# Theoretical aspects of Drell-Yan and $J/\psi$ production physics in polarized collisions at NICA

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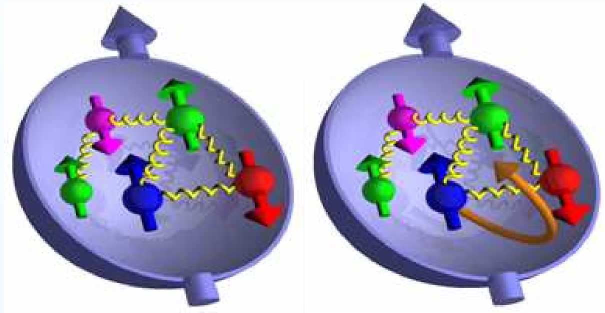
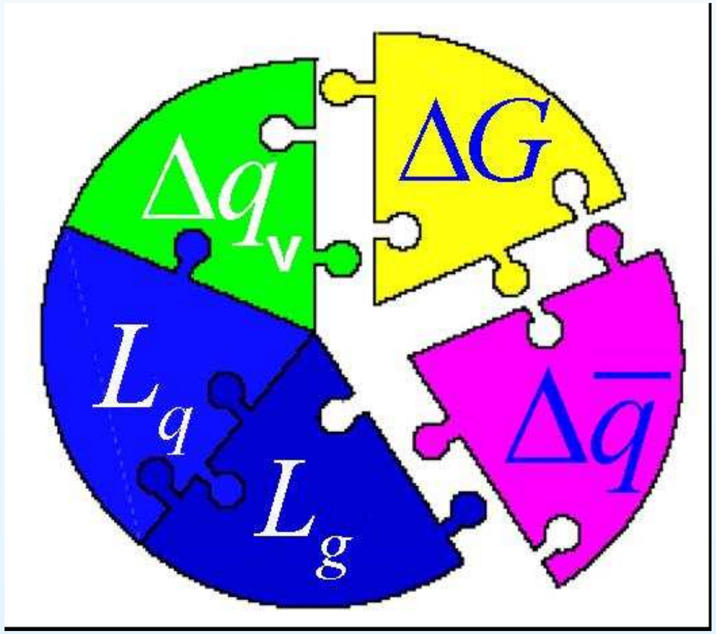
# Proton spin puzzle

$$S_z^N = \frac{1}{2}[\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}] + \Delta G + L_q + L_g$$



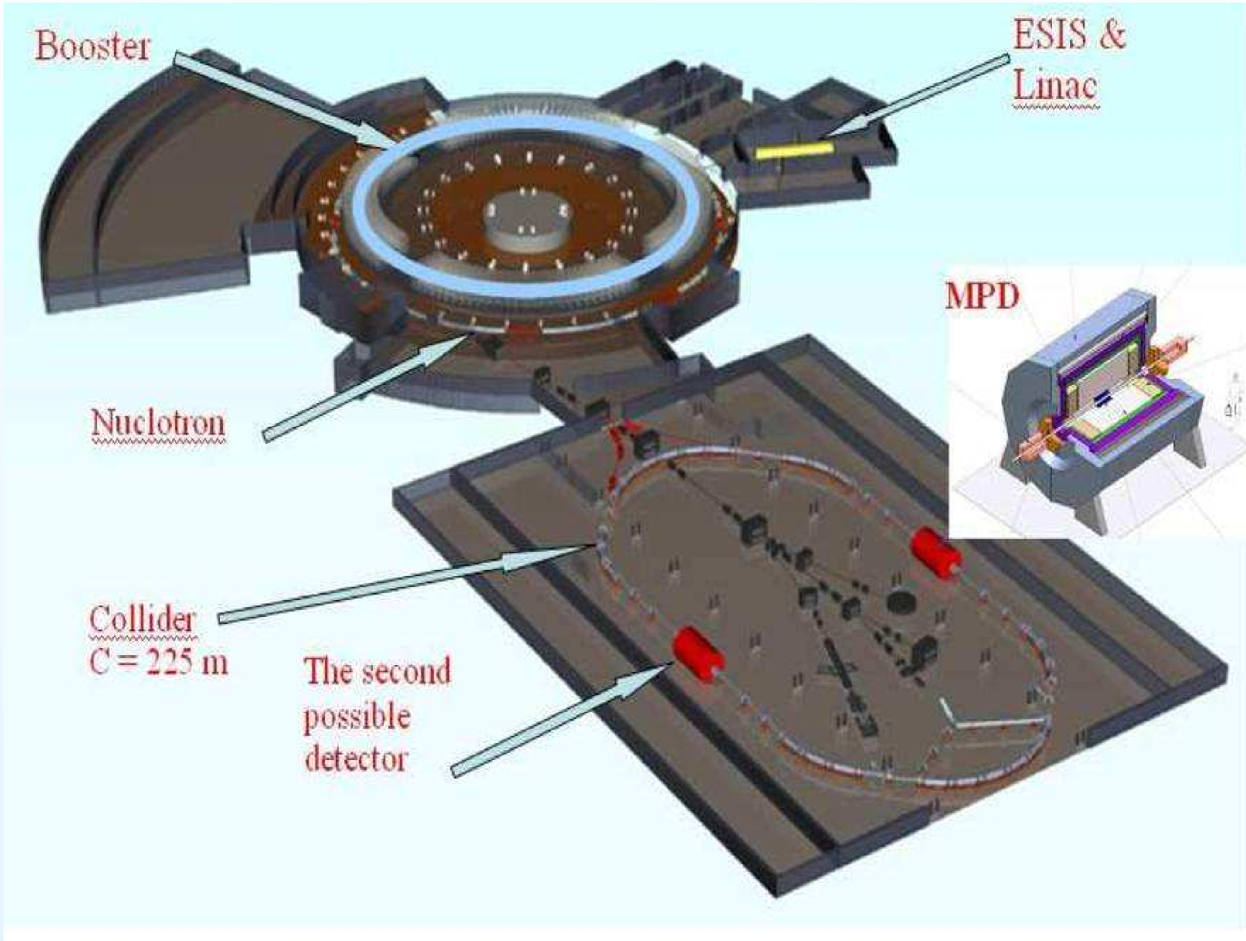



**Polarization data has often been the graveyard for fashionable theories. If theorists had they way they might well ban such measurements altogether out of self-protection.**
**J.D. Bjorken, 1987**

# Second IP at NICA

NICA could provide the unique possibilities for the spin program:

- High energy proton and deutron polarized colliding beams ($\sqrt{s}$ up to 20-26 GeV for pp collisions)
- High luminosity ($> 10^{30} cm^{-2}c^{-1}$)
- Transversely and longitudinally polarized proton and deutron beams with high polarization degree (>50%)
- Spin rotation L $\leftrightarrow$ T
- Precise beam polarization measurements (~3%)
- $4\pi$ geometry detector

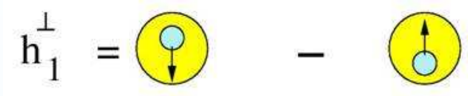


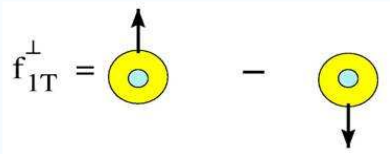
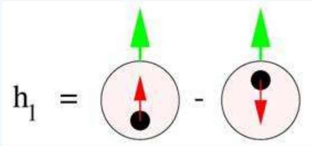
Working group at JINR is organised and started to work on the spin program for the second IP at NICA with the polarized proton and deutron colliding beams

Preliminary topics:

- Studies of Drell-Yan processes with transversely and longitudinally polarized p and D beams. Extraction of unknown PDFs in proton
- Studies of $J/\psi$ and other quarkonium production processes with decay to lepton pair in polarized $p$ and $D$ collisions. Tests on duality of Drell-Yan and $J/\psi$ production processes. Extraction of unknown PDFs from $J/\psi$ production at $\sqrt{s} < 10\,GeV$. Comprehensive tests of all existing theoretical models on $J/\psi$ production
- Spin effects in inclusive processes with baryon and meson production in collisions of polarized protons and deutrons
- Studies of spin effects in various exclusive reactions
- Studies of diffractive processes
- Cross-sections and double spin asymmetries in elastic reactions. Krisch effect in collisions of polarized protons and deutrons
- Spectroscopy of quarkoniums with any available decay modes

**Studies of Drell-Yan processes with polarized p and D beams. Extraction of unknown (poorly known) parton distribution functions (PDFs):**

- $p(D)p(D) \to \gamma^\star X \to e^+e^- X$: **Boer-Mulders PDFs** 
  [NA10, E615, E886]

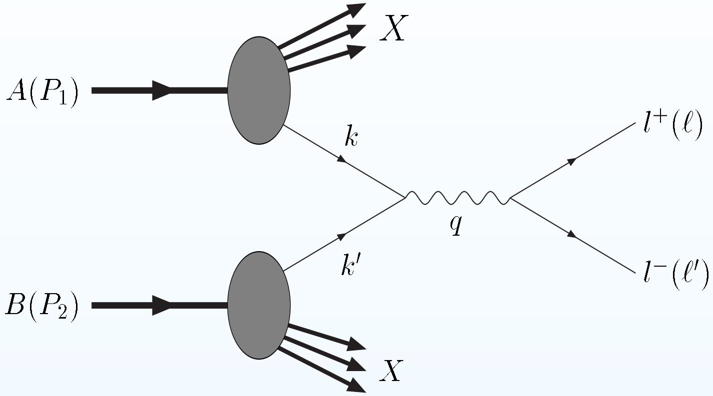
- $p^\uparrow(D^\uparrow)p(D) \to \gamma^\star X \to e^+e^- X$: **Sivers PDF** 
  [Efremov, Collins, . . . PLB 612 (2005), PRD 73 (2006)];
  :transversity 
  and **Boer-Mulders PDFs**
  [Sissakian, Shevchenko, Nagajcev, Ivanov PRD72 (2005), EPJ C46 (2006)]

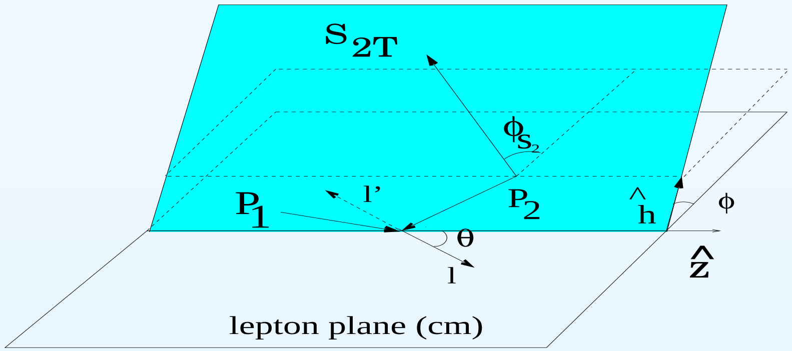
- $p^\uparrow(D^\uparrow)p^\uparrow(D^\uparrow) \to \gamma^\star X \to e^+e^- X$: **transversity**
- $p^\leftarrow(D^\leftarrow)p^\rightarrow(D^\rightarrow) \to \gamma^\star X \to e^+e^- X$: **longitudinally polarized sea and strange PDFs and tenzor deutron structure**
  [Teryaev, Kumano, . . . ]
- **The same PDFs from $J/\psi$ production processes with decay to lepton pairs ($\sqrt{s} < 10\,GeV$)**
- **Studies of all possible quarkoniums with decay to lepton pairs in collisions of polarized protons and deutrons**

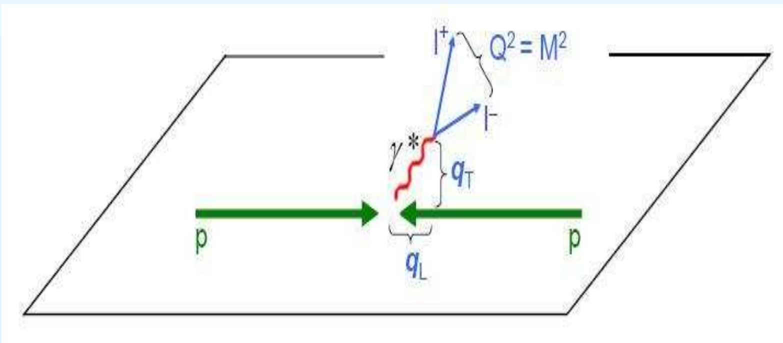
# Experiments on DY measurements

| Experiment | Status | Remarks |
|---|---|---|
| E615 | Finished | Only unpolarized DY |
| NA10 | Finished | Only unpolarized DY |
| E866 | Running | Only unpolarized DY |
| RHIC | Running | Detector upgrade for DY measurements is required (collider) |
| PAX | Plan>2016 | Problem with $\bar{p}$ polarization (collider) |
| COMPASS | Plan>2010 | Only valence PDFs |
| J-PARC | Plan>2011 | low $s$ (60-100 GeV$^2$), only unpolarized proton beam |
| SPASCHARM | Plan? | $s \sim 140, GeV^2$ for unpolarized proton beam |
| NICA | Plan 2014 | $s \sim 630 GeV^2$ for polarized proton beams, high luminosity (collider) |

# Kinematics




- $x_1 = \frac{Q^2}{2p_1 q}, \quad x_2 = \frac{Q^2}{2p_2 q}$ – **fractions of the longitudinal momentum of the hadrons A and B carried by the quark and antiquark which annihilate into virtual photon**
- $s = (p_1 + p_2)^2 \simeq 2p_1 p_2$ – **the center of mass energy squared**
  $Q^2 = M^2 \simeq x_1 x_2 s \equiv \tau s$
  $y = \frac{1}{2} \ln \frac{x_1}{x_2}$
  $x_F = x_1 - x_2$
  $x_1 = \frac{\sqrt{x_F^2 + 4\tau} + x_F}{2} = \sqrt{\tau} e^y$
  $x_2 = \frac{\sqrt{x_F^2 + 4\tau} - x_F}{2} = \sqrt{\tau} e^{-y}$
- $\theta$ – **production angle in the dilepton rest frame – polar angle of the lepton pair in the dilepton rest frame**
- $\phi$ – **azimuthal angle of lepton pair**
- $\phi_S$ – **azimuthal angle of the hadron polarization measured with respect to lepton plane**

# Unpolarized DY $H_1 H_2 \to l^+ l^- X$

$$\frac{d\sigma^{(0)}(H_1 H_2 \to l\bar{l}X)}{d\Omega dx_1 dx_2 d^2\mathbf{q}_T} = \frac{\alpha^2}{12Q^2} \sum_q e_q^2 \Big\{ (1+\cos^2\theta)\mathcal{F}[\bar{f}_{1q} f_{1q}] +$$
$$\sin^2\theta \cos(2\phi) \mathcal{F}\Big[ (2\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\,\hat{\mathbf{h}}\cdot\mathbf{k}_{2T} - \mathbf{k}_{1T}\cdot\mathbf{k}_{2T}) \frac{\bar{h}_{1q}^{\perp} h_{1q}^{\perp}}{M_1 M_2} \Big] \Big\}$$

$$R = \frac{3}{16\pi}(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + k\sin^2\theta\cos 2\phi), \quad (\lambda \simeq 1, \mu \simeq 0, k \equiv \nu/2)$$

$$h_{1q}^{\perp}(x, \mathbf{p}_T^2) = \frac{\alpha_T}{\pi} \frac{M_C M_H}{\mathbf{p}_T^2 + M_C^2} \mathrm{e}^{-\alpha_T \mathbf{p}_T^2} f_{1q}(x) \qquad (M_c = 2.3\,GeV, \alpha_T = 1 GeV^{-2})$$

# Factorization

$$\hat{k} = \frac{\int d^2\mathbf{q}_T[\mathbf{q}_T^2/M_1M_2]\sum_q e_q^2\mathcal{F}[(2\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\hat{\mathbf{h}}\cdot\mathbf{k}_{2T} - \mathbf{k}_{1T}\cdot\mathbf{k}_{2T})\frac{\bar{h}_1^\perp h_1^\perp}{M_1M_2}]}{\int d^2\mathbf{q}_T\sum_q e_q^2\mathcal{F}[\bar{f}_1 f_1]}$$

$$\mathcal{F}[f\bar{f}] \equiv \int d^2\mathbf{k}_{1T}\, d^2\mathbf{k}_{2T}\, \delta^2(\mathbf{k}_{1T}+\mathbf{k}_{2T}-\mathbf{q}_T) f_q(x_1,\mathbf{k}_{1T}^2)\bar{f}_q(x_2,\mathbf{k}_{2T}^2)$$

$$\delta^2(\mathbf{k}_{1T}+\mathbf{k}_{2T}-\mathbf{q}_T)(2\frac{(\mathbf{q}_T\mathbf{k}_{1T})(\mathbf{q}_T\mathbf{k}_{2T})}{\mathbf{q}_T^2} - \mathbf{k}_{1T}\mathbf{k}_{2T})\mathbf{q}_T^2$$
$$= 2\,\mathbf{k}_{1T}^2\mathbf{k}_{2T}^2 + \underbrace{\mathbf{k}_{1T}^2(\mathbf{k}_{1T}\mathbf{k}_{2T})}_{\to 0} + \underbrace{\mathbf{k}_{2T}^2(\mathbf{k}_{1T}\mathbf{k}_{2T})}_{\to 0} + 2(\mathbf{k}_{1T}\mathbf{k}_{2T})^2 - 2(\mathbf{k}_{1T}\mathbf{k}_{2T})^2$$

$$\hat{k} = 8\frac{\sum_q e_q^2(\bar{h}_{1q}^{\perp(1)}(x_1)h_{1q}^{\perp(1)}(x_2)+(1\leftrightarrow 2))}{\sum_q e_q^2(\bar{f}_{1q}(x_1)f_{1q}(x_2)+(1\leftrightarrow 2))}$$

$$h_{1q}^{\perp(n)}(x) \equiv \int d^2\mathbf{k}_T\left(\frac{\mathbf{k}_T^2}{2M^2}\right)^n h_{1q}^\perp(x,\mathbf{k}_T^2)$$

# Unpolarized DY $H_1 H_2 \to l^+ l^- X$

$$\hat{R} = \frac{\int d^2\mathbf{q}_T [|\mathbf{q}_T|^2 / M_1 M_2][d\sigma^{(0)}/d\Omega]}{\int d^2\mathbf{q}_T \sigma^{(0)}}$$

$$\hat{R} = \frac{3}{16\pi}(\gamma(1+\cos^2\theta) + \hat{k}\,\sin^2\theta\cos 2\phi)$$

PRD 72 (2005) 054027

EPJ C46 (2006) 147

$$h_{1q}^{\perp(1)}(x) \equiv \int d^2\mathbf{k}_T \left(\frac{\mathbf{k}_T^2}{2M_p^2}\right) h_{1q}^{\perp}(x_p, \mathbf{k}_T^2)$$

$$\hat{k}_{AB\to l^+l^-X} = 8\frac{\sum_q e_q^2(\bar{h}_{1q}^{\perp(1)}(x_A) h_{1q}^{\perp(1)}(x_B) + (q \leftrightarrow \bar{q}))}{\sum_q e_q^2(\bar{f}_{1q}(x_A) f_{1q}(x_B) + (q \leftrightarrow \bar{q}))}$$

## $\bar{p}p$ collisions (PAX)

$$\hat{k}_{\bar{p}p\to l^+l^-X} = 8\frac{\sum_q e_q^2[h_{1q}^{\perp(1)}(x_1)h_{1q}^{\perp(1)}(x_2)+\bar{h}_{1q}^{\perp(1)}(x_1)\bar{h}_{1q}^{\perp(1)}(x_2)]}{\sum_q e_q^2[f_{1q}(x_1)f_{1q}(x_2)+\bar{f}_{1q}(x_1)\bar{f}_{1q}(x_2)]}$$

$$\simeq 8\frac{h_{1u}^{\perp(1)}(x_1)h_{1u}^{\perp(1)}(x_2)}{f_{1q}(x_1)f_{1q}(x_2)}$$

## $\pi^-p$, $\pi^-D$ collisions (COMPASS)

$$\hat{k}(x_\pi, x_p)|_{\pi^-p\to l^+l^-X} \simeq 8\frac{\bar{h}_{1u}^{\perp(1)}(x_\pi)|_{\pi^-}h_{1u}^{\perp(1)}(x_p)}{\bar{f}_{1u}(x_\pi)|_{\pi^-}f_{1u}(x_p)}$$

$$\hat{k}(x_\pi, x_p)|_{\pi^-D\to l^+l^-X} \simeq 8\frac{\bar{h}_{1u}^{\perp(1)}(x_\pi)|_{\pi^-}\left[h_{1u}^{\perp(1)}(x_p)+h_{1d}^{\perp(1)}(x_p)\right]}{\bar{f}_{1u}(x_\pi)|_{\pi^-}[f_{1u}(x_p)+f_{1d}(x_p)]}$$

$$\frac{\hat{k}(x_\pi,x_p)|_{\pi^-D}}{\hat{k}(x_\pi,x_p)|_{\pi^-p}} \simeq \frac{1+h_{1d}^{\perp(1)}/h_{1u}^{\perp(1)}}{1+f_{1d}/f_{1u}}$$

## $pp$, $pD$ collisions (E866, RHIC, J-PARC, NICA)

$$\hat{k}_{pp\to l^+l^-X}(x_1 \ll x_2) \simeq 8\frac{\bar{h}_{1u}^{\perp(1)}(x_1)h_{1u}^{\perp(1)}(x_2)}{\bar{f}_{1u}(x_1)f_{1u}(x_2)}$$

$$\hat{k}_{pD\to l^+l^-X}(x_1 \ll x_2) \simeq 8\frac{[4\bar{h}_{1u}^{\perp(1)}(x_1)+\bar{h}_{1d}^{\perp(1)}(x_1)][h_{1u}^{\perp(1)}(x_2)+h_{1d}^{\perp(1)}(x_2)]}{[4\bar{f}_{1u}(x_1)+\bar{f}_{1d}(x_1)][f_{1u}(x_2)+f_{1d}(x_2)]}$$

## Single polarized DY processes $H_1 H_2^{\uparrow} \to l^+ l^- X$

$$\hat{A}_{h(f)} = \frac{\int d\Omega d\phi_{S_2} \int d^2\mathbf{q}_T (|\mathbf{q}_T|/M) \sin(\phi \pm \phi_{S_2}) [d\sigma(\mathbf{S}_{2T}) - d\sigma(-\mathbf{S}_{2T})]}{\int d\Omega d\phi_{S_2} [d\sigma(\mathbf{S}_{2T}) + d\sigma(-\mathbf{S}_{2T})]}$$

$$\hat{A}_h = -\frac{1}{2} \frac{\sum_q e_q^2 [\bar{h}_{1q}^{\perp(1)} h_{1q} + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2 [\bar{f}_{1q} f_{1q} + (q \leftrightarrow \bar{q})]}, \quad \hat{A}_f = \frac{\sum_q e_q^2 [\bar{f}_1^q f_{1T}^{\perp q(1)} + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2 [\bar{f}_{1q} f_{1q} + (q \leftrightarrow \bar{q})]}$$

$\downarrow$ A. Sissakian et al, PRD,2005

$\downarrow$ Anselmino et al, PRD, 2003; Efremov et al, PLB, 2005

By analogy with SIDIS SSA (Efremov et al):

$$A_{UT}^{\sin(\phi - \phi_S)\frac{q_T}{M_N}} = 2\hat{A}_f$$

For comparison purposes we use:

$$A_{UT}^{\sin(\phi + \phi_S)\frac{q_T}{M_N}} = 2\hat{A}_h$$

# SSA for DY in $pp^{\uparrow}$ collisions

$$x_p \gg x_{p^\uparrow}$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}}\Big|_{x_p\gg x_{p^\uparrow}} \simeq 2\frac{\bar{f}_{1T}^{\perp(1)u}(x_{p^\uparrow})f_{1u}(x_p)}{\bar{f}_{1u}(x_{p^\uparrow})f_{1u}(x_p)} = 2\frac{\bar{f}_{1T}^{\perp(1)u}(x_{p^\uparrow})}{\bar{f}_{1u}(x_{p^\uparrow})}$$

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}}\Big|_{x_p\gg x_{p^\uparrow}} \simeq -\frac{h_{1u}^{\perp(1)}(x_p)\bar{h}_{1u}(x_{p^\uparrow})}{f_{1u}(x_p)\bar{f}_{1u}(x_{p^\uparrow})}$$

$$x_p \ll x_{p^\uparrow}$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}}\Big|_{x_p\ll x_{p^\uparrow}} \simeq 2\frac{f_{1T}^{\perp(1)u}(x_{p^\uparrow})\bar{f}_{1u}(x_p)}{f_{1u}(x_{p^\uparrow})\bar{f}_{1u}(x_p)} = 2\frac{f_{1T}^{\perp(1)u}(x_{p^\uparrow})}{f_{1u}(x_{p^\uparrow})}$$

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}}\Big|_{x_p\ll x_{p^\uparrow}} \simeq -\frac{\bar{h}_{1u}^{\perp(1)}(x_p)h_{1u}(x_{p^\uparrow})}{\bar{f}_{1u}(x_p)f_{1u}(x_{p^\uparrow})}$$

# Extraction of $h_1/h_1^{\perp(1)}$ and $\bar f_{1T}^{\perp(1)}$ from NICA data

**Extraction of $\bar f_{1T}^{\perp(1)}$ from DY in $pp^\uparrow$ collisions**

$$x_p > x_{p^\uparrow}$$

$A_{UT}^{\sin(\phi-\phi_S)} \neq 0$ while $A_{UT}^{\sin(\phi+\phi_S)} \simeq 0$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}}\Big|_{x_p \gg x_{p^\uparrow}} \simeq 2\frac{\bar f_{1T}^{\perp(1)u}(x_{p^\uparrow}) f_{1u}(x_p)}{\bar f_{1u}(x_{p^\uparrow}) f_{1u}(x_p)} = 2\frac{\bar f_{1T}^{\perp(1)u}(x_{p^\uparrow})}{\bar f_{1u}(x_{p^\uparrow})},$$

**Extraction of $h_1/h_1^{\perp(1)}$ from DY in $pp$ and $pp^\uparrow$ collisions**

$$x_{p^\uparrow} \equiv x_1 > x_p \equiv x_2$$

$A_{UT}^{\sin(\phi+\phi_S)} \neq 0$ while $A_{UT}^{\sin(\phi-\phi_S)} \simeq 0$

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}}\Big|_{x_p \ll x_{p^\uparrow}} \simeq -\frac{\bar h_{1u}^{\perp(1)}(x_p) h_{1u}(x_{p^\uparrow})}{\bar f_{1u}(x_p) f_{1u}(x_{p^\uparrow})},$$

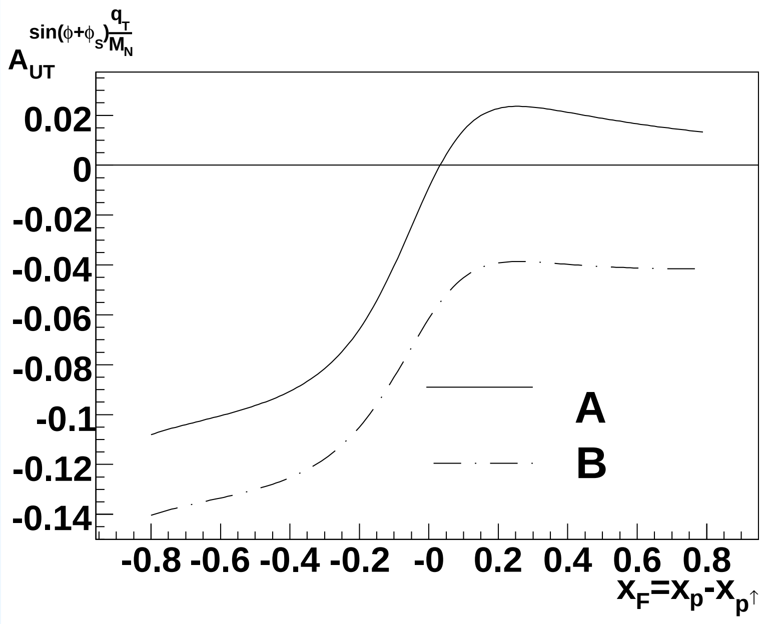
Unpolarized case with $x_1 = x_{p^\uparrow}$, $x_2 = x_p$

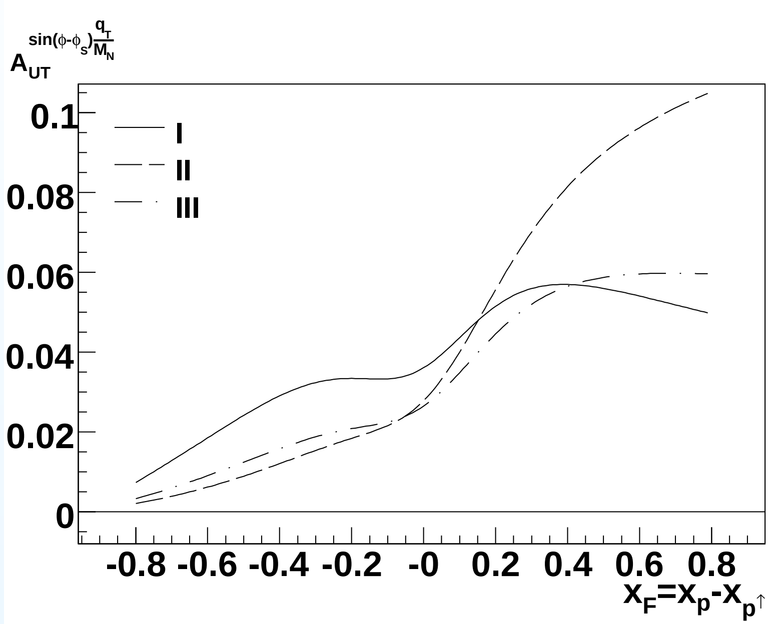
$$\hat k\Big|_{x_1 \gg x_2} \simeq 8\frac{h_{1u}^{\perp(1)}(x_1)\bar h_{1u}^{\perp(1)}(x_2)}{f_{1u}(x_1)\bar f_{1u}(x_2)}$$

Thus

$$\frac{h_{1u}(x_1)}{h_{1u}^{\perp(1)}(x_1)} \simeq -8\frac{\hat A_{UT}^{\sin(\phi+\phi_S)}}{\hat k}\Bigg|_{x_1 \gg x_2}$$

# NICA kinematics



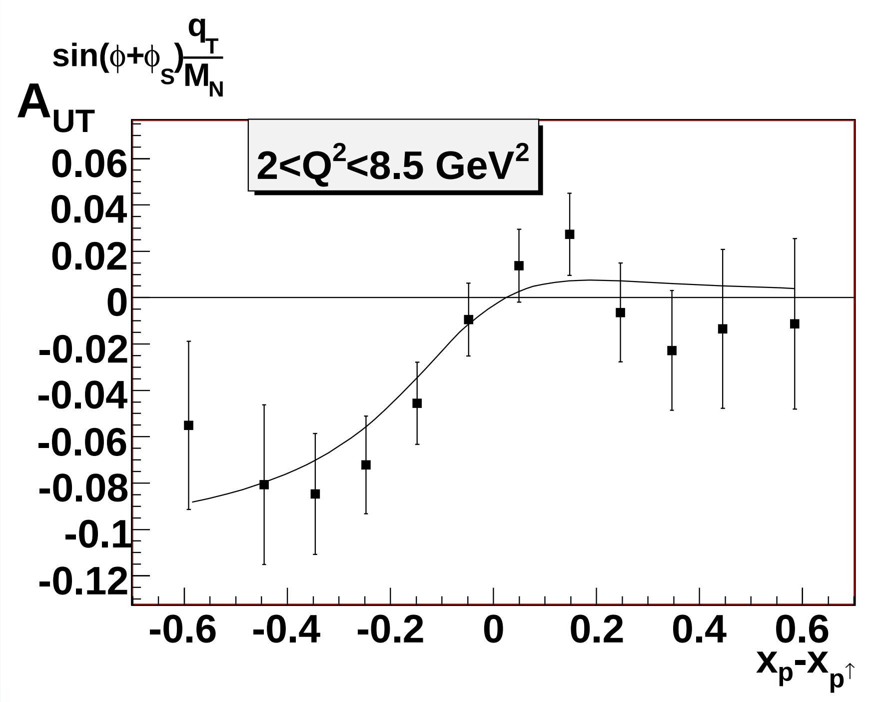

$s = 400\,GeV^2$, $Q^2 = 4GeV^2$. A: $h_{1q,\bar{q}} = \Delta q, \Delta\bar{q}$; B: $h_{1q} = (\Delta q + q)/2$, $h_{1\bar{q}} = (\Delta\bar{q} + \bar{q})/2$ at $Q_0^2 = 0.23GeV^2$. We use three fits for the Sivers function I, II and III (from papers by Efremov et al; Collins, Efremov et al).

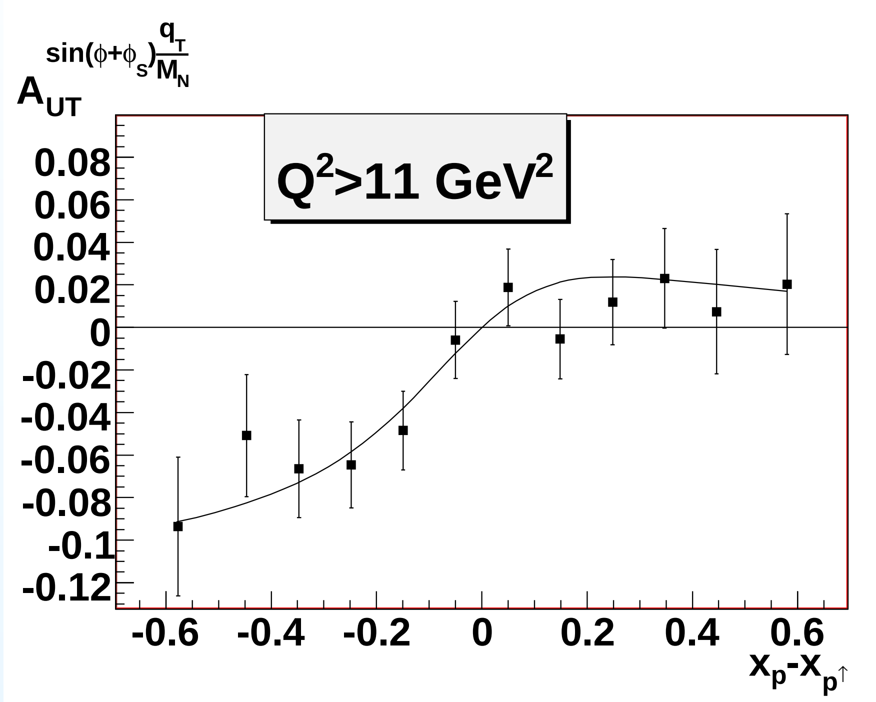
# Simulation package

The set of original software packages is developed for MC studies of polarized Drell-Yan processes

- New MC generator of polarized Drell-Yan events is mainly completed
- Now it is under hard testing/cross-checking
- To be done: to include it to PYTHIA replacing there the existing standard part for Drell-Yan process (only unpolarized and without correct $q_T$ and $\cos 2\phi$ dependence)
- Detector simulation package is also under development

# Simulations, NICA kinematics



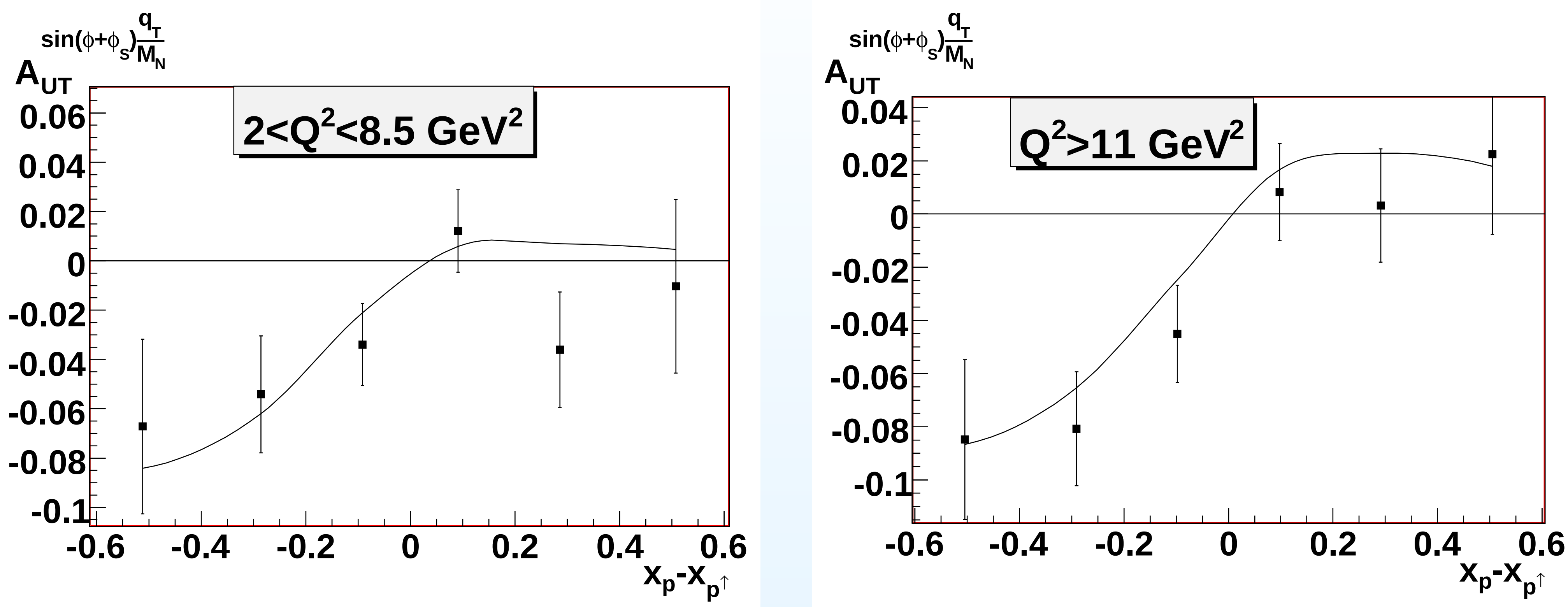




$A_{UT}^{\sin(\phi+\phi_s)\frac{q_T}{M_N}}$ in $pp^{\uparrow}$ collisions, $s = 400\, GeV^2$, 100K events.

Left: $\langle Q^2 \rangle \simeq 3.5\, GeV^2$

Right: $\langle Q^2 \rangle \simeq 15\, GeV^2$

# Simulations, NICA kinematics

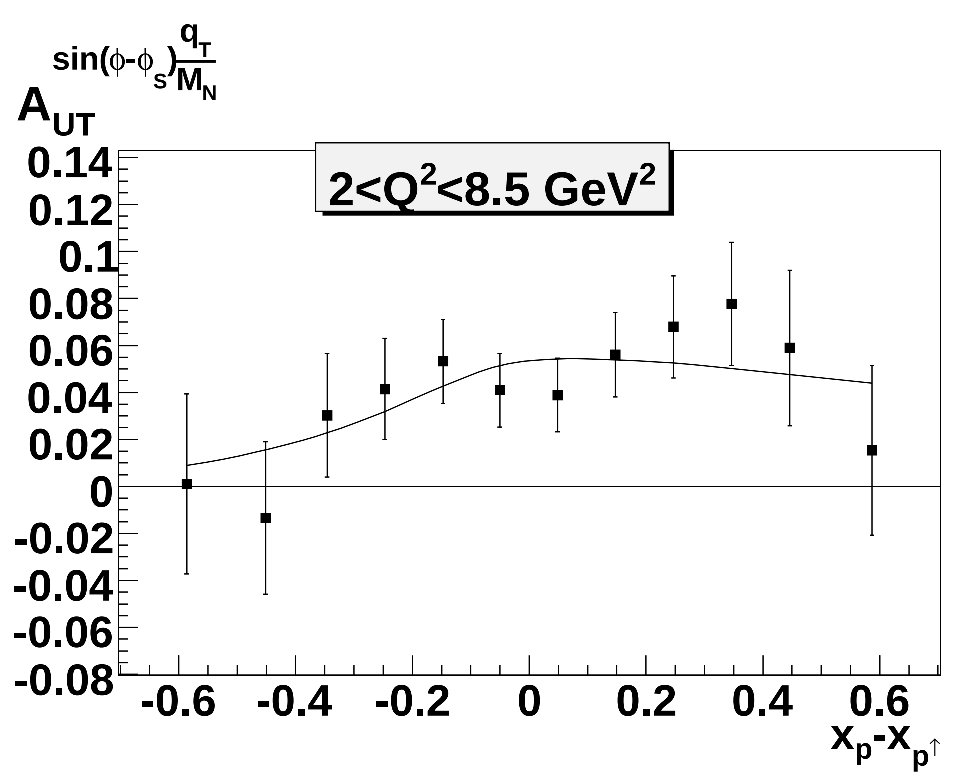


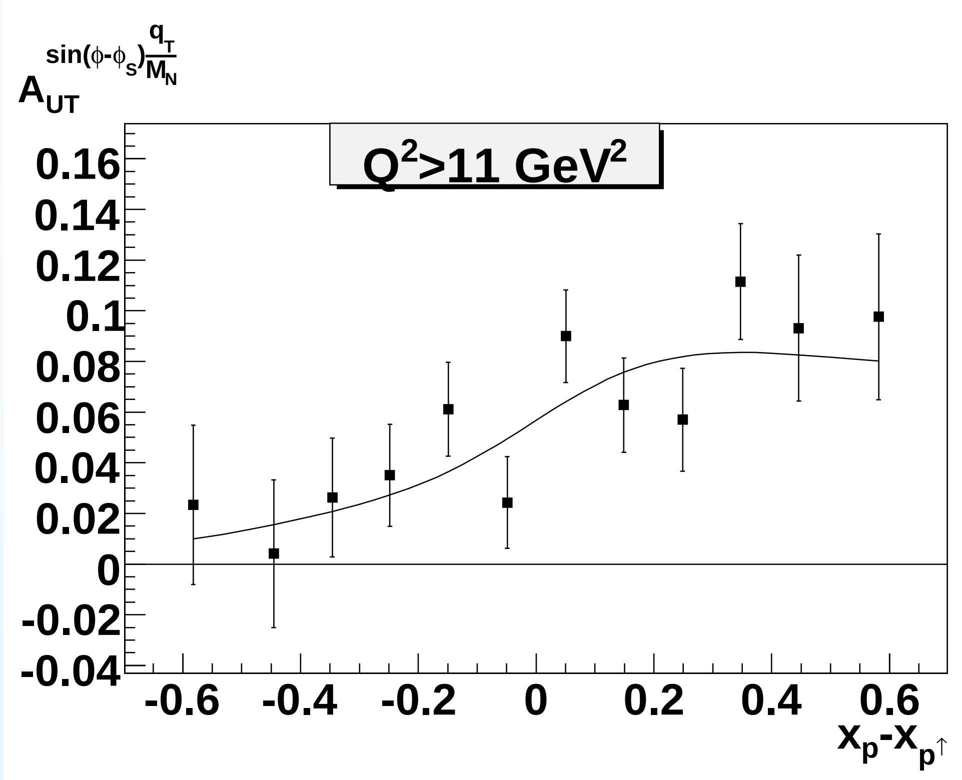

$A_{UT}^{\sin(\phi+\phi_s)\frac{q_T}{M_N}}$ in $pp^\uparrow$ collisions, $s = 400\, GeV^2$, 50K events.

Left: $\langle Q^2 \rangle \simeq 3.5\, GeV^2$

Right: $\langle Q^2 \rangle \simeq 15\, GeV^2$

# Simulations, NICA kinematics




$A_{UT}^{\sin(\phi-\phi_s)\frac{q_T}{M_N}}$ in $pp^\uparrow$ collisions, $s = 400\,GeV^2$, 100K events.

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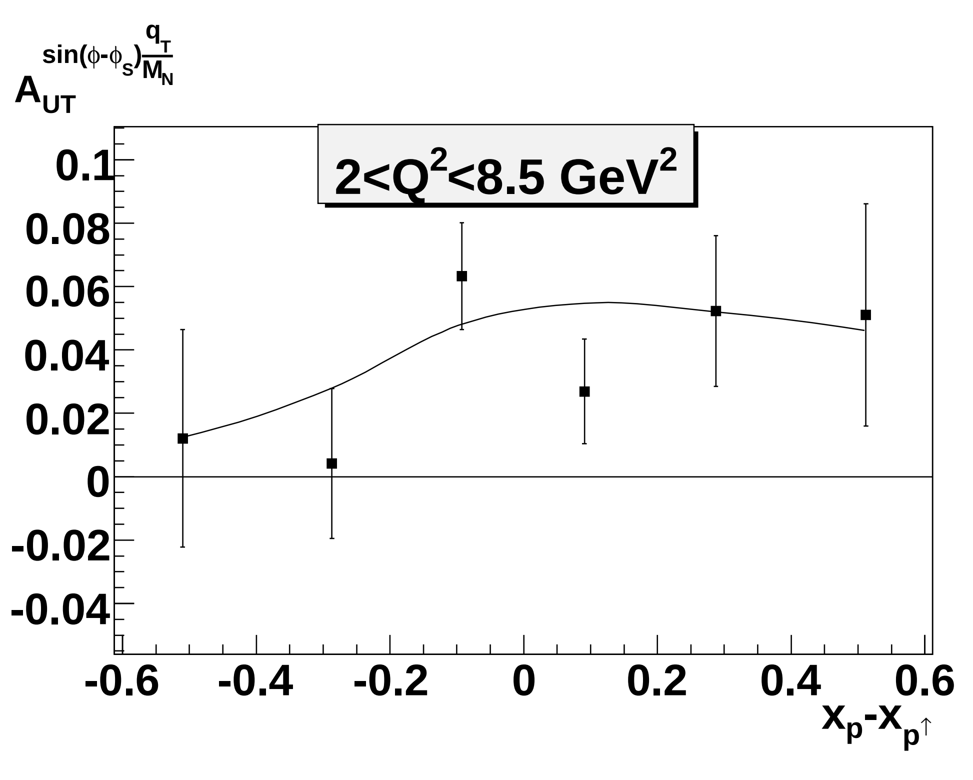
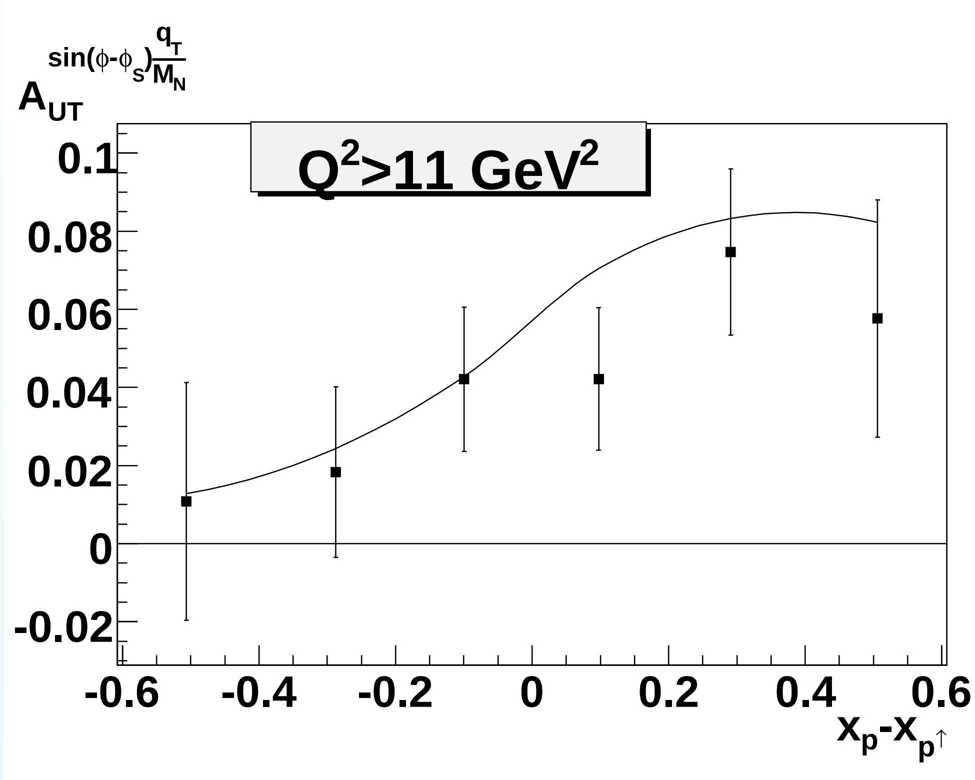
# Simulations, NICA kinematics




$A_{UT}^{\sin(\phi-\phi_s)\frac{q_T}{M_N}}$ in $pp^\uparrow$ collisions, $s = 400\,GeV^2$, 50K events.

Left: $\langle Q^2 \rangle \simeq 3.5\,GeV^2$

Right: $\langle Q^2 \rangle \simeq 15\,GeV^2$

# SSA from DY with $pD^\uparrow$, $p^\uparrow D$ and $DD^\uparrow$ collisions

Last COMPASS results on transversity:

$$h_{1u} + h_{1d} \simeq 0,$$

$1/N_c$ expansion predicts:

$$f_{1T}^{\perp(1)u} + f_{1T}^{\perp(1)d} \simeq 0.$$

Thus, the only non-zero SSA are:

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}}(x_D \gg x_{p^\uparrow})\Big|_{Dp^\uparrow\to l^+l^-X} \simeq 2\frac{4\bar{f}_{1T}^{\perp(1)u}(x_{p^\uparrow})+\bar{f}_{1T}^{\perp(1)d}(x_{p^\uparrow})}{4\bar{f}_{1u}(x_{p^\uparrow})+\bar{f}_{1d}(x_{p^\uparrow})},$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}}(x_D \ll x_{p^\uparrow})\Big|_{Dp^\uparrow\to l^+l^-X} \simeq 2\frac{4f_{1T}^{\perp(1)u}(x_{p^\uparrow})+f_{1T}^{\perp(1)d}(x_{p^\uparrow})}{4f_{1u}(x_{p^\uparrow})+f_{1d}(x_{p^\uparrow})},$$

for Sivers PDF and

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}}(x_D \gg x_{p^\uparrow})\Big|_{Dp^\uparrow\to l^+l^-X} \simeq -\frac{[h_{1u}^{\perp(1)}(x_D)+h_{1d}^{\perp(1)}(x_D)][4\bar{h}_{1u}(x_{p^\uparrow})+\bar{h}_{1d}(x_{p^\uparrow})]}{[f_{1u}(x_D)+f_{1d}(x_D)][4\bar{f}_{1u}(x_{p^\uparrow})+\bar{f}_{1d}(x_{p^\uparrow})]},$$

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}}(x_D \ll x_{p^\uparrow})\Big|_{Dp^\uparrow\to l^+l^-X} \simeq -\frac{[\bar{h}_{1u}^{\perp(1)}(x_D)+\bar{h}_{1d}^{\perp(1)}(x_D)][4h_{1u}(x_{p^\uparrow})+h_{1d}(x_{p^\uparrow})]}{[\bar{f}_{1u}(x_D)+\bar{f}_{1d}(x_D)][4f_{1u}(x_{p^\uparrow})+f_{1d}(x_{p^\uparrow})]},$$

for Boer-Mulders and transversity PDF.

# $J/\psi$ and DY

E. Leader and E. Predazzi, “An introduction . . . ”, Cambridge Univ. Press. 1982
N. Anselmino, V. Barone, A. Drago, N. Nikolaev, Phys. Lett. B594 (2004) 1997
V. Barone, Z. Lu, B. Ma, Eur. Phys. J. C49 (2007) 967
A. Sissakian, O. Shevchenko, O. Ivanov, JETP Lett 86 (2007) 751

Since $J/\psi$ is a vector particle like $\gamma$ and the same helicity structure of $(q\bar{q})(J/\psi)$ coupling and $(q\bar{q})\gamma^*$ coupling one can apply the replacement

$$16\pi^2\alpha^2 e_q^2 \rightarrow (g_q^V)^2\,(g_\ell^V)^2$$

$$\frac{1}{M^4} \rightarrow \frac{1}{(M^2-M_{J/\psi}^2)^2+M_{J/\psi}^2\Gamma_{J/\psi}^2}$$

*The crucial point is now that, because of the identical helicity and vector structure of the $\gamma^*$ and $J/\psi$ elementary channels (all $\gamma^\mu$ couplings) the same replacements hold for the single-polarized and double polarized cross-sections.*

## $J/\psi$ and DY

### Duality model

$$\frac{d^2\sigma/dx_F dQ^2\Big|_{(AB\to J/\psi\to l^+l^-)}}{d^2\sigma/dx_F dQ^2\Big|_{(A'B'\to J/\psi\to l^+l^-)}} = \frac{\sum_q[\bar{q}(x_A)q(x_B)+q(x_A)\bar{q}(x_B)]}{\sum_q[\bar{q}(x_{A'})q(x_{B'})+q(x_{A'})\bar{q}(x_{B'})]},$$

$$x_{A,B} = \frac{1}{2}\left[\pm x_F + \sqrt{x_F^2 + 4Q^2/s}\right]$$

$$Q^2/s - 1 < x_F < 1 - Q^2/s$$

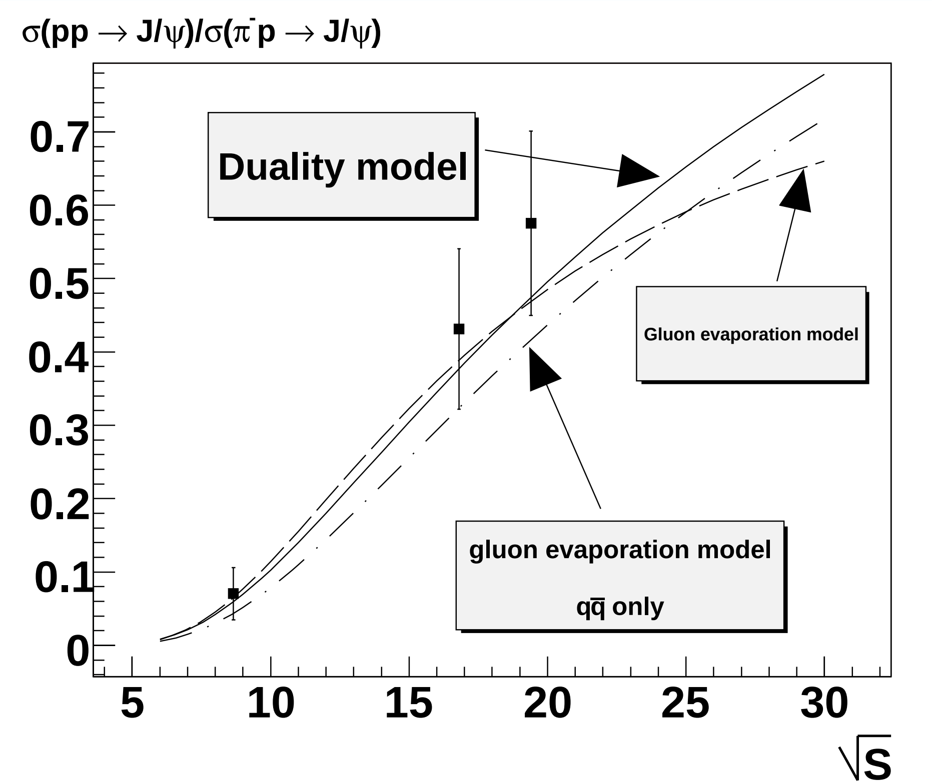
### Gluon evaporation model

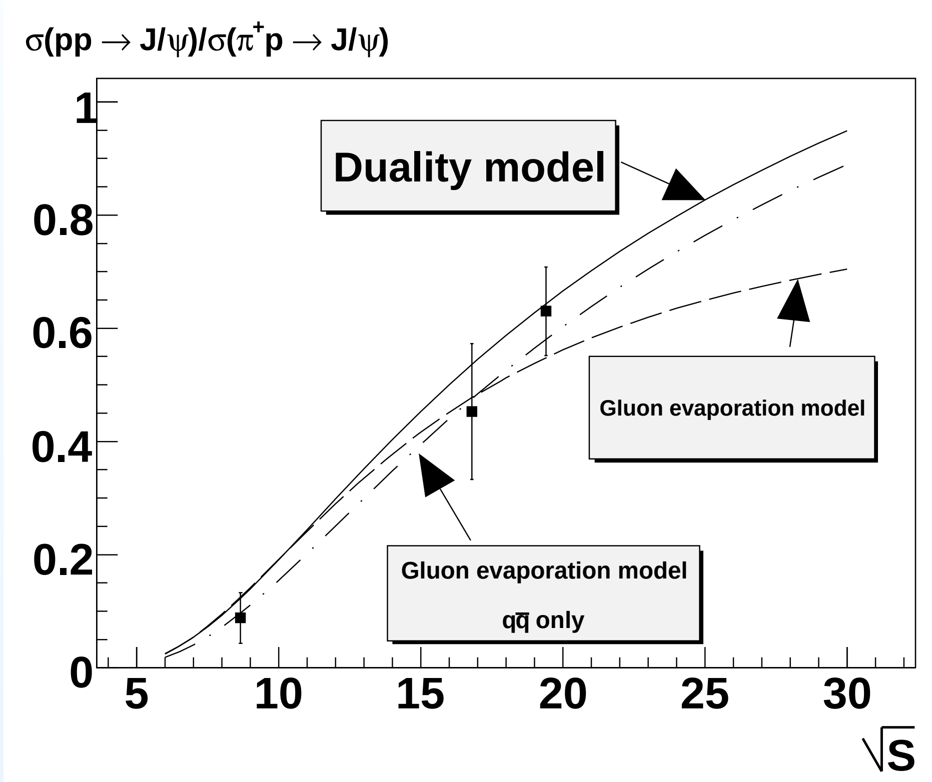
$$\frac{d^2\sigma/dx_F\Big|_{(AB\to J/\psi\to l^+l^-)}}{d^2\sigma/dx_F\Big|_{(A'B'\to J/\psi\to l^+l^-)}} = \frac{d^2(\sigma_{q\bar{q}}+\sigma_{gg})/dx_F\Big|_{(AB\to J/\psi\to l^+l^-)}}{d^2(\sigma_{q\bar{q}}+\sigma_{gg})/dx_F\Big|_{(A'B'\to J/\psi\to l^+l^-)}},$$

$$d\sigma_{q\bar{q}}^{AB}/dx_F = \int_{4m_c^2}^{4m_d^2} dQ^2 \sigma^{q\bar{q}\to c\bar{c}}(Q^2)\frac{x_A x_B}{Q^2(x_A+x_B)}[q^A(x_A)\bar{q}^B(x_B + \bar{q}^A(x_A)q^B(x_B))]$$

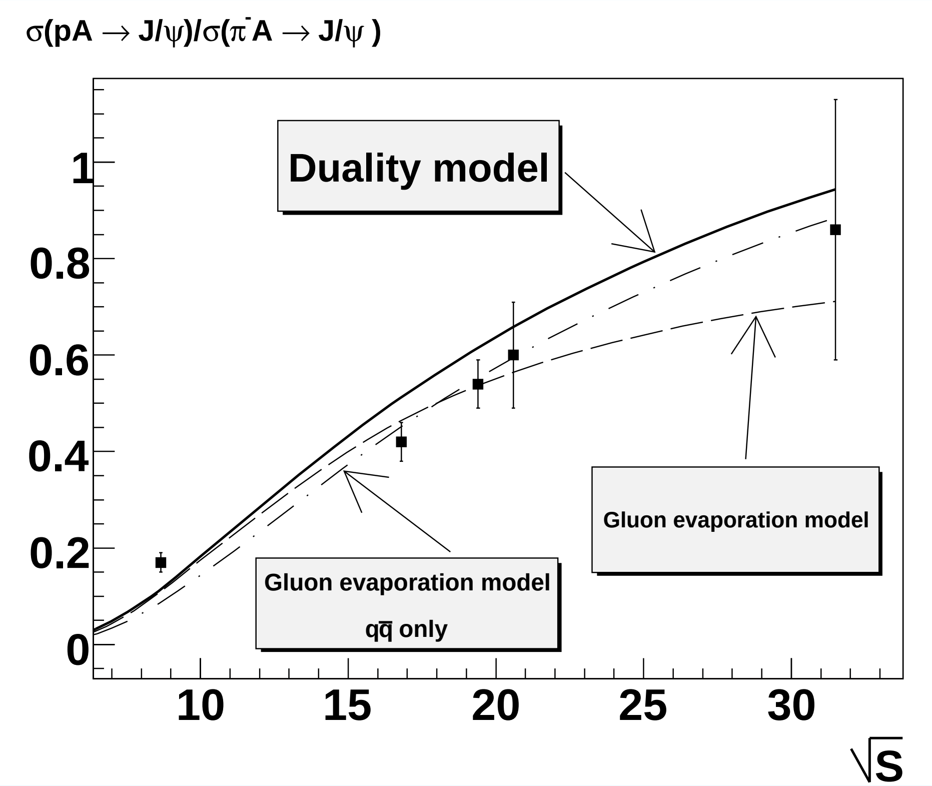
$$d\sigma_{gg}^{AB}/dx_F = \int_{4m_c^2}^{4m_d^2} dQ^2 \sigma^{gg\to c\bar{c}}(Q^2)\frac{x_A x_B}{Q^2(x_A+x_B)}G^A(x_A)G^B(x_B)$$

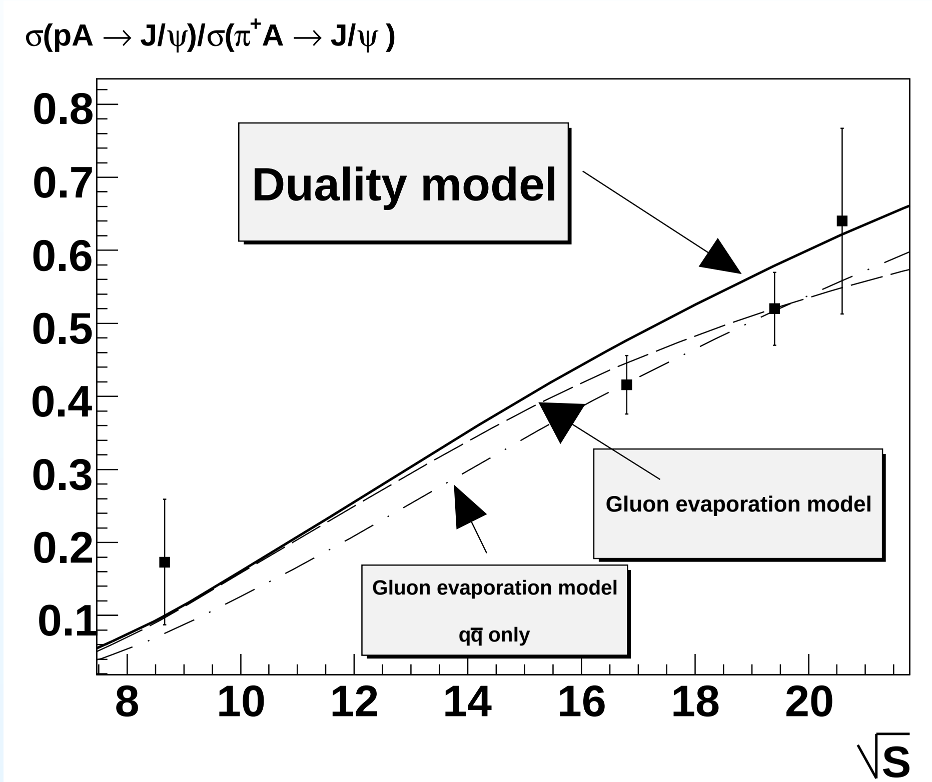
$$\sigma^{q\bar{q}\to c\bar{c}}(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2},\ \sigma^{gg\to c\bar{c}}(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2}.$$



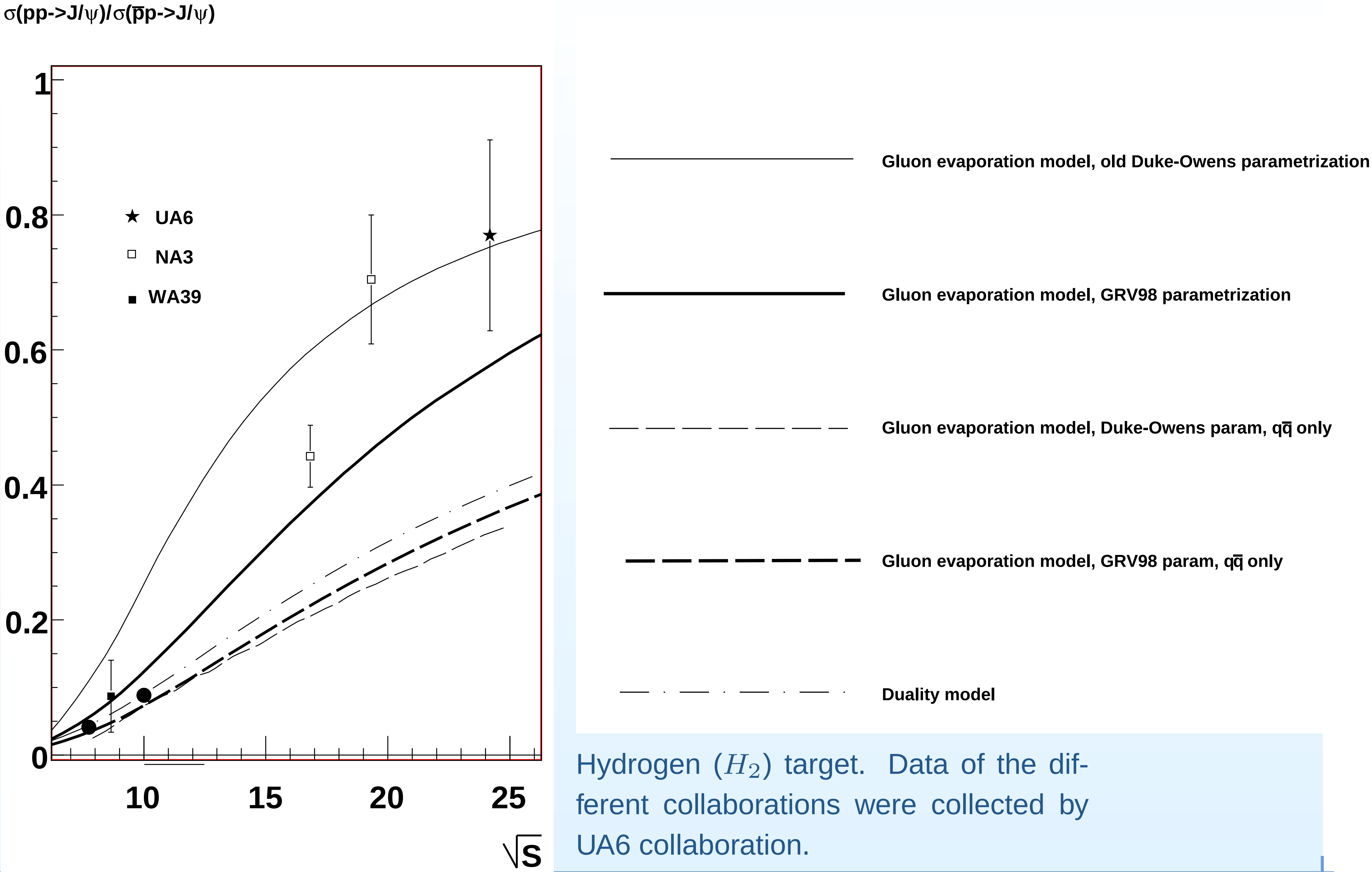




**Hydrogen ($H_2$) target. Data of WA39 and NA3 collaborations are used.**




First point: W, Z/A=0.40 (WA39 coll.); second and third points: Pt, Z/A=0.40 (NA3 coll.); fourth point: C, Z/A=0.5 (UA6 coll.); fifth point: Be, Z/A=0.44 (E672/E706 coll.).



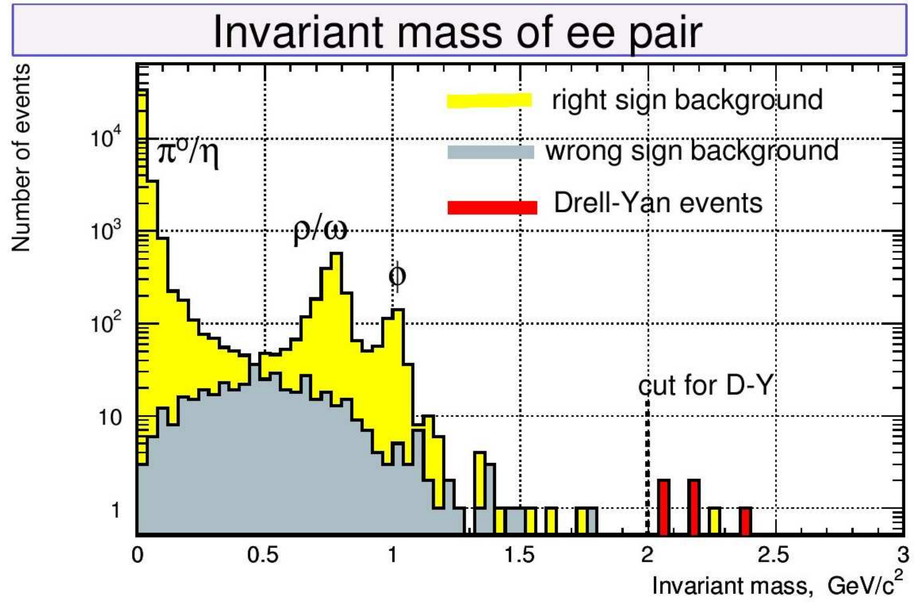

Hydrogen ($H_2$) target. Data of the different collaborations were collected by UA6 collaboration.

## Preliminary estimations of DY feasibility

**DY cross-sections (nb) in comparison with PAX (GSI, FAIR) and possibility to increase the statistics (month of data taking)**

| | $\sigma_{DY}$ total, nb | $L, cm^{-2}s^{-1}$ | K events |
|---|---|---|---|
| PAX, $\sqrt{s} = 14.6 GeV$ | $\sim 2$ | $\sim 10^{30}$ | $\sim 10$ |
| NICA, $\sqrt{s} = 20 GeV$ | $\sim 1$ | $\sim 10^{30}$ | $\sim 5$ |
| NICA, $\sqrt{s} = 26 GeV$ | $\sim 1.3$ | $\sim 10^{30}$ | $\sim 7$ |

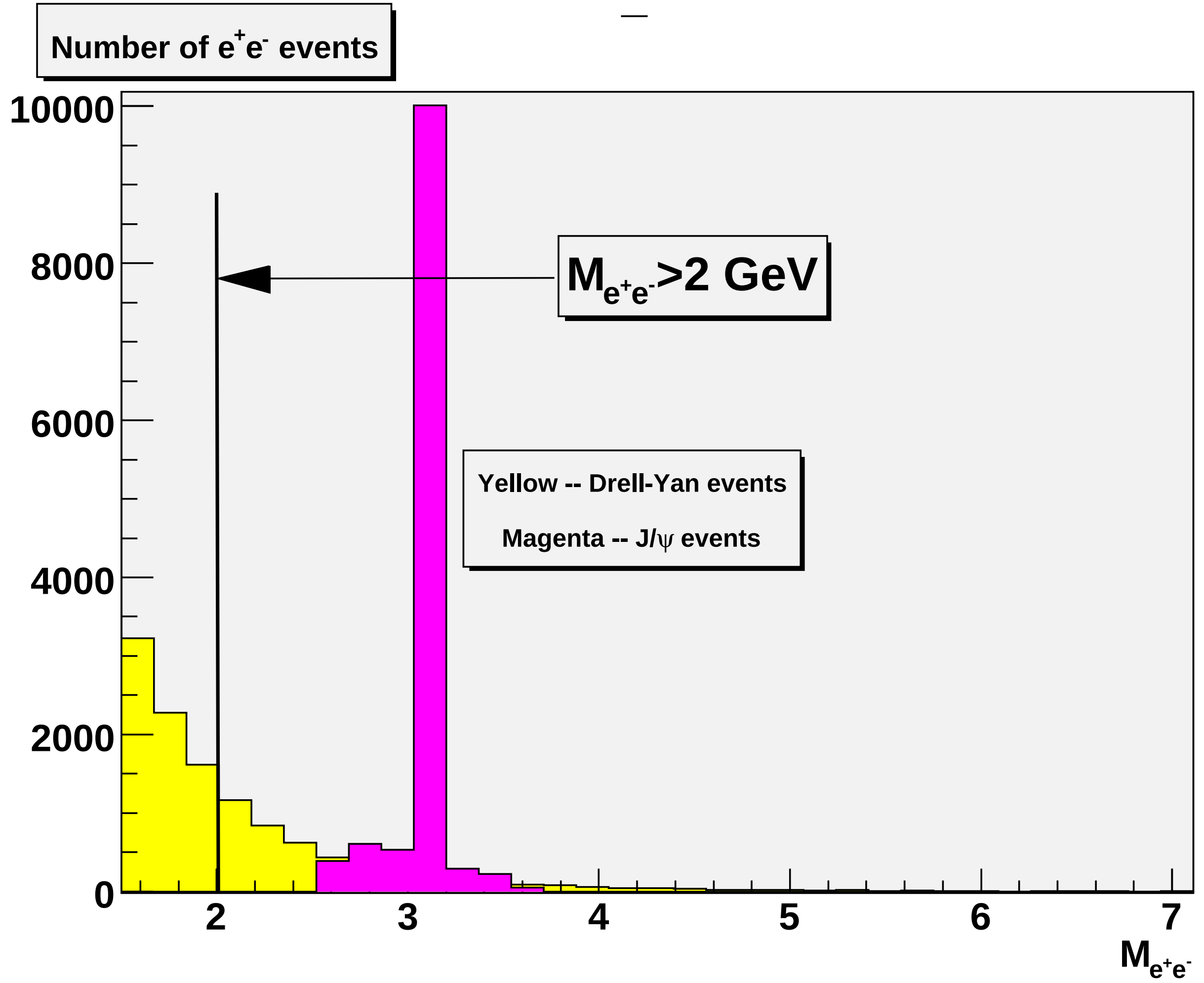
| cut on $Q$, GeV | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 |
|---|---|---|---|---|---|---|
| NICA, $\sqrt{s} = 20\,GeV$ | | | | | | |
| $\sigma_{DY}$ total,nb | 2.54 | 1.94 | 1.59 | 1.32 | 1.1 | 0.9 |
| N events for a month, K | 14.1 | 10.5 | 8.8 | 7.3 | 6.1 | 5 |
| NICA, $\sqrt{s} = 26\,GeV$ | | | | | | |
| $\sigma_{DY}$ total,nb | 3.3 | 2.7 | 2.3 | 1.9 | 1.6 | 1.3 |
| N events for a month, K | 18 | 15 | 13 | 10 | 9 | 7 |
| PAX, $\sqrt{s} = 14.6\,GeV$ | | | | | | |
| $\sigma_{DY}$ total,nb | 5.1 | 4.33 | 3.5 | 2.9 | 2.46 | 2.09 |
| N events for a month, K | 24.4 | 20.7 | 16.7 | 13.9 | 11.8 | 10 |



## Preliminary estimations of $J/\psi$ statistics in comparison with DY statistics

| $\sqrt{s}$, GeV | 20 | 26 |
|---|---|---|
| $\sigma_{J/\psi} \cdot B_{e^+e^-}$, nb | 10 | 16 |
| N events for a month, K | 55 | 88 |

| $\sqrt{s}$, GeV | 20 | 26 |
|---|---|---|
| $\sigma_{DY}$, nb | 0.9 | 1.3 |
| N events for a month, K | 5 | 7 |



# Spin program at NICA (preliminary):

- Studies of Drell-Yan processes with transversely and longitudinally polarized p and D beams. Extraction of unknown PDFs in proton
  – good progress
- Studies of $J/\psi$ and other quarkonium production processes with decay to lepton pair in polarized $p$ and $D$ collisions. Tests on duality of Drell-Yan and $J/\psi$ production processes. Extraction of unknown PDFs from $J/\psi$ production at $\sqrt{s} < 10\,GeV$. Comprehensive tests of all existing theoretical models on $J/\psi$ production
  – good progress
- Spin effects in inclusive processes with baryon and meson production in collisions of polarized protons and deutrons
  – in progress
- Studies of spin effects in various exclusive reactions – to be done
- Studies of diffractive processes – to be done
- Cross-sections and double spin asymmetries in elastic reactions. Krisch effect in collisions of polarized protons and deutrons – to be done
- Spectroscopy of quarkoniums with any available decay modes– to be done

# Welcome to the collaboration!

Our conveners:

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| Process | Available PDF combinations | Remarks |
|---|---|---|
| **Unpol** | **Boer-Mulders** | |
| $pp \to \gamma^\star X \to l^+ l^- X$ | $h_{1u}^{\perp(1)} \bar{h}_{1u}^{\perp(1)}$ | measurable |
| $pD \to \gamma^\star X \to l^+ l^- X$ | $h_{1u}^{\perp(1)} + h_{1d}^{\perp(1)}, \bar{h}_{1u}^{\perp(1)} + \bar{h}_{1d}^{\perp(1)}$ | (NA10, E615) |
| **Single-pol** | **Sivers** | |
| $pp^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $f_{1T}^{\perp(1)u}, \bar{f}_{1T}^{\perp(1)u}$ | SSA ∼5-10% |
| $Dp^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $4 f_{1T}^{\perp(1)u} + f_{1T}^{\perp(1)d}, 4\bar{f}_{1T}^{\perp(1)u} + \bar{f}_{1T}^{\perp(1)d}$ | -//- |
| **Single-pol** | **Transversity&Boer-Mulders** | |
| $pp^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $h_{1u}^{\perp(1)} \bar{h}_{1u}, \bar{h}_{1u}^{\perp(1)} h_{1u}$ | SSA ∼5-10% |
| $Dp^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $[h_{1u}^{\perp(1)} + h_{1d}^{\perp(1)}][4\bar{h}_{1u} + \bar{h}_{1d}]$ | -//- |
| $Dp^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $[\bar{h}_{1u}^{\perp(1)} + \bar{h}_{1d}^{\perp(1)}][4h_{1u} + h_{1d}]$ | -//- |
| **Double-pol** | **Transversity** | |
| $p^\uparrow p^\uparrow \to \gamma^\star X \to l^+ l^- X$ | $h_{1u} \bar{h}_{1u}$ | 1. very small DSA (sea transversity is about zero) 2. Very big uncertainties |
| **Double-pol** | **Helicity** | |
| $p^\Rightarrow p^\Rightarrow \to \gamma^\star X \to l^+ l^- X$ | $\Delta q \Delta \bar{q}$ | DSA$> 10\%$, gives direct access to the sea helicity PDF |

## $J/\psi$ production process $h_1 h_2 \to J/\psi X \to l^+ l^- X$

- Low $s$ region ($s < 100 GeV^2$)

| Process | Available PDF combinations | Remarks |
|---|---|---|
| Unpol | Boer-Mulders | |
| $pp \to J/\psi X \to l^+ l^- X$ | $h_{1u}^{\perp(1)} \bar{h}_{1u}^{\perp(1)}$ | measurable |
| Single-pol | Sivers | |
| $pp^\uparrow \to J/\psi X \to l^+ l^- X$ | $f_{1T}^{\perp(1)u}$, $\bar{f}_{1T}^{\perp(1)u}$ | SSA $\sim$5-10% |
| Single-pol | Transversity&Boer-Mulders | |
| $pp^\uparrow \to J/\psi X \to l^+ l^- X$ | $h_{1u}^{\perp(1)} \bar{h}_{1u}, \bar{h}_{1u}^{\perp(1)} h_{1u}$ | SSA $\sim$5-10% |
| Double-pol | Transversity | |
| $p^\uparrow p^\uparrow \to J/\psi X \to l^+ l^- X$ | $h_{1u} \bar{h}_{1u}$ | 1. very small DSA (sea transversity is almost zero) 2. Very big uncertainties ($1/P_{h_1} P_{h_2}$ factor) |

- High $s$ region ($s > 100 GeV^2$) – access to gluon PDFs

# Other possible processes

| Process | Quantities to be extracted | Remarks |
|---|---|---|
| Unpol | | |
| light nucl $\longrightarrow$ light nucl<br>$pp \longrightarrow pp\gamma\gamma$<br><br>$h_1 h_2 \longrightarrow h$+baryon+meson | form-factors<br>GPD<br><br>parameters of models | PID is required<br>1. very small $\sigma$<br>2. hardly detected<br>hardly detected<br>(very expensive apparatus) |
| Single-pol | | |
| $pp^{\uparrow} \longrightarrow \pi X$<br>$pp^{\uparrow} \longrightarrow DX$ | $f_{1T}^{q} \otimes D_q^h$+$f_{1q} \otimes \Delta_T^0 D_{q/h}$<br>$f_{1T}^{q} \otimes D_q^h$,$f_{1q} \otimes \Delta_T^0 D_{q/h}$ | very complicated combination of absolutely uknown<br>Sivers and Collins functions<br>1. very hardly detected<br>2. fragmentation functions are<br>very poorly known |
| Double-pol<br>$p^{\uparrow}p^{\uparrow} \longrightarrow everything$ | asymmetries, etc | 1. small asymmetries due<br>to sea antiquark PDF<br>2. very big uncertainties<br>$(1/P_{h_1}P_{h_2}$ factor) |