

## **(Some) Theoretical Aspects on Production of Hadron Exotics**



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Hadron Exusics: Theory



**QCD allows many possible color singlets:** 



### **Tetraquark Hadron Molecule**

## Hadron Exotics: Experiment





Many Many Important Discoveries



# 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.

в: Thanks, that's precisely what I am working on now.<sup>2</sup>

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 ASSZEIT

exopolitikschweiz NOVEMBER 1, 2015  $\cdot$  7:57 AM

China baut ein Super-CERN

*Marco Gersabeck, Charm 2016* **3** 3





#### Spectroscopy

1. Production of the Exotic Hadrons  $\phi(2170)$ , X(4260) and Y<sub>b</sub>(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 BB 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  $\frac{1}{2}X(3872)\frac{1}{9}$  in  $\frac{1}{5}B$  c $\frac{1}{5}$  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)





### **QCD allows many possible color singlets:**



#### **Tetraquark Hadron Molecule**

## **Hadron Molecule Production**



 $\overline{9}$ 

20

## Prompt production of  $X(3872)$

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





which allow  $k_{max}$  to be as large as 5 $m_{\pi}$ ,  $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$  nb  $\mu$  ×  $\mu$ <sub>1</sub>,  $\mu$  ×  $\mu$ <sub>mdx</sub>,  $\mu$  × 200 ms A solution can be FSI (rescattering of  $DD^*$ ),

ccattoring is However, the rescattering is flawed by the presence of pions that interfere with  $DD^*$ propagation. Estimating the effect of these pions increases  $\sigma$ , 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:

$$
\sigma(p\overline{p} \to X(3872)) \le \int_R d^3k \, k \, \text{SDD}^*(k) \, \text{I } p\overline{p} \text{>}^2
$$

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

*Local Constituent-Molecule 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.

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

### R value



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

## **R value measurements test QCD prediction**



## **Color Evaporation Model**



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

#### R value



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

## Effective Field Theory



The inclusive cross section for producing a quarkonium at large momentum transfer (*pT* ) can be Bodwin, Braaten, Lepage, Brambilla, et al.

### NRQCD as the convolved with a section convolved with a section convolved with an  $N_R$  and  $N_R$  a

*•* Conjecture (GTB, Braaten, Lepage (1995)):

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

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

#### $\mathcal{C}$ Hadron Level EFT  $\boldsymbol{D}$  $\sigma(D_{s0}) \sim \sigma(DK) |\langle D_{s0} | D_{s0} | D_{s0} | D_{s0} | D_{s0} |^2$  $D_{\rm so}$   $|DK|0>|^2$  $\sigma(X(3872)) = \sigma(DD^*)|\langle X(3872)|DD^*|0\rangle|^2$  $3872$  $|DD^*|0\rangle|^2$

 $\overline{P}$ 



**Mass pole corresponds to a resonance structure**



## **Hadron Molecule Production at LHC**





## $\Gamma$ **+**  $\Gamma$ **GV** +  $\Gamma$ GVGV+.... =  $\Gamma$  /(1-GV)

## **Γ is tree-level amplitude.**



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



 $\Box$ Herwig/Pythia: simulate production rates of constituents, Γ

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

 $\Box$ Use Rivet to analyze hadronic events

#### **EFT vs data: X(3872)** E. Eichten, A.D. Frawley, A.B. Meyer et al., Eur. Phys. J. C **71**, 2. S. K. Choi et al., Belle Collaboration, Phys. Rev. Lett. **91**, 262001 3. Y/ 3 3. B. Aubert et al., BaBar Collaboration, Phys. Rev. D **71**, 071103

 $\mathcal{L}(\mathcal{$ 



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



16. C. Bignamini, B. Grinstein, F. Piccinini, A.D. Polosa, C. Sabelli, 18. P. Artoisenet, E. Braaten, Phys. Rev. D 81, 114018 (2010). Phys. Rev. Lett. **103**, 162001 (2009). arXiv:0906.0882 [hep-ph]

1534 (2011)

upcoming 3*,*000 fb−1 data <mark>{</mark>

arXiv:0911.2016 [hep-ph]

#### **Large Prompt Production Rate is contact** arxiv:1007.287 [hepping] **Prompt Production Rate is compatible with m Large Prompt Production Rate is compatible with molecular interpretation!**



## **QCD** analysis



*d* s: square of collision energy

 $e^+$ 

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

$$
t = (p_a - p_b)^2 \rightarrow E^2(1 - \cos \theta)
$$

$$
n=n_a+n_b+n_c+n_d \hspace{1cm} \text{ n}_i\colon \text{ valence component in object } i
$$

 $\mathbf{r} = (\mathbf{p}_a - \mathbf{p}_c)$   $\rightarrow$   $\mathbf{r}_a$   $(\mathbf{r}_a - \mathbf{q}_b)$ 

Constituent Scaling Rule for Cross Section:	
$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}$	tree-level

in the three pieces in the participate  $\mathsf{true}$ 

derived by matching the former old theory. On the low-energy energy At very clean and straightforward!<br>
and  $\frac{1}{2}$  perturbation of  $\frac{1}{2}$ . Very clean and straightforward!<br>Very clean and straightforward! one simplest process is the east of the east of the east is the *ee*+ **e** in Fig. 1. This reaction for the *s*p. 10. This reaction for a specific for a specific for a specific for  $\alpha$  specific for  $\alpha$  specific for  $\alpha$  s Very clean and straightforward! for the longitudinal direction.

## **Effective Field Theory & Factorization**



### Fermi 4-quark interaction



#### So this new diagram will provide the dominant contribution and more importantly it does not obey Eq. (15)! Effective Field Theory *<sup>g</sup>* = (*pq*<sup>1</sup> + *pq*¯2) <sup>2</sup> ⇠ *<sup>s</sup>* (8) *<sup>|</sup>X*(3872)<sup>i</sup> <sup>=</sup> *<sup>|</sup>DD*⇤ i (7) *<sup>g</sup>* = (*pq*<sup>1</sup> + *pq*¯2) <sup>2</sup> ⇠ *<sup>s</sup>* (8) *<sup>|</sup>X*(3872)<sup>i</sup> <sup>=</sup> *<sup>|</sup>DD*⇤ *<sup>|</sup>X*(3872)<sup>i</sup> <sup>=</sup> *<sup>|</sup>DD*⇤







结论



## $\triangleright$  In  $e^+e^- \rightarrow \rho^0 \pi^0$  at high energy,  $\rho^0$  is produced by a photon  $\gamma$

## B decays

because the contract of the co





 $\mathbf{B}_\mathbf{s}$  $\rightarrow$   $\pi^+\pi^-\mu^+\mu^$ in the light-cone sum rules approach. Merging these quantities, we present our results for diagonal cone divis





**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 Badecays











## **Factorization in B decays**



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

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



*U.G. Meiβner, WW, arXiv:1312.3087*

## $\mathbf{B}_s \rightarrow \pi^+ \pi^- \mu^+ \mu^-$





PQCD:



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

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

**B**<sub>s</sub> $\rightarrow \pi^+\pi^-\mu^+\mu^-$ & D<sub>s</sub> $\rightarrow \pi^+\pi^-$ ev







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

11 *Y.J. Shi, WW, 1507.07692*



 $B_s \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  LHCb:1412.6433  $D_s \rightarrow \pi^+ \pi^- e \nu$  CLEO:0907.320  $\frac{1}{s}$  defined in Eq. (53). A comparison with the experimental data  $\frac{1}{s}$ ,  $\frac{1}{s}$  is not particle.  $\mathcal{L}(\mathbf{c})$  in particular data (with triangle markers) has been normalized to the central value of the branching fraction:  $B_s \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  *LHCb*:1412.6433  $D_s \rightarrow \pi^ D_s \rightarrow \pi^+ \pi^- e \nu$  *CLEO:0907.3201* 

*BES-III & Belle-II?*

结论



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



 $\rm{Z_C^-}$ 

±



## $Z_c \rightarrow J/\psi \pi \Rightarrow \overline{c}c$ charged  $\Rightarrow$  a pair of light quarks

 $\rm Z_{C}^{\rm -}$ 

±



### tetraquark and hadronic molecules? debate?

**Zc** *Not all ingredients will undergo the hard momentum transfer at the scale* p*s.* The fall-o↵ power scaling is determined by the leading-power operator at the scale *µ* = p*s* which has a nonzero matrix element with the hadron. Q<del>ED or QCD interactions at a lower scale can re-organize the valence quark-gluon content.</del> Actually, the original constituent counting rule is applicable at finite scattering angle. If the scattering angle is small,  $\overline{C}$ at least two of the involved particles are collinear, and thus it is not essential to undergo the hard momentum<br>Thus it is not estential to undergo the hard momentum transfer. The hard momentum transfer. The hard momentum





*,* !*,* as *n<sup>i</sup>* = 1 since it is produced by a photon. The lesson one can learn from the above example is:

Apparently, this production mechanism will become dominant at very high energy with <sup>p</sup>*<sup>s</sup> <sup>m</sup>c*. But in analogy Brodsky等人的错误。 with the *<sup>e</sup>*<sup>+</sup>*e* ! *V P* process, the helicity flip may introduce a suppression factor 1*/s*. (*e*<sup>+</sup>*e* ! *<sup>µ</sup>*<sup>+</sup>*µ*) / *<sup>s</sup>*<sup>6</sup> *,* ? (10) 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

#### $\Omega$  constituent constituent constituent constituent constituent  $\Omega$ Suppressed by 1/mc<sup>2</sup>, but irrelevant with s



结论



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Bc → X(3872) *b c* **b** *Z X*  $R_0 \rightarrow X (3872)$ 

*c*¯



Ø以Bc → X(3872)为例,指出 *<sup>H</sup>*e↵ <sup>=</sup> *<sup>G</sup><sup>F</sup>* p2 *VcbV* ⇤ *ud*⇢ *C*1*O*<sup>1</sup> + *C*2*O*<sup>2</sup> 衰变过程仅与一个非微扰参 数相关: <  $X(3872)$ | $\bar{c}\Gamma c$ |0 > பு  $X \times X$  and  $Y \times Y$  in the operators  $B_c$  and  $Y$  and  $B_c$ elements. If the above all the above e1 the above e1 the above e2 the above e2 t

<sup>+</sup>(*q*2) ⌥ *<sup>A</sup>*<sup>1</sup>



*c*¯ *Bc X*

▶半轻和非轻衰变分宽度比值 与内部结构无关, 可以精确 WW,Q.Zhao,PLB755,261(2016) softer the proof for the p  $f \mapsto f + \frac{1}{2} \pi f + f + \frac{1}{2} \pi f$  is the  $f \mapsto f + \frac{1}{2} \pi f$  is the above formula the above formula the above formulas,  $f \mapsto f + \frac{1}{2} \pi f + \frac{1}{2} \pi$ **In the factorization theorem, which can be proved at least the production of the proportion of the above ratios are**  $\mathcal{I}$ 

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

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

$$
R_0(\rho) = (10.9 \pm 0.1) \times 10^{-2},
$$
  
\n
$$
R_i(\rho) = \int_{(m_\rho - \delta)^2}^{(m_\rho + \delta)^2} dq^2 \frac{d\mathcal{B}(B_c^- \to X_i \ell^- \bar{\nu}_\ell)}{dq^2} \frac{1}{\mathcal{B}(B_c^- \to X_i \rho^-)} \frac{R_\perp(\rho) = (11.1 \pm 0.1) \times 10^{-2},}{R_\parallel(\rho) = (11.1 \pm 0.1) \times 10^{-2},}
$$
  
\n
$$
R_{\text{total}}(\rho) = (10.9 \pm 0.1) \times 10^{-2},
$$

Fig. 1: the upper two diagrams correspond to the ¯*cc* configuration, while the lower ones correspond 与LHCb实验物理学家讨论Bc→X(3872)π的测量  $\mathsf{U}\mathsf{D} \to \mathsf{I}\mathsf{U}$  form for an estimate, we have used the constant form form for  $\mathsf{I}\mathsf{V}$ 

结论



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

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 $\triangleright$  In  $e^+$   $e^ \rightarrow$   $Z_c^{\pm} \pi_c^{\mp}$ , the charged  $Z_c^{\pm}$  is produced by the  $\bar{u}d$  field.

 $\triangleright$  In  $B_c \to X(3872) \pi$ , the  $X(3872)$  is produced by  $\overline{cc}$ 

**Concept Clarification: mixing** On the constituent scaling rule in the production of multi-quark states at high energy





*e*

*dt* ⇠ <sup>1</sup>

Feng-Kun Guo?, Wei Wang<sup>1</sup>*,*<sup>2</sup>

 $\angle$   $\mu^-$ 

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



 $\mu^-$ 

 $\mu$ <sup>-</sup>

*<sup>s</sup>*<sup>4</sup><sup>2</sup> <sup>=</sup> <sup>1</sup>



**EXACLE THOW TO TEST THE PRODUCTION MECHANISM? O**1 = ∑c, O<sub>2</sub> = ∑c, O<sub>2</sub> = ∂c, O2 = ∂c,



$$
e^{+}e^{-} \to D_{s0}(2317)D_{s}^{*}
$$
  
\n
$$
e^{+}e^{-} \to \phi(\pi^{+}\pi^{-})_{S}
$$
  
\n
$$
\gamma\gamma \to \pi^{+}\pi^{-}
$$

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

### 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!** 

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



## Thank you very much for your attention!