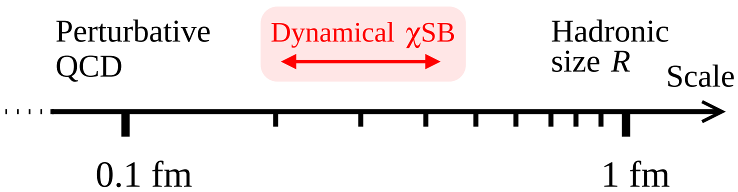
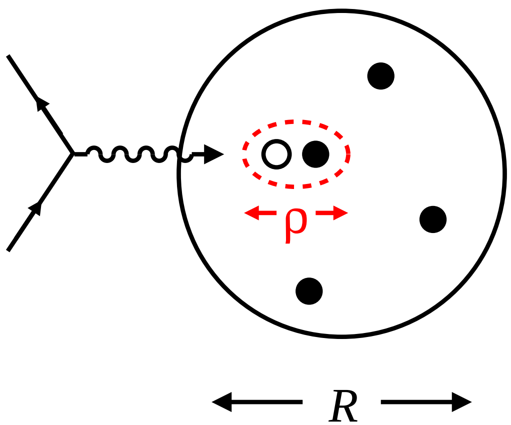
Parton correlations from dynamical chiral symmetry breaking

C. Weiss (JLab), Target Fragmentation Mini-Workshop, LNF Italy, 18–Mar–15





→ Intrinsic transverse momenta

→ Parton short-range correlations

Schweitzer, Strikman, Weiss, JHEP 1301 (2013) 163

- Transverse momentum in QCD

  Parton model

  QCD radiation, factorization

- Chiral symmetry breaking in QCD

  Non–perturbative scale $\rho \ll R$

- Effect on partonic structure

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

  Parton short–range correlations

- Experimental tests

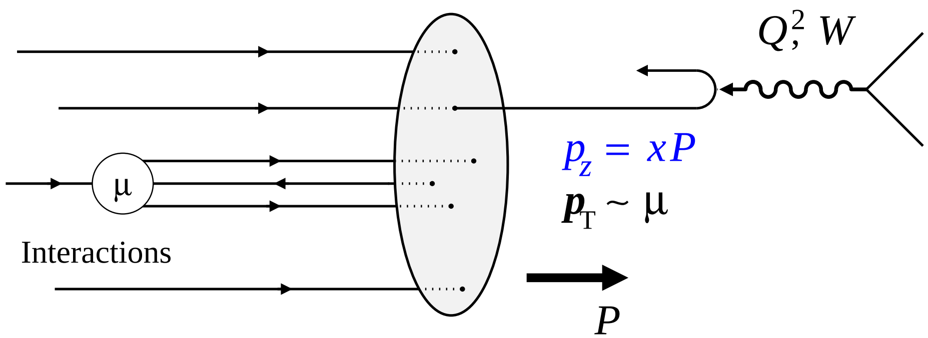
  SIDIS current region $P_{T,h}$ distributions
  HERMES, COMPASS, JLab12, EIC

  Correlations current $\leftrightarrow$ target regions
  CLAS12?, EIC

  Dileptons in pp and $\bar{p}p$
  FNAL, RHIC, GSI?

  Multiparton interactions in pp
  Tevatron, LHC

Transverse momentum: 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

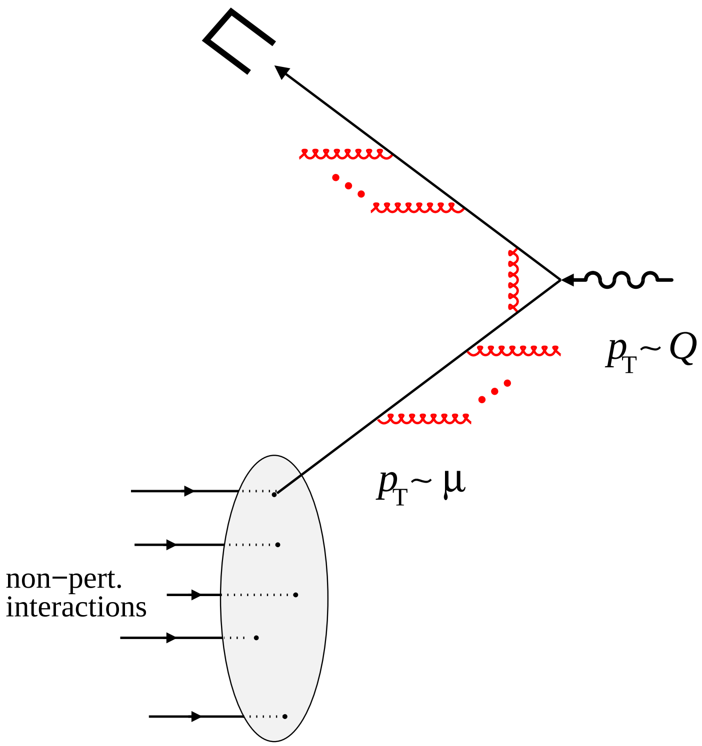
  Constituents' momenta
  longitudinal $p_z = xP$
  transverse $\boldsymbol{p}_T \sim \mu$

- 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 $p_T \sim \mu$

Transverse momentum: 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 $\gamma^* N \to X$:
  Net radiation effect simple

  Semi-inclusive $\gamma^* N \to h(\text{low } P_T) + X'$:
  Radiation effect more complex,
  final–state interactions of struck parton
  Factorization: Collins 11, Aybat, Rogers 11

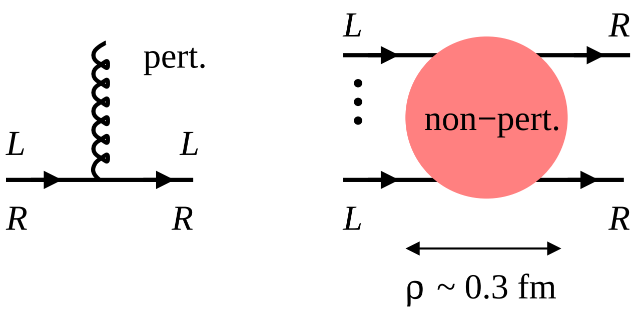
  Parton density as $\langle N | \, \text{QCD–operator} \, | N \rangle$,
  universal, process–independent
  Collins, Soper 82, ...

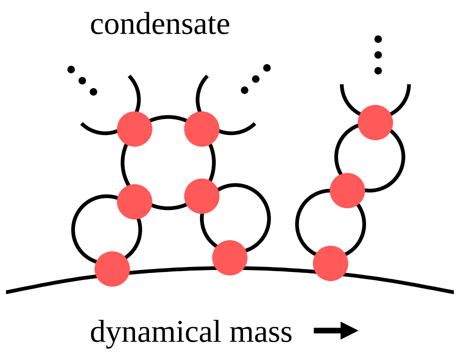
- Parton transverse momentum

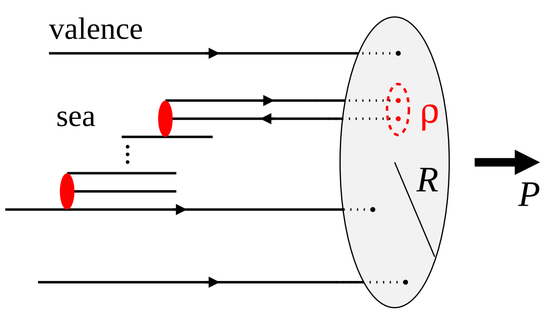
  $p_T \sim Q$ pert. QCD, calculable

  $p_T \sim \mu$ nonpert. interactions ← **This talk!**

Chiral symmetry breaking in QCD







- Chiral symmetry breaking

  Non-perturb. gluon fields can flip chirality

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

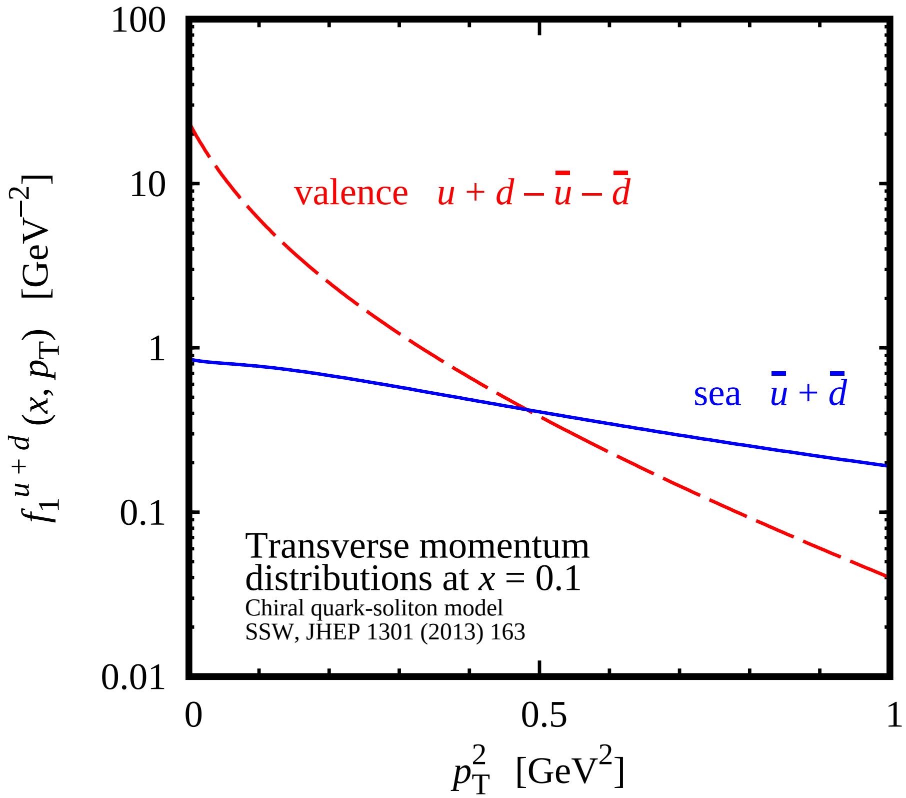
  Gauge–invariant measure of $q\bar{q}$ pair size
  $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle \sim 1\,\mathrm{GeV}^2$ "average virtuality"
  Lattice: Teper 87, Doi 02, Chiu 03. Instantons: Polyakov, CW 96

- How does it affect partonic structure?

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

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

Partonic structure: p_T distributions



$$f^{\bar{u}+\bar{d}}(x, p_T) \sim \frac{C^{\bar{u}+\bar{d}}(x)}{p_T^2 + M_{\text{const}}^2}$$

Power–like tail of sea quarks

- Dynamical model of χSB
  Diakonov, Eides 83; Diakonov, Petrov 86

  Effective degrees of freedom:
  Constituent quarks, Goldstone bosons

  Strongly coupled system, solved non-perturbatively in $1/N_c$ expansion
  Nucleon as chiral soliton

  PDFs at scale $\mu^2 \sim \rho^{-2} \approx 0.5\,\text{GeV}^2$

- Transverse momentum distributions

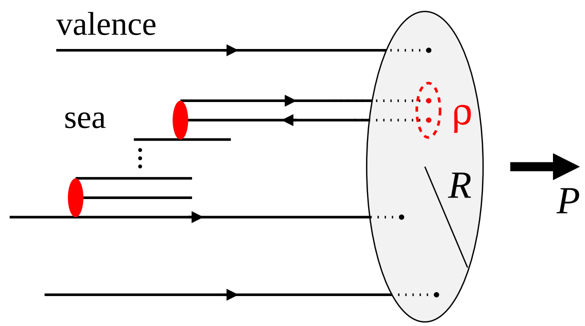
  Valence quarks: Drops steeply,
  $\langle p_T^2 \rangle \approx 0.15\,\text{GeV}^2 = O(R^{-2})$

  Sea quarks: Power-like tail extends up to cutoff scale ρ^{-2}

  Generic feature, rooted in χSB and dynamical scales $\rho \ll R$

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

Partonic structure: Short–range correlations



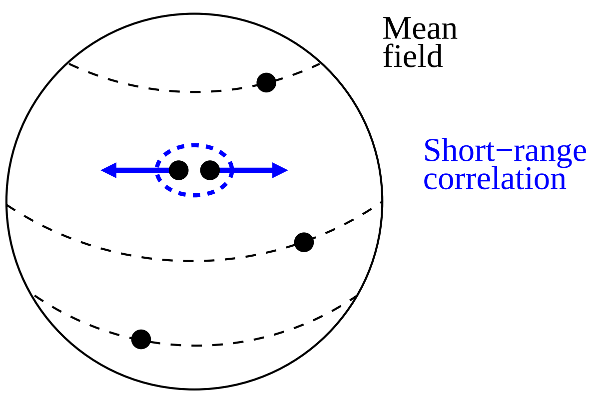
- Parton short–range correlations

  Sea quarks in nucleon LC wave function
  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 $p_T^2 \sim \rho^{-2}$

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



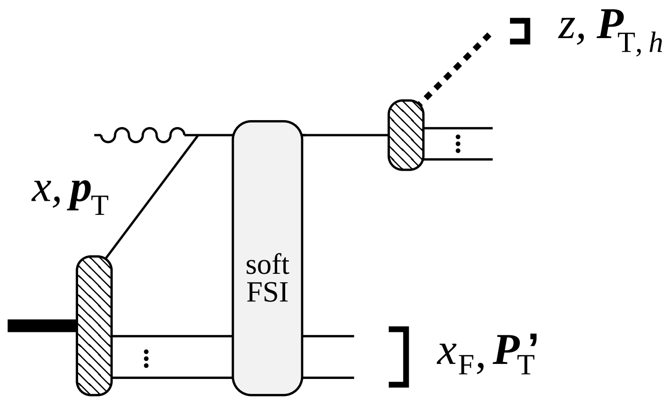
- Cf. NN short–range correlations in nuclei

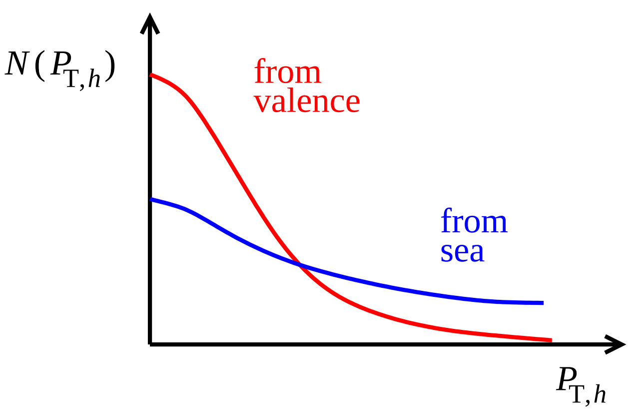
  Mean field $\Psi(\boldsymbol{r}_1, \ldots \boldsymbol{r}_N) \approx \prod_i^N \Phi(\boldsymbol{r}_i)$

  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





Sea quarks contribute only at $x \sim 0.1$
Intrinsic p_T manifest only at $z > 0.5$

Strikman, Weiss 14: Preliminary study based on HERMES/COMPASS/EMC/E665 multiplicity data

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

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

  External handles: $z \leftrightarrow x$, $z \leftrightarrow P_{T,h}$

- Separate valence and sea quarks in target

  Charge separation with pions

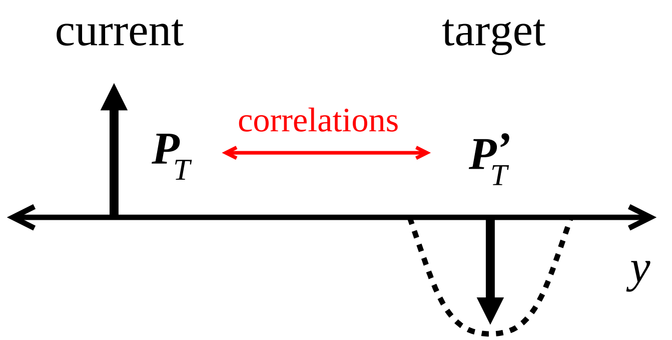
$$N(\pi^+ - \pi^-) \quad \propto \quad e_u^2(u - \bar{u}) - e_d^2(d - \bar{d})$$
$$N(\pi^+ + \pi^-) \quad \propto \quad e_u^2(u + \bar{u}) + e_d^2(d + \bar{d})$$

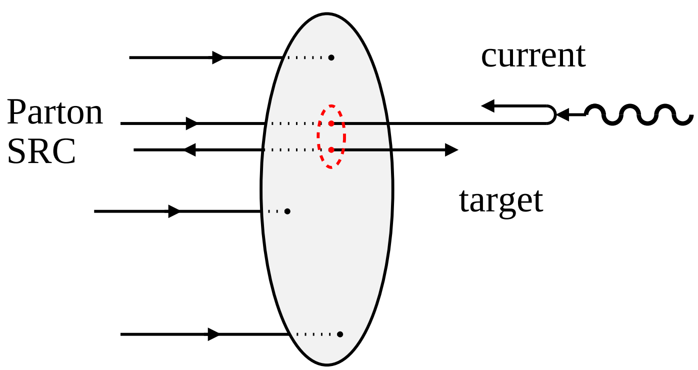
  Charge separation with kaons:
  u dominance, $s = \bar{s}$ fragmentation

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

- Need better understanding of SIDIS mechanism, especially at $z > 0.5$

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 from χSB?

- Kinematics for nonperturbative correlations

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

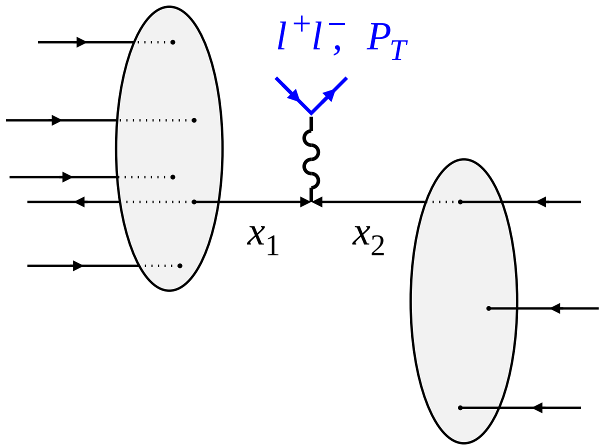
  Moderate virtuality to avoid pQCD radiation
  $Q^2 \sim$ few GeV^2

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

→ "Kinematic window" at $W^2 \approx$ 30 GeV^2, $P_{T,h}^2 \approx 0.5\,\mathrm{GeV}^2$

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

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

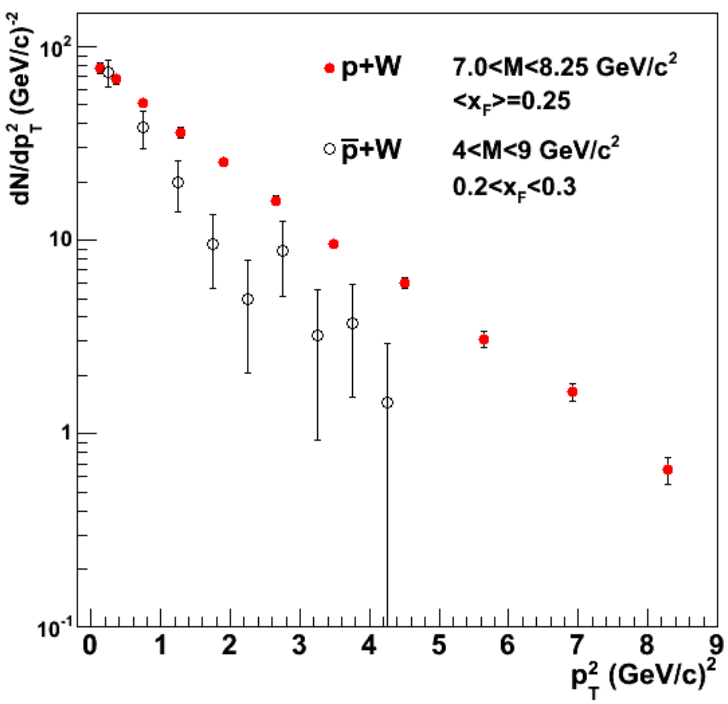
  pp valence $\times$ sea $x_{1,2} \gtrsim 0.1$
  $\bar{p}p$ valence $\times$ valence

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

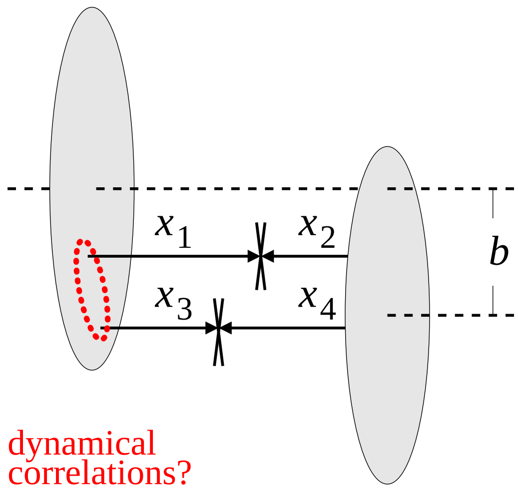
- Experimental data

  $P_T(pp) > P_T(\bar{p}p)$ seen in FNAL Drell-Yan data at $P_T^2 \sim$ few GeV^2
  Aidala, Field, Gamberg, Rogers 14

  Need more pp and $\bar{p}p$ in same kinematics, low $P_T \lesssim 1$ GeV



Measurements: Multiparton processes in pp



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

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

- Two parton–parton collisions in same pp event

  Rate parametrized by σ_{eff}^{-1}

  Calculable as geometric overlap if spatial distributions of partons are independent from each other (mean field)

- Observed enhancement

  CDF/D0 3jet + γ 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!

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. Needs detailed simulations.

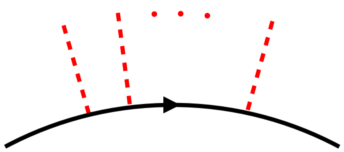
  Correlations between current and target fragmentation regions:
  Kinematic window for non–perturbative correlations.
  Needs detailed simulations. Ideal for medium-energy EIC.

  Comparison of dilepton distributions in $\bar{p}p$ and pp

  Multiparton interactions in high–energy pp collisions

Supplementary material

Chiral symmetry breaking: Dynamical model

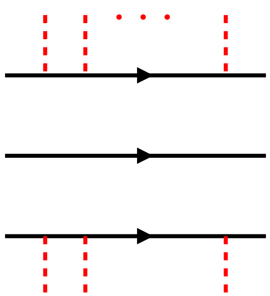


chiral field

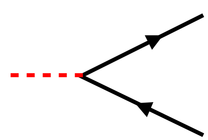
M dynamical mass

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

classical field



binds valence quarks



creates quark–antiquark pairs

- 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 $M/f_\pi =$ 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

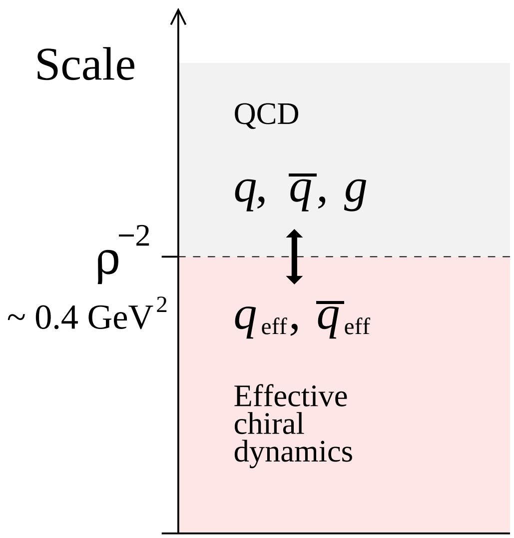
- Nucleon as chiral soliton
  Diakonov, Petrov, Pobylitsa 88; Kahana, Ripka 84

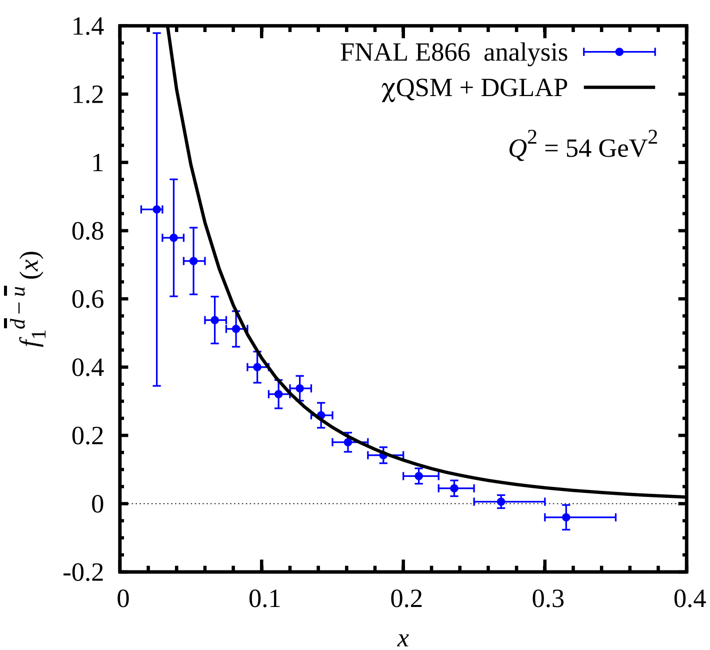
  Classical chiral field
  "Hedgehog" $\boldsymbol{\pi} \parallel \boldsymbol{r}$ in rest frame, cf. skyrmion

  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 $\langle N|\, \bar{\psi}(0) \ldots \psi(z)\, |N\rangle$ 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 $\to$ Talk Surrow