ADVANCED STUDIES INSTITUTE

SYMMETRIES AND SPIN

(SPIN-Praha-2008)

Prague, July 20 - July 26, 2008

Transverse Spin Physics at FAIR

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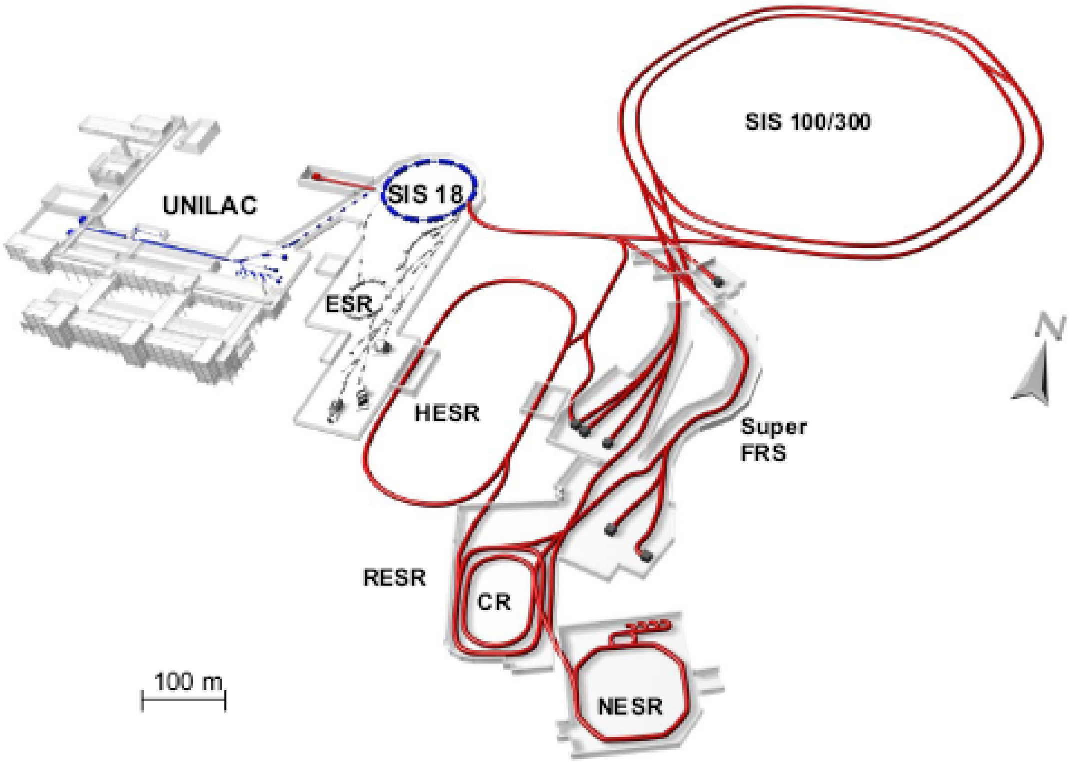
The future FAIR facility

Facility for Antiproton and Ion Research



Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 present in intensity
- 2(4)x10^{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

HESR - High Energy Storage Ring

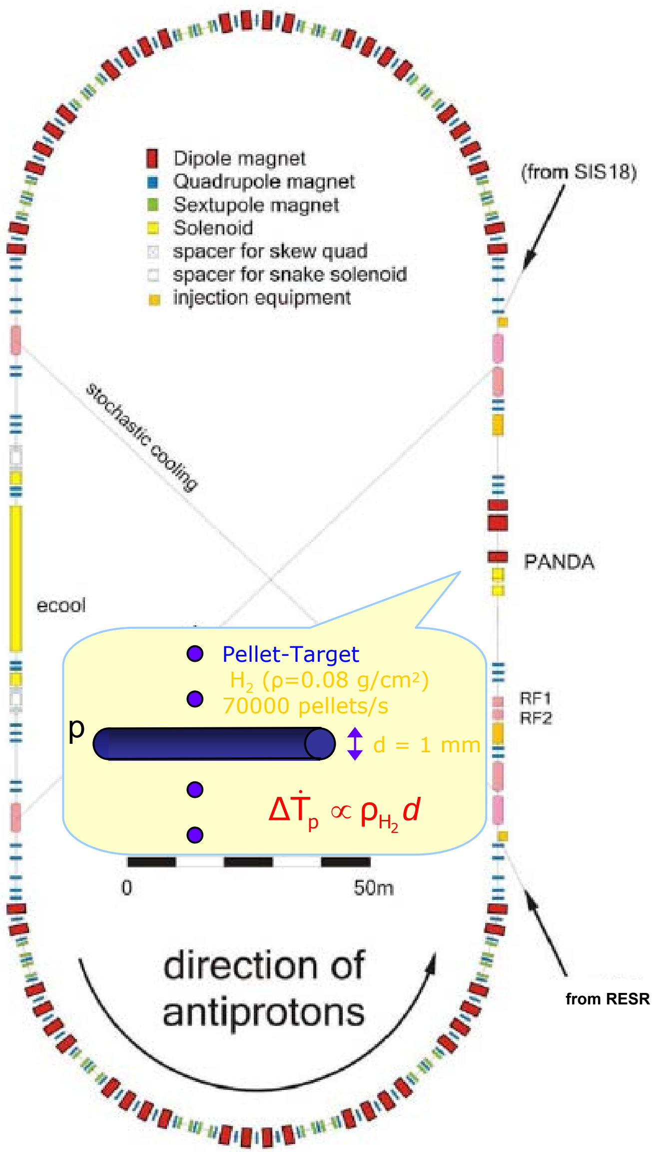
- Production rate 2×10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5×10^{10} $\bar{p}$
- Internal Target

High resolution mode

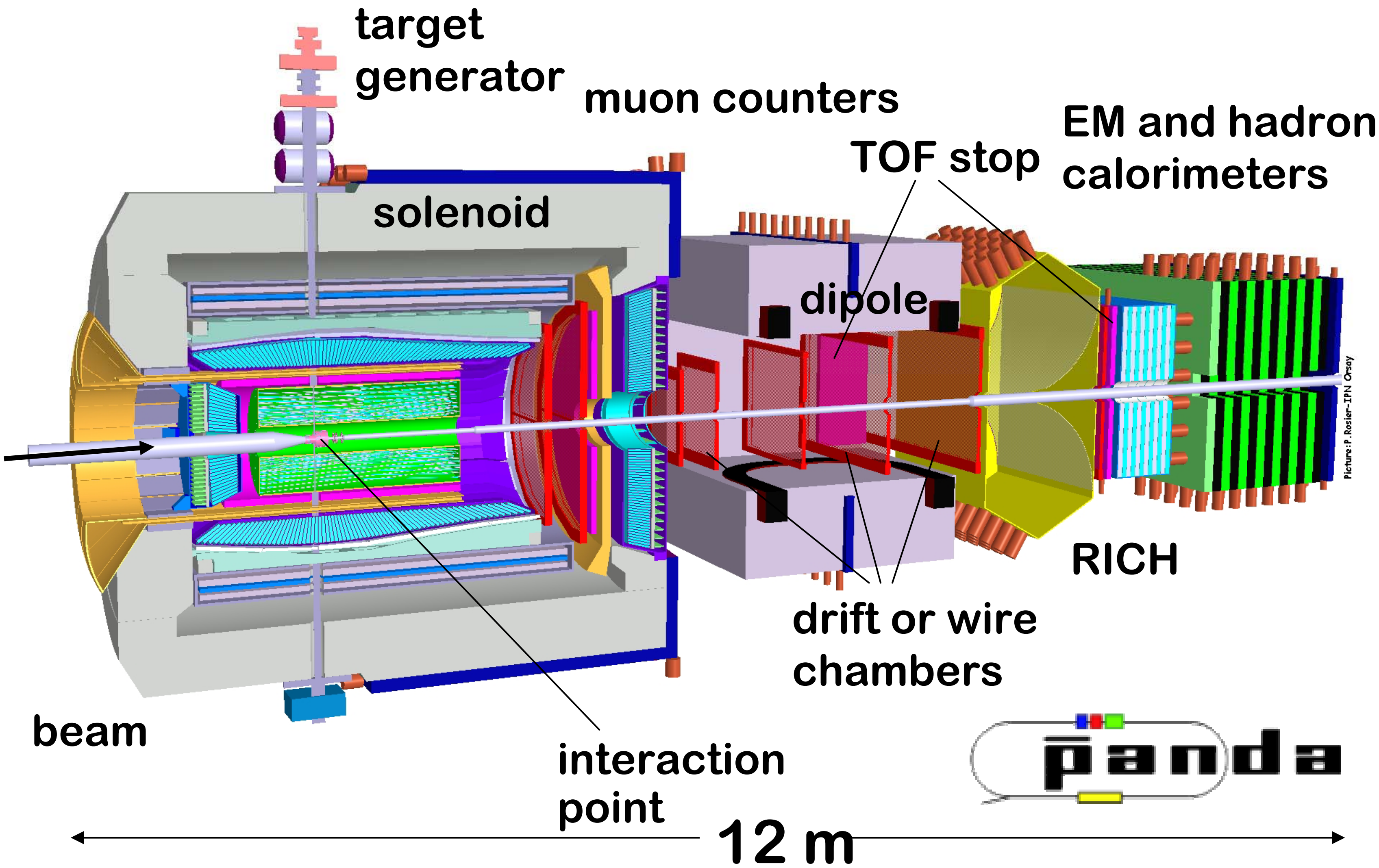
- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

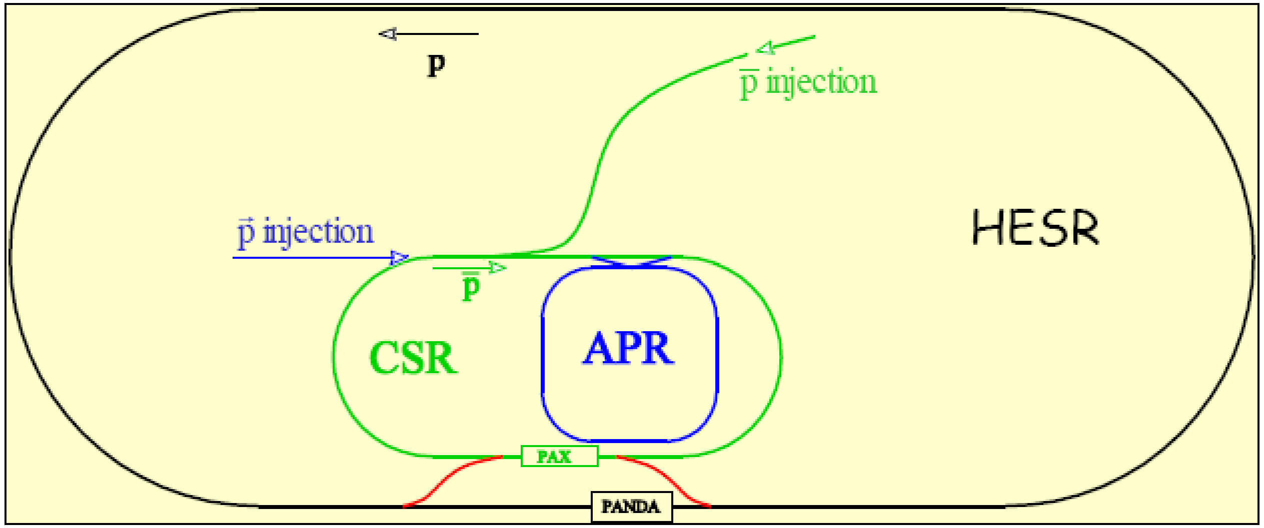
- Lumin. = 2×10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



The PANDA Detector



HESR: asymmetric collider layout

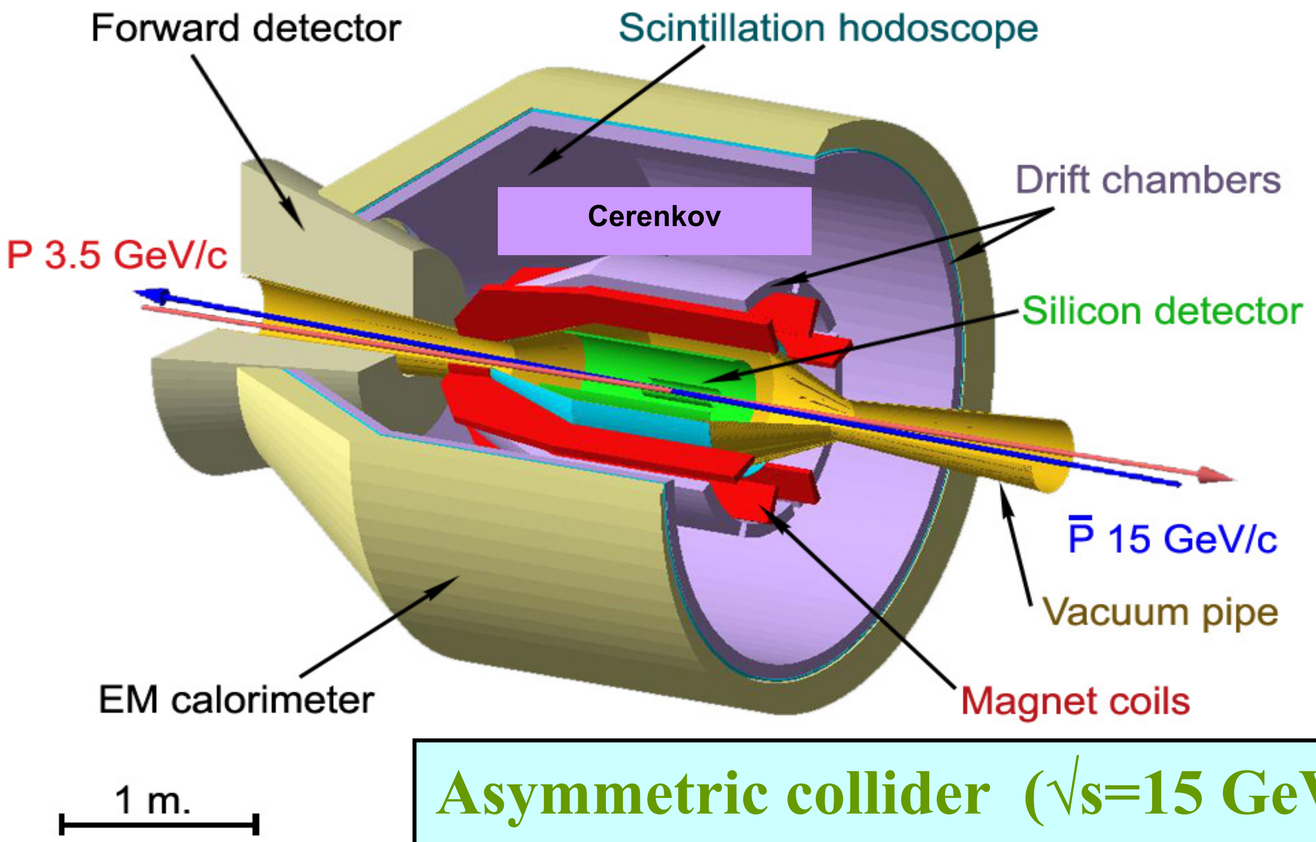


Asymmetric double-polarised collider mode
proposed by PAX people:

- 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 PAX detector

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

    Generalised Distribution Amplitudes (GDA)

Collinear kinematics: κ_T-independent Parton Distributions

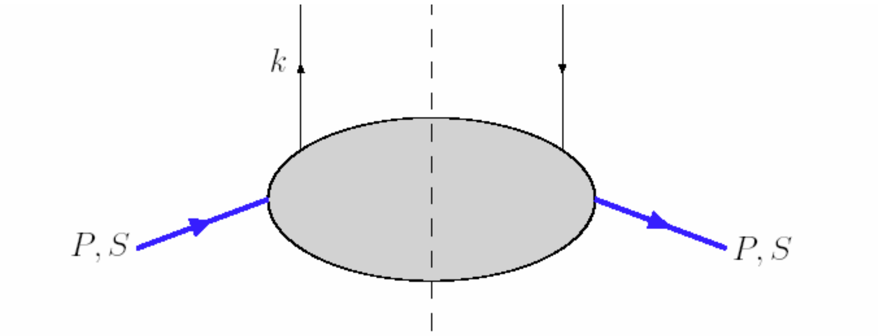
Partonic distributions $q = q_+^+ + q_-^+ \quad g = g_+^+ + g_-^+$

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:



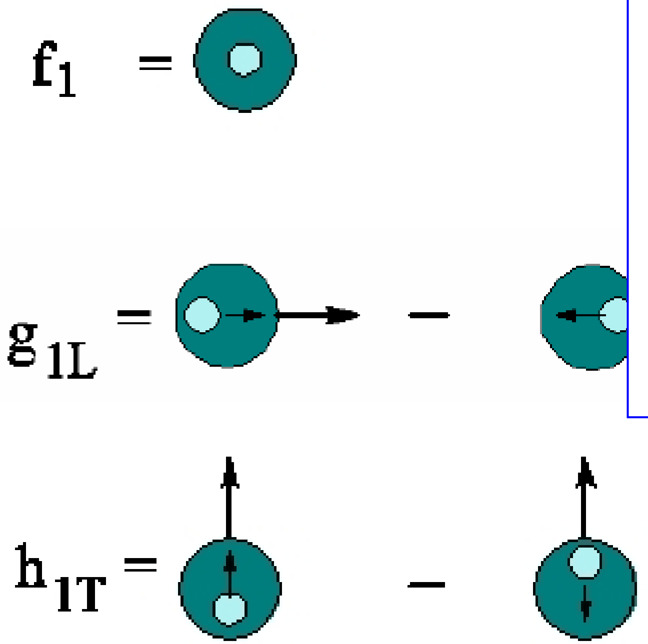
$$\Phi(x,k) = \frac{1}{2}\left[f_1 \not{n}_+ + g_{1L} \gamma^5 \not{n}_+ P_L + h_{1T} i\sigma_{\mu\nu}\gamma^5 \not{n}_+^\mu P_T^\nu \right]$$

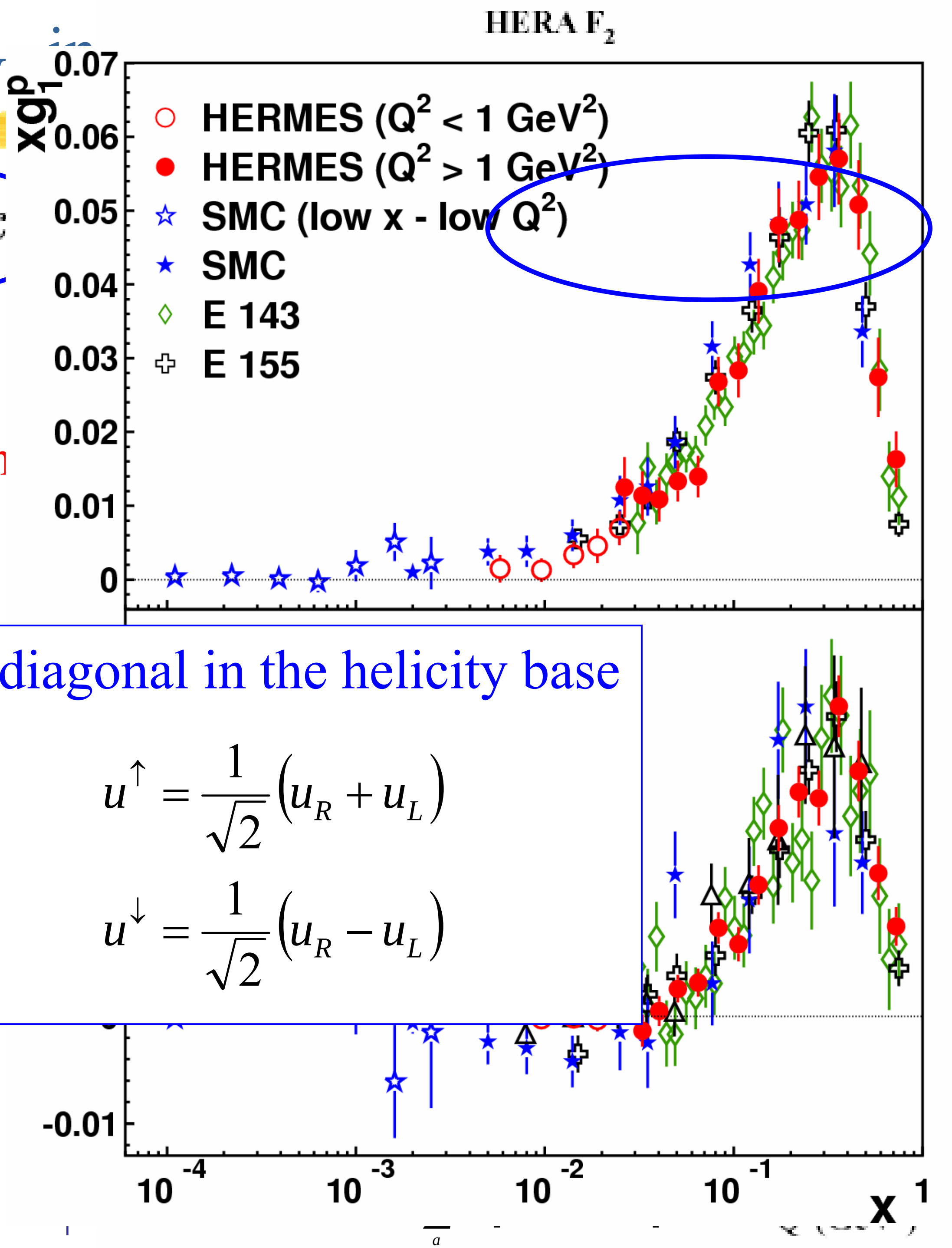
q $\quad$ Δq $\quad$ Δ_Tq

Collinear kinematics: κ_T in

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

Helicity base: probabilistic in



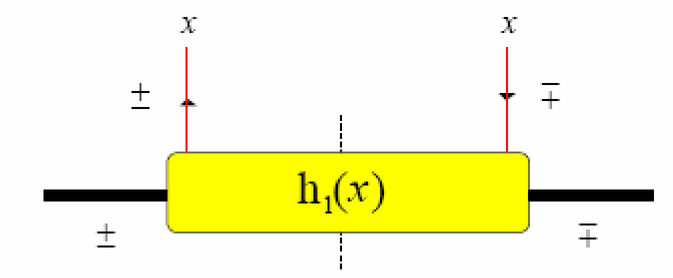


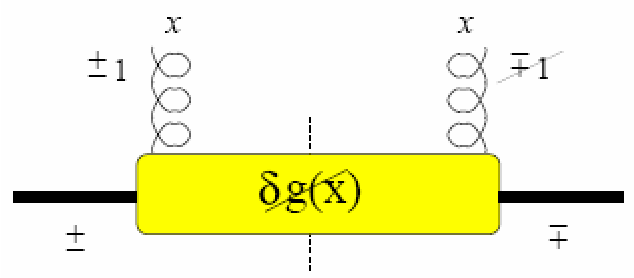
off diagonal in the helicity base

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

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

Transversity $h_1(x)$





δq(x): a chirally-odd, helicity flip distribution function

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

SOFFER INEQUALITY

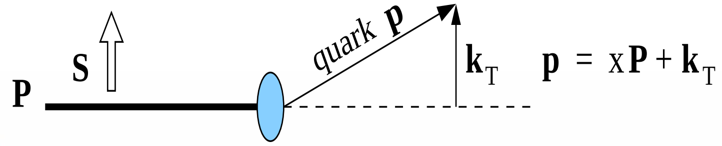
An upper limit: $$|h_1(x)| \leq \frac{1}{2}|f_1(x) + g_1(x)|$$

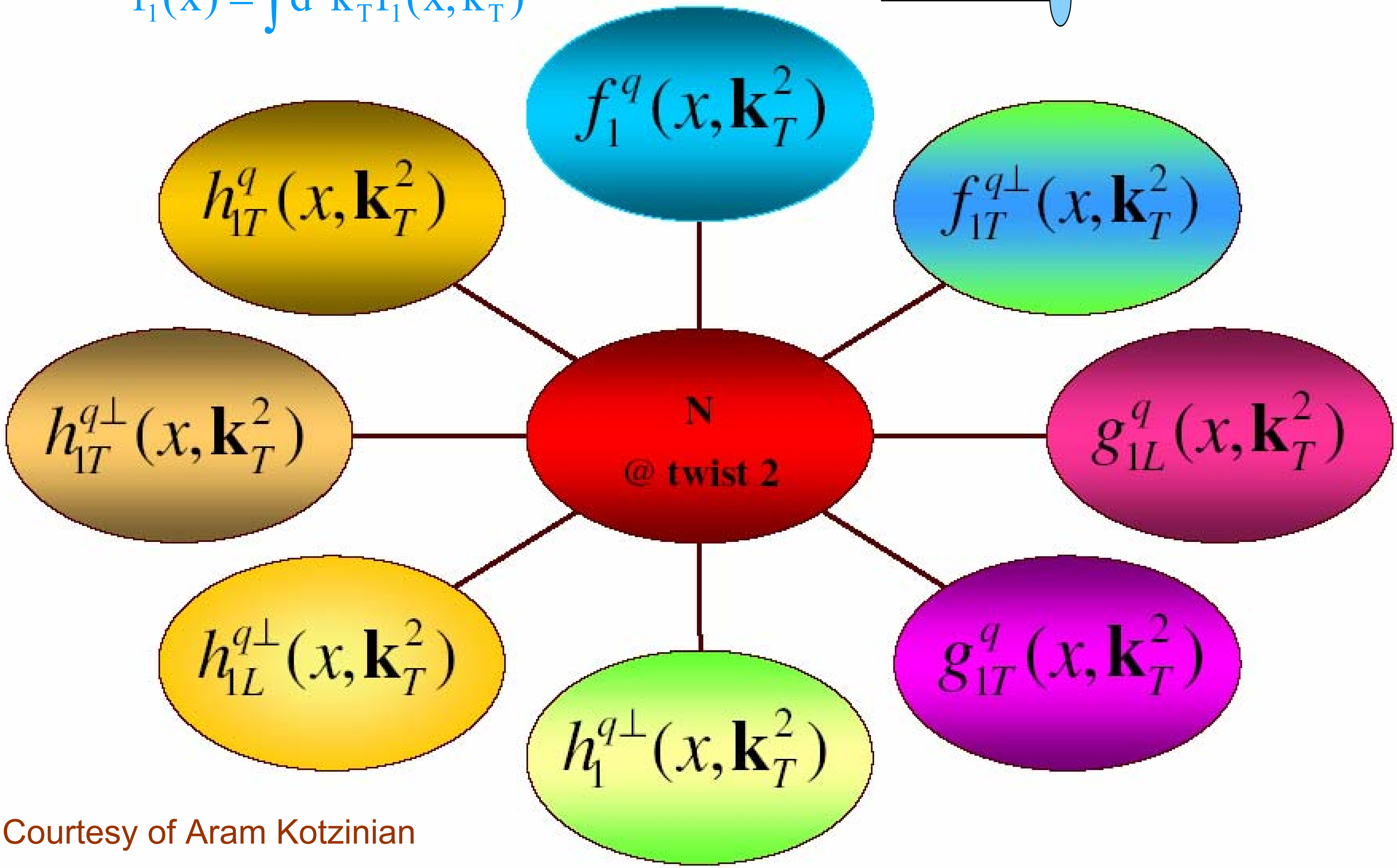
- can be violated by factorisation at NLO
- inequality preserved under evolution to lager scales only

TMD: κ_T-dependent Parton Distributions

Twist-2 PDFs:

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



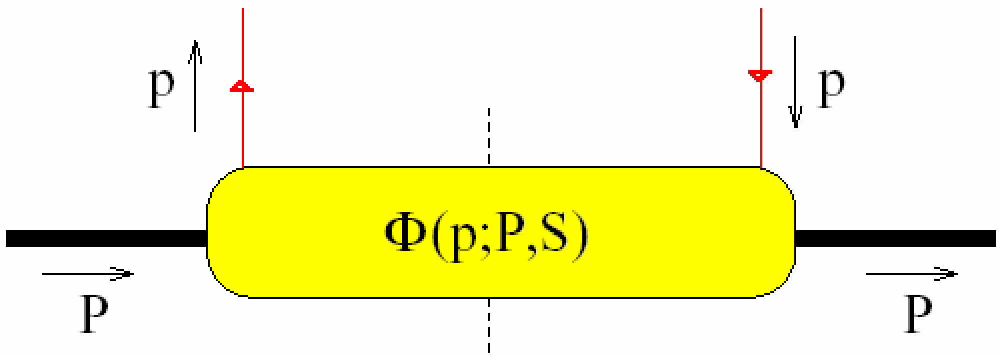


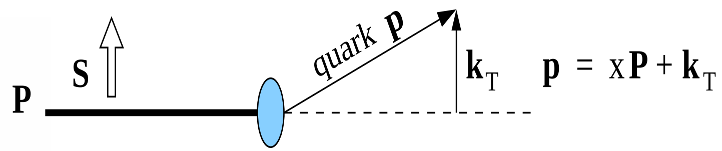
Courtesy of Aram Kotzinian

TMD: κ_T-dependent Parton Distributions

Leading-twist correlator depends on

five more distribution functions:

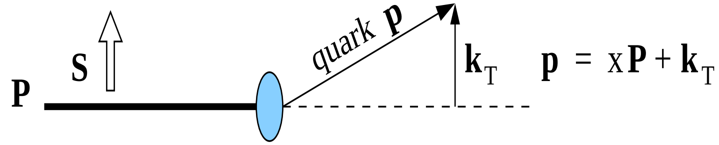


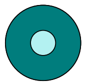


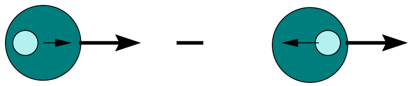
$$\Phi(x_a, \boldsymbol{k}_{\perp a}) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^{\perp} \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^{\mu} n_+^{\nu} k_{\perp a}^{\rho} (P_T^A)^{\sigma}}{M} + \Big(P_L^A g_{1L} + \frac{\boldsymbol{k}_{\perp a}\cdot \boldsymbol{P}_T^A}{M} g_{1T}^{\perp}\Big)\gamma^5 \not{n}_+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

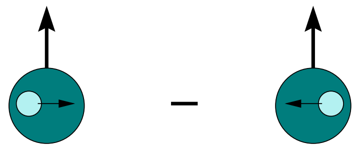
TMD: κ_T-dependent Parton Distributions

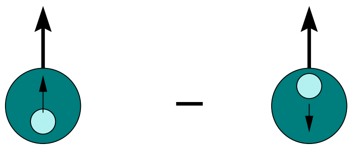
Twist-2 PDFs $\quad f_1(x) = \int d^2k_T f_1(x,k_T)$

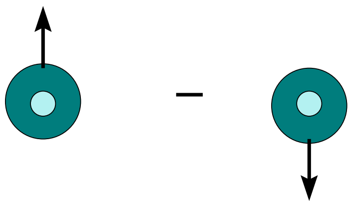


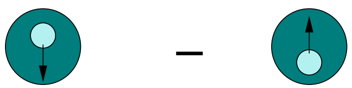
$f_1 =$ 

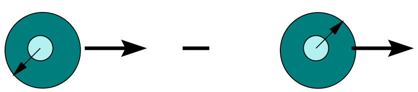
$g_{1L} =$ 

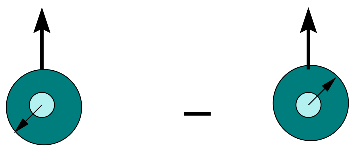
$g_{1T} =$ 

$h_{1T} =$  **Transversity**

$f_{1T}^{\perp} =$  **Sivers**

$h_1^{\perp} =$  **Boer-Mulders**

$h_{1L}^{\perp} =$ 

$h_{1T}^{\perp} =$ 

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 — $\bar{p}p \rightarrow \ell^+\ell^- X$

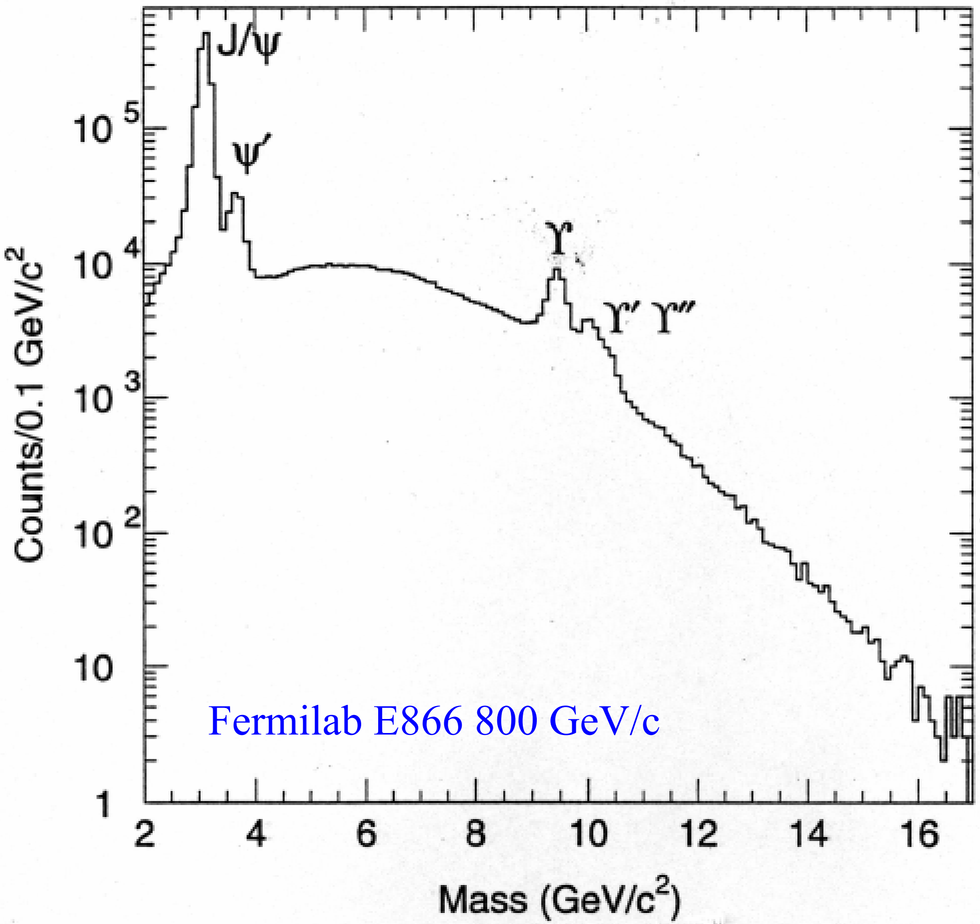
$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\alpha^2\pi}{9M^2 s}\frac{1}{x_1+x_2}\sum_a e_a^2\left[f^a(x_1)f^{\bar{a}}(x_2)+f^{\bar{a}}(x_1)f^a(x_2)\right]$$

Why Drell Yan?

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

3 planes: plane ⊥ to polarisation vectors

$p - \gamma^*$ plane



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

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

$$x_F = x_1 - x_2$$

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

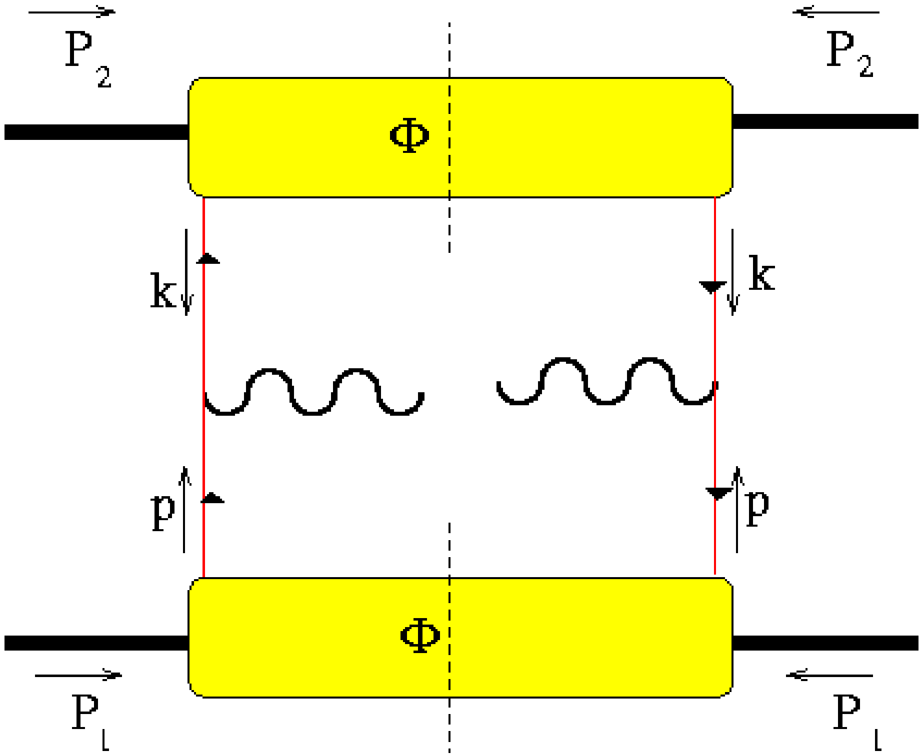
Drell-Yan Asymmetries — $\bar{p}^{\uparrow} p^{\uparrow} \to \ell^{+}\ell^{-}X$

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

TRANSVERSITY

Ideal because:

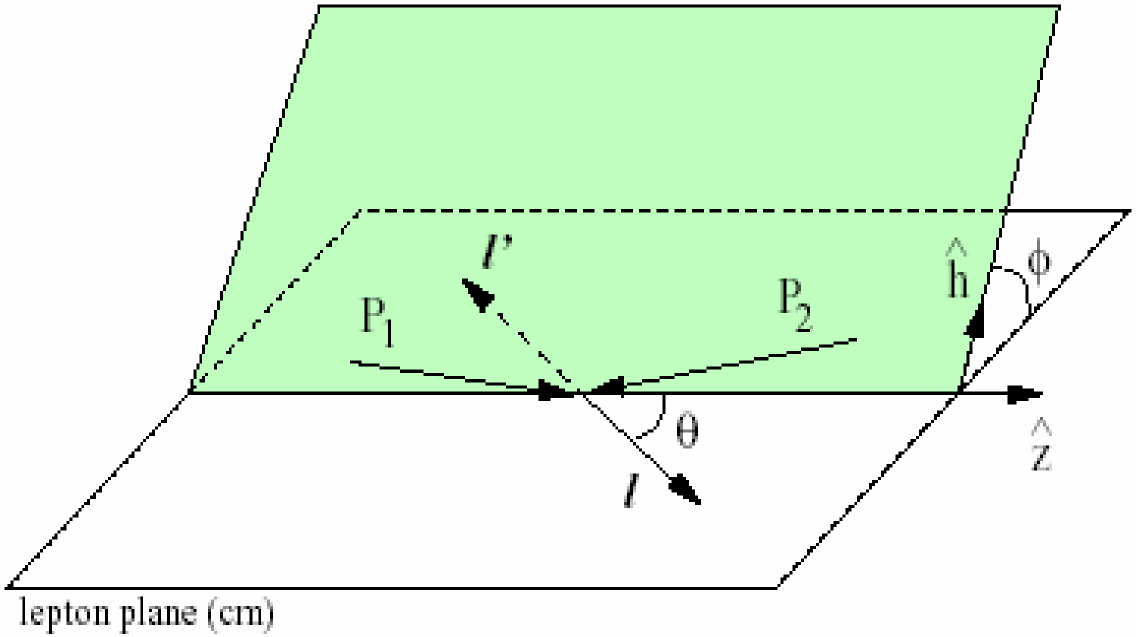
- h_1 not to be unfolded with fragmentation functions
- chirally odd functions not suppressed (like in DIS)



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

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

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



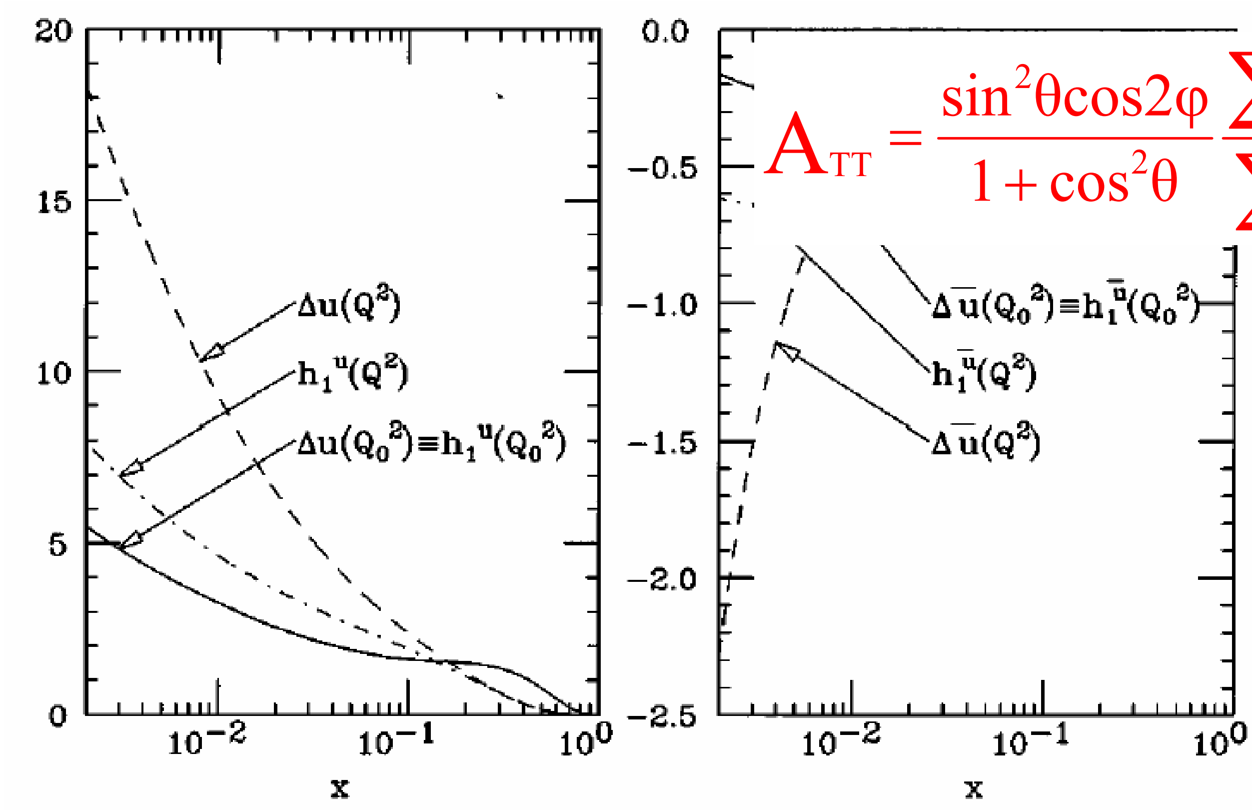
To be corrected for:

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

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

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

PROBLEMATIC MEASUREMENT



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

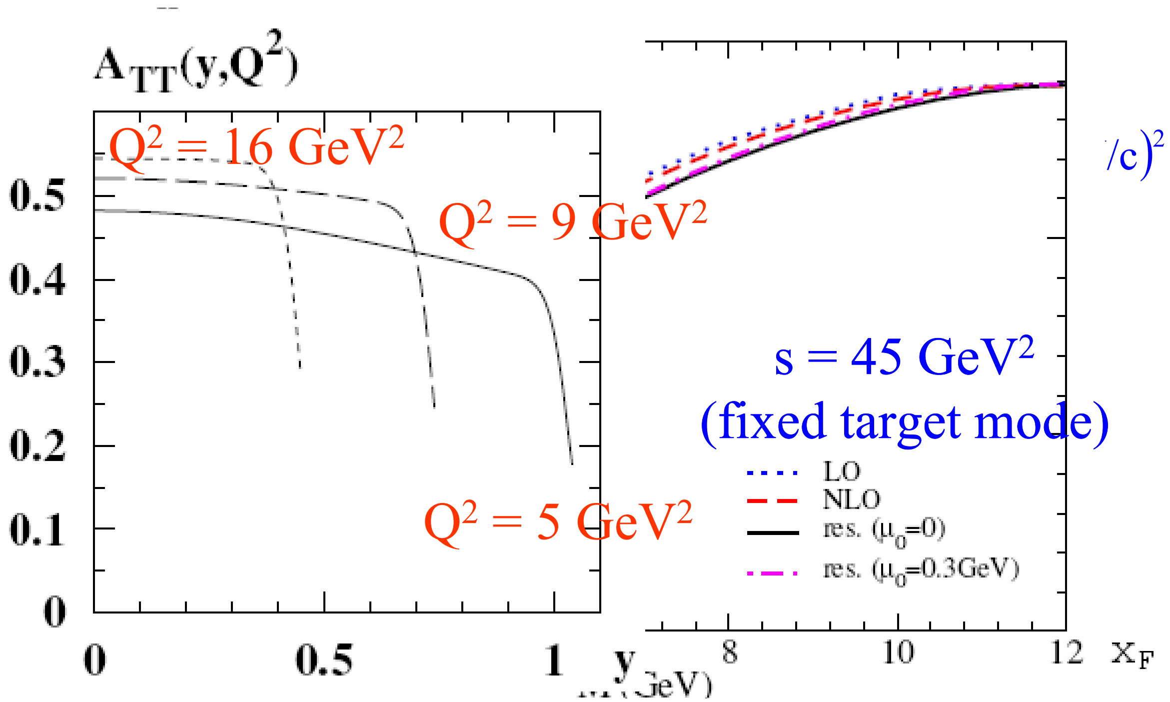
$$Q_0^2 = 0.23\ \mathrm{GeV}^2$$

$$Q^2 = 25\ \mathrm{GeV}^2$$

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

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

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



HESR: $s_{max} = 30 \div 45$ GeV²

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

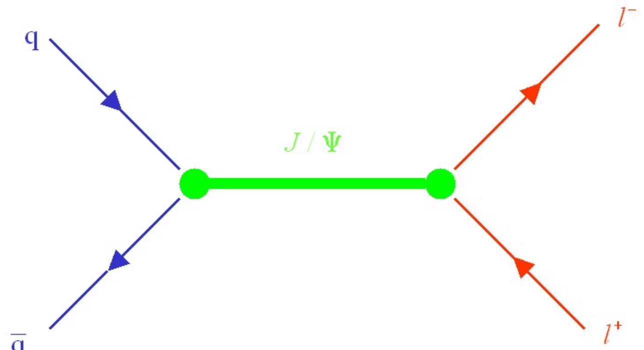
A_{TT} direct access to valence quark h_1

s = 45 GeV² (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 Di-Lepton Production $\bar{p}p \rightarrow J/\Psi \rightarrow \ell^+\ell^- X$

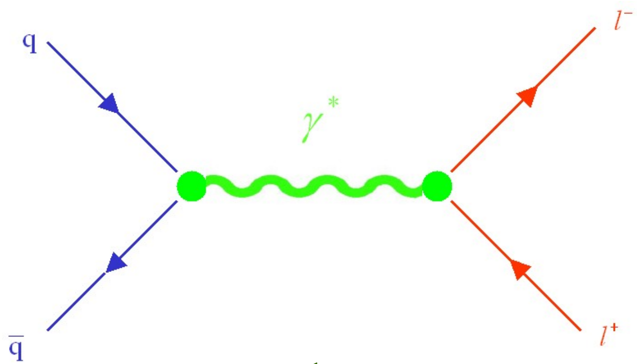


$$g_q^V \bar{v}\gamma^\mu u \frac{1}{M^2 - M^2_{J/\Psi} + i\Gamma M_{J/\Psi}} g_l^V \bar{u}\gamma^\mu v$$

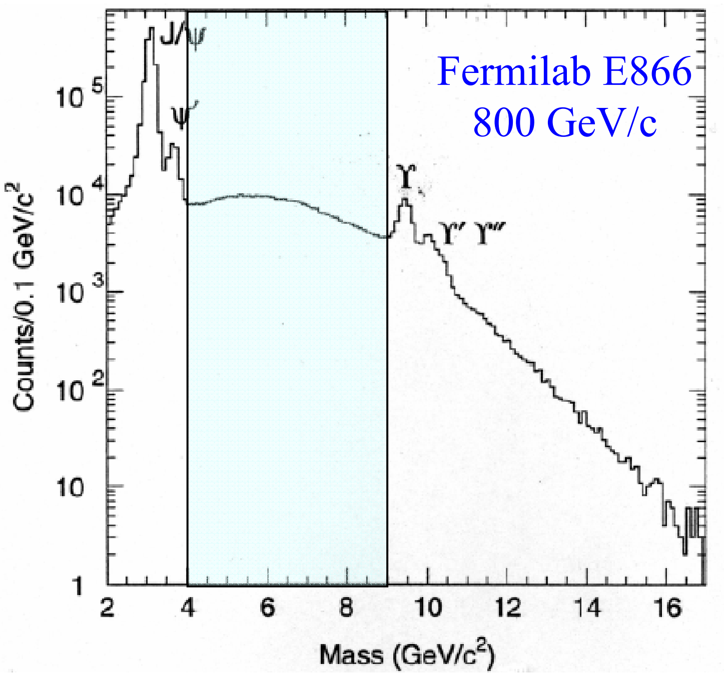
vector couplings

same spinor structure

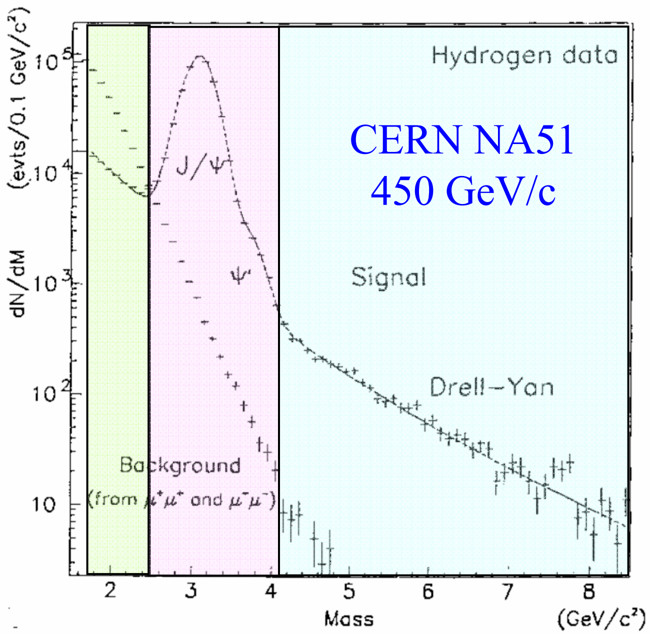
$$\hat{a}_{TT}^{J/\Psi} = \hat{a}_{TT}^{\gamma^*}$$



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

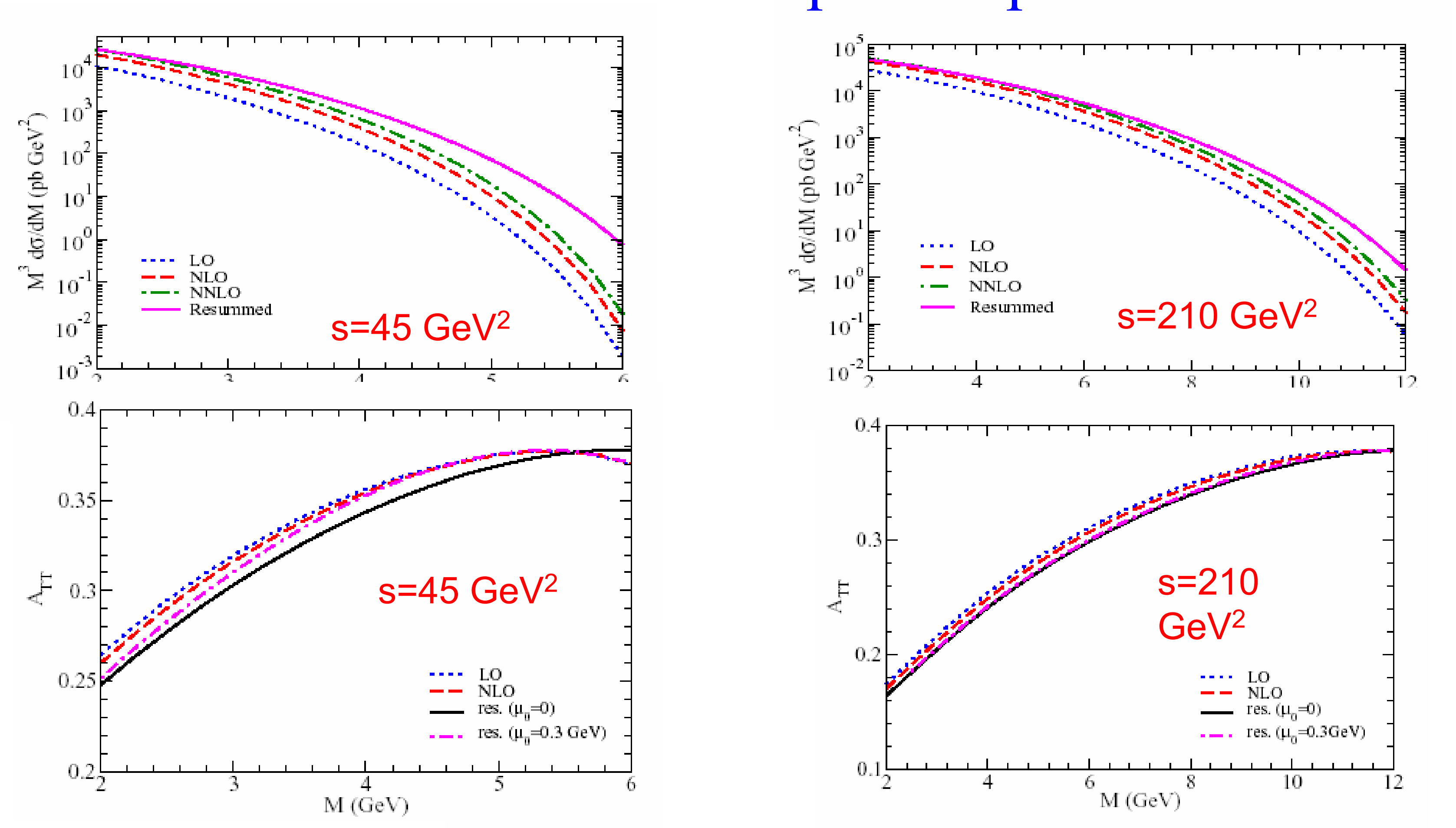


$Q^2 > 2.25\ GeV^2$



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

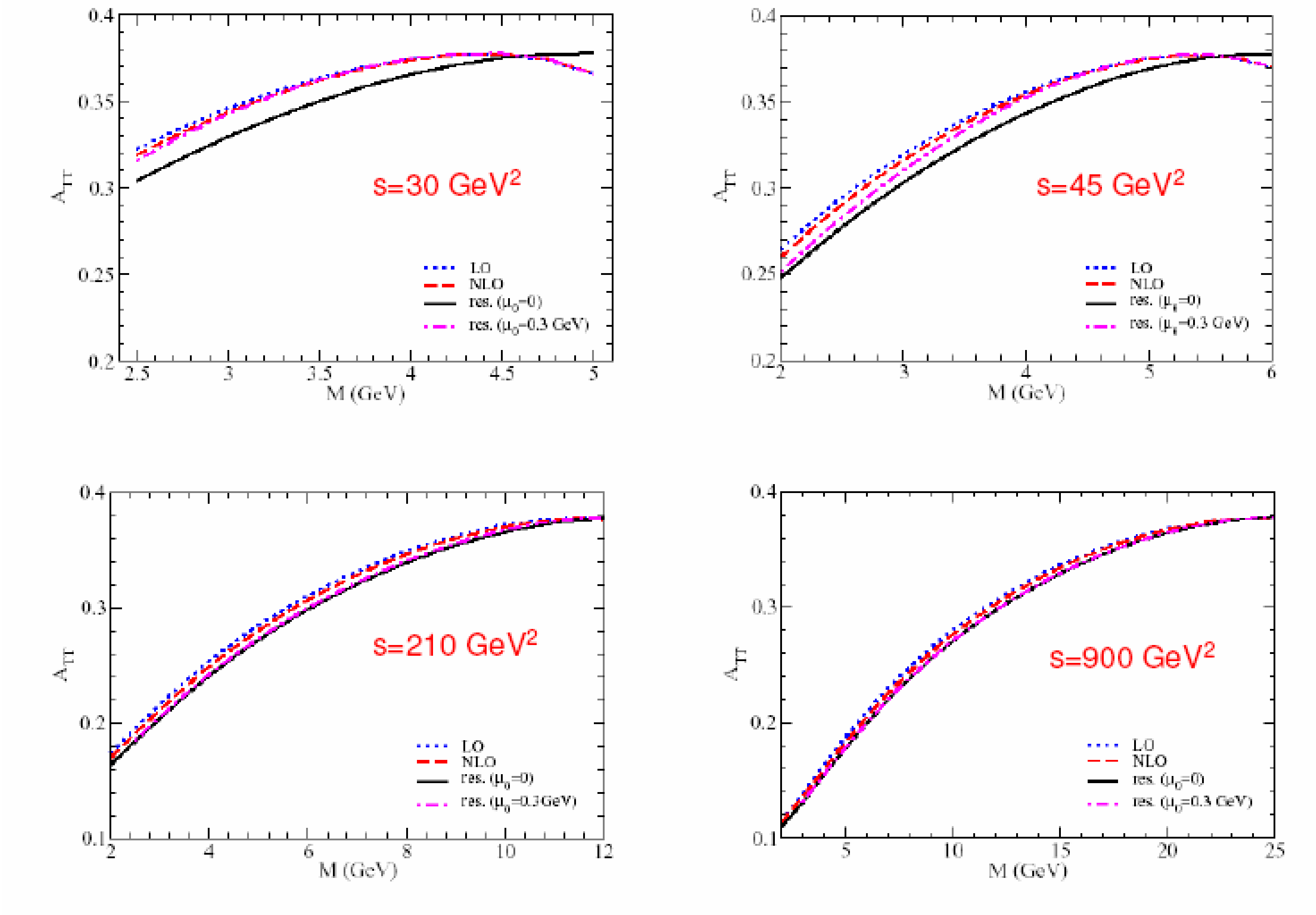
QCD higher order contributions might be sizeable at smaller M but cross-sections only are affected, NOT A_{TT}: K-factors are almost spin indipendent[1]



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

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

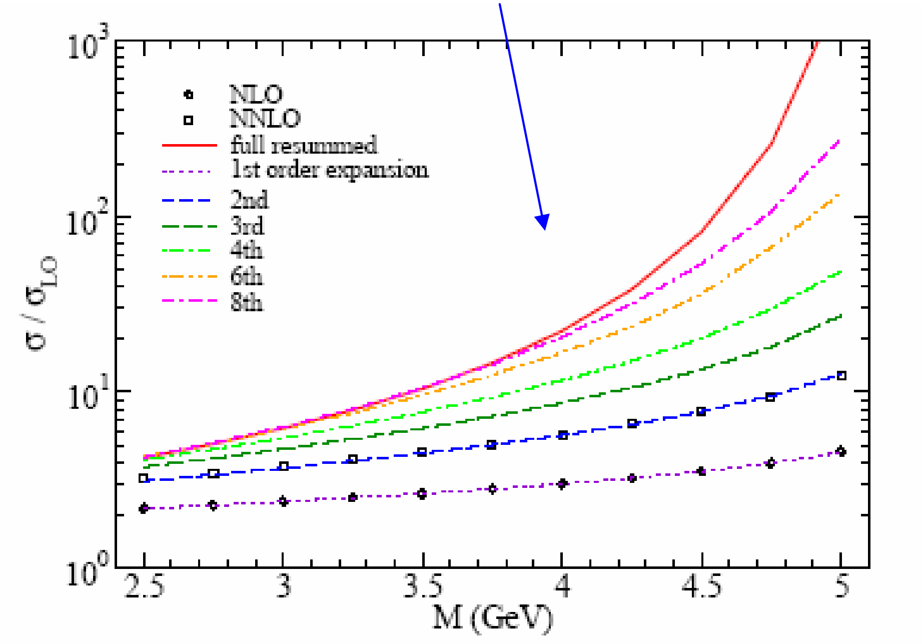
Moreover QCD contributions to A_{TT}: drop increasing energy[1]



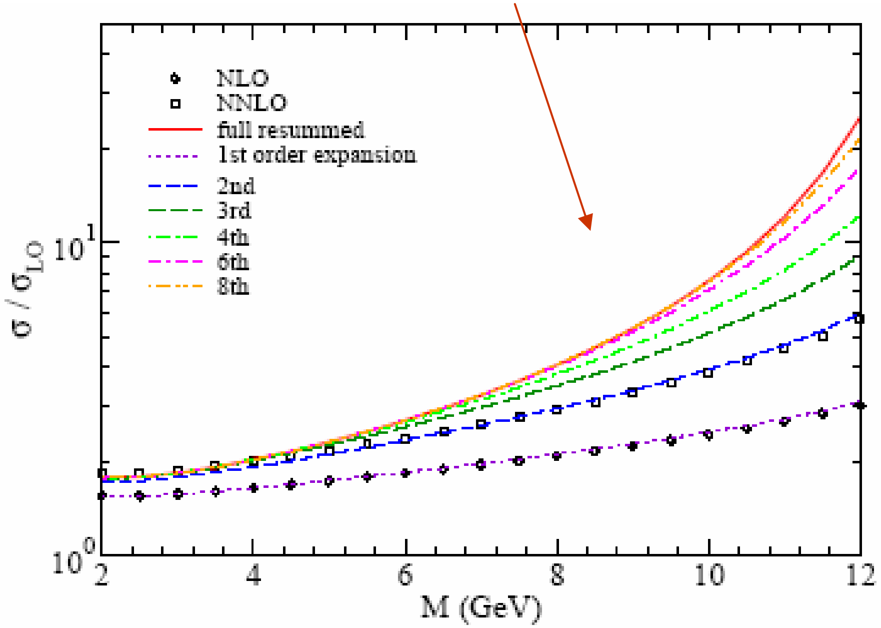
[1] Shimizu et al., hep-ph/0503270 .

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

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



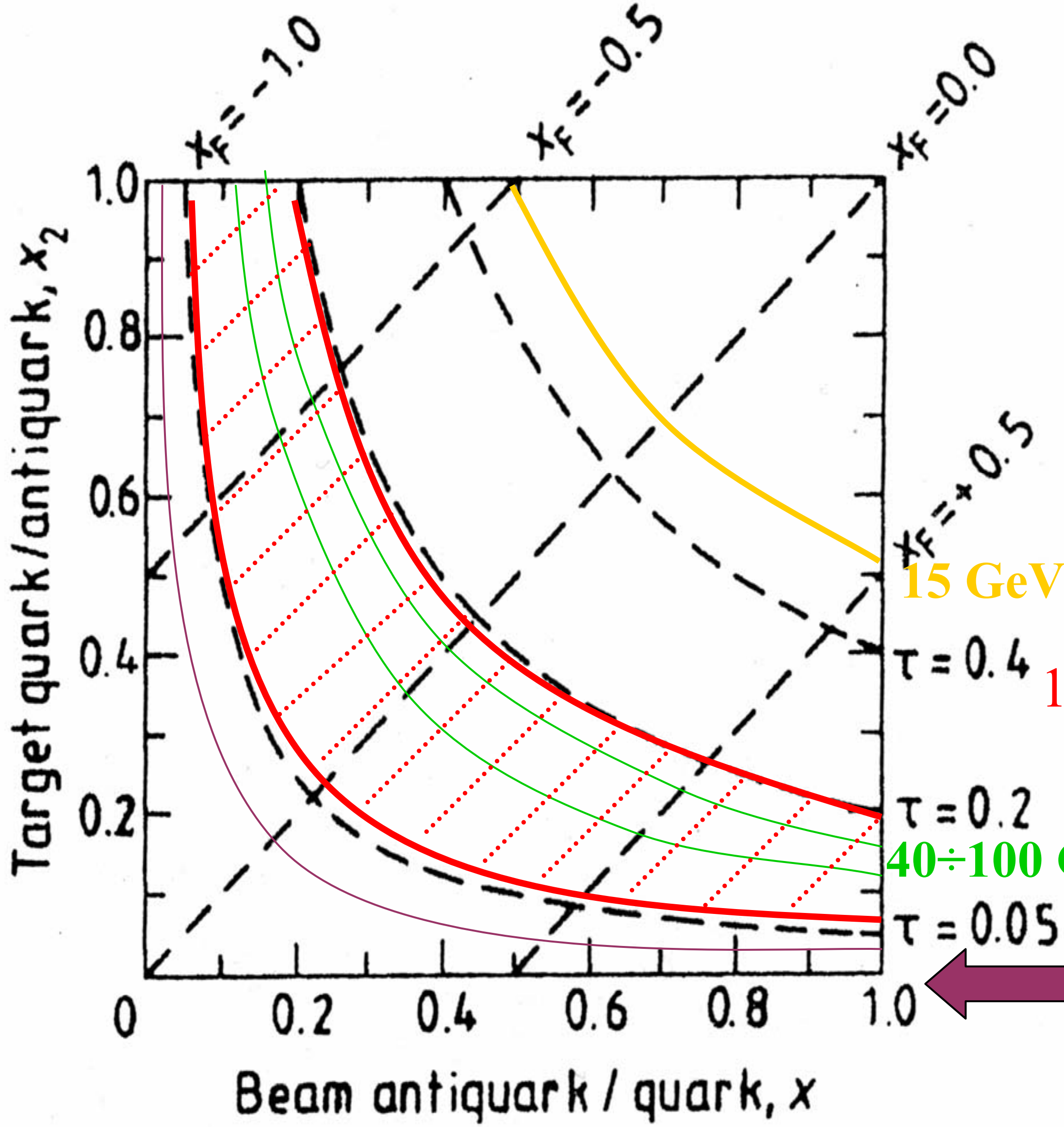
$s = 200\ \mathrm{GeV}^2$



At higher energy ($s \sim 200\ \mathrm{GeV}^2$)
perturbative corrections[1] are sensibly smaller
in the safe region even for cross-sections

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

Phase space for Drell-Yan processes



τ = const: hyperbolae

x_F = const: diagonal

PANDA/PAXfix

$1.5\,\mathrm{GeV/c^2} \leq M_{\mu\mu} \leq 2.5\,\mathrm{GeV/c^2}$

ASSIA/PAX
(SIS300 /acHESR)

symmetric HESR collider

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

Di-Lepton Rest Frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\varphi+\frac{\nu}{2}\sin^2\theta\cos2\varphi\right)$$

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]: $\upsilon \sim 30$ %

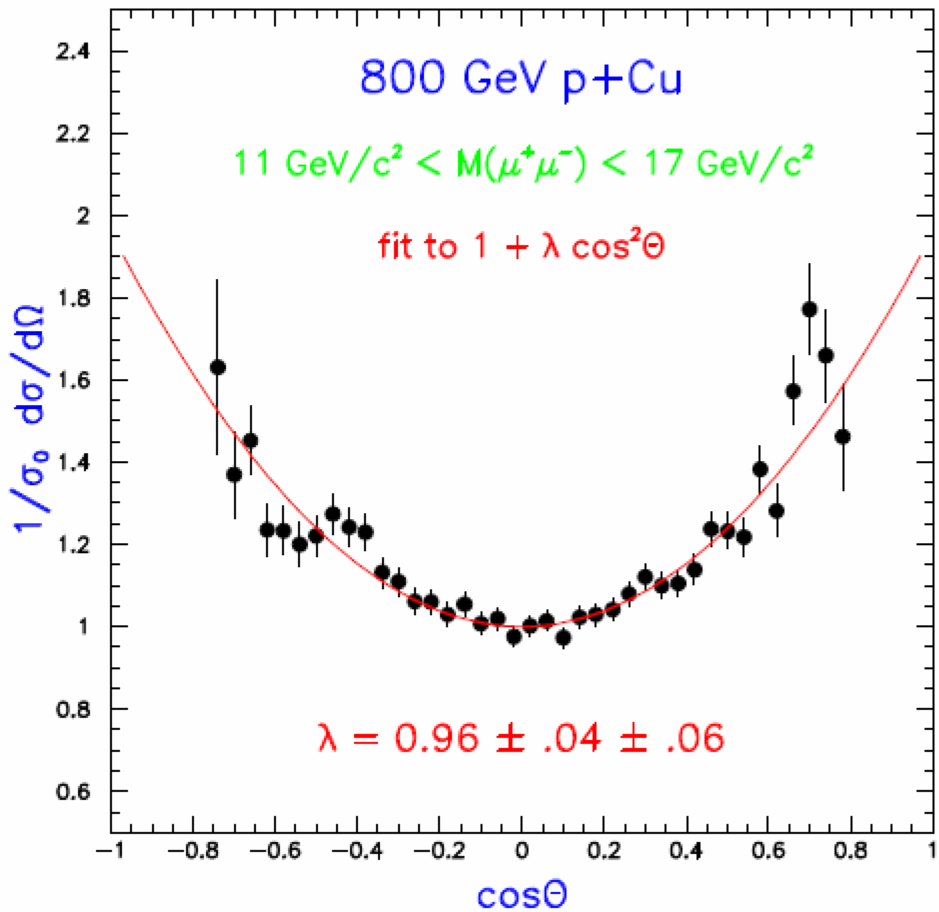
[1] J.S.Conway et al., Phys. Rev. D39 (1989) 92.

Expected polar distribution for DY dilepton production

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

E772 @ Fermilab

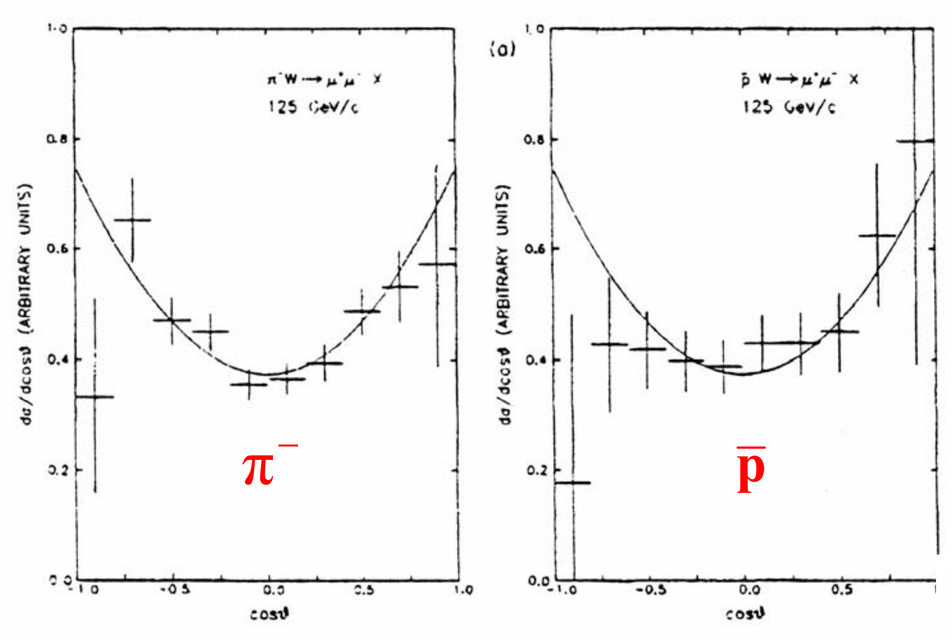
$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2\theta)$$



Perfect agreement with pQCD exptectations!

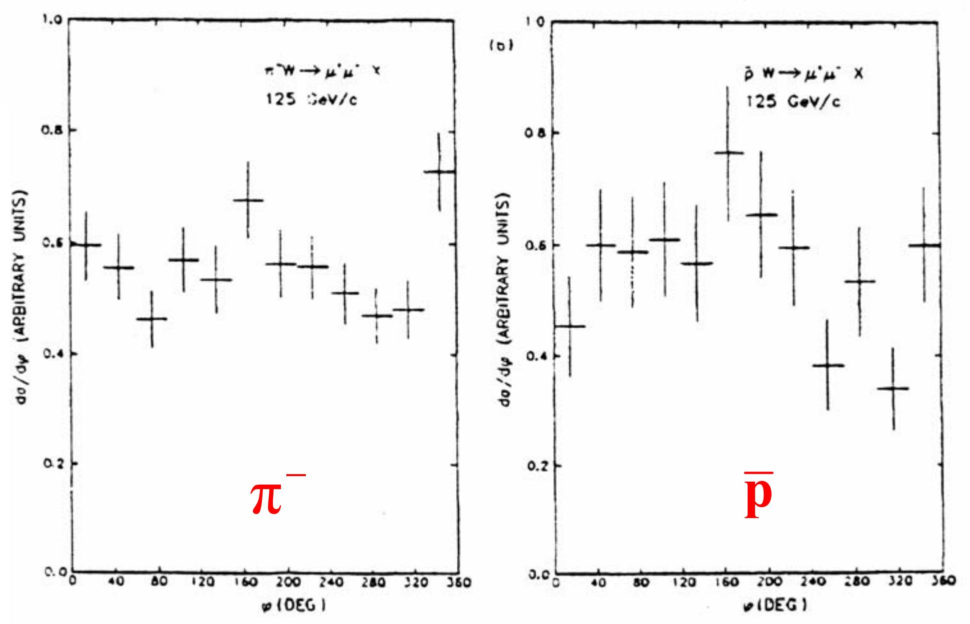
[1] McGaughey, Moss, JCP, Annu. Rev. Nucl. Part. Sci. 49 (1999) 217.

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 $\cos\varphi$



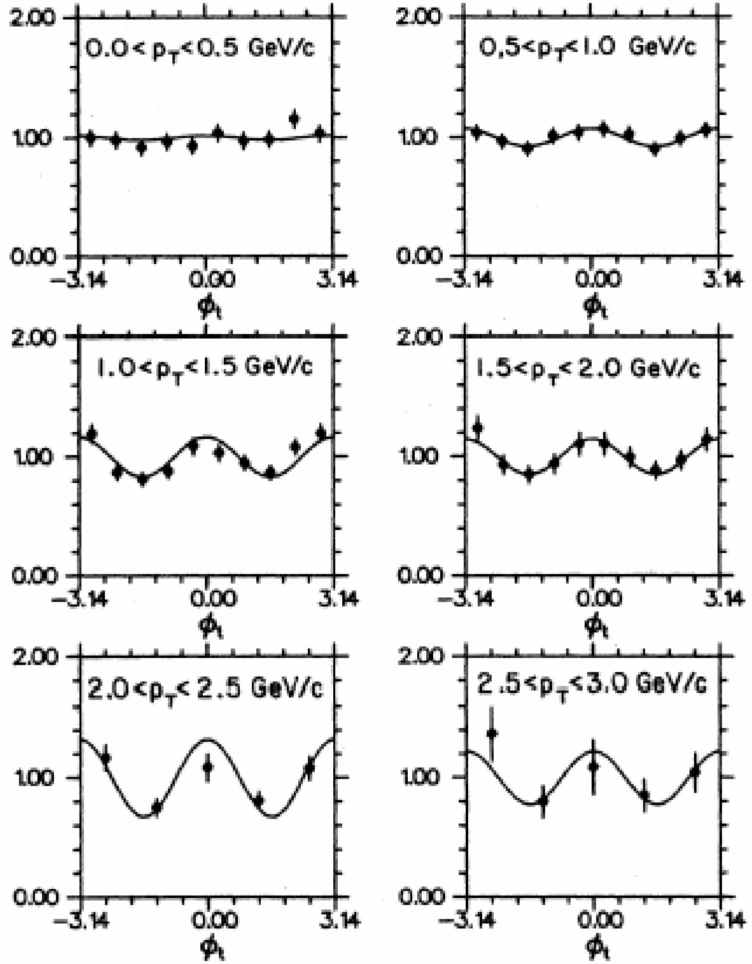
E537 @ Fermilab

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

Angular distribution in CS frame

E615 @ Fermilab

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



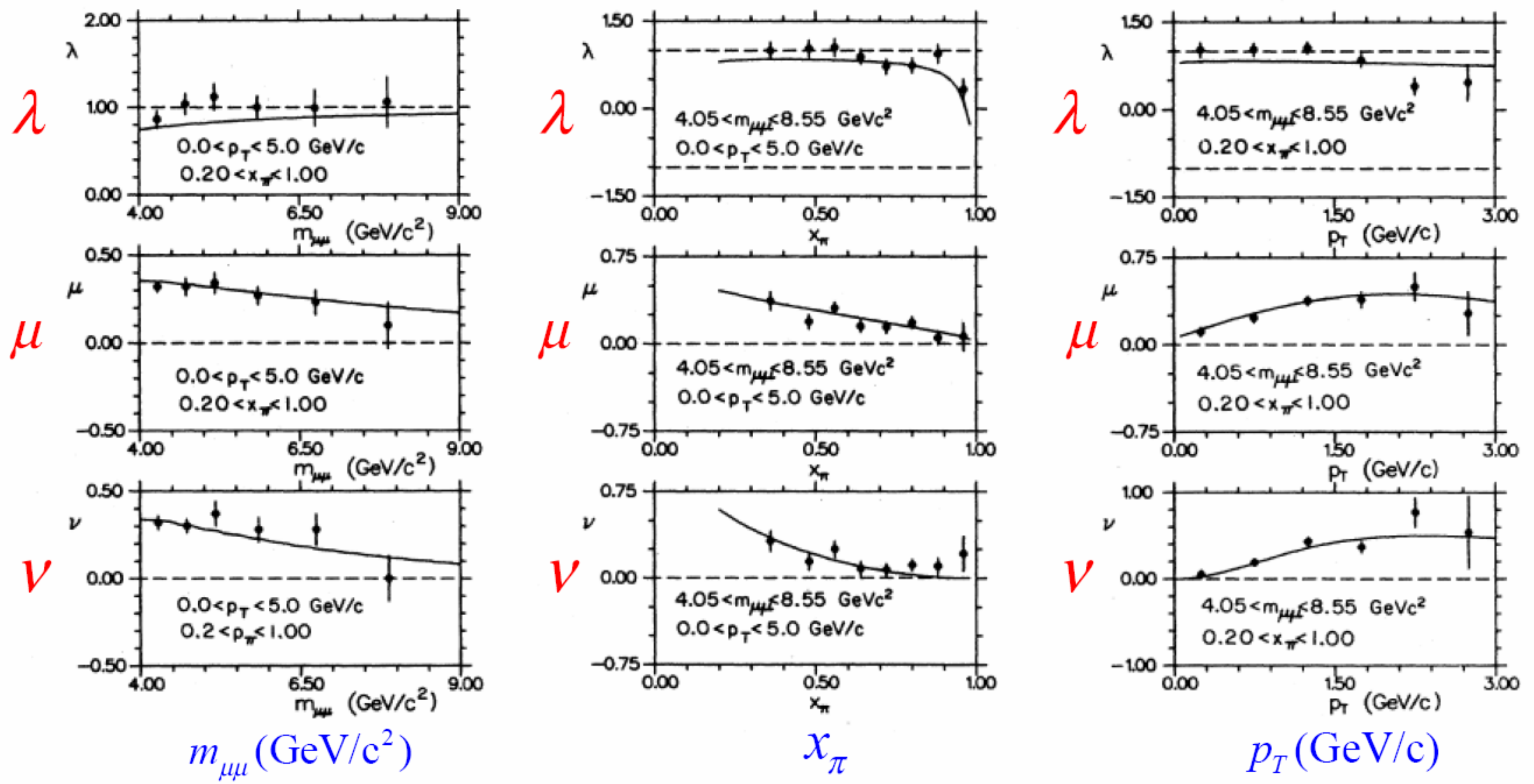
$-0.6 < \cos\vartheta < 0.6$

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

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

Angular distribution in CS frame

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

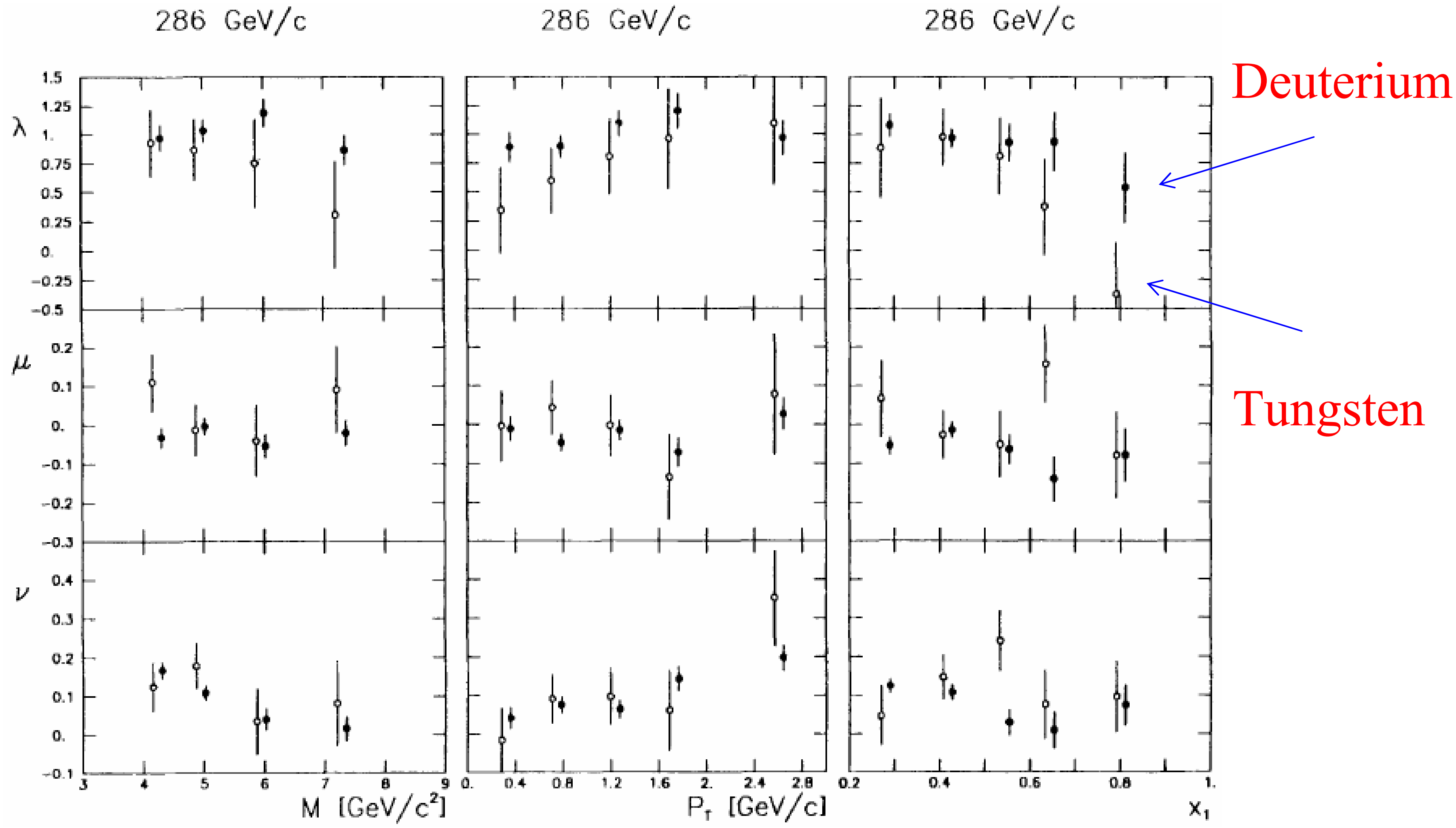


30% asymmetry observed for π^-

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

Does it come from a nuclear effect?

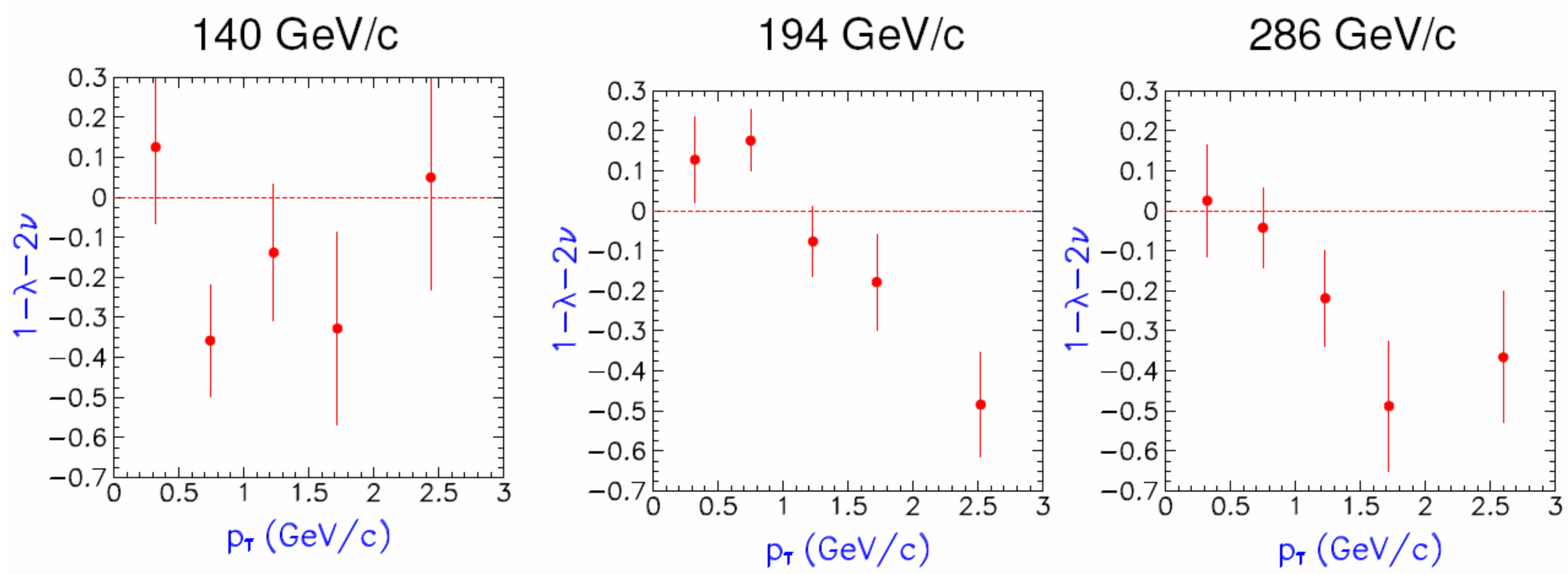
NA10 @ CERN π-N $\rightarrow \mu^+\mu^-$X @ 286 GeV/c



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:

$$h_1^{\perp}(x_2,\kappa_{\perp}^2) \times \bar{h}_1^{\perp}(x_1,\kappa_{\perp}'^2)$$

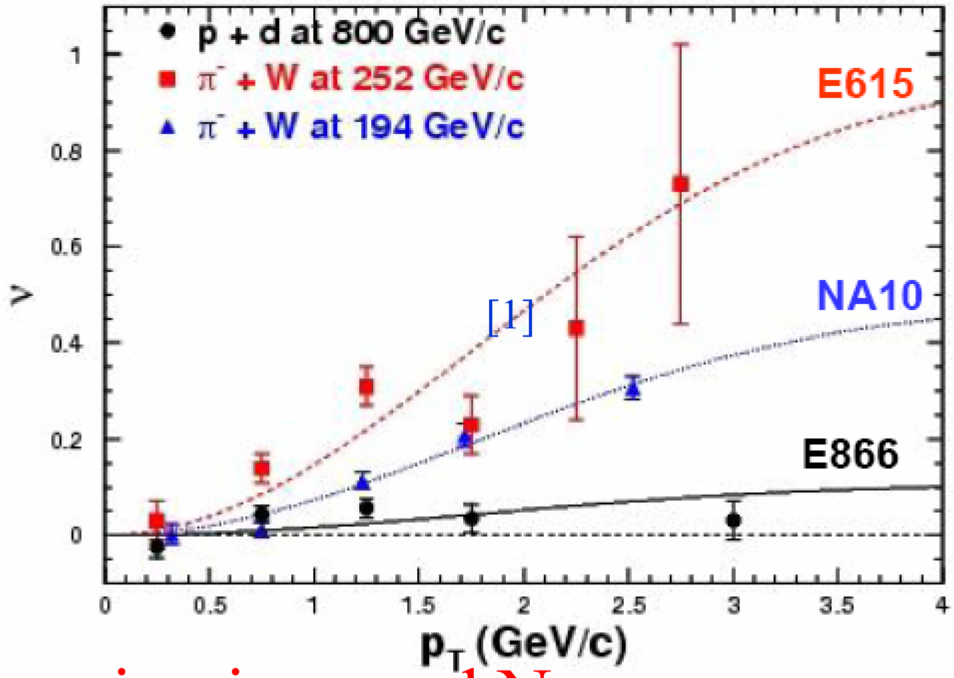
[2] D. Boer et al., Phys. Rev. D60 (1999) 014012.

[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



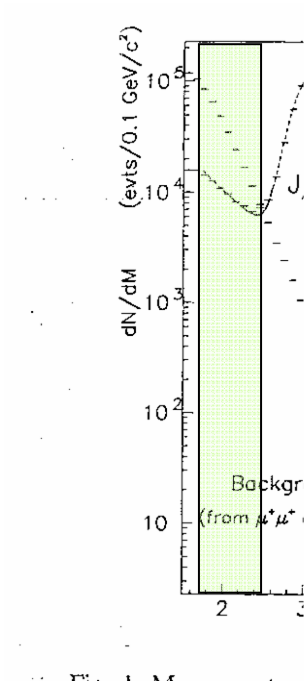
- $\nu > 0 \rightarrow$ valence $h_1^\perp$ has same sign in π and N
- $\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim h_1^\perp(\pi)_{valence} \times h_1^\perp(p)_{valence}$
- $\nu(pd \rightarrow \mu^+\mu^- X) \sim h_1^\perp(p)_{valence} \times h_1^\perp(p)_{sea}$
- $\nu > 0 \rightarrow$ valence and sea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

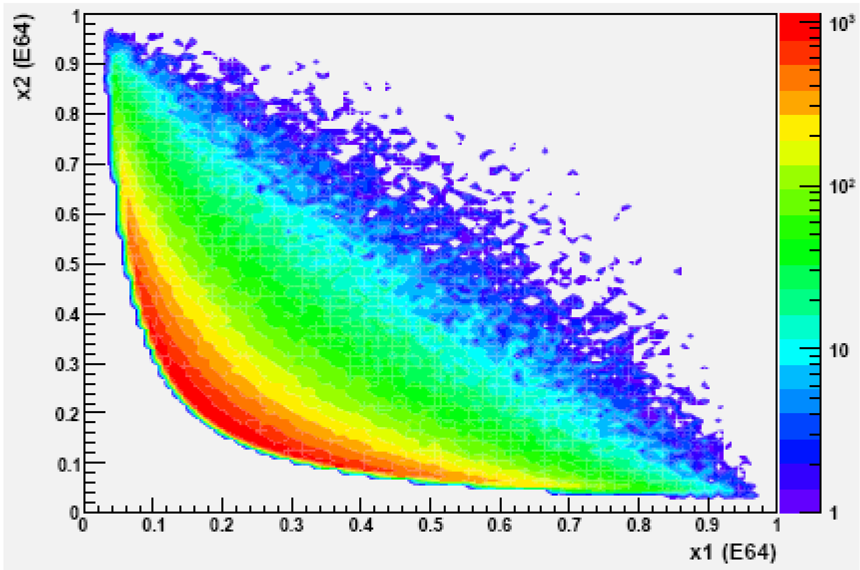
[1] L. Zhu et al, PRL 99 (2007) 082301; [12 D. Boer, Phys. Rew. D60 (1999) 014012.

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

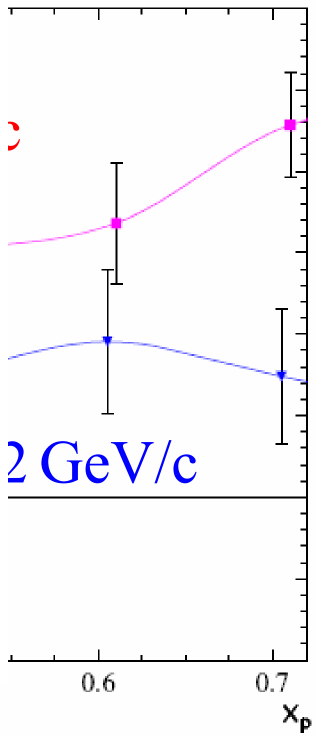
40K ev

eV/c^2





try
on

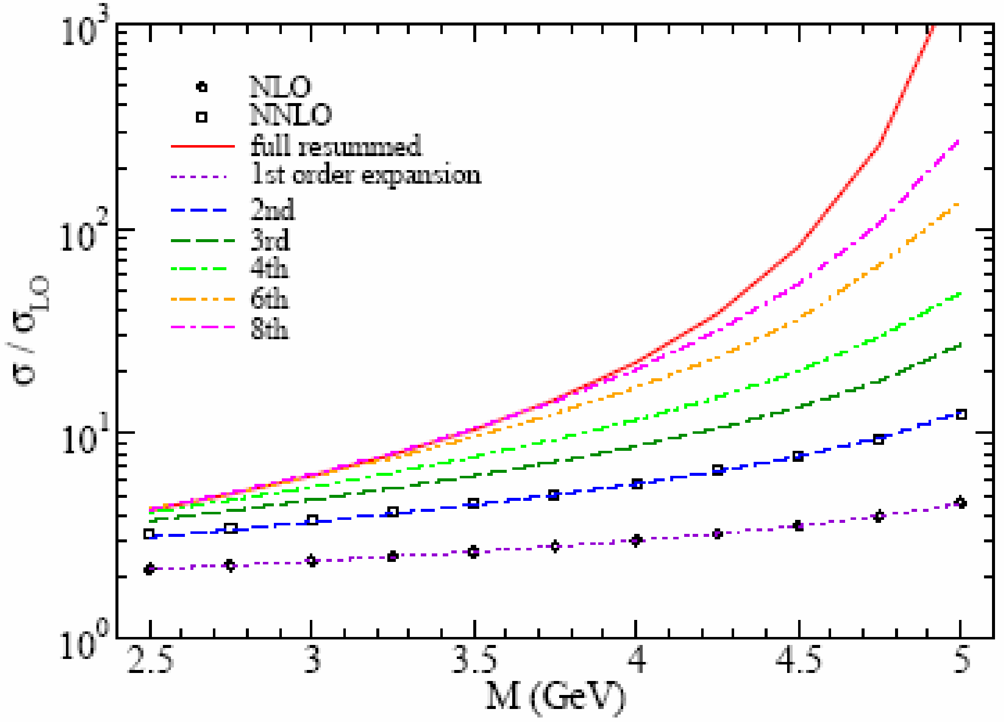


0.2 <

error bars allo
- small asymm
- their depende

[1]A. Bianconi and M. R

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

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

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

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

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

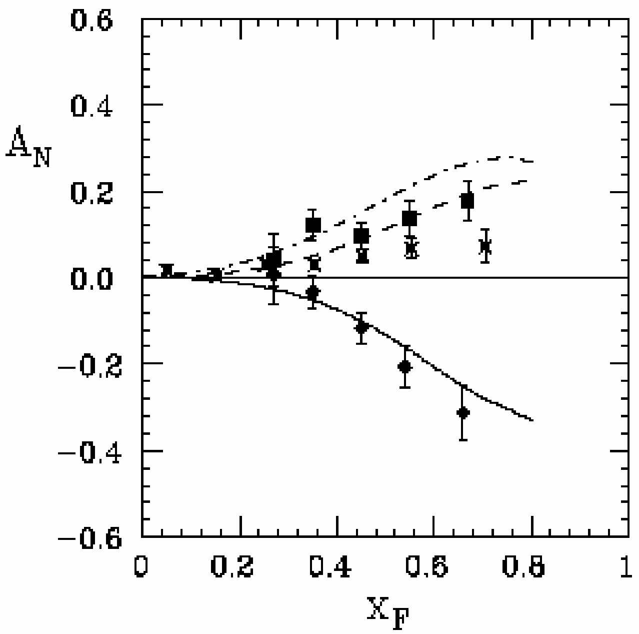
Even unpolarised $\bar{p}$ beam on polarised p,
or polarised $\bar{p}$ on unpolarised p
are powerful tools
to investigate κ_T dependence of QDF

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

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

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

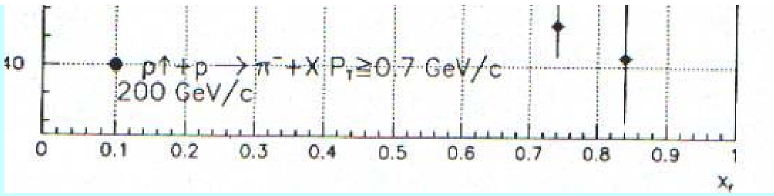
Transverse Single Spin Asymmetries in Drell-Yan



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

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

region:



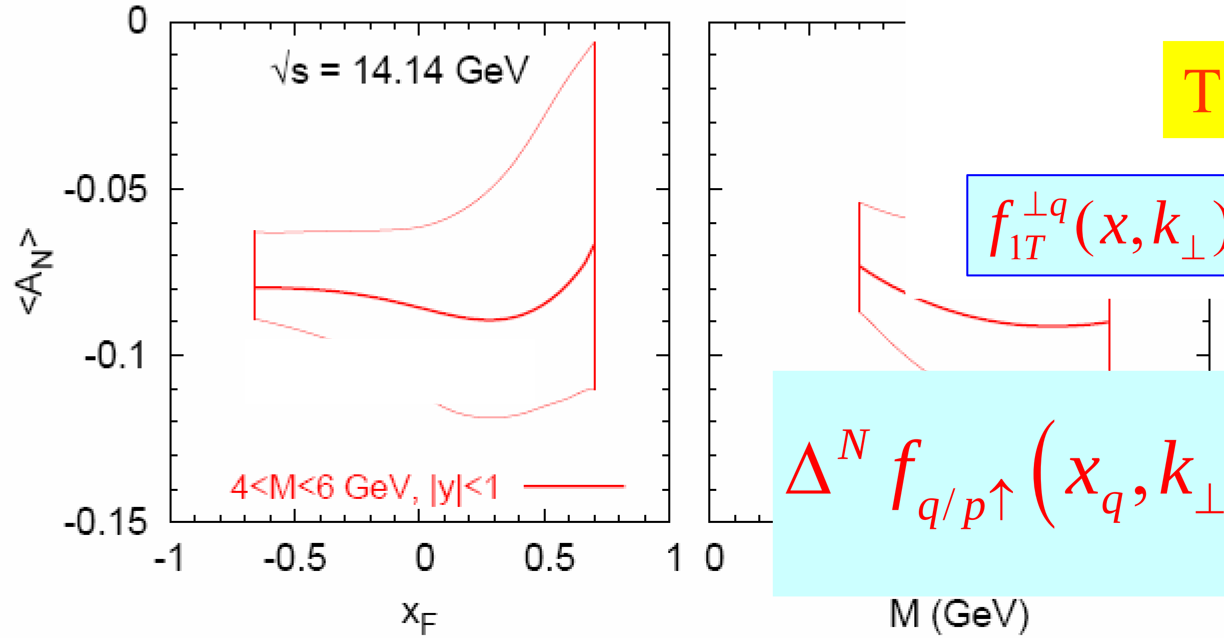
- new data available
- $A_{N,\bar{p}p^{\uparrow}\rightarrow\pi X}$ vs $A_{N,\bar{p}^{\uparrow}p\rightarrow\pi X}$
- DY-SSA (A_T) possible only @ RHIC, $p^{\uparrow}p$-scattering:

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

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

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}:

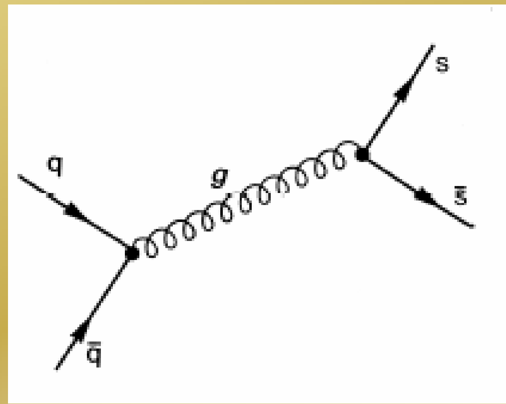
10 GeV^2	$D_{NN} < 0$
30 -40 GeV^2	$D_{NN} \sim 0$
400 GeV^2	$D_{NN} > 0$

D_{NN} @ 200 GeV^2 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_{NN}^{Λ} or K_{NN}^{Λ}.

NEW DATA NEEDED

Crossing GPD to GDA

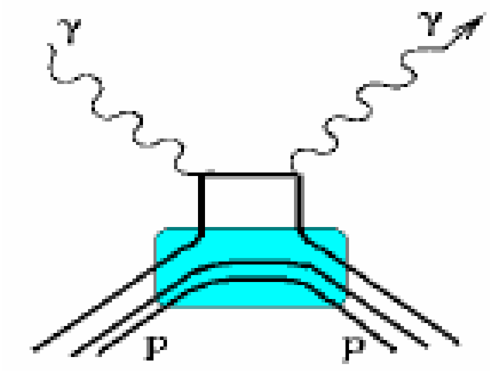
The real goal in a process is the
matrix element!

In exclusive channels ***crossing*** allow to:

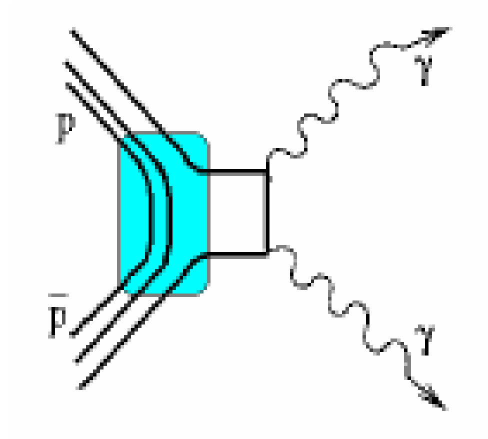
- measure the same matrix elements with completly different experiments and probes

- replacing Mandelstam *t* by *s* GPDs (General Parton Distributions) become GDAs (General Distribution Amplitudes)

$$\gamma p \rightarrow \gamma p$$



$$\bar{p} p \rightarrow \gamma\gamma$$

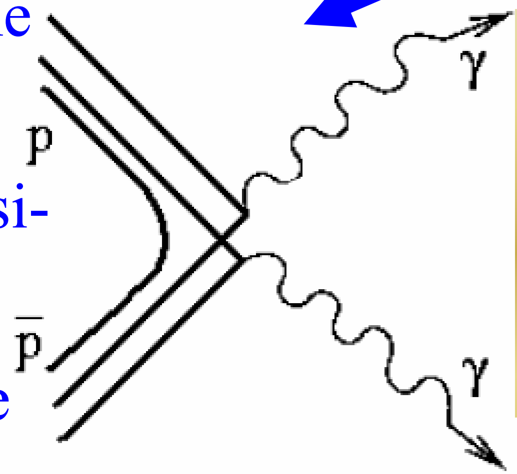


Accessing GDA in $\bar{p}p \rightarrow \gamma\gamma$

Data sample: ***large energies and angles***

suppressed

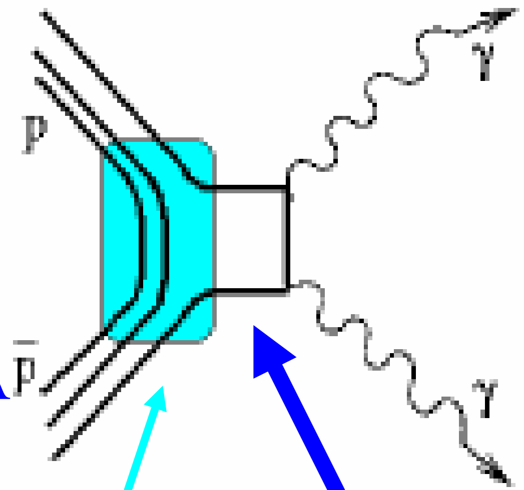
- the ***parton picture*** comes from the ***hard scale*** defined by a **large p_T**.
- ***single photon emission*** by a quasi-free parton ***is suppressed***
- ***two photon emission*** by the same parton ***is allowed***



Quasi-free partons cannot emit single photons

PANDA scenario (s~10 GeV)

1. hard interaction of one parton
2. a soft part parameterized by GDA

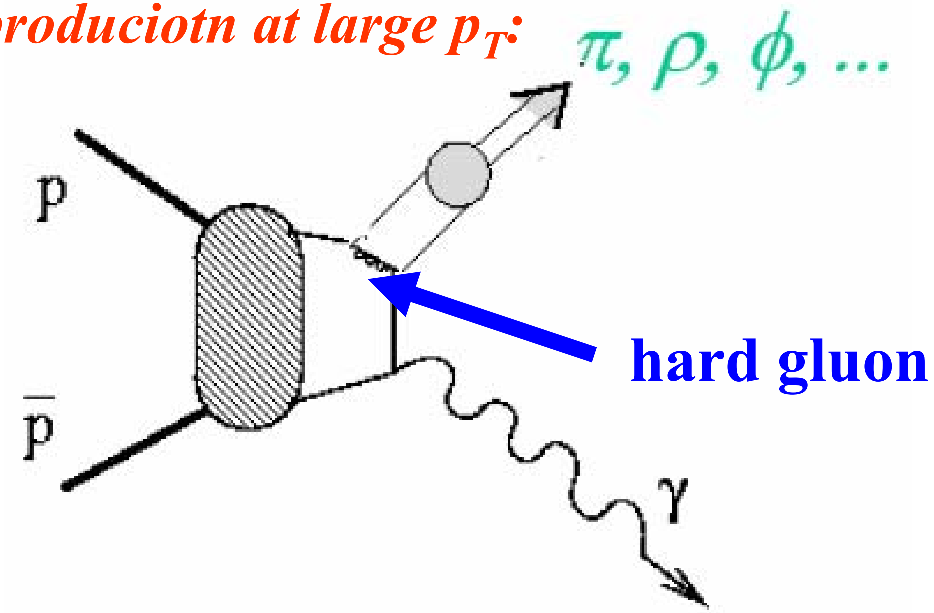


Hand bag diagram: one quark emits both the photons

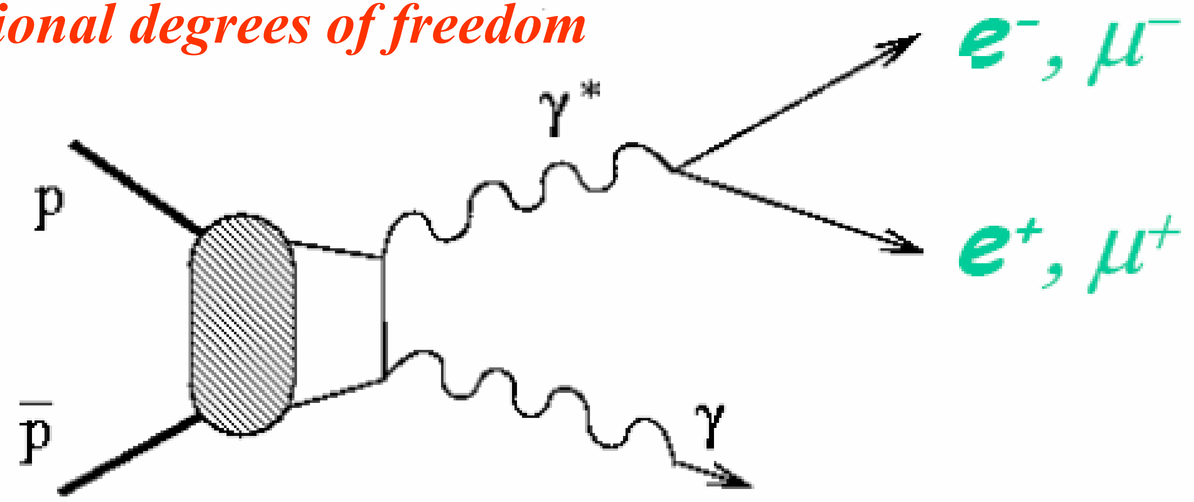
soft part **dominant mechanism**

Other processes with the QCD handbag diagram

- ***hard exclusive meson producioтn at large p_T:***

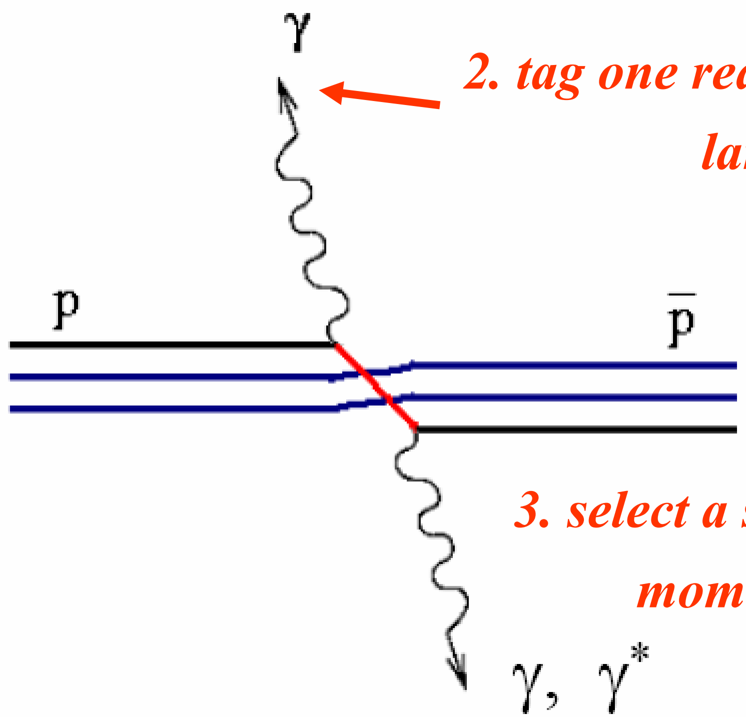


- ***small Q^2: like wide angle (large pT) crossed-channel Compton scattering***
- ***large Q^2: additional degrees of freedom***

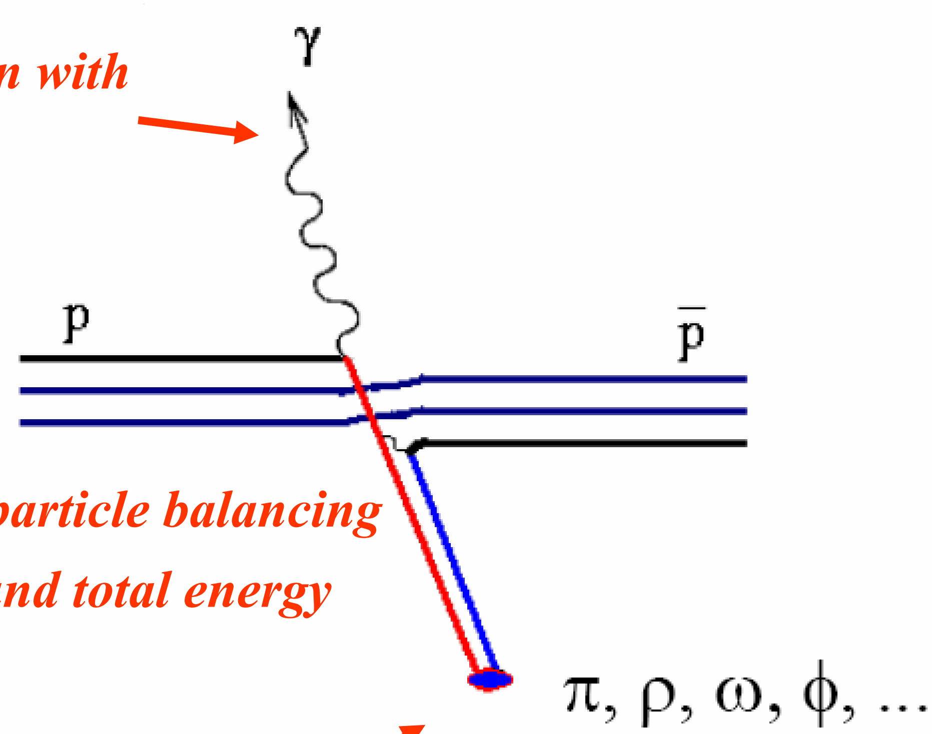


Roadmap for GDAs

1. reject events with more than 2 primary final state particle



2. tag one real photon with large pT



3. select a second particle balancing momentum and total energy

Cross section σ ≈ 2.5pb @ s ≈10 GeV^2
L = 2·10^{32} cm-2 s-1→ 10^3 events per month

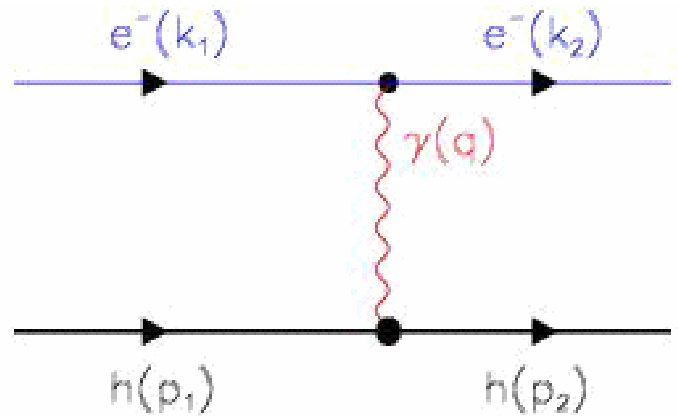
4. compare dσ of real photons and of any kind of neutral mesons (also charged on deuteron)

Ask theoreticians for predictions (spin observables can be defined for γ* and ρ)

Space-Like an Time-Like Electromagnetic form factors

- FFs are analytical functions.
- One Photon Exchange (OPE): FFs are function of the virtual photon squared momentum transfer: $t = q^2 = -Q^2$

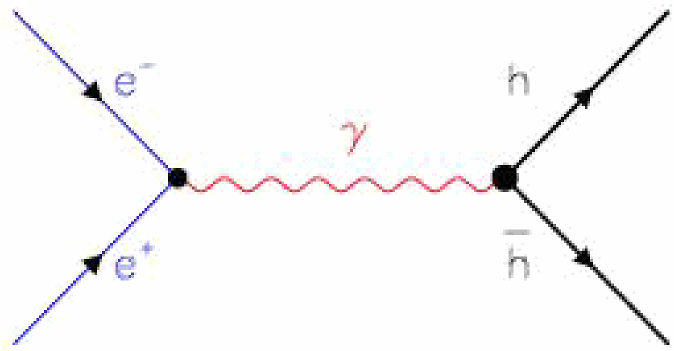
t < 0 : scattering



$$e^- + h \rightarrow e^- + h$$

Real FF: $q^2 \leq 0$

t > 0 : annihilation



$$e^- + e^- \rightarrow h + \overline{h}$$

Complex FF: $q^2 \geq 4M_p^2$

Imaginary part $\rightarrow$ Polarisation!

Phase can be measured!

Sachs Form Factors

Nucleon current operator
(Dirac and Pauli):

$$\Gamma^{\mu}(q) = \gamma^{\mu} F_1(q^2) \frac{ì}{2M_N} \sigma^{\mu\nu} q_\nu F_2(q^2) \quad \xrightarrow{\tau = \frac{q^2}{4M_N^2}} \quad \begin{aligned} G_E(q^2) &= F_1(q^2) + \tau F_2(q^2) \\ G_M(q^2) &= F_1(q^2) + F_2(q^2) \end{aligned}$$

t < 0 : scattering, space-like

- Fourier transfor of charge and magnetisation

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e^{'} \cos^2 \frac{\theta}{2}}{4 E_e^3 \sin^4 \frac{\theta}{2}} \left[G_E^2 + \tau \left(1 + 2(1+\tau) \tan^2 \frac{\theta}{2} \right) G_M^2 \right] \frac{1}{(1+\tau)}$$

t > 0 : annihilation, time-like

- at threshold, $\tau = 1$
- $G_E(4\ M_p^2) = G_M(4\ M_p^2)$
- G_E , G_M analytical continuation of nonspinflip and spinflip spacelike FF

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \sqrt{1 - \frac{1}{\tau}}}{4q^2} \left[\left(1 + 2\cos^2\theta\right) \left|G_M\right|^2 + \frac{1}{\tau} \sin^2\theta \left|G_E\right|^2 \right]$$

Sachs Form Factors

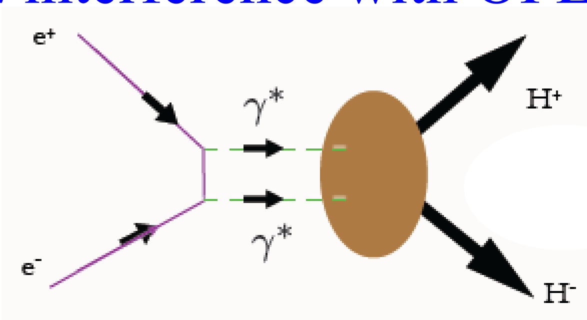
- all measurements cannot determine separately G_E and G_M
- only the ratio can be determined:

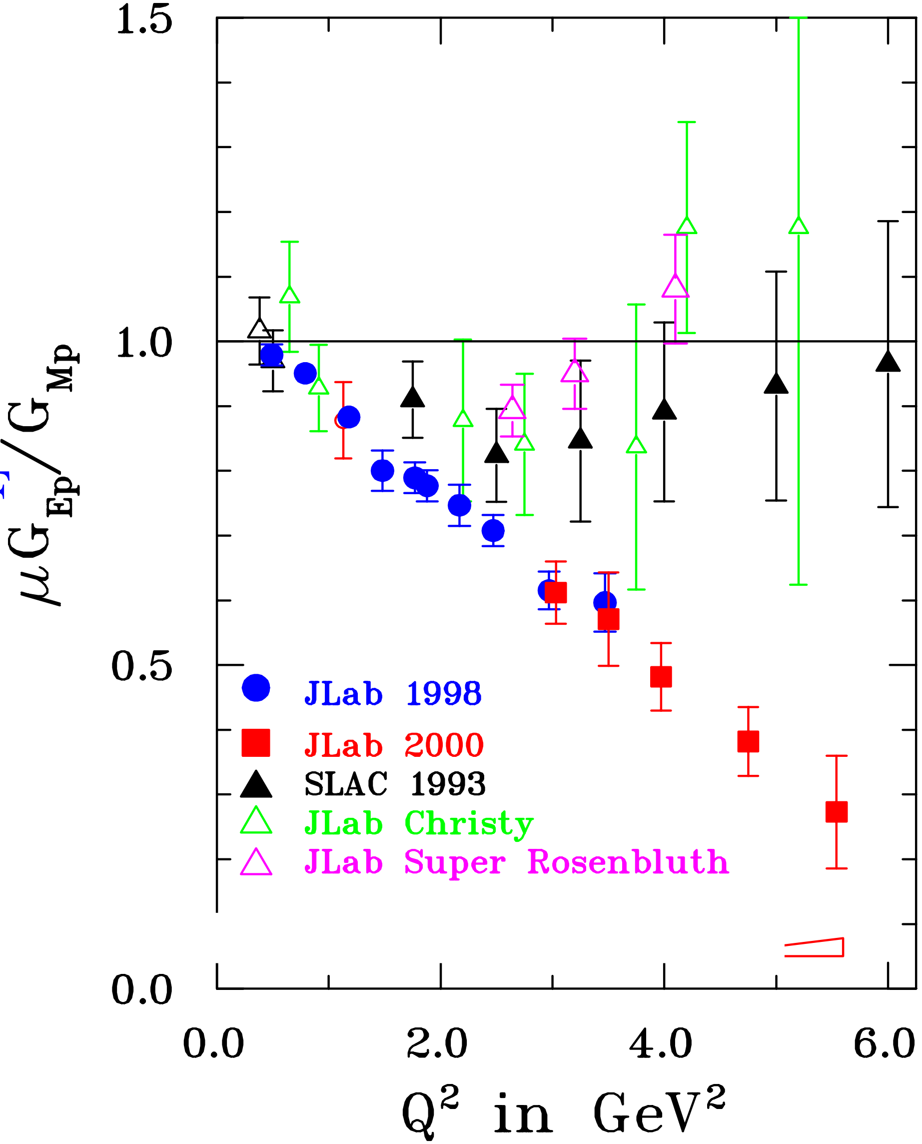
$$R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)}$$

- SL-FF show linear deviation from dipole:

$$\mu_p G_{Ep} \neq G_{Mp}$$

- significant difference between SL-FF data extracted with the Rosenbluth tecnique or with the "Polarisation transfer" technique: possible effect from TPE interference with OPE diagram?



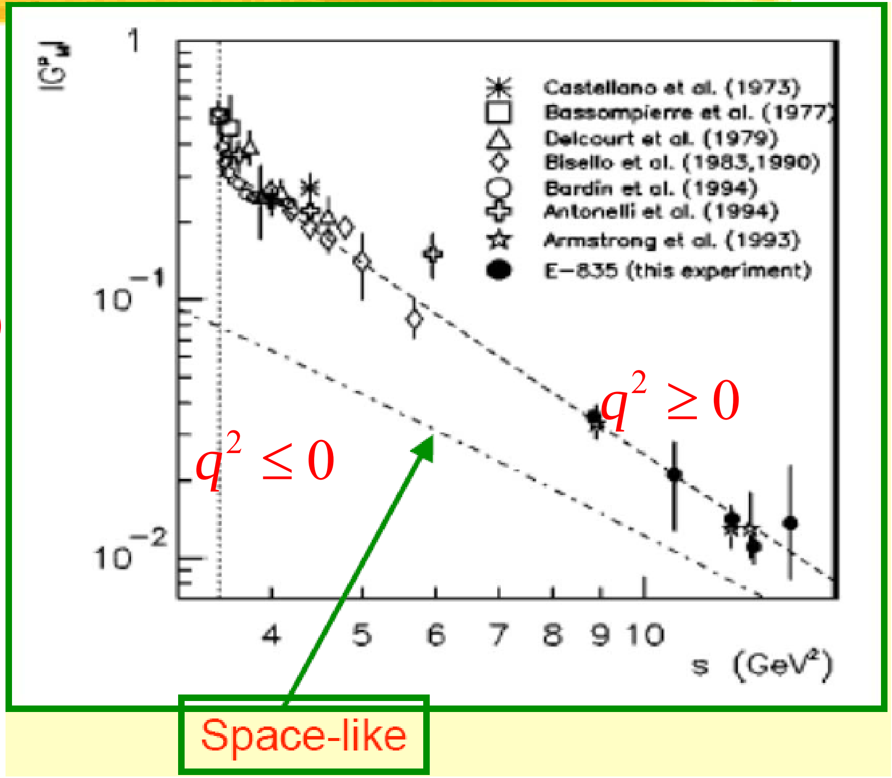


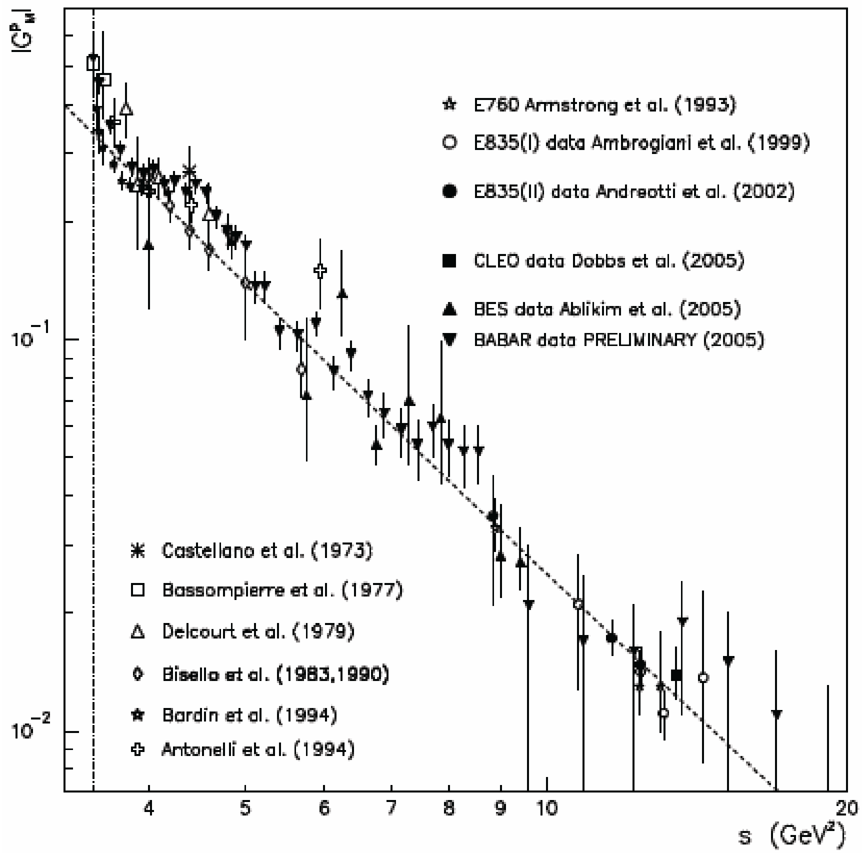
Sachs Form Factors

- pQCD predictions:

$$\lim_{q^2\to\infty}\left|G_M^p(q^2\geq 0)\right| = G_M^p(-q^2\geq 0)$$

experimental data $\Rightarrow \left|G_M^p(q^2)\right| \approx 2G_M^p(-q^2)$



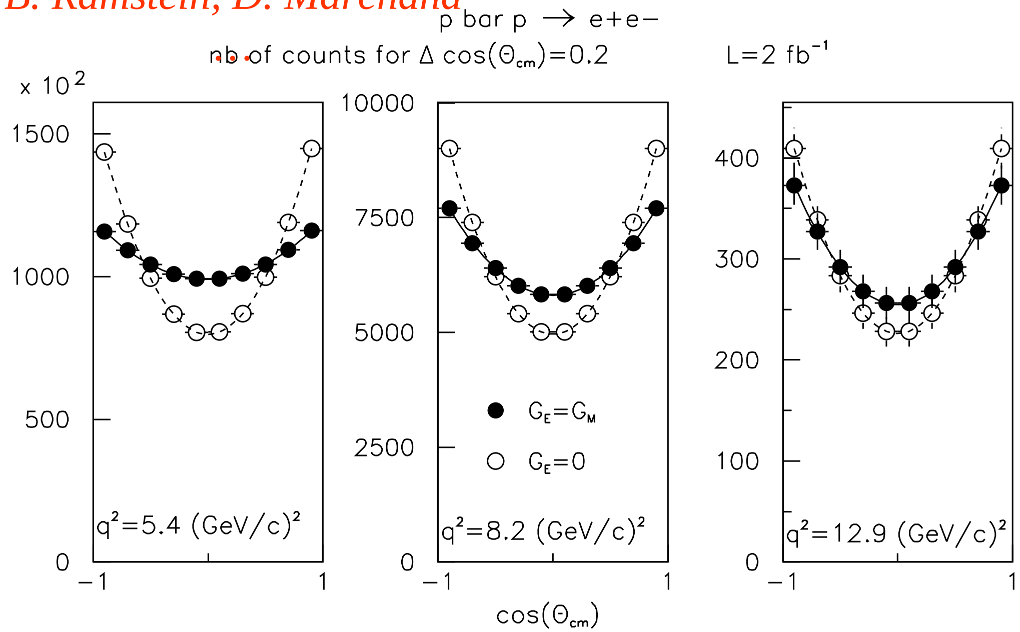


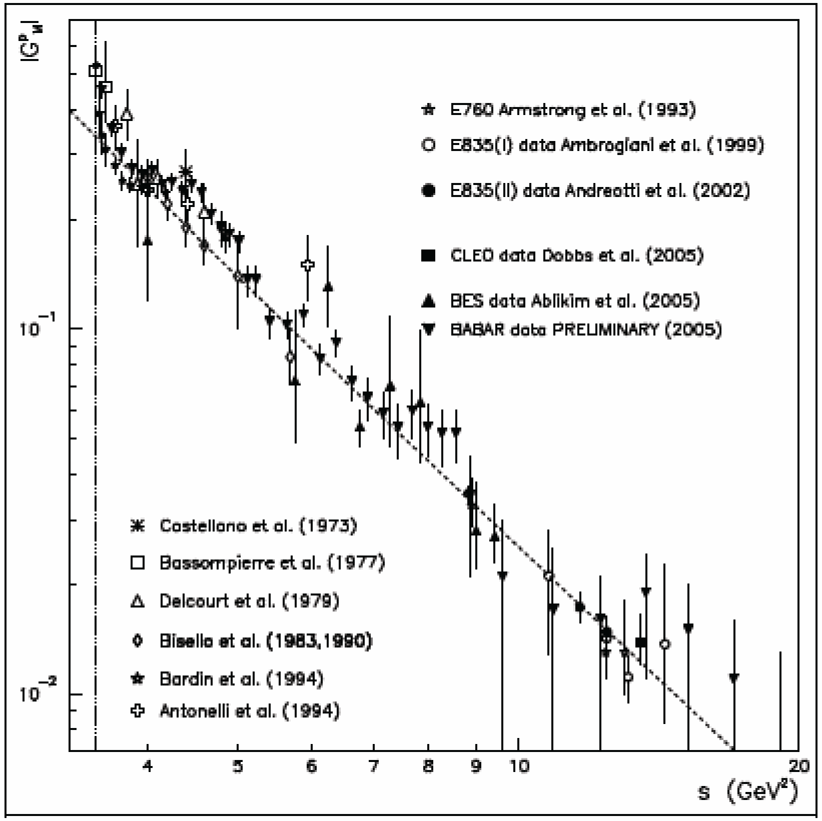
- in case of single FF quote, the absolute cross section is measured under the absuption $G_E = G_M$, even in the more recent TL-FF data
- recent data from BABAR points toward $G_E \neq G_M$

Sachs TL-FF in the HESR fixed target scenario (PANDA)

- widest kinematic range in a single experiment
- high satistics → independent measurement of G_E and G_M

B. Ramstein, D. Marchand





PANDA range

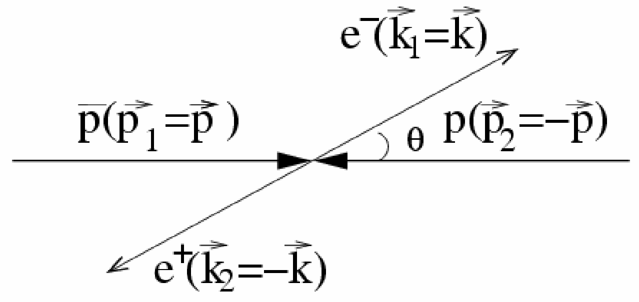
$T = 1$ GeV	$T = 5$ GeV	$T = 10$ GeV
$q^2 = 5.4\ \mathrm{GeV}^2/c$	$q^2 = 12.9\ \mathrm{GeV}^2/c$	$q^2 = 22.3\ \mathrm{GeV}^2/c$

100 days, L=2 10^{32} $cm^{-2}s^{-1}$, 2 fb^{-1}

$N_{tot} = 10^6$	$N_{tot} = 2750$	$N_{tot} = 82$

Fermilab, 14 ev. at 13 $(GeV/c)^2$

Sachs TL-FF Spin Observables in $\bar{p}^{(\uparrow)} p^{\uparrow} \to e^+ e^-$



Analyzing power, A

$$\frac{d\sigma}{d\Omega}(P_y) = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \mathcal{A} P_y],$$

$$\mathcal{A} = \frac{\sin 2\theta \, Im G_E^* G_M}{D\sqrt{\tau}}, \quad D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta$$

- relative G_E and G_M phase in the TL region

Double spin observables

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} = \sin^2\theta \left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{yy} = -\sin^2\theta \left(|G_M|^2 - \frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{zz} = \left[(1+\cos^2\theta)|G_M|^2 - \frac{1}{\tau}\sin^2\theta |G_E|^2\right]\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xz} = \left(\frac{d\sigma}{d\Omega}\right)_0 A_{zx} = \frac{1}{\sqrt{\tau}}\sin 2\theta \, Re G_E G_M^* \mathcal{N}.$$

- indipendent G_E - G_M separation
- Rosenbluth separation test in TL region

The hunt for the nucleon structure @ FAIR

Drell-Yan dilepton production

- double spin DY is the dream option
- new physics from unpolarised DY since the very beginning
- extense SSA program in DY and in hadron production

Generalised Distribution Amplitudes

- investigation of the TPE diagramm al large p_T
- large p_T lepton and meson production
- test on factorisation (GDA + HB diagram)

Time-Like Electromagnetic Form Factors

- TL-FF investigation
- test on Rosenbluth separation in the TL region
- separate estimation of G_E and G_M
- accessing single and double spin asymmetries

Collaborations: PANDA & PAX

Question time

THANK YOU!