EXCLUSIVE B_C-MESON DECAYS AT LHC

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Phys.Rev.D81:014015,2010 [arXiv:0910.3089]
Phys.Rev.D82:014012,2010 [arXiv:1004.0087]

B_C-MESONS

Intermediate between charmonium and bottomonium mseons

$B_c^{\pm}$

$I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predicitions.

Mass $m = 6.277 \pm 0.006$ GeV   (S = 1.6)
Mean life $\tau = (0.453 \pm 0.041) \times 10^{-12}$ s

B_c^- modes are charge conjugates of the modes below.

B_c^+ DECAY MODES $\times$ B($\bar{b} \to B_c$)	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times$ B($\bar{b} \to B_c$).			
$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$		–
$J/\psi(1S)\pi^+$	$< 8.2 \times 10^{-5}$	90%	2372
$J/\psi(1S)\pi^+\pi^+\pi^-$	$< 5.7 \times 10^{-4}$	90%	2352
$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%	2171
$D^*(2010)^+\bar{D}^0$	$< 6.2 \times 10^{-3}$	90%	2468

Nothing else is known experimentally.
Additional information after LHC launch (~$5*10^{10}$ B_c events per year)

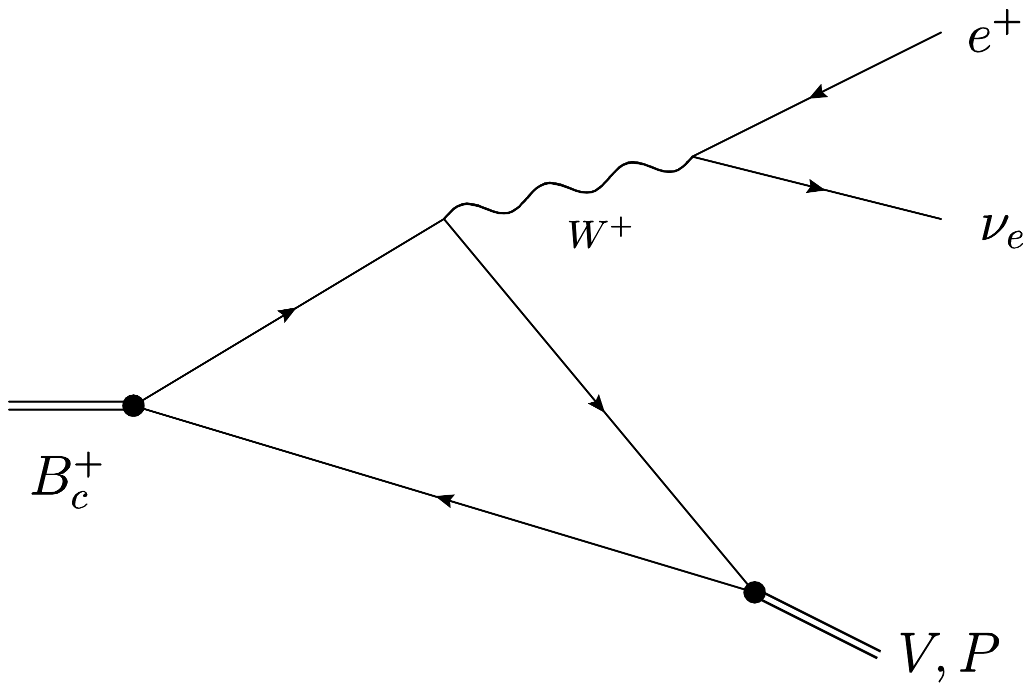
Dominant Decay Modes

- b-quark decays (z.B. $B_c \rightarrow J/\psi + X$) ~ 20%
- c-quark decays (z.B. $B_c \rightarrow B_s + X$) ~70%
- annihilation decays (z.B. Bc $\rightarrow \tau \nu_\tau$) ~ 5%

Dominant Decay Modes

Decay mode	free quarks	B_c^+	BR	Decay mode	free quarks	B_c^+	BR
$\bar{b} \to \bar{c} + e^+\nu_e$	62	62	4.7	$c \to s + e^+ + \nu_e$	124	74	5.6
$\bar{b} \to \bar{c} + \mu^+\nu_\mu$	62	62	4.7	$c \to s + \mu^+ + \nu_\mu$	124	74	5.6
$\bar{b} \to \bar{c} + \tau^+\nu_\tau$	14	14	1.0	$c \to s + u + \bar{d}$	675	405	30.5
$\bar{b} \to \bar{c} + \bar{d} + u$	248	248	18.7	$c \to s + u + \bar{s}$	33	20	1.5
$\bar{b} \to \bar{c} + \bar{s} + u$	13	13	1.0	$c \to d + e^+\nu$	7	4	0.3
$\bar{b} \to \bar{c} + \bar{s} + c$	87	87	6.5	$c \to d + \mu^+ + \nu_\mu$	7	4	0.3
$\bar{b} \to \bar{c} + \bar{d} + c$	5	5	0.4	$c \to d + u + \bar{d}$	39	23	1.7
$B_c^+ \to \tau^+ + \nu_\tau$	–	63	4.7	$B_c^+ \to c + \bar{s}$	–	162	12.2
$B_c^+ \to c + \bar{d}$	–	8	0.6	$B_c^+ \to$ all	–	1328	100

Semileptonic B_C-meson Decays



$$M\left[B_c(p_1)\to V(p_2,\varepsilon_V)+e^+\nu_e\right]=\frac{G_F V_{12}}{\sqrt{2}}H^\mu\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\right]$$

Semileptonic B_C-meson Decays

- $B_c(p_1) \to P(p_2) e\nu_e$

$$H_\mu = f_+(q^2) p_\mu + f_-(q^2) q_\mu$$

- $B_c(p_1) \to V(p_2, \varepsilon) e\nu_e$

$$p = p_1 + p_2$$
$$q = p_1 - p_2$$

$$H_\mu = F_0^A(q^2)\varepsilon_\mu + F_+^A(q^2)(\varepsilon p) p_\mu + F_-^A(q^2)(\varepsilon p) q_\mu + iF_V(q^2) e_{\mu\nu\alpha\beta}\varepsilon^\nu p^\alpha q^\beta$$

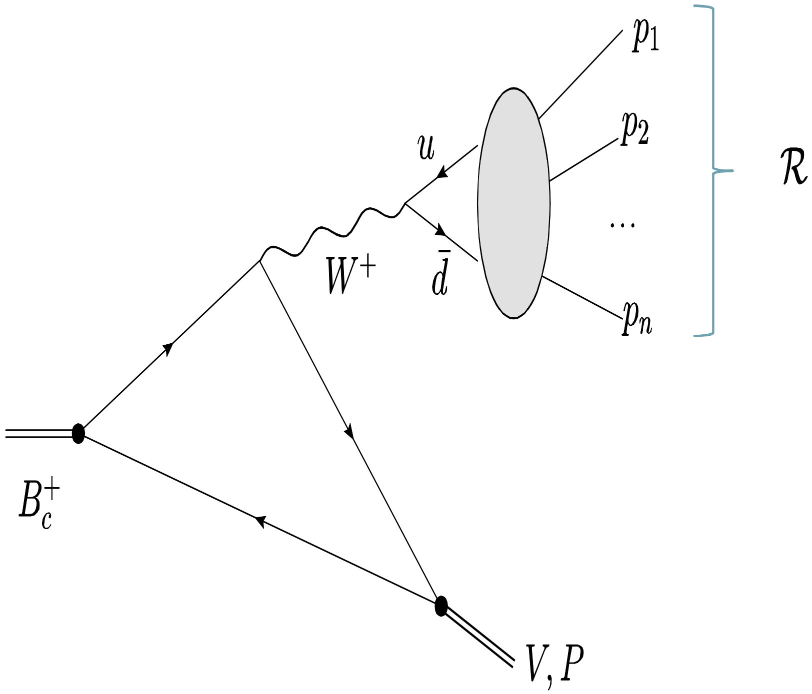
Form-factors

$$F_i\left(q^2\right) \approx F_i(0)\exp\left\{c_1 q^2 + c_2 q^4\right\}$$

$$B_c \to B_s^{(*)} + W$$

		SR [5]	PM [5]	LF [7]			SR [5]	PM [5]	LF [7]
	$F(0)$	1.3	1.1	0.73		$F(0)$	8.1	8.2	6.1
F_+	c_1, ГэВ$^{-2}$	0.30	0.30	0.56	F_0^A, ГэВ	c_1, ГэВ$^{-2}$	0.30	0.52	0.56
	c_2, ГэВ$^{-4}$	0.069	0.069	0.030		c_2, ГэВ$^{-4}$	0.069	0.02	0.087
	$F(0)$	-5.8	-5.9	-1.7		$F(0)$	0.15	0.30	0
F_-	c_1, ГэВ$^{-2}$	0.30	0.30	0.70	F_+^A, ГэВ$^{-1}$	c_1, ГэВ$^{-2}$	0.30	0.30	1
	c_2, ГэВ$^{-4}$	0.069	0.069	-0.02		c_2, ГэВ$^{-4}$	0.069	0.069	1
	$F(0)$, ГэВ$^{-1}$	1.08	1.1	0.31		$F(0)$	1.8	1.4	0
F_V	c_1, ГэВ$^{-2}$	0.30	0.30	0.12	F_-^A, ГэВ$^{-1}$	c_1, ГэВ$^{-2}$	0.30	0.30	1
	c_2, ГэВ$^{-4}$	0.69	0.069	-0.02		c_2, ГэВ$^{-4}$	0.069	0.069	1

HADRONIC DECAYS



$$H_{\rm eff} = \frac{G_F}{2\sqrt{2}} V_{QQ'} V_{ud} \left\{ C_+(\mu) O_+ + C_-(\mu) O_- \right\}$$

$$O_\pm = \left(\bar{d}_i u_j\right)_{V-A} \left(\bar{Q}_i Q'_j\right)_{V-A} \pm \left(\bar{d}_i u_j\right)_{V-A} \left(\bar{Q}_j Q'_i\right)_{V-A}$$

$$a_1(\mu) = \frac{1}{2N_c}\left[(N_c - 1) C_+(\mu) + (N_c + 1) C_-(\mu)\right]$$

$$M\left[B_c \to V(P) + R\right] = \frac{G_F V_{QQ'} V_{ud}}{\sqrt{2}} a_1^Q H^\mu \varepsilon_\mu^R$$

$$a_1^b = 1.17 \qquad a_1^c = 1.2$$

$d\Gamma/dq^2$

$$d\Gamma = \frac{1}{2M}\sum_{\lambda}\left|M\right|^2 d\Phi_{n+1}\left(p_1 \to p_2 k_1 \ldots k_n\right) =$$

$$d\Phi_{n+1}\left(p_1 \to p_2 k_1 \ldots k_n\right) = (2\pi)^4 \delta^4\left(p_1 - p_2 - \sum_i k_i\right)\frac{d^3\mathbf{p}_2}{2E_2(2\pi)^3}\prod_i \frac{d^3\mathbf{k}_i}{2\omega_i(2\pi)^3} = \frac{dq^2}{2\pi} d\Phi_2\left(p_1 \to p_2 q\right) d\Phi_n\left(q \to k_1 \ldots k_n\right)$$

$$\frac{d\Gamma}{dq^2} = \sum_{\lambda} H_\mu H_\nu^* \int d\Phi_n\left(q \to k_1 \ldots k_n\right)\varepsilon_\mu^R \varepsilon_\nu^{*R}$$

$$\frac{1}{2\pi}\int d\Phi_n\left(q \to k_1 \ldots k_n\right)\varepsilon_\mu^R \varepsilon_\nu^{*R} = \left(q_\mu q_\nu - q^2 g_{\mu\nu}\right)\rho_T^R\left(q^2\right) + q_\mu q_\nu \rho_L^R\left(q^2\right)$$

spectral functions

$d\Gamma/dq^2$

$$\frac{d\Gamma(B_c \to P+R)}{dq^2} = \frac{G_F^2 V_{QQ'}^2 a_1^2}{32\pi M_1} \beta \left\{ |f_+|^2 \left[M_1^4 \beta^2 \rho_T^R + \left(M_1^2 - M_2^2\right)^2 \rho_L^R \right] + |f_-|^2 q^2 \rho_L^R + \right.$$

$$\left. +2\mathrm{Re}\left(f_+ f_-\right) q^2 \left(M_1^2 - M_2^2\right) \rho_T^R \right\}$$

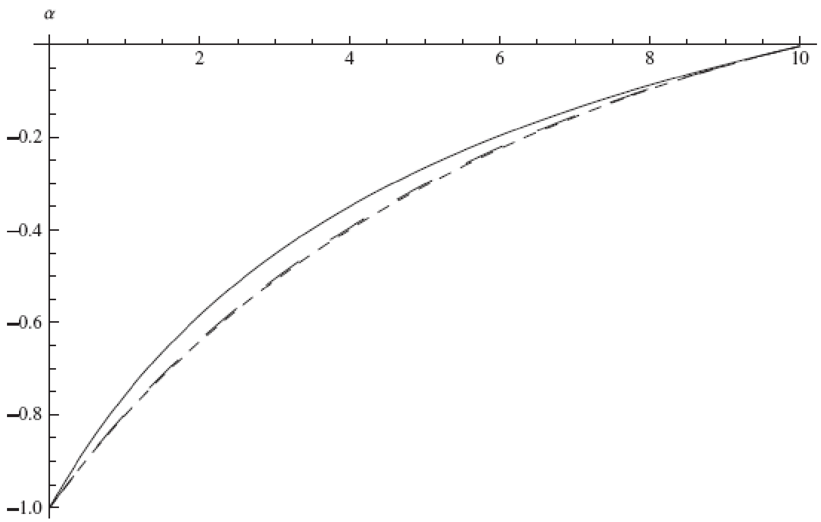
$$\frac{d\Gamma(B_c \to V+R)}{dq^2} = \frac{G_F^2 V_{QQ'}^2 a_1^2}{128\pi} \frac{M_1^2}{M_2^3} \rho_T^R \left\{ |F_0^A|^2 \left(12 \frac{q^2 M_2^2}{M_1^2} + \beta^2 \right) + \beta^4 M_1^4 |F_+^A|^2 + \right.$$

$$\left. +8\beta^2 q^2 M_2^2 |F_V|^2 + 2\left(M_1^2 - M_2^2 - q^2\right) \beta^2 \mathrm{Re}\left(F_0^A F_+^A\right) \right\}$$

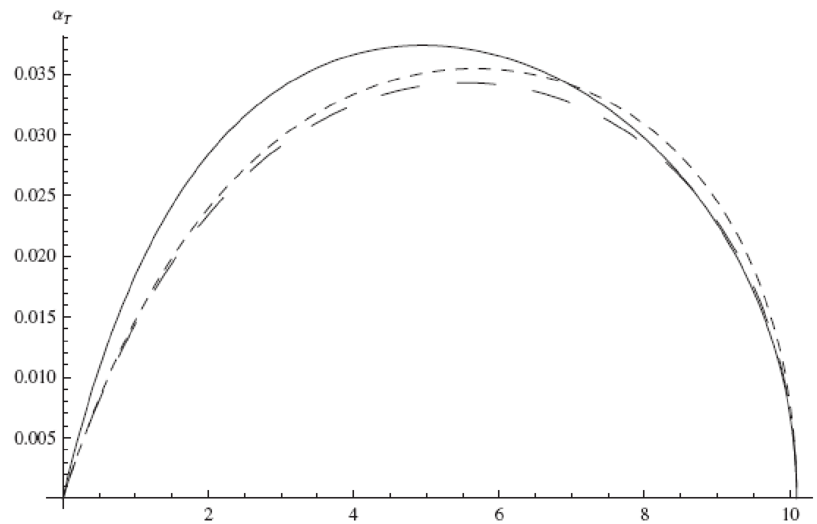
Spin asymmetries

$$\alpha_T = \frac{d\Gamma_T - 2d\Gamma_L}{d\Gamma_T + 2d\Gamma_L} = \begin{cases} 0, & \text{непол.} \\ -1, & \text{прод.пол.} \end{cases}$$

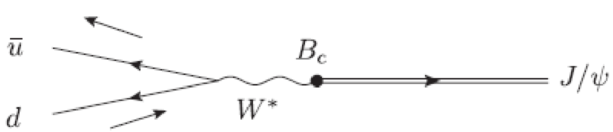
$$\alpha_T = \frac{d\Gamma_{\lambda=1} - d\Gamma_{\lambda=-1}}{d\Gamma}$$

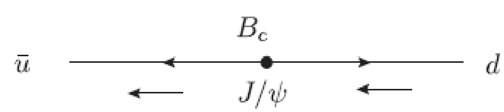


$q^2 \ll M_V^2$



$q^2 \approx (M_{B_c} - M_V)^2$





In factorization approximation these asymmetries do not depend on final state

Spectral Functions

- $\rho_L^{\pi}(q^2) = f_\pi^2 \delta(q^2 - m_\pi^2)$, $\rho_T^{\pi}(q^2) = 0$
- $\rho_L^{\rho}(q^2) = 0$, $\rho_T^{\rho}(q^2) = f_\rho^2 \delta(q^2 - m_\rho^2)$
- CVC, PCAC $\Longrightarrow$ $\rho_L^{R}(q^2) \approx 0$
- ud, eν

$$\rho_T^{ud}(q^2) = \frac{1}{2\pi^2}, \qquad \rho_T^{e\nu}(q^2) = \frac{1}{N_c a_1^2}\frac{1}{2\pi^2}$$

- n π

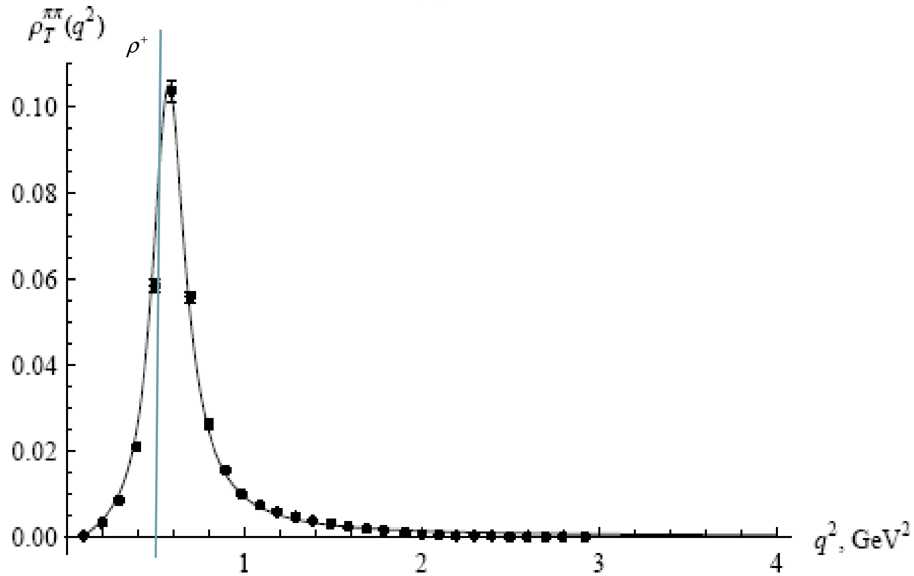
$$\frac{d\Gamma(\tau \to \nu_\tau + R)}{dq^2} = \frac{G_F^2}{16\pi m_\tau}\frac{(m_\tau^2 - q^2)^2}{m_\tau^3}(m_\tau^2 + 2q^2)\rho_T^R(q^2)$$

$$\sigma(e^+e^- \to R) = \frac{4\pi\alpha^2}{s}\rho_T^R(s)$$

$$\frac{dBr(B_c \to V, P + R)}{dq^2} \sim \frac{dBr(B_c \to V, P + \bar{u}d)}{dq^2}\rho_T^R(q^2)$$

Spectral Functions

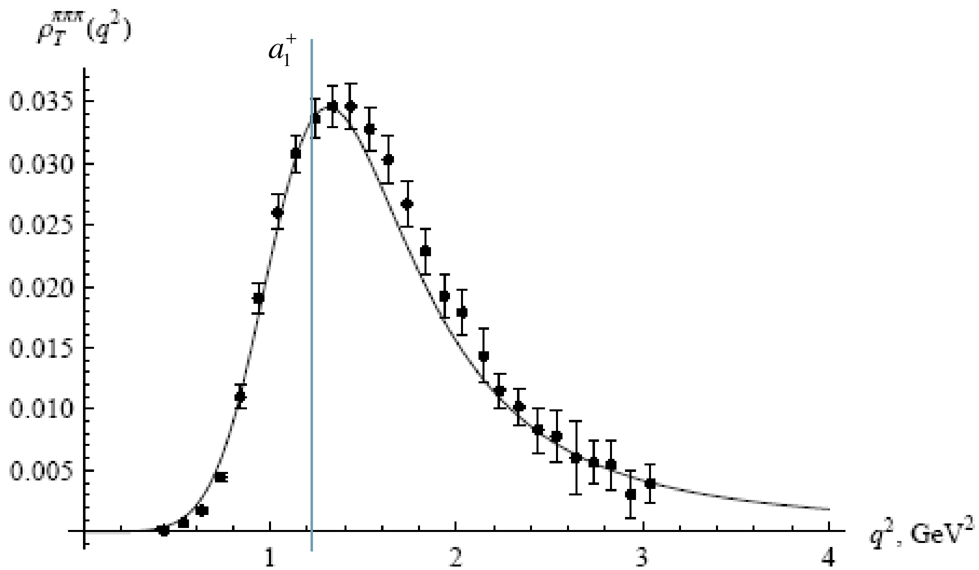
R= 2π -- $\tau \rightarrow \nu_\tau + 2\pi$



$$\rho_T^{2\pi}(s) \approx 1.35 \times 10^{-3} \left(\frac{s - 4m_\pi^2}{s} \right)^2 \frac{1 + 0.64s}{(s - 0.57)^2 + 0.013}.$$

Spectral Functions

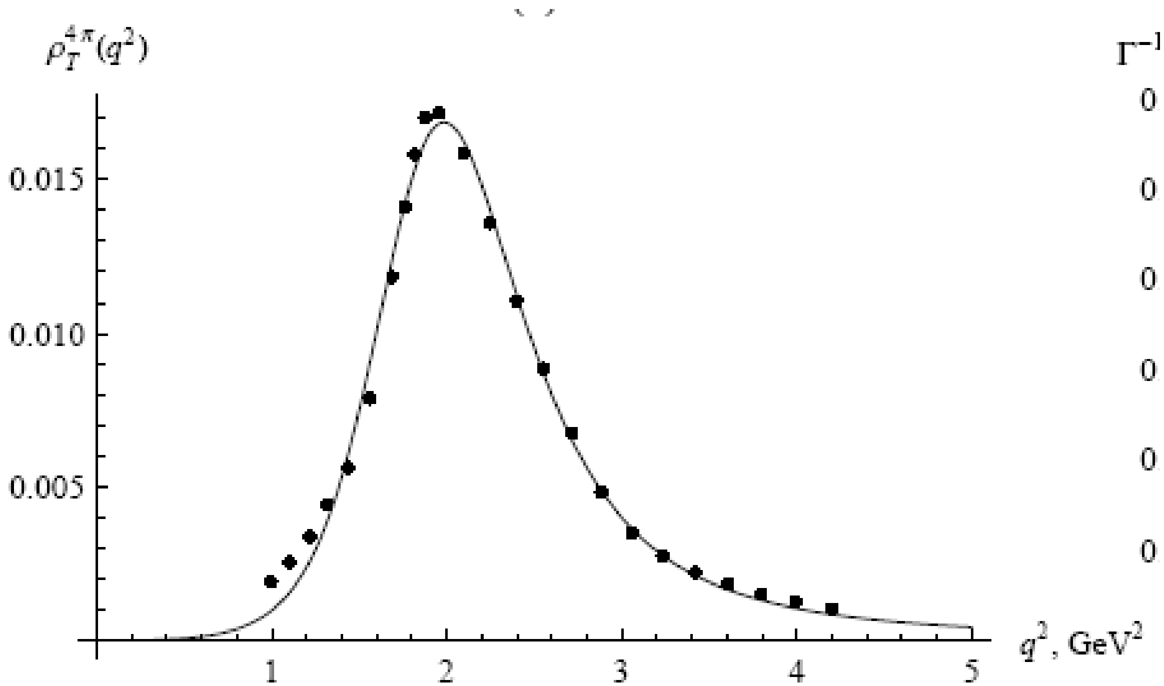
R=3π -- $\tau \rightarrow \nu_\tau + 3\pi$



$$\rho_T^{3\pi}(s) \approx 5.86 \times 10^{-5} \left(\frac{s - 9m_\pi^2}{s} \right)^4 \frac{1 + 190.s}{\left[(s - 1.06)^2 + 0.48 \right]^2}.$$

Spectral Functions

R = 4π -- $e^+e^- \to 4\pi$



$$\rho_T^{4\pi}(s) \approx 1.8 \times 10^{-4} \left(\frac{s - 16m_\pi^2}{2} \right) \frac{1 + 5.07s + 8.63s^2}{\left[(s - 1.83)^2 + 0.61 \right]^2}.$$

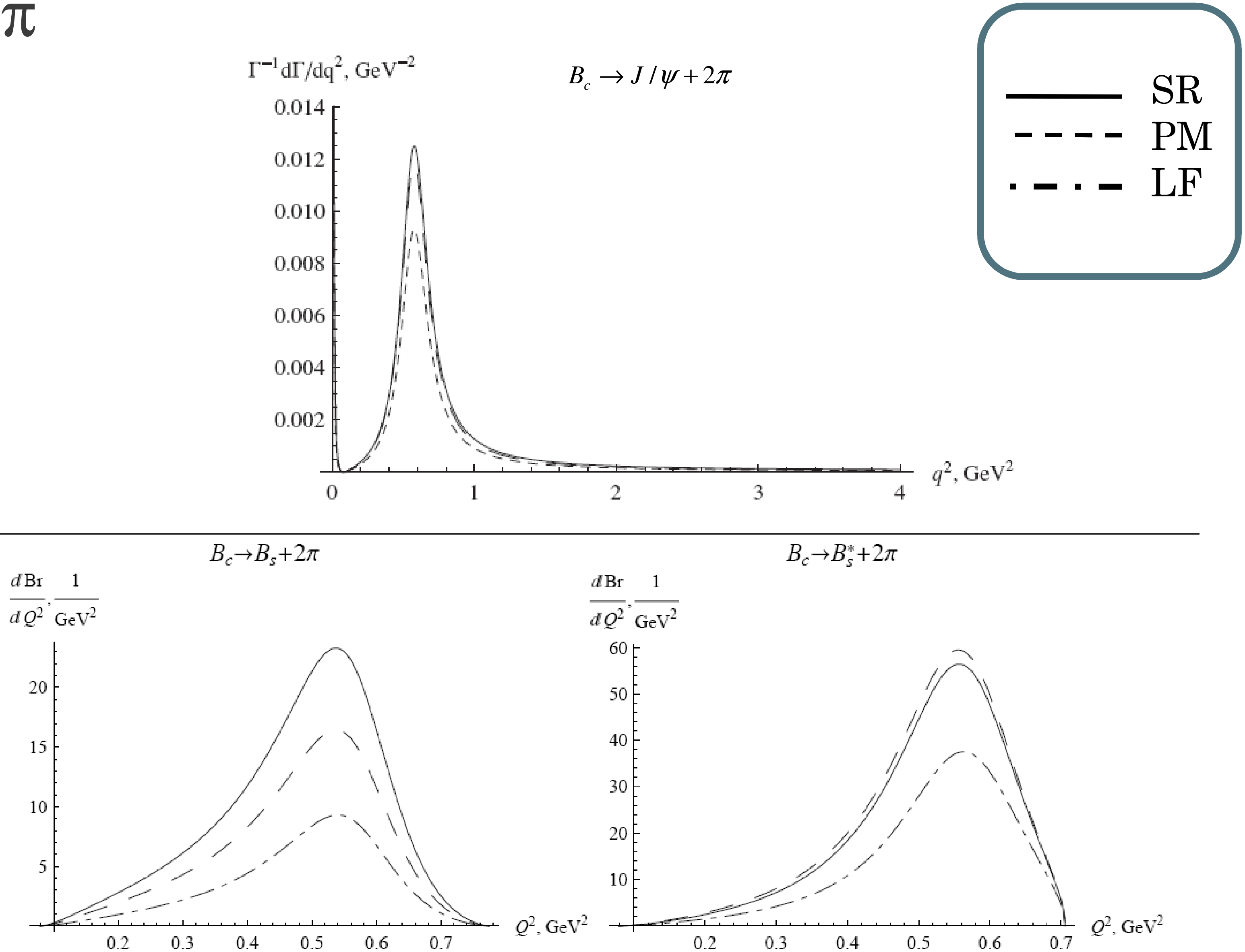
π

	SR	PM	LC
$B_c \to J/\psi$	0.17	0.17	0.13
$B_c \to B_s$	18	12	5.5
$B_c \to B_s^*$	7	9.4	2.8

ρ

	SR	PM	LC
$B_c \to J/\psi$	0.48	0.44	0.38
$B_c \to B_s$	7.6	5.4	3.1
$B_c \to B_s^*$	21	22	14

2π

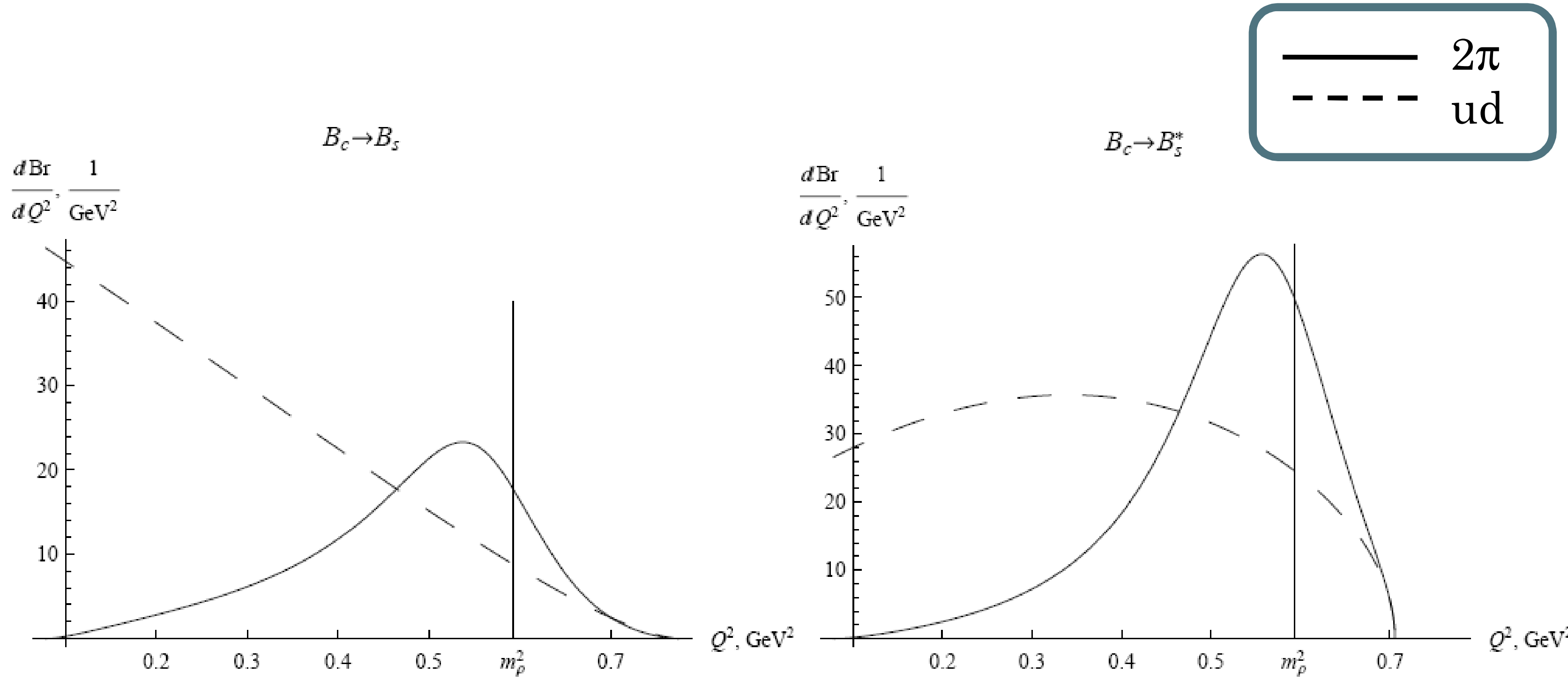

SR
PM
LF
$B_c \to J/\psi + 2\pi$
$\Gamma^{-1} d\Gamma/dq^2$, GeV^{-2}
q^2, GeV^2
$B_c \to B_s + 2\pi$
$\frac{d\,\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
Q^2, GeV^2
$B_c \to B_s^* + 2\pi$
$\frac{d\,\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
Q^2, GeV^2

2π

Br, %	SR	PM	LC
$B_c \to J/\psi$	0.48 (0.48)	0.44 (0.44)	0.35 (0.38)
$B_c \to B_s$	6.1 (7.6)	4.3 (5.4)	2.4 (3.1)
$B_c \to B_s^*$	13 (21)	14 (22)	8.3 (14)

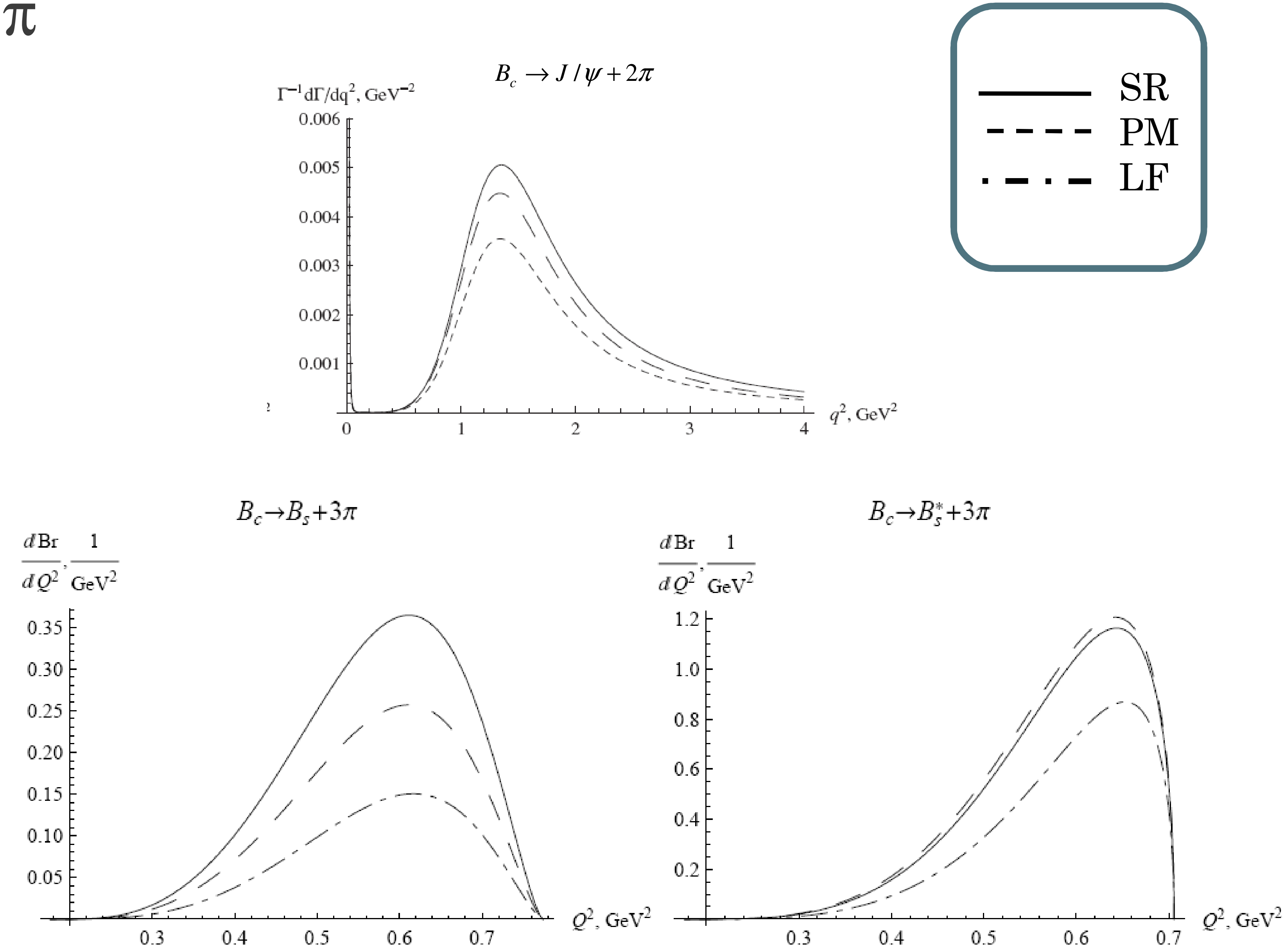
ρ-meson width can be ignored for $B_c \to J/\psi\rho$ decay, but is extremely important for $B_c \to B_s$-decays!

2π



ρ-meson width can be ignored for $B_c \to J/\psi\rho$ decay, but is extremely important for $B_c \to B_s$-decays!

3π



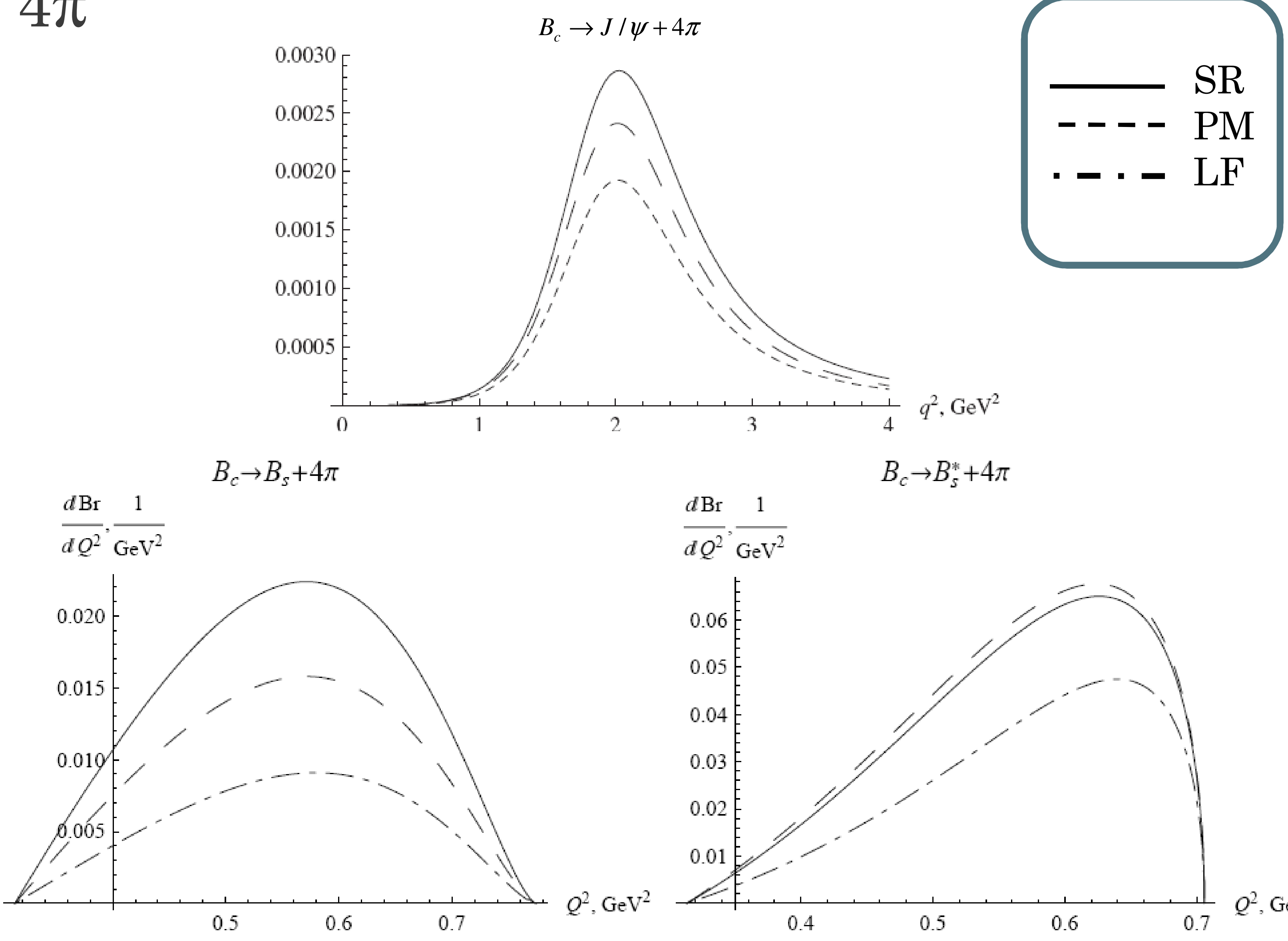
SR
PM
LF
$B_c \to J/\psi + 2\pi$
$\Gamma^{-1} d\Gamma/dq^2$, GeV^{-2}
0.006
0.005
0.004
0.003
0.002
0.001
0
1
2
3
4
q^2, GeV^2
$B_c \to B_s + 3\pi$
$\frac{d\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.3
0.4
0.5
0.6
0.7
Q^2, GeV^2
$B_c \to B_s^* + 3\pi$
$\frac{d\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
1.2
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
0.6
0.7
Q^2, GeV^2

3π

Br, %	SR	PM	LC
$B_c \to J/\psi$	0.77	0.64	0.52
$B_c \to B_s$	0.096	0.068	0.039
$B_c \to B_s^*$	0.23	0.24	0.16

Phase-space suppression is stronger then CKM-enhancement

4π



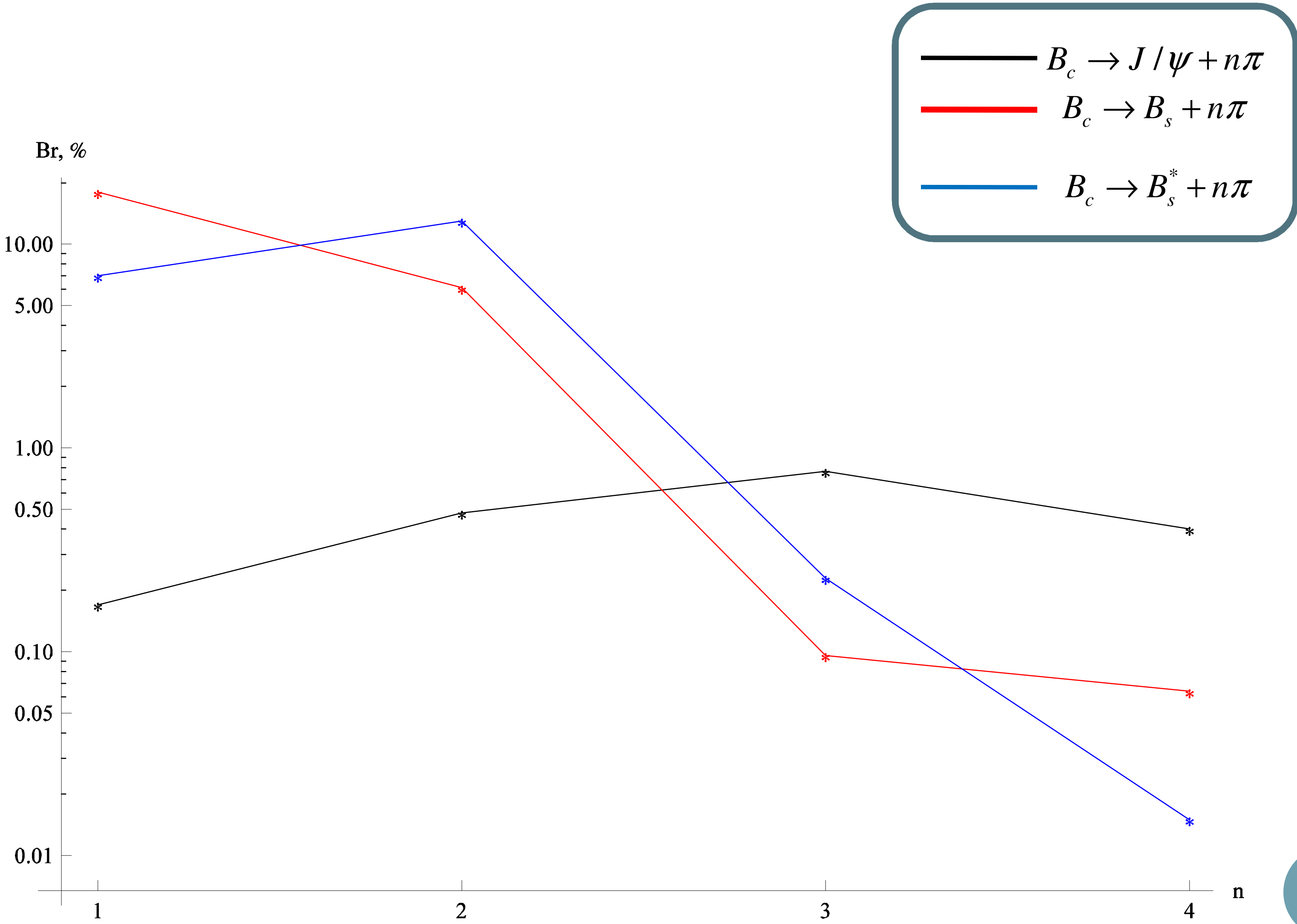
$B_c \to J/\psi + 4\pi$
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0
1
2
3
4
q^2, GeV^2
SR
PM
LF
$B_c \to B_s + 4\pi$
$\frac{d\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
0.020
0.015
0.010
0.005
0.5
0.6
0.7
Q^2, GeV^2
$B_c \to B_s^* + 4\pi$
$\frac{d\mathrm{Br}}{dQ^2}, \frac{1}{\mathrm{GeV}^2}$
0.06
0.05
0.04
0.03
0.02
0.01
0.4
0.5
0.6
0.7
Q^2, GeV^2

4π

Br, %	SR	PM	LC
$B_c \to J/\psi$	0.40	0.33	0.26
$B_c \to B_s$	0.0064	0.0045	0.0026
$B_c \to B_s^*$	0.015	0.016	0.01

Phase-space suppression is stronger then CKM-enhancement

MULTIPLICITY



EvtGen Package

Decay amplitudes used instead of probabilities

- EvtGen works with amplitudes to correctly handle sequential decays:

$$B \to D^* \quad \tau\nu$$
$$\quad \hookrightarrow D\pi \quad \hookrightarrow \pi\nu$$

$$d\Gamma = |A|^2 d\phi \qquad A = \sum_{\lambda_{D^*}\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} A^{D^*\to D\pi}_{\lambda_{D^*}} A^{\tau\to\pi\nu}_{\lambda_\tau}$$

$$A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} \equiv \langle \lambda_{D^*}\lambda_\tau | H | B \rangle$$

$$\sum_{\lambda_{D^*}} |\lambda_{D^*}\rangle\langle\lambda_{D^*}| = I$$

- Nodes in the decay tree are implemented as "models". The framework of EvtGen handles the bookkeeping needed to correctly generate the full decay tree.

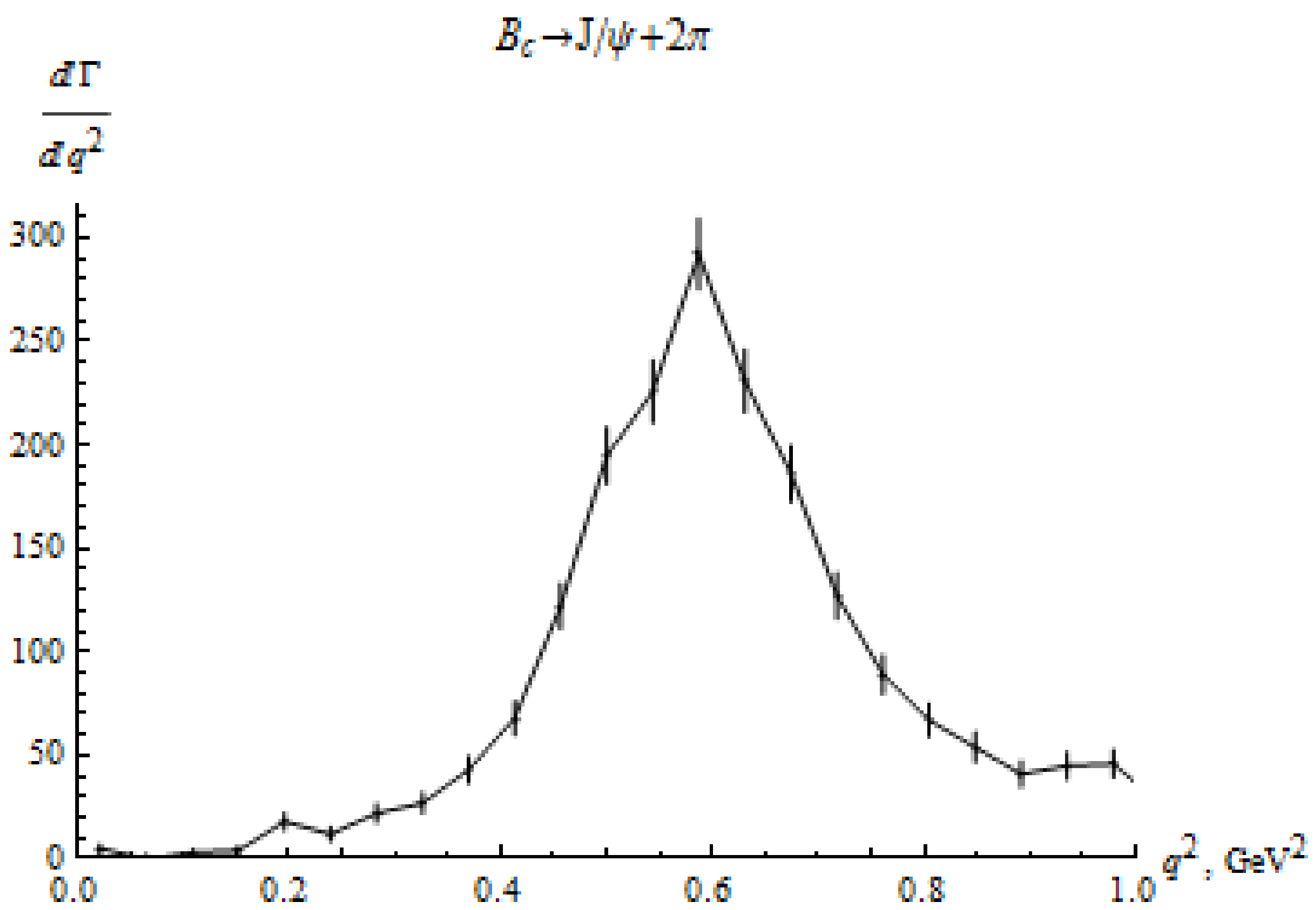
DECAY.DEC File

- This file is provided with the release of EvtGen.
- Contains a very extensive list of particle decays (~8000), organised by mother-type.
- For each decay mode, includes BF, list of daughters and a default decay model.
- Eg. (small sample of file):

```
Decay anti-B0
0.00044      J/psi  K_S0               SVS;
0.00044      J/psi  K_L0               SVS;
0.00133      J/psi  anti-K*0           SVV_HELAMP 0.5 0.0 1.0 0.0 0.5 0.0;
0.0000205      J/psi  pi0               SVS;
0.0002      J/psi  K-  pi+           PHSP;
0.0001      J/psi  anti-K0   pi0            PHSP;
```

```
  Decay Bc+
# Bc -> J/psi pi+ pi0, SR form-factors set
     0.0017  J/psi pi+ pi0     BC_V_NPI
               330.                  # maxProp
               5.9 0.049 0.0015      # FA0
               -0.074 0.049 0.0015   # FAp
               0.11 0.049 0.0015;     # FV

# Bc -> Bs pi+ , SR form-factors set
     0.18     B_s0  pi+        BC_P_NPI
               250                   #maxProb
               1.3      0.30   0.069; # Fp
  Enddecay
```



$B_c \to J/\psi + 2\pi$
$\frac{d\Gamma}{dq^2}$
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
q^2, GeV^2

CONCLUSION

- Bc-meson decays into heavy quarkonia and set of π-meons is considered
  - $B_c \to J/\psi + n\ \pi$
  - $B_c \to B_s + n\ \pi$

  $1 \le n \le 4$

- Distributions over final quarkonium energy can be used to determine spectral functions of π-meson system

- MC package for EvtGen generator is described