"Target fragmentation physics with EIC" On-line Meeting
Center for Frontiers in Nuclear Science (CFNS)
Stony Brook, September 28-30, 2020

Probing parton correlations with current and target fragmentation

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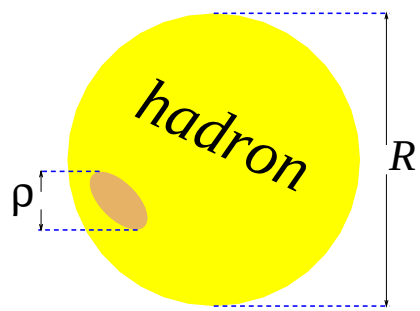
Outline

- **hadron structure**
  $q_{\text{val}} \to$ hadronic scale R
  $q_{\text{sea}} \to$ nonpert. short-distance scale ρ
  spontaneous breaking of chiral symmetry
  parton correlations at scale $\rho \to$ consequences

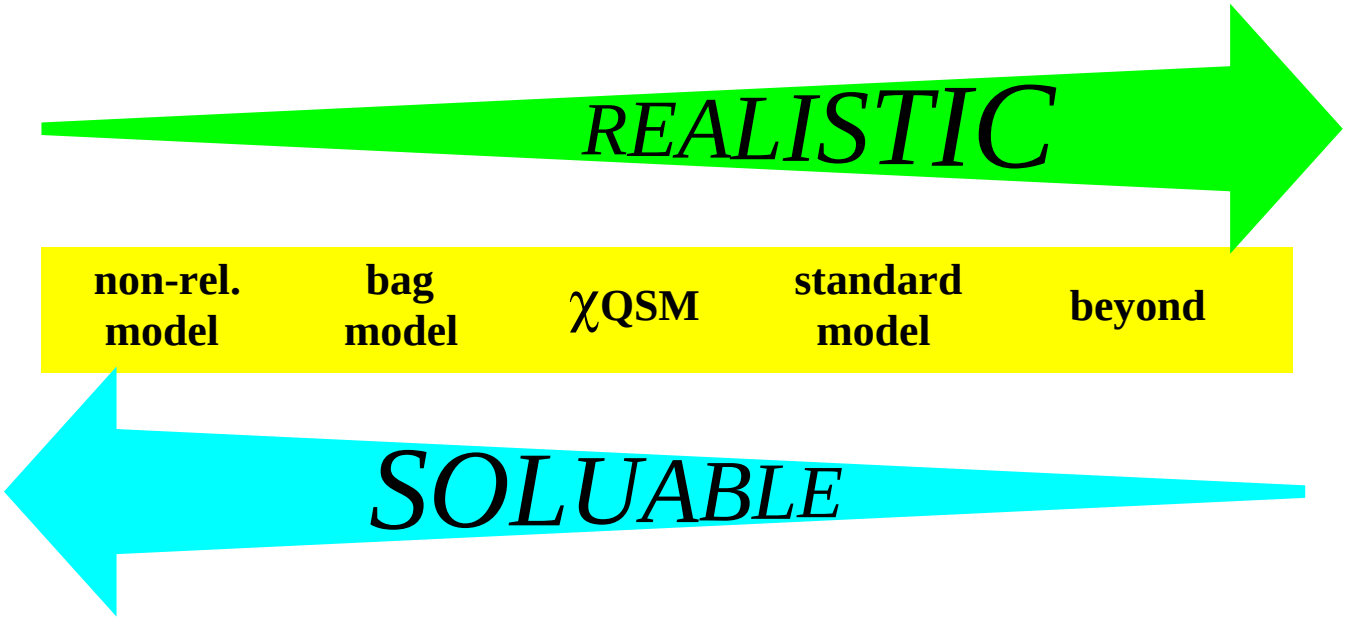


- **current fragmentation**
  PDFs dimensionless $\to$ "less" insightful
  TMDs and $\langle p_T \rangle$ dimensionful $\to$ "more" insightful
  nonperturbative calculations in chiral quark soliton model
  quantitative predictions (Strikman, Weiss, PS, JHEP 2013)

- **target fragmentation** qualitative predictions
  correlations across current and target fragmentation
  how to describe quantitatively in effective chiral theory?

- **experimental tests at EIC**
  conclusions and outlook

- illustration of concepts using models:



- non-rel. model: Efremov, PS, Teryaev, Zavada, PRD80, 014021 (2009)
- bag model: Avakian, Efremov, PS, Yuan, PRD81, 074035 (2010)
- chiral quark soliton: PS, Strikman, Weiss, JHEP 01, 163 (2013)

non-relatitivistic model

- TMDs $\boldsymbol{f_1^q(x, p_T) = N^q\, \delta(x - \frac{1}{3})\, \delta^{(2)}(\vec{p}_T)}$
- p_T not strictly zero, but p_T/M_N negligible
- justified only for a weakly interacting system

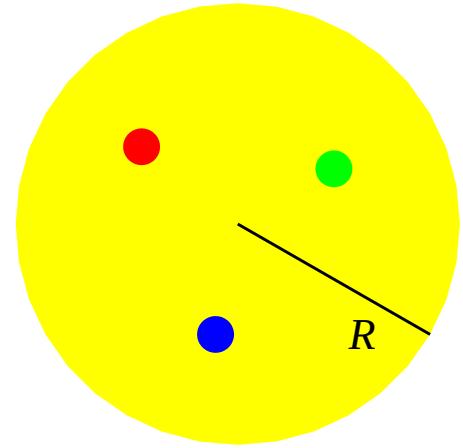
QED

- imagine "structure of positronium in DIS" experiments
- size of system $R_{\text{Bohr}} = \frac{1}{\alpha}\frac{\hbar}{mc} \sim 10^{-10}$m (where $m = m_e/2 =$ reduced mass)
- $E_{\text{bind}} = -\frac{1}{2}\alpha^2 mc^2$ with $M_{positronium} = 2m_e c^2 + \mathcal{O}(\alpha^2)$
- $\alpha \approx \frac{1}{137}$ $\rightarrow$ non-relativistic Schrödinger equation, etc.

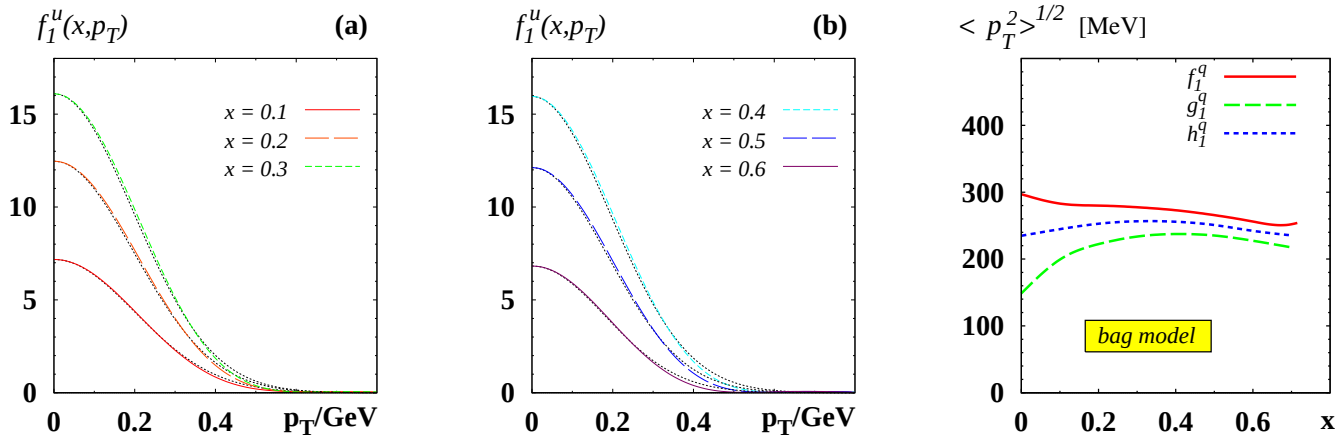
QCD

- much different: $\alpha_s(M_N) \sim 1$, $R_{\text{proton}} \sim 10^{-15}$m
- we need to model:
  - small-size system
  - relativistic system

quark models e.g. bag (more realistic)

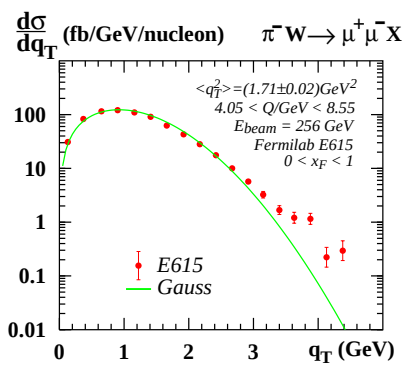


- relativistic & confined quarks within $R_{\text{bag}} \approx 1\,\text{fm}$
- since 50 years in service, lucid, can be still be insightful
- interesting: TMDs exhibit nearly Gaussian-p_T (at low scale)
  $\rightarrow \begin{cases} \text{colored thick lines: } \textbf{exact bag results} \\ \text{dotted black lines: } \textbf{Gaussian approximation} \end{cases}$

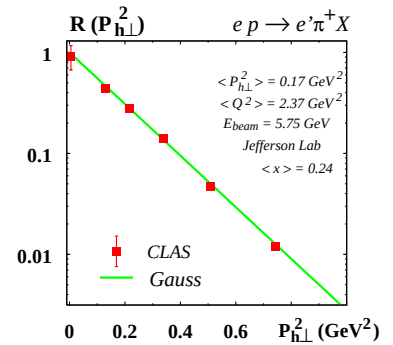


- valence quarks
  $\langle p_T \rangle_{val} \approx 250\,\text{MeV} \sim 1/R$
  scale set by 1/(hadron size)
- other quark models similar:
  spectator, LFCQM, NJL, ...

- Gaussian-p_T is seen in data
  DY, COMPASS, JLab, $p_T \ll Q$



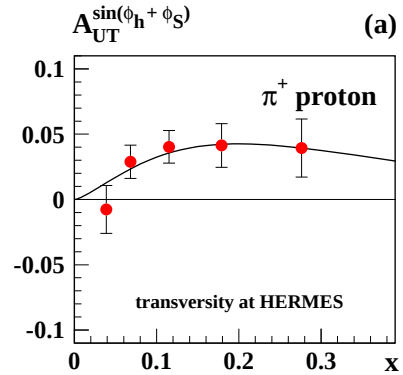
Conway et al (1989)



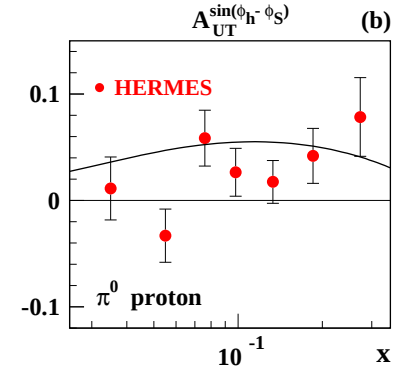
Osipenko et al (2009)

quark models

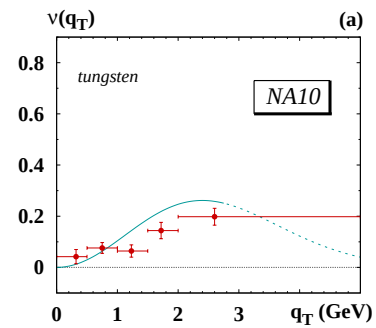
- initial scale $\mu_0 \sim 0.5\,\text{GeV}$ + evolution describe TMD effects at valence-x
- e.g. **LFCQM** for nucleon and pion "accuracy" $\sim$(20-40) %
- **SIDIS** at JLab, HERMES, COMPASS for $x \gtrsim 0.1$
- **Drell-Yan** at NA10, E615, COMPASS $x \sim \langle Q \rangle / \sqrt{s} \sim 0.25$
- useful estimates of q_{val} effects
  Boffi, Efremov, Pasquini, PS, PRD 79 (2009)
  Pasquini, PS, PRD 83, 114044 (2011)
  Bastami et al, arXiv:2005.14322



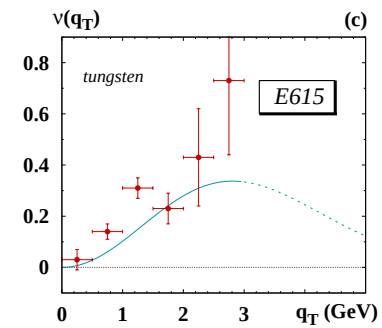
$\propto h_1^{q/p} H_1^{\perp q/\pi}$



$\propto f_{1T}^{q/p} D_1^{q/\pi}$

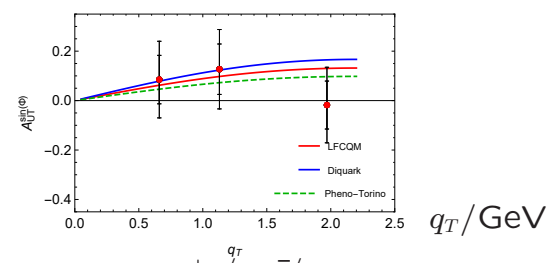


$\propto h_1^{\perp q/p} h_1^{\perp \bar{q}/\pi^-}$



$\propto h_1^{\perp q/p} h_1^{\perp \bar{q}/\pi^-}$

- limitations: valence-x
  no chiral symmetry
- small x (EIC) beyond quark models
  sea quark degrees of freedom
- quantum fluctuations, QCD vacuum
  more realistic model $\leftrightarrow$ chiral symmetry



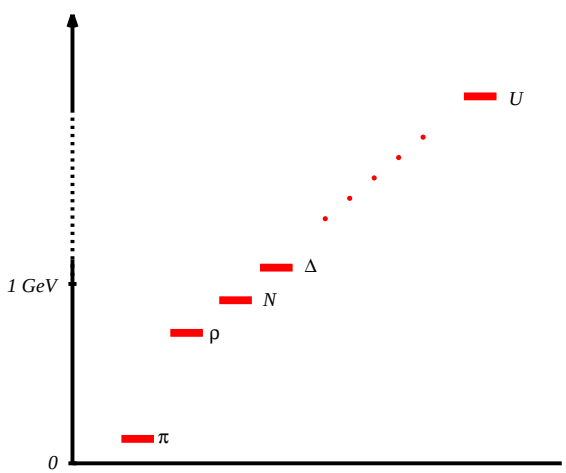
$\propto f_{1T}^{\perp q/p} f_1^{\bar{q}/\pi^-}$ COMPASS

chiral symmetry

- $\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm QCD}(\bar\psi_q, \psi_q, A_\mu)$ with $m_{u,d,s} \ll M_{\rm hadronic} \sim \mathcal{O}(M_\rho, M_N) \sim$ (770–940) MeV
- chirality $\psi_{R,L} = \frac{1}{2}(1 \pm \gamma_5)\,\psi \quad \rightarrow \quad$ vector symmetry $V = L + R$, axial symmetry $A = L - R$
- $U(3)_L \otimes U(3)_R = \underbrace{U(1)_V}_{\text{baryon number}} \otimes \underbrace{U(1)_A}_{\text{axial anomaly}} \otimes \underbrace{SU(3)_V}_{SU(N_f)\text{ flavor symmetry}} \otimes \underbrace{SU(3)_A}_{\text{spontanuous breaking}}$

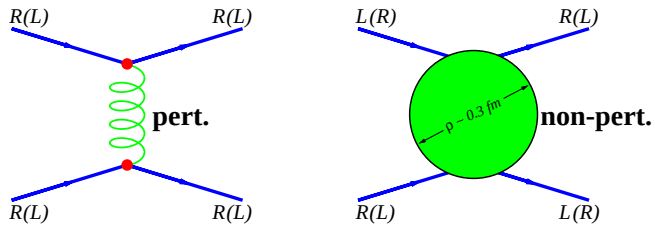
SU(N_f) octets and decuplets
small $m_q \neq 0 \rightarrow$ mass splittings
$\Downarrow$
realized in hadron spectrum

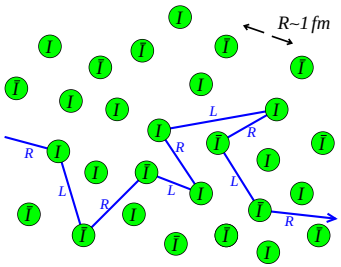
$J^P = \frac{1}{2}^{\pm}$ $N(940)$ vs $N(1535)$
chiral partner of N much heavier
$\Downarrow$
spontaneously broken

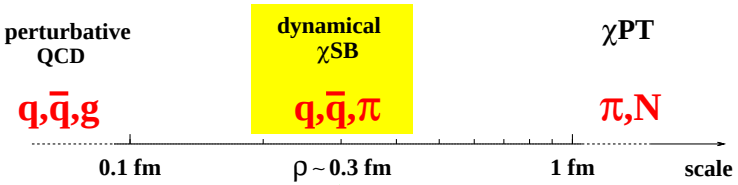


- $N_f^2 - 1$ Goldstone bosons
  π, K, η with masses $\ll$ 1 GeV
- chiral symmetry dynamically broken in QCD
  at scale $\rho \sim 0.3$ fm (Shuryak, Diakonov, Petrov 1980s)

chiral symmetry $\rightarrow$ dynamically broken at short-distance non-pert. scale $\rho \sim 0.3$ fm







What are the consequences

for hadron structure

due to scale ρ?

physical picture

- perturb. interactions preserve quark chirality
  non-perturbative gluon fields can flip it
  (topological gauge fields, instantons)

- QCD vacuum structure (quark condensate)
  order parameter of symmetry breaking
  $\langle 0|\bar{\psi}\psi|0\rangle = \langle 0|\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L|0\rangle$

- **Goldstone bosons:** pions π^a
  collective excitation

- **dynamical mass generation:** effective q, $\bar{q}$
  constituent mass M $\rightarrow$ hadron structure

- **short-range interactions $\rho \sim 0.3$ fm**
  new **dynamical** scale $\rho \ll R \sim 1$ fm
  Shuryak; Diakonov & Petrov 1980s

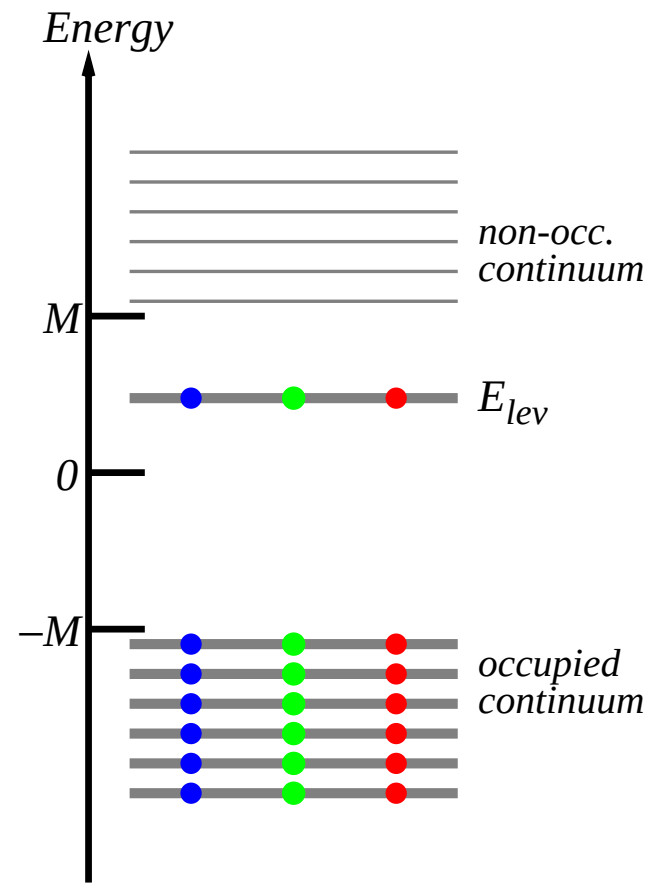
- **practical implementation**
  $\longrightarrow$ **chiral quark soliton model**

dynamical model of χSB

Diakonov, Eides 1983; Diakonov, Petrov 1986

$$\mathcal{L}_{\rm eff} = \overline{\Psi}\Big(i\,\partial\!\!\!/ + M\,U^{\gamma_5}\Big)\Psi$$

- effective $q, \bar{q}$ degrees of freedom with **dynamical mass** $M \sim 350\,\mathrm{MeV}$
- coupled to chiral field $U^{\gamma_5} = \exp(i\gamma_5\tau^a\pi^a/F_\pi)$ coupling constant $f_{\pi q\bar{q}} = M/F_\pi \sim 4$ is large!
- valid for energies $\lesssim \rho^{-1} \simeq 600\,\mathrm{MeV}$ (cutoff)
- solved non-perturbatively in $1/N_c$ **expansion**
  nucleon = chiral soliton (large N_c picture, Witten 1979)
- **chiral quark-soliton model** (no free parameters!)
  Diakonov, Petrov, Pobylitsa 1986; Kahana, Ripka 1984
- full Dirac sea, no Fock space truncation:
  (completeness of states, locality, analyticity)
  consistent effective field theory!
- **success!** in systematic $1/N_c$ expansion:
  mass spectrum, form factors, PDFs, (10-30)% accuracy
  Goeke et al, Christov et al, Diakonov et al 1996, ...



$$H\psi_n = E_n\psi_n$$

$$M_N = \min_U E_{\rm sol}[U]$$

$$\langle N'|\overline{\Psi}\ldots\Psi|N\rangle = A\sum_n \bar{\psi}_n\ldots\psi_n$$

PDFs in chiral quark soliton model

- $f_1^q(x,p_T) \overset{!}{=} \int \frac{dz^-}{4\pi}\, e^{ixP^+z^-} \langle N(P)|\bar\psi(0)\,\gamma^+\psi(z)|N(P)\rangle\big|_{z^+=0,\vec z_\perp=0}$ in any (including rest) frame

  $\overset{!!}{=} \lim\limits_{P\to\infty} \langle N(P)|a^\dagger(xP,p_T)a(xP,p_T)|N(P)\rangle =$ parton density in infinite mom. frame

  Diakonov et al, 1996, 1997; Ji, PRL 2013 $\to$ quasi PDFs on lattice

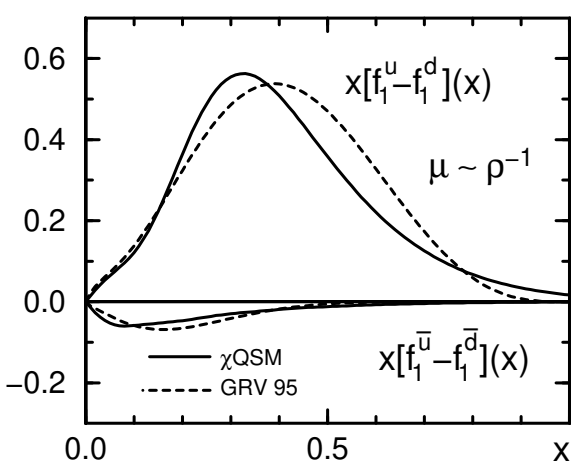
  Son, Tandogan, Polyakov PLB (2020)

- $f_1^a(x,\mu) = \int\limits_0^{\mu^2} d^2p_T\, f_1^a(x,p_T)$ UV-divergent $\Rightarrow$ cutoff $\to$ scale $\mu \sim \rho^{-1} \sim 0.6\,\text{GeV}$ $(\rho \sim 0.3\,\text{fm})$

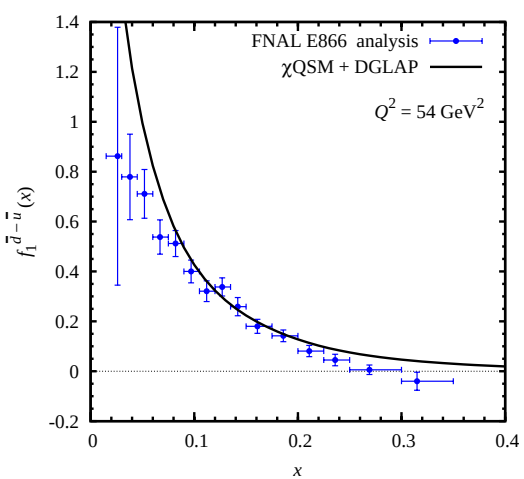
- **consistent field theory:** positivity & sum rules (PDFs), polynomiality & stability (GPDs)

- **matching:** **effective $q,\bar q$ = QCD $q,\bar q$ at $\mu \sim \rho^{-1}$** (fits at low scales see 30% gluons (GRV), accuracy of matching can be improved in principle by higher orders in instanton vacuum)

- **tested!** E.g. explains flavor asymmetry in unpolarized sea $f_1^{\bar d} > f_1^{\bar u}$ ✓ (Pobylitsa et al 1998)



evolution $\longrightarrow$



model works $\pm 30\,\%$

prediction: $\exists$ asymmetry in **helicity sea** $g_1^{\bar{u}} > g_1^{\bar{d}}$, even larger than in unpolarized case **!!!**
Diakonov et al, NPB, **480** (1996) 341

- in QCD for $N_c \to \infty$ $\underbrace{|(g_1^{\bar{u}} - g_1^{\bar{d}})(x)|}_{\mathcal{O}(N_c^2)} \gg \underbrace{|(f_1^{\bar{u}} - f_1^{\bar{d}})(x)|}_{\mathcal{O}(N_c)}$

- in nature $N_c = 3$ seems modest, but: supported by dynamical calculations
  Diakonov et al, NPB 480 (1996) 341
  Pobylitsa et al, PRD 59 (1999) 034024

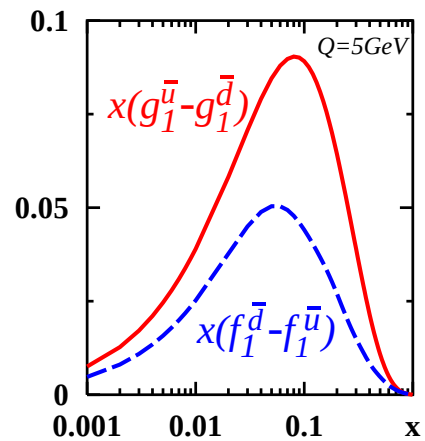
- can be seen in SIDIS
  Dressler et al, EPJC14 (2000) 147

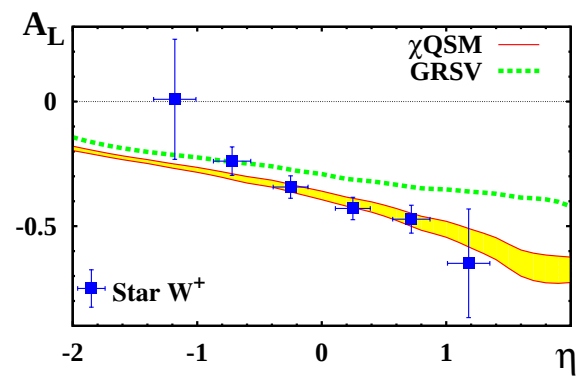
- **most clear in Drell-Yan**
  Dressler et al, EPJC18 (2001) 719

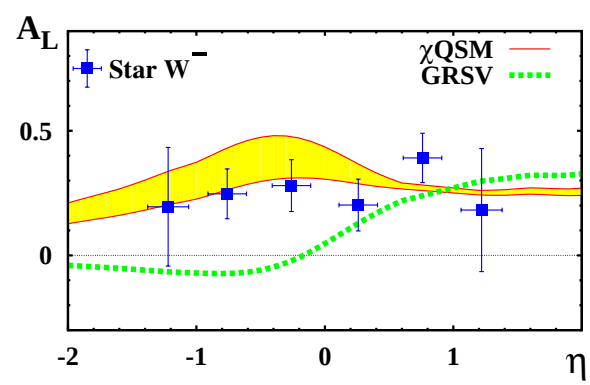
- seen in DSSV parameterization (since 2009)

- **RHIC data** $A_L(W^{\pm})$ PRL 113 (2014) 072301

- important test: χSB effects in proton structure
  (Polyakov, PS, Strikman, Vogelsang, Weiss, in progress)







TMDs in chiral quark soliton model

what we can (presently)

- **intrinsic p_T of $q, \bar{q}$ in nucleon**
  3D picture in momentum space at scale $1/\rho$

- LO N_c: $\underbrace{(f_1^u + f_1^d)}_{\gg (f_1^u - f_1^d)}$ and $\underbrace{(g_1^u - g_1^d)}_{\gg (g_1^u + g_1^d)}$ other flavor comb. and other TMDs ↓ ongoing work

- gluons "frozen out" at $\mu_0 \sim \rho^{-1}$,
  break χSB, cause **short-distance correlations**,
  implicit: included in structure of effective q, $\bar{q}$
  explicit: suppressed $f_1^g \ll f_1^q$ at μ_0, non-small x

what we cannot (ultimate goal, future work)

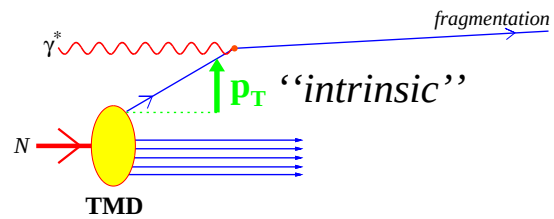
- fully non-perturbative treatment of Wilson lines
  ISI/FSI, T-odd TMDs (possible in instanton vacuum)

  ("perturbative" treatment, "one-gluon-exchange"
  Brodsky, Hwang, Schmidt; Collins 2002, ...)

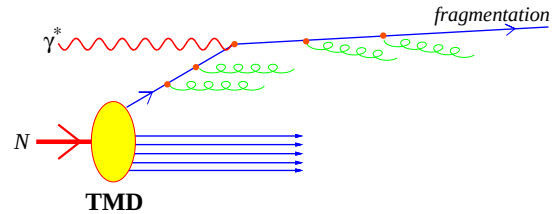
studies so far

- $f_1^a(x), g_1^a(x)$ PS, Strikman, Weiss JHEP (2013)
  $f_1^a(x)$ Wakamatsu, PRD (2009)

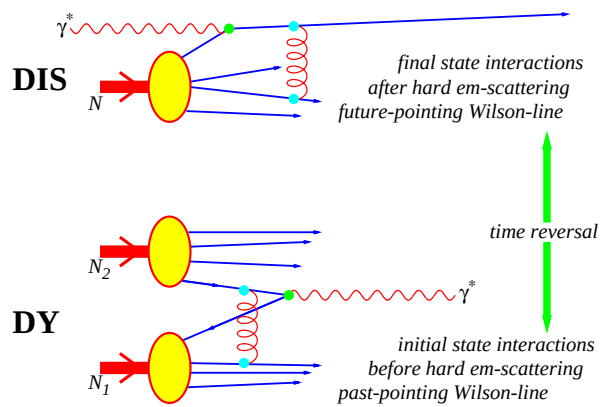
here:



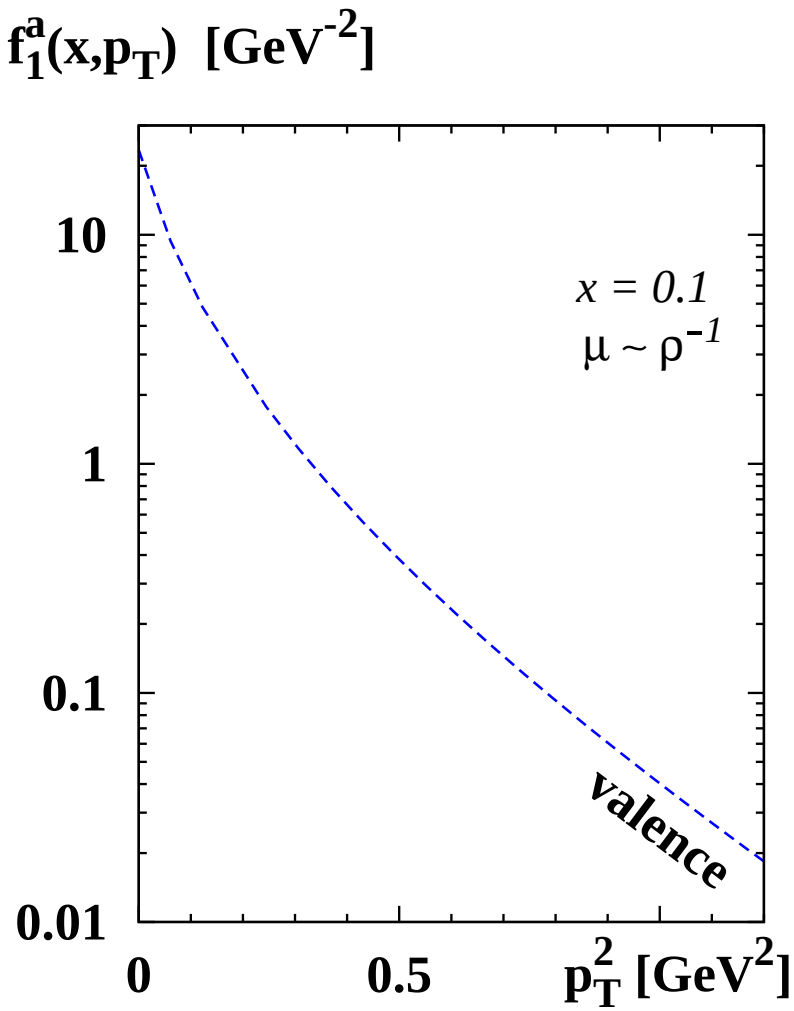
future work:



ultimate goal:



Results

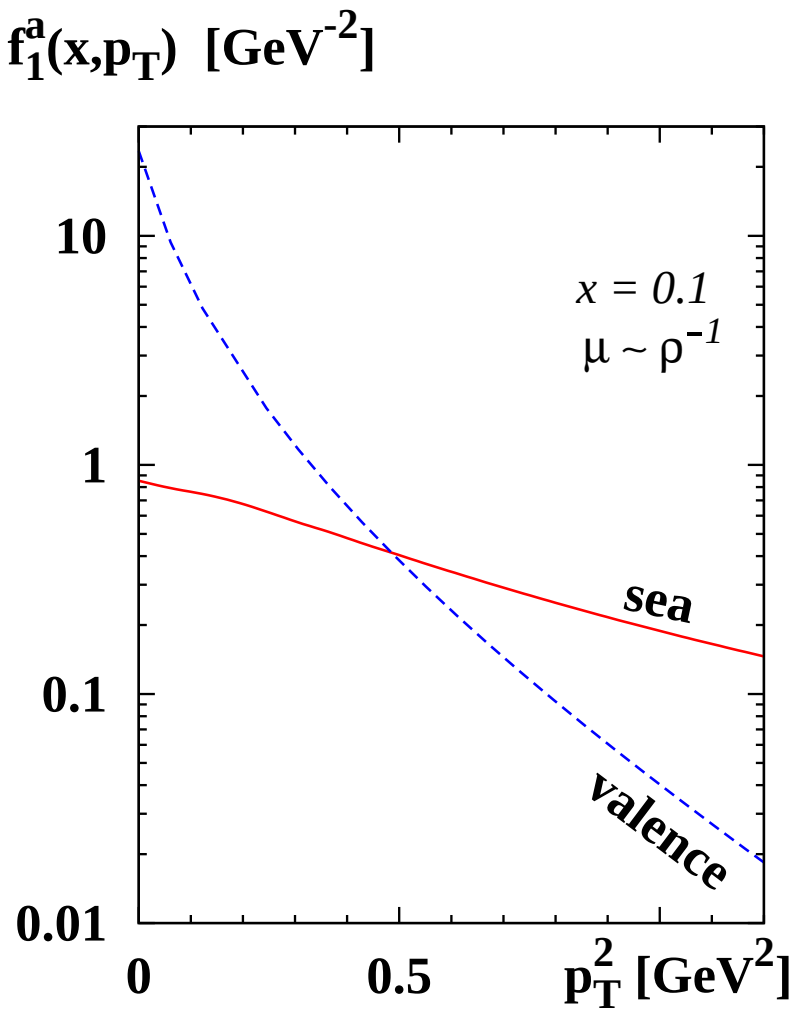


- **valence quarks** $\equiv q - \bar{q}$

  $\langle p_T^2 \rangle_{\rm val} \sim 0.15 {\rm GeV}^2 \sim 1/R^2_{\rm hadron}$ ("bound state")

  no Gauss, but also no extreme disagreement

Results



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- **sea quarks** $\equiv \bar{q} \equiv (\bar{u} + \bar{d})$ **!**

  $p_T \sim 1/\rho$ power-like behavior

  quasi model-independent:

$$f_1^{\bar{q}}(x, p_T) \approx f_1^{\bar{q}}(x) \, \frac{C_1 \, M^2}{M^2 + p_T^2}$$

$$C_1 = \frac{2N_c}{(2\pi)^3 F_\pi^2} \quad \leftarrow \text{chiral dynamics!}$$

- **valence vs sea: qualitatively different!**

  numerically $\langle p_T^2 \rangle_{\rm sea} \sim 3 \, \langle p_T^2 \rangle_{\rm val}$!!!

- $g_1^{\rm val}(x, p_T)$ **vs.** $g_1^{\rm sea}(x, p_T)$ **similar behavior**

  here: val $\equiv (u - d) - (\bar{u} - \bar{d})$, sea $\equiv (\bar{u} - \bar{d})$

  remarkable: $$g_1^{\bar{q}}(x, p_T) \approx g_1^{\bar{q}}(x) \, \frac{C_1 \, M^2}{M^2 + p_T^2}$$

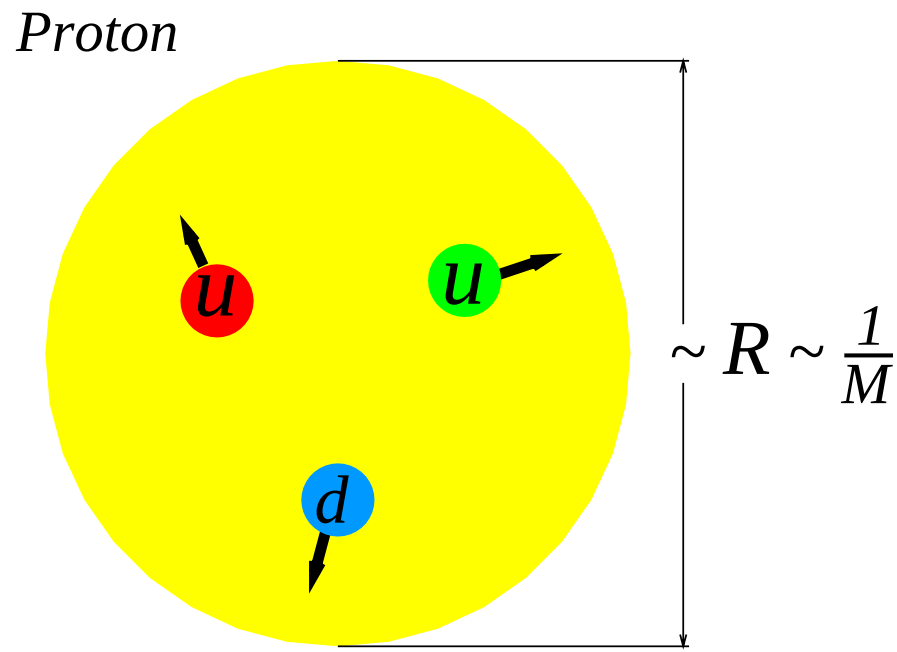
  same coefficient $C_1 \leftarrow$ **chiral dynamics!!**

Why is that ...?

valence quark picture

realized in quark models:
spectator (Jakob et al), LFCQM (Pasquini et al),
bag (Avakian et al), NJL-jet (Matevosyan et al),
here also seen in the **bound-state** of χQSM

$$\langle p_T^2 \rangle_{\rm val} \sim M^2$$



but what binds these valence quarks?
it's the **soliton field** due to χSB,
strong coupling $f_{\pi q\bar{q}} = M/F_\pi \sim 4$
chiral field generates $\bar{q}q$ pairs
correlated at χSB scale ρ!

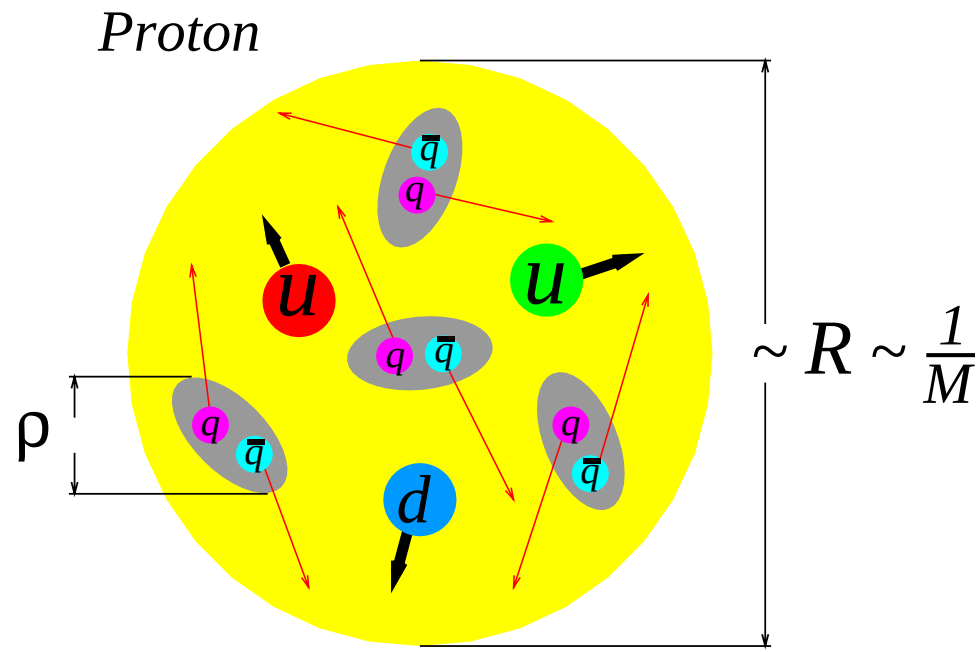
... because of chiral symmetry breaking!

short-range correlations of $q, \bar{q}$ pairs !!!

QCD vacuum structure
(**"Dirac sea"** in model)
PS, Strikman, Weiss 2013

$$\langle p_T^2 \rangle_{\rm val} \sim M^2$$

$$\langle p_T^2 \rangle_{\rm sea} \sim \rho^{-2}$$



$$\langle p_T^2 \rangle_{\rm val} / \langle p_T^2 \rangle_{\rm sea} \sim M^2 \rho^2 \sim M^2/({\rm cutoff})^2 \ll 1$$

('diluteness' of instanton medium) Diakonov, Petrov, Weiss 1996

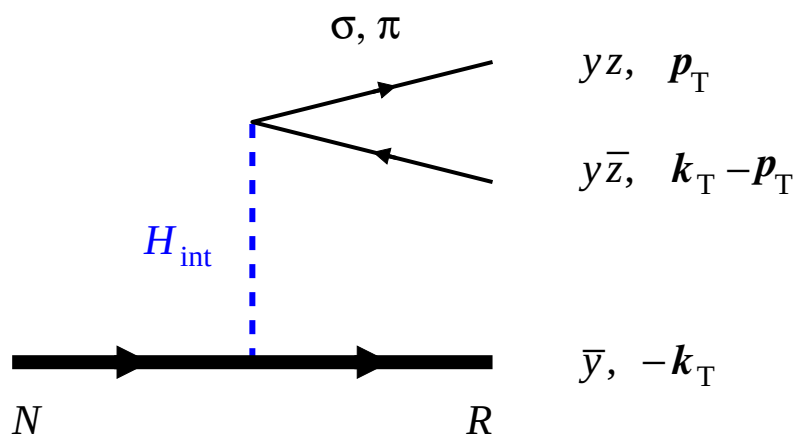
quantum numbers of correlated $\bar{q}q$-pairs

nucleon's light-cone wave function
approximation valid at $p_T^2 \gg M^2$

nucleon acts as classical source
which produces a color–singlet $\bar{q}q$

outgoing state $|R\rangle$ can have
quantum numbers of $|N\rangle$, $|\Delta\rangle$

$\bar{q}q$ pair can have
quantum numbers:
scalar–isoscalar (σ) or
pseudoscalar–isovector (π)



$\boldsymbol{f_1^{\bar{q}}(x, p_T) \propto \sigma^*\sigma + \pi^*\pi}$ $\leftrightarrow$ Vector current
$\boldsymbol{g_1^{\bar{q}}(x, p_T) \propto \sigma^*\pi + \pi^*\sigma}$ $\leftrightarrow$ Axial vector current

Dressler et al, EPJC14, 147 (2000); PS, Strikman, Weiss JHEP (2013)
starting point for modeling: Fries, Schäfer, Weiss EPJA 17 (2003) 509

other TMDs $\rightarrow$ work in progress h_1, ... Kemal Tezgin, Weiss, PS

applications:

- may inform TMD fits $\tilde{f}_1^{val}(x, b_T)$ vs $\tilde{f}_1^{sea}(x, b_T)$ for $\rho \lesssim b_T \lesssim R$
  current fits: same non-pert. parameters for val. vs sea (Prokudin, Rogers, ...)
- how to implement in Montecarlo, correlations, spin-orbit effect?
  both: current and target fragmentation ($\rightarrow$ talk Avakian)

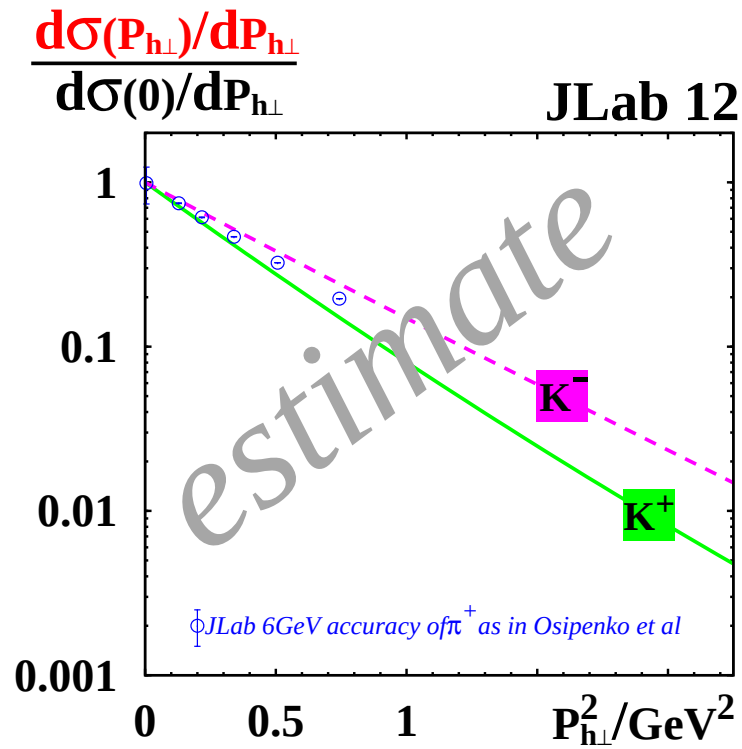
current fragmentation (TMDs)

in process: $q = \text{val} + \text{sea}$, $\bar{q} = \text{sea}$ (and not val$= q - \bar{q}$)

- experimental tests in SIDIS
  HERMES, COMPASS, JLab12, EIC
  difficulty: fragmentation; need kinematic leverage
  potentially promising: $K^+ = u\bar{s}$ vs $K^- = \bar{u}s$

- multi parton correlations (Tevatron, LHC)
  ($\rightarrow$ L. Frankfurt, M. Strikman, C. Weiss)
  short-range correlations play a role

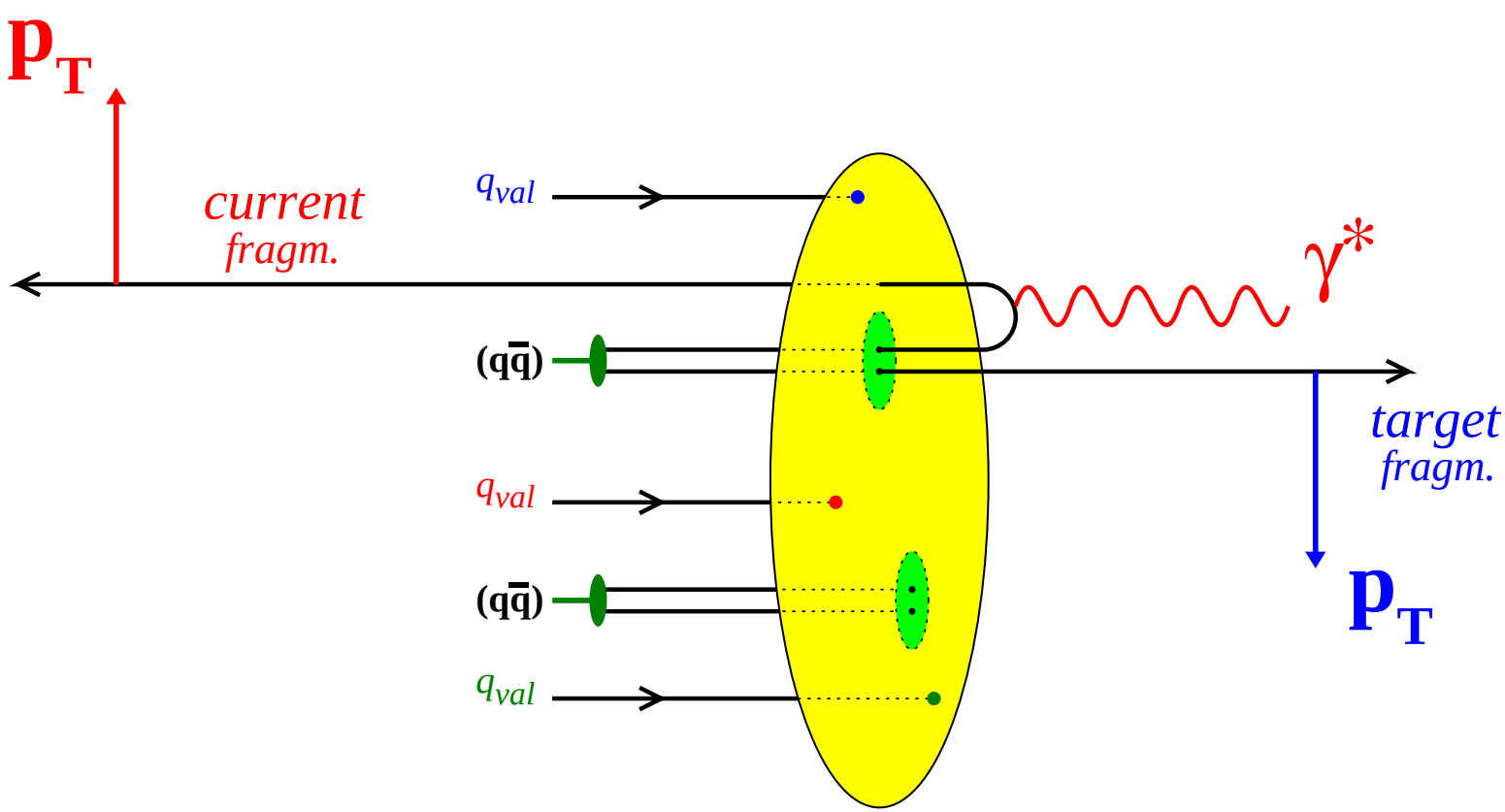
- Drell-Yan process
  pp vs $\bar{p}p$
  (no fragmentation)
  Fermilab? FAIR!?



if $K^\pm$ yield at JLab12 (EIC)
like $\pi^\pm$ at JLab6 $\rightarrow$ measure!

target fragmentation

- correlations in current $\leftrightarrow$ target fragmentation
  when correlated $q\bar{q}$ pair "split up"!
  $Q^2 \sim$ few GeV^2 not too large
  (to avoid loss of correlation
  due to gluon radiation)



Conclusions

- **valence quark** $\rightarrow$ quark models, valuable insights
  useful quantitative description for $x \gtrsim 0.1$, $\langle p_T \rangle_{\rm val} \sim 1/R_{\rm hadron}$

- **sea quarks** $\rightarrow$ need realistic description of χSB, QCD vacuum, correlations
  associated scale $\rho \sim 0.3\,\text{fm} \ll R_{\rm hadron}$, $\langle p_T \rangle_{\rm sea} \sim 1/\rho$

- **prediction for** $f_1^a(x, p_T)$, $g_1^a(x, p_T)$: $\langle p_T \rangle_{\rm sea} \gg \langle p_T \rangle_{\rm val}$

- interplay of 2 scales: **hadronic scale** $1/R \rightarrow \langle p_T \rangle_{\rm val}$
  short-range correlations $1/\rho \rightarrow \langle p_T \rangle_{\rm sea} \rightarrow \chi$**SB**

- correlations between **current** and **target fragmentation**
  qualitatively expected. How to describe quantitatively?

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Thank you!