Glauber-gluon and η_C-mixing effects in $B \to \pi\pi$ decays

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Outlines

- Introduction
- Glauber gluons
- η_C mixing
- Numerical results
- Summary

Introduction

A serious puzzle in B decays

- $B(\pi^0\pi^0)$ is becoming a serious puzzle

$$\mathcal{B}(B^0 \to \pi^0\pi^0) \;=\; \begin{cases} (1.83 \pm 0.21 \pm 0.13) \times 10^{-6} & \text{(BABAR)} \\ (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6} & \text{(Belle)}\ , \\ (1.91^{+0.22}_{-0.23}) \times 10^{-6} & \text{(HFAG)}\ ; \end{cases}$$

6 times larger than PQCD prediction

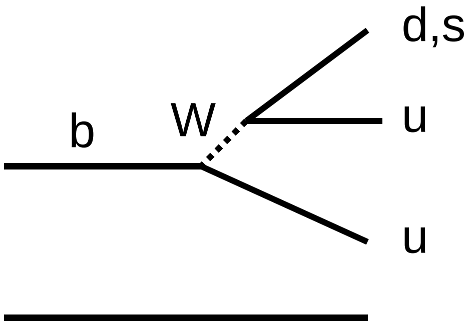
- While

$$\mathcal{B}(B^0 \to \rho^0\rho^0) \;=\; \begin{cases} (0.92 \pm 0.32 \pm 0.14) \times 10^{-6} & \text{(BABAR)} \\ (0.4 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6} & \text{(Belle)}\ , \\ (0.73^{+0.27}_{-0.28}) \times 10^{-6} & \text{(HFAG)}\ . \end{cases}$$

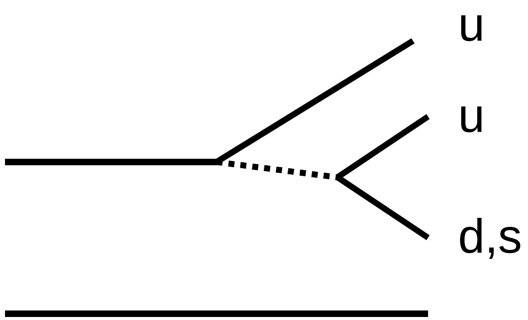
consistent with PQCD and QCDF predictions

Color-suppressed tree

- $B(\pi^0\pi^0)$, $B(\rho^0\rho^0)$ both depend on color-suppressed tree amplitude C



Color-allowed tree T

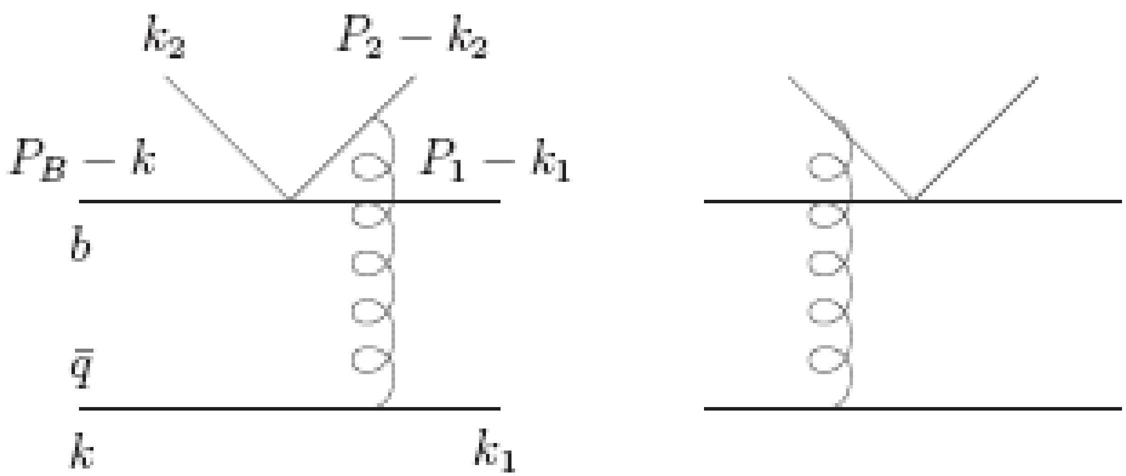


Color-suppressed tree C

- C is an important but least understood quantity in B decays

Smallness of C at LO

- Factorizable contribution is proportional to Wilson coefficient $a_2(m_b) \sim 0$
- Spectator contribution cancels between



- Sensitive to subleading corrections or new QCD mechanism. Can C be large?
- Mechanism must differentiate π from ρ

NLO PQCD results

Hadronic uncertainty

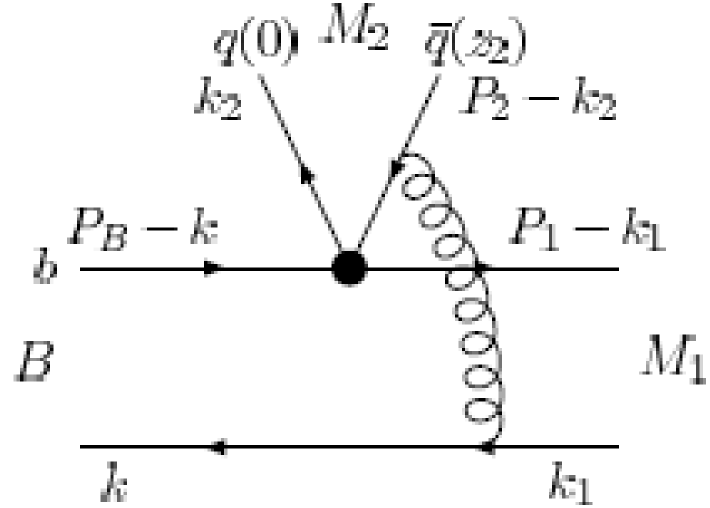
Mode	Data [1]	LO	$\mathrm{LO}_{\mathrm{NLOWC}}$	+VC	+QL	+MP	+NLO
$B^\pm \to \pi^\pm K^0$	24.1 ± 1.3	17.3	32.9	31.6	34.9	24.5	$24.9^{+13.9\,(+13.2)}_{-\ 8.2\,(-\ 8.2)}$
$B^\pm \to \pi^0 K^\pm$	12.1 ± 0.8	10.4	18.7	17.7	19.7	14.2	$14.2^{+10.2\,(+\ 7.1)}_{-\ 5.8\,(-\ 4.3)}$
$B^0 \to \pi^\mp K^\pm$	18.9 ± 0.7	14.3	28.0	26.9	29.7	20.7	$21.1^{+15.7\,(+11.1)}_{-\ 8.4\,(-\ 6.6)}$
$B^0 \to \pi^0 K^0$	11.5 ± 1.0	5.7	12.2	11.9	13.0	8.8	$9.2^{+\ 5.6\,(+\ 5.1)}_{-\ 3.3\,(-\ 3.0)}$
$B^0 \to \pi^\mp \pi^\pm$	5.0 ± 0.4	7.1	6.8	6.6	6.9	6.7	$6.6^{+\ 6.7\,(+\ 2.7)}_{-\ 3.8\,(-\ 1.8)}$
$B^\pm \to \pi^\pm \pi^0$	5.5 ± 0.6	3.5	4.2	4.1	4.2	4.2	$4.1^{+\ 3.5\,(+\ 1.7)}_{-\ 2.0\,(-\ 1.2)}$
$B^0 \to \pi^0 \pi^0$	1.45 ± 0.29	0.12	0.28	0.37	0.29	0.21	$0.30^{+0.49\,(+0.12)}_{-0.21\,(-0.09)}$

Mode	BABAR [1]	Belle [1]	LO	$\mathrm{LO}_{\mathrm{NLOWC}}$	+VC	+QL	+MP	+NLO
$B^0 \to \rho^\mp \rho^\pm$	$30 \pm 4 \pm 5$	$22.8 \pm 3.8^{+2.3}_{-2.6}$	27.8	26.1	25.2	26.6	25.9	$25.3^{+25.3\,(+12.1)}_{-13.8\,(-\ 7.9)}$
$B^\pm \to \rho^\pm \rho^0$	$17.2 \pm 2.5 \pm 2.8$	$31.7 \pm 7.1^{+3.8}_{-6.7}$	13.7	16.2	16.0	16.2	16.2	$16.0^{+15.0\,(+\ 7.8)}_{-\ 8.1\,(-\ 5.3)}$
$B^0 \to \rho^0 \rho^0$	< 1.1	—	0.33	0.56	1.02	0.62	0.45	$0.92^{+1.10\,(+0.64)}_{-0.56\,(-0.40)}$

Glauber gluons

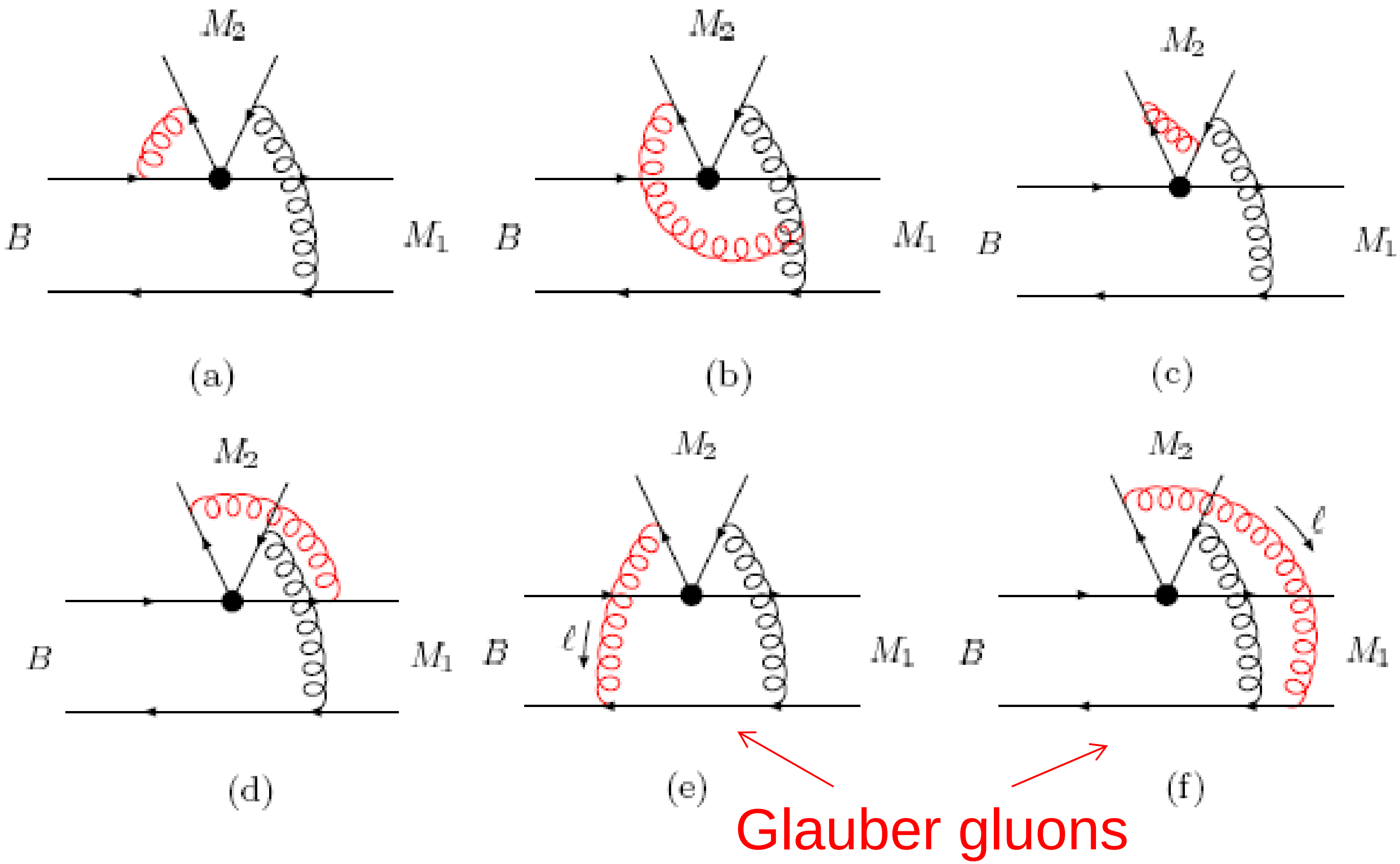
Spectator diagram

- Have checked k_T factorization of spectator diagram
- Considered factorization of M_2 wave function from this diagram



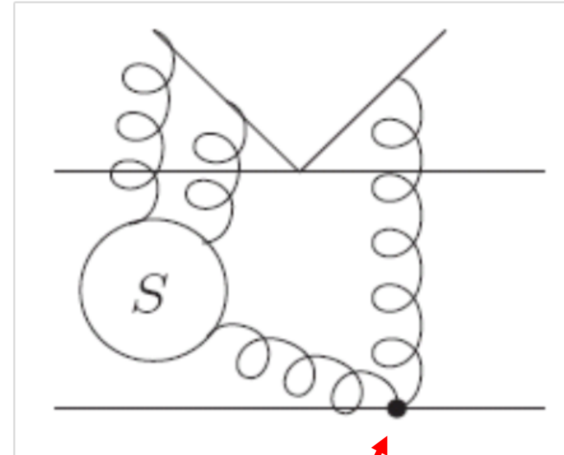
- Found existence of Glauber gluons, which give additional phase factors (Li, Mishima, 11)
- Interference between two LO diagrams becomes constructive

Relevant diagrams for M_2

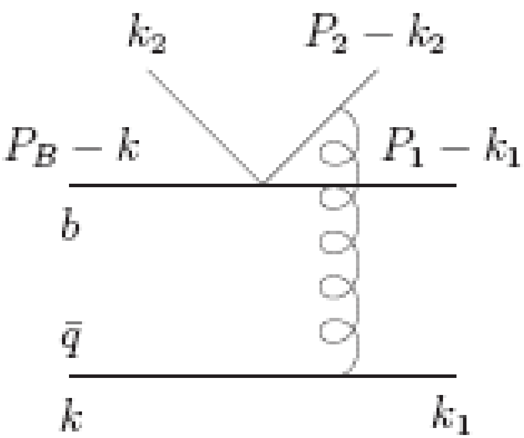


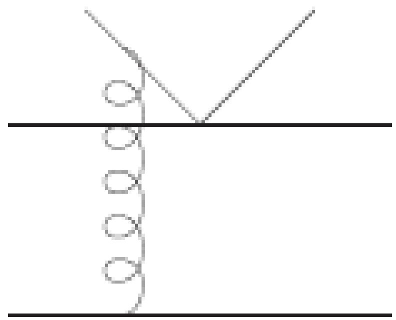
Soft effect

- Resum Glauber divergence to all orders, like summing collinear divergence into meson wave function



delta function





minus sign due to radiation from anti-quark

$I_a \approx e^{iS_e} \mathcal{M}_a^{(0)}$ $\qquad$ $I_b \approx e^{-iS_e} \mathcal{M}_b^{(0)}$

- like $1-1 \Rightarrow e^{iS_e} - e^{-iS_e}$, large imaginary C

Glauber gluons for M_1?

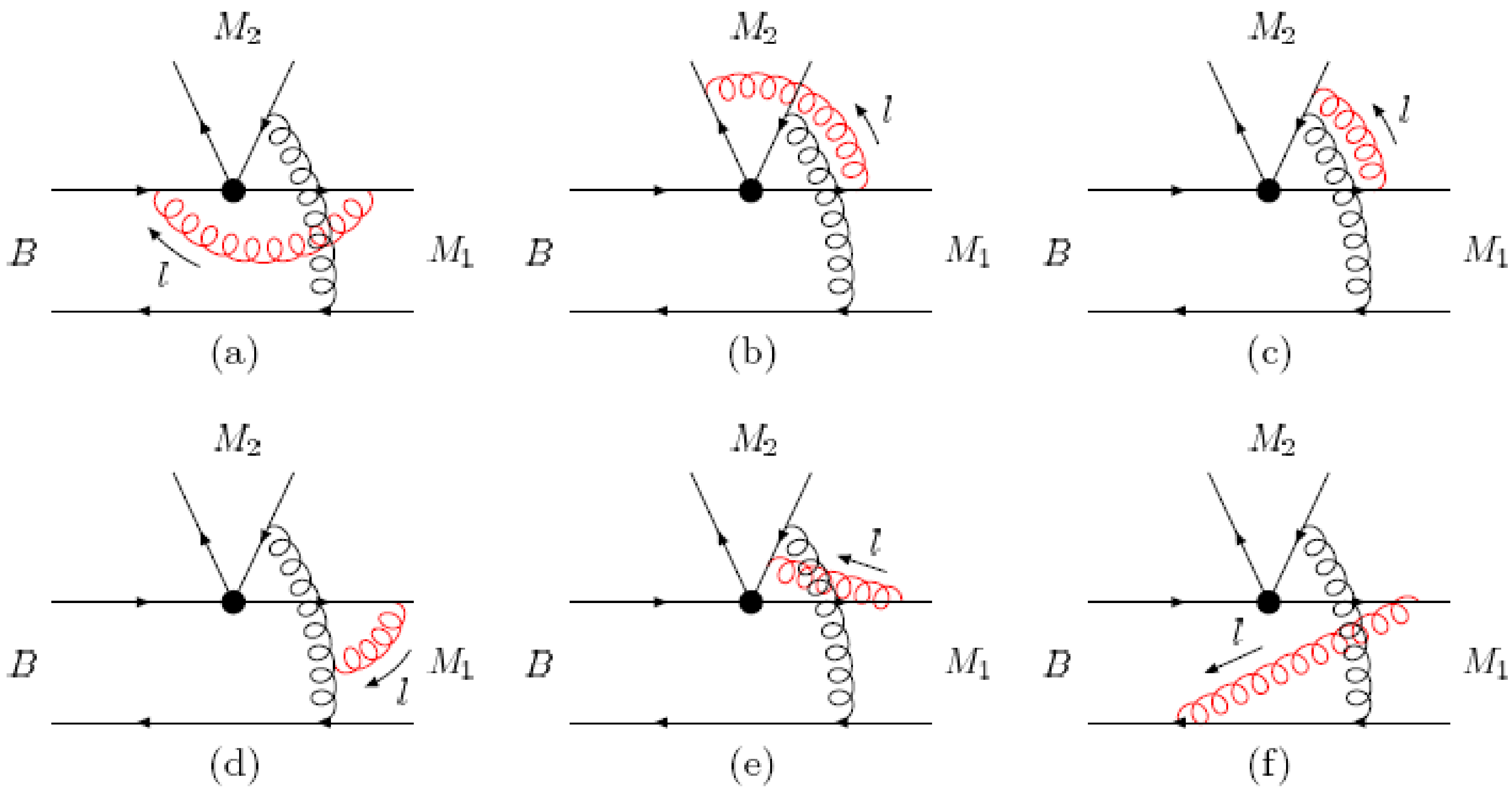
Yes, they couple M_1 and B-M_2 system,

and have the same strength as

M_2 Glauber effect.

Li, Mishima, in preparation

Relevant diagrams for M_1



Glauber gluons

Nambu-Goldstone boson

- Pion as a $q\bar{q}$ bound state and as a massless Nambu-Goldstone boson?
- Massless boson => huge spacetime => large separation between $q\bar{q}$ => high mass under confinement => contradiction!
- Reconciliation: leading $q\bar{q}$ state is tight, higher Fock state gives soft cloud (Lepage, Brodsky 79; Nussinov, Shrock 08; Duraisamy, Kagan 08) Pion is unique.
- Our soft factor corresponds to this soft cloud: 3 partons in k_T space

C-sensitive quantities

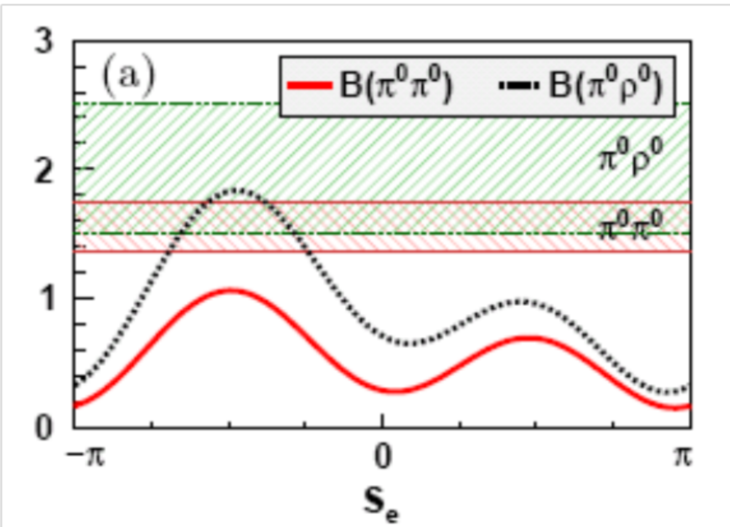
- Se dependence

for Se ~ -pi/2

$$C/T = 0.53e^{-2.2i}$$

Acp(pi- K+) and S(rho0 KS) are almost not affected

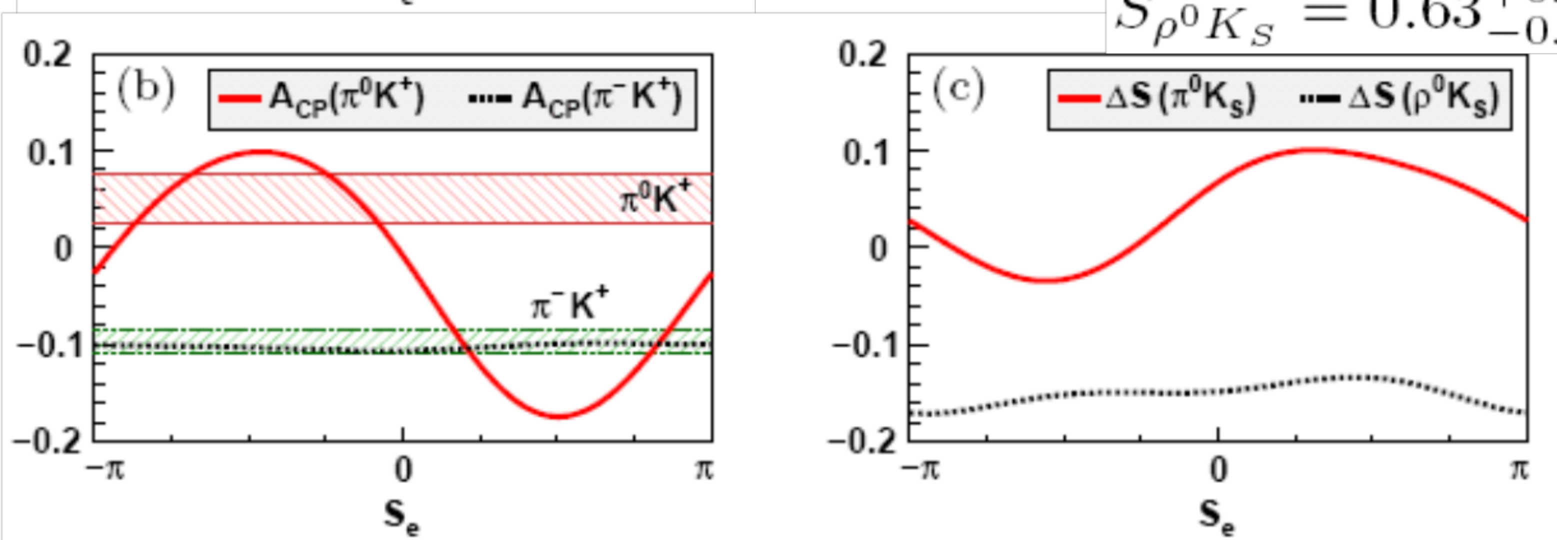
Li, Mishima, 2011



$$S_{c\bar{c}s} = 0.672 \pm 0.024$$

$$S_{\pi^0 K_S} = 0.57 \pm 0.17$$

$$S_{\rho^0 K_S} = 0.63^{+0.17}_{-0.21}$$



Two questions

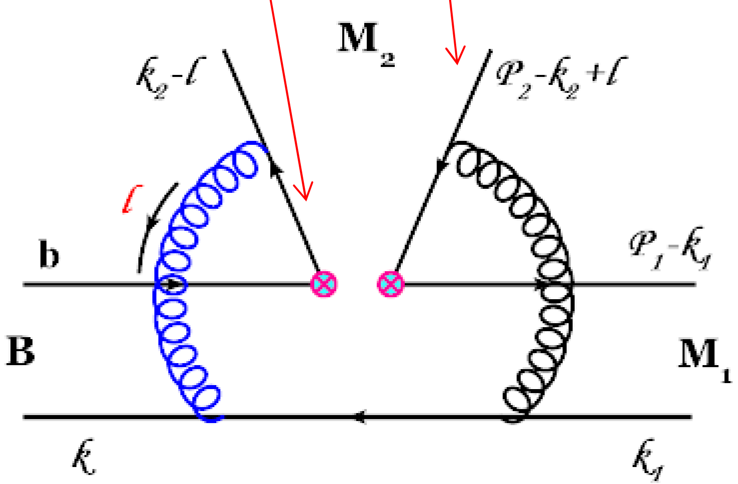
- Can Glauber phase Se be so large?
- Se is factorized and universal. How is it different between π , ρ?
- Though Glauber gluons are factorized, loop momentum l_T flows through mesons
- If mesons have different intrinsic k_T dependence, Glauber effects are different
- Can any available models of intrinsic k_T dependence answer the above two questions?

Convolution in k_T space

- Consider intrinsic k_T dependence

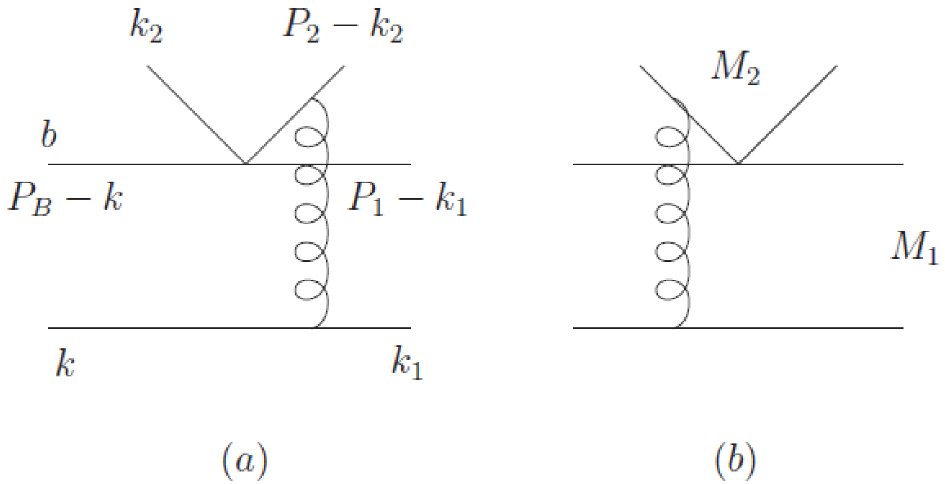
$$\int \frac{d^2 k_T}{(2\pi)^2}\frac{d^2 k_{1T}}{(2\pi)^2}\frac{d^2 k_{2T}}{(2\pi)^2}\int \frac{d^2 l_T}{(2\pi)^2}\phi_B(k_T)\phi_1(k_{1T})$$

$$\bar{\phi}_2(k_{2T}, -k_{2T}+l_T)G_2(l_T)H_a(k_T, k_{1T}, k_{2T}, l_T)$$



Factorization formulas

- Performing Fourier transformation, we have



$$\int d^2b_1 d^2b_2 d^2b' \phi_B(b_1)\phi_1(b_1)\bar{\phi}_2(b_1+b', b_2+b_1+b')$$
$$\exp[iS(b')]H_a(b_1,b_2).$$

$$\int d^2b_1 d^2b_2 d^2b' \phi_B(b_1)\phi_1(b_1)\bar{\phi}_2(b_2+b_1+b', b_1+b')$$
$$\exp[-iS(b')]H_b(b_1,b_2)$$

Include M_1 Glauber gluons

$$\int \frac{d^2k_T}{(2\pi)^2}\frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\int \frac{d^2l_{1T}}{(2\pi)^2}\frac{d^2l_{2T}}{(2\pi)^2}\phi_B(k_T)\bar{\phi}_1(k_{1T}+l_{2T},-k_{1T}-l_{1T}-l_{2T})$$
$$\times\bar{\phi}_2(k_{2T}+l_{1T}+l_{2T},-k_{2T}-l_{1T})G_1(l_{1T})G_2(l_{2T})H_a(k_T,k_{1T},k_{2T}).$$

$$\int d^2b_1d^2b_2\int d^2b_{s1}d^2b_{s2}\bar{\phi}_B(b_1)\bar{\phi}_1(b_{s1}+b_1+b_2,b_{s1}+b_2)$$
$$\times\bar{\phi}_2(b_{s2}+b_1,b_{s2}+b_1+b_2)\exp\left[-iS(b_{s1})+iS(b_{s2})\right]H_a(b_1,b_2)$$

$$\int d^2b_1d^2b_2\int d^2b_{s1}d^2b_{s2}\bar{\phi}_B(b_1)\bar{\phi}_1(b_{s1}+b_1+b_2,b_{s1}+b_2)$$
$$\times\bar{\phi}_2(b_{s2}+b_1+b_2,b_{s2}+b_1)\exp\left[-iS(b_{s1})-iS(b_{s2})\right]H_b(b_1,b_2)$$

Glauber gluon effects

- M_2 Glauber gluons modify interference between the two LO spectator diagrams into constructive one
- Increase of C enhances $B(\pi^0\pi^0)$
- M_1 Glauber gluons rotate C, and modify interference between T and C
- Increase $B(\pi^+\pi^0)$
- Expect to improve consistency for all modes

η_C mixing

Tetramixing

- Have studied $\eta-\eta'-G$ (see X Liu's talk)
- Have studied tetramixing $\eta-\eta'-G-\eta_C$ (Tsai, Li, Zhao, 2012)
- Found charm content of η' important for understanding large observed $Br(B\to\eta' K)\approx 70\times 10^{-6}$
- Peng and Ma (2011) have studied $\pi-\eta-\eta'-\eta_C$ and $\omega-\rho-\phi-J/\psi$
- Determined charm content in π and ρ

Intrinsic charm content

- charmonium mixing effects different by an order of magnitude also differentiate π, ρ

$$U_{\pi\eta\eta'\eta_c} = \begin{pmatrix} 0.9895 & 0.0552 & -0.1119 & 0.0342 \\ -0.1082 & 0.8175 & -0.5614 & -0.0259 \\ 0.0590 & 0.5696 & 0.8160 & 0.0452 \\ -0.0395 & -0.0065 & -0.0478 & 0.9960 \end{pmatrix}$$

$$U_{\omega\rho\phi J/\psi} = \begin{pmatrix} 0.9886 & -0.0122 & -0.1429 & 0.0076 \\ 0.0299 & 0.9910 & 0.1221 & -0.0025 \\ 0.1400 & -0.1250 & 0.9808 & 0.0258 \\ -0.0111 & 0.0058 & -0.0239 & 0.9986 \end{pmatrix}$$

Add $B \to \eta_C \pi$ amplitudes

- NLO PQCD give

$$BR(B^0 \to \eta_c \pi^0)_{\rm NLO} \;=\; 1.24^{+0.36}_{-0.28}(\omega_B)^{+0.12}_{-0.12}(a_2^\pi) \times 10^{-5}$$
$$BR(B^+ \to \eta_c \pi^+)_{\rm NLO} \;=\; 2.66^{+0.77}_{-0.60}(\omega_B)^{+0.26}_{-0.26}(a_2^\pi) \times 10^{-5}$$

- Same formalism explained $B \to \eta_C K$ data
- Add the above two amplitudes into hard kernels of corresponding $B \to \pi\pi$ decays
- Adopt the mixing matrix elements

$$U^{14}_{\pi\eta\eta'\eta_c} \approx 0.1 \quad U^{24}_{\omega\rho\phi J/\psi} \approx 0$$

- The former comes from normalization

Numerical results

Model of Brodsky et al

- Adopt model of Brodsky et al (1980) for intrinsic k_T dependence

$$\phi_p(x,k_T) = \frac{f_p}{2\sqrt{2N_c}} \frac{24\pi m_p^2}{[m_p^2 + k_T^2/x + k_T^2/(1-x)]^2}$$

$$\phi_p(x,b) \equiv \int \frac{d^2k_T}{(2\pi)^2} \exp(-ik_T \cdot b)\phi_p(x,k_T)$$

Contain higher Gegenbauer

$$= \phi_p(x)\sqrt{x(1-x)}m_p b K_1\left(\sqrt{x(1-x)}m_p b\right)$$

- Expect to differentiate π and ρ, due to very different meson masses

Two-argument TMD

- Include Glauber gluon transverse momentum

$$\bar{\phi}_p(x, b', b)$$
$$= \phi_p(x)\frac{m_p^2}{2\pi}\int \frac{K_1(\sqrt{x m_p^2 b'^2 + t^2})}{\sqrt{x m_p^2 b'^2 + t^2}} J_0\left(\frac{\sqrt{(1-x)}b}{\sqrt{x}b'}t\right) t dt$$

- Parameterization of Glauber factor

$$S(b) = -\alpha b^2$$

- Normalization from RHIC physics (H Liu et al. 2006)

Numerical results

- With $\alpha = -0.42$ for all followng

Mode	Data [1]	NLO [4]	NLO (this work)
$B^0 \to \pi^+\pi^-$	5.11 ± 0.22	$6.5^{+\ 6.7\,(+\ 2.7)}_{-\ 3.8\,(-\ 1.8)}$	$6.58^{+2.21}_{-1.62}(\omega_B)^{+0.24}_{-0.19}(a_2^\pi)$
$B^+ \to \pi^+\pi^0$	$5.48^{+0.35}_{-0.34}$	$4.0^{+\ 3.4\,(+\ 1.7)}_{-\ 1.9\,(-\ 1.2)}$	$5.60^{+0.00}_{-1.90}(\omega_B)^{+0.00}_{-2.39}(a_2^\pi)$
$B^0 \to \pi^0\pi^0$	$1.91^{+0.22}_{-0.23}$	$0.29^{+0.50\,(+0.13)}_{-0.20\,(-0.08)}$	$1.10^{+0.00}_{-0.88}(\omega_B)^{+0.00}_{-0.65}(a_2^\pi)$
$B^0 \to \rho^0\rho^0$	$0.73^{+0.27}_{-0.28}$	$0.92^{+1.10\,(+0.64)}_{-0.56\,(-0.40)}$	$0.61^{+1.02}_{-0.00}(\omega_B)^{+0.15}_{-0.06}(a_2^\rho)$

$$Br(B^0 \to \pi^0\pi^0) = \begin{cases} 4.11 \times 10^{-7} & \text{with Glauber} \\ 3.38 \times 10^{-7} & \text{with } \eta_C \end{cases}$$

- Glauber alone is not enough. Glauber and η_C mixing effects are equally important

Model of Huang, Ma et al

- If adopting model of Huang et al, Ma et al.

$$\phi_\pi(x, k_T) = A_\pi \frac{m}{\sqrt{x(1-x)}\mathcal{M}} \exp\left(-\frac{\mathcal{M}^2}{8\beta_\pi^2}\right),$$

$$\phi_\rho(x, k_T) = A_\rho \frac{2x(1-x)\mathcal{M}+m}{\sqrt{x(1-x)}(\mathcal{M}+2m)} \exp\left(-\frac{\mathcal{M}^2}{8\beta_\rho^2}\right)$$

$$\mathcal{M}^2 = \frac{k_T^2+m^2}{x} + \frac{k_T^2+m^2}{1-x}$$

- π and ρ do not differ much

Numerical results

- For $\alpha = -0.12$, which gives the best fit, and stretching parameter difference

$\beta_\pi \sim 0.4 \quad \beta_\rho \sim 0.7$

$$\mathrm{BR}(B^0 \to \pi^0\pi^0) = 0.65 \times 10^{-6}$$

$$\mathrm{BR}(B^0 \to \pi^+\pi^-) = 5.52 \times 10^{-6}$$
$$\mathrm{BR}(B^+ \to \pi^+\pi^0) = 4.40 \times 10^{-6}$$
$$\mathrm{BR}(B^0 \to \rho^0\rho^0) = 1.10 \times 10^{-6}$$

- Cannot explain the data

Summary

- Imaginary Glauber divergences exist in spectator B decay amplitudes
- Glauber effects change interference between two LO spectator diagrams and between T,C
- Glauber effects from pion and rho differ through convolution of universal Glauber factor with different transverse momentum dependence
- 1% charmonium in pion further differentiates pion and rho. Its effect is equally important
- Using Brodsky’s model, consistency between theory and data for all $B \to \pi\pi, \rho\rho$ is improved but $B(\pi^0\pi^0)$ still not resolved