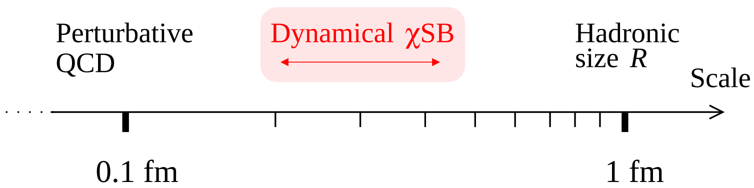
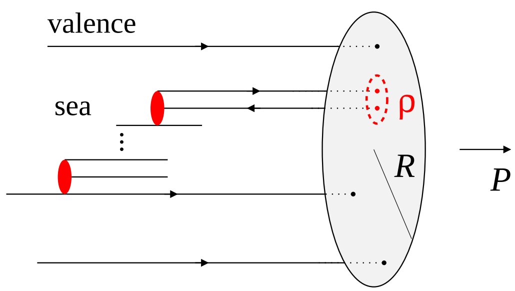
Sea quark transverse momentum and parton short-range correlations in QCD

C. Weiss (JLab), KEK Seminar, 12–Nov–13 JHEP 1301 (2013) 163





Q: How does χSB scale $\rho \sim 0.3$ fm express itself in nucleon's partonic structure?

→ Intrinsic transverse momenta
→ Parton correlations

- Nucleon structure in QCD

  Parton model

  QCD radiation, factorization

- Chiral symmetry breaking in QCD

  Non–perturbative scale $\rho \ll R$

  Effective description: Constituent quarks, Goldstone bosons

- Effect on partonic structure

  $p_T(\text{sea}) \;\gg\; p_T(\text{valence})$

  Short–range correlations of partons

- Experimental tests

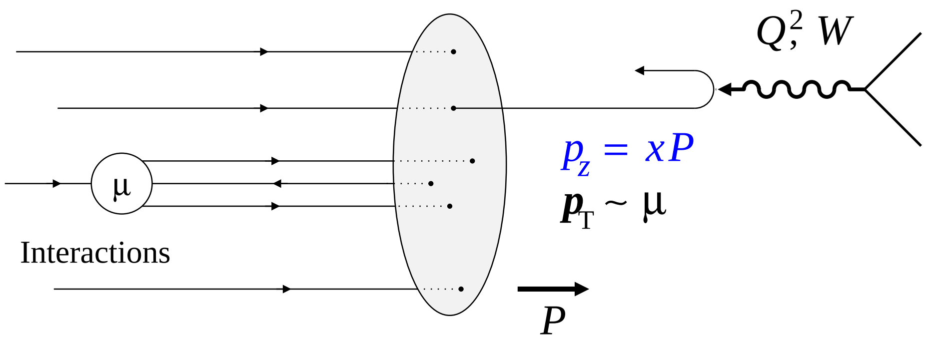
  Inclusive hadrons in ep HERMES, COMPASS, EIC

  Exclusive processes in ep, pp JLab12, J-PARC

  Dileptons in $NN, \pi N$ FNAL, J-PARC, FAIR

  Multiparton interactions in pp Tevatron, LHC

Nucleon structure: Parton model



$$\sigma_T \quad \sim \quad \frac{x f(x)}{Q^2}$$

Bjorken scaling

$$f(x) \quad = \quad \int d^2 p_T \; f(x, p_T)$$

Parton density in longit. momentum

- Relativistic composite system

  Pointlike constituents with interactions of finite range μ^{-1}

  Particles created/annhilated

  System moves with $P \gg \mu$, internal motion "frozen"
  Wave function description: Feynman, Gribov 70's

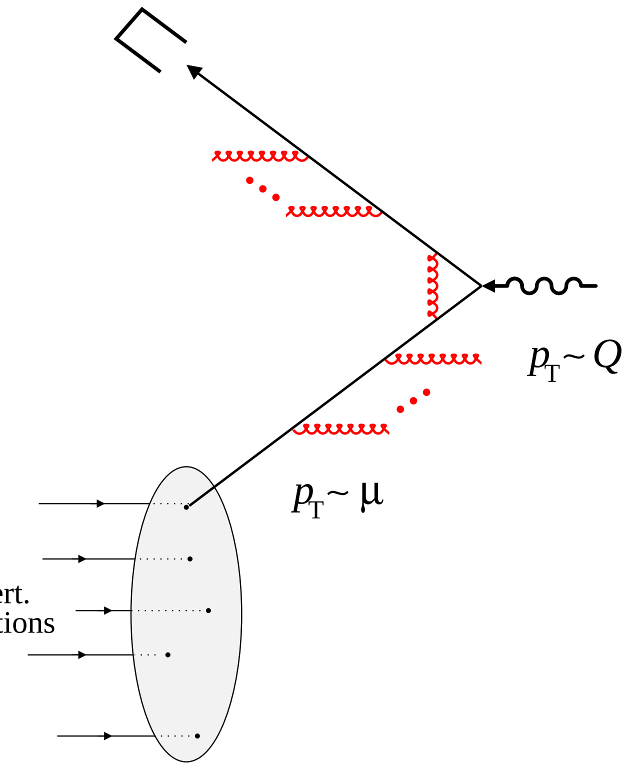
  Constituents' momenta
  longitudinal $p_z = xP$
  transverse $\boldsymbol{p}_T \sim \mu$

- Scattering process $Q^2, W^2 \gg \mu^2$

  Electron scatters from quasi–free constituent with momentum fraction $x \;=\; Q^2/(W^2 - M_N^2 + Q^2)$

  Transverse momenta integrated over, integral converges $p_T \sim \mu$

Nucleon structure: QCD



$\sigma_T \sim$ [parton density] $\sim \mu$

$\times$ [radiation]

$\times$ [scattering process] $\sim Q$

- QCD radiation

  Real emissions with p_T from $\sim \mu$ to Q

  Virtual radiation renormalizes couplings

- Factorization

  Separation of scales in regime $Q^2 \gg \mu^2$

  Inclusive scttering $\gamma^* N \rightarrow X$:
  Net radiation effect simple

  Semi-inclusive $\gamma^* N \rightarrow h(\text{low } P_T) + X'$:
  Radiation effect more complex,
  final–state interactions of struck parton
  Progress with factorization: Collins 11, ...

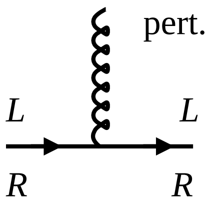
  Parton density as $\langle N|\, \text{QCD–operator} \,|N\rangle$,
  universal, process–independent Collins, Soper 82, ...

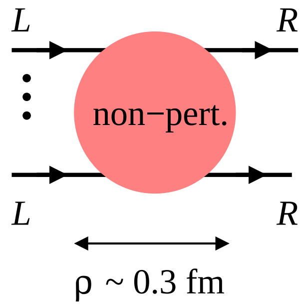
- Parton transverse momentum

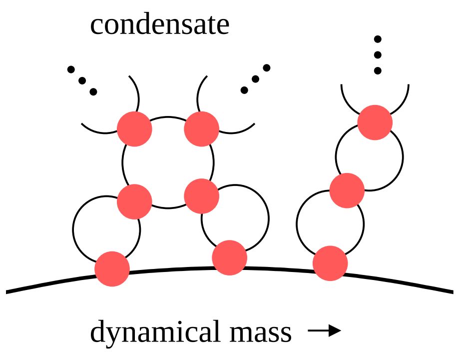
  $p_T \sim Q$ pert. QCD, calculable

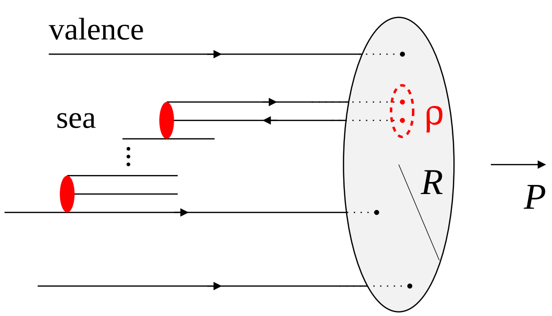
  $p_T \sim \mu$ nonpert. interactions ← this talk!

Chiral symmetry breaking: Physical picture









- Chiral symmetry breaking in QCD

  Non-perturb. gluon fields can flip chirality
  Topological gauge fields, instantons

  Condensate of $q\bar{q}$ pairs $\langle \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \rangle$,
  pion as collective excitation
  Order parameter, Goldstone boson

  Dynamical mass generation:
  Constituent quarks, hadron structure
  Euclidean correlation functions $\rightarrow$ Lattice, analytic methods

- Short–range interactions $\rho \sim 0.3\,\mathrm{fm}$

  New dynamical scale $\rho \ll R$
  Shuryak; Diakonov, Petrov 80's

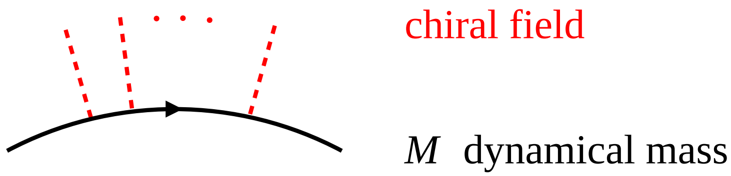
  Gauge–invariant measure of $q\bar{q}$ pair size
  $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle \sim 1\,\mathrm{GeV}^2$ "average virtuality"
  Lattice: Teper 87, Doi 02, Chiu 03. Instantons: Polyakov, CW 96

- How does it affect partonic structure?

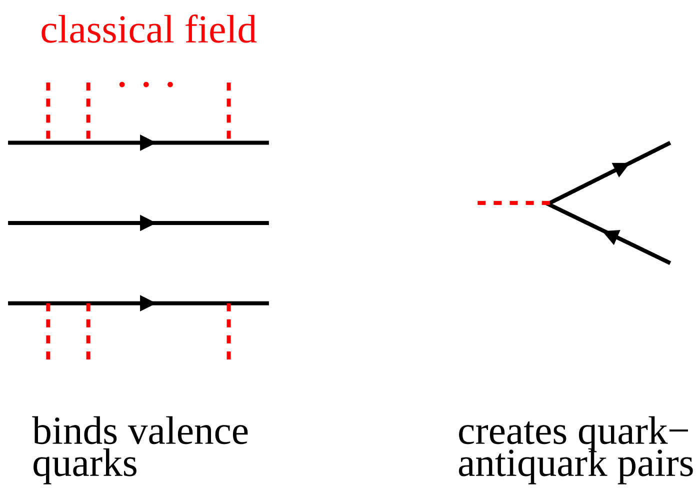
  Valence quark mostly in configurations of size $\sim R$

  Sea quarks in correlated pairs of size $\lesssim \rho$

Chiral symmetry breaking: Dynamical model



$$L_{\text{eff}} = \bar{\psi}\left(i\partial\!\!\!/ - M e^{i\gamma_5 \boldsymbol{\tau}\boldsymbol{\pi}/f_\pi}\right)\psi$$



- Effective description of χSB
  Diakonov, Eides 83; Diakonov, Petrov 86

  Constituent quarks/antiquarks
  with dynamical mass $M \sim$ 0.3-0.4 GeV

  Coupled to chiral field (Goldstone boson)
  with eff. coupling M/f_π = 3–4 strong!

  Valid up to χSB scale ρ^{-2}:
  Matching with QCD quarks/gluons

  Field theory, solved non–perturbatively
  in $1/N_c$ expansion

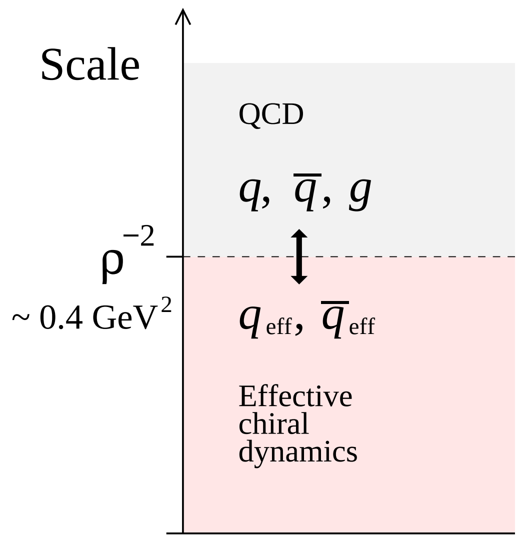
- Nucleon as chiral soliton
  Diakonov, Petrov, Pobylitsa 88; Kahana, Ripka 84

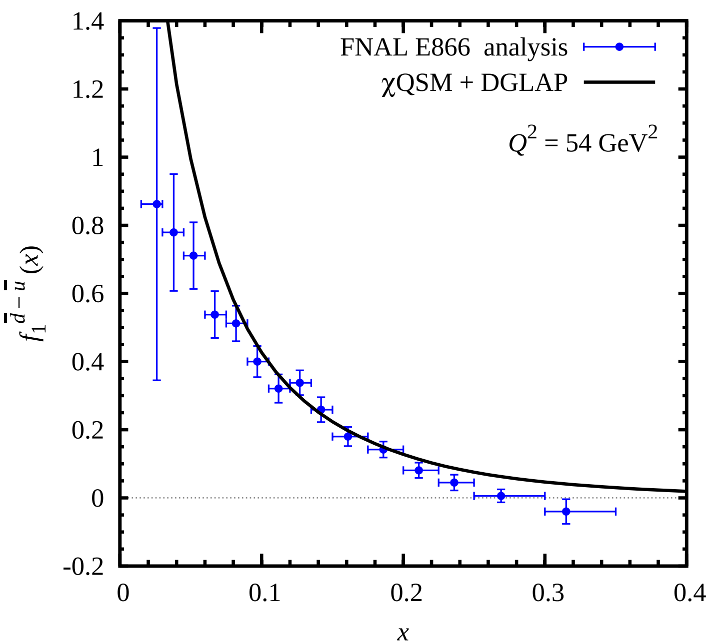
  Classical chiral field
  "Hedgehog" $\boldsymbol{\pi} \parallel \boldsymbol{r}$ in rest frame, cf. skyrmion

  Binds valence quarks,
  creates quark–antiquark pairs
  Relativistic mean–field approximation

  Field theory: Completeness,
  conservation laws, positivity $\rho^{-2} \gg M^2$
  No Fock space truncation! $\rightarrow$ PDFs, sea quarks

Chiral symmetry breaking: Parton distributions





- Parton densities in chiral soliton model
  Diakonov, Petrov, Pobylitsa, Polyakov, CW 96+; Wakamatsu et al. 97+

$$f^q(x, \boldsymbol{p}_T) = \langle N|\, a^\dagger a(xP, \boldsymbol{p}_T)\, |N\rangle_{P\to\infty}$$
$$f^{\bar{q}}(x, \boldsymbol{p}_T) = \qquad b^\dagger b$$

  Equivalent to quark field correlation function $\langle N|\, \bar{\psi}(0) ... \psi(z)\, |N\rangle$ in rest frame

  p_T integral convergent due to UV cutoff ρ^{-2}
  No final-state interaction. Model extension possible

- Interpretation

  x and p_T distribution of effective DOF: Constituent quarks and antiquarks

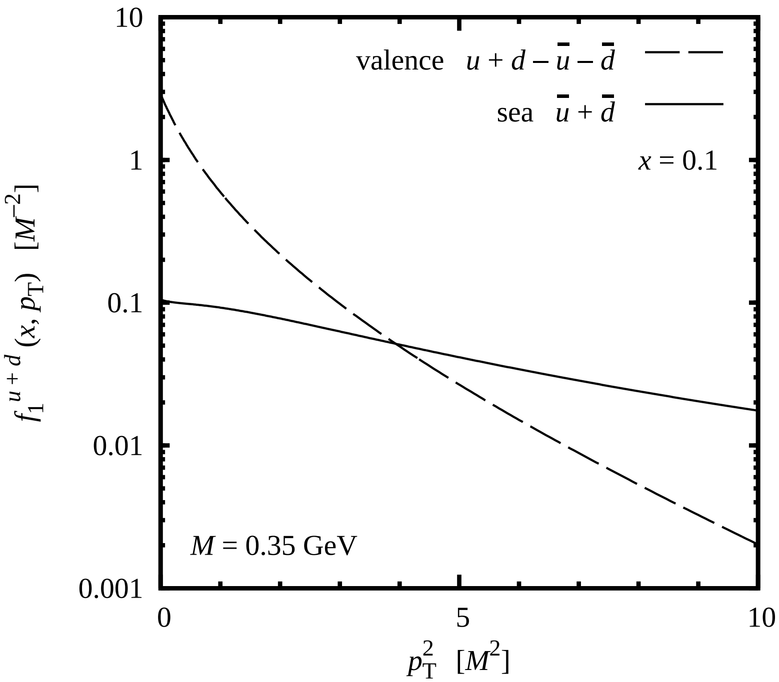
  Matching with QCD $q, \bar{q}, g$ at scale ρ^{-2}

  PDF fits at $\mu^2 \sim 0.5\,\mathrm{GeV}^2$ show 30% of nucleon momentum carried by gluons
  "Accuracy" of matching

- Flavor asymmetries

  Describes well measured $\bar{d} - \bar{u}$ E866 Drell-Yan
  Predicts sizable $\Delta\bar{u} - \Delta\bar{d}$ DSSV, RHIC W → Talk Surrow

Partonic structure: p_T distributions



Sea quark p_T distribution qualitatively different from valence quarks!

- Valence quarks $q - \bar{q}$

  $p_T \sim R^{-1}$, approximate Gaussian shape

  $\langle p_T^2 \rangle \approx 0.15\,\mathrm{GeV}^2$, weakly x–dependent

- Sea quarks $\bar{q}$
  Schweitzer, Strikman CW 12; Wakamatsu 09

  Power-like tail $f^{\bar{q}}(x, p_T) \sim C(x)/p_T^2$ up to cutoff scale ρ^{-2}

  Structure determined by low–energy chiral dynamics, model–independent

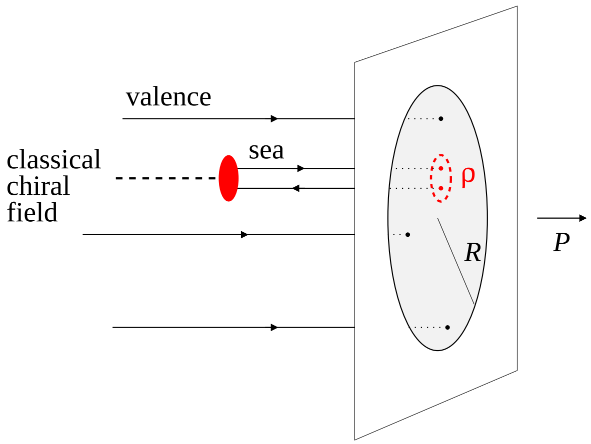
  $p_T^2 \sim \rho^{-2}$: Some model dependence from UV cutoff

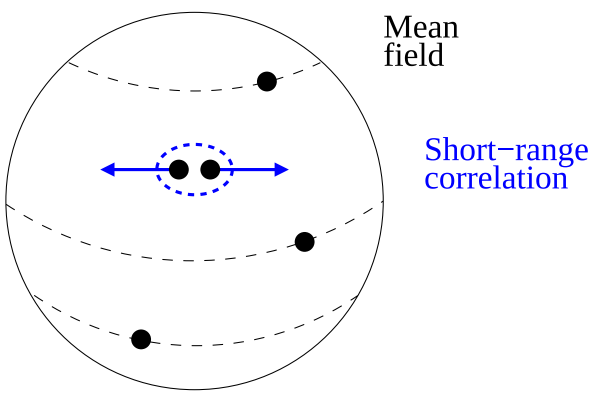
  Similar tail in $\Delta\bar{u} - \Delta\bar{d}$

- Qualitative difference

  Generic feature, rooted in dynamical scale $\rho \ll R$

Partonic structure: Short–range correlations





Parton SRCs as imprint of χSB on partonic structure

- Parton short–range correlations

  Sea quarks in nucleon LC wave function partly in correlated pairs of size $\rho \ll R$
  Explains high-momentum tail of p_T distribution

  Pairs have distinctive spin-isospin structure: Scalar–isoscalar Σ, pseudoscalar–isovector Π

  Restoration of chiral symmetry at high p_T: $|\Psi_\Sigma|^2 = |\Psi_\Pi|^2$ at $p_T^2 \sim \rho^{-2} \gg M^2$

  Large effect: Fraction of correlated sea is $O(1)$

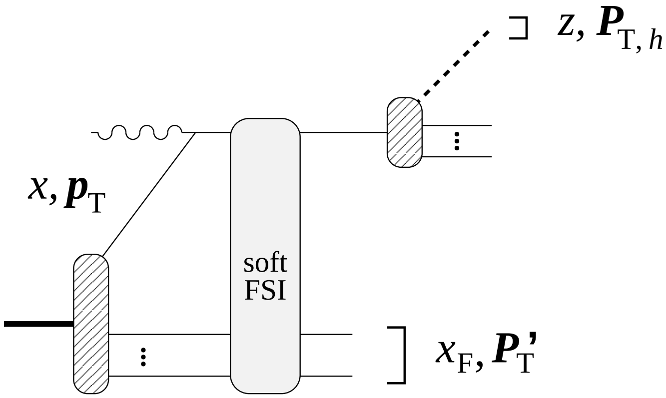
- Cf. NN short–range correlations in nuclei

  Mean field $\Psi(\boldsymbol{r}_1, \dots \boldsymbol{r}_N) \approx \prod_i^N \Phi(\boldsymbol{r}_i)$

  Rare configs with $|\boldsymbol{r}_i - \boldsymbol{r}_j| \ll$ average experience short-range NN interaction, generate high momentum components

  Indirect probes: Momentum distributions, $x > 1$
  Direct probes: $(e, e'NN)$ in special kinematics
  JLab Hall A, CLAS, Hall C at 12 GeV

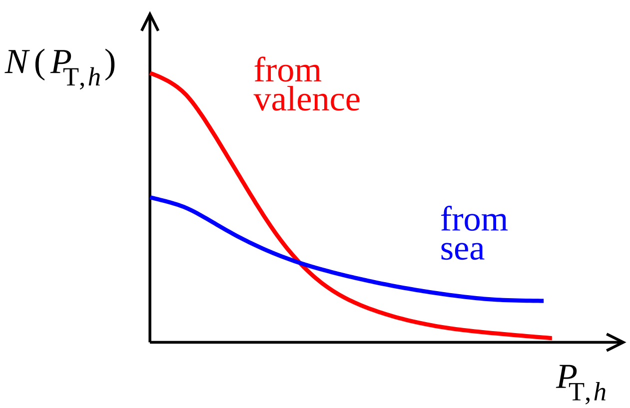
Measurements: Inclusive hadrons in ep



- Hadron $P_{T,h}$ distributions in SIDIS

  Intrinsic p_T in WF
  Final–state interaction
  Parton fragmentation
  } Observable $P_{T,h}$

  External handles: $z \leftrightarrow x$, $z \leftrightarrow P_{T,h}$
  To be explored with CLAS12: Kinematic coverage



- Separate valence and sea quarks in target

  Charge separation with pions

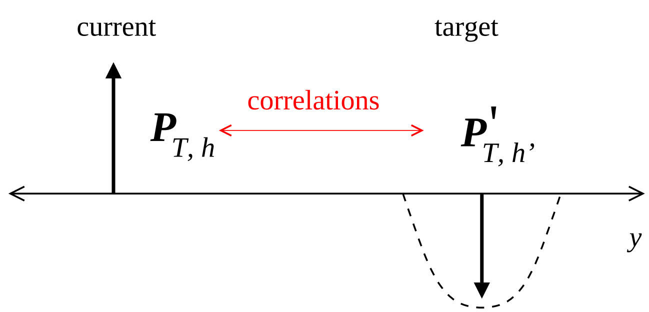
$$N(\pi^+ - \pi^-) \quad \propto \quad e_u^2(u - \bar{u}) - e_d^2(d - \bar{d})$$
$$N(\pi^+ + \pi^-) \quad \propto \quad e_u^2(u + \bar{u}) + e_d^2(d + \bar{d})$$

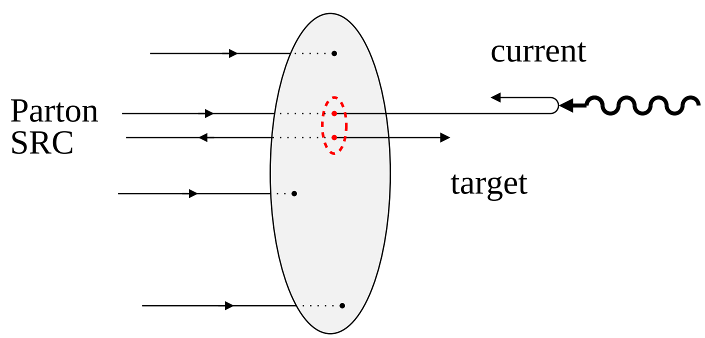
  Charge separation with kaons:
  u dominance, $s = \bar{s}$ fragmentation

$$N(K^+) \ \propto \ u \quad \text{mostly valence}$$
$$N(K^-) \ \propto \ \bar{u}$$

Sea quarks contribute only at $x \sim 0.1$
Intrinsic p_T manifest only at $z > 0.5$
12 GeV kinematics probably marginal.
Schweitzer, Strikman, CW 12; simulations in progress

Measurements: Hadron correlations in ep





- Hadron correlations between current and target fragmentation regions

  Unravel SIDIS mechanism:
  What balances observed $P_{T,h}$?

  Observe nonpert. correlations induced by χSB

- Kinematics for nonperturbative correlations

  Sufficient separation in rapidity
  $\Delta y \approx \ln[W^2/(P^2_{T,h} + m^2_h)] \gtrsim 4$

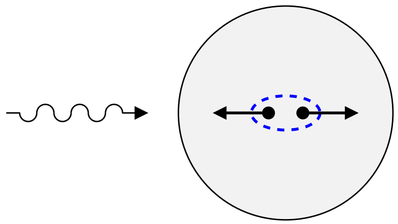
  Moderate virtuality to avoid pQCD radiation
  $Q^2 \sim$ few GeV^2

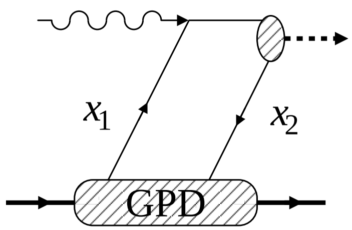
  Momentum fractions of nonperturbative sea
  $x \sim$ 0.05–0.1

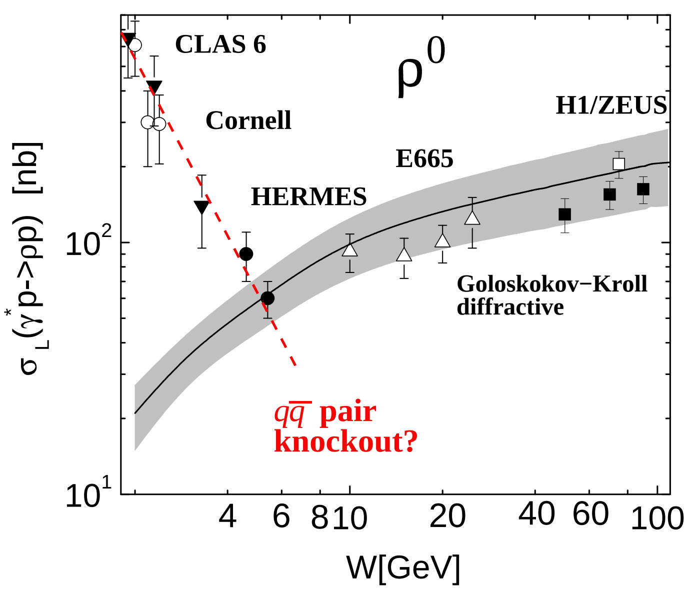
$\rightarrow$ "Kinematic window" at $W^2 \approx 30$ GeV^2, $P^2_{T,h} \approx 0.5\,\mathrm{GeV}^2$

COMPASS: Detection of target fragments?
EIC: Medium energies ideal
JLab12: Probably marginal, but should be explored

Measurements: Exclusive meson production







- Meson production at $Q^2 \sim \rho^{-2}$, low t

  "Knockout" of correlated $q\bar{q}$ pair

  ERBL region of nucleon GPD

  Non-perturbative $q\bar{q}$ correlations
  in both initial and final state
  Soft overlap. Formulation in progress

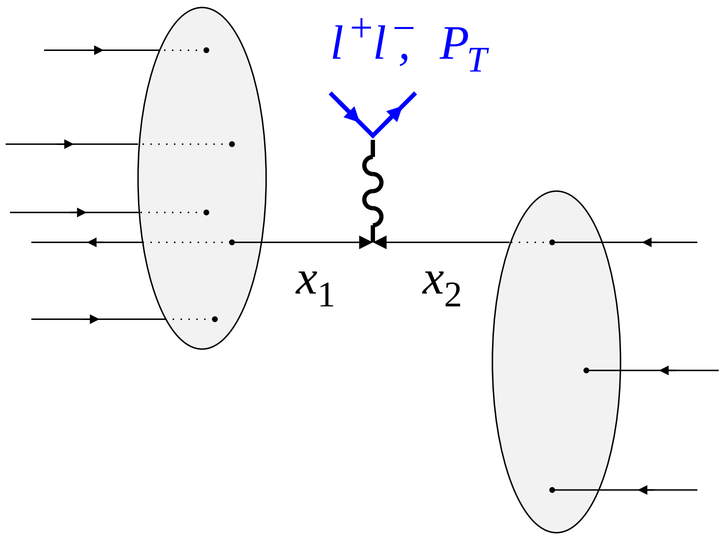
  Hints in JLab 6 GeV data:
  Energy dependence of ρ^0
  Also ρ^+. Guidal et al 08+

  Extensive program with JLab 12 GeV
  $\pi^+, \pi^0, \phi, \rho^0, \rho^+$

- Hadron–induced wide–angle production
  Kumano, Strikman, Sudoh 09

  Experimental opportunities
  COMPASS, GSI FAIR, J-PARC

Measurements: Dileptons in pp and $\bar{p}p$



- l^+l^- produced in parton–parton collision

  P_T distribution of l^+l^- pairs sensitive to intrinsic p_T of quarks/antiquarks

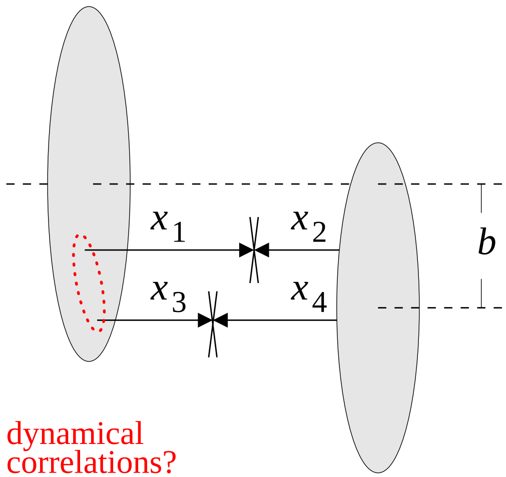
pp	valence $\times$ sea	$x_{1,2} \gtrsim 0.1$
$\bar{p}p$	valence $\times$ valence	

  Expect broader P_T distribution in pp than in $\bar{p}p$ at same $x_{1,2}$

- Experimental data
  FNAL, GSI FAIR

  Need pp and $\bar{p}p$ in same kinematics!

Measurements: Multiparton processes in pp



$$\frac{\sigma(12;34)}{\sigma(12)\sigma(34)} = \frac{1}{\sigma_{\text{eff}}}$$

$$\times \frac{f(x_1, x_3) f(x_2, x_4)}{f(x_1) f(x_2) f(x_3) f(x_4)}$$

- Double dijet rate parametrized by σ_{eff}^{-1}

  Mean field $\sigma_{\text{eff}} = \pi R_{13}^2$ avg distance btw collision points.
  Calculable from transverse distributions

  $$\sigma_{\text{eff}}^{-1} \text{ (mean field)} = \int d^2 b \, P_{12}(b) \, P_{34}(b)$$

- Observed enhancement

  CDF/D0 3jet $+ \gamma$ rate two times larger than mean field with realistic radius

  Possible explanation: Parton correlations
  FSW, Annalen Phys. 13 (2004)

  Perturbative vs. nonperturbative correlations?
  Higher–order vs. mulitparton processes?
  Many challenges. Blok, Dokshitzer, Frankfurt, Strikman 11

- LHC: High rates for multijet events

  Background to new physics processes

  Detailed studies of parton correlations
  New field of study. Great interest! MPI@TAU Tel Aviv 2012

Summary

- Dynamical χSB in QCD creates short–distance scale $\rho \ll R \sim 1\,\mathrm{fm}$

  Natural scale for separating soft wave function $\leftrightarrow$ pQCD radiation

- Qualitatively different p_T distributions of valence and sea quarks

  Valence quarks $p_T \sim R^{-1}$

  Sea quarks "tail" $p_T \lesssim \rho^{-1}$

- Parton short–range correlations in nucleon

  Imprint of QCD vacuum on partonic structure

- Experimental tests

  Separate valence and sea quarks in single–particle inclusive DIS:
  Charged pions, kaons. Details simulations in progress.

  Correlations between current and target fragmentation regions:
  Kinematic window for non–perturbative correlations. Ideal for medium-energy EIC

  Exclusive meson production: Knockout of correlated $q\bar{q}$ pair.
  Exploratory studies in progress.

  Multiparton interactions in high–energy pp collisions