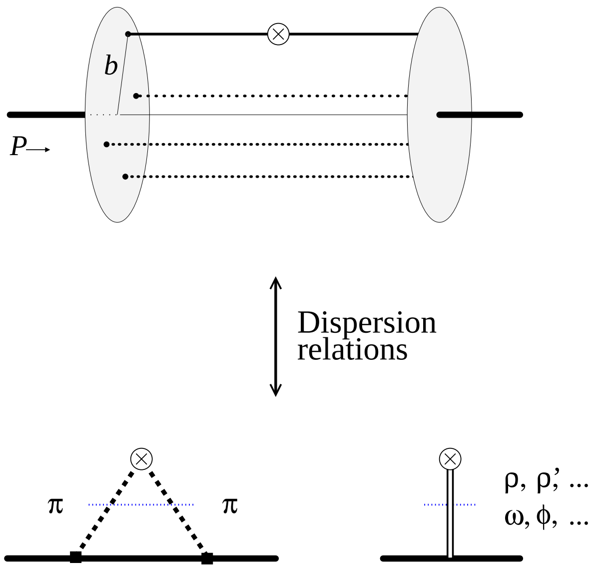
Quantifying the nucleon's meson cloud with transverse charge densities

C. Weiss (JLab), JLab Physics Seminar, 21–Apr–11



Quantify pion cloud, vector meson dominance in QCD!

New insights in partonic structure!

Study vector meson couplings in t–channel kinematics!

- Nucleon structure in QCD

  Why partonic description

  Transverse densities from elastic form factors

  Connection with GPDs

- Scanning the nucleon's periphery

  Dispersion representation of transverse density
  Strikman, CW, PRC82 (2010) 042201

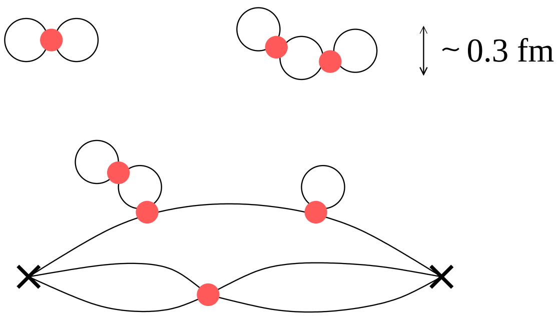
  Large distances $b \sim 2\,\mathrm{fm}$:
  Pion cloud from chiral dynamics

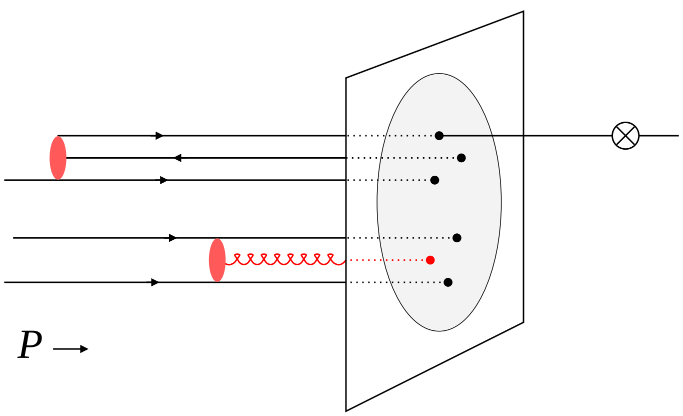
  Intermediate distances $b \sim 1\,\mathrm{fm}$:
  Vector mesons ρ, ω
  Miller, Strikman, CW, PRC84 (2011) 045205

- Pion transverse charge density

  Timelike pion form factor from e^+e^- data:
  Pointlike $q\bar{q}$ configurations in pion
  Miller, Strikman, CW, PRD83 (2011) 013006

Nucleon structure: Partonic description





- QCD vacuum not empty

  Strong non-perturbative gluon fields
  of size $\ll 1\,\text{fm}$ ← Lattice QCD, analytic models

  Chiral symmetry breaking: $\bar{q}q$ pair condensate,
  π as collective excitation

- Nucleon at rest

  $\langle N | J_\mu | N \rangle$ from Euclidean correlation functns

  No concept of particle content!
  Cannot separate "constituents" from vacuum fluctuations

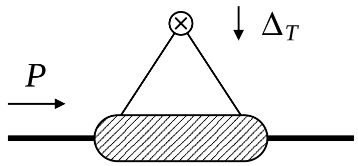
- Fast–moving nucleon $P \gg \mu_{\text{vac}}$

  Closed system: Wave function description
  variable particle number, x_i, $\boldsymbol{k}_{Ti}$ Gribov, Feynman

  Current operators "count" particle nr × charge

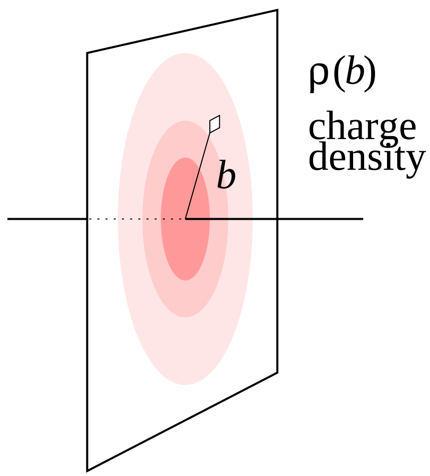
  Physical properties:
  Longitudinal momentum densities PDFs
  Transverse distributions → Form factors, GPDs
  Orbital motion TMDs

Nucleon structure: Transverse densities



- Current matrix element parametrized by invariant form factors

$$\langle N'|J_\mu|N\rangle \;\rightarrow\; F_1(t), F_2(2) \quad \text{Dirac, Pauli}$$



- Transverse charge density $t = -\boldsymbol{\Delta}_T^2$

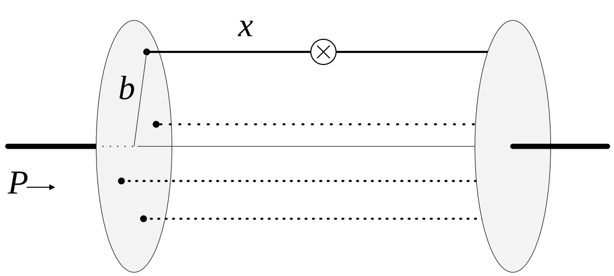
$$F_1(t) \;=\; \int d^2 b \; e^{i\boldsymbol{\Delta}_\mathrm{T}\boldsymbol{b}} \; \rho(b) \quad \text{2D Fourier}$$

Transverse density of charge in fast–moving nucleon
$\boldsymbol{b}$ displacement from transverse C.M.

- Proper density for relativistic system

$$\rho(b) = \sum_N \text{charge} \int dx \; \psi^*(x, \boldsymbol{b}/\bar{x}, ..)\psi(x, \boldsymbol{b}/\bar{x}, ..)$$

Cumulative charge of constituents at transv. position $\boldsymbol{b}$
Breit frame distribution not density: Miller 07

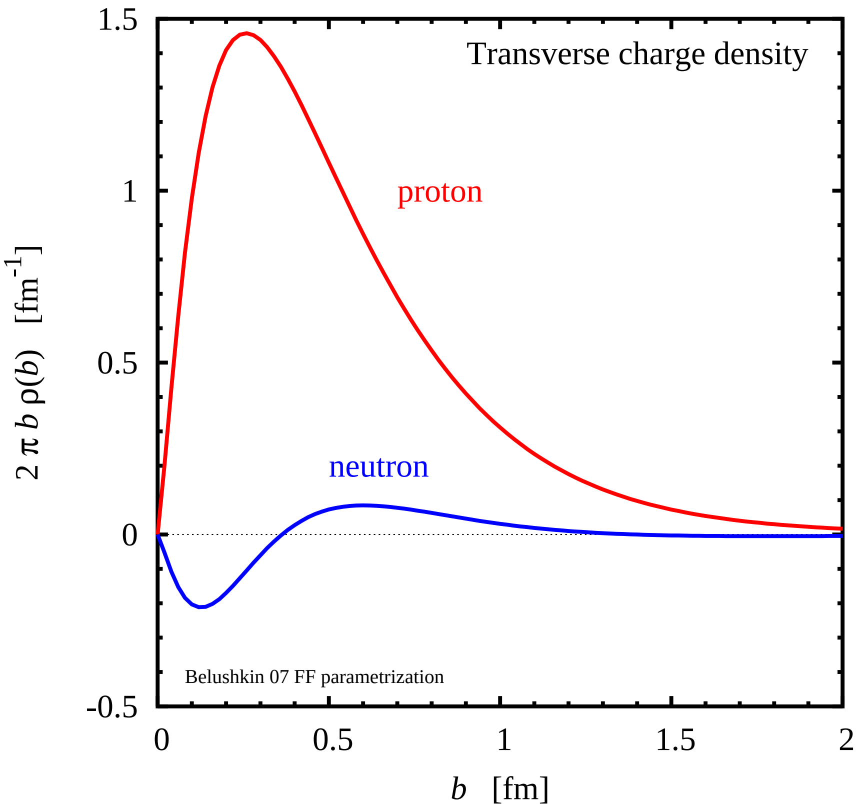


- Universal, process–independent

Reduction of GPD: $\rho(b) = \int dx \; f_{q-\bar{q}}(x, \boldsymbol{b})$

Transverse size in hard exclusive processes

Nucleon structure: Densities from spacelike FFs



$$\rho(b) = \int_0^\infty \frac{d\Delta}{2\pi} \Delta \, J_0(\Delta b) \; F_1(t = -\Delta^2)$$

- Nucleon transverse charge density from spacelike form factor data

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

  Recent low–$|t|$ data incorporated MAMI: Vanderhaeghen, Walcher 10

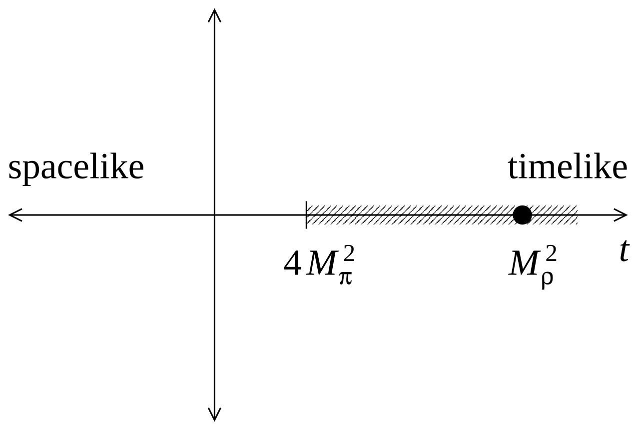
- Neutron density positive at distances $b \sim 0.5 - 1$ fm Miller 07

  Contradicts naive picture of $n = p$(center) $+ \pi^-$(cloud)

  Dynamical explanation?

  Nucleon periphery $\leftrightarrow$ exchange mechanisms?

Periphery: Dispersion representation

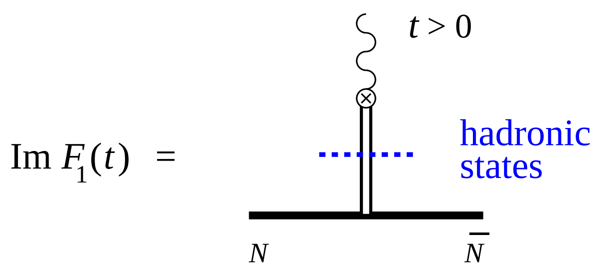


- Dispersion representation of form factor

$$F_1(t) = \int_{4m_\pi^2}^{\infty} \frac{dt'}{t' - t - i0} \frac{\text{Im}\, F_1(t')}{\pi}$$

Spectral function $\text{Im}\, F_1(t')$ describes "process"
current $\rightarrow$ hadronic states $\rightarrow$ $N\bar{N}$

$\text{Im}\, F_1(t')$ from form factor fits and theory:
χPT near threshold, dispersion rels, pQCD $t \rightarrow \infty$



- Transverse density

$$\rho(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b)\, \text{Im}\, F_1(t)$$

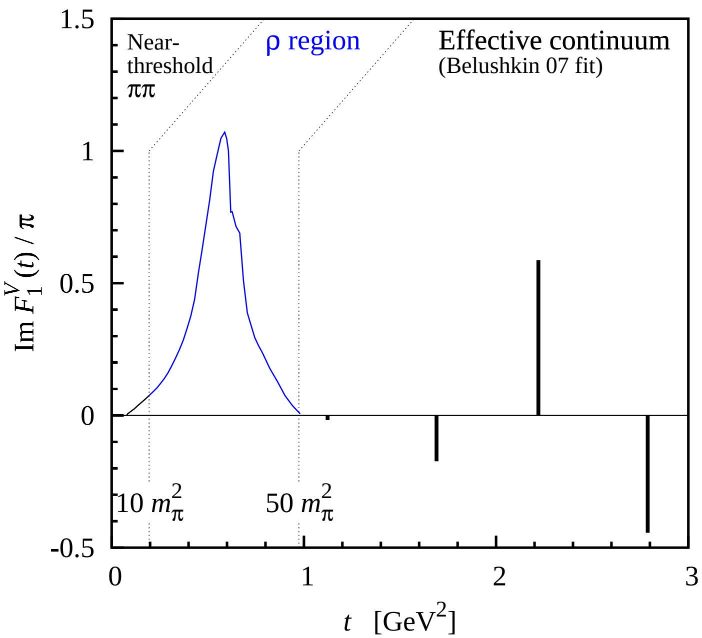
$K_0 \sim e^{-b\sqrt{t}}$ exponential suppression of large t

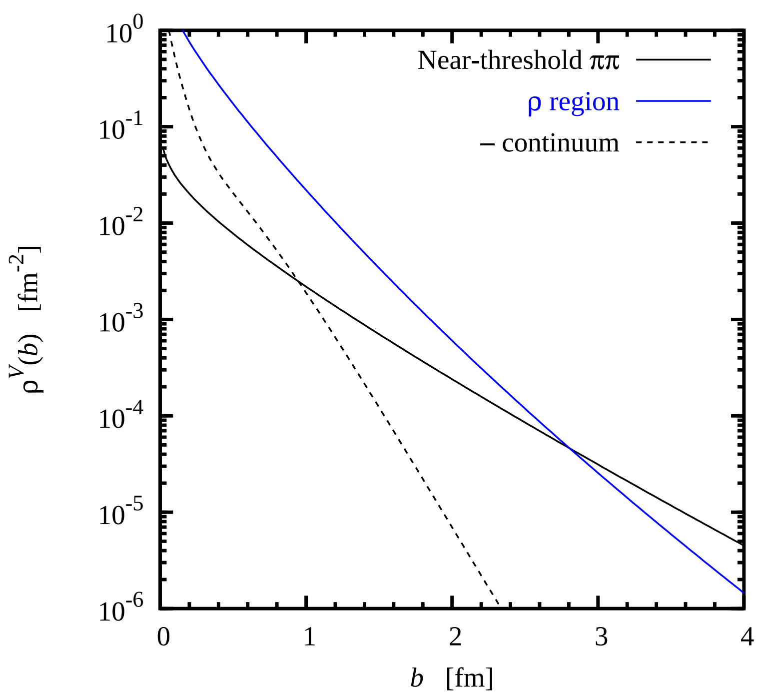
Distance b selects masses $\sqrt{t} \sim 1/b$: "Filter"
Cf. Borel transformation in QCD sum rules. Strikman, CW 10

Peripheral $\rho(b) \longleftrightarrow$ low–mass hadronic states

Isovector: $\pi\pi,\ \rho,\ \rho', \ldots$
Isoscalar: $\omega,\ \phi,\ K\bar{K}, \ldots$

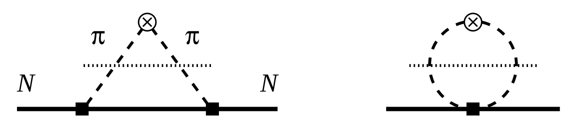
Periphery: Isovector density





- Isovector spectral function

  Near–threshold $\pi\pi$ from chiral dynamics
  Universal, calculable in χPT. Becher, Leutwyler 99; Kaiser 03



  ρ region from $\pi\pi$ phase shifts Höhler 76

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07

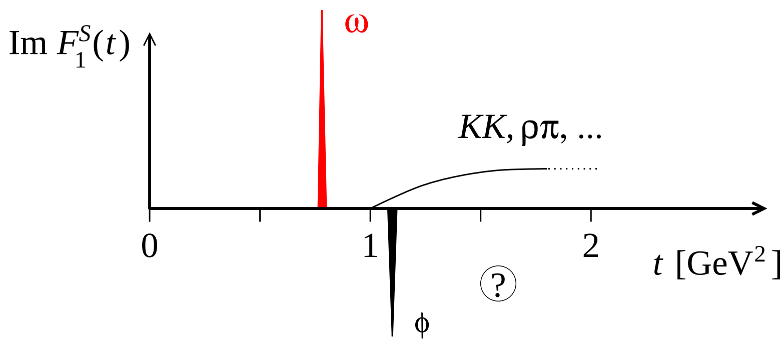
- Spectral analysis of isovector density
  Strikman, CW 10; Miller, Strikman, CW 11

  Near–threshold $\pi\pi$ relevant only at $b > 2\,\mathrm{fm}$
  Contradicts traditional picture of "pion cloud" at distances $\sim 1\,\mathrm{fm}$

  Intermediate $b = 0.5 - 1\,\mathrm{fm}$ dominated by ρ, with $\sim 10\%$ correction from higher masses
  "Vector dominance" quantified

Model–independent quantitative assessment of pion cloud, vector dominance in QCD

Periphery: Isoscalar density

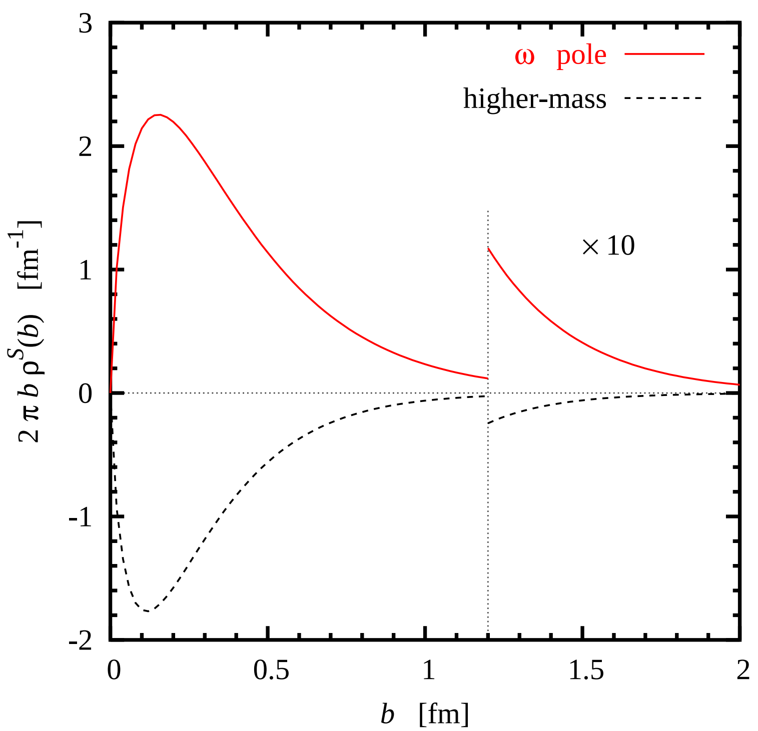


- Isoscalar spectral function

  ω exhausts strength below $1\,\mathrm{GeV}^2$
  Non-resonant 3π negligible

  Large negative strength above $1\,\mathrm{GeV}^2$, dynamical origin unclear
  ϕNN coupling $\leftrightarrow$ $s\bar{s}$ content of nucleon

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07



- Spectral analysis of isoscalar density
  Miller, Strikman, CW 11

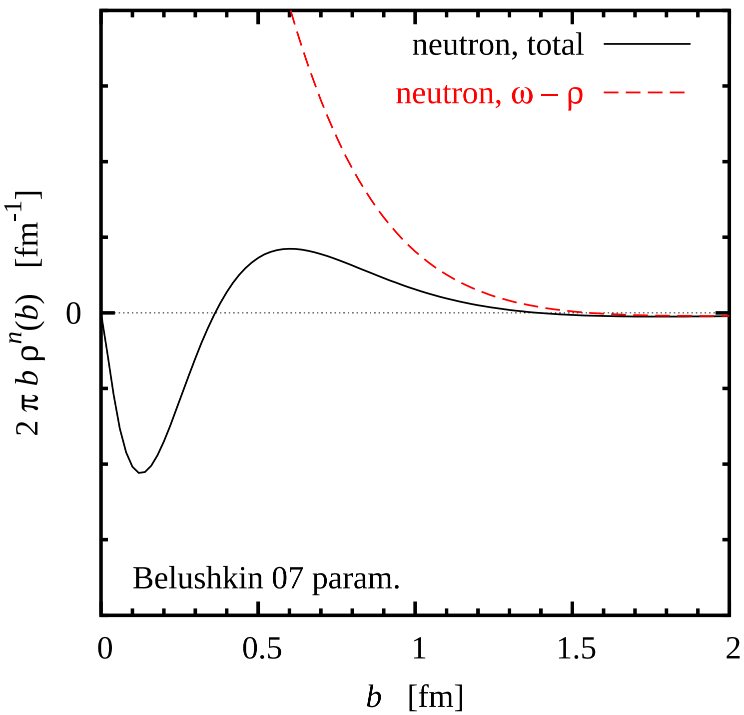
  ω dominates at $b > 1.5\,\mathrm{fm}$
  Fit uncertainty in ωNN coupling $\pm 15\%$

  Large cancellations between ω and higher–mass states at $b = 0.5 - 1\,\mathrm{fm}$

- Impact of future form factor data

  Sensitivity to ωNN coupling broadly distributed at spacelike $|t| \lesssim 1\,\mathrm{GeV}^2$
  Does not require measurements at extemely small $|t|$

Periphery: Neutron density



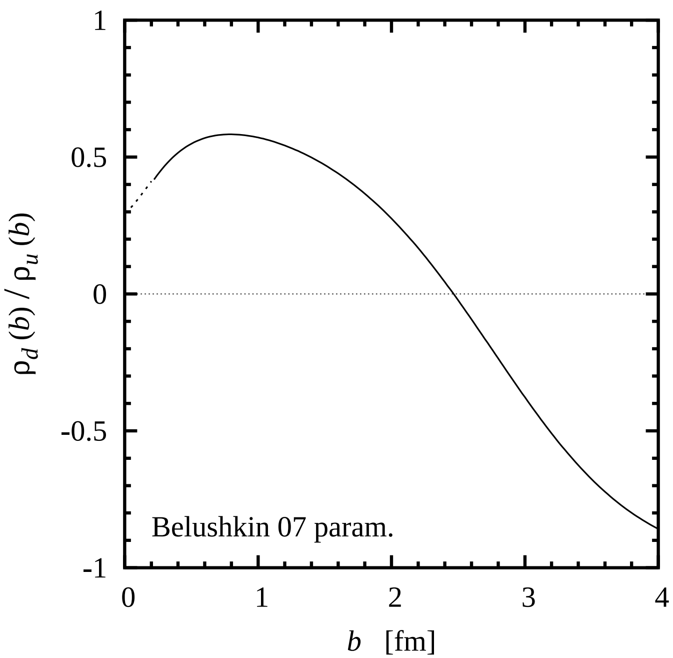
- Spectral analysis of neutron density

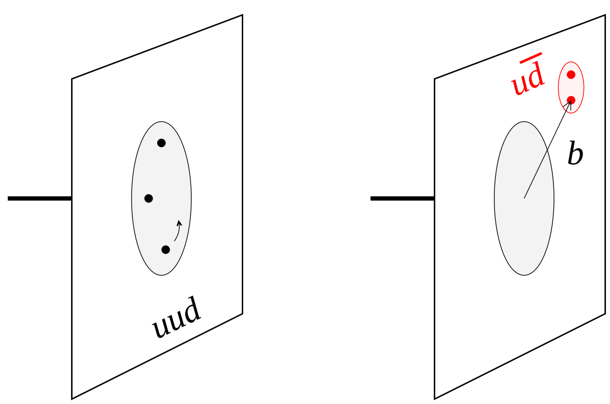
  $\omega - \rho$ alone gives large positive density!

  Substantially reduced by higher–mass states in isoscalar spectral function

  Neutron form factor measurements can help to determine isoscalar spectral function $\rightarrow\ \phi NN$ coupling, $s\bar{s}$ in nucleon

Periphery: Partonic interpretation





mean−field motion of valence quarks

peripheral πn configuration

- Transverse density of u and d quarks

$$\rho_u(b) = \int_0^1 dx\, [u(x, b) - \bar{u}(x, b)] \text{ etc.}$$

Constructed from $\rho^{V,S}$ from dispersion fit

Results agree with flavor–separated FFs of Cates et al. 11

- Partonic interpretation of ratio ρ_d/ρ_u

Large b: $\rho_d/\rho_u \rightarrow -1$ due to peripheral πN configurations in nucleon light–cone wave function

Equivalence of invariant and light–cone χPT: Strikman, CW 10

Same configs govern chiral contributions to PDFs: Strikman, CW 09

Many interesting theoretical issues!

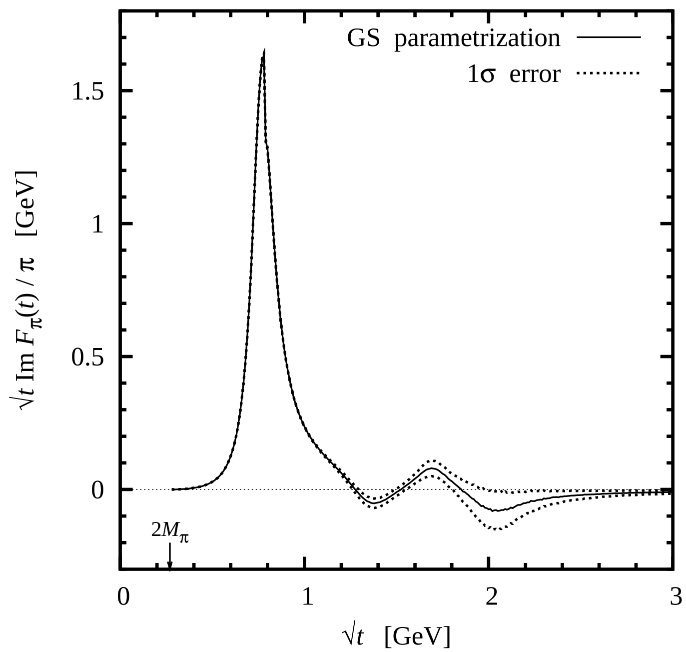
Intermediate $b \sim 0.5 - 1\,\text{fm}$: $\rho_d/\rho_u \sim 1/2$ supports mean-field picture of motion of valence quarks

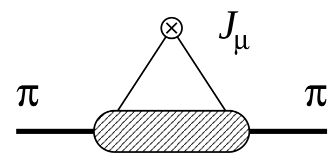
Cf. quark model, chiral quark-soliton model

"Dual" to vector meson exchange!

Model–independent statements about partonic structure!

Pion: Transverse density from timelike data



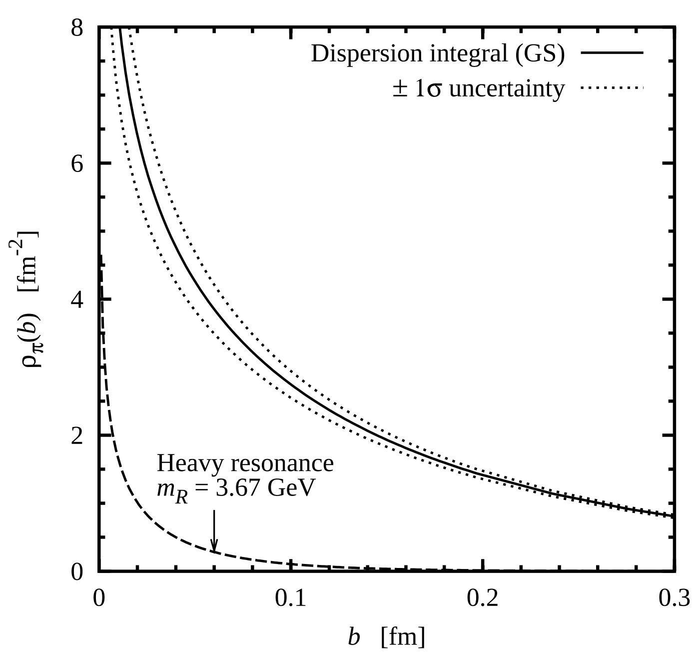


- Spacelike FF poorly known at $|t| > 1\,\mathrm{GeV}^2$
  Electroproduction on nucleon, model-dependent. JLab Hall C 6/12 GeV

- Timelike FF from e^+e^- annihilation

  $|F_\pi|^2$ from cross secn, phase from models/theory

  Resonance–based parametrization from fit to data
  Bruch, Khodjamirian, Kuhn 04. CLEO 05 results not included.



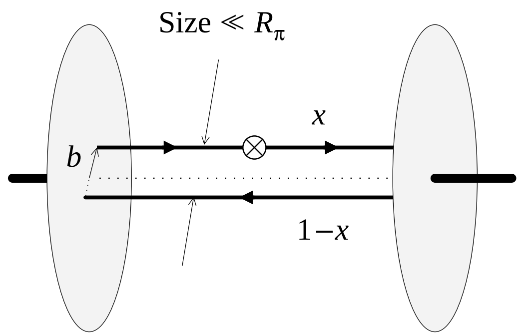
- Transverse density from dispersion integral
  Miller, Strikman, CW 10

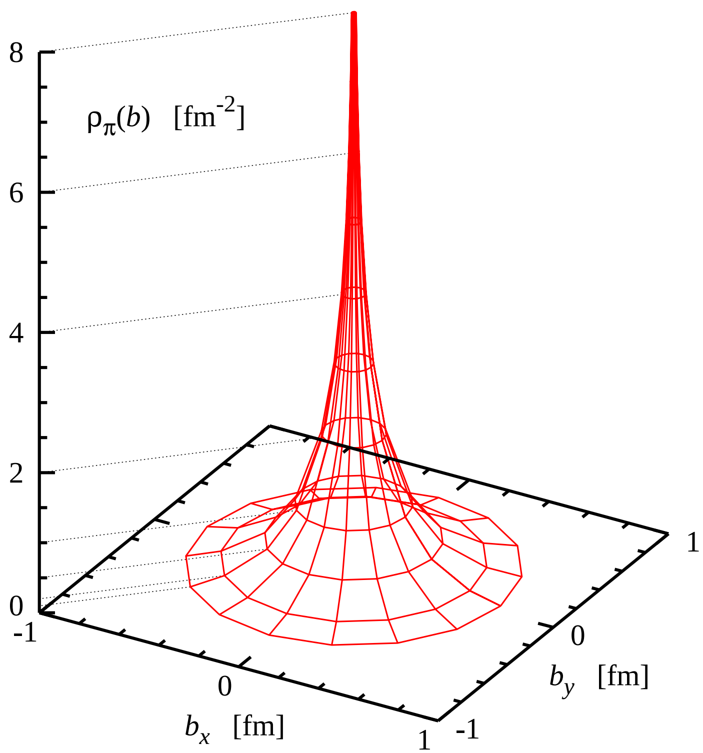
$$\rho_\pi(b) \; = \int\limits_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2}\, K_0(\sqrt{t}b)\; \mathrm{Im}\, F_\pi(t)$$

  Fully calculable, precise, error estimates

  Singular charge density at center of pion

Pion: Partonic interpretation





- Singular charge density at center due to point-like configurations in pion wave functn

  Configs of size $r \ll R_\pi$, mostly elementary $q\bar{q}$

  Observable in other high–momentum transfer processes: $\gamma^*\gamma \rightarrow \pi^0, \; \pi + A \rightarrow 2\,\text{jets}, \ldots$
  Universal property

  Large–size configurations with $x \rightarrow 1$ at scales $Q^2 > 1\,\text{GeV}^2$ cannot account for empirical charge density at $b \rightarrow 0$
  Miller, Strikman, CW 10

  Detailed modeling with light–cone wave functions in progress

- 2D image of fast–moving pion

  First accurate transverse image based on data!

Summary: Theory

- Transverse densities connect partonic structure with hadronic spectrum

  Fully quantitative, consistent with QCD

  New approach to quark–hadron duality in t–channel

- Dispersion integral for $\rho(b)$ samples spectral function at masses $\sqrt{t} \sim 1/b$

  Systematic study of exchange mechanisms

  Mathematical properties: Asymptotic behavior, error analysis, . . .

- Nucleon charge density at intermediate distances $b = 0.5 - 1.5\,\text{fm}$ governed by vector mesons

  Chiral component relevant only at $b > 2\,\text{fm}$

  Origin of isoscalar strength beyond ω still unclear

- Pion charge density from timelike form factor data

  Precise 2D image with controlled accuracy

  Singular charge density at center attributed to pointlike $q\bar{q}$ configurations

Summary: Experiment

- Can the chiral component be studied experimentally?

  Effect on low–Q^2 form factors? $\rightarrow$ Extra slide for discussion

  CLAS/PRIMEX 12 GeV measurement at $10^{-4} - 10^{-2}\,\mathrm{GeV}^2$ PR12-11-106 Gasparian et al.

  Test fundamental χPT predictions!

  Affects extrapolation to $Q^2 \rightarrow 0$

- Dispersion fits to form factors provide much more information than Q^2–dependent parametrizations

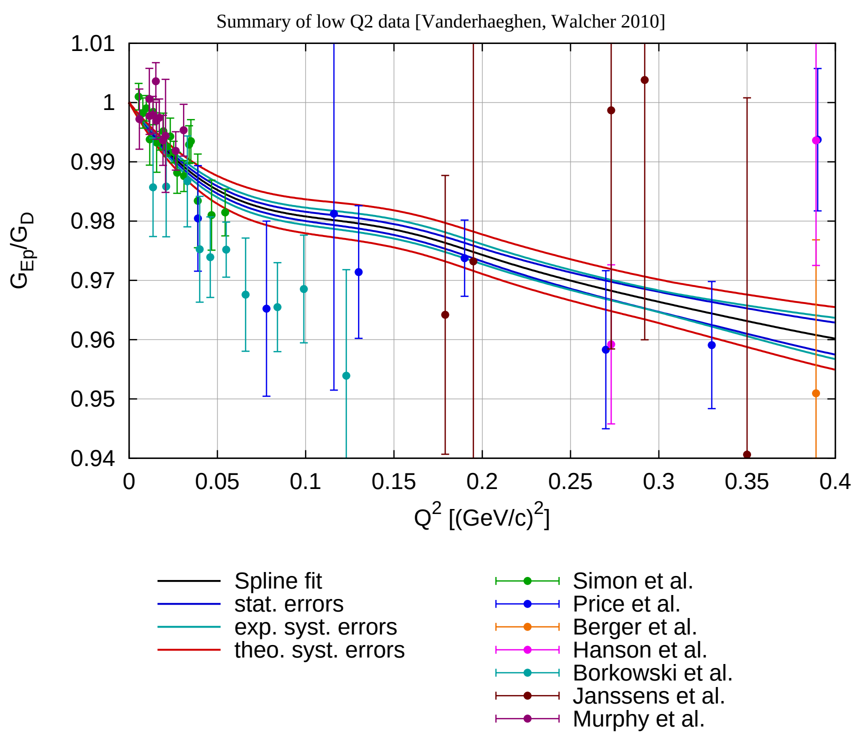
  Should be updated with new 6 and 12 GeV data!

  Analyticity essential for studying nucleon's periphery

- Neutron form factor data crucial for determining isoscalar spectral function

  Impact on $s\bar{s}$ content of nucleon

Chiral component: Effect on form factors



- Moments of transverse charge density

$$\langle b^2 \rangle = \int d^2b \; b^2 \rho(b) = 4\, F_1'(0)$$

$$\langle b^4 \rangle = 32\, F_1''(0)$$

- Contribution of chiral component (isovector)

$$\langle b^2 \rangle_{\text{chiral}} \approx 0.2 \times \langle b^2 \rangle_{\text{fit}} \qquad \text{small}$$

$$\langle b^4 \rangle_{\text{chiral}} \approx 1.5 \times \langle b^2 \rangle^2_{\text{fit}} \qquad \text{sizable}$$

"Unnatural" second derivative

Chiral component should be "visible" in second + higher derivatives at $t = 0$

. . . can we extract it?