XX INTERNATIONAL BALDIN SEMINAR
ON HIGH ENERGY PHYSICS PROBLEMS

RELATIVISTIC NUCLEAR PHYSICS & QUANTUM CHROMODYNAMIC

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Transverse Parton Distributions Functions in Drell-Yan Processes at FAIR

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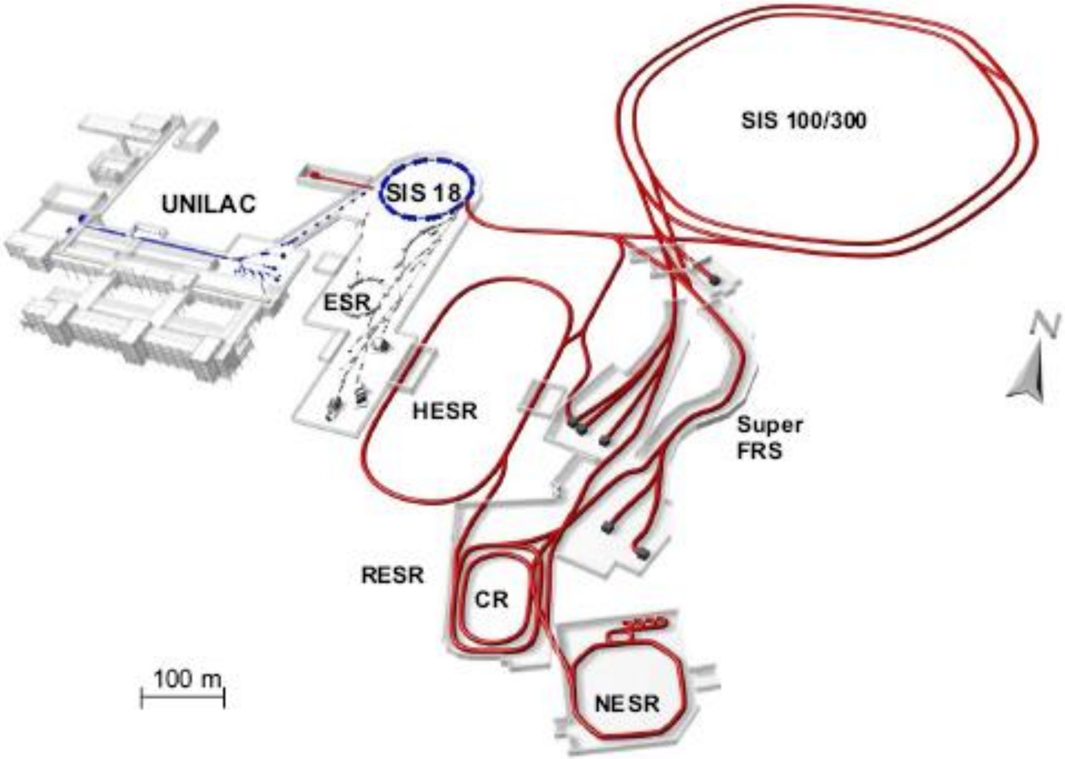
The future FAIR facility

Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 present in intensity
- $2(4)\times10^{13}$/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

HESR - High Energy Storage Ring

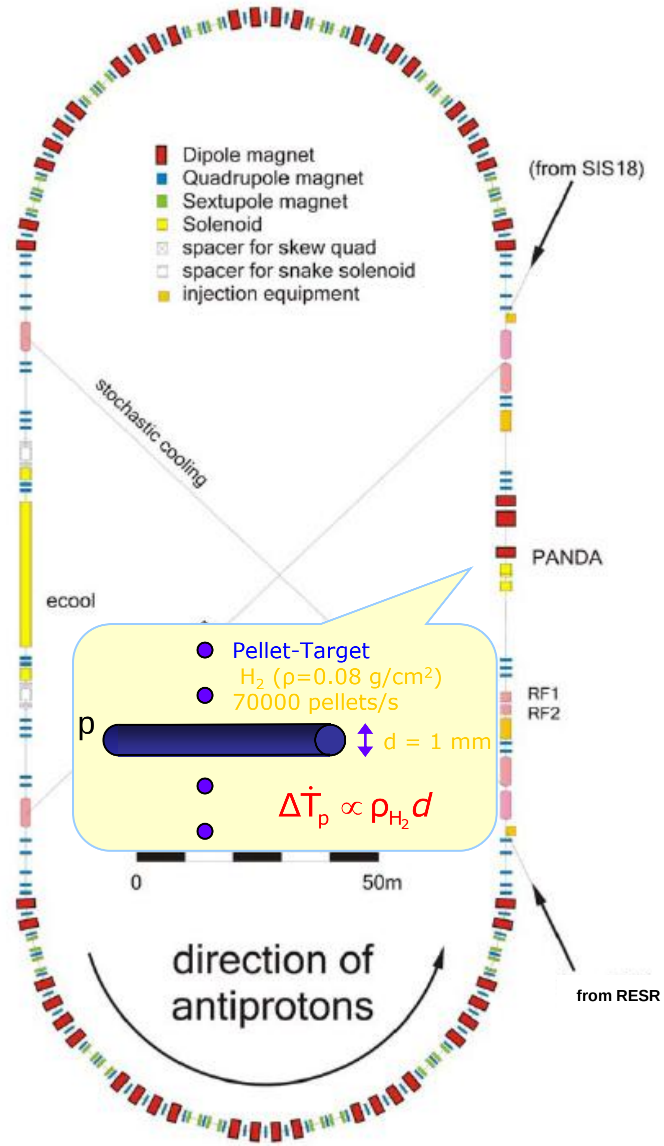
- Production rate $2x10^7$/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = $5x10^{10}$ $\bar{p}$
- Internal Target

High resolution mode

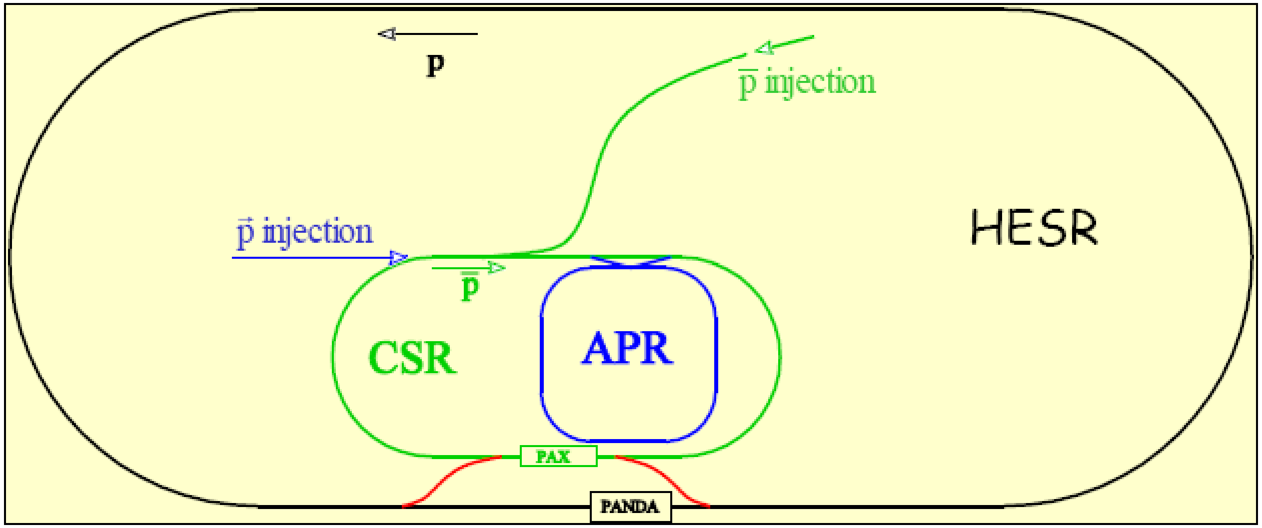
- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

- Lumin. = 2 x 10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



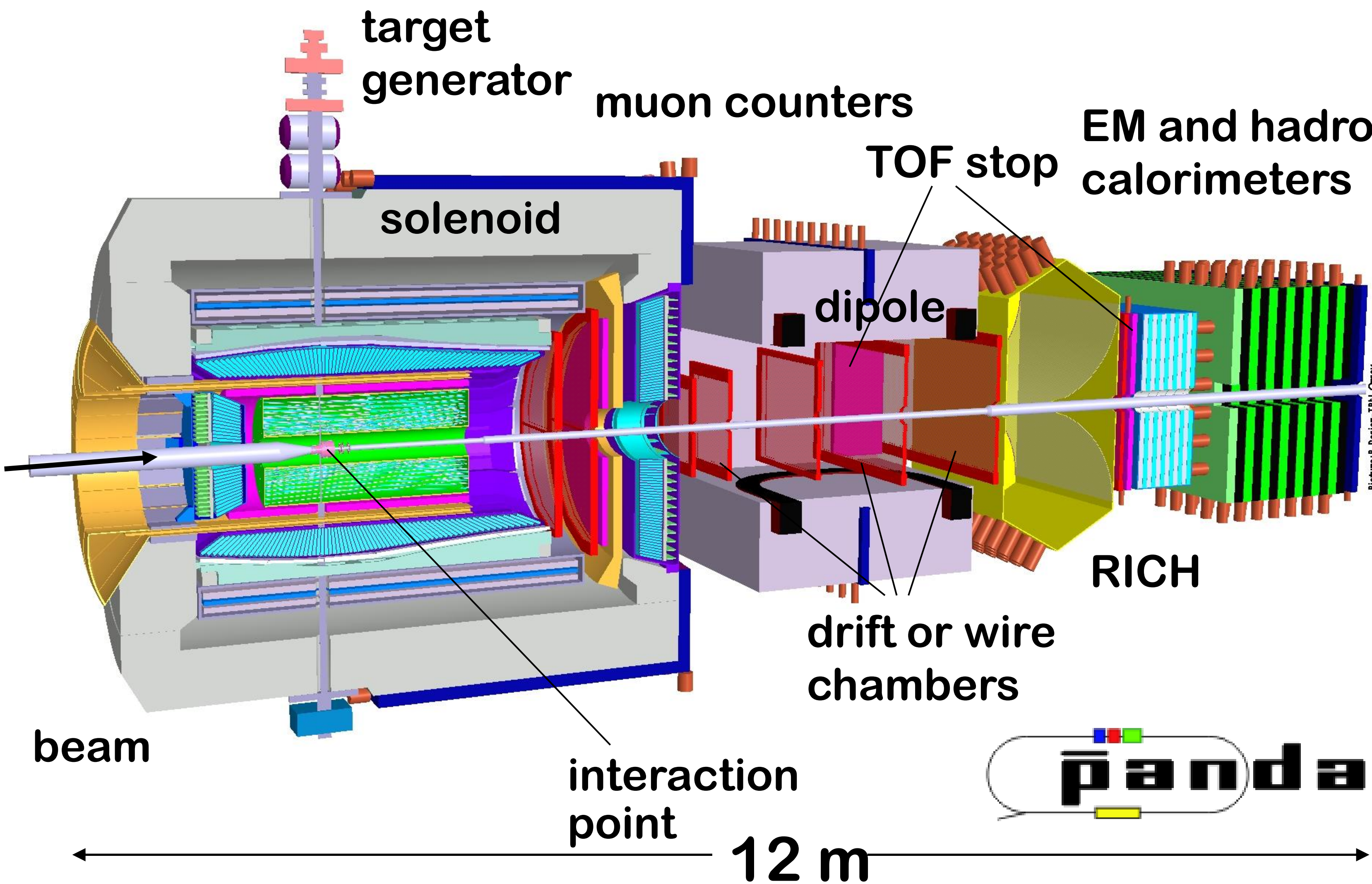
HESR: asymmetric collider layout



Asymmetric double-polarised collider mode
proposed by PAX people:

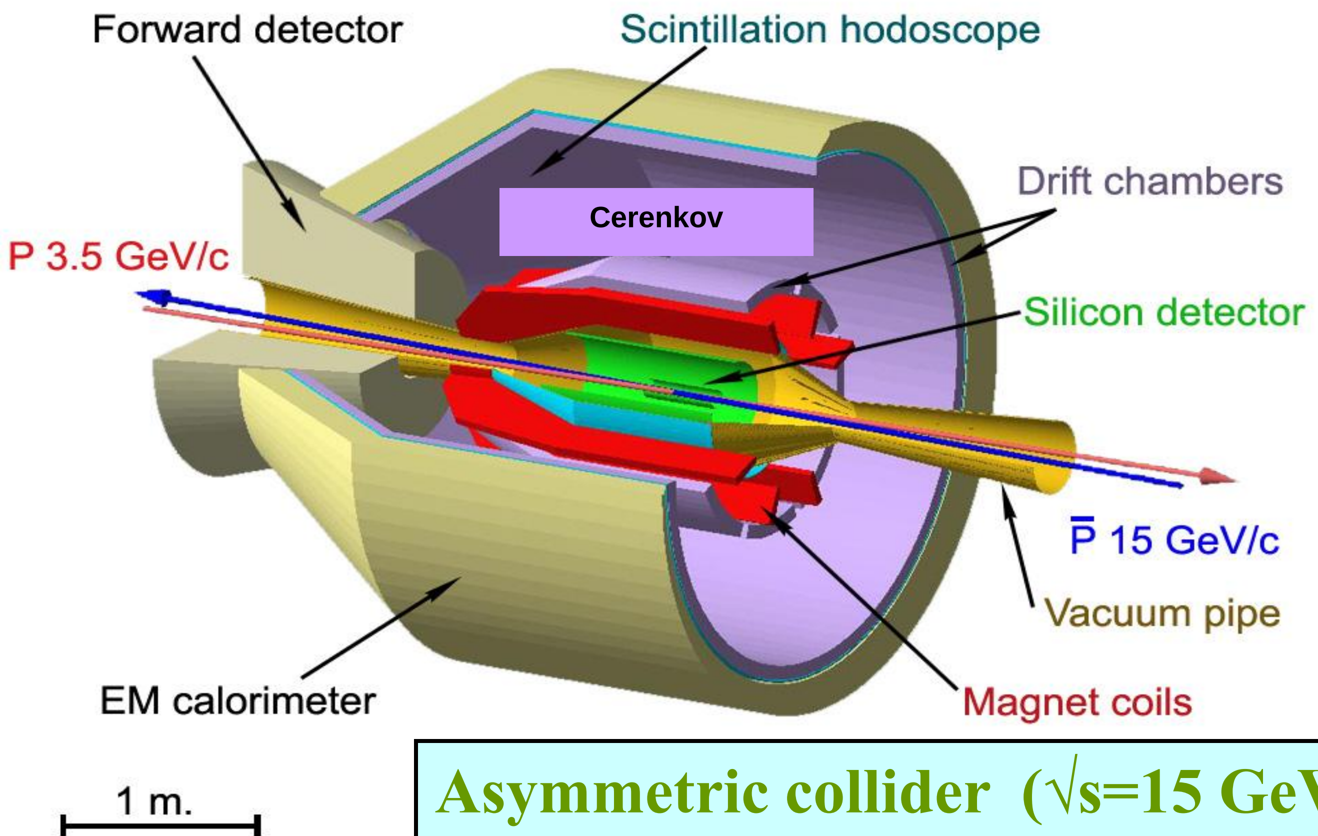
- APR (Antiproton Polariser Ring): polarising antiprotons, p > 0.2 GeV/c
- CSR (Cooled Synchrotron Ring): polarised antiprotons, p = 3.5 GeV/c
- HESR: polarised protons, p = 15 GeV/c

The PANDA Detector



Physics Performance Report for PANDA arXiv:0903.3905

Polarized Antiproton eXperiments



Asymmetric collider ($\sqrt{s}$=15 GeV):

polarized protons in HESR (p=15 GeV/c)

polarized antiprotons in CSR (p=3.5 GeV/c)

A common goal: the nucleon structure

- A complete description of nucleonic structure requires:
  - quark and gluon distribution functions (PDF)
  - quark fragmentation functions (FF)

@ leading twist and @ NLO; including k_T dependence:

  - Transverse Momentum Dependent (TMD) PDF and FF

Physics Performance Report for PANDA

arXiv:0903.3905

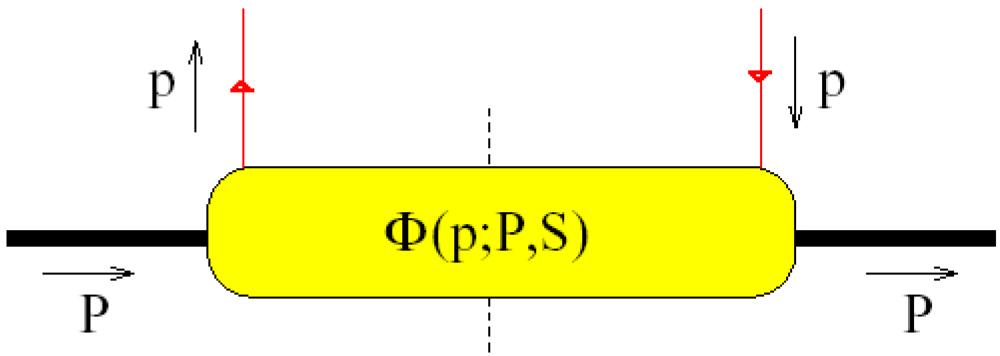
- Physics objectives:
  - Drell-Yan (DY) di-lepton production
  - electromagnetic form factors
  - Generalised Parton Distribution (GPD) =>

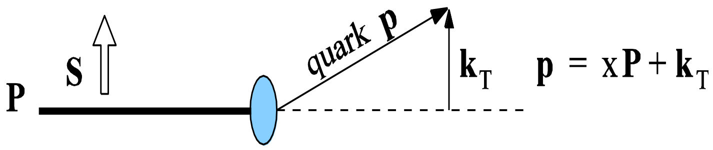
    Generalised Distribution Amplitudes (GDA)

TMD: κ_T-dependent Parton Distributions

Leading-twist correlator depends on

five more distribution functions:



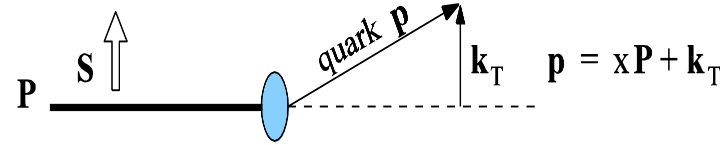


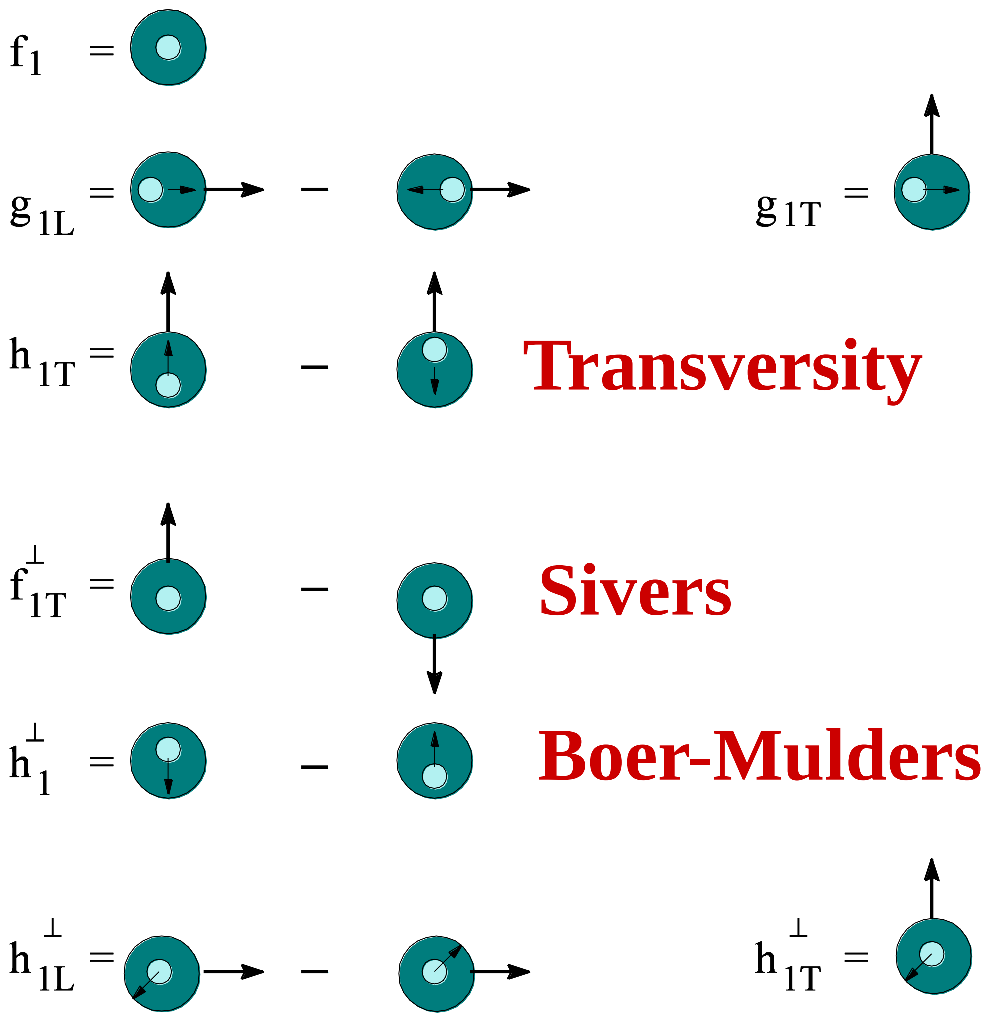
$$\Phi(x_a, \boldsymbol{k}_{\perp a}) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_{\perp a}^\rho (P_T^A)^\sigma}{M} + \left(P_L^A g_{1L} + \frac{\boldsymbol{k}_{\perp a}\cdot \boldsymbol{P}_T^A}{M} g_{1T}^\perp \right)\gamma^5 \not{n}_+$$
$$+ h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu (P_T^A)^\nu + \left(P_L^A h_{1L}^\perp + \frac{\boldsymbol{k}_{\perp a}\cdot \boldsymbol{P}_T^A}{M} h_{1T}^\perp \right) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_{\perp a}^\nu}{M}$$
$$+ h_1^\perp \frac{\sigma_{\mu\nu} k_{\perp a}^\mu n_+^\nu}{M} \Big] .$$

TMD: κ_T-dependent Parton Distributions

Twist-2 PDFs

$$f_1(x) = \int d^2k_T f_1(x,k_T)$$





Distribution functions		Chirality even	Chirality odd
Twist-2	U	f_1	$h_1^{\perp}$
	L	g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}, g_{1T}$	$h_1,\ h_{1T}^{\perp}$

Drell-Yan Di-Lepton Production — $\bar{p}p \rightarrow \ell^+\ell^- X$

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\alpha^2\pi}{9M^2 s}\frac{1}{x_1+x_2}\sum_a e_a^2\left[f^a(x_1)f^{\bar{a}}(x_2)+f^{\bar{a}}(x_1)f^a(x_2)\right]$$

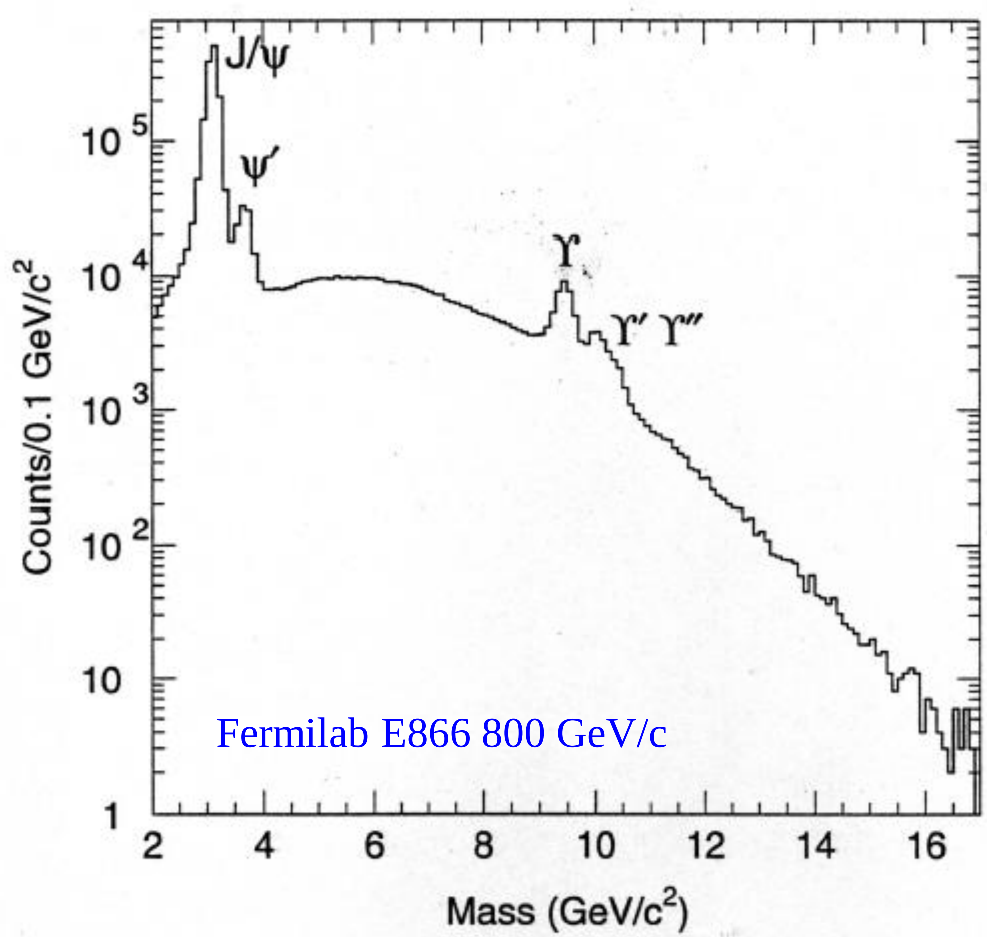
Why Drell Yan?

Asymmetries depend on PD only (SIDIS→convolution with QFF)

3 planes: plane $\perp$ to polarisation vectors

$p-\gamma^*$ plane

it



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Scaling:

$$\frac{d^2\sigma}{d\sqrt{\tau}dx_F} \propto \frac{1}{s}$$

Full x_1,x_2 range $\Rightarrow \tau \in [0,1]$

Kinematics

$$x_1 = \frac{M^2}{2P_1 \bullet q} \qquad x_2 = \frac{M^2}{2P_2 \bullet q}$$

$$x_F = x_1 - x_2$$

$$\tau = x_1 x_2 = \frac{M^2}{s}$$

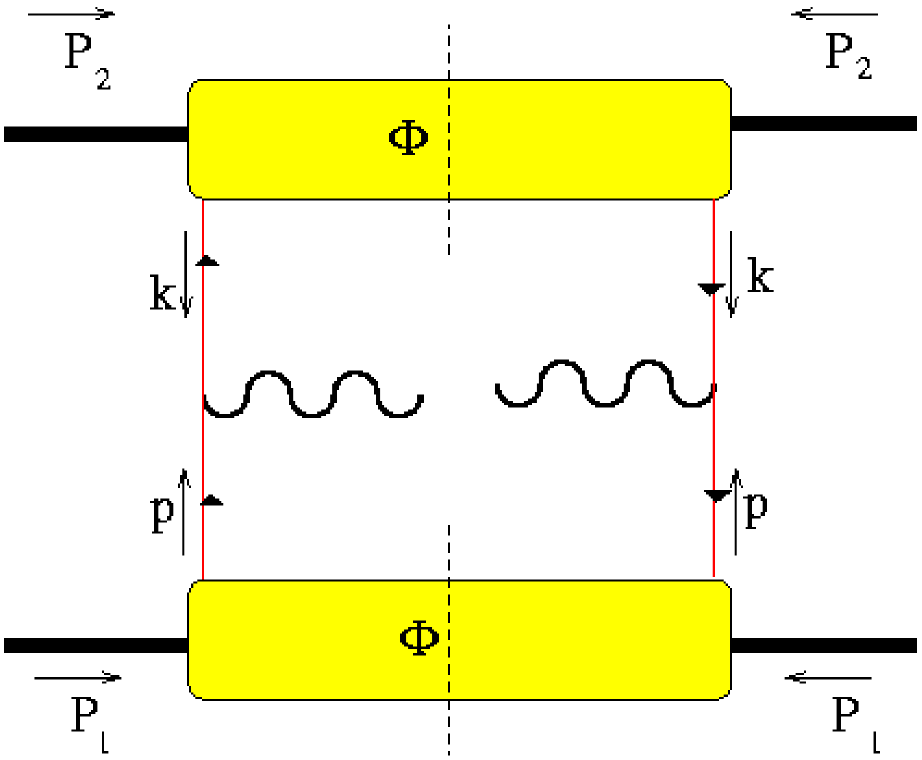
Drell-Yan Asymmetries — $\bar{p}^{\uparrow} p^{\uparrow} \to \ell^{+}\ell^{-}X$

Uncorrelated quark helicities $\Rightarrow$ access chirally-odd functions

TRANSVERSITY

Ideal because:

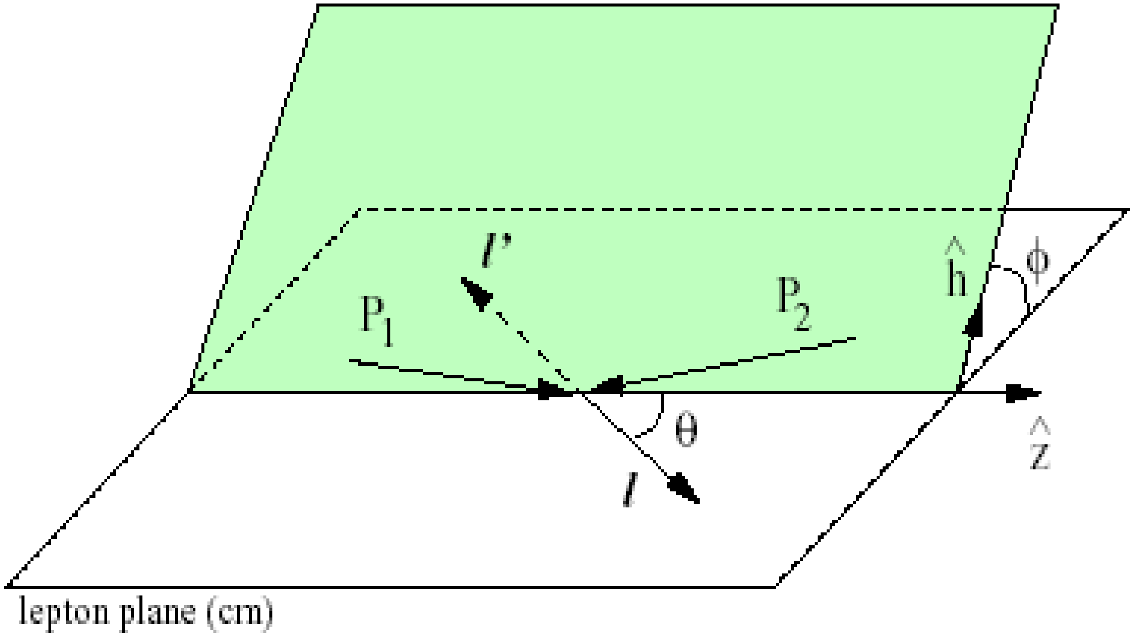
- h_1 not to be unfolded with fragmentation functions
- chirally odd functions not suppressed (like in DIS)



Drell-Yan Asymmetries — $\bar{p}^{\uparrow}p^{\uparrow} \to \ell^{+}\ell^{-}X$

$$A_{LL} = \frac{\sum_a e_a^2 g_1^a(x_1) g_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \qquad A_{TT} = \frac{\sin^2\theta \cos 2\varphi}{1+\cos^2\theta} \frac{\sum_a e_a^2 h_1^a(x_1) h_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

$$A_{LT} = \frac{2\sin 2\theta \cos\varphi}{1+\cos^2\theta} \frac{M}{\sqrt{Q^2}} \frac{\sum_a e_a^2 \left(g_1^a(x_1) x_2 g_T^{\bar{a}}(x_2) - x_1 h_L^a(x_1) h_1^{\bar{a}}(x_2) \right)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

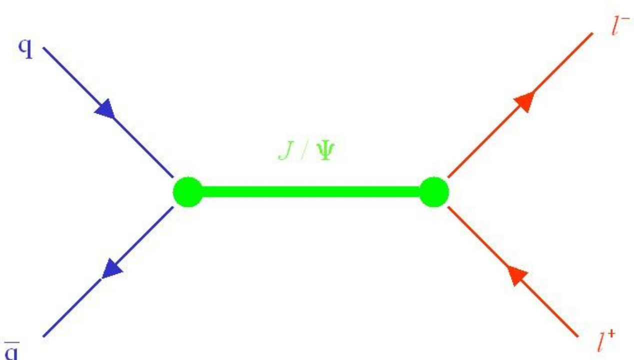


To be corrected for:

$$\frac{1}{P_{\vec{p}}\ f\ P_{\vec{\bar{p}}}}$$

Collins-Soper frame: [1]Phys. Rev. D16 (1977) 2219.

Drell-Yan Di-Lepton Production $\bar{p}p \rightarrow J/\Psi \rightarrow \ell^+\ell^- X$

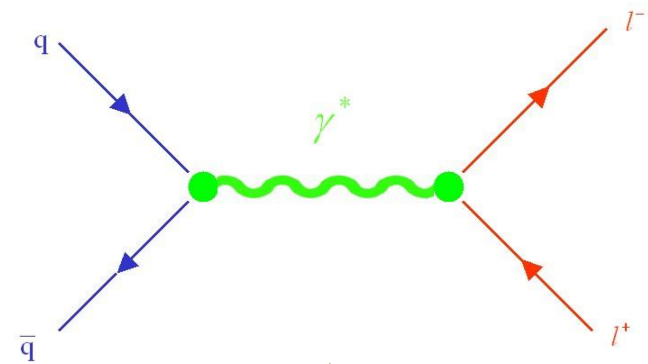


$$g_q^V \bar{v}\gamma^\mu u \frac{1}{M^2 - M_{J/\Psi}^2 + i\Gamma M_{J/\Psi}} g_l^V \bar{u}\gamma^\mu v$$

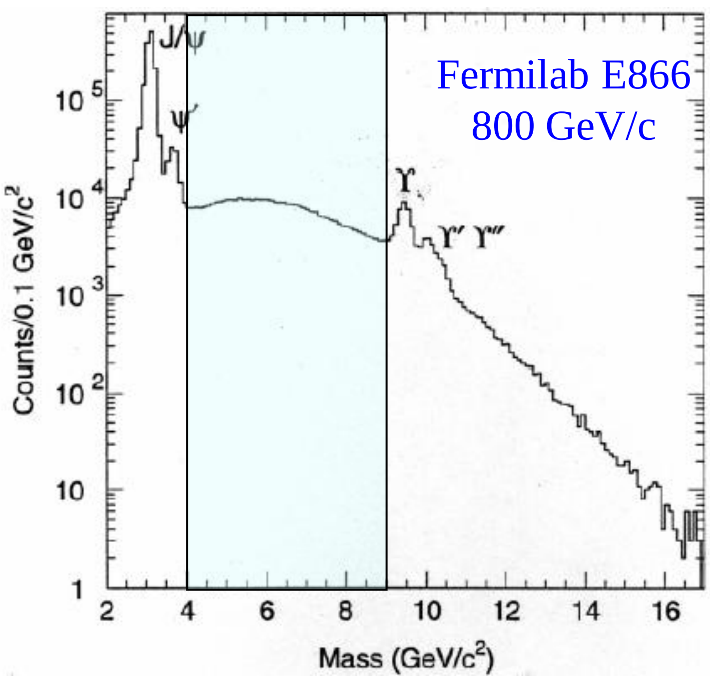
vector couplings

same spinor structure

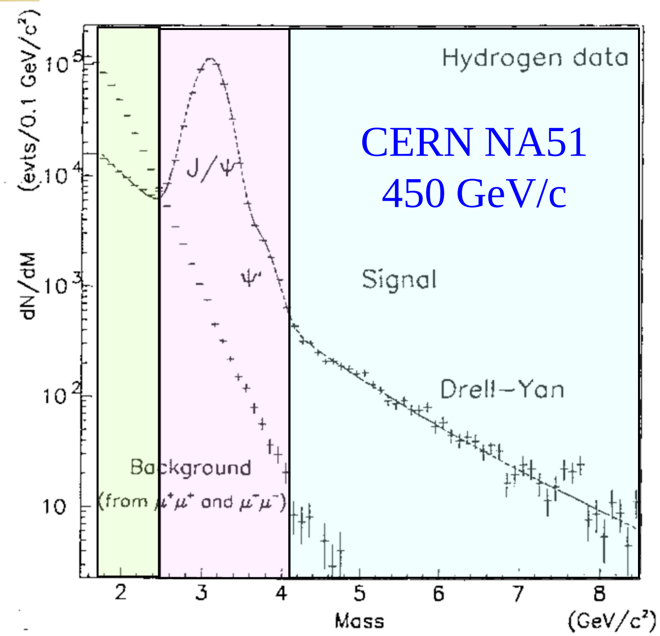
$$\hat{a}_{TT}^{J/\Psi} = \hat{a}_{TT}^{\gamma^*}$$



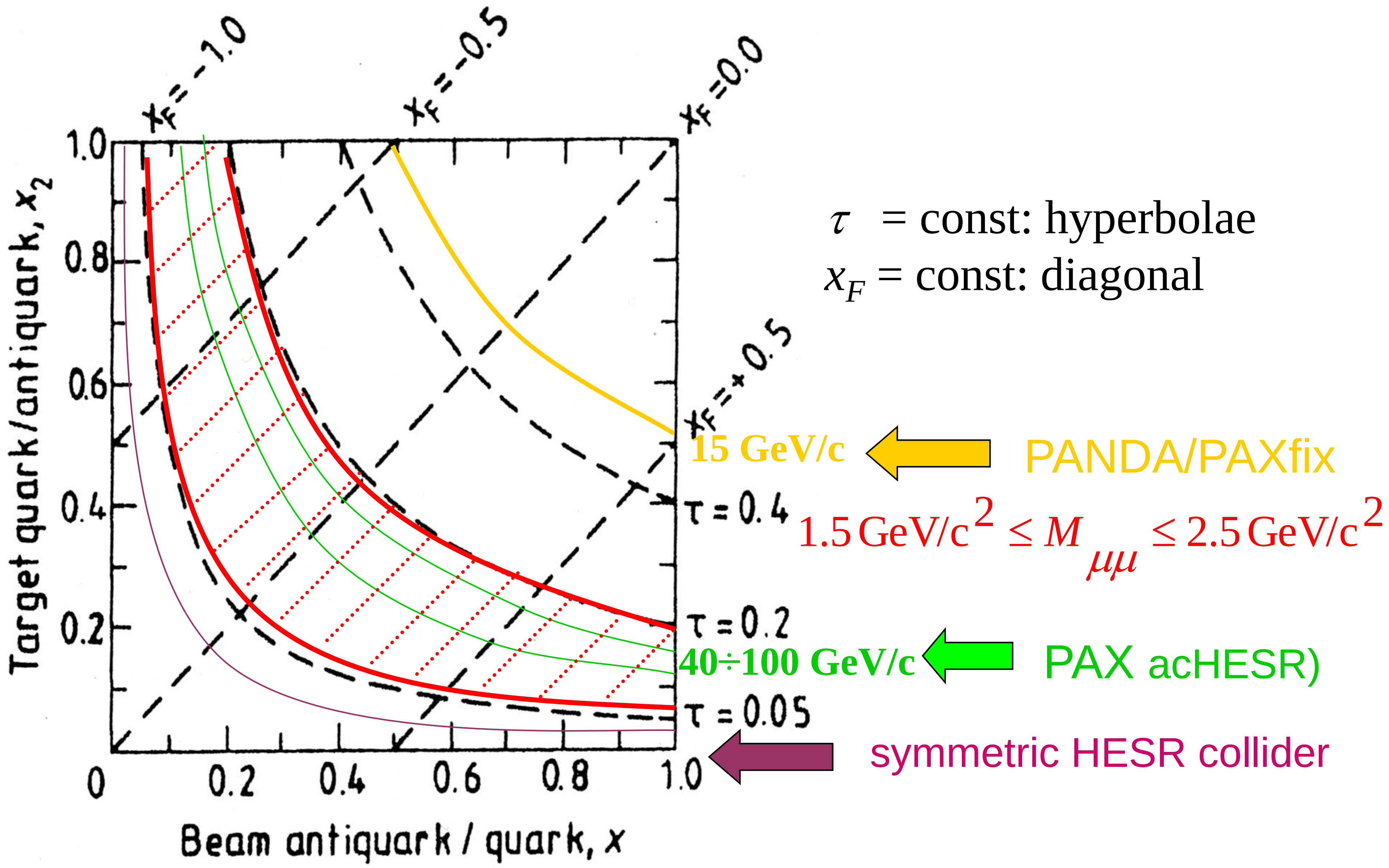
$$\bar{v}\gamma^\mu u \frac{1}{M^2} \bar{u}\gamma^\mu v$$



$Q^2 > 2.25\ GeV^2$



Phase space for Drell-Yan processes

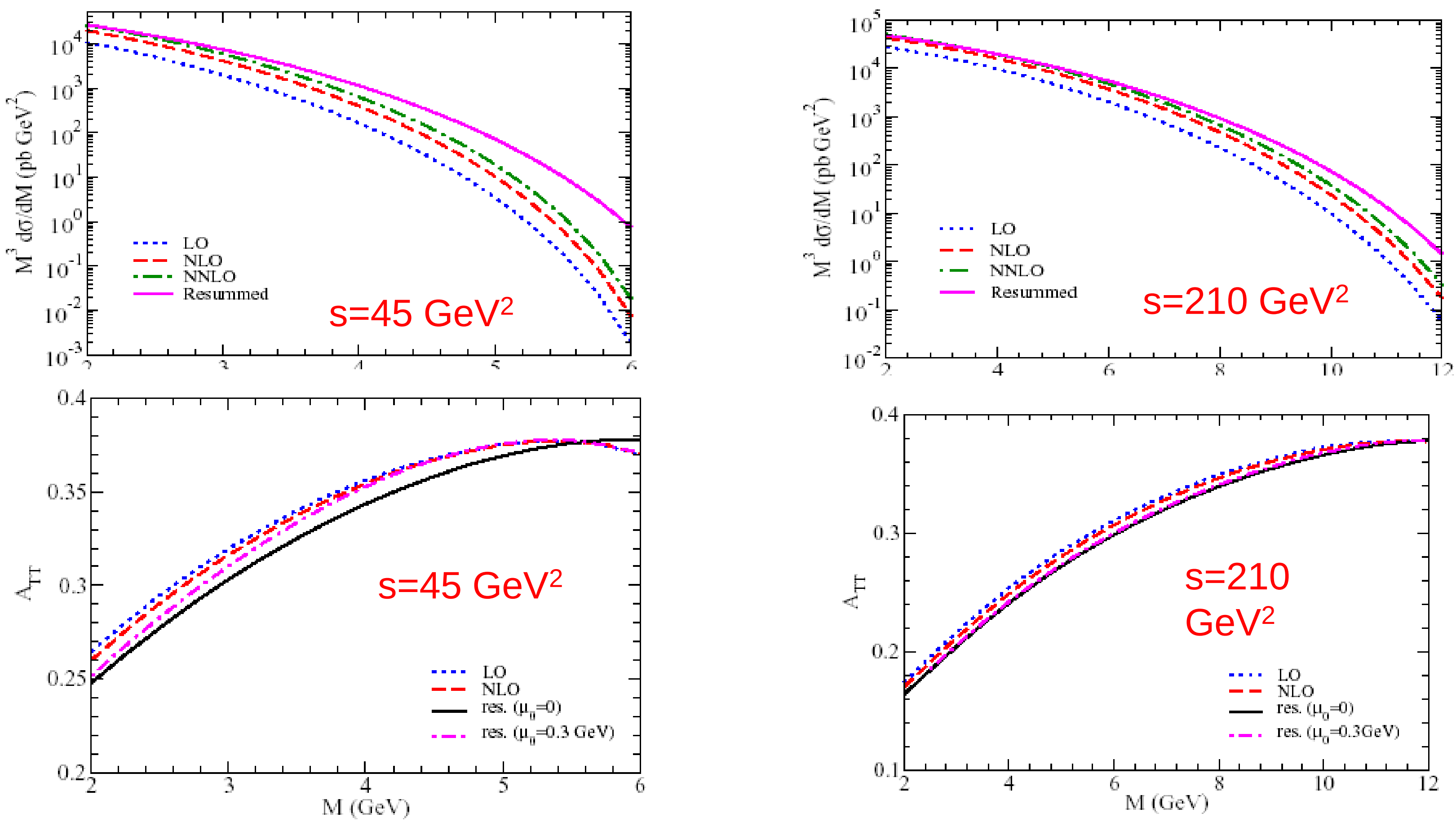


τ = const: hyperbolae

x_F = const: diagonal

Drell-Yan Di-Lepton Production $\bar{p}p \to J/\Psi \to \ell^+\ell^- X$

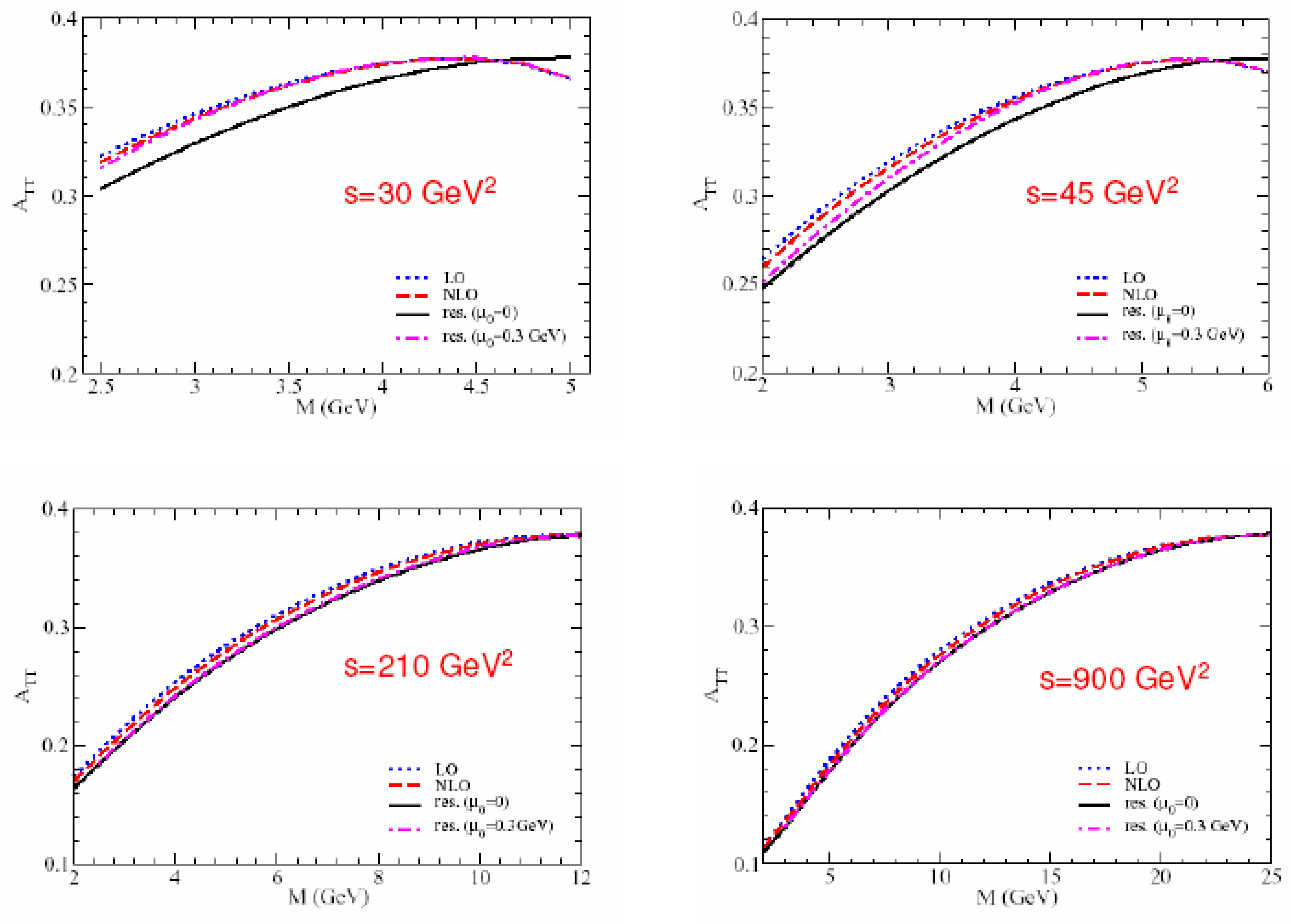
QCD higher order contributions might be sizeable at smaller M but cross-sections only are affected, NOT A_{TT}: K-factors are almost spin indipendent[1]



[1] Shimizu et al., hep-ph/0503270 .

Drell-Yan Di-Lepton Production $\bar{p}p \to J/\Psi \to \ell^+\ell^- X$

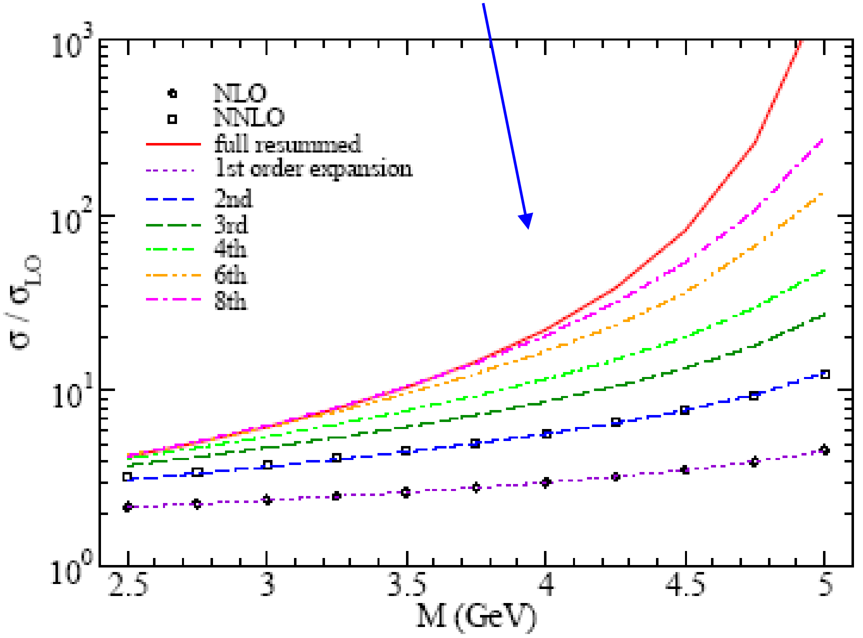
Moreover QCD contributions to A_{TT}: drop increasing energy[1]



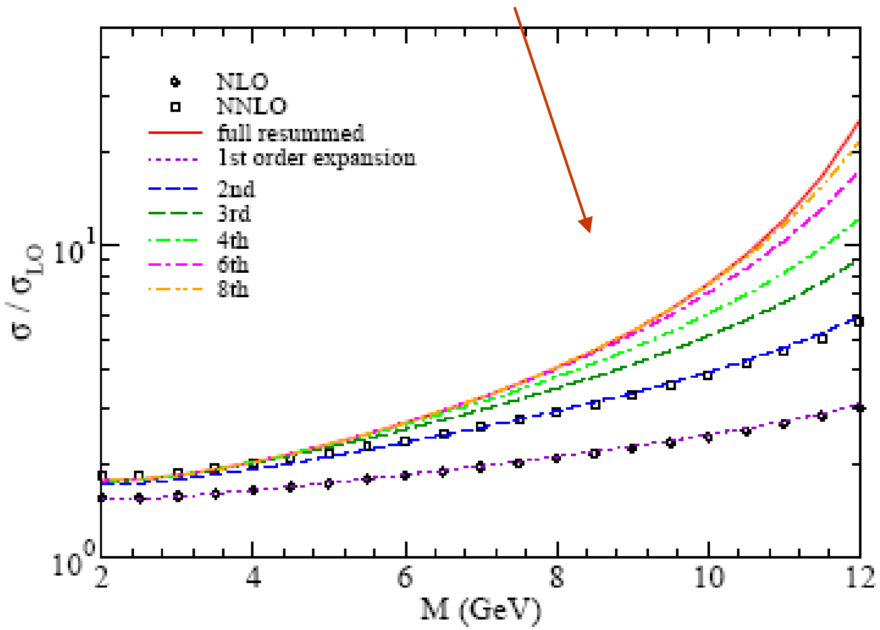
[1] Shimizu et al., hep-ph/0503270 .

Drell-Yan Asymmetries — $\bar{p}p \to \ell^+\ell^- X$

$s = 30\,\mathrm{GeV}^2$



$s = 200\,\mathrm{GeV}^2$

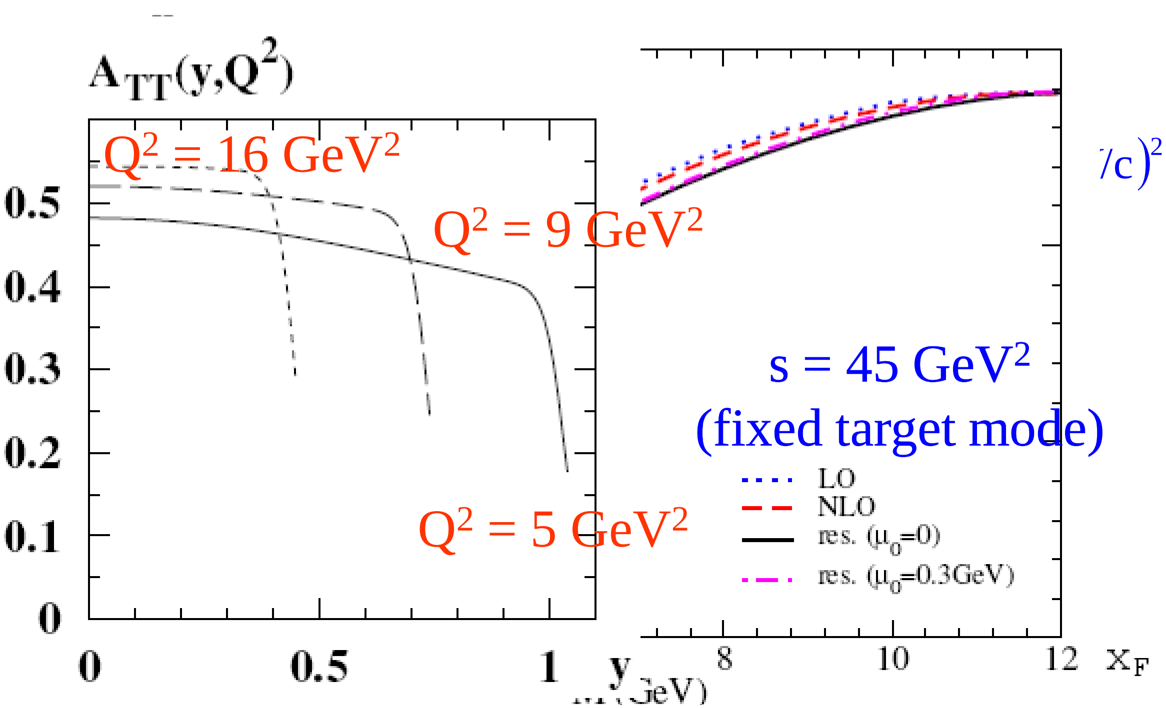


At higher energy (s ~ 200 GeV^2)
perturbative corrections[1] are sensibly smaller
in the safe region even for cross-sections

[1]H. Shimizu et al., Phys. Rev. D71 (2005) 114007

Double Spin Asymmetries — $\bar{p}^{\uparrow} p^{\uparrow} \to \ell^{+}\ell^{-}X$

$$\bar{h}_1^{\bar{a}}(x_1) h_1^{a}(x_2) \Rightarrow A_{TT} = \frac{\sigma\left(\bar{p}^{\uparrow} p^{\uparrow} \to \ell\bar{\ell}X\right) - \sigma\left(\bar{p}^{\uparrow} p^{\downarrow} \to \ell\bar{\ell}X\right)}{\sigma\left(\bar{p}^{\uparrow} p^{\uparrow} \to \ell\bar{\ell}X\right) + \sigma\left(\bar{p}^{\uparrow} p^{\downarrow} \to \ell\bar{\ell}X\right)} \propto \sum_a e_a^2 h_1^a(x_1) h_1^a(x_2)$$



HESR: $s_{max} = 30 \div 45\ GeV^2$

$M^2 \geq M^2_{J/\Psi} \longrightarrow \tau \geq 0.3$

A_{TT} direct access to valence quark h_1

$s = 45\ GeV^2$ (fixed target mode)

$$A_{TT} \propto \sum_q h_{1q}(x_1) \otimes h_{1\bar{q}}(x_2)$$

[3] Efremov et al, Eur. Phys. J. C 35 (2004) 207. .

Drell-Yan Asymmetries — $\bar{p}p \rightarrow \mu^+\mu^- X$

Di-Lepton Rest Frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\varphi+\frac{\nu}{2}\sin^2\theta\cos 2\varphi\right)$$

NLO pQCD: $\lambda \sim 1$, $\mu \sim 0$, $\upsilon \sim 0$

Lam-Tung sum rule: $1-\lambda = 2\nu$

- reflects the spin-½ nature of the quarks
- insensitive top QCD-corrections

Experimental data [1]: $\upsilon \sim 30\,\%$

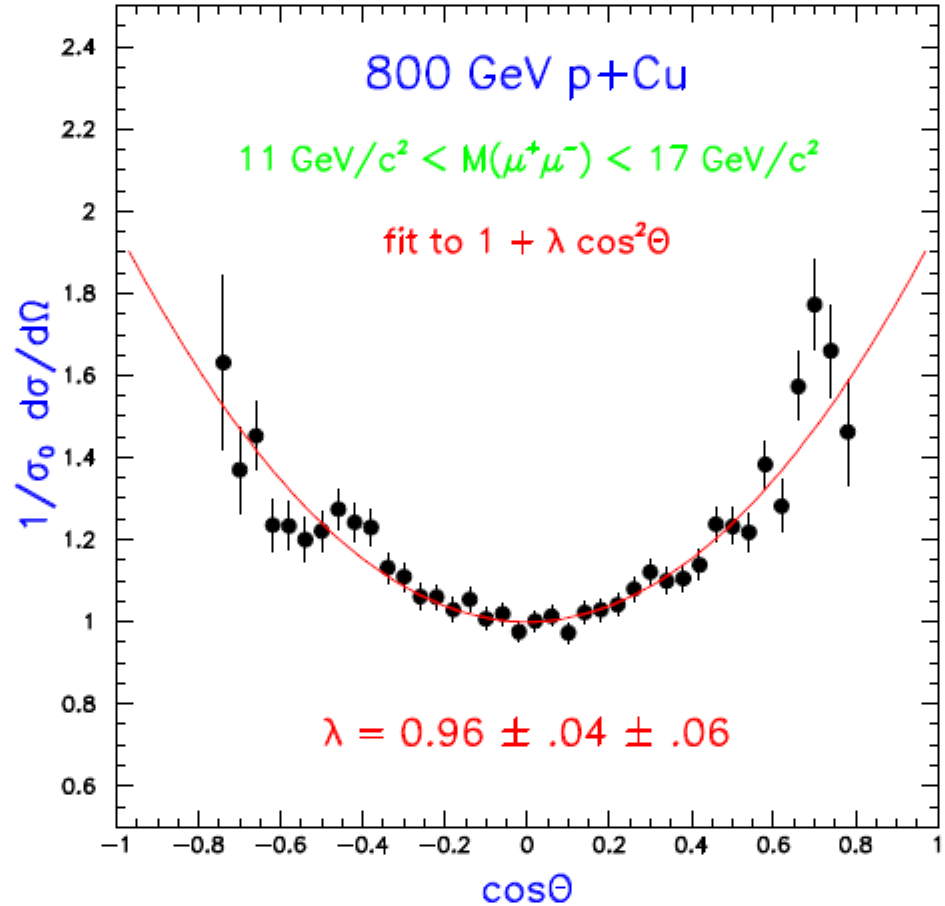
[1] J.S.Conway et al., Phys. Rev. D39 (1989) 92.

Expected polar distribution for DY dilepton production

λ, μ, ν measured[1] in p N→$\mu^+\mu^-$ X

E772 @ Fermilab

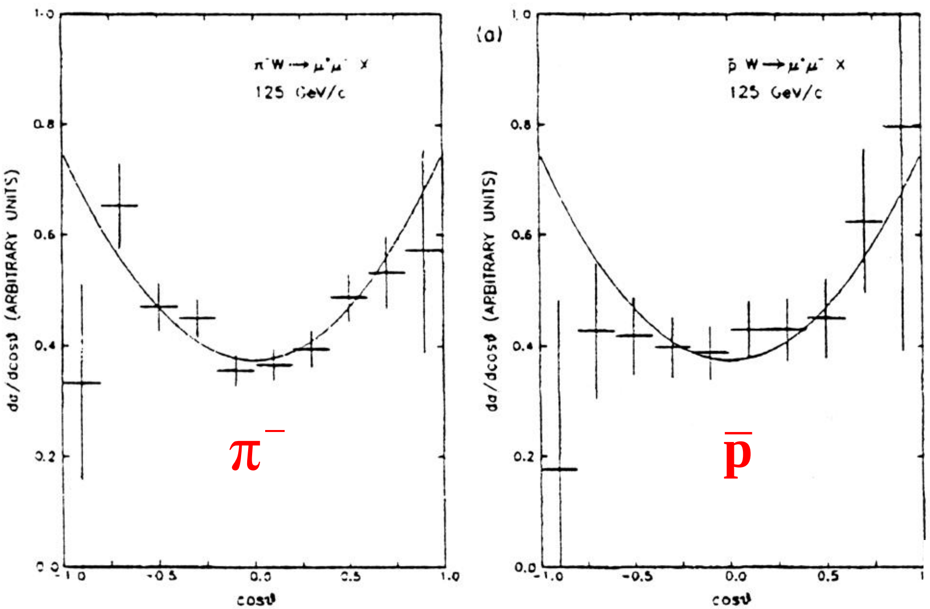
$$\frac{d\sigma}{d\Omega} = \sigma_0 (1+\cos^2\theta)$$



Perfect agreement with pQCD exptectations!

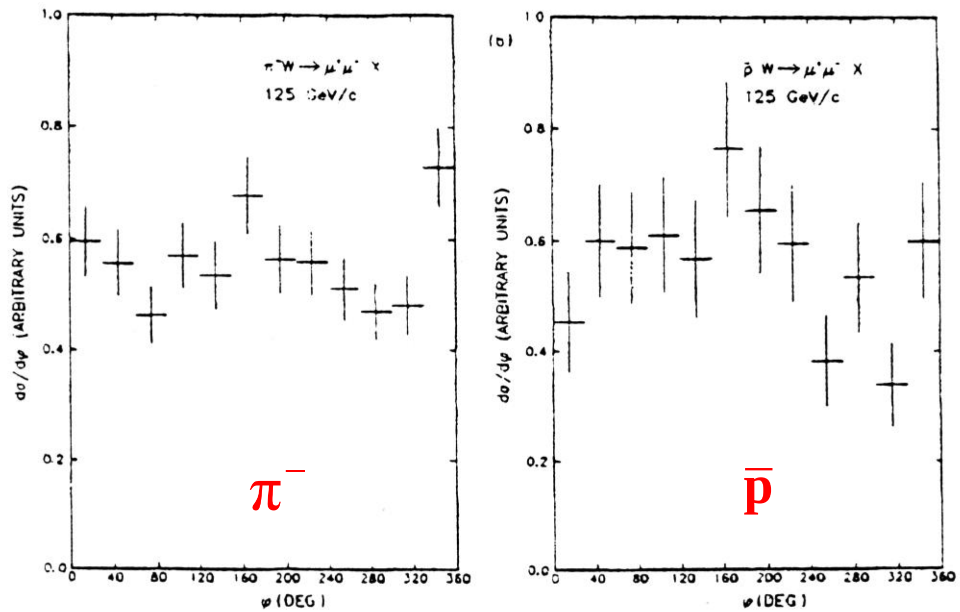
[1] McGaughey, Moss, JCP, Annu. Rev. Nucl. Part. Sci. 49 (1999) 217.

Angular distributions for $\bar{p}$ and π^- — π-N, $\bar{p}$N @ 125 GeV/c



- $\dfrac{d\sigma}{d\cos\vartheta}$ vs $\cos\vartheta$

- $\dfrac{d\sigma}{d\cos\varphi}$ vs $\cos\varphi$



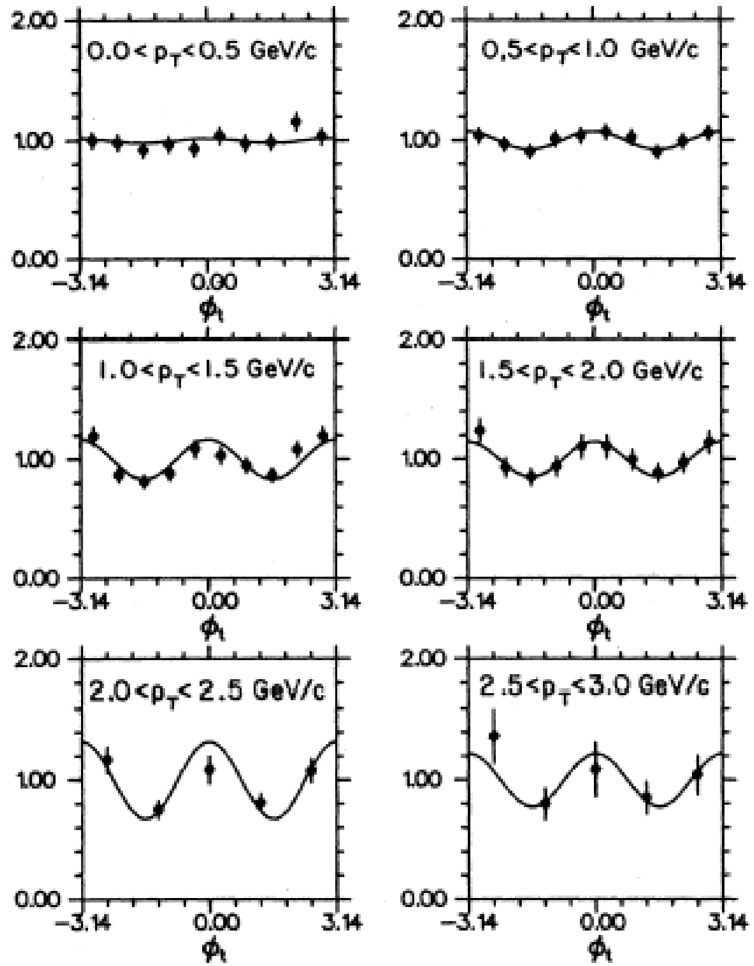
E537 @ Fermilab

Anassontzis et al., Phys. Rev. D38 (1988) 1377

Angular distribution in CS frame

E615 @ Fermilab

π-N $\rightarrow$ $\mu^+\mu^-$X @ 252 GeV/c



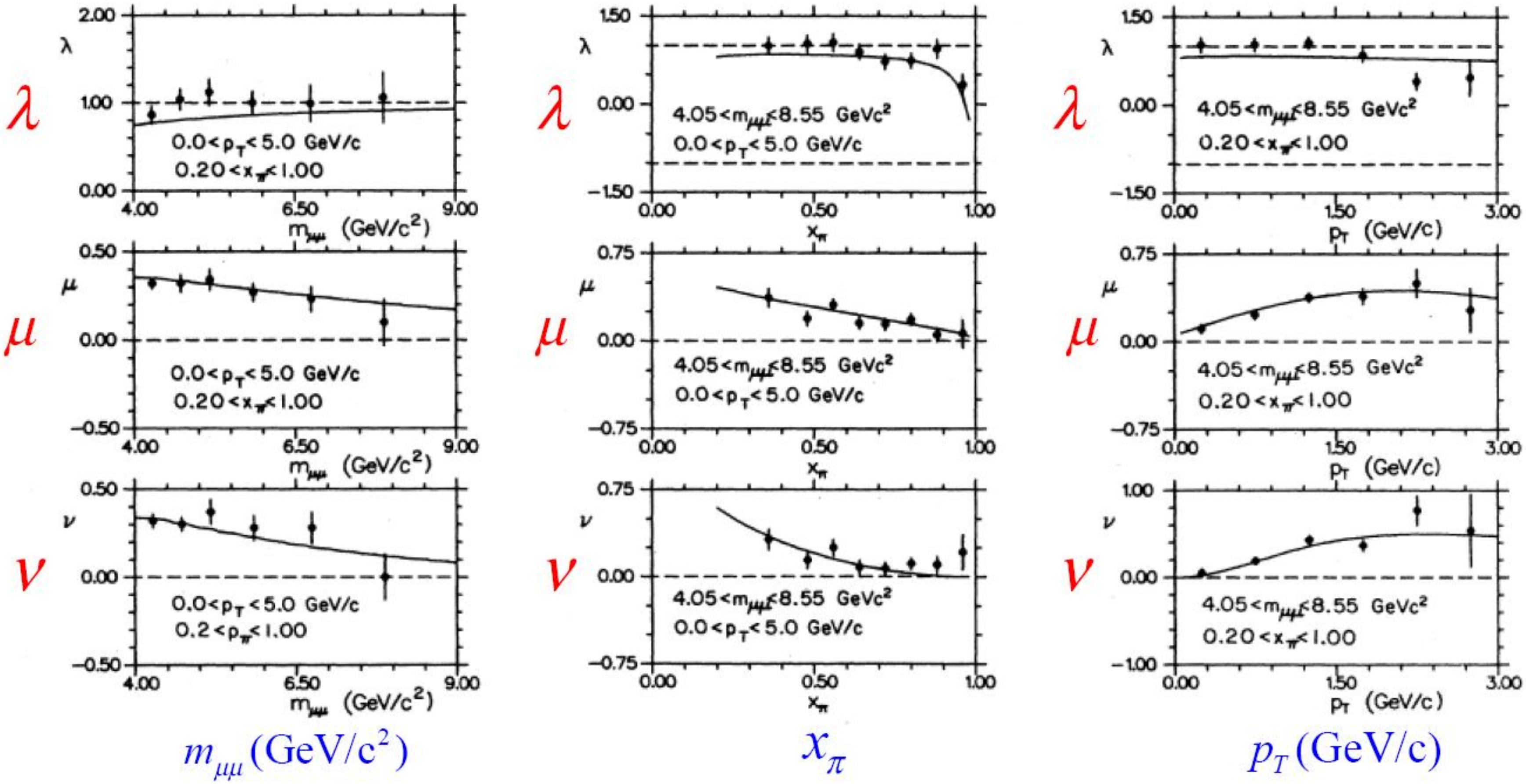
$-0.6 < \cos\vartheta < 0.6$

$4 < M < 8.5$ GeV/c^2

Conway et al, Phys. Rev. D39 (1989) 92

Angular distribution in CS frame

E615 @ Fermilab π-N → $\mu^+\mu^-$X @ 252 GeV/c

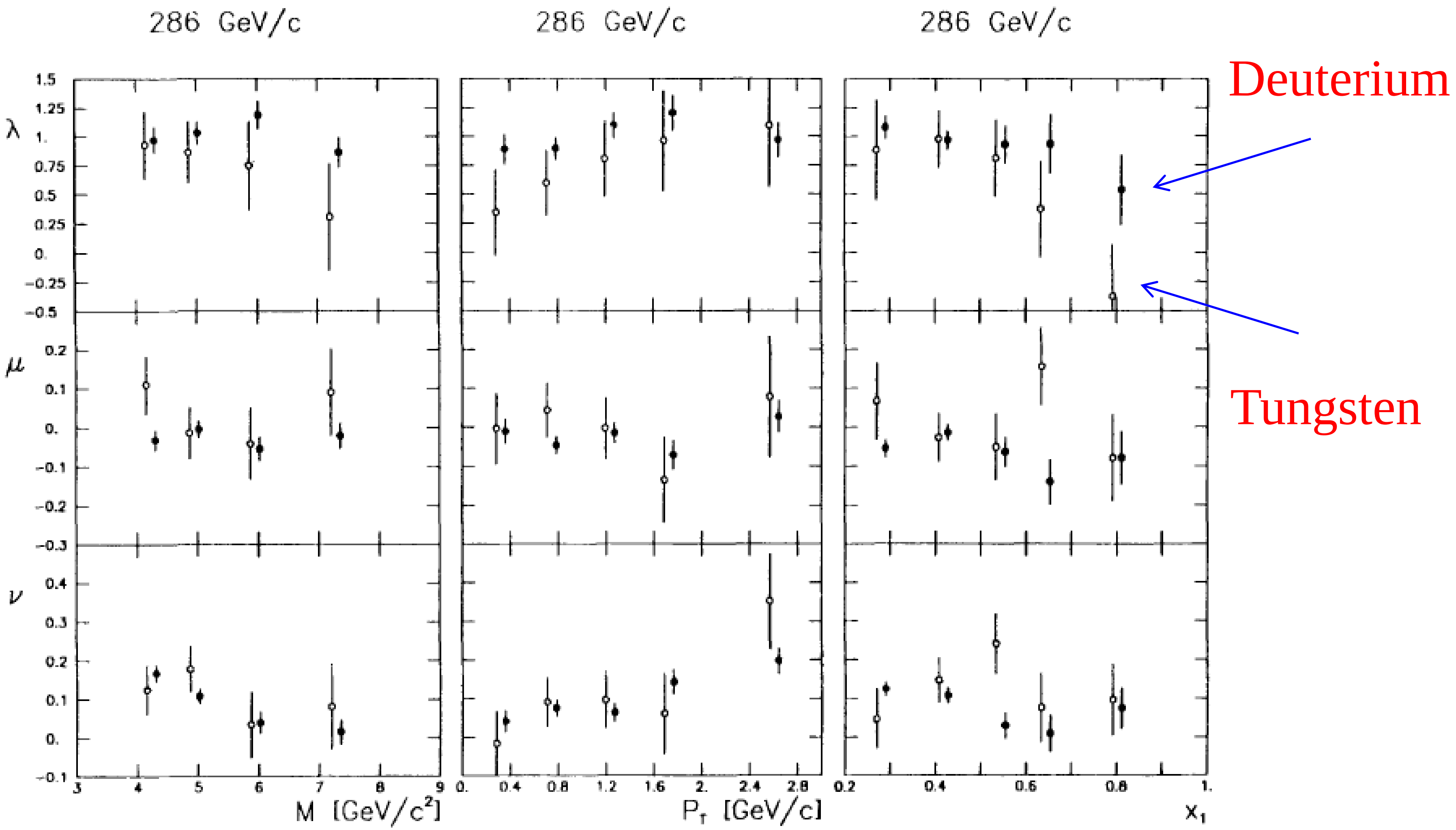


30% asymmetry observed for π^-

Conway et al, Phys. Rev. D39 (1989) 92

Does it come from a nuclear effect?

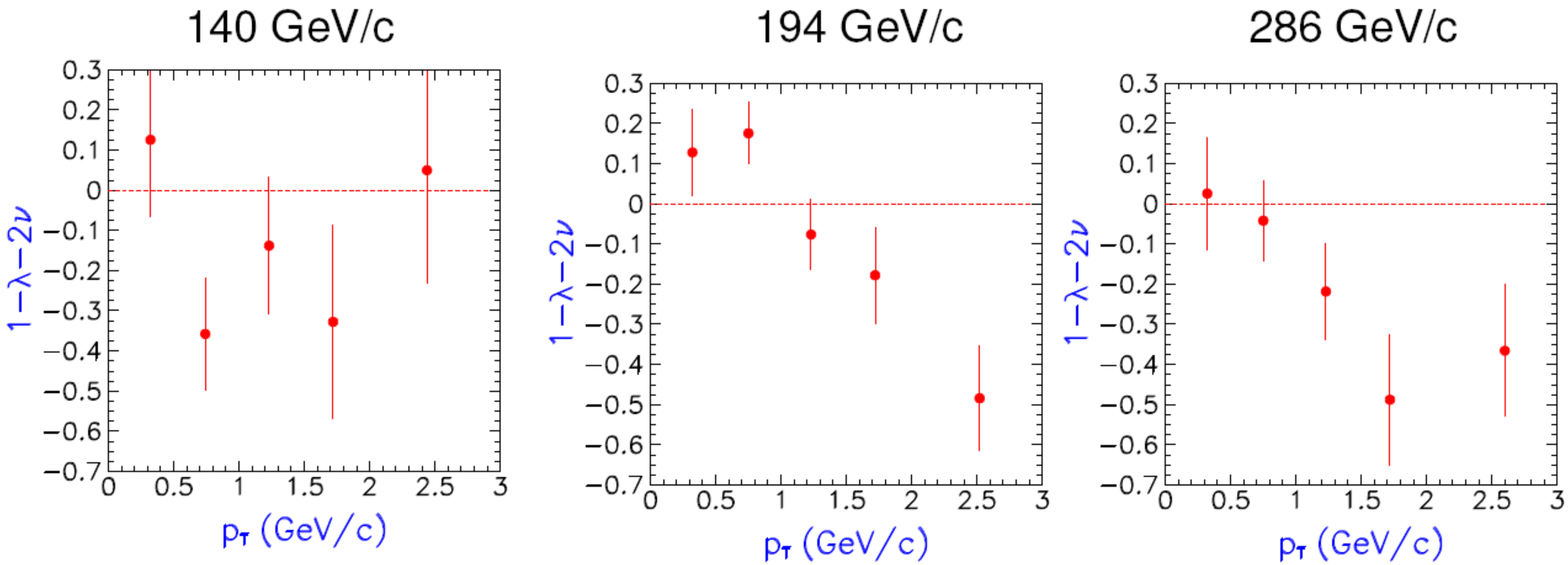
NA10 @ CERN π-N $\rightarrow \mu^+\mu^- X$ @ 286 GeV/c



NA10 coll., Z. Phys. C37 (1988) 545

Remarkable and unexpected violation of Lam-Tung rule

λ, μ, ν measured in $\pi\, N \rightarrow \mu^+ \mu^- X$ NA10 @ CERN



υ involves transverse spin effects at leading twist [2]

If unpolarised DY σ is kept differential on k_T ,

cos2φ contribution to angular distribution provide:

$$h_1^{\perp}(x_{2},\kappa_{\perp}^2) \times \bar{h}_1^{\perp}(x_1,\kappa'^2_{\perp})$$

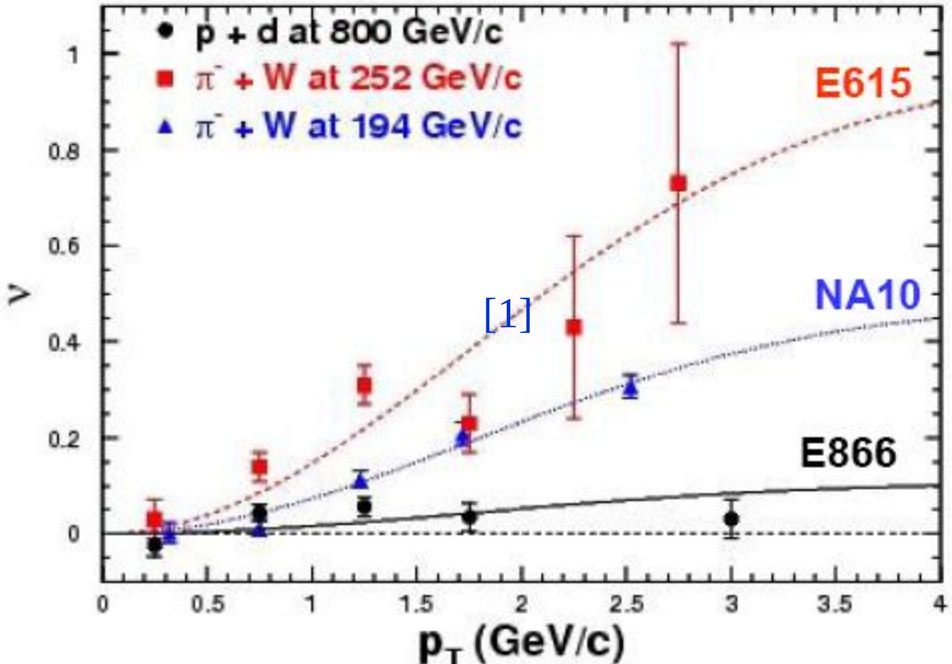
[2] D. Boer et al., Phys. Rev. D60 (1999) 014012.

[1] NA10 coll., Z. Phys. C37 (1988) 545

Drell-Yan Asymmetries — $\bar{p}p \rightarrow \mu^+\mu^- X$

Boer-Mulders

T-odd Chiral-odd TMD



- $\nu > 0 \rightarrow$ valence $h_1^{\perp}$ has same sign in π and N
- $\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim h_1^{\perp}(\pi)_{valence}$ x $h_1^{\perp}(p)_{valence}$
- $\nu(pd \rightarrow \mu^+\mu^- X) \sim h_1^{\perp}(p)_{valence}$ x $h_1^{\perp}(p)_{sea}$
- $\nu > 0 \rightarrow$ valence and sea $h_1^{\perp}$ has same sign, but sea $h_1^{\perp}$ should be significantly smaller

[1] L. Zhu et al, PRL 99 (2007) 082301; [12 D. Boer, Phys. Rew. D60 (1999) 014012.

Drell-Yan Asymmetries — $\bar{p}p^{\uparrow} \to \mu^+\mu^- X$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1+\cos^2\theta+\frac{\nu}{2}\sin^2\theta\cos 2\varphi+\rho\left|S_{1T}\right|\sin^2\theta\sin(\varphi-\varphi_{S_1})+\cdots\right)$$

$\lambda \sim 1,\ \mu \sim 0$

$$A_T = \left|S_{1T}\right| \frac{2\sin 2\theta \sin(\varphi-\varphi_{S_1})}{1+\cos^2\theta} \frac{M}{\sqrt{Q^2}} \frac{\sum_a e_a^2 \left[x_1 f_1^{a\perp}(x_1) f_1^{\bar{a}}(x_2) + x_2 h_1^a(x_1) h_1^{\bar{a}\perp}(x_2)\right]}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

Even unpolarised $\bar{p}$ beam on polarised p,
or polarised $\bar{p}$ on unpolarised p
are powerful tools
to investigate κ_T dependence of QDF

D. Boer et al., Phys. Rev. D60 (1999) 014012.

Transverse Single Spin Asymmetries: correlation functions

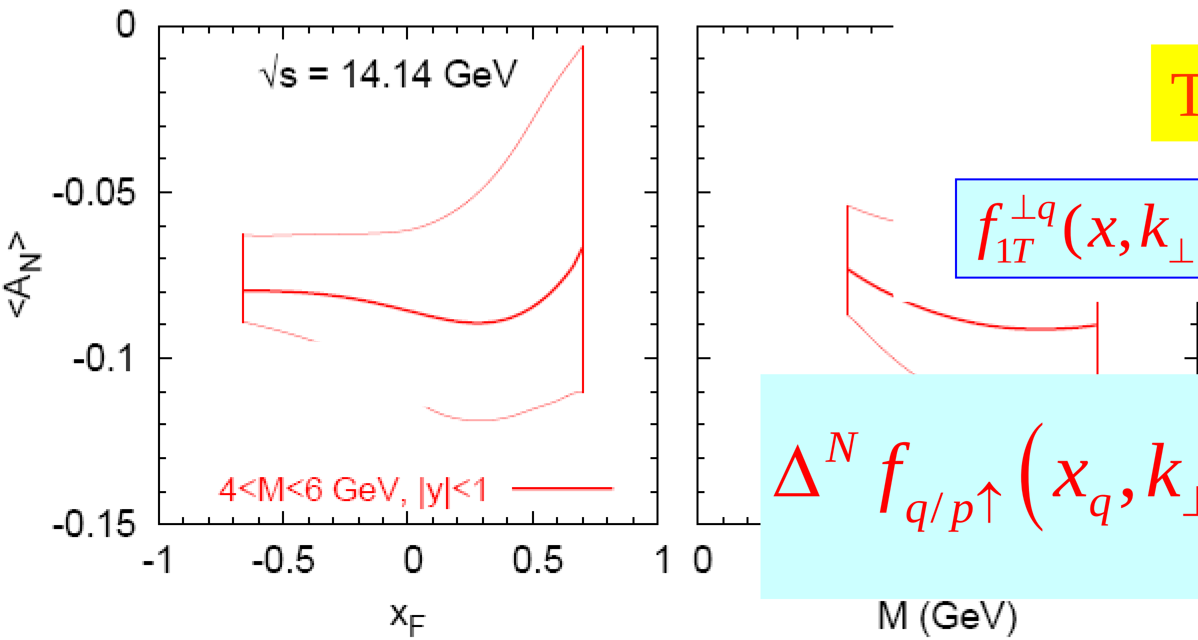
All these effects may may lead to Single Spin Asymmetries (SSA):

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

Transverse Single Spin Asymmetries in Drell-Yan

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

expected[1] to be small but not negligible for HESR layout on fixed target



Test of Universality

$$f_{1T}^{\perp q}(x,k_{\perp})_{SIDIS} = -f_{1T}^{\perp q}(x,k_{\perp})_{DY}$$ [2]

$$\Delta^N f_{q/p\uparrow}\left(x_q, k_{\perp q}\right) = -\frac{2k_{\perp}}{m_p} f_{1T}^{\perp q}\left(x, k_{\perp}\right)$$

Originates from the Sivers function[1]:

$$A_N = \frac{\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp \bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - q_T\right) \Delta^N f_{q/p\uparrow}\left(x_q, \mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}}\right)}{2\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp \bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - q_T\right) f_{q/p}\left(x_q, \mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}}\right)}$$

[1] Anselmino et al., Phys. Rev. D72, 094007 (2005).
[2] J.C. Collins, Phys. Lett. B536 (2002) 43

Experimental Asymmetries @ PANDA — $\bar{p}\, p^{(\uparrow)} \to \mu^+\mu^- X$

Unpolarised:

$A^{\cos 2\phi}$

$$\frac{d\sigma^0}{d\Omega dx_1 dx_2 d\boldsymbol{k}_T} = \frac{\alpha^2}{12Q^2}\sum_a e_a^2 \left\{ \left(1+\cos^2\theta\right)\mathcal{F}\left[\bar{f}_1^a f_1^a\right] + \sin^2\theta\cos 2\phi\,\mathcal{F}\left[\left(2\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\,\boldsymbol{h}\cdot\boldsymbol{p}_{2T} - \boldsymbol{p}_{1T}\cdot\boldsymbol{p}_{2T}\right)\frac{\bar{h}_1^{\perp a} h_1^{\perp a}}{M_1 M_2}\right]\right\}$$

$$\mathcal{F}\left[\bar{f}_1^a f_1^a\right] \equiv \int d\boldsymbol{p}_{1T} d\boldsymbol{p}_{2T}\,\delta\left(\boldsymbol{p}_{1T}+\boldsymbol{p}_{2T}-\boldsymbol{k}_T\right)\left[\bar{f}_1^a\left(x_1,\boldsymbol{p}_{1T}\right) f_1^a\left(x_2,\boldsymbol{p}_{2T}\right) + \left(1\leftrightarrow 2\right)\right]$$

Single Spin:

$A^{\sin(\phi-\phi_{S_2})}$

$$\frac{d\Delta\sigma^{\uparrow}}{d\Omega dx_1 dx_2 d\boldsymbol{k}_T} = \frac{\alpha^2}{12sQ^2}\sum_a e_a^2 \left|\boldsymbol{S}_{2T}\right| \left\{ \left(1+\cos^2\theta\right)\sin\left(\phi-\phi_{S_2}\right)\mathcal{F}\left[\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\frac{\bar{f}_1^a f_{1T}^{\perp a}}{M_2}\right] + \right.$$

$$-\sin^2\theta\sin\left(\phi+\phi_{S_2}\right)\mathcal{F}\left[\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\frac{\bar{h}_1^{\perp a} h_{1T}^a}{M_1}\right]$$

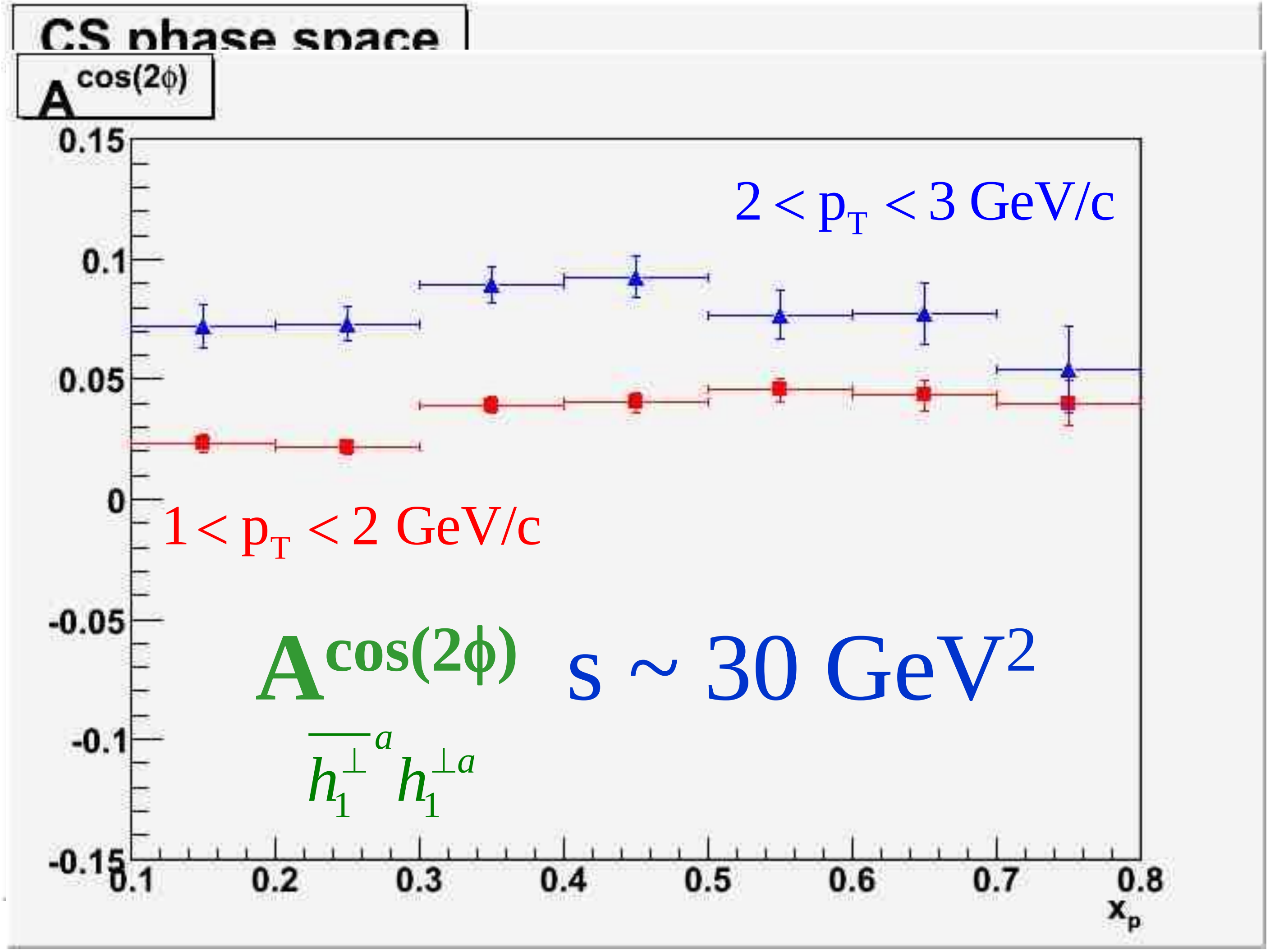
$A^{\sin(\phi+\phi_{S_2})}$

$$\left. -\sin^2\theta\sin\left(3\phi-\phi_{S_2}\right)\mathcal{F}\left[\left(4\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\left(\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\right)^2 - 2\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\,\boldsymbol{p}_{1T}\cdot\boldsymbol{p}_{2T} - \boldsymbol{h}\cdot\boldsymbol{p}_{1T}\,\boldsymbol{p}_{2T}^2\right)\frac{\bar{h}_1^{\perp a} h_{1T}^{\perp a}}{2M_1 M_2^2}\right]\right\}$$

Unpolarised DY Asymmetries @ PANDA — $\bar{p}\,p \to \mu^+\mu^- X$

480K ev ... .5 GeV/c^2

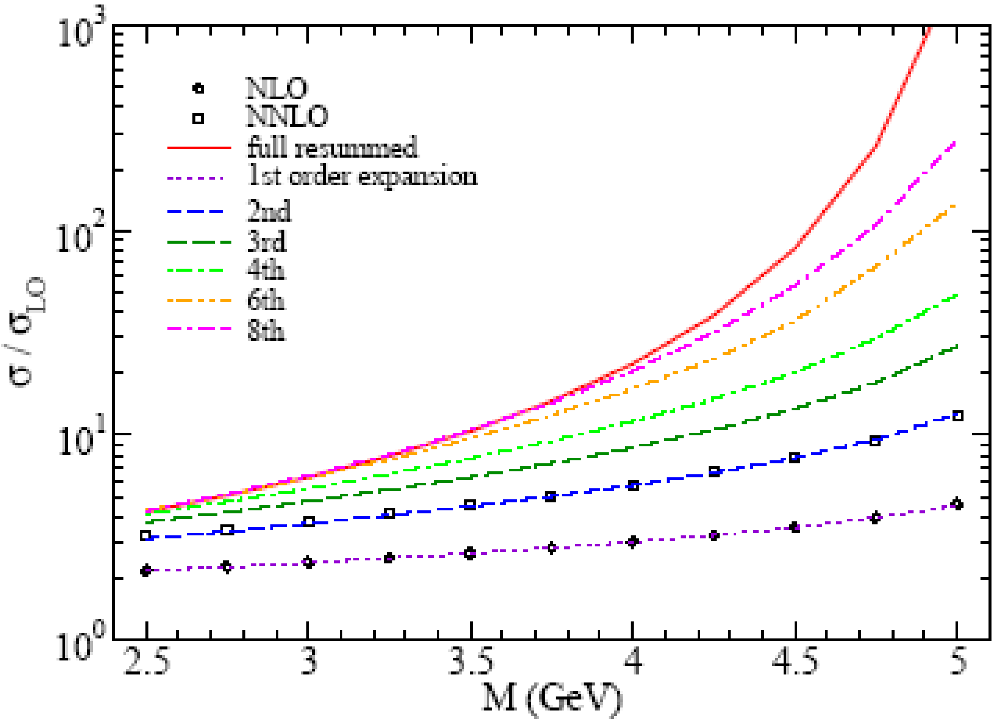
R_D ... s^{-1}



[1]A. Bianconi and M. Radici, Phys. Rev. D71 (2005) 074014

[2]Physics Performance Report for PANDA, arXiv: 0903.3905

Unpolarised Drell-Yan — $\bar{p}p \rightarrow \mu^+\mu^-X$



$s = 30\,GeV^2$

Perturbative corrections[1] are expected to be large in the PANDA energy range

Unpolarised DY cross-section allow the investigation of:

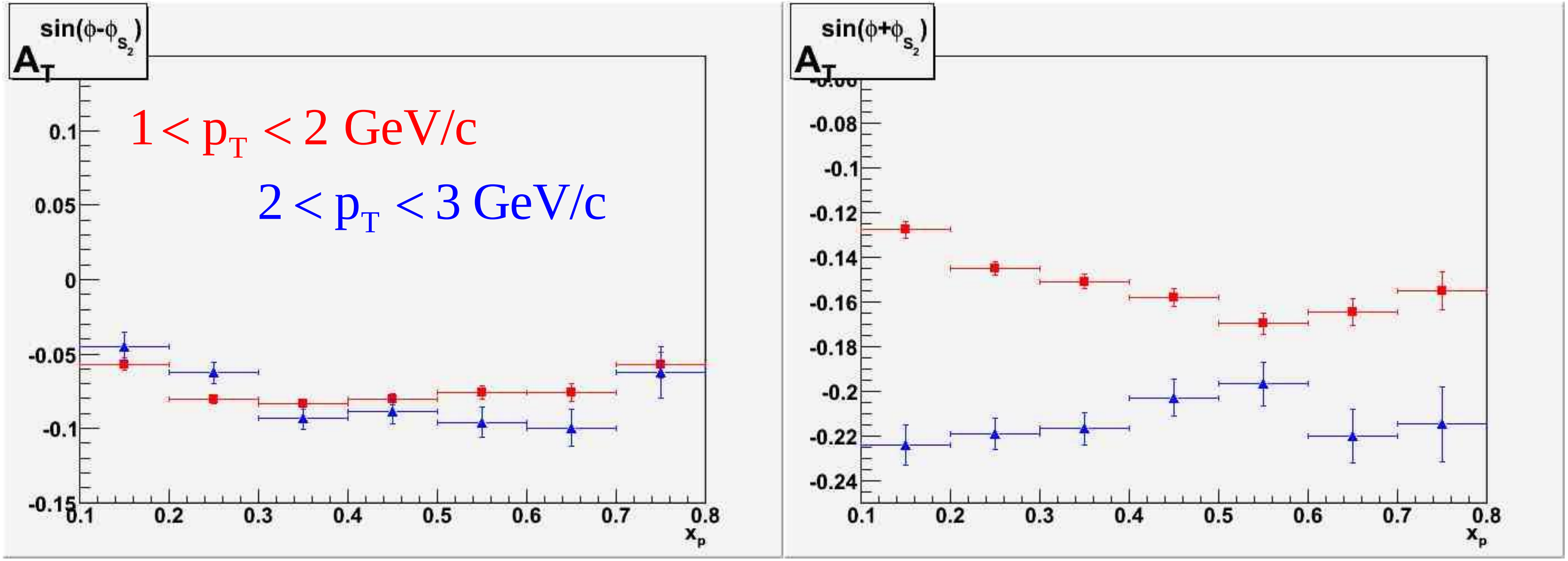
- limits of the factorisation and perturbative approach
- relation of perturbative and not perturbative dynamics in hadron scattering

[1]H. Shimizu et al., Phys. Rev. D71 (2005) 114007

DY Single Spin Asymmetries @ PANDA — $\bar{p}\,p^{\uparrow} \to \mu^+\mu^- X$

$$480\text{K ev}^{[1]} \text{ with } E_{\bar{p}} = 15 \text{ GeV on fixed target}, \quad 1.5 < M_{\mu\mu} < 2.5 \text{ GeV/c}^2$$

$$R_{DY\text{-}\mu\mu}{}^{[2]} \left(1.5 < M_{\mu\mu} < 2.5 \text{ GeV/c}^2\right) = 2\cdot 10^{32}\text{cm}^{-1}\text{s}^{-1} \times 0.8\cdot 10^{-33}\text{cm}^{-2} = 0.16\text{s}^{-1}$$



$A^{\sin(\phi - \phi_{S_2})}$ $\qquad$ $A^{\sin(\phi + \phi_{S_2})}$

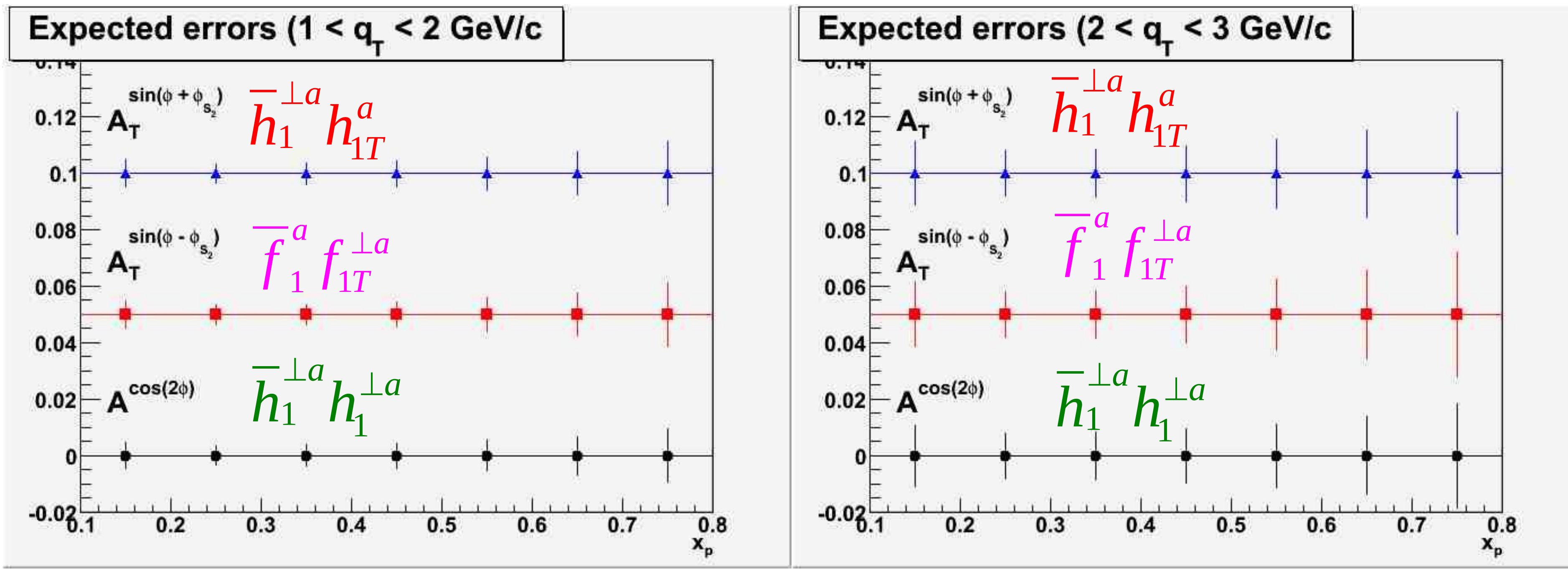
$\bar{f}_1^{\,a} f_{1T}^{\perp a}$ $\qquad$ $s \sim 30$ GeV^2 $\qquad$ $\bar{h}_1^{\perp a} h_{1T}^{a}$

[1]A. Bianconi and M. Radici, Phys. Rev. D71 (2005) 074014
[2]Physics Performance Report for PANDA, arXiv: 0903.3905

Experimental Asymmetries @ PANDA — $\bar{p}\, p^{(\uparrow)} \to \mu^+ \mu^- X$

480K ev[1] with $E_{\bar{p}} = 15$ GeV on fixed target, $1.5 < M_{\mu\mu} < 2.5$ GeV/c^2

Eff $R_{DY\text{-}\mu\mu}$[2] $\left(1.5 < M_{\mu\mu} < 2.5 \text{ GeV/c}^2\right) = 0.16\ \text{s}^{-1} \times \frac{1}{2} = 0.08\ \text{s}^{-1}$ □ 200K Ev month^{-1}



$s \sim 30$ GeV^2

[1]A. Bianconi and M. Radici, Phys. Rev. D71 (2005) 074014
[2]Physics Performance Report for PANDA, arXiv: 0903.3905

The transverse spin physics program @ FAIR

Drell-Yan dilepton production

- double spin DY is the dream option: can antiproton be polarised?
- new physics from unpolarised DY since the very beginning
- extense SSA program in DY and in hadron production

Collaborations: PANDA & PAX

THANK YOU!

QUESTION TIME

Collinear kinematics: κ_T-independent Parton Distributions

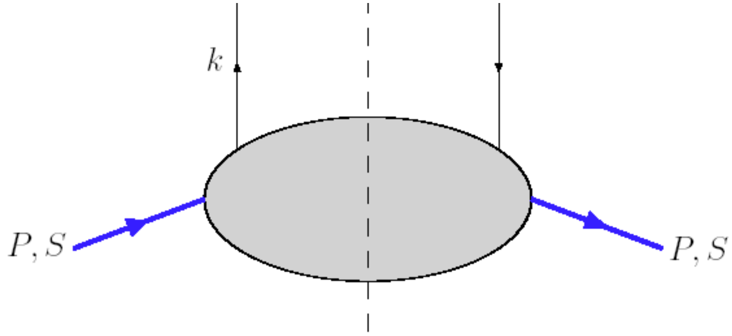
Partonic distributions $q = q_+^+ + q_-^+ \quad g = g_+^+ + g_-^+$

helicity distributions $\Delta q = q_+^+ - q_-^+ \quad \Delta g = g_+^+ - g_-^+$

Unpolarized $q(x,Q^2)$,$g(x,Q^2)$ and long. polarized $\Delta q(x,Q^2)$: well known

Gluon $\Delta g(x,Q^2)$: under investigation

CORRELATOR:



$$\Phi(x,k) = \frac{1}{2}\left[f_1 \not{n}_+ + g_{1L}\gamma^5 \not{n}_+ P_L + h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^{\mu} P_T^{\nu} \right]$$

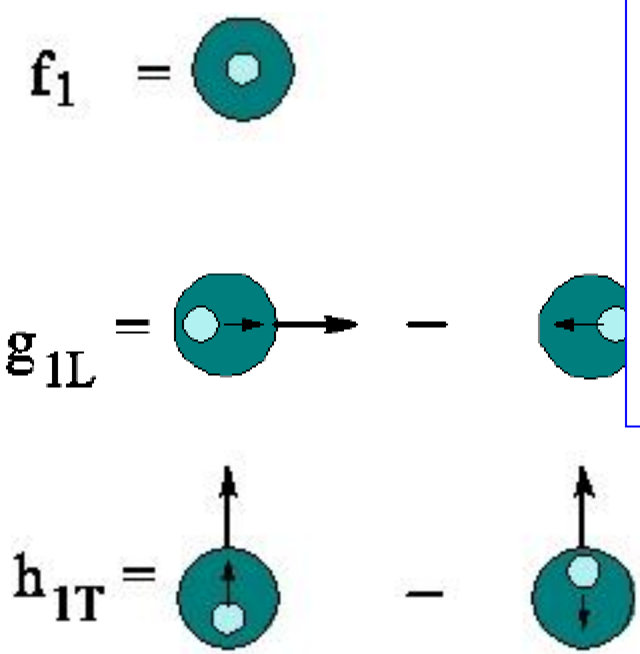
q $\quad$ Δq $\quad$ Δ_Tq

Collinear kinematics: κ$_T$ in

Twist-2 PDFs $f_1^u(x) \equiv u(x$

R.L.Jaffe and
J. L. Cortes, B

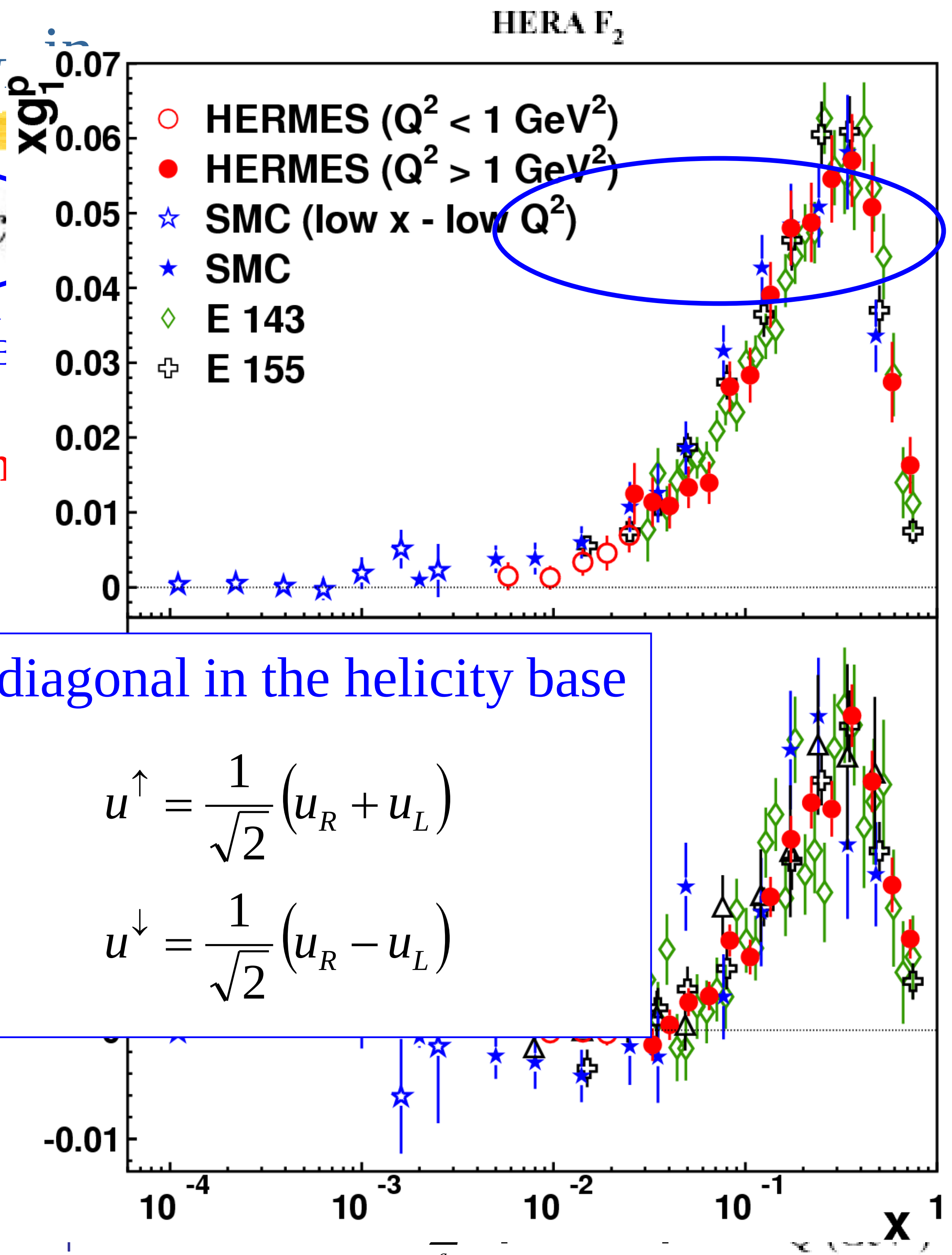
Helicity base: probabilistic in



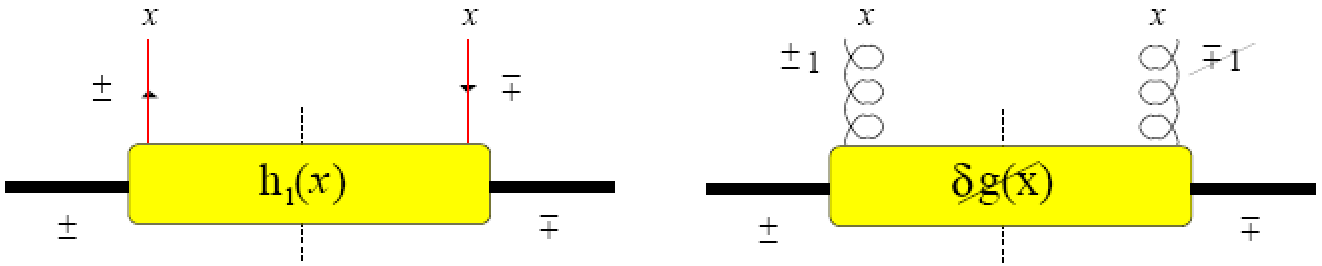
off diagonal in the helicity base

$$u^{\uparrow} = \frac{1}{\sqrt{2}}\left(u_R + u_L\right)$$

$$u^{\downarrow} = \frac{1}{\sqrt{2}}\left(u_R - u_L\right)$$



Transversity $h_1(x)$



$\delta q(x)$: a chirally-odd, helicity flip distribution function

$\delta g(x)$: there's no gluon transversity distribution; transversely polarised nucleon shows transverse gluon effects at twist-3 (g_2) only

SOFFER INEQUALITY

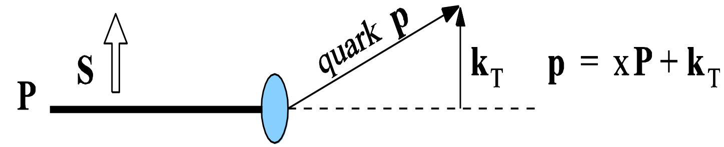
An upper limit: $$|h_1(x)| \leq \frac{1}{2}|f_1(x) + g_1(x)|$$

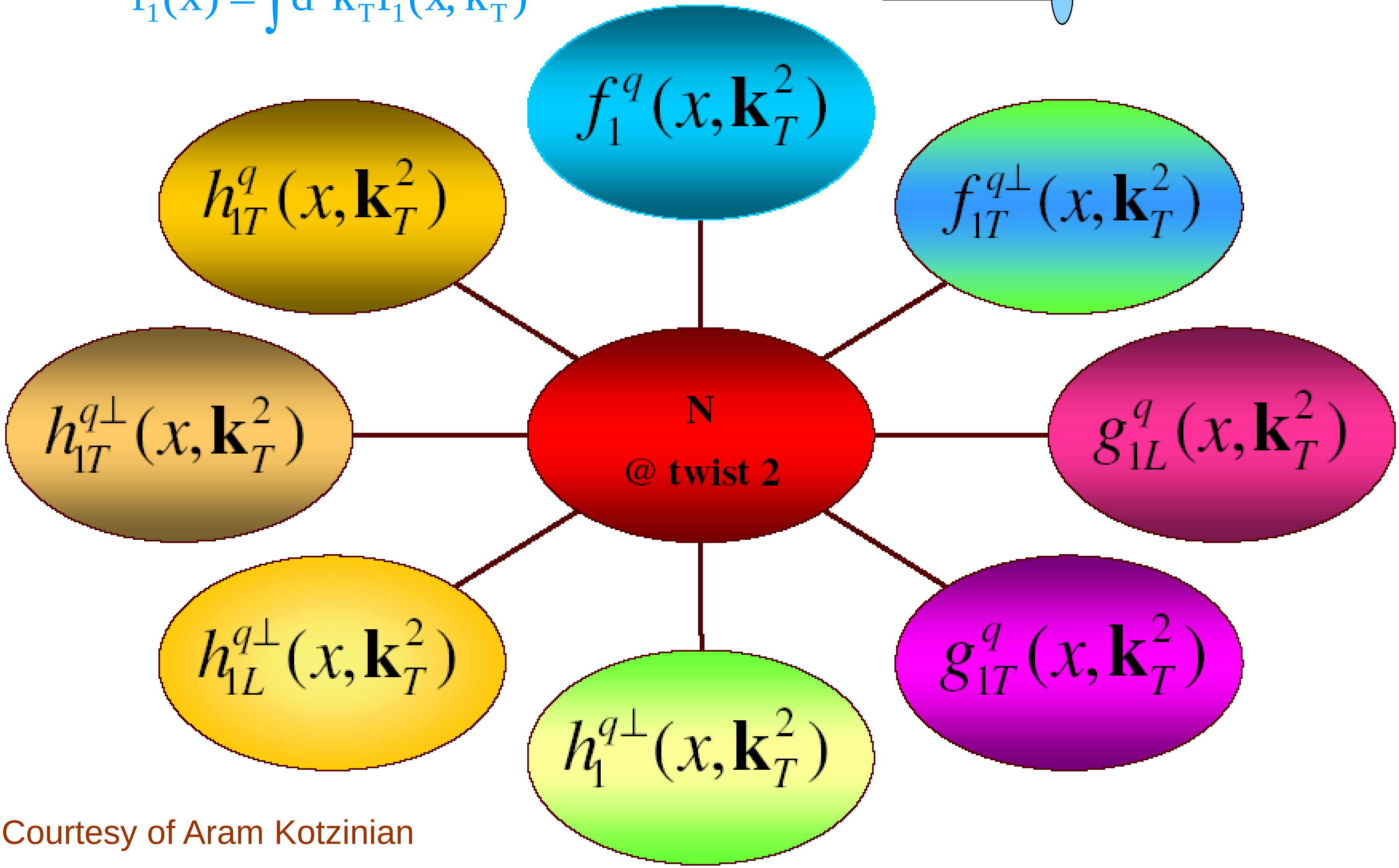
- can be violated by factorisation at NLO
- inequality preserved under evolution to larger scales only

TMD: κ_T-dependent Parton Distributions

Twist-2 PDFs:

$$f_1(x) = \int d^2k_T f_1(x, k_T)$$

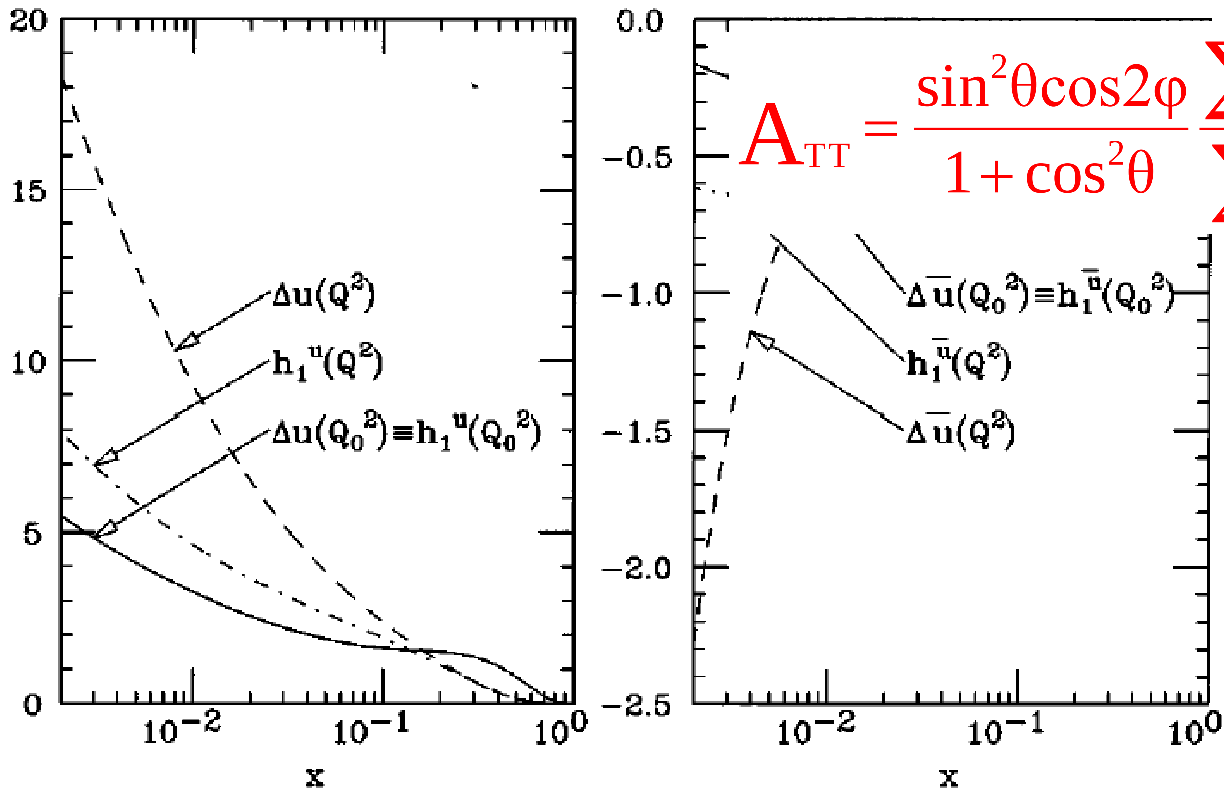




Courtesy of Aram Kotzinian

Drell-Yan Asymmetries — $p^{\uparrow}p^{\uparrow} \rightarrow \mu^{+}\mu^{-}X$

PROBLEMATIC MEASUREMENT



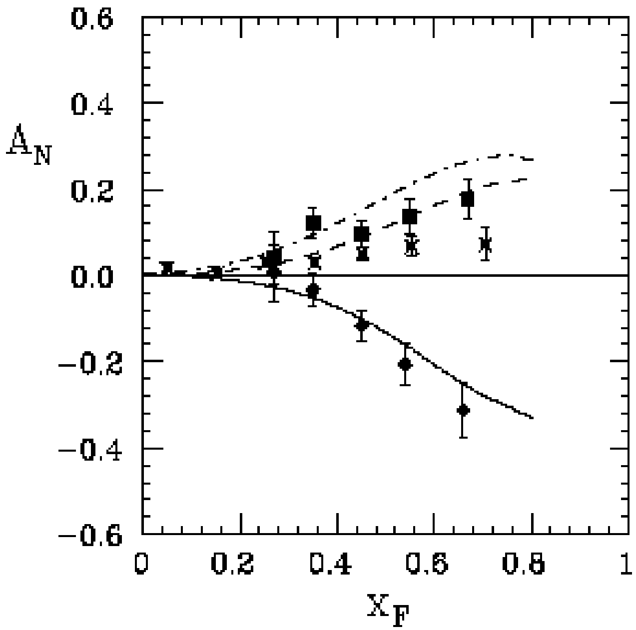
$$A_{TT} = \frac{\sin^2\theta\cos 2\varphi}{1+\cos^2\theta} \frac{\sum_a e_a^2 h_1^a(x_1) h_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

$$Q_0^2 = 0.23\,\text{GeV}^2$$

$$Q^2 = 25\,\text{GeV}^2$$

[1] Martin et al, Phys.Rev. D60 (1999) 117502.
[2] Barone, Colarco and Drago, Phys.Rev. D56 (1997) 527.

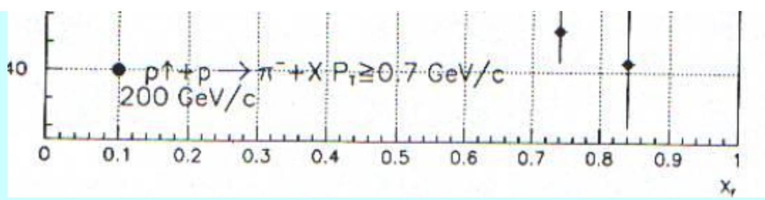
Transverse Single Spin Asymmetries in Drell-Yan



E704 $\sqrt{s} = 20$ GeV
$0.7 < p_T < 2.0$

$\bar{p}^{\uparrow} p \to \pi X$

region:



- new data available
- $A_{N,\bar{p}p^{\uparrow}\to\pi X}$ vs $A_{N,\bar{p}^{\uparrow}p\to\pi X}$
- DY-SSA (A_T) possible only @ RHIC, $p^{\uparrow}p$-scattering:

$\sigma^{DY}_{\bar{p}p}$ @ smaller s >> σ^{DY}_{pp} @ large s

Hyperon production Spin Asymmetries

Λ production in unpolarised pp-collision:

Several theoretical models:

• Static SU(6) + spin dependence in parton fragmentation/recombination [1-3]

• pQCD spin and transverse momentum of hadrons in fragmentation [4]

[1] T.A.DeGrand et al.,Phys. Rev. D23 (1981) 1227.

[2] B. Andersoon et al., Phys. Lett. B85 (1979) 417.

[3] W.G.D.Dharmaratna, Phys. Rev. D41 (1990) 1731.

[4] M. Anselmino et al.,Phys. Rev. D63 (2001) 054029.

Analysing power

$$A_N = \frac{1}{P_B \cos\theta} \frac{N_\uparrow(\varphi) - N_\downarrow(\varphi)}{N_\uparrow(\varphi) + N_\downarrow(\varphi)}$$

Depolarisation

$$D_{NN} = \frac{1}{2P_B \cos\varphi}\left[P_{\Lambda\uparrow}\left(1 + P_B A_N \cos\varphi\right) - P_{\Lambda\downarrow}\left(1 - P_B A_N \cos\varphi\right)\right]$$

Key to distinguish between these models

Data available for D_{NN}:

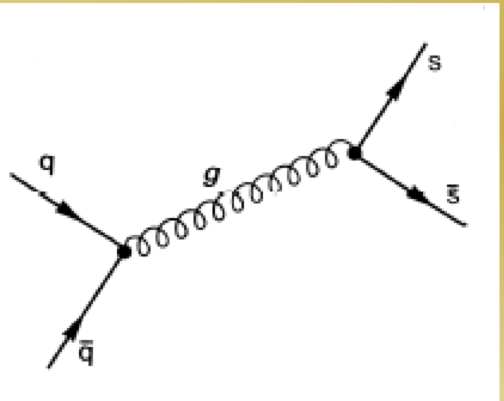
3.67 GeV/c	$D_{NN} < 0$
13.3 -18.5 GeV/c	$D_{NN} \sim 0$
200 GeV/c	$D_{NN} > 0$

D_{NN} @ 100 GeV/c MISSING

Hyperon production Spin Asymmetries

Polarised target: $\bar{p}p^{\uparrow} \rightarrow \bar{\Lambda} + \Lambda$.

Transverse target polarisation ➡ [1] complete determination of the spin structure of reaction



Existing data: PS185 (LEAR) [2]

[1] K.D. Paschke et al., Phys. Lett. B495 (2000) 49.
[2] PS185 Collaboration, K.D: Paschke et al., Nucl. Phys. A692 (2001) 55.

Models account correctly for cross sections.

Models do not account for D^{Λ}_{NN} or K^{Λ}_{NN}.

NEW DATA NEEDED