GENERALIZED PARTON DISTRIBUTIONS

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(AACHEN)

- THE ESSENTIALS IN A NUTSHELL — WHAT ?
- PHYSICS INTERPRETATION
  DYNAMICS OF GPDS — WHY ?
- FROM EXCLUSIVE PROCESSES TO GPDS — HOW ?
- CONCLUSIONS — WHAT AGAIN ?

NB : LITERATURE > 100 DEDICATED PAPERS

THESE SLIDES : NO REFERENCES FROM 19..

→ PROCEEDINGS

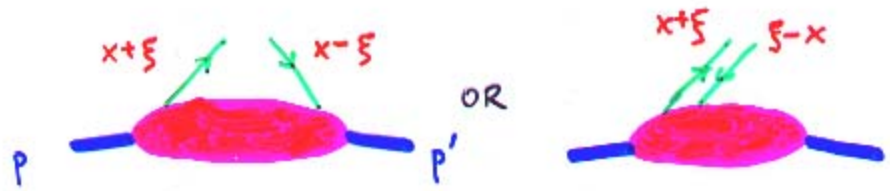
WHAT ARE GPDs ?

CONNECTED TO ?

FOURIER TRANSFORMED HADRONIC MATRIX ELEMENTS

$z^{\pm} = (z^0 \pm z^3)/\sqrt{2}$

$$\int dz^- \, e^{i x z^- (p+p')^+} \langle p',s' | \left[\bar{\psi}(-z) \ldots \psi(z) \right]_{\mu^2} | p,s \rangle_{z^+=0}$$



RESOLUTION SCALE

PARAMETERIZE BY FUNCTIONS $H, E, \tilde{H}, \tilde{E}, \ldots$ OF x, ξ, t, μ^2

FOR DIFFERENT HADRON AND PARTON SPINS

$t = (p-p')^2$

$\xi = 0$
$t = 0$

$\int dx \, x^n \ldots$

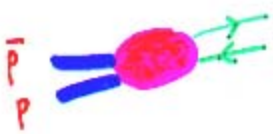
CROSSING

USUAL PARTON DENSITIES

$q(x)$, $\Delta q(x)$, ...

$$\int dz^- e^{\cdots} \langle p,s | \left[\bar{\psi}(-z) \ldots \psi(z) \right]_{\mu^2} | p,s \rangle$$

GENERALIZED DISTRIBUTION AMPLITUDES



$$\int dz^- \ldots \langle \bar{p}\, p | \left[\bar{\psi}(-z) \ldots \psi(z) \right]_{\mu^2} | 0 \rangle$$

LIKE

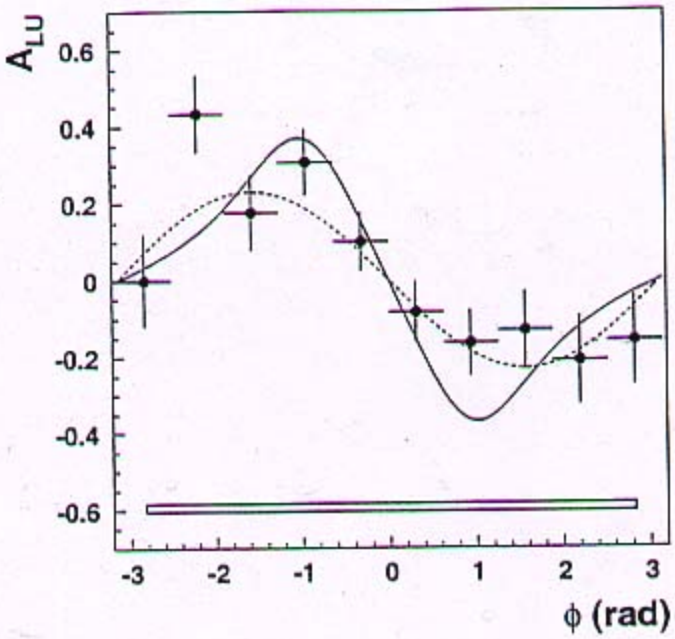
FORM FACTORS

$$\langle p',s' | \left[\bar{\psi}(0) \ldots \psi(0) \right]_{\mu^2} | p,s \rangle$$

LOCAL CURRENT

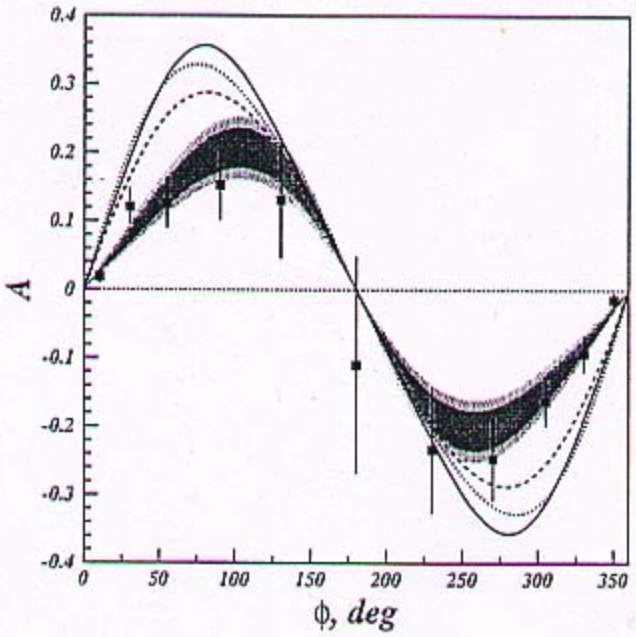
e.g. $F_1(t)$ $F_2(t)$

INDEPENDENT OF μ^2



HERMES
PRL 87 (2001)

$$A = \frac{N_{e\uparrow} - N_{e\downarrow}}{N_{e\uparrow} + N_{e\downarrow}}$$



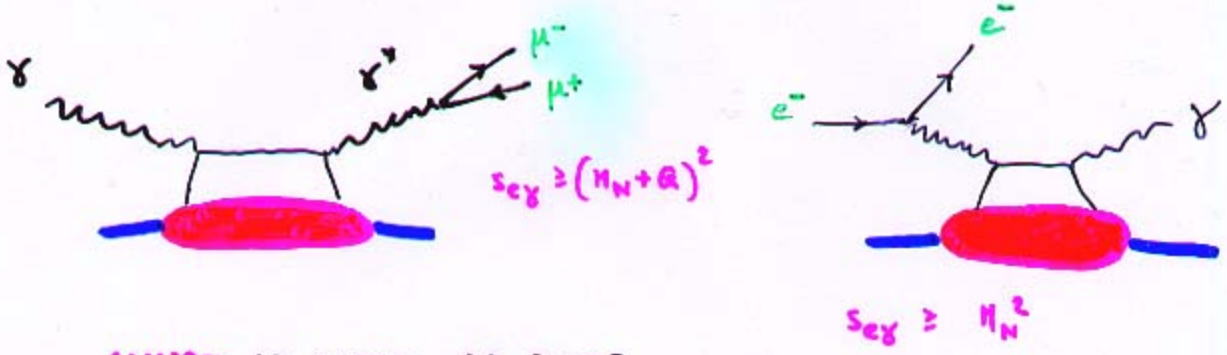
CLAS
PRL 87 (2001)

OTHER PROCESSES

E. BERGER et al '01

TIMELIKE COMPTON SCATTERING

KINEMATIC THRESHOLD: DVCS



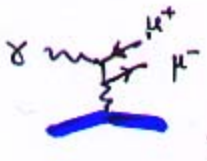
ALMOST AS CLEAN AS DVCS

- AT LEADING ORDER IN $1/Q$ AND LO (α_s) :

SAME AMPLITUDE

TO NLO (α_s) : DIFFERENT → EXTRA HANDLE ON GPDS

- GET INTERFERENCE WITH BETHE - HEITLER



γ SPIN ASY Im e SPIN ASY.

$\mu^+\mu^-$ ANGULAR DISTRIBUTION Re e BEAM CHARGE ASY.

• A FIRST COMPARISON WITH DATA

McDERMOTT, FREUND '01
BELITSKY, MÜLLER '01

ZEUS, H1 $x_B \ll 1$

HERMES, CLAS $x_B \approx 0.\ldots$

STILL HAVE THEOR. UNCERTAINTIES

e.g. t - DEPENDENCE ⇒ NORMALIZATION OF t-INTEGRATED CROSS SECTION

← NOT CALCULATED FOR $m_c \neq 0$

BUT BEGIN TO

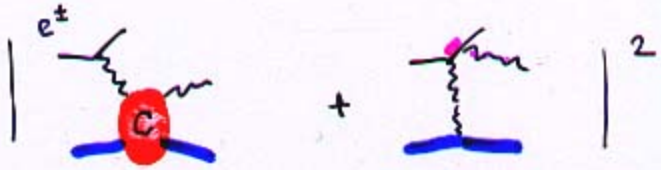
- RULE OUT CERTAIN ANÄTZE FOR GPDs

A KEY QUANTITY :

$$\frac{GPD(x=\xi,\xi,t)}{q(x=\xi)} \longleftrightarrow \frac{\mathrm{Im}\,(\gamma^* p \to \gamma p)}{\mathrm{Im}\,(\gamma^* p \to \gamma^* p)}$$

- OBSERVABLES

BELITSKY, KÜLLER '07

DVCS $d\sigma \sim$ 

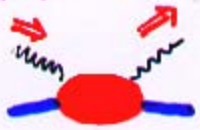
BETHE - HEITLER

IN $d\sigma^+ - d\sigma^-$ NO BH^2, NO VCS^2
FROM C INVARIANCE

IN $d\sigma^\uparrow - d\sigma^\downarrow$ NO BH^2
P AND T INVARIANCE
FOR ANY SINGLE SPIN
(BEAM OR TARGET
LONG. OR TRANSV.)

GPDs → CALCULATE → COMPTON AMPLITUDES

ANSATZ, MODEL

FIND $O(1)$  $O(1/Q)$ 

1 - 1 IF HAVE BEAM + TARGET POLARIZ.

$d\sigma/(d\varphi\, dQ^2\, dx_B\, dt)$

UP TO CORRECTIONS $\sim 1/Q^2$

LEPTON PROPAGATORS → $\frac{1}{P(\phi)}$ { $\cos\phi$, $\sin\phi$ }

$\frac{1}{P(\phi)}$ { $\cos 2\phi$, $\sin 2\phi$ } IN INTERFERENCE

PROJECT OUT FOURIER COEFFICIENTS

ETC.

ASYMMETRIES

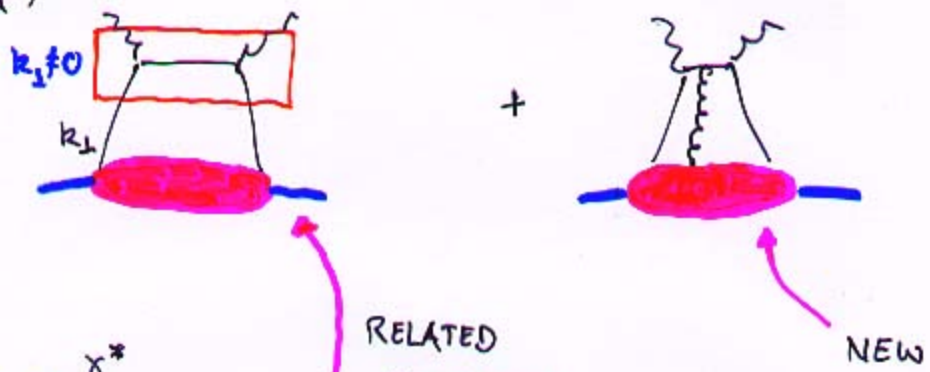
$$\frac{d\sigma^\uparrow(\phi) - d^\downarrow(\sigma)}{d\sigma^\uparrow(\phi) + d^\downarrow(\sigma)} = A(\phi)$$

$$\sim \frac{\text{INTERF. + CORRECT'S}}{BH^2 + \text{CORRECT'S}}$$

CLEAN INFORMATION

- CORRECTIONS IN $1/Q$
  - FOR MESON PRODUCTION : MUST MODEL
    NO SYSTEMATIC THEORY
  - FOR DVCS : $1/Q$ LEVEL CAN DESCRIBE
    ANALOG TO g_2 STRUCT. FUNCT.
    >10 PAPERS '00, '01
    ANIKIN, BELITSKY, MÜLLER,
    RADYUSHKIN, WEISS, ...

AT $O(1/Q)$



RELATED "WANDZURA WILCZEK RELATION"

NEW

AT $O(1)$

→ STILL HAVE FACTORIZATION
(SHOWN FOR $O(\alpha_s^0)$)

HOW PRECISELY CAN WE ACCESS GPDs ?

AS PRECISELY AS UNDERSTAND RELEVANT PROCESSES

- CORRECTIONS IN α_s

NLO KNOWN FOR COMPTON SCATT.

AND $\gamma^* p \to \pi^+ n$ BELITSKY, MÜLLER '01

FOR DVCS NUMERICAL STUDIES MoDERHOTT, FREUND '01
BELITSKY, MÜLLER '01

LO :

NLO:

+

RATHER MODERATE

IMPORTANT

FOR GIVEN GDPs, AT INPUT SCALE $\mu^2 = Q^2$

NB : DIAGRAMS / GPDs MIX UNDER EVOLUTION

$x \sim \xi = \frac{x_B}{2 - x_B}$

HOW MIGHT GPDs LOOK LIKE ?

2 STRATEGIES :

- **THE ART OF ANSATZ**

  MAKE ANSATZ THAT

  - SATISFIES ALL SYMMETRY REQUIREMENTS (NONTRIVIAL)

    DOUBLE DISTRIBUTIONS $\xrightarrow{\text{GENERATE}}$ GPDs

    $\xleftarrow{\text{NONTRIVIAL}}$:

    BELITSKY et al '00
    TERYAEV '01

  - CAPTURES ESSENTIAL PHYSICS

    (EVEN MORE N.-T.)

    GOEKE et al '01
    BELITSKY et al. '01

- **(TOY) FIELD THEORIES** ..... **MODELS OF QCD**

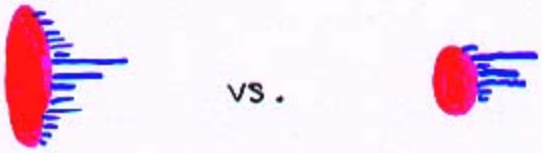
  QED — BRODSKY et al '00
  QCD 1+1 DIMENSION — BURKARDT '00
  χ SOLITON MODEL, LARGE N_c LIMIT
  MIT BAG — ANIKIN et al '01
  CONSTITUENT MODELS — SCOPETTA, VENTO '02
  BETHE - SALPETER — CHOI et al. '01, TIBURZI et al '01
  LIGHT-CONE WAVE FCTS
  PARTON - HADRON DUALITY — CLOSE, ZHAO '02

- EMPLOY + DEVELOP TECHNIQUES FOR APPROACHING NON-PERT. QCD

- GAIN DYNAMICAL INSIGHT

CAN e.g. EXPLORE

- TRANSVERSE DISTRIBUTION OF SLOW vs FAST PARTONS



- ANTIQUARKS

  GLUONS

- HAVE ACCESS TO ORBITAL ANGULAR MOMENTUM

  ALONG z - AXIS

  SINCE PROBE IS NOT ROTATIONALLY SYMMETRIC

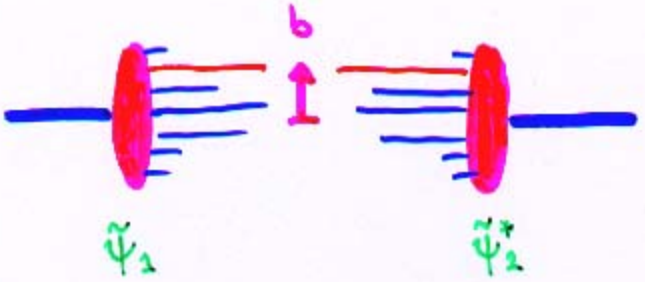
  Δ_1 / b_1 PROVIDE REFERENCE DIRECTION

  IN SUM RULES e.g.

$$\int dx\,(H+E) = G_M(t) \quad \leftrightarrow \quad \vec{r} \times \vec{J}$$

$$\frac{1}{2}\int dx\, x\,(H+E) = J_q(t) \quad \leftrightarrow \quad \vec{r} \times \vec{T}$$

- THEN MEASURE TRANSVERSE LOCATION OF PARTONS



RESOLUTION $(\Delta b)^2 \sim \frac{1}{|t|}$

- IF $\xi = 0$ HAVE DENSITY $|\tilde{\Psi}|^2$
- OTHERWISE CORRELATION BETWEEN $x+\xi$, $x-\xi$

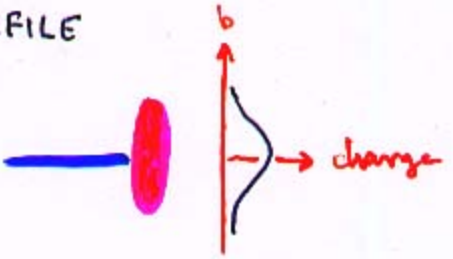
↕ QCD - QUANTUM THEORY
PROTON NOT A CLASSICAL SYSTEM

COMPARE WITH

- USUAL PARTON DENSITIES $t = 0 \leftrightarrow \int d^2 b_\perp$
NO TRANSVERSE INFO
- FORM FACTORS STILL HAVE REPRESENTATION THROUGH WAVE FCTS. DRELL, YAN « 2000

BUT $\int dx$ NO LONGIT. INFO

GET e.g. TRANSVERSE CHARGE PROFILE



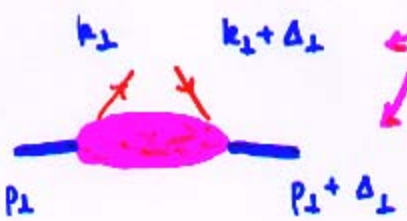
GPDs : COMBINE TRANSVERSE
+ LONGITUDINAL INFORMATION

A 3-DIMENSIONAL IMAGE OF HADRONS

OR: HOW CAN WE INTERPRET GPDs ?

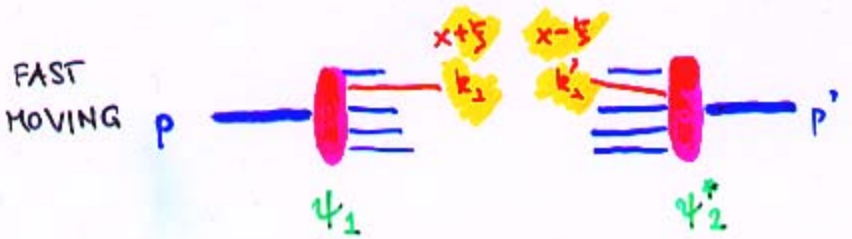
GPDs DEPEND ON $x \pm \xi$ AND $t \xrightarrow[\text{FOR}]{\text{TRADE}} \Delta_\perp$

TRANSVERSE MOM. TRANSFER



- IN TERMS OF LIGHT-CONE WAVE FCTS: MD et al '00, BRODSKY et al '00

CORRELATE PARTONS WITH DIFFERENT LONGITUD. AND TRANSVERSE MOMENTUM



- ALTERNATIVE DESCRIPTION — BURKARDT '00, RALSTON, PIRE '01

FOURIER TRANFORM FROM $\Delta_\perp$ TO IMPACT PARAMETER $b_\perp$

$$\int d^2\Delta_\perp \; e^{-i \Delta_\perp b_\perp} \qquad H(x,\xi,\Delta_\perp)$$

↳ OR $E, \tilde{H}, \tilde{E}$

FORM PROTON WAVE PACKETS LOCALIZED IN TRANSV. PLANE

$$\int d^2p_\perp \; \Phi(p_\perp) \; |p\rangle$$

IS PHYSICALLY SENSIBLE IF PROTON MOVES FAST

GPDs APPEAR IN HARD EXCLUSIVE PROCESSES

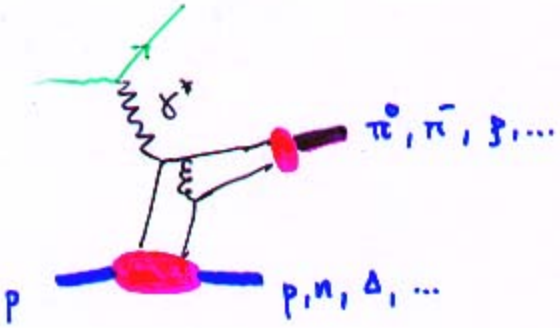
LARGE VIRTUALITY Q^2
" C.M. ENERGY
SMALL t
$\Rightarrow$ DYNAMICS FACTORIZES

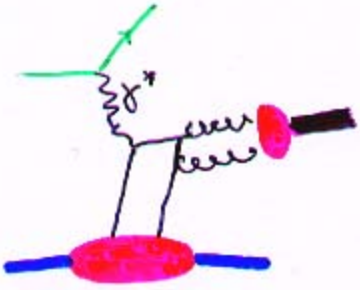
DEEPLY VIRTUAL COMPTON SCATTERING

COMPARE TO DIS

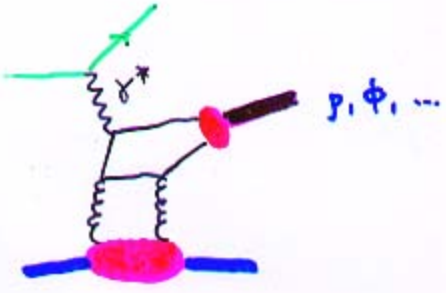
$\sigma_{Tot} \sim$ Im

MESON PRODUCTION





BRAUN, KIVEL '00



- MANY CHANNELS
  - → FLAVOR DECOMPOS. OF GPDs
  - → MESON PROPERTIES
  - → TRANSITION TO UNSTABLE BARYONS
- REQUIRE BIGGER Q^2

- ALSO WITH ν BEAMS $\nu^* p \to D_s p$ LEHMANN-DRONKE et al '01
  OR π BEAMS $\pi p \to \gamma^* p \to \mu^+\mu^- p$ BERGER et al '01

THE AIM:

EXPLORE STRUCTURE OF HADRONS IN TERMS OF QUARKS + GLUONS

DYNAMICS OF QUARKS + GLUONS WITHIN HADRONS

A VERSATILE TOOL:

GPDs

- CONNECT MANY ASPECTS OF HADRON STRUCTURE
- UNIQUE GLIMPSES AT LONGITUDINAL & TRANSVERSE STRUCT.
  SPIN AND ORBITAL ANGULAR MOMENTUM
  Q. M. INTERFERENCE
- ONGOING EFFORT TO MANAGE COMPLEXITY IN