Unraveling hadron P_T in SIDIS: Measurements and non-perturbative dynamics

C. Weiss (JLab), Precision Radiative Corrections Workshop, JLab, 16-19 May 2016

- What measurements can help determine the mechanisms producing hadron P_T in SIDIS?

  Charged pion multiplicities: Separating favored–unfavored fragmentation

  Lower W: Choice of kinematic variables

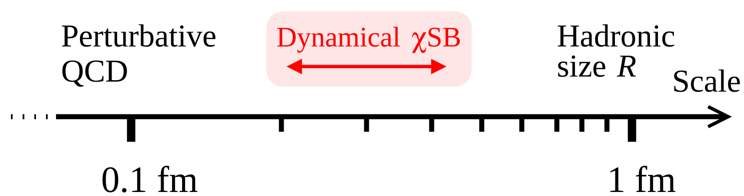
  Transition photo/hadroproduction $\leftrightarrow$ low–Q^2 electroproduction

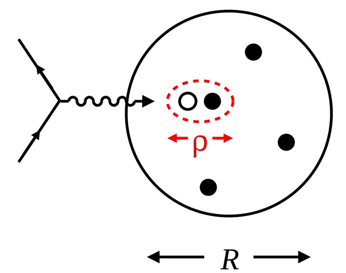
  Correlations current $\leftrightarrow$ target fragmentation regions

- What does non-pert. QCD tell us about TMDs at low scales?

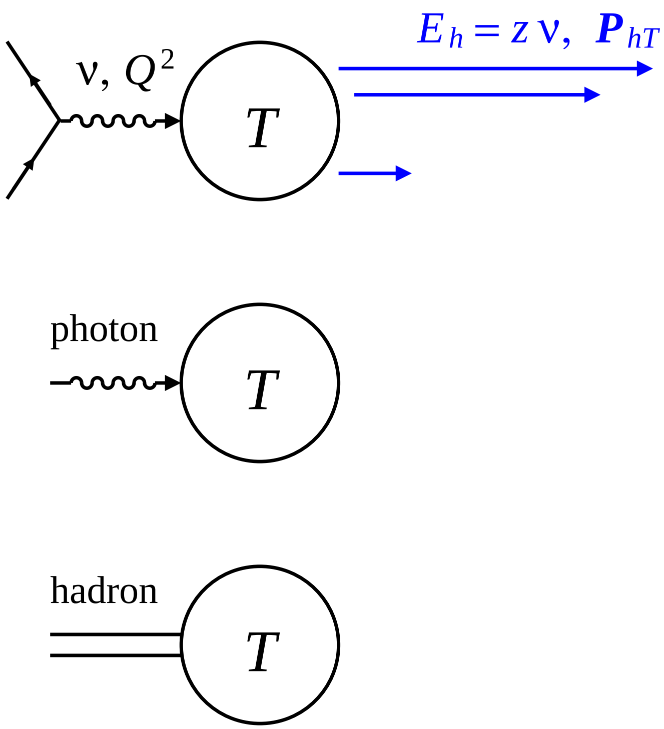
  Short-range interactions in dynamical chiral symmetry breaking

  Intrinsic $p_T(\mathrm{sea}) \gg p_T(\mathrm{valence})$, parton short-range correlations





Hadron production in high-energy scattering



- High–energy scattering $\nu \gg \Lambda_h$

  Large number of hadrons $\sim \log(\nu/\Lambda_h)$

- Longitudinal momentum/energy

  $z = E_h/\nu$ energy fraction rest frame

  $x_L = P_{hL}/P_{hL}^{\max}$ momentum fraction CM

  $\eta = \frac{1}{2}\log P_h^+/P_h^-$ rapidity

- Transverse momentum P_{hT}

  $P_{hT} \sim \Lambda_h$ "soft," $P_{hT} \gg \Lambda_h$ "hard"

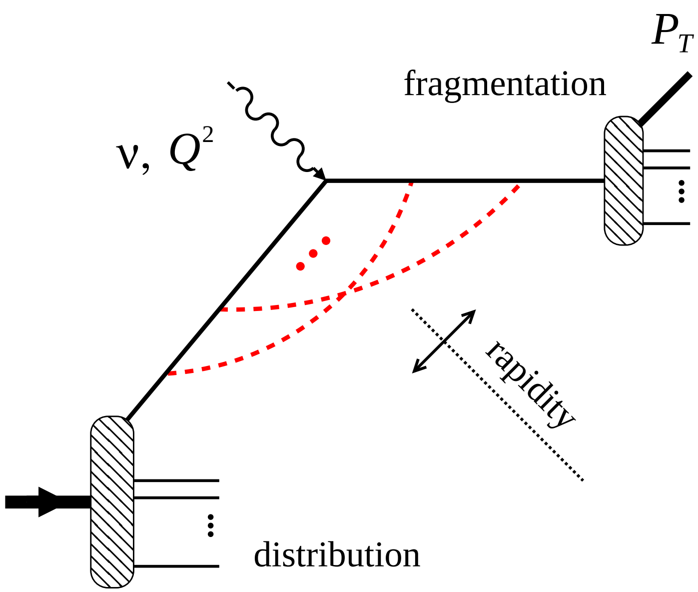
- Theoretical approaches

  Soft photo/hadroproduction: Regge expansions based on generalized optical theorem, hadronic structure of photon (VMD)

  Hard processes $P_{hT} \gg \Lambda_h$: pQCD, collinear factorization

  Electroproduction high Q^2, low P_{hT}: TMD factorization

TMD factorization: Structure



$$\frac{d\sigma}{dP_T} \sim \mathrm{FT}\ f(\boldsymbol{b}_T, x, \zeta_1, \mu) \times D(\boldsymbol{b}_T, z, \zeta_2, \mu)$$

$$+ \quad \text{"Y-term"}$$

$$(P_T \ll Q,\ \zeta_1\zeta_2 = Q^2)$$

- QCD radiation, real and virtual

  Effect different from inclusive σ:
  Sudakov suppression due to $P_T \ll Q$
  Collins, Soper Sterman 84

- Separation in rapidity
  distribution $\leftrightarrow$ fragmentation
  Collins 11, Collins Rogers. Also SCET-based approaches

  Arbitrary, but contolled by ζ_1, ζ_2

- TMD distribution/fragmentation fns

  QCD operator definition

  Wilson lines describe QCD
  initial/final state interactions

  Universality

- CSS evolution equations govern
  scale and rapidity dependence

  Kernel involves non-perturbative
  structure: VEV of Wilson lines

TMD factorization: Questions

- Region of applicability?

  Effective scale – where do perturbative dependencies become relevant?

  Is there a "natural" rapidity separation in SIDIS?

- Structure of TMD distribution and fragmentation functions?

  Relation to inclusive PFDs/FFs, hadronic structure?

  Valence vs. sea TMD PDFs, favored vs. unfavored TMD FF?

- Transition from low to high Q^2?

  Matching of TMD factorization with hadronic description?

  Dynamical origin of soft P_{hT}?

- Characteristics of small and large x?

  $x \gtrsim 0.1$: Non-singlet structures: valence quarks, non-perturbative sea

  $x \ll 0.1$: Singlets dominate, large radiative parton densities

$\uparrow$ **Measurements** $\quad$ $\uparrow$ **Knowledge of non-perturbative dynamics**

Measurements: Hadron multiplicity distributions

- Unpolarized hadron multiplicity distributions are the basic material for studying the mechanisms of P_{Th} generation and the applicability of TMD factorization.
  Publication of HERMES and COMPASS multiplicities was major advance!

- Need distributions differential in W, Q^2, z, P_{Th} ← **QED rad corr**

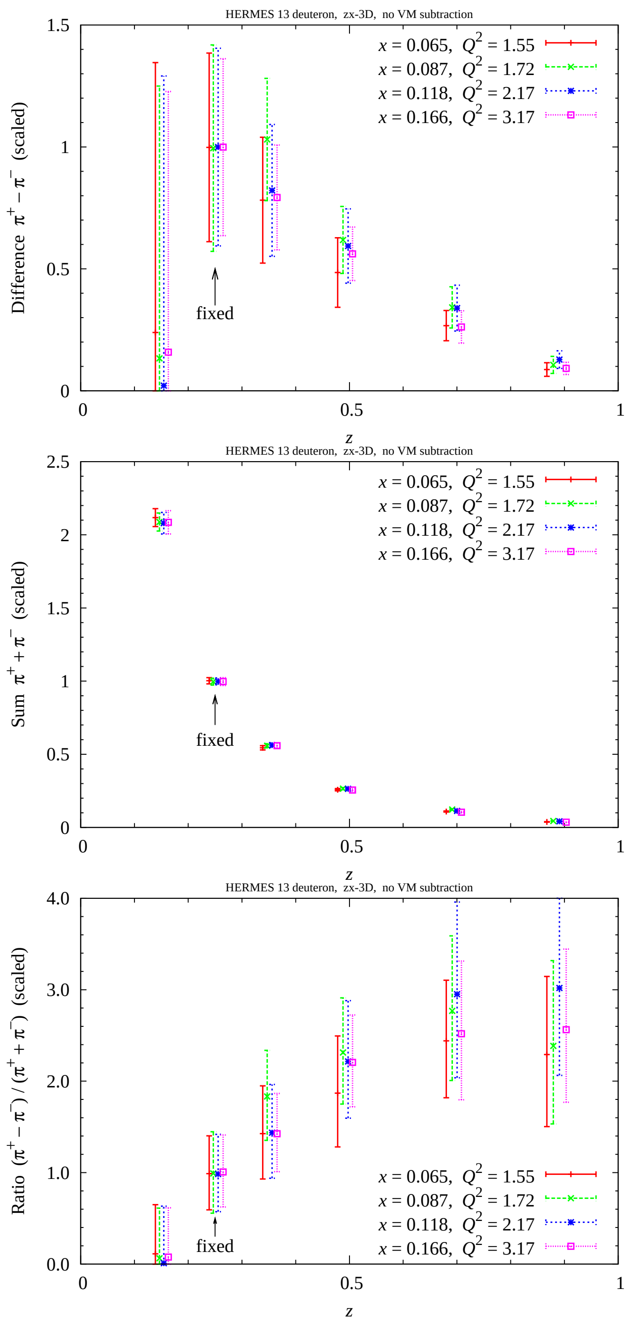
- Need actual P_{Th} distributions, not just Gaussian slopes at low P_{Th}.
  Tail at $P_{Th} \sim \text{few GeV}$ carries important pert & non-pert information

- Need flexible binning, cf. HERMES multiplicity downloader

Experiment	W [GeV]	Q^2 [GeV^2]	x
HERA H1 Alexa13		$5 - 100$	$10^{-4} - 10^{-2}$
HERA ZEUS Derrick95	$75 - 175$	$10 - 160$	$10^{-4} - 10^{-2}$
E665 Adams97	$7.5 - 30$	$0.15 - 20$	$1.5 \times 10^{-4} - 0.6$
EMC Ashman91	$6 - 20$	$2 - 250$	$0.01 - 1$
COMPASS Adolph13	$6 - 15$	$1 - 10$	$0.004 - 0.12$
HERMES Airapetian12		$1 - 15$	$0.023 - 0.6$
JLab6 Hall C Mkrtchyan07		$2 - 4$	$0.2 - 0.5$
JLab6 CLAS Osipenko08		$2 - 7$	$0.1 - 0.8$

Summary of $eN/\mu N$ DIS experiments reporting hadron multiplicity distributions

Measurements: Favored vs. unfavored FFs



- Combined multiplicities $\pi^+ \mp \pi^-$

$$N(\pi^+ - \pi^-) \;\propto\; [\sum \text{PDFs}](x) \times [D_{\text{fav}} - D_{\text{unf}}](z)$$

$$N(\pi^+ + \pi^-) \;\propto\; [\sum' \text{PDFs}](x) \times [D_{\text{fav}} + D_{\text{unf}}](z)$$

$$D_{\text{fav}} \equiv D_{u\to\pi+}, \quad D_{\text{unf}} \equiv D_{u\to\pi-} \quad \text{etc.}$$

  Separate unfavored and favored FFs.
  Model-indpendent!

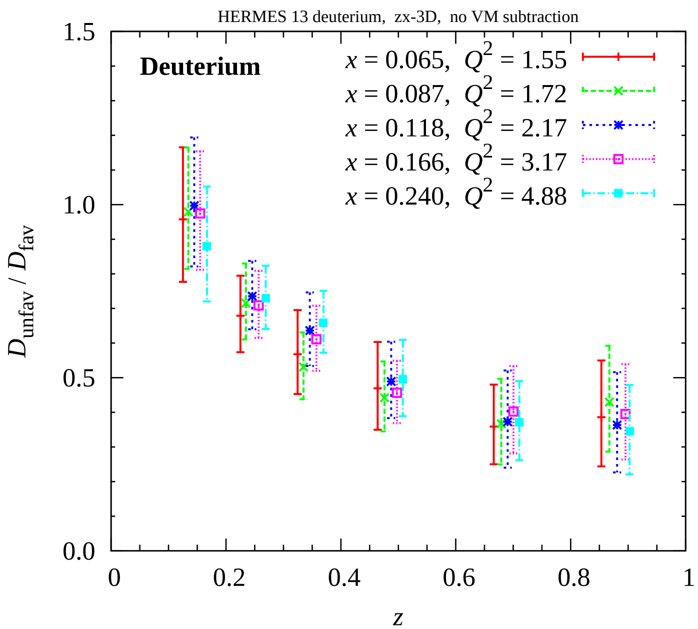
  Use deuteron and proton data
  Strangeness can be included

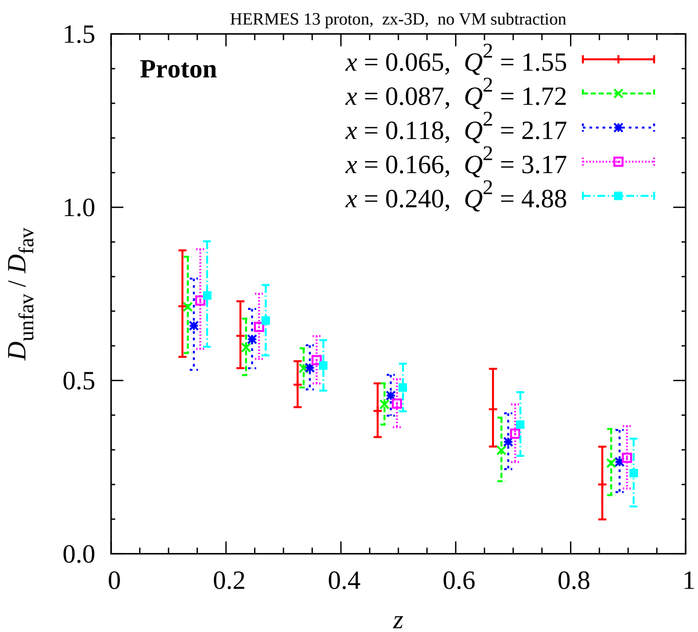
- Phenomenological analysis
  HERMES 2012 data. Strikman, CW 14/16

  x and z dependences factorize ✓

  Data reveal different shapes of
  unfavored and favored FFs ✓

Measurements: Favored vs. unfavored FFs





- Unfavored/favored FF ratio extracted from $\pi^+ \mp \pi^-$ data

  Reasonable agreement between deuteron and proton data

  Ratio surprisingly large at $z > 0.5$
  Dynamical explanation?

  Simple analysis: Just plotting data

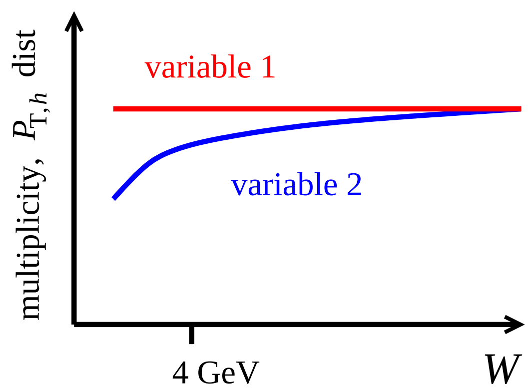
- Could be extended to P_T–dependent multiplicities

- Alt method: Convolution model fits
  Torino group: Prokudin et al.; Bacchetta et al. 13

Measurements: Kinematic variables for lower W

- Rich SIDIS data will become available at $W \lesssim< 4$ GeV with JLab12. Kinematics challenging for independent fragmentation or QCD factorization

- Size of apparent "change" of P_T distributions at low W depends on choice of longitudinal momentum variable ← **QED rad corr**

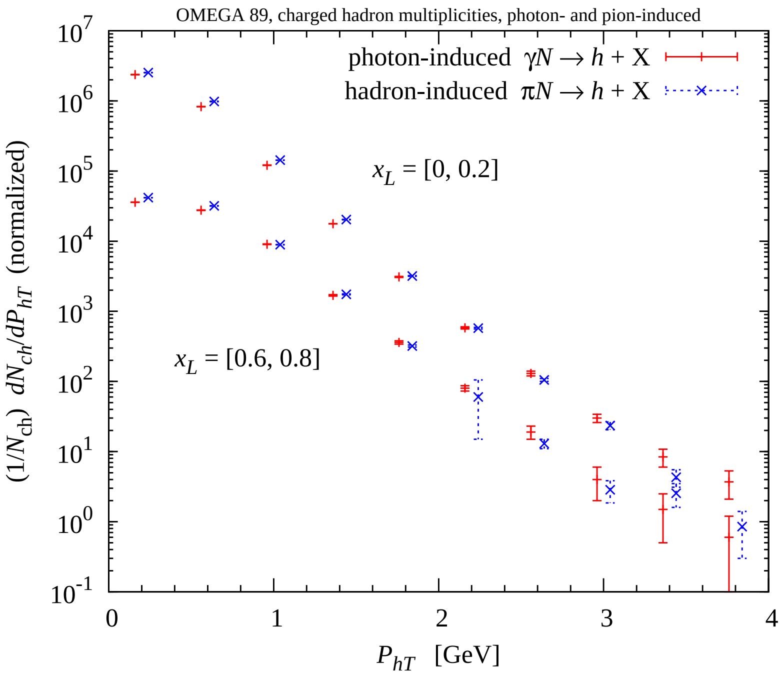


$z = E_h/\nu$	energy fraction rest frame
$x_L = P_{hL}/P_{hL}^{\max}$	momentum fraction CM
$\eta = \frac{1}{2}\log P_h^+/P_h^-$	rapidity
$\zeta = P_h^+/P_{\text{target}}^+$	light-cone fraction

- Effect of different choices can be studied using data at higher W and/or MC simulations (are they accurate enough?)

- Theoretical models of low-W corrections are ambiguous: No separation between "kinematic" and "dynamical" effects

Measurements: Transition low to high Q^2 in SIDIS



CERN OMEGEA 89 data

Similar plots should be made with low–Q^2 electroproduction data, comparison at fixed W

- Dynamical origin of low–P_T hadrons in DIS at $Q^2 \sim$ few GeV^2?

  Non-perturbative dynamics?

  Soft gluon radiation – CSS evolution?

- Explore transition between $Q^2 = 0$ and $Q^2 \sim$ few GeV^2

  Photo– and hadroproduction have similar P_{hT} distributions

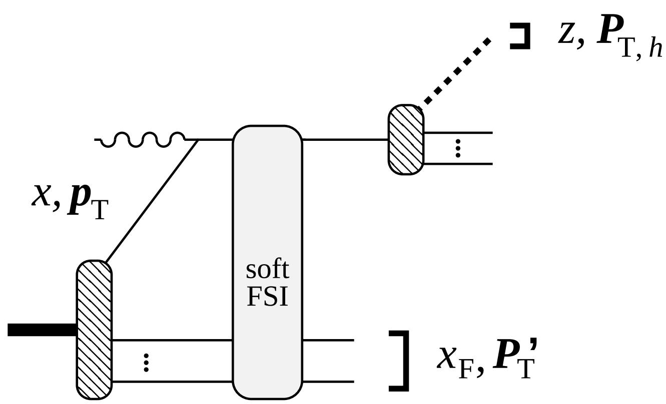
  Expect smooth transition between photo–production and $Q^2 \sim$ few GeV^2

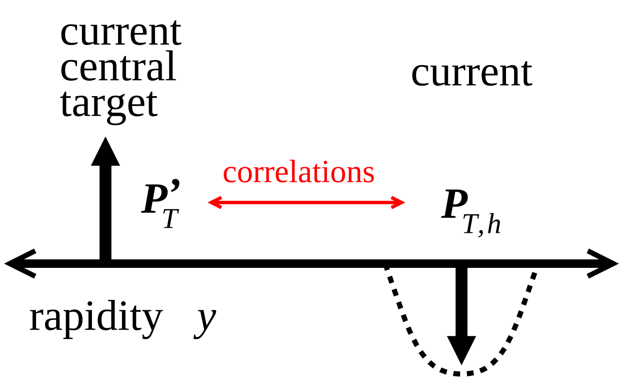
  Successful studies of soft–hard transition at HERA: inclusive, exclusive, diffractive

- Enable hadronic modeling of P_T distributions at $Q^2 \sim$ few GeV^2

  Initial condition of CSS evolution

Measurements: Hadron correlations





- What is source of observed hadron $P_{T,h}$?

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

  Cannot separate different sources
  with single-inclusive measurements alone

- Correlation measurements

  What "balances" observed $P_{T,h}$?

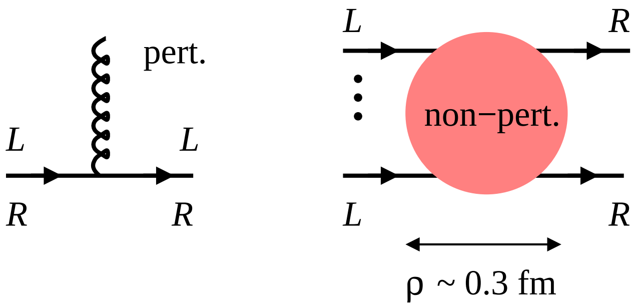
  Is $P_{T,h}$ balanced by broad distribution
  or single back-to-back hadron?

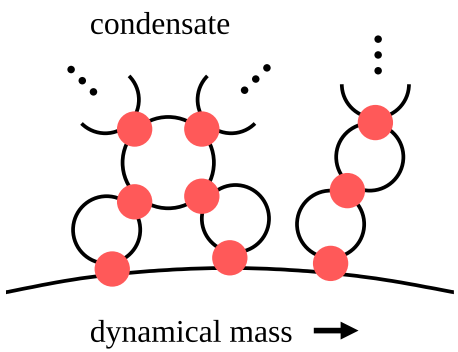
  Where in rapidity is it balanced:
  Current, central, or target region?

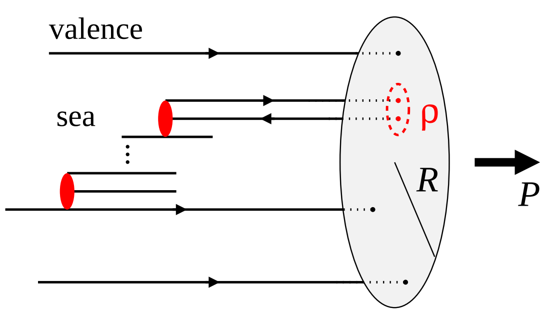
  Dynamical pictures: String fragmentation,
  parton short-range correlations

- Next–generation SIDIS measurements
  JLab12, EIC

Dynamics: 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 → Lattice, analytic methods

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

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

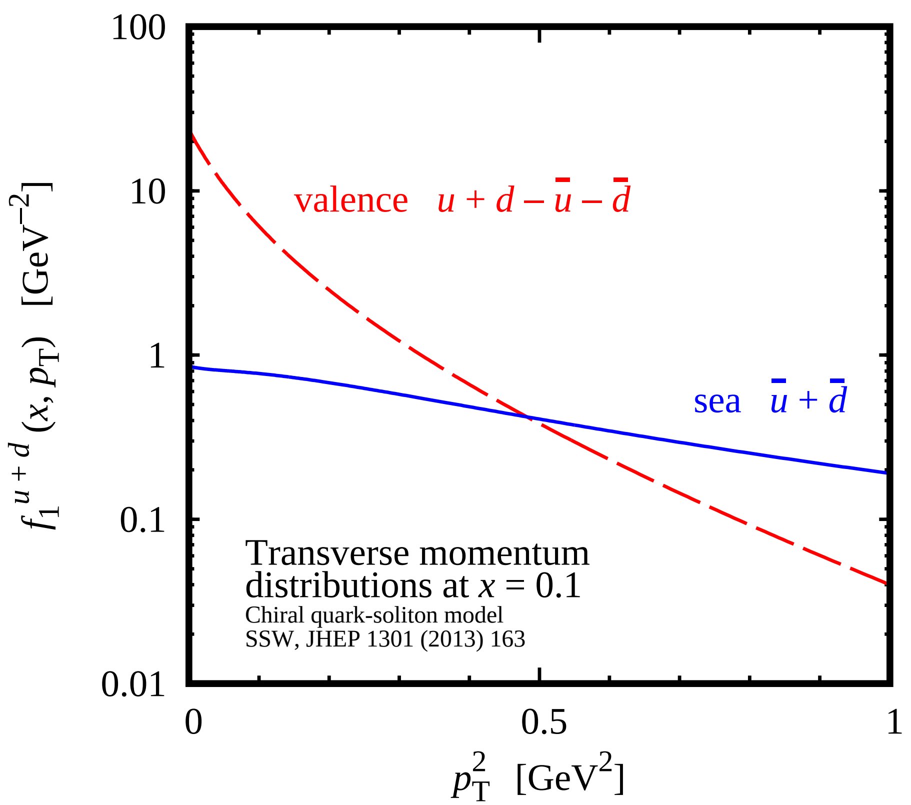
  Gauge–invariant measure of $q\bar{q}$ pair size
  $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle \sim 1\,\text{GeV}^2$ "average virtuality"
  Lattice: Teper 87, Doi 02, Chiu 03. Instantons: Polyakov, CW 96

- How does it affect partonic structure?

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

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

Dynamics: Non-perturbative 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
  Schweitzer, Strikman, Weiss, JHEP 1301 (2013) 163

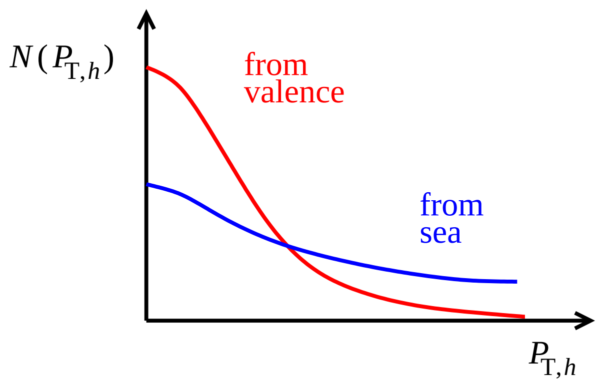
  Valence quarks: Drops steeply, $\langle p_T^2 \rangle \approx 0.15\,\text{GeV}^2 = O(R^{-2})$

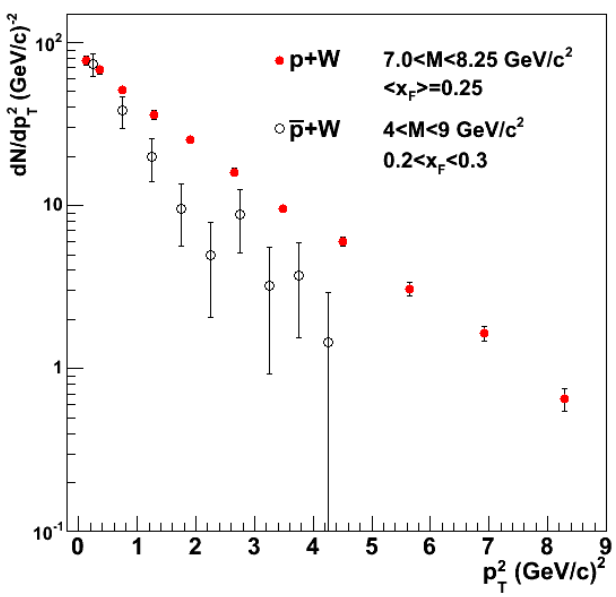
  Sea quarks: Power-like tail extends up to cutoff scale ρ^{-2}

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

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

Dynamics: Non-perturbative p_T consequences





$P_T(pp) > P_T(\bar{p}p)$ seen in FNAL DY data
Aidala, Field, Gamberg, Rogers 14

- SIDIS: Different $P_{T,h}$ distributions of hadrons produced from valence and sea quarks
Schweitzer, Strikman, CW 13

$$\pi^+ - \pi^- \sim u - \bar{u},\ d - \bar{d} \quad \text{valence}$$
$$\pi^+ + \pi^- \sim u + \bar{u},\ d + \bar{d} \quad \text{valence + sea}$$

$$K^+ \sim u \quad \text{mostly valence}$$
$$K^- \sim \bar{u} \quad \text{sea}$$

Need better understanding of fav/unfav FF at $z > 0.5$ to make quantitative predictions

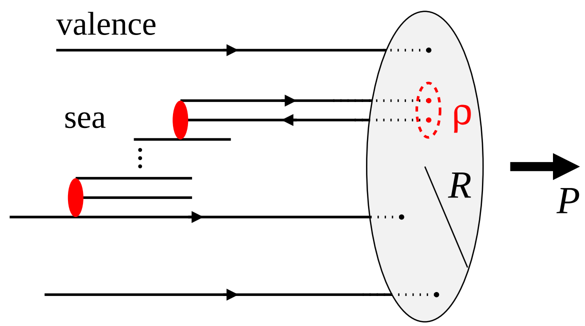
- Dileptons: Different $P_{T,\mathrm{pair}}$ distns in $pp/p\bar{p}$

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

Need $pp/\bar{p}p$ in same kinematics, $P_{T,\mathrm{pair}} \lesssim 1$ GeV

- Large p–n differences, isovector structures, in longitud. polarized SIDIS at $P_{T,h} \gtrsim 1$ GeV

Dynamics: Parton short–range correlations

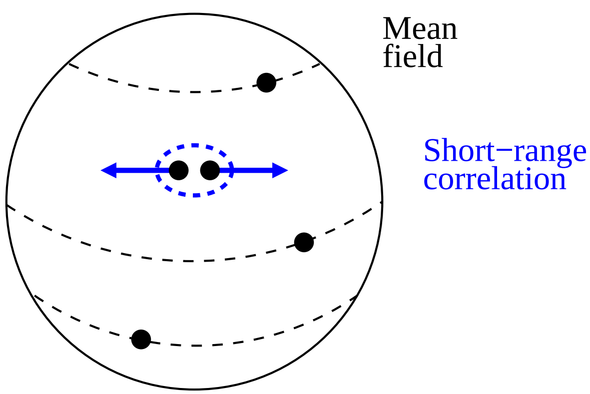


- Parton short–range correlations

  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 $p_T^2 \sim \rho^{-2}$



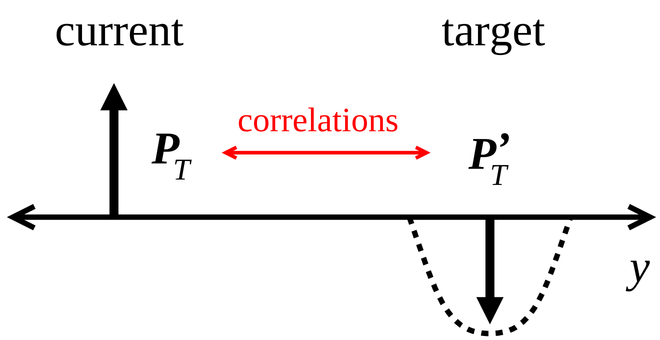
- Cf. NN short–range correlations in nuclei

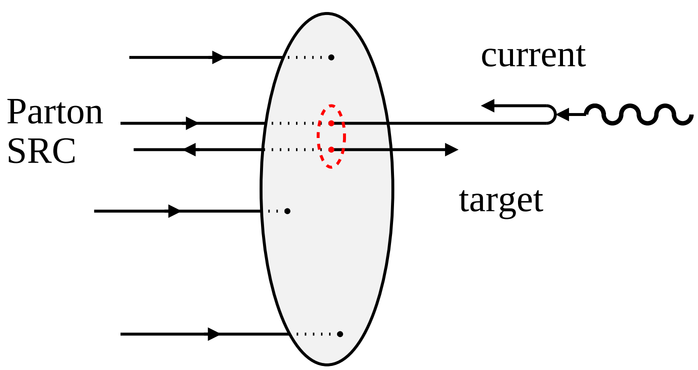
  Mean field $\Psi(\boldsymbol{r}_1, \ldots \boldsymbol{r}_N) \approx \prod_i^N \Phi(\boldsymbol{r}_i)$

  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

Dynamics: Hadron correlation measurements





- Back-to-back P_T correlations between hadrons in current and target regions

  Require special kinematics

  Other possible sources of correlations

- 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
  $Q^2 \sim \text{few GeV}^2$

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

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

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

Summary

- Determining the dynamical origin of soft hadron P_T in SIDIS remains challenging . . . very interesting problem!

- Unfavored fragmentation looks surprisingly strong at $z \gtrsim 0.5$ and $P_T \sim 1\,\mathrm{GeV}$

  Dynamical reason?
  Impact on TMD extraction?
  Should be tested with e^+e- hadron correlation data

- Qualitative differences predicted between non-perturbative p_T distributions of valence and sea quarks

- Unpolaried SIDIS multiplicity data with separated dependences and flexible binning are essential for further progress, together with Drell-Yan, e^+e^-, and photo/hadroproduction data

- Large p–n difference (isovector) expected in longit. pol. SIDIS at $P_T \gtrsim 1$ GeV