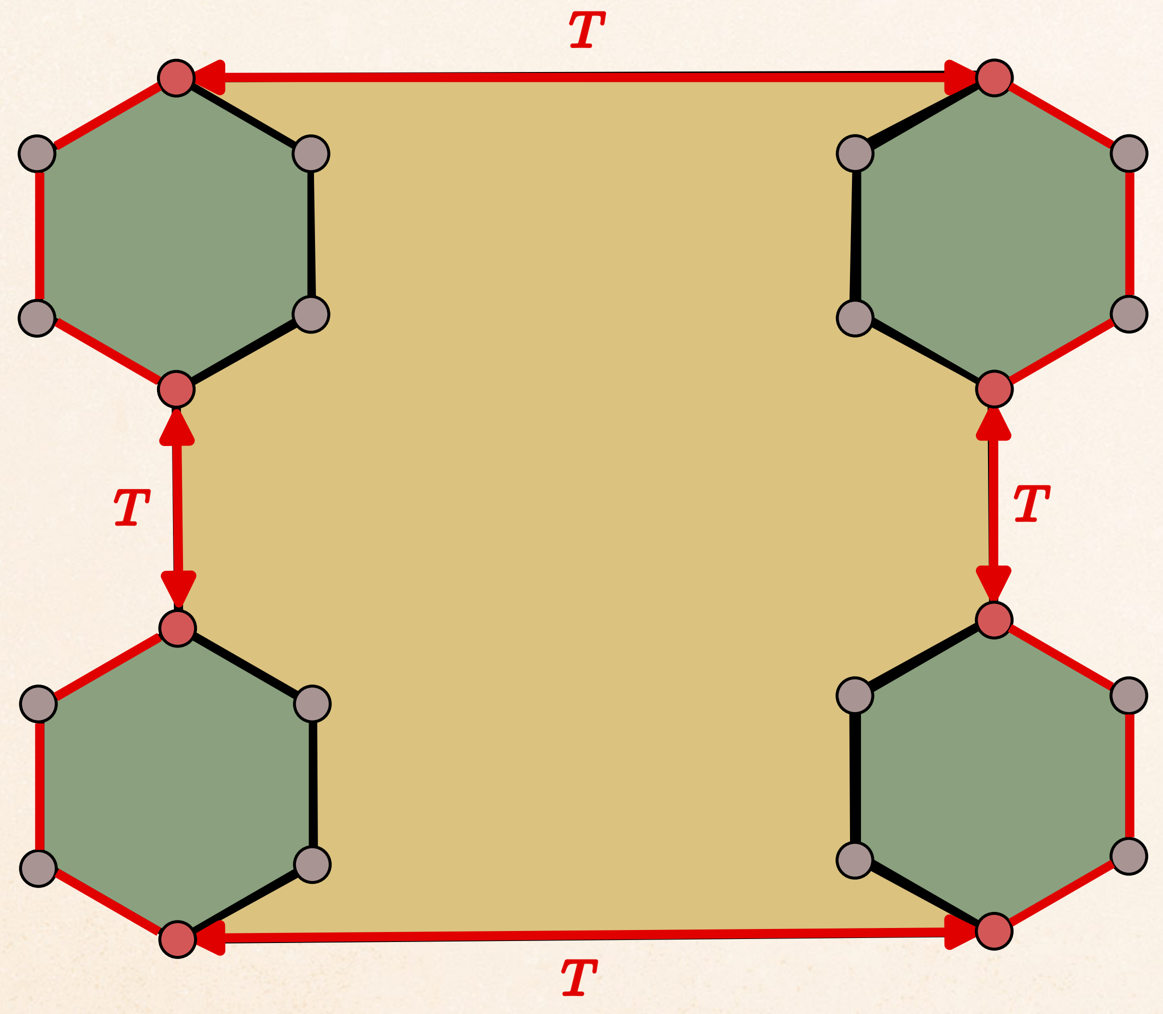

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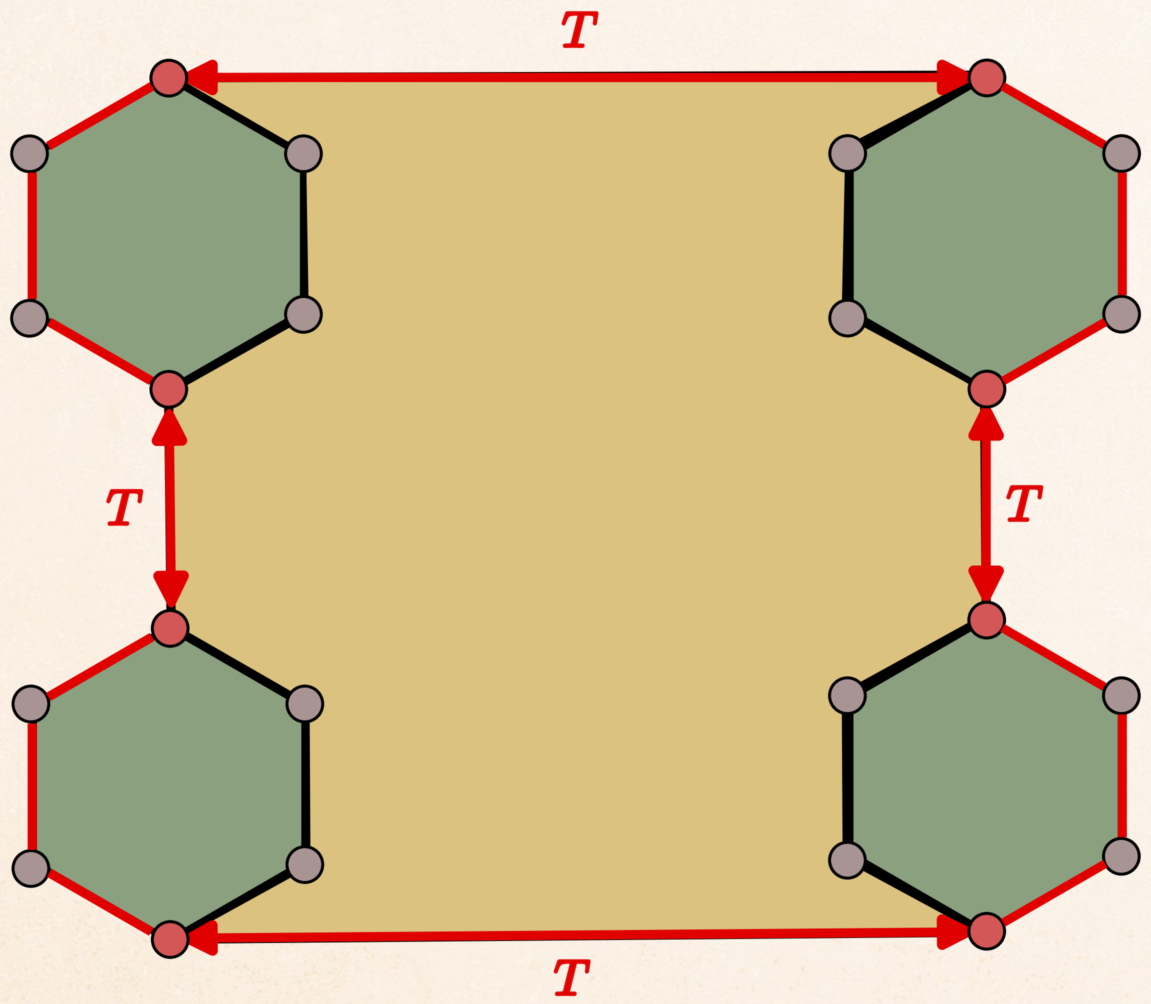
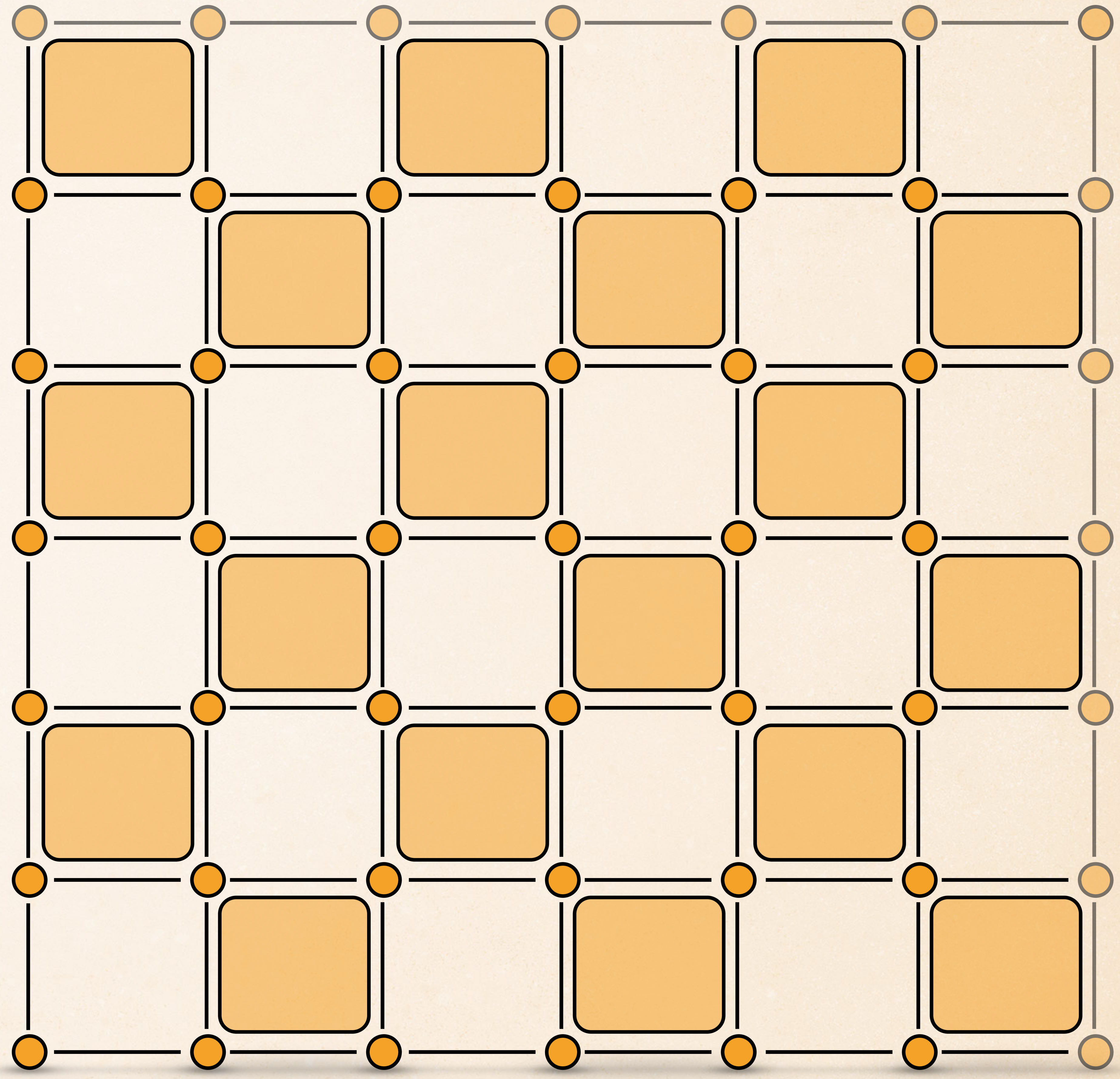
CHESSBOARD PLANES FOR S_6

- <u>Chessboard Planes</u>
  - 18 plaquettes $\rightarrow$ 144 elements





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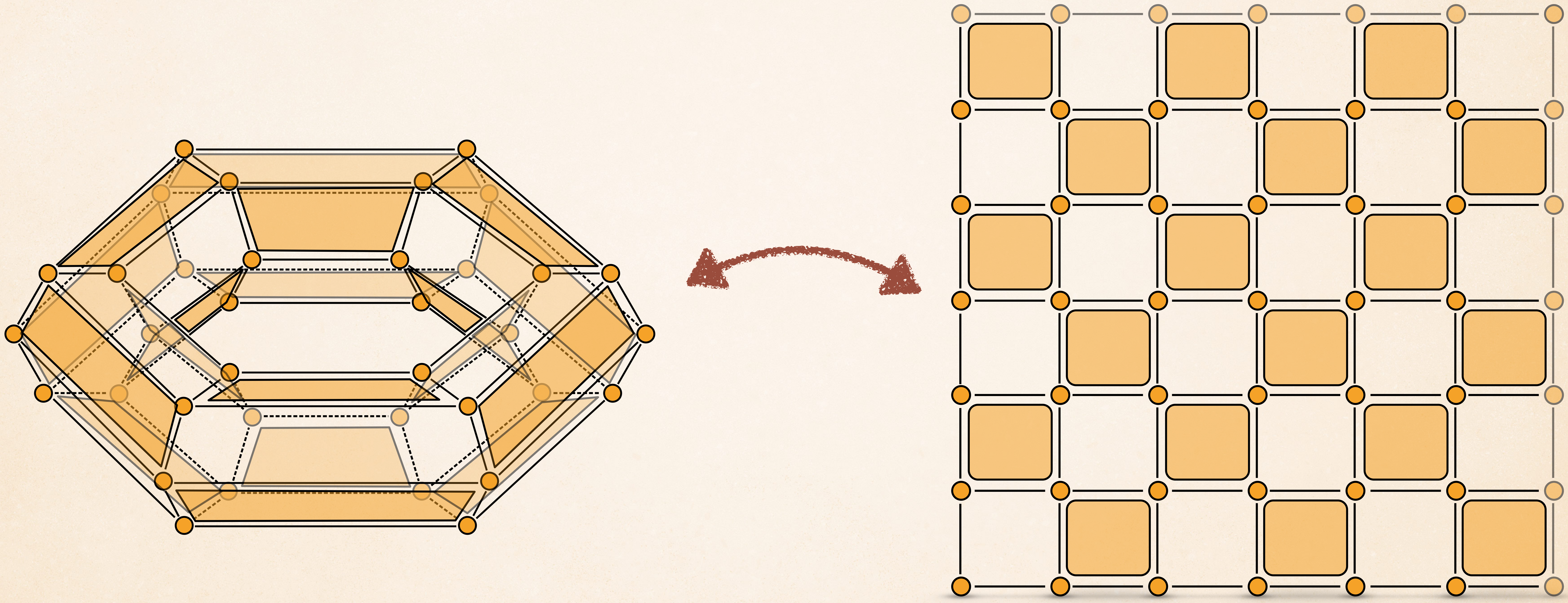


Eichmann, JH, in preparation

CHESSBOARD PLANES FOR S_6

- 10 unique Chessboard Planes with 18 “plaquettes”
- Pick 9 “plaquettes” per Chessboard Plane → get all 90 once

1

	4		58		77
24		72		12	
	6		60		74
21		69		9	
	1		54		82
19		67		7	

2

	79		51		12
15		3		63	
	80		50		11
13		1		61	
	81		49		10
14		2		62	

3

	39		63		40
90		60		59	
	33		70		34
81		42		41	
	18		85		19
84		48		47	

4

	73		7		59
11		23		71	
	78		5		57
6		18		66	
	83		2		53
8		20		68	

5

83		46		44	
	16		86		21
80		40		38	
	31		71		36
89		58		56	
	37		62		42

6

	82		45		43
20		17		87	
	79		39		37
35		32		72	
	88		57		55
41		38		61	

7

8		55		76	
	70		10		22
9		56		75	
	65		5		17
3		52		84	
	64		4		16

8

	27		65		48
87		54		51	
	25		68		46
76		34		28	
	13		88		24
78		36		30	

9

47		28		64	
	86		53		50
45		26		69	
	75		33		27
23		14		89	
	77		35		29

10

44		30		66	
	85		52		49
43		29		67	
	73		31		25
22		15		90	
	74		32		26

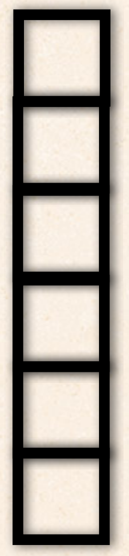
Eichmann, JH, in preparation

CHESSBOARD PLANES FOR S_6

- 10 unique Chessboard Planes with 18 "plaquettes"
- Pick 9 "plaquettes" per Chessboard Plane → get all 90 once
- Sum elements to get explicit expressions of <u>irreducible representations</u> of S_6

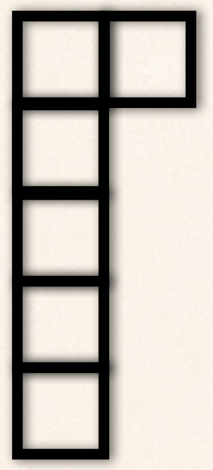
Eichmann, JH, in preparation

IRREDUCIBLE REPRESENTATIONS OF S_6



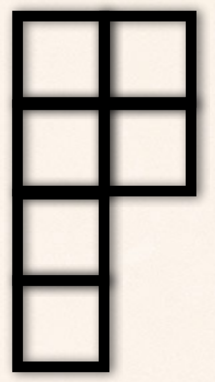
$\bar{\mathbf{1}}$

$\mathscr{A}$



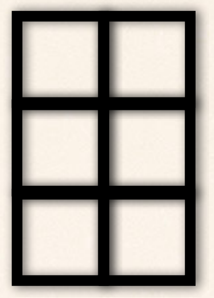
$\bar{\mathbf{5}}$

$\mathscr{V}^-$



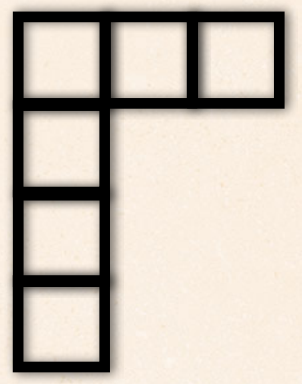
$\bar{\mathbf{9}}$

$\mathscr{N}^-$



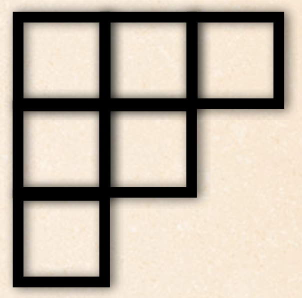
$\bar{\mathbf{5}}'$

$\mathscr{Q}^-$



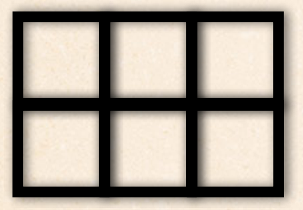
$\overline{\mathbf{10}}$

$\mathscr{D}^-$



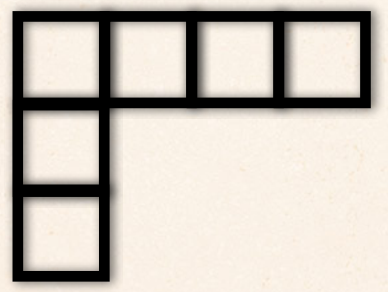
$\mathbf{16}$

$\mathscr{X}$



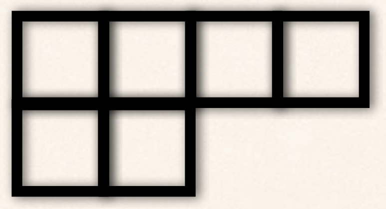
$\mathbf{5}'$

$\mathscr{Q}^+$



$\mathbf{10}$

$\mathscr{D}^+$



$\mathbf{9}$

$\mathscr{N}^+$

$\mathbf{5}$

$\mathscr{V}^+$

$\mathbf{1}$

$\mathscr{S}$

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

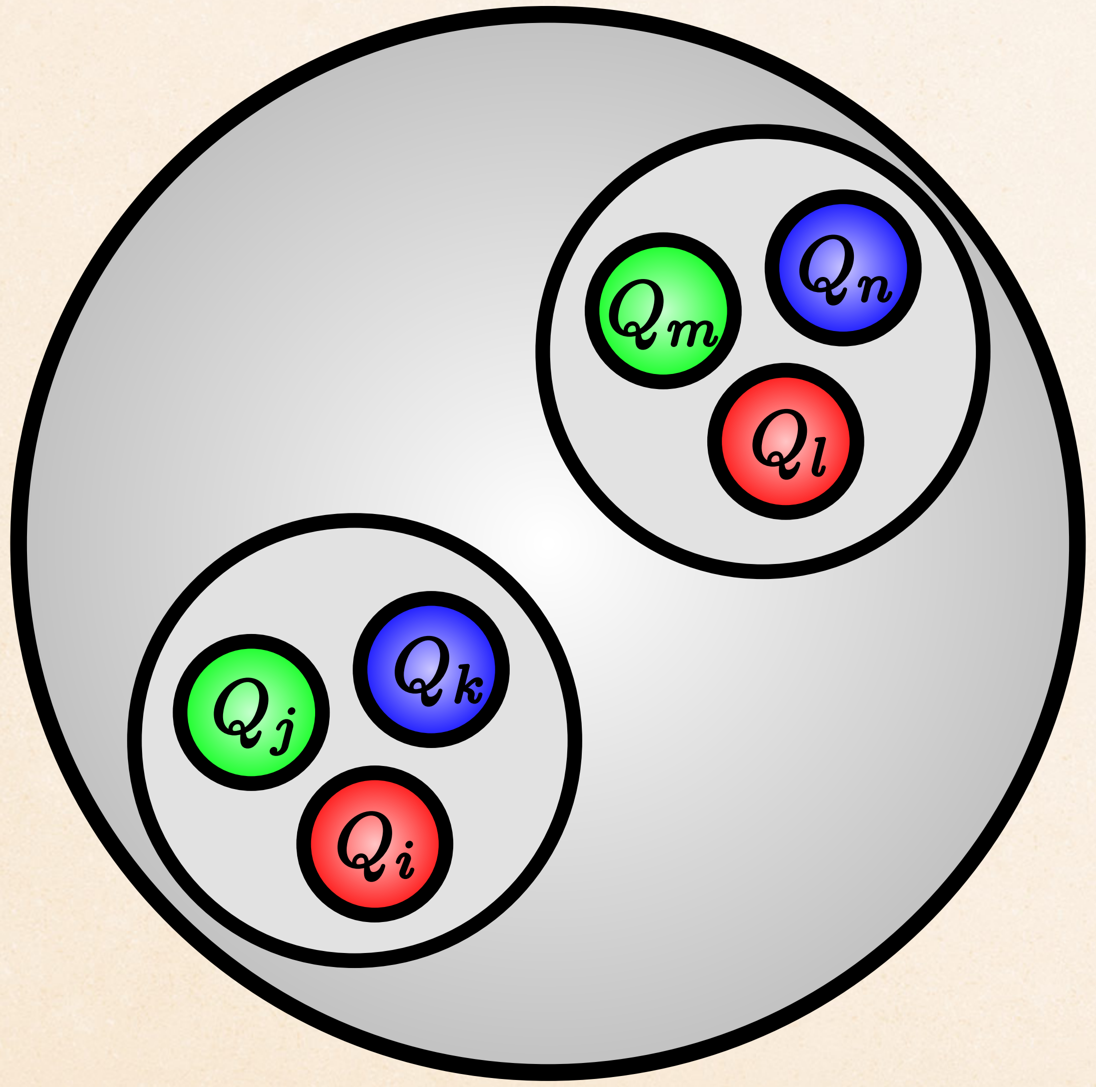
- Overall BSA needs to be antisymmetric under quark exchange → Express in terms of <u>irreducible representations of</u> S_6 → antisinglet $\bar{\mathbf{1}}$
- $\mathbf{M}_\mathrm{D} \otimes \mathbf{M}_\mathrm{C} \otimes \mathbf{M}_\mathrm{F} = \bar{\mathbf{1}}$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \boxed{\Gamma_\mathrm{C}} \otimes \Gamma_\mathrm{F}$$

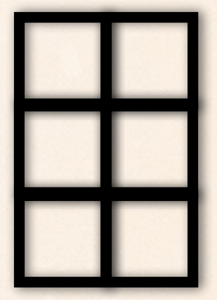
$$\Gamma_\mathrm{C} = \varepsilon^{A_i A_j A_k}\,\varepsilon^{A_l A_m A_n}$$



Eichmann, JH, in preparation

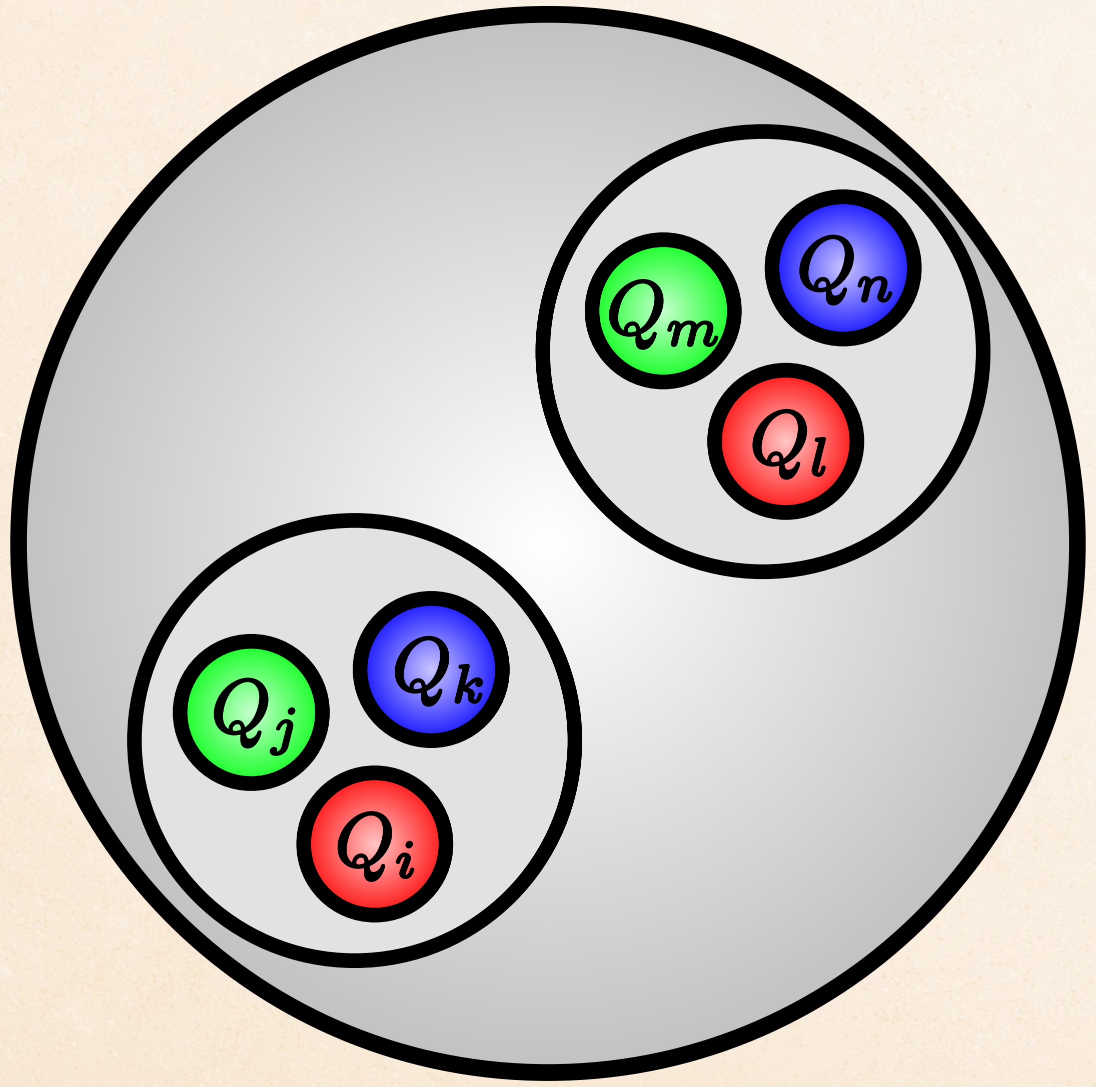
SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \boxed{\Gamma_\mathrm{C}} \otimes \Gamma_\mathrm{F}$$



$\bar{\mathbf{5}}'$

$$\Gamma_\mathrm{C} = \varepsilon^{A_i A_j A_k}\, \varepsilon^{A_l A_m A_n}$$

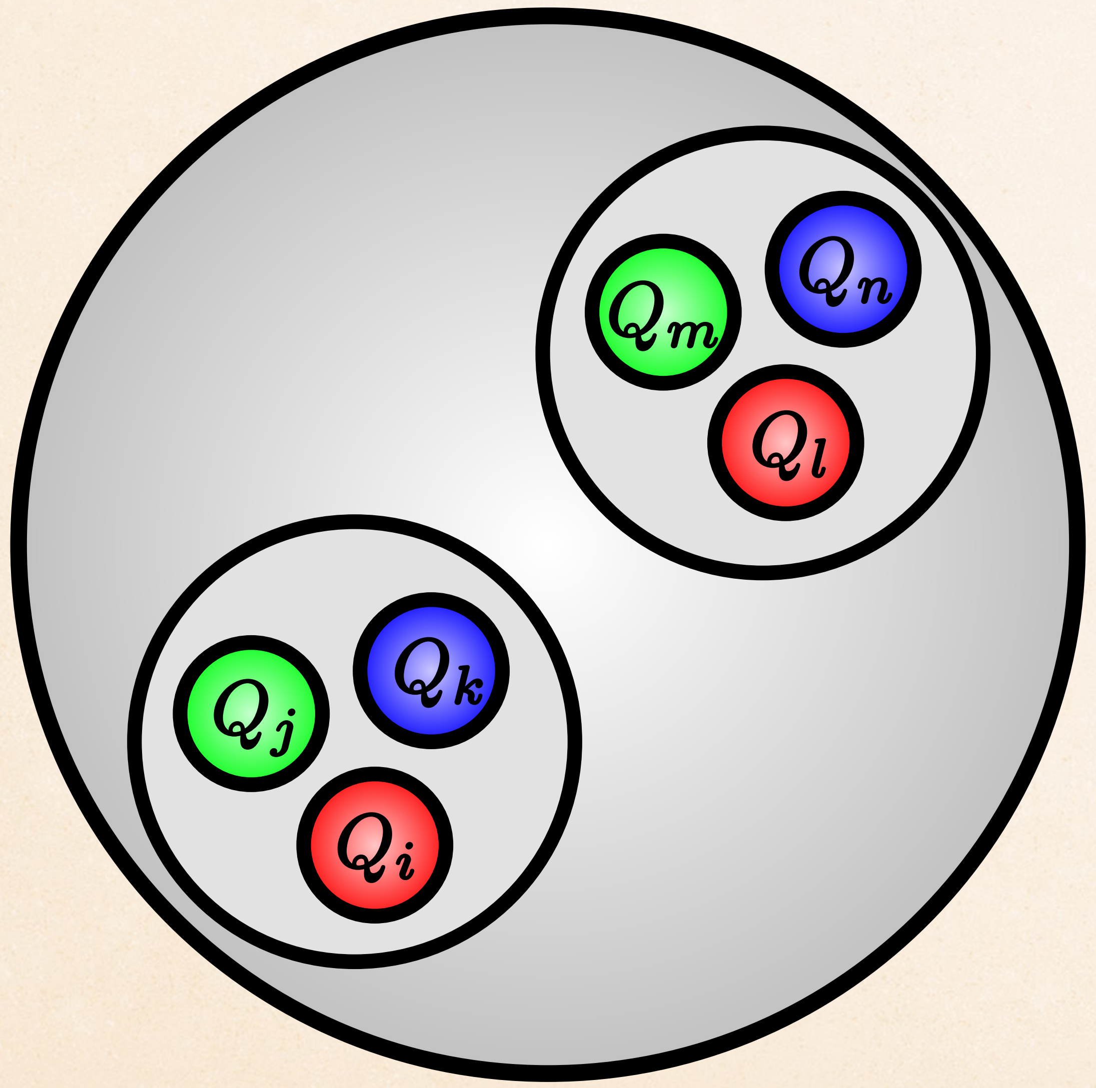


Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \Gamma_\mathrm{C} \otimes \boxed{\Gamma_\mathrm{F}}$$

$$Q_i\, Q_j\, Q_k\, Q_l\, Q_m\, Q_m = u\, u\, d\, u\, d\, d$$

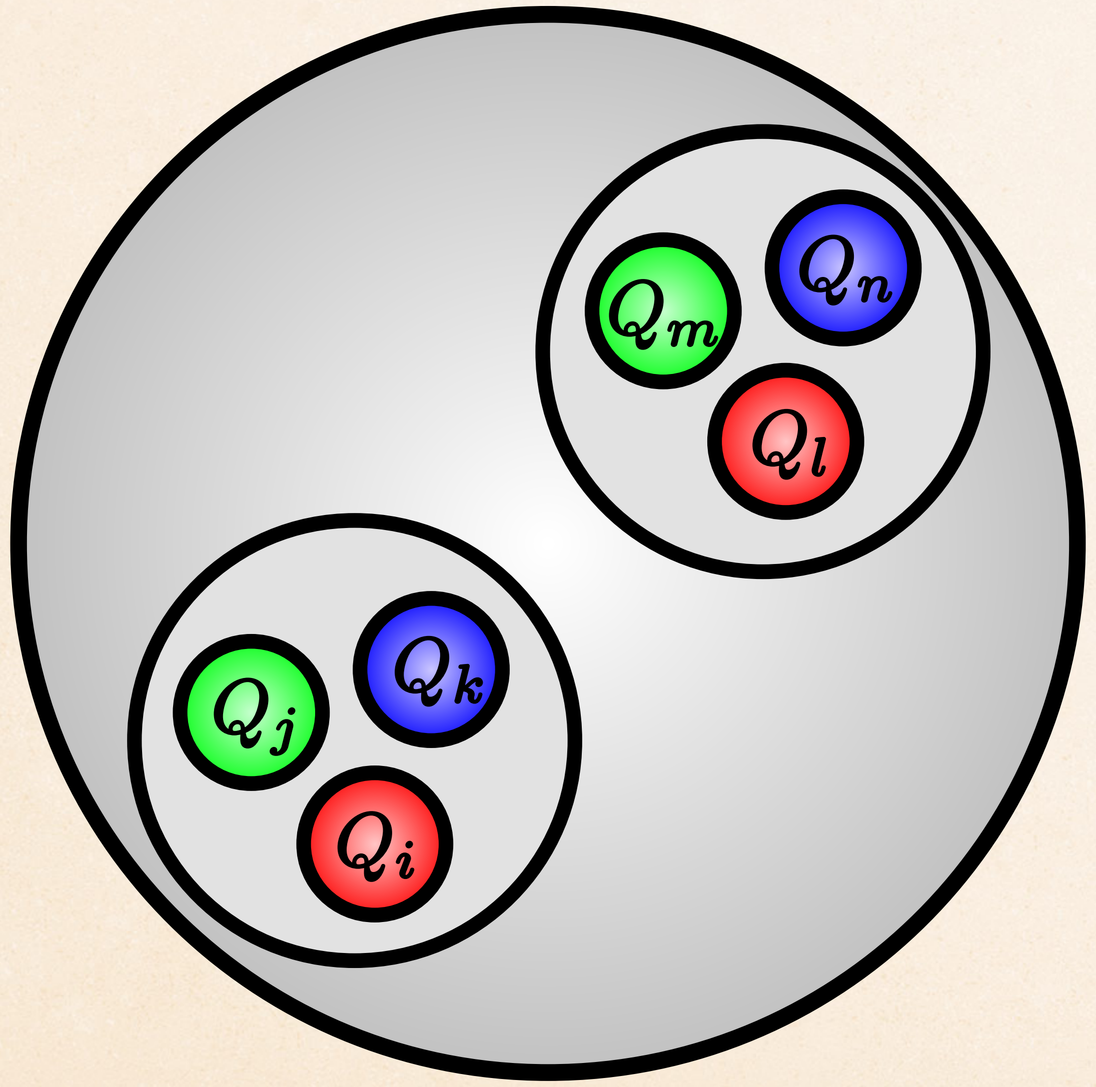


Eichmann, JH, in preparation

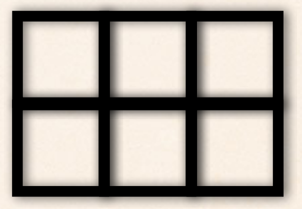
SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)\otimes\Gamma_{\mathrm{C}}\otimes\boxed{\Gamma_{\mathrm{F}}}$$

$$Q_i\,Q_j\,Q_k\,Q_l\,Q_m\,Q_m = u\,u\,d\,u\,d\,d$$



$\mathbf{5}'$



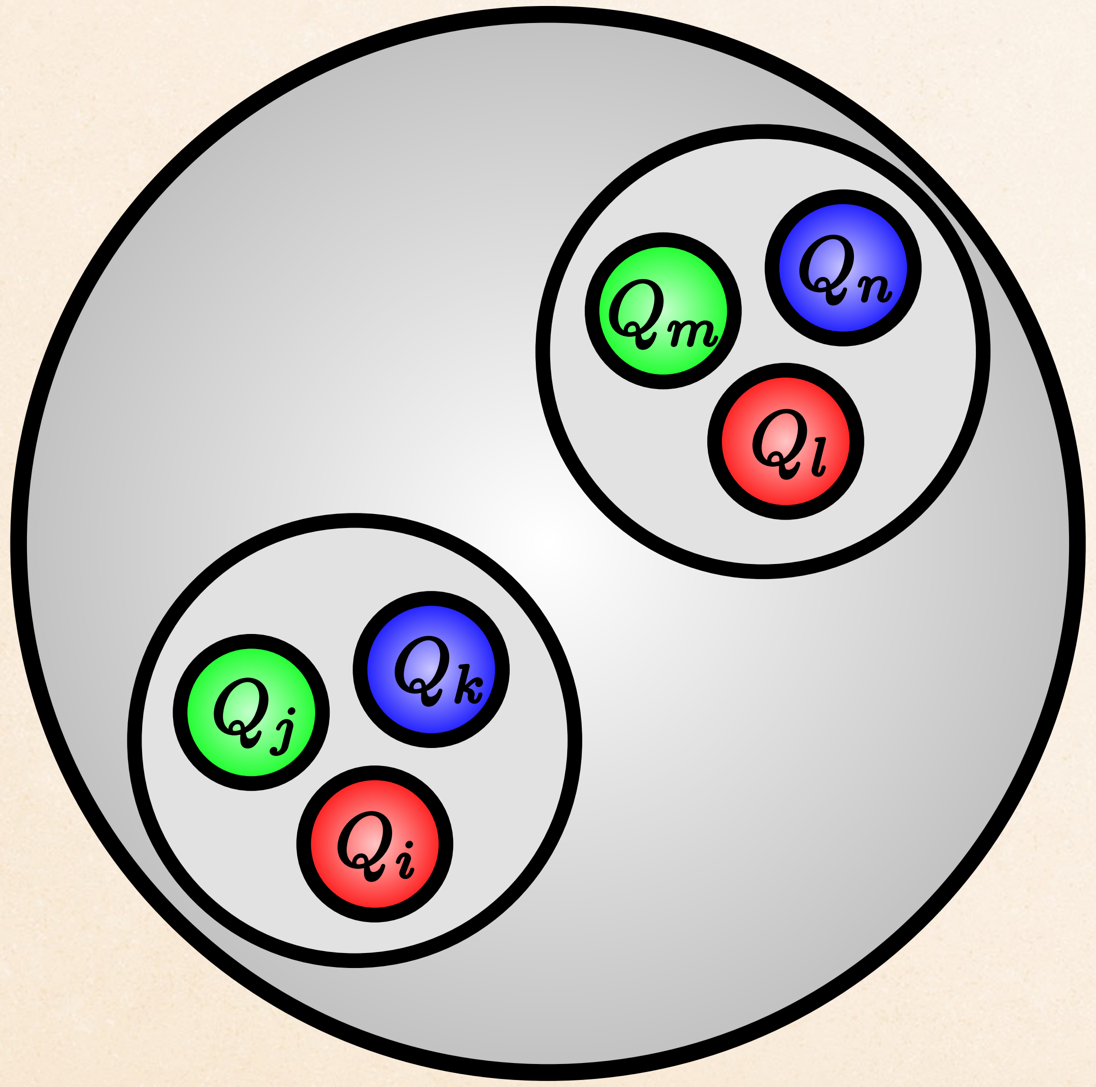
$I = 0$

Eichmann, JH, in preparation

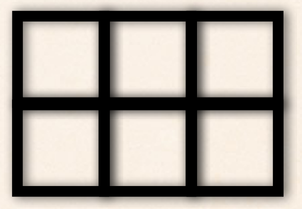
SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \Gamma_C \otimes \boxed{\Gamma_F}$$

$$Q_i\, Q_j\, Q_k\, Q_l\, Q_m\, Q_m = u\, u\, d\, u\, d\, d$$

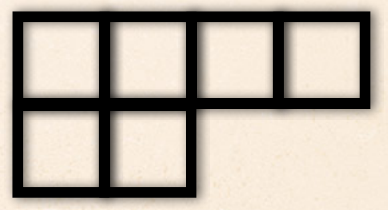


5′



$I = 0$

9



$I = 1$

Eichmann, JH, in preparation

SIX-QUARK BSA

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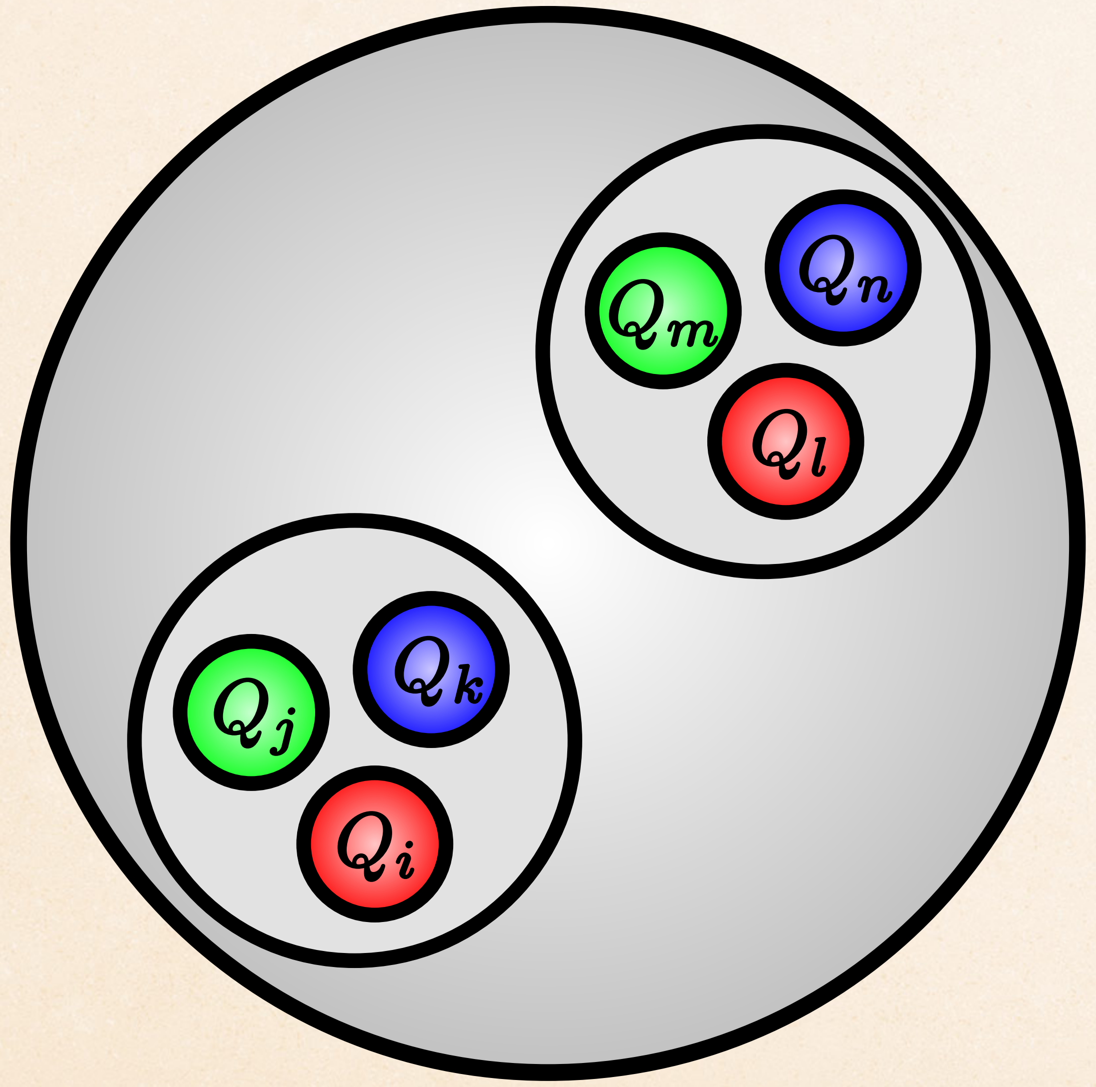
$$Q_i\,Q_j\,Q_k\,Q_l\,Q_m\,Q_m = u\,u\,d\,u\,d\,d$$



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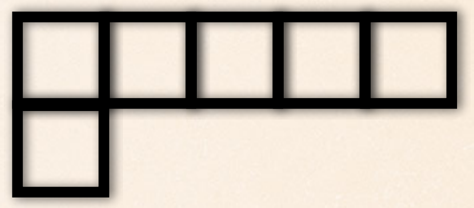

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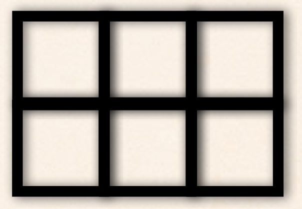
5′



$I = 0$

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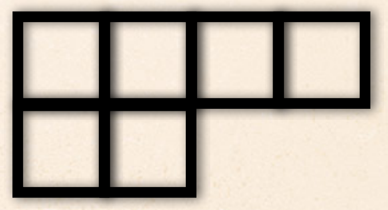

$I = 1$

Eichmann, JH, in preparation

SIX-QUARK BSA

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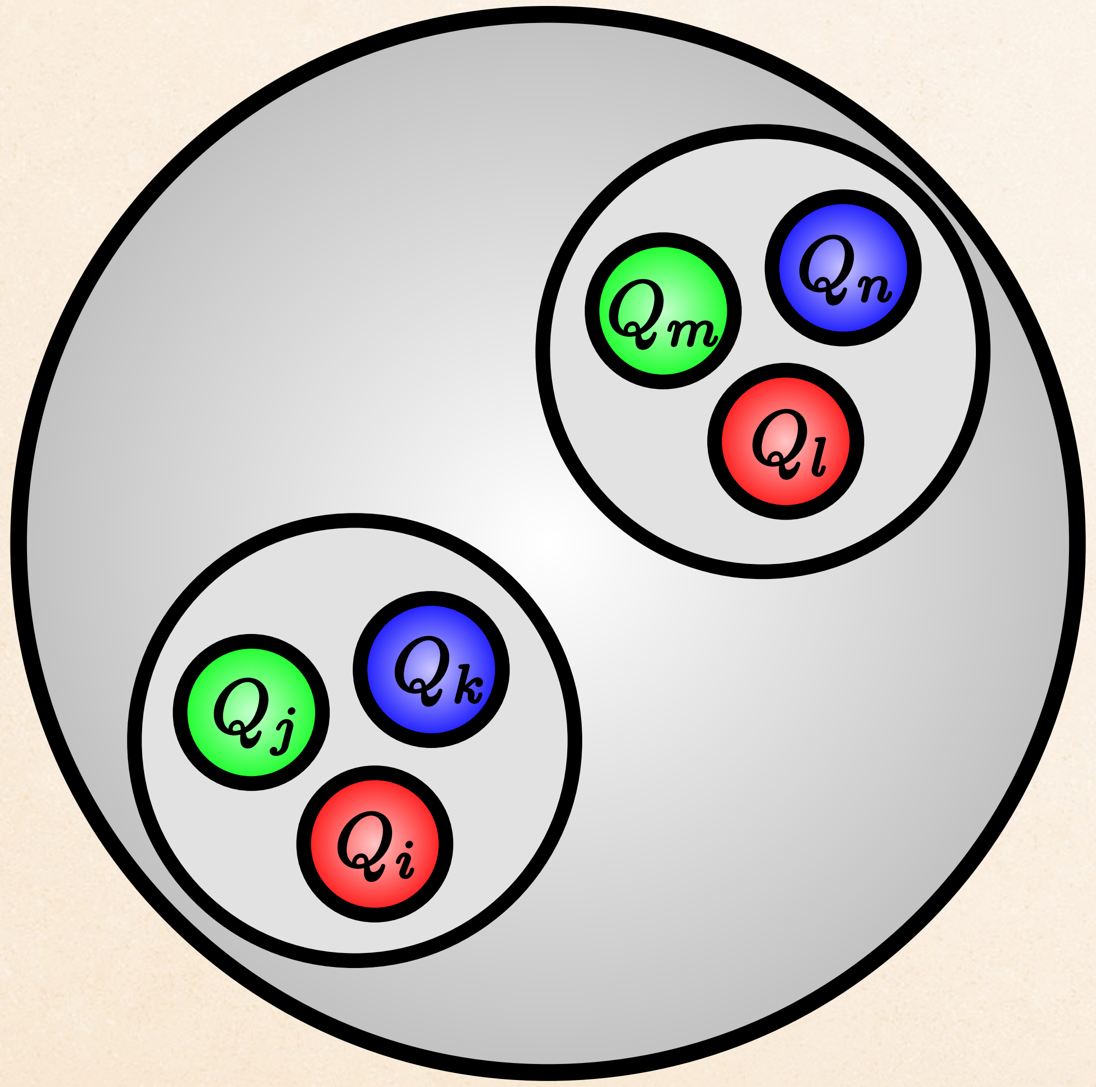
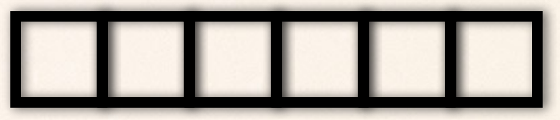
$$Q_i\, Q_j\, Q_k\, Q_l\, Q_m\, Q_m = u\,u\,d\,u\,d\,d$$

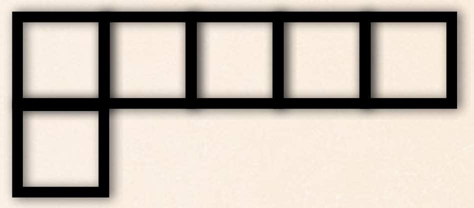


1



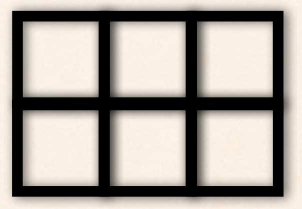
$I = 3$

5



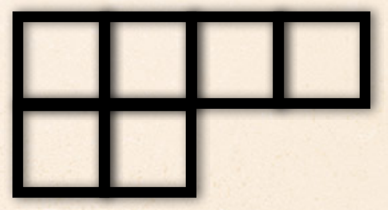
$I = 2$

5′



$I = 0$

9



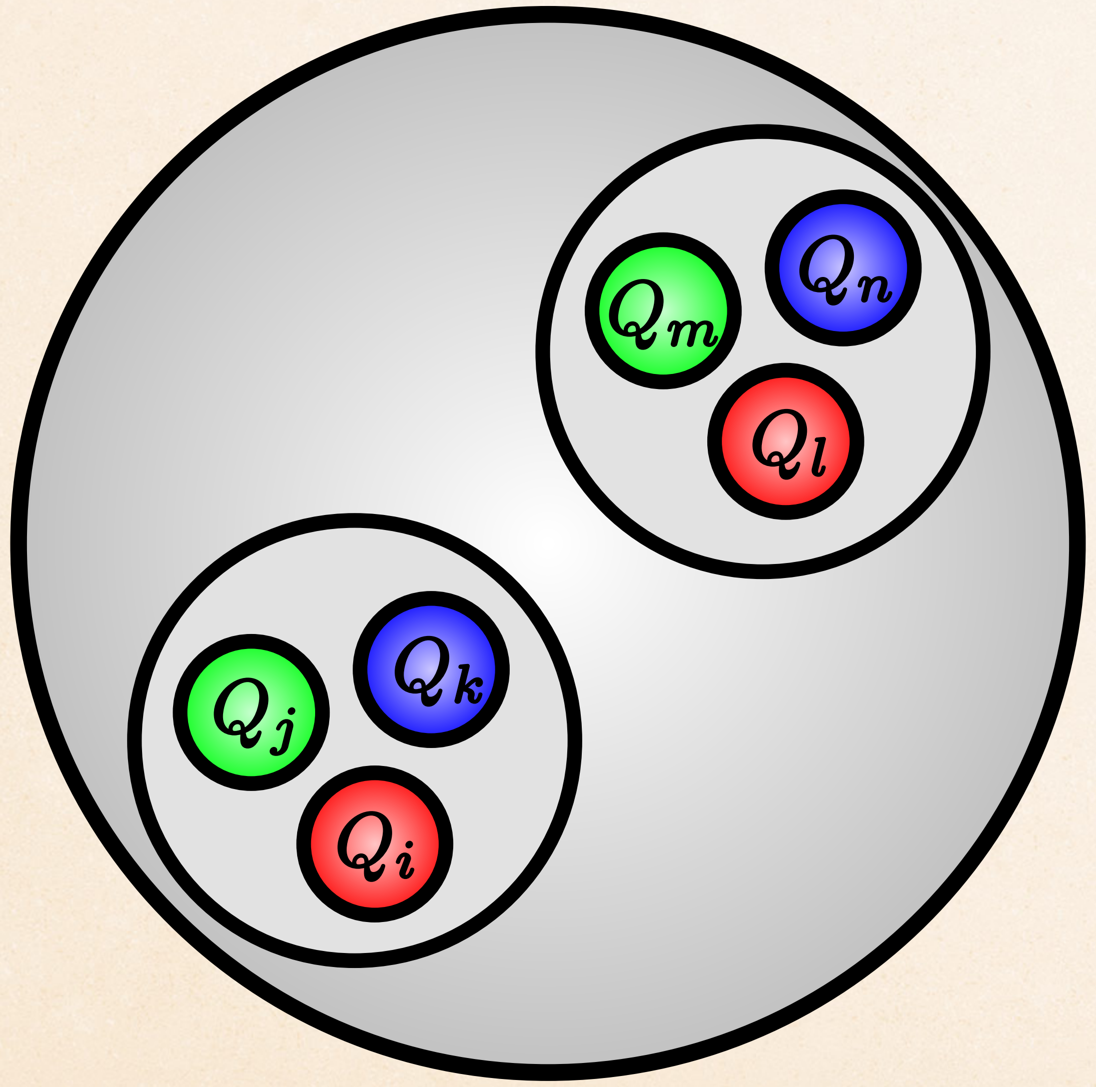
$I = 1$

Eichmann, JH, in preparation

SIX-QUARK BSA

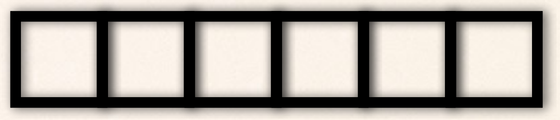
$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P) \otimes \Gamma_{\mathrm{C}} \otimes \boxed{\Gamma_{\mathrm{F}}}$$

$$Q_i\,Q_j\,Q_k\,Q_l\,Q_m\,Q_m = u\,u\,d\,u\,d\,d$$



Deuteron

1



$I = 3$

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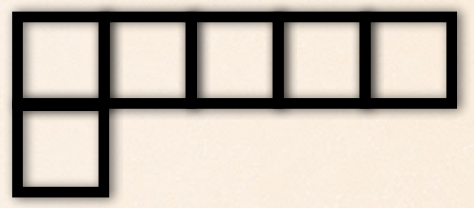

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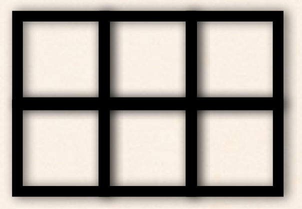
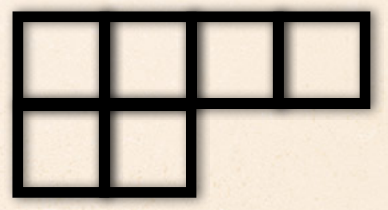
5′



$I = 0$

9



$I = 1$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- Example Deuteron:

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- Example Deuteron:
  - $\mathbf{M}_\mathrm{D} \otimes \mathbf{M}_\mathrm{C} \otimes \mathbf{M}_\mathrm{F} = \mathbf{M}_\mathrm{D} \otimes \bar{\mathbf{5}}' \otimes \mathbf{5}' \overset{!}{=} \bar{\mathbf{1}}$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- Example Deuteron:
  - $\mathbf{M}_\mathrm{D} \otimes \mathbf{M}_\mathrm{C} \otimes \mathbf{M}_\mathrm{F} = \mathbf{M}_\mathrm{D} \otimes \bar{\mathbf{5}}' \otimes \mathbf{5}' \stackrel{!}{=} \bar{\mathbf{1}}$
  - Restrictions on representations $\mathbf{M}_\mathrm{D}$ for Dirac part of BSA

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_{\mathrm{C}} \otimes \Gamma_{\mathrm{F}}$$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_{\mathrm{C}} \otimes \Gamma_{\mathrm{F}}$$

- Number of needed Dirac tensors N
  - 4096 for $J = 0 \rightarrow 320$ S-wave
  - 12288 for $J = 1 \rightarrow 576$ S-wave

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_C \otimes \Gamma_F$$

- Number of needed Dirac tensors N
  - 4096 for $J = 0 \rightarrow 320$ S-wave
  - 12288 for $J = 1 \rightarrow 576$ S-wave
- Lorentz invariants Ω:
  - Singlet: $\mathcal{S}_0$ Quintets: $\mathcal{V}_1^+, \mathcal{V}_2^+$ Nonet: $\mathcal{N}^+$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- Strategy for solution:

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_{\mathrm{C}} \otimes \Gamma_{\mathrm{F}}$$

- Strategy for solution:
  - Neglect “subleading” Lorentz invariants
    - $f_i(\mathcal{S}_0, \mathcal{V}_1^+, \mathcal{V}_2^+, \mathcal{N}^+) \to f_i(\mathcal{S}_0, \mathcal{N}^+)$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- Strategy for solution:
  - Neglect "subleading" Lorentz invariants
    - $f_i(\mathcal{S}_0, \mathcal{V}_1^+, \mathcal{V}_2^+, \mathcal{N}^+) \rightarrow f_i(\mathcal{S}_0, \mathcal{N}^+)$
  - Dynamic three-body pole generation in $\mathcal{N}^+$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_C \otimes \Gamma_F$$

- Strategy for solution:
  - Neglect "subleading" Lorentz invariants
    - $f_i(\mathcal{S}_0, \mathcal{V}_1^+, \mathcal{V}_2^+, \mathcal{N}^+) \;\rightarrow\; f_i(\mathcal{S}_0, \mathcal{N}^+)$
  - Dynamic three-body pole generation in $\mathcal{N}^+$
  - "Physical basis" Ansatz:

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_C \otimes \Gamma_F$$

- Strategy for solution:
  - Neglect "subleading" Lorentz invariants
    - $f_i(\mathcal{S}_0, \mathcal{V}_1^+, \mathcal{V}_2^+, \mathcal{N}^+) \;\rightarrow\; f_i(\mathcal{S}_0, \mathcal{N}^+)$
  - Dynamic three-body pole generation in $\mathcal{N}^+$
  - "Physical basis" Ansatz:
    - $f_i(\mathcal{S}_0, \mathcal{N}^+) \;\rightarrow\; f_i(\mathcal{S}_0) \cdot \mathrm{P}_1 \cdot \mathrm{P}_2$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

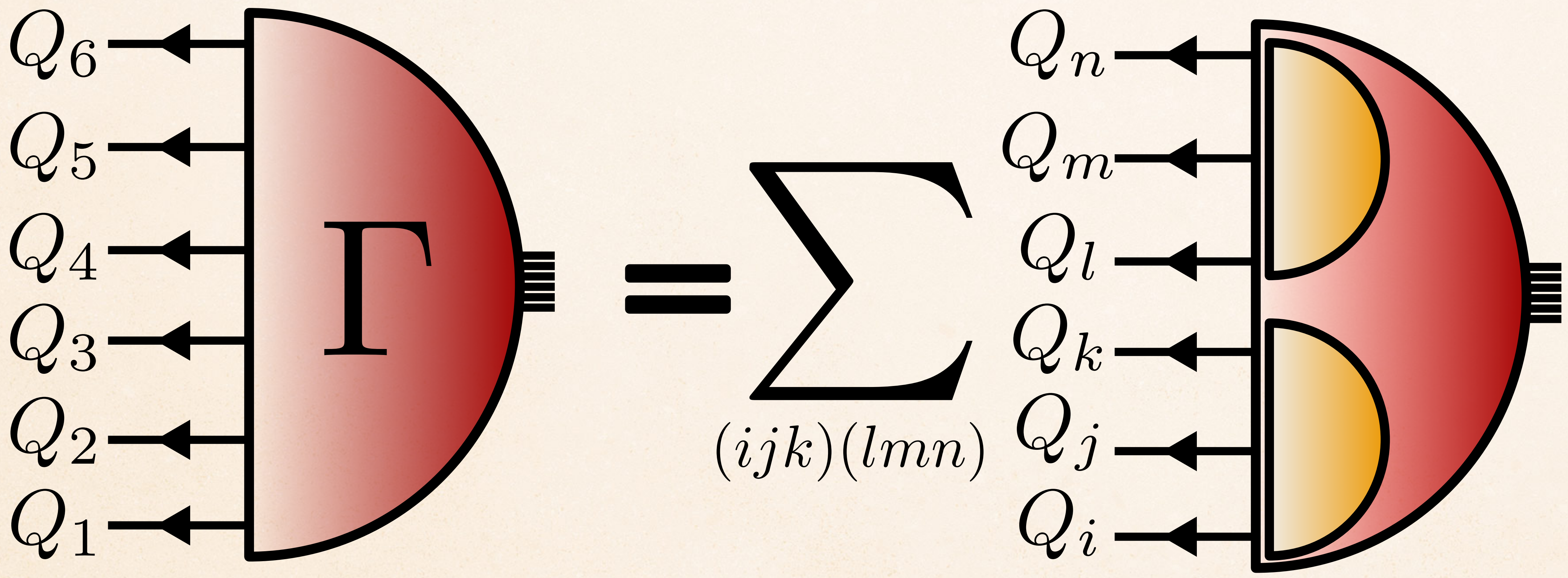
- “Physical” BSA:

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\,\tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_\mathrm{C} \otimes \Gamma_\mathrm{F}$$

- "Physical" BSA:



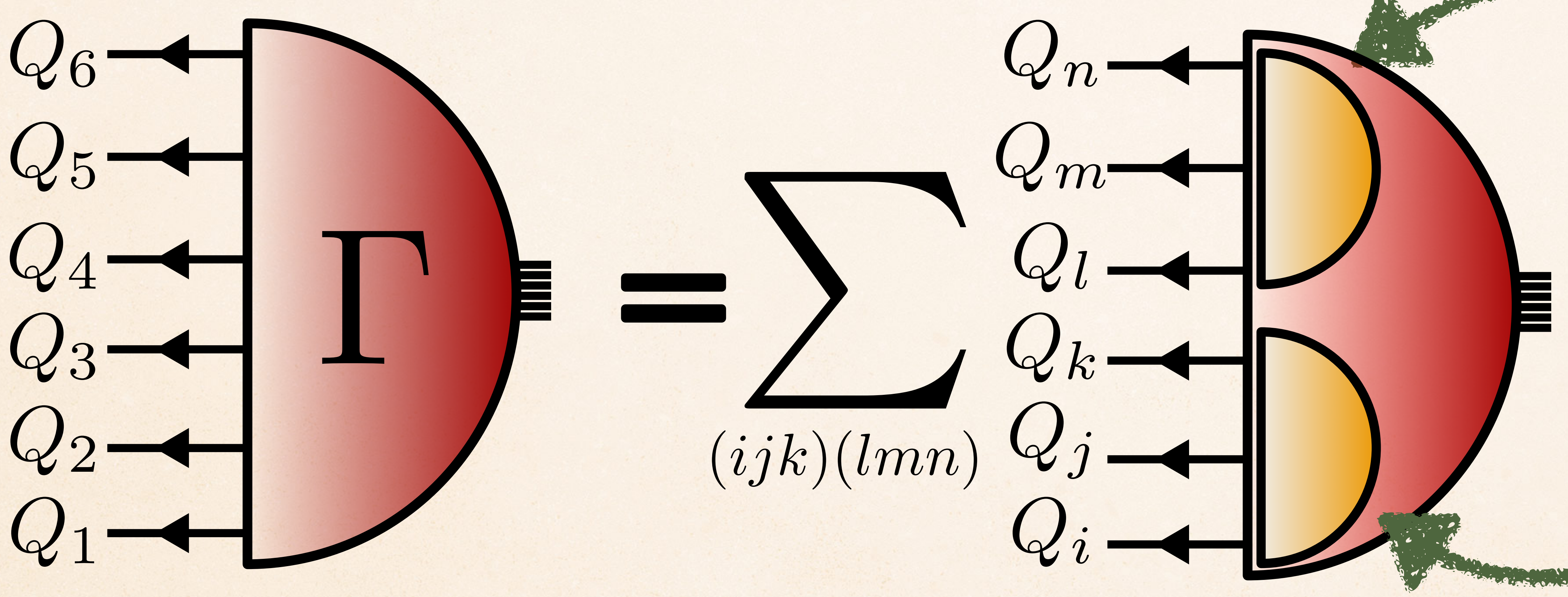
with $\quad i<j<k \quad \& \quad l<m<n$

Eichmann, JH, in preparation

SIX-QUARK BSA

$$\Gamma^{(\mu)}(k,q,p,r,l,P) = \boxed{\sum_{i=1}^{N} f_i(\Omega)\, \tau_i^{(\mu)}(k,q,p,r,l,P)} \otimes \Gamma_{\mathrm{C}} \otimes \Gamma_{\mathrm{F}}$$

- “Physical” BSA:



Combine dominant S-wave tensors of baryons, e.g., nucleon and Δ

with $i<j<k$ & $l<m<n$

Eichmann, JH, in preparation

CONCLUSION & OUTLOOK

- Construct hexaquark BSA using the “physical” Ansatz and in terms of the S_6 multiplets
- Calculate the dibaryon spectrum numerically
  - E.g., Deuteron and cousins, H-dibaryon, all-charm dibaryons
- Investigate the internal structure