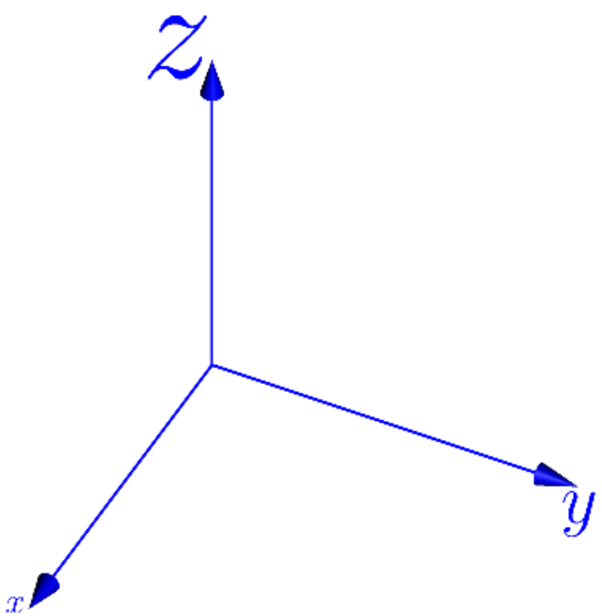
(Some) Theoretical Aspects on Production of Hadron Exotics



Wei Wang

Shanghai JiaoTong University

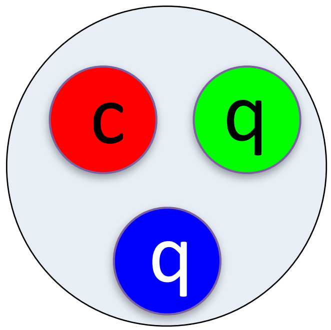
4th Workshop on XYZ particles

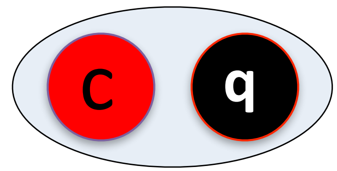
Beihang University

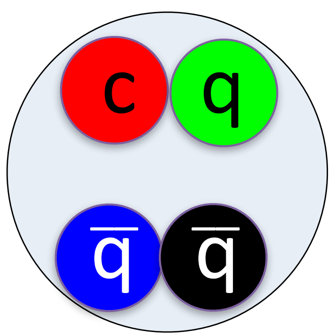
November 25, Beijing

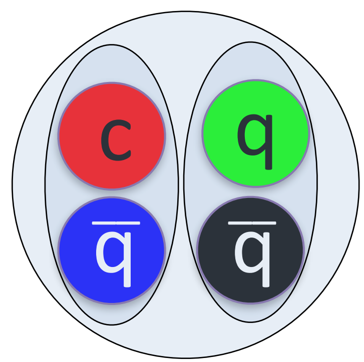
Hadron Exotics: Theory

QCD allows many possible color singlets:









Tetraquark **Hadron Molecule**

Many
Many
Important
Discoveries

MANCHESTER 1824
The University of Manchester

Echoes from the past

A: I would think it worthwhile to study the spectroscopy, decay modes, and production mechanisms of the charmed particles, assuming their masses are within reach at Fermilab, Super CERN and ISR, or at the next generation of accelerators like PEP, etc., even though I personally am not convinced of their existence.

B: Thanks, that's precisely what I am working on now.[2]

From a fictitious dialogue between two researchers
—an enthusiast and a devil's advocate.
(Gaillard, Lee, Rosner 1975)

Plädoyer für Super-CERN

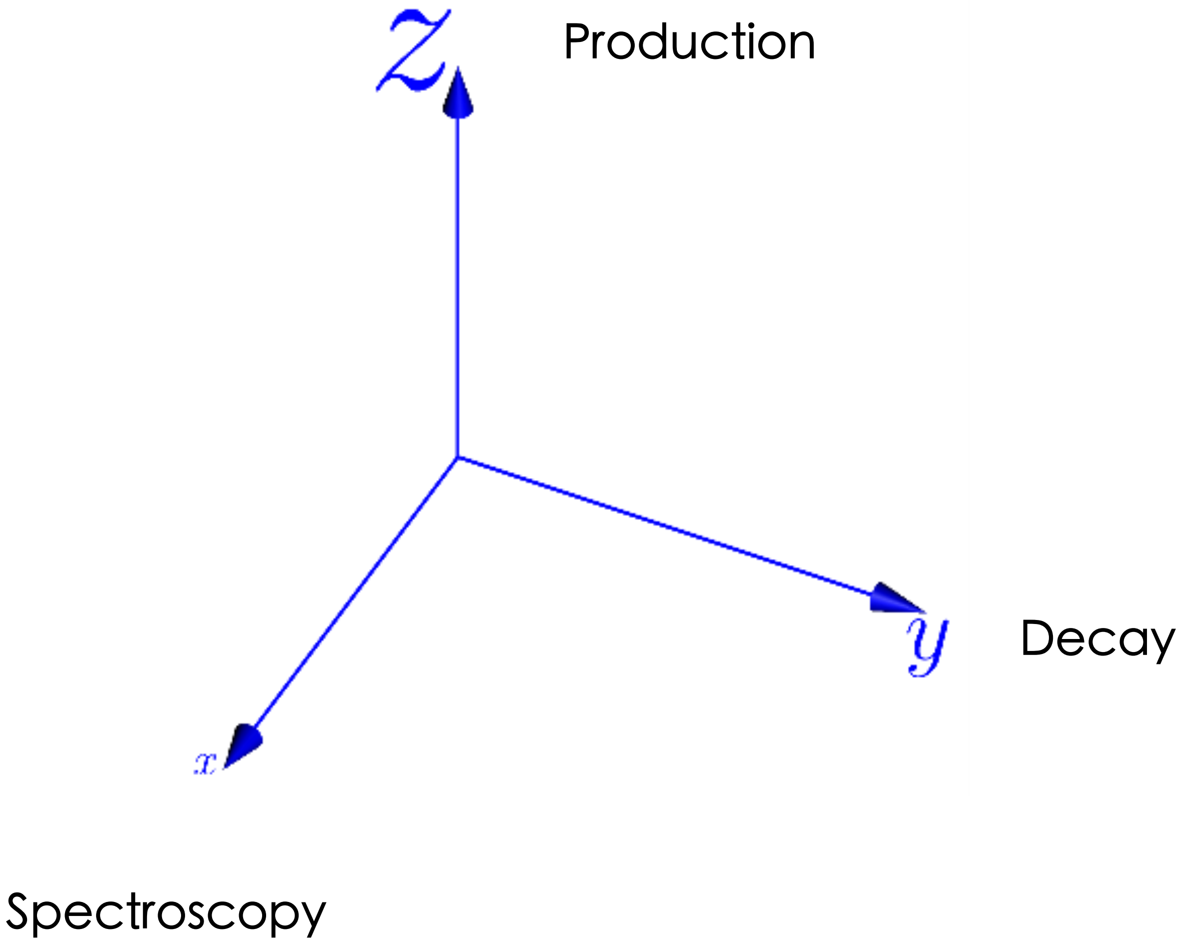
Wer bezahlt den neuen Beschleuniger?

4. Dezember 1970, 7:00 Uhr DIE ZEIT

NOVEMBER 1, 2015 · 7:57 AM exopolitikschweiz

China baut ein Super-CERN

27



z
Production
y
Decay
x
Spectroscopy

1. Production of the Exotic Hadrons $\phi(2170)$, X(4260) and $Y_b(10890)$ at the LHC and Tevatron via the Drell-Yan Mechanism
A Ali, **W.Wang**, Phys.Rev.Lett., 106, 192001(2011)

2. Hadroproduction of Y(nS) above $B\bar{B}$ Thresholds and Implications for the Yb(10890)
A.Ali, C. Hambrock, **W.Wang**, Phys.Rev.D 88, 054026(2013)

3. Production of charged heavy quarkonium-like states at the LHC and the Tevatron
F.K. Guo, U.G. Meißner, **W. Wang**, Com.Theor.Phys. 61,353 (2014)

4. Production of charm-strange hadronic molecules at the LHC
F.K. Guo, U.G. Meißner **W.Wang**, Z.Yang, JHEP 1405, 138(2014)

5. Production of the bottom analogues and the spin partner of the X(3872) at hadron colliders, F.K. Guo, U.G. Meißner **W.Wang**, Z.Yang, EPJC 74, 3063(2014)

6. Decipher the short-distance component of $X(3872)$ in B_c decays
W.Wang, Q.Zhao, Phys.Lett., B 755, 261 (2016)

7. On the constituent counting rules for hard exclusive processes involvingmultiquark states, F.K. Guo, U.G. Meißner **W.Wang**, 1607.04020

- Hadron Level EFT

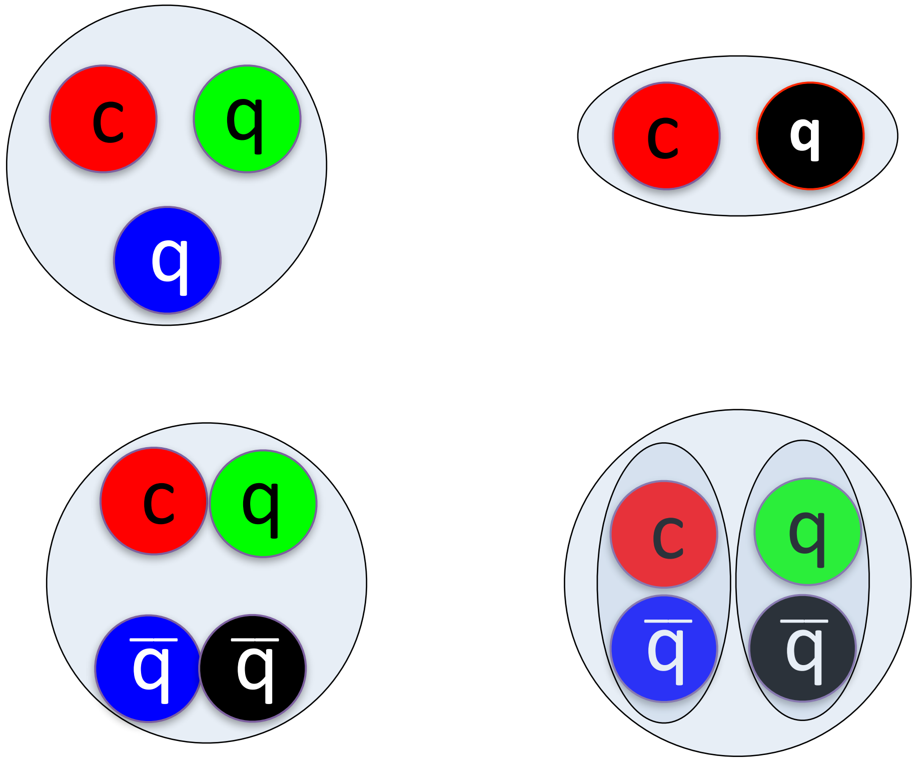
- QCD Analysis

Hadron Exotics: X(3872)

till 25.11.2016

Hadron Exotics: X(3872)

QCD allows many possible color singlets:

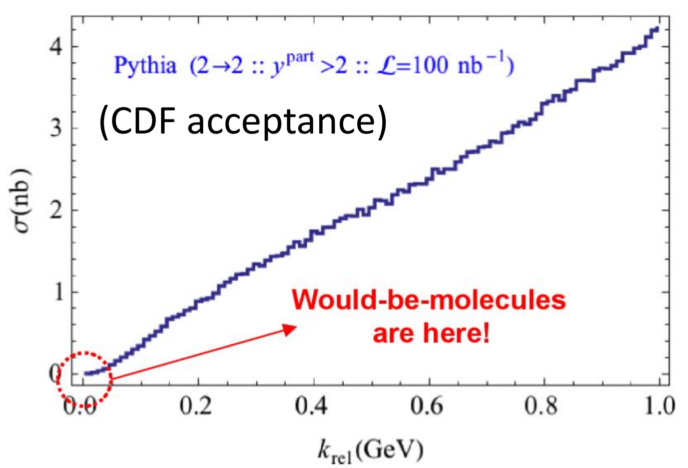


Tetraquark **Hadron Molecule**

Hadron Molecule Production

Prompt production of $X(3872)$

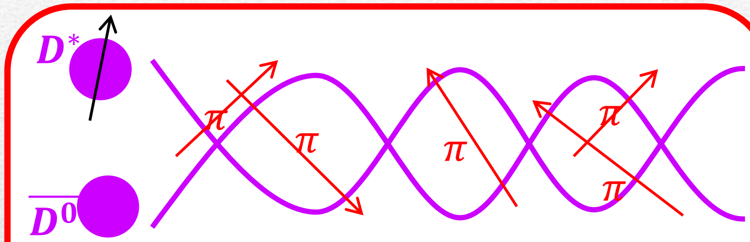
$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders



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

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

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

Hadron Molecule Production

A key assumption:

$$\sigma(p\bar{p} \to X(3872)) \le \int_R d^3k \, |\langle DD^*(k) | p\bar{p} \rangle|^2$$

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

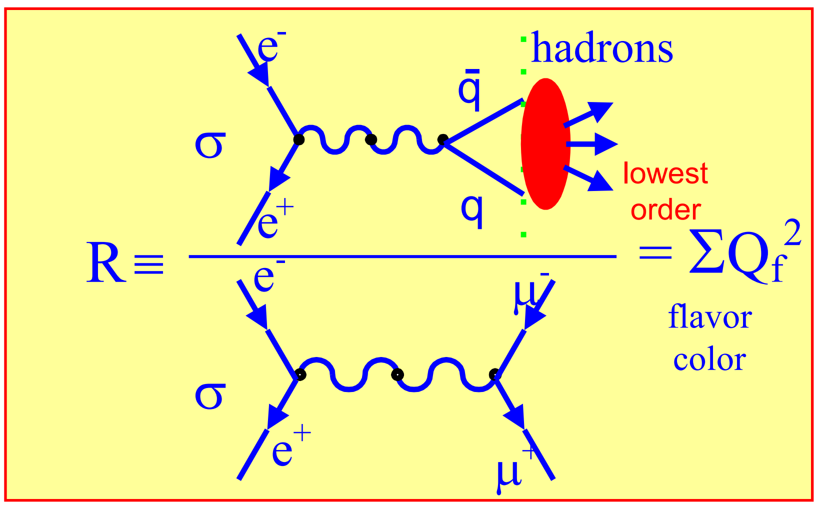
Production rate of a hadron is equivalent to that of quark pairs

R Value

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

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

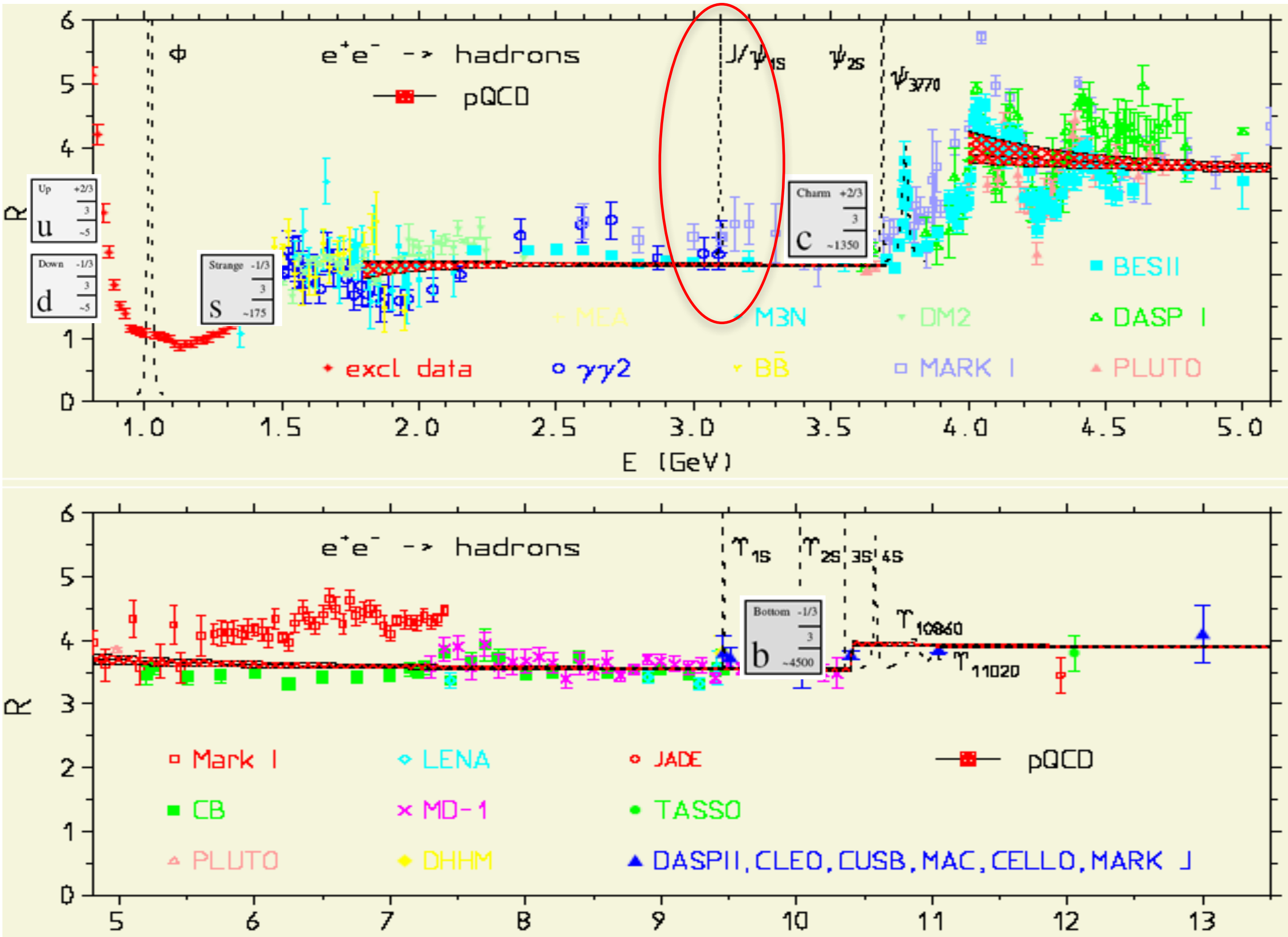
R value



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

R value measurements test QCD prediction

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

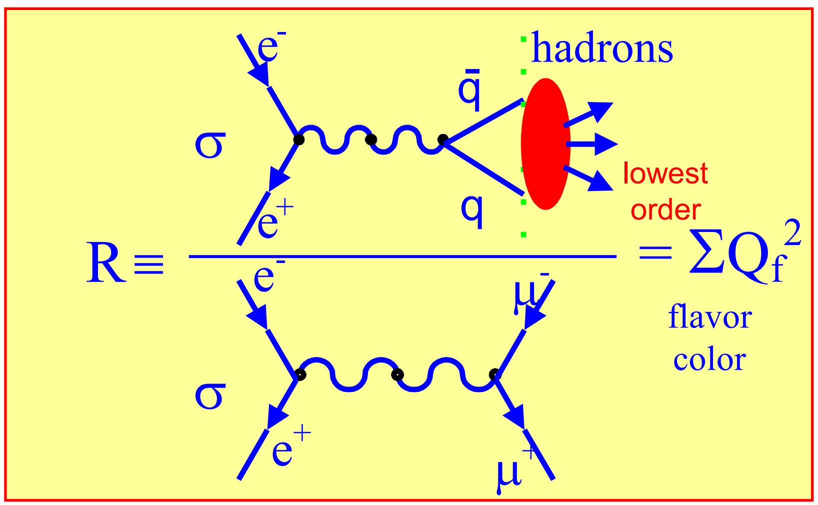


Color Evaporation Model

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



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

Effective Field Theory

NRQCD

Bodwin, Braaten, Lepage, Brambilla, et al.

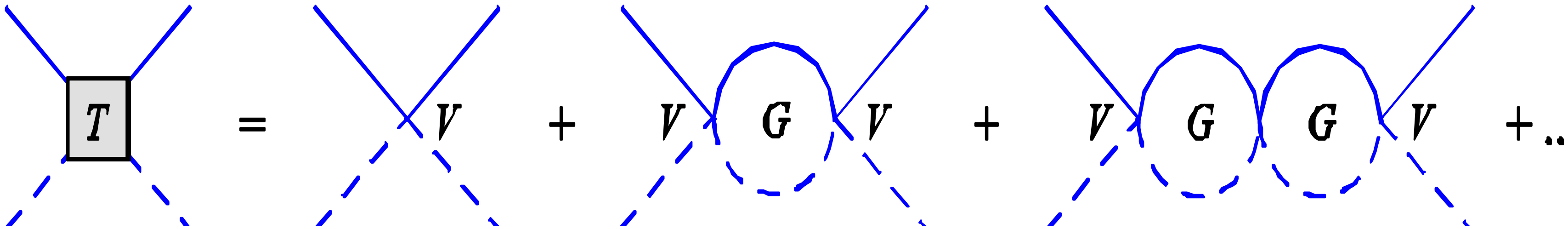
$$\sigma(H) = \sum_n F_n(\Lambda)\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle$$

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

Hadron Level EFT

$$\sigma(X(3872)) = \sigma(D\bar{D}^*)|\langle X(3872)|D\bar{D}^*|0\rangle|^2$$

Hadron Molecule In EFT

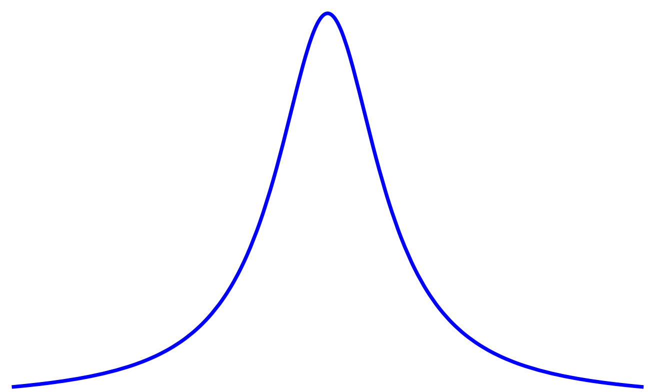


Summing All order contributions:

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

1-GV＝0

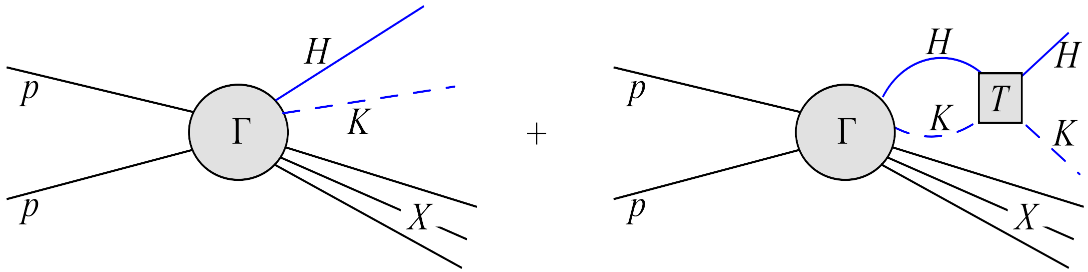
s=s$_0$



Mass pole corresponds to a resonance structure

→ Hadron Molecule

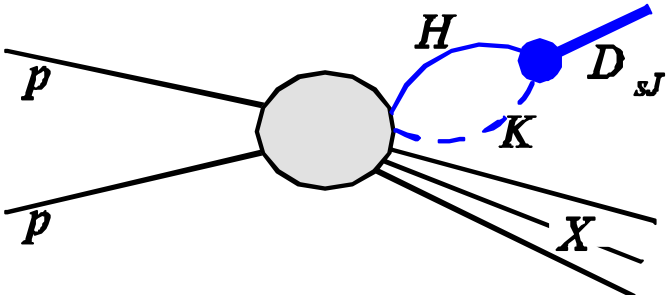
Hadron Molecule Production at LHC



Γ+ ΓGV + ΓGVGV+…. = Γ /(1-GV)

Γ is tree-level amplitude.

1-GV＝0 ⟺



Herwig/Pythia: simulate production rates of constituents, Γ

Monte Carlo Event Generator

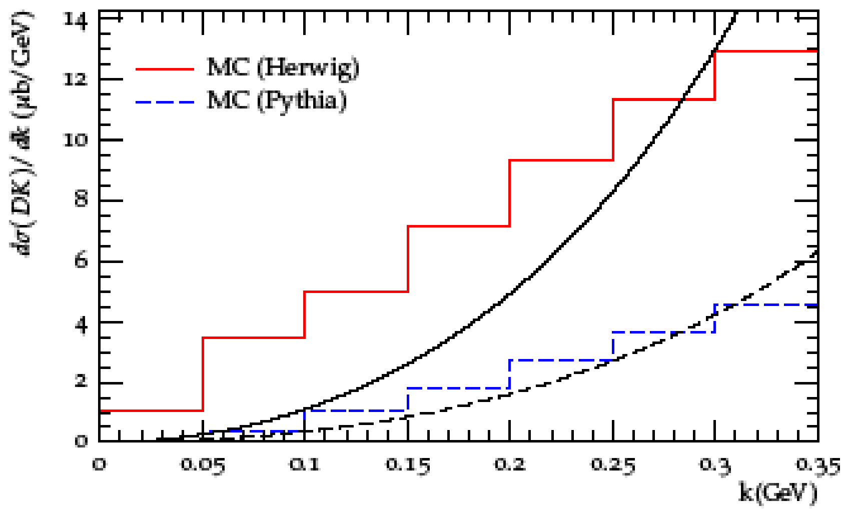
- Herwig/Pythia: simulate production rates of constituents, Γ

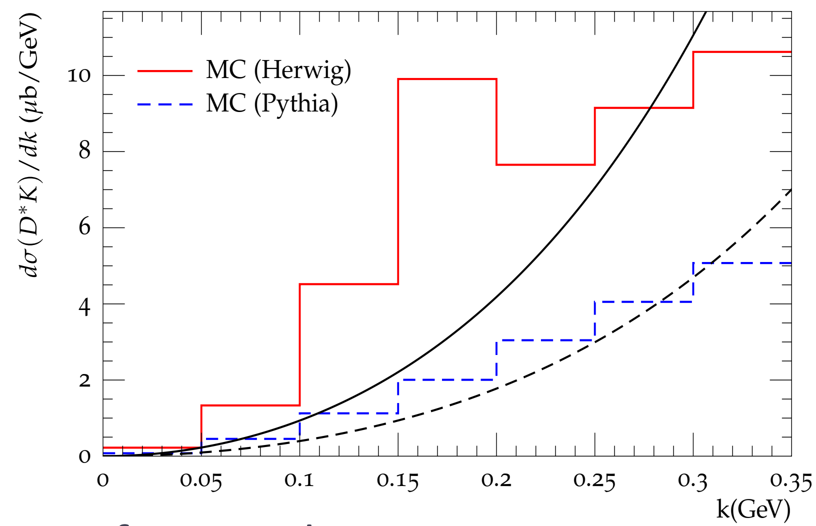
- For charmonium/bottomonium-like states, heavy quarks move together, and a third parton is requested. 2→ 3 process: use Madgraph

- Use Rivet to analyze hadronic events

EFT vs data: X(3872)

F.K. Guo, U.G. Meissner, WW, Z.Yang 1403.4032





Histograms: MC event generators Curves: fit according to EFT.

$\sigma(pp/p\bar{p} \to X(3872))$	Ref. [16]	Ref. [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]

F.K. Guo, U.G. Meissner, WW, Z.Yang 1402.6236

16. C. Bignamini, B. Grinstein, F. Piccinini, A.D. Polosa, C. Sabelli, Phys. Rev. Lett. **103**, 162001 (2009). arXiv:0906.0882 [hep-ph]

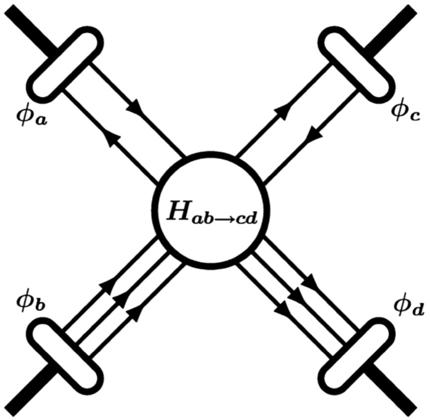
18. P. Artoisenet, E. Braaten, Phys. Rev. D **81**, 114018 (2010). arXiv:0911.2016 [hep-ph]

Large Prompt Production Rate is compatible with molecular interpretation!

QCD analysis

Constituent Scaling Rule?

$$a + b \to c + d$$



s: square of collision energy

$$s = (p_a + p_b)^2 \to 4E^2$$

$$t = (p_a - p_c)^2 \to E^2(1 - \cos\theta) \sim s$$

$$n = n_a + n_b + n_c + n_d$$

n_i: valence component in object i

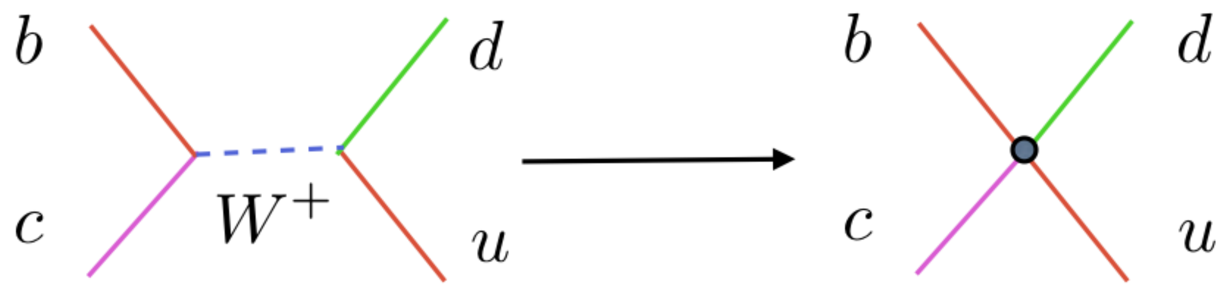
Constituent Scaling Rule for Cross Section:

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}$$

tree-level

Very clean and straightforward!

Fermi 4-quark interaction

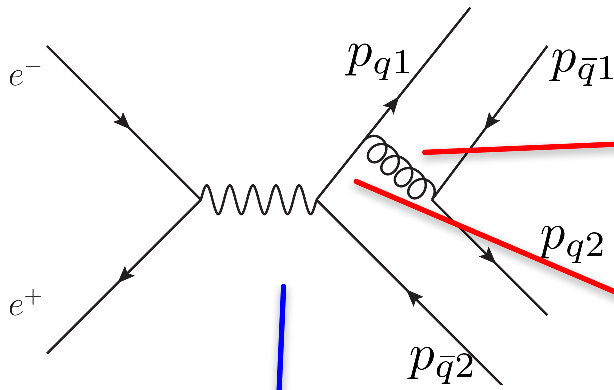


$$A = [\bar{d}\gamma_\mu P_L u]\frac{g^2}{M_W^2 - q^2}[\bar{c}\gamma^\mu P_L b] \to \frac{g^2}{M_W^2}[\bar{d}\gamma_\mu P_L u][\bar{c}\gamma^\mu P_L b] + O(p_q^2/M_W^2)$$

$$G_F = \frac{g^2}{M_W^2}$$ Fermi constant

Local interaction

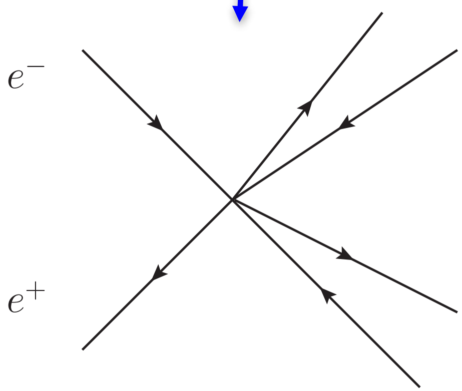
Effective Field Theory



$$p_g^2 = (p_{q2} + p_{\bar{q}1})^2 \sim s$$

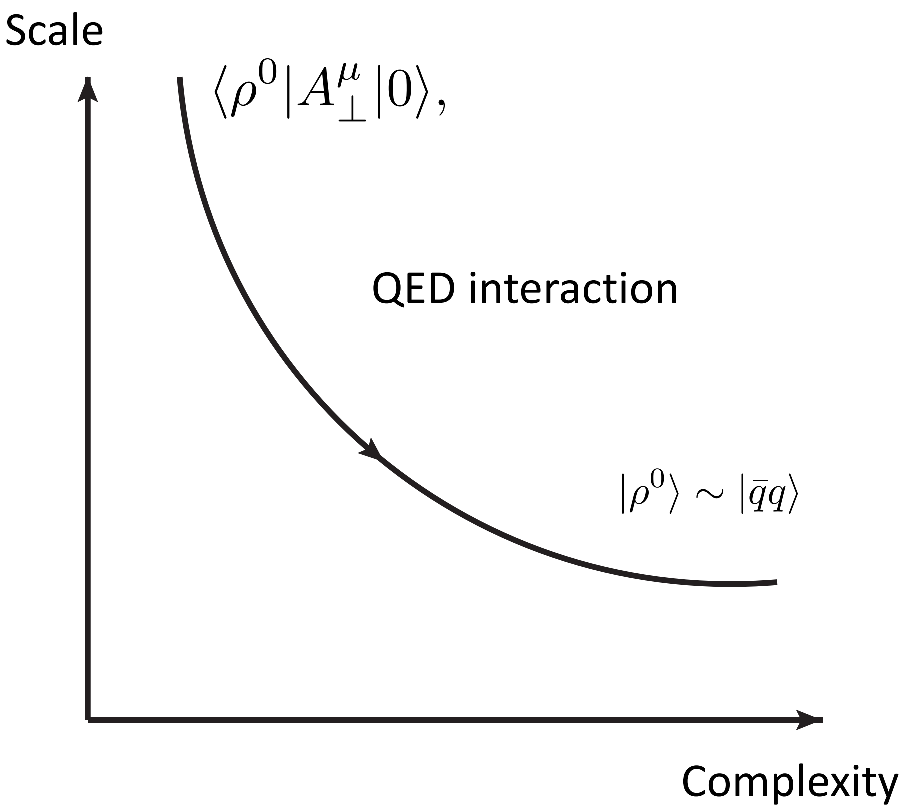
$$p_q^2 = (p_{q2} + p_1)^2 \sim s$$

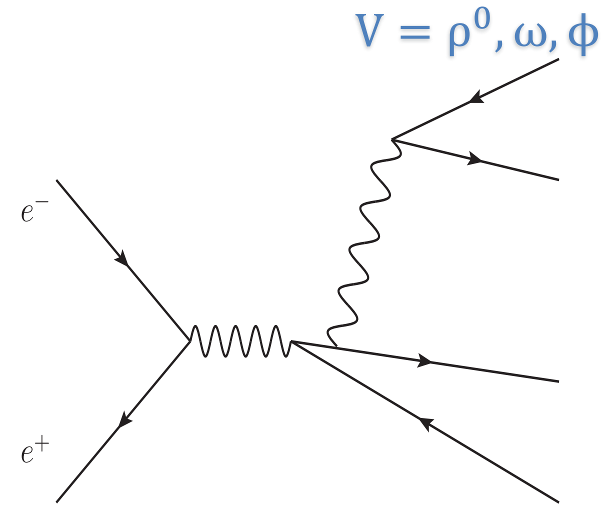
Integrating out

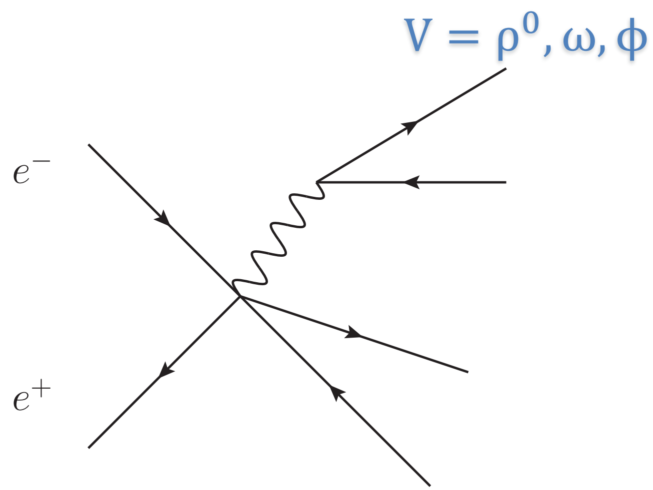


$$\langle \rho\pi | j^{\mu}_{em} | 0 \rangle \sim \langle \pi | \bar{\psi}\Gamma\psi | 0 \rangle \times \langle \rho | \bar{\psi}\Gamma'\psi | 0 \rangle$$

$e^+ e^- \to \rho^0 \pi^0$



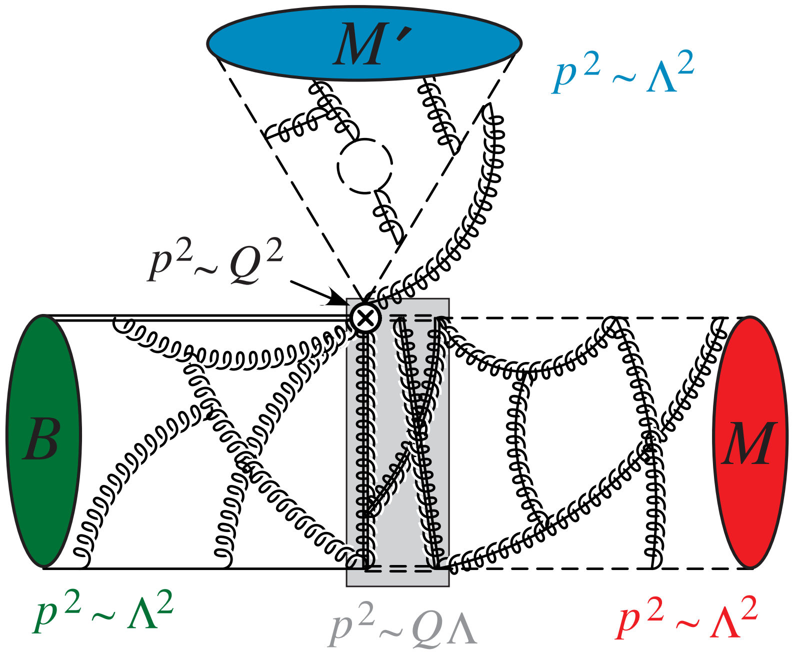




结论

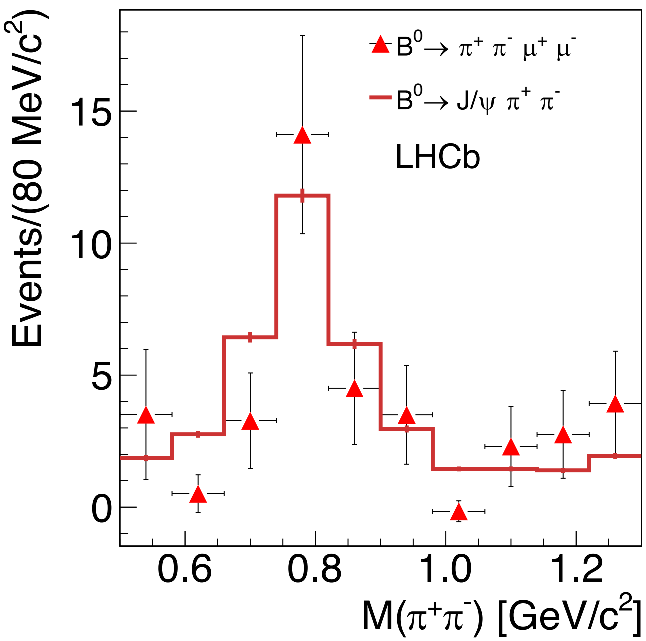
- In $e^+ e^- \to \rho^0 \pi^0$ at high energy, ρ^0 is produced by a photon γ

B decays



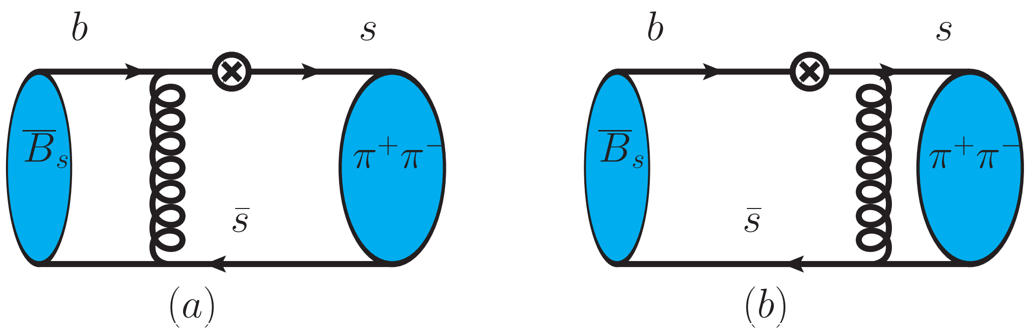
M′
$p^2 \sim \Lambda^2$
$p^2 \sim Q^2$
B
M
$p^2 \sim \Lambda^2$
$p^2 \sim Q\Lambda$
$p^2 \sim \Lambda^2$

$B_s \rightarrow \pi^+\pi^-\mu^+\mu^-$

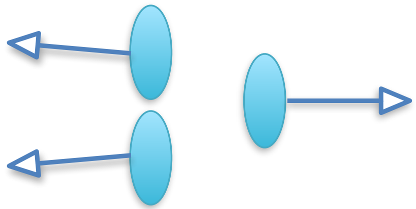


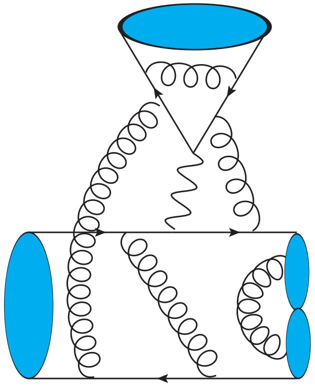
LHCb, 1412.6433

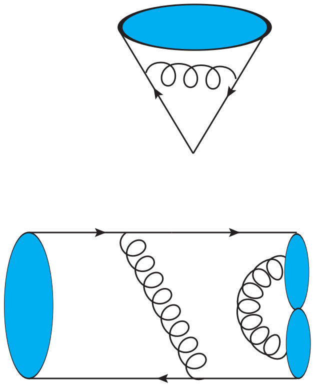
$$\mathcal{B}(B_s \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5 \pm 0.7 \pm 0.7) \times 10^{-8}$$



Factorization in B decays







Factorization in B decays

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

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

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

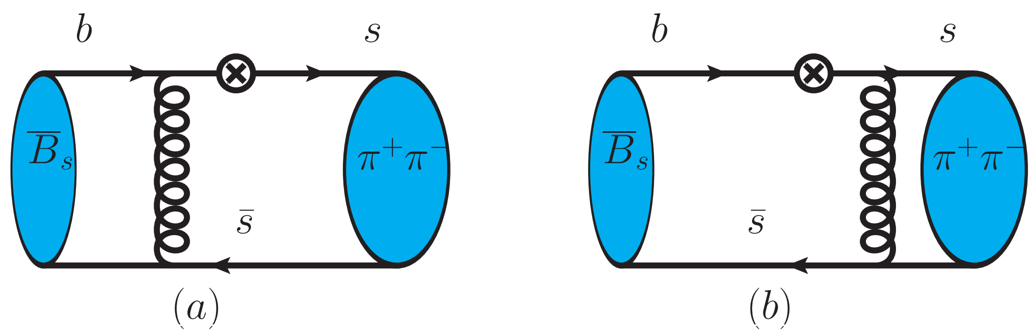
$$\langle (K\pi)_0|\bar{s}(x)\gamma_\mu d(0)|0\rangle$$

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

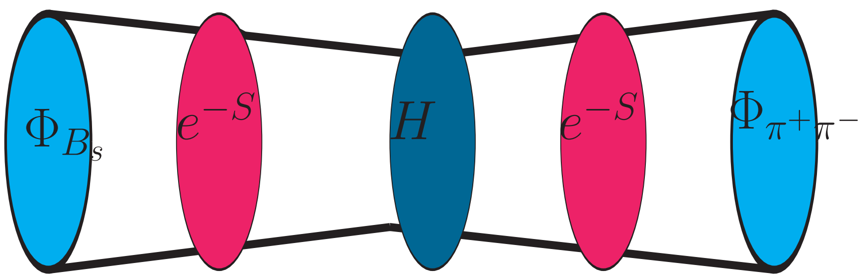
$$\langle (K\pi)_0|\bar{s}(x)\sigma_{\mu\nu}d(0)|0\rangle$$

U.G. Meiβner, WW, arXiv:1312.3087

$B_s \to \pi^+\pi^-\mu^+\mu^-$



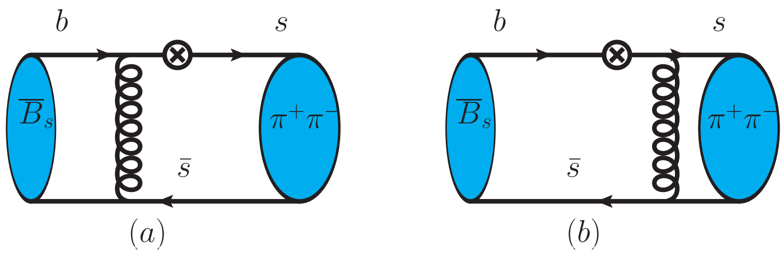
PQCD:



$$\langle \pi^+\pi^- | \bar{s}(x) s(0) | 0 \rangle$$

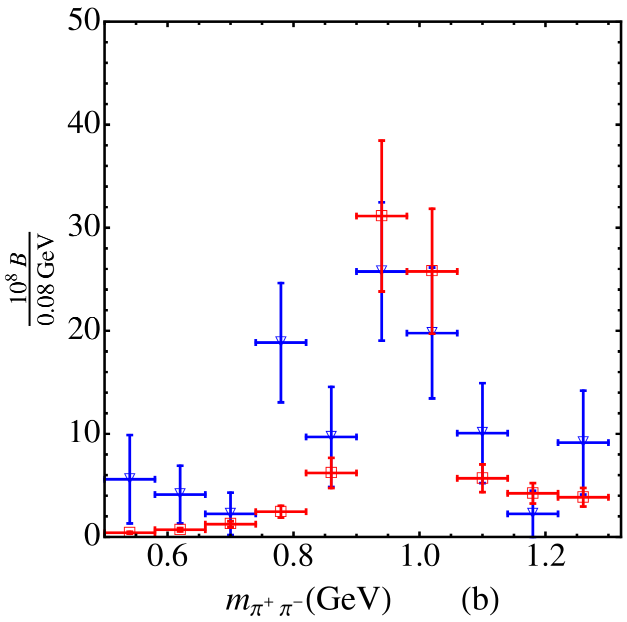
$$F \sim \int d^4k_1\, d^4k_2\, \mathrm{Tr}\, [\, C(t)\, \Phi_B(k_1)\, \Phi_1(k_2)\, H(k_1,k_2,t)\,]\, \exp\{-S(t)\}$$

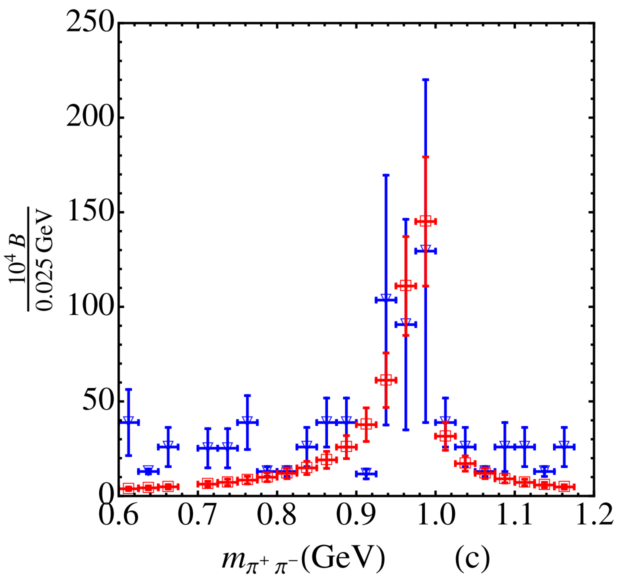
$B_s \to \pi^+\pi^-\mu^+\mu^-$ & $D_s \to \pi^+\pi^- e\nu$



$$\langle \pi^+\pi^- | \bar{s}(x) s(0) | 0 \rangle$$

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?

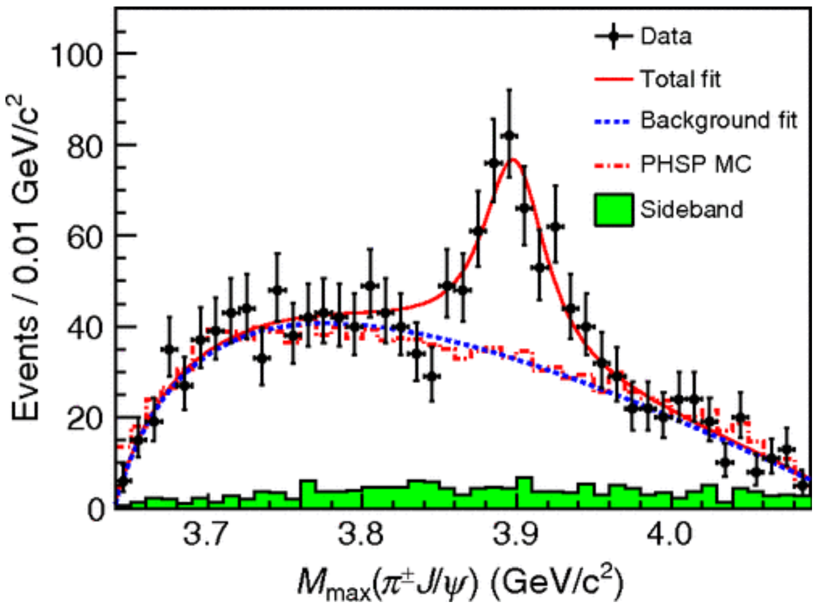
结论

- In $e^+ e^- \to \rho^0 \pi^0$ at high energy, ρ^0 is produced by a photon γ

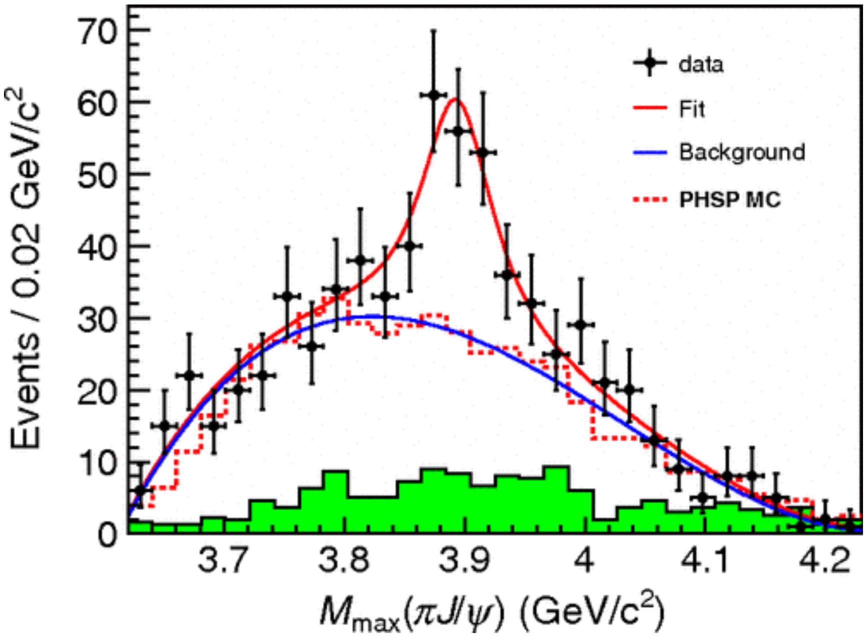
- In $B_s \to \pi^+ \pi^- l^+ l^-$, the $\pi^+ \pi^-$ pair is produced by the $\bar{s}s$ field.

$Z_c^{\pm}$

BES: PRL 110, 252001



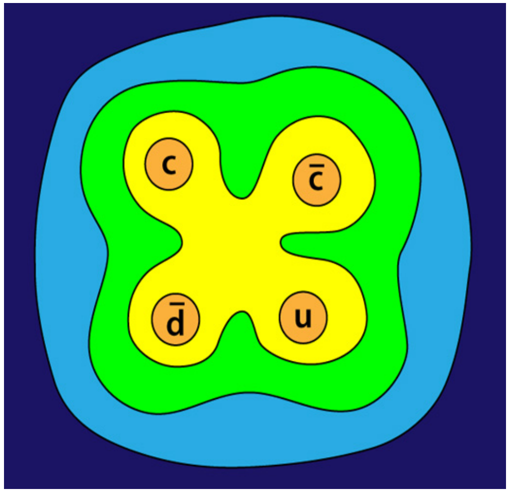
Belle: PRL 110, 252002



$Z_c^{\pm}$

$Z_c \rightarrow J/\psi\, \pi \Rightarrow \bar{c}c$

charged $\Rightarrow$ a pair of light quarks



tetraquark and hadronic molecules? debate?

Zc

Brodsky, Lebed: PhysRevD.91.114025

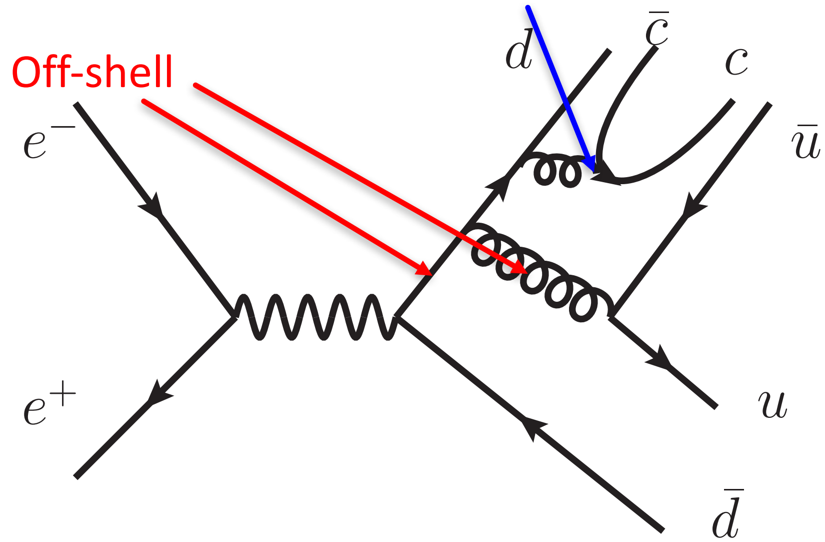
$$\frac{\sigma(e^+e^- \to Z_c^+(\bar{c}c\bar{d}u)\pi^-(\bar{u}d))}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{1}{s^4}$$

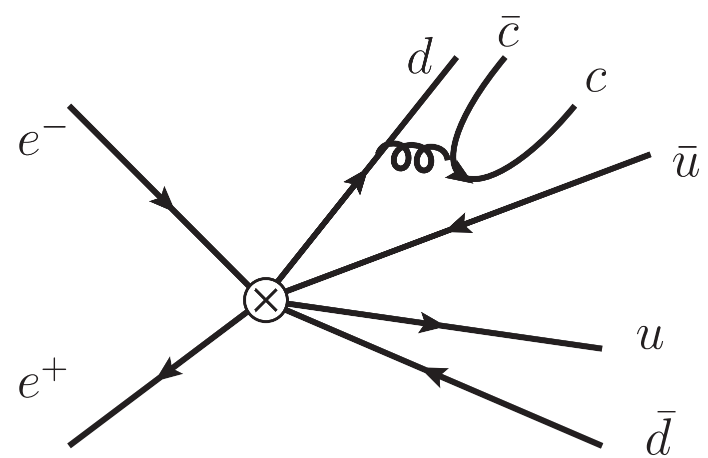
Guo, Meissner, WW: 1607.04020

$$\frac{\sigma(e^+e^- \to Z_c^+\pi^-)}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{1}{s^2}$$

对于含隐味道的强子（如Zc），指出高能产生与低能结构并无关系，纠正了Brodsky等人的错误。

Suppressed by 1/mc², but irrelevant with s



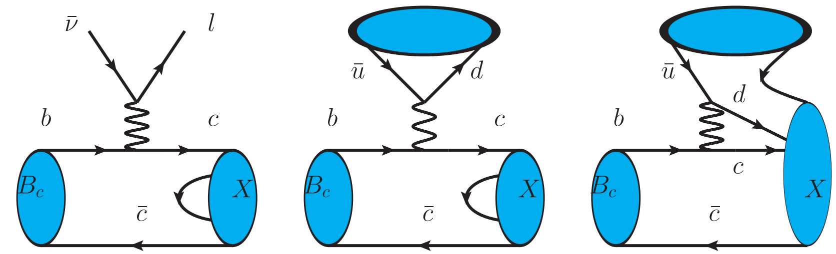


结论

- In $e^+ e^- \to \rho^0 \pi^0$ at high energy, ρ^0 is produced by a photon γ
- In $B_s \to \pi^+ \pi^- l^+ l^-$, the $\pi^+ \pi^-$ pair is produced by the $\bar{s}s$ field.
- In $e^+ e^- \to Z_c^{\pm} \pi_c^{\mp}$, the charged $Z_c^{\pm}$ is produced by the $\bar{u}d$ field.

Bc → X(3872)

- 以Bc → X(3872)为例，指出衰变过程仅与一个非微扰参数相关：$< X(3872)|\bar{c}\Gamma c|0 >$



- 半轻和非轻衰变分宽度比值与内部结构无关，可以精确预言！

WW, Q.Zhao, PLB755,261(2016)

$$R_0(\rho) = (10.9 \pm 0.1) \times 10^{-2},$$
$$R_\perp(\rho) = (11.1 \pm 0.1) \times 10^{-2},$$
$$R_{||}(\rho) = (11.1 \pm 0.1) \times 10^{-2},$$
$$R_{\rm total}(\rho) = (10.9 \pm 0.1) \times 10^{-2},$$

$$R_i(\rho) = \int_{(m_\rho-\delta)^2}^{(m_\rho+\delta)^2} dq^2 \frac{d\mathcal{B}(B_c^- \to X_i \ell^- \bar{\nu}_\ell)}{dq^2} \frac{1}{\mathcal{B}(B_c^- \to X_i \rho^-)}$$

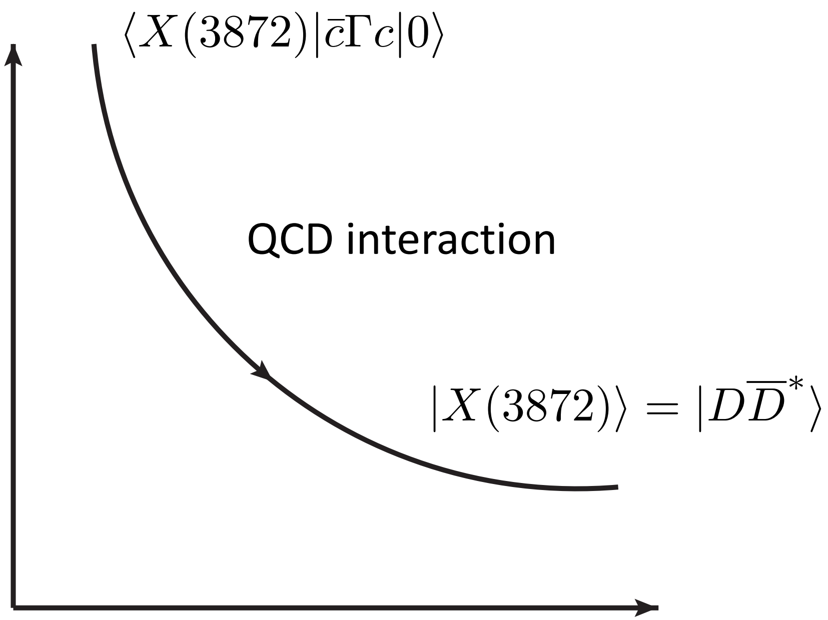
与LHCb实验物理学家讨论Bc→X(3872)π的测量

结论

- In $e^+ e^- \to \rho^0 \pi^0$ at high energy, ρ^0 is produced by a photon γ
- In $B_s \to \pi^+ \pi^- l^+ l^-$, the $\pi^+ \pi^-$ pair is produced by the $\bar{s}s$ field.
- In $e^+ e^- \to Z_c^{\pm} \pi_c^{\mp}$, the charged $Z_c^{\pm}$ is produced by the $\bar{u}d$ field.
- In $B_c \to X(3872)\, \pi$, the $X(3872)$ is produced by $\overline{cc}$

Concept Clarification: mixing

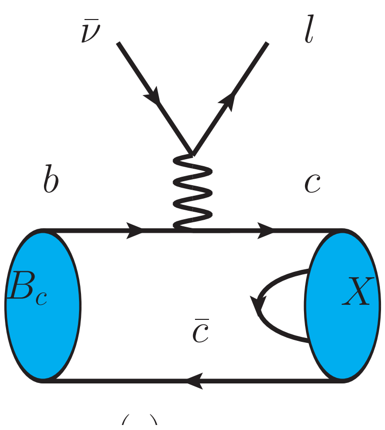
- Factorization in EFT:



- Mixing

$$|X(3872)\rangle = a|\bar{c}c\rangle + b|D\overline{D}^*\rangle$$

$$a^2 + b^2 = 1$$



How to test the production mechanism?

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

$$e^+e^- \to \phi(\pi^+\pi^-)_S$$

$$\gamma\gamma \to \pi^+\pi^-$$

$$\Gamma(B^- \to X(3872)K^-) = \Gamma(\overline{B}^0 \to X(3872)\overline{K}^0),$$
$$\Gamma(B^- \to X(3872)K^{*-}) = \Gamma(\overline{B}^0 \to X(3872)\overline{K}^{*0}) = \Gamma(\overline{B}_s^0 \to X(3872)\phi),$$
$$\Gamma(B^- \to X(3872)\pi^-) = 2\Gamma(\overline{B}^0 \to X(3872)\pi^0) = \Gamma(\overline{B}_s^0 \to X(3872)\overline{K}^0),$$
$$\Gamma(B^- \to X(3872)\rho^-) = 2\Gamma(\overline{B}^0 \to X(3872)\rho^0) = \Gamma(\overline{B}_s^0 \to X(3872)\overline{K}^{*0}).$$

Summary

Hadron Level EFT

$$\sigma(X(3872)) = \sigma(D\bar{D}^*)|\langle X(3872)|D\bar{D}^*|0\rangle|^2$$

X(3872):
Large Prompt Production Rate is compatible with molecular interpretation!

QCD analysis

- In $e^+ e^- \to \rho^0 \pi^0$ at high energy, ρ^0 is produced by a photon γ
- In $B_s \to \pi^+ \pi^- l^+ l^-$, the $\pi^+ \pi^-$ pair is produced by the $\bar{s}s$ field.
- In $e^+ e^- \to Z_c^{\pm} \pi_c^{\mp}$, the charged $Z_c^{\pm}$ is produced by the $\bar{u}d$ field.
- In $B_c \to X(3872)\, \pi$, the $X(3872)$ is produced by $\bar{c}c$.
- …

Thank you very much for your attention!