First results of exclusive p and $\bar{p}$ annihilation into a pion pair at large scattering angles

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2. Reaction Mechanism of $p\ \bar{p} \to \pi^+\ \pi^-$
3. Modeling
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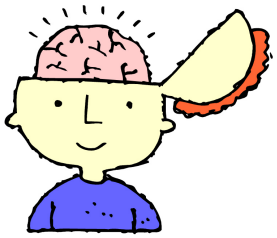
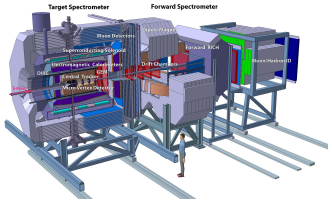
Motivation



Theoretically

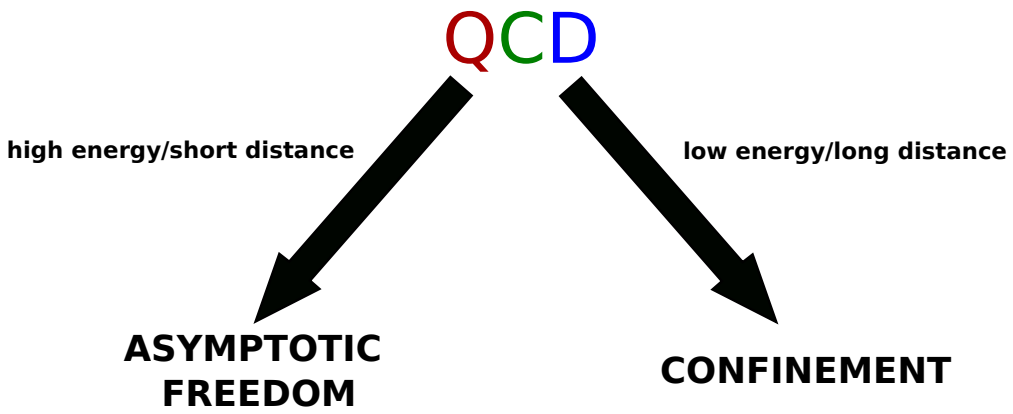
- investigate the exclusive process $p\ \bar{p} \to \pi^+\ \pi^-$ in the QCD *collinear factorization framework*
- help to understand the interior of hadrons in terms of the fundamental degrees of freedom of QCD



Experimentally

- can be measured by PANDA at FAIR
- cross section measurement $\Rightarrow$ test of QCD factorization and access to TDAs

The General Setting



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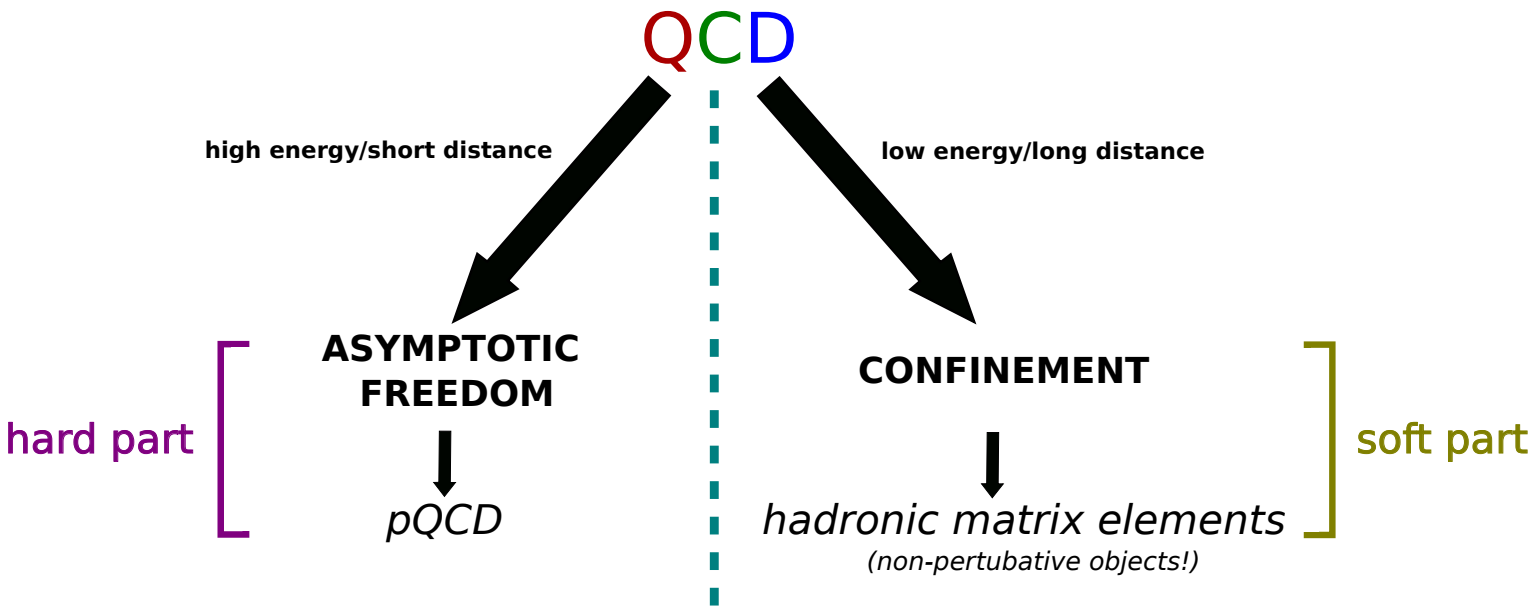

a welcome feature of QCD: **FACTORIZATION**
(for specific processes in specific kinematics)

divide process into: hard part and soft part (at the amplitude level)

Kinematics in a Nutshell

incoming momenta

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

$$q = \left[q^+, q^-, +\frac{\mathbf{\Delta}_\perp}{2}\right] \qquad \left(q^2 = m^2\right)$$

outgoing momenta

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

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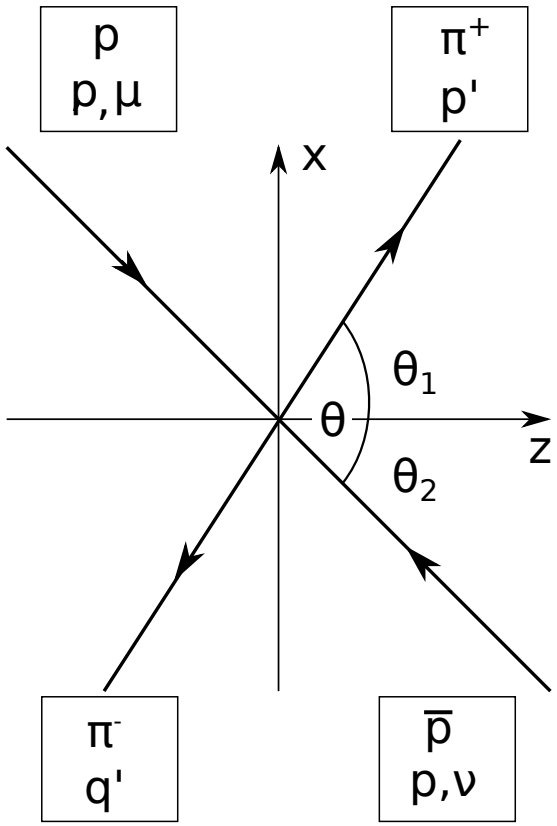
$$a^\pm = \frac{a^0 \pm a^3}{\sqrt{2}}, \mathbf{a}_\perp = (a_1, a_2)$$



- $\bar{p} := \frac{1}{2}(p + p')$
- $\xi := \frac{p'^+ - p^+}{p^+ + p'^+} = \frac{\Delta^+}{2\bar{p}^+}$
- $\Delta := p' - p = q - q'$

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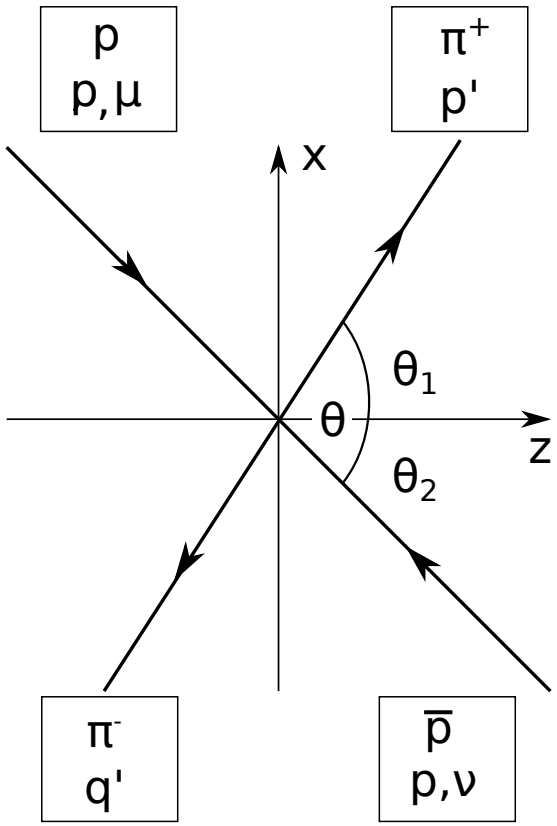

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Double Handbag Contribution to $p\ \bar{p} \to \pi^+\ \pi^-$

Assumptions:

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- scalar diquark configurations are dominant

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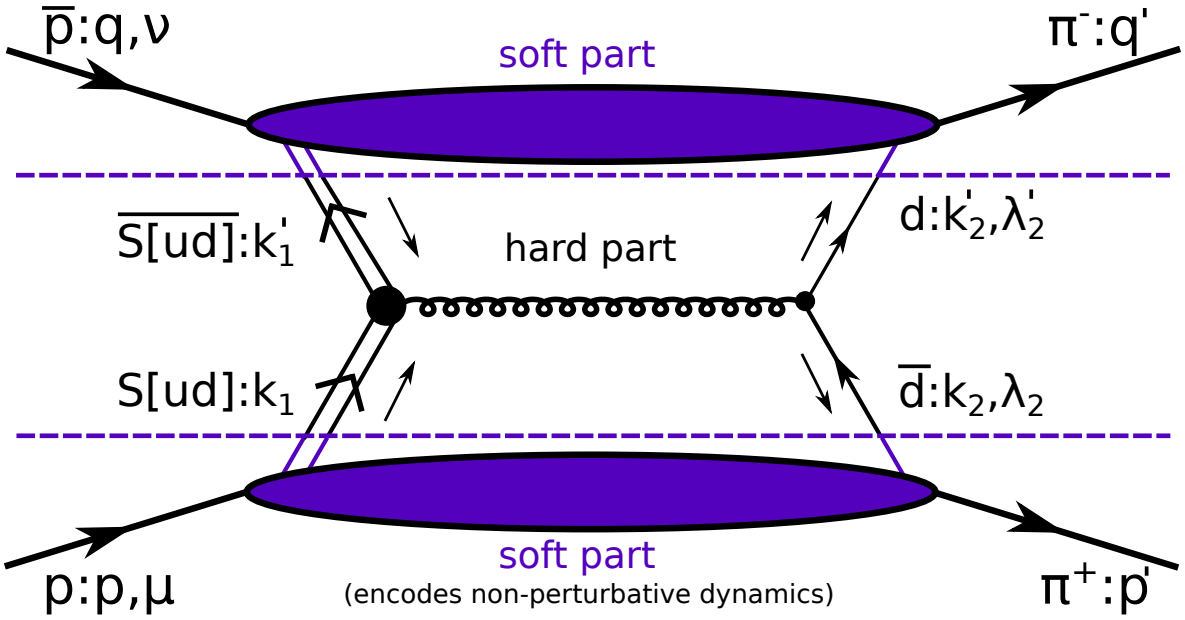

hard scale: large scattering angles = large Mandelstam t and u, i.e. $t, u \geq 1\ \text{GeV}^2$

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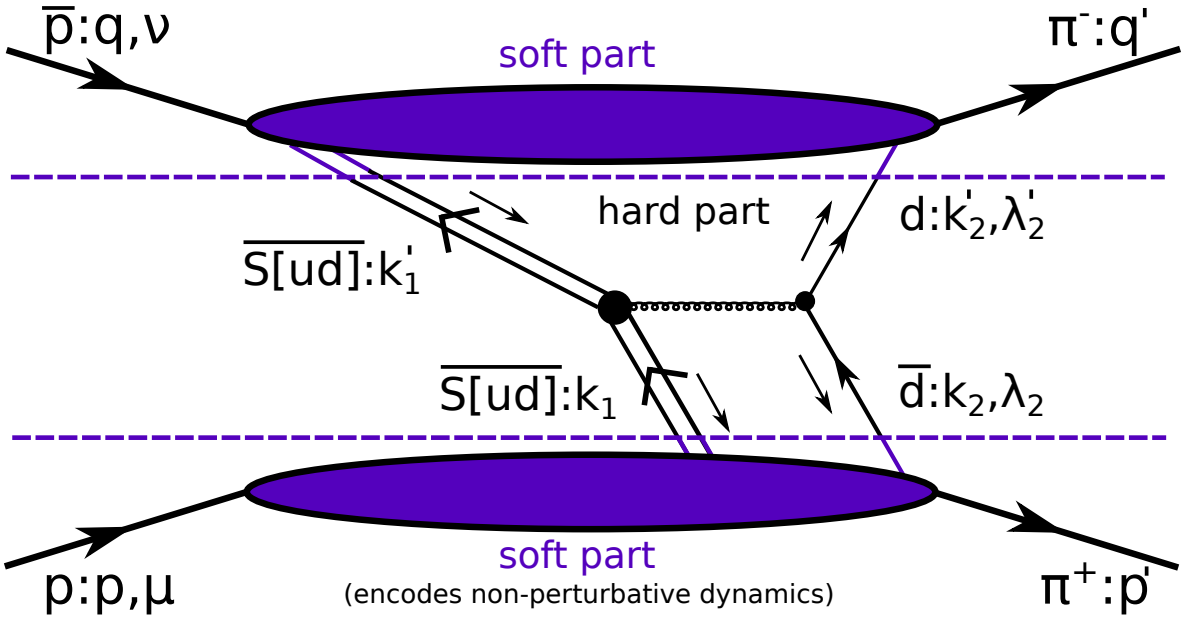

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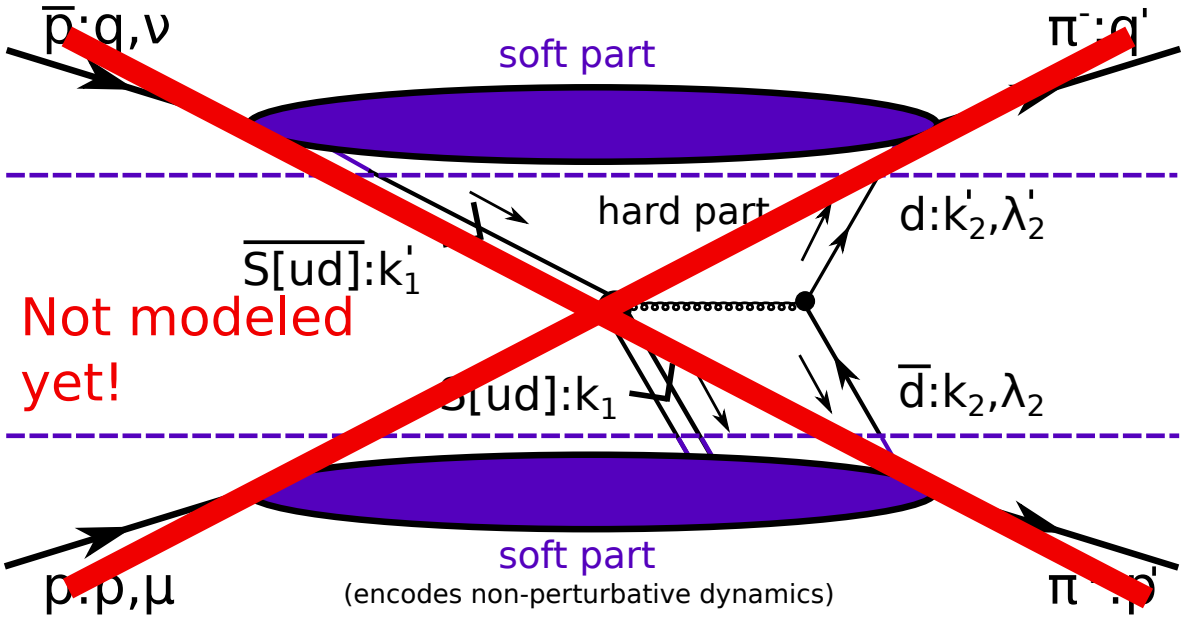

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Process Amplitude

$$\mathscr{M}_{\mu\nu} \propto \int \mathrm{d}\bar{x} \int \mathrm{d}\bar{x}' \boxed{H\left(\bar{x}, \bar{x}'\right)}$$

hard part

$$\times \bar{p}^+ \int \mathrm{d}z^- e^{i\bar{x}\bar{p}^+ z^-} \langle \pi^+ : p' | \, \bar{v}\gamma^+ \Psi^d \left(-\frac{z^-}{2}\right) \phi^{S[ud]} \left(\frac{z^-}{2}\right) \, |p : p, \mu\rangle$$

$$\times \bar{p}^+ \int \mathrm{d}z'^+ e^{i\bar{x}'\bar{p}^+ z'^+} \langle \pi^- : q' | \, \phi^{S[ud]\dagger} \left(\frac{z'^+}{2}\right) \bar{\Psi}^d \left(-\frac{z'^+}{2}\right) \gamma^- u \, |\bar{p} : q, \nu\rangle$$

soft part

$$\bar{x}^{(\prime)} = \frac{\bar{k}^{+\,(\prime)}}{\bar{p}^+} \quad \left(\bar{k}^{(\prime)} = \frac{k_1^{(\prime)} + k_2^{(\prime)}}{2}\right)$$

Assumptions on parton momenta: Λ . . . hadronic scale $\Lambda \approx 1$ GeV

- for virtualities: $k_i^{(\prime)} \lesssim \Lambda^2$
- for *intrinsic* transverse momenta: $k_{i\perp}^{(\prime)2} / x_i^{(\prime)} \lesssim \Lambda^2$

$\Rightarrow$ partons are on-mass shell and move collinear to their parent hadron

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$\bar{v}\gamma^+ \left(\gamma^- u\right)$ project out good-field components of Ψ^d $\left(\bar{\Psi}^d\right)$

Modeling the DGLAP-Part: Overlap Formalism

extent formalism of LCWFs overlap developed in
[Diehl, Feldmann, Jakob and Kroll, Nucl.Phys. B596 (2001)]

$$\mathscr{H}^{\bar{c}S}_{\lambda_2\mu} \equiv \bar{p}^+\,\bar{v}\,(k_2,\lambda_2)\,\gamma^+ \int \frac{\mathrm{d}z^-}{2\pi}\, e^{i\bar{x}\bar{p}^+ z^-}\,\langle\pi^+|\Psi^d\left(-\frac{z^-}{2}\right)\phi^{S[ud]}\left(\frac{z^-}{2}\right)|p\rangle$$

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valence Fock state expansion of proton- and π^+-state:

- $|p:p,\mu\rangle \propto \int \Psi_p(\tilde{x},\tilde{\mathbf{k}}_\perp)\quad |\mathbf{S[ud]}:\tilde{x}p^+,\tilde{\mathbf{k}}_\perp\rangle \quad |\mathbf{u}:(1-\tilde{x})p^+,-\tilde{\mathbf{k}}_\perp,\mu\rangle$

  Ψ_p... proton LCWF $\qquad$ $\tilde{x},\tilde{\mathbf{k}}_\perp$ ... hadron-in frame ($\mathbf{p}_\perp = 0$)

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analogous for the $\bar{p} \to \pi^-$-transition

Modeling the DGLAP-Part: LCWFs

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

[Kroll, Quadder and Schweiger, Nucl.Phys.B 316 (1989)]

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N_p and a_p chosen such that

- $P_p = 0.5$
- $\sqrt{\langle \mathbf{k}_\perp^2 \rangle_p} \approx 0.280$ GeV

$(\Rightarrow N_p = 61.8\ \mathrm{GeV}^2\ a_p = 1.1\ \mathrm{GeV}^{-1})$

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N_π and a_π chosen such that

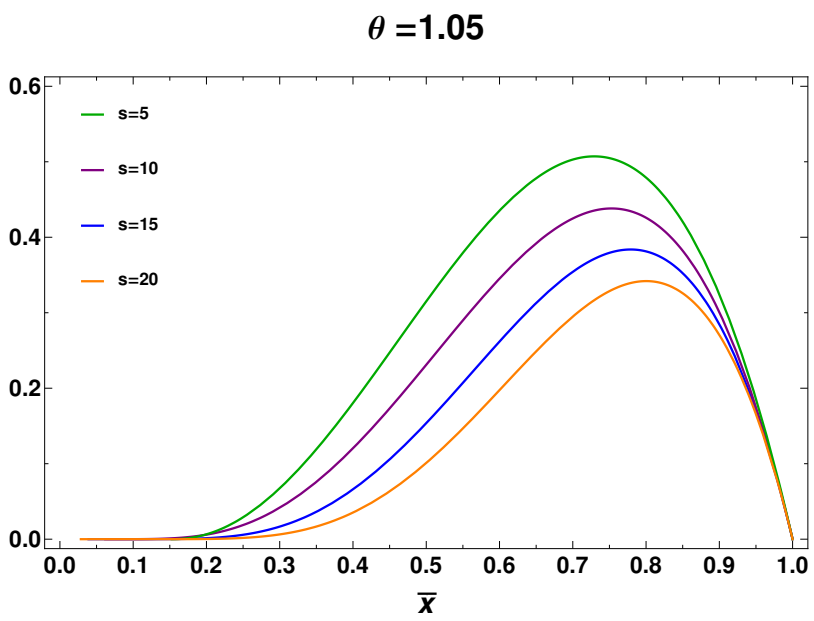
- $P_\pi = 0.132$
- $f_\pi = 0.130$ GeV

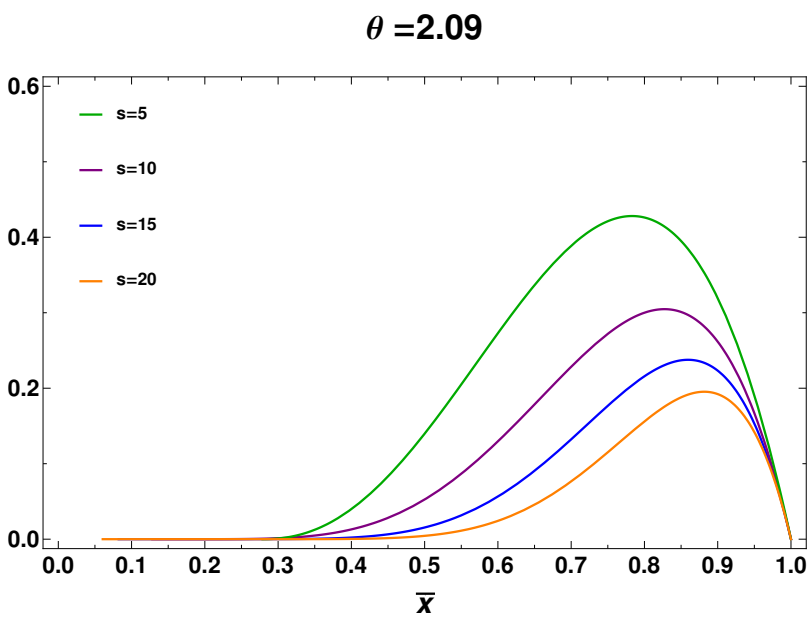
$(\Rightarrow N_\pi = 17\ \mathrm{GeV}^2\ a_\pi = 0.69\ \mathrm{GeV}^{-1})$

Modeling the DGLAP-Part: Result

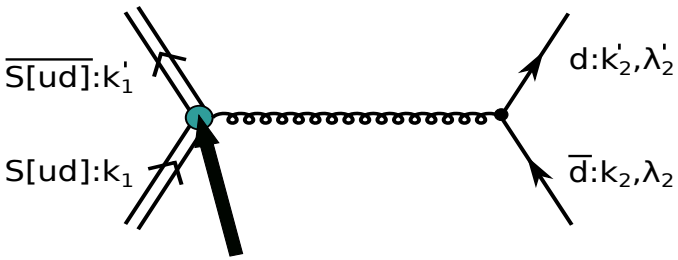
$$\mathscr{H}^{\bar{c}S}_{\lambda_2\mu} \propto \delta_{-\lambda_2,\mu} \int \mathrm{d}\bar{\mathbf{k}}_\perp \Psi_\pi \left(\hat{x}(\bar{x},\xi), \hat{\mathbf{k}}_\perp(\bar{\mathbf{k}}_\perp,\bar{x},\xi)\right) \Psi_p \left(\tilde{x}(\bar{x},\xi), \tilde{\mathbf{k}}_\perp(\bar{\mathbf{k}}_\perp,\bar{x},\xi)\right)$$

$$\Psi_p = N_p\, \tilde{x}\, \exp\left[-\frac{a_p^2}{\tilde{x}(1-\tilde{x})}\,\tilde{\mathbf{k}}_\perp^2\right] \qquad \Psi_\pi = N_\pi \exp\left[-\frac{a_\pi^2}{\hat{x}(1-\hat{x})}\,\hat{\mathbf{k}}_\perp^2\right]$$





Hard Part-DGLAP



$$H_{++} = H_{--} = 0$$

$$H_{\underset{\lambda_2}{+},\underset{\lambda_2'}{-}} = H_{-,+} = -4\pi\, C\, \alpha_s(s)\, F_s(s)\, \sin\theta$$

$C = \frac{4}{9}$ ... color factor
α_s ... strong coupling
F_s ... form factor

$$F_s(s) = \left|\frac{Q_0^2}{Q_0^2 - s}\right|$$

$Q_0^2 = 3.22\ \mathrm{GeV}^2$
$s > Q_0^2$

$$x_1^{(\prime)} = x_2^{(\prime)} = 1 \implies \begin{aligned} k_1 &\approx p \\ k_2 &\approx p' \\ k_1' &\approx q \\ k_2' &\approx q' \end{aligned}$$

F_s taken from Ref.
[Kroll, Pilsner, Schürmann and Schweiger, Phys.Lett.B 316 (1993)]

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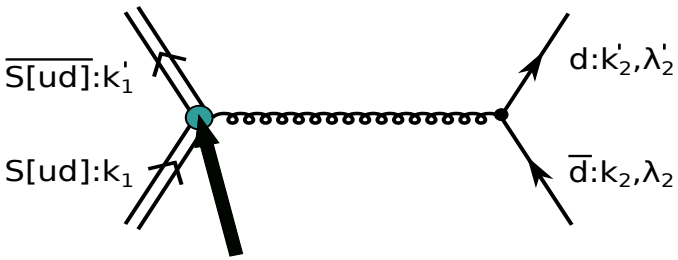

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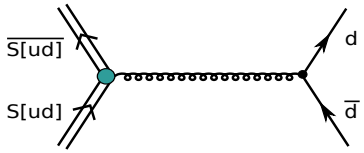
$$x_1^{(\prime)} = x_2^{(\prime)} = 1 \implies \begin{array}{l} k_1 \approx p \\ k_2 \approx p' \\ k_1' \approx q \\ k_2' \approx q' \end{array} \qquad \int \mathrm{d}\bar{x} \int \mathrm{d}\bar{x}'\, H(\bar{x}, \bar{x}') \Rightarrow H \int \mathrm{d}\bar{x} \int \mathrm{d}\bar{x}'$$

F_s taken from Ref.
[Kroll, Pilsner, Schürmann and Schweiger, Phys.Lett.B 316 (1993)]

Summary Modeling (DGLAP)

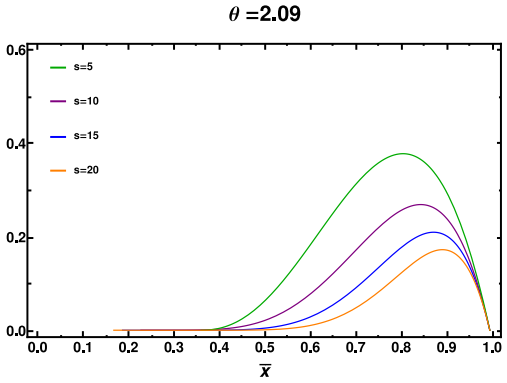


Feynman Diagram

$$\mathscr{M}_{\mu\nu} \propto \boxed{H} \int \mathrm{d}\bar{x} \int \mathrm{d}\bar{x}'$$

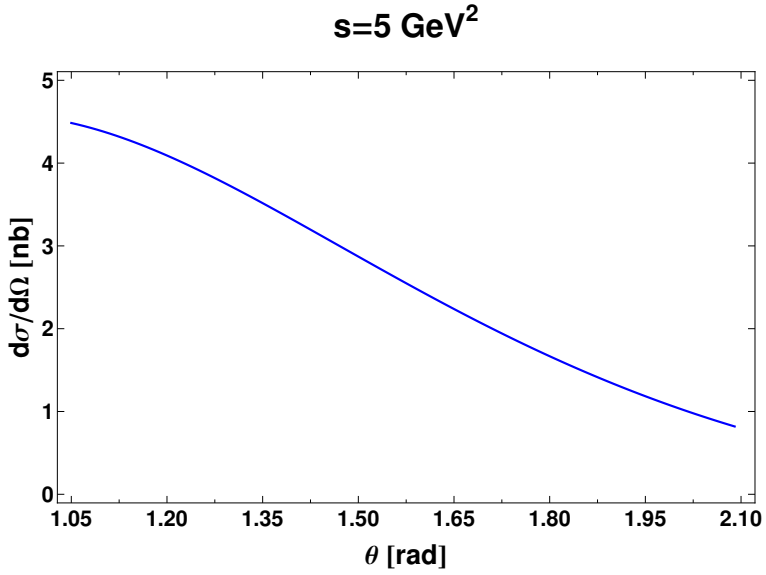
$$\times\, \bar{p}^+ \int \mathrm{d}z^- e^{i\bar{x}\bar{p}^+ z^-} \langle \pi^+ : p' |\, \bar{v}\gamma^+ \Psi^d \left(-\frac{z^-}{2}\right) \phi^{S[ud]} \left(\frac{z^-}{2}\right) |p : p, \mu\rangle$$

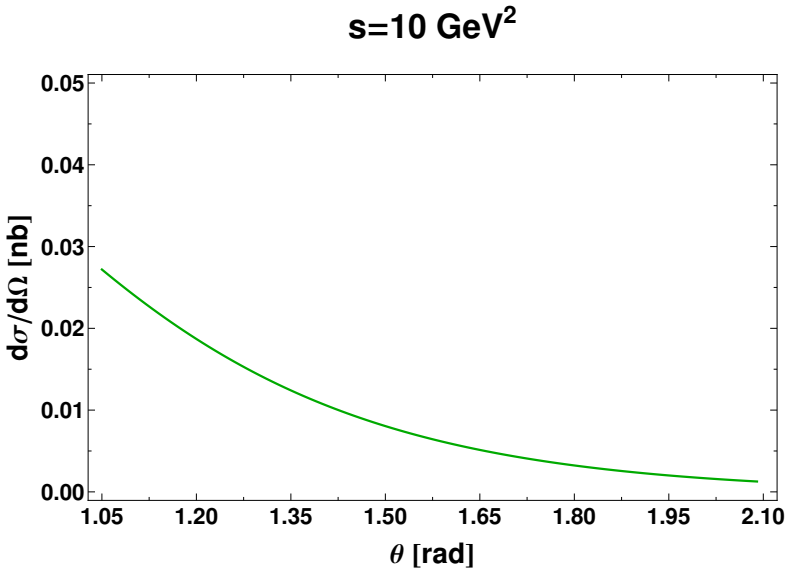
$$\times\, \bar{p}^+ \int \mathrm{d}z'^+ e^{i\bar{x}'\bar{p}^+ z'^+} \langle \pi^- : q' |\, \phi^{S[ud]\dagger} \left(\frac{z'^+}{2}\right) \bar{\Psi}^d \left(-\frac{z'^+}{2}\right) \gamma^- u\, |\bar{p} : q, \nu\rangle$$

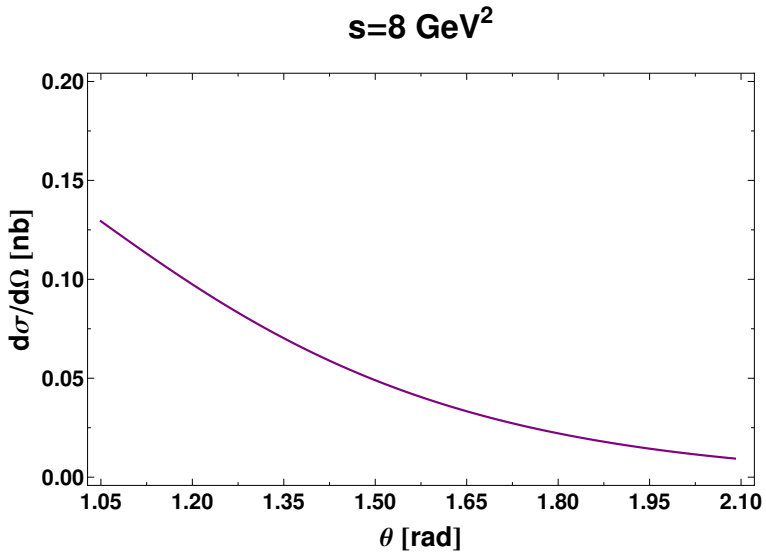


Overlap of LCWFs

Estimation of Differential Cross Section

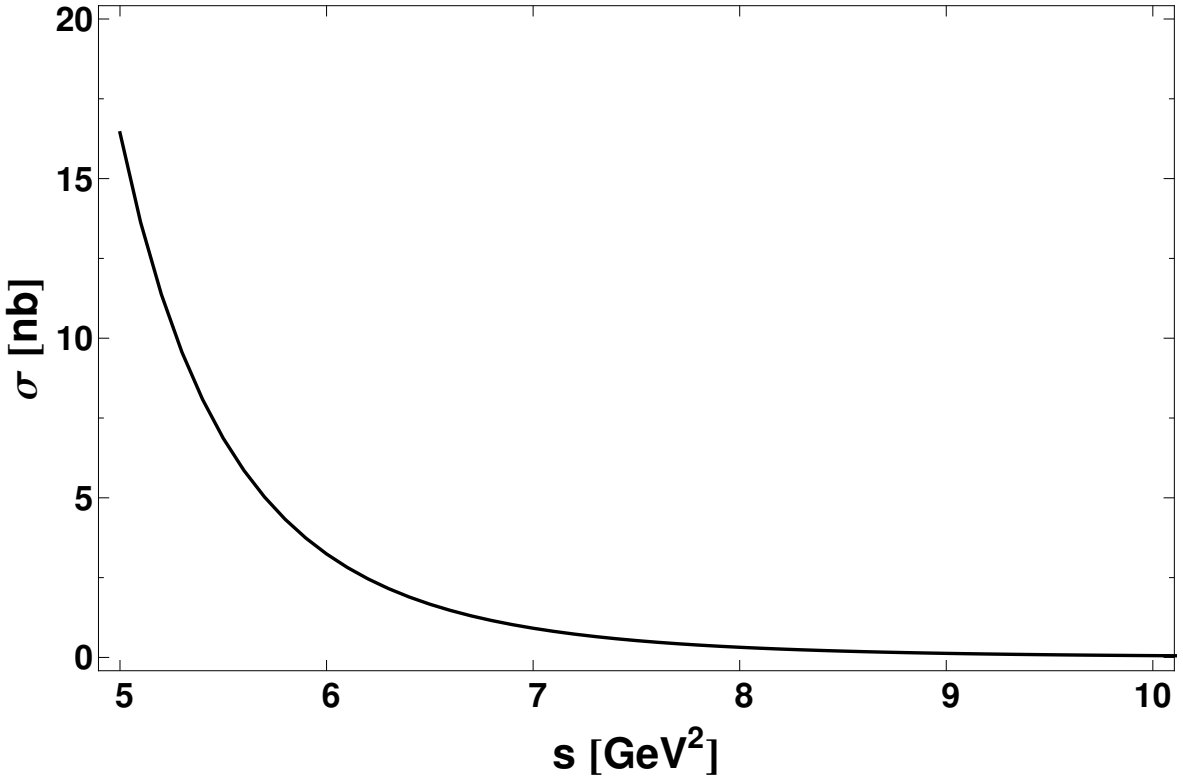






- CMS angle: $\frac{\pi}{3} \leq \theta \leq \frac{2\pi}{3}$
- for $s > 10$ GeV^2 basically zero

Estimation for Integrated Cross Section



- best measurable at small CMS energies

Summary and Outlook

- presented you a *"QCD inspired"* model for $p\ \bar{p} \to \pi^+\ \pi^-$
- partonic subprocess treated by means of pQCD
- hadronic matrix elements modeled as an overlap of LCWFs
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- **include ERBL-region**
- use other LCWFs available on the market
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Thank you very much for your attention!

DGLAP-Region and ERBL-Region

$$\bar{p}^+\,\bar{v}\,(k_2,\lambda_2)\,\gamma^+ \int \frac{\mathrm{d}z^-}{2\pi}\, e^{i\bar{x}\bar{p}^+ z^-}\, \langle \pi^+ | \Psi^d \left(-\frac{z^-}{2}\right) \phi^{S[ud]} \left(\frac{z^-}{2}\right) | p \rangle$$

$$\Psi^d \propto b_d u + d^\dagger_d v$$

$$\phi^{S[ud]} \propto a_S + b^\dagger$$

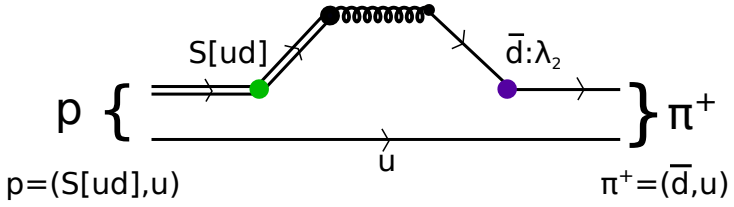
$$\Psi^d \phi^{S[ud]}$$

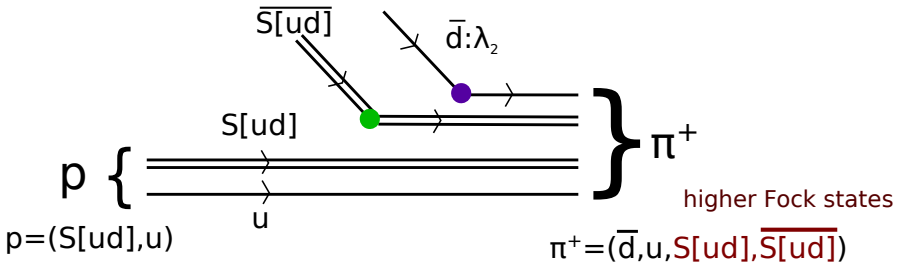
DGLAP
$\bar{x}>\xi$

ERBL
$\bar{x}<\xi$

$$d^\dagger_d a_S$$

$$d^\dagger_d b^\dagger_S$$





DGLAP-Region and ERBL-Region

$$\mathscr{H}^{\bar{c}S}_{\lambda_2\mu} \equiv \bar{p}^+\,\bar{v}\,(k_2,\lambda_2)\,\gamma^+ \int \frac{\mathrm{d}z^-}{2\pi}\, e^{i\bar{x}\bar{p}^+ z^-}\, \langle \pi^+ | \Psi^d\left(-\frac{z^-}{2}\right)\phi^{S[ud]}\left(\frac{z^-}{2}\right)|p\rangle$$

$$\Psi^d \propto b_d u + d^\dagger_d v$$

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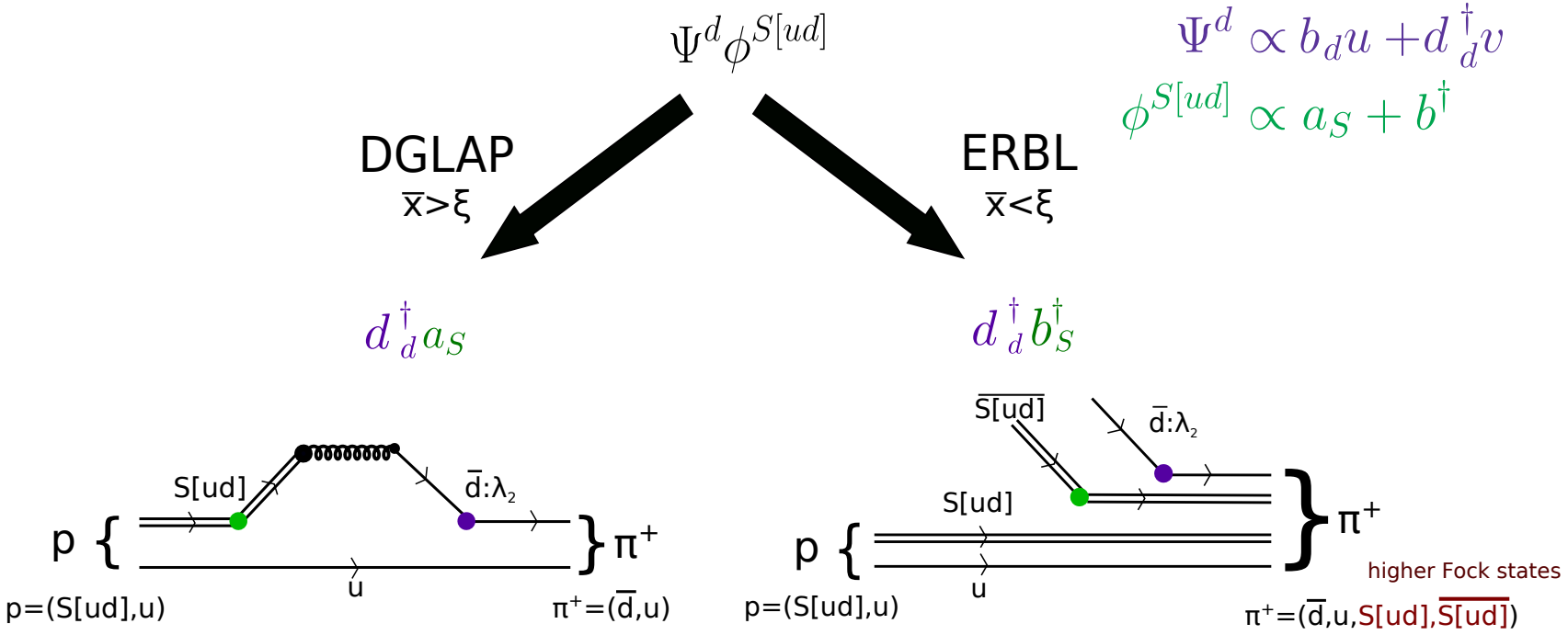

analogous for $\bar{p} \to \pi^-$-transition