Charmonium Breakup in Hadronic Matter

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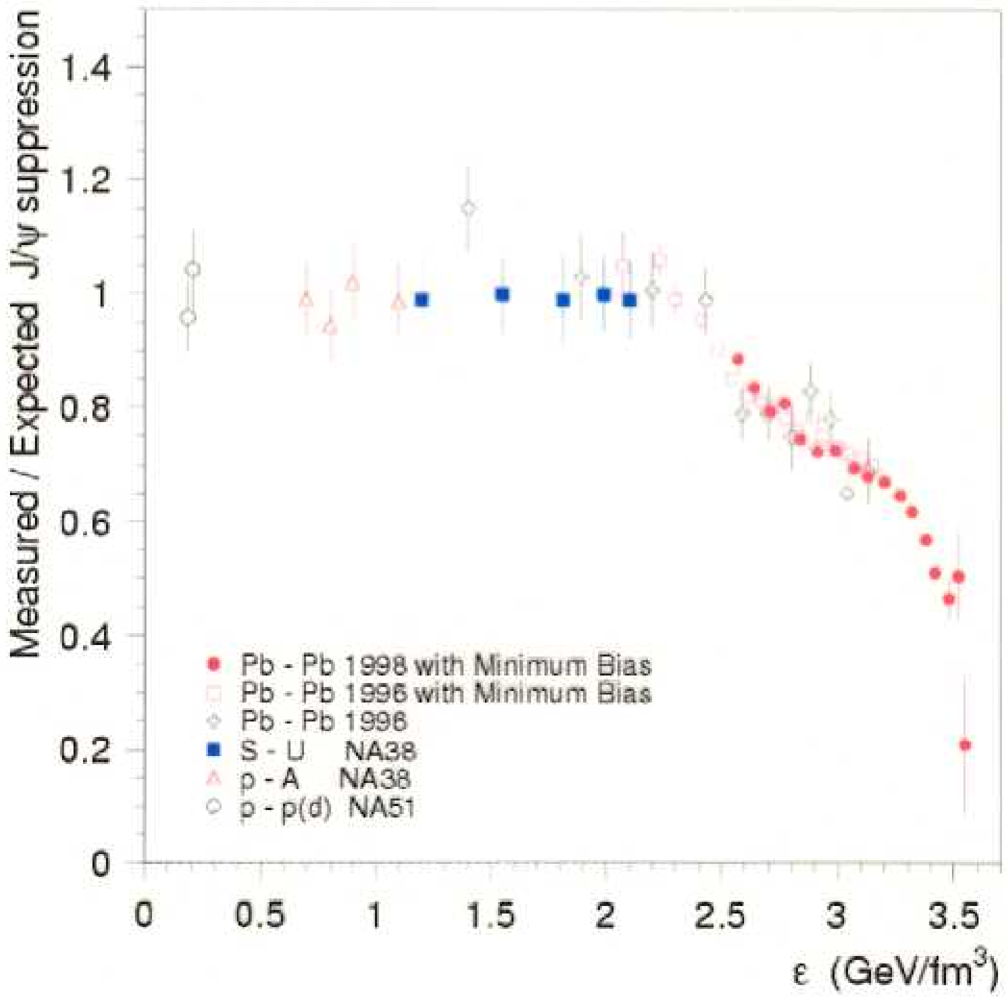
Contents:

- Remarks about J/ψ suppression
- Quark-quark potential, bound-state structure
- Effective chiral Lagrangian
- J/ψ elastic and dissociation cross sections
- Form factors
- Dissociation rates in a fireball
- Spectral function for J/ψ
- Flow??



Measured / Expected J/ψ suppression
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
ε (GeV/fm³)
Pb - Pb 1998 with Minimum Bias
Pb - Pb 1996 with Minimum Bias
Pb - Pb 1996
S - U NA38
p - A NA38
p - p(d) NA51

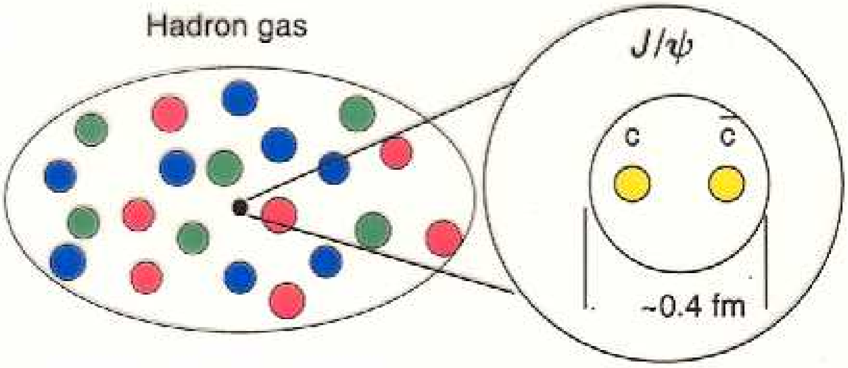
Signals of QGP formation

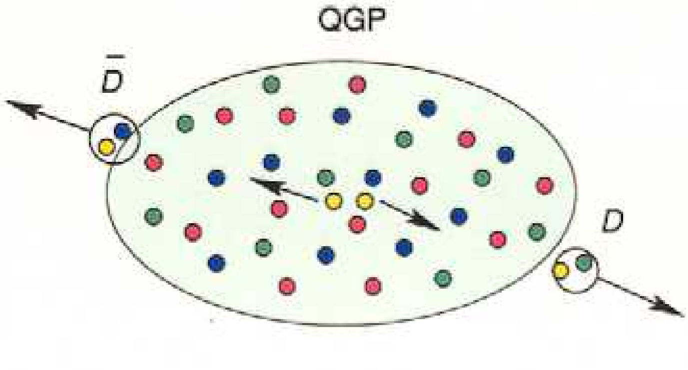
- Flow (directed, radial, elliptical)
- Flavor equilibration
- J/ψ suppression
- Broadening or disappearance of ρ meson
- Charge fluctuations??

J/ψ suppression due to plasma formation

T. Matsui & H. Satz

PLB **178**, 416 (86).





Bound State ($c\bar{c}$)

Schrödinger equation...

$$\frac{-\hbar^2}{2\mu}\frac{d^2u}{dr^2} + \left[V + \frac{\hbar^2}{2\mu}\frac{\ell(\ell+1)}{r^2}\right]u = Eu$$

where

$$V = -\frac{\kappa}{r} + \lambda r^p + \Lambda + \frac{2\pi\kappa'}{3m_q m_{\bar{q}}}\frac{\exp(-r^2/r_0^2)}{\pi^{3/2}r_0^3}\vec{\sigma}_q\cdot\vec{\sigma}_{\bar{q}}$$

and the range of the hyperfine term is

W. Roberts et al.

PRD 57 1694 (98)

$$r_0(m_q m_{\bar{q}}) = A\left(\frac{2m_q m_{\bar{q}}}{m_q + m_{\bar{q}}}\right)^{-B}$$

$m_u = m_d = 0.315$ GeV; $m_s = 0.577$ GeV;

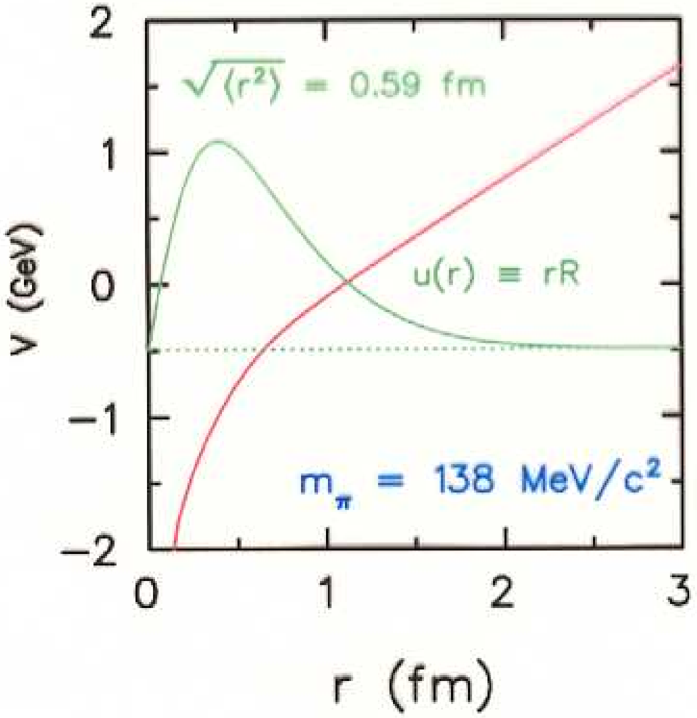
$m_c = m_d = 1.836$ GeV; $m_b = 5.227$ GeV;

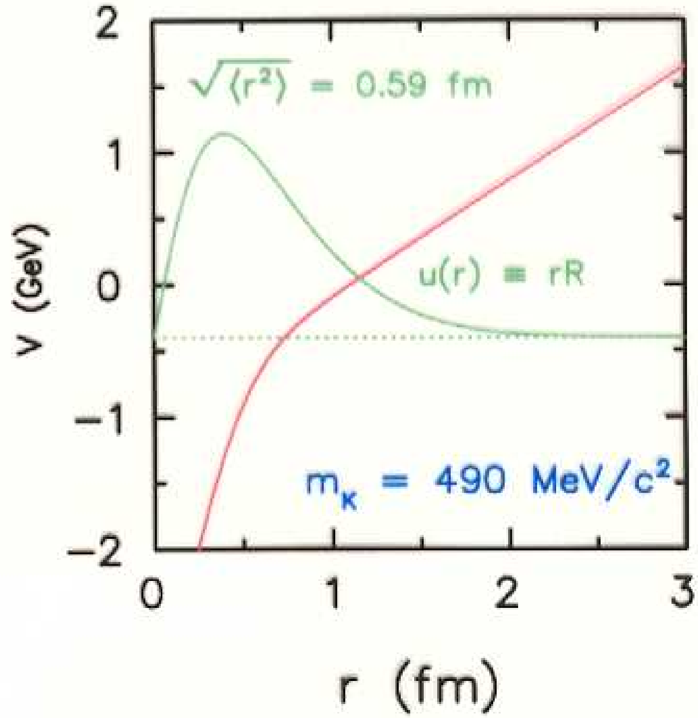
$\kappa = 0.5069$; $\kappa' = 1.8609$; $\lambda = 0.1653\ \mathrm{GeV}^2$;

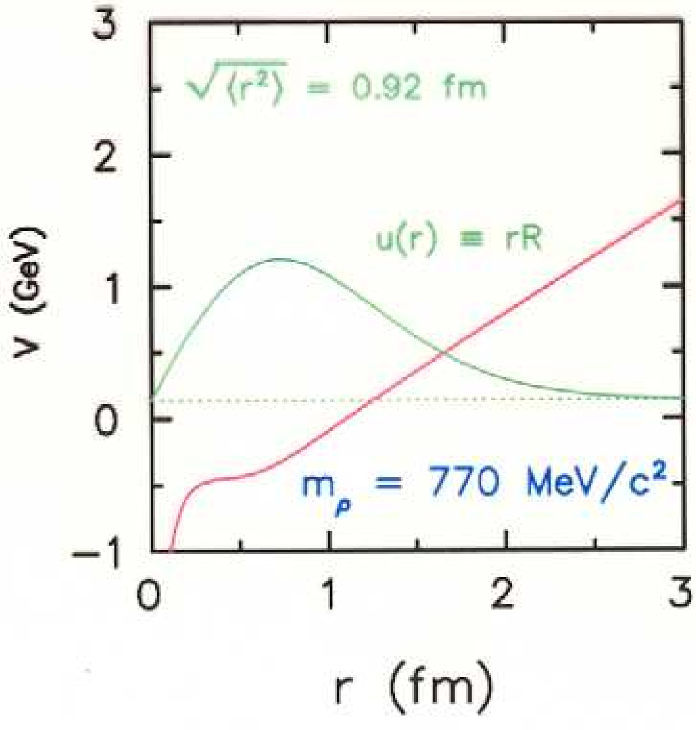
$B = 0.2204$; $A = 1.6553\ \mathrm{GeV}^{B-1}$;

$\Lambda = -0.8321$ GeV; $p = 1$

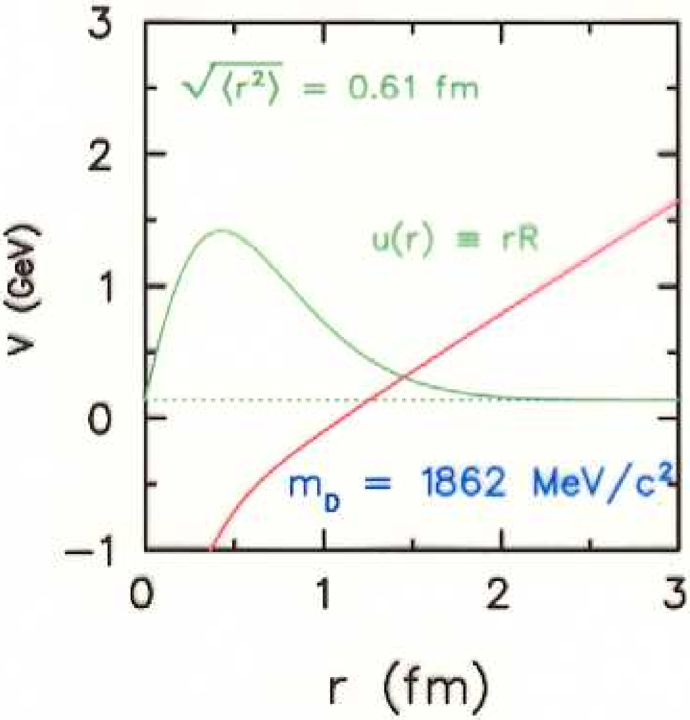
Wave functions, masses and sizes...

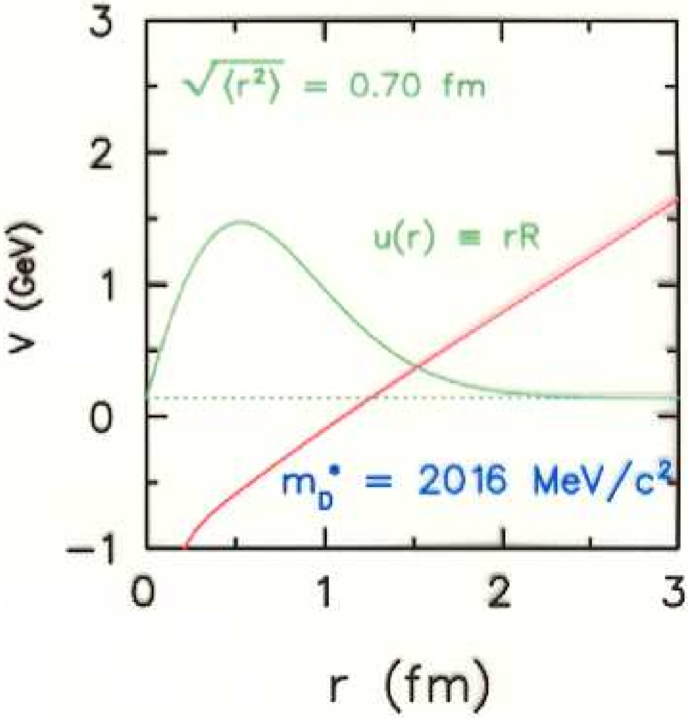




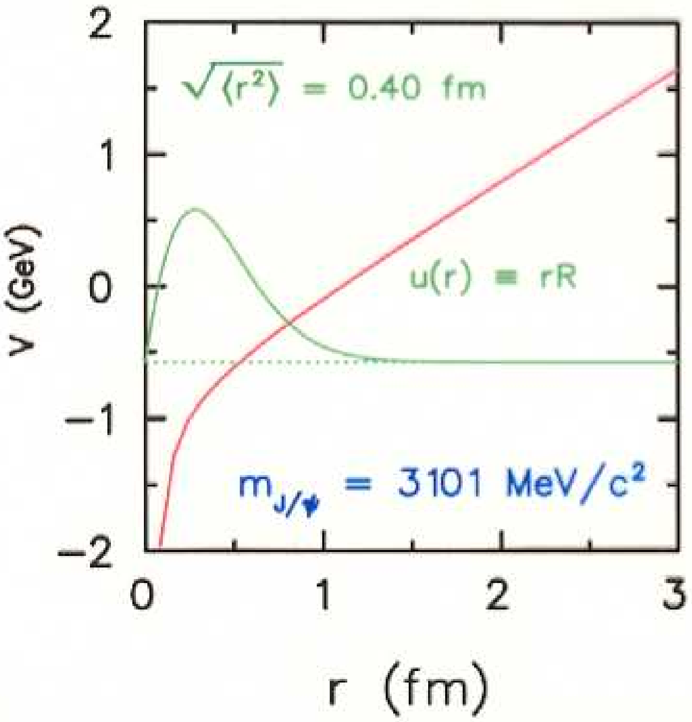


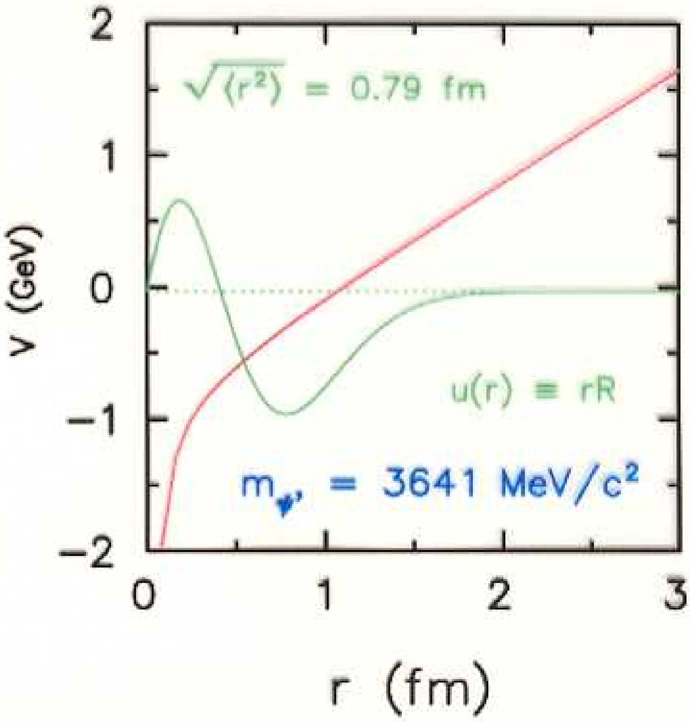
D states' wave functions, masses and sizes...

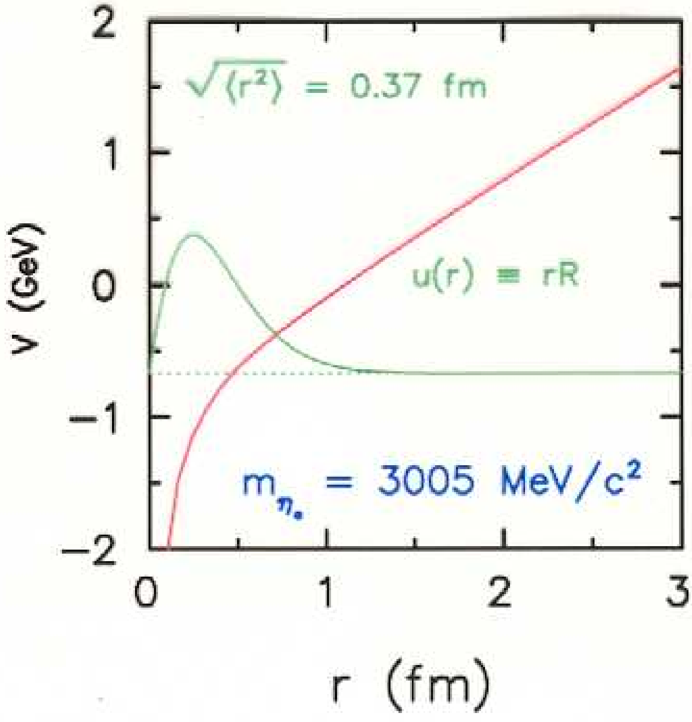




Charmonium wave functions, masses and sizes...







Light Meson Oservables...

particle	mass - expt. (MeV)	mass - model (MeV)
π	138	138
K	496	490
ρ	769	770
ω	783	770
K*	893	903
ϕ	1019	1020
a_1	1251	1208
f_1	1245	1208

Charmed Meson Oservables...

particle	mass - expt. (MeV)	mass - model (MeV)
D	1867	1862
D^*	2008	2016
η_c	2980	3005
J/ψ	3097	3101
ψ'	3686	3641

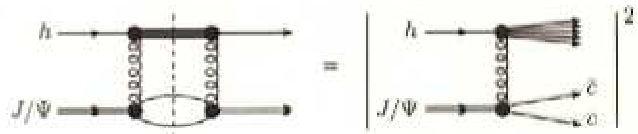
The crucial question: $\sigma(J/\psi + h)$?

- perturbative approach, gluonic contents interact

M. E. Peskin, NPB**156**, 365 (79)

G. Bhanot & M. E. Peskin, NPB**156**, 391 (79)

D. Kharzeev & H. Satz, PLB**334**, 155 (94)

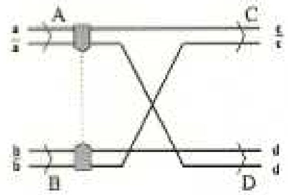


$\sigma \lesssim 0.1$ mb

- nonperturbative strategy, quark exchange w/ confining potential

K. Martins, D. Blaschke & E. Quack

PRC**51**, 2723 (95)

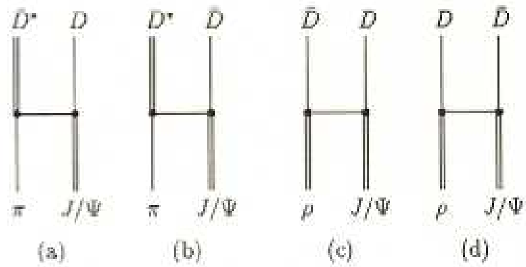


$\sigma \lesssim 7.0$ mb

- effective hadronic field theory

S. G. Matinyan & B. Müller

PRC**58**, 2994 (98)



$\sigma \lesssim 1$ mb

Heavy meson chiral Lagrangian

$$\mathscr{L}_0 = \frac{-F_\pi^2}{8}\,\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right),$$

$$U = \exp\left[\frac{2i\phi}{F_\pi}\right], \qquad F_\pi \simeq 135\ \mathrm{MeV}$$

where the pseudoscalar multiplet is

$$\phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}}+\frac{\eta_c}{\sqrt{12}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}}+\frac{\eta_c}{\sqrt{12}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta+\frac{\eta_c}{\sqrt{12}} & D_s^- \\ D^0 & D^+ & D_s^+ & -\frac{3\eta_c}{\sqrt{12}} \end{pmatrix}$$

A gauge-invariant extension...

$$\partial_\mu U \rightarrow D_\mu U \equiv \partial_\mu U - igA_\mu^L U + igUA_\mu^R,$$

and by adding the terms

$$\mathscr{L}_1 = -\frac{1}{2}\mathrm{Tr}\left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu}\right) + \gamma\mathrm{Tr}\left(F_{\mu\nu}^L U F^{R\mu\nu} U^\dagger\right)$$

where

$$F_{\mu\nu}^L = \partial_\mu A_\nu^L - \partial_\nu A_\mu^L - ig\left[A_\mu^L, A_\nu^L\right]$$

$$F_{\mu\nu}^R = \partial_\mu A_\nu^R - \partial_\nu A_\mu^R - ig\left[A_\mu^R, A_\nu^R\right]$$

$\mathscr{L}_0 + \mathscr{L}_1$ is invariant under chiral $U(4) \times U(4)$ gauge

transformation

$$U \rightarrow U_L U U_R^\dagger$$

$$A_\mu^L \rightarrow U_L A_\mu^L U_L^\dagger + \frac{i}{g} U_L \partial_\mu U_L^\dagger$$

$$A_\mu^R \rightarrow U_R A_\mu^R U_R^\dagger + \frac{i}{g} U_R \partial_\mu U_R^\dagger$$

We break the local invariance in a minimal way

$$\mathscr{L}_2 = -m_0^2 \operatorname{Tr}\left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu}\right) + B \operatorname{Tr}\left(A_\mu^L U A^{R\mu} U^\dagger\right) + C \operatorname{Tr}\left(A_\mu^L A^{R\mu} + A_\mu^R A^{L\mu}\right)$$

Then the full Lagrangian is

$$\mathscr{L}_{\text{full}} = \mathscr{L}_0 + \mathscr{L}_1 + \mathscr{L}_2 + \text{ mass terms.}$$

Now we gauge away the axial fields

$$\begin{aligned} A_\mu^L &\equiv \xi \rho_\mu \xi^\dagger + \frac{i}{g} \xi \partial_\mu \xi^\dagger, \\ A_\mu^R &\equiv \xi^\dagger \rho_\mu \xi + \frac{i}{g} \xi^\dagger \partial_\mu \xi, \\ U &\equiv \xi \mathbf{1} \xi \end{aligned}$$

where

$$U_L = U^{1/2} = \xi,$$
$$U_R = U^{-1/2} \equiv \xi^{\dagger}:$$

and where the vector multiplet is

$$\rho_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & -\omega\sqrt{\frac{2}{3}} + \frac{J/\psi}{\sqrt{12}} & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & -\frac{3J/\psi}{\sqrt{12}} \end{pmatrix}_\mu$$

We have then a chiral model of heavy ϕ and ρ_μ mesons

$$\mathscr{L}_0 = 0$$
$$\mathscr{L}_1 = (\gamma - 1)\,\mathrm{Tr}\left[F_{\mu\nu}(\rho)\,F^{\mu\nu}(\rho)\right]$$
$$F_{\mu\nu} \equiv \partial_\mu \rho_\nu - \partial_\nu \rho_\mu - ig\,[\rho_\mu, \rho_\nu], \quad \gamma = \frac{3}{4}$$
$$\begin{aligned} \mathscr{L}_2 = {} & \left(B + 2C - 2m_0^2\right) \mathrm{Tr}\,(\rho_\mu \rho^\mu) \\ & + \frac{2i}{F_\pi^2 g}\left(B + 2C - 2m_0^2\right) \mathrm{Tr}\,(\rho_\mu [\partial^\mu \phi, \phi]) \\ & + \frac{4C}{F_\pi^2} \mathrm{Tr}\,[\phi, \rho_\mu]^2 \\ & - \frac{\left(B + 2C + 2m_0^2\right)}{F_\pi^2 g^2} \mathrm{Tr}\,(\partial_\mu \phi \partial^\mu \phi), \qquad g_{\rho\pi\pi} = \frac{m_V^2}{g F_\pi^2} \end{aligned}$$

Correct normalization of pseudoscalar fields requires

$$\frac{B + 2C + 2m_0^2}{g^2 F_\pi^2} = \frac{1}{2}$$

Calibrate the model to light vector spectroscopy

$$\Gamma(\rho) = 151 \text{ MeV} \quad ; \quad m_\rho = 770 \text{ MeV}$$

$$\Downarrow$$

$$g_{\rho\pi\pi} = 8.54 \quad ; \quad g = \frac{g_{\rho\pi\pi}}{2}$$

[using only F_π, m_ρ and $\Gamma(\rho)$]

We 'predict' heavy meson observables...

Minimally substitute & gauge away axial fields...

$$\mathscr{L}_{\text{int}} = i\, g \operatorname{Tr}\left(\rho_\mu \left[\partial^\mu \phi, \phi\right]\right) - \frac{g^2}{2} \operatorname{Tr}\left(\left[\phi, \rho^\mu\right]^2\right) + i\, g \operatorname{Tr}\left(\partial_\mu \rho_\nu \left[\rho^\mu, \rho^\nu\right]\right) + \frac{g^2}{4} \operatorname{Tr}\left(\left[\rho^\mu, \rho^\nu\right]^2\right)$$

where the vector field matrix is

$$\rho_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & -\omega\sqrt{\frac{2}{3}} + \frac{J/\psi}{\sqrt{12}} & D_S^{*-} \\ D^{*0} & D^{*+} & D_S^{*+} & -\frac{3J/\psi}{\sqrt{12}} \end{pmatrix}_\mu$$

Calibrate the model to ρ meson properties

$$\Gamma(\rho) = 151\ \text{MeV} \quad ; \quad m_\rho = 770\ \text{MeV}$$

$$\Downarrow$$

$$g_{\rho\pi\pi} = 8.54 \quad ; \quad g = \frac{g_{\rho\pi\pi}}{2}$$

[using only F_π, m_ρ and $\Gamma(\rho)$]

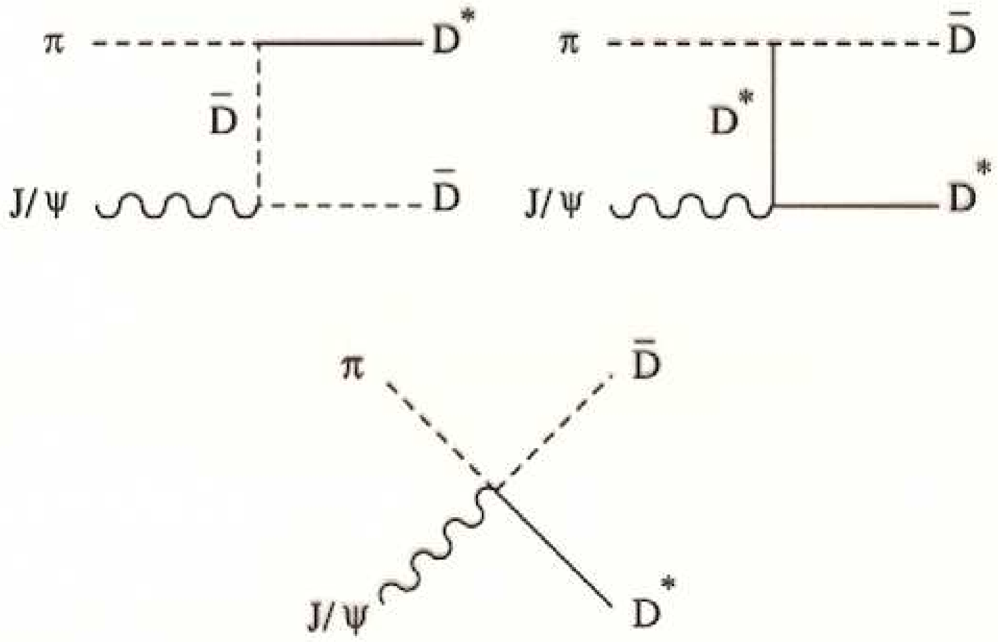
We 'predict' heavy meson observables...

particle	chiral model	experiment
$K(892)^0$	44.5 MeV	50.5 ± 0.6 MeV
$K(892)^\pm$	44.5 MeV	49.8 ± 0.8 MeV
$D(2007)^0$	10.1 keV	< 2.1 MeV, 90% CL
$D(2010)^\pm$	21.1 keV	$94 \pm 4 \pm 22$ keV

Other model calculations

	particle	full width
C. Roberts et al., PRD 60, 034018 (99)	$D(2007)^0$	20 keV
	$D(2010)^\pm$	37.9 keV
P. Colangelo et al., PLB 278, 480 (94)	$D(2010)^\pm$	46 keV
F.S. Navarra et al., PLB 489, 319 (00)	$D(2010)^\pm$	6.3 keV

Feynman graphs for pion-induced breakup

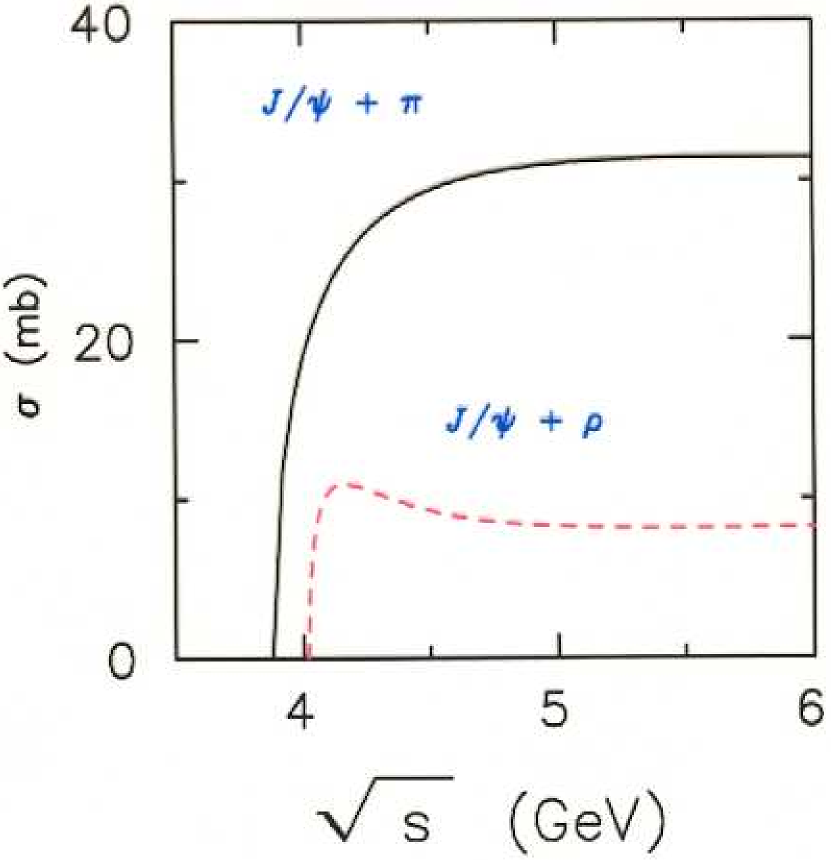


Comparison with recent works
(using effective Lagrangians)

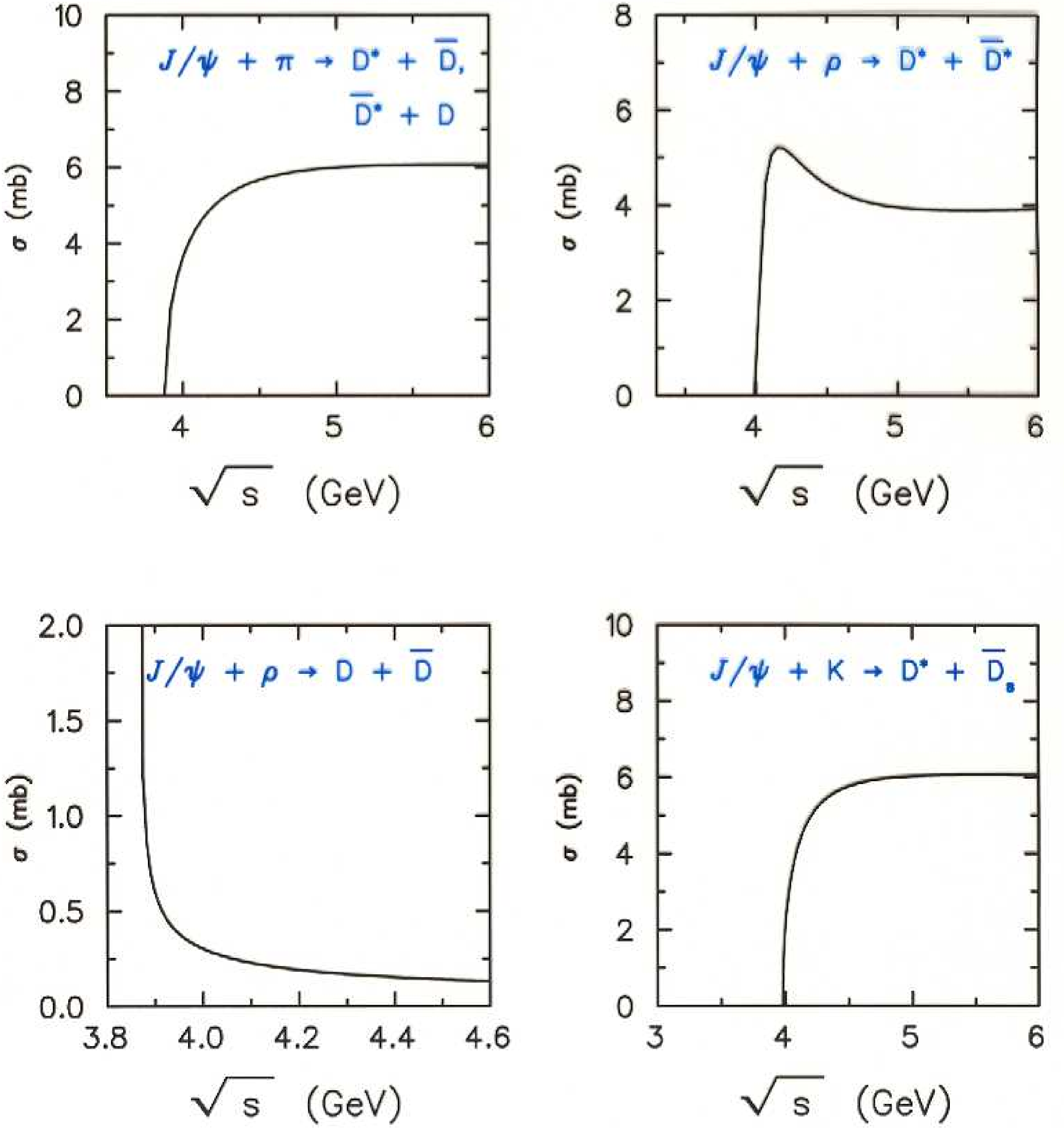
K.H., PRC **61**, 031902 (00)

K.H. & C. Gale, PRC **63**, 0452XX (01)

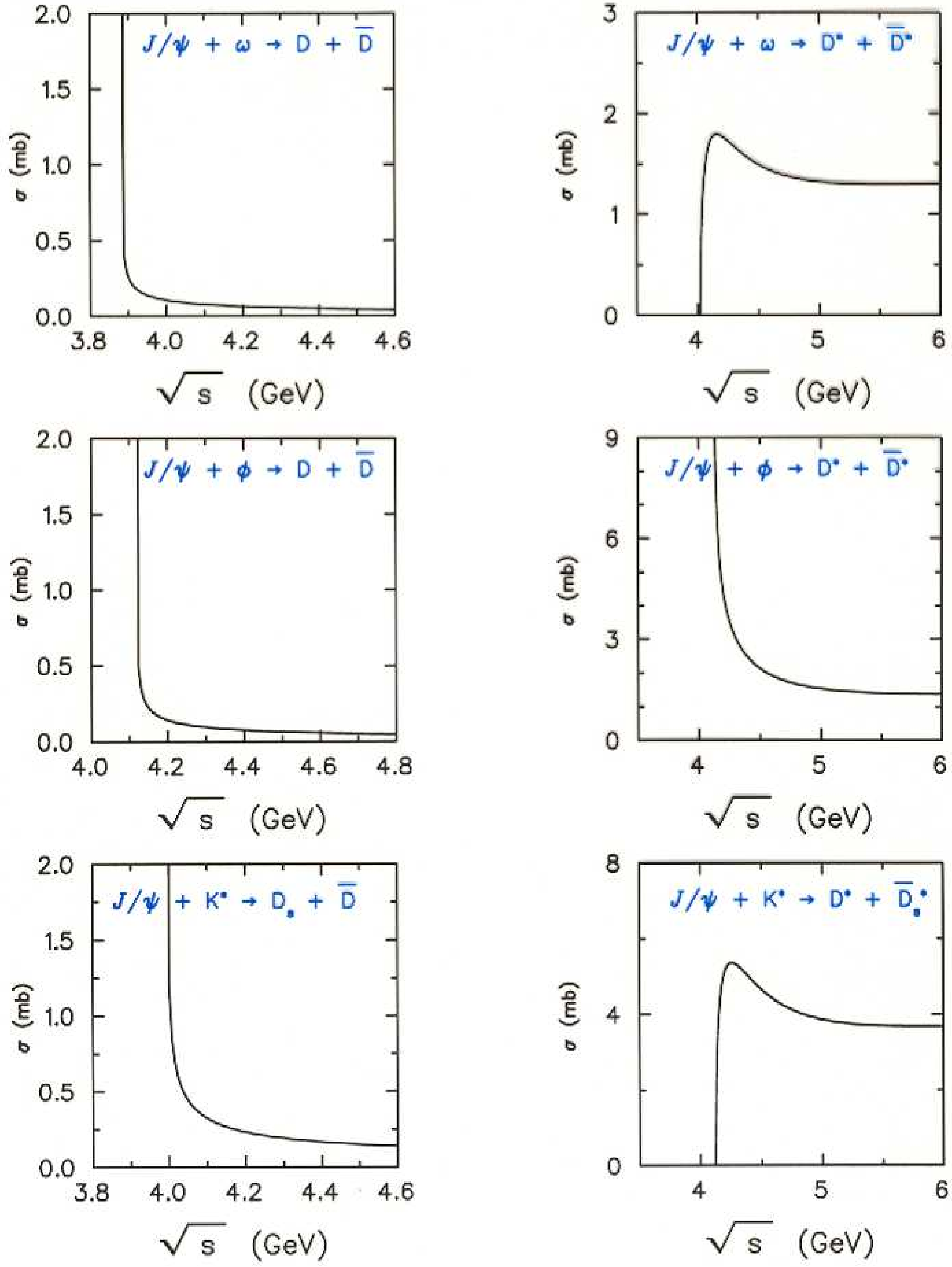
Z. Lin & C.M. Ko, PRC **62**, 034903 (00)



Dissociation cross sections: pion, kaon, rho meson



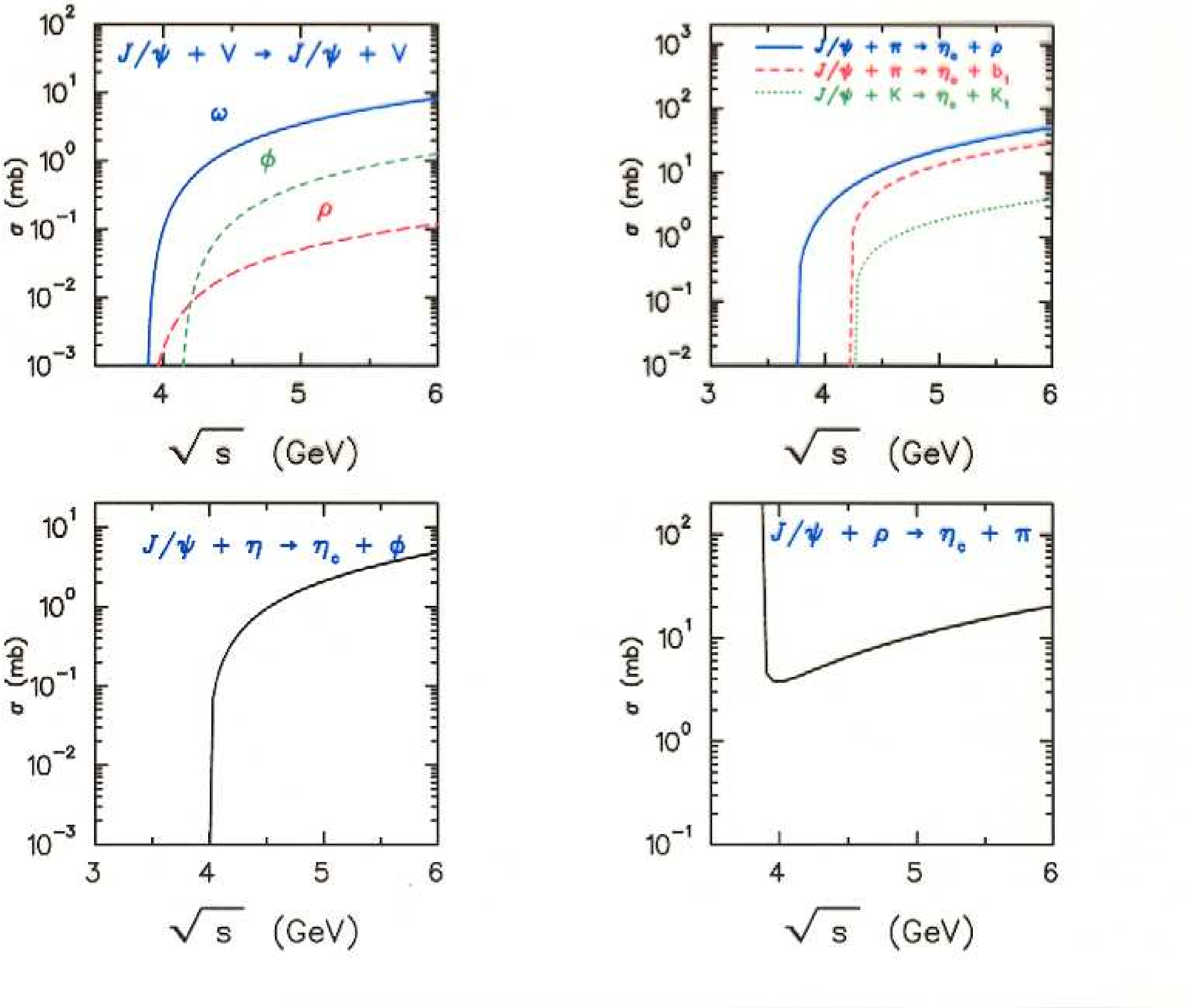
Survey the hadronic landscape...



Processes with anomalous (Wess-Zumino) couplings

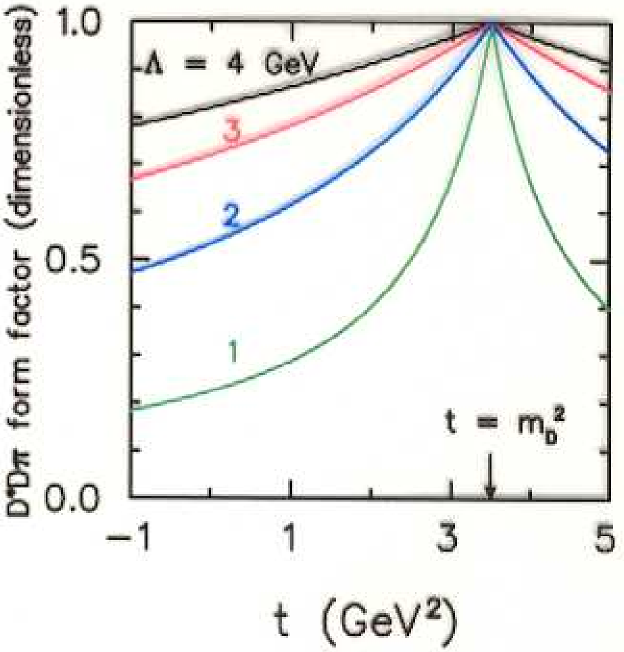
$$\mathcal{L}_{VV\phi} = g_{VV\phi}\,\epsilon_{\mu\nu\alpha\beta}\,\partial^\mu V^\nu\,\partial^\alpha V^\beta\,\phi, \quad \mathcal{L}_{\gamma V} = -\frac{e}{2g_V}A^{\mu\nu}G_{\mu\nu}$$

Vector dominance used to fix individual couplings



Form factors:

$$F(t) = \frac{\Lambda^2}{\Lambda^2 + |t - m_\alpha^2|}$$



- Coupling constants are related to on-shell decays.
- Off-shell behavior ($J/\psi \rightarrow \pi^0\gamma$) is used to fix Λ, with VMD. We find Λ = 1.25 GeV.
- Data on charm photoproduction points to $\Lambda \approx$ 2.0 GeV.

1.25 GeV $\leq \Lambda \leq$ 2.0 GeV

'fff'— form factor formalism

e.g. $J/\psi + \pi \rightarrow \bar{D} + D^*$

$$\mathcal{M}(\text{t-channel}) \rightarrow \mathcal{M}(\text{t-channel})^* h_1$$
$$\mathcal{M}(\text{u-channel}) \rightarrow \mathcal{M}(\text{u-channel})^* h_2$$
$$\mathcal{M}(\text{contact}): -g^{\mu\nu} \rightarrow X^{\mu\nu} = A g^{\mu\nu}$$
$$+ B\left(p_D^\mu p_\pi^\nu + p_\pi^\mu p_D^\nu\right) + C\left(p_{D^*}^\mu p_\pi^\nu + p_\pi^\mu p_{D^*}^\nu\right)$$
$$+ D\left(p_\pi^\mu p_\pi^\nu + p_D^\mu p_D^\nu\right) + E\left(p_\pi^\mu p_\pi^\nu + p_{D^*}^\mu p_{D^*}^\nu\right)$$

Gauge invariant solution...

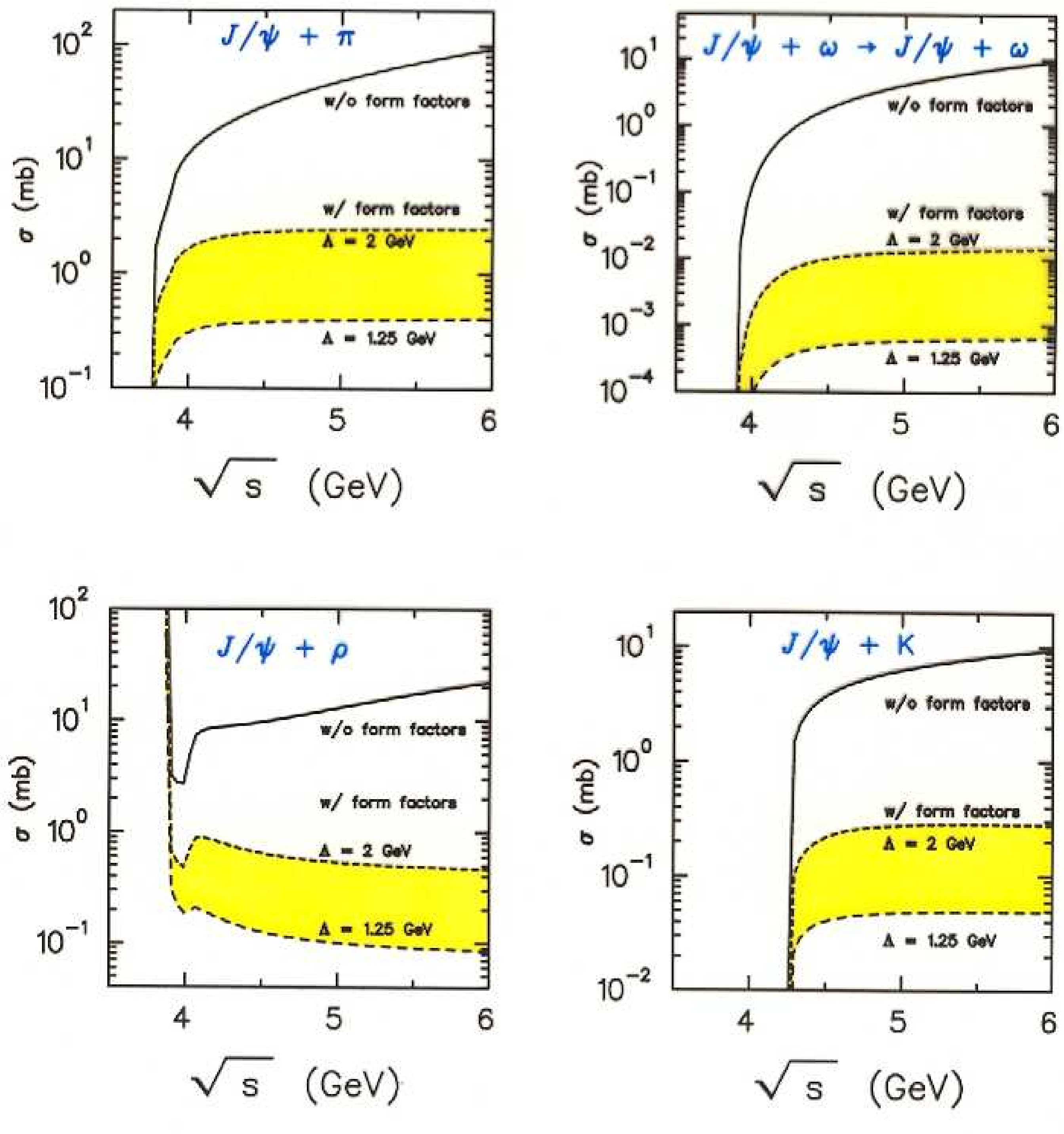
$$A = -h_1$$
$$B = D = \frac{h_1 - h_2}{\left(p_{J/\psi} \cdot p_\pi + p_{J/\psi} \cdot p_D\right)}$$
$$C = E = 0$$

Lorentz invariant monopoles...

$$h_1 = \left(\frac{\Lambda^2_{J/\psi DD}}{\Lambda^2_{J/\psi DD} + |t - m_D^2|}\right)\left(\frac{\Lambda^2_{D^* D\pi}}{\Lambda^2_{D^* D\pi} + |t - m_D^2|}\right)$$
$$h_2 = \left(\frac{\Lambda^2_{J/\psi D^* D^*}}{\Lambda^2_{J/\psi D^* D^*} + |u - m_{D^*}^2|}\right)\left(\frac{\Lambda^2_{DD^*\pi}}{\Lambda^2_{DD^*\pi} + |u - m_{D^*}^2|}\right)$$

Effect on cross sections

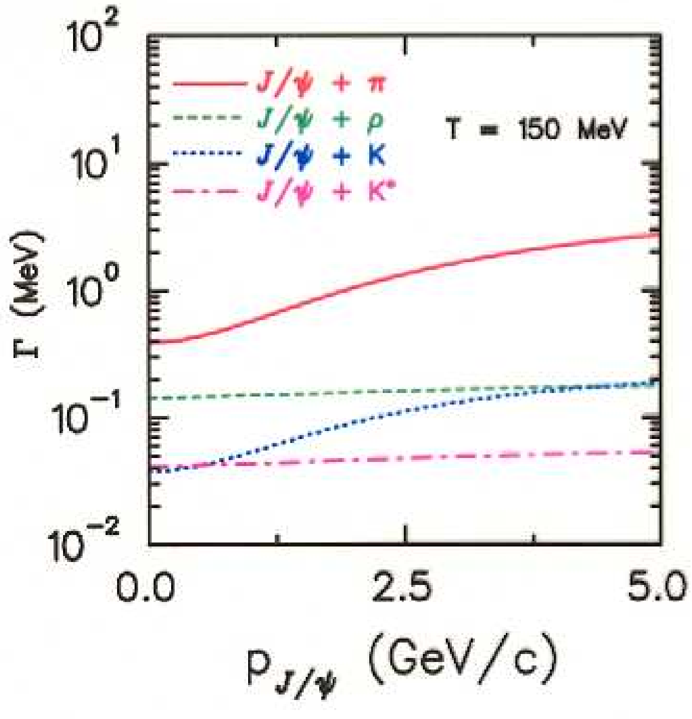
- Form factor choices admit a wide range in cross sections.

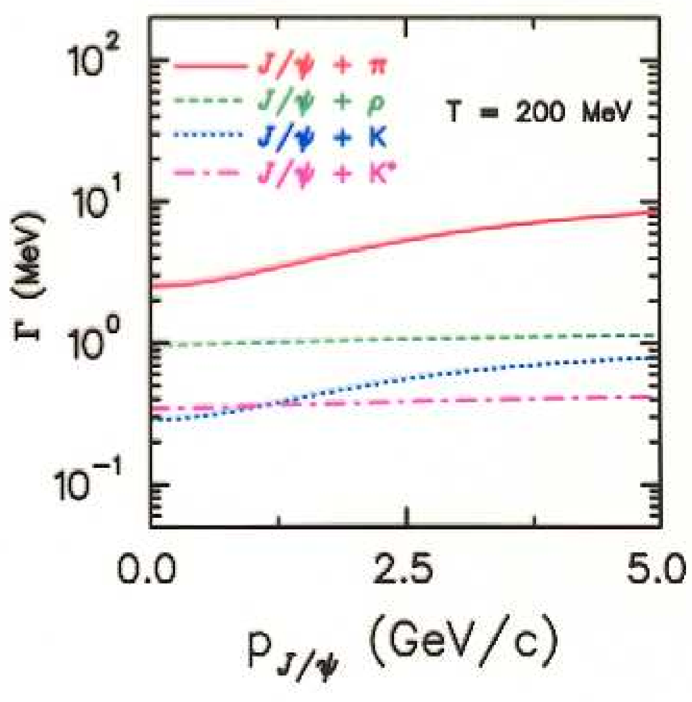


Momentum dependence in scattering rate?

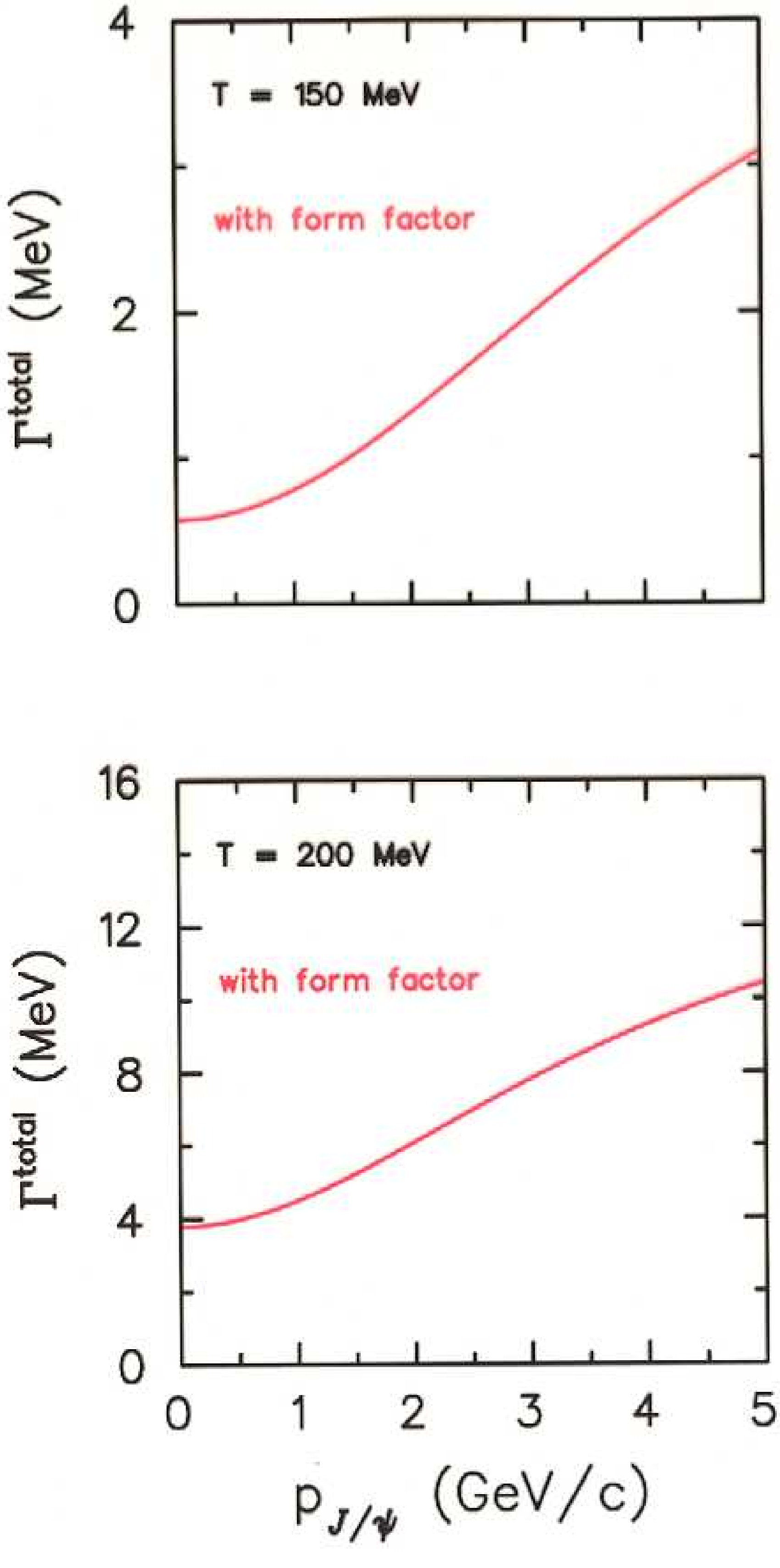
$$J/\psi + b \rightarrow 1 + 2$$

$$d\Gamma_{J/\psi} = d_b \frac{d^3p_b}{(2\pi)^3 2E_b} f_b \frac{|\overline{\mathcal{M}}|^2}{2E_{J/\psi}} \tilde{f}_1 \tilde{f}_2 (2\pi)^4$$
$$\times \delta^4(p_{J/\psi} + p_b - p_1 - p_2) \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2}$$





Sum over light mesons for total dissociation rate



J/ψ spectral function

$$A_{J/\psi}(\omega,\vec{p}) = \frac{2m_{J/\psi}\Gamma_{J/\psi}}{\left(p^2 - m_{J/\psi}^2\right)^2 + m_{J/\psi}^2\Gamma_{J/\psi}^2}$$

KH & C. Gale

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nucl-th/0010017

PRC, 63, [redacted](01)

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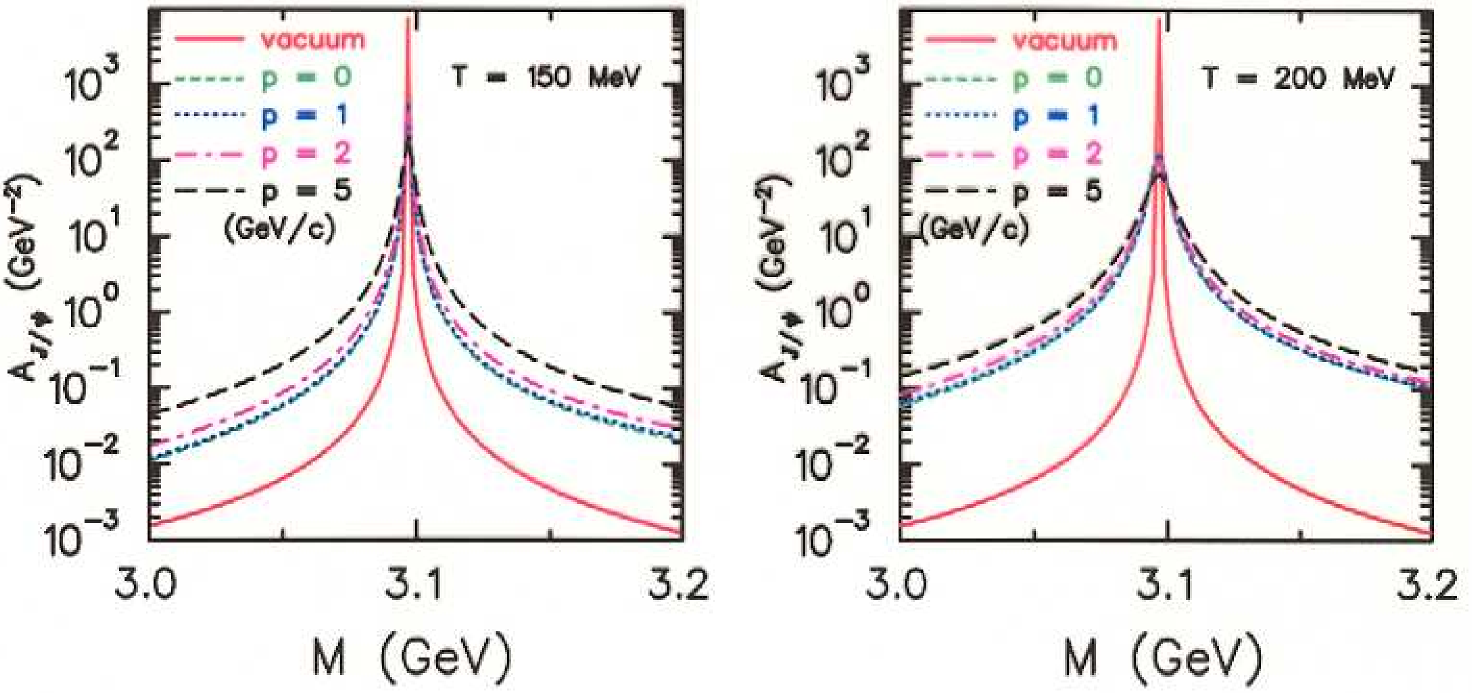
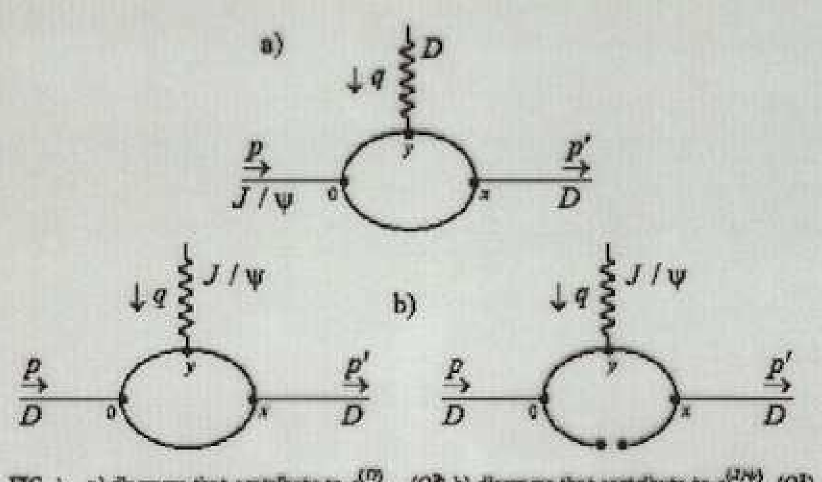


Form factors from QCD sum rules

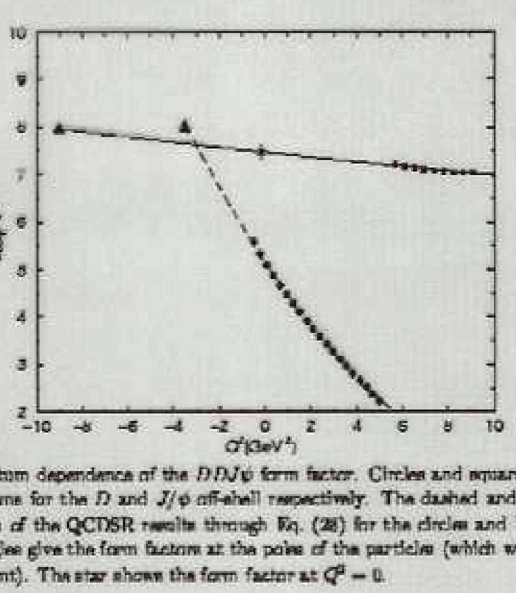
R. D. Matheus et al.

PL**B541**, 265 (02).



FIC. 1. a) diagrams that contribute to $g^{(D)}_{DDJ/\psi}(Q^2)$ b) diagrams that contribute to $g^{(J/\psi)}_{DDJ/\psi}(Q^2)$

$g_{DDJ/\psi}(t)$



$-Q^2 = t$

FIG. 2. Momentum dependence of the $DDJ\psi$ form factor. Circles and squares represent our numerical calculations for the D and J/ψ off-shell respectively. The dashed and solid lines give the parametrization of the QCDSR results through Eq. (28) for the circles and Eq. (30) for the squares. The triangles give the form factors at the poles of the particles (which we indentify with the coupling constant). The star shows the form factor at $Q^2 = 0$.

10

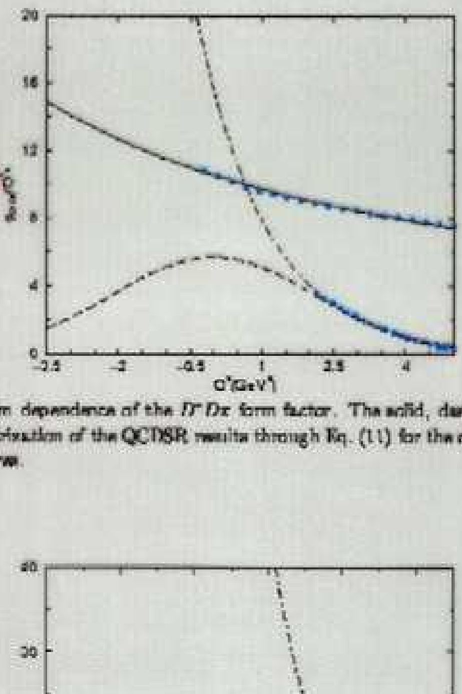
$D^*D\pi$ vertex, offshell D

F. S. Navarra et al.

PRD **65**, 037502 (02).

FIGURES

$g_{D^*D\pi}(t)$



$-Q^2 = t$

FIG. 1. Momentum dependence of the $D^*D\pi$ form factor. The solid, dashed and dot-dashed lines give the parametrization of the QCDSR results through Eq. (11) for the circles, and Eqs. (12) and (13) for the squares.

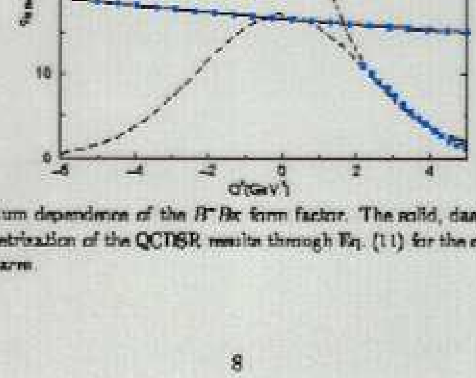


FIG. 2. Momentum dependence of the $B^*B\pi$ form factor. The solid, dashed and dot-dashed lines give the parametrization of the QCDSR results through Eq. (11) for the circles, and Eqs. (12) and (13) for the squares.

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DDρ vertex, offshell D

M. E. Bracco et al.

PLB521, 1 (02).

FIGURES

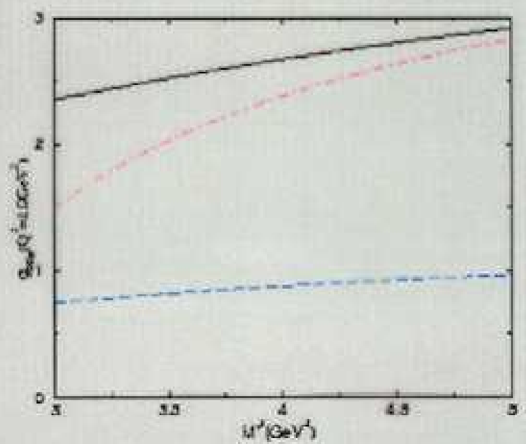
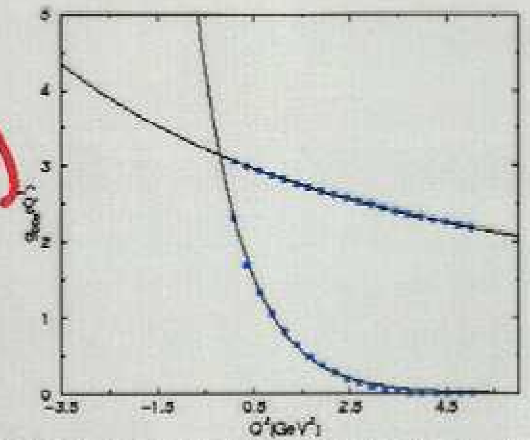


FIG. 1. M^2 dependence of the $DD\rho$ form factors at $Q^2 = 1$ GeV^2 for $\Delta_s = \Delta_u = 0.5$ GeV. The dashed line gives the QCDSR result for $g^{(s)}_{DD\rho}(Q^2)$ and the dot-dashed and solid lines give the QCDSR results for $g^{(D)}_{DD\rho}(Q^2)$ in the p_μ and p'_μ structures respectively.

$g_{DD\rho}(t)$



$-Q^2 = t$

FIG. 2. Momentum dependence of the $DD\rho$ form factor for $\Delta_s = \Delta_u = 0.5$ GeV. The solid lines give the parametrization of the QCDSR results through Eq. (21) for the circles, and Eq. (22) for the squares.

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QCD Sum Rule Form Factors

$$g_{DDJ/\psi}(t) = g_{DDJ/\psi} e^{-\left[(t-16.2)^2/228\right]}$$

$$g_{D^*D\pi}(t) = g_{D^*D\pi} \left(\frac{\Lambda_D^2 - m_D^2}{\Lambda_D^2 - t} \right)$$

$$g_{DD\rho}(t) = g_{DD\rho} \left(\frac{\Lambda_D^2 - m_D^2}{\Lambda_D^2 - t} \right)$$

where

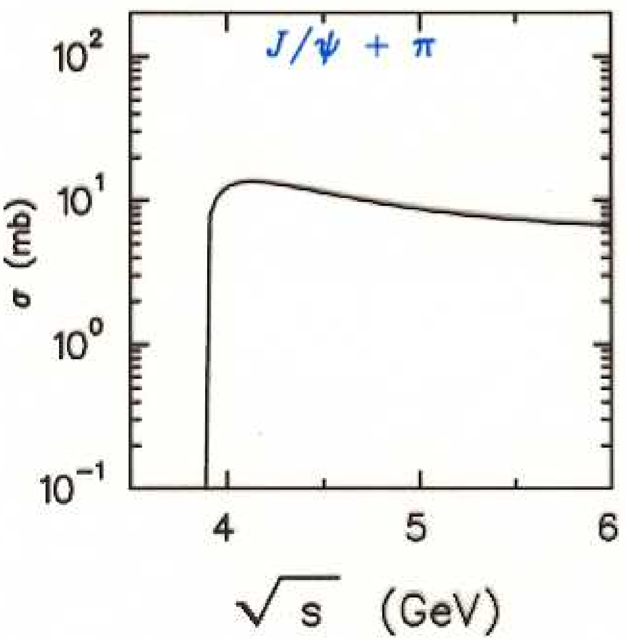
$$\Lambda_D = 3.5 \text{ GeV}$$

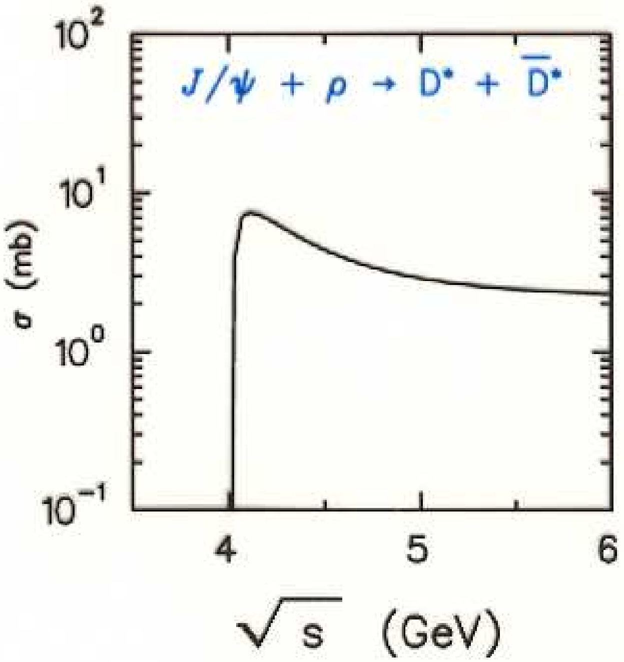
$$g_{DD\rho} = 4.4$$

$$g_{D^*D\pi} = 6.5$$

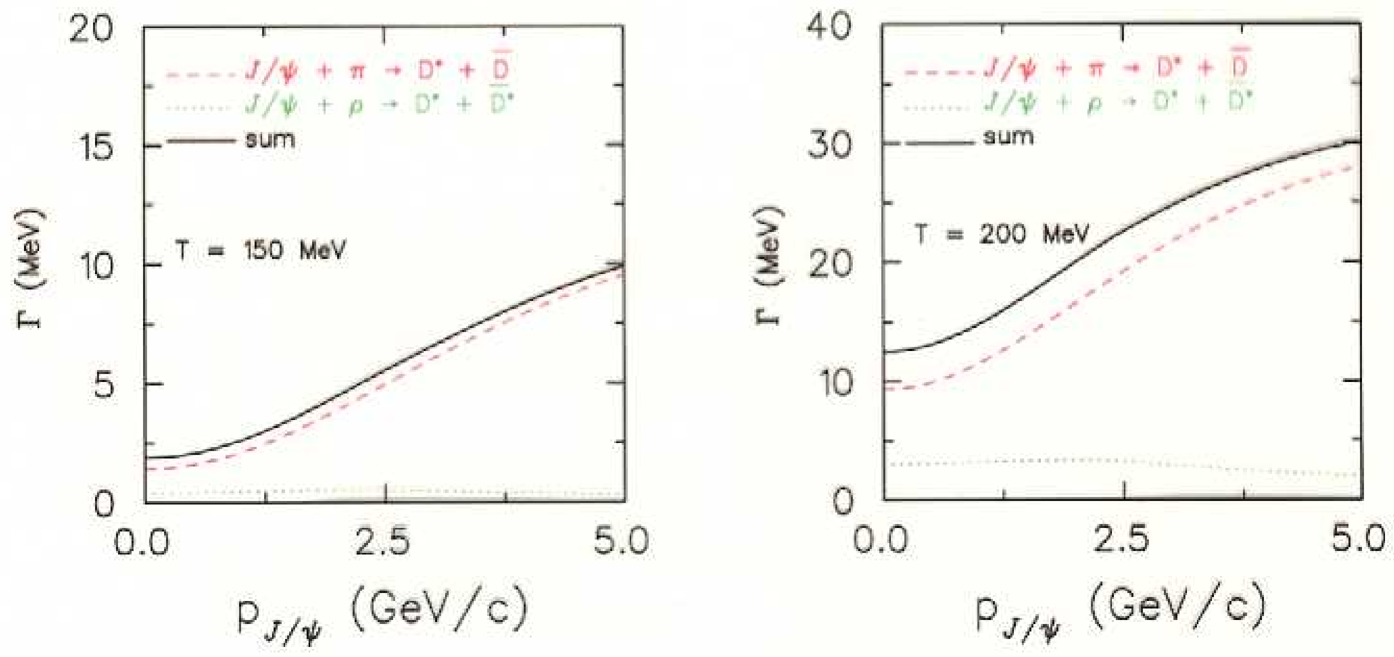
$$g_{DDJ/\psi} = 16.4$$

Revised Cross Sections





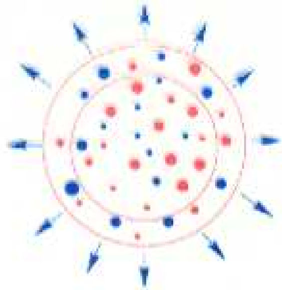
Revised Breakup Rate

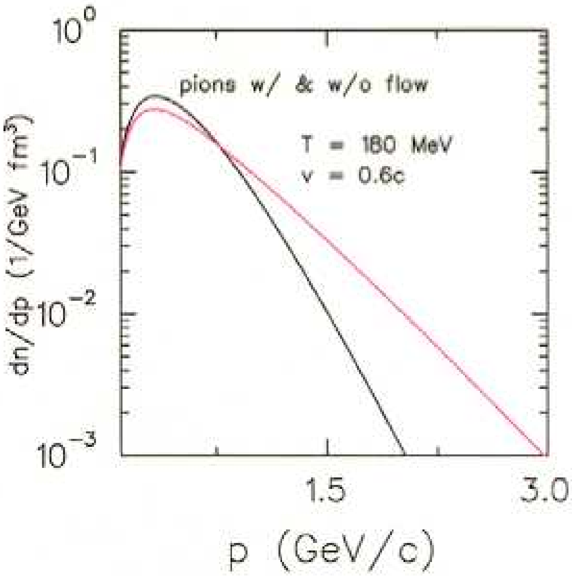


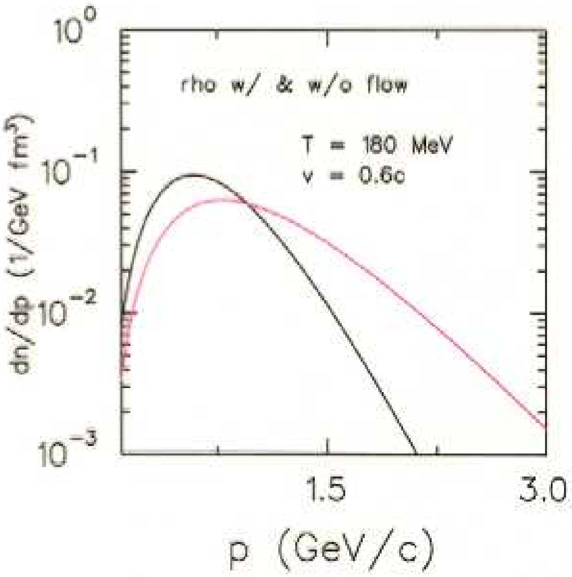
Fireball with radial flow

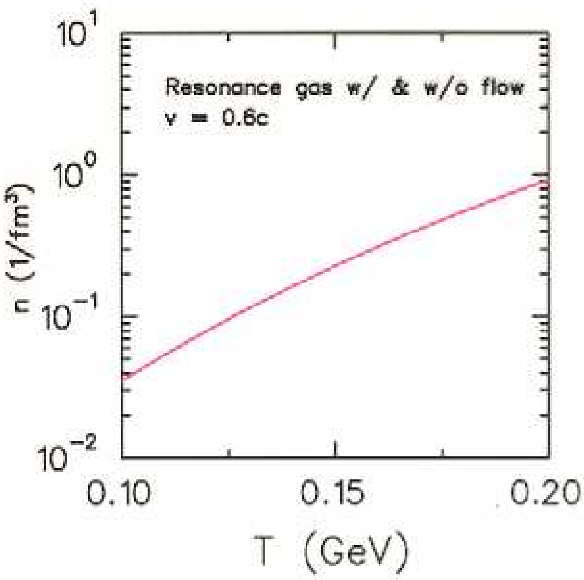
$$dn = \frac{d^3p}{p_0}\left(p\cdot U\right) f_{eq}\left(p\cdot U\right)$$

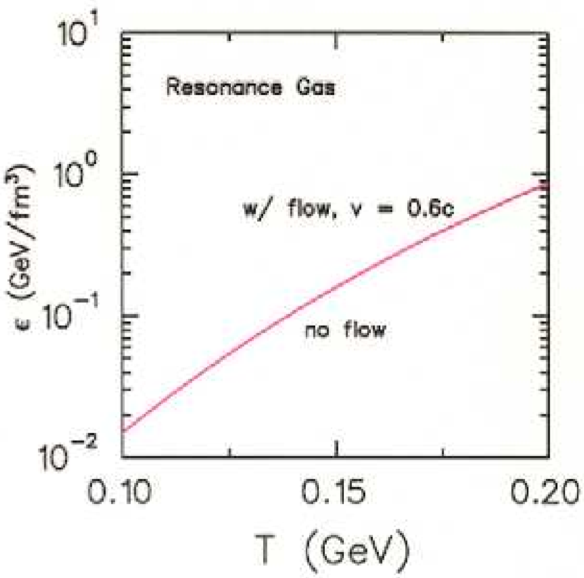
$$d\epsilon = \frac{d^3p}{p_0}\left(p\cdot U\right)^2 f_{eq}\left(p\cdot U\right)$$





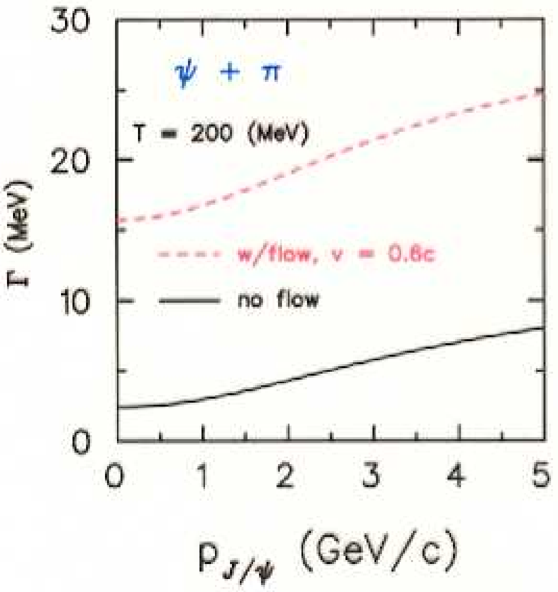


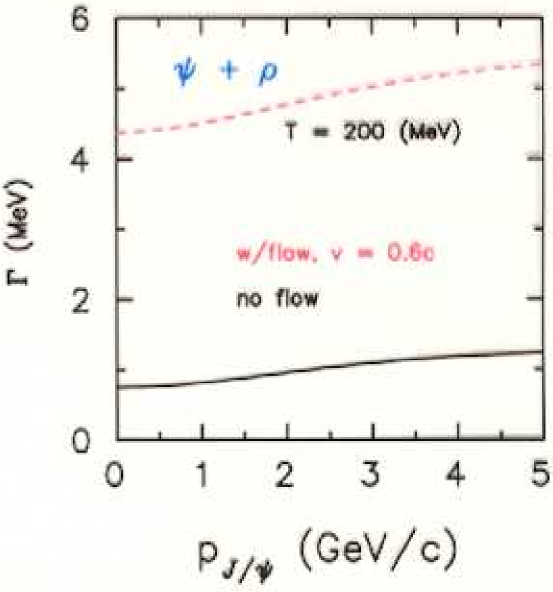




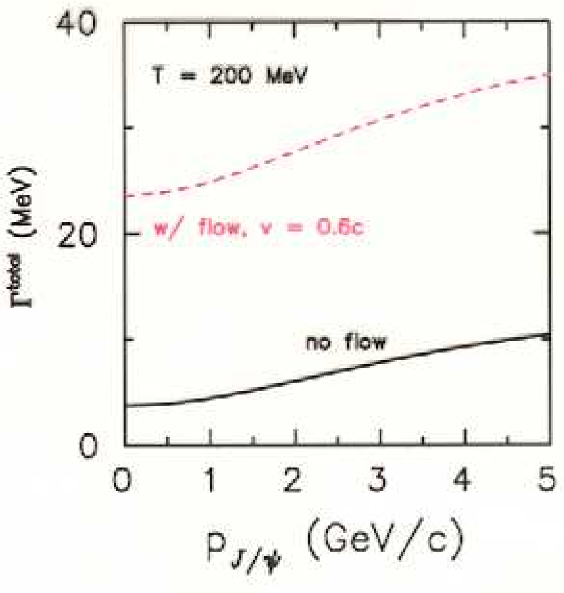
Effect on J/ψ dissociation...

K.H., nucl-th/0205049





Sum over pions, kaons, rho and K*



Summary & Conclusions

- Cross sections are all energy-dependent
- Lorentz- and gauge-invariant form factors constrained by data & QCD sum rule calculations
- QCD sum-rule form factors allow possibly large cross sections
- Lifetime of the J/ψ is shortened by hadronic interactions
- Flow could have an important effect on the picture!