DLSA in light and heavy meson production at NICA

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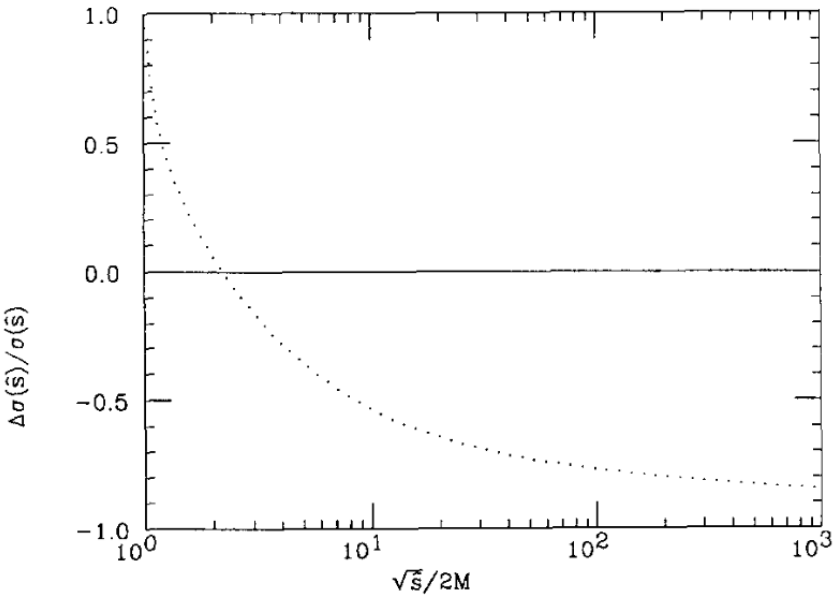

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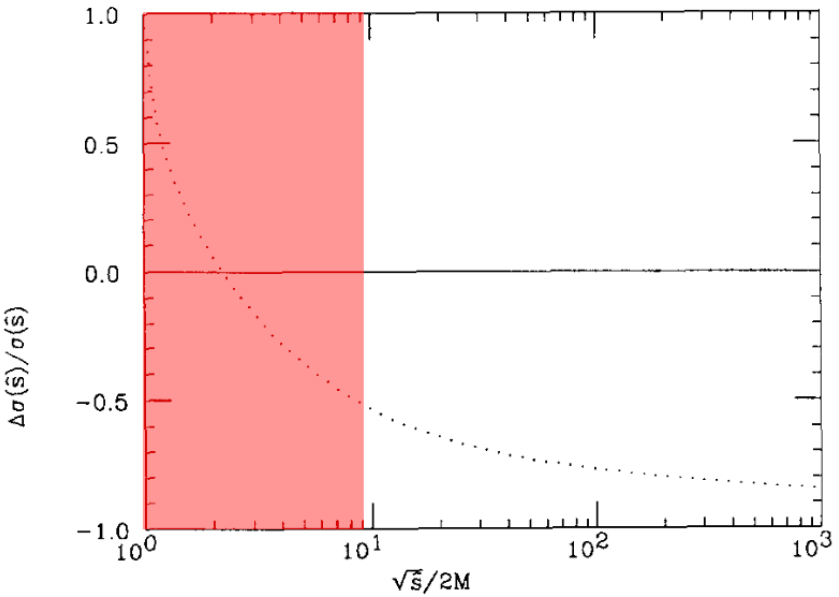

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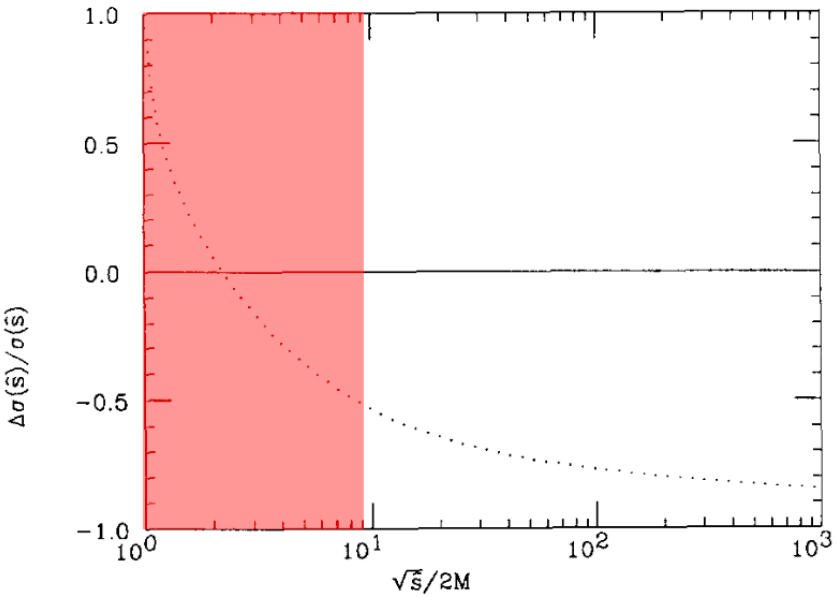

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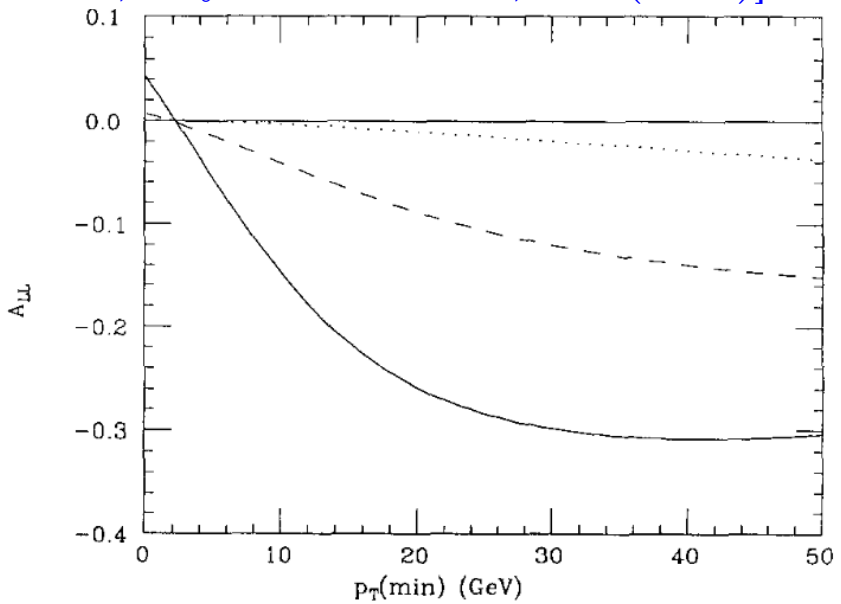

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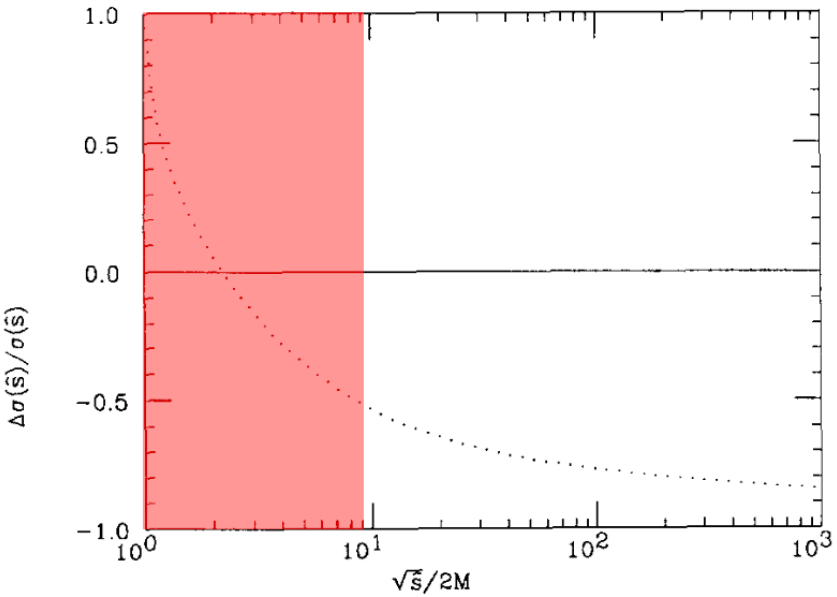

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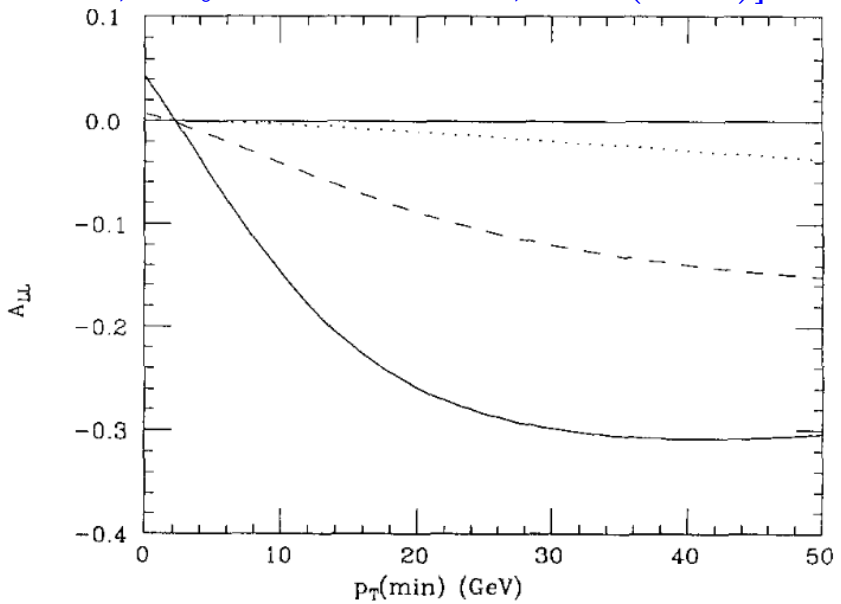

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Their conclusions:

- While at the LO A_{LL}^b demonstrates a good applicability to extraction of $\Delta G(x, \mu)$, adding NLO *real* corrections may lead to cancellation between LO and NLO in A_{LL}^b. Then we can still test structure of LO/NLO contributions.

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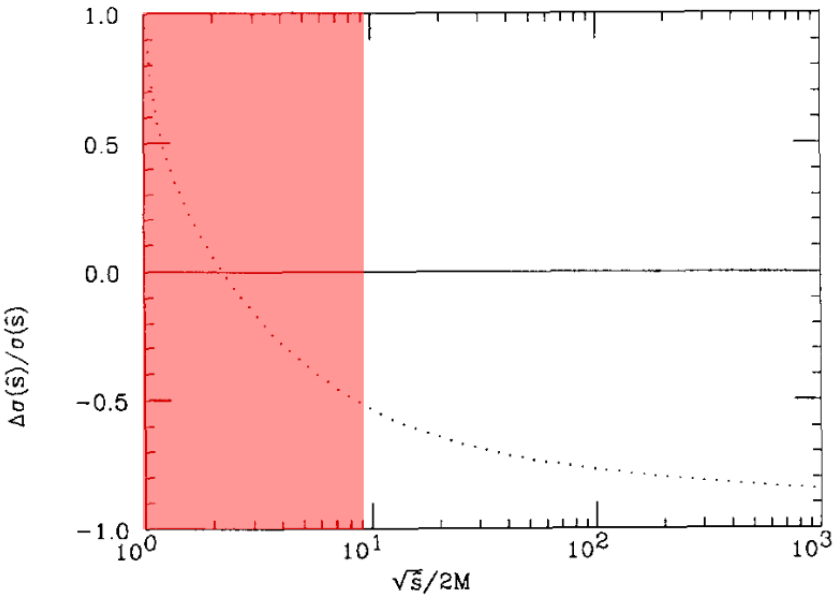

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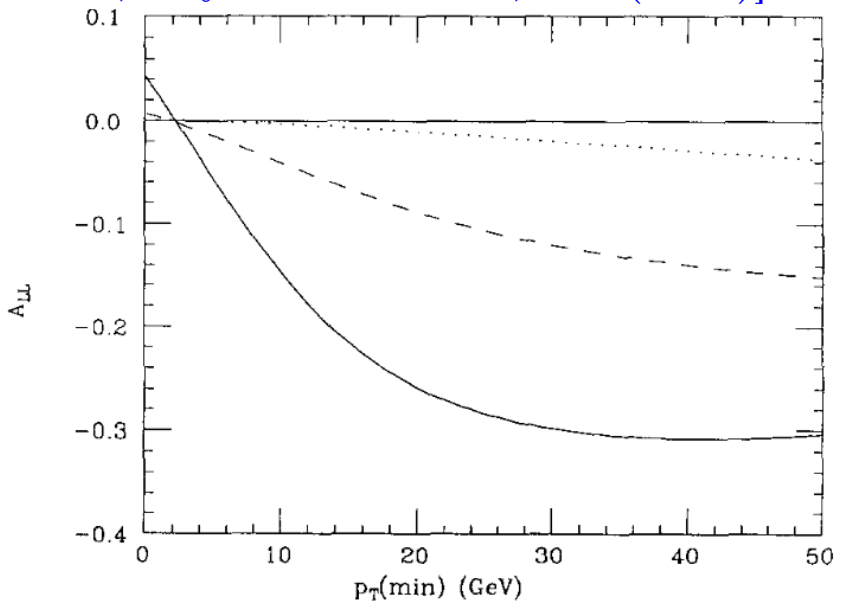

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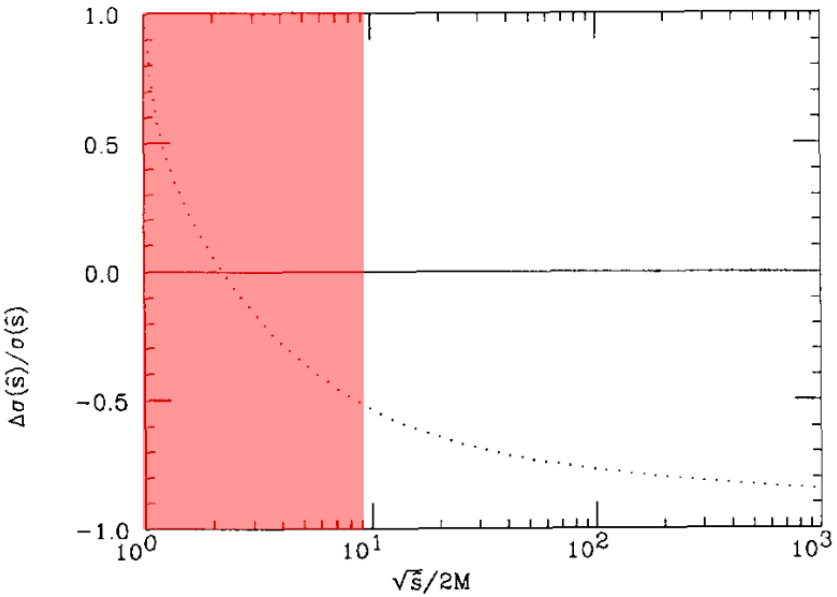

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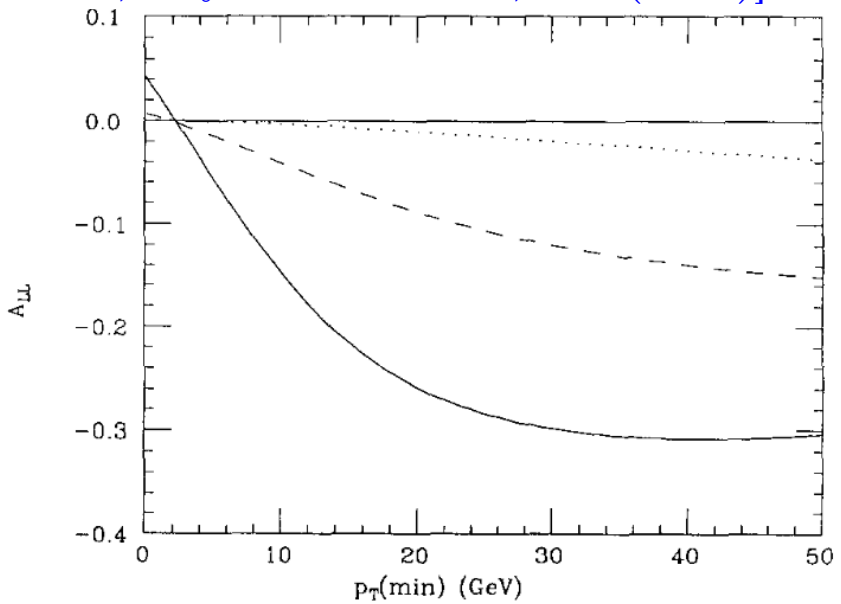

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- In case of small A_{LL}^b we need another process with good analyzing power.
- At different perturbative orders different mechanisms of polarized production of b-quarks dominates. At NLO it is a gluon fragmentation to $b\bar{b}$-pairs.

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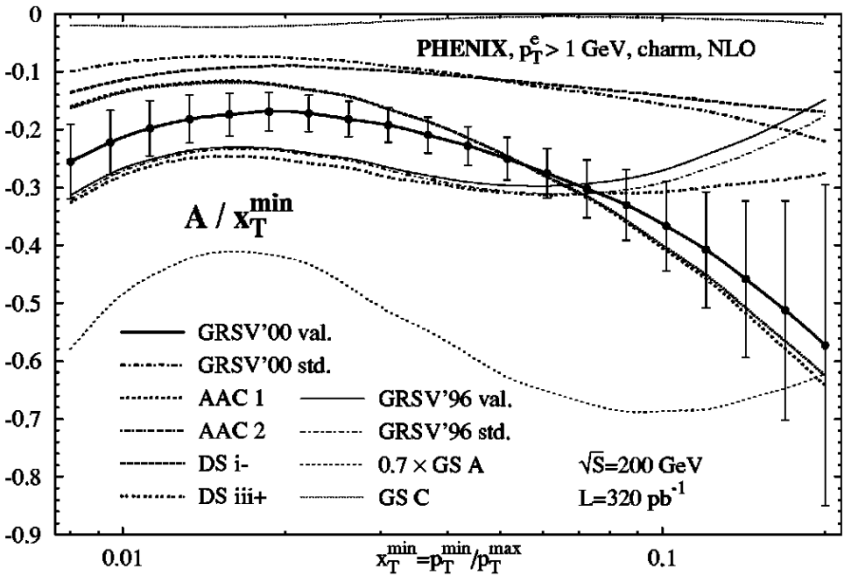

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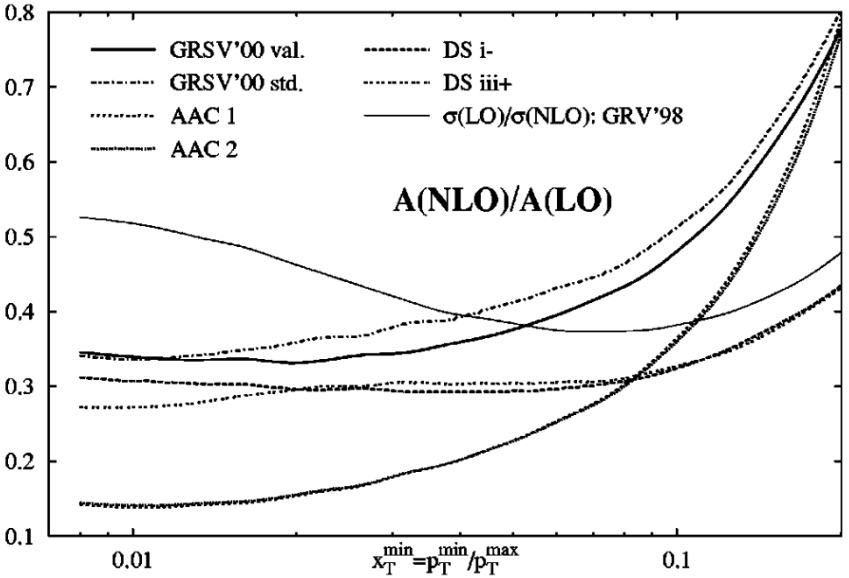

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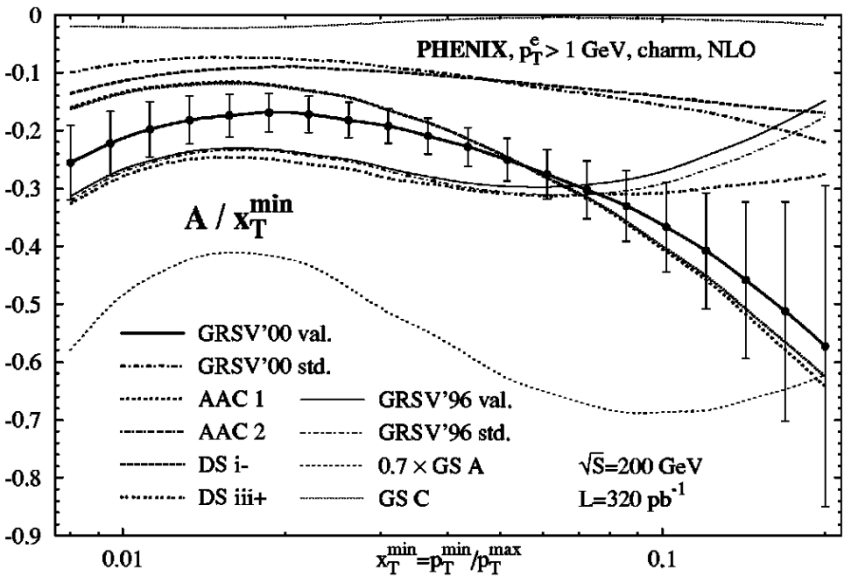

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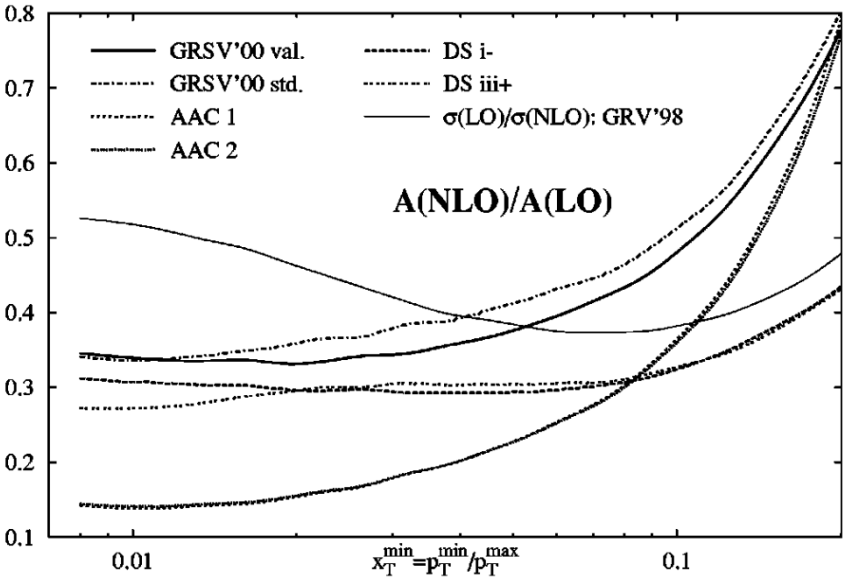

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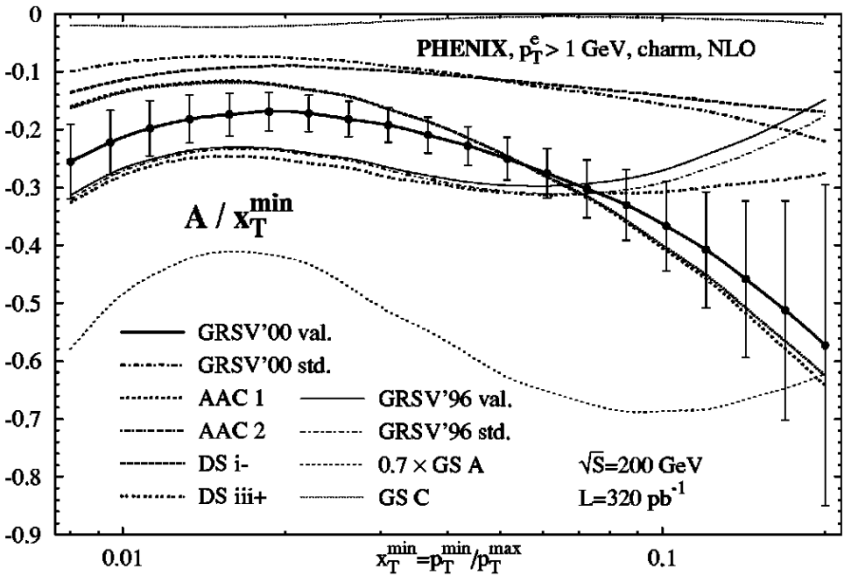

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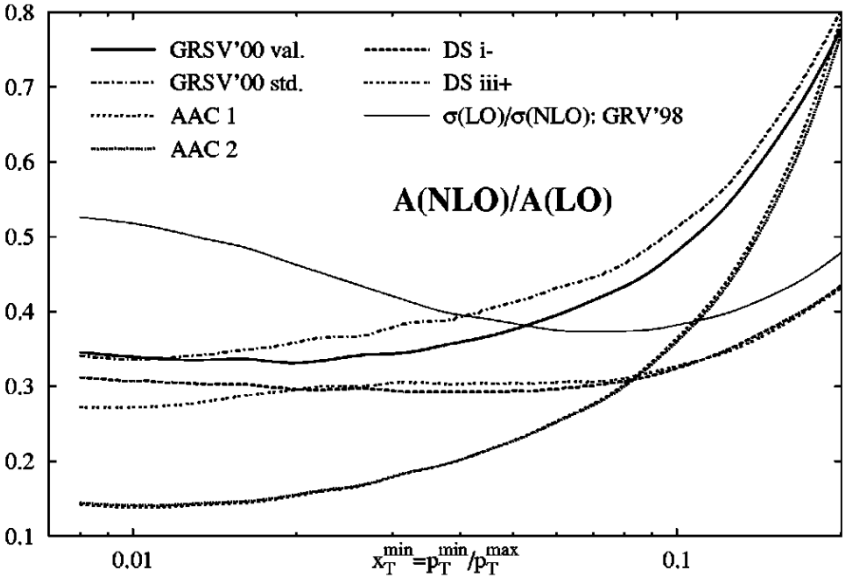

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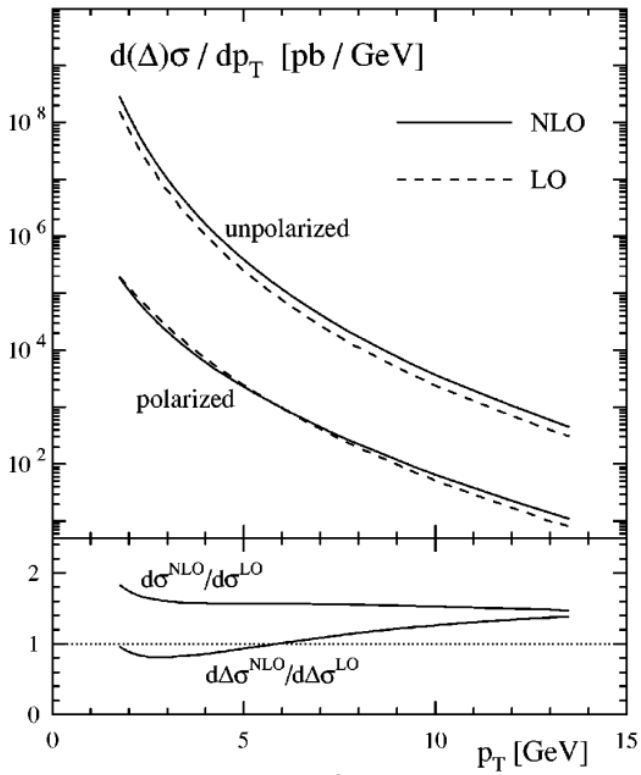
- Much of the reduction of the asymmetry in NLO stems from the unpolarized cross section in NLO with K-factor ≈ 2.

Some previous investigations for π^0 mesons

Another complete NLO result concerns A_{LL} in π^0 meson production in [B. Jäger, A. Schäfer, M. Stratmann, W. Vogelsang, Phys. Rev. D **67**, 054005 (2003)]:



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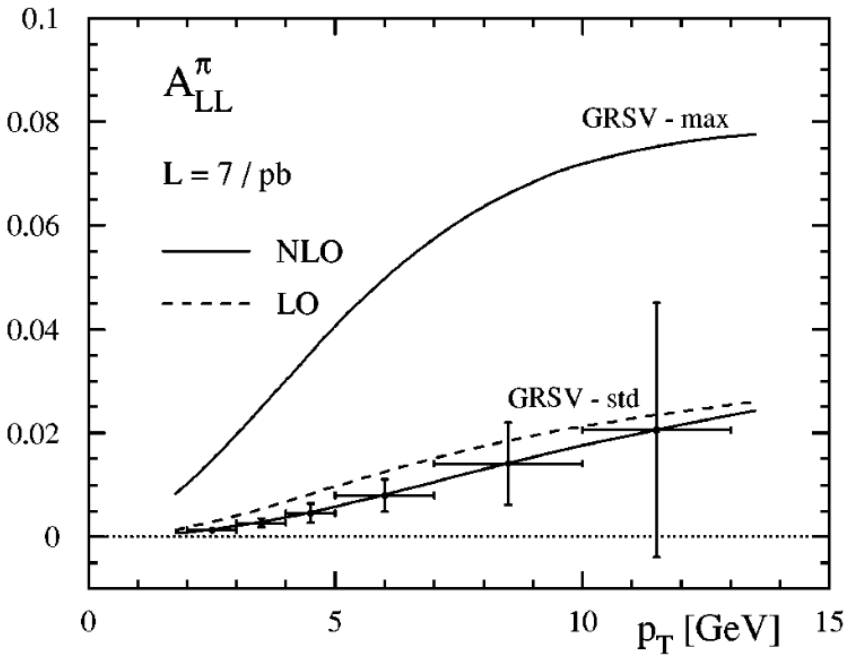

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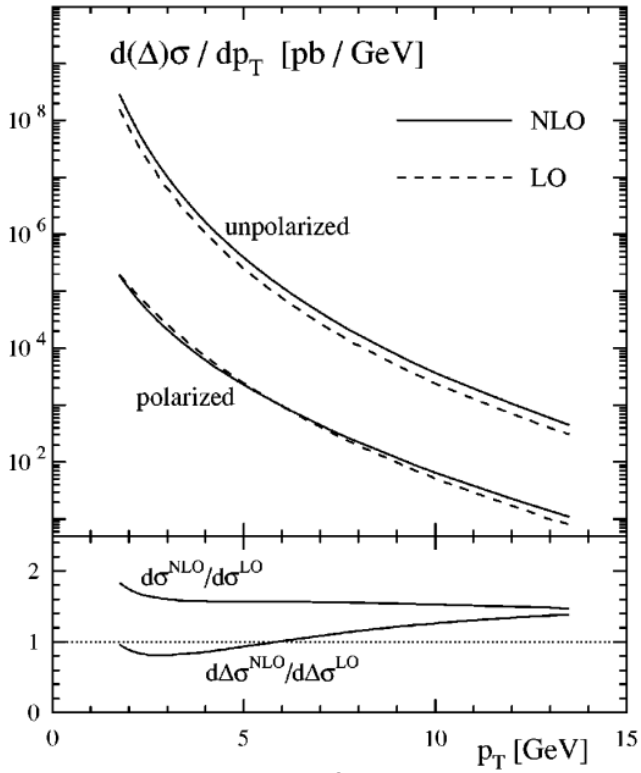

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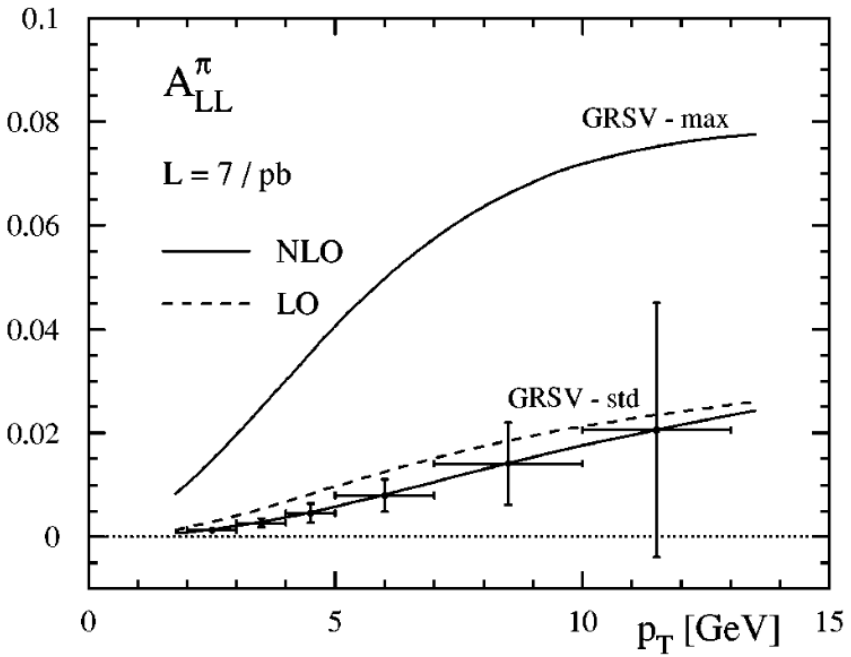

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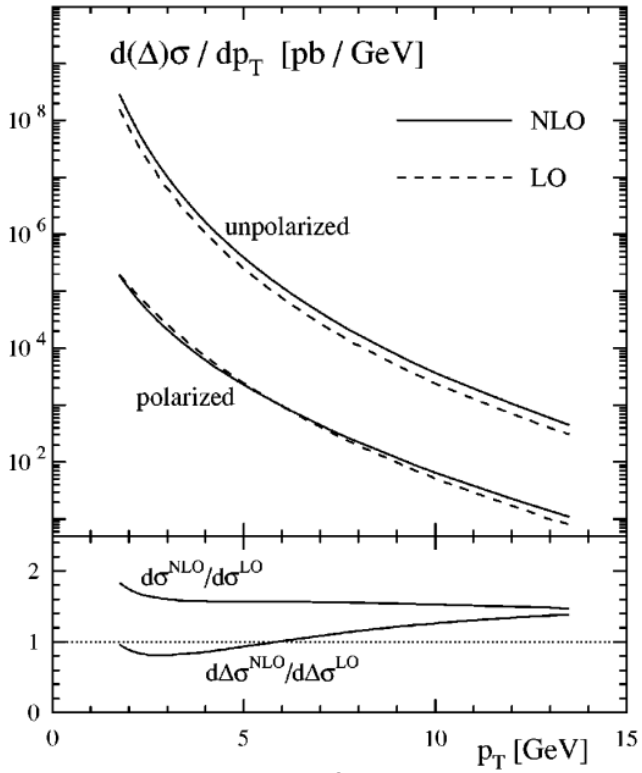

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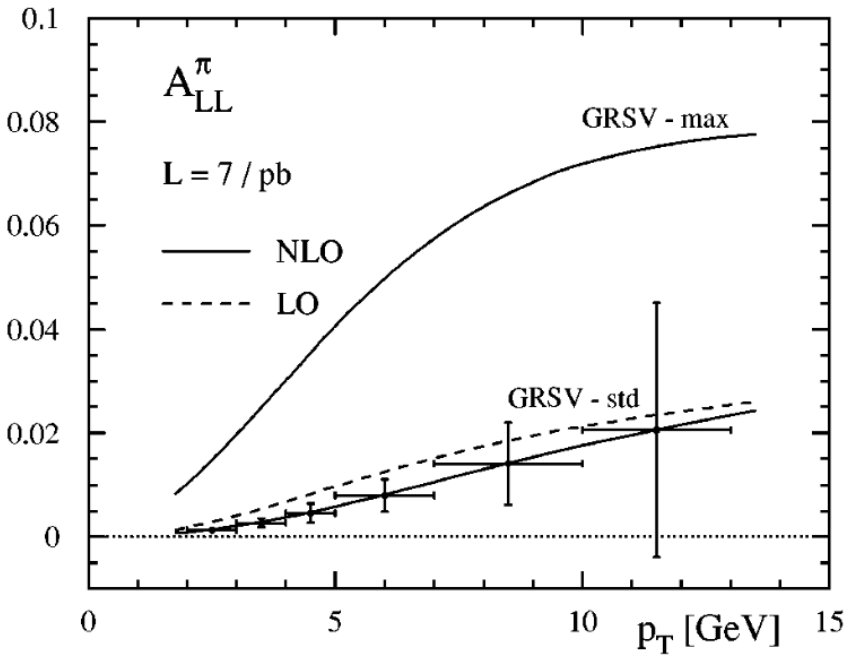

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- In the unpolarized case the corrections are roughly constant and $\sim 50\%$.
- NLO corrections to the $\Delta\sigma$ are even smaller than those in the σ.

Outline of the technical framework

The double longitudinal spin asymmetry (DLSA)

The double helicity asymmetry A_{LL} of a final parton c has the following definition:

$$A_{LL}(p_A p_B \to cX) = \frac{d\Delta\sigma}{d\sigma} \tag{1}$$

$$d\Delta\sigma = \frac{1}{2}\left(E\frac{d^3\sigma_{++}(p_A p_B \to cX)}{d^3p} - E\frac{d^3\sigma_{+-}(p_A p_B \to cX)}{d^3p}\right) \tag{2}$$

$$d\sigma = E\frac{d^3\sigma_{++}(p_A p_B \to cX)}{d^3p} + E\frac{d^3\sigma_{+-}(p_A p_B \to cX)}{d^3p}. \tag{3}$$

Polarized cross section at hadron level is defined through the partonic cross section:

$$\begin{aligned} &E\frac{d^3\sigma_{\xi_A\xi_B}}{d^3p}(p_A p_B \to cX) = \\ &= \sum_{a,b}\int dx_a \Delta f_{a/A}(x_a,\mu_F)\int dx_b \Delta f_{b/B}(x_b,\mu_F) E\frac{d^3\hat{\sigma}_{\xi_a\xi_b}}{d^3p}(ab \to cX), \end{aligned} \tag{4}$$

where $a, b = g, q, \bar{q}$ (with q is for u, d or s), x_i – light-cone momentum fraction of parton i in proton, $\xi_A, \xi_B = \pm 1$ – helicities of initial protons, μ_F – hard scale of factorization.
The polarized PDFs $\Delta f_{a/A}(x_a,\mu_F) = f^+_{a(+)/A(+)}(x_a,\mu_F) - f^-_{a(-)/A(-)}(x_a,\mu_F)$ for the case when the spin of parton a is (anti)parallel to that of proton A ($\xi_A\xi_a = \pm 1$), and $E\frac{d^3\hat{\sigma}_{++(+-)}}{d^3p}(ab \to cX)$ corresponds to $\xi_a\xi_b = \pm 1$.

Matrix elements (MEs) within the Collinear Parton Model (CPM)

In QCD $E\frac{d^3\hat{\sigma}_{++(+-)}}{d^3p}(ab \to cX)$ only depends on the product $\xi_a\xi_b = \pm 1$. To our goals we consider two cases:

1. Light meson production (π^0): all suitable LO partonic subprocesses at the massless limit

$$\begin{array}{lllll} gg \to q\bar{q} & gq \to gq & qq \to qq & q\bar{q} \to q\bar{q} & q\bar{q} \to gg \\ gg \to gg & g\bar{q} \to g\bar{q} & qq' \to qq' & q\bar{q} \to q'\bar{q}' & q\bar{q}' \to q\bar{q}' \end{array}$$

   These well-known MEs $|M|^2_{++}(|M|^2_{+-})$ can be found in [Babcock, Monsay, Sivers, Phys. Rev. D 19, 1483 (1979)].

2. Heavy meson production (D): dominating LO subprocesses ($m_c \neq 0$)

$$\begin{aligned} gg &\to c\bar{c} \\ q\bar{q} &\to c\bar{c} \end{aligned}$$

   Using unpolarized MEs $\overline{|M|^2}$ and polarized $\Delta|M|^2$ from [Contogouris, Papadopoulos, Kamal, Phys. Lett. B 246, 523 (1990)] or [Karliner, Robinett, Phys. Lett. B 324, 209 (1994)], we simultaneously obtain them for arbitrary helicities by formula

$$|M|^2_{\xi_a\xi_b} = \overline{|M|^2} + \xi_a\xi_b\Delta|M|^2. \tag{5}$$

Fragmentation approach (massive case)

In the fragmentation approach [D'Alesio *et.al.*, Phys. Rev. D **70**, 074009 (2004)], the cross-section of the inclusive production of D-meson is related with the partonic cross-section as follows:

$$E_D \frac{d\sigma}{d^3 p_D}(a+b \to D(p_D)+\bar{c}) = \int_0^1 dz J(z) D_{D/c}(z,\mu^2) \times$$
$$\times E_c \frac{d\hat{\sigma}}{d^3 k_c}(a+b \to c(k_c)+\bar{c}(k_{\bar{c}}))\,, \quad (6)$$

where $D_{D/c}(z,\mu^2)$ – fragmentation function (FF) of c-quark to D meson, light-cone momentum fraction of D meson is defined as $z = p_D^+/k_c^+$ and $J(z)$ – Jacobian, which connects phase-spaces of c-quark and D-meson and is defined through $\frac{d^3 k_c}{E_c} = J(z)\frac{d^3 p_D}{E_D}$ (then for massless particles it is just $\frac{1}{z^2}$).

In collinear case (where $\frac{\vec{k}_c}{k_c} = \frac{\vec{p}_D}{p_D}$) $J(z) = \frac{k_c}{p_D}\frac{dE_c}{dE_D}$. Then for $E_c = \frac{E_D+p_D}{2z}\left[1+\frac{m_c^2 z^2}{(E_D+p_D)^2}\right]$ and $k_{Tc} = p_{TD}\frac{|\vec{k}_c|}{|\vec{p}_D|} = p_{TD}\frac{\sqrt{E_c^2-m_c^2}}{\sqrt{E_D^2-m_D^2}}$ Jacobian is:

$$J(z) = \frac{(E_D+p_D)^2}{4p_D^2 z^2}\left[1-\frac{m_c^2 z^2}{(E_D+p_D)^2}\right]^2. \quad (7)$$

Fragmentation function (massive case)

In our analysis we use the phenomenological FF of Peterson in the following form [C. Peterson *et.al.*, Phys. Rev. D **27**, 105 (1983)]:

$$D_{D/c}(z) = \frac{N}{[1 - 1/z - \epsilon/(1-z)]^2}, \tag{8}$$

which satisfies normalization condition:

$$\int dz\, D_{D/c}(z) = 1. \tag{9}$$

For the Peterson parametrization we take $\epsilon = 0.06$ [J. Chrin, Z. Phys. C 36 (1987) 163].

Fragmentation approach (massless case)

In case of massless π^0-meson we use a simpler formula for its cross section [J. F. Owens, E. Reya, M. Glück, 1978]

$$E_\pi \frac{d\sigma}{d^3 p_\pi}\left(a+b\to\pi^0+d\right) = \int_0^1 \frac{dz}{z^2} D_{\pi/c}(z,\mu^2)\times$$

$$\times\, E_c \frac{d\hat{\sigma}}{d^3 k_c}\left(a+b\to c+d\right), \quad (10)$$

where $D_{\pi/c}(z,\mu^2)$ – FF of parton c to π^0 meson, here longitudinal fraction of π meson is defined as $z=(p_\pi^\mu)/(k_c^\mu)$.
As FFs we use sets KKP [Kniehl, Kramer, Pötter, 2001] and NNFF1.0 [Bertone *et al.*, 2017]. As unpolarized parton distribution functions we use NNPDF4.0 [Ball *et al.*, 2022], and for polarized parton distribution functions NNPDFPol1.1 [Nocera *et al.*, 2016].

The double sinlge spin asymmetries for D and π^0 mesons

The DLSA of D-meson at the RHIC, $|y_D| \leq 0.35$, $\sqrt{s} = 200$ GeV.

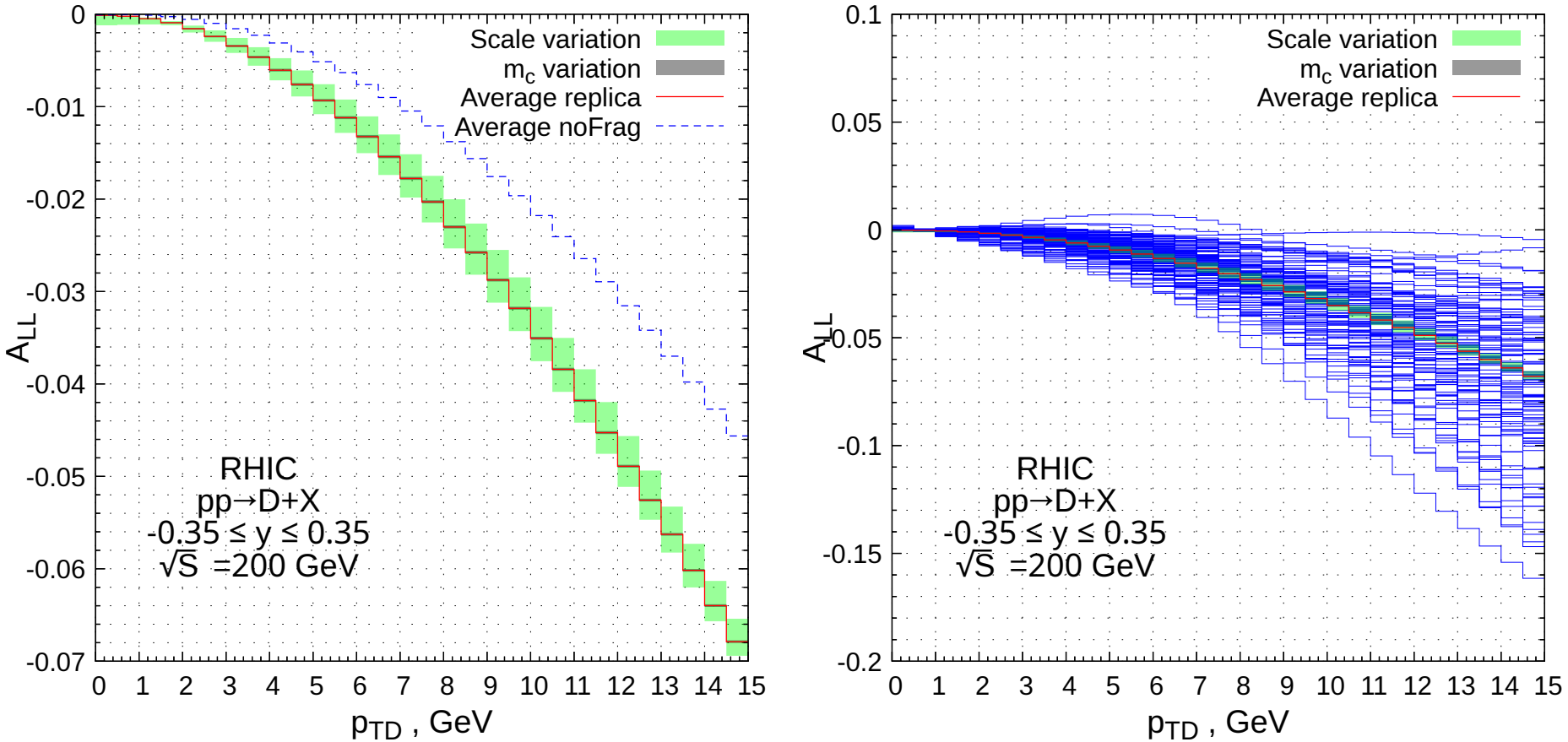

Figure 5: Predictions for the A_{LL}^D of D-meson production at $\sqrt{S} = 200$ GeV and $|y_D| \leq 0.35$. The **green** band is for the hard scale variation by factor 2, the **gray** band – variation of c-quark mass $1.2 \leq m_c \leq 1.5$ GeV with center at $m_c = 1.35$ GeV. Left panel – **average** on all the replicas of PDF, right panel – different **replicas** together with the **average** one.

The DLSA of D-meson at the NICA, $|y_D| \leq 3$, $\sqrt{s} = 27$ GeV.

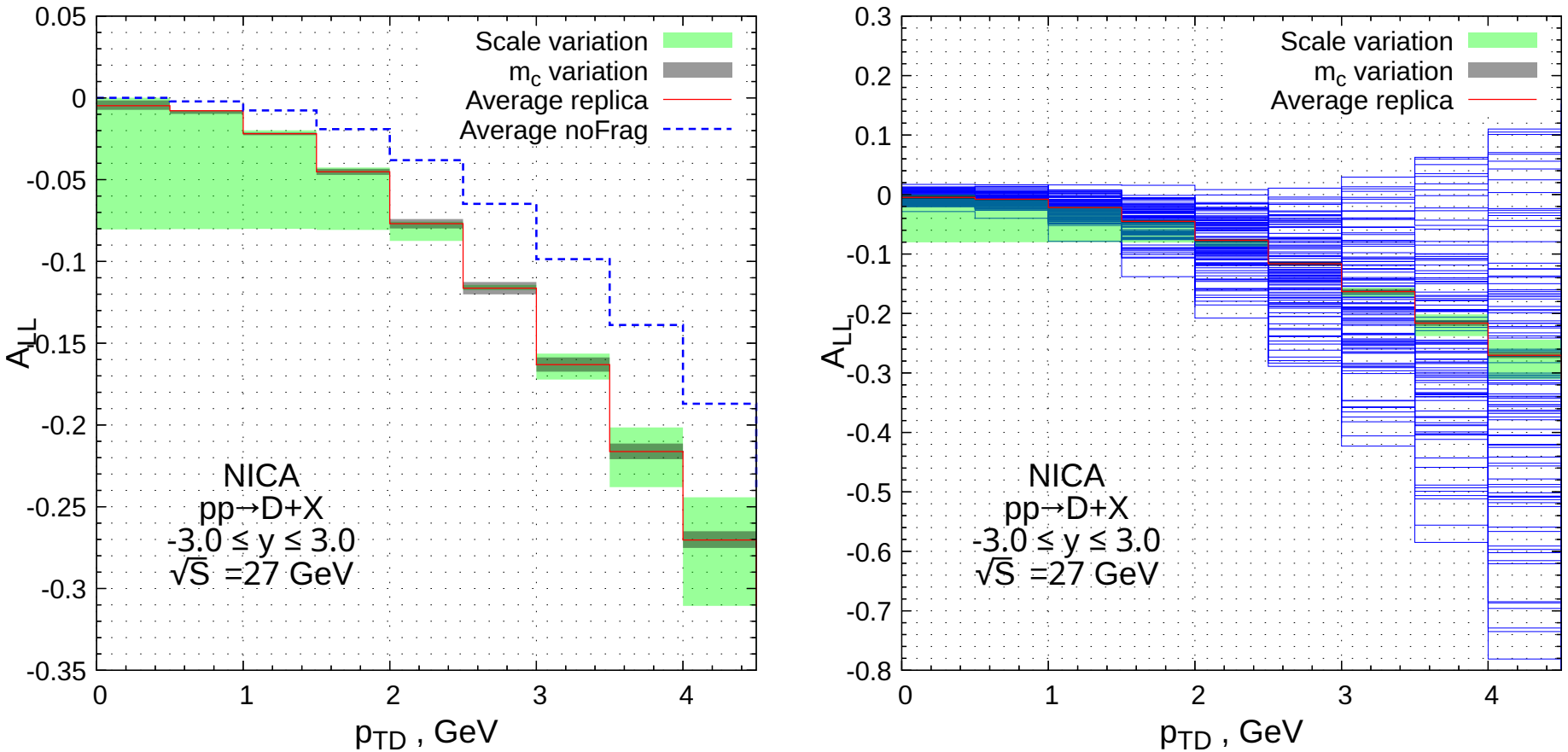

Figure 6: Predictions for the A_{LL}^D of D-meson production at $\sqrt{S} = 27$ GeV and $|y_D| \leq 3$. The **green** band is for the hard scale variation by factor 2, the **gray** band – variation of c-quark mass $1.2 \leq m_c \leq 1.5$ GeV with center at $m_c = 1.35$ GeV. Left panel – **average** on all the replicas of PDF, right panel – different **replicas** together with the **average** one.

Unpolarized π^0-production cross section (STAR data)

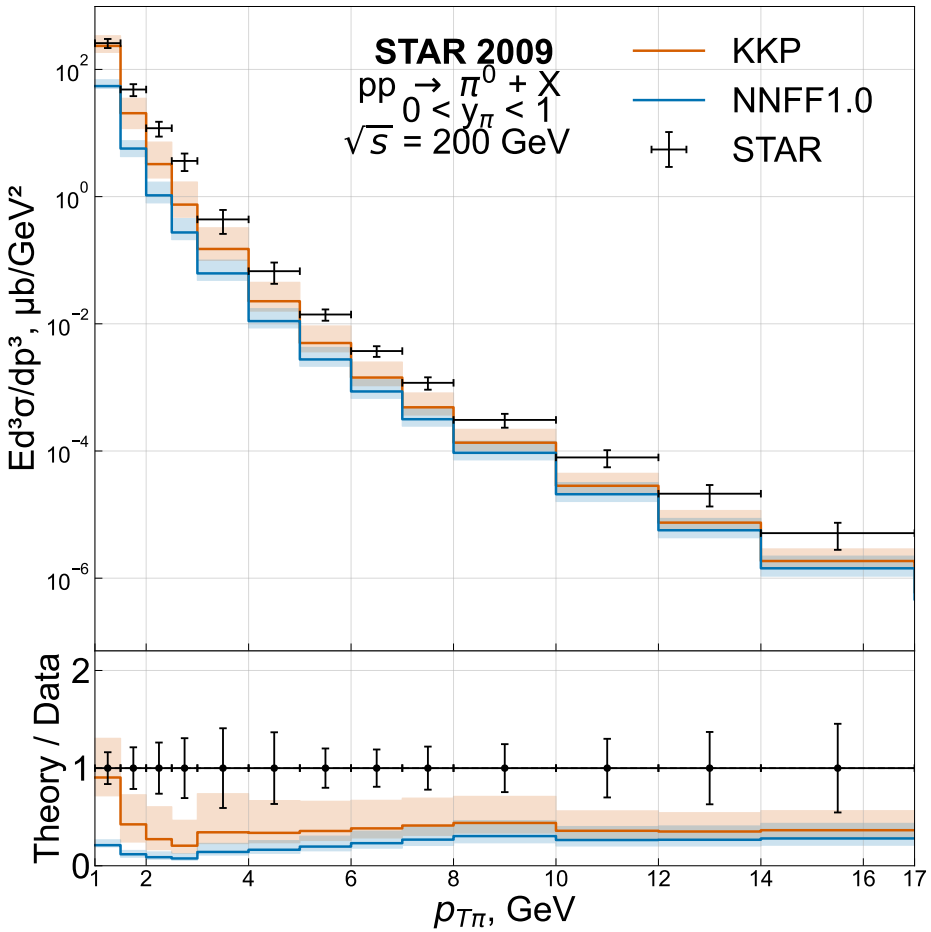

Figure 7: Unpolarized invariant cross section of π^0 production vs. transverse momentum $p_{T\pi}$ in comparison with STAR data [STAR, Phys. Rev. D **80**, 111108 (2009)] at $\sqrt{s} = 200$ GeV, $0 \leq y \leq 1$ and $1 \leq p_{T\pi} \leq 17$ GeV. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

DLSA of π^0 meson (PHENIX data)

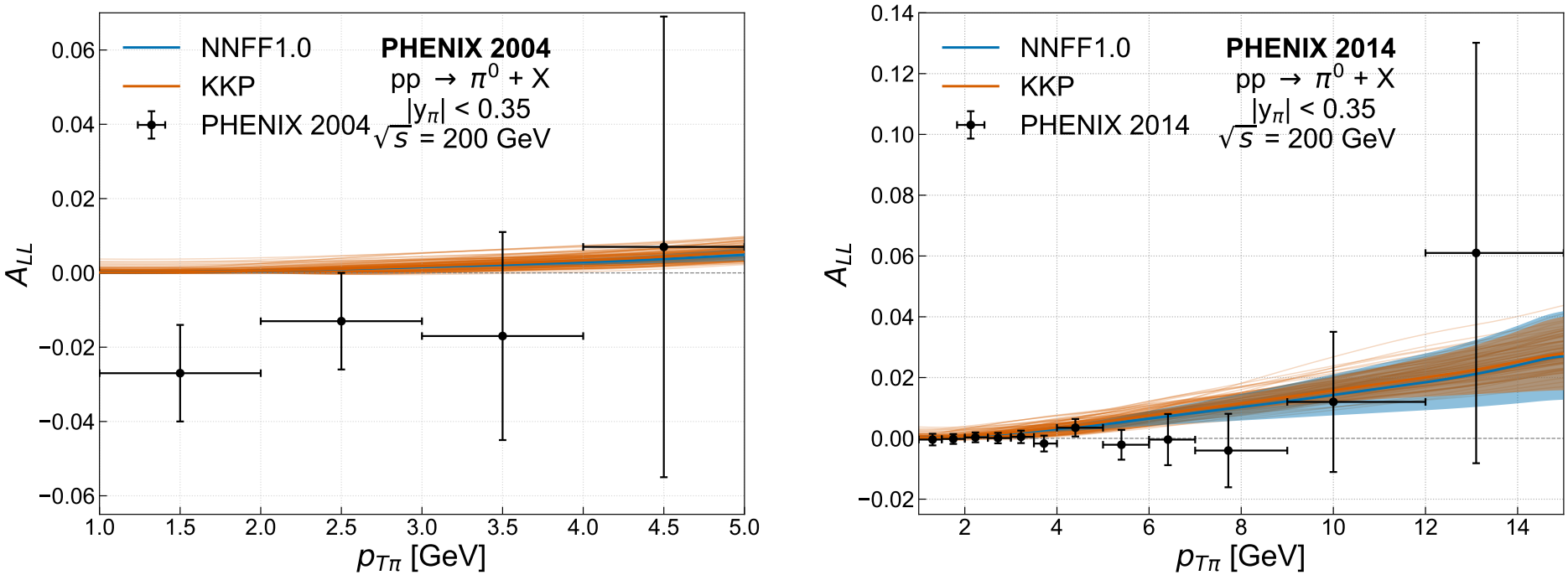

Figure 8: DLSA of π^0 production vs. transverse momentum p_T in comparison with PHENIX data at $\sqrt{s} = 200$ GeV, $|y| \leq 0.35$. Left panel: $1 \leq p_T \leq 5$ GeV [PHENIX, Phys. Rev. Lett. **93**, 202002 (2004)], right panel: $1 \leq p_T \leq 14$ GeV [PHENIX, Phys. Rev. D **90**, 012007 (2014)]. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

DLSA of π^0 meson (STAR data)

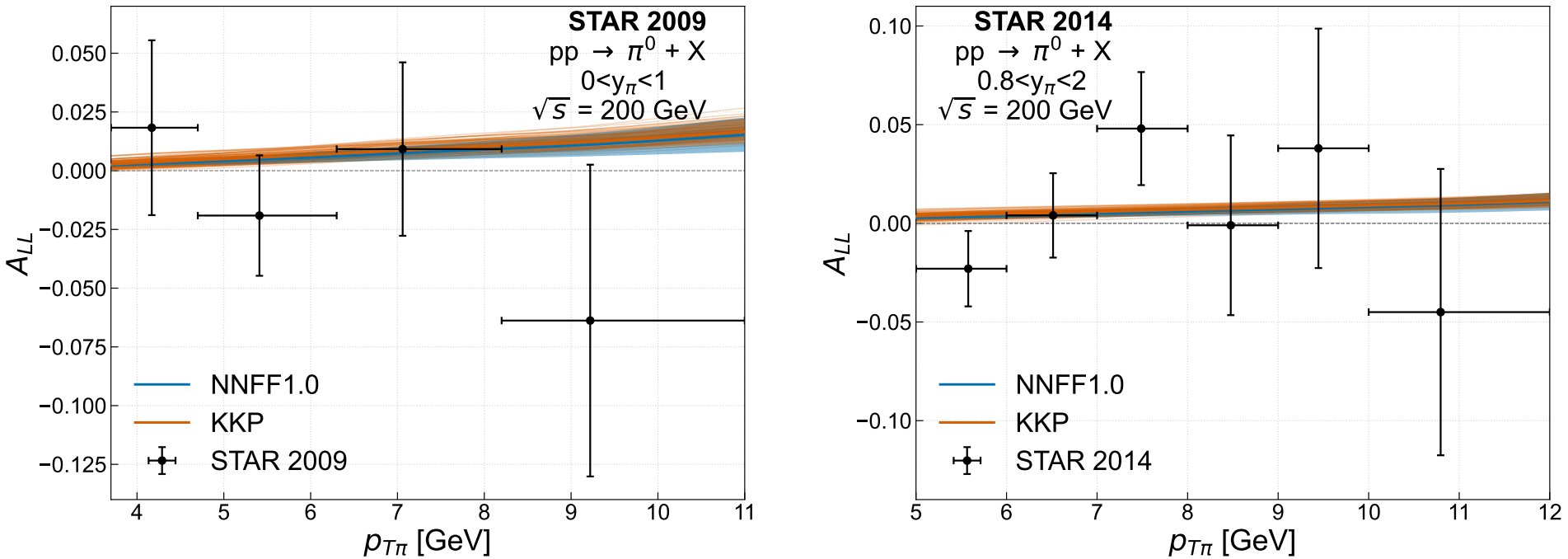

Figure 9: DLSA of π^0 production vs. transverse momentum p_T in comparison with STAR data. Left panel: $\sqrt{s} = 200$ GeV, $0 \leq y \leq 1$, $1 \leq p_T \leq 5$ GeV [STAR, Phys. Rev. D. **80**, 111108 (2009)]. Right panel: $\sqrt{s} = 510$ GeV, $0.8 \leq y \leq 2$, $5 \leq p_T \leq 12$ GeV [STAR, Phys. Rev. D **89**, 012001 (2014)]. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

DLSA of π^0 meson (STAR data)

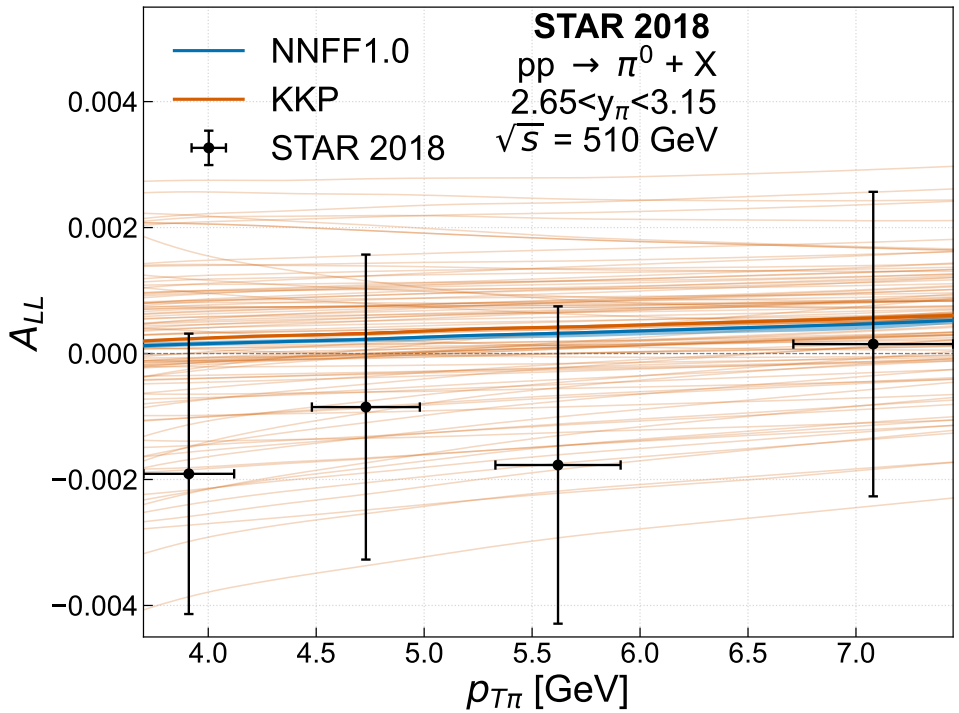

Figure 10: DLSA of π^0 production vs. transverse momentum p_T in comparison with STAR data at $\sqrt{s} = 510$ GeV, $2.65 \leq y \leq 3.15$, $3.7 \leq p_T \leq 7.45$ GeV [STAR, Phys. Rev. D **98**, 032013 (2018)]. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

Predictions of π^0-meson DLSA for NICA

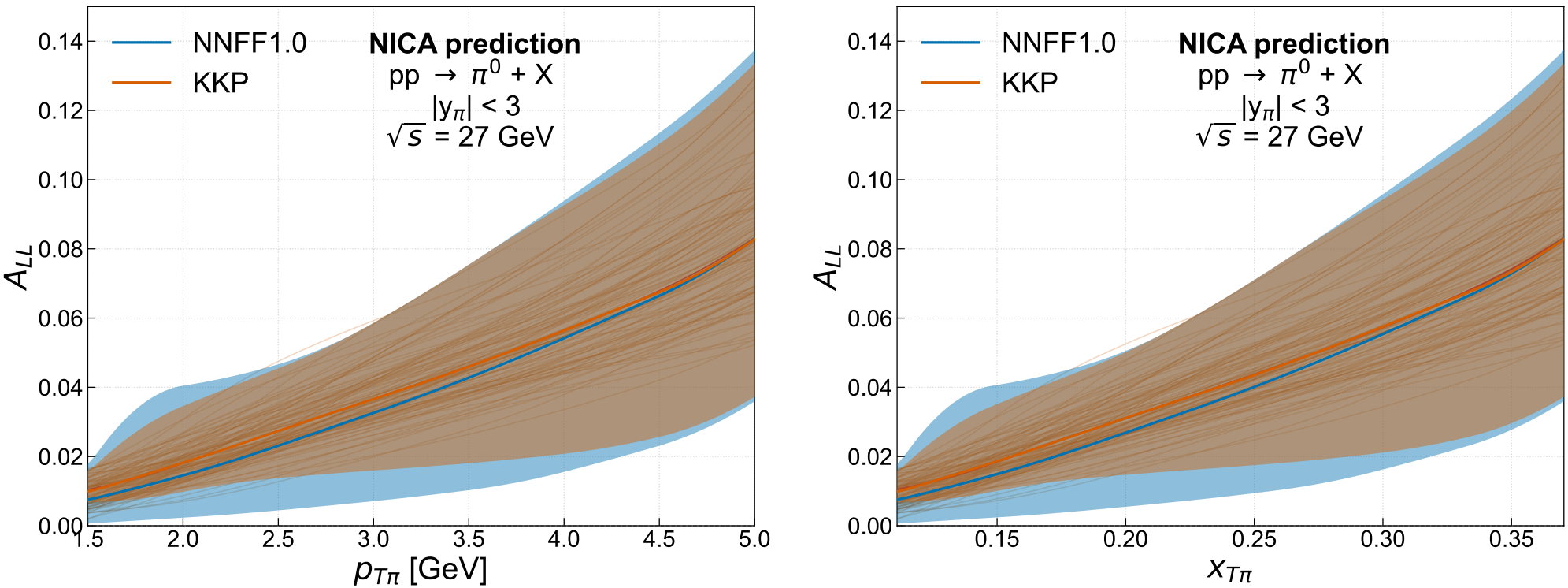

Figure 11: Theoretical predictions of A_{LL}^{π} for NICA at $\sqrt{s} = 27$ GeV, $|y| \leq 3$, $1.5 \leq p_T \leq 5$ GeV. Left panel: p_T-distribution, right panel: $x_T = 2p_T/\sqrt{s}$-distribution. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

Predictions of π^0-meson DLSA for NICA

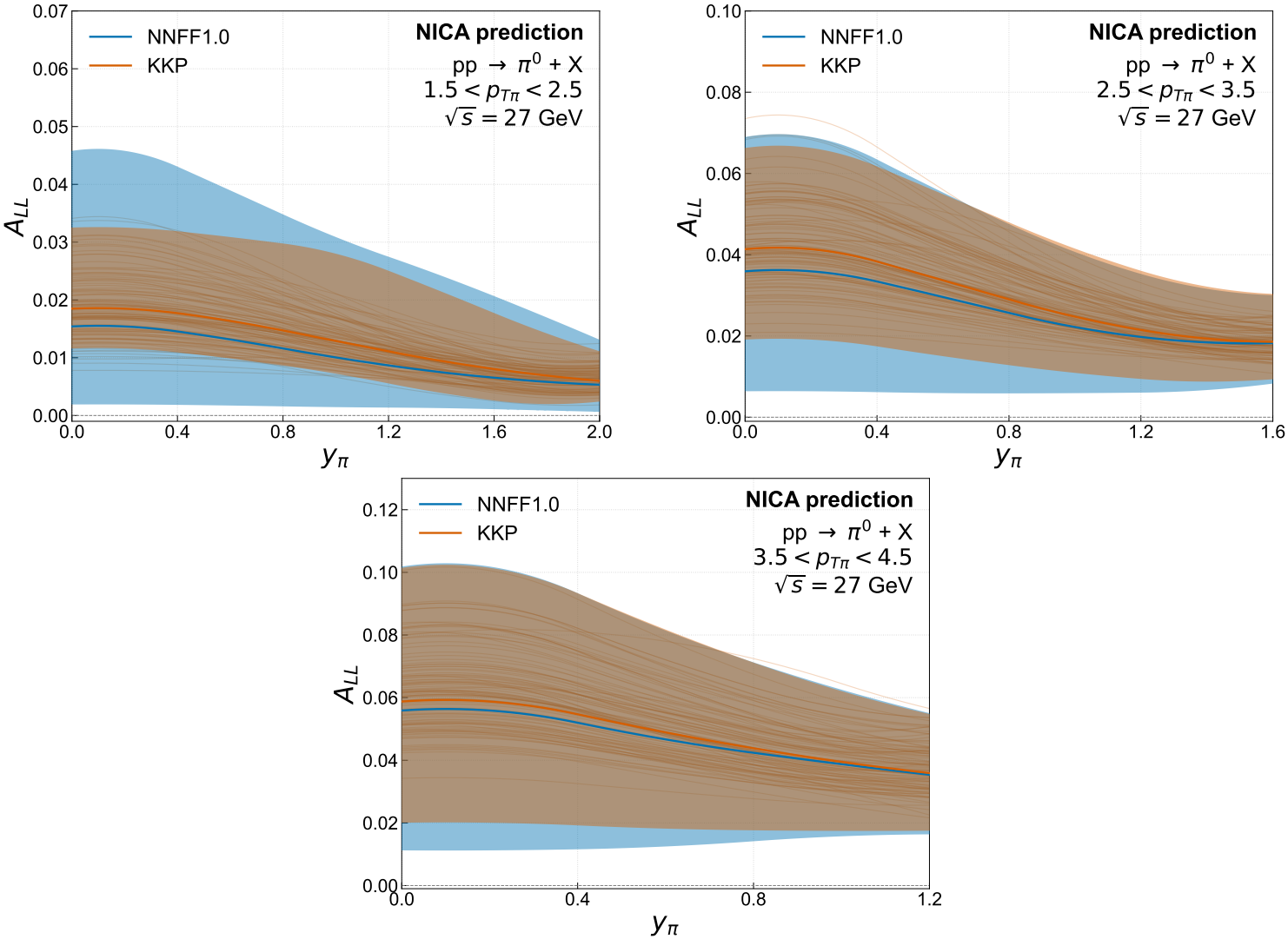

Figure 12: Theoretical predictions of A_{LL}^{π} vs. pion rapidity y for NICA at $\sqrt{s} = 27$ GeV. Left panel: $1.5 \leq p_T \leq 2.5$ GeV, right panel: $2.5 \leq p_T \leq 3.5$ GeV, down panel: $3.5 \leq p_T \leq 4.5$ GeV. Red solid line – KKP FFs, blue solid line – NNFF1.0 FFs.

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- It is crucial to perform NLO calculations both for heavy and light mesons production. Based on previous studies, with including NLO corrections one should anticipate reducing of scale uncertainties and parhaps even changing of the asymmetry sign.

Thank you for your attention!