Hard Exclusive Processes at COMPASS

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Probing Hadron Structure from Hard Exclusive Processes

9-11 November 2009, Garching (Munich)

Analyses of hard exclusive processes at COMPASS

- Results on exclusive ρ^0 and φ muoproduction
  - transverse target spin asymmetry ρ^0 on p, d
  - double spin asymmetry ρ^0, φ on d
  - SDMEs ρ^0, φ on p, d
  - cross sections, R($=\sigma_L/\sigma_T$), t-slopes ρ^0, φ on p, d

- Feasibility studies of colour transparency
  - hard exclusive VM muoproduction
  - hard coherent diffractive dissociation of pion beam

COMPASS setup

as in μ run
NIM A 577(2007) 455

- **high energy beam**
- **large angular acceptance**
- **broad kinematical range**

two stages spectrometer

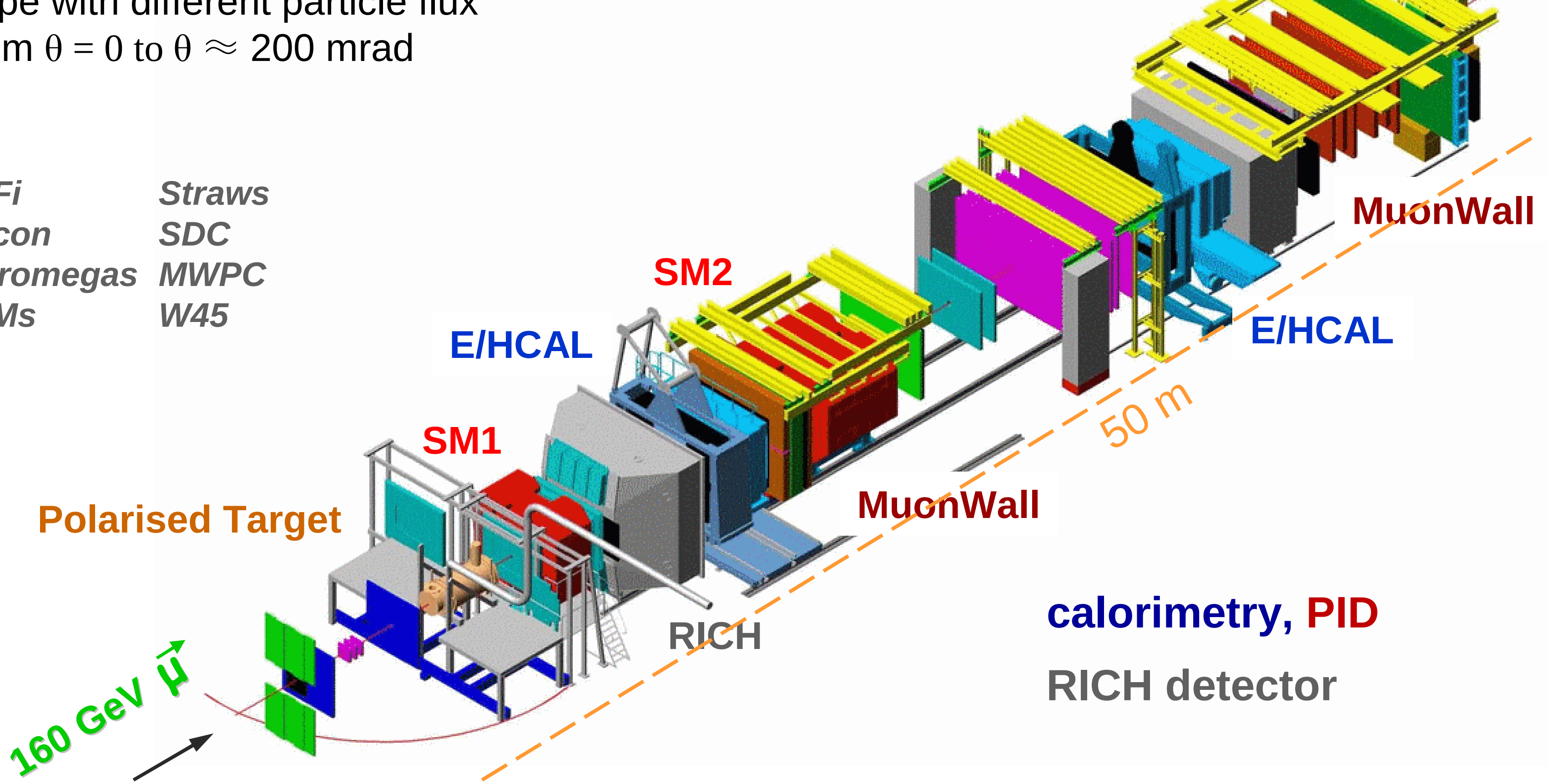
Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

Luminosity $5 \cdot 10^{32}\ cm^{-2}s^{-1}$

variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



calorimetry, PID

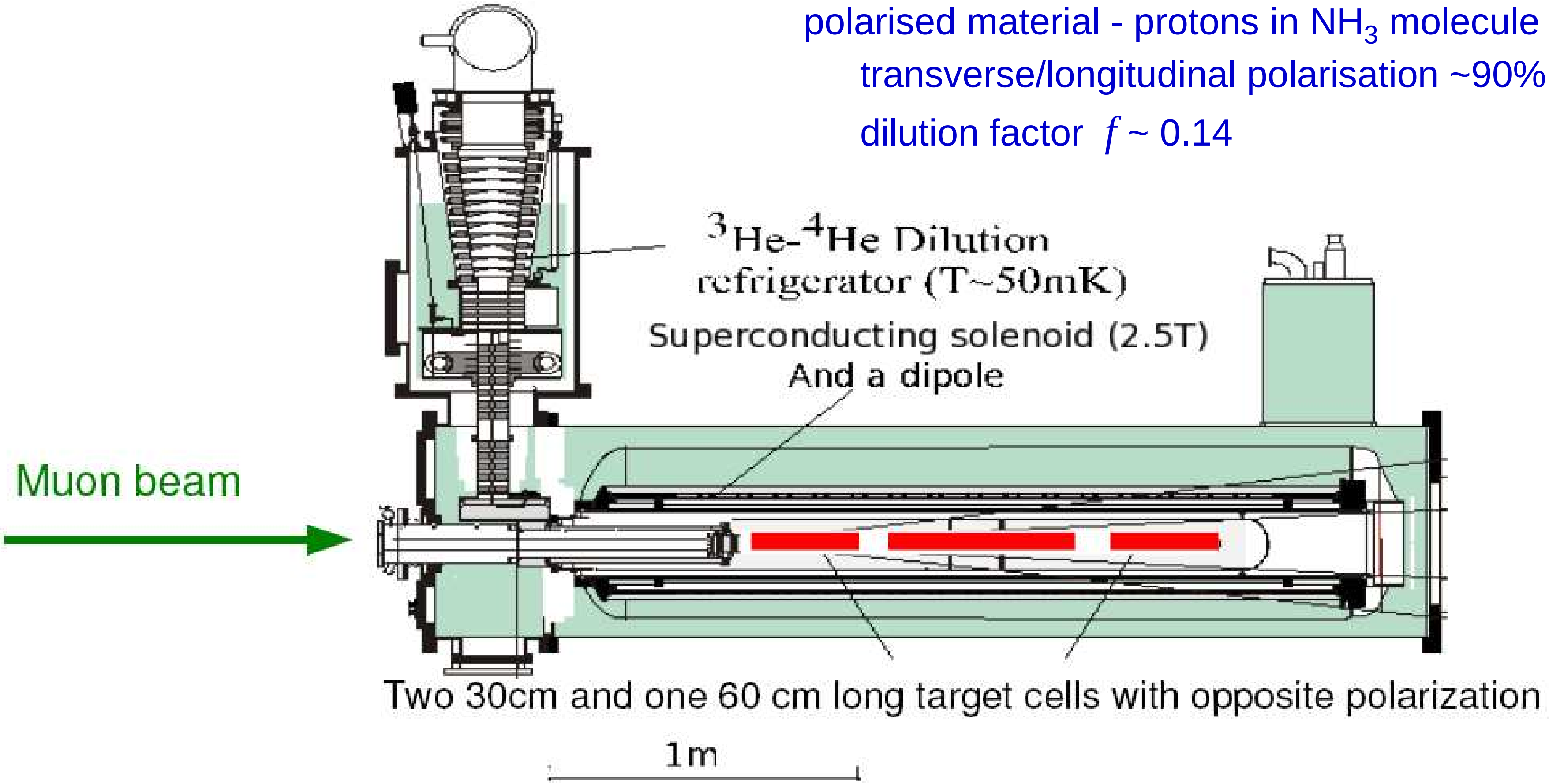
RICH detector

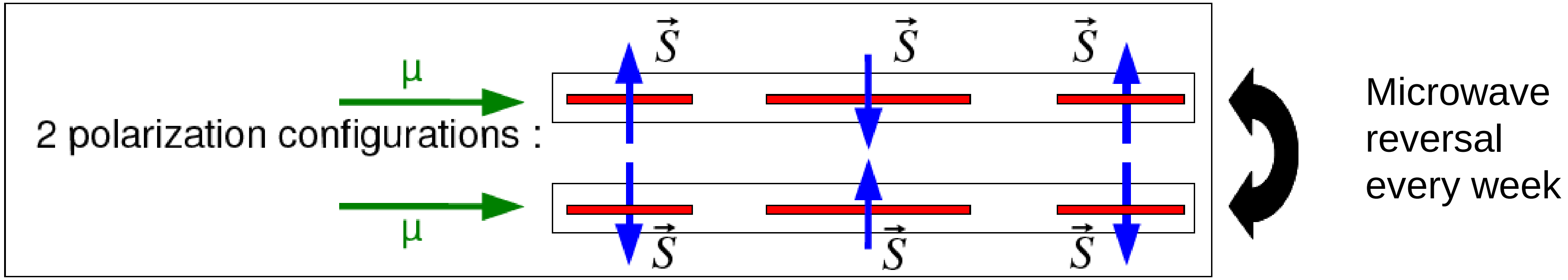
COMPASS polarised ammonia target (2007)

polarised material - protons in NH_3 molecule

transverse/longitudinal polarisation ~90%

dilution factor $f \sim 0.14$

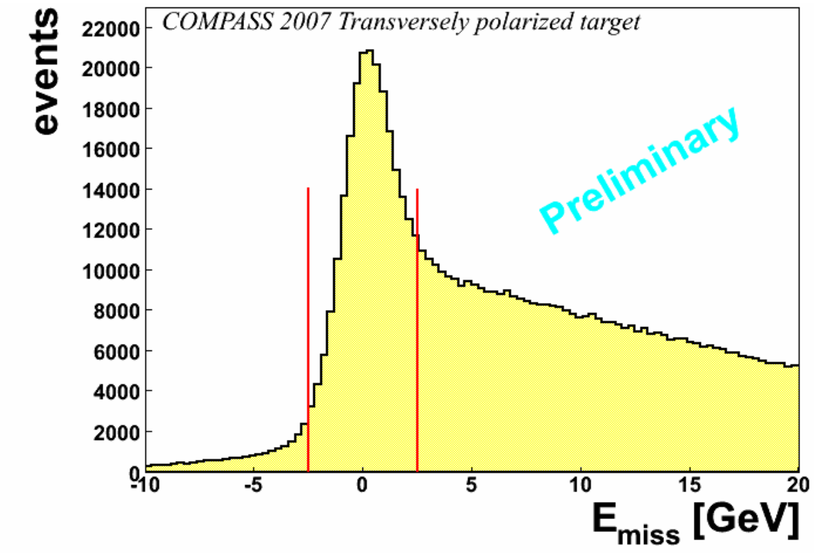




Selections of exclusive ρ^0 events

Transversely polarised proton target (NH_3), $P_T \approx 90\%$, 2007 data

$Q^2 > 1$ GeV^2
W > 5 GeV
$0.005 < x_{Bj} < 0.1$
$0.05 < p_t^2 < 0.5$ GeV^2



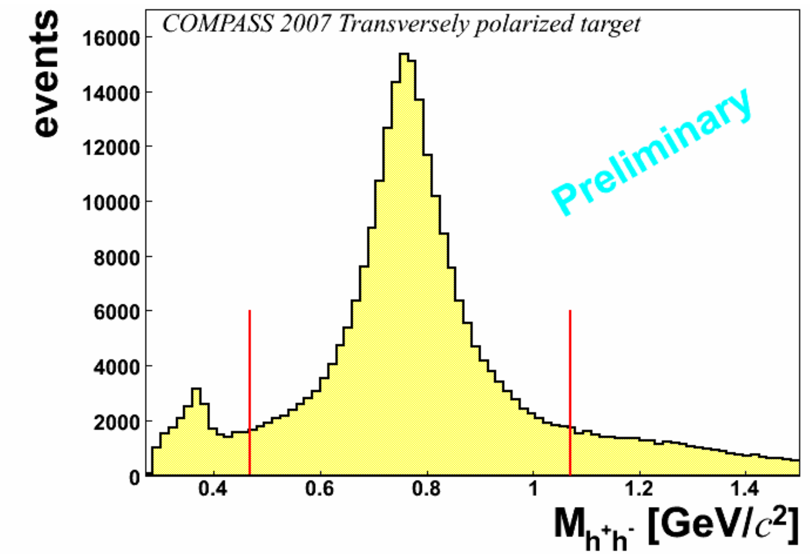
- recoil proton (recoiling system) not detected

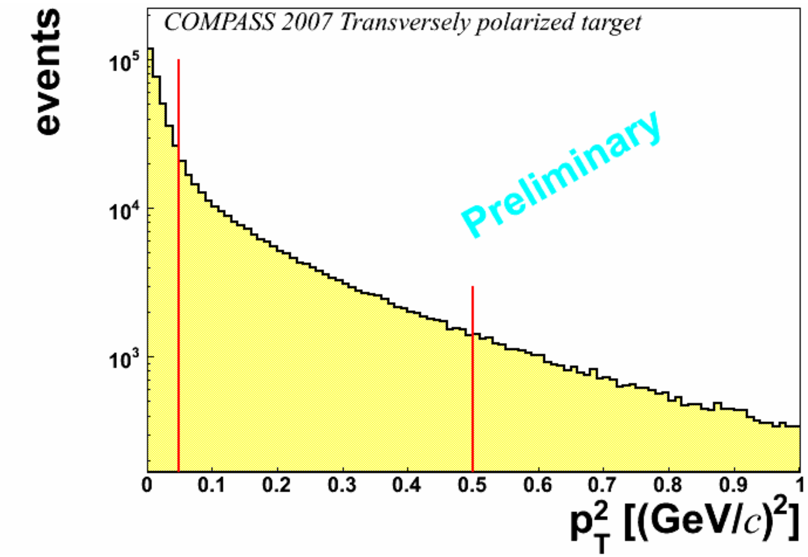
$$E_{miss} = \frac{M_X^2 - M_{proton}^2}{2M_{proton}} \in [-2.5, 2.5]\,GeV$$

- charged pion mass assumed for $h^+(h^-)$

$$-0.3 < M_{\pi\pi} - M_{\rho(\mathrm{PDG})} < 0.3\ \mathrm{GeV}/c^2$$

- cuts on p_t^2 to remove coherent production from N and further suppress non-exclusive background





Observables in hard exclusive meson production relevant for GPDs

for vector mesons

unpolarised cross section ($\sigma_{00}^{++} \equiv \sigma_L$)

$$\frac{1}{\Gamma'}\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)\,|\mathcal{H}_M|^2 - \left(\xi^2 + \frac{t}{4M_p^2}\right)|\mathcal{E}_M|^2 - 2\xi^2\,\mathrm{Re}\,(\mathcal{E}_M^*\mathcal{H}_M),$$

transverse target spin asymmetry

$$\frac{1}{\Gamma'}\,\mathrm{Im}\,\frac{d\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}\,(\mathcal{E}_M^*\mathcal{H}_M)$$

access to GPD E

related to orbital momentum

$\mathcal{H}_M, \mathcal{E}_M$ are weighted sums of integrals of the GPDs $H_{q,g}$, $E_{q,g}$

weights depend on contributions of various quark flavours and of gluons to the production of meson M

$$\Gamma' = \frac{\alpha_{\mathrm{em}}}{Q^6}\,\frac{x_B^2}{1-x_B}$$

$$\xi = \frac{x_B}{2-x_B}, \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

(large Q^2 approximation)

Give access to the orbital angular momentum of quarks

$$\boxed{\frac{1}{2}\int_{-1}^{1} dx\; x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] \overset{t\to 0}{=} J_q = \frac{1}{2}\Delta\Sigma + L_q}$$

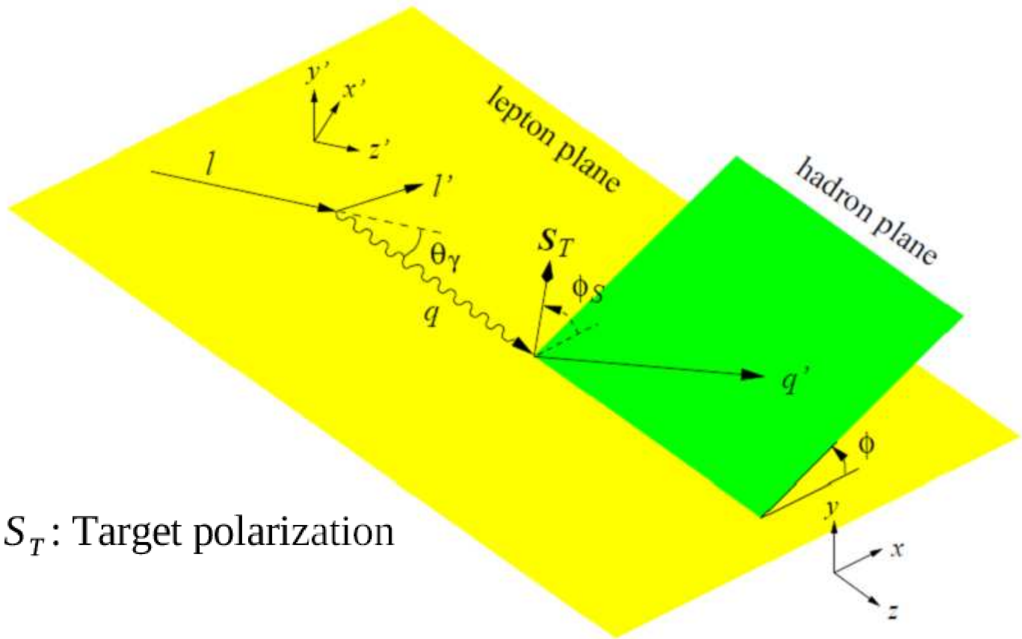
Ji's sum rule

So far GPD E poorly constrained by data (mostly by Pauli form factors)

Transverse target spin asymmetry for exclusive ρ^0 production

$$\mu + P^{\uparrow} \rightarrow \mu' + P' + \rho^0$$

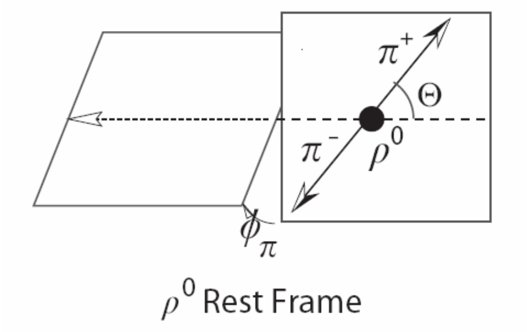
definitions



S_T: Target polarization

to disentangle contributions from γ_L and γ_T the distribution of ρ^0 decay polar angle needed in addition

Diehl and Sapeta (2005)



- Spin-dependent photoabsorption cross sections and interference terms σ^{ij}_{mn}

$$\boxed{\sigma^{ij}_{mn}(x_B, Q^2, t) \propto \sum_{spins} (A^i_m)^* A^j_n}$$

A^i_m amplitudes for subprocess $\gamma^* p \rightarrow \rho^0 p$ with proton polarisation i and photon polarisation m

- Virtual photon polarisation parameter $\varepsilon = \dfrac{1 - y - \frac{1}{4}y^2\gamma^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2\gamma^2}$,

(if m_l can be neglected)

Cross sections in terms of target polarisation wrt virtual photon

(in deep inelastic kinematics)

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_S}$$

$$= \underbrace{\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}} - \varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++} - \sqrt{\varepsilon(1+\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$- P_\ell\sqrt{\varepsilon(1-\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$- S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\,\sigma_{+-}^{++}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$+ S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$- S_T\Big[\underbrace{\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-}}) + \frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-} + \frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}$$

$$+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\Big]$$

$$+ S_T P_\ell\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}$$

$$-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\,\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\Big].$$

Extraction of transverse target spin asymmetry

Flux Acceptance Dilution factor Mean target polarisation

$$N(\phi-\phi_s) = F\, n\, a(\phi-\phi_s)\,\sigma_0\,(1 \pm f\,\langle P_T\rangle A_{UT}\sin(\phi-\phi_s))$$

Numer of target nucleons

$$\sigma_0 = \frac{1}{2}(\sigma_{++}^{++} + \sigma_{++}^{--}) + \varepsilon\,\sigma_{00}^{++} \equiv \sigma_T + \varepsilon\,\sigma_L \qquad A_{UT} = -\frac{\mathrm{Im}(\sigma_{++}^{+-} + \varepsilon\,\sigma_{00}^{+-})}{\sigma_0}$$

Asymmetry extraction from double ratio method using 3 targets with two polarisations each

$$DR(\phi-\phi_s) = \frac{N^{\uparrow}_{Up/Down}(\phi-\phi_s)\,N^{\uparrow}_{Center}(\phi-\phi_s)}{N^{\downarrow}_{Center}(\phi-\phi_s+\pi)\,N^{\downarrow}_{Up/Down}(\phi-\phi_s+\pi)}$$

$$= \frac{F^{\uparrow}_{Up/Down}F^{\uparrow}_{Center}}{F^{\downarrow}_{Center}F^{\downarrow}_{Up/Down}}\;\frac{a^{\uparrow}_{Up/Down}(\phi-\phi_s)\,a^{\uparrow}_{Center}(\phi-\phi_s)}{a^{\downarrow}_{Center}(\phi-\phi_s+\pi)\,a^{\downarrow}_{Up/Down}(\phi-\phi_s+\pi)}\;\frac{(1+f\,\langle P_T\rangle A_{UT}\sin(\phi-\phi_s))^2}{(1-f\,\langle P_T\rangle A_{UT}\sin(\phi-\phi_s))^2}$$

in the double ratio Flux and σ_0 cancel

also Acceptance cancels provided no changes between spin reversals

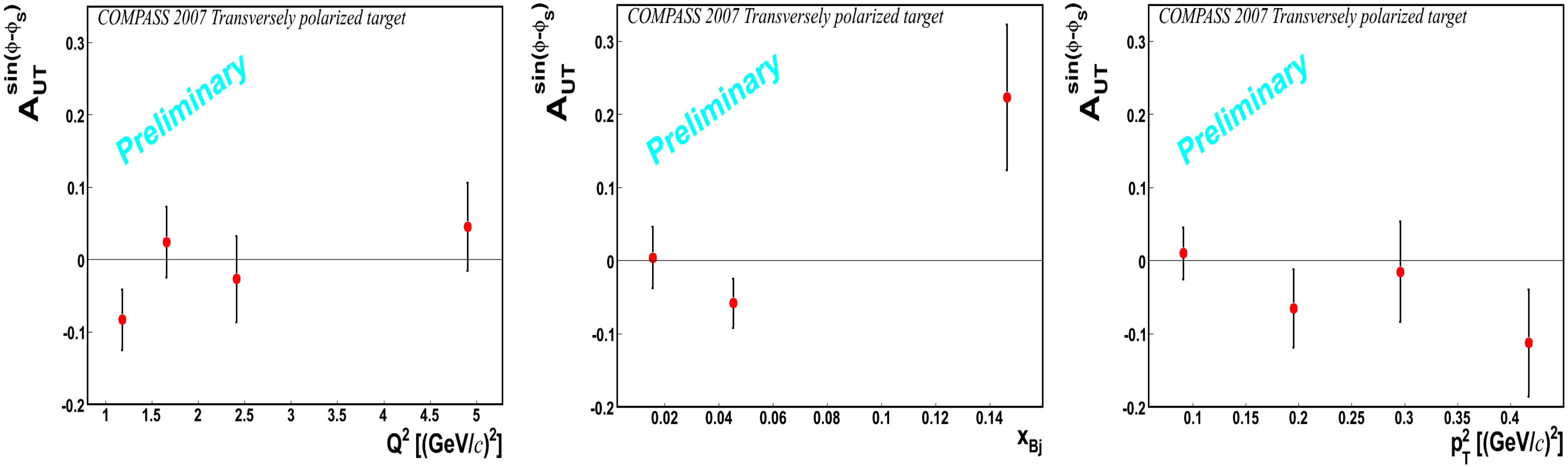
A_{UT} from a fit to $DR\ (\phi\text{-}\phi s)$

Transverse target spin asymmetry: polarised protons (2007)

new

NH_3 target

$< Q^2 > \approx 2.2\ (\mathrm{GeV}/c)^2$ $< x_{Bj} > \approx 0.04$ $< p_t^2 > \approx 0.18\ (\mathrm{GeV}/c)^2$



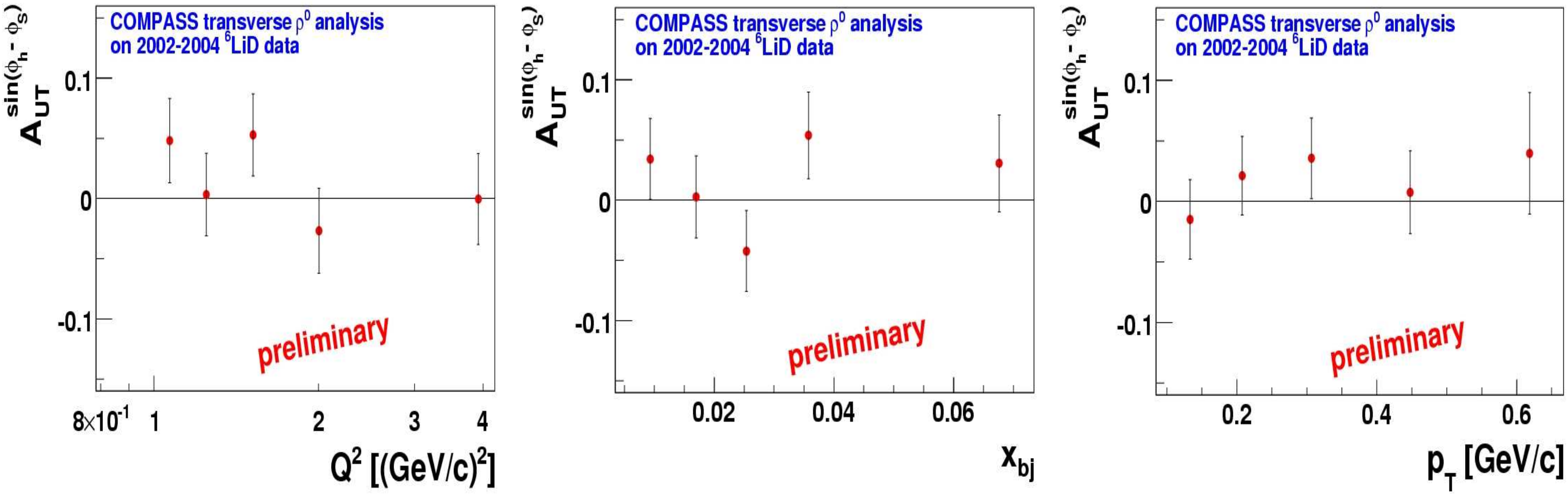
$A_{UT}^{\sin(\phi-\phi_s)}$ compatible with 0

In progress: L/T γ^* separation (using ρ^0 decay angular distribution)

Transverse target spin asymmetry: polarised deuterons (2002-2004)

^{6}LiD target

$< Q^2 > \approx 2.0\ (\mathrm{GeV}/c)^2$ $\quad < x_{Bj} > \approx 0.03$ $\quad < p_t > \approx 0.11\ \mathrm{GeV}/c$



$\boxed{A_{UT}^{\sin(\phi-\phi_s)} \text{ compatible with } 0}$

In progress: L/T γ^* separation (using ρ^0 decay angular distribution)

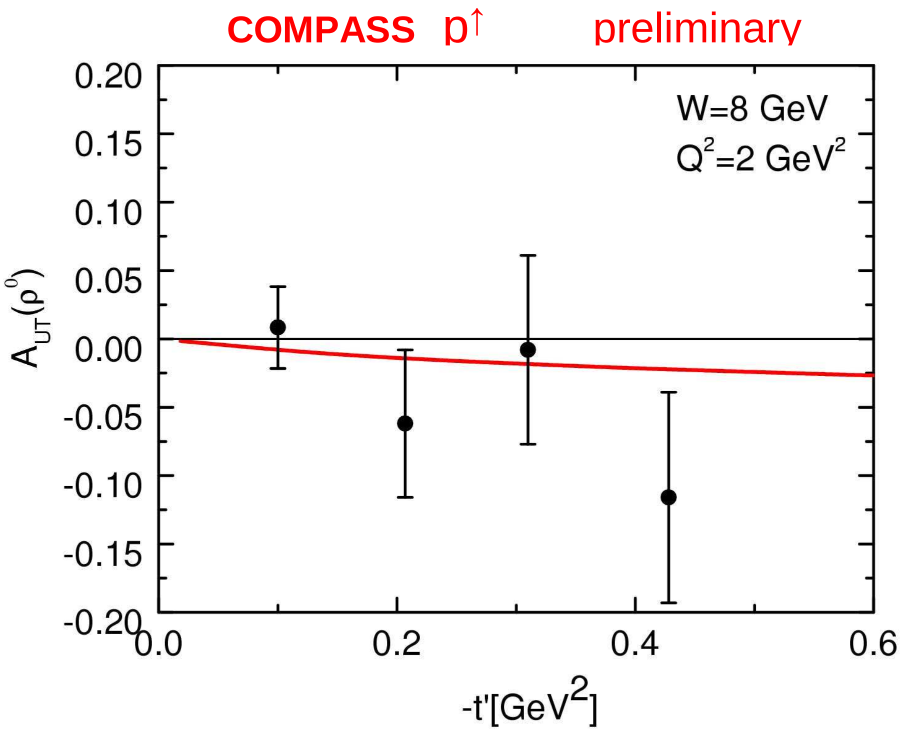
and coherent / incoherent separation for deuteron

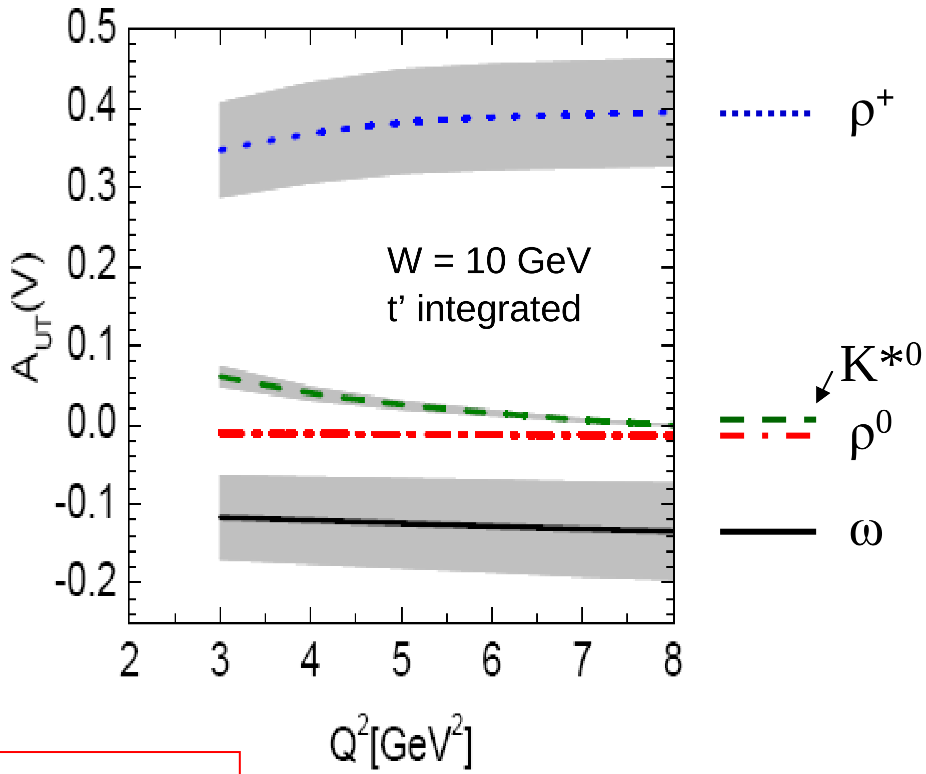
Comparison to a GPD model

- Goloskokov-Kroll

[EPJ C53 (2008) 367]

'Hand-bag model'; GPDs from DD using CTEQ6
power corrections due to k_t of quarks included
→ both contributions of γ^*_L and γ^*_T included





predictions for protons

$A_{UT}(\rho) \approx -0.02$
$A_{UT}(\omega) \approx -0.10$

Longitudinal double-spin asymmetry for exclusive ρ^0 production

EPJ C 52 (2007)

$<P_B>$ = -0.76   longitudinally polarised deuteron target (^{6}LiD) $P_T \approx$ 50% $f \approx$ 0.37

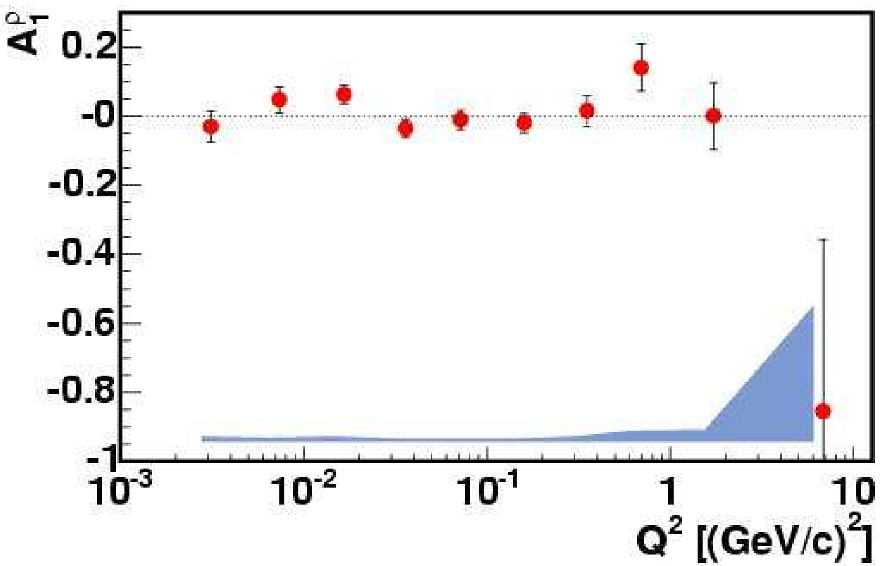
wide range of Q^2 and x ,   W > 7.5 GeV ,   0.15 < p_t^2 < 0.5 GeV²

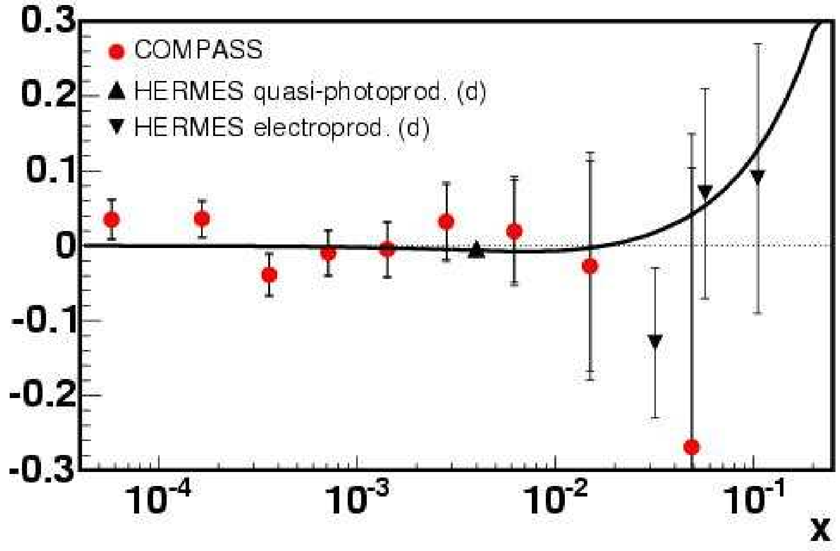
$$A_{LL}(\mu N \to \mu N \rho^0) = \frac{\sigma(\mu N)_{\uparrow\Downarrow} - \sigma(\mu N)_{\uparrow\Uparrow}}{\sigma(\mu N)_{\uparrow\Downarrow} + \sigma(\mu N)_{\uparrow\Uparrow}} = \frac{1}{f}\cdot\frac{1}{P_b}\cdot\frac{1}{P_t}\cdot A_{LL}^{raw}$$

$$A_1^\rho(\gamma^* N \to \rho^0 N) \approx \frac{1}{D} A_{LL}(\mu N \to \mu N \rho^0)$$

curve: $A_1^\rho = \frac{2\,A_1}{1 + (A_1)^2}$

where A_1 – inclusive asymmetry (d)





A_1^ρ on polarised deuterons consistent with 0

Longitudinal double-spin asymmetry for exclusive ρ^0 production (cont.d)

estimate of contribution of unnatural exchanges (π, a_1)

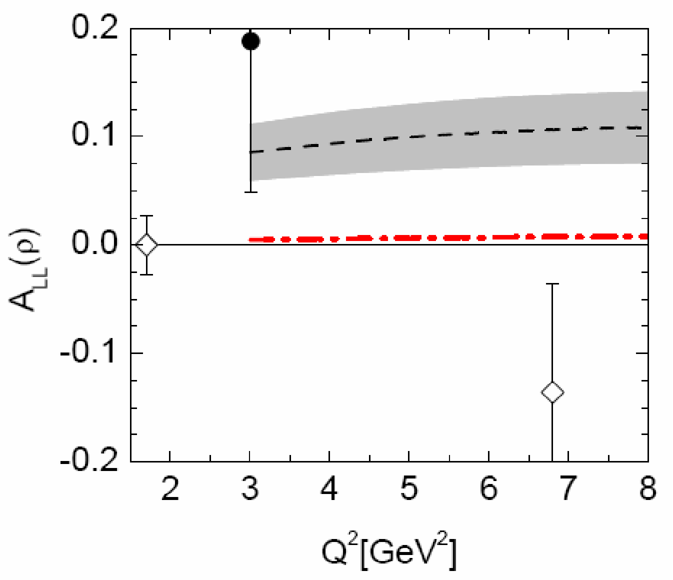
$$A_1^\rho = \frac{\sum_{\lambda_\rho \lambda_{N'}} 2Re\left\{T^N_{\lambda_\rho\lambda_{N'},++} \cdot T^{*U}_{\lambda_\rho\lambda_{N'},++}\right\}}{\sum_{\lambda_\rho \lambda_{N'}}\left\{|T^N_{\lambda_\rho\lambda_{N'},++}|^2 + |T^U_{\lambda_\rho\lambda_{N'},++}|^2\right\}} \Rightarrow \frac{2Re\left\{T^N_{++,++} \cdot T^{*U}_{++,++}\right\}}{|T^N_{++,++}|^2 + |T^U_{++,++}|^2}$$

if SCHC

The asymmetry is a sensitive probe of unnatural parity exchanges

- at small Q^2 and x data provides precise limits on their contribution

- at large Q^2 A_1^ρ related to GPDs (higher-twist) $\propto k_T^2 \tilde{H}_{g(sea)} / (Q^2 H_{g(sea)})$



Goloskokov, Kroll (2007)

W = 5 GeV ● HERMES

W = 10 GeV ◇ COMPASS

small value of A_1^ρ at W ≥ 10 GeV due to approximate cancellation of gluon and sea contributions

Spin Density Matrix Elements

VM angular distributions $W(\cos\theta, \varphi_\pi, \phi)$ depend on the spin density matrix elements (SDME) ⇨ 23 (15) observables with polarized (unpolarized) beam

SDMEs are bilinear combinations of the helicity amplitudes $\boxed{T_{\lambda m\, \lambda\gamma}(\gamma^* N \longrightarrow mN)}$

$\lambda\gamma = \pm 1, 0 \qquad \lambda m = \pm 1, 0$

(averaged over nucleon spins)

- describe helicity transfer from γ^* to VM

  s-channel helicity conservation (SCHC)

- describe parity of t-channel exchange

  (NPE vs. UPE)

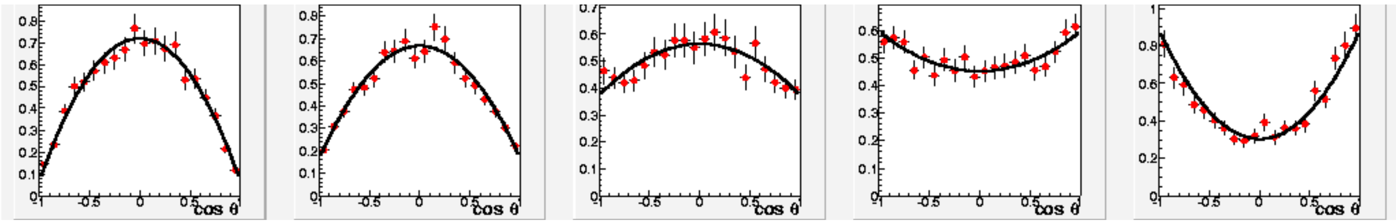
- impact on GPD studies – determination of σ_L

  SDME $r_{00}^{04} \xrightarrow{SCHC} R = \dfrac{\sigma_L}{\sigma_T}$

Measurement of r^{04}_{00} and determination of $R = \sigma_L/\sigma_T$

0.01 < Q^2 < 0.05 < Q^2 < 0.3 < Q^2 < 0.6 < Q^2 < 2.0 < Q^2 < 10 GeV²

W(cos θ)



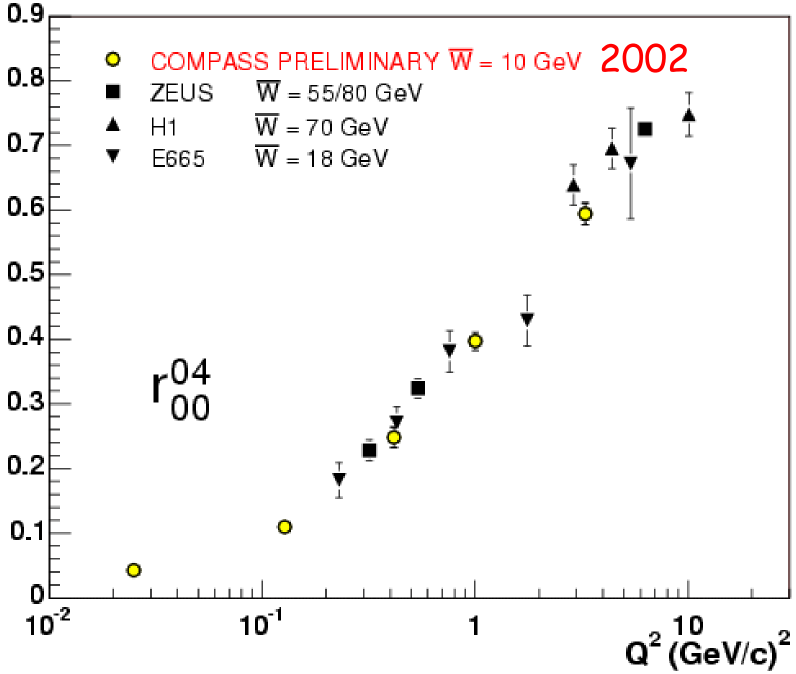
$$W(\cos\theta) = \frac{3}{4}\left[(1 - r^{04}_{00}) + (3r^{04}_{00} - 1)\cos^2\theta\right]$$

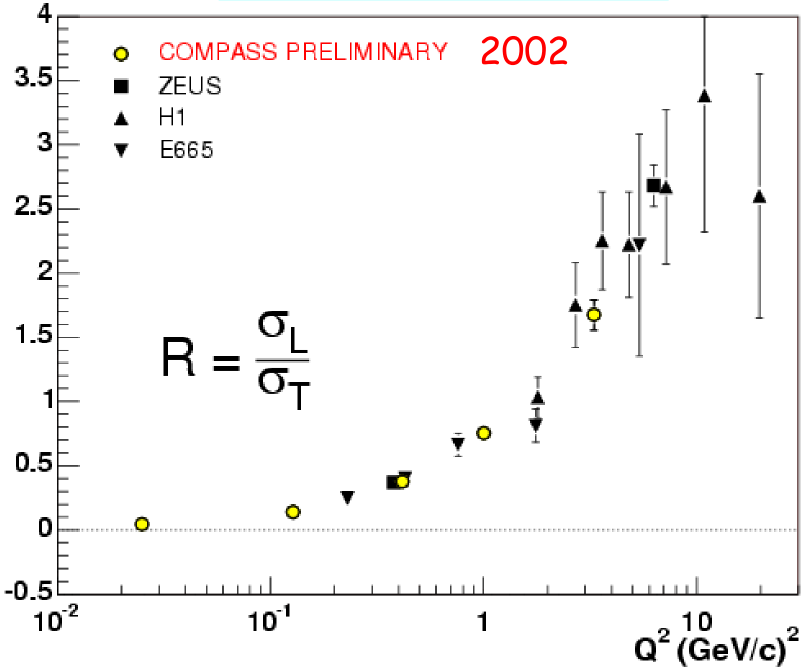
$$r^{04}_{00} \sim \frac{\cancel{|T_{01}|^2} + (\varepsilon + \delta)|T_{00}|^2}{\sigma_T + (\varepsilon + \delta)\sigma_L}$$

$T_{\lambda\rho\,\lambda\gamma}$ helicity amplitudes

meson photon

$$r^{04}_{00} \xrightarrow{\text{SCHC}} R = \frac{\sigma_L}{\sigma_T}$$



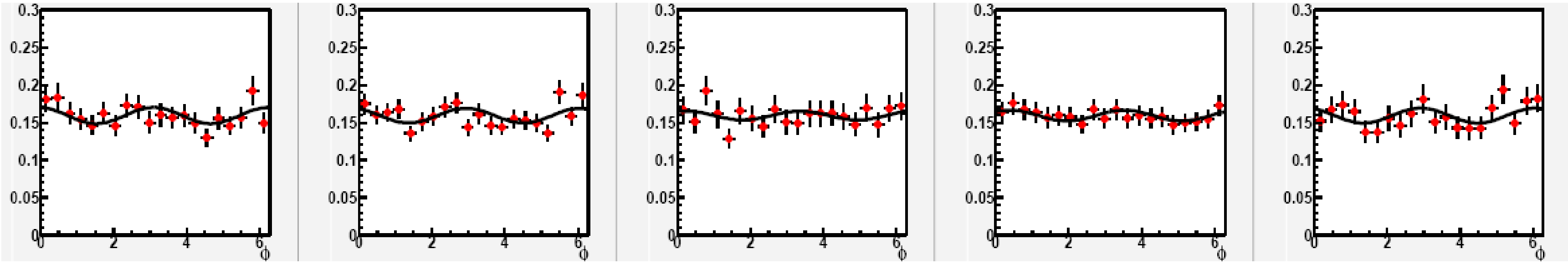


- High statistics from quasi-photoproduction to hard production
- Impact on GPD studies; determination of σ_L

Measurement of r^{04}_{1-1} and Im r^{3}_{1-1}

$0.01 < Q^2 < 0.05 < Q^2 < 0.3 < Q^2 < 0.6 < Q^2 < 2.0 < Q^2 < 10$ GeV²

W(φ)



($\varphi \equiv \varphi_\pi$)

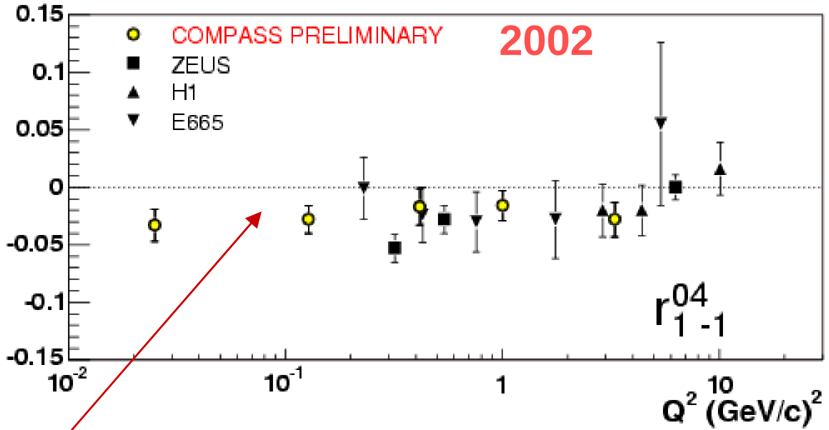
$$W(\varphi) = \frac{1}{2\pi}[1 - 2r^{04}_{1-1}\cos 2\varphi + 2\,\mathrm{Im}\,r^{3}_{1-1} P_\mu \sqrt{1-\varepsilon^2}\,\sin 2\varphi]$$

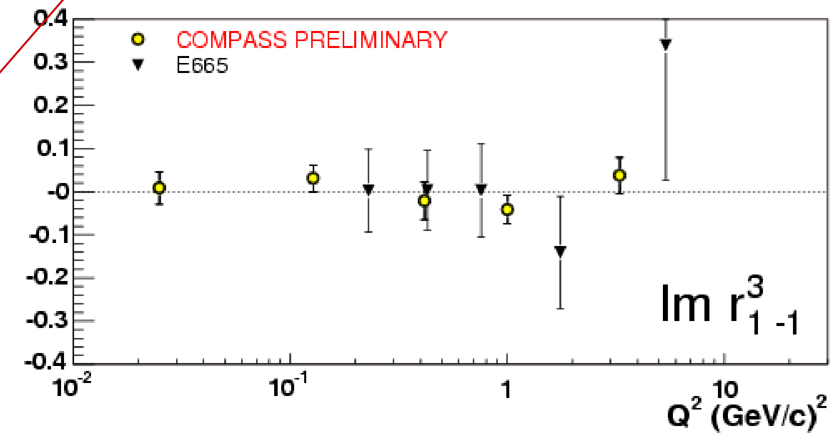
beam polarisation

$$r^{04}_{1-1} = \frac{\mathrm{Re}(T_{11}T^{*}_{-11}) - (\varepsilon+\delta)|T_{10}|^2}{N_T(1+(\varepsilon+\delta)R)} = 0$$

$$\mathrm{Im}\,r^{3}_{1-1} = \ldots = 0$$

if SCHC holds





weak violation of SCHC

Mini-introduction to color transparency

prediction of pQCD

small-size colour singlet object interacts with hadrons with small cross section

$$\sigma_{q\bar{q},N}(b,x) = \frac{\pi^2}{3} b^2 \alpha_s(Q^2)\, x\, g(x,Q^2)$$

b transverse size of the object

e.g. for b=0.3 fm $\sigma_{q\bar{q},N} \approx$ 3 mb at x = 10^{-2} (color transparency)

but $\sigma_{q\bar{q},N} \approx$ 28 mb at x = 10^{-6} (color opacity)

- How to 'measure' $\sigma_{q\bar{q},N}$ of small-size color singlet (mostly) short-living system

  propagate it in the nuclear matter and study A-dependence of cross section

  $\sigma_A = \sigma_0 A^\alpha$ for t-integrated coherent cross section $\alpha = 4/3$ for CT

  or $\alpha = 2/3$ for $\sigma_{q\bar{q},N}$ comparable to pion-nucleon

- How to access small size object

  hard scale μ^2 involved in the interaction; large Q^2, large quark mass or high p_T

  $<b> \approx k/\sqrt{\mu^2}$ e.g $b_{u\bar{u}} \cong b_{d\bar{d}} \cong$ 0.3 fm at Q^2 = 10 GeV^2

  $b_{c\bar{c}} \cong$ 0.23 fm already at $Q^2 = 0$

- System stays small when propagating through the nucleus

  large energy of the projectile in the nucleus system

  → large coherence length (l_c) and formation length

  $l_c = 2\nu/(Q^2 + M_V^2)$

  or

  $l_c = 2 p_\pi^{lab}/(M_{q\bar{q}}^2 - m_\pi^2)$

Prospects for color transparency with muon beam at COMPASS

from hard exclusive vector meson muo-production

Color Transparency at COMPASS – Feasibility Study

A.S., O. Grajek, M. Moinester, E. Piasetzky arXiv:hep-ex/0106076v2 (2001)

Proposed processes $\mu\, A \rightarrow \mu\, V\, A$ (coherent) and $\mu\, A \rightarrow \mu\, V\, N\, (A-1)$ (incoherent)

$$V = \rho^0,\ J/\psi,\ \varphi,\ \psi',\ \rho'$$

Program to demonstrate CT unambigously

- A-, Q^2- and x-dependence of cross sections for various mesons (of different size)
- measure both coherent and incoherent cross sections
- sample different polarisations of γ^*
- control coherence length

An example from simulations of measurements of ρ^0 production with 190 GeV μ^- on Pb and C targets (70 g/cm^2 each) assuming 38 days (divided between two targets)

$4 < Q^2 < 6$ GeV^2 , $p_t^2 < 0.02$ GeV^2

$l_c > 11$ fm , $|\cos\theta| > 0.7$

$\rightarrow$ $\boxed{\alpha = 1.55 \pm 0.03}$

(CT assumed in the event generator)

Conclusions for color transparency with muon beam at COMPASS

- CT studies in hard vector meson production at COMPASS feasible
  even with the assumed modest integrated luminosity

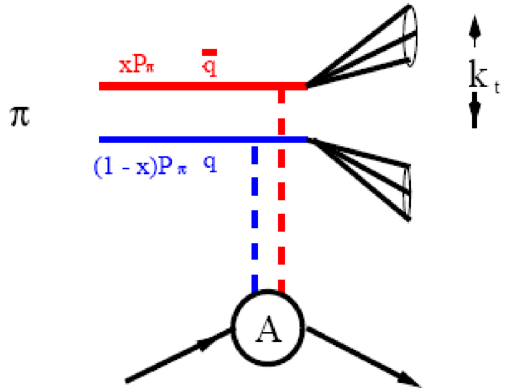
- Kinematic region of COMPASS more favourable for CT
  than at JLAB and HERMES

- COMPASS could provide precise results on CT long before proposed future
  electron-ion/proton colliders

Reminder: A-dependence of $\sigma_{coh}(\pi \rightarrow$ di-jet) from FNAL

Aitala et al., PRL 86 4773 (2001)

Coherent diffractive dissociation of 500 GeV/c π^+ on Pt and C targets



$$M_{2j}^2 = \frac{k_t^2}{x(1-x)} \qquad b_{q\bar{q}} \sim \frac{1}{M_{2j}}$$

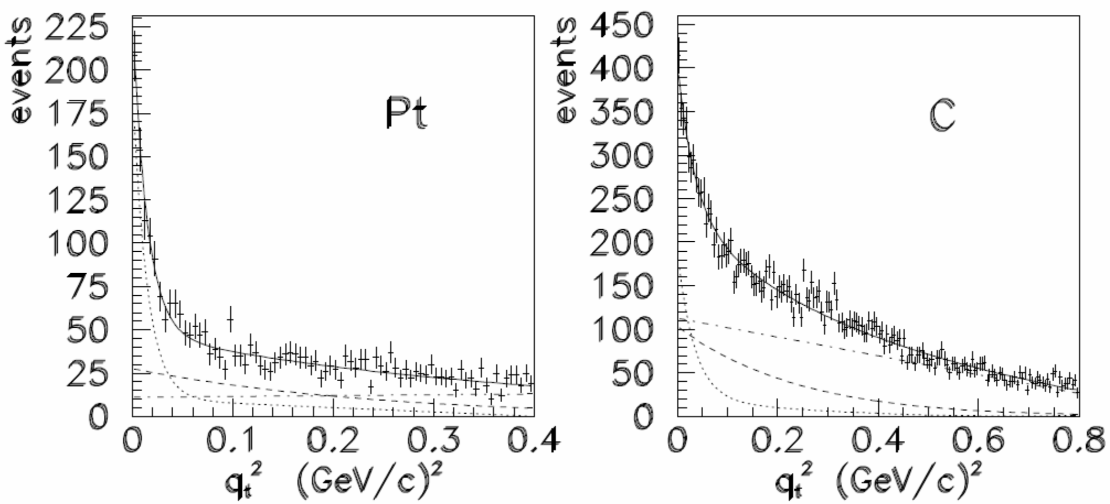
$b \leq 0.1$ fm for $k_t > 1.5$ GeV

$$\sum_{charged} E_i \;\geq\; 0.9 E_{beam}$$

2-jet events - JADE algorithm

$1.25 < k_t < 2.5$ GeV

extraction of coherent signal



q_t^2 distributions of di-jets for $1.5 < k_t < 2.0$ GeV

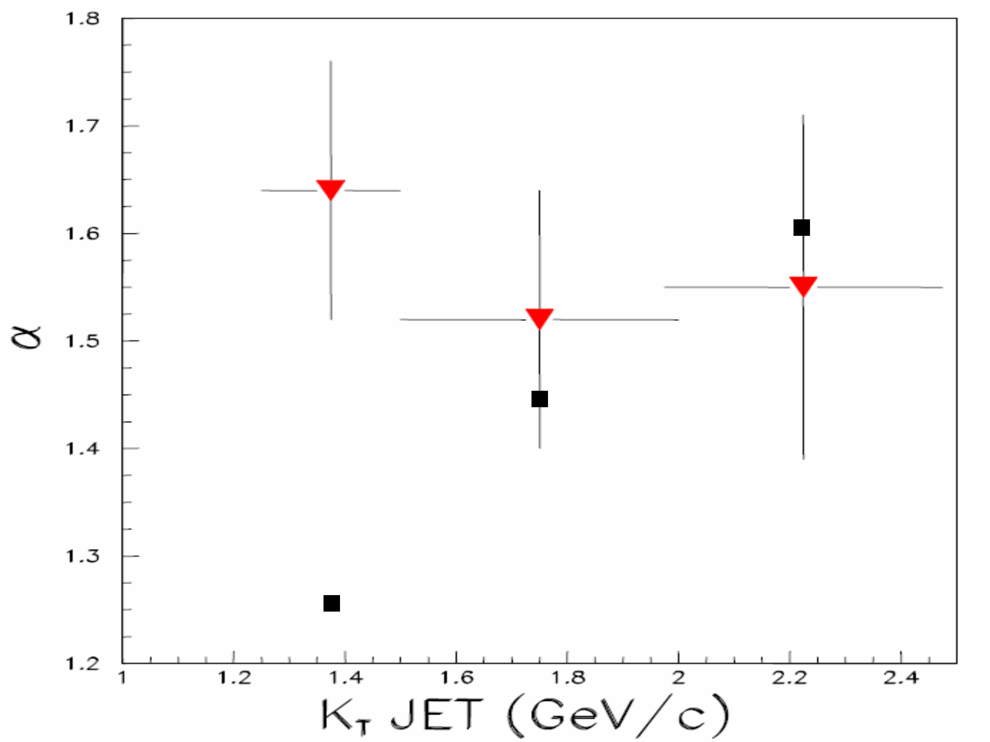
fitted
- coherent
- incoherent
- background
- total

shape from MC (coherent, incoherent)

A-dependence of $\sigma_{coh}(\pi \rightarrow \text{di-jet})$ from FNAL (cont.d)

Fit to $\sigma = \sigma_0 A^{\alpha}$

Aitala et al., PRL 86 4773 (2001)



- ■ L.L. Frankfurt, G.A. Miller, M. Strikman (1993)

Study of color transparency with hadron beam at COMPASS

Coherent diffractive dissociation of 190 GeV/c π^- to a pair of (mini-) jets on nuclear targets

Data from hadron pilot run in 2004

conditions were optimised for measurements of pion polarisability (Primakoff) and diffractive meson production

for color transparency analysis data from 3 nuclear targets

	Pb	Cu	C
thickness	2 + 1 mm	3.5 mm	23.5 mm
analysed spills	8600	2803	3545

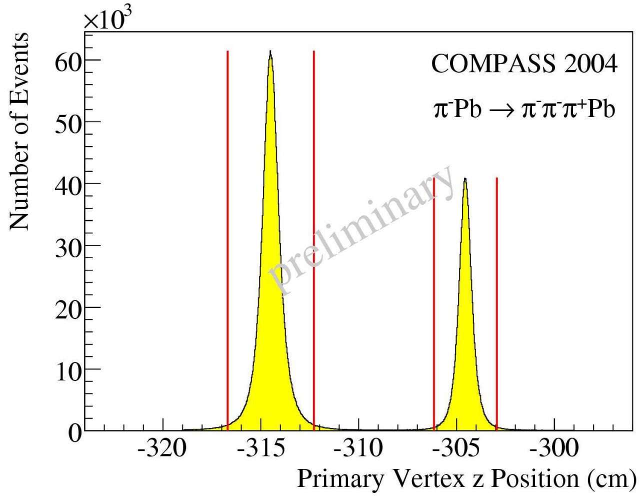
only charged hadrons used in this analysis, assumed pions

all data taken in less than 4 days

statistics for Pb before cuts on t' and jet-finding algorithm

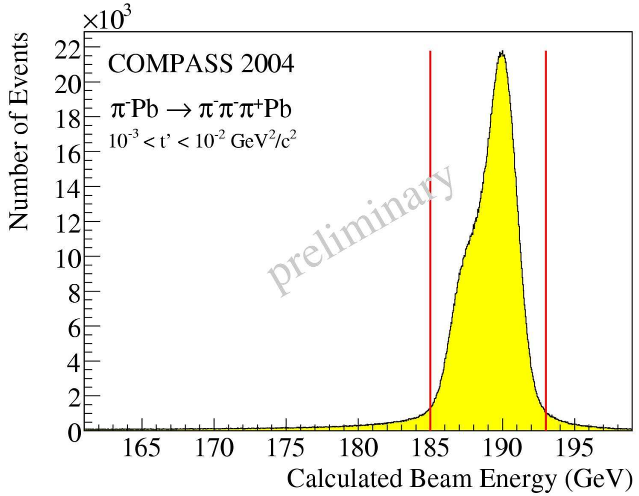
$N_{3\pi} \approx$ 4 000 000, $N_{5\pi} \approx$ 380 000, $N_{7\pi} \approx 0.01\, N_{3\pi}$, $N_{9\pi} \approx 0.001\, N_{3\pi}$

Selections of events and analysis



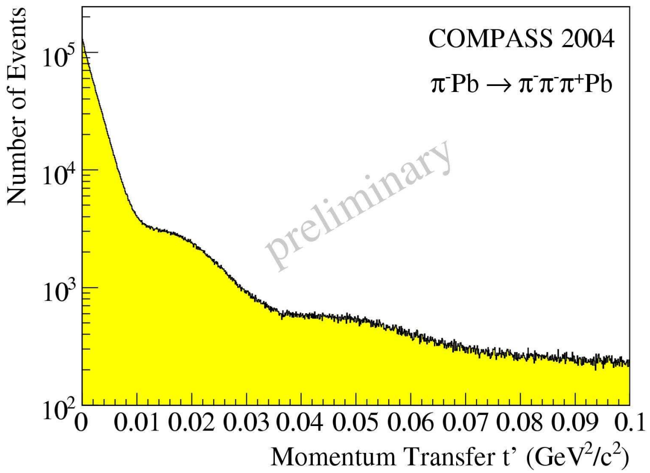
- position of the primary vertex in the target

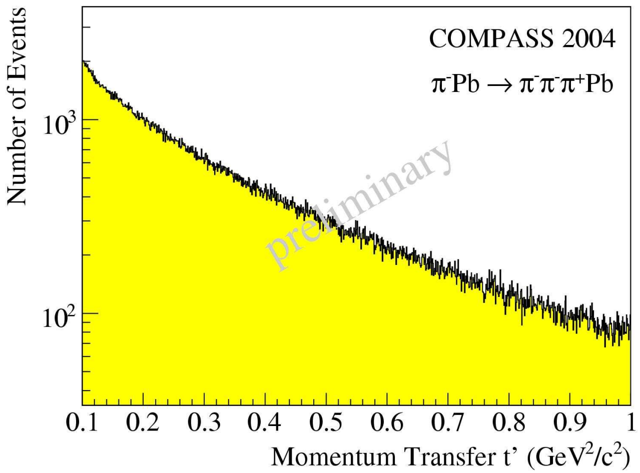
- exclusivity cut



- coherent production: t' < 0.1 GeV²

$t' = |t| - |t_{min}|$





Selections of events and analysis (cont.d)

- grouping of hadrons in mini-jets (clusters)

  JADE algorithm threshold mass for clusters = 3 GeV/c^2

- only events with 2 mini-jets kept for CT analysis

  covered range

  $3 < M_{2j} < 5$ GeV/c^2 → $l_c \geq 10$ fm

  due to limited integrated luminosity

  $1.0 < k_t < 2.0$ GeV/c

- ratios of luminosities for different targets

  as no direct information on beam flux was available

  instead a tricky method consisting in counting decays of beam kaons (≈ 3%)

- corrections for non-coherent events and extrapolation for $t_{min} \to 0$

- fit to $\sigma_A^{coh} = \sigma_0 A^\alpha$

  first results on α – very preliminary (waiting for cross-check)

Prospects for CT from hadron run 2009

Since 2008 COMPASS mostly took data with hadronic beams and liquid H_2 target with significant improvement of electromagnetic calorimetry and added RPD

In 2009 the program included also measurements with π^- beam, small $|t|$ triggers and liquid H_2, Pb and Ni targets

The number of particles on target for this part of 2009 run is expected to be about 50 times higher compared to 2004 pilot run

The data taking for the last target (Ni) continues until November 18

Conclusions and outlook

- New results on transverse target spin asymmetries for ρ^0 production

  compatible with 0 both for the proton and the deuteron targets
  ongoing work on L/T separation, and coh./incoh. separation for d

- Published results on double spin asymmetry for ρ^0 production on d

  compatible with 0 in a wide x and Q^2 range
  precise upper limits on contribution of unnatural parity exchanges

- Expected high precision results on ρ^0 and φ SDMEs and cross sections

- Potential for color transparency studies both with muon and hadron beams