(Some) Theoretical Aspects on Open Charm Spectroscopy and Production

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Content

Spectroscopy

- ✦ $c\bar{q}$ $c\bar{s}$
- ✦ **Hadron Molecule**
- ✦ **Tetraquark**

Production

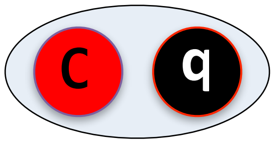
- ✦ **Approach for Molecule**
- ✦ **QCD factorization**
- ✦ **B decays**

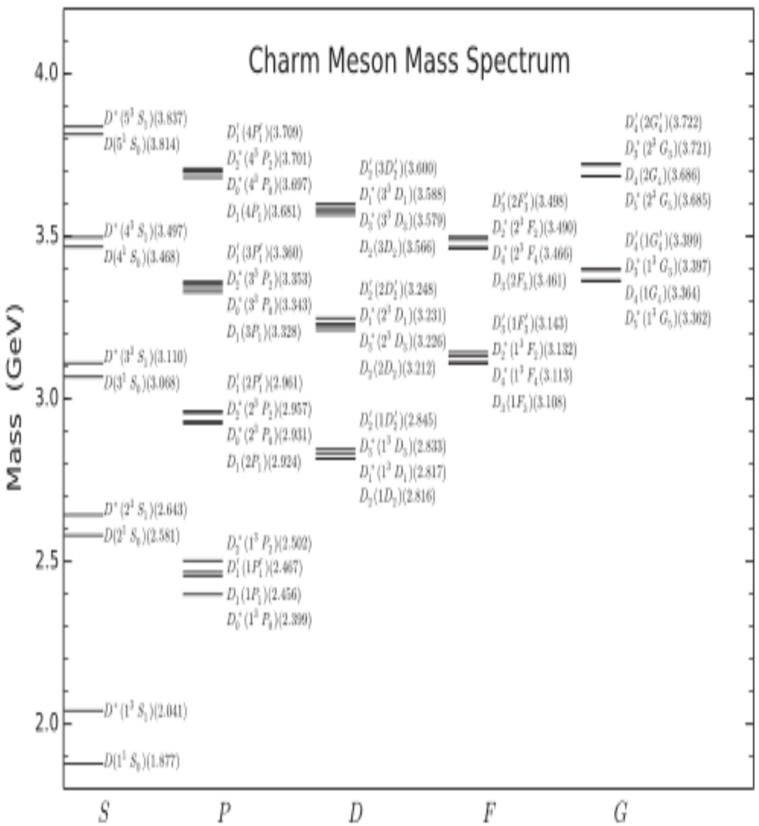
Open Charm Spectroscopy

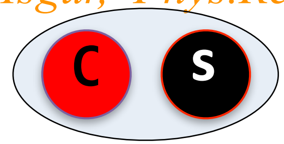
Open Charm Spectroscopy

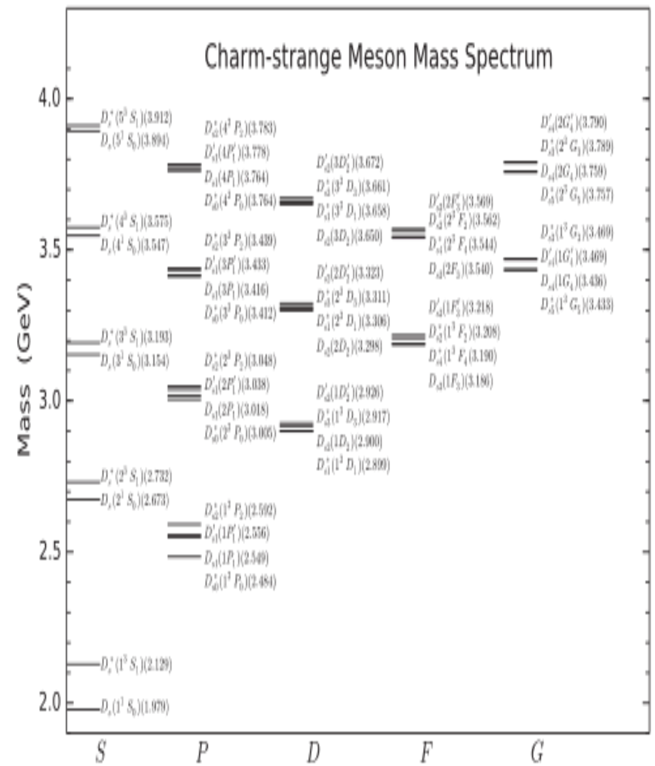
Quark model has predicted a number of states with different quantum numbers.

Godfrey & Isgur, Phys.Rev.D32,189(1985)









54 states

Charm Spectroscopy

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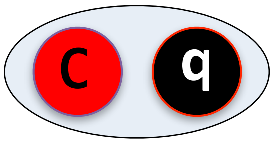

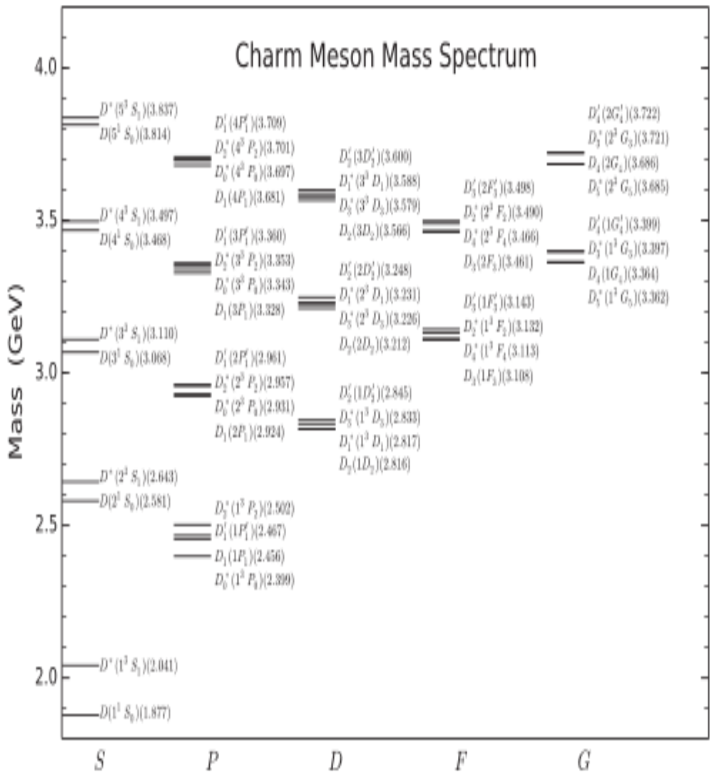

$n\ ^{2s+1}\ell_J$	J^{PC}	$\mathrm{I}=\frac{1}{2}$ $c\bar{u},\ c\bar{d};\ \bar{c}u,\ \bar{c}d$	$\mathrm{I}=0$ $c\bar{s};\ \bar{c}s$
$1\ ^1S_0$	0^{-+}	D	$D_s^{\pm}$
$1\ ^3S_1$	1^{--}	D^*	$D_s^{*\pm}$
$1\ ^1P_1$	1^{+-}	$D_1(2420)$	$D_{s1}(2536)^{\pm}$
$1\ ^3P_0$	0^{++}	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$
$1\ ^3P_1$	1^{++}	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$
$1\ ^3P_2$	2^{++}	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$
$1\ ^3D_1$	1^{--}		$D_{s1}^*(2860)^{\pm\ddagger}$
$1\ ^3D_3$	3^{--}		$D_{s3}^*(2860)^{\pm}$
$2\ ^1S_0$	0^{-+}	$D(2550)$	
$2\ ^3S_1$	1^{--}		$D_{s1}^*(2700)^{\pm\ddagger}$
$2\ ^1P_1$	1^{+-}		
$2\ ^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		
$3\ ^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		

Charm Spectroscopy

The relativized quark model has been used to derived their masses and wave functions.

They are used to calculate radiative transition partial widths and the $^3P_0$ quark-pair-creation model to calculate their strong decay widths.

PHYSICAL REVIEW D **93,** 034035 (2016)

Properties of excited charm and charm-strange mesons

Stephen Godfrey* and Kenneth Moats

We used our results to identify recently observed charm and charm-strange mesons in terms of quark model spectroscopic states. Our results support the previously made assignment of the $D_J(2550)^0$ and $D_J^*(2600)^0$ as the $2^1S_0(c\bar{q})$ and $2^3S_1(c\bar{q})$ states respectively. We identify the $D_1^*(2760)^0$ and $D_3^*(2760)^0$ as the $1^3D_1(c\bar{q})$ and $1^3D_3(c\bar{q})$ respectively and tentatively identify the $D_J(2750)^0$ as the $1D_2(c\bar{q})$ state. In the latter case further measurements are needed to strengthen the assignment. We suggested that measurements of BRs to $D\rho$ and $D^*\pi$ would be useful. We tentatively identified the $D_J^*(3000)^0$ as the $D_4^*(1^3F_4)$ state and favor the $D_J(3000)^0$ to be the $D(3^1S_0)$ although we do not rule out the $1F_3$ and $1F_3'$ assignments. For the recently observed charm-strange mesons we identify the $D_{s1}^*(2709)^\pm$, $D_{s1}^*(2860)^-$, and $D_{s3}^*(2860)^-$ as the $2^3S_1(c\bar{s})$, $1^3D_1(s\bar{c})$, and $1^3D_3(s\bar{c})$ respectively and suggest that the $D_{sJ}(3044)^\pm$ is most likely the $D_{s1}(2P_1')$ or $D_{s1}(2P_1)$ although it might be the $D_{s2}^*(2^3P_2)$ with the DK final state too small to be observed with current statistics.

Data Vs Quark Model

$n\,^{2s+1}\ell_J$	J^{PC}	$I=\frac{1}{2}$ $c\bar{u},\ c\bar{d};\ \bar{c}u,\ \bar{c}d$	$I=0$ $c\bar{s};\ \bar{c}s$
$1\,^1S_0$	0^{-+}	D	$D_s^{\pm}$
$1\,^3S_1$	1^{--}	D^*	$D_s^{*\pm}$
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$1\,^3P_0$	0^{++}	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$
$1\,^3P_1$	1^{++}	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$
$1\,^3P_2$	2^{++}	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$
$1\,^3D_1$	1^{--}		$D_{s1}^*(2860)^{\pm\ddagger}$
$1\,^3D_3$	3^{--}		$D_{s3}^*(2860)^{\pm}$
$2\,^1S_0$	0^{-+}	$D(2550)$	
$2\,^3S_1$	1^{--}		$D_{s1}^*(2700)^{\pm\ddagger}$
$2\,^1P_1$	1^{+-}		
$2\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		
$3\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		

$D_{s0}^{*}: 2484\,MeV$

$D_{s1}: 2549\,MeV$

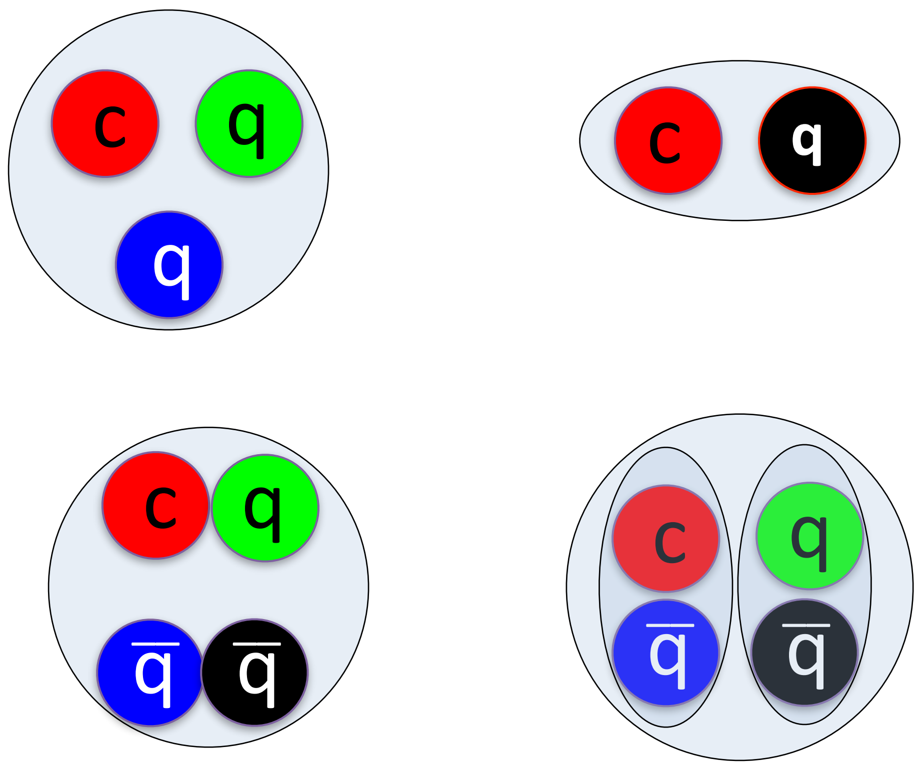
$\Gamma = 220\,MeV$

$\Gamma < 3.8\,MeV$

✓$D_{s0}(2317)$ and $D_{s1}(2460)$ are lighter and narrower than expected from quark models!

Hadron Exotics: Theory

QCD allows many possible color singlets:



Tetraquark **Hadron Molecule**

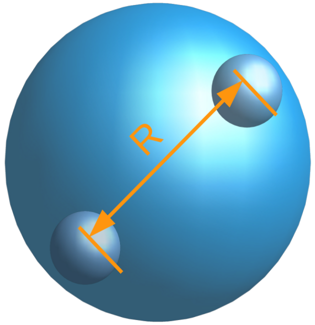
Hadron Molecule

- Hadronic molecule:
  the dominant component is 2 or more hadrons

Ds0(2317): DK; Ds1(2460): D*K

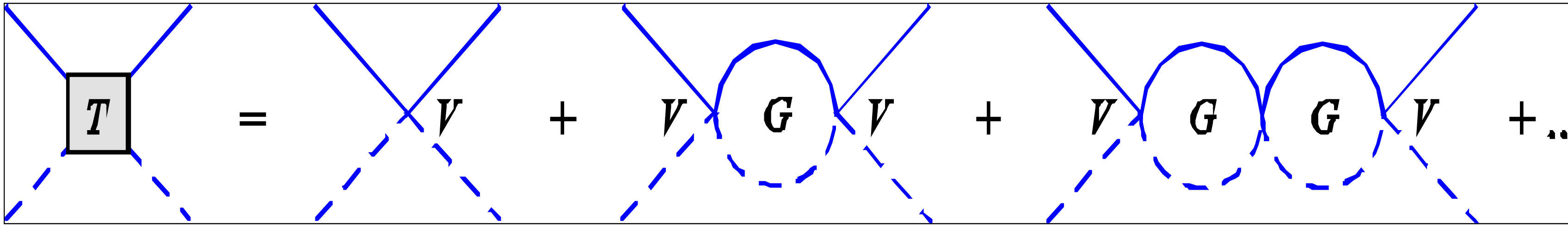
- Concept at large distances, so that can be approximated by system of multi-hadrons at low energies ➡hadron EFT
  Consider a 2-body bound state with a mass $M = m_1 + m_2 - E_B$

size: $$R \sim \frac{1}{p} \sim \frac{1}{\sqrt{2\mu E_B}} \gg r_{\text{hadron}}$$



- Only narrow hadrons can be considered as components of hadronic molecules,
  $\Gamma_h \ll 1/r$, r: range of forces

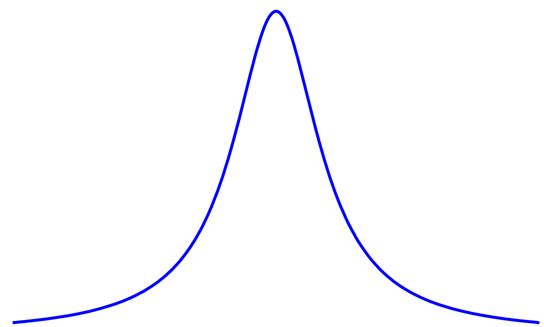
Hadron Molecule



Summing All order contributions:

$$V + VGV + VGVGV + \cdots = \frac{V}{1 - GV}$$

1-GV = 0



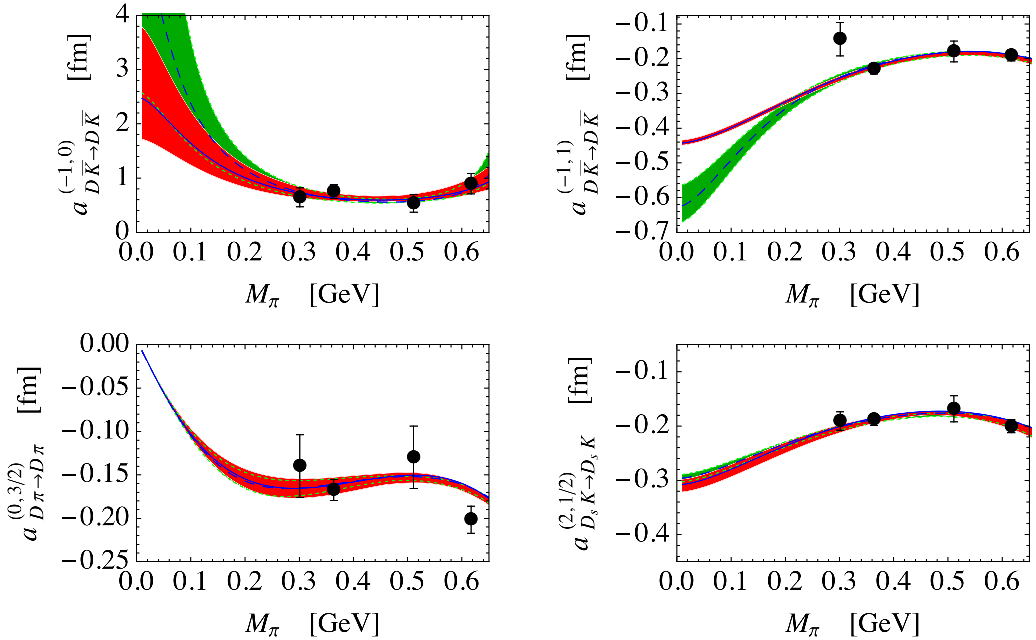
$s=s_0$

Mass pole corresponds to a resonance structure

→Hadron Molecule

Hadron Molecule

Hadron EFT can be used to study the DK scattering:



Yao, et al. 1502.05981

Graham Moir, Charmed Meson Scattering from Lattice QCD

S-wave

- Bound-state pole ≈ 2380 MeV ; ≈ 55 MeV below DK threshold (at $m_\pi = 391$)
- Expt. $D^*_{s0}(2317)$: 2317.7 ± 0.6 MeV ; ≈ 45 MeV below DK threshold

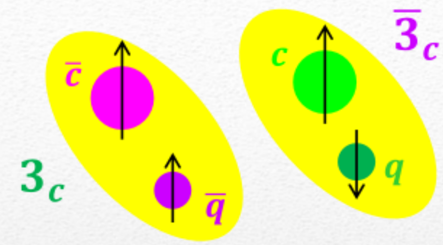
Tetraquark

A lot of versions for tetraquarks!

Tetraquark

In a constituent (di)quark model, we can think of a **diquark-antidiquark compact state**

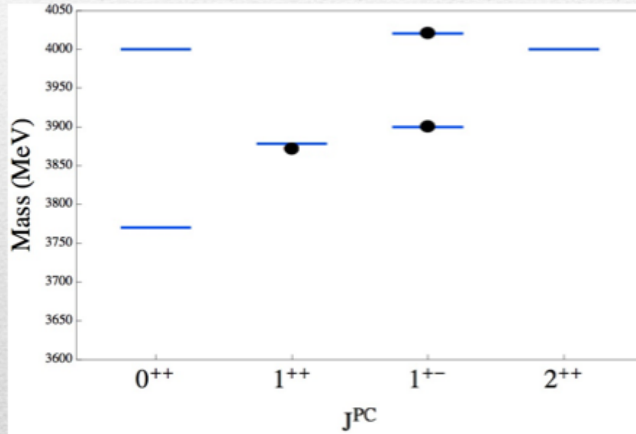
$$[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} + h.c.$$



Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to color-spin hamiltonian (all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

$$H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij} \vec{S_i} \cdot \vec{S_j} \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$

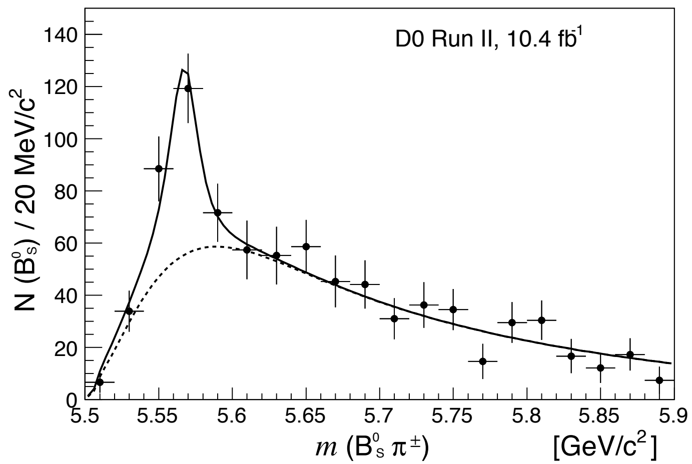


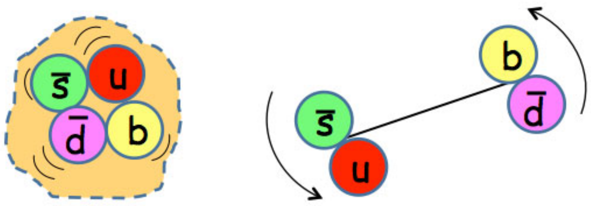
Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

New ansatz: the diquarks are compact objects spacially separated from each other, only $\kappa_{cq} \neq 0$

Existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

X(5568)





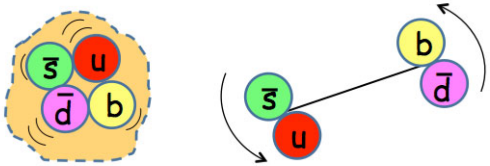
D0: 1602.07588

LHCb did not confirm, 1608.00435

How about charm sector?

Open Charm Tetraquarks

$$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{3} \oplus \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$$



Sextet:

$$m(X'_{ds\bar{u}}) = m(X'_{su\bar{d}}) = m(Y'_{(u\bar{u},d\bar{d})s}) = \begin{cases} 2.44\text{GeV}\ , & J^P = 0^+\ , \\ 2.48\text{GeV}\ , & J^P = 1^+\ , \end{cases}$$

$$m(X'_{ud\bar{s}}) = \begin{cases} 2.36\text{GeV}\ , & J^P = 0^+\ , \\ 2.41\text{GeV}\ , & J^P = 1^+\ , \end{cases}$$

$$m(Y'_{(u\bar{u},s\bar{s})d}) = m(Y'_{(d\bar{d},s\bar{s})u}) = \begin{cases} 2.40\text{GeV}\ , & J^P = 0^+\ , \\ 2.45\text{GeV}\ , & J^P = 1^+\ . \end{cases}$$

He, WW, Zhu, 1606.00097

15-plet:

$$m(X_{ds\bar{u}}) = m(X_{su\bar{d}}) = m(Y_{\pi s}) = \begin{cases} 2.47\text{GeV}\ , & J^P = 0^+\ , \\ 2.51\text{GeV}, 2.60\text{GeV}\ , & J^P = 1^+\ , \\ 2.67\text{GeV}\ , & J^P = 2^+\ , \end{cases}$$

$$m(X_{ud\bar{s}}) = m(Z_{uu\bar{s}}) = m(Z_{dd\bar{s}}) = \begin{cases} 2.49\text{GeV}\ , & J^P = 0^+\ , \\ 2.52\text{GeV}, 2.61\text{GeV}\ , & J^P = 1^+\ , \\ 2.69\text{GeV}\ , & J^P = 2^+\ , \end{cases}$$

All can be produced in B decays!!

Open Charm Production

Andrea Beraudo
Open charm physics with Heavy Ions: theoretical overview

In the past charm conferences,
there are rare theoretical talks on open charm productions.

In the past charm conferences,
there are rare theoretical talks on open charm productions.

➡The production is not interesting/ important?

➡The production mechanism is too simple for every participant?

➡The production mechanism is too difficult?

Is the production interesting/important? Yes!

Experimental talks:

- *Achim Geiser,Charm production at HERA, proton structure, the charm mass, and Higgs Yukawa couplings*
- *Bilas Pal,Open charm Production and Spectroscopy at B-factories*
- *George Wei-Shu Hou, Open charm production and spectroscopy at ATLAS and CMS*
- *Patrick Spradlin,Open charm production and spectroscopy at LHCb*
- …

Production

The production mechanism is too simple for every participant?

Production

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A few simplest example:

$pp \to D_{s0}^*(2317)$

$e^+e^- \to D_s D_{s0}^*(2317)$

Production

The production mechanism is too simple for every participant?

A few simplest example:

pp -> D_{s0}*(2317)

$pp \to J/\psi$

$e^+e^- \to \rho\pi$

e^+e^-->$D_s D_{s0}$*(2317)

$e^+e^- \to J/\psi\eta_c$

SCET

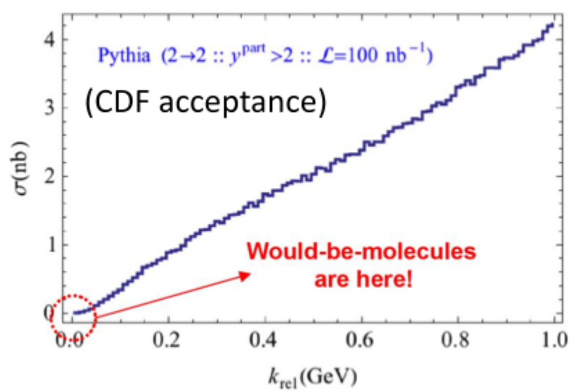
???

NRQCD

Hadron Molecule Production

Prompt production of $X(3872)$

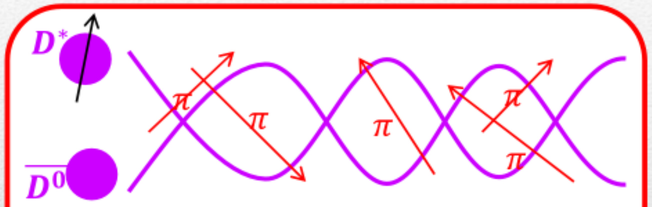
$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders



$$\sigma_{MC}(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1 \text{ nb}$$

$$\sigma_{exp}(p\bar{p} \to X(3872)) \approx 30 - 70 \text{ nb!!!}$$

Bignamini *et al.* PRL103 (2009) 162001



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi$, $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with DD^* propagation. Estimating the effect of these pions increases σ, but not enough

Bignamini *et al.* PLB684, 228-230
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

A key assumption:

$$\sigma(p\bar{p} \to X(3872)) \leq \int_R d^3k \,|< DD^*(k) \,|\, p\bar{p} >|^2$$

Production rate of X(3872) is equivalent to production rate of the DD in limited phase space*

Local Constituent-Molecule Duality

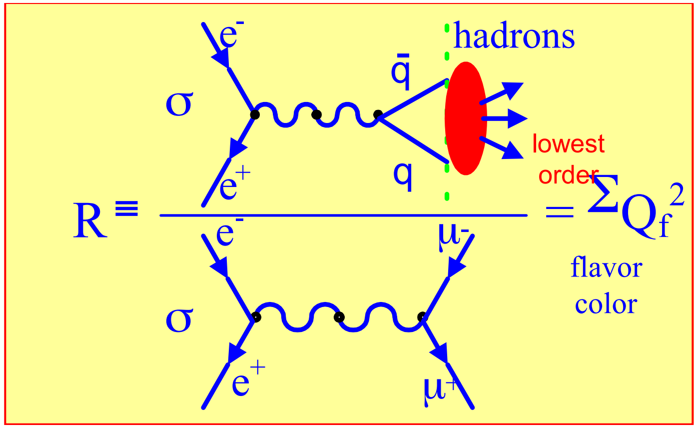
Local Quark-Hadron Duality

Production rate of a hadron is equivalent to that of quark pairs

The Born cross section of e^+e^- annihilation into hadrons normalized by theoretical $\mu^+\mu^-$ cross section.

$$R = \frac{\sigma^0_{had}(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma^0_{\mu\mu}(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

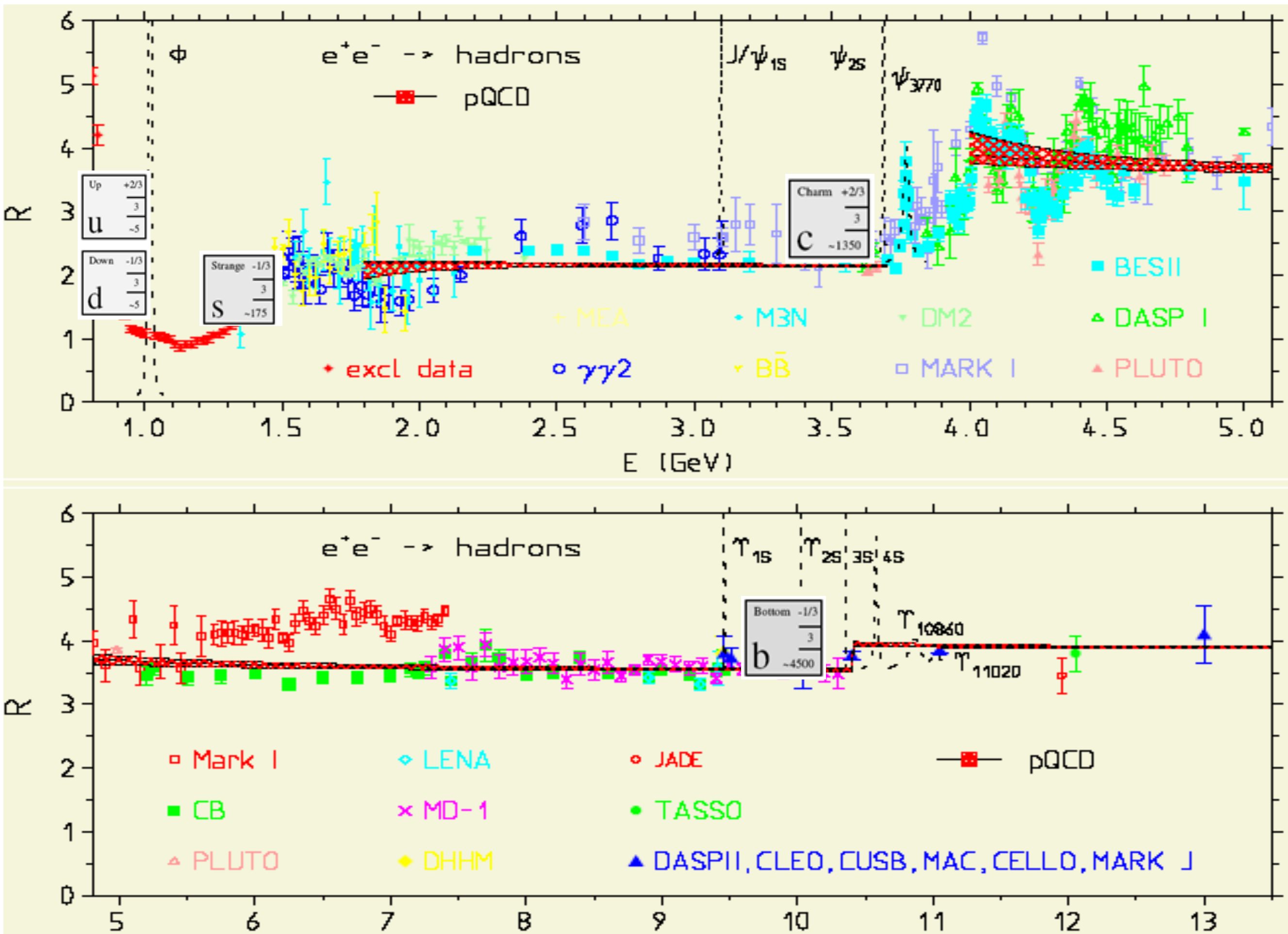
R value



$$= \begin{cases} 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2 \\ 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = \frac{11}{3} \end{cases}$$

R value

$$R = 3\sum_f Q_f^2[1 + (\frac{\alpha_s(s)}{\pi}) + 1.411(\frac{\alpha_s(s)}{\pi})^2 - 12.8(\frac{\alpha_s(s)}{\pi})^3 + ...]$$



See Xiaoyan Shen's talk on BES-III

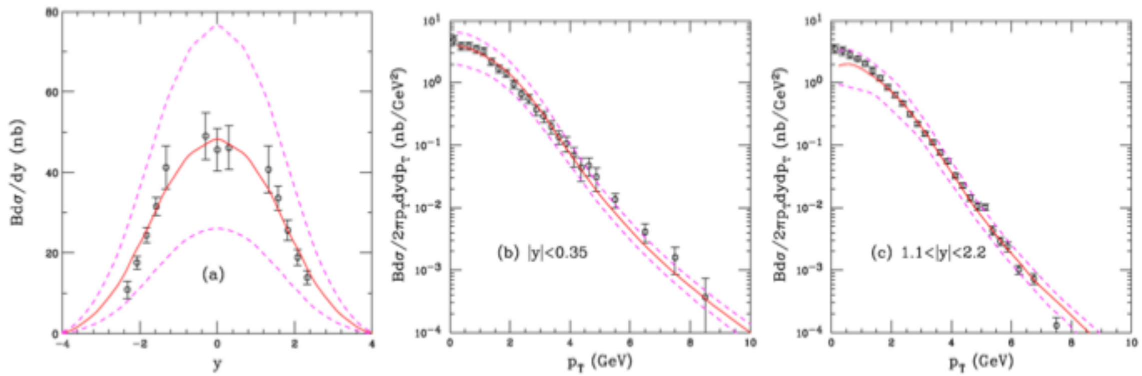
Color Evaporation Model

- Fritsch (1977); Halzen (1977); Glück, Owens, Reya (1978):

$$\sigma = F_H \int_{(2m_c)^2}^{(2m_D)^2} dm^2 \frac{d\sigma_{c\bar{c}}}{dm^2_{c\bar{c}}}$$

- Consider **open $c+\bar{c}$** production, regardless of $c+\bar{c}$ color, spin, momenta.
- Integrate over invariant $c+\bar{c}$ mass up to formation of next heavier meson pair.
- F_H: Number describing formation of quarkonium H by color "evaporation".
- Qualitative picture rather than rigorous theory.

CEM Predictions For RHIC data [Nelson, Voigt, Frawley (2013)]:



For X(3872), this amounts to adjust the phase-space cutoff

Artoisenet, Braaten, 0911.2016;1007.2868

NRQCD

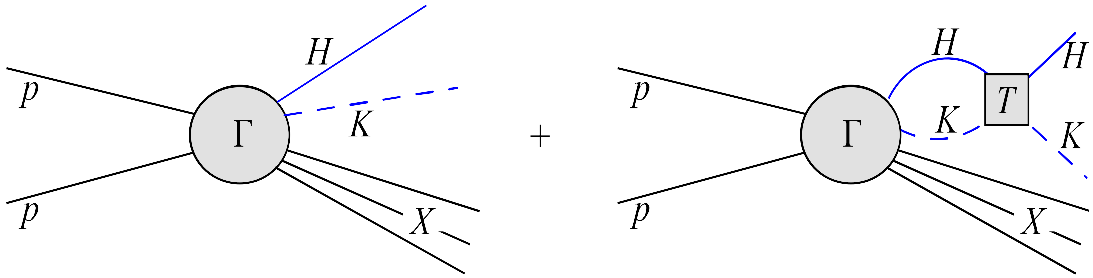
Bodwin, Braaten, Lepage, Brambilla, et al.

$$\sigma(H) = \sum_n F_n(\Lambda) \langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle .$$

$$\mathcal{O}_n^H(\Lambda) = \langle 0 | \chi^\dagger \kappa_n \psi \Big(\sum_X | H + X \rangle \langle H + X | \Big) \psi^\dagger \kappa'_n \chi | 0 \rangle$$

Hadron Level EFT

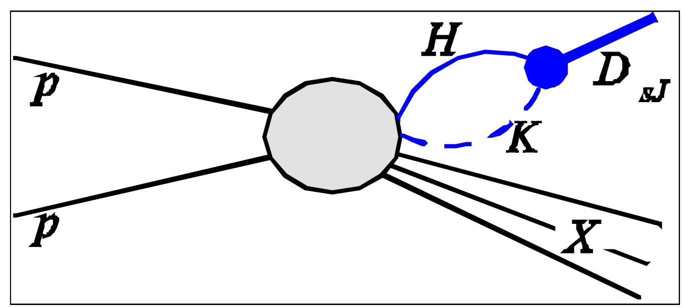
$$\sigma(D_{s0}) \sim \sigma(DK) | < D_{s0} | DK | 0 > |^2$$



$$\Gamma + \Gamma G V + \Gamma G V G V + \ldots = \Gamma / (1 - G V)$$

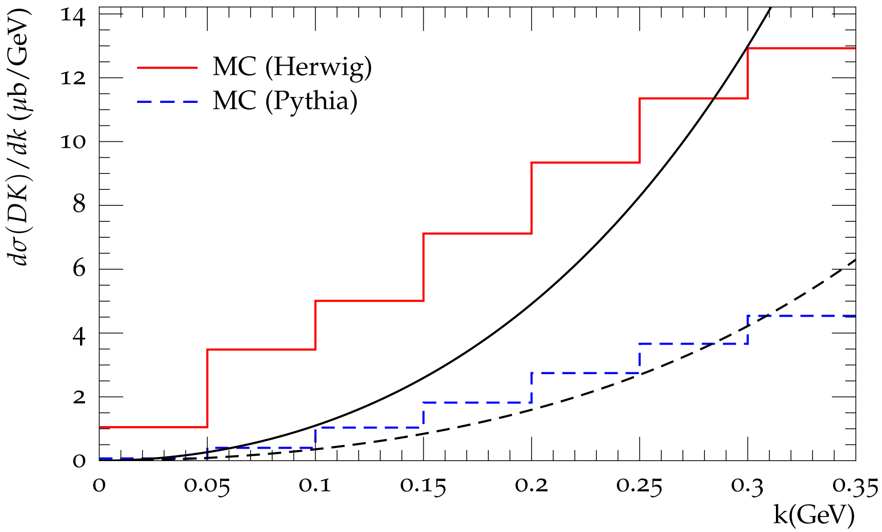
Γ is tree-level amplitude

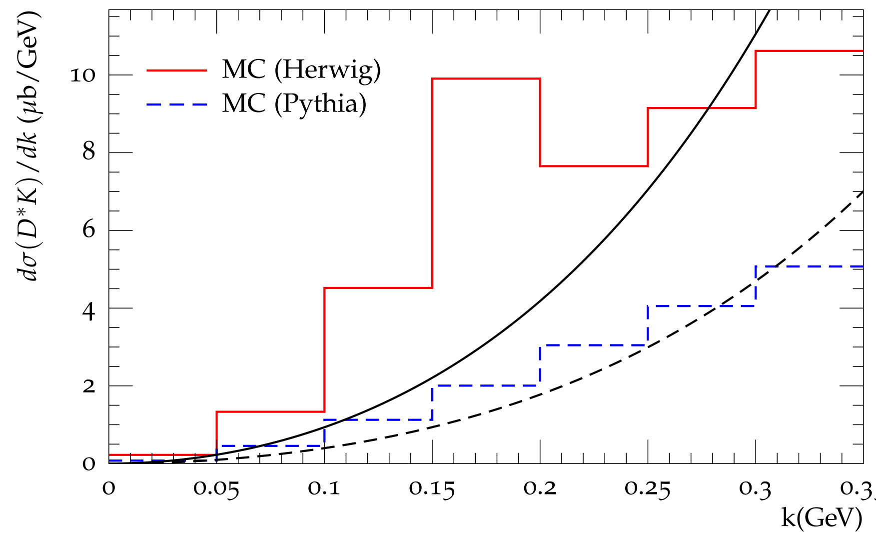
$$1 - GV = 0$$



Herwig/Pythia: **simulate production rates of constituents**

Hadron Molecule Production at Hadron Collider



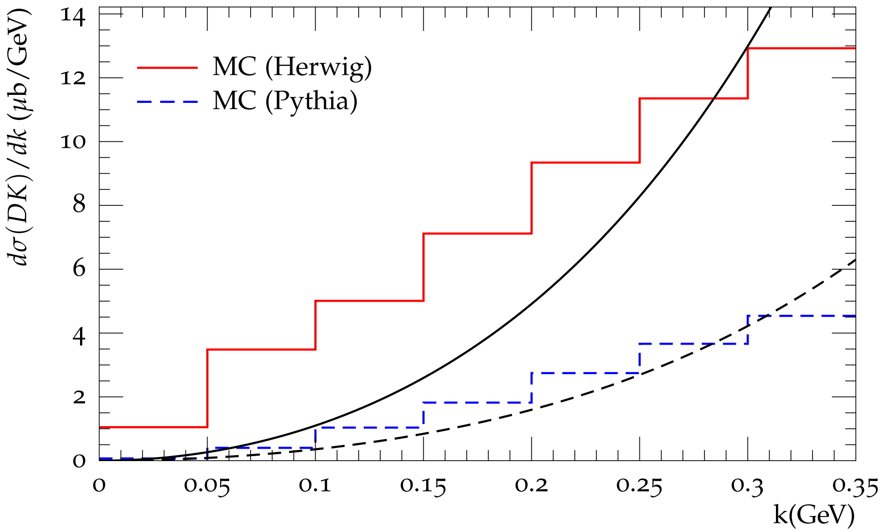


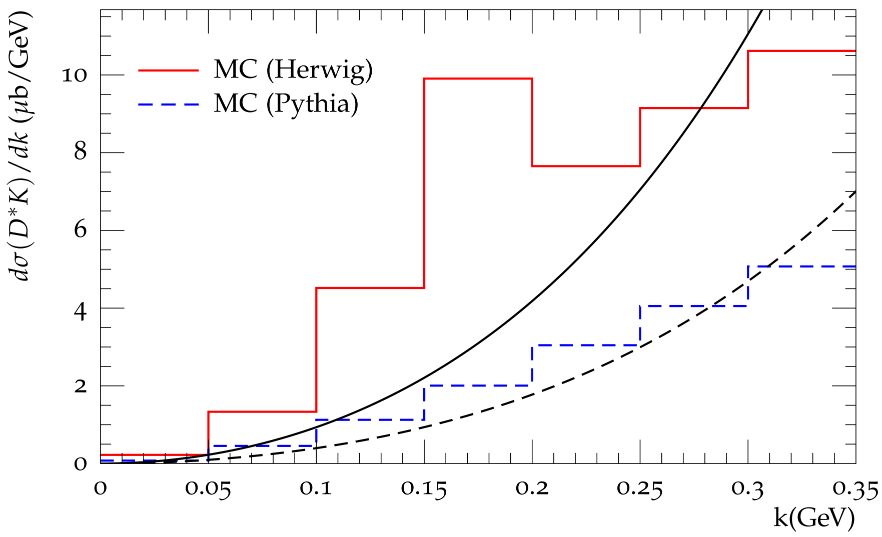
	$D_{s0}^*(2317)$	$D_{s1}(2460)$	$D_{sJ}(2860)$	$D_{s2}(2910)$
LHC 7	2.5(0.83)	2.1(0.91)	0.21(-)	0.27(-)
LHCb 7	0.61(0.15)	0.5(0.17)	0.05(-)	0.06(-)
LHC 8	2.9(0.94)	2.4(1.0)	0.24(-)	0.32(-)
LHCb 8	0.74(0.18)	0.61(0.2)	0.06(-)	0.08(-)
LHC 14	5.5(1.6)	4.7(1.7)	0.5(-)	0.65(-)
LHCb 14	1.6(0.35)	1.3(0.38)	0.13(-)	0.17(-)

Table 2. Integrated normalized cross sections (in units of μb) for the inclusive processes $pp \to D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{sJ}(2860)$ and $D_{s2}(2910)$ at LHC. The results outside (inside) brackets are obtained using Herwig (Pythia). Here the rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS), while the rapidity range $2.0 < y < 4.5$ is used for the LHCb.

Guo, Meissner, WW, Yang, 1403.4032

Hadron Molecule Production at Hadron Collider



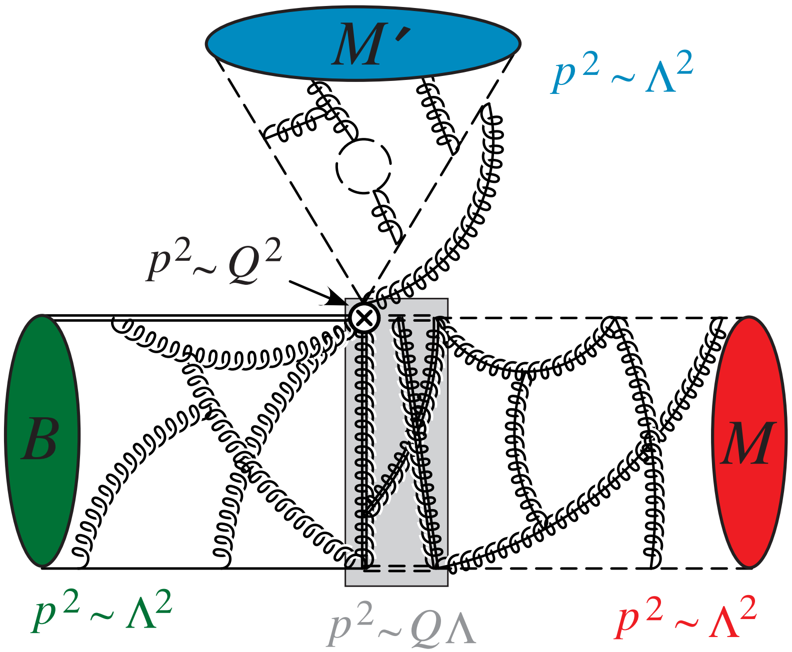


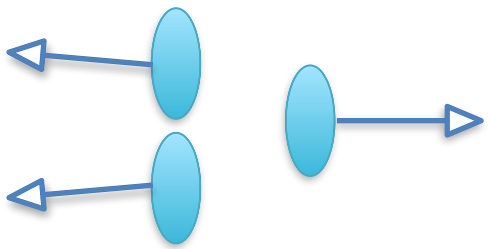
$\sigma(pp/p\bar{p} \to X(3872))$	Reference [16]	Reference [18]	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	Experiment
Tevatron	<0.085	1.5–23	10 (7)	47 (33)	37–115 [43]
LHC7	–	45–100[a]	16 (7)	72 (32)	13–39 [6]

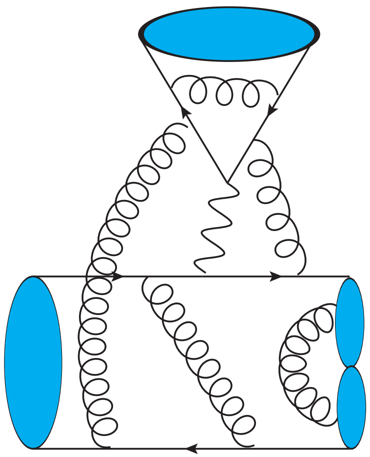
[a] Estimate based on non-relativistic QCD

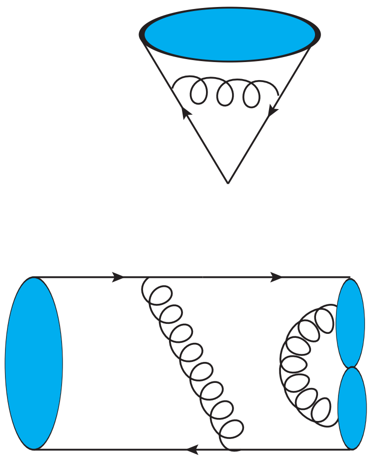
Guo, Meissner, WW, Yang, 1402.6236

B decays









Generalized Form factors in LCSR

$$\langle (K\pi)_0(p_{K\pi})|\bar s\gamma_\mu\gamma_5 b|\overline{B}(p_B)\rangle = -i\frac{1}{m_{K\pi}}\left\{\left[P_\mu - \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\right]\mathcal{F}_1^{B\to K\pi}(m_{K\pi}^2,q^2) + \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\mathcal{F}_0^{B\to K\pi}(m_{K\pi}^2,q^2)\right\},$$

$$\langle (K\pi)_0(p_{K\pi})|\bar s\sigma_{\mu\nu}q^\nu\gamma_5 b|\overline{B}(p_B)\rangle = -\frac{\mathcal{F}_T^{B\to K\pi}(m_{K\pi}^2,q^2)}{m_{K\pi}(m_B+m_{K\pi})}[q^2P_\mu - (m_B^2-m_{K\pi}^2)q_\mu],$$

Consider a generic correlation function

$$\Pi(p_{K\pi},q) = i\int d^4x\, e^{iq\cdot x}\langle (K\pi)_0(p_{K\pi})|\mathrm{T}\{j_{\Gamma_1}(x), j_{\Gamma_2}(0)\}|0\rangle$$

Hadron level:

$$\frac{\langle (K\pi)_0(p_{K\pi})|j_{\Gamma_1}|\overline{B}(p_{K\pi}+q)\rangle\langle \overline{B}(p_{K\pi}+q)|j_{\Gamma_2}|0\rangle}{m_B^2-(p_{K\pi}+q)^2} + \int_{s_0}^{\infty} ds\frac{\rho^h(s,q^2)}{s-(p_{K\pi}+q)^2},$$

↔ **Quark Hadron Duality** ↔

Quark level: Light cone OPE

$$\langle (K\pi)_0|\bar s(x)\gamma_\mu d(0)|0\rangle$$

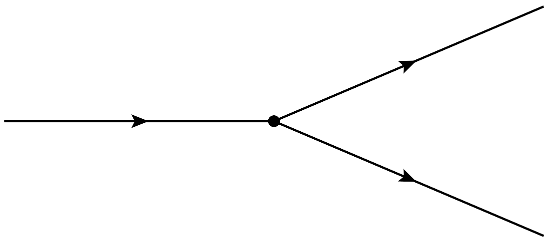
$$\langle (K\pi)_0|\bar s(x) d(0)|0\rangle$$

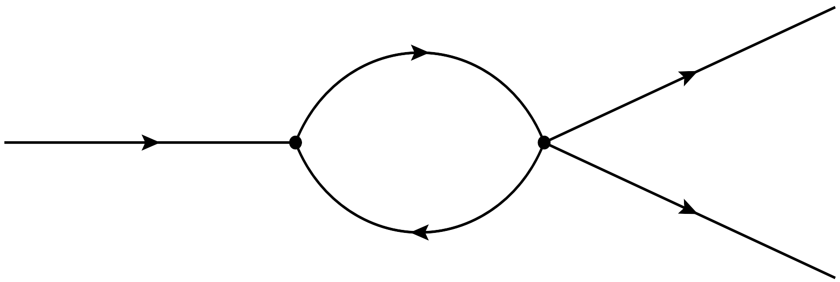
$$\langle (K\pi)_0|\bar s(x)\sigma_{\mu\nu} d(0)|0\rangle$$

Meissner, WW, 1312.3087

Scalar form factors

$$\langle 0|\bar{s}d|K\pi\rangle = C_X B_0 F_{K\pi}(m_{K\pi}^2)$$



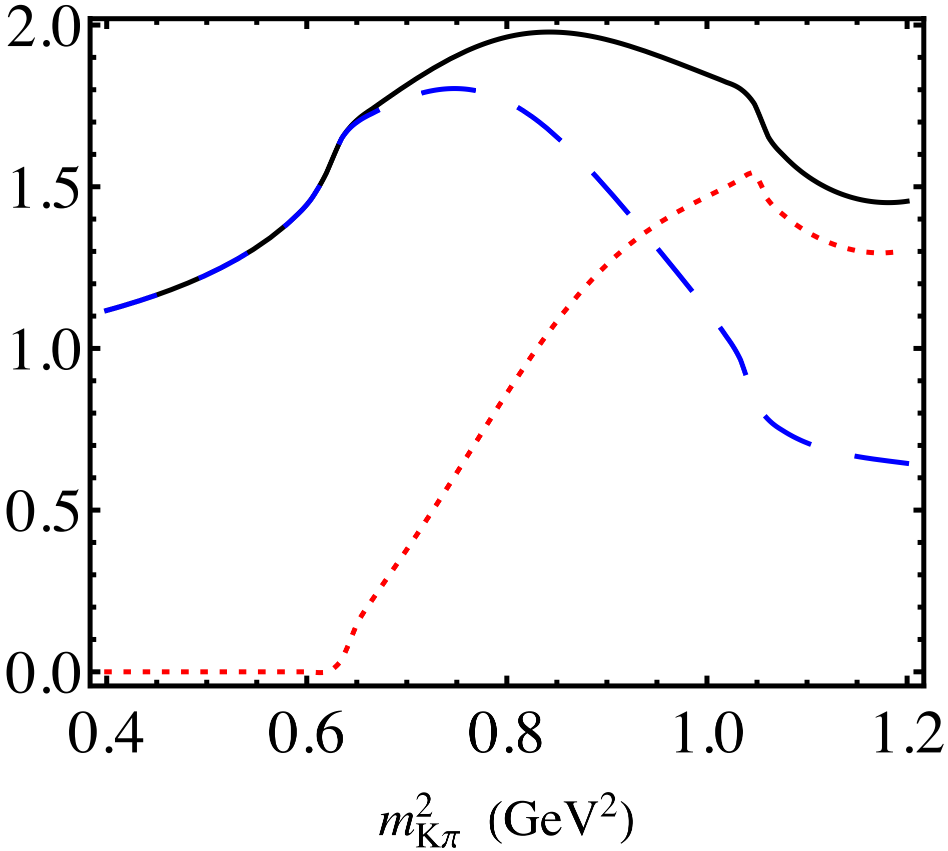


In elastic region:

$$\text{Im}[F] = F\ \sigma_i\ T^*$$

F and T carry the same strong phase!

Scalar form factors in χPT



$$\langle 0|\bar{s}d|K\pi\rangle = C_X B_0 F_{K\pi}(m^2_{K\pi})$$

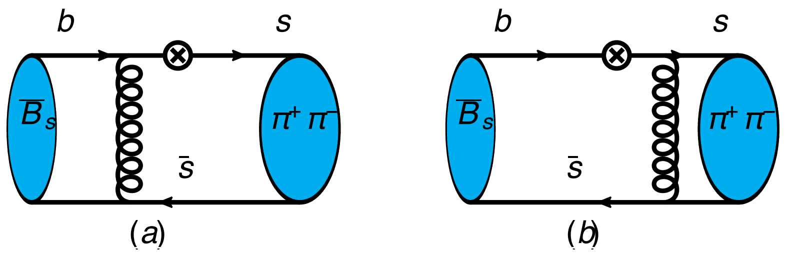
twice-subtracted Omnes solution matched onto χPT

Imaginary part
Real part
Magnitude

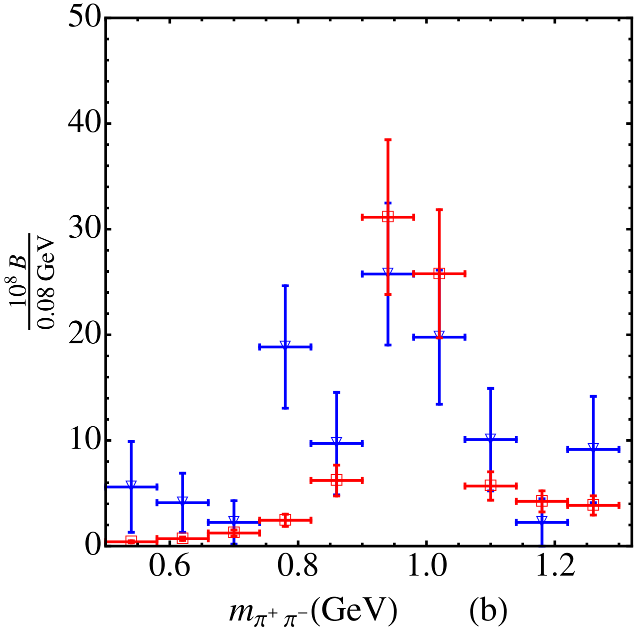
Meissner, WW, 1312.3087

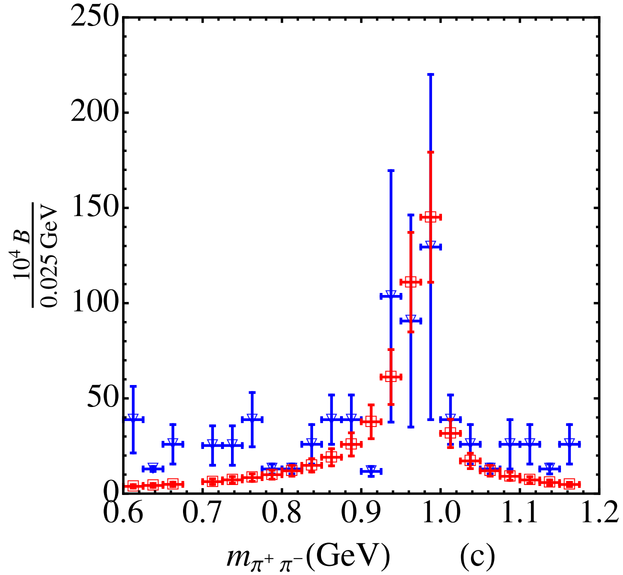
It simultaneously combines the perturbation theory at the m_b scale based on the operator product expansion and the low-energy effective theory inspired by the chiral symmetry to describe the S-wave ππ and Kπ scattering.

$B_s \to \pi^+\pi^-\mu^+\mu^-$ & $D_s \to \pi^+\pi^- e\nu$



Y.J. Shi, WW, 1507.07692





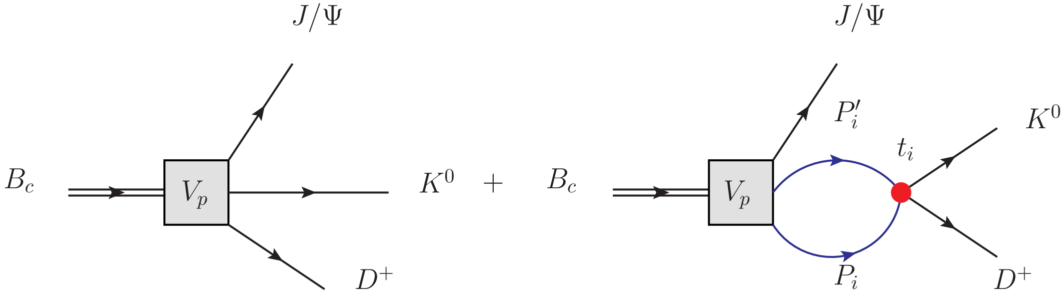
$B_s \to \pi^+\pi^-\mu^+\mu^-$ LHCb:1412.6433

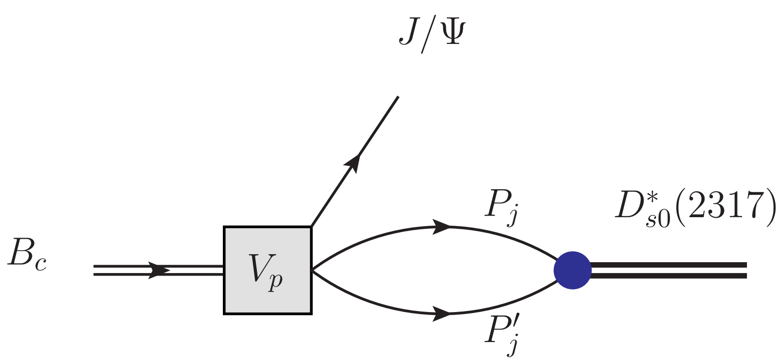
$D_s \to \pi^+\pi^- e\nu$ CLEO:0907.3201

BES-III & Belle-II?

B decays into $D_{s0}(2317)$

Miguel Albaladejo, Marina Nielsen, Eulogio Oset, 1501.03455
F. S. Navarra, M. Nielsen, E. Oset, T. Sekihara,1501.03422
Sun, Bayar, Fernandez-Soler, Oset, 1510.06316





➡$e^+e^- \rightarrow D_{s0}(2317)\ D_s$ at Belle-II?

Summary

Open Charm Spectroscopy

- ➢ Quark Model
- ➢ Hadron Molecule
- ➢ Tetraquark

Production

- ➢Hadron Level Approach
- ➢QCD factorization
- ➢B decays

Apologize for a lot others not covered here

Many thanks for your attention!