What We Would Like to Learn from EIC

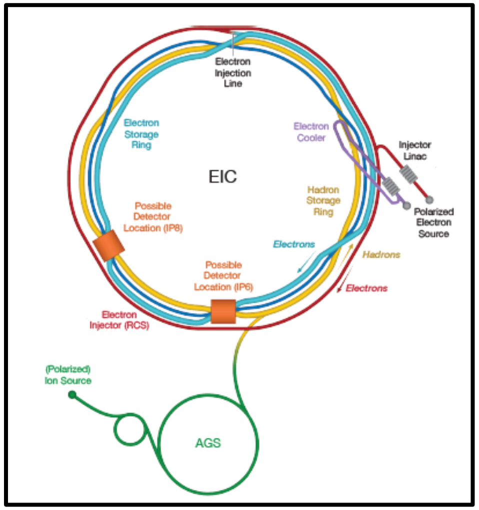
Jen-Chieh Peng

University of Illinois at Urbana-Champaign

TIDC EIC Workshop

NCKU, Taiwan, August 18-19, 2022

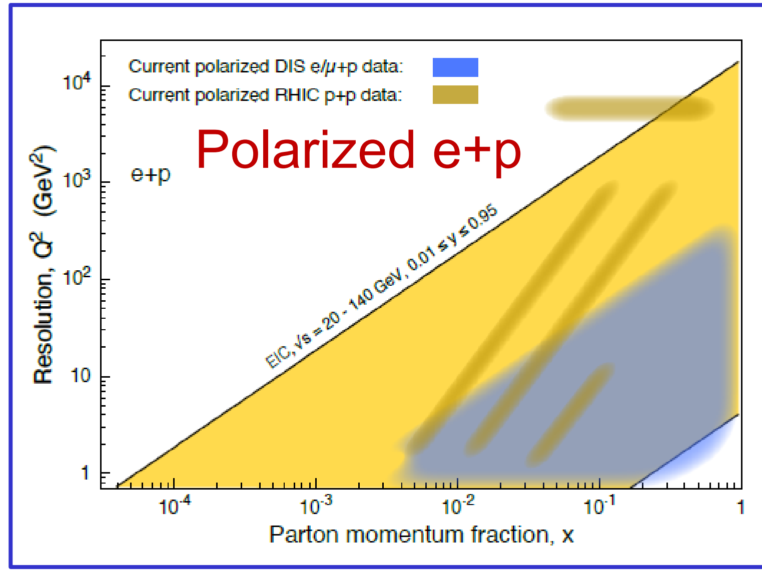
Brief History of EIC

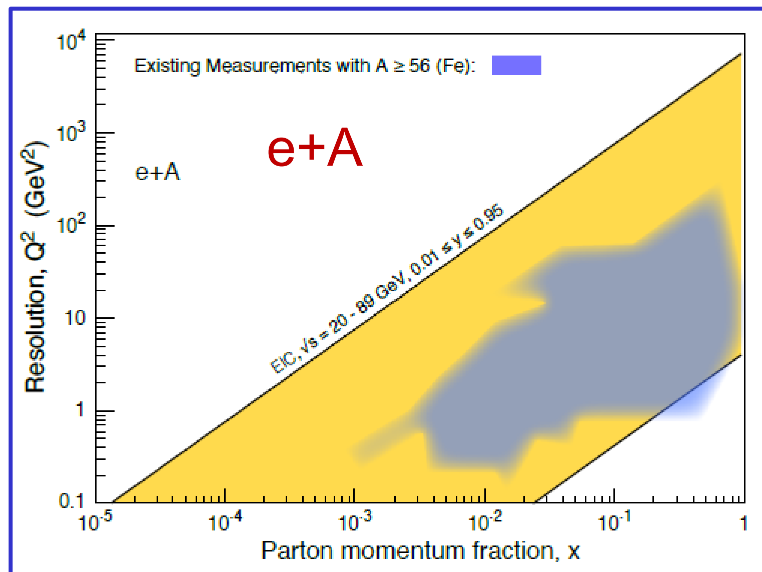


- In 2015, EIC became the highest priority for new construction in the US Nuclear Physics Long Range
- In 2018, A committee of the National Academy of Science favorably endorsed the science of EIC
- In 12/2019 EIC was granted CD0 by the US DOE with site selected at BNL
- In 2021 EIC Yellow Report (~900 pages) was completed

Unique Features of EIC (relative to HERA)

- Polarized electron and proton beams (rather than unpolarized proton beam at HERA)
- Ion beams from deuteron to uranium, with polarized ^{3}He also possible (no ion beams at HERA)
- High electron-nucleon luminosity at $10^{33} – 10^{34}$ cm^{-2} s^{-1}





Major Physics Measurements (from Yellow Report)

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

2103.05419

- Origin of Nucleon Spin
  -- Spin decomposition
- Origin of Nucleon Mass
  -- Mass decomposition
- TMDs and GPDs of Nucleon
  -- SIDIS, DVCS, DVMP
- Gluon Saturation at small - x
  -- Color Glass Condensate

Three topics in this talk

- Origin of hadron mass
- Partonic structure of mesons
- Intrinsic sea in the proton

Origin of mass

CERN COURIER
July/Aug 2022

The Higgs Enigma

HIGGS AND ELECTROWEAK | FEATURE

The origin of particle masses

1 July 2022

Gilad Perez links the Higgs boson to the puzzling pattern of the fermion masses.

Furthermore, the masses and sizes of nuclei, protons and neutrons cannot simply be obtained by "adding up" smaller degrees of freedom; they are rather dictated by the coupling constant of the strong force, which below a certain energy scale, Λ_{QCD}, becomes so large that the force between two particles becomes approximately independent of their distance, inducing confinement.

Origin of the Nucleon Mass

Peculiar behavior of hadron mass

- Consider the hydrogen atom, which is a bound system of e^- and p

$$mass(e^-) = 0.511999\,\text{MeV};\ \ mass(p) = 938.272088\,\text{MeV}$$

$$mass(H) = 938.7840734\,\text{MeV}$$

$$mass(H) < mass(e^-) + mass(p)$$ (due to 13.6 eV binding energy)

- Consider the nucleus ^{12}C consisting of 6 protons and 6 neutrons

$$mass(p) = 938.3\,\text{MeV};\ mass(n) = 939.6\,\text{MeV}$$

$$mass(^{12}C) = 11{,}178\ \text{MeV}$$

$$mass(^{12}C) < 6\times mass(p) + 6\times mass(n)$$ (due to nuclear binding energy)

- Now, consider the proton, made of 2 up-quarks and 1 down-quark

$$mass(u) = 1.7 - 3.3\,\text{MeV};\ mass(d) = 4.1 - 5.8\,\text{MeV}$$

$$mass(p) = 938.3\,\text{MeV}$$

$$mass(p) >> 2\times mass(u) + mass(d)$$

Unlike the other composite systems of atoms and nuclei, the mass of a hadron is greater than the sum of the masses of the constituents

Hadron Mass from Lattice QCD

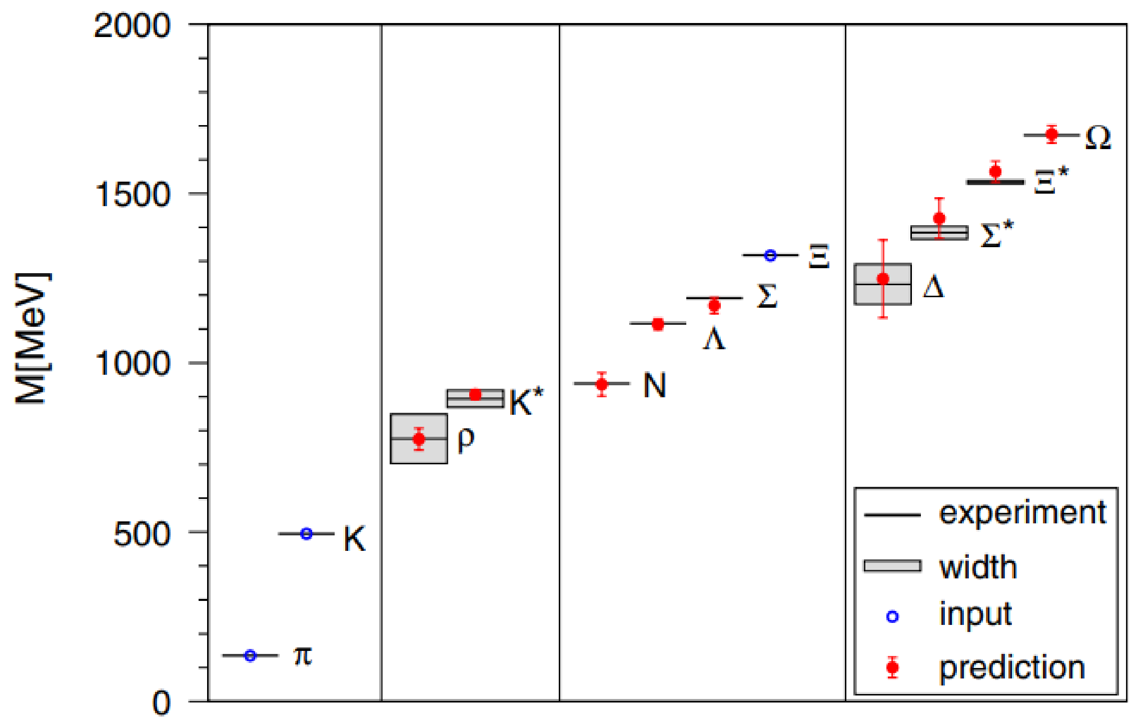


FIG. 22 (color online). Prediction of the light hadron spectrum in full $N_f = 2 + 1$ QCD according to Durr *et al.* (2008). Open circles are input quantities while filled circles are predictions. Experimental masses of hadrons that are stable in QCD are given with a vertical bar while for resonant states the box indicates the decay width. Experimental numbers are from Amsler *et al.*, 2008.

However, we need some “insights” on the origin of hadron mass

Hadron Mass from Constituent Quark Model

$$M(\text{baryon}) = m_1 + m_2 + m_3 + A'\left[\frac{\mathbf{S}_1 \cdot \mathbf{S}_2}{m_1 m_2} + \frac{\mathbf{S}_1 \cdot \mathbf{S}_3}{m_1 m_3} + \frac{\mathbf{S}_2 \cdot \mathbf{S}_3}{m_2 m_3}\right]$$

The magnetic moment of baryon B, then, is

$$\mu_B = \langle B\uparrow|(\mu_1 + \mu_2 + \mu_3)_z|B\uparrow\rangle = \frac{2}{\hbar}\sum_{i=1}^{3}\langle B\uparrow|(\mu_i S_{i_z})|B\uparrow\rangle$$

TABLE 5.6 BARYON OCTET AND DECUPLET MASSES (MeV/c^2)

Baryon	Calculated	Observed
N	939	939
Λ	1116	1114
Σ	1179	1193
Ξ	1327	1318
Δ	1239	1232
Σ^*	1381	1384
Ξ^*	1529	1533
Ω	1682	1672

TABLE 5.5 MAGNETIC DIPOLE MOMENTS OF OCTET BARYONS

Baryon	Moment	Prediction	Experiment
p	$(\frac{4}{3})\mu_u - (\frac{1}{3})\mu_d$	2.79	2.793
n	$(\frac{4}{3})\mu_d - (\frac{1}{3})\mu_u$	−1.86	−1.913
Λ	μ_s	−0.58	−0.61
Σ^+	$(\frac{4}{3})\mu_u - (\frac{1}{3})\mu_s$	2.68	2.33 ± 0.13
Σ^0	$(\frac{2}{3})(\mu_u + \mu_d) - (\frac{1}{3})\mu_s$	0.82	
Σ^-	$(\frac{4}{3})\mu_d - (\frac{1}{3})\mu_s$	−1.05	−1.41 ± 0.25
Ξ^0	$(\frac{4}{3})\mu_s - (\frac{1}{3})\mu_u$	−1.40	−1.253 ± 0.014
Ξ^-	$(\frac{4}{3})\mu_s - (\frac{1}{3})\mu_d$	−0.47	−0.69 ± 0.04

From Griffiths' textbook

$$m(u) = m(d) = 363\ \text{MeV};\ m(s) = 538\,\text{MeV}$$

The mass of proton is now less than the sum of the 3 constituent quarks

Decomposition of Proton's Mass

Decomposition of Proton's Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_Q(\mu) + L_G(\mu)$$

- Extensive effort at CERN, JLab, RHIC, SLAC over the last 30 years
- It remains one of the major physics topics at EIC

Decomposition of Proton's Mass

$$M = M_q + M_g + M_m + M_a$$

- M_q is from the quark kinetic and potential energies
- M_g is from the gluon kinetic and potential energies
- M_m is from the quark mass contribution
- M_a is from the trace anomaly contribution

This could become a major physics topic at EIC

Decomposition of Proton's Mass

VOLUME 74, NUMBER 7 PHYSICAL REVIEW LETTERS 13 FEBRUARY 1995

QCD Analysis of the Mass Structure of the Nucleon

Xiangdong Ji
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 13 October 1994)

PHYSICAL REVIEW D VOLUME 52, NUMBER 1 1 JULY 1995

Breakup of hadron masses and the energy-momentum tensor of QCD

Xiangdong Ji
Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 2 February 1995)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm GS}$$

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathcal{L}_{\rm GF} = -\frac{1}{2\xi}(\partial^\mu A_\mu)^2$$

$$\mathcal{L}_{\rm gs} = \partial^\mu\bar{\omega}D_\mu\omega$$

From the invariance of translation in space and time, the Noether's theorem gives a conserved energy-momentum tensor $T^{\mu\nu}$

$$T^{\mu\nu} = -g^{\mu\nu}\mathcal{L}_{\rm eff} - F^{\mu\alpha}F^{\nu}{}_{\alpha} + \frac{1}{2}\bar{\psi}iD^{(\mu}\gamma^{\nu)}\psi + \frac{1}{2}\bar{\psi}i\overleftarrow{D}^{(\mu}\gamma^{\nu)}\psi - g^{\mu\nu}\xi^{-1}\partial^\alpha(A_\alpha\partial\cdot A) + 2\xi^{-1}A^{(\mu}\partial^{\nu)}(\partial\cdot A)$$
$$+2\partial^{(\mu}\bar{\omega}D^{\nu)}\omega - \frac{\delta S}{\delta A_\mu}A_\nu - \frac{\delta S}{\delta\psi}\frac{1}{8}[\gamma^\mu,\gamma^\nu]\psi - \bar{\psi}\frac{1}{8}[\gamma^\mu,\gamma^\nu]\frac{\delta S}{\delta\bar{\psi}}\ ,$$

Decomposition of Proton's Mass

PHYSICAL REVIEW D VOLUME 52, NUMBER 1 1 JULY 1995

Breakup of hadron masses and the energy-momentum tensor of QCD

Xiangdong Ji

Decomposition of EMT into two parts: $T^{\mu\nu} = \bar{T}^{\mu\nu} + \hat{T}^{\mu\nu}$

Traceless part: $\bar{T}^{\mu\nu} = \bar{T}_q^{\mu\nu R}(\mu^2) + \bar{T}_g^{\mu\nu R}(\mu^2)$

Trace part: $\hat{T}^{\mu\nu} = \hat{T}_a^{\mu\nu R}(\mu^2) + \hat{T}_m^{\mu\nu R}(\mu^2)$

Matrix element of EMT in a hadron: $\langle P|T^{\mu\nu}|P\rangle = P^\mu P^\nu/M$

Traceless part: $\langle P|\bar{T}^{\mu\nu}|P\rangle = \left(P^\mu P^\nu - \frac{1}{4}g^{\mu\nu}M^2\right)\Big/M$

Trace part: $\langle P|\hat{T}^{\mu\nu}|P\rangle = \frac{1}{4}g^{\mu\nu}M$.

Decomposition of Proton's Mass

Matrix element of EMT in a hadron: $\langle P|T^{\mu\nu}|P\rangle = P^\mu P^\nu / M$

Traceless part: $\langle P|\bar{T}^{\mu\nu}|P\rangle = \left(P^\mu P^\nu - \frac{1}{4}g^{\mu\nu}M^2\right) \Big/ M$

Traceless part for quarks: $\langle P|\bar{T}_q^{\mu\nu}|P\rangle = a(\mu^2)\left(P^\mu P^\nu - \frac{1}{4}g^{\mu\nu}M^2\right) \Big/ M$

Traceless part for gluons: $\langle P|\bar{T}_g^{\mu\nu}|P\rangle = [1 - a(\mu^2)]\left(P^\mu P^\nu - \frac{1}{4}g^{\mu\nu}M^2\right) \Big/ M$

Trace part from quark mass: $\langle P|\hat{T}_m^{\mu\nu}|P\rangle = b(\mu^2)\frac{1}{4}g^{\mu\nu}M$

Trace part from anomaly: $\langle P|\hat{T}_a^{\mu\nu}|P\rangle = [1 - b(\mu^2)]\frac{1}{4}g^{\mu\nu}M$

Knowing $a(\mu^2)$ and $b(\mu^2)$ is sufficient to perform the mass decomposition

$$a(\mu^2) = \sum_f \int_0^1 dx\, x[q_f(x,\mu^2) + \bar{q}_f(x,\mu^2)]$$

$a(\mu^2)$ is simply the momentum fraction of the hadron carried by quarks and antiquarks !

Decomposition of Proton's Mass

Knowing $a(\mu^2)$ and $b(\mu^2)$ is sufficient to perform the mass decomposition

$$a(\mu^2) = \sum_f \int_0^1 dx\, x[q_f(x,\mu^2) + \bar{q}_f(x,\mu^2)]$$

$$\begin{aligned} bM_N &= \langle N|m_u\bar{u}u + m_d\bar{d}d|N\rangle + \langle N|m_s\bar{s}s|N\rangle \\ &= m_l\langle N|\bar{u}u + \bar{d}d|N\rangle + m_s\langle N|\bar{s}s|N\rangle \\ &= \Sigma_{\pi N} + \Sigma_{sN}. \end{aligned}$$

$b(\mu^2)$ is from πN sigma-term and the scalar charge of strange quark

TABLE I. A separation of the nucleon mass into different contributions. The matrix elements a and b are defined in Eqs. (15) and (20).

Mass type	H_i	M_i	$m_s \to 0$ (MeV)	$m_s \to \infty$ (MeV)
Quark energy	$\psi^\dagger(-i\mathbf{D}\cdot\boldsymbol{\alpha})\psi$	$3(a-b)/4$	270	300
Quark mass	$\bar{\psi}m\psi$	b	160	110
Gluon energy	$\frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2)$	$3(1-a)/4$	320	320
Trace anomaly	$\frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2)$	$(1-b)/4$	190	210

Trace anomaly from J/Ψ photoproduction

When Color meets Gravity; Near-Threshold Exclusive J/ψ Photoproduction on the Proton

B. Duran[3,1], Z.-E. Meziani[1,3**], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[6], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[5], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]

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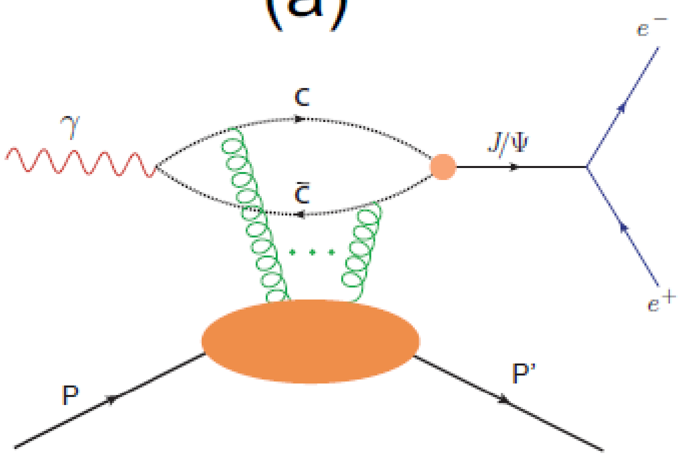
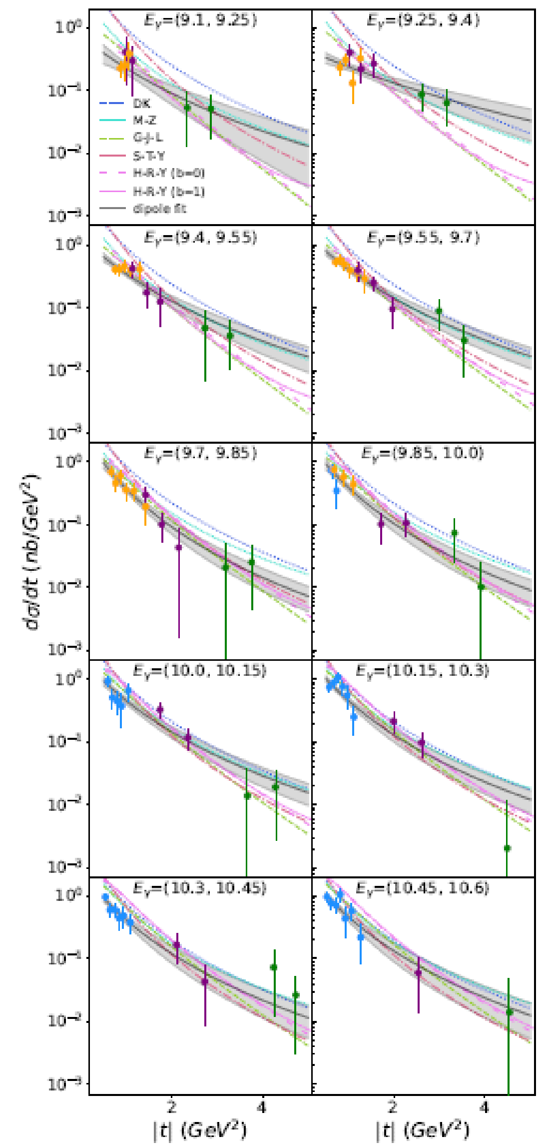
(a)





Trace anomaly from J/Ψ photoproduction

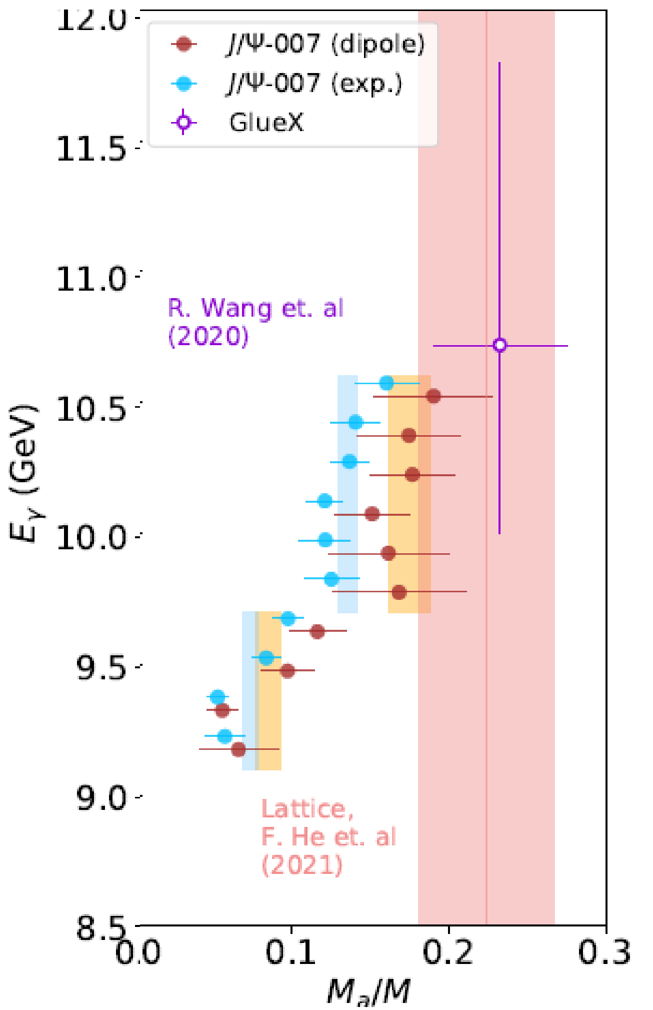
$$\left.\frac{d\sigma_{\gamma N\to J/\Psi N}}{dt}\right|_{t=0} = \frac{3\Gamma(J/\Psi\to e^+e^-)}{\alpha m_{J/\psi}}\left(\frac{k_{J/\Psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\Psi N\to J/\Psi N}}{dt}\right|_{t=0},$$

Extrapolate $d\sigma / dt$ to $t = 0$

$$\left.\frac{d\sigma_{J/\Psi N\to J/\Psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi}\frac{1}{m_{J/\psi}^2(\lambda^2 - m_N^2)}\left|F_{J/\Psi N}\right|^2$$

$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N\left|\sum_{i=u,d,s} m_i \bar{q}_i q_i\right|N\right\rangle\right) \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right)$$

(From D. Karzeev, nucl/th 9601029)



Hence, b (and M_a) can be obtained from $d\sigma / dt$ at $t = 0$

Mass radius from J/Ψ photoproduction

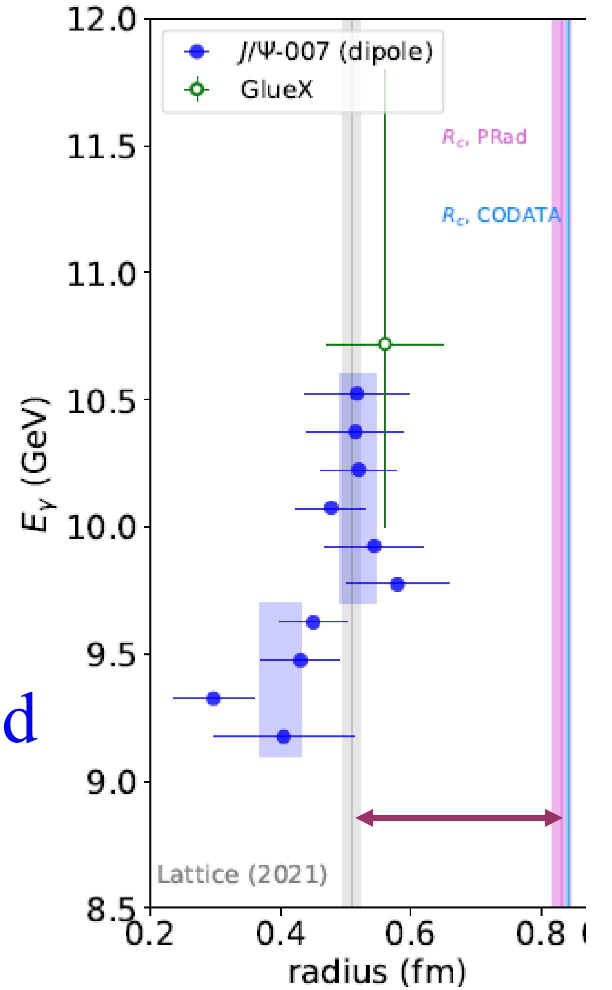
$$\frac{d\sigma}{dt} = \frac{1}{64\pi s}\frac{1}{|p_{\gamma cm}|^2}(Q_e c_2)^2\left(\frac{16\pi^2 M^2}{b}\right)^2 G(t)^2$$

$$G(t) = M(1 - t/m_s^2)^{-2}$$

Use a dipole form factor

$$\langle r_m^2 \rangle = \frac{6}{M}\frac{dG}{dt}\Big|_{t=0} = \frac{12}{m_s^2}$$

Hence, the mass radius r_m can be determined



The proton mass radius $\langle r_m^2 \rangle^{1/2} = 0.52 \pm 0.03$ fm
is much smaller than the charge radius of 0.84 fm !

What's next?

- More theoretical studies are needed
- Threshold photoproduction of Ψ'
  (possible at EIC or JLab 22 GeV upgrade)
- Threshold photoproduction of Υ (possible at EIC)
- Threshold J/Ψ production using pion beam
  $\pi^- + p \to J/\Psi + n$ (possible at J-PARC)
- Should perform similar analysis for
  threshold photoproduction of $\phi -$meson
  (data already exist from Spring-8 and JLab)
- What are the mass decompositions for mesons?

Partonic structures of pion and kaon

Why is it interesting?

- Lightest $q\overline{q}$ bound states, and Goldstone bosons
- A simpler hadronic system than the nucleon
- Spin-0 π and K contrasting spin-1/2 nucleon
- Compared to nucleons, very little is known experimentally for the partonic structures of mesons
- Mass decomposition of pion and kaon

Partonic structures of pion and kaon

Spin-0 for π and K implies:

- No helicity distributions ($\Delta q(x) = 0,\ \Delta G(x) = 0$)
- No TMDs such as Transversity, Sivers, Prezelocity distributions (Boer-Mulders functions for π and K do exist)

Number of unpolarized partonic distributions is reduced from symmetry consideration (charge-conjugation and SU(2) flavor symmetries)

- $u^V_{\pi^+}(x) = \bar{d}^V_{\pi^+}(x) = \bar{u}^V_{\pi^-}(x) = d^V_{\pi^-}(x) \equiv V_\pi(x)$
- $\bar{u}_{\pi^+}(x) = d_{\pi^+}(x) = u_{\pi^-}(x) = \bar{d}_{\pi^-}(x) \equiv S_\pi(x)$

For kaons, more PDFs are needed (breaking of SU(3) flavor symmetry)

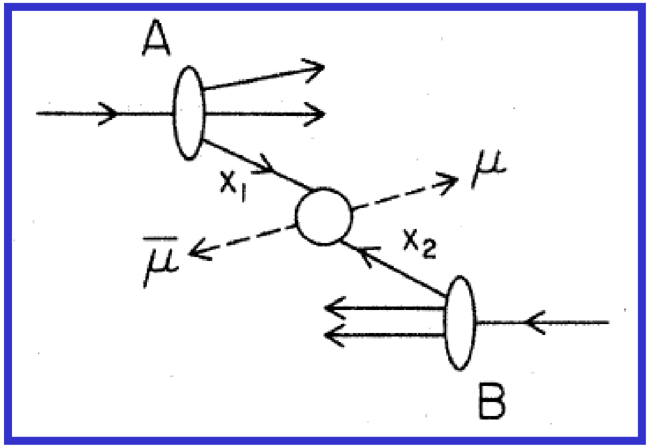
- $u^V_{K^+}(x) \neq \bar{s}^V_{K^+}(x)$ (analogous to $u^V_p(x) \neq d^V_p(x)$)
- $\bar{u}_{K^+}(x) \neq \bar{d}_{K^+}(x)$ (analogous to $\bar{u}_p(x) \neq \bar{d}_p(x)$)

Many interesting questions can be raised on the comparison between pion and kaon parton distributions

Meson partonic content from the Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)



$$p+p\rightarrow(\mu^+\mu^-)+\cdots. \quad (1)$$

Our remarks apply equally to any colliding pair such as (pp), $(\bar{p}p)$, (πp), (γp) and to final leptons $(\mu^+\mu^-)$, $(e\bar{e})$, $(\mu\nu)$, and $(e\nu)$.

(4) The full range of processes of the type (1) with incident p, $\bar{p}$, π, K, γ, etc., affords the interesting possibility of comparing their parton and antiparton structures.

List of Drell-Yan experiments with π^- beam

Experiments at CERN and Fermilab

Exp	P (GeV)	targets	Number of D-Y events
WA11	175	Be	500 (semi-exclusive)
WA39	40	W (H_2)	3839 (all beam, M > 2 GeV)
NA3	150, 200, 280	Pt (H_2)	21600, 4970, 20000 (535, 121, 741)
NA10	140, 194, 286	W (D_2)	~84400, ~150000, ~45900 (3200, --, 7800)
E331/E444	225	C, Cu, W	500
E326	225	W	
E615	80, 252	W	4060, ~50000

- Relatively pure π^- beam; J/Ψ production also measured
- Relatively large cross section due to $\bar{u}d$ contents in π^-

For a very long time, only four pion parton distribution functions were available

- Third: GRV-P (Z. Phys. C53, 651 (1992))
  - Only valence and valence-like gluon at initial scale. Sea is entirely from QCD evolution
  - Valence distribution from fit to direct photon data

- Fourth: SMRS (PR D45, 2349 (1992))
  - NA10 and E615 D-Y data
  - WA70 direct photon data

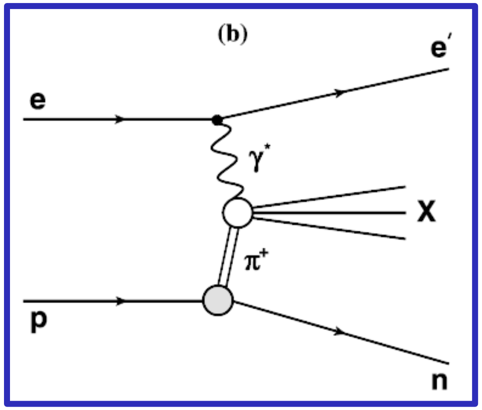
- Need new global fits to all existing data
- Need new experimental data with pion and kaon beams

First Monte Carlo global QCD analysis of pion parton distributions

P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

JAM Collaboration

PRL 121, 152001 (2018)



- Drell-Yan data from NA10 and E615
- Leading-neutron tagged DIS from HERA provides information on the pion PDFs at small x
- The Q^2 evolution allows extraction of gluon distribution

Tagged DIS can be performed at EIC to study pion and kaon parton structures

A New Extraction of Pion Parton Distributions in the Statistical Model

Claude Bourrely[a], Franco Buccella[b], Jen-Chieh Peng[c]

Physics Letters B 813 (2021) 136021

$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (7)$$

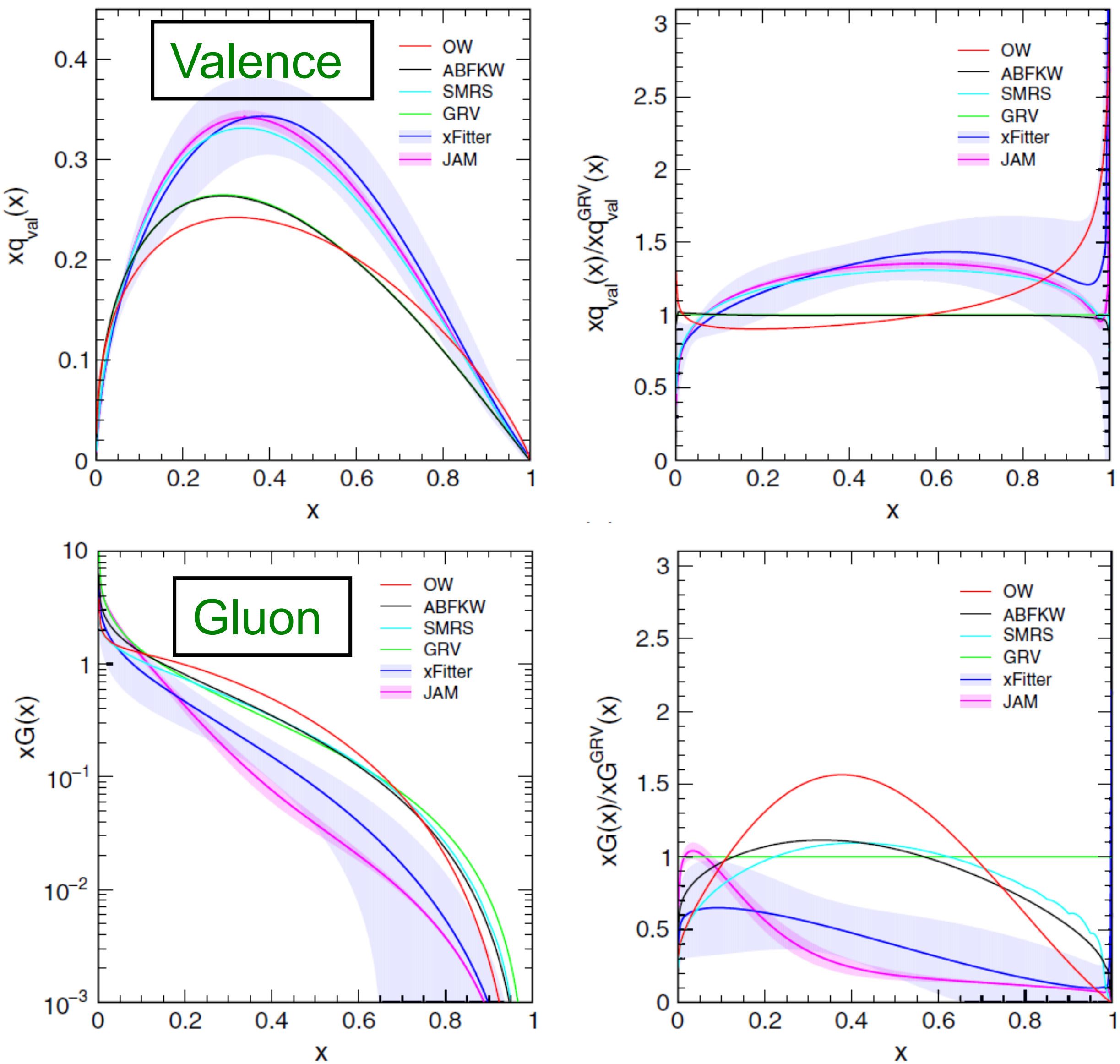
$$x\bar{U}(x) = x\bar{D}(x) = \frac{A_U (X_U)^{-1} x^{b_U}}{\exp[(x + X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (8)$$

$$xS(x) = x\bar{S}(x) = \frac{\tilde{A}_U x^{\tilde{b}_U}}{2[\exp(x/\bar{x}) + 1]} . \quad (9)$$

$$xG(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1} . \quad (10)$$

- The statistical model describes proton's PDF very well
- The antiquark's flavor structure is related to quark's flavor structure
- The antiquark's spin structure is related to quark's spin structure
- It is not clear if the statistical model also works for meson's PDFs

Valence and gluon distributions for various pion PDFs

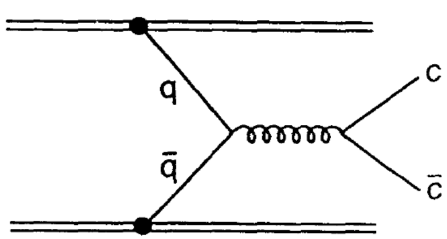


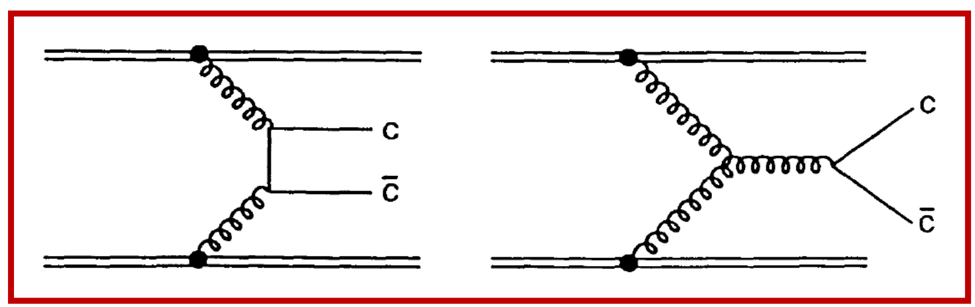
- Quite good agreements for valence quark PDFs
- Much larger variations for the gluon PDFs

Constraining gluon distribution of pion with pion-induced J/Ψ production

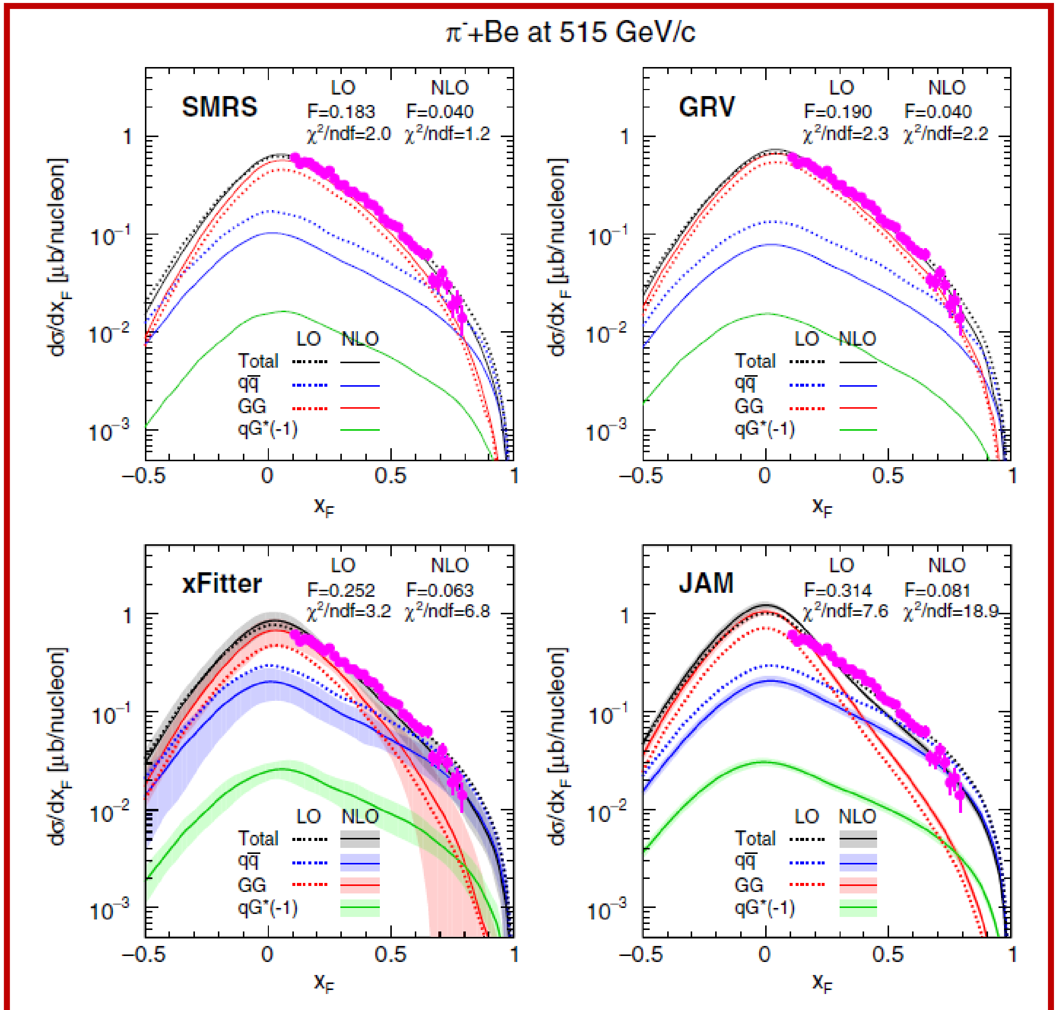
Chang, Platchkov, Sawada, JCP, PRD 102 (2020) 054024

- An attempt to compare existing pion PDFs in their abilities to describe existing pion-induced *J/Ψ* production data
- The existing data are sensitive to the gluon PDF in pion, which is poorly known and is of much theoretical interest





Comparison between data and calculations for different PDFs

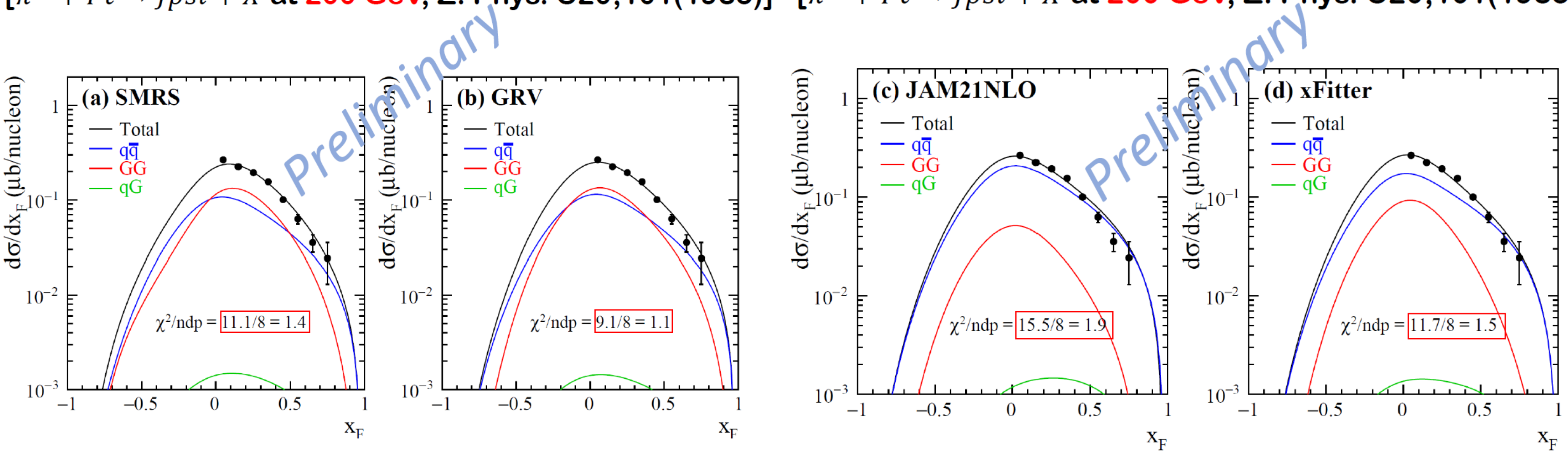


- At the highest available beam energy (515 GeV), GG fusion dominates at wider range of x_F for all PDFs
- JAM and xFitter GG fusion contribution falls off rapidly at large x_F

Chang, Platchkov, Sawada, JCP, PRD 102 (2020) 054024

Comparison between J/Ψ $d\sigma/dx_F$ data and NRQCD calculations for different pion PDFs

[$\pi^- + Pt \rightarrow Jpsi + X$ at 200 GeV, Z. Phys. C20,101(1983)] [$\pi^- + Pt \rightarrow Jpsi + X$ at 200 GeV, Z. Phys. C20,101(1983)]



Chang, JCP, Platchkov, Sawada, preliminary 2022

- The SMRS and GRV give smaller smaller χ^2 than JAM and xFitter
- It would be very important to include the J/Ψ data in the global fit to better constrain gluon distribution in mesons

Pion PDFs using DY and J/Ψ data

Phys.Rev.D 105 (2022) 076018 ; arXiv: 2202.12547

PHYSICAL REVIEW D **105,** 076018 (2022)

Pion partonic distributions in a statistical model from pion-induced Drell-Yan and J/Ψ production data

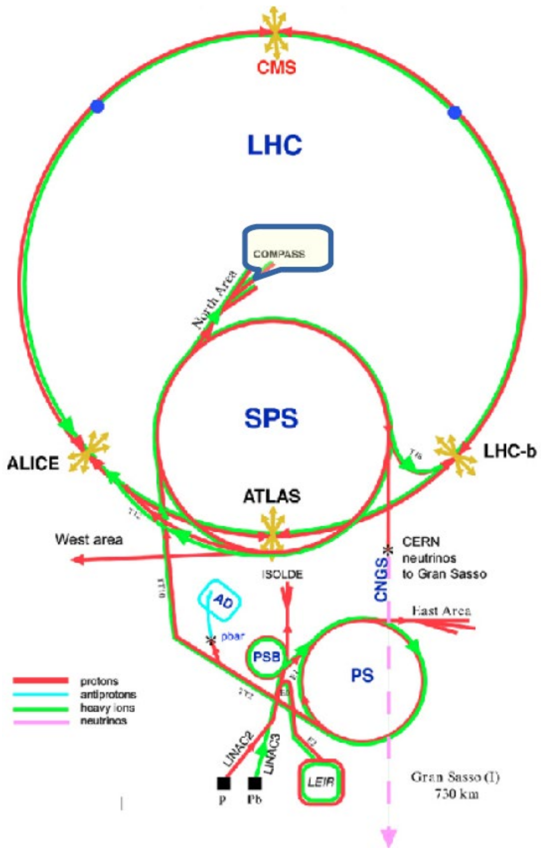
Claude Bourrely,[1] Wen-Chen Chang,[2] and Jen-Chieh Peng[3]

[1]*Aix Marseille Univ, Université de Toulon, CNRS, CPT, Marseille, France*
[2]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[3]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

(Received 23 February 2022; accepted 6 April 2022; published 26 April 2022)

We present a new analysis to extract pion parton distribution functions (PDFs) within the framework of the statistical model. Starting from the statistical model first developed for the spin-1/2 nucleon, we extend this model to describe the spin-0 pion. Based on a combined fit to both the pion-induced Drell-Yan data and the pion-induced J/Ψ production data, a new set of pion PDFs has been obtained. The inclusion of the J/Ψ production data in the combined fit has provided additional constraints for better determining the gluon distribution in the pion. We also compare the pion PDFs obtained in the statistical model with other existing pion PDFs.

AMBER (Phase-I was approved)



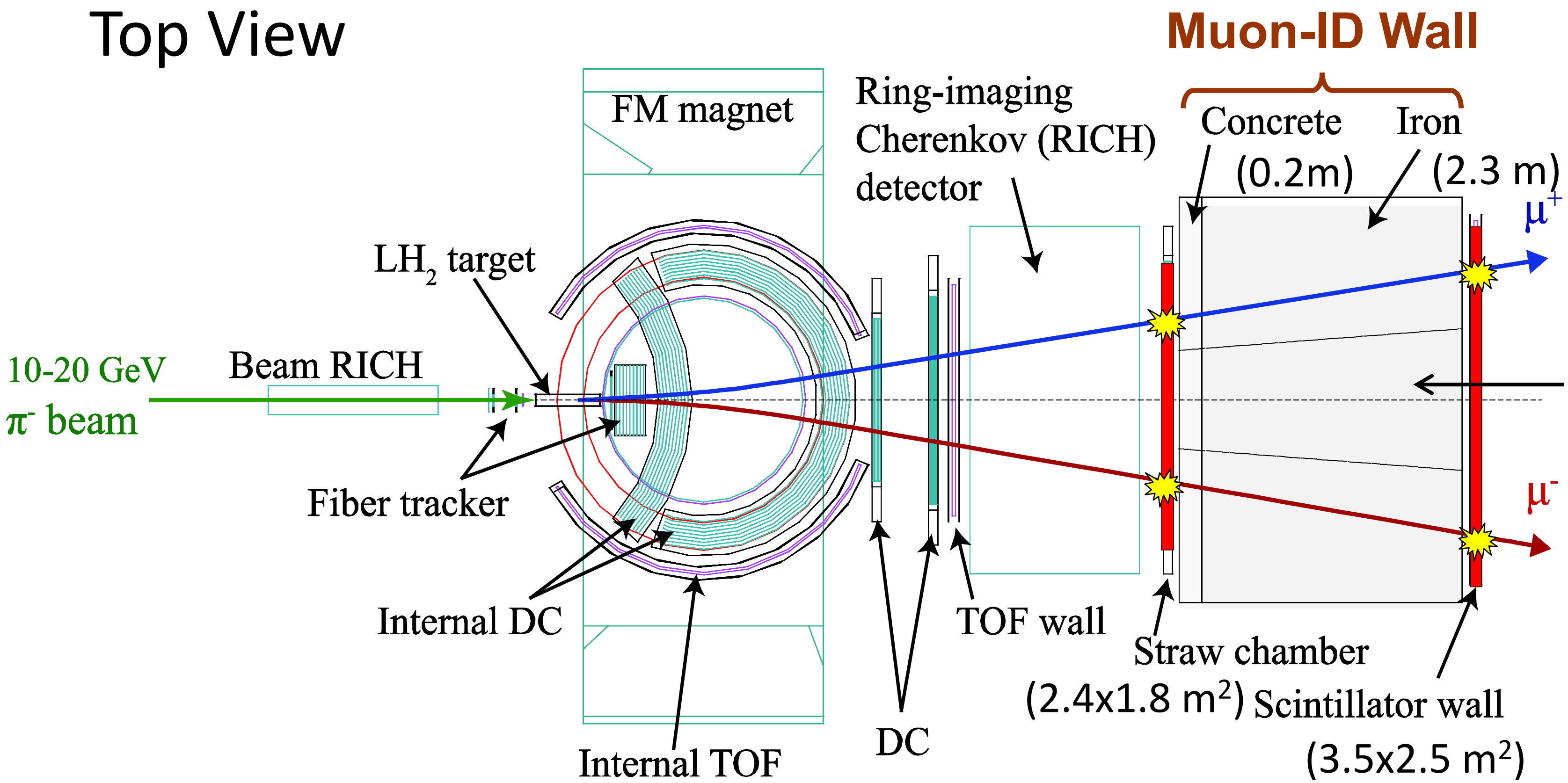
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity $[s^{-1}]$	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^{\pm}$	high-pressure H2	2022 1 year
Hard exclusive reactions	GPD *E*	160	$2 \cdot 10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years

- Expect new Drell-Yan and J/Ψ production data with pion (kaon) beams in the near future !

Proposal for exclusive Drell-Yan and J/Ψ at J-PARC with pion beam (W. Chang et al.)

(sensitive to the pion distribution amplitude)

Top View



Original Configuration for Charmed Baryon Spectroscopy

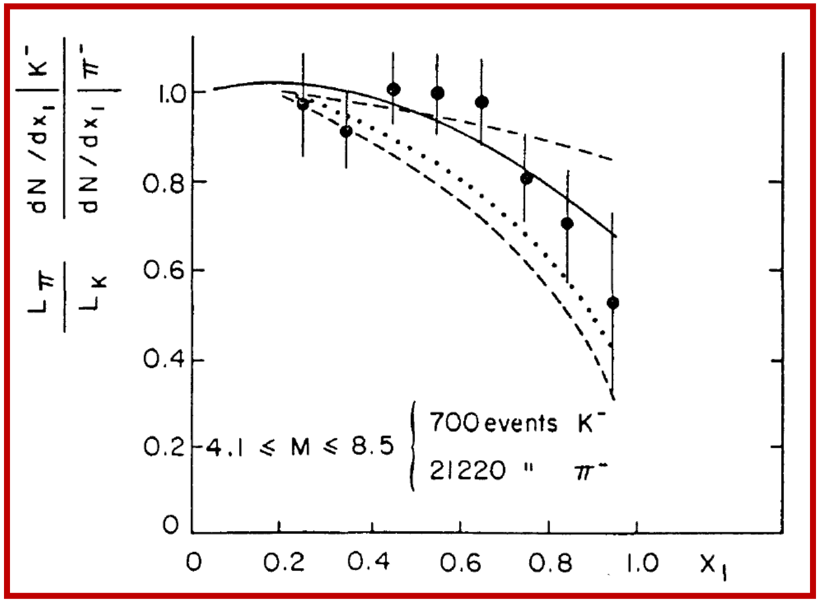
Stage-1 approved by J-PARC PAC-18, August 12, 2014.

Extension part

Proposal is currently being prepared.

What do we know about the kaon PDF (very little!)

$\sigma(K^- + \mathrm{Pt}) / \sigma(\pi^- + \mathrm{Pt})$ Drell-Yan ratios



From NA3; 150 GeV, Pt target

$$R = \frac{\sigma_{DY}(K^- + D)}{\sigma_{DY}(\pi^- + D)}$$

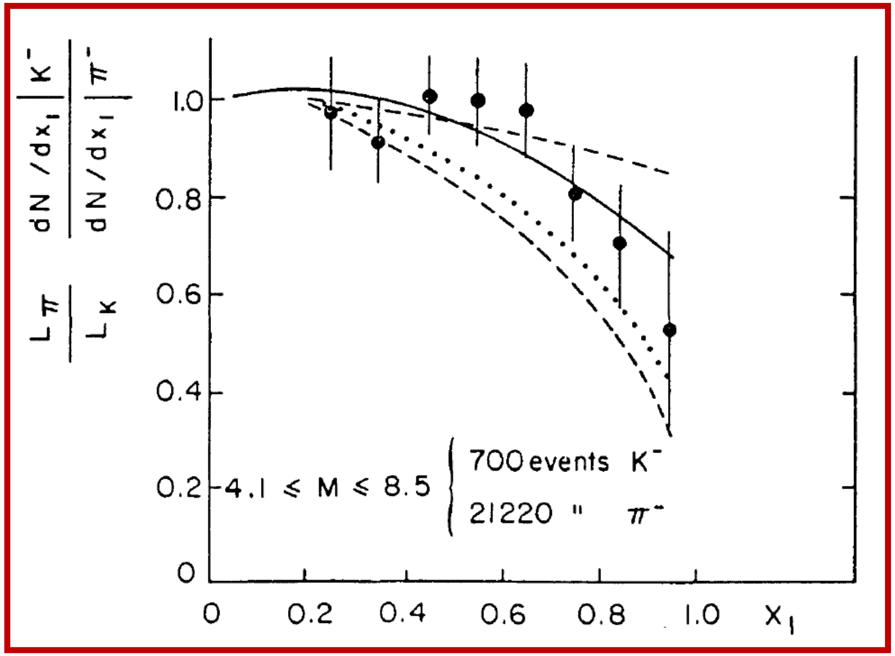
$$\simeq \frac{4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

$R \simeq (1-x)^{0.18\pm0.07} \Rightarrow$ softer u-valence in kaon than in pion

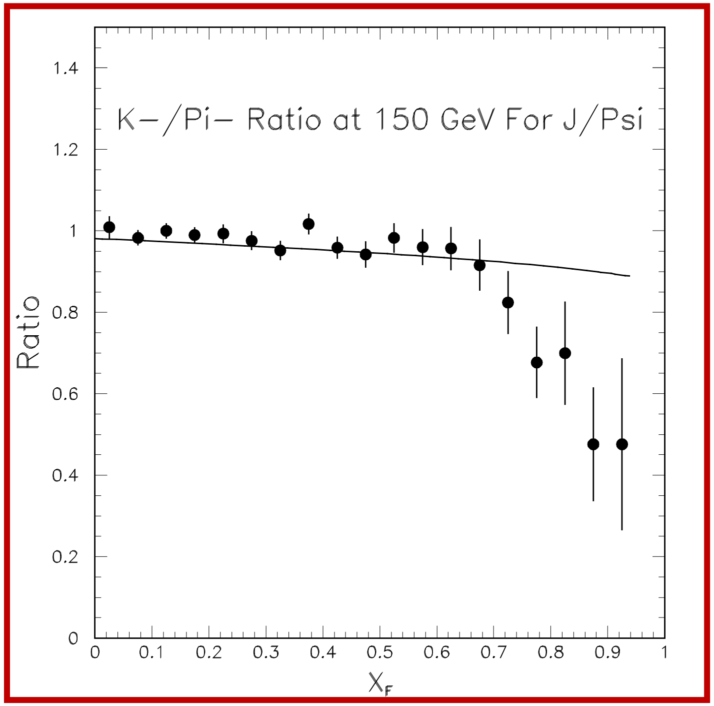
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y

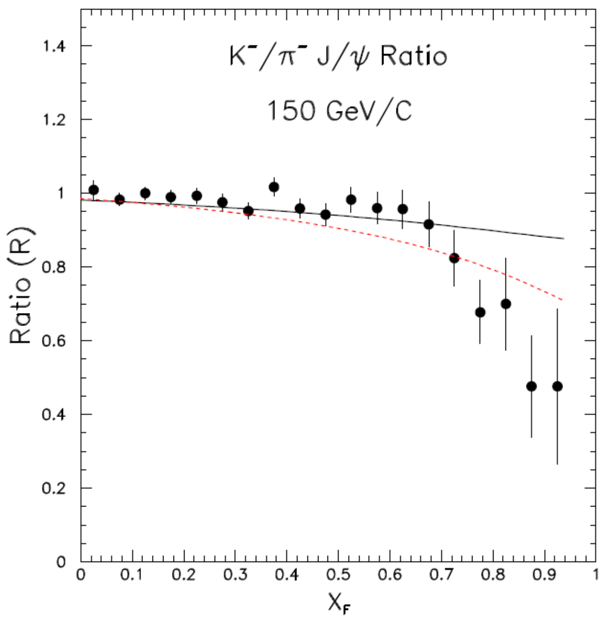


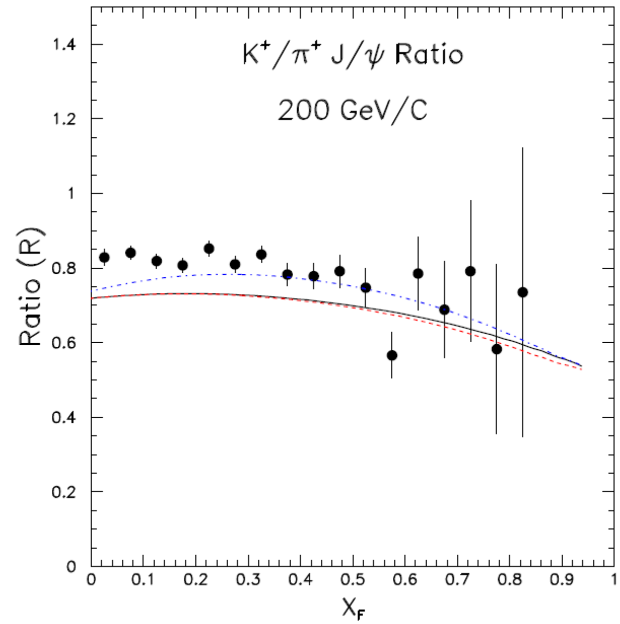
Ratios for J/Ψ



Similar behavior at large x_F for D-Y and J/Ψ production?

(K^+/π^+) ratios versus (K^-/π^-) ratios for J/Ψ production





Black solid curve:

same PDF for π^- and K^- in LO

Red dashed curve:

Modified K^- pdf

$\bar{u}_K^V(x) = 1.061\bar{u}_\pi^V(x)(1-x)^{0.203}$

$s_K^V(x) = 0.937\bar{u}_\pi^V(x)(1-x)^{-0.203}$

JCP, Chang, Platchkov, Sawada: 1711.00839

- Blue dot-dashed curve:

gluons in kaon carry 5% more momemtum than gluons in pion (in disagreement with the expectation that gluons in kaon carry less momentum than gluons in pion)

A global fit to extract the kaon PDF using the (K/π) Drell-Yan and J/Ψ data in the statistical model is underwat (Bourrely, Buccela, Chang, JCP)

Complementarity between AMBER and EIC in probing the partonic structure of mesons

A) Drell−Yan and quarkonium production in AMBER with meson beams

• Drell−Yan with π^- or K^- beam probe the valence−quark distributions in pion and kaon
• Comparison between Drell−Yan with π^- and π^+ beams can separate the valence and sea distributions in pion. Similarly for kaons

B) Tagged DIS (TDIS) with forward neutron tagging in e − p collisions can probe meson PDF using the Sullivan process

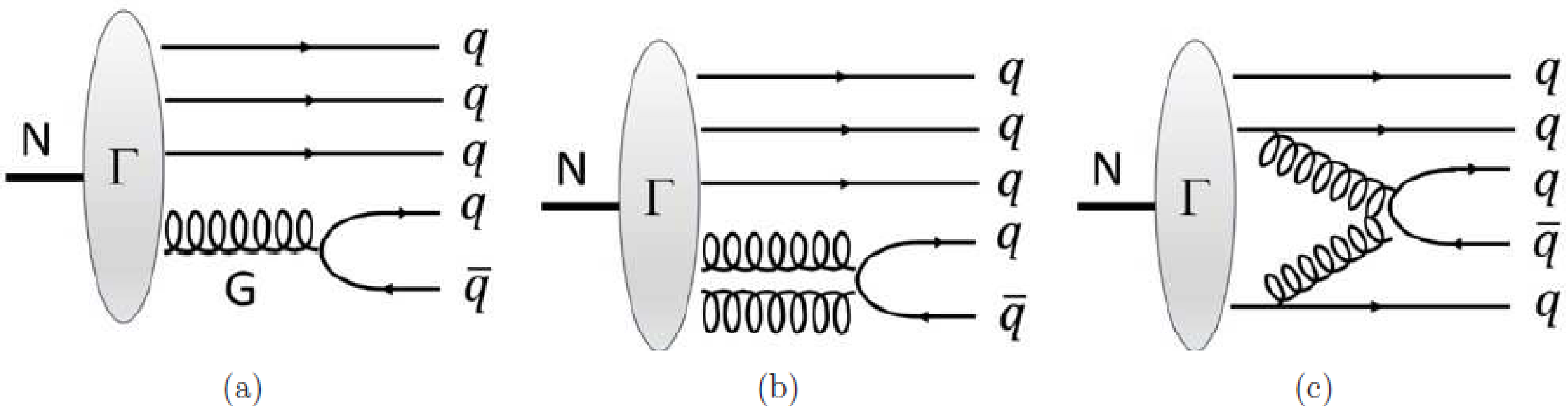
• TDIS measures F_2(**x**) structure function of pion, which is a combination of valence and sea distributions.
• The Q2-evolution of TDIS can be used to constrain the gluon distribution of pion

Search for the "intrinsic" quark sea

In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

$$| p\rangle = P_{3q} \, | uud \rangle + P_{5q} \, | uud Q\bar{Q} \rangle + \cdots\cdots$$

The "intrinsic"-charm from $| uudc\bar{c} \rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \rightarrow c\bar{c}$)



"extrinsic sea"

"intrinsic sea"

Search for the "intrinsic" quark sea

In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

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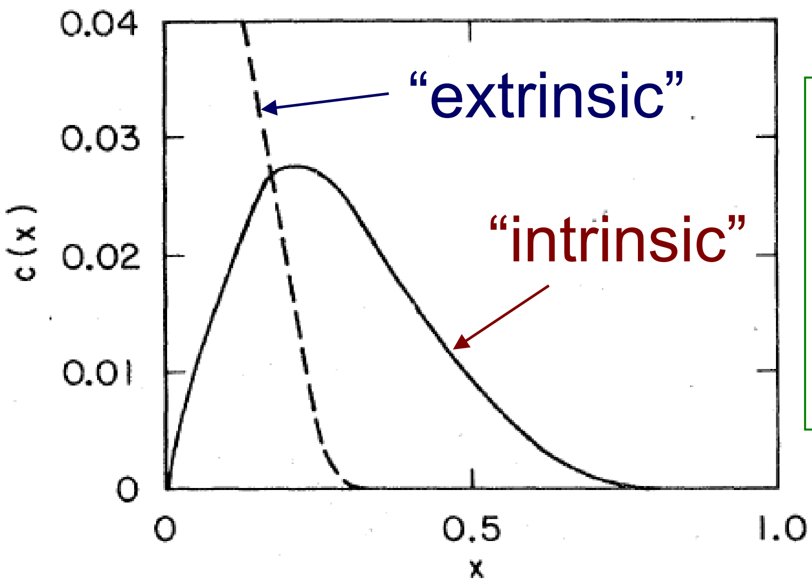
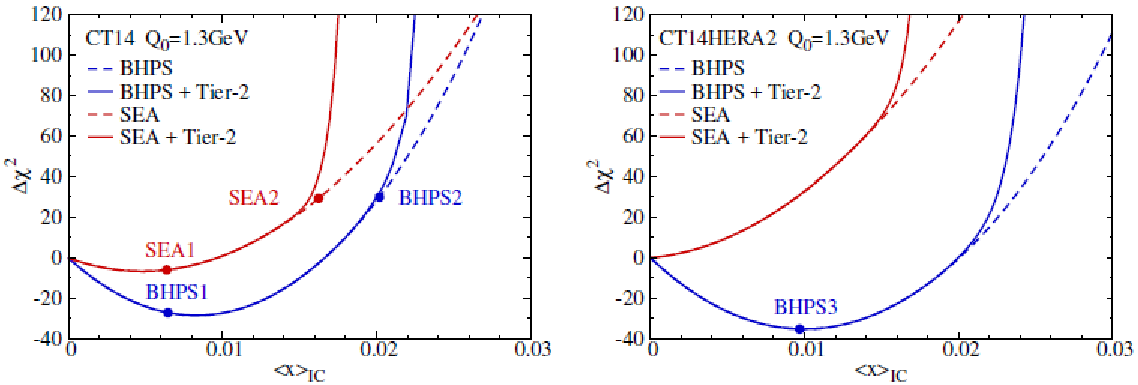


The "intrinsic charm" in $| uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

A recent global fit by CTEQ-TEA to extract intrinsic-charm (JHEP02 (2018) 059)

CT14 intrinsic charm parton distribution functions from CTEQ-TEA global analysis

Tie-Jiun Hou,[a] Sayipjamal Dulat,[b,c,d] Jun Gao,[e] Marco Guzzi,[f,g] Joey Huston,[d] Pavel Nadolsky,[a] Carl Schmidt,[d] Jan Winter,[d] Keping Xie[a] and C.-P. Yuan[d]



We see from figure 5 that large amounts of intrinsic charm are disfavored for all models under scrutiny. A mild reduction in χ^2, however, is observed for the BHPS fits, roughly at $\langle x\rangle_{\rm IC} = 1\%$, both in the CT14 and CT14HERA2 frameworks.

No conclusive evidence for intrinsic-charm (However, possible new evidence from LHC)

Search for the "intrinsic" light-quark sea

Work in collaboration with Wen-Chen Chang

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

Some tantalizing, but not conclusive, experimental evidence for intrinsic-charm so far

Are there experimental evidences for the intrinsic light-quark sea: $|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$?

$$P_{5q}^2 \sim 1/m_Q^2$$

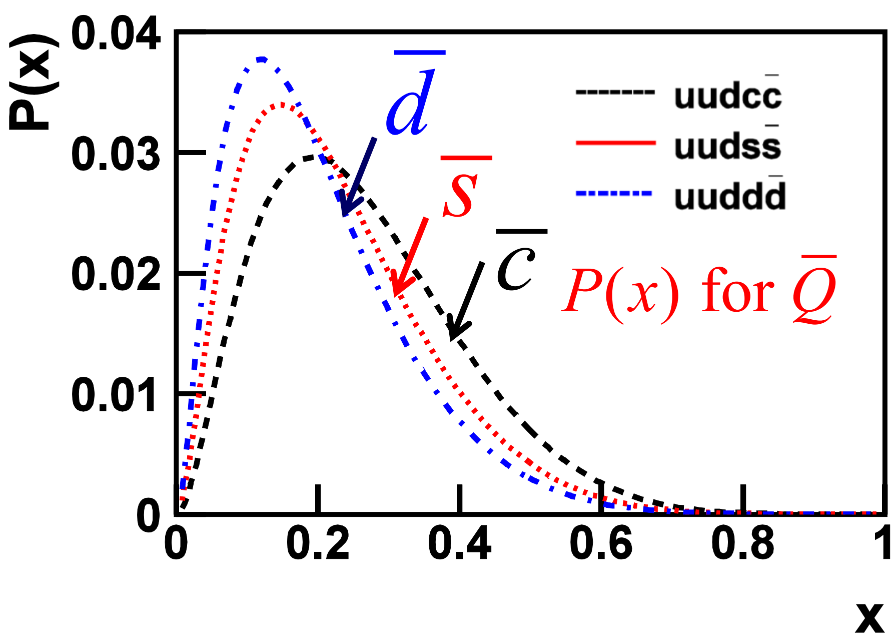
The "intrinsic" sea for lighter quarks have larger probabilities!

x-distribution for "intrinsic" light-quark sea

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

Brodsky et al. (BHPS) give the following probability for quark i (mass m_i) to carry momentum x_i

$$P(x_1,\cdots,x_5) = N_5\delta(1-\sum_{i=1}^{5}x_i)[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}$$



In the limit of large mass for quark Q (charm):

$$P(x_5) = \frac{1}{2}\tilde{N}_5 x_5^2[(1-x_5)(1+10x_5+x_5^2) - 2x_5(1+x_5)ln(1/x_5)]$$

One can calculate $P(x)$ for antiquark $\bar{Q}$ $(\bar{c},\bar{s},\bar{d})$ numerically

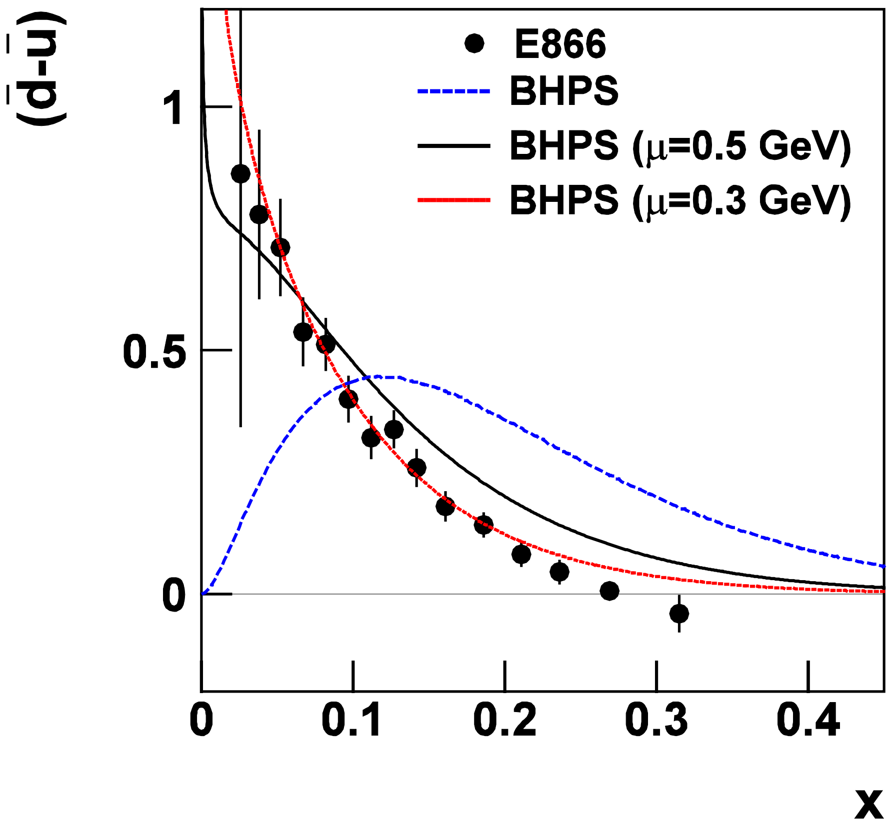
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no contributions from the "extrinsic sea"

$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \rightarrow \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$

How to measure $\bar{d}$ - $\bar{u}$?

Comparison between the $\bar{d}(x)-\bar{u}(x)$ data with the intrinsic-sea model



(W. Chang and JCP , PRL 106, 252002 (2011))

The data are in good agreement with the BHPS model after evolution from the initial scale μ to Q^2=54 GeV^2

The difference in the two 5-quark components can also be determined

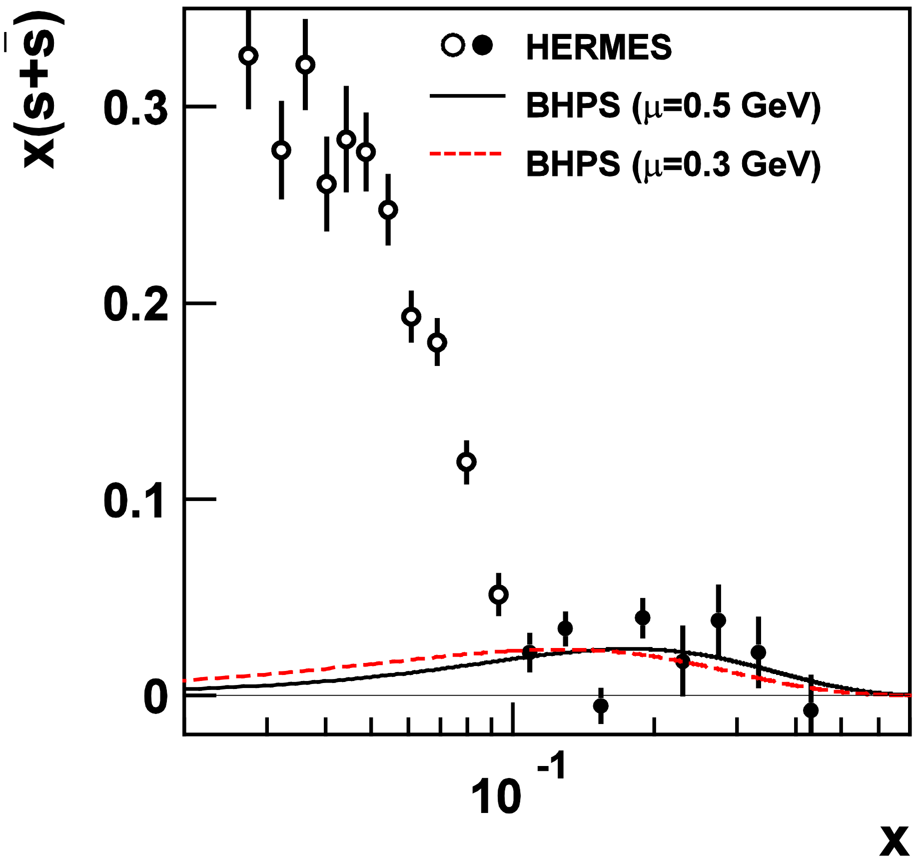
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

How to separate the "intrinsic sea" from the "extrinsic sea"?

- "Intrinsic sea" and "extrinsic sea" are expected to have different *x*-distributions
  - Intrinsic sea is "valence-like" and is more abundant at larger *x*
  - Extrinsic sea is more abundant at smaller *x*

An example is the $s(x)+\bar{s}(x)$ distribution

Comparison between the $s(x)+\bar{s}(x)$ data with the intrinsic 5-q model



$s(x)+\bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2 \rangle = 2.5\ \text{GeV}^2$

Assume $x > 0.1$ data are dominated by intrinsic sea (and $x < 0.1$ are from QCD sea)

This allows the extraction of the intrinsic sea for strange quarks

(W. Chang and JCP, PL B704, 197(2011))

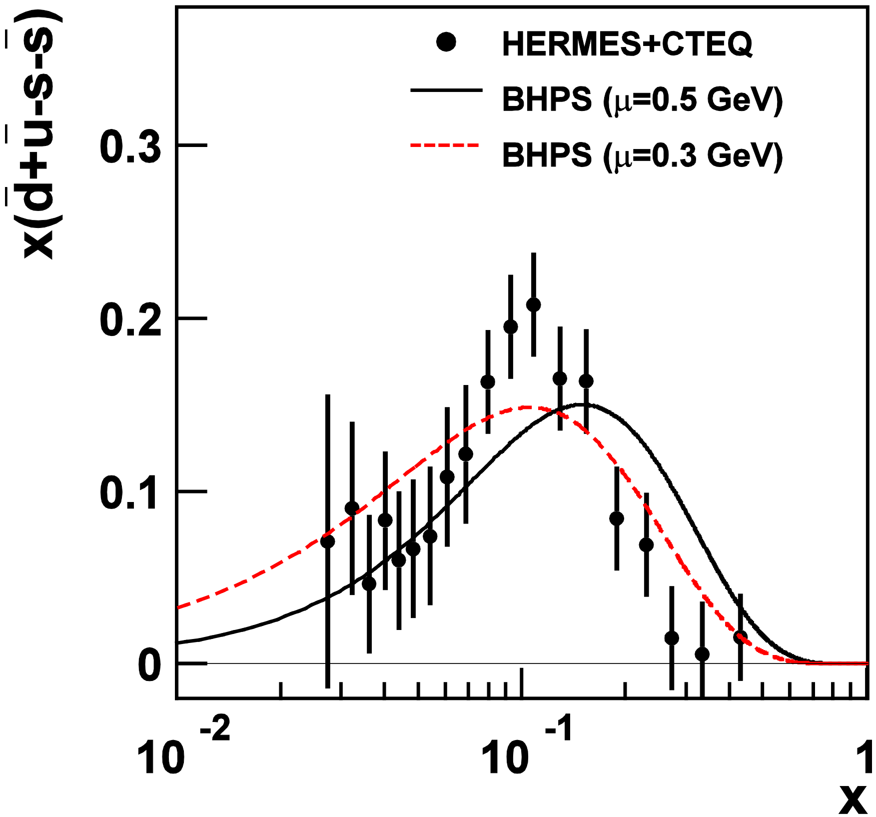
$$P_5^{uuds\bar{s}} = 0.024$$

How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no contributions from the "extrinsic sea"

$$\bar{d} + \bar{u} - s - \bar{s} \text{ has no contribution from extrinsic sea } (g \to \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$

Comparison between the $\bar{u}(x)+\bar{d}(x) - s(x)-\bar{s}(x)$ data with the intrinsic 5-q model



$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$$\bar{u}+\bar{d}-s-\bar{s}$$

$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

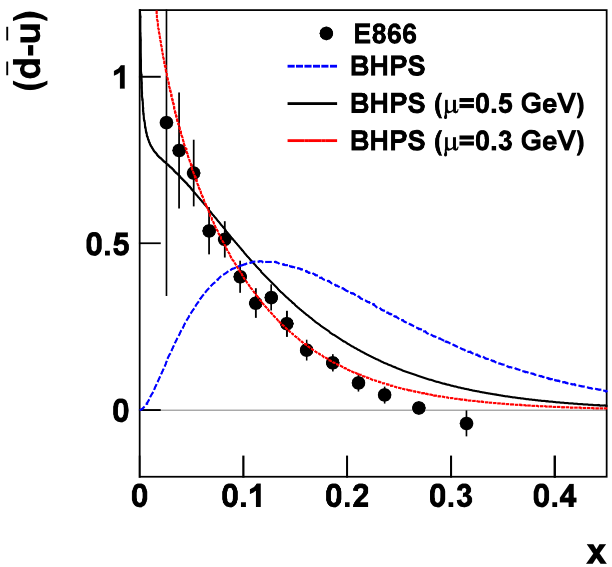
(not sensitive to extrinsic sea)

A valence-like distribution peaking at $x \sim 0.1$ is observed

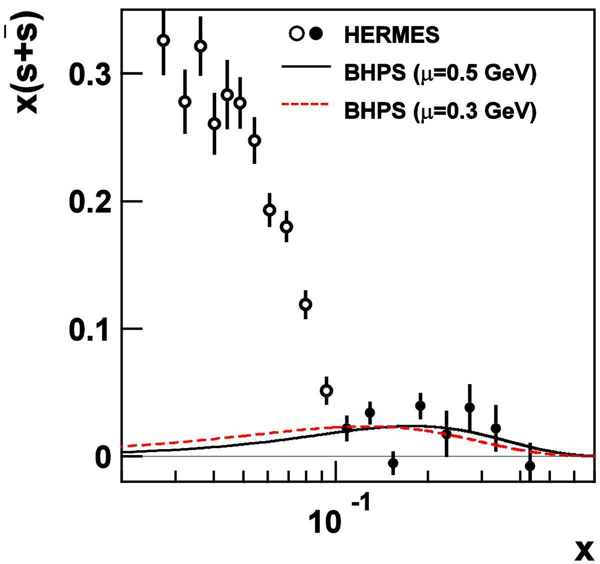
(W. Chang and JCP, PL B704, 197(2011))

$$P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}=0.314$$

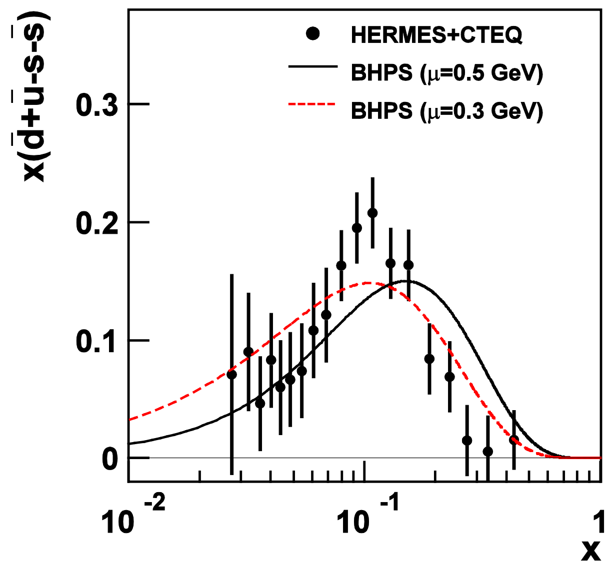
Extraction of the various five-quark components for light quarks



$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$



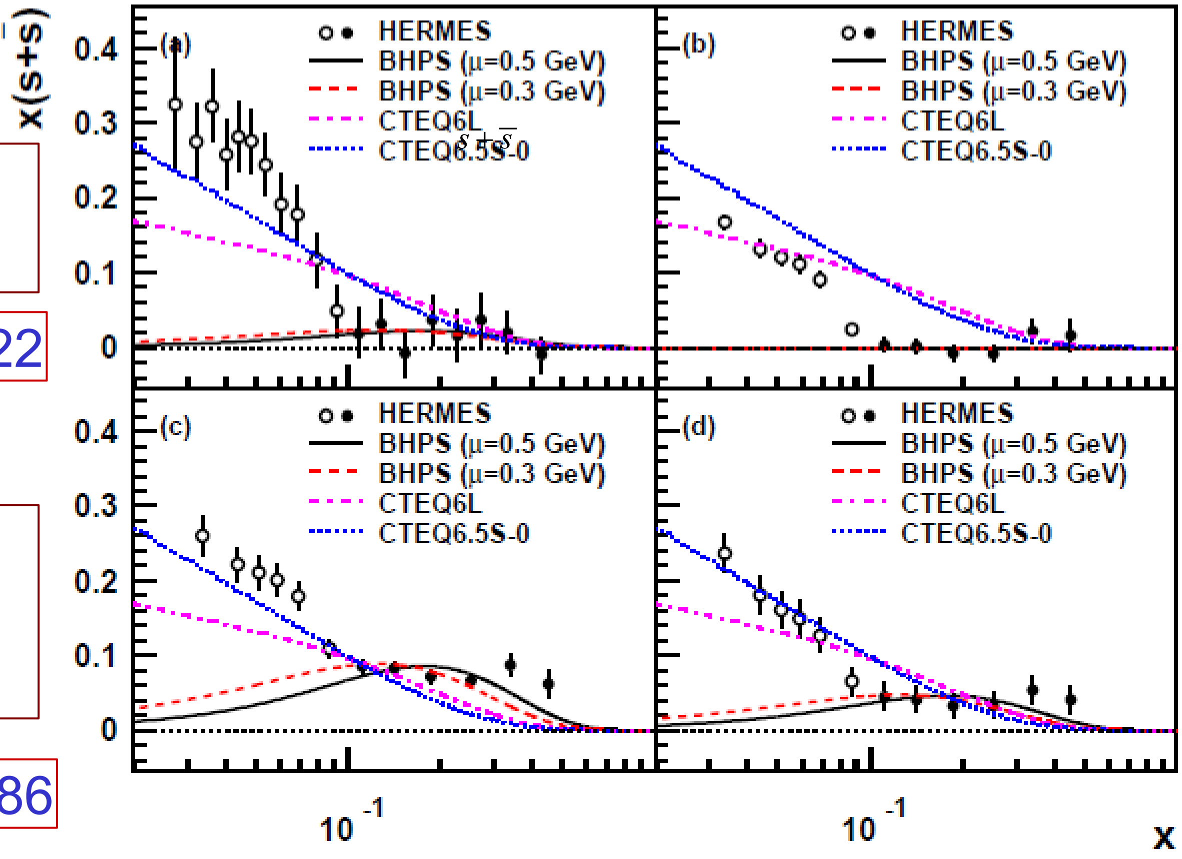
$$P_5^{uuds\bar{s}} = 0.024$$



$$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

$$P_5^{uudd\bar{d}} = 0.240; \ \ P_5^{uudu\bar{u}} = 0.122; \ \ P_5^{uuds\bar{s}} = 0.024$$

Dependence of $s+\bar{s}$ extraction on the kaon fragmentation functions



2008 HERMES

$P_5^{uuds\bar{s}}$=0.022

2014 HERMES

$P_5^{uuds\bar{s}}$=0.00

2014 HERMES DSS FF

$P_5^{uuds\bar{s}}$=0.086

2014 HERMES Intermediate FF

$P_5^{uuds\bar{s}}$=0.046

Wen-Chen Chang and JCP, PRD 92, 054020 (2015)

PHYSICAL REVIEW LETTERS **128,** 082001 (2022)

Study of Z Bosons Produced in Association with Charm in the Forward Region

R. Aaij *et al.**
(LHCb Collaboration)

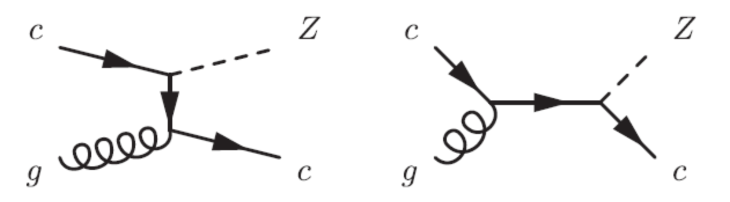
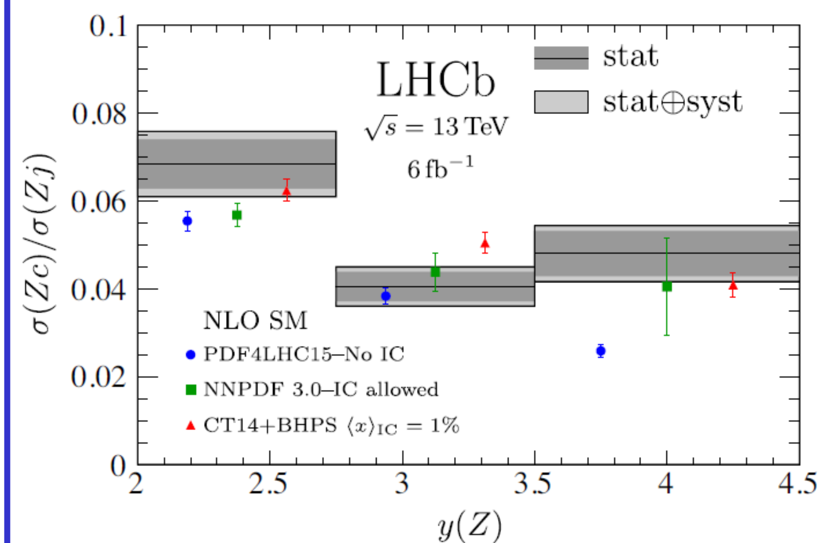


FIG. 1. Leading-order Feynman diagrams for $gc \to Zc$ production.



charm jets is determined in intervals of Z-boson rapidity in the range $2.0 < y(Z) < 4.5$. A sizable enhancement is observed in the forwardmost $y(Z)$ interval, which could be indicative of a valencelike intrinsic-charm component in the proton wave function.

"…However, conclusion about whether the proton contains valence-like intrinsic charm can only be drawn after incorporating these results into global PDF analyses"

Article

Evidence for intrinsic charm quarks in the proton

Nature 608, 483-487 (2022)

https://doi.org/10.1038/s41586-022-04998-2

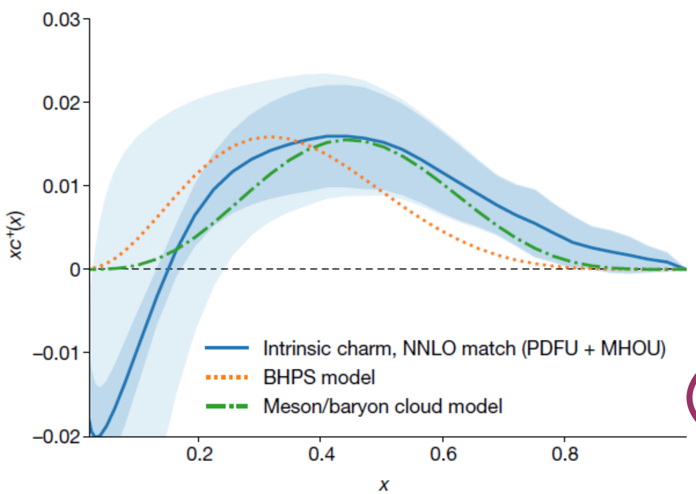
Received: 18 January 2022

Accepted: 20 June 2022

Published online: 17 August 2022

The NNPDF Collaboration*

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–antiquark pairs. Both light and heavy quarks, whose mass is respectively smaller or bigger than the mass of the proton, are revealed inside the proton in high-energy collisions. However, it is unclear whether heavy quarks also exist as a part of the proton wavefunction, which is determined by non-perturbative dynamics and accordingly unknown: so-called intrinsic heavy quarks[1]. It has been argued for a long time that the proton could have a sizable intrinsic component of the lightest heavy quark, the charm quark. Innumerable efforts to establish intrinsic charm in the proton[2] have remained inconclusive. Here we provide evidence for intrinsic charm by exploiting a high-precision determination of the quark–gluon content of the nucleon[3] based on machine learning and a large experimental dataset. We disentangle the intrinsic charm component from charm–anticharm pairs arising from high-energy radiation[4]. We establish the existence of intrinsic charm at the 3-standard-deviation level, with a momentum distribution in remarkable agreement with model predictions[1,5]. We confirm these findings by comparing them to very recent data on Z-boson production with charm jets from the Large Hadron Collider beauty (LHCb) experiment[6].



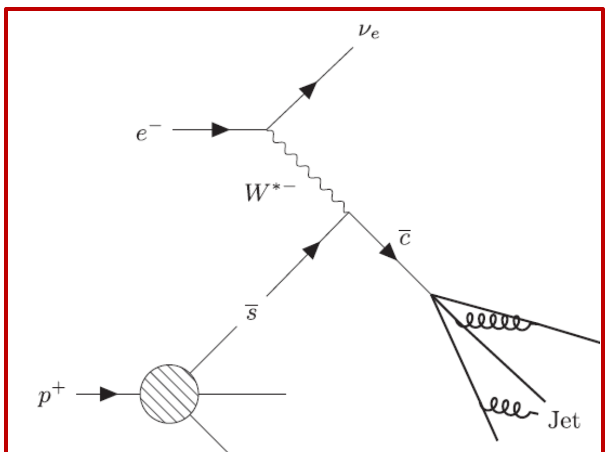
Possibility to search for intrinsic sea at EIC

- Evidences for the existence of "intrinsic" light-quark seas $(\bar{u}, \bar{d}, \bar{s})$ in the nucleons.
- Future SIDIS measurements at EIC could provide very useful new information on intrinsic strange sea.
- Clear evidence for intrinsic charm remains to be found

Charm jets as a probe for strangeness at the future Electron-Ion Collider

Miguel Arratia,[1,2] Yulia Furletova,[2] T. J. Hobbs,[3,4,5] Fredrick Olness,[3] and Stephen J. Sekula[3,*]

PHYSICAL REVIEW D **103,** 074023 (2021)



Conclusions

- EIC represents a major opportuniy for nuclear/particle physicists in Taiwan
- Building upon the experience and expertise from other previous research, the Taiwan group can readily explore related and compelling physics at this major future facility
- A staged approach with on-going and near-future projects at RHIC (sPHENIX, STAR), JLab, J-PARC, CERN (AMBER) converging on EIC would be very attractive
- Research related to EIC physics offers an excellent opportunity to form strong collaboration between experimentalists and theorists in Taiwan