A study of J/ψ decays into baryon-antibaryon pairs

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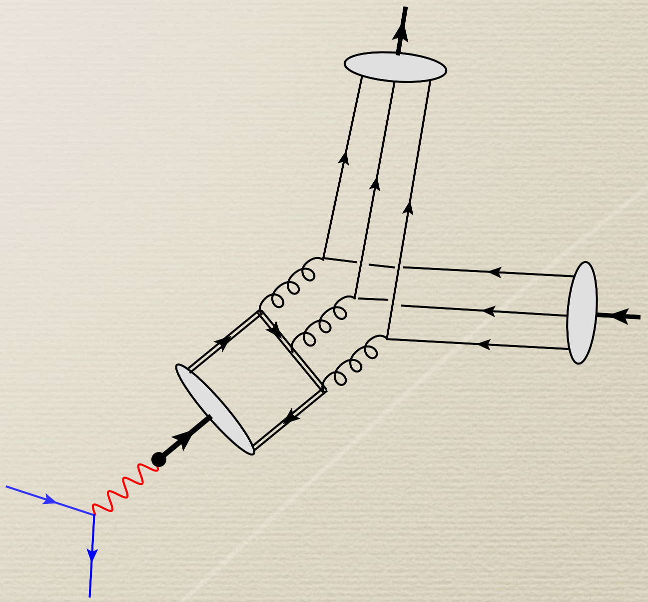

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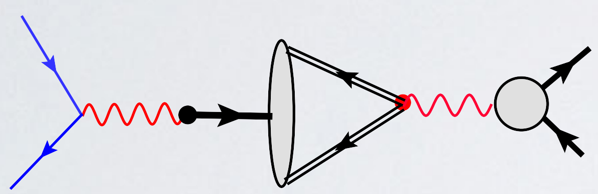
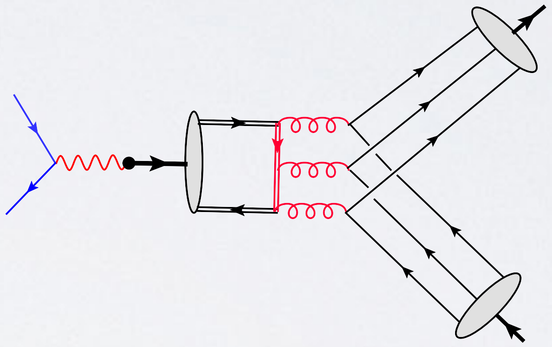
J/ψ baryonic decays

$$\mathrm{Br}[J/\psi \to B\bar{B}] = \frac{M_\psi \beta}{12\pi\Gamma_{tot}} |G_M^g + G_M|^2 \left(1 + \frac{2m_B^2}{M_\psi^2}\gamma_B^2\right) \qquad \gamma_B = \left|\frac{G_E^g + G_E}{G_M^g + G_M}\right|$$



em FF's

G_M, G_E



QCD amplitudes

G_M^g, G_E^g

Hard kernel

$$G_M^g \simeq R_{10}(0)\,\varphi_3(x_i) * H(x_i, y_i) * \varphi_3(y_i)$$

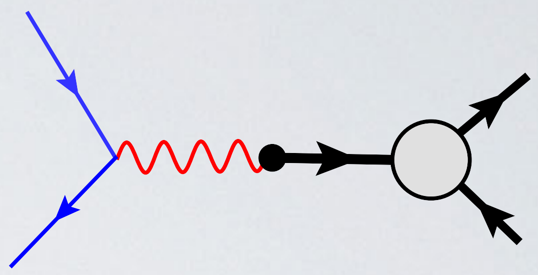
Baryon LCDA

Brodsky, Lepage 1981

Chernyak, Zhitnitski 1984

J/ψ baryonic decays

$$\frac{dN}{dcos\theta} = \mathcal{N}(1 + \alpha \cos^2 \theta)$$



$$\alpha_B = \frac{1 - 4m_B^2\gamma_B^2/M_\psi^2}{1 + 4m_B^2\gamma_B^2/M_\psi^2}$$

$$\gamma_B = \left| \frac{G_E^g + G_E}{G_M^g + G_M} \right|$$

$$m_Q \to \infty \qquad \alpha = 1$$

Brodsky, Lepage 1981

$$\frac{4m_N^2}{M_\psi^2} \simeq 0.37 \qquad \frac{4m_N^2}{M_\Upsilon^2} \simeq 0.04$$

$$\gamma_N^2 = 1 \qquad \alpha_N = \frac{1 - 4m_N^2/M_\psi^2}{1 + 4m_N^2/M_\psi^2} = 0.463$$

Claudson, Glashow, Wise 1982

J/ψ baryonic decays

BESIII publications & PDG

Baryon	$\mathrm{Br}[J/\psi \to B\bar{B}] \times 10^3$	α_B	$\gamma_B = \frac{G_E^g + G_E}{G_M^g + G_M}$	$Q_B = \frac{\mathrm{Br}[\psi(2S)\to B\bar{B}]}{\mathrm{Br}[J/\psi\to B\bar{B}]} \times 100$
p	2.121(29)	0.595(12)	0.823	13.86(3)
n	2.09(16)	0.50(4)	0.943	14.64(14)
Λ	1.89(9)	0.469(26)	0.834	20.43(11)
Σ^0	1.172(32)	−0.449(20)	2.11	20.96(27)
$\Sigma^\pm$	1.50(29)	−0.510(20)	2.27	7.22(48)
$\Xi^\pm$	0.97(8)	0.58(4)	0.606	26.73(50)

asymptotic criteria

$$Q_B \overset{m_c\to\infty}{\approx} Q_l = \frac{\mathrm{Br}[\psi(2S) \to e^+e^-]}{\mathrm{Br}[J/\psi \to e^+e^-]} \times 100 = 13, 21$$

Theoretical estimates

Largest amount of papers are dedicated to Br's and constrains of baryon DAs

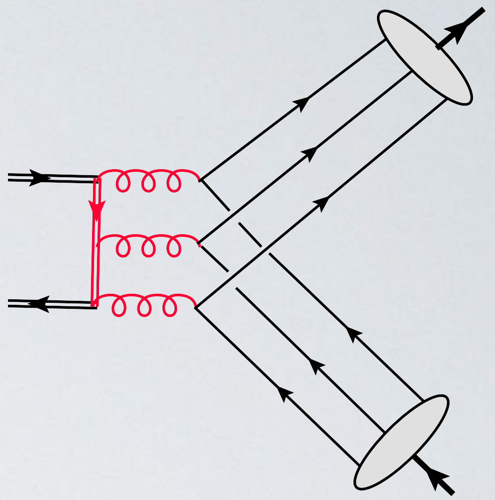
Carimalo, 1987 $\alpha_N = 0.70$ constituent quarks, non-relativistic nucleon WF

Murgia, Melis, 1995 $\alpha_N = 0.561 - 0.963$ constituent quark mass $m_i = x_i m_N$ in the LT factorisation formula

$J/\Psi \to p\bar{p}$ decay

$\mathcal{A}_{Q\bar{Q}}$ can be systematically computed within EFT framework

$$\mathcal{A}_{Q\bar{Q}}[Q\bar{Q} \to 3g \to p\bar{p}] = \mathcal{A}^{(0)} \left(\frac{\Lambda^2}{m_c^2}\right)^4 + \mathcal{A}^{(1)} \left(\frac{\Lambda^2}{m_c^2}\right)^6 + \ldots$$

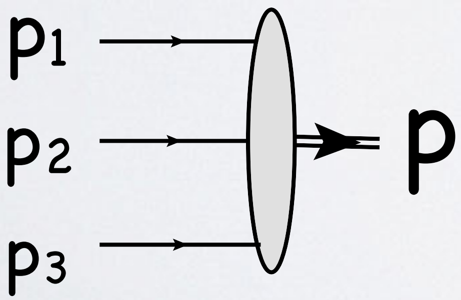


$$\mathcal{A}_0 = \int Dx_i \varphi_3(x_i) \int Dy_i \varphi_3(y_i)\, T_H(x_i, y_i, m_c^2)$$

int. measure $Dx_i = dx_1 dx_2 dx_3\, \delta(x_1 + x_2 + x_3 - 1)$

Long distance physics associated with the nucleon WF's

Distribution amplitude $\varphi_3(x_i)$ describes how the long. momentum is shared between the constituents



$$\varphi_N(x_1, x_2, x_3) \sim \int_{k_{i\perp} \sim \Lambda} dk_{i\perp} \Psi_P(x_1, x_2, x_3, k_{i\perp})$$

$p_i = x_i\, p + p_{\perp i}$ $\quad p_i^2 \sim \Lambda^2$ $\quad p_{\perp i} \sim \Lambda$ $\quad (p_i)_0 \sim (p_i)_3 \sim m_c$

$J/\Psi \to p\bar{p}$ decay : challenges in the calculation G_E

A systematic description of G_E involves higher twist nucleon DA's

$$G_E^g \simeq R_{10}\, \varphi_3(x_i) * \alpha_s^3 H(x_i, y_i) * \varphi_4(y_i)$$

Schematically:

twist-3

$$\langle 0\,|u(a_1 z)u(a_2 z)d(a_3 z)|\,p\rangle_{z^2=0} \overset{FT}{\to} \varphi_3(x_i)$$

3 quarks with L_q = 0

twist-4

$$\langle 0\,|u(a_1 z)[D_\perp u(a_2 z)]d(a_3 z)|\,p\rangle_{z^2=0} \overset{FT}{\to} \varphi_4(x_i)$$

3 quarks with L_q=1

$$\langle 0\,|u(a_1 z)u(a_2 z)]d(a_3 z)A_\perp(a_4 z)|\,p\rangle_{z^2=0} \overset{FT}{\to} \varphi_4(x_i)$$

3 quarks & gluon

Baryon LCDA's $B = N, \Lambda, \Sigma, \Xi$

Braun et al, '00, '08,
Manashov, Anikin '13
Anikin '15
Shäfer, Wein '15

	chiral odd	chiral even		
twist 3	$\Phi^B_{3\pm}(x_i)$	$\Pi^B_3(x_i)$		
twist 4	$\Phi^B_{4\pm}(x_i)$	$\Xi^B_{4\pm}(x_i)$	$\Pi^B_4(x_i)$	$\Upsilon^B_4(x_i)$

WW decomposition: $\Phi^B_{4\pm} = \Phi^{B,WW}_{4\pm} + \bar{\Phi}^B_{4\pm}$ $\quad \Pi^B_4 = \Pi^{B,WW}_4 + \bar{\Pi}^B_4$

models:
(examples)

$$\phi^B_{3+} = f_B x_1 x_2 x_3 (1 + \phi^B_{11}(x_1 - 2x_2 + x_3) + \dots)$$

$$\bar{\Phi}^B_{4+}(x_i) = \lambda^B_1 \; 24 x_1 x_2 \left(\; - \eta^B_{11}(2x_1 - x_2 - 2x_3)\right)$$

$$\bar{\Phi}^B_{4-}(x_i) = \lambda^B_1 \; 24 x_1 x_2 \left(1 + \eta^B_{10}(4 - 10x_2)\right)$$

quark-gluon operators contribute starting from η^B_{2i} and will be neglected

J/ψ baryonic decays: hard kernels   N.Kivel, 2019/21 (updated in Arxiv)

Result
$$G_E^g = \frac{f_\psi}{m_c^2}\frac{f_B^2}{m_c^4}\frac{10\pi^3}{81}\int Dx_i\,\varphi_3^B(x_i)\int Dy_i\,\varphi_4^B(y_i)\,\alpha_s^3 H_B(x_i,y_j)$$

$m_c \to \infty \qquad \gamma_B = G_E^g/G_M^g \sim \mathcal{O}(1)$ multiplicative factors cancel

NRQCD m.e. $\langle 0|\,\chi_\omega^\dagger(0)\gamma^\mu\psi_\omega(0)\,|P\rangle = \epsilon_\psi^\mu\, f_\psi . \qquad f_\psi = \sqrt{2M_{J/\psi}}\sqrt{\frac{3}{2\pi}}\,R_{10}(0)$

Nucleon m.e. $\langle 0|[u(0)C\not{z}u(0)]\gamma_5\not{z}d(0)|p_N\rangle = f_N(pz)\not{z}N(p_N) \qquad z^2=0$

Comments to the hard kernel calculations: Im G_E = 0   absence of phys. cuts

Twist-4 projection of the m.e. includes the derivatives with respect to quark transverse momenta, which makes the calc to be more involved comparing to G_M

Individual diagrams have the IR end-point singularities (soft gluon limit), which cancel in the sum of all diagrams (color neutrality). Hence collinear factorisation is not violated.

4-dim integrals over the mom. fractions can be easily computed in mathematica using the standard integration package

$J/\Psi \to p\bar{p}$ decay   non-perturbative input

$$f_\psi = \sqrt{2M_{J/\psi}}\sqrt{\frac{3}{2\pi}}\,R_{10}(0) \qquad \Gamma[J/\psi \to e^+e^-] = \frac{16}{9}\frac{\alpha_{em}^2}{M_\psi^2}\,|R_{10}(0)|^2\left(1 - \frac{16}{3}\frac{\alpha_s}{\pi}\right)$$

$$|R_{10}(0)|^2 \simeq 0.81\mathrm{GeV}^3$$

$$m_c = 1.5\ \mathrm{GeV}^2,$$

Eichten, Quigg 1995 (Buchmüller-Tye potential)

Renormalisation scale:

$$\mu^2 = 2m_c^2 - 1.5\ \mathrm{GeV}^2 \qquad \alpha_s(\mu^2) = 0.30\text{–}0.35$$

These parameters are important for the description of the branching ratios and remain the same for all baryons

$J/\psi \to N\bar{N}$ decay   non-perturbative input

Nucleon DAs are fixed from LCSR analysis of nucleon FF's

Anikin, Braun, Offen (NLO LCSR), 2013

overlap with lattice calc   Bali et al (RQCD), 2019

twist-3 $\mu^2 = 4\ \mathrm{GeV}^2$ twist-4

model	f_N, GeV^2	φ_{10}	φ_{11}	φ_{20}	φ_{21}	φ_{22}	λ_1/f_N	η_{10}	η_{11}
ABO	4.8×10^{-3}	0.047	0.047	0.069	−0.024	0.15	−6.27	−0.037	0.13

$$\varphi_3(x_i) \simeq 120 x_1 x_2 x_3 \left(1 + \varphi_{10}\mathcal{P}_{10}(x_i) + \varphi_{11}\mathcal{P}_{11}(x_i) + \varphi_{20}\mathcal{P}_{20}(x_i) + \varphi_{21}\mathcal{P}_{21}(x_i) + \varphi_{22}\mathcal{P}_{22}(x_i)\right)$$

$\Phi^N_{4\pm}$ Π^N_4

$$\bar{\Phi}_4(x_1, x_2, x_3) = 24 x_1 x_2 \left(1 + \eta_{10}\mathcal{R}_{10}(x_3, x_1, x_2) - \eta_{11}\mathcal{R}_{11}(x_3, x_1, x_2)\right)$$

$$\bar{\Psi}_4(x_1, x_2, x_3) = 24 x_1 x_3 \left(1 + \eta_{10}\mathcal{R}_{10}(x_2, x_3, x_1) + \eta_{11}\mathcal{R}_{11}(x_2, x_3, x_1)\right)$$

Υ^N_4 $\Xi^N_{4\pm}$ do not contribute at this order

$J/\psi \to N\bar{N}$ decay

$$\mathrm{Br}[J/\psi \to B\bar{B}] = \frac{M_\psi \beta}{12\pi\Gamma_{tot}} |G_M^g + G_M|^2 \left(1 + \frac{2m_B^2}{M_\psi^2}\gamma_B^2\right) \qquad \gamma_B = \left|\frac{G_E^g + G_E}{G_M^g + G_M}\right|$$

exp. data

$$10^3\mathrm{Br}[J/\psi \to p\bar{p}] = 2.121(29) \qquad \gamma_p = 0.823(9)$$

$$10^3\mathrm{Br}[J/\psi \to n\bar{n}] = 2.09(16) \qquad \gamma_n = 0.94(10)$$

$$G_E = G_M = 0 \qquad 10^3\mathrm{Br}[J/\psi \to N\bar{N}] = 0.47\text{–}1.43 \qquad \gamma_N^g = 0.66\text{–}0.68$$

$\mu^2 = 2m_c^2 - 1.5\ \mathrm{GeV}^2$

☞ small scale gives a better description for Br

☞ γ_N is sufficiently stable (as expected) and quite sensitive to the value of the twist-4 moment η_{11}

☞ The numerical effect from the interference with em FF's can also provide a sizable impact

$J/\psi \to B\bar{B}$ decays

Anikin '15
Shäfer, Wein '15

Λ	DA	twist-3	$\varphi^{\Lambda}_{3\pm}$		Π^{Λ}_3	twist-4	$\Phi^{\Lambda}_{4\pm}$		Π^{Λ}_4
	parameters	f_Λ	φ^{Λ}_{10}	φ^{Λ}_{11}	π^{Λ}_{10}	λ^{Λ}_1	η^{Λ}_{10}	η^{Λ}_{11}	$\lambda^{\Lambda}_\perp$	ζ^{Λ}_{10}

$B = \Sigma, \Xi$	DA	twist-3	$\varphi^{B}_{3\pm}$		Π^{B}_3		twist-4	$\Phi^{B}_{4\pm}$		Π^{B}_4
	parameters	f_B	φ^{B}_{10}	φ^{B}_{11}	$f^{B}_\perp$	π^{Λ}_{11}	λ^{B}_1	η^{B}_{10}	η^{B}_{11}	ζ^{B}_{11}

numerical estimates are from lattice calc   Bali et al (RQCD), 2019

SU(3) estimates $\lambda^{\Lambda}_1 \eta^{\Lambda}_{10} \simeq \lambda^{\Lambda}_1 \xi^{\Lambda}_{10} \simeq \lambda^{N}_1 \eta^{N}_{10} \qquad \lambda^{B}_1 \eta^{B}_{11} \simeq \lambda^{N}_1 \eta^{N}_{11}$

$B = \Sigma, \Xi \qquad \lambda^{B}_1 \eta^{B}_{11} \simeq \lambda^{B}_1 \zeta^{B}_{11} \simeq \lambda^{N}_1 \eta^{N}_{11} \qquad \lambda^{B}_1 \eta^{B}_{10} \simeq \lambda^{N}_1 \eta^{N}_{10}$

$J/\psi \to B\bar{B}$ decays: results $G_E = G_M = 0$ N.Kivel, in preparation

$$\text{Br}[J/\psi \to B\bar{B}] = \frac{M_\psi \beta}{12\pi\Gamma_{tot}} |G_M^g + G_M|^2 \left(1 + \frac{2m_B^2}{M_\psi^2}\gamma_B^2\right) \qquad \gamma_B = \left|\frac{G_E^g + G_E}{G_M^g + G_M}\right|$$

$\mu^2 = 2m_c^2 - 1.5$

	$\text{Br} \times 10^3$, exp	$\text{Br} \times 10^3$, th	γ_B, exp	γ_B^g, th	$\frac{2m_B^2}{M_\psi^2}\lvert\gamma_B\rvert^2$
p	2.12	0.47-1.43	0.82	0.66-0.68	0.13
n	2.09		0.94		
Λ	1.94	0.27-0.81	0.83	0.81-0.84	0.18
Σ^0	1.16	0.51-1.42	2.10	(0.81-0.84)*	1.53!
$\Sigma^\pm$	1.50		2.27	1.30-1.36	1.31!
$\Xi^\pm$	1.04	0.52-1.48	0.61	0.51-0.53	0.22

☞ G_E & G_M are important for a better description Br and the ratio γ_B

Conclusions

Both decay amplitudes G_E & G_M, associated with the 3g annihilation, are computed within the QCD EFT framework.

The existing models for baryon DAs provide reliable description of Br's for the relatively low norm. scale only

The interference of the QCD amplitudes and the e.m. baryon FF's are important! However includes unknown relative phases and e.m. $|G_E|$ (in preparation)

The numerical ratios of these 3g-amplitudes are in agreement with the exp. data within 10-30% accuracy, except for the Σ-channel.

A description of the Σ-channels requires a much stronger SU(3) violation, which can only give a very large ratio $|G_E/G_M| \simeq 2$. Dynamical origin of this effect is not clear, perhaps a final state interaction?

The power corrections of order Λ^2/m_c^2 to G_M are also computed (higher twist 3q DAs). Preliminary: they give about 9% effect for N/Λ, which is not large. (in progress)

Thanks!