# Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams

More details can be found at: arXiv:1408.3959 [hep-ex]

**Meeting of the working group on theory of hadronic matter under extreme conditions**

***A. Guskov, JINR (Dubna)* on behalf of the drafting committee***

***Dubna, 3.11.2016***

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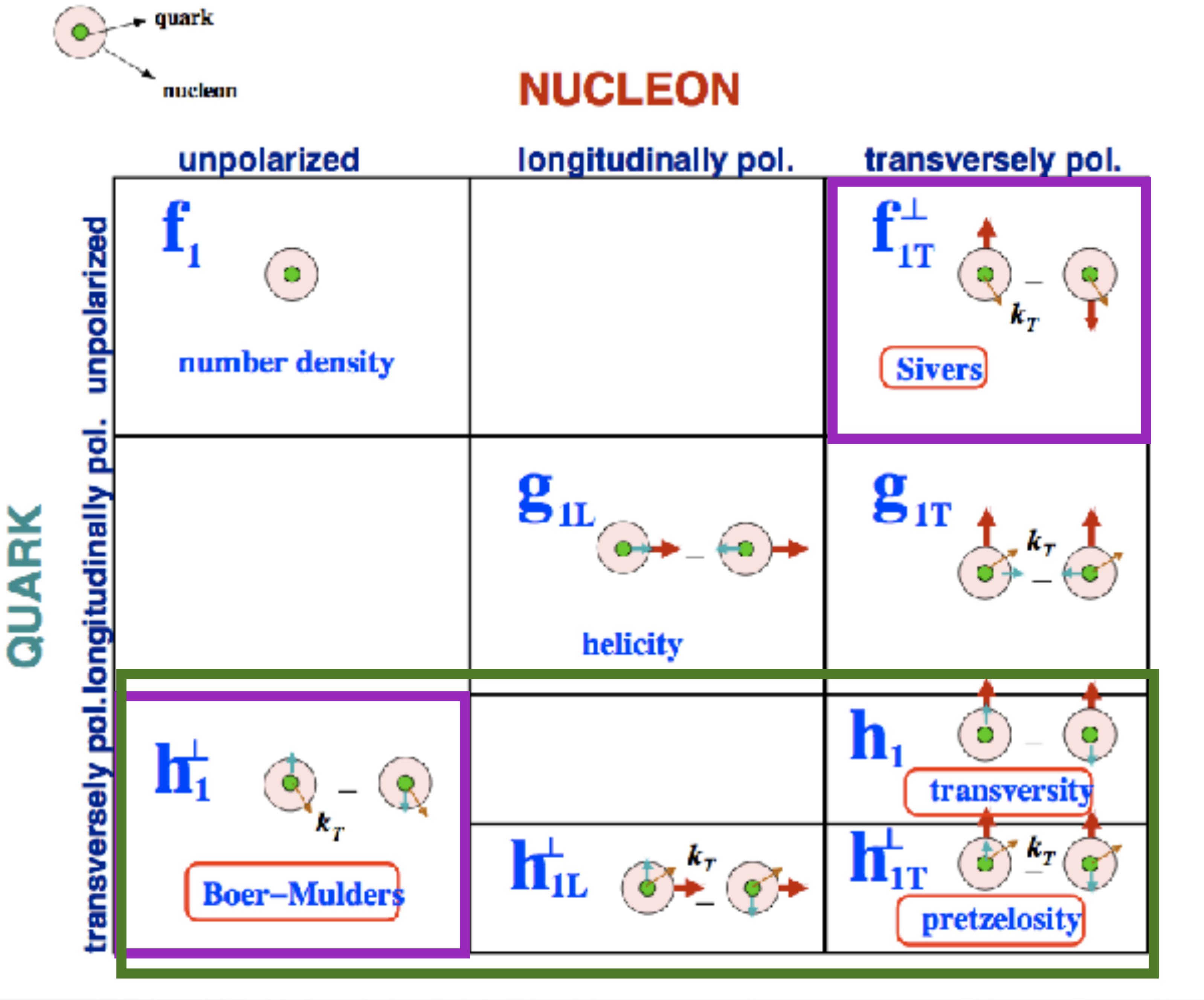
# Nucleon structure and PDFs



***T-odd***

***chiral-odd***

3 PDFs are needed to describe nucleon structure in collinear approximation

8 PDFs are needed if we want to take into account intrinsic transverse momentum $k_T$ of quarks (LO)

# Twist-2 PDFs of nucleons

$(x, Q^2)$

$f_1$ - ***density*** of partons in non-polarized nucleon;
$g_1$ - ***helicity*** , longitudinal polarization of quarks in longitudinally polarized nucleon;
$h_1$ - ***transversity***, transverse polarization of quarks in transversely polarized nucleon;

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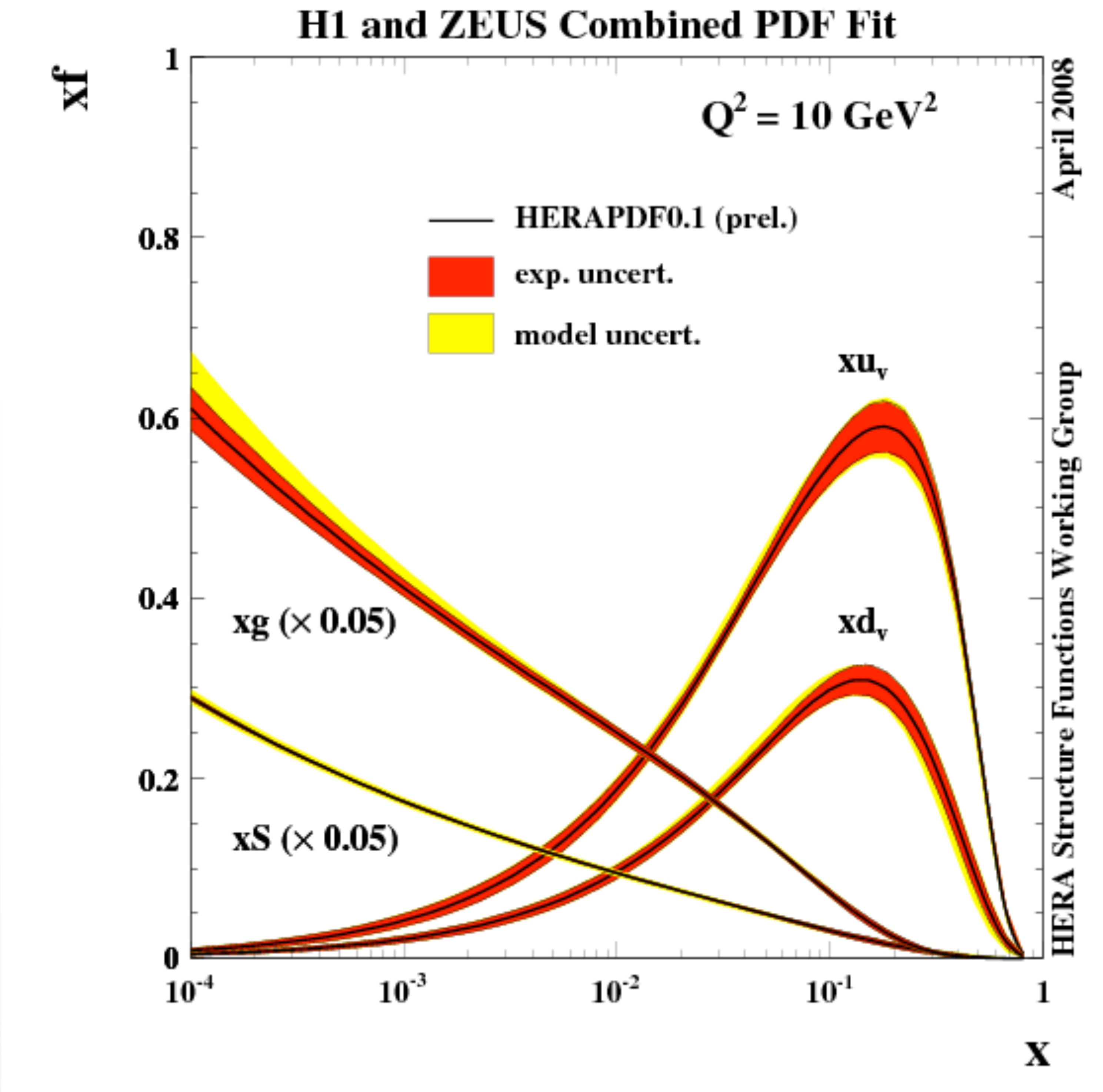
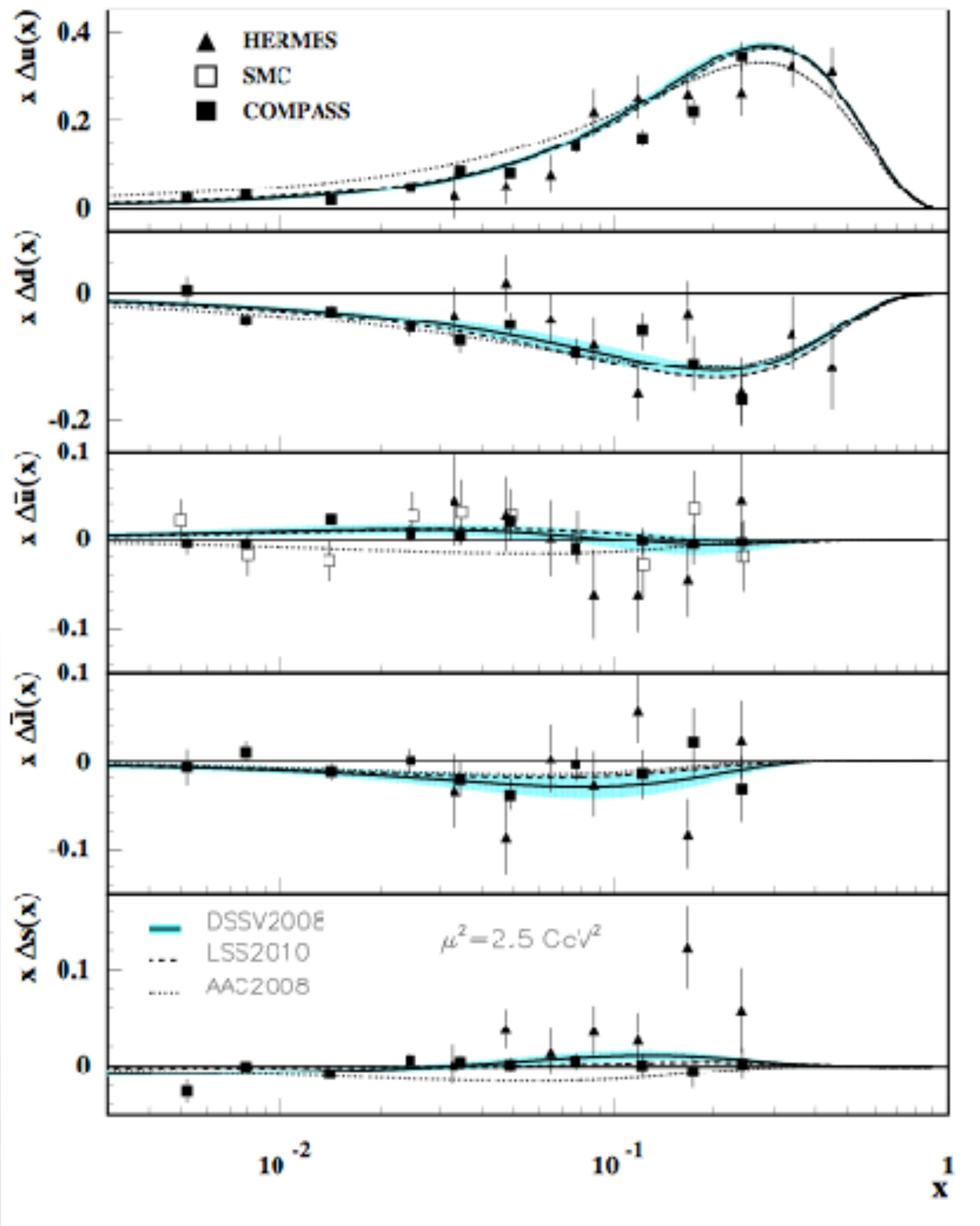
$(x, k_T\ Q^2)$

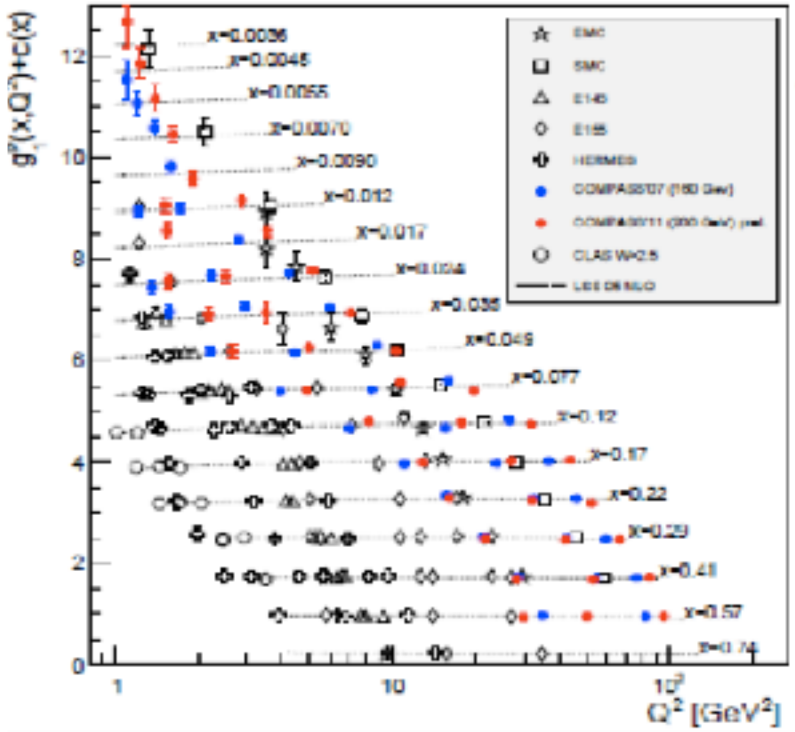
$f^{\perp}_{1T}$ - ***Sivers***, correlation between the transverse polarization of nucleon (transverse spin) and the transverse momentum of non-polarized quarks;
$g^{\perp}_{1T}$ - ***worm-gear-T,*** correlation between the transverse spin and the longitudinal quark polarization;
$h^{\perp}_{1}$ - ***Boer-Mulders***, transverse polarization of quarks in the non-polarized nucleon;
$h^{\perp}_{1L}$ - ***worm-gear-L***, correlation between the longitudinal polarization of the nucleon (longitudinal spin) and the transverse momentum of quarks;
$h^{\perp}_{1T}$ - ***pretzelosity***, distribution of the transverse momentum of quarks in the transversely polarized nucleon.

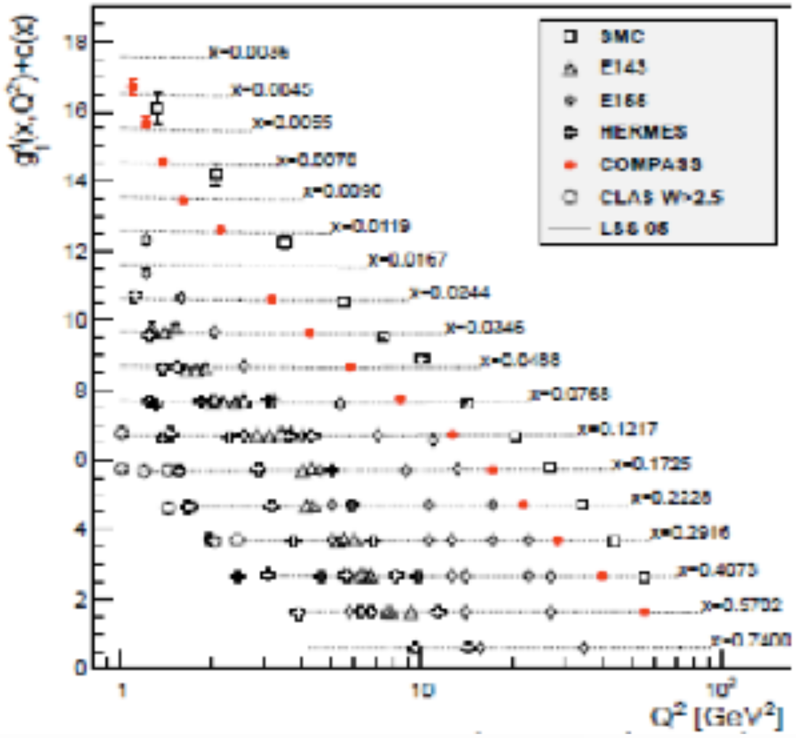
# $f_l$ PDF


H1 and ZEUS Combined PDF Fit
xf
$Q^2 = 10\ GeV^2$
HERAPDF0.1 (prel.)
exp. uncert.
model uncert.
$xu_v$
$xd_v$
xg (× 0.05)
xS (× 0.05)
1
0.8
0.6
0.4
0.2
0
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
x
April 2008
HERA Structure Functions Working Group

# $g_1$ PDF

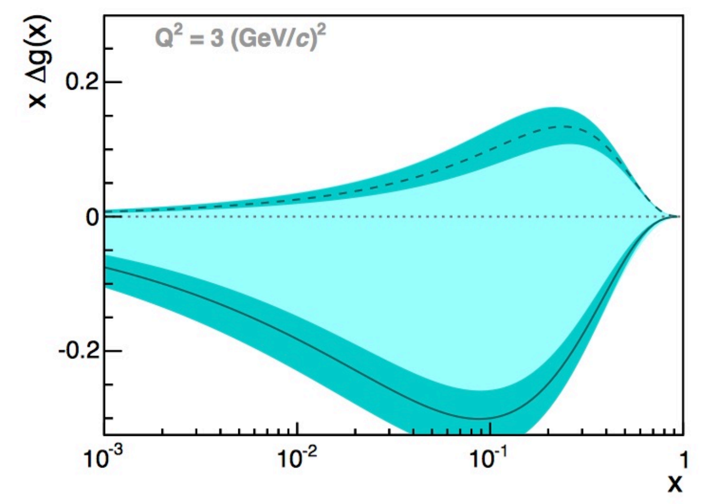






$$A_{//} = \frac{\Delta\sigma_{//}}{2\sigma^{unp}} = \frac{\sigma^{\rightarrow\Rightarrow} - \sigma^{\rightarrow\Leftarrow}}{\sigma^{\rightarrow\Leftarrow} + \sigma^{\rightarrow\Rightarrow}}$$

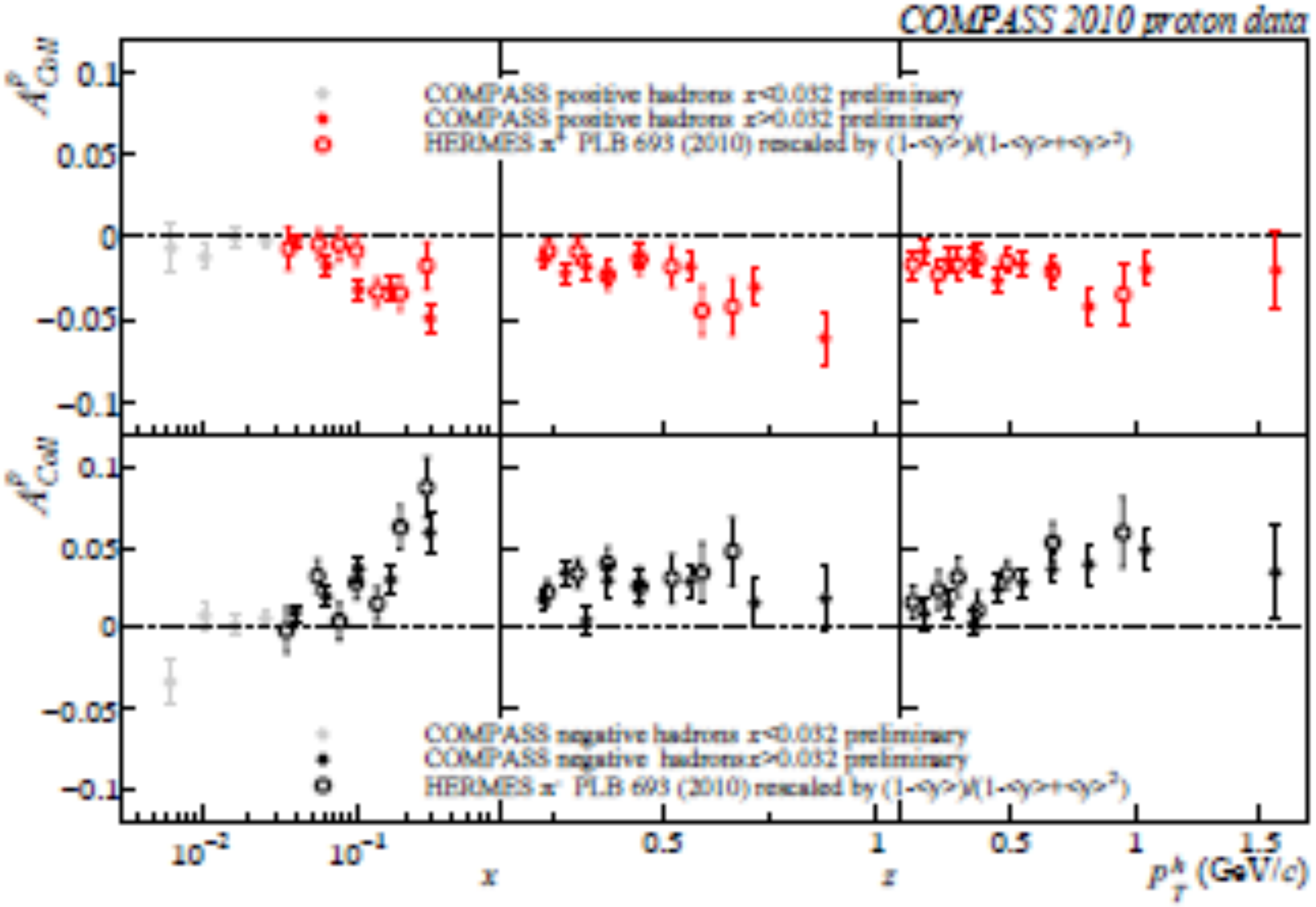
$$g_1(x) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \Delta q(x) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \left[q^+(x) - q^-(x)\right]$$

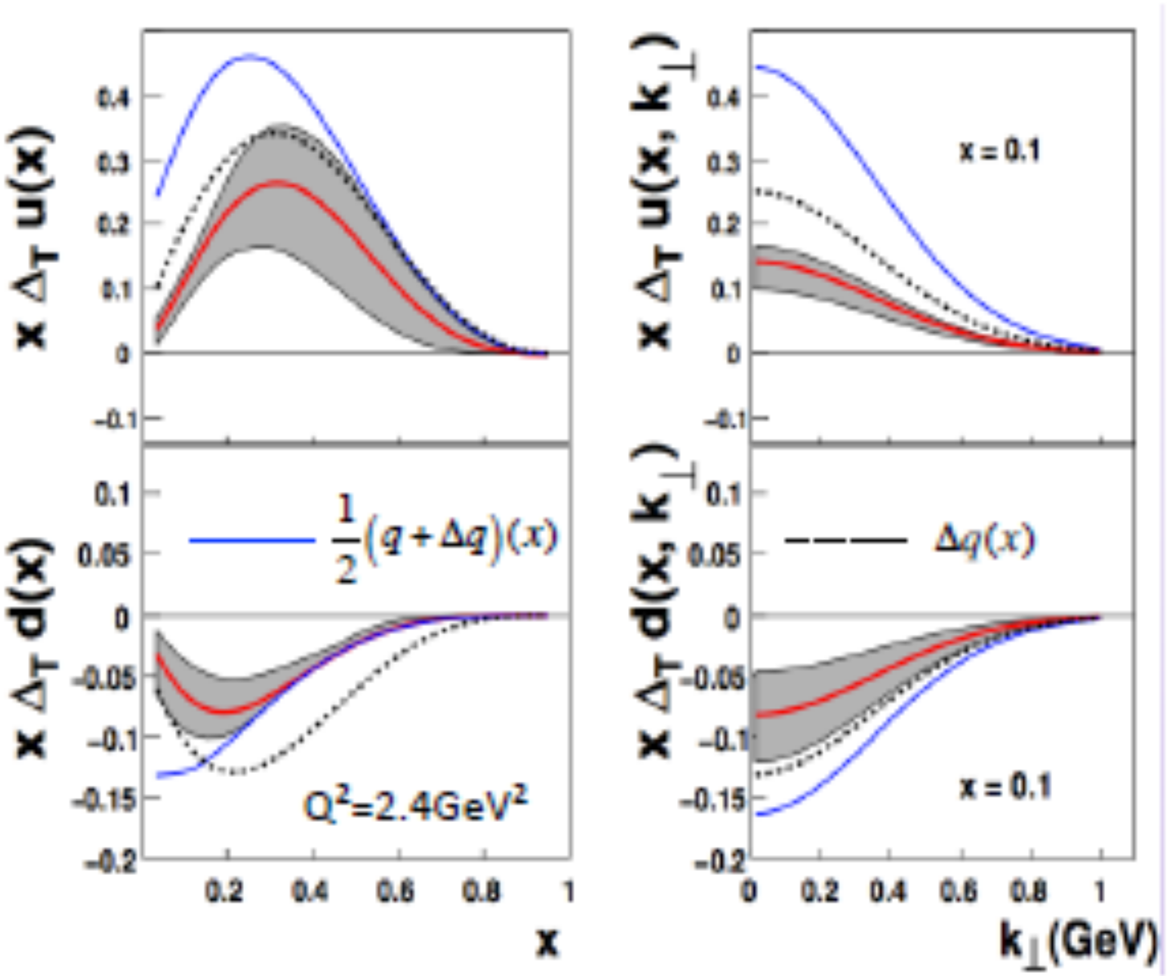


SIDIS for flavor separation but FF!

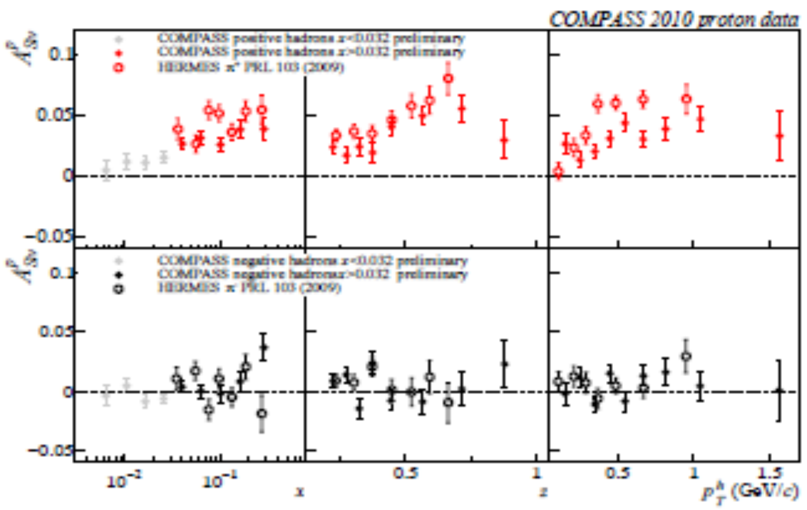
# $h_1$ PDF

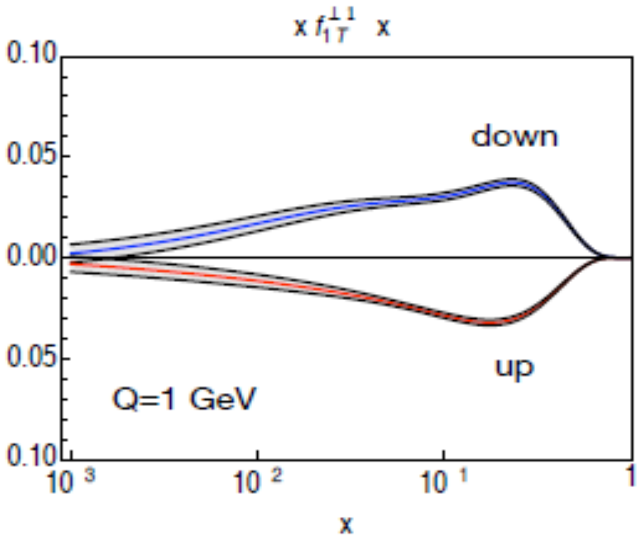
SIDIS


COMPASS 2010 proton data
$A^p_{Coll}$
COMPASS positive hadrons z<0.032 preliminary
COMPASS positive hadrons z>0.032 preliminary
HERMES π⁺ PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
COMPASS negative hadrons z<0.032 preliminary
COMPASS negative hadrons z>0.032 preliminary
HERMES π⁻ PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
0.1
0.05
0
−0.05
−0.1
10⁻²
10⁻¹
x
0.5
1
z
0.5
1
1.5
$p^h_T$ (GeV/c)

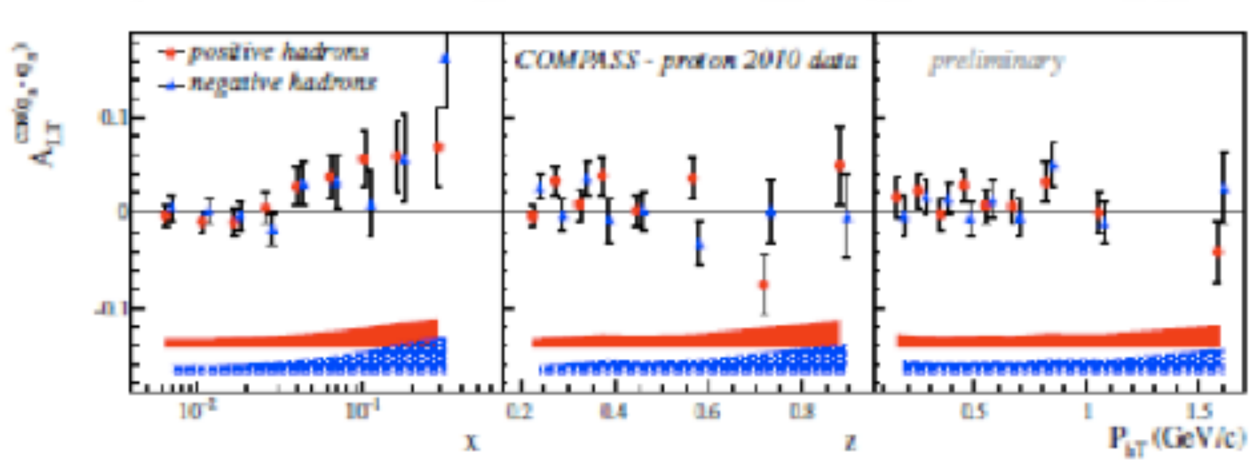

x Δ_T u(x)
x Δ_T d(x)
x Δ_T u(x, k_⊥)
x Δ_T d(x, k_⊥)
$\frac{1}{2}(q+\Delta q)(x)$
$\Delta q(x)$
Q²=2.4GeV²
x = 0.1
x = 0.1
0.4
0.3
0.2
0.1
0
-0.1
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.2
0.4
0.6
0.8
1
x
0
0.2
0.4
0.6
0.8
1
k_⊥(GeV)

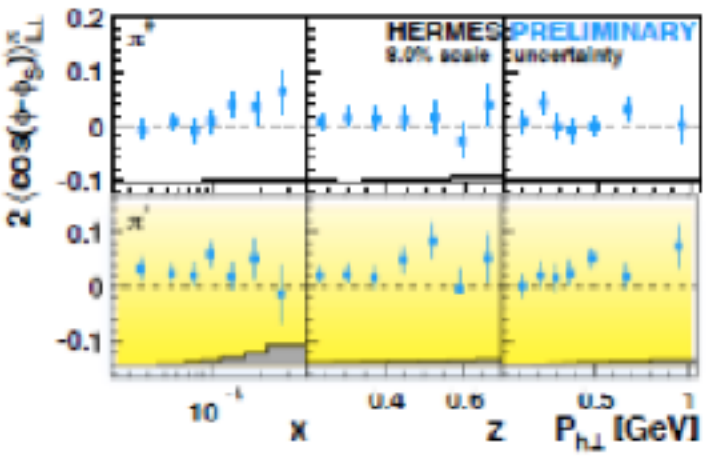
# TMD PDFs





*Sivers asymmetry*
*and*
*Sivers PDF* $f^{\perp}_{1T}$.





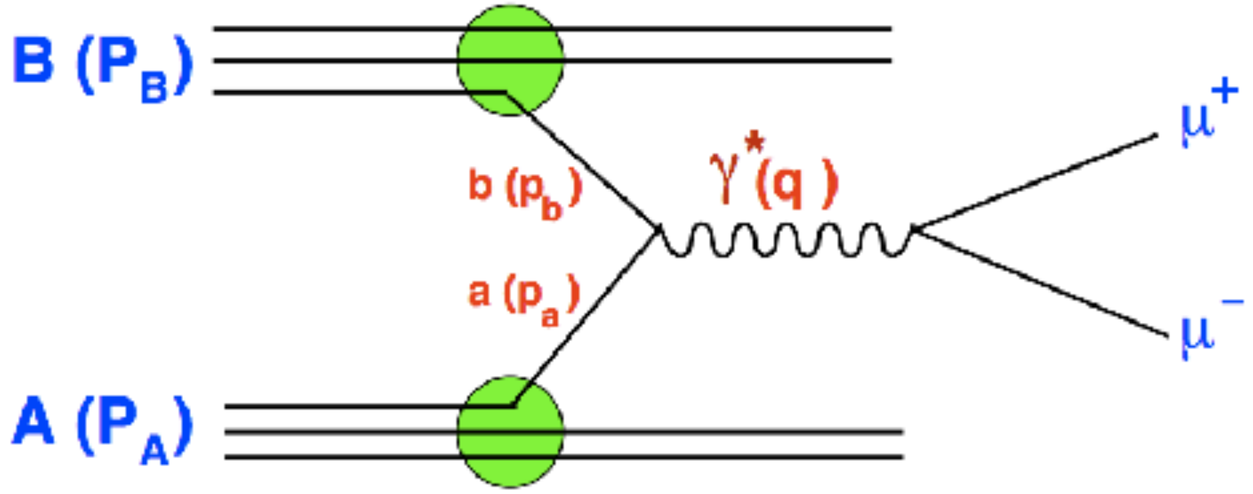
*Worm-gear-T*
$g^{\perp}_{1T}$

*Pretzelosity PDF* $h^{\perp}_{1T}$
*Worm-gear-L* $h^{\perp}_{1L}$
*Boer-Mulders* $h^{\perp}_{1}$

**- NO DATA !**

**We want to measure at the NICA-SPD the full set of PDFs**

# Drell-Yan process



$$p_a = \sqrt{s}/2\, x_a(1,0,1)$$

$$p_b = \sqrt{s}/2\, x_b(1,0,-1)$$

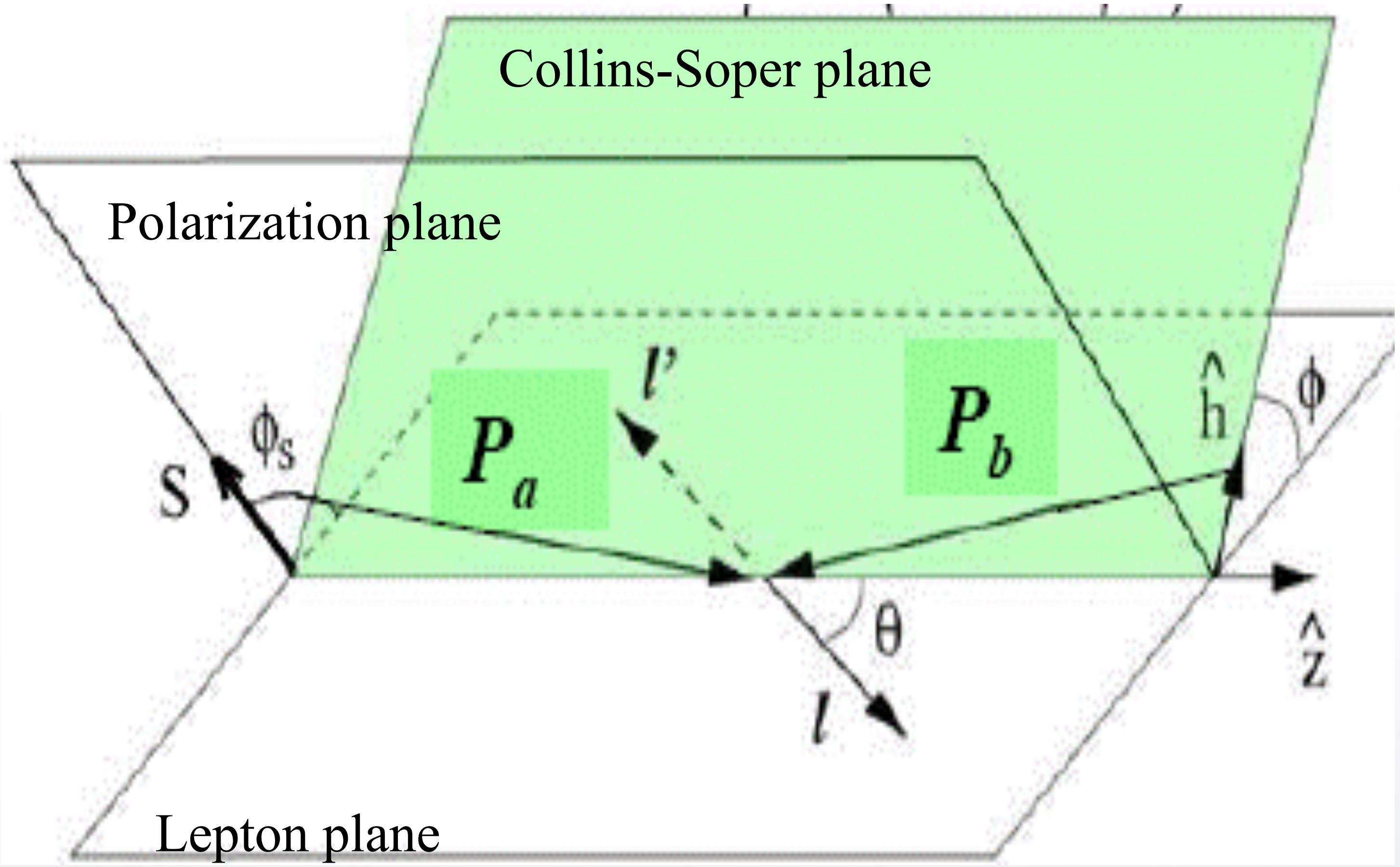
$$q = p_a + p_b = (q_0, 0, q_L)$$

$$\frac{d\sigma}{dQ^2} = \sum_{q=u,d,s} \int dx_a \int dx_b \left(q(x_a)\bar{q}(x_b) + \bar{q}(x_a)q(x_b)\right) \hat{\sigma}_0\, \delta(Q^2 - \hat{s})$$

Drell-Yan cross section includes a convolution of parton distribution functions from both hadrons

# Collins-Soper frame

The kinematics of the Drell-Yan process is considered usually in the Collins-Soper (CS) reference frame [ J.C. Collins, D.E. Soper, and G. Sterman, Nucl. Phys. B250, 199 (1985).]



Results of the most complete theoretical analysis of this process [S. Arnold, A. Metz and M. Schlegel, Phys.Rev. D79 (2009) 034005 [arXiv:hep-ph/0809.2262] are used .

# Drell-Yan cross section

$$\frac{d\sigma}{dx_a dx_b d^2 q_T d\Omega} = \frac{\alpha^2}{4Q^2} \times$$

$F_{XX}$ - structure functions connected to PDFs

$$
\begin{aligned}
&\Big\{\Big((1+\cos^2\theta)F_{UU}^{1} + \sin^2\theta\cos 2\phi F_{UU}^{\cos 2\phi}\Big) + S_{aL}\sin^2\theta\sin 2\phi F_{LU}^{\sin 2\phi} + S_{bL}\sin^2\theta\sin 2\phi F_{UL}^{\sin 2\phi}\\
&+\left|\vec{S}_{aT}\right|\Big[\sin(\phi-\phi_{S_a})\big(1+\cos^2\theta\big)F_{TU}^{\sin(\phi-\phi_{S_a})} + \sin^2\theta\Big(\sin(3\phi-\phi_{S_a})F_{TU}^{\sin(3\phi-\phi_{S_a})} + \sin(\phi+\phi_{S_a})F_{TU}^{\sin(\phi+\phi_{S_a})}\Big)\Big]\\
&+\left|\vec{S}_{bT}\right|\Big[\sin(\phi-\phi_{S_b})\big(1+\cos^2\theta\big)F_{UT}^{\sin(\phi-\phi_{S_b})} + \sin^2\theta\Big(\sin(3\phi-\phi_{S_b})F_{UT}^{\sin(3\phi-\phi_{S_b})} + \sin(\phi+\phi_{S_b})F_{UT}^{\sin(\phi+\phi_{S_b})}\Big)\Big]\\
&+S_{aL}S_{bL}\Big[\big(1+\cos^2\theta\big)F_{LL}^{1} + \sin^2\theta\cos 2\phi F_{LL}^{\cos 2\phi}\Big] \qquad (2.1.2)\\
&+S_{aL}\left|\vec{S}_{bT}\right|\Big[\cos(\phi-\phi_{S_b})\big(1+\cos^2\theta\big)F_{LT}^{\cos(\phi-\phi_{S_b})} + \sin^2\theta\Big(\cos(3\phi-\phi_{S_b})F_{LT}^{\cos(3\phi-\phi_{S_b})} + \cos(\phi+\phi_{S_b})F_{LT}^{\cos(\phi+\phi_{S_b})}\Big)\Big]\\
&+\left|\vec{S}_{aT}\right|S_{bL}\Big[\cos(\phi-\phi_{S_a})\big(1+\cos^2\theta\big)F_{TL}^{\cos(\phi-\phi_{S_a})} + \sin^2\theta\Big(\cos(3\phi-\phi_{S_a})F_{TL}^{\cos(3\phi-\phi_{S_a})} + \cos(\phi+\phi_{S_a})F_{TL}^{\cos(\phi+\phi_{S_a})}\Big)\Big]\\
&+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[\big(1+\cos^2\theta\big)\Big(\cos(2\phi-\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})} + \cos(\phi_{S_b}-\phi_{S_a})F_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})}\Big)\Big]\\
&+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[\sin^2\theta\Big(\cos(\phi_{S_a}+\phi_{S_b})F_{TT}^{\cos(\phi_{S_a}+\phi_{S_b})} + \cos(4\phi-\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(4\phi-\phi_{S_a}-\phi_{S_b})}\Big)\Big]\\
&+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[\sin^2\theta\Big(\cos(2\phi-\phi_{S_a}+\phi_{S_b})F_{TT}^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})} + \cos(2\phi+\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}\Big)\Big]\Big\}
\end{aligned}
$$

# Drell-Yan asymmetries

$$A_{UU} \equiv \frac{\sigma^{00}}{\sigma^{00}_{\text{int}}} = \frac{1}{2\pi}\left(1 + D\cos 2\phi A_{UU}^{\cos 2\phi}\right)$$

$$A_{LU} \equiv \frac{\sigma^{\rightarrow 0} - \sigma^{\leftarrow 0}}{\sigma^{\rightarrow 0}_{\text{int}} + \sigma^{\leftarrow 0}_{\text{int}}} = \frac{|S_{aL}|}{2\pi} D\sin 2\phi A_{LU}^{\sin 2\phi}$$

$$A_{UL} \equiv \frac{\sigma^{0\rightarrow} - \sigma^{0\leftarrow}}{\sigma^{0\rightarrow}_{\text{int}} + \sigma^{0\leftarrow}_{\text{int}}} = \frac{|S_{bL}|}{2\pi} D\sin 2\phi A_{UL}^{\sin 2\phi}$$

$$A_{TU} \equiv \frac{\sigma^{\uparrow 0} - \sigma^{\downarrow 0}}{\sigma^{\uparrow 0}_{\text{int}} + \sigma^{\downarrow 0}_{\text{int}}} = \frac{|\vec{S}_{aT}|}{2\pi}\left[A_{TU}^{\sin(\phi-\phi_{S_a})}\sin(\phi-\phi_{S_a}) + D\left(A_{TU}^{\sin(3\phi-\phi_{S_a})}\sin(3\phi-\phi_{S_a}) + A_{TU}^{\sin(\phi+\phi_{S_a})}\sin(\phi+\phi_{S_a})\right)\right]$$

$$A_{UT} \equiv \frac{\sigma^{0\uparrow} - \sigma^{0\downarrow}}{\sigma^{0\uparrow}_{\text{int}} + \sigma^{0\downarrow}_{\text{int}}} = \frac{|\vec{S}_{bT}|}{2\pi}\left[A_{UT}^{\sin(\phi-\phi_{S_b})}\sin(\phi-\phi_{S_b}) + D\left(A_{UT}^{\sin(3\phi-\phi_{S_b})}\sin(3\phi-\phi_{S_b}) + A_{UT}^{\sin(\phi+\phi_{S_b})}\sin(\phi+\phi_{S_b})\right)\right]$$

$$A_{LL} \equiv \frac{\sigma^{\rightarrow\rightarrow} + \sigma^{\leftarrow\leftarrow} - \sigma^{\rightarrow\leftarrow} - \sigma^{\leftarrow\rightarrow}}{\sigma^{\rightarrow\rightarrow}_{\text{int}} + \sigma^{\leftarrow\leftarrow}_{\text{int}} + \sigma^{\rightarrow\leftarrow}_{\text{int}} + \sigma^{\leftarrow\rightarrow}_{\text{int}}} = \frac{|S_{aL}S_{bL}|}{2\pi}\left(A_{LL}^{1} + DA_{LL}^{\cos 2\phi}\cos 2\phi\right)$$

$$A_{TL} \equiv \frac{\sigma^{\uparrow\rightarrow} + \sigma^{\downarrow\leftarrow} - \sigma^{\downarrow\rightarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow}_{\text{int}} + \sigma^{\downarrow\leftarrow}_{\text{int}} + \sigma^{\downarrow\rightarrow}_{\text{int}} + \sigma^{\uparrow\leftarrow}_{\text{int}}} = \frac{|\vec{S}_{aT}|S_{bL}}{2\pi}\left[A_{TL}^{\cos(\phi-\phi_{S_a})}\cos(\phi-\phi_{S_a}) + D\begin{pmatrix} A_{TL}^{\cos(3\phi-\phi_{S_a})}\cos(3\phi-\phi_{S_a}) \\ + A_{TL}^{\cos(\phi-\phi_{S_a})}\cos(\phi+\phi_{S_a}) \end{pmatrix}\right]$$

$$A_{LT} \equiv \frac{\sigma^{\rightarrow\uparrow} + \sigma^{\leftarrow\downarrow} - \sigma^{\rightarrow\downarrow} - \sigma^{\leftarrow\uparrow}}{\sigma^{\rightarrow\uparrow}_{\text{int}} + \sigma^{\leftarrow\downarrow}_{\text{int}} + \sigma^{\rightarrow\downarrow}_{\text{int}} + \sigma^{\leftarrow\uparrow}_{\text{int}}} = \frac{S_{aL}|\vec{S}_{bT}|}{2\pi}\left[A_{LT}^{\cos(\phi-\phi_{S_b})}\cos(\phi-\phi_{S_b}) + D\begin{pmatrix} A_{LT}^{\cos(3\phi-\phi_{S_b})}\cos(3\phi-\phi_{S_b}) \\ + A_{LT}^{\cos(\phi+\phi_{S_b})}\cos(\phi+\phi_{S_b}) \end{pmatrix}\right]$$

$$A_{TT} \equiv \frac{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow} - \sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\uparrow}_{\text{int}} + \sigma^{\downarrow\downarrow}_{\text{int}} + \sigma^{\uparrow\downarrow}_{\text{int}} + \sigma^{\downarrow\uparrow}_{\text{int}}} = \frac{|\vec{S}_{aT}||\vec{S}_{bT}|}{2\pi}\Big[A_{TT}^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})}\cos(2\phi-\phi_{S_a}-\phi_{S_b}) + A_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})}\cos(\phi_{S_b}-\phi_{S_a})$$

$$+D\Big(A_{TT}^{\cos(\phi_{S_b}+\phi_{S_a})}\cos(\phi_{S_a}+\phi_{S_b}) + A_{TT}^{\cos(4\phi-\phi_{S_a}-\phi_{S_b})}\cos(4\phi-\phi_{S_a}-\phi_{S_b})$$

$$+A_{TT}^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})}\cos(2\phi-\phi_{S_a}+\phi_{S_b}) + A_{TT}^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}\cos(2\phi+\phi_{S_a}-\phi_{S_b})\Big)\Big]$$

$A^{i}_{jk} = F^{i}_{jk}/F^{1}_{UU}$ --amplitude of SF modulation

**23 modulations with amplitudes normalized to the unpolarized one.**

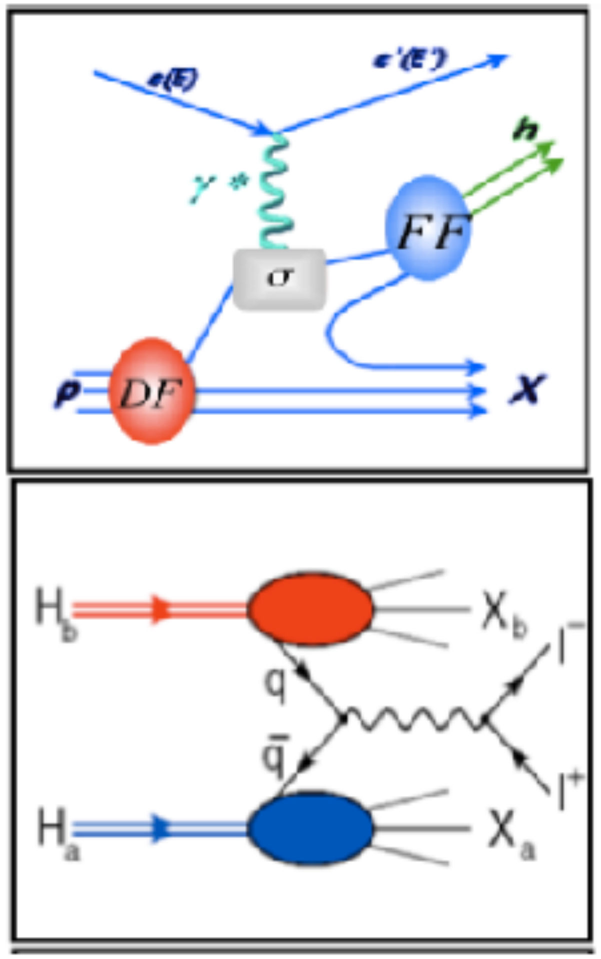
***8 asymmetries to be measured***

***each asymmetry contains a convolution of 2 PDFs (from each hadron)***

**Fourier analysis!**

# Why Drell-Yan process?

## *TMD PDFs can be accessed via SIDIS but ...*



**SIDIS: rich phenomenology, the most explored so far**

SIDIS $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$

hermes COMPASS Jefferson Lab

**$e^+e^-$: B-factories as powerful fragmentation laboratories**

$e^+e^-$ $\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$

BELLE

**DY: challenging for experiments (only unpolarized so far)**

DY $\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$

Fermilab

## DY: no fragmentation functions !

# PDFs in duality model

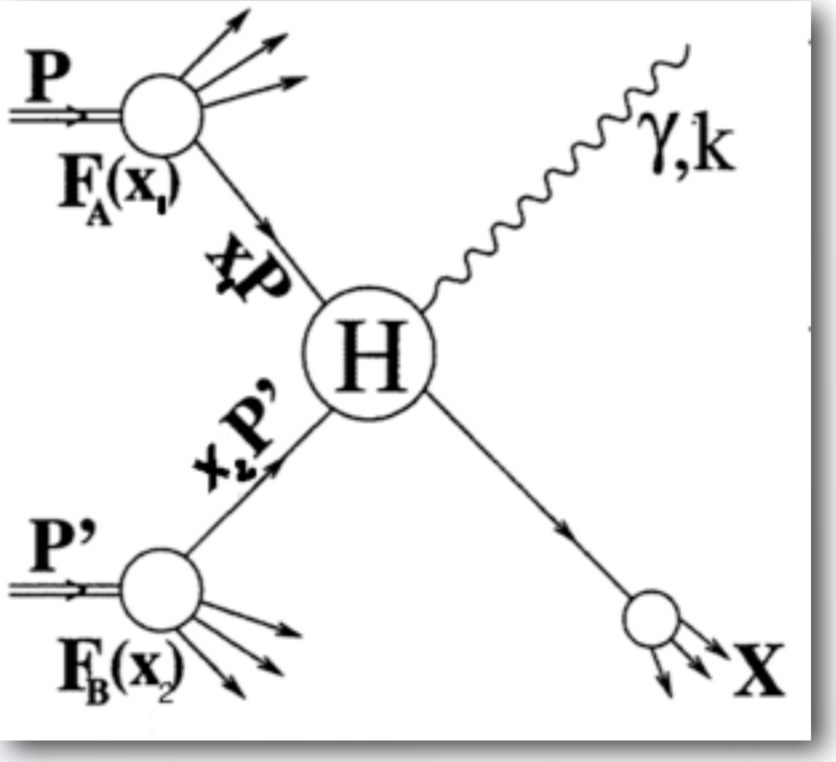
q qbar → J/ψ
g g → J/ψ — main mechanisms of J/ψ production
$X_c$ decay

**Duality model** predicts similar behavior for azimutal asymmetries for lepton pairs produced in DY and via J/ψ decay in case if q qbar mechanism dominates

$X_c$ decay is ~30 % - previous measurements at ~30 GeV

# Direct photons

*Direct (prompt) photons - photons produced in parton-parton interaction*



*Hard processes:*

*q g→q γ 85%*

*q qbar→g γ 15 %*

*g g→g γ*

*q qbar→ γ γ*

*g g→ γ γ*

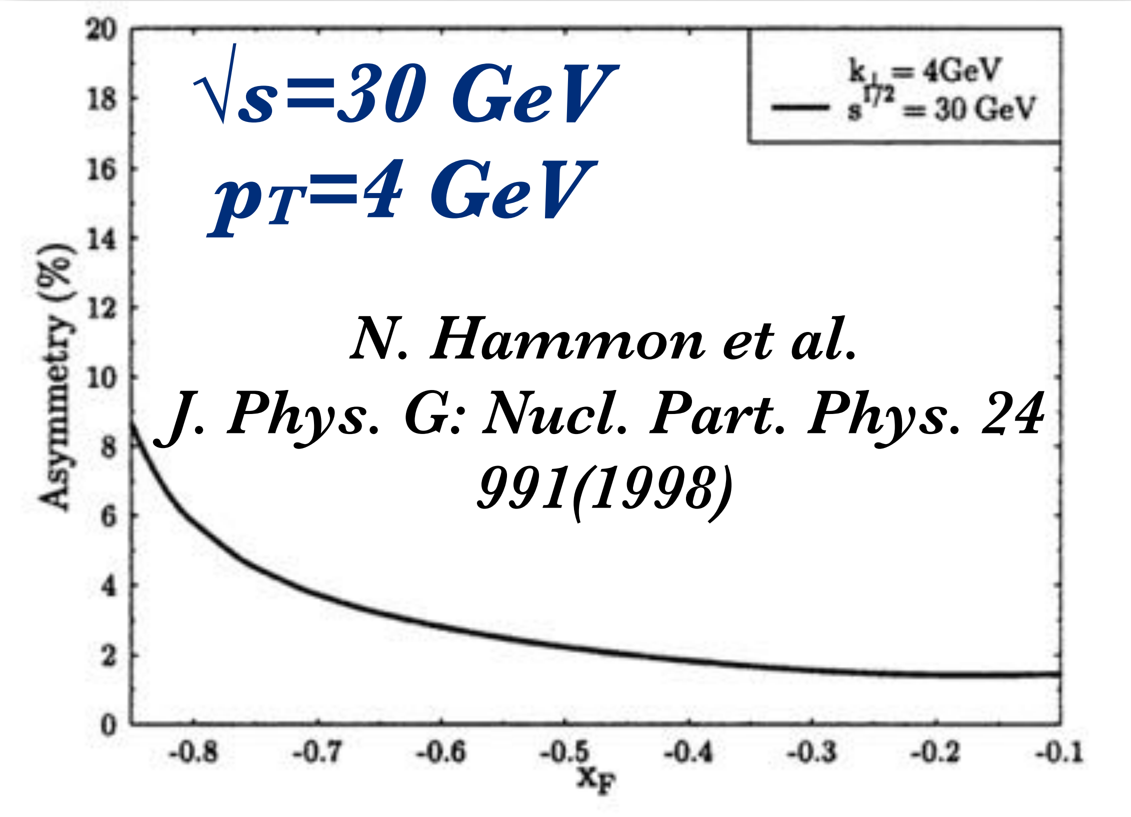
***No fragmentation functions!***

# Direct photons

$$\mathrm{A_N} = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$ - single transverse spin asymmetry

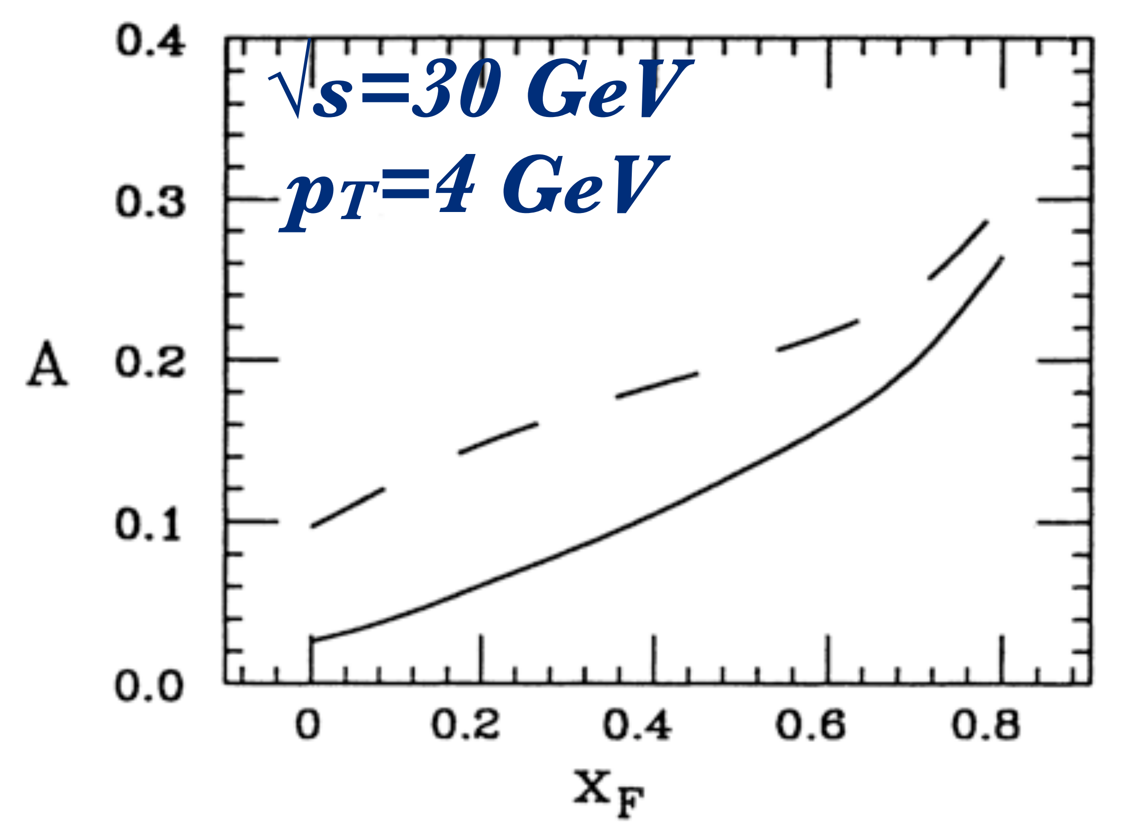
gluon
Sivers function

$$\sigma^\uparrow - \sigma^\downarrow = \sum_i \int_{x_{min}}^{1} dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})\, e^y} \Big[ q_i(x_a, \mathbf{k}_{Ta}) \boxed{\Delta_N G(x_b, \mathbf{k}_{Tb})} \times \frac{d\hat\sigma}{d\hat t}(q_i G \to q_i \gamma) + G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat\sigma}{d\hat t}(G q_i \to q_i \gamma) \Big]$$



***$\sqrt{s}$=30 GeV***
***$p_T$=4 GeV***

*N. Hammon et al.*
*J. Phys. G: Nucl. Part. Phys. 24 991(1998)*



***$\sqrt{s}$=30 GeV***
***$p_T$=4 GeV***

*J. Qui and G. Sterman, Phys. Rev. Lett. 67 (1991) 2264*

# Direct photons

## *Double longitudinal spin asymmetry $A_{LL}$*

$$A_{LL} = \frac{(\sigma_{++} + \sigma_{--}) - (\sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}$$

*G. Bunce et. al. Ann.Rev.Nucl.Part.Sci.50:525-575,2000*

$$A_{LL} \approx \boxed{\frac{\Delta g(x_1)}{g(x_1)}} \cdot \left[\frac{\sum_q e_q^2 \left[\Delta q(x_2) + \Delta\bar{q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_2) + \bar{q}(x_2)\right]}\right] + (1 \leftrightarrow 2)$$

↓ $\Delta g$

↓ $A_1^P$ - *well known from polarized DIS*

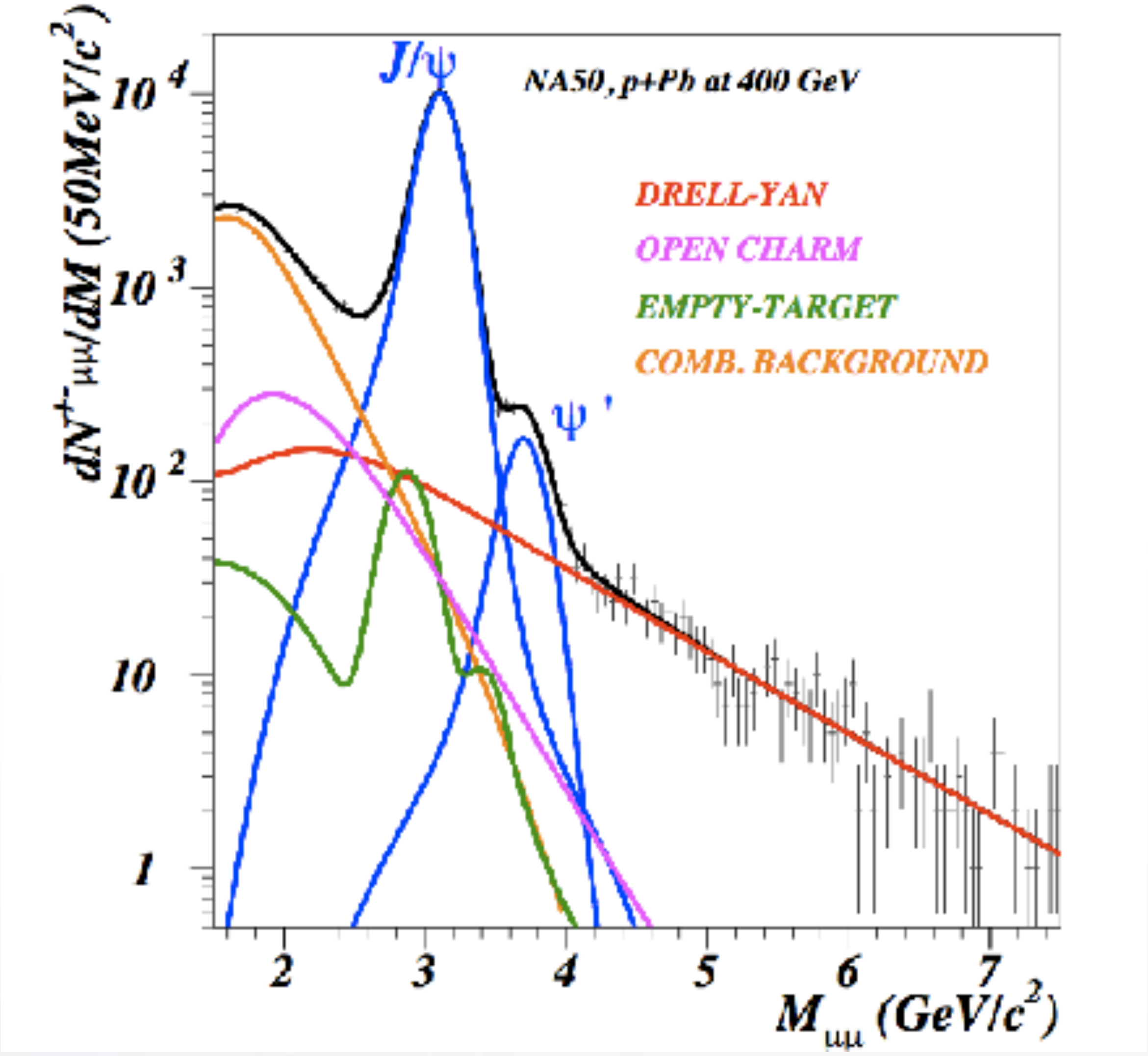
# Other physical tasks

***- Spin-dependent effects in elastic pp, dp and dd scattering***

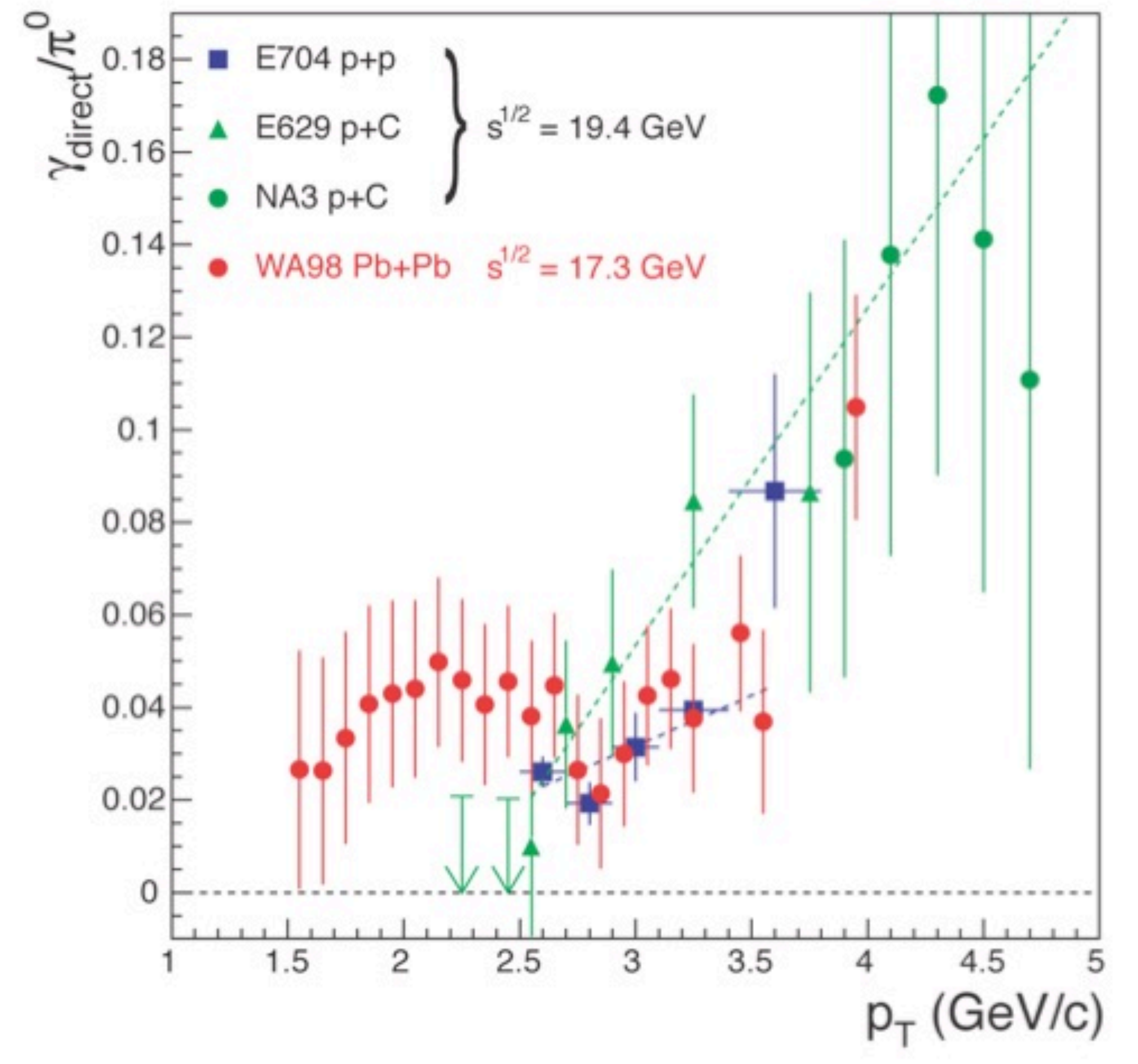
***- Spin-dependent high-$p_T$ reactions.***

***- Spin effects in heavy ion collisions***

# Background processes

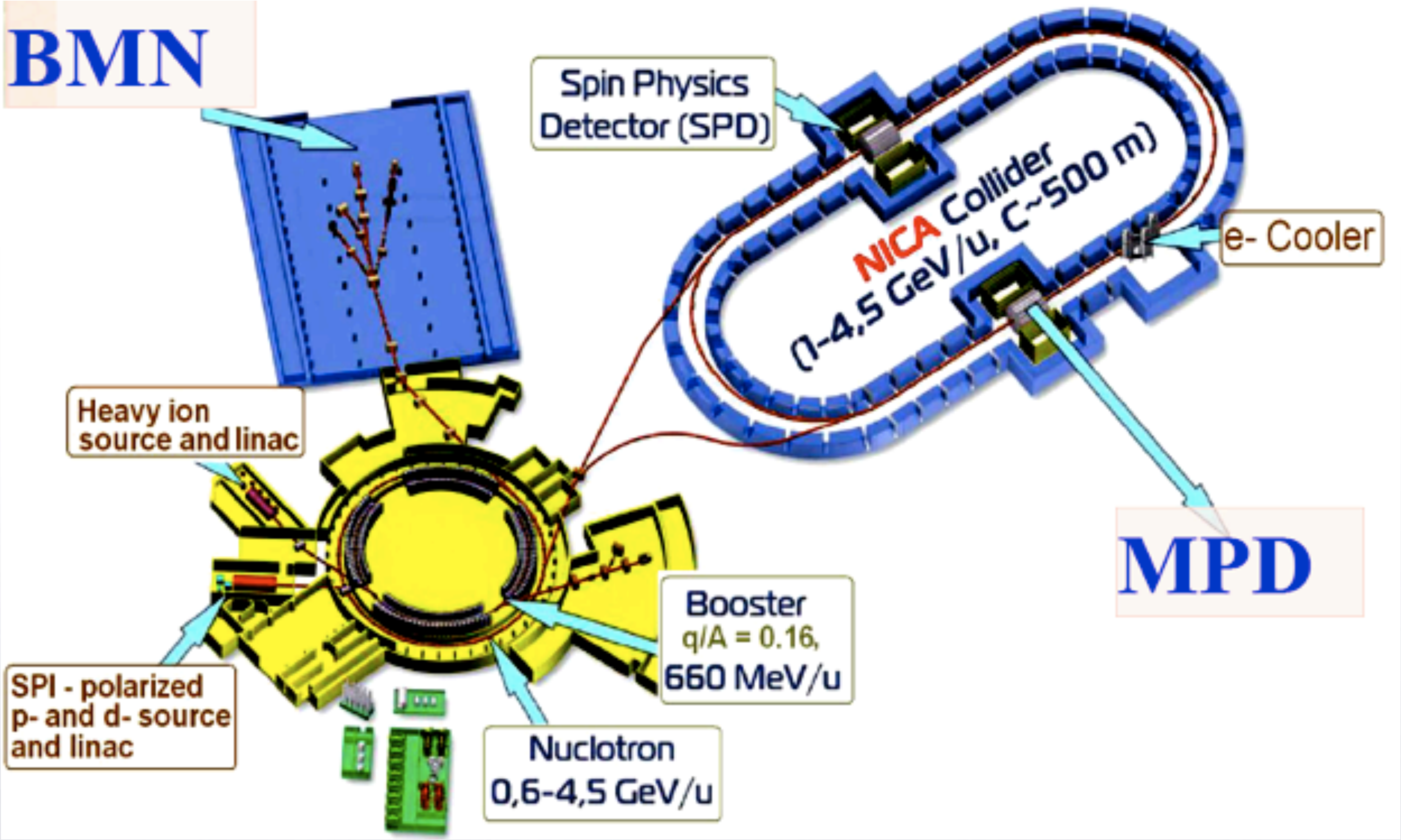


***dimuon spectrum***



***Direct photons and $\pi^0$ decay***

# NICA facility



# Wanted beams

*Beams. The following beams will be needed, polarized and non-polarized: pp, pd, dd, pp, pd, pp, pd, dd.*

*Beam polarizations both at MPD and SPD: longitudinal and transversal. Absolute values of polarizations should be ≥ 50%.The life time of the beam polarization should be long enough. Measurements of Single Spin and Double Spin asymmetries in DY require running in different beam polarization modes: UU, LU, UL,TU, UT,LL ,LT and TL (spin flipping for every bunch or group of bunches should be considered).*

*Beam energies:*

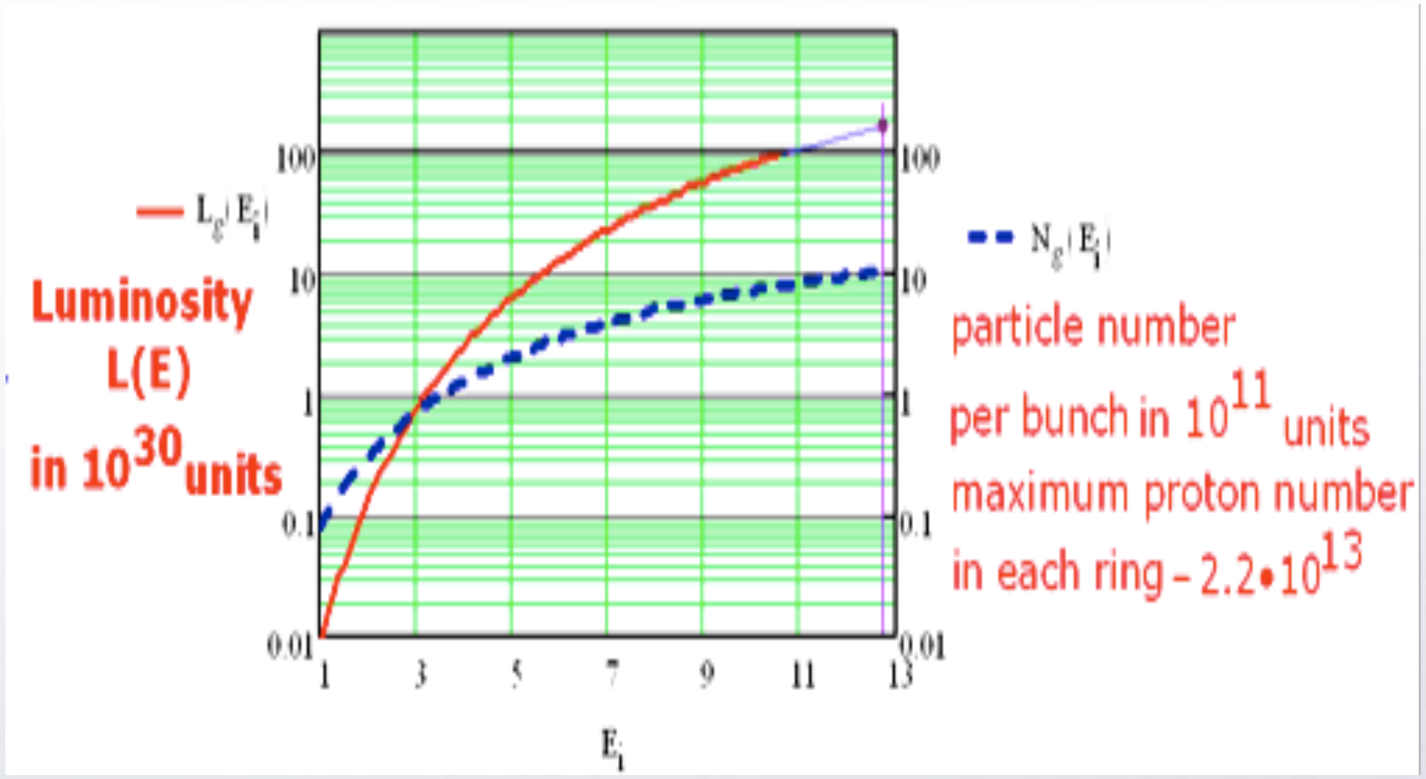
$p\uparrow p\uparrow(\sqrt{s_{pp}}) = 12 \div \geq 27$ *GeV* ($5 \div \geq 12.6$ *GeV kinetic energy*),

$d\uparrow d\uparrow(\sqrt{s_{NN}}) = 4 \div \geq 13.8$ *GeV* ($2 \div \geq 5.9$ *GeV/u ion kinetic energy*).

*Beam luminosities:*

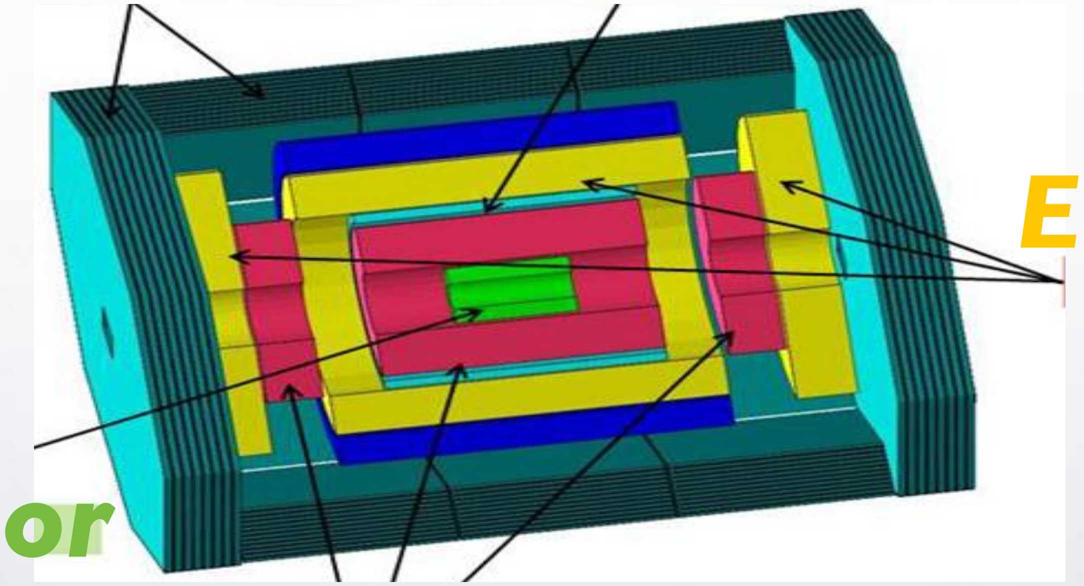
*in the pp mode:* $L_{average}$ $1\cdot 10^{32}$ $cm^{-2}s^{-1}$ (*at* $s_{pp} = 27$ *GeV*),

*in the dd mode:* $L_{average}$ $1\cdot 10^{30}$ $cm^{-2}s^{-1}$ (*at* $s_{NN} = 14$ *GeV*).



# SPD detector

- 4π geometry
- <0.1 $X_0$ before ECAL



Muon & hadron identification system

Trigger elements

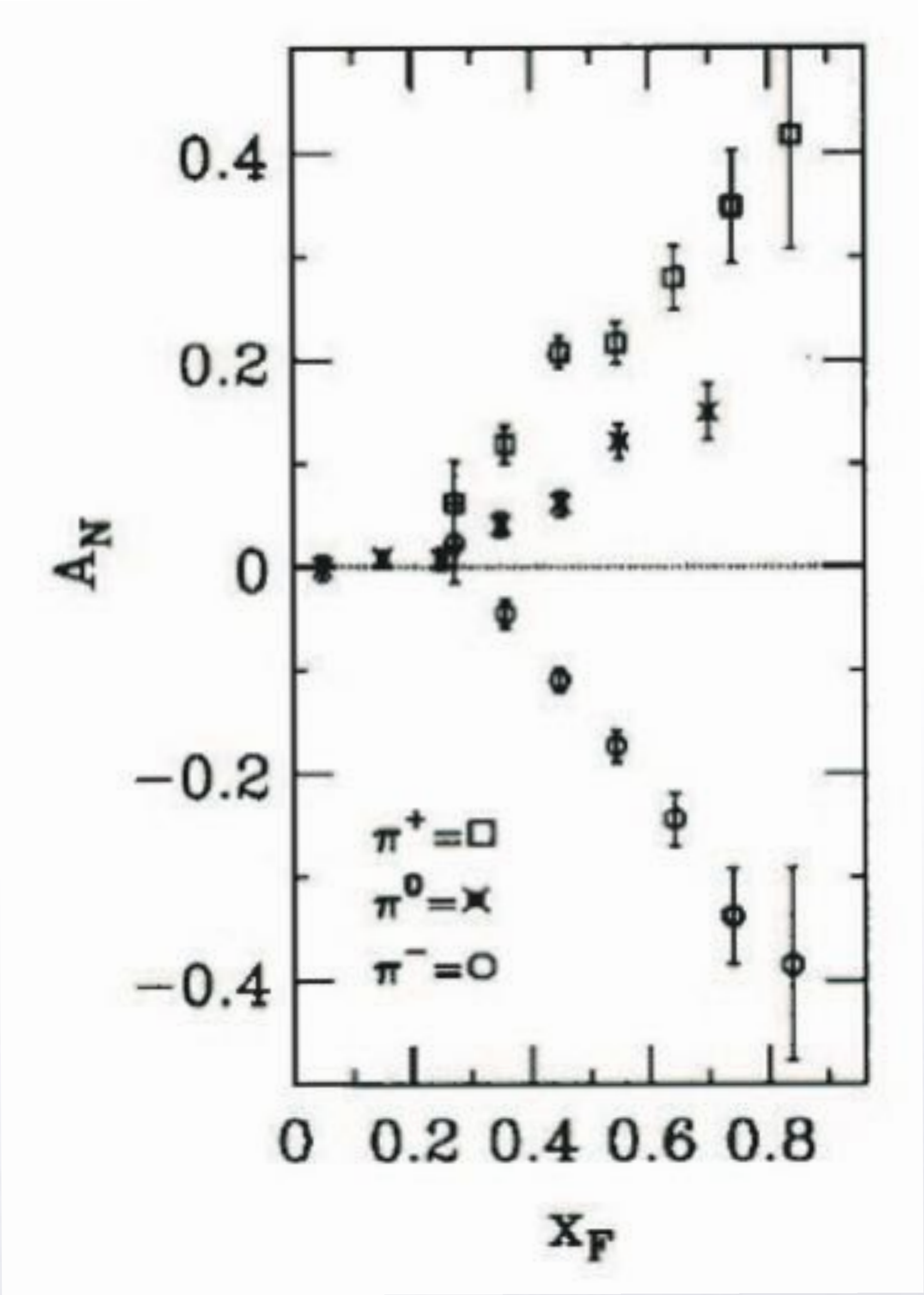
Electromagnetic calorimeter

Vertex detector

Tracker

# Local polarimetry

- known asymmetries
- pp- and dd- elastic scattering

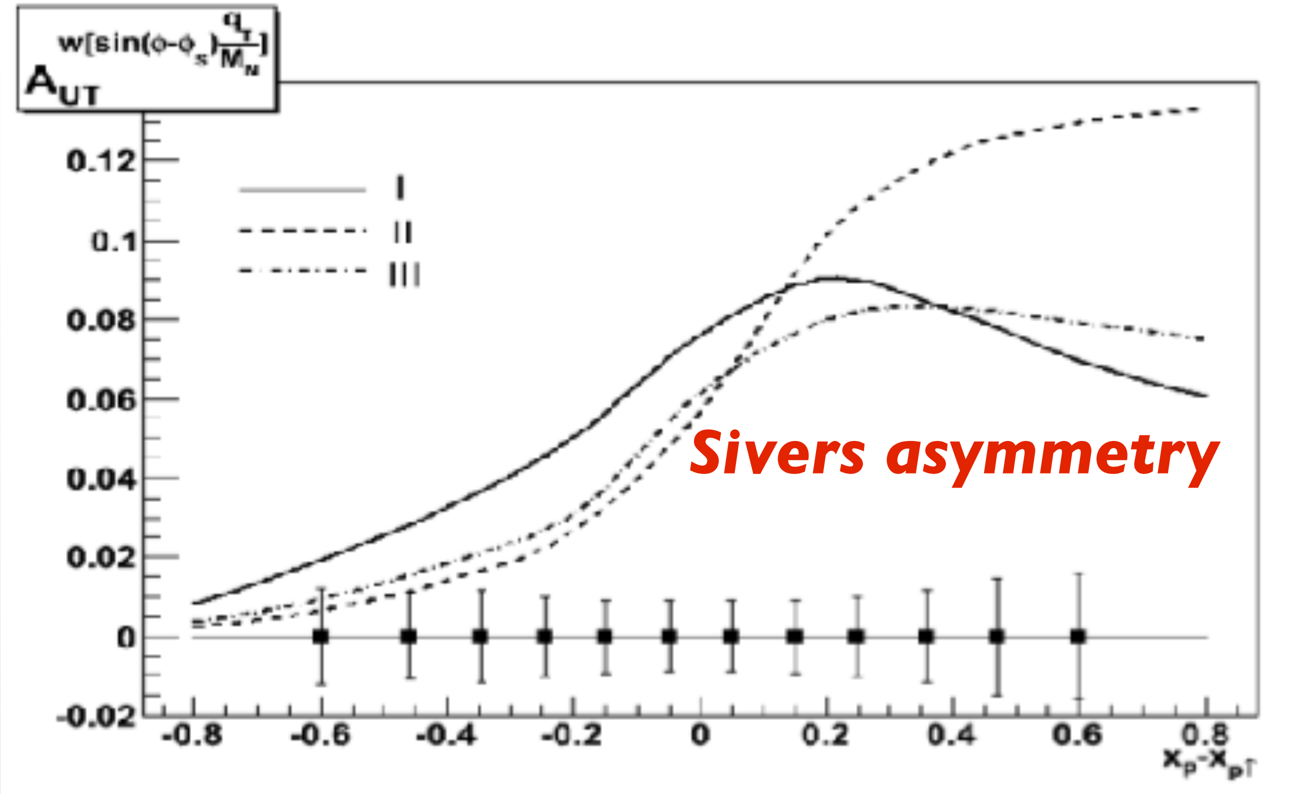


# Expectations: DY

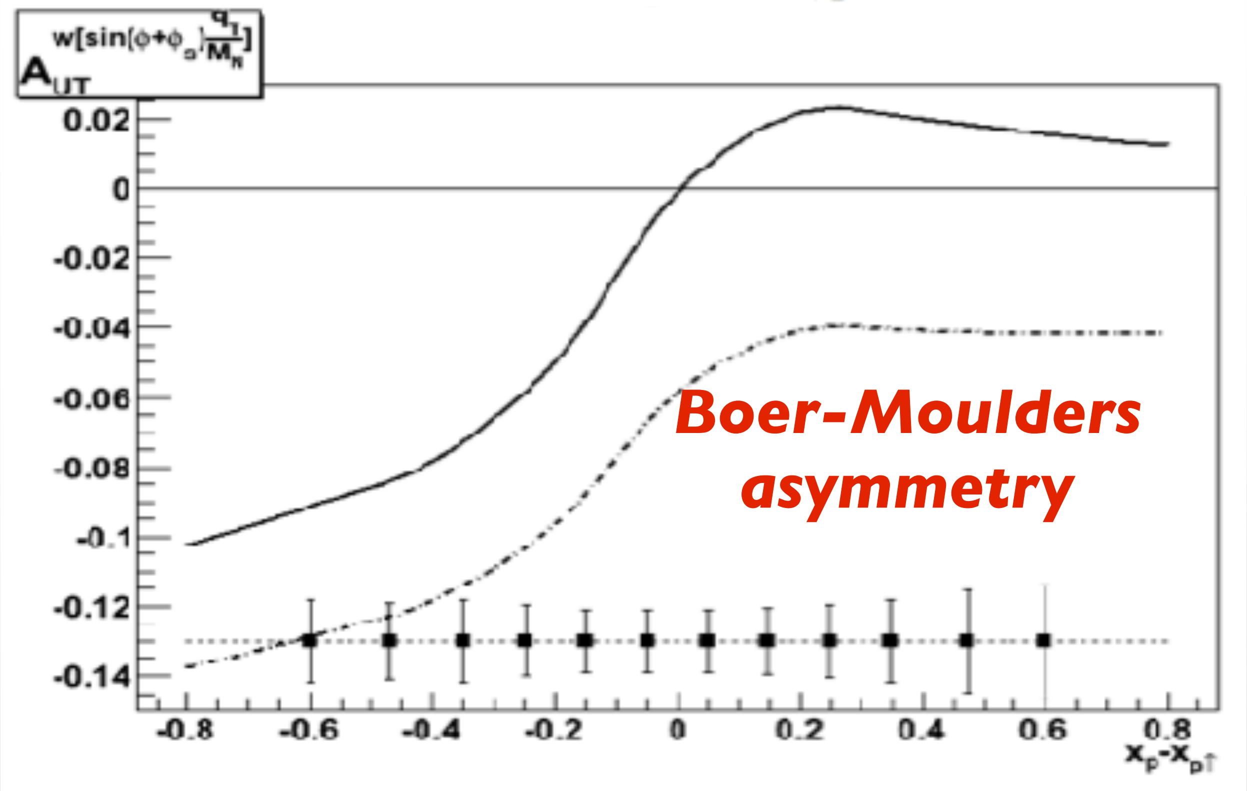
| Lower cut on $M_{l^+l^-}$, *GeV* | 2.0 | 3.0 | 3.5 | 4.0 |
|---|---|---|---|---|
| $\sqrt{s}=24$ *GeV* ($L \approx 1.0\ 10^{32}\ cm^{-2}\ s^{-1}$) | | | | |
| $\sigma_{DY}$ total, *nb* | 1.15 | 0.20 | 0.12 | 0.06 |
| events per year, $10^3$ | 1800 | 313 | 179 | 92 |
| $\sqrt{s}=26$ *GeV* ($L \approx 1.2\ 10^{32}\ cm^{-2}\ s^{-1}$) | | | | |
| $\sigma_{DY}$ total, *nb* | 1.30 | 0.24 | 0.14 | 0.07 |
| events per year, $10^3$ | 2490 | 460 | 269 | 142 |

***100k events***

$\sqrt{s}$ =26 GeV with $Q^2$ = 15 GeV$^2$

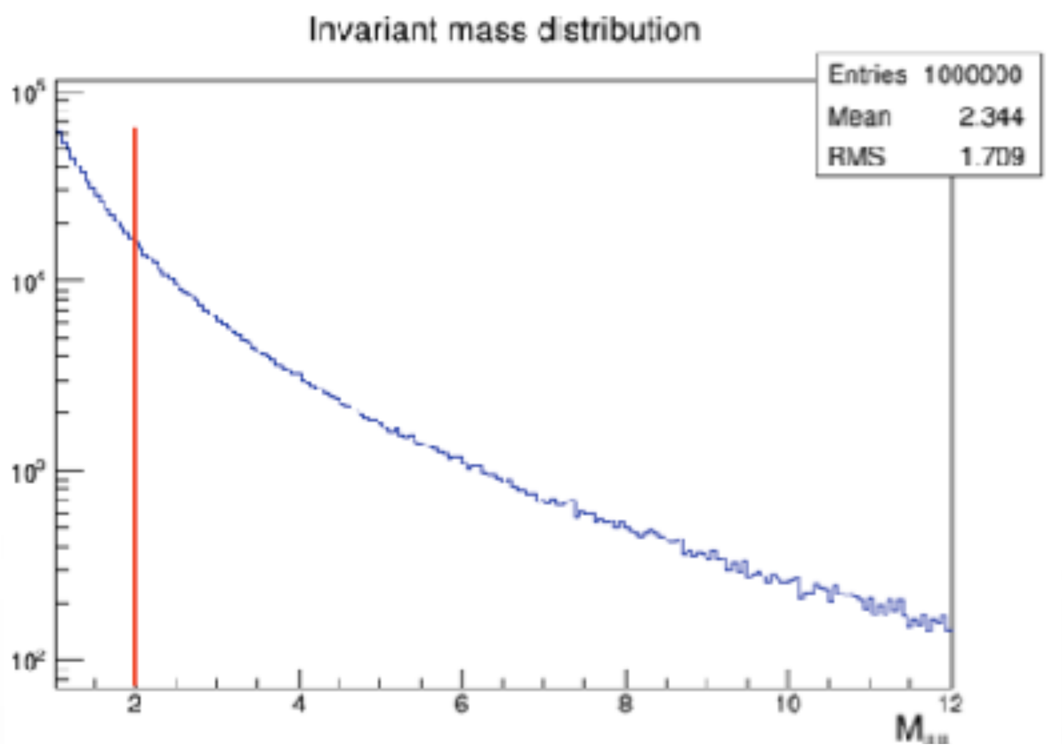


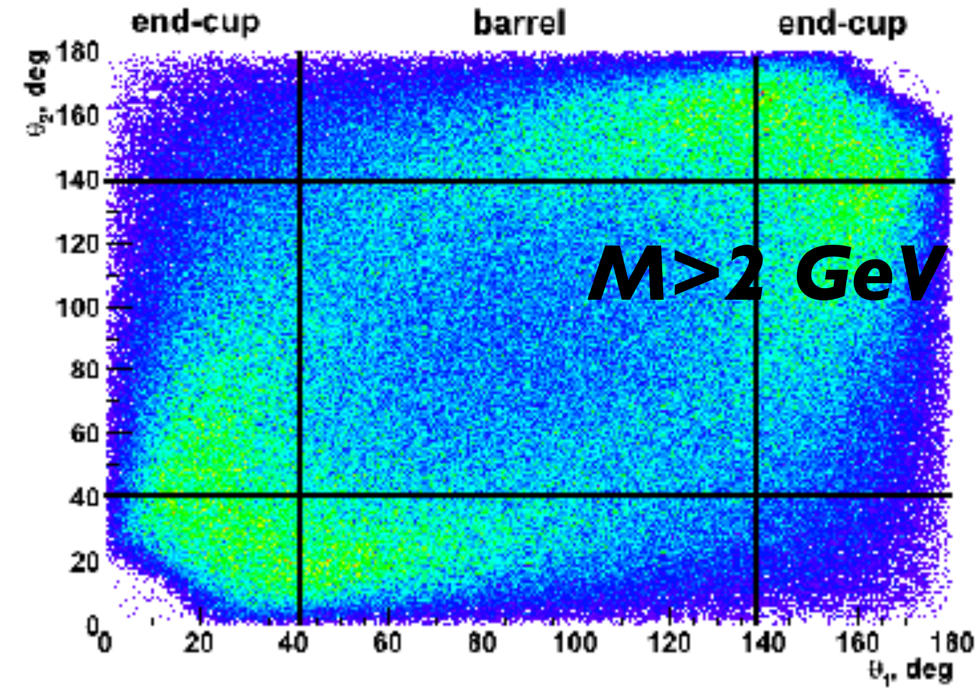
**Sivers asymmetry**

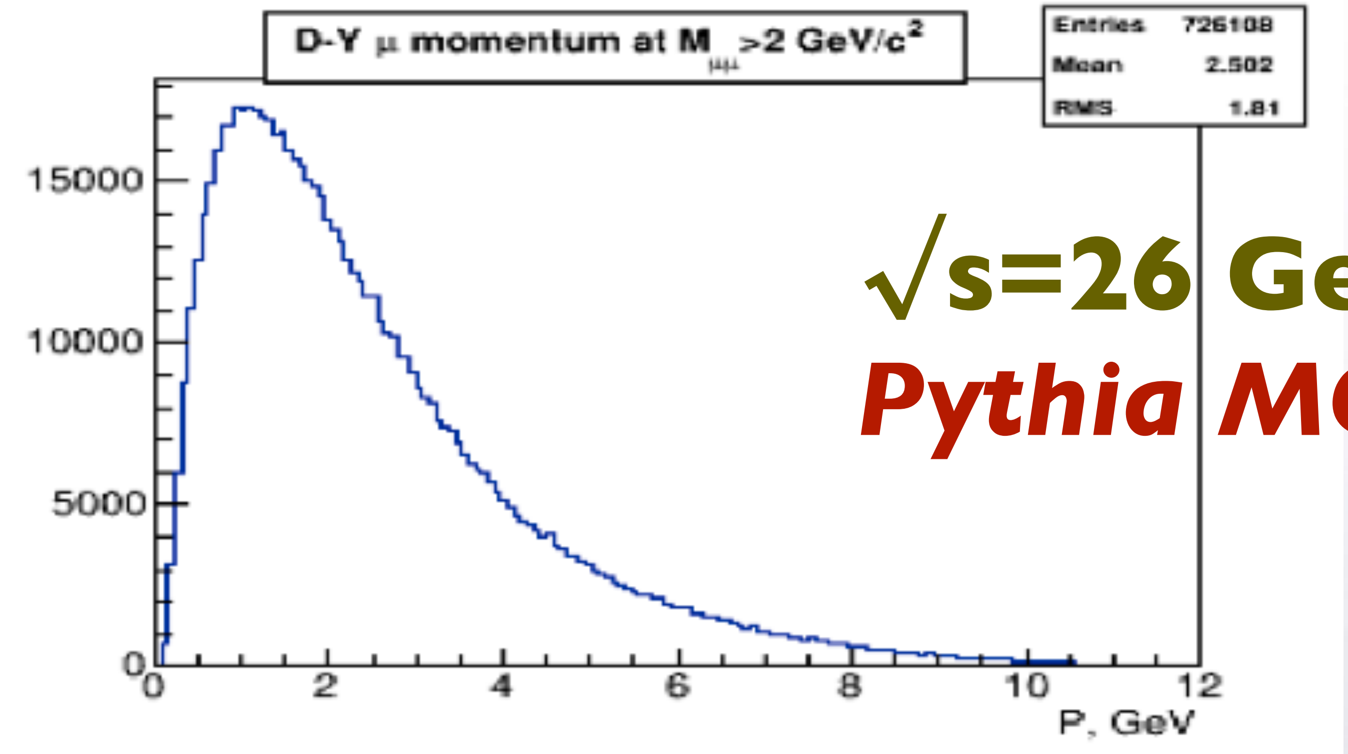


**Boer-Moulders asymmetry**

# DY events at SPD

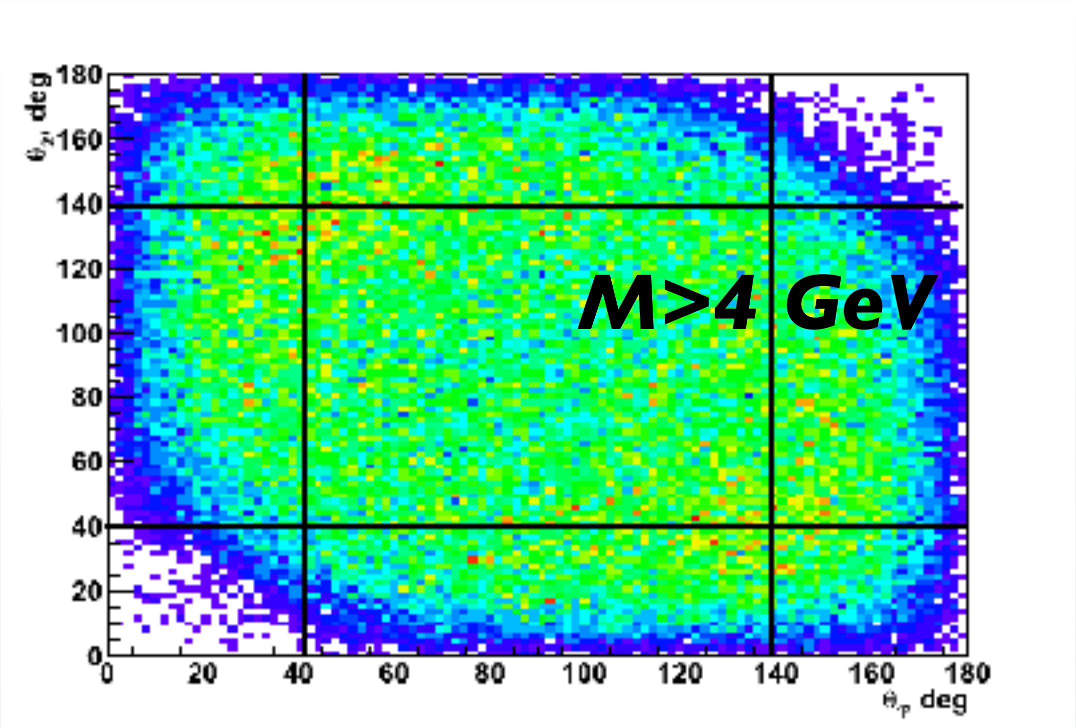




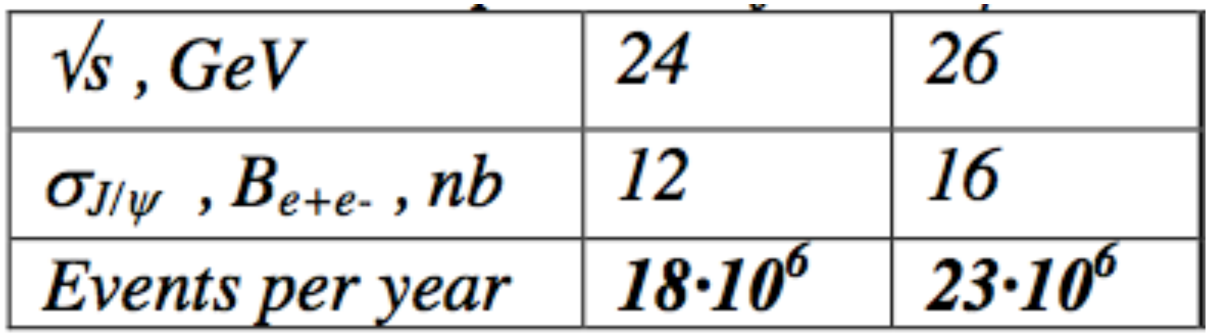


**$\sqrt{s}$=26 GeV**

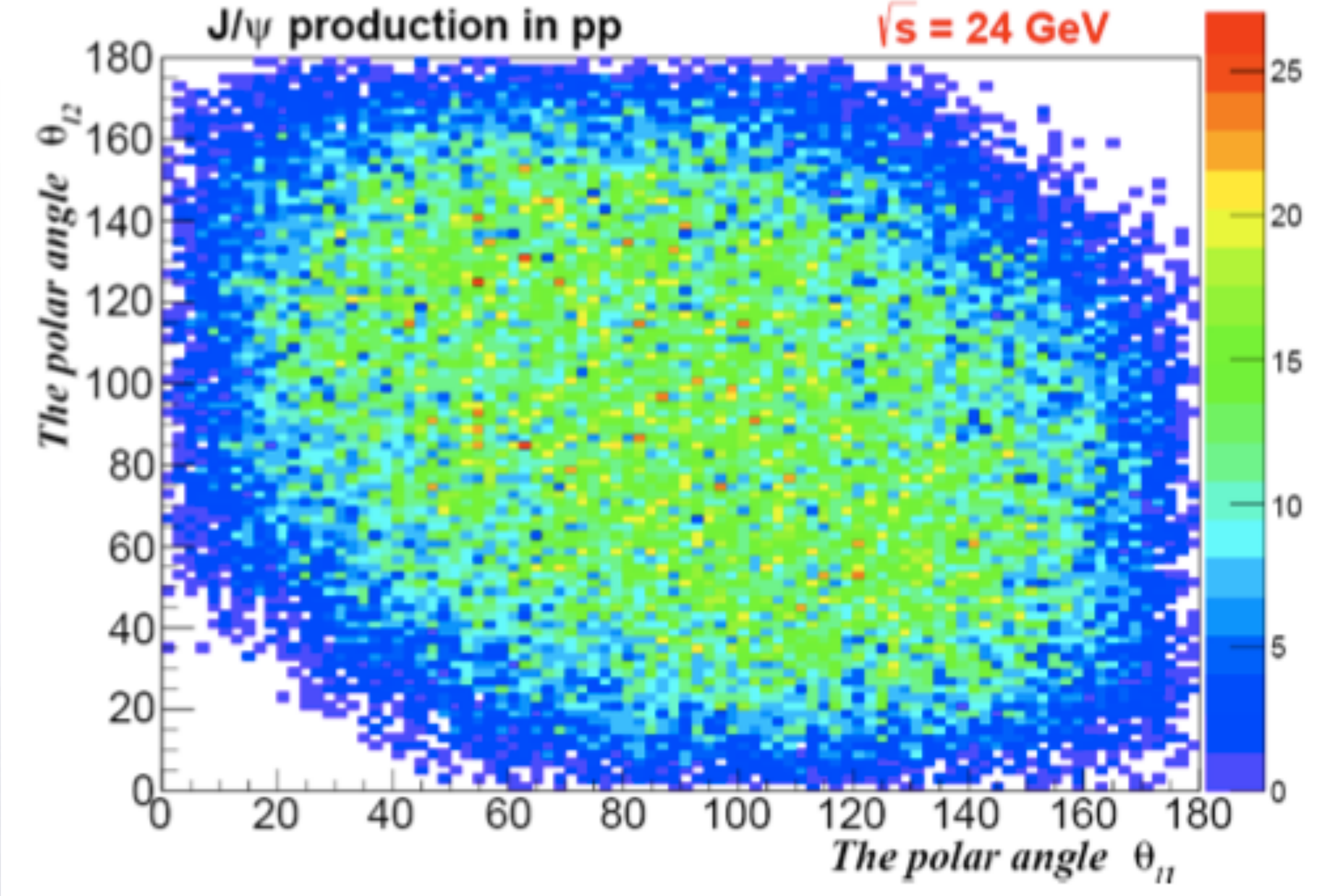
***Pythia MC***

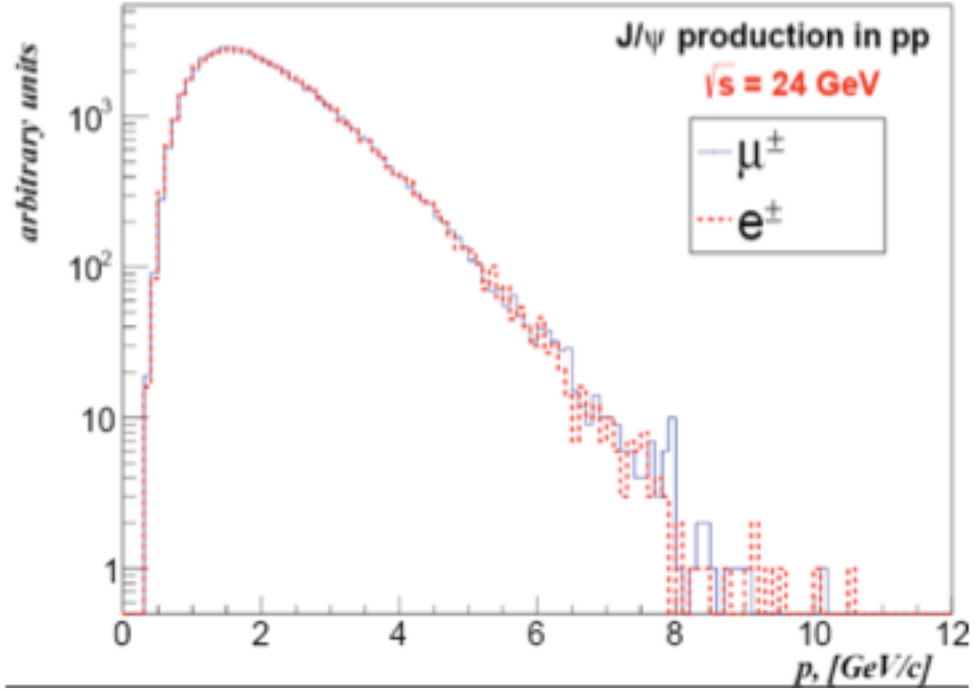


# J/ψ events at SPD



| $\sqrt{s}$ , GeV | 24 | 26 |
|---|---|---|
| $\sigma_{J/\psi}$ , $B_{e+e-}$ , nb | 12 | 16 |
| Events per year | $18 \cdot 10^6$ | $23 \cdot 10^6$ |

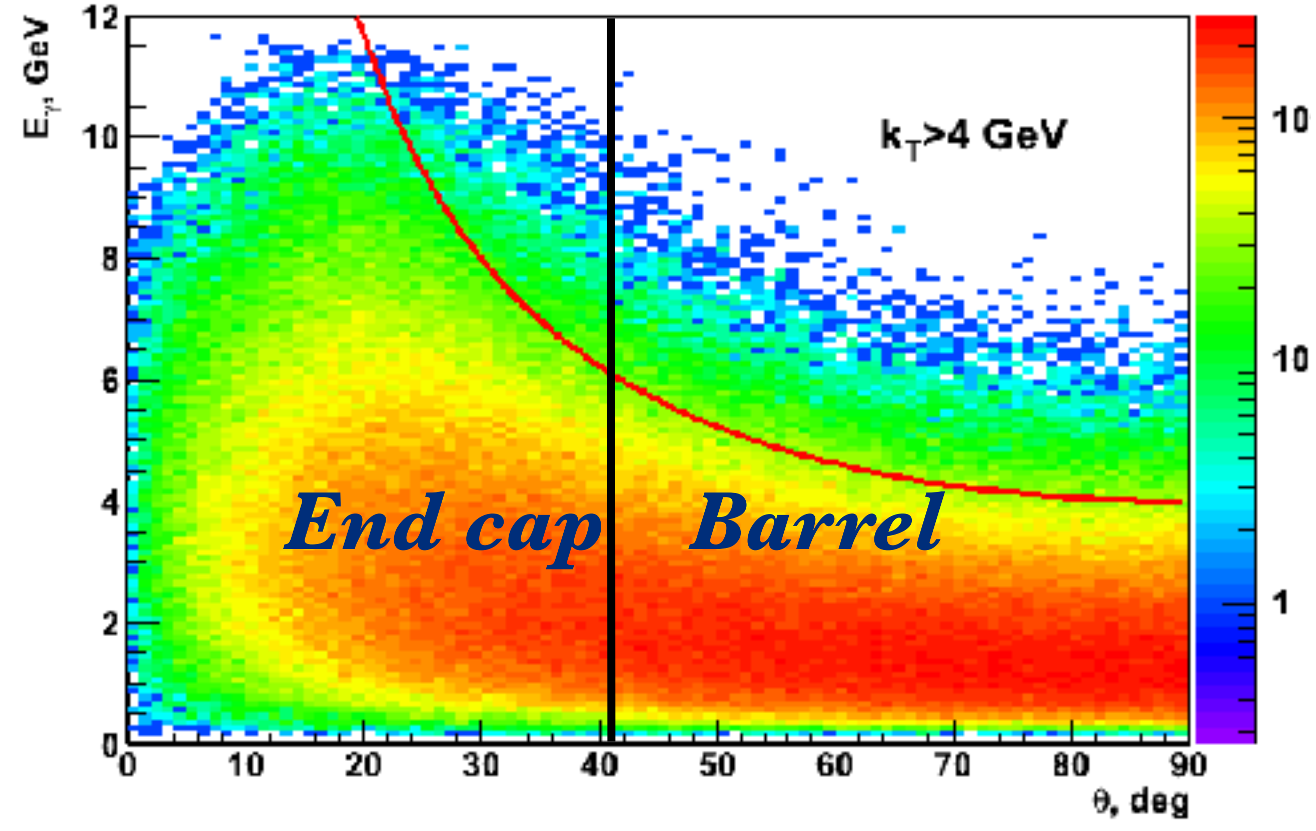




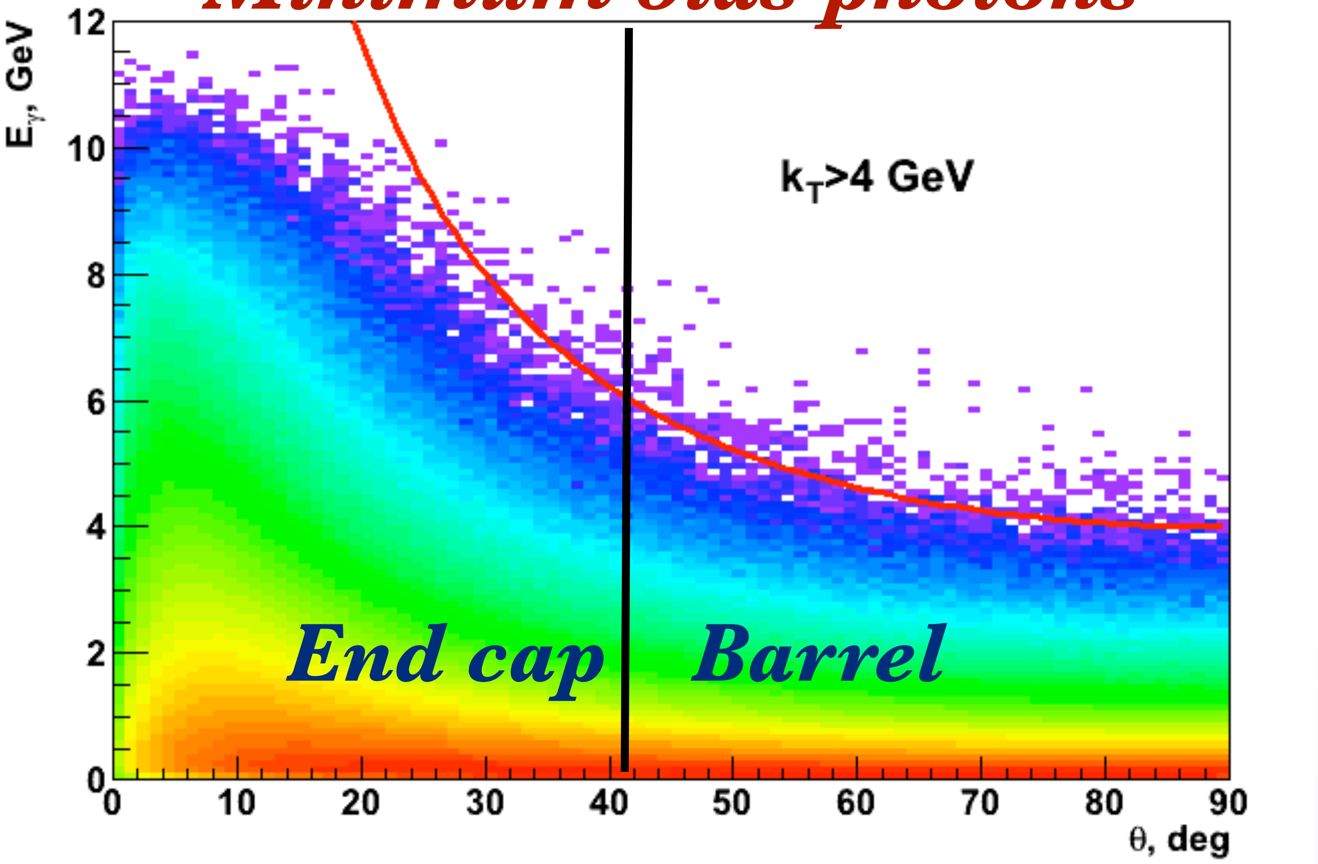
**Pythia MC**

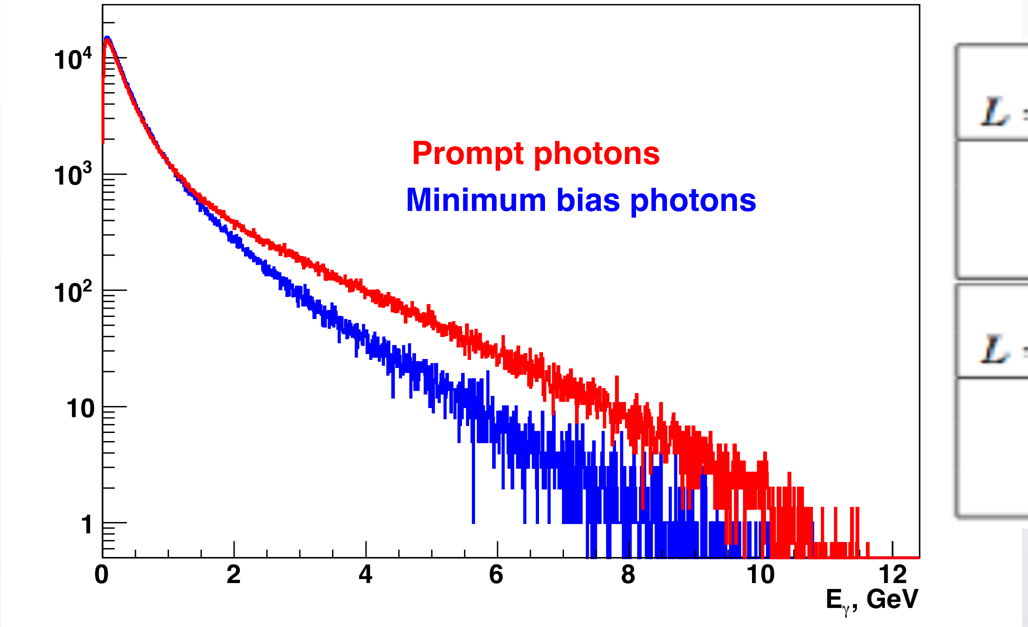
# Direct photons at SPD

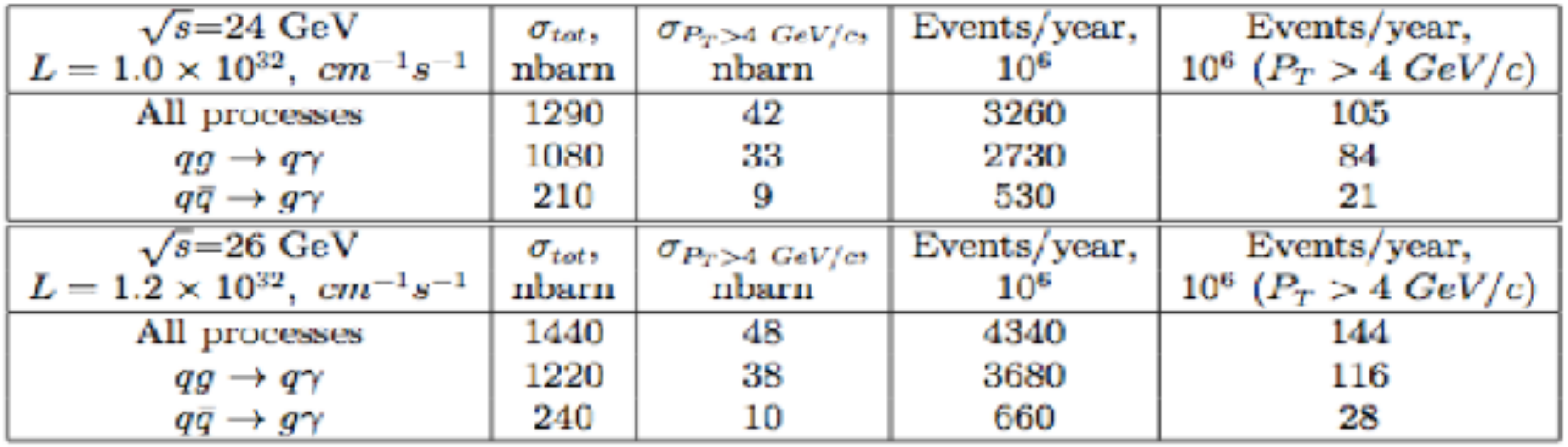
Direct photons



Minimum bias photons

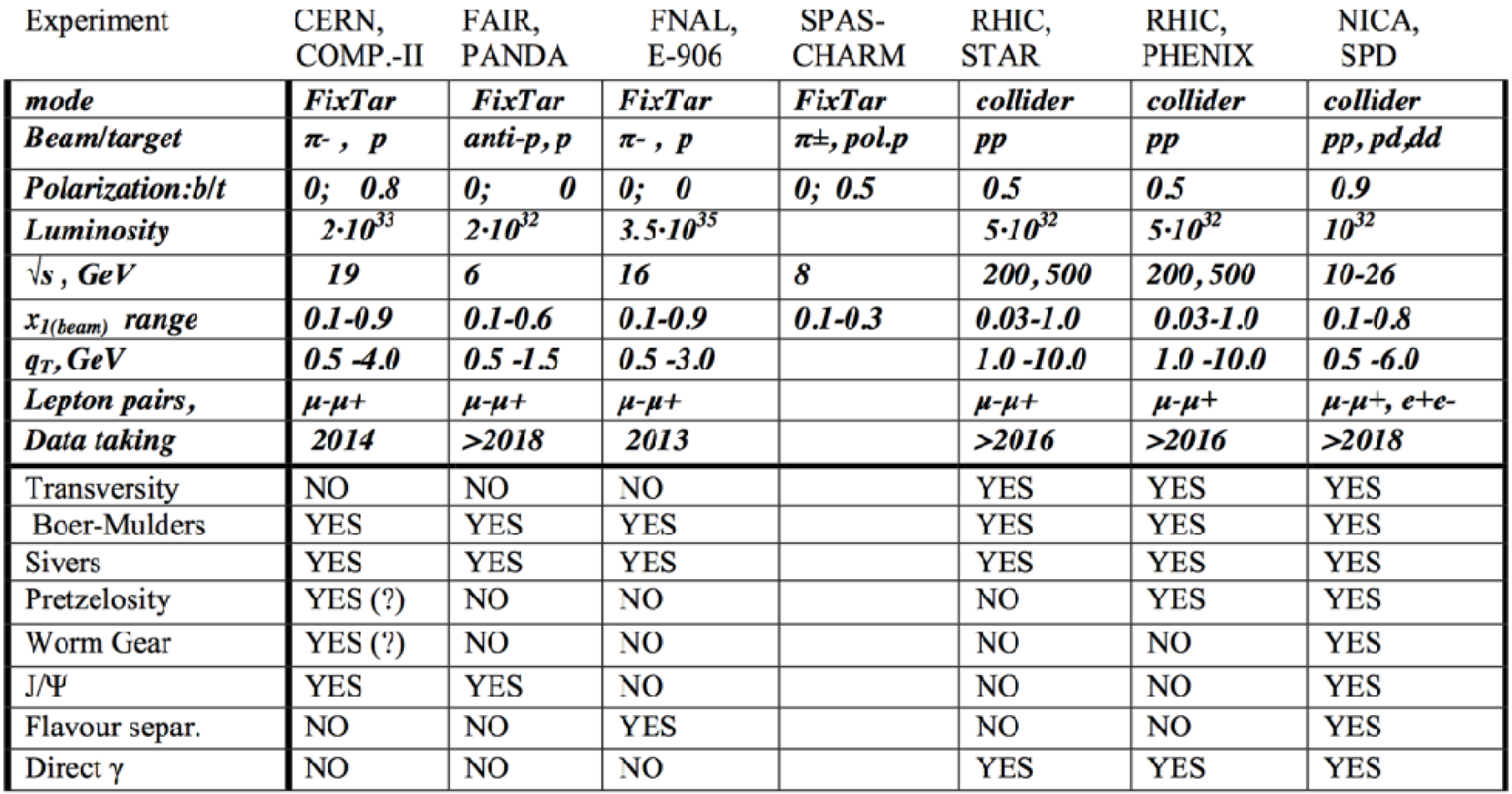






| $\sqrt{s}$=24 GeV<br>$L = 1.0 \times 10^{32}$, $cm^{-1}s^{-1}$ | $\sigma_{tot}$,<br>nbarn | $\sigma_{P_T>4\ GeV/c}$,<br>nbarn | Events/year,<br>$10^6$ | Events/year,<br>$10^6$ ($P_T > 4\ GeV/c$) |
|---|---|---|---|---|
| All processes | 1290 | 42 | 3260 | 105 |
| $qg \to q\gamma$ | 1080 | 33 | 2730 | 84 |
| $q\bar{q} \to g\gamma$ | 210 | 9 | 530 | 21 |
| $\sqrt{s}$=26 GeV<br>$L = 1.2 \times 10^{32}$, $cm^{-1}s^{-1}$ | $\sigma_{tot}$,<br>nbarn | $\sigma_{P_T>4\ GeV/c}$,<br>nbarn | Events/year,<br>$10^6$ | Events/year,<br>$10^6$ ($P_T > 4\ GeV/c$) |
| All processes | 1440 | 48 | 4340 | 144 |
| $qg \to q\gamma$ | 1220 | 38 | 3680 | 116 |
| $q\bar{q} \to g\gamma$ | 240 | 10 | 660 | 28 |

# NICA-SPD vs others



| Experiment | CERN, COMP.-II | FAIR, PANDA | FNAL, E-906 | SPAS-CHARM | RHIC, STAR | RHIC, PHENIX | NICA, SPD |
|---|---|---|---|---|---|---|---|
| ***mode*** | ***FixTar*** | ***FixTar*** | ***FixTar*** | ***FixTar*** | ***collider*** | ***collider*** | ***collider*** |
| ***Beam/target*** | $\pi^-$ , $p$ | ***anti-p, p*** | $\pi^-$ , $p$ | $\pi^\pm$, ***pol.p*** | ***pp*** | ***pp*** | ***pp, pd,dd*** |
| ***Polarization:b/t*** | ***0; 0.8*** | ***0; 0*** | ***0; 0*** | ***0; 0.5*** | ***0.5*** | ***0.5*** | ***0.9*** |
| ***Luminosity*** | $2{\cdot}10^{33}$ | $2{\cdot}10^{32}$ | $3.5{\cdot}10^{35}$ |  | $5{\cdot}10^{32}$ | $5{\cdot}10^{32}$ | $10^{32}$ |
| $\sqrt{s}$ ***, GeV*** | ***19*** | ***6*** | ***16*** | ***8*** | ***200, 500*** | ***200, 500*** | ***10-26*** |
| $x_{1(beam)}$ ***range*** | ***0.1-0.9*** | ***0.1-0.6*** | ***0.1-0.9*** | ***0.1-0.3*** | ***0.03-1.0*** | ***0.03-1.0*** | ***0.1-0.8*** |
| $q_T$***, GeV*** | ***0.5 -4.0*** | ***0.5 -1.5*** | ***0.5 -3.0*** |  | ***1.0 -10.0*** | ***1.0 -10.0*** | ***0.5 -6.0*** |
| ***Lepton pairs,*** | $\mu^-\mu^+$ | $\mu^-\mu^+$ | $\mu^-\mu^+$ |  | $\mu^-\mu^+$ | $\mu^-\mu^+$ | $\mu^-\mu^+$, $e^+e^-$ |
| ***Data taking*** | ***2014*** | ***>2018*** | ***2013*** |  | ***>2016*** | ***>2016*** | ***>2018*** |
| Transversity | NO | NO | NO |  | YES | YES | YES |
| Boer-Mulders | YES | YES | YES |  | YES | YES | YES |
| Sivers | YES | YES | YES |  | YES | YES | YES |
| Pretzelosity | YES (?) | NO | NO |  | NO | YES | YES |
| Worm Gear | YES (?) | NO | NO |  | NO | NO | YES |
| J/Ψ | YES | YES | NO |  | NO | NO | YES |
| Flavour separ. | NO | NO | YES |  | NO | NO | YES |
| Direct γ | NO | NO | NO |  | YES | YES | YES |
| Exclusive DY |  |  |  |  |  |  | YES |

# SUMMARY

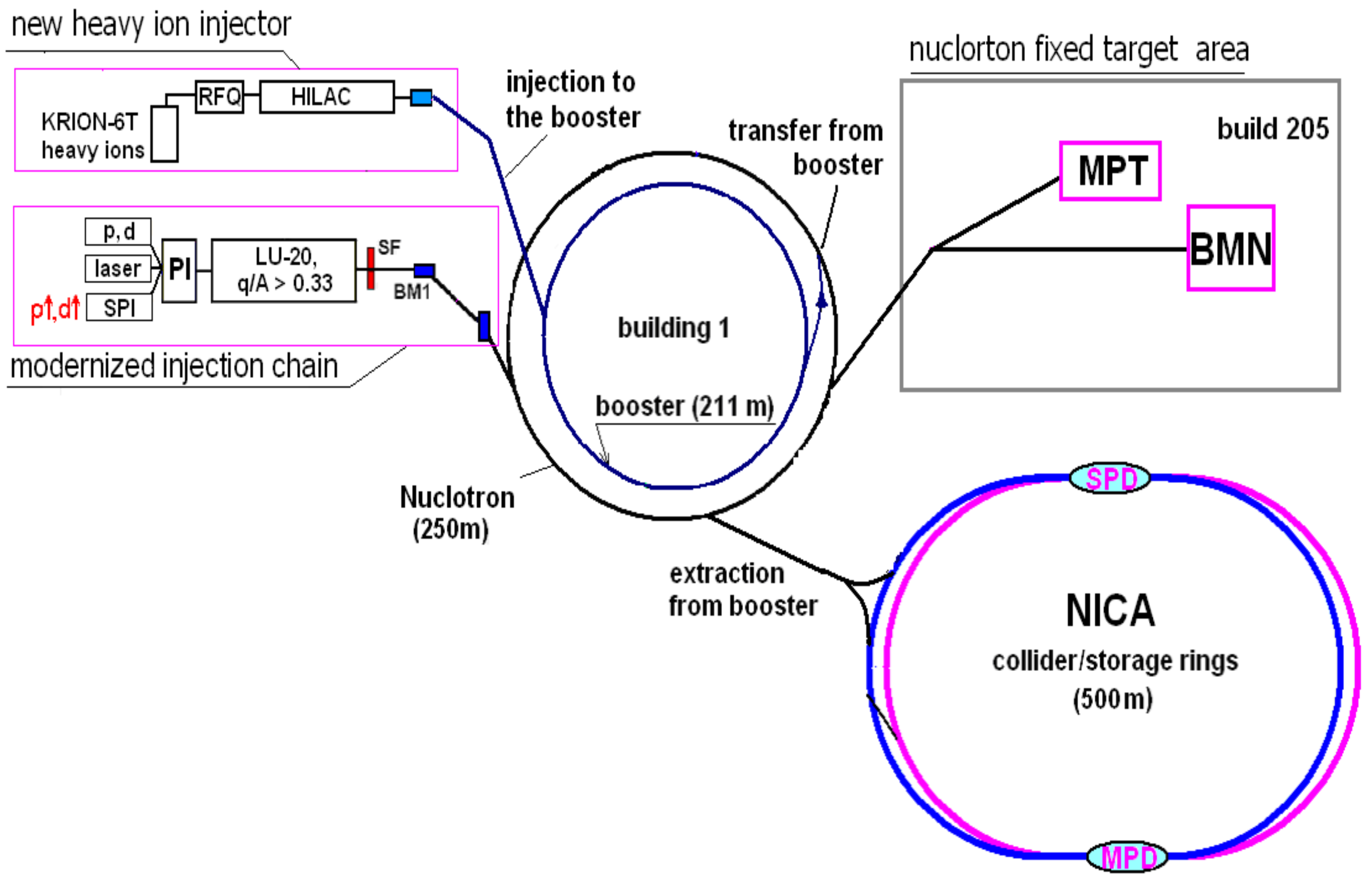
- *The comprehensive program of the nucleon structure study is suggested. It can be realized at NICA using the polarized proton, deuteron and heavy ion beams. The text of LoI is available at http://arxiv.org/abs/1408.3959*

- *LoI was approved by the JINR PAC on particle physics in 2014*

- *The International collaboration should be organized for preparations of the Proposal.*

# Backup slides

# NICA facility



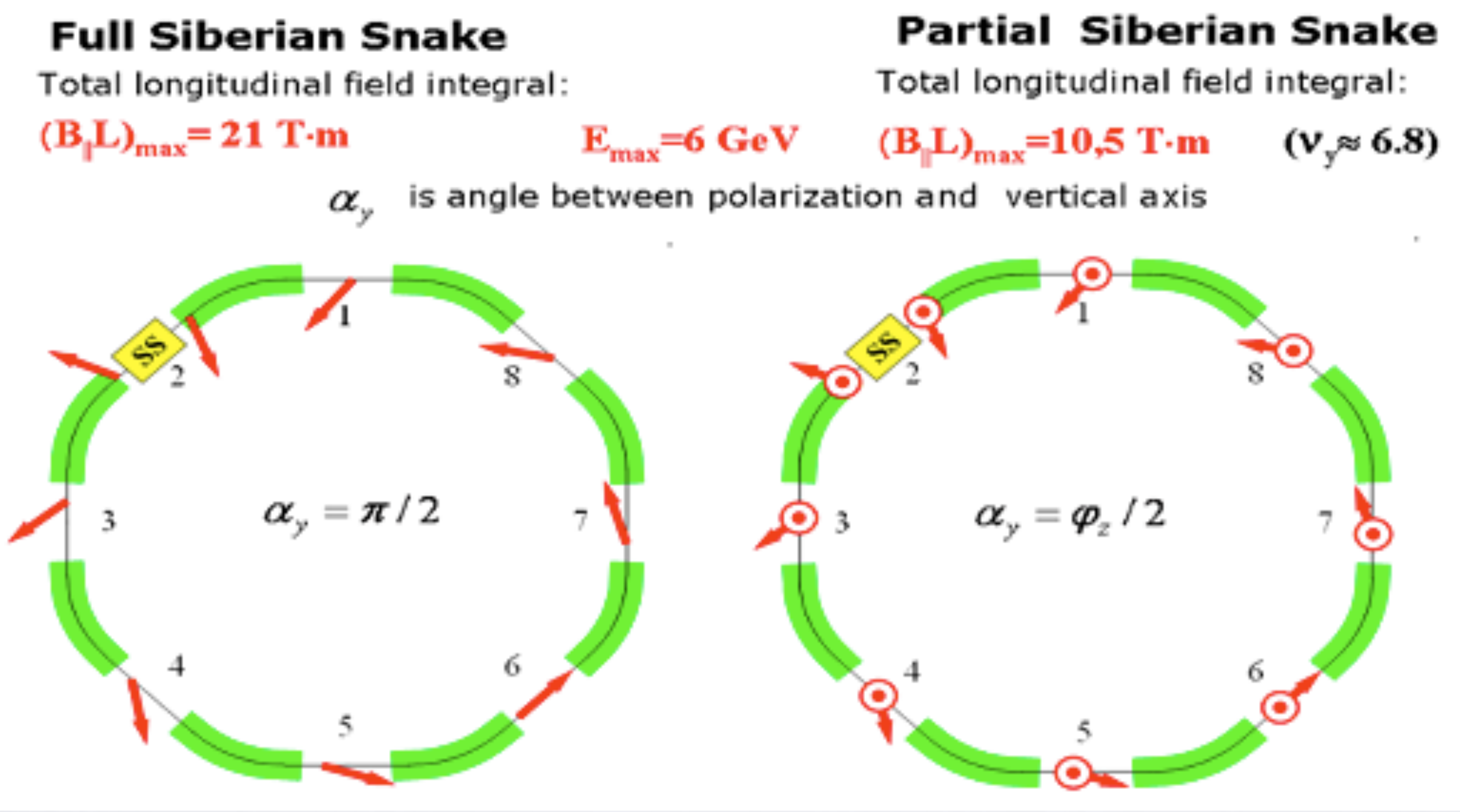
# Polarized beams

***Problem: depolarization of accelerating beam during crossing of the spin resonances***

$$\nu_{sp} = G\gamma$$

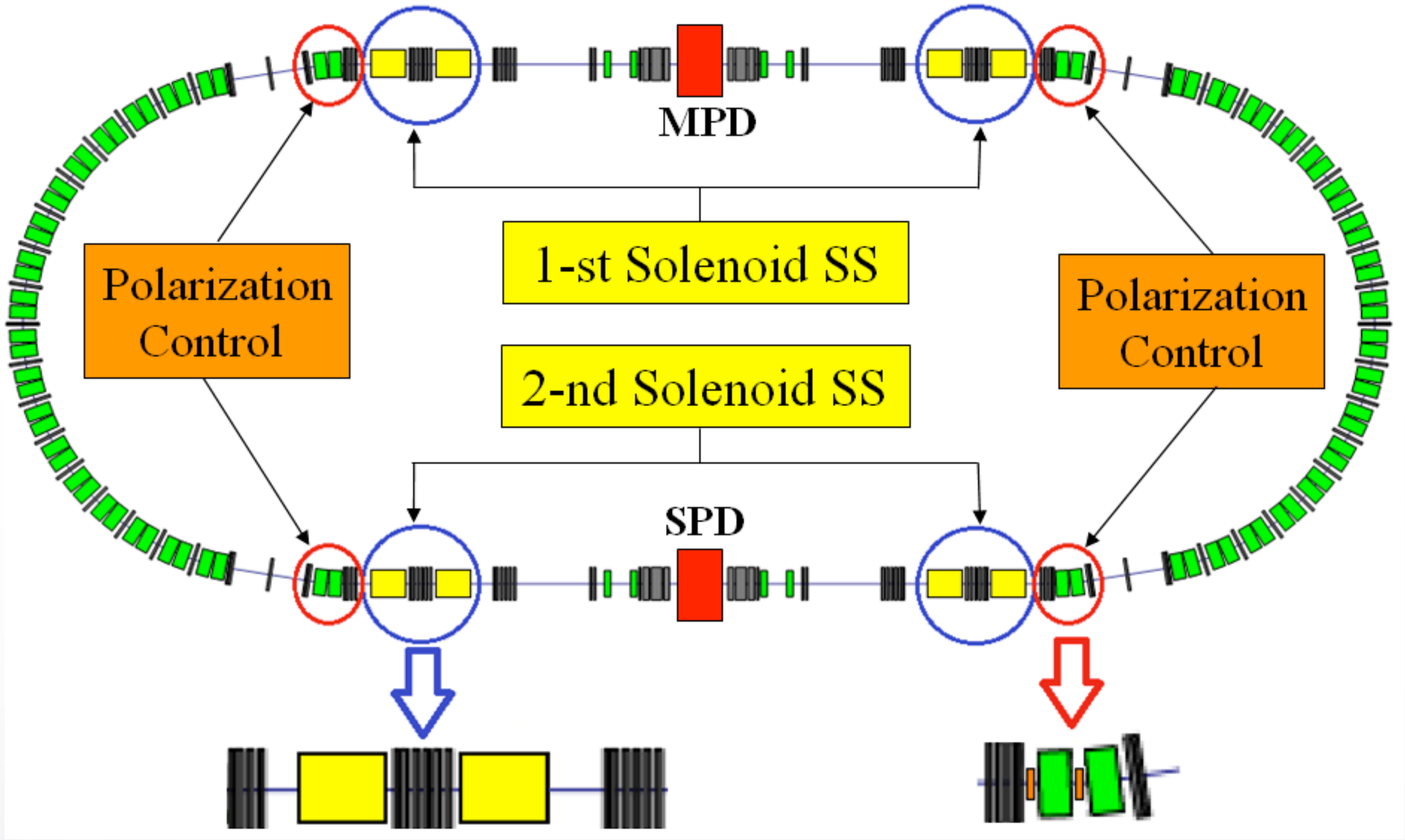
*>100 SR for p, just a few SR for d*

**Nuclotron**



*Polarized deuterons acceleration in Nuclotron is possible up to the energy of 5.6 GeV/u*

# Polarized beams



***NICA***

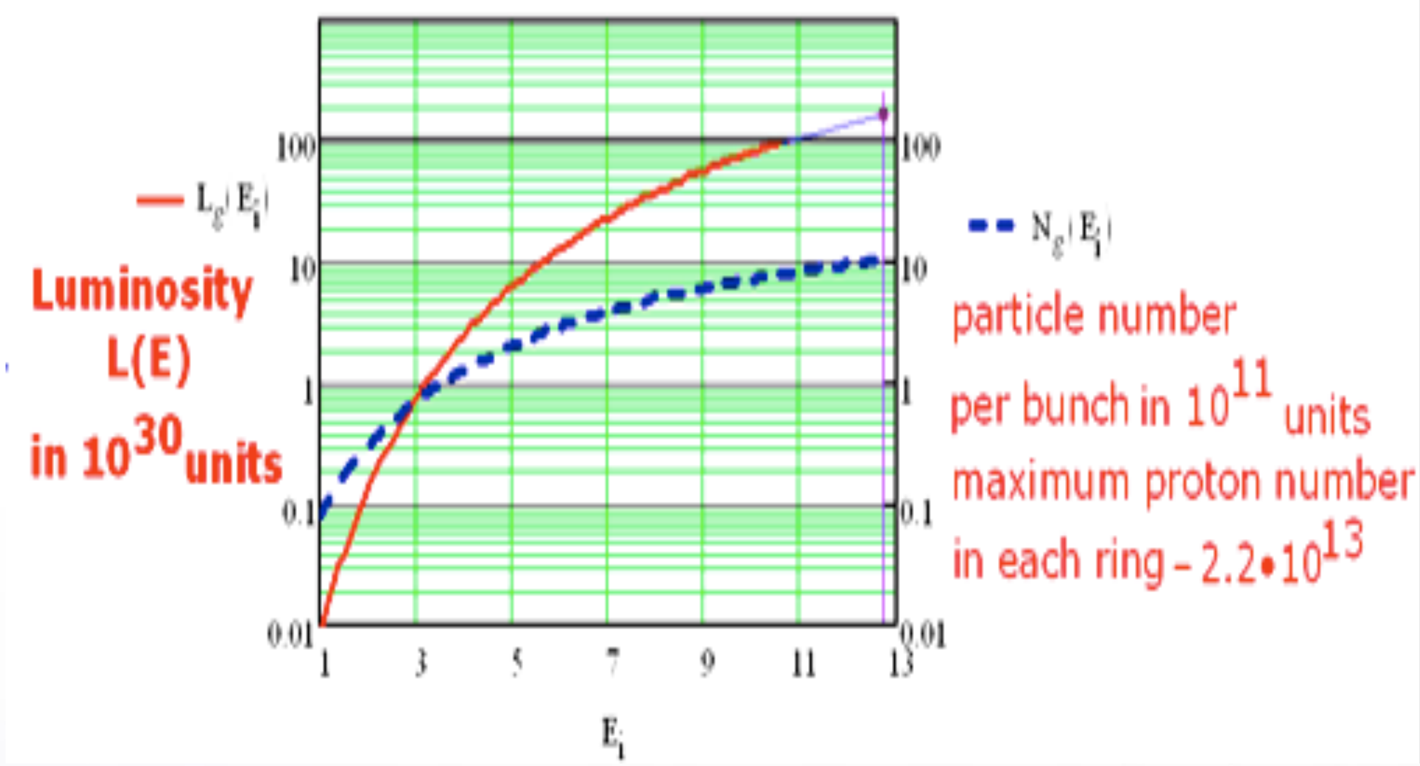
protons $(B_{||}L)_{max}$=8× (2.5÷12.5) T·m

deuterons $(B_{||}L)_{max}$=8×(7.5÷40) T·m

**Small control solenoids**

$(B_{||}L)_{max}$=8×0.25 T·m

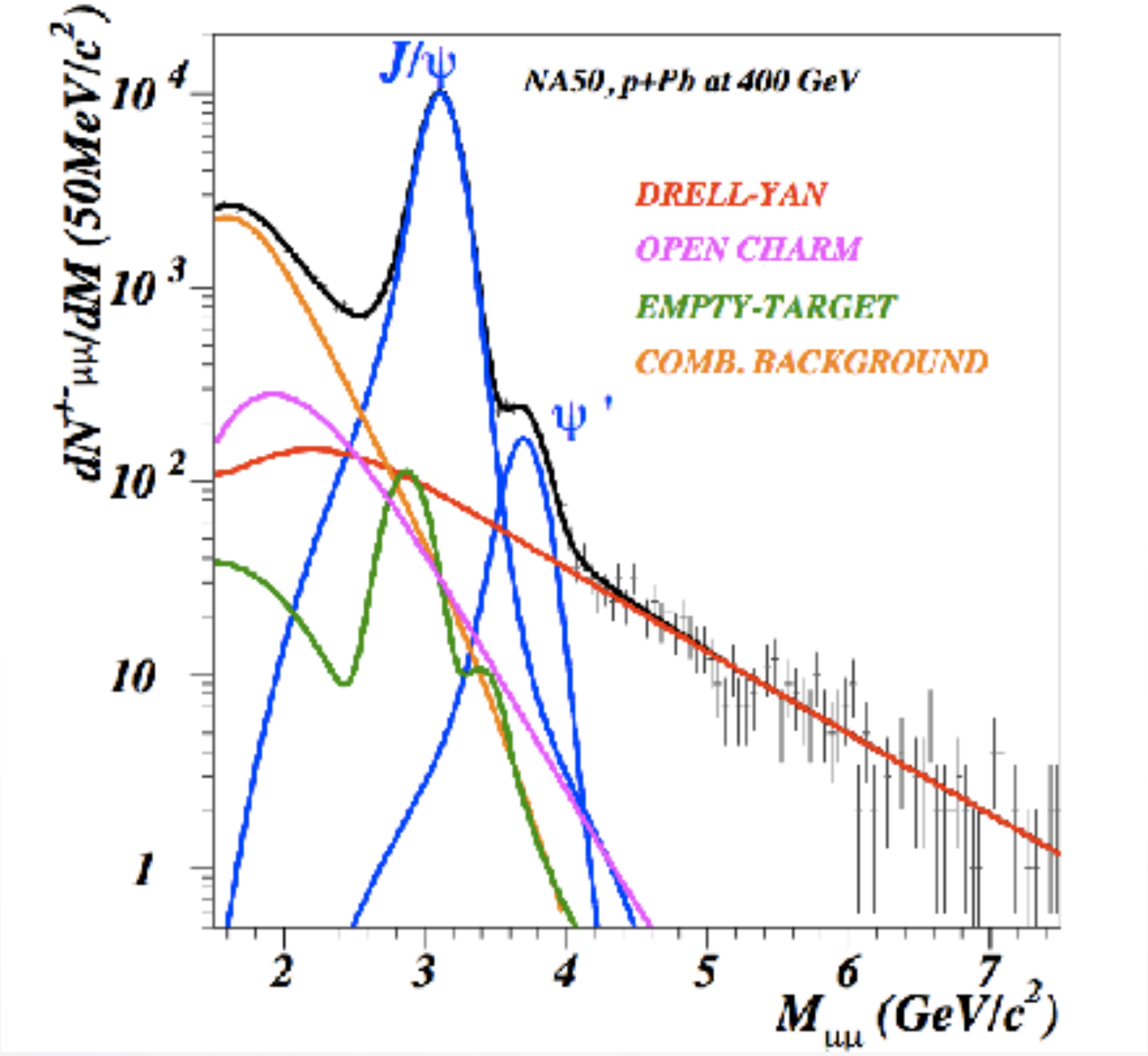
# Beam parameters



| | |
|---|---|
| circumference | - 503 m, |
| number of collision points (IP) | - 2, |
| beta function $\beta_{min}$ in the IP | - 0.35 m, |
| number of protons per bunch | - $\sim 1 \cdot 10^{12}$, |
| number of bunches | - 22, |
| RMS bunch length | - 0.5 m, |
| incoherent tune shift, $\Delta_{Lasslett}$ | - 0.027, |
| beam-beam parameter, $\xi$ | - 0.067, |
| beam emittance $\varepsilon_{nrm}$ (normalized) at 12.5 GeV, $\pi$ mm mrad | - 0.15. |

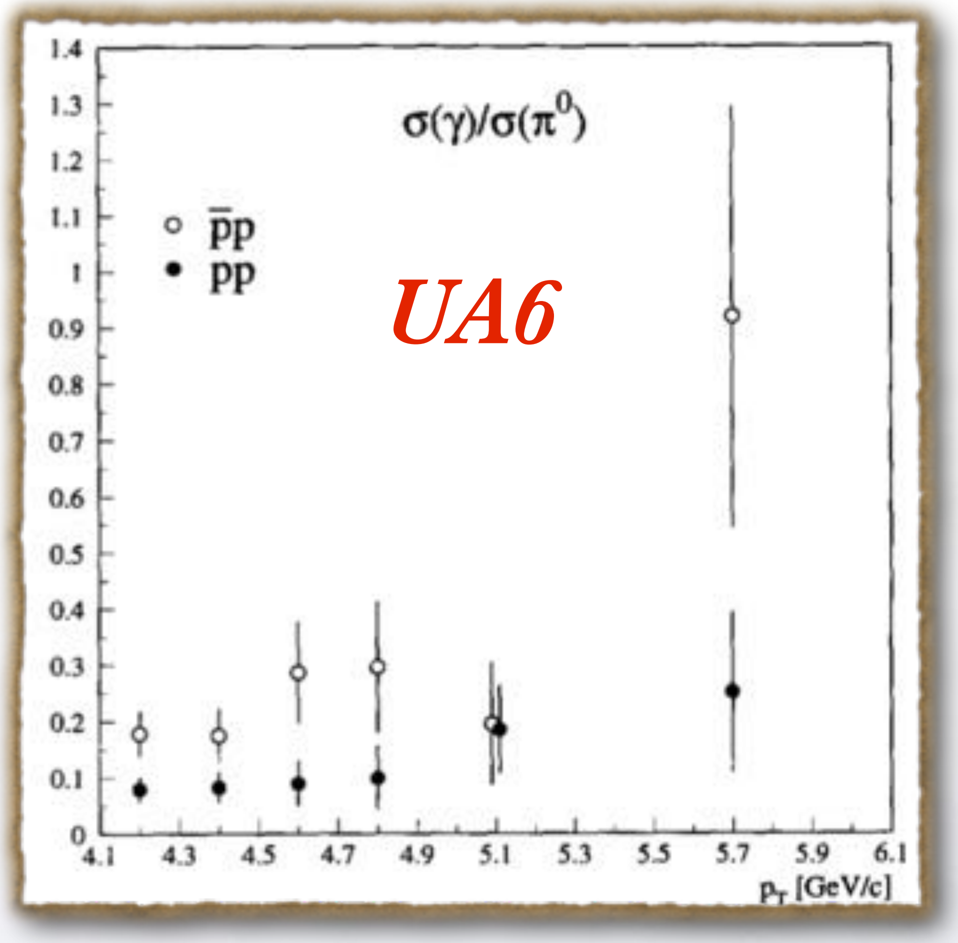
The number of particles reaches a value about $2.2 \cdot 10^{13}$ in each ring and the peak luminosity $L_{peack} = 2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ at 12.7 GeV. One can estimate also an average luminosity. Assuming the cooling time $T_{cool} = 1500$ s, the luminosity life time $T_{Llf} = 20000$ s and the machine reliability coefficient $k_r = 0.95$, the average luminosity will be $L_{aver} = L_{peack} \cdot 0.86$ or $1.7 \cdot 10^{32}$ cm $^{-2}$ s$^{-1}$ [12].

# Background processes



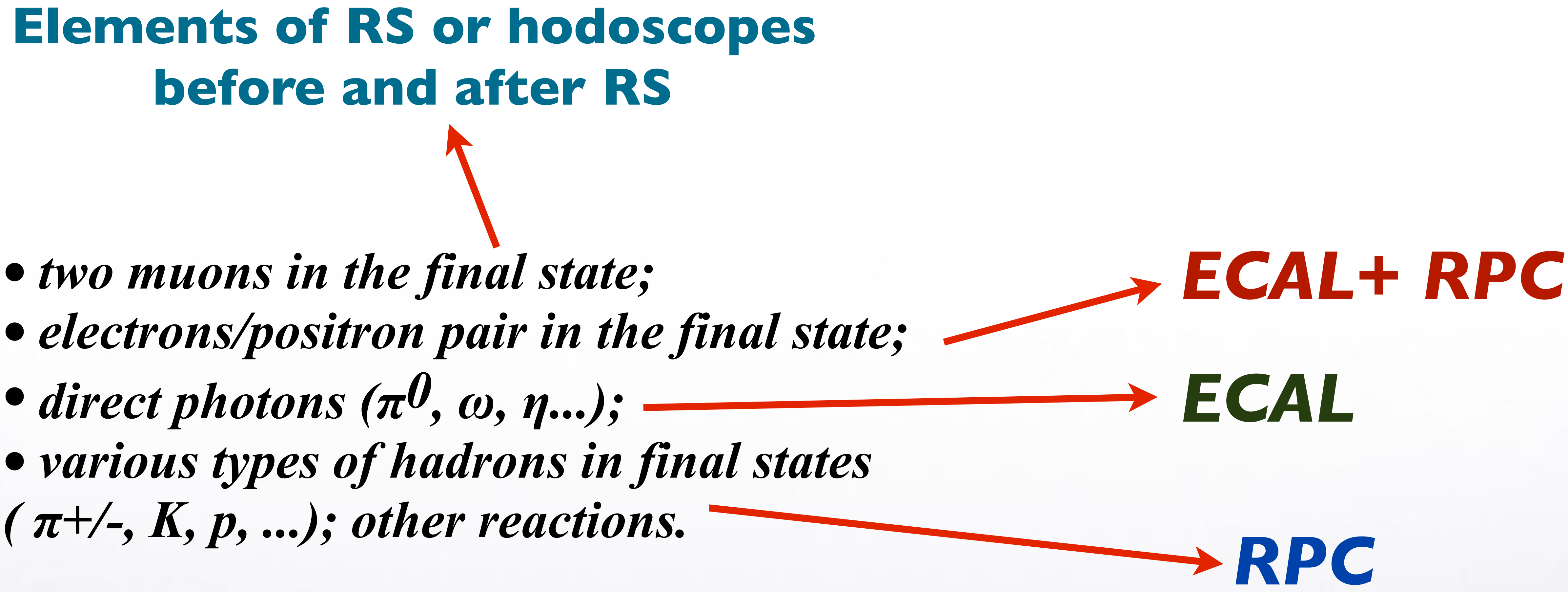
**dimuon spectrum**

- $\sqrt{s}=24.3$ GeV



**Direct photons and $\pi^0$ decay**

# Trigger system



**Elements of RS or hodoscopes before and after RS**

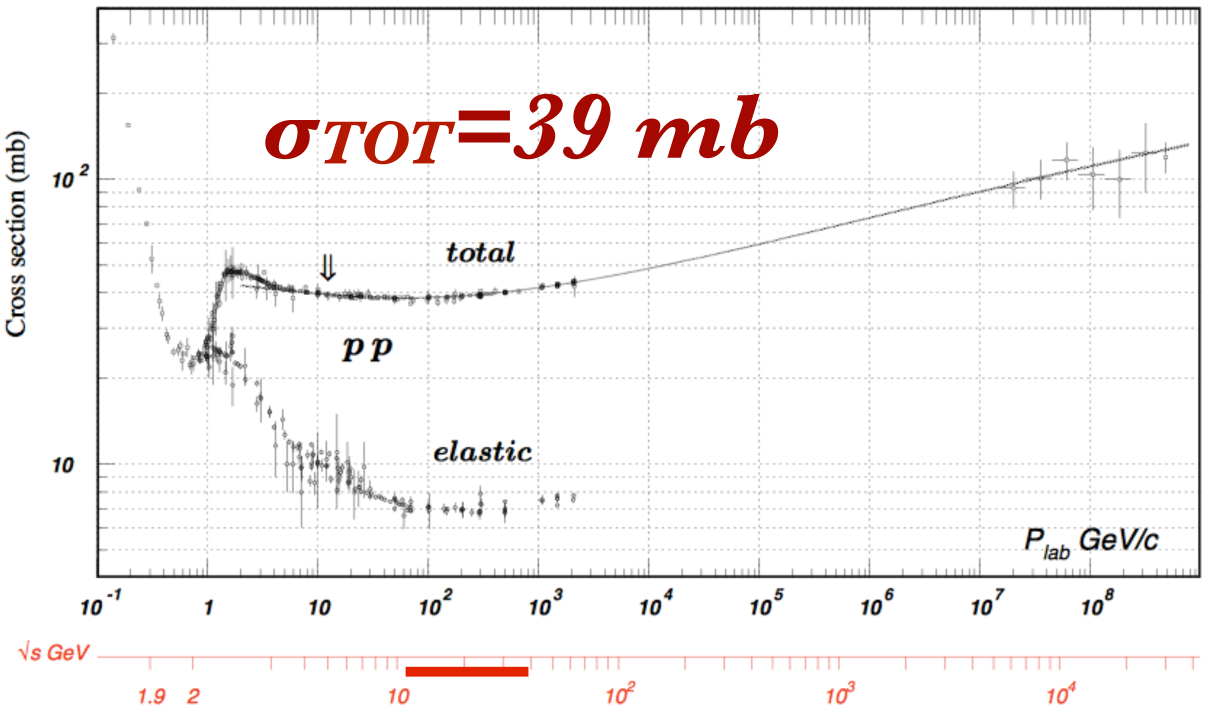
- *two muons in the final state;*
- *electrons/positron pair in the final state;*
- *direct photons ($\pi^0$, $\omega$, $\eta$...);*
- *various types of hadrons in final states ( $\pi$+/-, K, p, ...); other reactions.*

**ECAL+ RPC**

**ECAL**

**RPC**

# Expected rates



$\sigma_{TOT}$=39 mb

**$L=1.2\times10^{32}$ cm$^{-2}$ s$^{-1}$**

**Event rate - 4 MHz**

**4 MHz vs 8 Hz**

| *process* | cross section, nb | *rate, Hz (√s=26 GeV, L=1.2*$10^{32}$)* |
|---|---|---|
| Direct photons ($p_T$>4 GeV/c) | 48 | 5.8 |
| DY (M>2 GeV) ee+μμ | 2.6 | 0.3 |
| J/ψ | 16 | 1.9 |
| TOTAL | 67 | 8 |