Pion parton distribution functions

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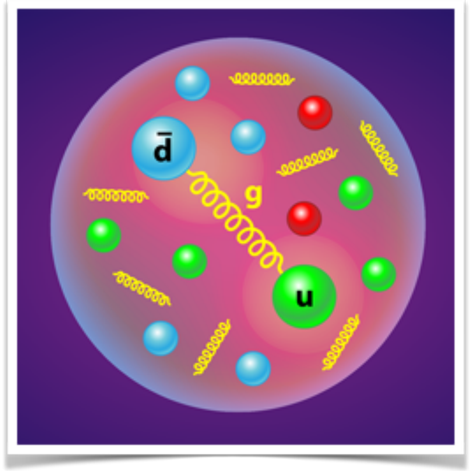
The pion in QCD

- Consequence of Standard Model:
  - Lightest meson
  - Nambu-Goldstone boson of spontaneously broken chiral symmetry
  - Mediate the interaction between nucleons, Yukawa interaction



APS/Alan Stonebraker

- Parton model:
  - valence quarks : 1 up quark + 1 down antiquark
  - sea quarks
  - gluons
- Infinite many body dynamic system of quarks and gluons

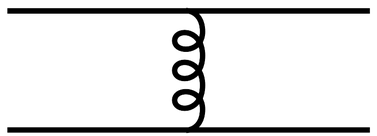
Pion parton distribution function

If pion is

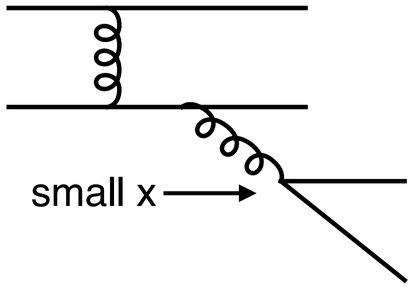
a quark

valence quark
+valence
antiquark

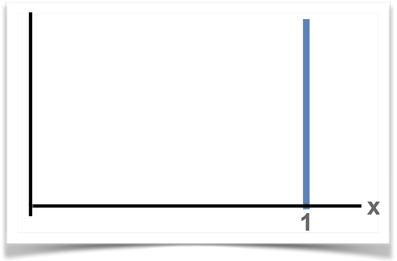
valence quark bound
valence antiquark

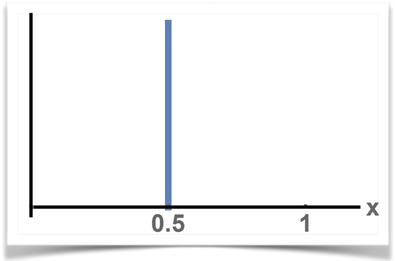


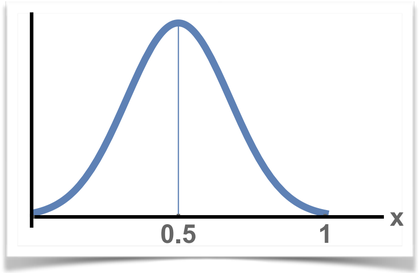
+ some slow debris,
e.g., g → $q\bar{q}$

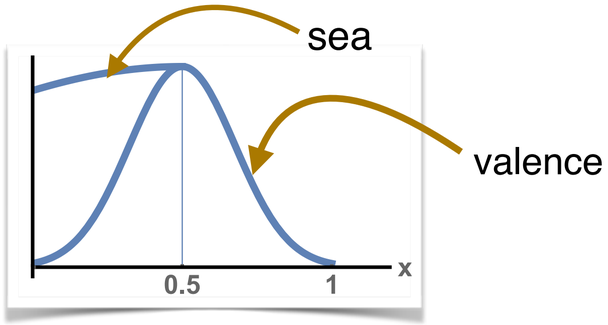


then $q(x)$ is







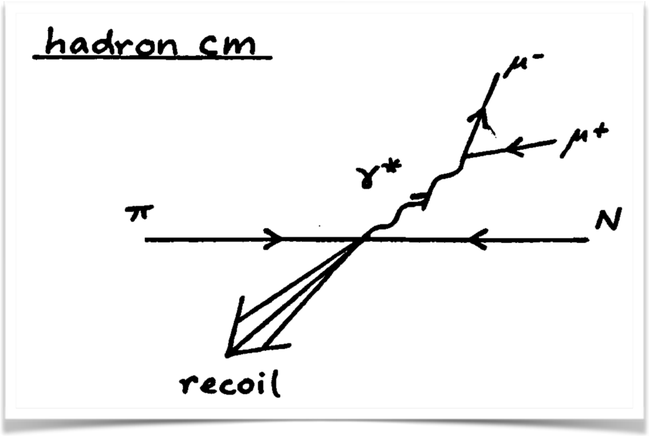


Halzen and Martin (1984)

PDFs depend on the detailed dynamics of the pion, not *a priori* known and obtained from experiment.

Experiments: Valence distribution: $\bar{q}q \to \gamma^*$

- π-induced Drell-Yan $\pi^- N \to \mu^+\mu^- X$

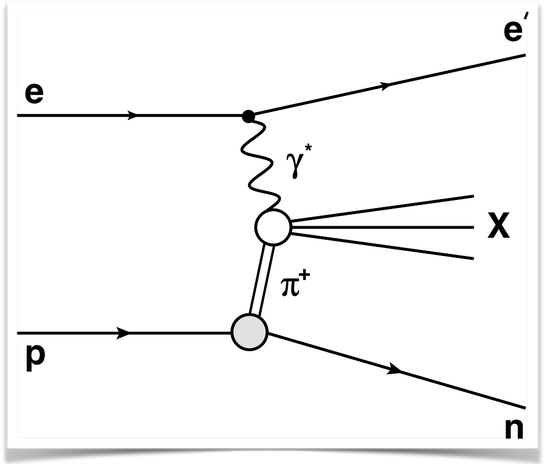


- CERN: NA3 (1983), NA10 (1985), Omega (1980)
- FNAL: E615 (1989)

J.S.Conway et al.. Phys. Rev. D 39 (1989) 92-122

- Leading Neutron DIS

$ep \to e'nX$



- HERA: ZEUS (2002), H1 (2010)

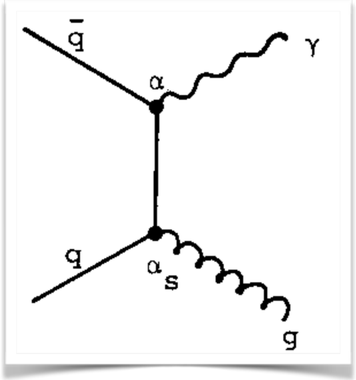
Sullivan process, EIC

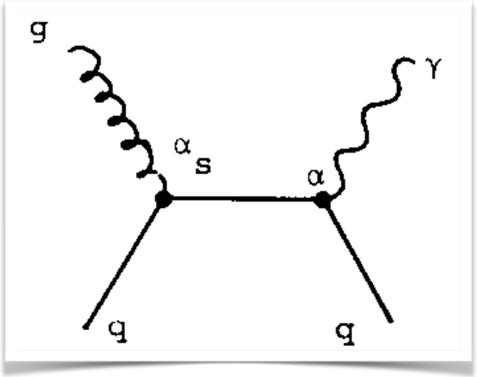
H1 Collaboration, Eur. Phys. J. C 68 (2010) 381-399

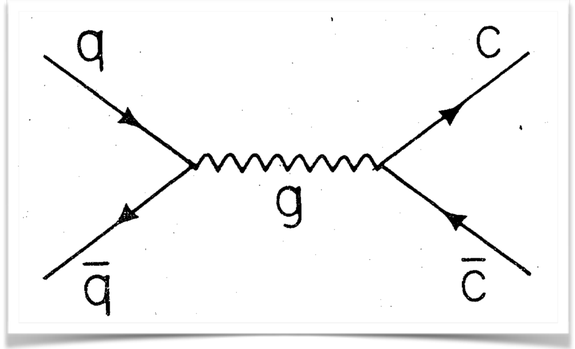
Experiments: Gluon and Sea distribution

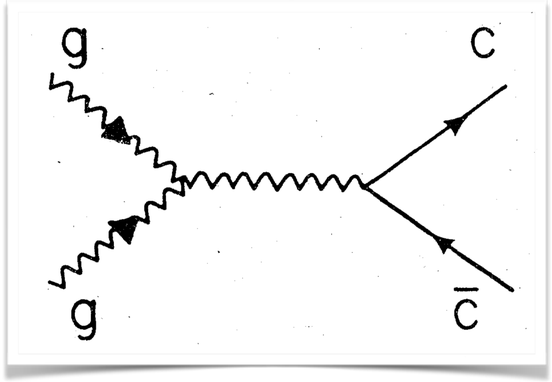
- Gluon distribution: $\bar{q}q \to \gamma g, gq \to \gamma q$ $\quad \bar{q}q, gg \to c\bar{c} \to J/\psi$

  - Prompt photon production, $\pi^+ p \to \gamma X$
  - J/ψ production, $\pi^+ p \to J/\psi\, X$









- ☑ CERN NA24 (1987), WA70 (1988)

P.J. Sutton et al., Phys.Rev.D 45 (1992) 2349-2359

- ☑ CERN: NA3 (1983)

J.F. Owens, Phys.Rev.D 30 (1984) 943

- Sea distribution: momentum sum rule (MSR)

Experiments:

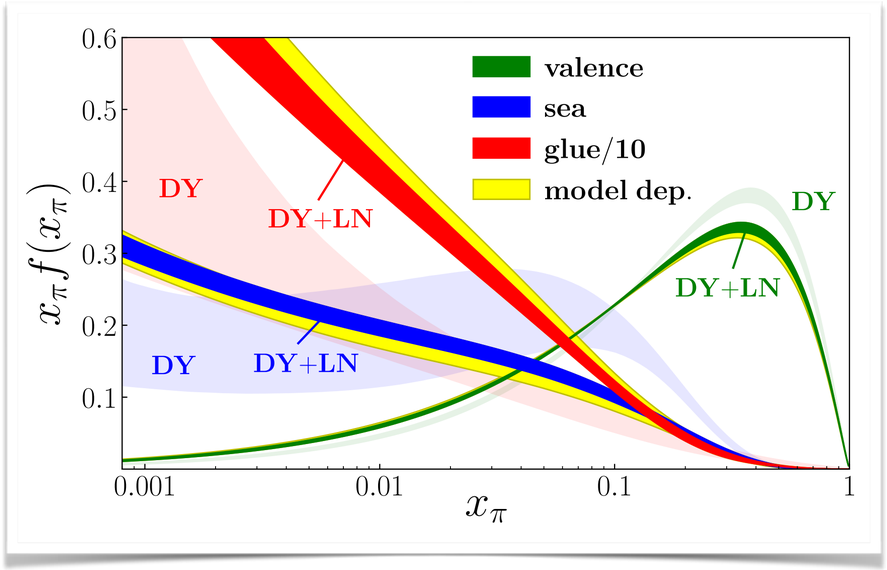
Group	Year	Set	Q_0^2 (GeV^2)	Fac. Sch.	Model	Data	N_f	$\Lambda_{\overline{\rm MS}}^{N_f=4}$ (MeV)
ABFKW	1989	NLO	2.00	$\overline{\rm MS}$	$v^\pi = \gamma X$, DY	WA70,NA24	4	229
					$s^\pi = $ DY	NA3		
					$g^\pi = \gamma X$, MSR	WA70,NA24		
SMRS	1992	10%	4.00	$\overline{\rm MS}$	$v^\pi = $ DY	NA10, E615	4	190
		15%			$s^\pi = $ DY	NA3		
		20%			$g^\pi = \gamma X$, MSR	WA70		
GRV	1992	LO	0.25	LO	$v^\pi = $ ABFKW	WA70,NA24	6	200
		NLO	0.30	$\overline{\rm MS}$	$s^\pi = 0$			
					$g^\pi = $ MSR			
GRSc	1999	LO	0.26	LO	$v^\pi = $ DY, MSR	NA10, E615	3	204
		NLO	0.40	$\overline{\rm MS}$	$s^\pi = (v^\pi/v^p)\, s^p$	H1, ZEUS		299
					$g^\pi = (v^\pi/v^p)\, g^p$	H1, ZEUS		

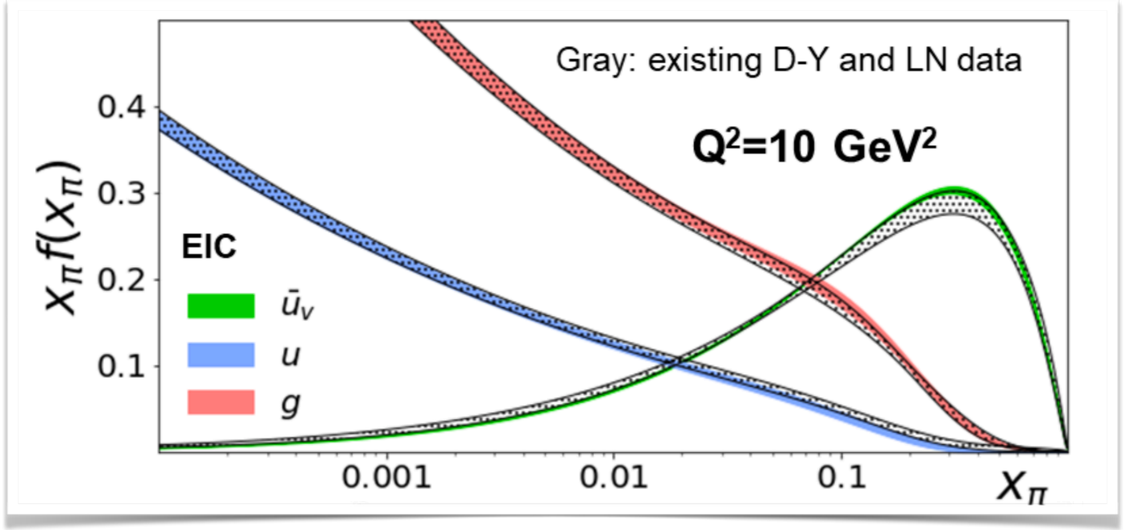
- Valence distribution is mainly determined by DY
- Gluon distribution is constrained by γX and MSR

* Leading Neutron DIS can also make contribution

Michael Klasen, J.Phys.G 28 (2002) 1091-1102

Leading Neutron (LN) DIS





- Global QCD Analysis: JAM Collaboration

- DY + LN yields significantly reduced uncertainties on pion sea and gluon distributions at low x.

Barry, Sato, Melnitchouk, Ji, Phys. Rev. Lett. 121 (2018) no.15, 152001

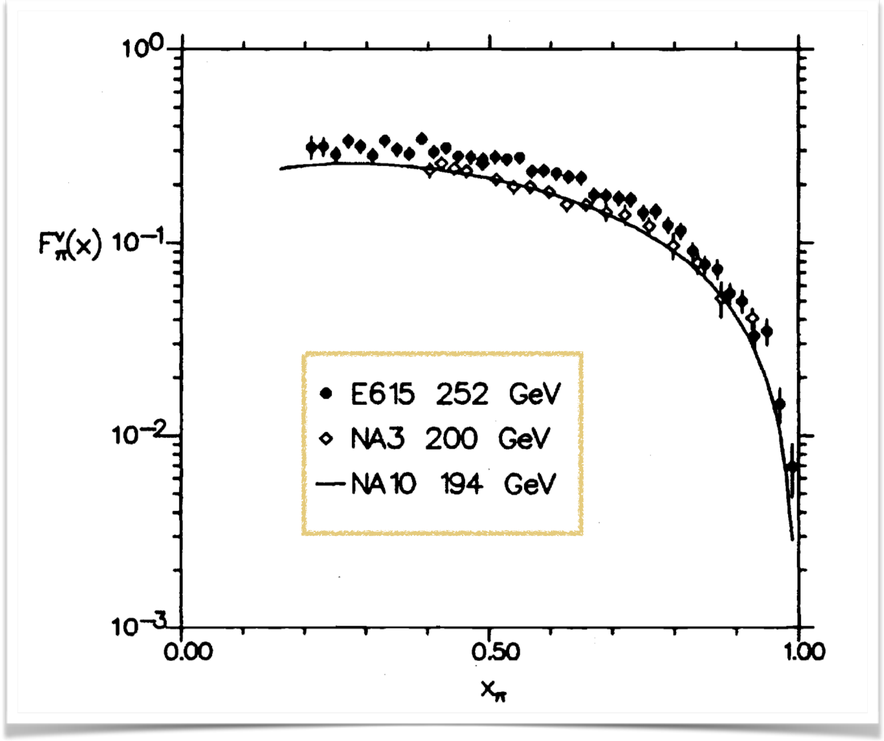
- LN: HERA: ZEUS (2002), H1 (2010)

Sullivan process, EIC

A.C. Aguilar et a., Eur. Phys. J. A55 (2019) no.10, 190

S.-X. Qin, C. Chen, C. Mezrag and C. D. Roberts, Phys. Rev. C 97, 015203 (2018)

Experiment: π-induced Drell-Yan process



J.S.Conway et al.. Phys. Rev. D 39 (1989) 92-122

$$F^v_\pi(x) = A^v[x^\alpha(1-x)^\beta + \gamma\frac{2x^2}{9m^2_{\mu\mu}}]$$

CERN NA3 (1983):
$\alpha = 0.45 \pm 0.03, \beta = 1.17 \pm 0.02$

CERN NA10 (1985):
$\alpha = 0.40 \pm 0.02, \beta = 1.17 \pm 0.03$

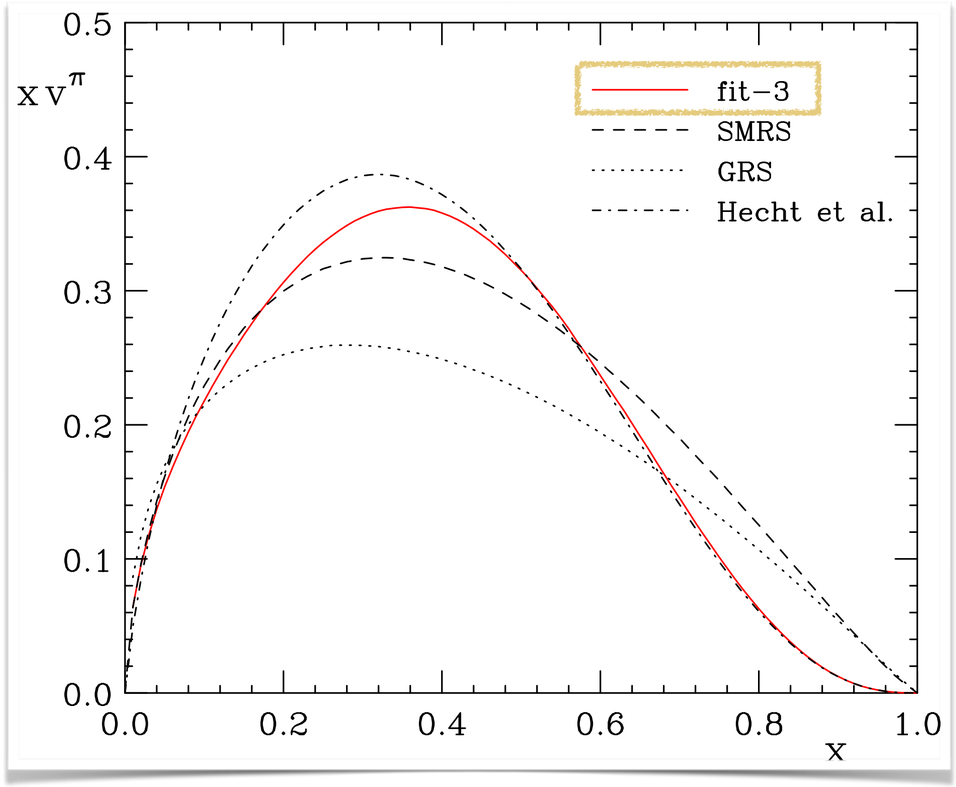
FNAL E615 (1989):
$\alpha = 0.60 \pm 0.03, \beta = 1.26 \pm 0.04$

$\gamma\frac{2x^2}{9m^2_{\mu\mu}}$: higher twist

Perturbative QCD: hadronic $Q^2, x \to 1$.	Finite scale calculation or measurement
$\beta = 2$	$\beta = 2 + \delta, (\delta \gtrsim 0)$

E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. 42, 940 (1979)

Soft-Gluon Resummation Reanalysis of E615 Data



Soft-Gluon Resummation and the Valence Parton Distribution Function of the Pion

Matthias Aicher, Andreas Schafer and Werner Vogelsang, PRL 105, 252003 (2010)

E615 (2010): $\alpha = 0.7 \pm 0.07$

$\beta = 2.03 \pm 0.06$

Evolve to $Q = 4$ GeV

$\beta = 2.34$

Hecht et al.. Phys. Rev. C 63, 025213 (2001) DSE in 2001

Theoretical perspective of pion

- Dyson-Schwinger Equations: a symmetry-preserving approach
  - Lightest pseudoscalar meson: γ_5 group
  - Goldberger Treiman relation: $f_\pi E_\pi(k; P=0) = B(k^2)$
    - ☑ Nambu - Goldstone boson: chiral limit $m_u = 0$, dynamical chiral symmetry breaking $B(k^2) \neq 0$, massless pion $E_\pi(k; P=0) \neq 0$
  - Gell-Mann Oakes Renner relation: $f_\pi^2 M_\pi^2 = 2m_u \langle \bar{q}q \rangle^0$
    - ☑ Axial-vector Ward-Green-Takahashi Identity $P_\mu \Gamma_{5\mu}(k;P) = S^{-1}(k_+) i\gamma_5 + i\gamma_5 S^{-1}(k_-) - 2im_u \Gamma_5(k;P)$
    - ☑ Pion pole contribution in $\Gamma_{5\mu}(k;P)$ and $\Gamma_5(k;P)$

P. Maris, C. D. Roberts, and P. C. Tandy, Phys. Lett. B 420 (1998) 267-273

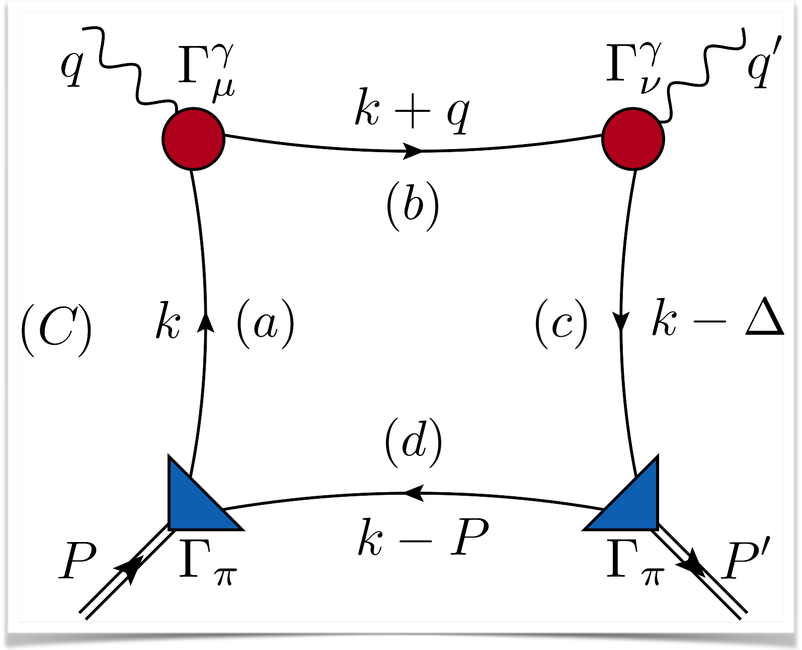
Dyson-Schwinger equations: PDF Definition

Twist-2 valence quark PDF

$$q(x) = \int d\lambda e^{-ixP\cdot n\lambda} \langle \pi(P) \,|\, \bar{\psi}(\lambda n)\gamma \cdot n\psi(0) \,|\, \pi(P) \rangle$$

- Forward virtual quark-target scattering amplitude

$$q(x) = \int dk \delta(n \cdot k - xn \cdot P) Tr[i\gamma \cdot nG(k, P)]$$



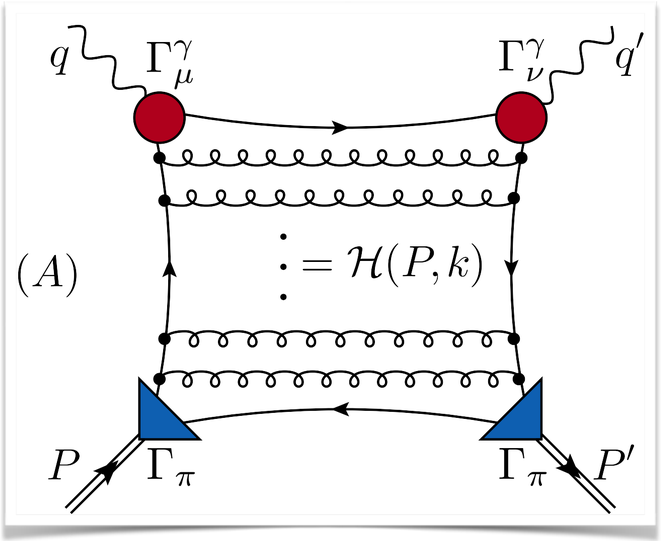
"Handbag diagram"

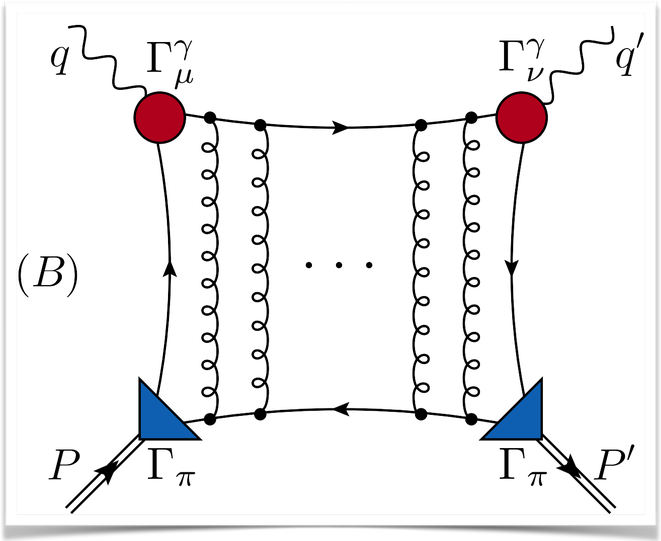
M.B. Hecht et al.. Phys. Rev. C 63 (2001) 025213

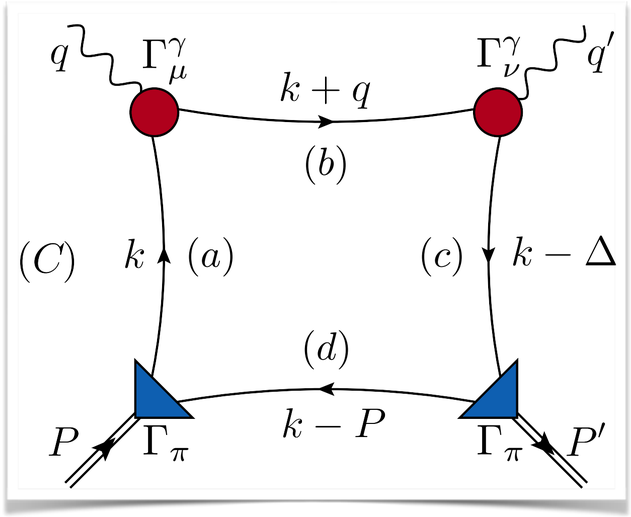
R. J. Holt and C. D. Roberts, Rev. Mod. Phys. 82 (2010) 2991-3044

T. Nguyen et al..Phys. Rev. C 83 (2011) 062201 et al..

Dyson-Schwinger equations: PDF Definition







Rainbow Ladder approximation

$$q_A^\pi(x;\zeta_H) = N_c \mathrm{tr} \int_{dk} \delta_n^x(k_\eta)\, i\Gamma_\pi(k_\eta, -P)\, S(k_\eta) i\Gamma^n(k;x;\zeta_H)\, S(k_\eta)\, i\Gamma_\pi(k_{\bar\eta}, P)\, S(k_{\bar\eta})$$

Failure of impulse approximation

$$q_{BC}^\pi(x;\zeta_H) = N_c \mathrm{tr} \int_{dk} \delta_n^x(k_\eta)\, \Gamma_\pi^n(k_\eta, -P;\zeta_H) S(k_\eta) \Gamma_\pi(k_{\bar\eta}, P)\, S(k_{\bar\eta})$$

L. Chang, C. Mezrag, H. Moutarde, C. D. Roberts, J. Rodríguez-Quintero and P. Tandy, Phys. Lett. B 737 (2014) 23-29

Dyson-Schwinger equations: A & BC term

Pion PDF

$$q^{\pi}(x;\zeta_H) = q^{\pi}_{\rm A}(x;\zeta_H) + q^{\pi}_{\rm BC}(x;\zeta_H)$$

$q^{\pi}_{\rm A}$ & $q^{\pi}_{\rm BC}$

$$\int_0^1 dx\, q^{\pi}_A(x;\zeta_H) = 1\,, \quad \int_0^1 dx\, q^{\pi}_{BC}(x;\zeta_H) = 0$$

- $q^{\pi}_{\rm BC}(x;\zeta_H)$ does not contribute to $\langle x^0_\pi\rangle_{\zeta_H}$.
- $q^{\pi}_{\rm BC}(x;\zeta_H)$ does contribute to $\langle x^1_\pi\rangle_{\zeta_H}$.

- Pion is purely a bound-state of a dressed-quark and dressed-antiquark at the hadronic scale ζ_H, so $\langle x^1_\pi\rangle_{\zeta_H} = 1/2$.

- $q^{\pi}_{\rm BC}(x;\zeta_H)$ is necessary to keep $q^{\pi}(x;\zeta_H) = q^{\pi}(1-x;\zeta_H)$ and then $\langle x^1_\pi\rangle_{\zeta_H} = 1/2$.

Valence quark PDF Mellin moments $\longrightarrow$ $\langle x^0_\pi\rangle_{\zeta_H} = 1\,, \quad \langle x^1_\pi\rangle_{\zeta_H} = 1/2$

Dyson-Schwinger equations: Ward Identity

- Vector Ward-Takahashi Identity $iP_\mu \Gamma_\mu(k;P) = S^{-1}(k+P/2) - S^{-1}(k-P/2)$
  - Differential Ward identity $P=0$ $i\Gamma^n(k;x;\zeta_H) = n\cdot\partial_{k_\eta} S^{-1}(k_\eta)$
  - "pierced" pion Bethe-Salpeter amplitude $\Gamma^n_\pi(k_\eta,-P;\zeta_H) = n\cdot\partial_{k_\eta}\Gamma_\pi(k_\eta,-P;\zeta_H)$

- PDF A term $q^\pi_A(x;\zeta_H) = N_c \mathrm{tr}\int_{dk} \delta^x_n(k_\eta)\,\Gamma_\pi(k_\eta,-P)\,S(k_\eta)\,i\Gamma^n(k;x;\zeta_H)\,S(k_\eta)\,\Gamma_\pi(k_{\bar\eta},P)\,S(k_{\bar\eta}) = N_c \mathrm{tr}\int_{dk} \delta^x_n(k_\eta)\left[\Gamma_\pi(k_\eta,-P)\,n\cdot\partial_{k_\eta}S(k_\eta)\right]\Gamma_\pi(k_{\bar\eta},P)\,S(k_{\bar\eta})$
- PDF BC term $q^\pi_{BC}(x;\zeta_H) = N_c \mathrm{tr}\int_{dk} \delta^x_n(k_\eta)\,\Gamma^n_\pi(k_\eta,-P;\zeta_H)S(k_\eta)\Gamma_\pi(k_{\bar\eta},P)\,S(k_{\bar\eta}) = N_c \mathrm{tr}\int_{dk} \delta^x_n(k_\eta)\left[n\cdot\partial_{k_\eta}\Gamma_\pi(k_\eta,-P;\zeta_H)S(k_\eta)\right]\Gamma_\pi(k_{\bar\eta},P)\,S(k_{\bar\eta})$
- Pion PDF $q^\pi(x;\zeta_H) = q^\pi_{\mathrm{A}}(x;\zeta_H) + q^\pi_{\mathrm{BC}}(x;\zeta_H) = N_c \mathrm{tr}\int_{dk} \delta^x_n(k_\eta)\; n\cdot\partial_{k_\eta}\left[\Gamma_\pi(k_\eta,-P;\zeta_H)S(k_\eta)\right]\Gamma_\pi(k_{\bar\eta},P)\,S(k_{\bar\eta})$

- $S(k)$ quark propagator
- $\Gamma(k,P)$ Bethe-Salpeter amplitude

Computing inputs: interaction kernel

- $q^{\pi}(x;\zeta_H)$ is completely determined once an interaction kernel is specified

$$K_{\alpha_1\alpha_1',\alpha_2\alpha_2'} = G_{\mu\nu}(k)[i\gamma_\mu]_{\alpha_1\alpha_1'}[i\gamma_\nu]_{\alpha_2\alpha_2'}\,, \quad G_{\mu\nu}(k) = \tilde{G}(k^2)T_{\mu\nu}(k)$$

$$\frac{1}{Z_2^2}\tilde{G}(s) = \frac{8\pi^2 D}{\omega^4}e^{-s/\omega^2} + \frac{8\pi^2\gamma_m\mathscr{F}(s)}{\ln\left[\tau + (1+s/\Lambda_{\rm QCD}^2)^2\right]}\,, \quad k^2T_{\mu\nu}(k) = k^2\delta_{\mu\nu} - k_\mu k_\nu$$

- Mass-independent renormalisation scheme
  - Z_2 & Z_4 defined in chiral limit and invariant for any current quark mass
- Renormalisation scale ζ
  - A scale where dressed quasiparticles are the correct degrees-of-freedom
  - Meson's Poincare covariant wave function must evolve with ζ

Computing inputs: Hadronic scale ζ_H

Daniele Binosi et al.. Phys. Rev. D 96, 054026 (2017)

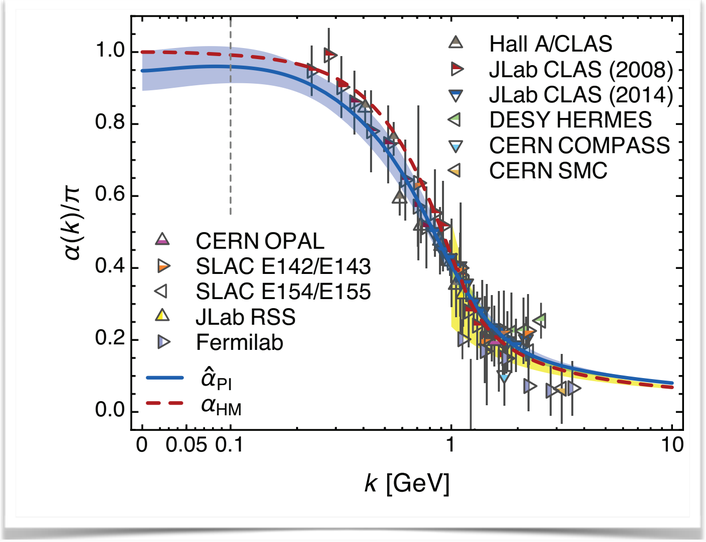
- Process-independent effective charge $\alpha_{\rm PI}(k^2)$
  - Saturates in the infrared: $\alpha_{\rm PI}(0)/\pi \approx 1$
  - Emergence of a nonzero gluon mass-scale

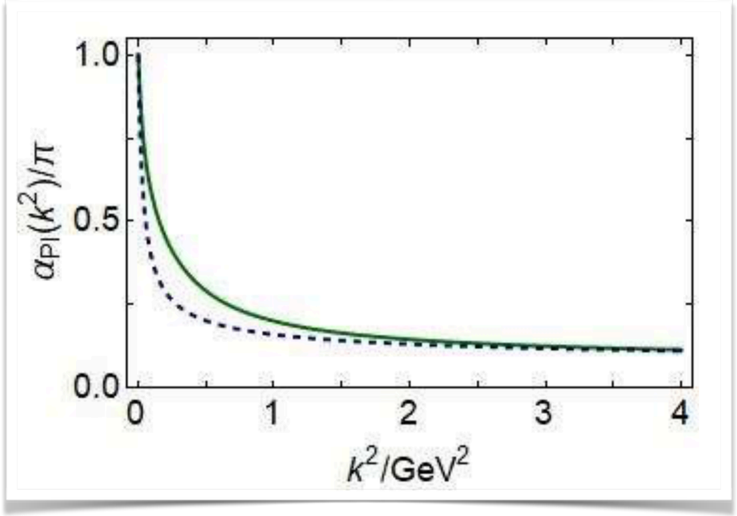
$$\alpha_{PI}(k) = \frac{4\pi}{\beta_0 \ln[(m_\alpha{}^2 + k^2)/\Lambda^2_{\rm QCD}]}$$

- $m_\alpha = 0.30\,GeV \gtrsim \Lambda_{\rm QCD}$ is an nonperturbative scale ensures modes with $k^2 \lesssim m_\alpha^2$ are screened from interactions.

- Renormalisation scale $\zeta_H = m_\alpha$

- m_α therefore serves to define the natural boundary between soft and hard physics





Solid Green = original Dashed Blue = simplified expression

Mellin moments

- $q^{\pi}(x;\zeta_H)$ is reconstructed from Mellin moments

$$\langle x^m\rangle^{\pi}_{\zeta_H} = \int_0^1 dx\, x^m q^{\pi}(x;\zeta_H) = \frac{N_c}{n\cdot P} tr\int_{dk}\left[\frac{n\cdot k_\eta}{n\cdot P}\right]^m \Gamma_\pi(k_{\bar\eta},P)\, S(k_{\bar\eta})\; n\cdot\partial_{k_\eta}\left[\Gamma_\pi(k_\eta,-P)S(k_\eta)\right]$$

- Odd moments are not independent
- Schlessinger point method (SPM)
  - Direct can compute m=0~5
  - SPM Extrapolate m=6~10

$$\langle x\rangle^{\pi}_{\zeta_H} = \frac{1}{2}\langle x^0\rangle^{\pi}_{\zeta_H} = \frac{1}{2},$$

$$\langle x^3\rangle^{\pi}_{\zeta_H} = -\frac{1}{4}\langle x^0\rangle^{\pi}_{\zeta_H} + \frac{3}{2}\langle x^2\rangle^{\pi}_{\zeta_H},$$

$$\langle x^5\rangle^{\pi}_{\zeta_H} = \frac{1}{2}\langle x^0\rangle^{\pi}_{\zeta_H} - \frac{5}{2}\langle x^2\rangle^{\pi}_{\zeta_H} + \frac{5}{2}\langle x^4\rangle^{\pi}_{\zeta_H},$$

$$\langle x^7\rangle^{\pi}_{\zeta_H} = -\frac{17}{8}\langle x^0\rangle^{\pi}_{\zeta_H} + \frac{21}{2}\langle x^2\rangle^{\pi}_{\zeta_H} - \frac{35}{4}\langle x^4\rangle^{\pi}_{\zeta_H} + \frac{7}{2}\langle x^6\rangle^{\pi}_{\zeta_H}.$$

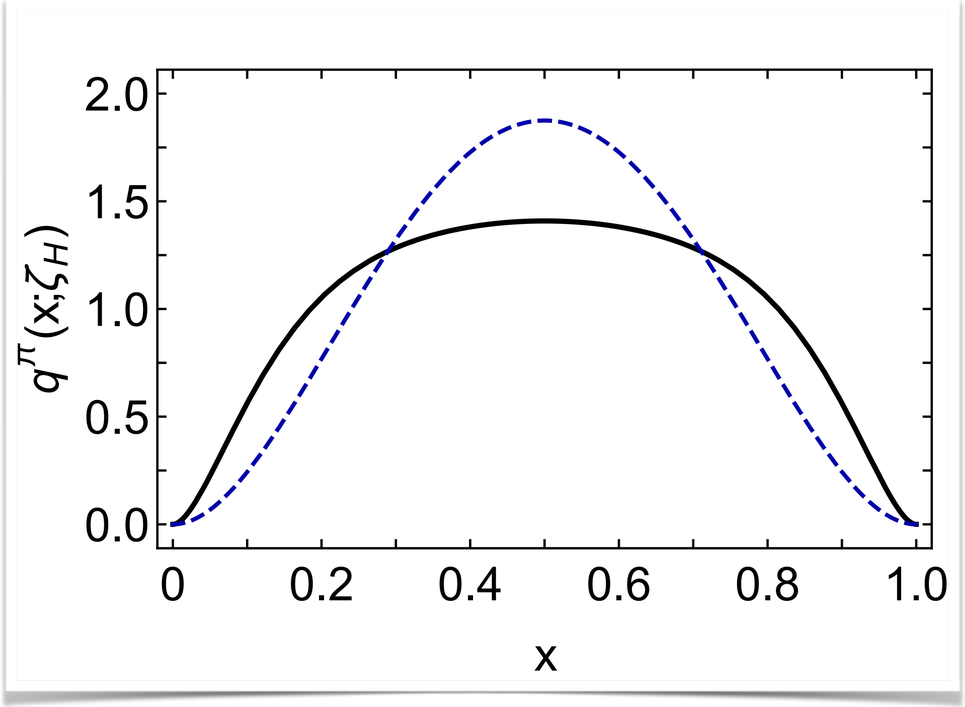
L. Schlessinger and C. Schwartz, Phys. Rev. Lett. 16, 1173 (1966)

L. Schlessinger, Phys. Rev. 167, 1411 (1968)

Valence quark PDF at ζ_H

- $q^\pi(x;\zeta_H)$ is reconstructed from Mellin moments

$$q^\pi(x;\zeta_H) = 213.32\, x^2(1-x)^2[1 - 2.9342\sqrt{x(1-x)} + 2.2911\, x(1-x)]$$



Solid Black = $q^\pi(x;\zeta_H)$

Dashed Blue = scale free distribution

$$q_{\rm sf}(x) \approx 30\, x^2(1-x)^2$$

- Broad function
- Dynamical chiral symmetry breaking
- PDA, form factors

Evolution of pion PDFs

* Existing Lattice QCD calculations of low-order moments and phenomenological fits to pion parton distributions are typically quoted at $\zeta_2 = 2$ GeV.

$\zeta_H = m_\alpha \longrightarrow \zeta_2 = 2$ GeV

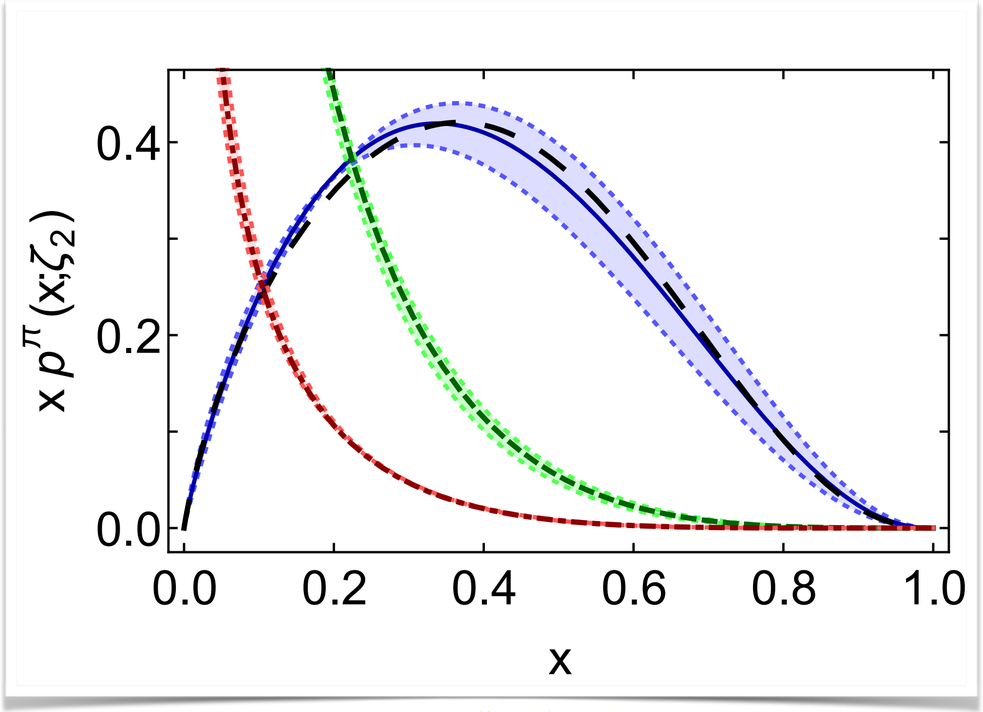
* Experiment take the scale $\zeta_5 = 5.2$ GeV

$\zeta_H = m_\alpha \longrightarrow \zeta_5 = 5.2$ GeV

- Process-independent running coupling $\alpha_{\rm PI}(\zeta_H)/(2\pi) = 0.20\,, [\alpha_{\rm PI}(\zeta_H)/(2\pi)]^2 = 0.04$
  - Leading order DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) equation should serve as a good approximation.
- Results report with $\zeta \to (1 \pm 0.1)\zeta$

see talks by Khépani and Pepe on Thursday

Pion PDFs at $\zeta_2 = 2$ GeV



	n_{q^π}	α	β	ρ	γ
ζ_2	9.83	−0.080	2.29	−1.27	0.511
	8.31	−0.127	2.37	−1.19	0.469
	7.01	−0.162	2.47	−1.12	0.453

$\beta(\zeta_2) = 2.38(9)$

- Solid (blue) curve embedded in shaded band $q^\pi(x;\zeta_2)$

$$q^\pi(x) = n_{q^\pi}\, x^\alpha (1-x)^\beta [1 + \rho\, x^{\alpha/4}(1-x)^{\beta/4} + \gamma\, x^{\alpha/2}(1-x)^{\beta/2}]$$

- Long-dashed (black), ζ_2 result from DSE in 2001

  Hecht et al.. Phys. Rev. C 63, 025213 (2001)

- Dashed (green), gluon; Dot-dashed (red), sea-quark.

$$xp^\pi(x;\zeta) = A\, x^\alpha\, (1-x)^\beta$$

- First Moment $\langle x \rangle_g^\pi = 0.41(2)$, $\langle x \rangle_{\rm sea}^\pi = 0.11(2)$.

  - Agree with P.C. Barry et al..(JAM Collaboration), Phys. Rev. Lett. 121, 152001 (2018)

Valence quark PDF at $\zeta_2 = 2$ GeV: first moment $\langle x^1 \rangle_u^\pi$

- Low-order moments in comparison with Lattice QCD simulations

  - Both continuum and lQCD results agree

$$\langle 2x \rangle_q^\pi = 0.48(3)$$

  - Roughly one-half of the light front momentum fraction is carried by the valence quarks

ζ_2	$\langle x \rangle_u^\pi$	$\langle x^2 \rangle_u^\pi$	$\langle x^3 \rangle_u^\pi$
Ref. [33]	0.24(2)	0.09(3)	0.053(15)
Ref. [34]	0.27(1)	0.13(1)	0.074(10)
Ref. [35]	0.21(1)	0.16(3)	
average	0.24(2)	0.13(4)	0.064(18)
Herein	0.24(2)	0.098(10)	0.049(07)

W. Detmold et al.. Phys. Rev. D 68, 034025 (2003) M. Oehm et al.. Phys. Rev. D 99, 014508 (2019)

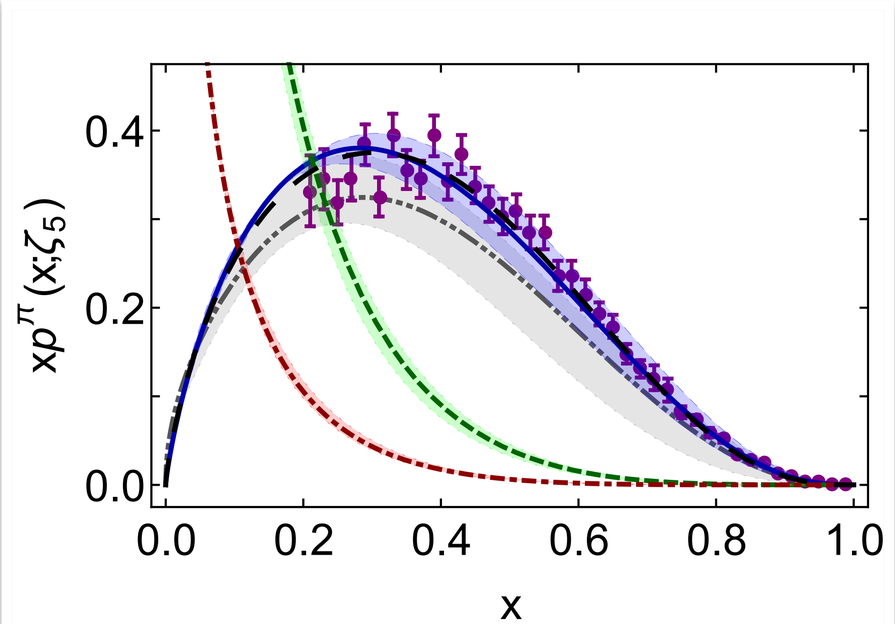
D. Brömmel et al. (QCDSF-UKQCD Collaboration), PoS LAT2007, 140 (2007)

  - Global QCD Analysis: Phenomenological analysis π-nucleus Drell-Yan and leading neutron DIS data.

$$\langle 2x \rangle_q^\pi = 0.48(1)\,, \zeta = 2.24 \text{ GeV}$$

P.C. Barry et al..,JAM Collaboration, Phys. Rev. Lett. 121, 152001 (2018)

Pion PDFs at $\zeta_5 = 5.2$ GeV



	n_{q^π}	α	β	ρ	γ
ζ_5	7.81	−0.153	2.54	−1.20	0.505
	7.28	−0.169	2.66	−1.21	0.531
	6.48	−0.188	2.78	−1.19	0.555

$\beta(\zeta_5) = 2.66(12)$

- Agree with Lattice QCD $\beta_{\rm lQCD}(\zeta_5) = 2.45(58)$

- Solid (blue), $q^{\pi}(x;\zeta_5)$

$$q^{\pi}(x) = n_{q^\pi}\, x^{\alpha}(1-x)^{\beta}[1 + \rho\, x^{\alpha/4}(1-x)^{\beta/4} + \gamma\, x^{\alpha/2}(1-x)^{\beta/2}]$$

- Long-dashed (black), DSE in 2001 — Hecht et al.. Phys. Rev. C 63, 025213 (2001)
- Dot-dot-dashed (grey), Lattice QCD — Raza Sabbir Sufian et al.. Phys. Rev. D 99, 074507 (2019)
- Data (purple) from — J.S.Conway et al.. Phys. Rev. D 39 (1989) 92-122
- Rescaled analysis — Matthias Aicher et al.. PRL 105, 252003 (2010)

- Low-order moments in comparison with Lattice QCD

ζ_5	$\langle x\rangle_u^\pi$	$\langle x^2\rangle_u^\pi$	$\langle x^3\rangle_u^\pi$
Ref. [31]	0.17(1)	0.060(9)	0.028(7)
Herein	0.21(2)	0.076(9)	0.036(5)

- Dashed (green), gluon; Dot-dashed (red), sea-quark.
- First Moment $\langle x\rangle_g^\pi = 0.45(1)$, $\langle x\rangle_{\rm sea}^\pi = 0.14(2)$.

Future Facilities & experiments on pion PDFs

- COMPASS++/AMBER:
  - The Compass++/Amber (proto-) collaboration proposes to establish a “New QCD facility at the M2 beam line of the CERN SPS” and perform in phase-1, i.e. starting in the year 2022, three experiments that will use either muons or hadrons delivered by the existing M2 beam line:
    - (1) Proton charge radius measurement using muon-proton elastic scattering
    - (2) Drell-Yan and J/Psi production experiments using the conventional M2 hadron beam
    - (3) Measurement of proton-induced antiproton production cross sections for dark matter searches.

Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS (COMPASS++/AMBER), arXiv:1808.00848 [hep-ex]

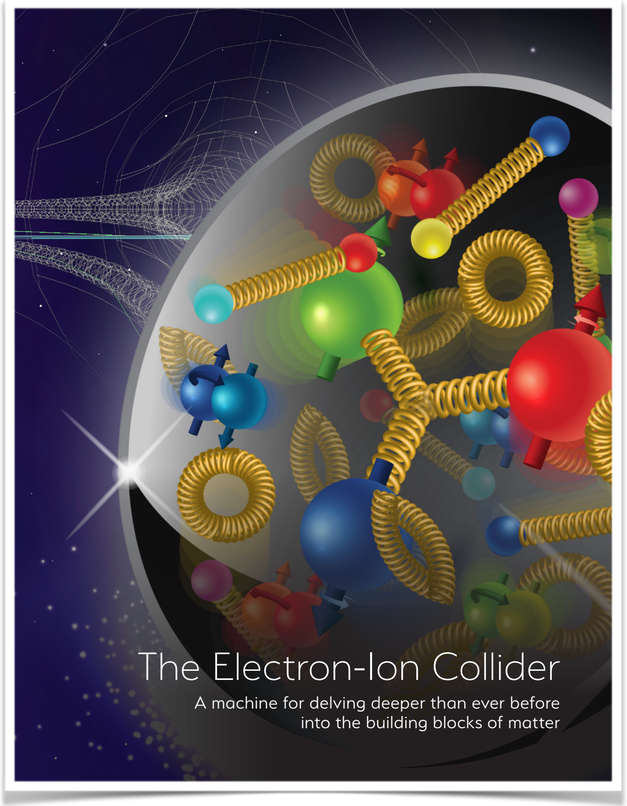
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	”active absorber”, vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Future Facilities & experiments on pion PDFs

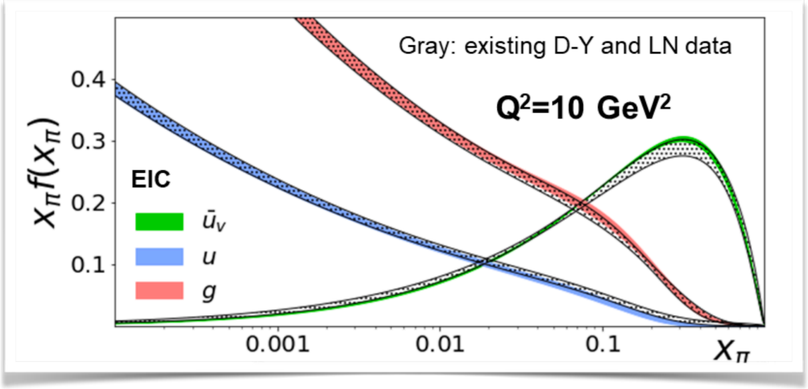
- The Electron Ion Collider (EIC):

  A machine for delving deeper than ever before into the building blocks of matter



- Scientific goals:
  - Precision 3D imaging of protons and nuclei
  - Search for saturation: color glass condensate
  - Solve the proton spin puzzle

Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all, EIC white paper, Eur.Phys.J.A 52 (2016) 9, 268



Sullivan process

A.C. Aguilar et a., Eur. Phys. J. A55 (2019) no.10, 190

- Pion and Kaon Structure Functions

Summary and outlook

✤ Summary

- Using a continuum approach, presented a symmetry-preserving calculation of the pion's PDF.
  - A novel term $q^{\pi}_{\rm BC}(x;\zeta_H)$ is necessary to keep $q^{\pi}(x;\zeta_H) = q^{\pi}(1-x;\zeta_H)$ and then $\langle x^1_{\pi}\rangle = 1/2$;
  - $\zeta_H = 0.30\,\mathrm{GeV}$ is the hadronic scale, and is determined by connecting the one-loop running coupling with QCD's process-independent effective charge.
  - $q^{\pi}(x;\zeta_H)$ is a broad function and is a consequence of dynamical chiral symmetry breaking.
  - Valence quark $q^{\pi}(x;\zeta_2)$ large x behaviour $\beta(\zeta_2) = 2.38(9)$, and first moment $\langle 2x\rangle^{\pi}_{q} = 0.48(3)$. Valence quark $q^{\pi}(x;\zeta_5)$ agrees with rescaled E615 data and lQCD prediction, large x behaviour $\beta(\zeta_5) = 2.66(12)$, and first moment $\langle 2x\rangle^{\pi}_{q} = 0.42(4)$.
  - Gluon and sea quark PDFs ζ_2, $\langle x\rangle^{\pi}_{g} = 0.41(2)$, $\langle x\rangle^{\pi}_{\rm sea} = 0.11(2)$, ζ_5, $\langle x\rangle^{\pi}_{g} = 0.45(1)$, $\langle x\rangle^{\pi}_{\rm sea} = 0.14(2)$.

✤ Outlook

- Kaon PDFs.
- Nucleon PDFs.

Thank you