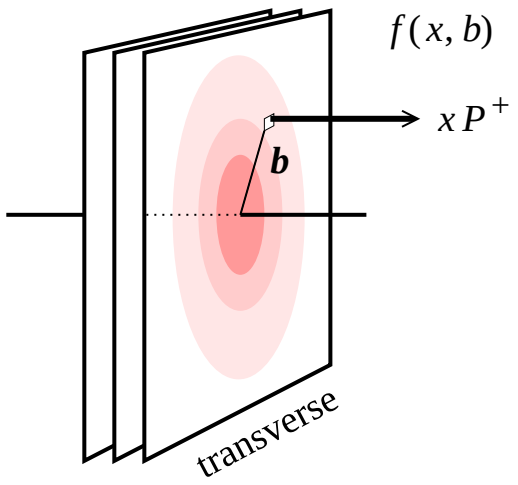
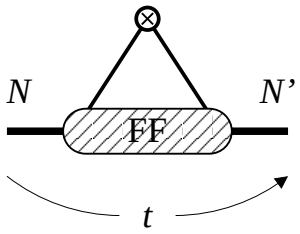
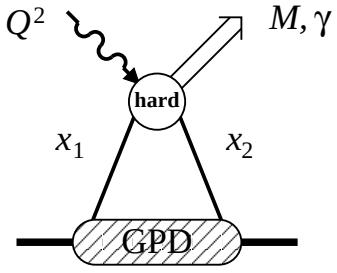
Nucleon structure on the light-front

C. Weiss (JLab), APS April Meeting 2014, Savannah, GA, 05–Apr–14







New operators!

Longitud. structure,
x dependence!

- Why light–front/partonic view

  Relativistic system!

  Spatial structure, densities
  cf. Few-body systems

- Form factors and transverse densities

  Nucleon transverse densities:
  Center, chiral periphery $b \sim 1/M_\pi$

  $N \to \Delta, N^*$ transition densities:
  Resonance structure in QCD

  Pion density: Small-size $q\bar{q}$ configurations

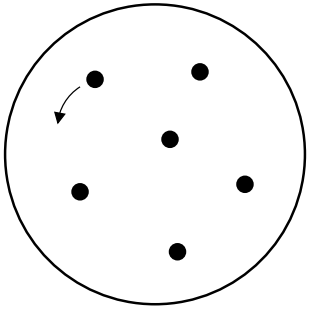
- Hard exclusive processes and GPDs
  Generalized Parton Distributions

  Gluonic form factor with $J/\psi, \phi$

  Quark helicity–flip with π, η

- Orbital motion and correlations Brief!

Light–front view: Relativistic system

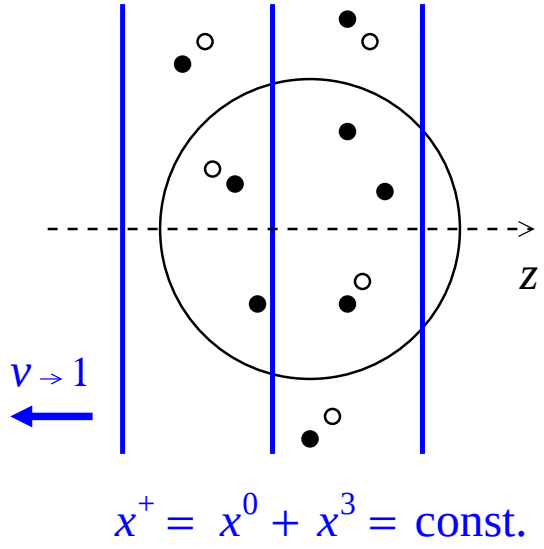


- Non–relativistic quantum system

  Particle number fixed, time absolute

  $\psi(\boldsymbol{x}_1, ..\boldsymbol{x}_N; t)$ Schrödinger WF

  $\rho(\boldsymbol{x}) = \sum \psi^\dagger(..\boldsymbol{x}..; t)\psi(..\boldsymbol{x}..; t)$ Densities



- Relativistic quantum system

  Vacuum fluctuations: Particles appear/disappear

  Time not absolute: How to synchronize clocks?

  Light–front time $x^+ = x^0 + x^3$:
  Observer moving with velocity $v \to 1$

  Wave function at fixed x^+: Components with different particle number

  Densities at fixed x^+: Boost–invariant!

Alt. view: Observer at rest, system moves with $v \to 1$. Infinite–momentum frame

Light–front view: Advantages

- Spatial representation of relativistic system

  Visualization

  Approximation methods based on spatial structure

  Space-time evolution of reactions

- High–energy scattering $E_{\rm probe} \gg E_{\rm internal}$ probes system at fixed LF time

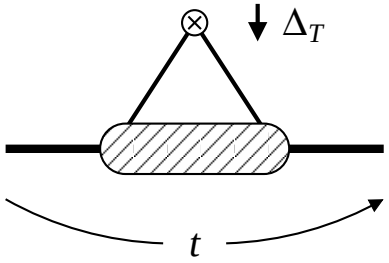
  But use not limited to high energies – it's just a "view!"
  Here: Low–t form factors, resonances, ...

- Used with QCD and effective degrees of freedom

  Equivalent to parton picture of nucleon in deep–inelastic processes

  Helps to connect QCD with effective dynamics

Transverse densities: Form factors

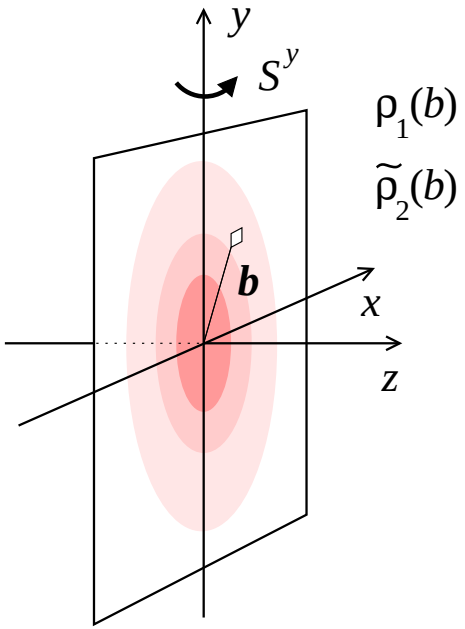


- Current matrix element parametrized by invariant form factors

$$\langle N'|J_\mu|N\rangle \;\to\; F_1(t), F_2(t)$$ Dirac, Pauli

- Transverse charge/magnetization density
Soper 76, Burkardt 00, Miller 07

$$F_{1,2}(t) \;=\; \int d^2b\; e^{i\boldsymbol{\Delta}_T \boldsymbol{b}}\; \rho_{1,2}(b), \qquad t = -\boldsymbol{\Delta}_T^2$$



$\boldsymbol{b}$ displacement from transverse C.M.

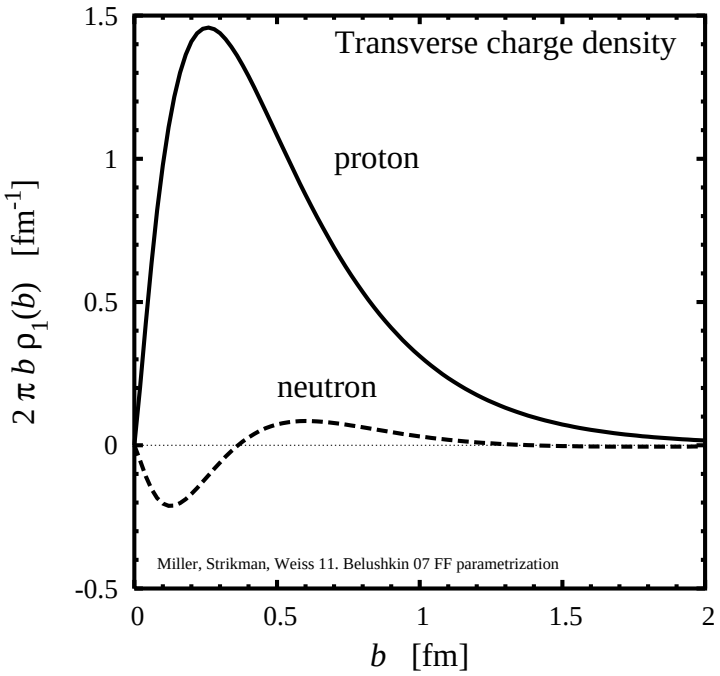
Describe spin–independent/dependent $\langle J^+(\boldsymbol{b})\rangle$ seen by observer with $v \to 1$

- Projection of quark GPDs

$$\rho_1(b) = \sum_q e_q^2 \int dx\; f_{q-\bar{q}}(x, \boldsymbol{b})$$

Connect low–t elastic FFs with QCD structure, high–energy processes

Transverse densities: Nucleon

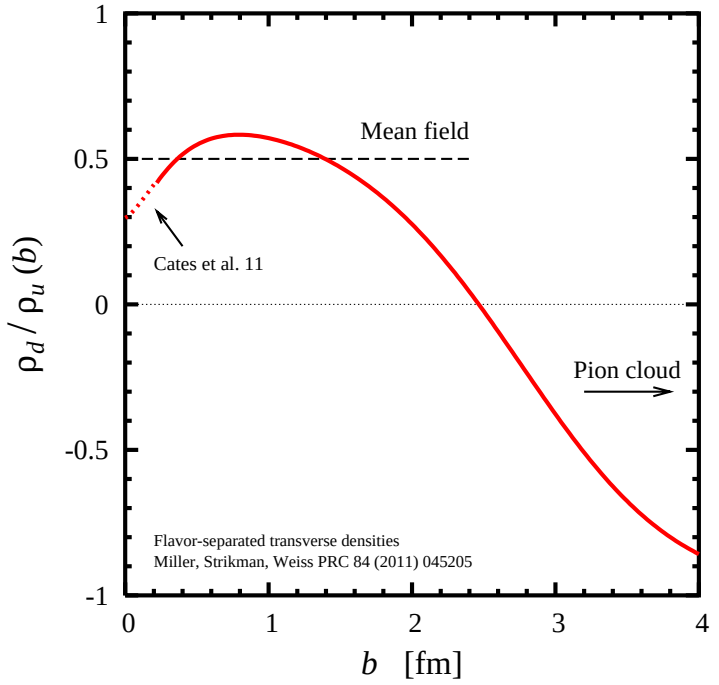


- Empirical densities from form factor data

  Experimental and incompleteness errors estimated Venkat, Arrington, Miller, Zhan 10

  Recent low– and high–$|t|$ data included
  MAMI: Vanderhaeghen, Walcher 10. JLab Hall A Riordan et al.

  Many interesting questions: Neutron, flavor structure, charge vs. magnetization



- Flavor–separated densities $u-\bar{u},\ d-\bar{d}$

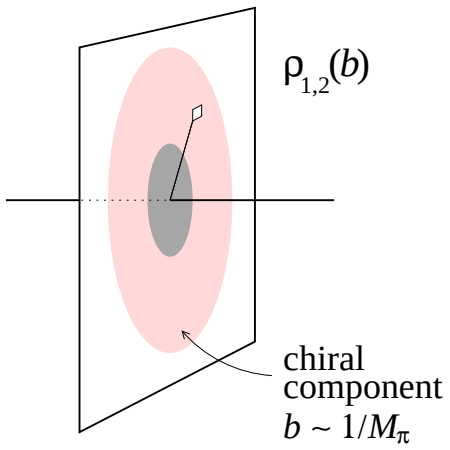
  $b \sim 1$ fm $\qquad \rho_d/\rho_u \approx 1/2$

  mean field picture
  cf. quark model

  $b > 2$ fm $\qquad \rho_d/\rho_u \to -1$

  pion cloud
  peripheral π^-

Transverse densities: Chiral component

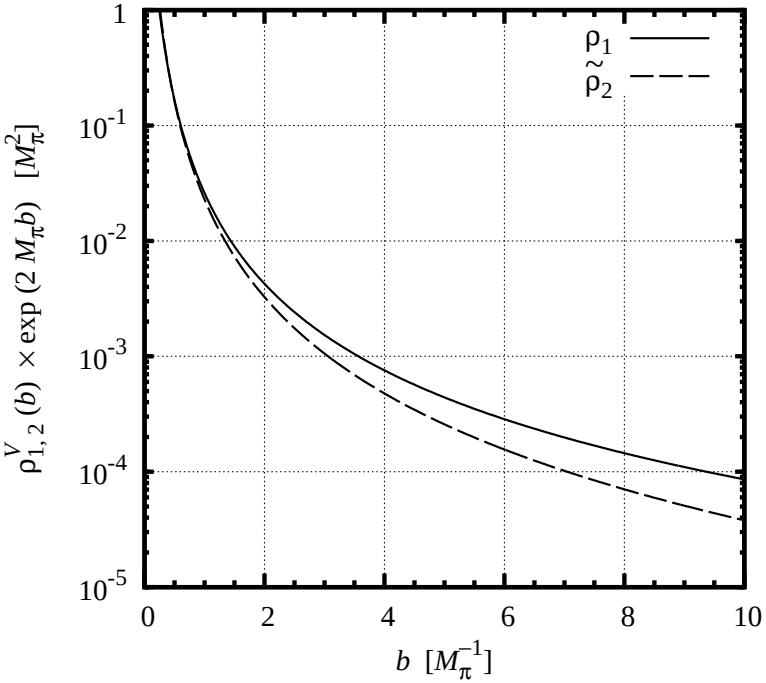


- Peripheral densities at $b = O(M_\pi^{-1})$

  Governed by chiral dynamics:
  Universal, model–independent

  Calculable in chiral EFT
  Strikman, CW 10; Granados, CW 13

  Dominant at $b \gtrsim 2\,\mathrm{fm}$

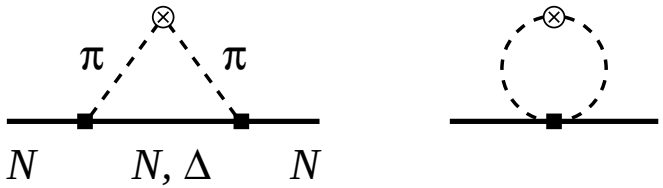


- Many interesting insights

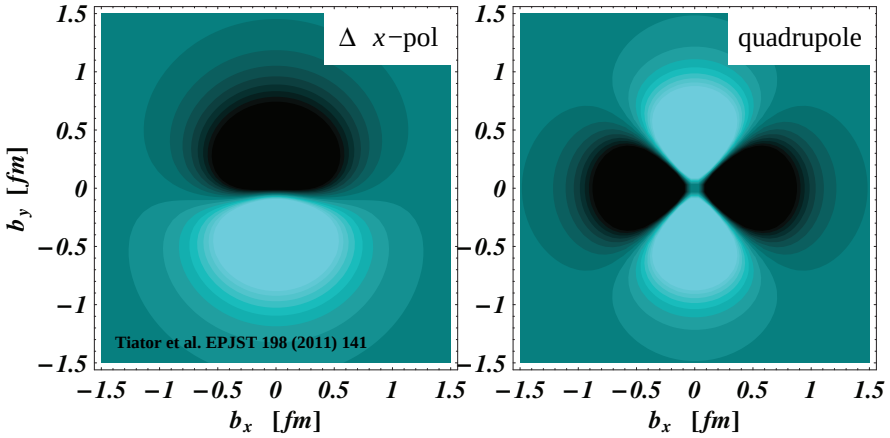
  "Yukawa tail" $\sim e^{-2M_\pi b}$, rich structure

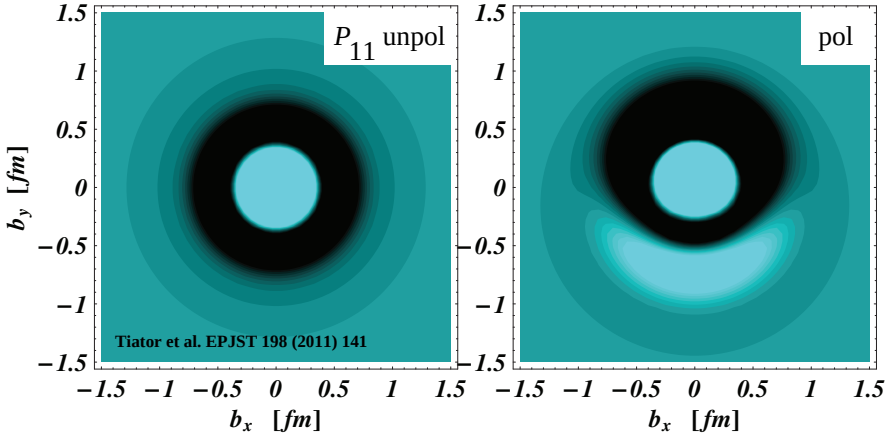
  Relation between spin-independent
  and -dependent densities $\widetilde{\rho}_2(b) < \rho_1(b)$
  Granados, CW, JHEP 1401 (2014) 092

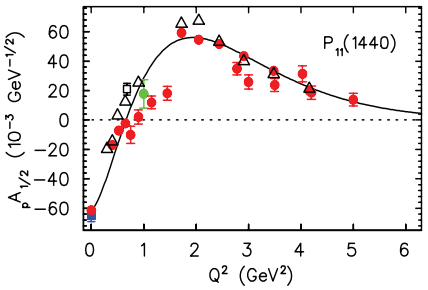
  Space–time picture of chiral dynamics

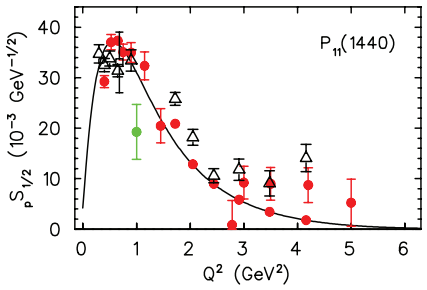


Transverse densities: $N \to \Delta, N^*$









- Transition densities $N \to \Delta, N^*$

  $\langle N^* | J^+(\boldsymbol{b}) | N \rangle \sim \rho^S_{N^*N}(b)$

  Spin components

  Empirical densities extracted from transition form factors
  Carlson, Vanderhaeghen 09; Tiator et al. 11

- Resonance structure in QCD

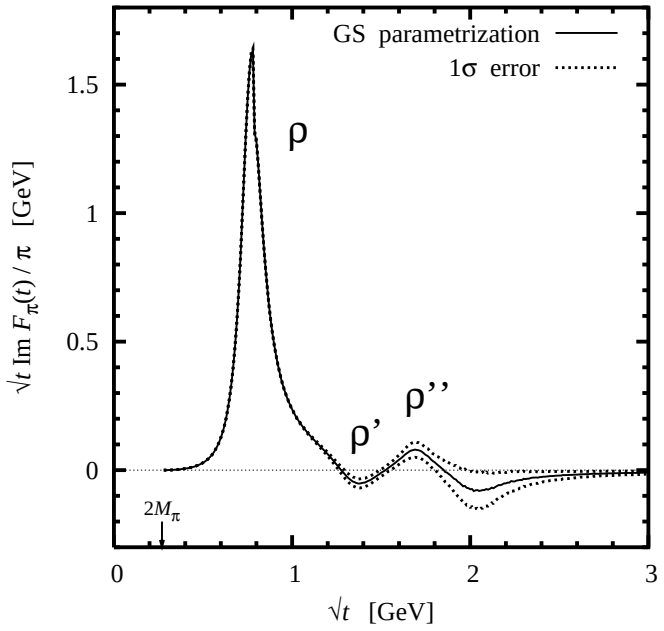
  Polarization effects: Spin–orbit interactions, deformation

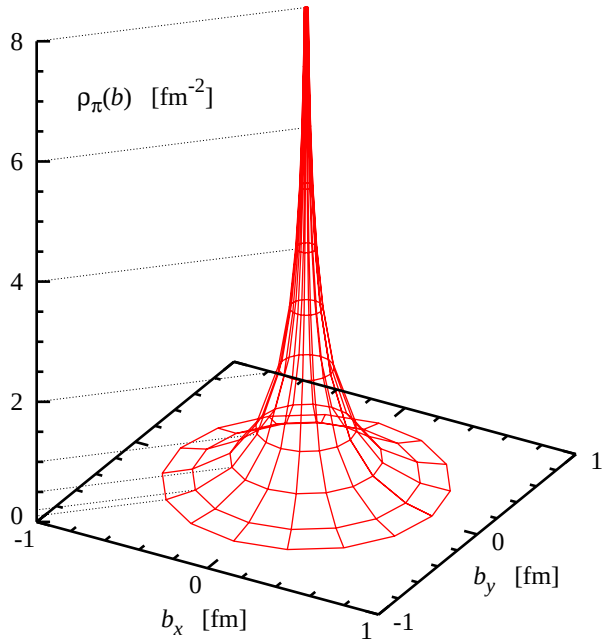
  Comparison of N and N^*: More central or more peripheral?

  Lattice QCD results
  Alexandrou et al. 09

  Effective models: Quark orbital angular momentum Lorce, Pasquini et al.

Transverse densities: Pion from e^+e^-





- Timelike pion FF from $e^+e^- \to \pi^+\pi^-$

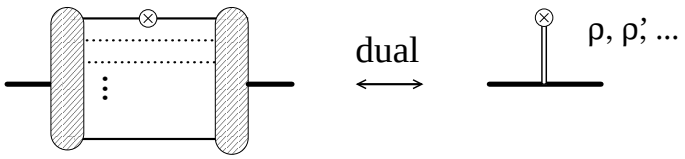
  Precise data on $|F_\pi|^2$, phase from fits/theory
  Bruch, Khodjamirian, Kuhn 04. Also CLEO 05+

- Transverse density as dispersion integral
  Miller, Strikman, CW 10

$$\rho_\pi(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b) \, \mathrm{Im}\, F_\pi(t)$$

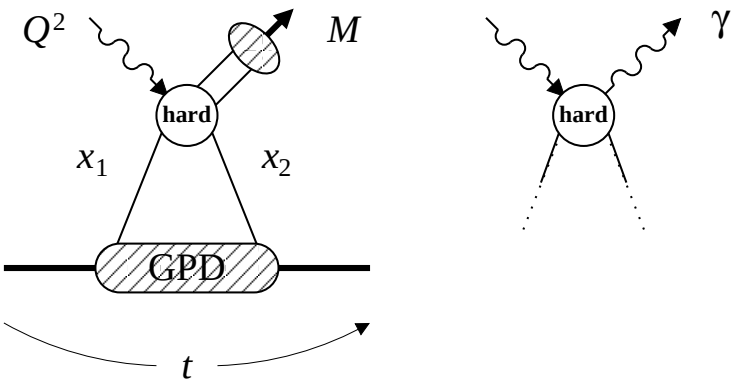
Singular charge density at center of pion:
Small–size $q\bar{q}$ configurations

Dual to vector meson exchange



partonic structure meson exchange

Hard exclusive processes: New probes

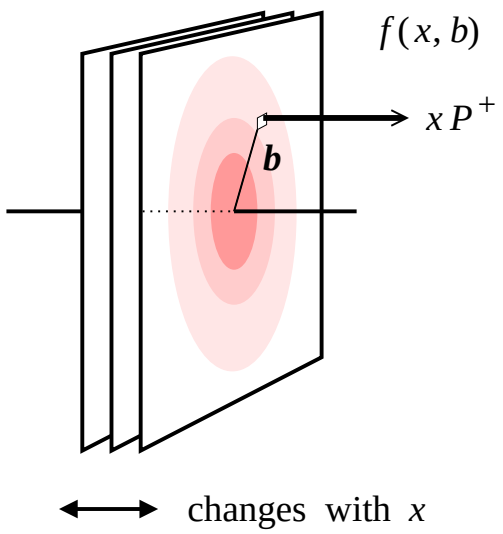


- QCD factorization $Q^2 \to \infty$, t fixed
  Ji 96; Radyushkin 96; Collins, Frankfurt, Strikman 96

  GPDs universal, process–independent

  Form factor of light–front momentum density

  $\langle N'|\bar{\psi}(0)...\psi(z)|N\rangle$ at $z^2 = 0$
  QCD operator: Renormalization, non-pert. methods, lattice



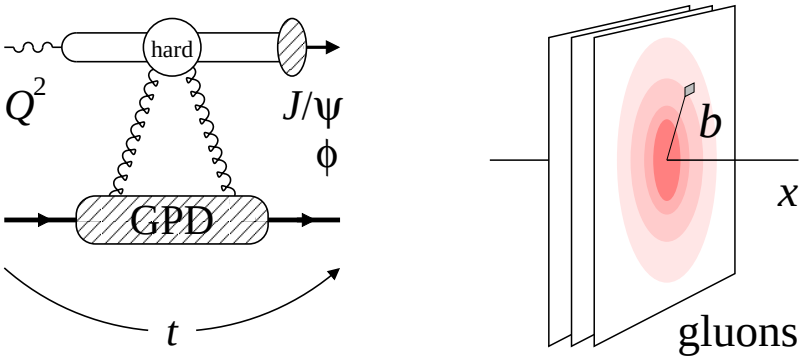
- Uses of hard exclusive processes

  Transverse densities of partons with given $x = x_1 = x_2$: Nucleon tomography
  Burkardt 00, Diehl 02

  New operators for structure and spectroscopy: Quark spin, flavor, C–parity; gluons

- Experimental programs
  HERMES, COMPASS, JLab 12 GeV, Electron-Ion Collider EIC

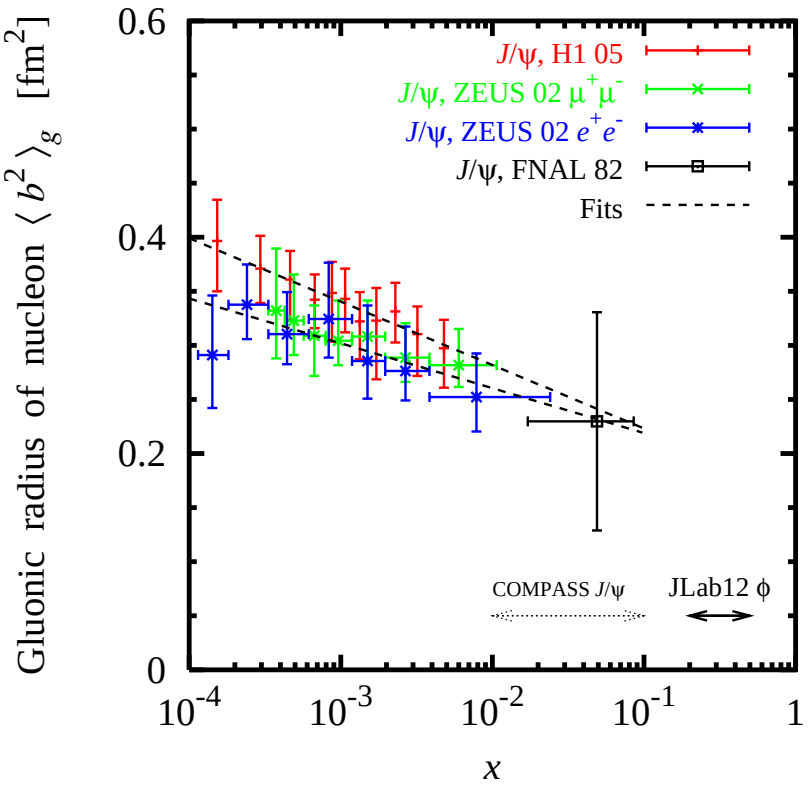
Hard exclusive processes: Gluons with $J/\psi, \phi$



- Gluon GPD with J/ψ and ϕ

  $x < 10^{-1}$ HERA, COMPASS, EIC

  $x > 0.2$ JLab 12 GeV ϕ



- Gluonic size of nucleon

  Increases with $x \to 0$

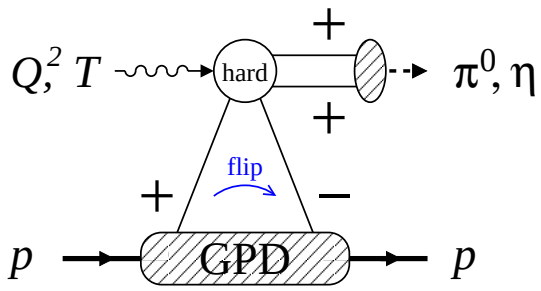
  $\langle b^2 \rangle_g < \langle b^2 \rangle_{q+\bar{q}}$ at $x > 10^{-2}$
  Gluons more central than valence quarks

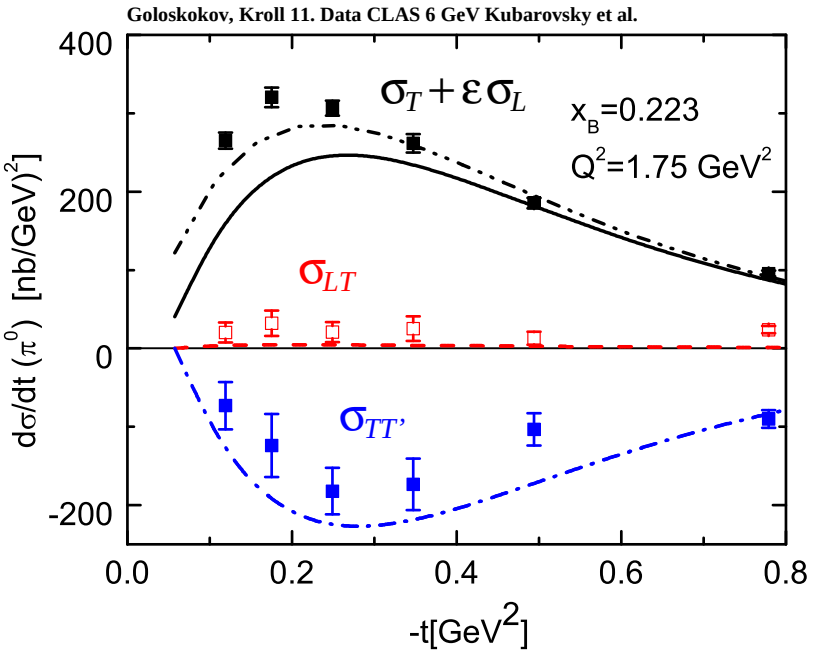
  Input for pp@LHC, saturation models

- ϕ also probes intrinsic strangeness at large x

  Hints from semi-inclusive DIS HERMES

Hard exclusive processes: Transversity with π, η





- Quark helicity flip in pion WF

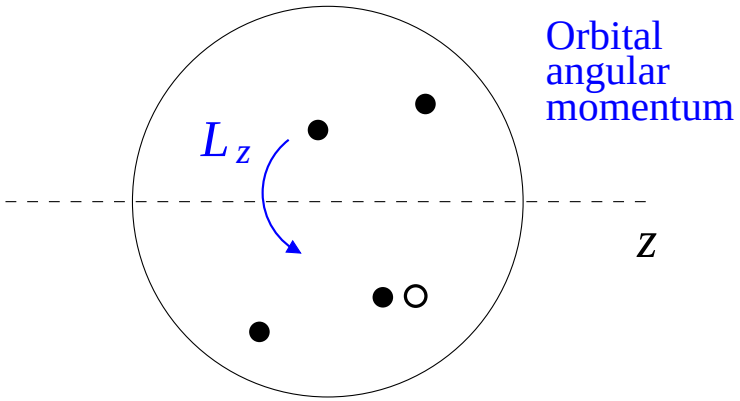
  Chiral symmetry breaking in QCD

  Dominates σ_T at $W \sim$ few GeV
  Goldstein Liuti 08, Goloskokov, Kroll 11. Higher W non-flip

  Probes quark transversity GPD
  cf. transversity in SIDIS, Drell–Yan

- JLab 12 GeV π^+, π^0, η program

Beyond densities: Orbital motion, correlations

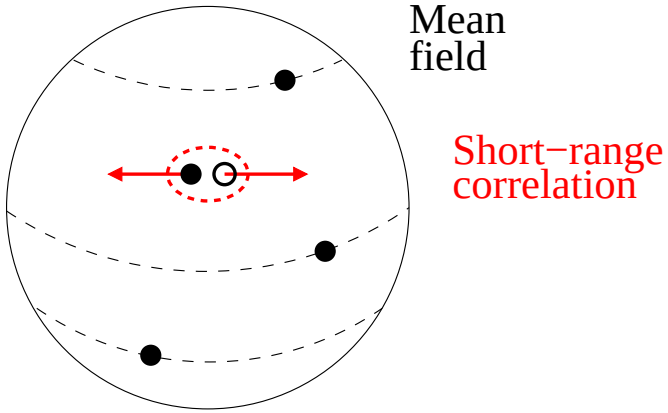


- Transverse motion of constituents

  Transverse momentum p_T,
  orbital angular momentum L_z
  well-defined in light–front view!
  Mechanical picture of relativistic system

  Orbital angular momentum manifest in
  Pauli/Dirac FF at $|t| \gg 1\,\mathrm{GeV}^2$,
  structure functions at $x \to 1$,
  azimutal asymmetries in $eN \to h + X$

  QCD: Observables sensitive to transverse
  motion generally involve explicit interactions
  Major challenge, much progress!
  Transverse momentum-dependent distributions (TMDs)



- Dynamical correlations

  Multiparticle distributions

  QCD: Short-range correlations between sea
  quarks caused by χSB interactions
  Schweitzer, Strikman, Weiss, JHEP 1301 (2013) 163

  Multiparton processes in $pp \to 2\,\mathrm{jets}$ LHC
  target fragmentation in DIS JLab12, COMPASS EIC

Summary

- Light-front view enables composite description of relativistic system

  Essential tool for theory and phenomenology

- Transverse densities offer new insight into hadron and resonance structure

  Directly accessible from low–t elastic/transition form factors

  Projections of QCD quark densities

- Hard exclusive processes provide new operators

  Longitudinal structure, x–dependence

  New quantum numbers: Gluons, quark helicity–flip

- Much more structure

  Transverse motion of constituents: Momentum $\boldsymbol{p}_T$, angular momentum L_z
  QCD: Major challenge, much progress! Transverse momentum-dependent distributions (TMDs)

  Dynamical correlations: Multiparticle distributions
  QCD: Short-range $q\bar{q}$ correlations from non-perturbative chiral-symmetry-breaking interactions