X(3872): is it really an exotic?

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Why do we care about exotic hadrons?

exotic means non $q\bar{q}$ or qqq structures ... **what else**?

(1) Strongly interacting clusters of hadrons: molecules
(Voloshin; Tornqvist; Close; Braaten; Swanson...)

(2) Tetraquark mesons, Pentaquarks, ...
(Maiani,Piccinini,Polosa,Riquer ...)

(3) Hybrids
(Close, Kou&Pene, ...)

X(3872) is considered a good candidate of exotic hadron

What do we know about X(3872)?

[see talks by
Vishal Bhardwaj on May 19
Arafat Gabareen Mokhtar on May 20]

Mass and width: very narrow

- 2 Measurements of the mass

$J/\psi\ \pi^+\pi^-$: $M=(3871.61 \pm 0.16(\text{stat}) \pm 0.19(\text{syst}))$ MeV

::CDF II, arXiv:0906.5218 [hep-ex]::

$\approx 3.5\ \sigma$

$D^0\bar{D}^{0*}$: $M=(3873.49 \pm 0.51)$ MeV

::Belle, arXiv:0810.0358v3 [hep-ex]::
::BaBar, arXiv:0708.1565v2 [hep-ex]::

- 2 Measurements of the width

$D^0\bar{D}^{0*}$: $\Gamma=(3^{+1.9}_{-0.4} \pm 0.9)$ MeV ::BaBar, arXiv:0708.1565 [hep-ex]::

$J/\psi\ \pi^+\pi^-$: $\Gamma < 2.3$ MeV @ 90% c.l.

Quantum numbers

- From $X \to J/\psi\,\gamma \Rightarrow C=+1$

:: Belle, arXiv:hep-ex/0505037 ::

- Angular distribution of $X \to J/\psi\,\pi^+\pi^-$

$\Rightarrow$ $J^P=1^+$ preferred
$J^P=2^-$ not excluded

:: Belle, arXiv:hep-ex/0505038 :: :: CDF, arXiv:hep-ex/0612053 ::

- It was observed a large isospin violation

$$\frac{\mathcal{B}(X \to J/\psi\omega)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 0.8 \pm 0.3(\mathrm{stat.}) \pm 0.1(\mathrm{syst.})$$

:: Belle, arXiv:hep-ex/0408116 ::

[the $\pi^+\pi^-$ pair comes from ρ]

X seems to contain I=0 and I=1 at the same level

A $J^{PC}=1^{++}$ tetraquark?

X as a tetraquark (1)

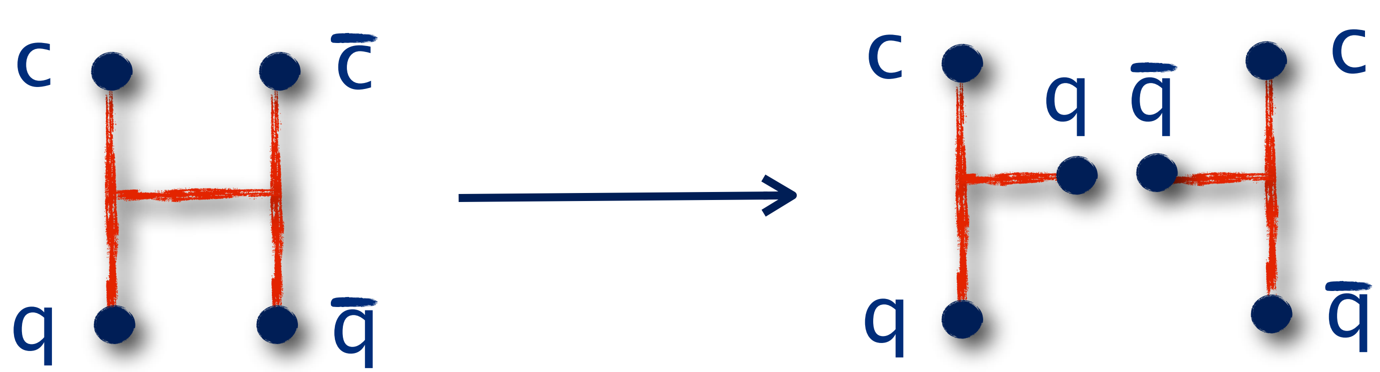
:: Maiani, Piccinini, Polosa, Riquer, Phys.Rev.D71:014028,2005 ::

- X can be a compact bound state of 4quark:
  a diquark-antidiquark bound state

- 1^{++} quantum numbers are obained if one picks up one S=1 diquark and one S=0 diquark

$$X_q = \frac{[cq]_1[\bar{c}\bar{q}]_0 + [cq]_0[\bar{c}\bar{q}]_1}{\sqrt{2}}$$

- A tetraquark has a strong affinity to the baryon-antibaryon mode, but the X is below threshold ⇒ narrow state



X as a tetraquark (2)

:: Maiani, Polosa, Riquer, Phys.Rev.Lett.99:182003,2007 ::

- Two different flavour for the light quarks:

Two neutral states

$$X_u = [cu][\bar{c}\bar{u}]$$
$$X_d = [cd][\bar{c}\bar{d}]$$

not established?

Two charged states

$$X^+ = [cu][\bar{c}\bar{d}]$$
$$X^- = [cd][\bar{c}\bar{u}]$$

still missing!

- But there are still some tetraquark candidates among the XYZ particles: $Z^+(4430)$, $Y(4660)$

:: Maiani,Polosa,Riquer, New J.Phys.10:073004,2008 ::

:: Cotugno,Faccini,Polosa,Sabelli,Phys.Rev.Lett.104:132005,2010 ::

A $J^{PC} = 1^{++}$ molecule?

The molecular hypothesis

- $M_D + M_{D^*} \cong 3872\,\mathrm{MeV} \Rightarrow$ X is an S-wave $D^0\bar{D}^{0*}$ molecule

:: Tornqvist, Z. Phys. C 61, 525 (1994) ::
:: Braaten, Phys.Rev.D69:074005 (2004) ::
:: Swanson, Phys.Lett.B588:189-195 (2004) ::

- If one assumes $J^P=1^{++}$ the wavefunction is

$$|X\rangle = \frac{|D^0\bar{D}^{0*}\rangle + |\bar{D}^0 D^{0*}\rangle}{\sqrt{2}}$$

this would explain the large Isospin violation

$$[c\bar{u}][\bar{c}u] \Rightarrow |I=0\rangle \oplus |I=1\rangle$$

- Extremely small binding energy

$$E_B = M_X - M_D - M_{D^*} = (-0.25 \pm 0.40)\,\mathrm{MeV}$$

Can such a loosely bound state be produced promptly in high energy $p\bar{p}$ collisions?

X prompt production

$p\bar{p} \to X(3872)$ @ CDFII

:: CDF, arXiv:hep-ex/0612053 ::
:: CDF, arXiv:0905.1982 [hep-ex] ::
:: CDF, Phys. Rev. Lett. 79, 572 (1997) ::

CDF II performed an analysis to distinguish the fraction of $\psi(2S)$ and X produced promptly from the fraction produced from B decays on an integrated luminosity of 220 pb^{-1} $p\bar{p}$ collisions

- Assuming the same rapidity and $p_\perp$ distribution per X e $\psi(2S)$:

$$\boxed{\sigma(p\bar{p} \to X(3872) + \text{All})_{\text{prompt}}\,\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \simeq (3.1 \pm 0.7)\text{nb}}$$

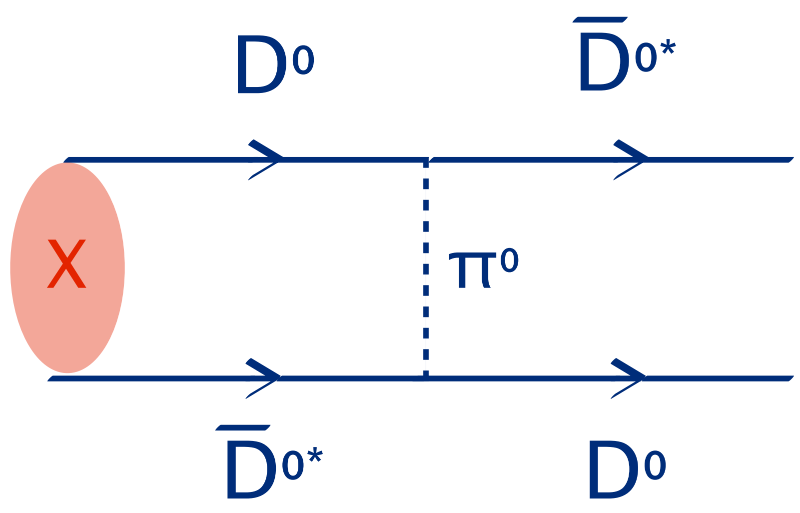
- Moreover: $0.042 < \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.093$

:: BaBar, Phys.Rev.Lett.96:052002,2006 ::

$$\Rightarrow \boxed{33 \text{ nb} < \sigma(p\bar{p} \to X(3872) + \text{All})_{\text{prompt}} < 72 \text{ nb}}$$

$p\bar{p} \rightarrow X(3872)$ as loosely bound molecule

D mesons interact via π^0-exchange:



$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-m_\pi r_0}}{r_0} = |E_B| \simeq 0.25 \text{ MeV}$$

using the fact that $g^2/4\pi \sim 10$ we find a characteristic size

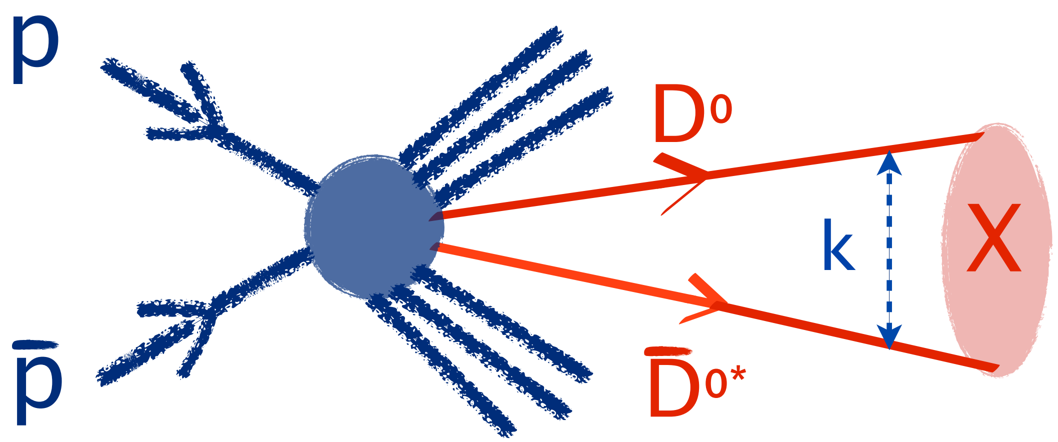
(1) $r_0 \simeq 8 \text{ fm} \quad \Rightarrow \quad \Delta k \sim 1/2r_0 \simeq 20 \text{ MeV}$

(uncertainty principle)

(2) $k_0 = \dfrac{\sqrt{\lambda(m_X^2, m_D^2, m_{D^*}^2)}}{2m_X} \simeq 30 \text{ MeV}$

$p\bar{p} \to X(3872)$ as loosely bound molecule

:: Bignamini, Grinstein, Piccinini, Polosa, Sabelli, Phys. Rev. Lett. 103 (2009) 162001 ::



$$\mathcal{R}: \; 0 \le k \le k_0 + \Delta k$$

$$\sigma(p\bar{p} \to X(3872)) \sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2$$

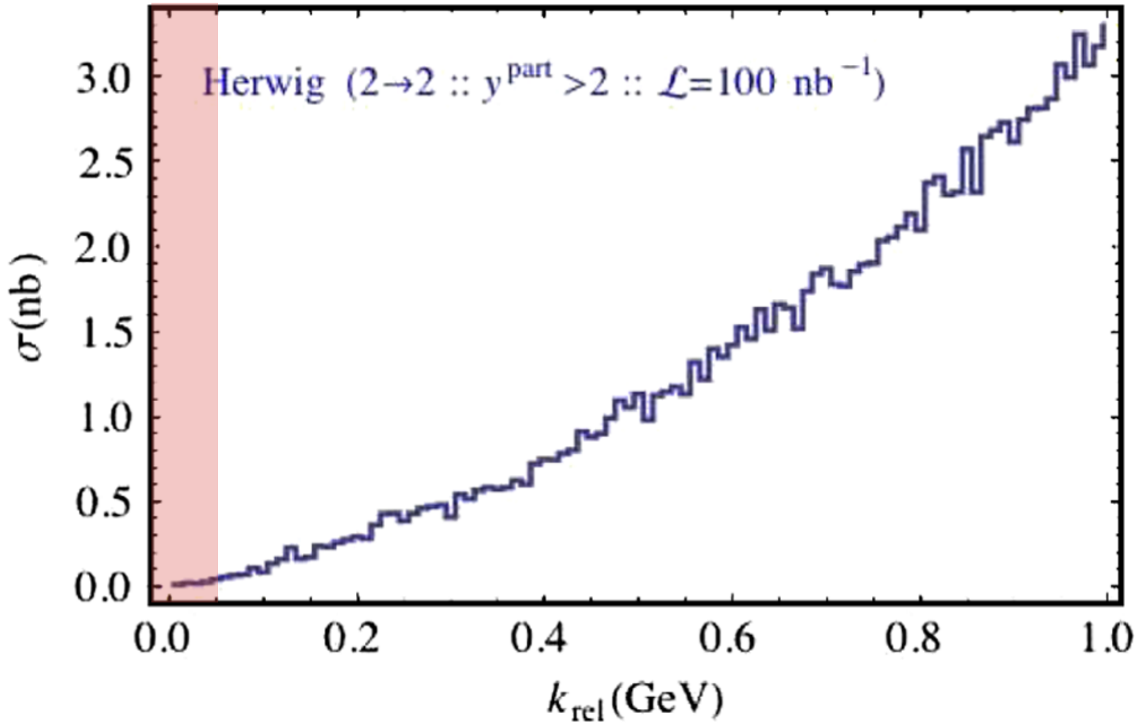
$$\le \int d^3\mathbf{k} |\psi(\mathbf{k})|^2 \int d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$

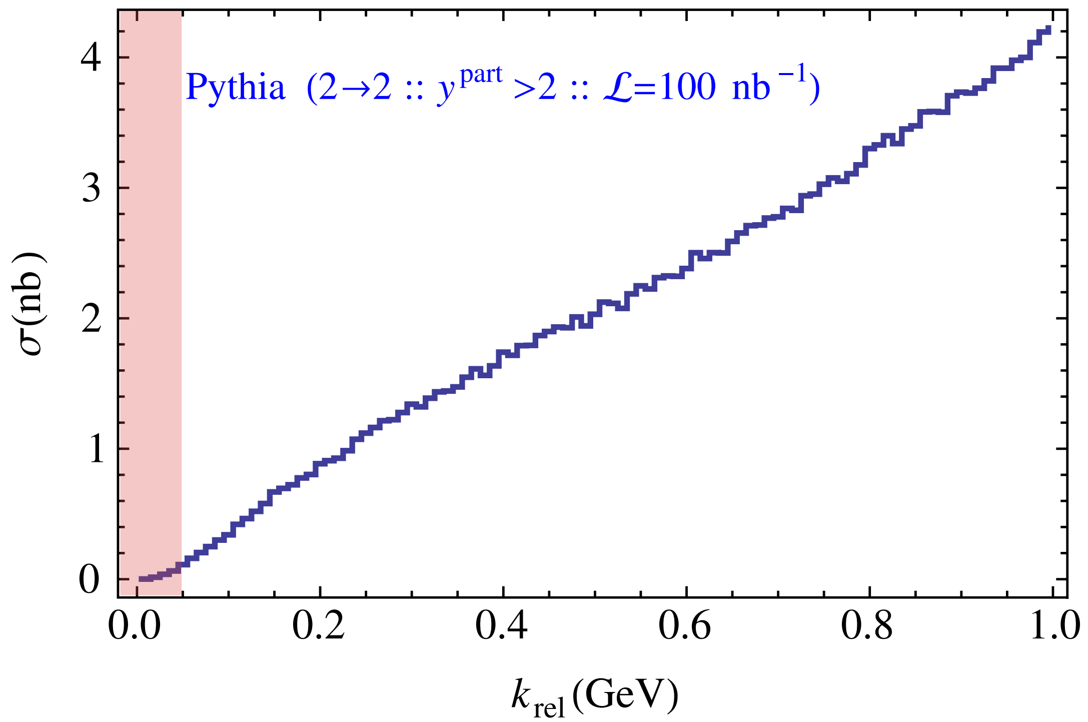
$$\le \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\max}$$

Schwartz Inequality

MC:
Herwig Pythia

$p\bar{p} \to X(3872)$ @ Pythia and Herwig





We rescale the Herwig cross section values by a factor K= 1.8 to best fit the data on open charm production. As for Pythia we need K=0.74.

$$\boxed{\sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{max}}_{\mathrm{th}} \simeq 0.085 \ \mathrm{nb}}$$

$\sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{max}}_{\mathrm{th}} \simeq 3 \ \mathrm{nb}$ if k ranges up to ~200 MeV for Herwig
~130 MeV for Pythia

$p\bar{p} \to X(3872)$ @ Pythia and Herwig

To be compared with

$$\sigma_{\rm exp}^{\rm min} \simeq 33 \text{ nb}$$

... which gives

$$\frac{\sigma_{\rm exp}^{\rm min}}{\sigma_{\rm th}^{\rm max}} \simeq 300$$

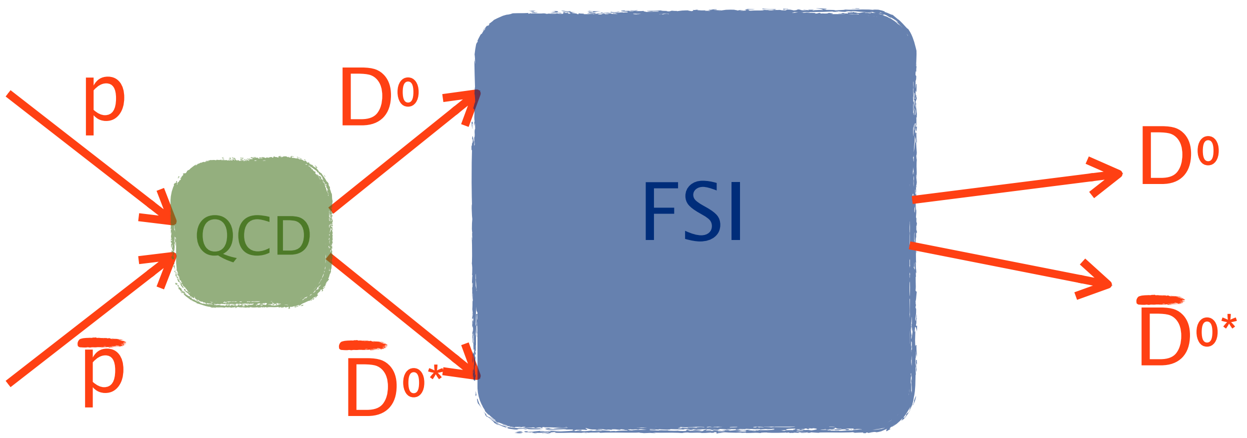
The molecular picture of the X
seems to be in trouble ...

FSI came into play

Is really the molecular picture in trouble?

:: Braaten & Artoisenet arXiv:0911.2016 ::

FSI can enhance the theoretical cross-section



$$\sigma(p\bar{p} \to X + \text{all})_{\text{prompt}} \simeq \boxed{\left[\sigma\left(p\bar{p} \to D^0 \bar{D}^{0*}(k < \Lambda) + \text{all}\right)\right]_{\text{MC}}} \times \frac{6\pi\sqrt{2\mu E_X}}{\Lambda}$$

Pythia & Herwig

FSI enhancement factor

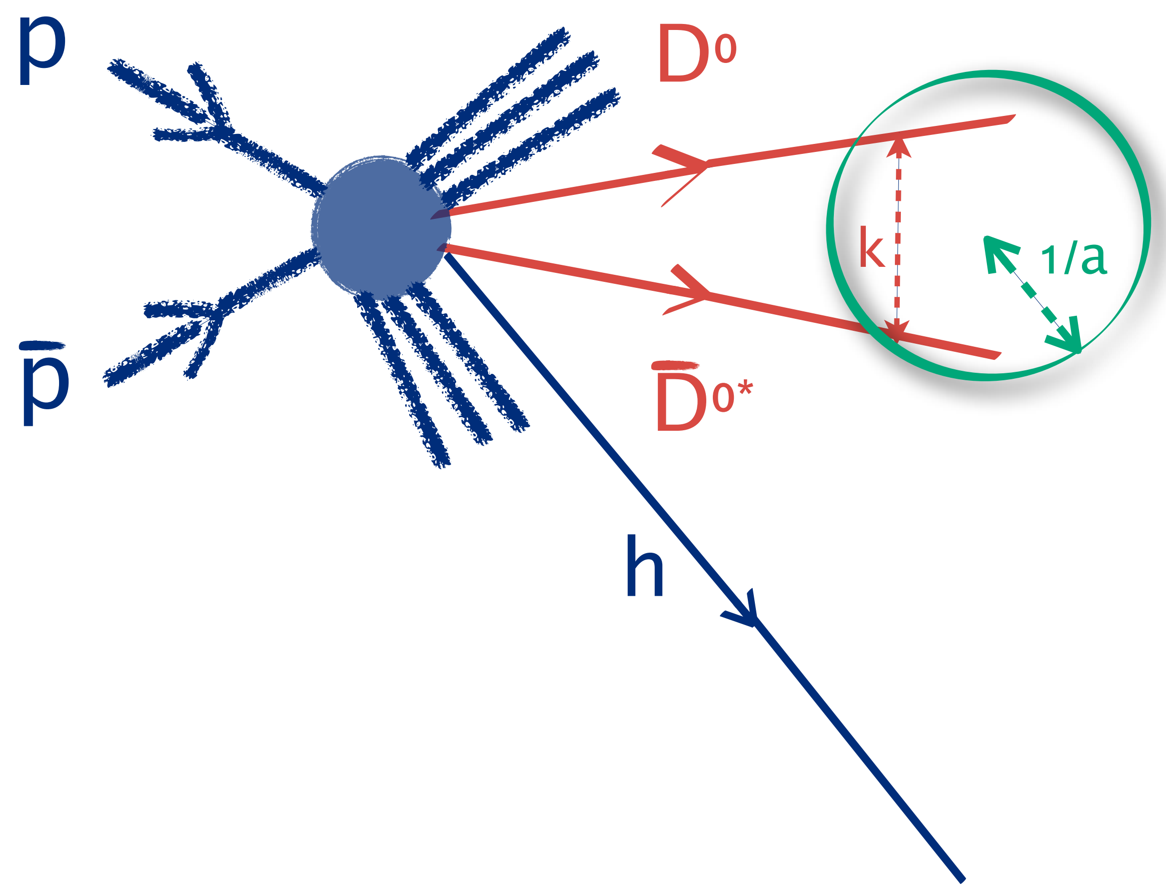
(1) FSI can make a high relative momentum pair to rescatter in a lower relative momentum pair: k can range up to $\Lambda \approx 2m_\pi$

(2) Enhancement factor

In this way σ^{th} and σ^{exp} can be reconciled... but ...

FSI: Watson theorem

:: Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::



a is the range of strong interaction: <u>a~1fm</u>

k<1/a~200MeV

FSI: Watson theorem

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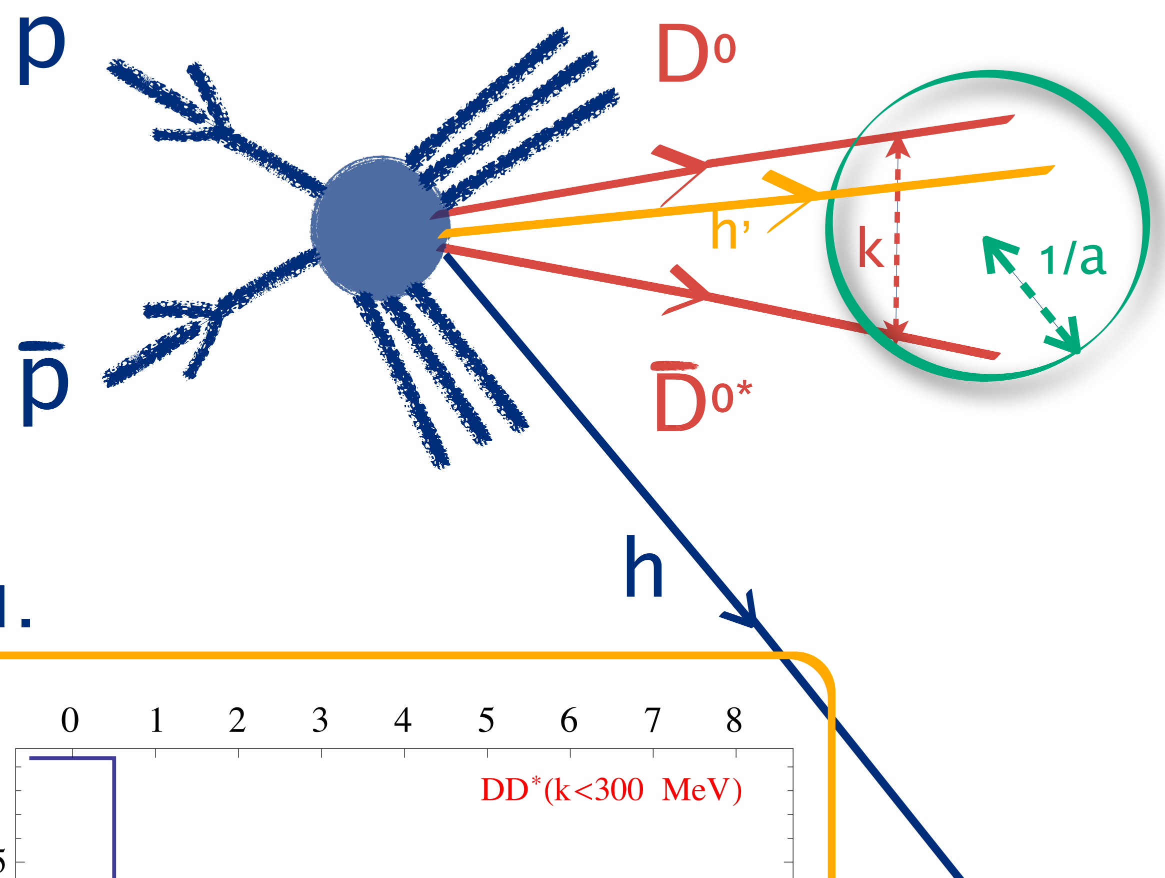

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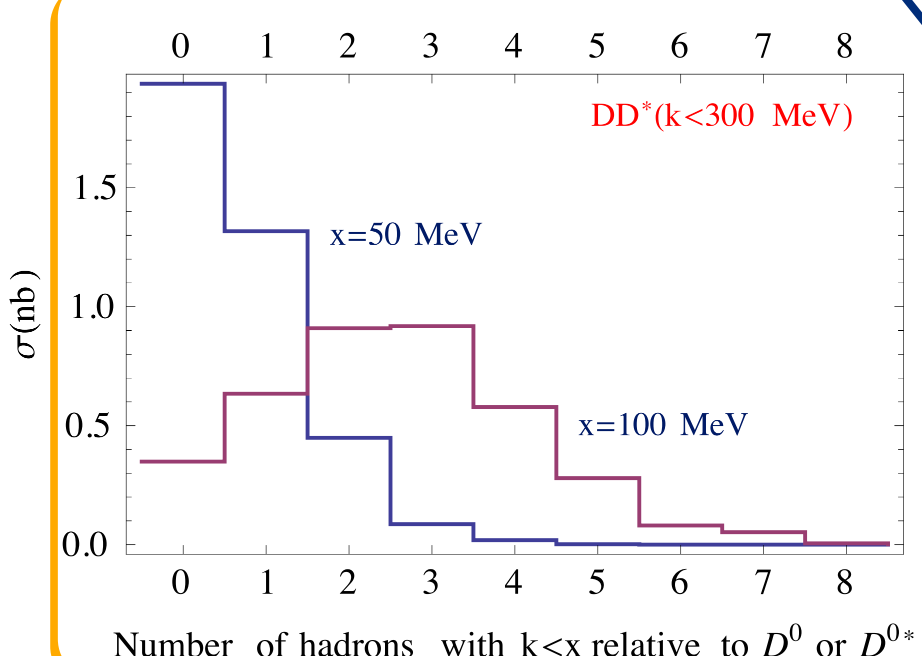
<u>a~1fm</u>
k<1/a~200MeV

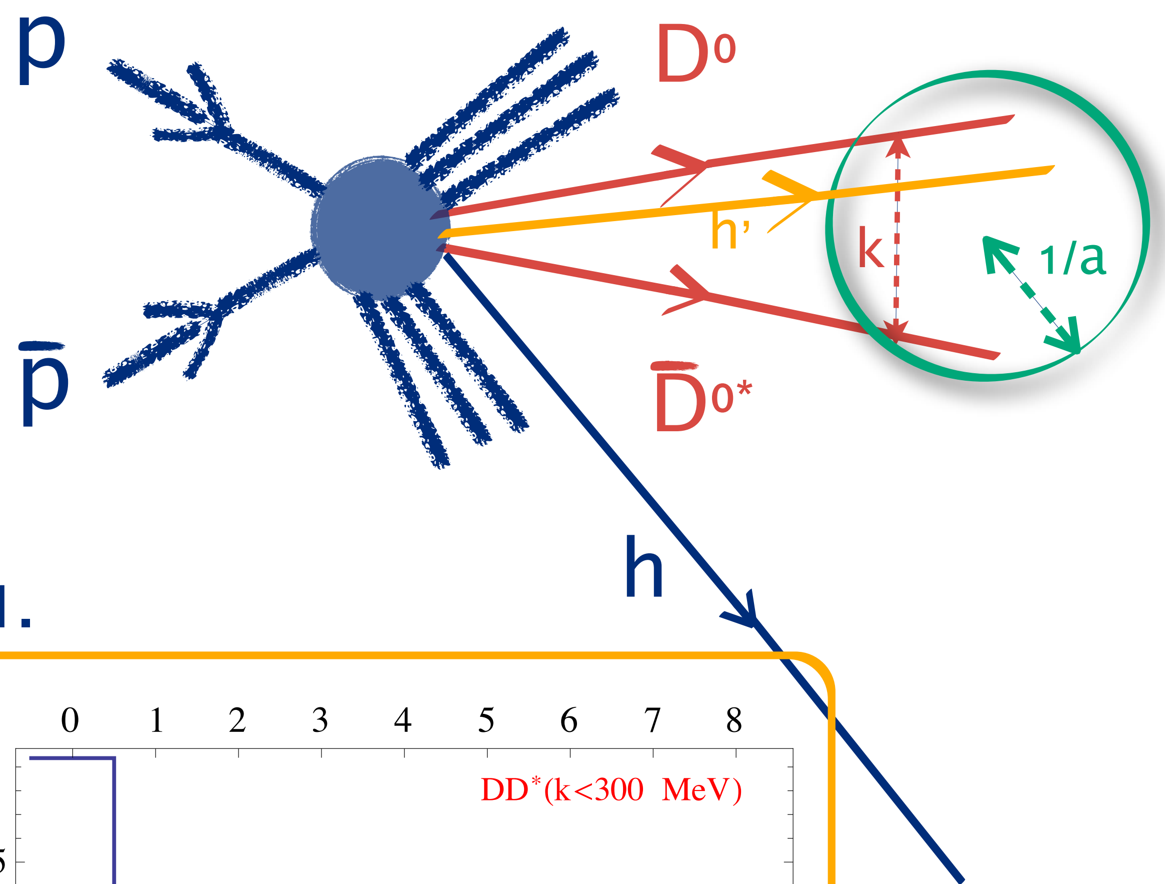
1.



In the standard treatment of FSI (Watson Theorem) one should have no more than two particles rescattering in the final state.
We find that this is not the case in the CDF simulation.

FSI: Watson theorem

:: Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::



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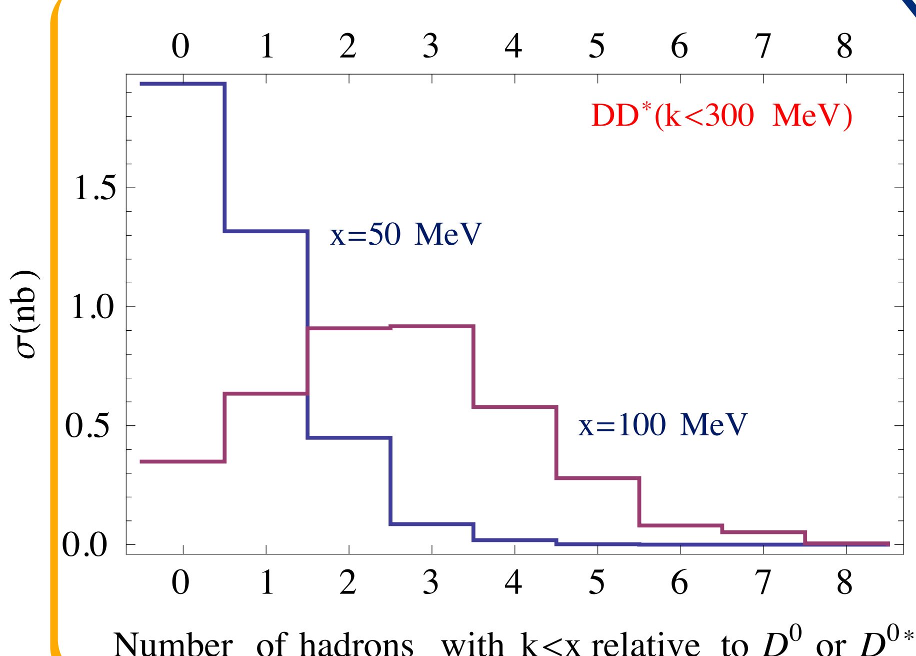
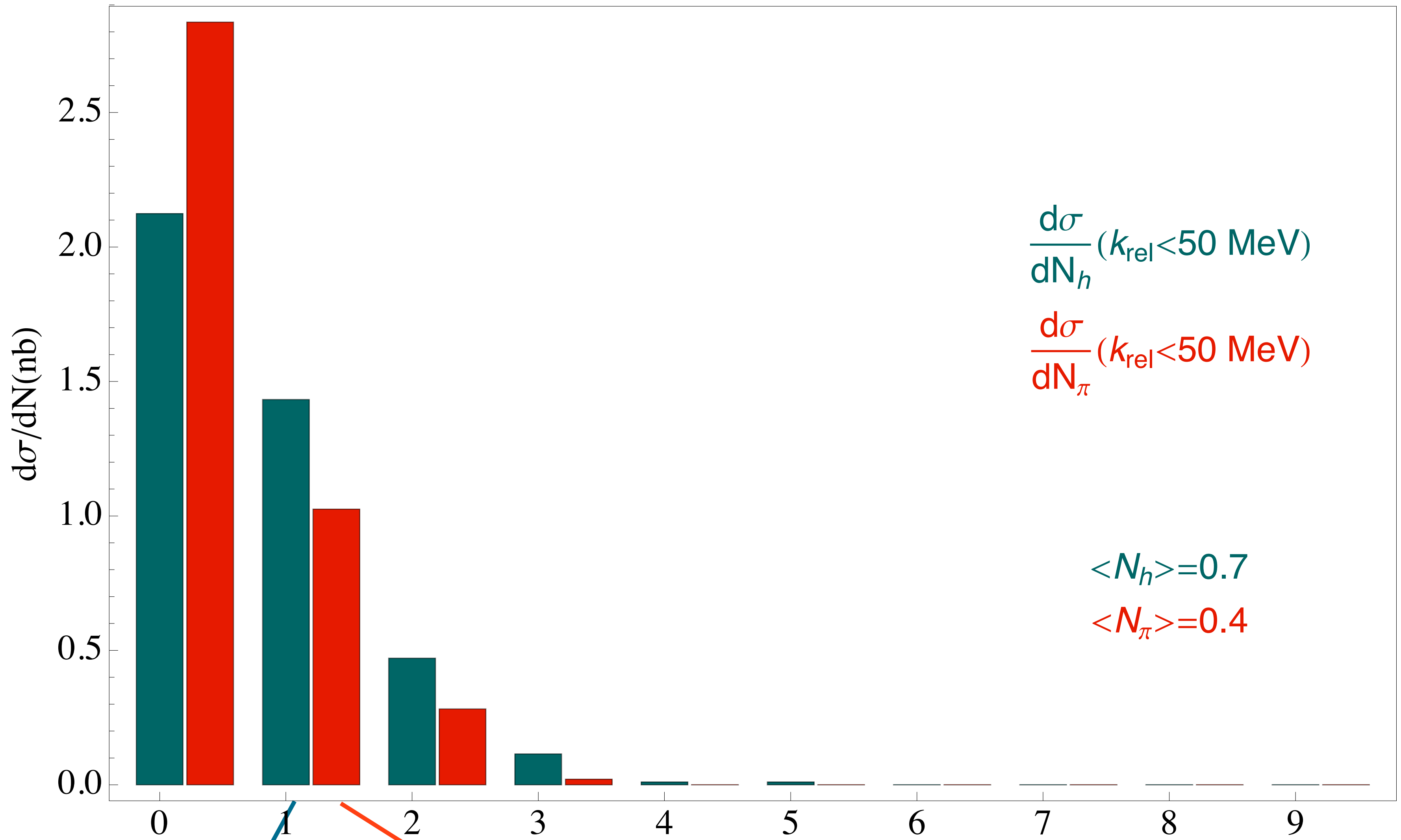


2.

s-wave scattering
⇒requires: ka<<1
k<<200 MeV

In the standard treatment of FSI (Watson Theorem) one should have no more than two particles rescattering in the final state.
We find that this is not the case in the CDF simulation.

Additional hadrons @ k_{rel} < 50 MeV

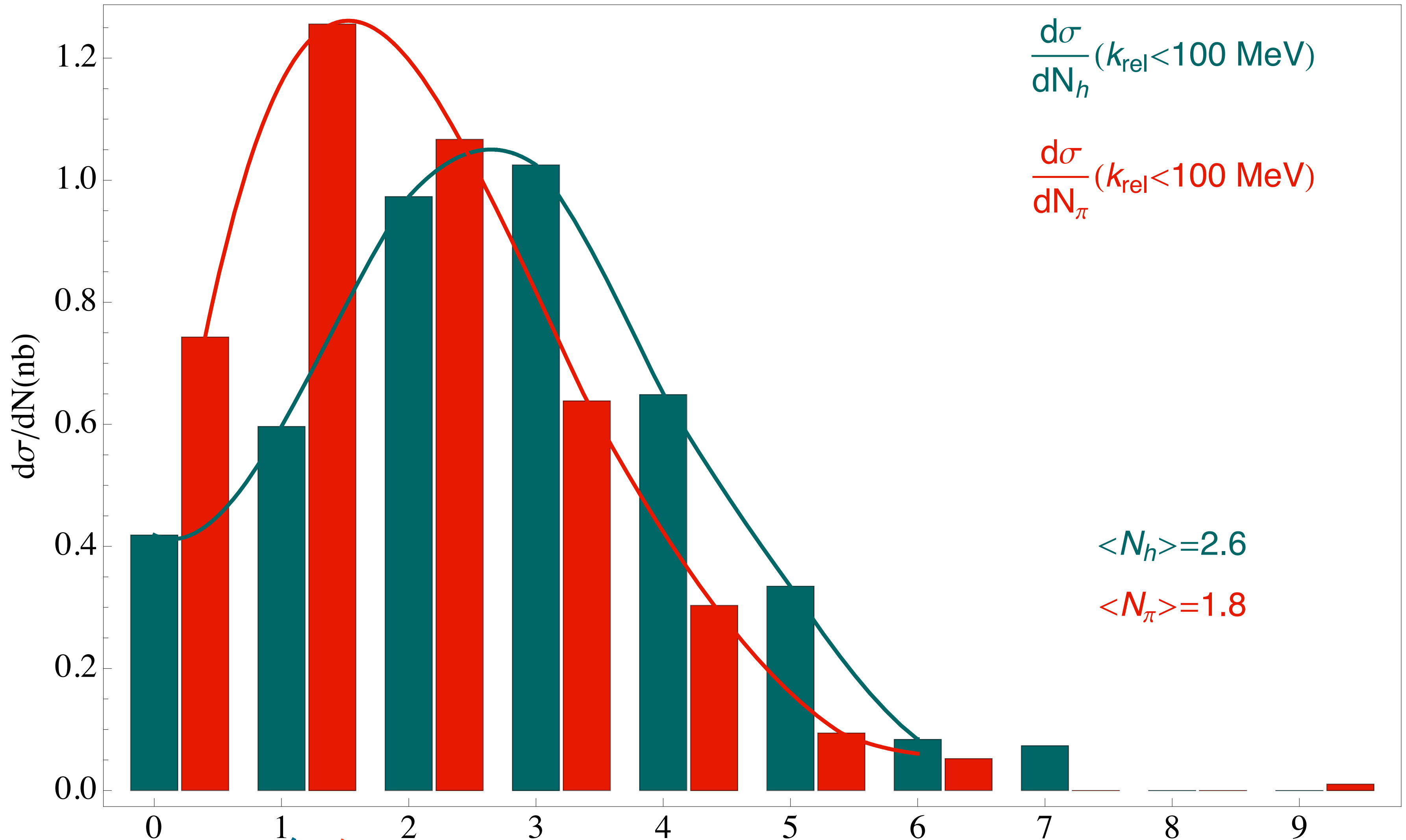


$1h = 1\pi \vee$ other

$\sum_n (1\pi + nh')$

$h' \neq \pi$ and not selected in k_{rel}

Additional hadrons @ k_{rel} < 100 MeV



$\sum_n (1\pi + nh')$

$1h = 1\pi \vee$ other

$h' \neq \pi$ and not selected in k_{rel}

Conclusions

(1) Problems of tetraquarks:
charged X states are still missing
X_u - X_d splitting?

(2) Problems of molecules:
prompt production cross section

(3) Other routes open:
hadro-charmonium?
D-wave standard charmonium?

Additional slides

$p\bar{p} \to X(3872)$ @ CDFII

CDF, arXiv:hep-ex/0612053.
CDF, arXiv:0905.1982 [hep-ex].
CDF, Phys. Rev. Lett. 79, 572 (1997)

- $$\frac{\sigma(p\bar{p} \to X(3872) + \text{All})_{\text{prompt}} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-))}{\sigma(p\bar{p} \to \psi(2S) + \text{All})_{\text{prompt}}} \simeq (4.6 \pm 0.1)\%$$

with: $p_\perp > 5 \text{ GeV}, |y| < 1$

- $\sigma(p\bar{p} \to \psi(2S) + \text{All})_{\text{prompt}} = (67 \pm 9) \text{ nb}$ with: $(p_\perp > 5 \text{ GeV}, |y| < 0.6)$

- Assuming the same rapidity and $p_\perp$ distribution per X e $\psi(2S)$:

$$\boxed{\sigma(p\bar{p} \to X(3872) + \text{All})_{\text{prompt}} \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \simeq (3.1 \pm 0.7)\text{nb}}$$

- Moreover: $0.042 < \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.093$

$$\Rightarrow \boxed{33 \text{ nb} < \sigma(p\bar{p} \to X(3872) + \text{All})_{\text{prompt}} < 72 \text{ nb}}$$

Schwartz inequality

$$\sigma(p\bar{p} \to X(3872)) \sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2$$

$$\leq \int d^3\mathbf{k} |\psi(\mathbf{k})|^2 \int d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$

Schwartz Inequality

$$\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\max}$$

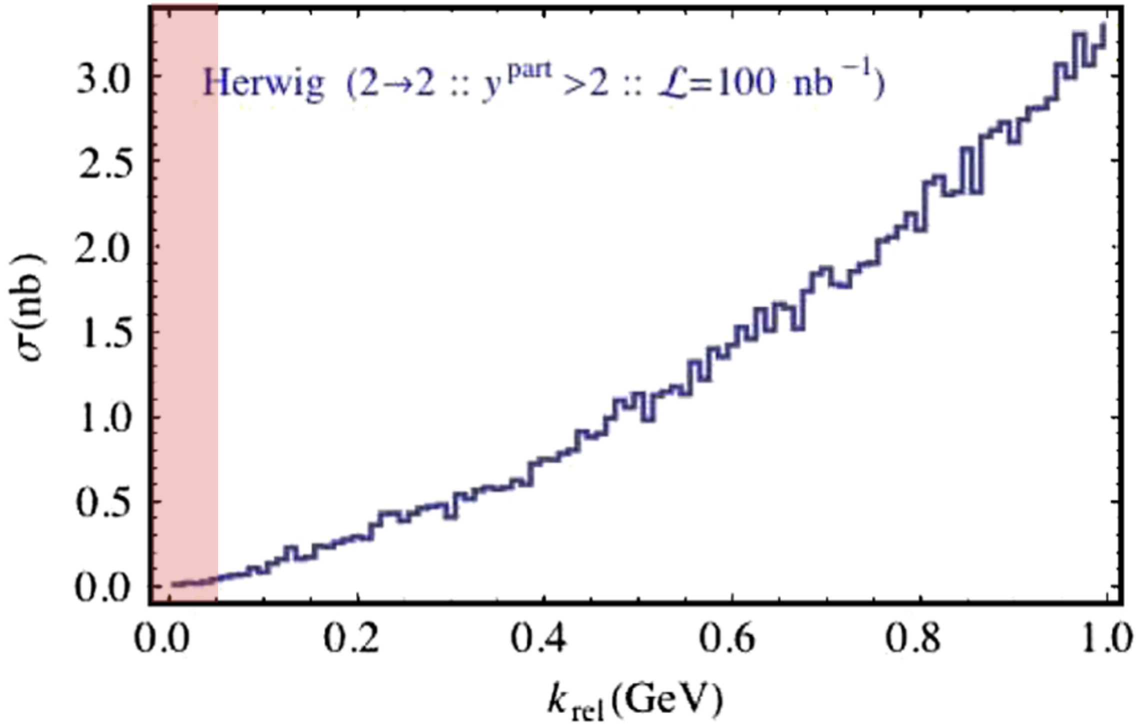
Cauchy-Schwartz inequality states that:

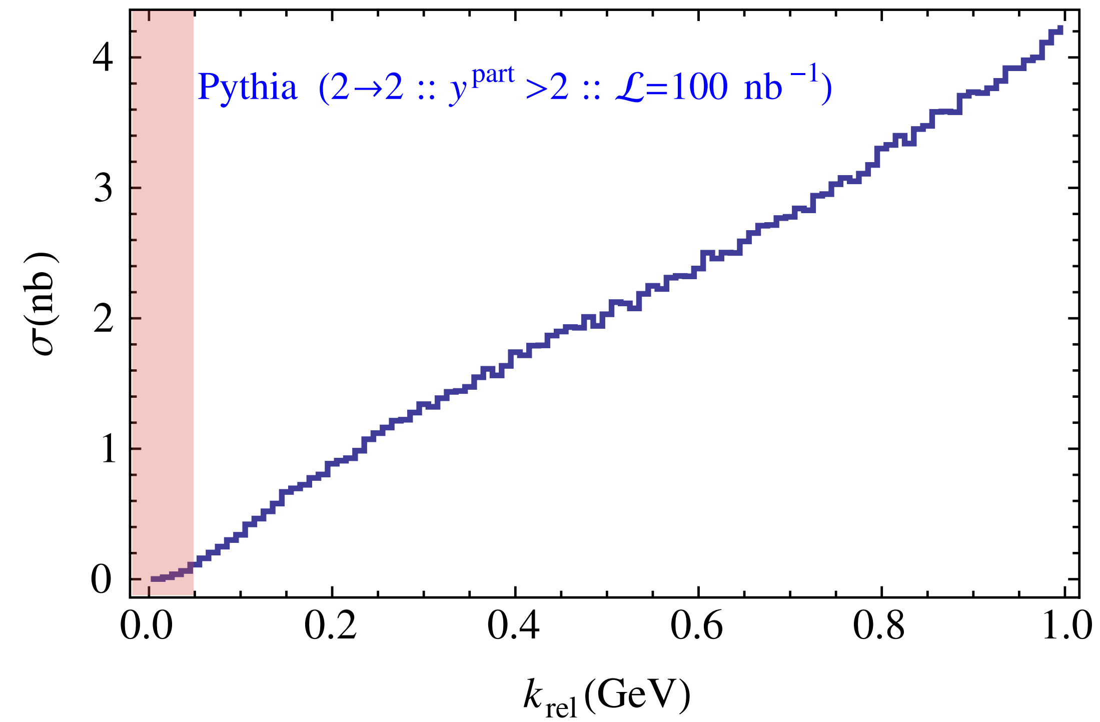
$$\phi(g, x) \leq \phi(g, g)\phi(f, f)$$

where ϕ is the inner product of to complex functions

$$\phi(g, f) = \int_a^b g^*(x) f(x)$$

$p\bar{p} \to X(3872)$ @ Pythia and Herwig





55×10^9 $2\to2$ events: $\mathcal{L} \sim 100\ \mathrm{nb}^{-1}$

Cuts on final D mesons are such that $p_\perp^X > 5$ GeV and $|y^X| < 0.6$

$[p_\perp^{part} > 2$ GeV and $|y^{part}| < 6]$

$$\boxed{\sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{max}}_{\mathrm{th}} \simeq 0.085\ \mathrm{nb}}$$

$\sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{max}}_{\mathrm{th}} \simeq 3\ \mathrm{nb}$ if k ranges up to ~200 MeV for Herwig

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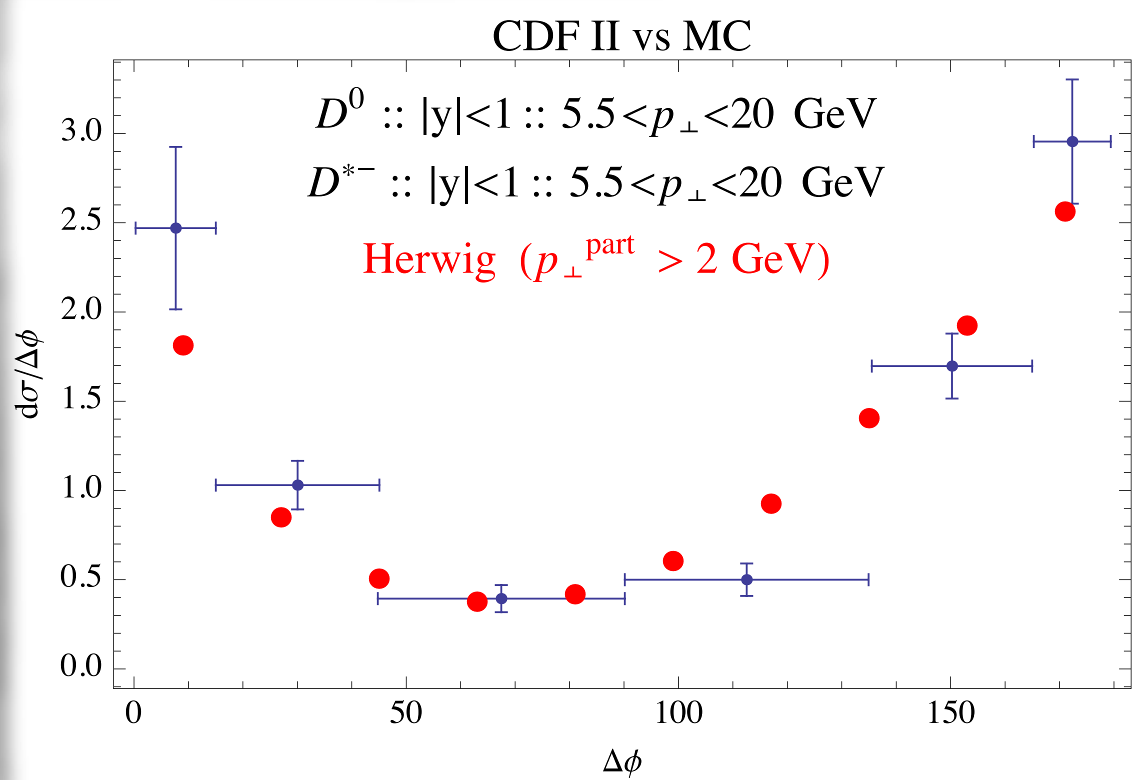
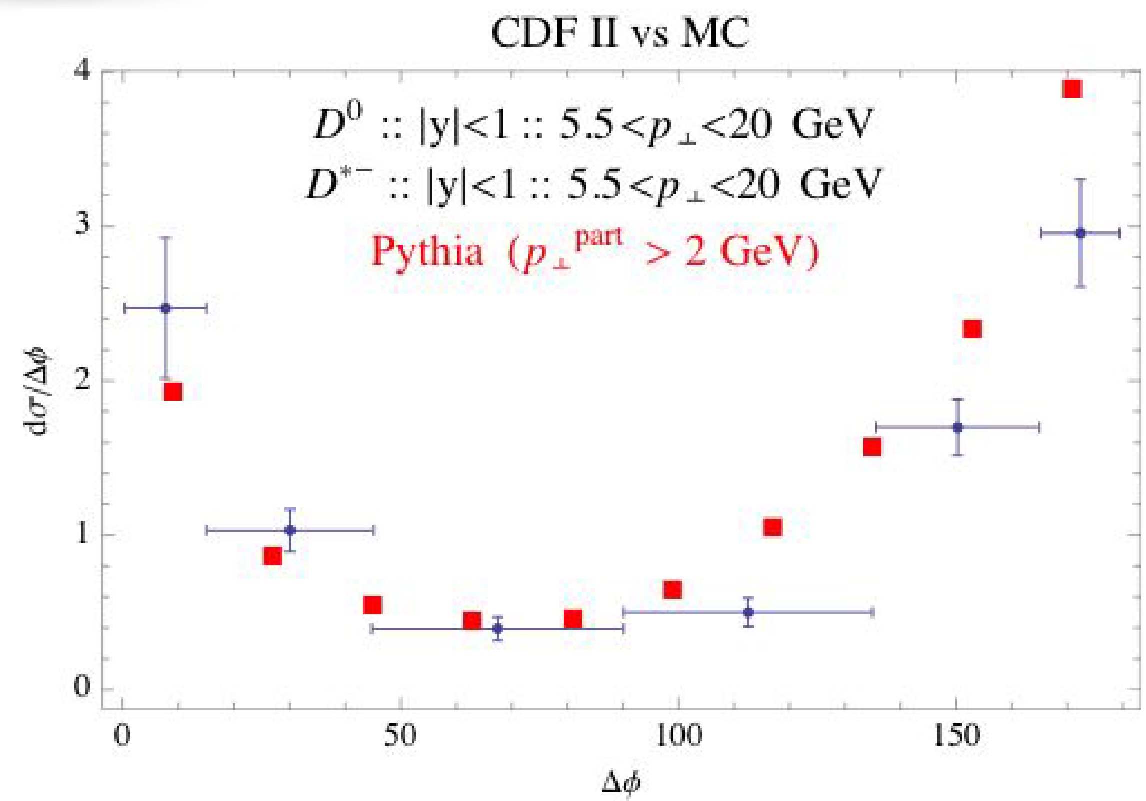
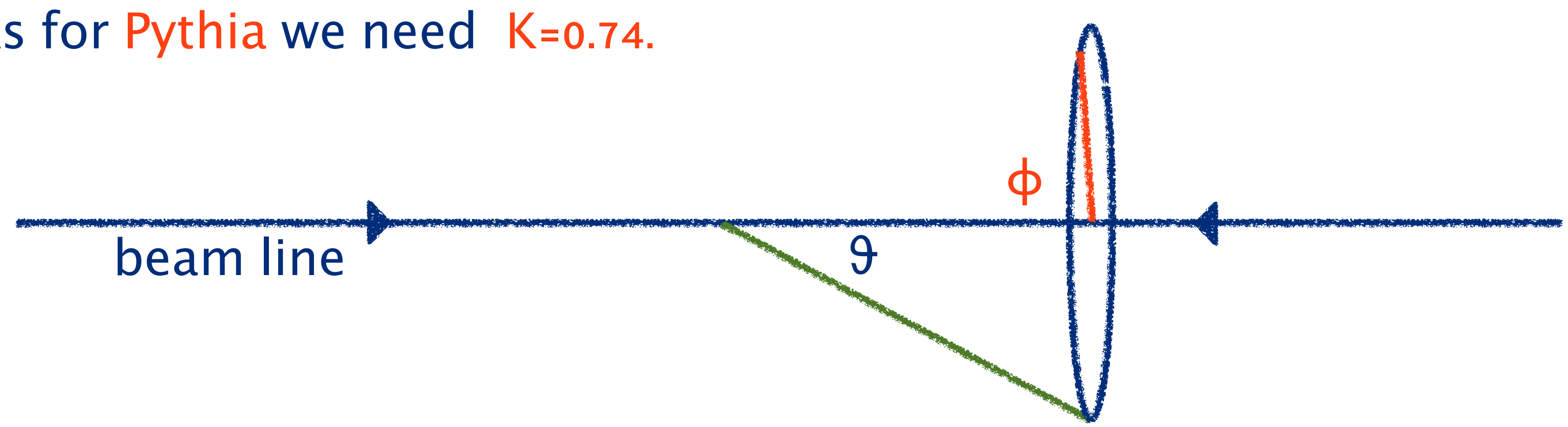
Tuning the MC

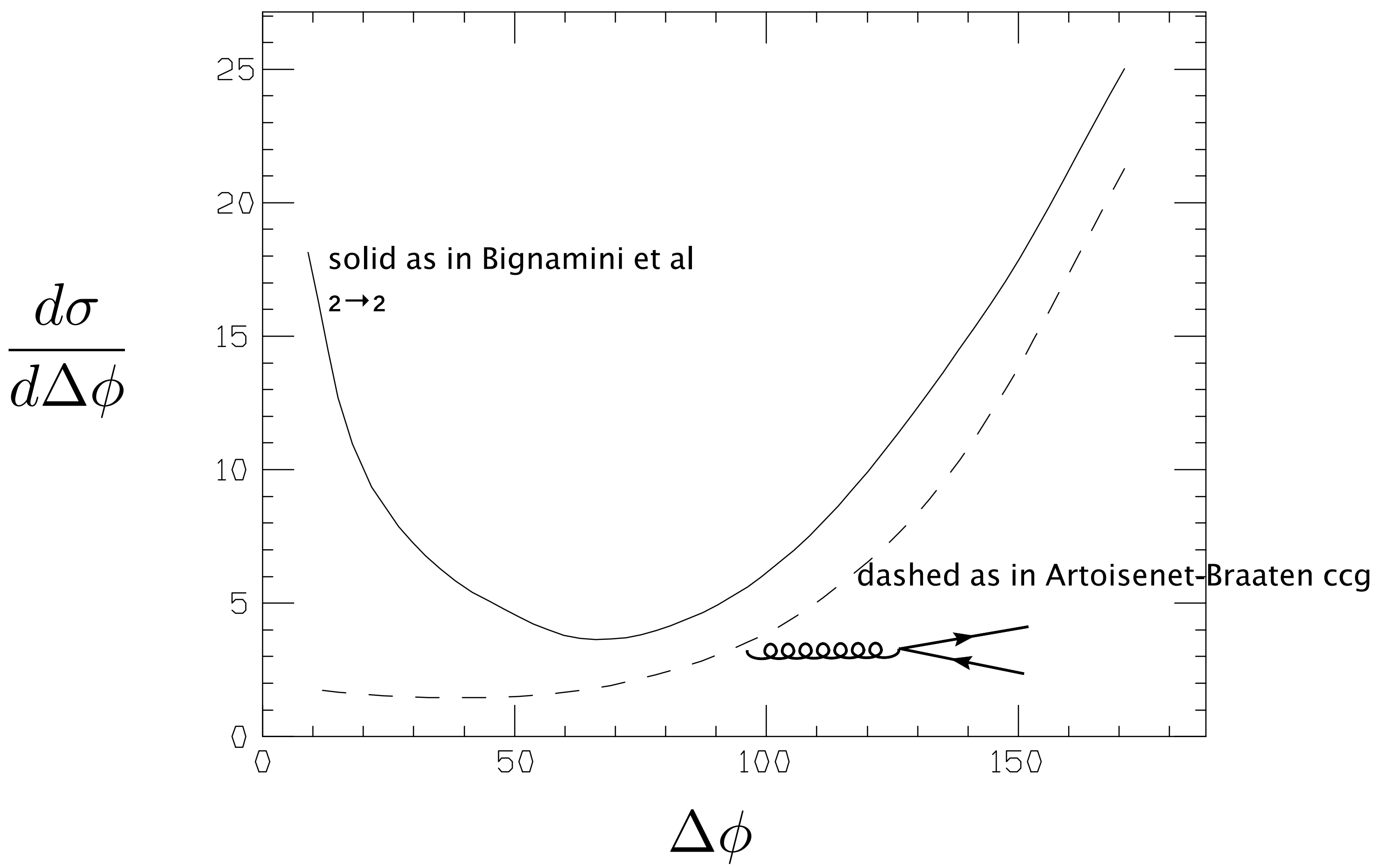




The D^0 D^{*-} pair cross section as function of $\Delta\phi$ at CDF Run II.
We find that we have to rescale the Herwig cross section values by a factor K= 1.8 to best fit the data on open charm production.
As for Pythia we need K=0.74.



Tuning the MC (2→2 vs ccg)



The region of small relative k is related to the small ΔΦ region. Data agree with the solid curve.

[Configurations with one gluon recoiling from a charm pair, are those configuration expected to produce two collinear charm quarks and in turn collinear open charm mesons. The parton shower algorithms in Herwig and Pythia treat properly these configurations at low pT (enhanced by collinear logarithms) whereas they are expected to be less important at higher pT. This has been verified using ALPGEN with pT(gluon)>5 and f.f. set to 1]

Watson theorem (1)

PHYSICAL REVIEW VOLUME 88, NUMBER 5 DECEMBER 1, 1952

The Effect of Final State Interactions on Reaction Cross Sections

KENNETH M. WATSON
Physics Department, Indiana University, Bloomington, Indiana
(Received August 18, 1952)

Particles produced in a reaction often interact strongly with each other before getting outside the range of their mutual forces. Formal effects of such interactions are discussed, and in particular it is shown that the effect for very strong attractive interactions can be calculated explicitly without having detailed knowledge of the properties of the reaction. Application is made to some meson phenomena.

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duced in the state B with rest masses M_i, momenta k_i, and energies W_i. The differential cross section for the reaction in the center-of-mass system is then (we set $\hbar=c=1$)

$$d\sigma=\frac{(2\pi)^4}{\mu_r}\int\delta\Big(\sum_{i=1}^{n}W_i-E_a\Big)\delta\Big(\sum_{i=1}^{n}\mathbf{k}i\Big)\times\prod_{i=1}^{n}d^3k_i\sum_{\text{spins}}|T_{Ba}|^2. \quad (23)$$

Here μ_r is the relative velocity of the colliding particles. The integration is to be carried out over four of the $3n$ momentum variables in such a way as to satisfy the conditions imposed by the δ-functions. The expression $\sum_{\text{spins}}$ is an appropriate average and sum over initial and final spin substates, respectively.

Let us suppose that there are at least three particles

where ξ is an appropriate set of coordinates. R is just the transition operator in a mixed representation and has been used previously[4] in the study of meson production in nucleon-nucleon collisions. Let $\mathbf{r}$ be that member of the coordinate set ξ which describes the relative position of particles "1" and "2." In accordance with the assumption that the reaction takes place within a certain volume, we suppose R to vanish as r becomes appreciably larger than a, the radius of this volume. Neglecting the interaction of particles "1" and "2" with others of the final state particles (phase space arguments lead one to expect a small probability that more than two particles will have small relative momenta) we can factor out of $\phi_B^{(-)}$ that part, $g_q^{(-)}(\mathbf{r})$, which describes the relative motion of particles "1" and "2." Writing $\phi_B^{(-)}=h_{B'}^{(-)}(\xi')g_q^{(-)}(\mathbf{r})$, where B' and ξ' do not contain q or r as variables, we next define

Watson theorem (1)

The factor $(f, \bar{R})$ is now essentially independent of q for small q-values (the only dependence coming from energy conservation, as remarked previously).

Inserting this expression into Eq. (23) and using (24) for the phase space factor, the cross section can be written as

$$d\sigma = \sin^2\delta \, dq \text{ times a factor independent of } q. \quad (33)$$

If we keep only the α-term in Eq. (29), this becomes

$$d\sigma \simeq q^2 dq/(\alpha^2+q^2). \quad (34)$$

In Eq. (30) we have neglected the term of order $\frac{1}{2}q^2a(r_0-a)$ compared to unity. Thus (34) is expected to be valid for q-values satisfying this condition or for a wavelength $\hbar/q$ large compared to the radius of the region of primary interaction. If α is larger than the maximum q-values for which Eq. (33) remains valid, Eq. (34) gives just the usual phase space dependence for the cross section which is expected to hold near threshold.[20] In this case we would not find so pronounced an effect from the final state interaction—and indeed might expect to be able to neglect it entirely.

We note that Eq. (33) agrees exactly with the estimate made in the introduction [Eq. (27)]. The criterion here found, that $|\alpha a|$ be appreciably less than unity, is just the condition described in the introduction, i.e., that the low energy scattering cross section of particles "1" and "2" be large compared to the cross section of the volume of primary interaction.

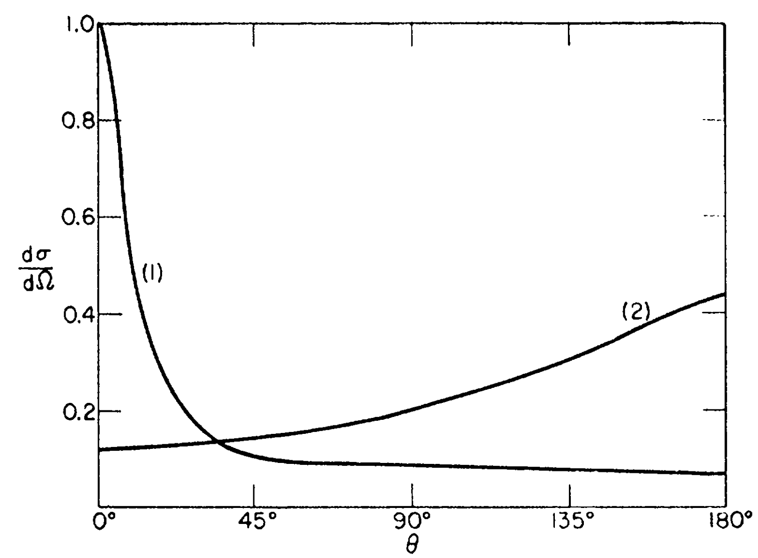

FIG. 2. The differential cross section for the production of a pair of interacting particles with an angular separation θ. Curve (1) is for an attractive interaction for which $\alpha^2/ME = 0.01$ [see Eq. (35)]. Curve (2) is the correlation to be expected to a repulsive interaction of about ten times the strength of that for curve (1).

If the low energy scattering is this orbital state in large, an analysis such as that made for S-states leads to

$$T_{Ba} = e^{i\delta_L}\frac{\sin\delta_L}{q^{L+1}} \text{ times a quantity independent of } q. \quad (36)$$

Here δ_L is the phase shift for the Lth partial wave in the scattering of particles "1" and "2." Equation (33) now becomes

$$d\sigma \simeq \frac{\sin^2\delta_L}{q^{2L}} dq. \quad (37)$$

Watson theorem (2)

The differential cross-section for the production of a DD* meson pair with fixed relative 3-momentum can be written as:

$$d\sigma(D^{*0}\bar{D}^0(\mathbf{k})) = \frac{1}{\text{flux}}\sum_{\text{all}}\int d\phi_{D^*\bar{D}+\text{all}}|T(D^{*0}\bar{D}^0(\mathbf{k})+\text{all})|^2\frac{d^3\mathbf{k}}{(2\pi)^3 2\mu}$$

Integrating up to k_{max} one obtains:

$$\sigma_{naive}(D^{*0}\bar{D}^0(|\mathbf{k}|<k_{max})) \sim \frac{1}{\text{flux}}\int d\phi_{D^{*0}\bar{D}^0+\text{all}}|T(D^{*0}\bar{D}^0(|\mathbf{k}|=k_{max})+all)|^2\times\frac{k_{max}^3}{12\pi^2\mu}$$

But is is the «naive» xsect, since FSI introduce an enhancement factor:

$$d\sigma(D^{*0}\bar{D}^0(\mathbf{k})) = \frac{1}{\text{flux}}\sum_{\text{all}}\int d\phi_{D^*\bar{D}+\text{all}}|T(D^{*0}\bar{D}^0(\mathbf{0})+\text{all})/f(0)|^2\times\boxed{\frac{1}{k^2+2\mu E_X}}\frac{d^3\mathbf{k}}{(2\pi)^3 2\mu}$$

this is true as far as only s-wave scattering is relevant since

$$f(k) = \frac{1}{k\cot\delta_0 - ik}\xrightarrow{k\sim 0}\frac{1}{-1/\alpha - ik}$$

[$\alpha^2=1/2\mu E_X$]

Watson theorem (3)

Since T(k)/f(k) is insensitive to the k value one can evaluate it at k_{max}

$$|f(k_{max})|^2 \sim 1/k_{max}^2$$

?! $k_{max} \approx 2m_\pi \approx 300$ MeV
$1/\alpha \approx 30$ MeV

and thus obtain the complete X prompt production cross section

$$\sigma(X) \sim \frac{1}{\text{flux}} \sum_{\text{all}} \int d\phi_{D^{*0}\bar{D}^0+\text{all}} |T(D^{*0}\bar{D}^0(|\mathbf{k}| = k_{max}) + \text{all})|^2 k_{max}^2 \frac{\sqrt{2\mu E_X}}{2\pi\mu}$$

which in turn means that

$$\boxed{\sigma(X) \sim \sigma_{naive}[(D^{*0}\bar{D}^0(|\mathbf{k}| < k_{max})] \times \frac{6\pi\sqrt{2\mu E_X}}{k_{max}}}$$

Other puzzling aspects

::Drenska,Faccini,Piccinini,Polosa,Renga,Sabelli::

:: BaBar, Phys. Rev. Lett., 96 (2006) 052002 ::

Absolute BF 68% intervals extracted using the upper limit $B(B^{\pm}\to K^{\pm}X)>3.2\times10^{-4}$ @ 90% c.l. from BaBar

Ratio of $B(X\to f)/B(X\to J/\psi\pi^+\pi^-)$

B Decay mode	X decay mode	B_{fit}	R_{fit}
$XK^{\pm}$	$X\to J/\psi\pi\pi$	$[0.035, 0.075]$	N/A
XK^0	$X\to J/\psi\pi\pi$	–	N/A
$XK^{\pm}$	$X\to D^{*0}D^0$	$[0.54, 0.8]$	$[3.9, 18.9]$
XK^0	$X\to D^{*0}D^0$	–	–
XK	$X\to \chi_c(1P)\gamma$	–	–
XK	$X\to J/\psi\gamma$	$[0.0075, 0.0195]$	$[0.19, 0.32]$
XK	$X\to \psi(2S)\gamma$	$[0.03, 0.09]$	$[0.75, 1.55]$
XK	$X\to \gamma\gamma$	< 0.0004	< 0.0078
XK	$X\to J/\psi\eta$	< 0.098	< 1.9
XK	$X\to J/\psi\pi\pi\pi^0$	$[0.015, 0.08]$	$[0.45, 1.44]$
XK^*	$X\to J/\psi\pi\pi$	–	–

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