# $\overline{D^0}\, D^0$-production at $p\,\bar{p}$-collisions within a Double Handbag Approach

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# Motivation: Why study $p\bar{p} \to \overline{D^0} D^0$?

## Experimental

- $p\bar{p} \to \overline{D^0} D^0$ could be measured by PANDA at FAIR.
- Comparison with alternative mechanisms which are on the market, e.g., the hadronic interaction model of the Jülich group.
- Testing the intrinsic charm content of the proton.

## Theoretical

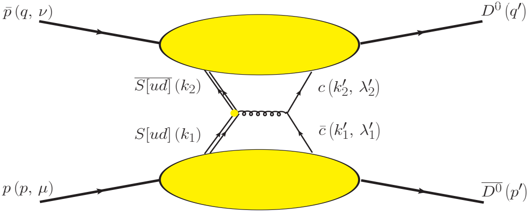
- Presence of heavy quarks often makes theoretical descriptions cleaner and simpler.
- $m_c$ provides hard scale $\Rightarrow$ perturbative QCD becomes applicable (under certain circumstances).
- Extension of the double handbag approach for $p\bar{p} \to \Lambda_c^+ \bar{\Lambda}_c^-$ in [ATG, P. Kroll and W. Schweiger, Eur.Phys.J. **A42** (2009)].

# Contents

# 1. Factorization of the Double Handbag

# Double Handbag Picture of $p\bar{p} \to \overline{D^0} D^0$

Heavy $D^0$-mass $M$ provides a large energy scale, $s > 4M^2 \approx 14\text{GeV}^2$.

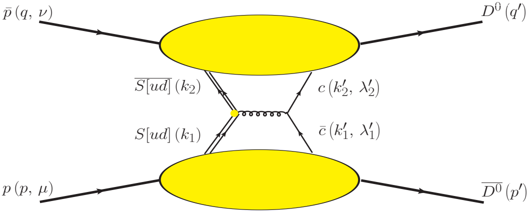



## Assuming that...

- ...explicite, intrinsic proton charm is negligible!
- ...proton can be considered as a quark-diquark system.
- ...scalar $S[ud]$-diquark configurations are dominant inside proton.

# Double Handbag Picture of $p\bar{p} \to \overline{D^0} D^0$

Heavy $D^0$-mass $M$ provides a large energy scale, $s > 4M^2 \approx 14\text{GeV}^2$.




- Hard Process:
  - $S[ud]\,(k_1)\ \overline{S[ud]}\,(k_2) \quad \to \quad \bar{c}\left(k_1^{'}, \lambda_1^{'}\right)\ c\left(k_2^{'}, \lambda_2^{'}\right)$
  - Described by perturbatively calculable Feynman diagrams.
- Soft Process:
  - Long distance effects of $p \to \overline{D^0}$ ($\bar{p} \to D^0$) transition.
  - Off-diagonal in flavor space; baryon number is changed.
  - Can be parametrized by Transition Distributions Amplitudes (TDAs).

# Kinematics of $p\bar{p} \to \overline{D^0} D^0$: Symmetric CMS

$$p = \left[ (1+\xi)\,\bar{p}^+, \frac{m^2 + \mathbf{\Delta}_\perp^2/4}{2\,(1+\xi)\,\bar{p}^+}, -\frac{\mathbf{\Delta}_\perp}{2} \right]$$

$$q = \left[ \frac{m^2 + \mathbf{\Delta}_\perp^2/4}{2\,(1+\xi)\,\bar{p}^+}, (1+\xi)\,\bar{p}^+, +\frac{\mathbf{\Delta}_\perp}{2} \right]$$

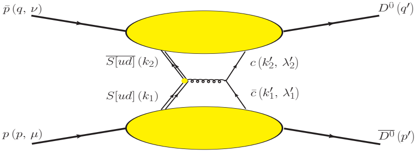
$$p' = \left[ (1-\xi)\,\bar{p}^+, \frac{M^2 + \mathbf{\Delta}_\perp^2/4}{2\,(1-\xi)\,\bar{p}^+}, +\frac{\mathbf{\Delta}_\perp}{2} \right]$$

$$q' = \left[ \frac{M^2 + \mathbf{\Delta}_\perp^2/4}{2\,(1-\xi)\,\bar{p}^+}, (1-\xi)\,\bar{p}^+, -\frac{\mathbf{\Delta}_\perp}{2} \right]$$

For the parametrization of the hadron momenta we have introduced

- $\bar{p} := \frac{1}{2}\,(p + p')$ with $\bar{\mathbf{p}}$ parallel to $\mathbf{e}_z$,
- $\Delta := p' - p = q - q' = k_1' - k_1 = k_2 - k_2'$,
- $\xi := \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2\bar{p}^+}$.

# $p\bar{p} \rightarrow \overline{D^0} D^0$ Process Amplitude

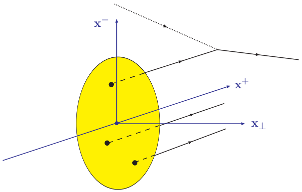


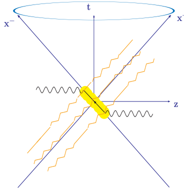

$$
\begin{aligned}
k_i^{(\prime)} &= \left[k_i^{(\prime)+},\, k_i^{(\prime)-},\, \mathbf{k_i^{(\prime)}}_{\perp}\right] \\
\bar{k}_i &= \left(k_i + k_i'\right)/2 \\
\bar{x}_1 &= \bar{k}_1^+/\bar{p}^+ \\
\bar{x}_2 &= \bar{k}_2^-/\bar{q}^-
\end{aligned}
$$

$$
\begin{aligned}
M_{\mu\nu} = \sum_{a_i^{(\prime)},\,\alpha_i'} \int d^4\bar{k}_1\,\theta\left(\bar{k}_1^+\right) \int d^4\bar{k}_2\,\theta\left(\bar{k}_2^-\right)\; \tilde{H}_{a_i^{(\prime)},\,\alpha_i'}\left(\bar{k}_1, \bar{k}_2\right) \\
\int \frac{d^4 z_1}{(2\pi)^4} e^{\imath \bar{k}_1 z_1} \langle \overline{D^0} : p' | \mathcal{T}\, \Psi^c_{a_1',\,\alpha_1'}\left(-\frac{z_1}{2}\right) \Phi^{S[ud]}_{a_1}\left(+\frac{z_1}{2}\right) | p : p, \mu \rangle \\
\int \frac{d^4 z_2}{(2\pi)^4} e^{\imath \bar{k}_2 z_2} \langle D^0 : q' | \mathcal{T}\, \Phi^{S[ud]\dagger}_{a_2}\left(+\frac{z_2}{2}\right) \overline{\Psi}^c_{a_2',\,\alpha_2'}\left(-\frac{z_2}{2}\right) | \bar{p} : q, \nu \rangle
\end{aligned}
$$

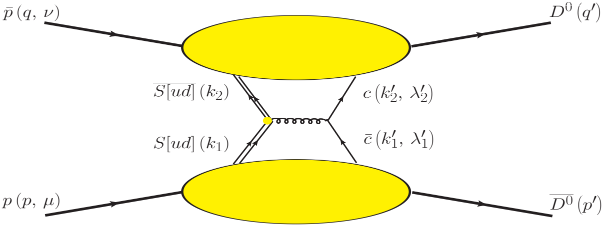
# Parton Kinematics for $p\bar{p} \rightarrow \overline{D^0} D^0$

- Restrictions on parton momenta:
  - $k_{\perp i}^2 / x_i \lesssim \Lambda^2$ for intrinsic transverse momenta
  - $k_i^2 \lesssim \Lambda^2$, $|k_{ic}^2 - m_c^2| \lesssim \Lambda^2$ for virtualities
- Consequences of restrictions:
  - $\mathbf{k}_{1\perp}^{(\prime)}$ and $k_1^{(\prime)-}$ much smaller than $k_1^{(\prime)+}$. Partons then almost on-shell and collinear with parent hadrons, i.e. $k_1^{(\prime)} \simeq x_1^{(\prime)} p^{(\prime)}$.
  - Emission of $S[ud]$-diquark and re-absorption of $\bar{c}-$quark at the same LC-time. Thus, time ordering can be dropped.



# $p\bar{p} \rightarrow \overline{D^0}D^0$ Process Amplitude: Simplification

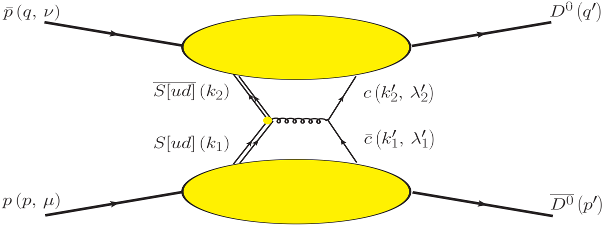



$$M_{\mu\nu} = \sum_{a_i^{(\prime)},\,\alpha_i'} \int d\bar{k}_1^+\,\theta\left(\bar{k}_1^+\right) \int d\bar{k}_2^-\,\theta\left(\bar{k}_2^-\right)\ \tilde{H}_{a_i^{(\prime)},\,\alpha_i'}\left(\bar{k}_1,\bar{k}_2\right)$$

$$\int \frac{dz_1^-}{2\pi} e^{\imath \bar{k}_1^+ z_1^-} \langle \overline{D^0} : p^{'} | \Psi^c_{a_1',\,\alpha_1'}\left(-\frac{z_1^-}{2}\right) \Phi^{S[ud]}_{a_1}\left(+\frac{z_1^-}{2}\right) | p : p, \mu \rangle$$

$$\int \frac{dz_2^+}{2\pi} e^{\imath \bar{k}_2^- z_2^+} \langle D^0 : q^{'} | \Phi^{S[ud]\dagger}_{a_2}\left(+\frac{z_2^+}{2}\right) \overline{\Psi}^c_{a_2',\,\alpha_2'}\left(-\frac{z_2^+}{2}\right) | \bar{p} : q, \nu \rangle$$

# $p\bar{p} \to \overline{D^0} D^0$ Process Amplitude: Simplification




$$M_{\mu\nu} = \sum_{a_i^{(\prime)},\,\alpha_i'} \int d\bar{x}_1\, \bar{p}^+ \int d\bar{x}_2\, \bar{q}^- \;\tilde{H}_{a_i^{(\prime)},\,\alpha_i'}(\bar{x}_1, \bar{x}_2)$$

$$\int \frac{dz_1^-}{2\pi} e^{\imath \bar{k}_1^+ z_1^-} \langle \overline{D^0} : p' | \Psi^c_{a_1',\,\alpha_1'}\left(-\frac{z_1^-}{2}\right) \Phi^{S[ud]}_{a_1}\left(+\frac{z_1^-}{2}\right) | p : p, \mu\rangle$$

$$\int \frac{dz_2^+}{2\pi} e^{\imath \bar{k}_2^- z_2^+} \langle D^0 : q' | \Phi^{S[ud]\dagger}_{a_2}\left(+\frac{z_2^+}{2}\right) \overline{\Psi}^c_{a_2',\,\alpha_2'}\left(-\frac{z_2^+}{2}\right) | \bar{p} : q, \nu\rangle$$

# 2. Calculation of the Double Handbag

# Soft $p \to \overline{D^0}$ and $\bar{p} \to D^0$ Transitions

The soft non-perturbative dynamics of the process $p\bar{p} \to \overline{D^0} D^0$ is encoded in the Fourier-transformed hadronic matrix elements

$$\bar{p}^+ \int \frac{dz_1^-}{(2\pi)} e^{\imath \bar{x}_1 \bar{p}^+ z_1^-} \langle \overline{D^0} : p' | \Psi^c \left( -\frac{z_1^-}{2} \right) \Phi^{S[ud]} \left( +\frac{z_1^-}{2} \right) | p : p, \mu \rangle$$

for the $p \to \overline{D^0}$ transition and

$$\bar{q}^- \int \frac{dz_2^+}{(2\pi)} e^{\imath \bar{x}_2 \bar{q}^- z_2^+} \langle D^0 : q' | \Phi^{S[ud]\dagger} \left( +\frac{z_2^+}{2} \right) \overline{\Psi}^c \left( -\frac{z_2^+}{2} \right) | \bar{p} : q, \nu \rangle$$

for the $\bar{p} \to D^0$ transition.

# $p \to \overline{D^0}$ Transition: Hadronic Matrix Element

When using that

- $\Psi^c\left(-\frac{z_1^-}{2}\right) = \frac{1}{2k_1'^+}\sum_{\lambda_1'} v(k_1',\lambda_1')\left(\bar{v}(k_1',\lambda_1')\gamma^+\Psi^c\left(-\frac{z_1^-}{2}\right)\right)$

and

- $\bar{v}(\cdots)\gamma^+\Psi^c(\cdots) = \bar{v}(\cdots)\gamma^+\Psi^c_+(\cdots)$ with $\Psi^c_+ := \frac{1}{2}\gamma^-\gamma^+\Psi^c$

the hadronic matrix element becomes

$$\bar{p}^+\int\frac{dz_1^-}{(2\pi)}e^{\imath\bar{x}_1\bar{p}^+z_1^-}\langle\overline{D^0}:p'|\Psi^c\left(-\frac{z_1^-}{2}\right)\Phi^{S[ud]}\left(+\frac{z_1^-}{2}\right)|p:p,\mu\rangle$$
$$=\frac{\bar{p}^+}{2k_1'^+}\sum_{\lambda_1'}v(k_1',\lambda_1')\int\frac{dz_1^-}{(2\pi)}e^{\imath\bar{x}_1\bar{p}^+z_1^-}\langle\overline{D^0}:p'|$$
$$\times\left(\bar{v}(k_1',\lambda_1')\gamma^+\Psi^c\left(-\frac{z_1^-}{2}\right)\right)\Phi^{S[ud]}\left(+\frac{z_1^-}{2}\right)|p:p,\mu\rangle\,.$$

# $p\bar{p} \to \overline{D^0} D^0$ Process Amplitude: Convolution

The $p\bar{p} \to \overline{D^0} D^0$ process amplitude becomes a convolution integral of the hard part

- $H_{\lambda_1', \lambda_2'}(\bar{x}_1, \bar{x}_2) := \bar{u}(k_2', \lambda_2')\, \tilde{H}(\bar{x}_1 \bar{p}^+, \bar{x}_2 \bar{q}^-)\, v(k_1', \lambda_1')$

and the soft part

- $\mathcal{H}^{\bar{c}S}_{\lambda_1' \mu} := \bar{v}(k_1', \lambda_1') \gamma^+ \bar{p}^+ \int \frac{dz_1^-}{(2\pi)} e^{\imath \bar{x}_1 \bar{p}^+ z_1^-} \langle \overline{D^0} : p' | \Psi^c_+ \Phi^{S[ud]} | p : p, \mu \rangle$ .

$$M_{\mu\nu} = \frac{1}{4(\bar{p}^+)^2} \sum_{\lambda_1', \lambda_2'} \int \frac{d\bar{x}_1}{\bar{x}_1 - \xi} \int \frac{d\bar{x}_2}{\bar{x}_2 - \xi} \times \mathcal{H}^{c\bar{S}}_{\lambda_2' \nu}(\bar{x}_2)\, H_{\lambda_1', \lambda_2'}(\bar{x}_1, \bar{x}_2)\, \mathcal{H}^{\bar{c}S}_{\lambda_1' \mu}(\bar{x}_1)$$

# $p\bar{p} \to \overline{D^0} D^0$ Process Amplitude: Peaking Approximation

Transition matrix element expected to exhibit a pronounced peak w.r.t. momentum fraction! The position of the peak is approximately at

$$x_0 = \frac{m_c}{M} = 0.68 .$$

C.f. [ATG, P. Kroll and W. Schweiger, Eur.Phys.J. **A42** (2009)] and HQET.

$$M_{\mu\nu} = \frac{1}{4(\bar{p}^+)^2} \sum_{\lambda_1', \lambda_2'} \int \frac{d\bar{x}_1}{\bar{x}_1 - \xi} \int \frac{d\bar{x}_2}{\bar{x}_2 - \xi} \times \mathcal{H}^{c\bar{S}}_{\lambda_2'\nu}(\bar{x}_2)\, H_{\lambda_1', \lambda_2'}(\bar{x}_1, \bar{x}_2)\, \mathcal{H}^{\bar{c}S}_{\lambda_1'\mu}(\bar{x}_1)$$

# $p\bar{p} \to \overline{D^0} D^0$ Process Amplitude: Peaking Approximation

Thus, in hard $S[ud]\overline{S[ud]} \to \bar{c}c$ subprocess amplitude only kinematical regions of the momentum fractions close to $x_0$ are enhanced.

$\Rightarrow$ Replacing $\bar{x}_1$ and $\bar{x}_2$ with $x_0$ in the hard subprocess amplitude! $\Rightarrow$

$$M_{\mu\nu} = \frac{1}{4(\bar{p}^+)^2} \sum_{\lambda_1', \lambda_2'} H_{\lambda_1', \lambda_2'}(x_0, x_0) \times \int \frac{d\bar{x}_1}{\bar{x}_1 - \xi} \mathcal{H}^{\bar{c}S}_{\lambda_1'\mu}(\bar{x}_1) \int \frac{d\bar{x}_2}{\bar{x}_2 - \xi} \mathcal{H}^{c\bar{S}}_{\lambda_2'\nu}(\bar{x}_2)$$

# $p \rightarrow \overline{D^0}$ Transition: Overlap Representation

$$\mathcal{H}^{\bar{c}S}_{\lambda_1'\mu} = \bar{v}(k_1', \lambda_1')\gamma^+\bar{p}^+ \int \frac{dz_1^-}{(2\pi)} e^{\imath\bar{x}_1\bar{p}^+z_1^-} \langle \overline{D^0} : p^{'} | \Psi_+^c(\cdots)\Phi^{S[ud]}(\cdots)| p : p, \mu\rangle$$

$$| \, p : \, p, \, \mu\rangle = \int \frac{d\tilde{x} d^2\tilde{k}_\perp}{16\pi^3} \psi_p(\tilde{x}, \, \tilde{\mathbf{k}}_\perp) \frac{1}{\sqrt{\tilde{x}(1-\tilde{x})}} \times | \, S[ud] : \, \tilde{x}, \, \tilde{\mathbf{k}}_\perp\rangle \, | \, u : \, 1-\tilde{x}, \, -\tilde{\mathbf{k}}_\perp\rangle$$

$$| \, \overline{D^0} : \, p'\rangle = \int \frac{d\hat{x}' d^2\hat{k}_\perp'}{16\pi^3} \psi_D(\hat{x}', \, \hat{\mathbf{k}}_\perp') \frac{1}{\sqrt{\hat{x}'(1-\hat{x}')}} \times \frac{1}{\sqrt{2}} \sum_{\lambda'} (2\lambda') \, | \, \bar{c} : \, \hat{x}', \, \hat{\mathbf{k}}_\perp^\perp\rangle \, | \, u : \, 1-\hat{x}', \, -\hat{\mathbf{k}}_\perp'\rangle$$

# $p \to \overline{D^0}$ Transition: Overlap Representation

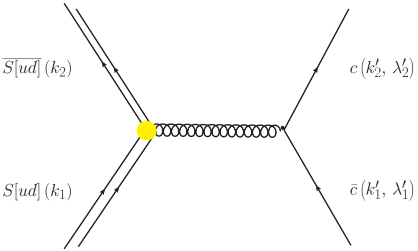
$$\mathcal{H}^{\bar{c}S}_{\lambda_1'\mu} = -\sqrt{2}\mu\bar{p}^+ \int \frac{d\bar{x}d^2\bar{k}_\perp}{16\pi^3}\sqrt{\frac{\bar{x}-\xi}{\bar{x}+\xi}}\delta(\bar{x}-\bar{x}_1)\delta_{-\lambda_1',\mu}$$
$$\psi_D\left(\hat{x}'(\bar{x},\,\xi),\,\hat{\mathbf{k}}'_\perp(\bar{\mathbf{k}}_\perp,\,\bar{x},\,\xi)\right)\psi_p\left(\tilde{x}(\bar{x},\,\xi),\,\tilde{\mathbf{k}}_\perp(\bar{\mathbf{k}}_\perp,\,\bar{x},\,\xi)\right)$$

$$|\,p:\ p,\,\mu\rangle = \int \frac{d\tilde{x}d^2\tilde{k}_\perp}{16\pi^3}\psi_p(\tilde{x},\,\tilde{\mathbf{k}}_\perp)\frac{1}{\sqrt{\tilde{x}(1-\tilde{x})}}\,|\,S[ud]:\ \tilde{x},\,\tilde{\mathbf{k}}_\perp\rangle$$
$$\times\,|\,u:\ 1-\tilde{x},\,-\tilde{\mathbf{k}}_\perp\rangle$$

$$|\,\overline{D^0}:\ p'\rangle = \int \frac{d\hat{x}'d^2\hat{k}'_\perp}{16\pi^3}\psi_D(\hat{x}',\,\hat{\mathbf{k}}'_\perp)\frac{1}{\sqrt{\hat{x}'(1-\hat{x}')}} \times \frac{1}{\sqrt{2}}\sum_{\lambda'}(2\lambda')\,|\,\bar{c}:\ \hat{x}',\,\hat{\mathbf{k}}^\perp_\perp\rangle$$
$$\times\,|\,u:\ 1-\hat{x}',\,-\hat{\mathbf{k}}'_\perp\rangle$$

Extension of [M. Diehl, Th. Feldmann, R. Jakob and P. Kroll, Nucl.Phys. **B596** (2001)].

# Hard $S[ud]\overline{S[ud]} \to \bar{c}c$ Amplitude: Peaking Approximation




$$H_{++} = +4\pi\alpha_s(x_0^2 s)F_s(x_0^2 s)\frac{4}{9}\frac{2M}{\sqrt{s}}\cos\theta$$
$$H_{+-} = -4\pi\alpha_s(x_0^2 s)F_s(x_0^2 s)\frac{4}{9}\sin\theta$$
$$H_{-+} = -4\pi\alpha_s(x_0^2 s)F_s(x_0^2 s)\frac{4}{9}\sin\theta$$
$$H_{--} = -4\pi\alpha_s(x_0^2 s)F_s(x_0^2 s)\frac{4}{9}\frac{2M}{\sqrt{s}}\cos\theta$$

$F_s(\hat{s}) = |\, Q_0^2/\left(Q_0^2 - \hat{s}\right) |$ is a diquark form factor at the $Sg\bar{S}$-vertex.
It is an analytical continuation into the time-like region of the one in [M. Anselmino, P. Kroll and B. Pire, Z.Phys. **C36** (1987)].
$(Q_0^2 = 3.22\text{GeV}^2,\ \hat{s} > Q_0^2.)$

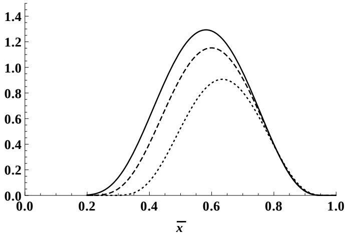
# 3. Modelling the $p \to \overline{D^0}$ Transitions, Results and Outlook

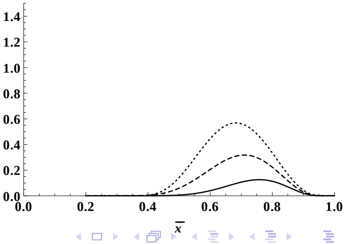
# Valence Quark-Diquark Model for $p\bar{p} \to \overline{D^0} D^0$

$$\psi_p\left(\tilde{x}, \tilde{\mathbf{k}}_\perp\right) = N_p\, \tilde{x} \exp\left[-\frac{a_p^2}{\tilde{x}\,(1-\tilde{x})}\tilde{\mathbf{k}}_\perp^2\right] \text{ for the proton},$$

$$\psi_D\left(\hat{x}', \hat{\mathbf{k}}'_\perp\right) = N_D \exp\left[-\frac{a_D^2}{\hat{x}'\,(1-\hat{x}')}\hat{\mathbf{k}}_\perp'^2\right] \exp\left[-a_D^2 M^2 \frac{(\hat{x}'-x_0)^2}{\hat{x}'\,(1-\hat{x}')}\right] \text{ for } D^0.$$

$N_p = 61.8\text{GeV}^{-2}$, $a_p = 1.1\text{GeV}^{-1}$ and $N_D = 55.2\text{GeV}^{-2}$, $a_D = 0.864\text{GeV}^{-1}$.
C.f. [P. Kroll, B. Quadder and W. Schweiger, Nucl.Phys. **B316** (1989)] and [ATG, P. Kroll and W. Schweiger, Eur.Phys.J. **A42** (2009)].



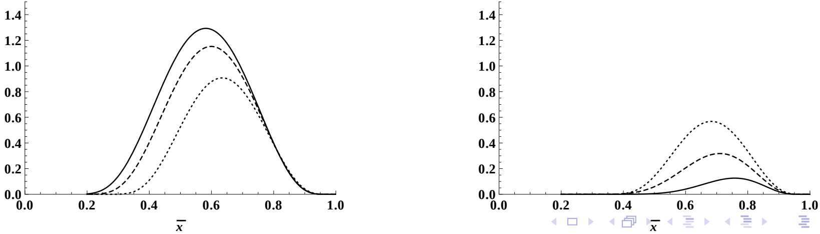



# Valence Quark-Diquark Model for $p\bar{p} \to \overline{D^0} D^0$

$$\psi_p\left(\tilde{x}, \tilde{\mathbf{k}}_\perp\right) = N_p\,\tilde{x}\,\exp\left[-\frac{a_p^2}{\tilde{x}\,(1-\tilde{x})}\tilde{\mathbf{k}}_\perp^2\right] \text{ for the proton},$$

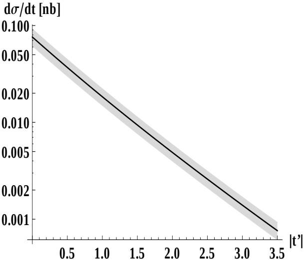
$$\psi_D\left(\hat{x}', \hat{\mathbf{k}}'_\perp\right) = N_D\,\exp\left[-\frac{a_D^2}{\hat{x}'\,(1-\hat{x}')}\hat{\mathbf{k}}_\perp'^2\right]\,\exp\left[-a_D^2 M^2 \frac{(\hat{x}'-x_0)^2}{\hat{x}'\,(1-\hat{x}')}\right] \text{ for } D^0 .$$

The wave function overlap is shown for Mandelstam $s = 30$, 20 and $15\text{GeV}^2$, corresponding to the *solid*, *dashed* and *dotted* curves, respectively. On the *left* and *right* panels the CMS scattering angle $\theta$ is 0 and $\pi/2$, respectively.

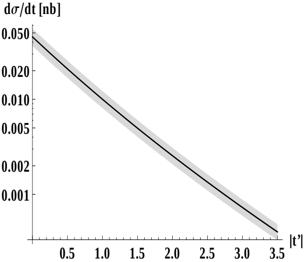


# Differential $p\bar{p} \to \overline{D^0} D^0$ Cross Sections

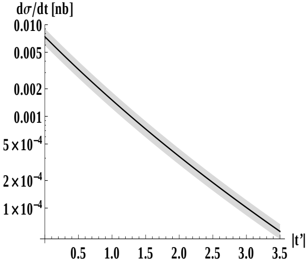
[A.T. Goritschnig, B. Pire and W. Schweiger, Phys.Rev. **D87** (2013)]




@ $s = 15\text{GeV}^2$




@ $s = 20\text{GeV}^2$

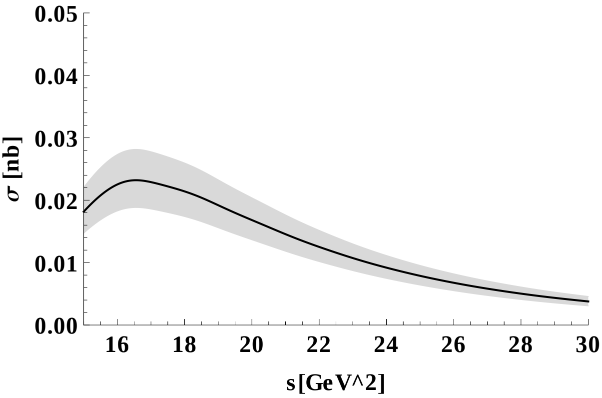



@ $s = 30\text{GeV}^2$

Comment: Compare with larger cross sections of Jülich-group, e.g. in [J. Haidenbauer and G. Krein, Few Body Syst. **50** (2011)].

# Integrated $p\bar{p} \to \overline{D^0}D^0$ Cross Section

[A.T. Goritschnig, B. Pire and W. Schweiger, Phys.Rev. **D87** (2013)]



# Conclusion and Outlook

- Handbag approach applied to charmed meson-pair production.
- Usual TDAs can be extended to flavor-changing TDAs.
- Predictions indicate that $p\bar{p} \rightarrow \overline{D^0} D^0$ cross sections could be still measureable at, e.g., FAIR.
- Comparison with other mechanisms possible.

- Extension to other meson channels.
- $p \rightarrow \overline{D^0}$ TDAs could be used in other processes.
- Claculation of heavy meson-pair production with other pQCD mechanisms.

Thank you for your attention!