Parity Doubling as a Tool for Right-Handed Currents (RHC) Searches

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Main idea and Outline

- SM-peculiarity: **V-A-interactions** $SU(2)_L$
  ⇒ "clear" leaves traces in **angular distributions/polarisations**

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$$\frac{\langle \phi\gamma | H^{\rm eff} |_{\rm Vector} | B_s \rangle}{\langle \phi\gamma | H^{\rm eff} |_{\rm Axial} | B_s \rangle} = 1 + \text{non-per-QCD}$$

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- **Parity doubling** of QCD helps to: 1) control uncertainties
  2) allows experimental assessment
  ⇒ study parity doublers (ratios)

$$\frac{\langle f_1(1420)\gamma | H^{\rm eff} | B_s \rangle}{\langle \phi(1020)\gamma | H^{\rm eff} | B_s \rangle} = 1 + O(m_q, \langle \bar{q} q \rangle)$$

improved situation

Before starting ....

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- Anomalies in B-physics are much discussed ..
  Concerning right-handed currents (**RHC**): interesting LHCb-result on time-dependent CP-asymmetry

$H_{B_s \to \phi\gamma} = -0.98(50)(20)$ LHCb'16

$H_{B_s \to \phi\gamma} = 0.047(25)$ Muheim, Xie, RZ'08

1. V-A interaction and Polarisation

still need to be more specific

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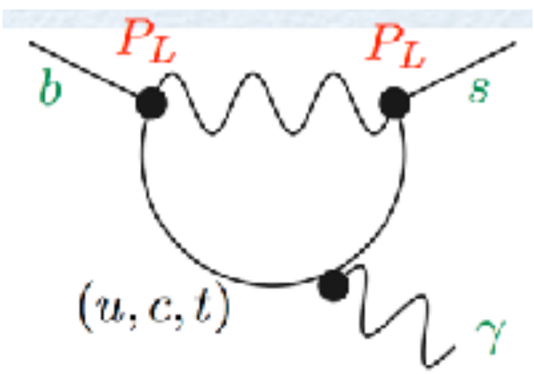
$$H^{eff} \sim m_b({\color{red}m_s})\bar{s}_{L({\color{red}R})}\sigma\cdot F b + \ldots$$



$b_R \to s_L \gamma_L \gg b_L \to s_R \gamma_R$

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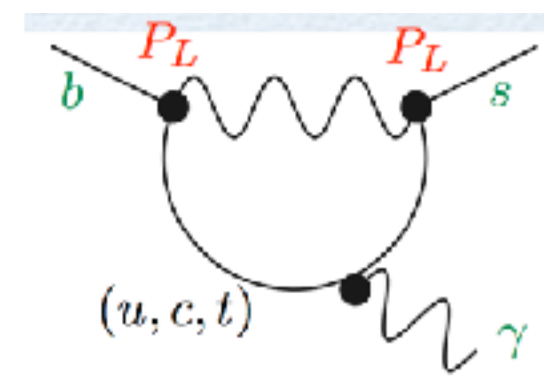

$b_R \to s_L\gamma_L \gg b_L \to s_R\gamma_R$

2. If **matrix elements** are sufficiently well-**known**

$$\frac{\langle V\gamma|H_V|B\rangle}{\langle V\gamma|H_A|B\rangle} = 1+\delta$$

can we predict δ with good accuracy?

where parity doubling can help

How to test hierarchy: need linear effect in ϵ_R

~~$\Gamma \sim 1 + |\epsilon_R|^2$~~

- $B_s \to \phi\gamma$ ($b \to s$) as a template

disentangle?

RHC

QCD

$$\epsilon_{\mathrm{R}} = \frac{A(\bar{B}_s \to \phi\gamma_R)}{A(\bar{B}_s \to \phi\gamma_L)} = \frac{m_s}{m_b} + \Delta_{\mathrm{R}} e^{i\phi_R} + \text{Long-Dist}$$

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RHC QCD

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- Effect linear in mixing: $\bar{B}_s \xrightarrow[m_b(m_s)]{} \phi\gamma_L(\gamma_R) \xleftarrow[m_s(m_b)]{} B_s$

$$B(\bar{B}_s[B_s] \to \phi\gamma) = B_0 e^{-\Gamma_s t}[\mathrm{ch}(\frac{\Delta\Gamma_s}{2}t) - H\,\mathrm{sh}(\frac{\Delta\Gamma_s}{2}t) \mp C\cos(\Delta m_s t) \pm S\sin(\Delta m_s t)]$$

… in t-odd quantities

Theoretical Status/activity in RHC-searches

- **New physics** aspects **Δ_{RHC}** Matias, Lunghi, Hiller, Becirevic, Kou …
  More complicated modes Becirevic, Taganouev , Kou, Gershon

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$\bar{\mathcal{A}}_{\chi}^{\bar{B}\to V\gamma}$	$\bar{A}_{SD,\chi}$	$\bar{A}_{LD,\chi}$	$\bar{A}'_{SD,\chi}$
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SD-form factor CKM-factor LD matrix element "**troublemaker**" Δ_{RHC} new physics

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SD-form factor

CKM-factor

LD matrix element "**troublemaker**"

Δ_{RHC} new physics

- Indirect argument: $\Delta S_{K^*\gamma}|_{LD} = 6\%$ (or more) inclusive-case Grinstein, Grossman, Ligeti,Pirjol '04

- Our computations: $\Delta S_{K^*\gamma}|_{LD} = 0.6\%$ Ball, RZ'06 - Gratrex, RZ to appear

This raises Questions:

Q1: Can LD-computation be assessed experimentally?

Q2: Can we understand smallness of LD-computation?

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With parity doubling:

A1: Usually only by resonance structure etc

Here: V-A transmutes into R-amplitude by QCD

$\Rightarrow$ Quantum-number change (parity sensitive!)

A2: Think so but intricate …

Use of Parity-doubling : ρ-meson (J^{PC}= 1−−) and a_1-meson (J^{PC}= 1^{++})

- QCD parity-invariant ⇒ states definite parity
  & **global** symmetries ⇒ **degeneracies** (e.g. isospin,supersymmetry)

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- or **chiral symmetry restoration limit**: m_q, <qq>,… → 0
  the flavour-symmetry **$SU(N_f)_V$ x $SU(N_f)_A$ x "$U(1)_A$"** is restored

parity doubling
(straightforward version)

Afonin'07 (history)

$SU(N_f)_A \Rightarrow m_\rho = m_{a1}$

Practice tricky lattice:
1) high-T or
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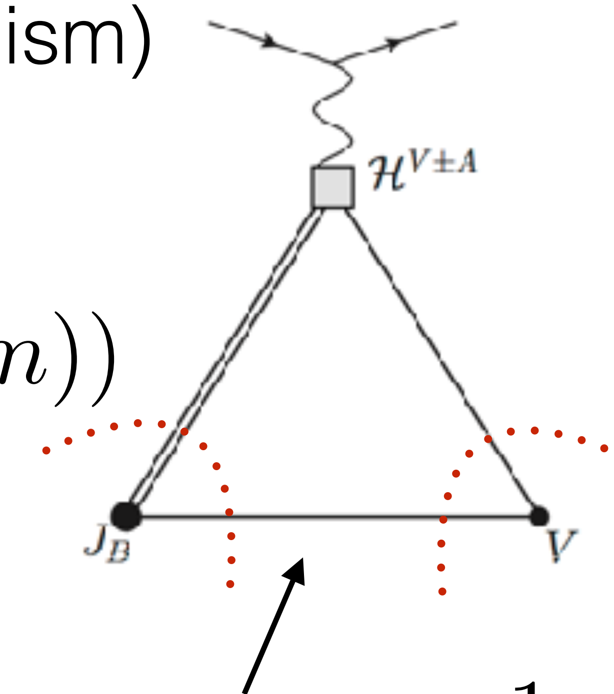
We advocate to study Parity Doubling beyond mass e.g. for form factors & long-distance effects

Path-Integral Representation of Correlation Functions

- Consider: **3-pt** function in **Path-integral** representation
  (physical matrix element via LSZ-formalism)



$$\langle T J_B(x) J_V(y) \mathcal{H}(0) \rangle = \int DG e^{iS(G)} \det(\not{D} + im))$$

as in lattice QCD
but here Minkowski space

$$S_G(x,y) = \langle x | \frac{1}{\not{D}} | y \rangle$$

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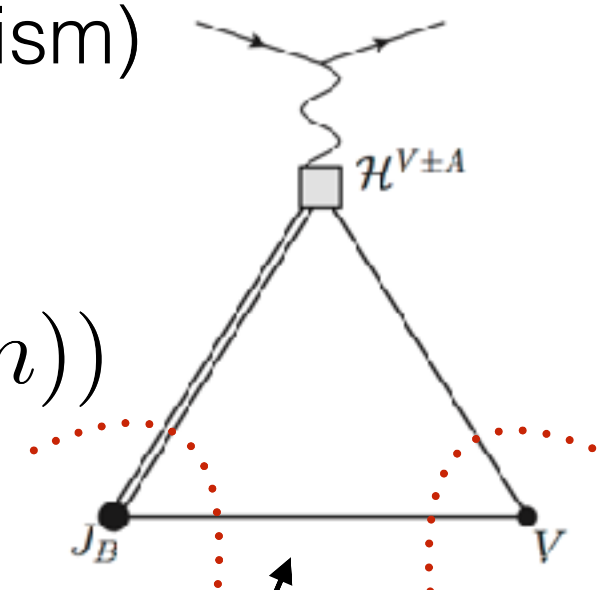

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O_7

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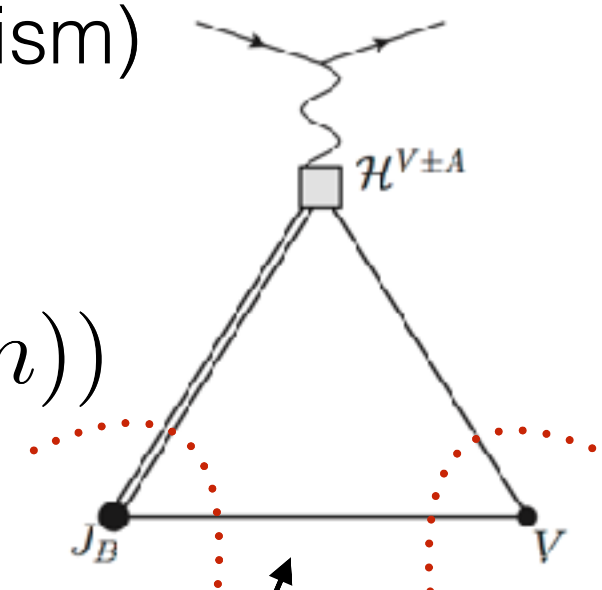

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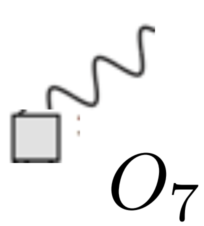
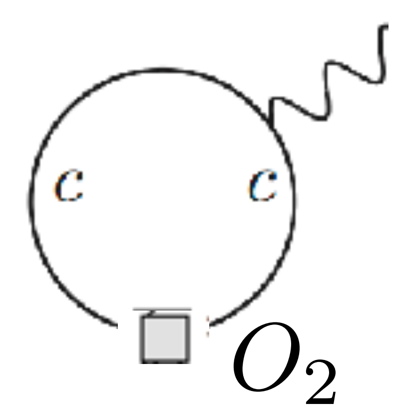
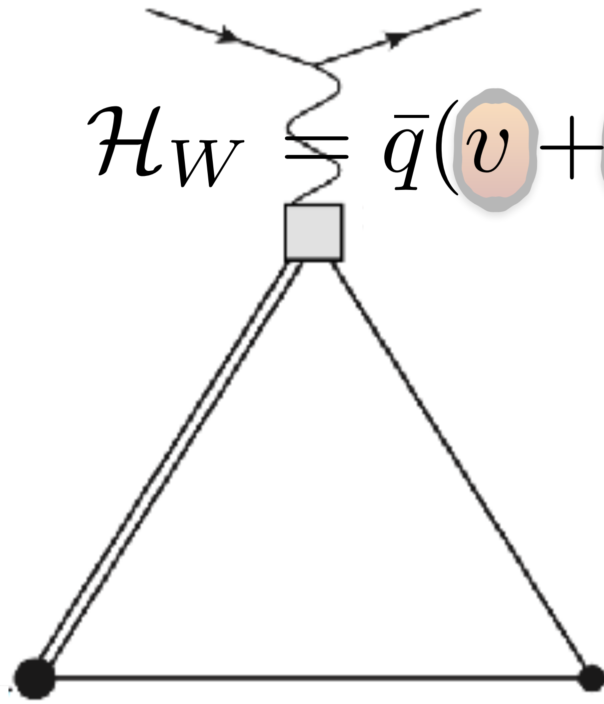


charm loop



Parity Doubling ➢ (+L,+R) → (-L,+R)

$B \to \rho\gamma$ $\qquad$ $B \to a_1\gamma$

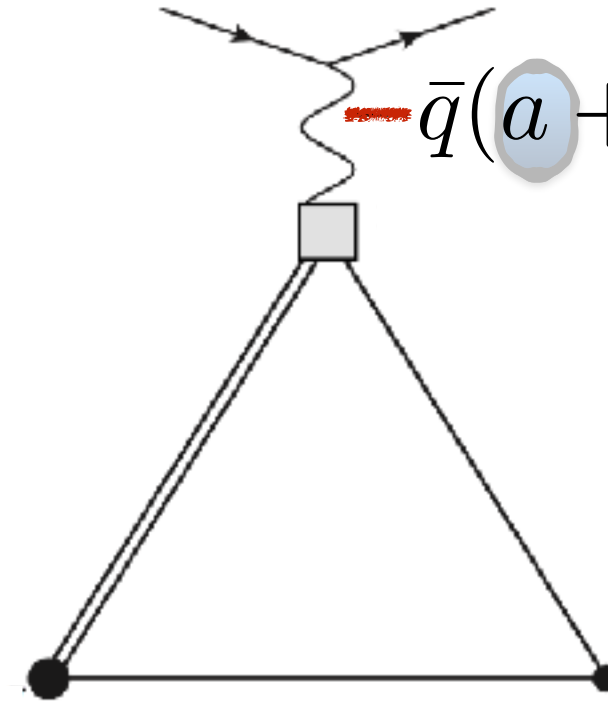


$\mathcal{H}_W = \bar{q}(v + a\gamma_5)\Gamma b$

$$=$$

$$\uparrow$$

$$\gamma_5 S^{(q)} = -S^{(q)}\gamma_5$$



$-\bar{q}(a + v\gamma_5)\Gamma b$

J_B $\qquad$ $\rho_\mu = \bar{q}t^a\gamma_\mu q$

J_B $\qquad$ $(a_1)_\mu = \bar{q}t^a\gamma_\mu\gamma_5 q$

$$L(R) \leftrightarrow (v, a) = (1, \pm 1)$$

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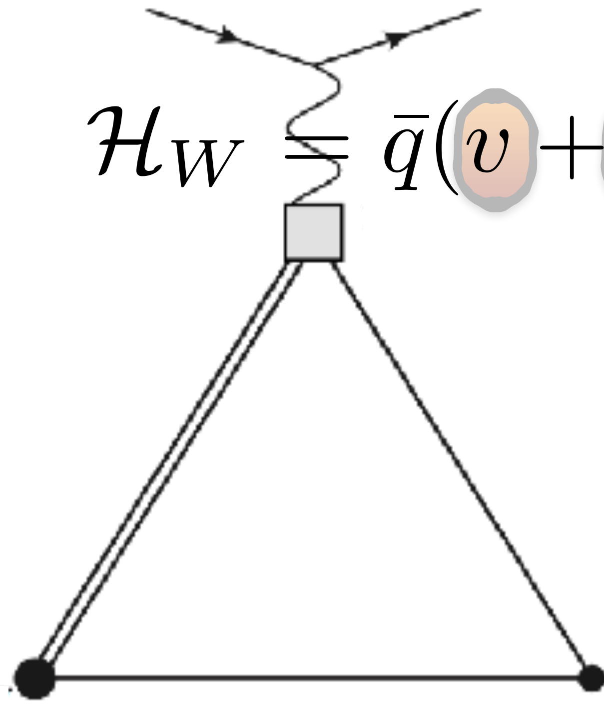

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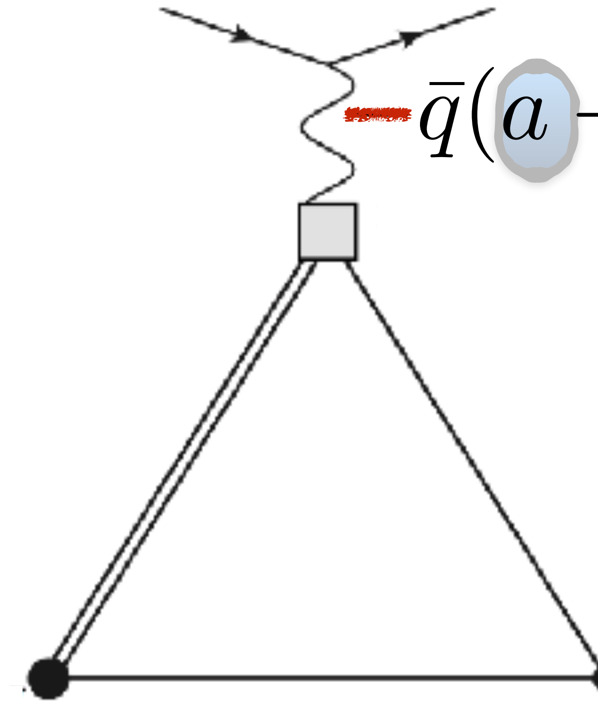

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- Ergo (up to irrelevant phase)

crucial sign

$$\mathcal{H}_{V-A}, \mathcal{H}_{V+A} \quad \Rightarrow \quad -\mathcal{H}_{V-A}, +\mathcal{H}_{V+A}$$

$$\bar{\mathcal{A}}_\chi^{\bar{B}\to\rho\gamma}(C, C') = \bar{\mathcal{A}}_\chi^{\bar{B}\to a_1\gamma}(-C, C')$$

2nd amplitude breakdown

- as a consequence of $H^{V\pm A}|_{\rho} \Rightarrow \pm H^{V\pm A}|_{a1}$ relative sign between the V-A and V+A structure between doublers!

$\bar{\mathcal{A}}_{\chi}^{\bar{B}\to\rho(a_1)\gamma}$	$\bar{A}_{SD,\chi}$	$\bar{A}_{LD,\chi}$	$\bar{A}'_{SD,\chi}$
$\chi = L$	± 1	$\pm \tilde{\lambda}_i \epsilon^i_{V,L}$	0
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Table of "parity doublers"

I^G	1^{--}	$\frac{\Gamma_V}{m_V}$	O_V	I^G	1^{++}	$\frac{\Gamma_V}{m_V}$	O_V	I^G	1^{+-}	$\frac{\Gamma_V}{m_V}$	O_V
1^+	$\rho(770)$	19.1(1)	$(V,T)^I$	1^-	$a_1(1260)$	35(14)	V_5^I	1^+	$b_1(1235)$	11.5(7)	T_5^I
0^-	$\omega(782)$	1.08(1)	V,T	0^+	$f_1(1285)$	1.77(1)	V_5	0^-	$h_1(1170)$	31.0(5)	T_5
0^-	$\phi(1020)$	0.417(2)	$(V,T)^{\bar{s}s}$	0^+	$f_1(1420)$	3.8(2)	$V_5^{\bar{s}s}$	0^-	$h_1(1380)$	6.3(16)	$T_5^{\bar{s}s}$
I	1^-				1^+				1^+		
$\frac{1}{2}$	$K^*(895)$	5.6(1)	$(V,T)^s$	$\frac{1}{2}$	$K_1(1270)$	7.1(16)	V_5^s	$\frac{1}{2}$	$K_1(1400)$	12.0(9)	T_5^s

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Going back to example of $B_s \to \phi\gamma$
& beyond symmetry limit (QCD)

Back to $B_s \to \phi\gamma$ template

- doubler: of ϕ(1020) $J^{PC}=1^{--}$ is the $f_1(1480)$ 1^{++}

$$H_{\phi[f_1]\gamma} \simeq 2\big(\pm (\frac{m_s}{m_b} + \Delta_R \cos(\phi_{\Delta_R})) - \mathrm{Re}[\epsilon^c_{\phi[f_1],R}]\big)$$

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- Hence we can either: … measure LD-charm (doubler-sum)

$$H_{\phi\gamma} + H_{f_1\gamma} \simeq -2\mathrm{Re}[\epsilon^c_{\phi,R} + \epsilon^c_{f_1,R}] = -2\mathrm{Re}[\epsilon^c_{\phi,R}](1 + \mathbb{R}^c_{f_1,\phi})$$

clean (exact form factor relation)

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- … RHC Δ_R with reduced LD-charm (doubler difference)

$$\Delta_R \cos(\phi_{\Delta_R}) = \frac{1}{4}(H_{\phi\gamma} - H_{f_1\gamma}) + \frac{1}{2}\mathrm{Re}[\epsilon^c_{\phi,R} - \epsilon^c_{f_1,R}] - \hat{m}_s$$

work on prediction controlled by V-meson DA work in progress

$$\mathbb{R}^i_{A,V} \equiv \frac{\mathrm{Re}[\epsilon^i_{A,R}]}{\mathrm{Re}[\epsilon^i_{V,R}]} = 1 + O(m_q, \langle \bar{q}q \rangle) \simeq 1.3(1)$$

Conclusions & outlook

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  2) **RHC** with reduced LD-contamination
  3) combination of 1) & 2) *data-driven/theory program*

e.g. compute doubler-ra $\mathbb{R}^i_{A,V}$ to 20%, allows to extract ε_R to 10% accuracy ⇒ much improved situation!

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- $\Delta S_{K^*\gamma}|_{LD}$ = 6% (skeptic)
  $\Delta S_{K^*\gamma}|_{LD}$ = 0.6% (computation)
  $\Delta S_{K^*\gamma}|_{LD}$ = 0.0x% (parity doubling) 'almost' O(magnitude)

SM-Null test

- Elimination of SM LD-effects on RHC: $\Delta C'_{7,8,910} \neq 0$, using **parity doubling** will continue to hold for **B→Vll** (powerful low q^2 (large recoil) where nearly null-test)

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- Measuring just **one parity doubler** provides invaluable info on LD-contamination. (Deserves more attention from experiment) Also useful to cross-check predictions going into P'_5.

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Thanks for your attention!

BACKUP

Quick summary: experiment & theory numbers

- **Experiment:**
- $S_{K^*\gamma}$ and $S_{\rho\gamma}$ good @ B-factories

$S_{B\to K^*\gamma}$ = -0.16(22)
$S_{B\to\rho\gamma}$ = -0.83(65)(18)

Belle, Babar (HFAG-values)

- $H_{\phi\gamma}$ feasible @ LHCb

Muheim, Xie, RZ'08

$H_{Bs\to\phi\gamma}$ = -0.98(50)(20)

LHCb'16

- **Theory:**

$$S_{K^*\gamma} = -\frac{m_s}{m_b}\sin(2\beta) + \text{LD} = -2.3(16)\%$$

$$S_{\rho\gamma} = \frac{m_d}{m_b} + \text{LD} = 0.2(16)\%$$

$$H_{\phi\gamma} = \frac{m_s}{m_b} + \text{LD} = 4.7(25)\%$$

Ball, Jones, RZ'06

show for completeness

$$\text{BelleII@50}ab^{-1} : \; \Delta S_{K^*\gamma} = 3\% \; , \Delta S_{\rho^0\gamma} = 6\%$$

So what's the trouble (besides statistics)?

2. Parity Doubling* - Global Symmetries

- QCD is parity symmetric - (parity not spontaneously broken Vafa, Witten'84)
- Parity discrete symmetry: Z_2 with irreps **1** and **1'**
  particles parity-eigenstates - either **singlet** or **doublet** of parity

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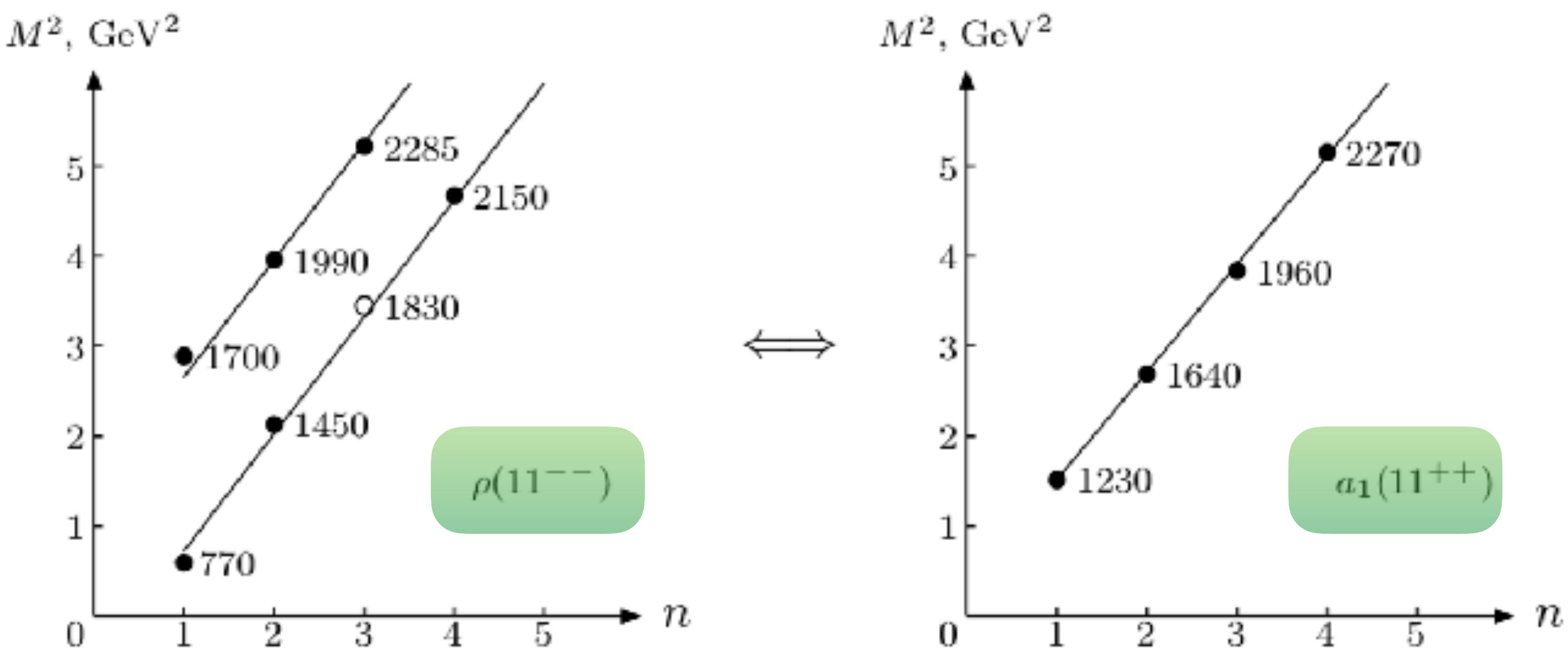
- Reality-check: Anisovich'04



Doubling pattern but not exact. Need a little help from ……

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(I_L, I_R) ↓		$V(I, J^{PC})$			
$(0,0)$		$f_1^{\parallel}(0,1^{++})$ $\gamma_k\gamma_5$		$\omega^{\parallel}(0,1^{--})$ γ_k	
$(\frac{1}{2},\frac{1}{2})_a$	$U(1)_A$	$b_1^{\perp}(1,1^{+-})$ $\sigma_{\kappa\lambda}\gamma_5 T^A$	← $SU(2)_A$ →	$\omega^{\perp}(0,1^{--})$ $\sigma_{\kappa\lambda}$	$U(1)_A$ — 4-plet ⟩ 8-plet?
$(\frac{1}{2},\frac{1}{2})_b$		$\rho^{\perp}(1,1^{--})$ $\sigma_{\kappa\lambda} T^A$	← $SU(2)_A$ →	$h_1^{\perp}(0,1^{+-})$ $\sigma_{\kappa\lambda}\gamma_5$	4-plet
$(1,0)\oplus(0,1)$		$\rho^{\parallel}(1,1^{--})$ $\gamma_k T^A$	← $SU(2)_A$ →	$a_1^{\parallel}(0,1^{++})$ $\gamma_k\gamma_5 T^A$	6-plet

Intermezzo: test of Symmetry on the Lattice

- Tested on lattice: T>T_χ Rohrhofer, Aoki, Cossu, Fukaya, Glozman, Hashimoto, Lang. Prelovsek'17
  truncate low Dirac eigenmodes Denissenya, Glozman,Lang '14'15

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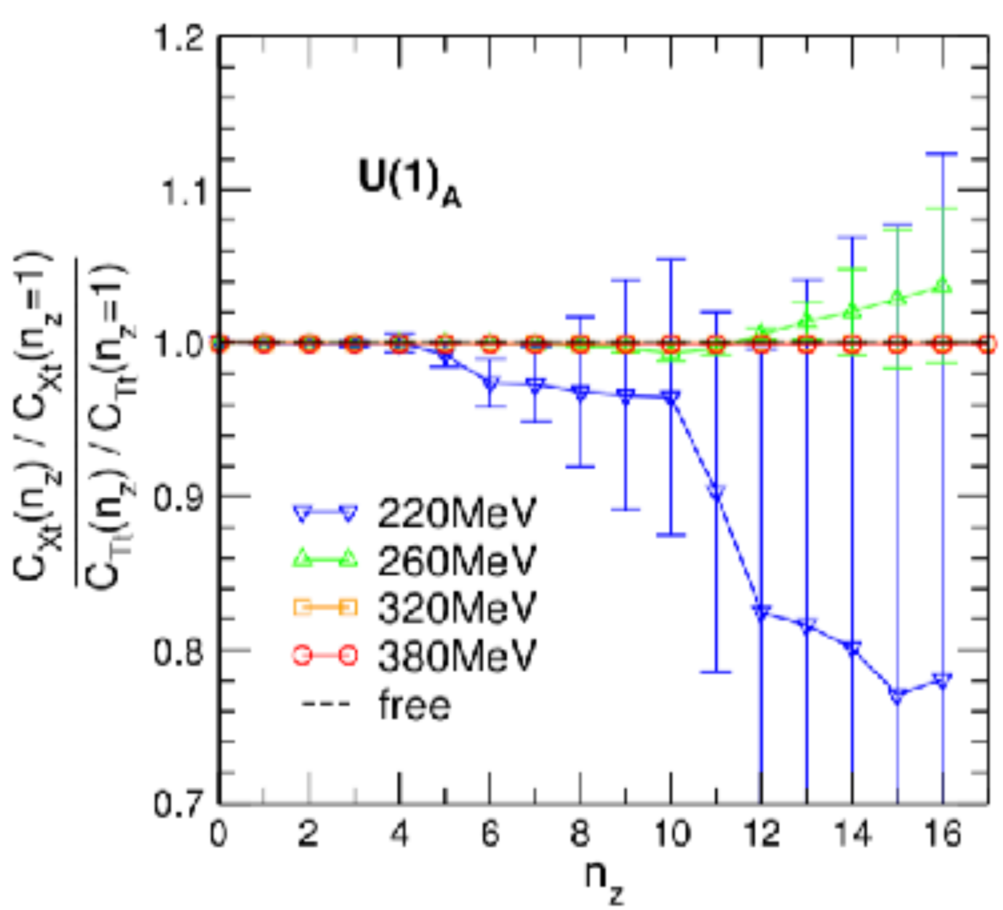
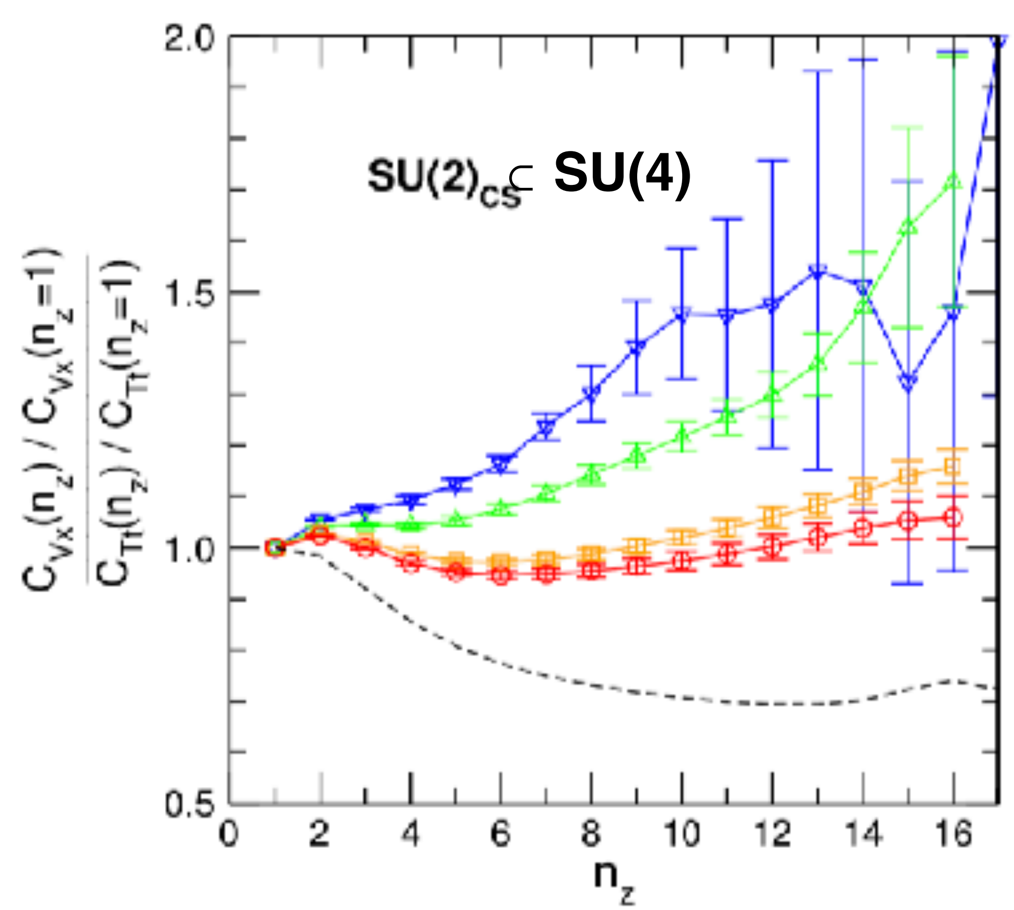


$U(1)_A$ restoration

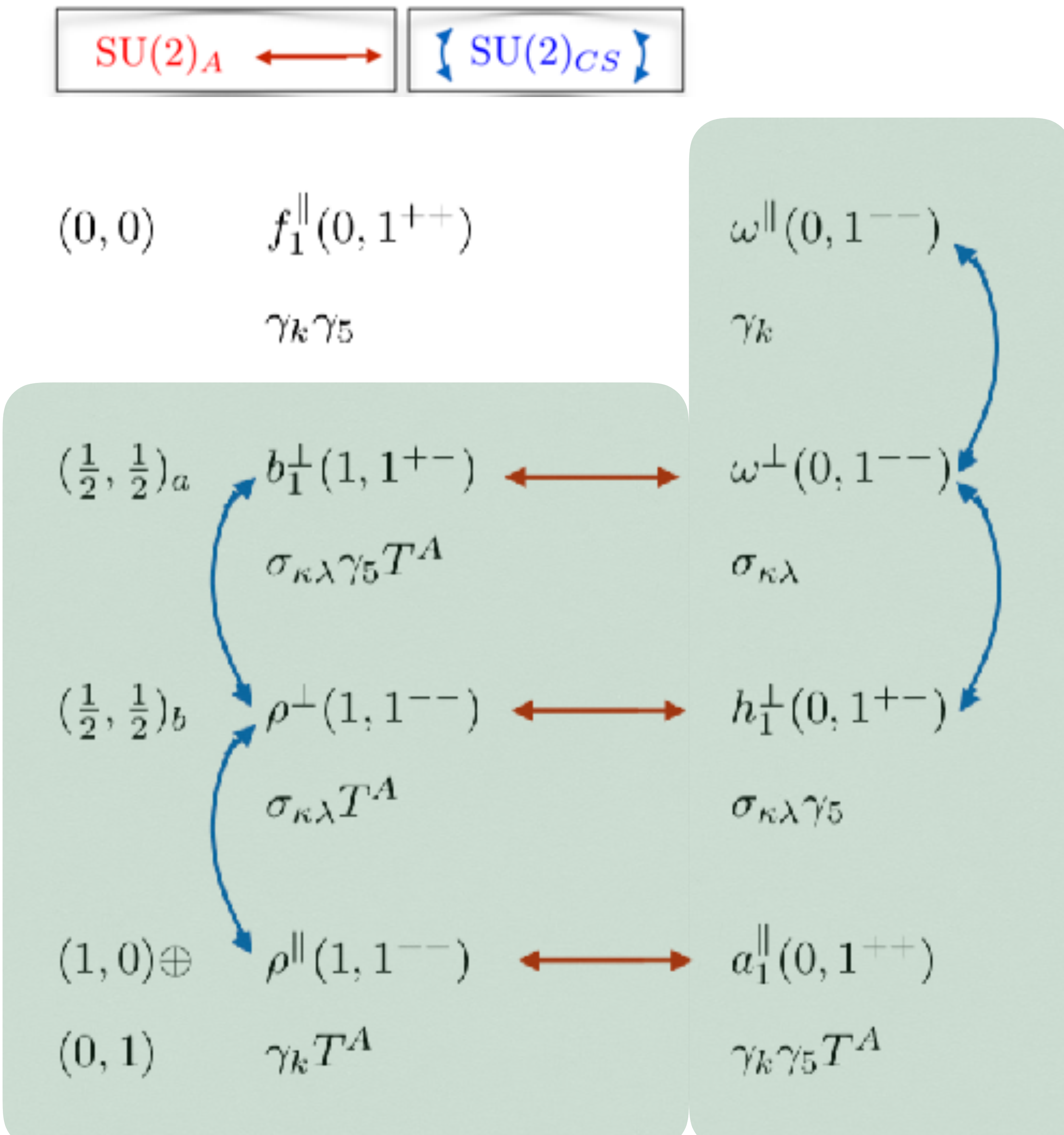


SU(2)Chiral spin emergence!

More concretely.....

$SU(2)_V \times SU(2)_A \times U(1)_A$

$SU(2)_{CS}$ $\Rightarrow$ **SU(4) ⊃15-plet**



$SU(2)_V$ **SU(4)**

$$\Psi = \begin{pmatrix} u \\ d \end{pmatrix} \rightarrow \Psi = \begin{pmatrix} u_L \\ u_R \\ d_L \\ d_R \end{pmatrix}$$

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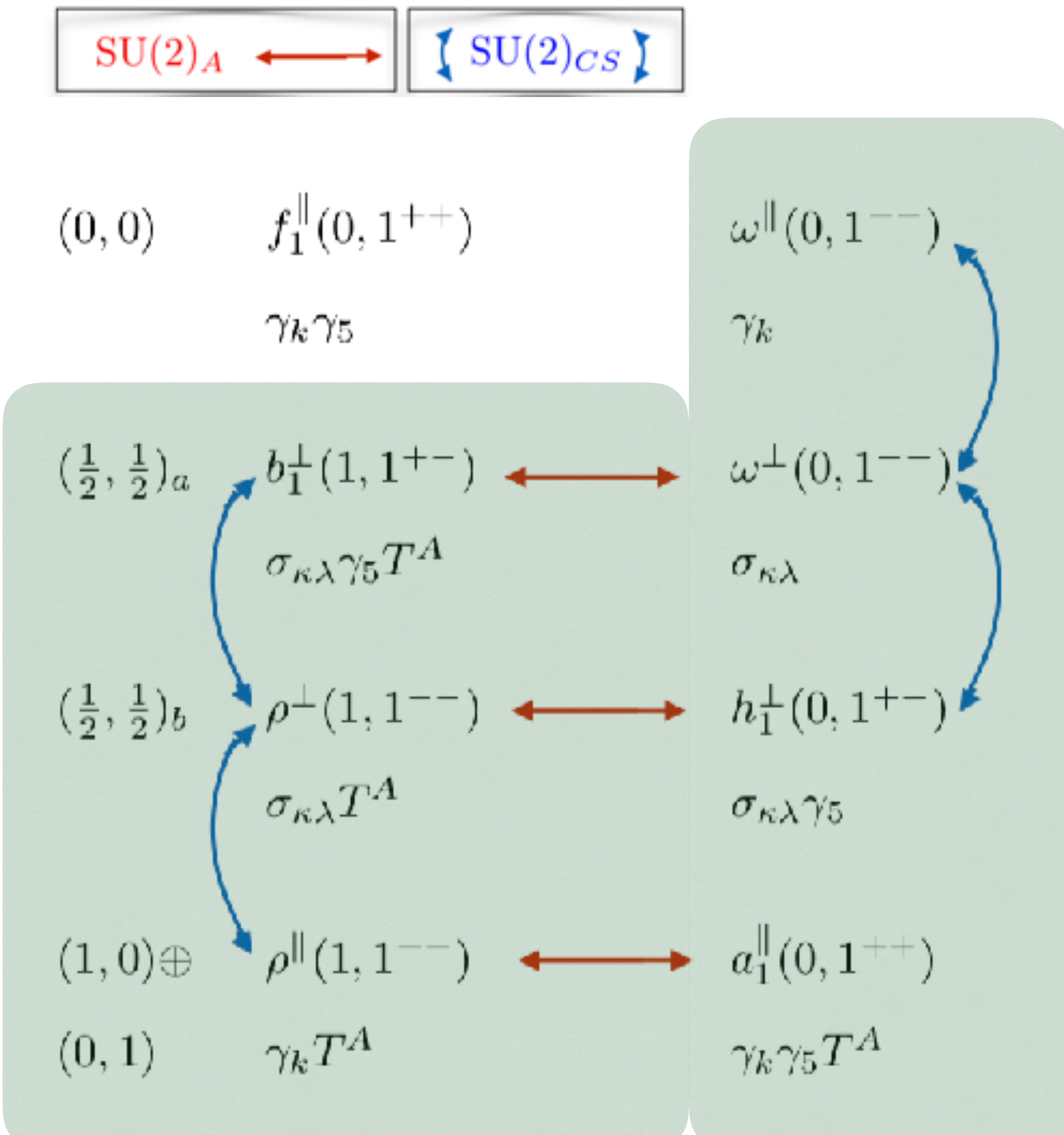

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Glozman, Pak'15 ....

- **$SU(2)_{CS}$** generated by
  $\{\gamma^k, -i\gamma^5\gamma^k, \gamma^5\}$ $, k = 1, ..., 4$ i
  CS = chiral spin
- $SU(2)_{CS}$ intact if one neglects
  $\bar{q}\vec{\gamma}\cdot\vec{D}q$ simplified picture of confinement?

Weinberg Sum Rules - parity splitting controlled by condensates

- combining **dispersion relations** and **group theory** Weinberg'67

$$\Pi^{ab}_{LR} \sim \begin{cases} \int_0^\infty ds \, \frac{\rho_V(s) - \rho_A(s)}{s - q^2 - i0} \\ \frac{\langle \bar{q}\gamma_\mu T^a \lambda^i q_L \bar{q}\gamma^\mu T^b \lambda^i q_R \rangle}{q^6} + \ldots \end{cases}$$

$$\rho_A(s) = F_\pi^2 \delta(s - m_\pi^2) + F_{a_1}^2 \delta(s - m_{a_1}^2) + \ldots \qquad \rho_V(s) = F_\rho^2 \delta(s - m_\rho^2) + \ldots$$

massless quarks

$$(\Pi^{a,b}_{LR})_{\mu\nu}(q^2) = i \int d^4x e^{iq\cdot x} \langle T J^{a,L}_\mu(x) J^{b,R}_\nu(x) \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi^{a,b}_{LR}(q^2) \; ;$$

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- Assuming perturbation theory to dominate above a₁-meson:

2-Weinberg sum rules:

$$F_\rho^2 - F_\pi^2 - F_{a_1}^2 = 0 \,,$$

$$m_\rho^2 F_\rho^2 - m_{a_1}^2 F_{a_1}^2 = 0 \,,$$

3rd sum rule:

$$m_\rho^4 F_\rho^2 - m_{a_1}^4 F_{a_1}^2 = (c\alpha_s + \dots)\, \underbrace{\langle \bar{q}..q_L q..q_R\rangle}_{\simeq \langle \bar{q}q\rangle^2} \,.$$