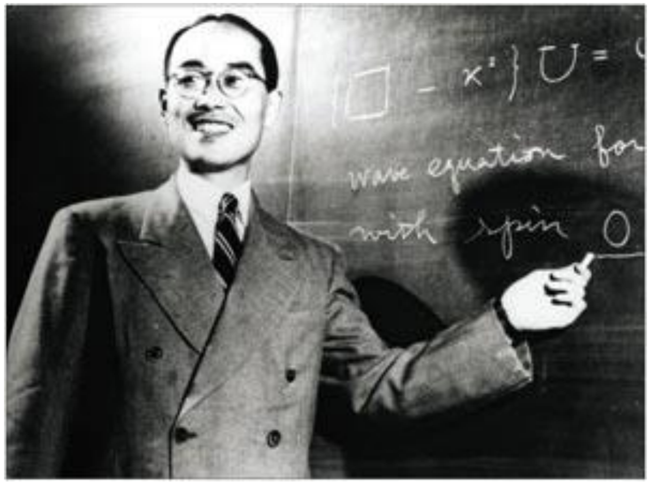
2024 ANPhA Symposium
SNCT, Huizhou, 13-16 November 2024

Pion and Kaon PDFs constrained by Drell Yan and J/Psi Production

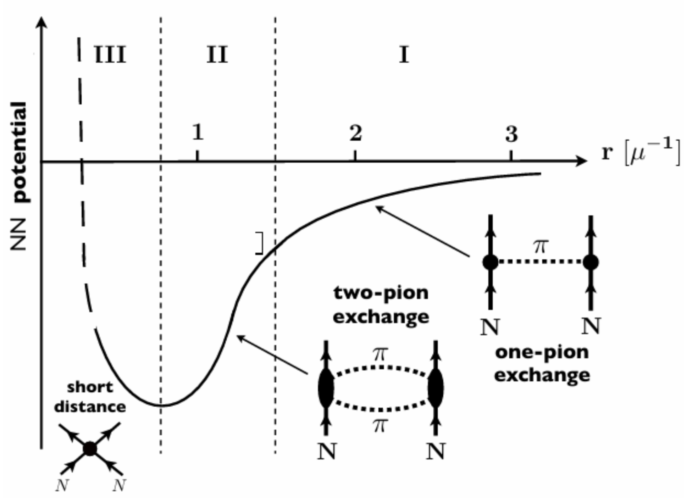
Wen-Chen Chang 章文箴

Institute of Physics, Academia Sinica

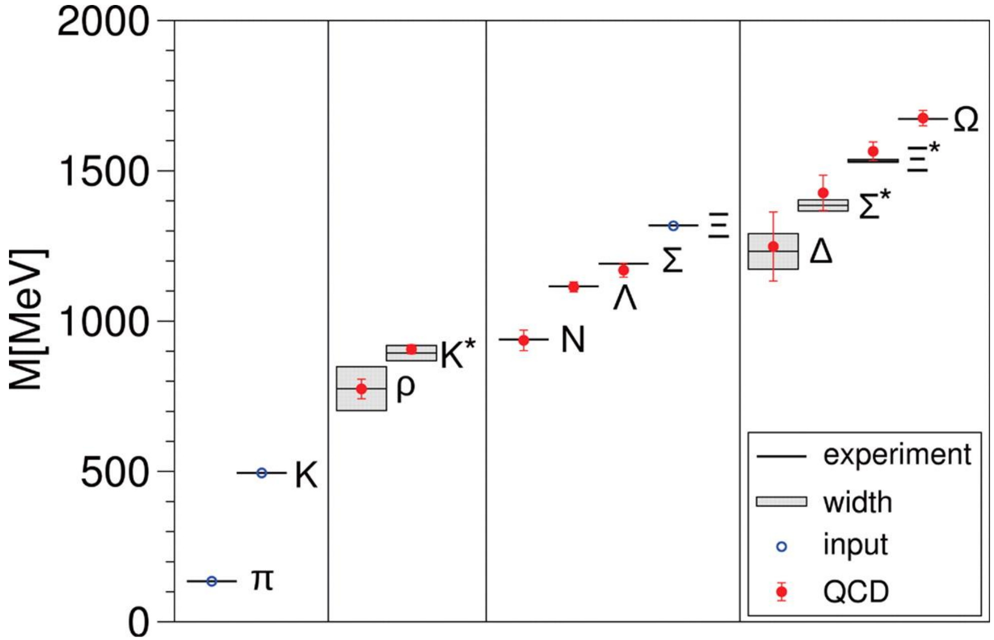
Pion/Kaon: Goldstone Bosons of Strong Interaction

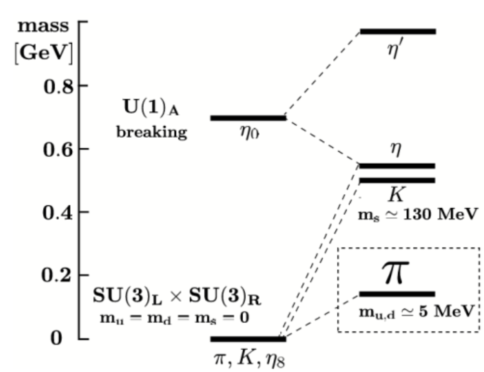


Hideki Yukawa, 1935



Science, 322, 1224 (2008)

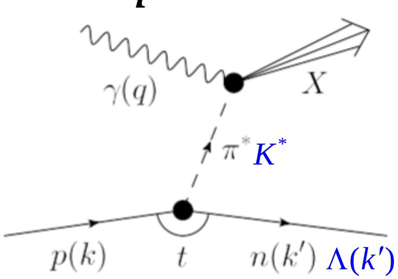




https://arxiv.org/pdf/0704.1992

Pion/Kaon PDFs

- **Drell-Yan:** $\pi, K^{\pm} p \to \mu^+\mu^- X$ (LO: sensitive to valence quarks)
  - **LO:** $\boldsymbol{q\bar{q} \to \mu^+\mu^-}$
  - NLO: $q\bar{q} \to \mu^+\mu^- G, qG \to \mu^+\mu^- q$ (large p_T)
  - NNLO: $q\bar{q}G \to \mu^+\mu^- G, qG \to \mu^+\mu^- qG, GG \to \mu^+\mu^- q\bar{q}$
- **Direct photon:** $\pi, K^{\pm} p \to \gamma X$ (LO: sensitive to gluons)
  - **LO:** $\boldsymbol{q\bar{q} \to \gamma G, qG \to \gamma q}$
- **Jpsi:** $\pi, K^{\pm} p \to J/\psi X$ (LO: sensitive to gluons)
  - **LO:** $\boldsymbol{q\bar{q} \to c\bar{c} \to J/\psi X, GG \to c\bar{c} \to J/\psi X}$
  - NLO: $q\bar{q} \to c\bar{c}G \to J/\psi X, GG \to c\bar{c}G \to J/\psi X, qG \to c\bar{c}q \to J/\psi X$
- **Leading neutron (LN) electroproduction:** Sullivan processes from a nucleon's pion cloud



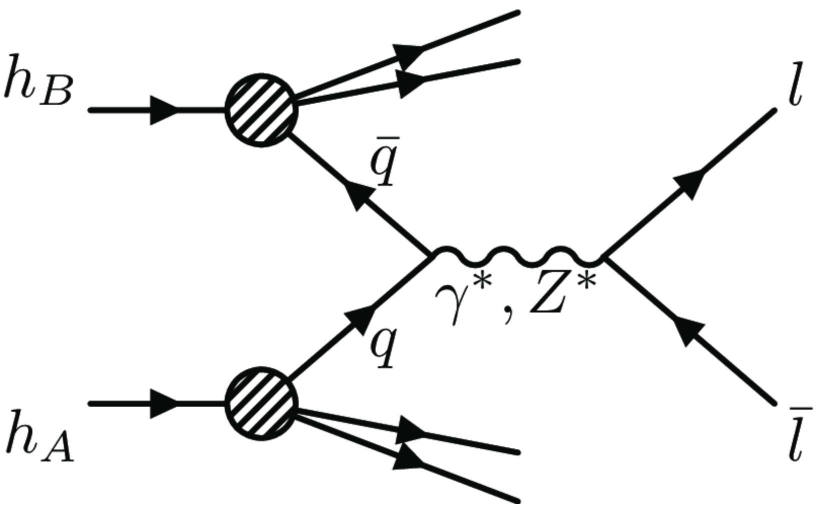
Drell-Yan Process

S.D. Drell and T.M. Yan, PRL 25 (1970) 316

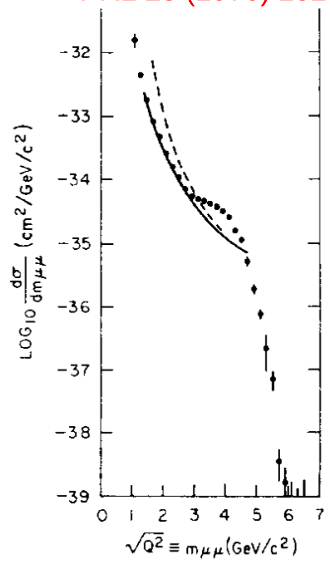
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

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

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s\to\infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s\to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



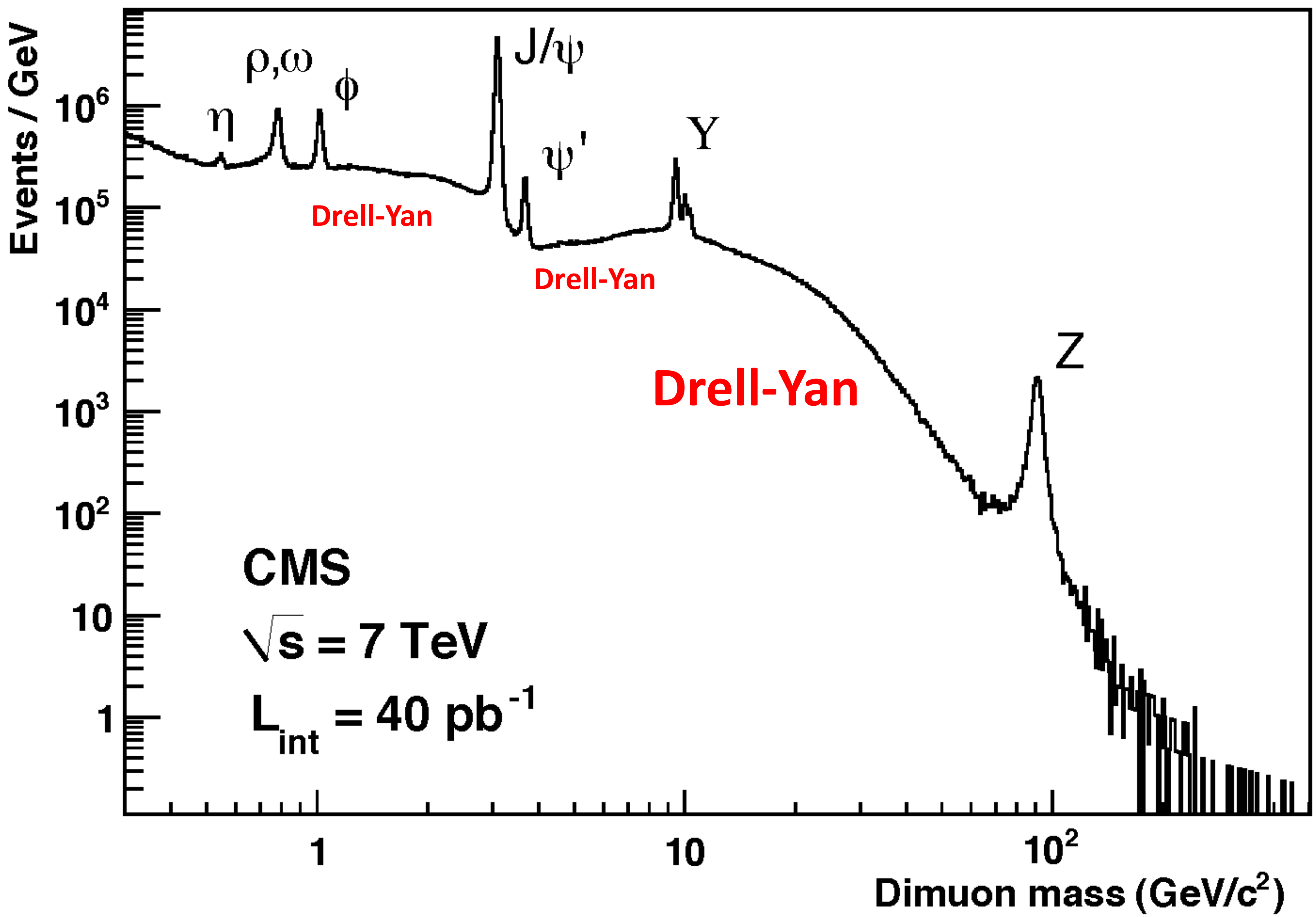
PRL 25 (1970) 1523



$$\tau = \frac{Q^2}{s} = x_1 x_2$$

$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1\int_0^1 dx_2\,\delta(x_1x_2-\tau)\sum\nolimits_a \lambda_a^{-2}F_{2a}(x_1)F_{2\bar{a}}'(x_2),$$

Dimuon Invariant Mass



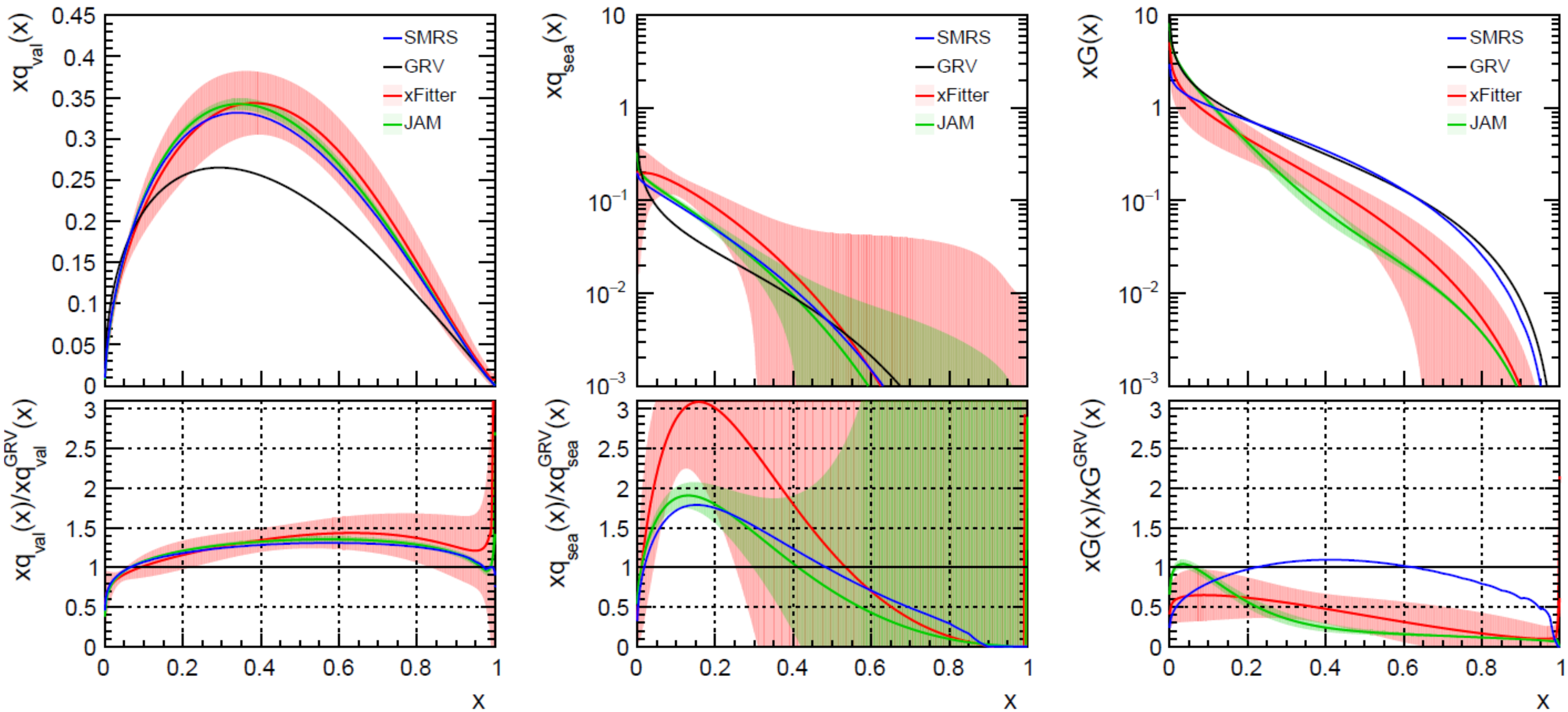
Pion PDFs (Global Analysis)

PDF	DY (xF, pT)	Direct γ	J/ψ	LN	Refs.
OW	*		*		PRD 1984
ABFKW	*	*			PLB 1989
SMRS	*	*			PRD 1992
GRV	*	*			ZPC 1992
GRS	*				EPJC 1999
JAM18	*			*	PRL 2018
BS, BBP	*				NPA 2019 PLB 2021
xFitter	*	*			PRD 2020
JAM21	*			*	PRD 2021 PRL 2021
Fanto	*	*		*	PRD 2024

Pion PDFs

PDF	$\int_0^1 x\bar{u}_{\mathrm{val}}(x)dx$	$\int_0^1 x\bar{u}_{\mathrm{sea}}(x)dx$	$\int_0^1 xG(x)dx$
OW	0.203	0.026	0.487
ABFKW	0.205	0.026	0.468
SMRS	0.245	0.026	0.394
GRV	0.199	0.020	0.513
JAM[a]	0.225 ± 0.003	0.028 ± 0.002	0.365 ± 0.016
xFitter[a]	0.228 ± 0.009	0.040 ± 0.020	0.291 ± 0.119

$Q^2 = 9.6\ \mathrm{GeV}^2$



A large discrepancy of pion PDFs!

Theoretical Models of Pion/Kaon PDFs

- **Nambu–Jona-Lasinio (NJL) Model:** PRC 94, 035201 (2016); PRD 105, 034021, (2022)
- **Chiral Constituent Quark Model:** PRD 86, 074005 (2012); PRD 97, 074015 (2018); PRD 109, 054040 (2024)
- **Dyson-Schwinger Equations (DSE):** PRD 93, 074021 (2016); PRD 93, 054029 (2018); PRL 124, 042002 (2020); EPJC 80, 1064 (2020)
- **Light-front & Holographic QCD:** PRD 101, 034024 (2020); PRD 106, 034003 (2022); PRD 107, 114023 (2023)
- **Maximum Entropy Input:** PLB 800, 135066 (2020); EPJC 81, 302 (2021)

Maximum Entropy Input

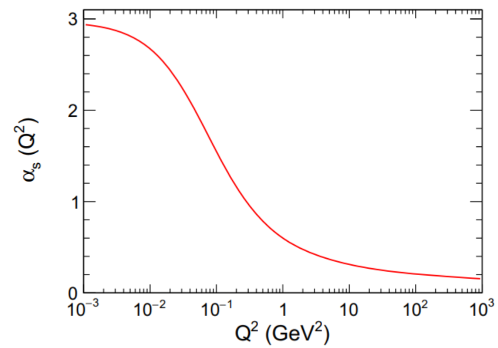
C. Han, H. Xing, X. Wang, F. Qiang, R. Wang, X. Chen, PLB 800, 135066 (2020)

C. Han, G. Xie, R. Wang, X. Chen, Eur. Phys. J. C 81:302 (2021)

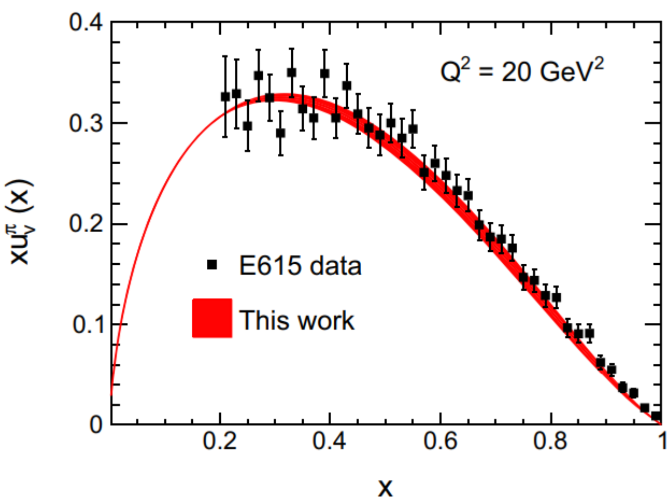
Model constructed at an intial scale Q_0

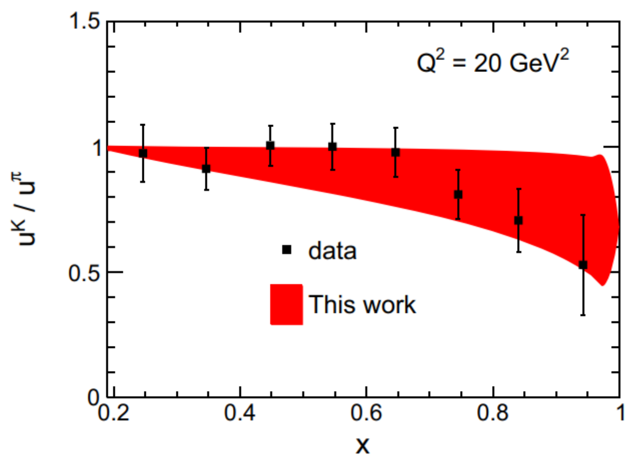
$$u_V^{\pi}(x, Q_0^2) = \bar{d}_V^{\pi}(x, Q_0^2) = 1.$$

$$u_V^{K}(x, Q_0^2) = \bar{s}_V^{K}(x, Q_0^2) = 1.$$



DGLAP + parton–parton recombination





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  - **LO:** $\boldsymbol{q\bar{q} \to c\bar{c} \to J/\psi X,\, GG \to c\bar{c} \to J/\psi X}$
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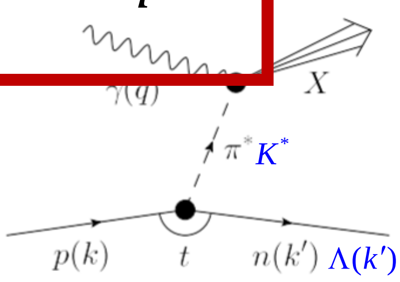
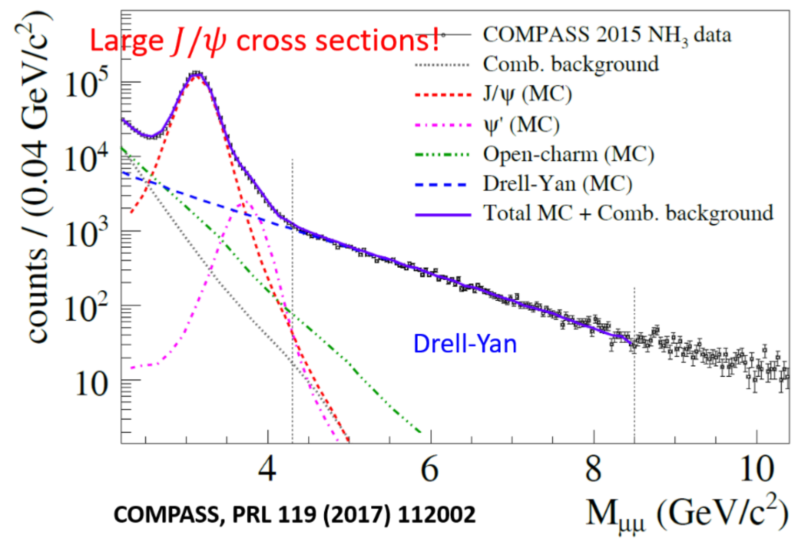


Pion-induced J/psi Production - Fixed-target Experiments

Paper	Reference	Year	Collab	E (GeV)	sqrt(s) (GeV)	Beam	Targets
Fermilab							
Branson	PRL 23, 1331	1977	Princ-Chicago	225	20.5	π-, π+, p	C, Sn
Anderson	PRL 42, 944	1979	E444	225	20.5	π-, π+, K+, p, ap	C, Cu, W
Abramov	Fermi 91-062-E	1991	E672/E706	530	31.5	π-	Be
Kartik	PRD 41, 1	1990	E672	530	31.5	π-	C, AL, Cu, Pb
Katsanevas	PRL 60, 2121	1988	E537	125	15.3	π-, ap	Be, Cu, W
Akerlof	PR D48, 5067	1993	E537	125	15.3	π-, ap	Be, Cu, W
Antoniazzi	PRD 46, 4828	1992	E705	300	23.7	π-, π+	Li
Gribushin	PR D53, 4723	1995	E672/E706	515	31.1	π-	Be
Koreshev	PRL 77, 4294	1996	E706/E672	515	31.1	π-	Be
CERN							
Abolins	PLB 82, 145	1979	WA11/Goliath	150	16.8	π-	Be
McEwen	PLB 121, 198	1983	WA11	190	18.9	π-	Be
Badier	Z.Phys. C20, 101	1983	NA3	150	16.8	π-, π+, K-, K+, p, ap	H, Pt
"	"	1983	NA3	200	19.4	π-, π+, K-, K+, p, ap	H, Pt
"	"	1983	NA3	280	22.9	π-, π+, K-, K+, p, ap	H, Pt
Corden	PLB 68, 96	1977	WA39	39.5	8.6	π-, π+, K-, K+, p, ap	Cu
Corden	PLB 96, 411	1980	WA39	39.5	8.6	π-, π+, K-, K+, p, ap	W
Corden	PLB 98, 220	1981	WA39	39.5	8.6	π-, π+, K-, K+, p, ap	p
Corden	PLB 110, 415	1982	WA40	39.5	8.6	π-, π+, K-, K+, p, ap	p, W
Alexandrov	NPB 557, 3	1999	Beatrice	350	25.6	π-	Si, C, W



COMPASS, PRL 119 (2017) 112002

LO & NLO Diagrams of $c\bar{c}$ Production

LO

NLO

A. Petrelli et al. / Nuclear Physics B 514 (1998) 245–309

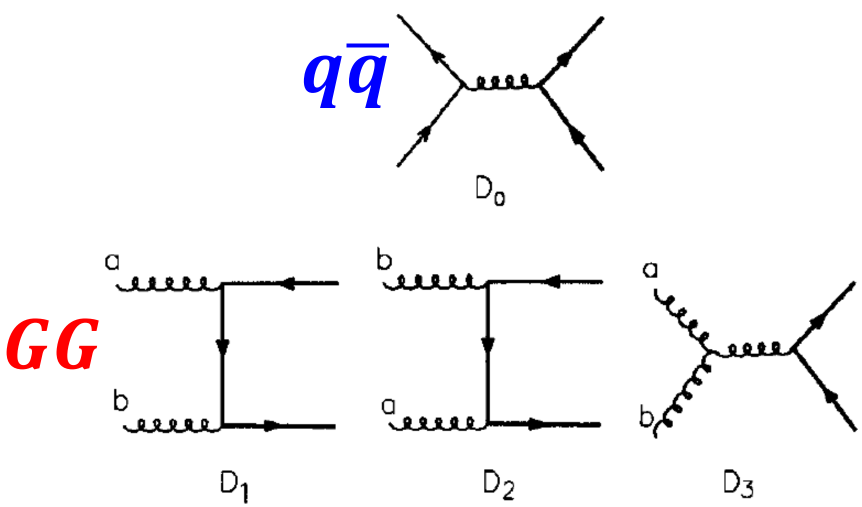


Fig. 2. Diagrams for the $q\bar{q}$ and g

A. Petrelli et al. / Nuclear Physics B 514 (1998) 245–309 287

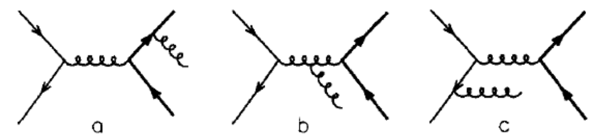
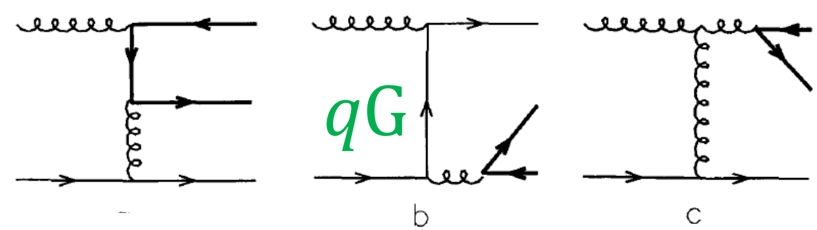
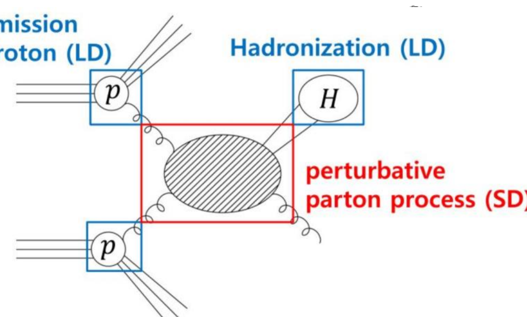


Fig. 8. Diagrams for the real corrections to the $q\bar{q}$ channels. Permutations of outgoing gluons and/or reversal of fermion lines are always implied.

286 A. Petrelli et al. / Nuclear Physics B 514 (1998) 245–309



the gq channels. Reversal of fermion lines is always implied.

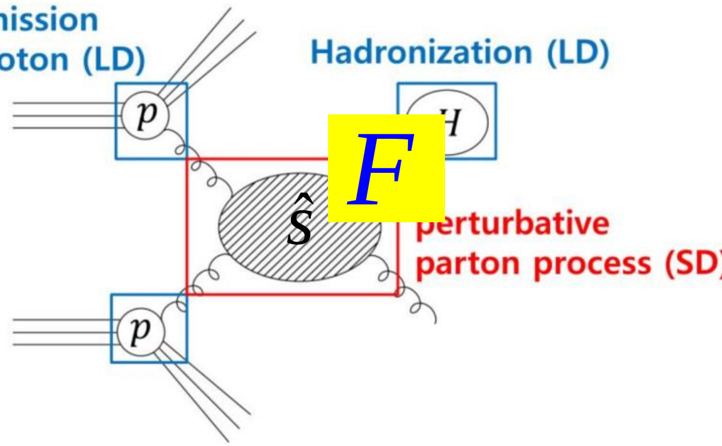


Color Evaporation Model

$$\sigma[AB \to J/\psi X]$$

$$= F \sum_{i,j} \int_{2m_c}^{2m_D} d\hat{s} \int dx_1 dx_2 \, f_{i/A}(x_1, \mu_F) f_{j/B}(x_2, \mu_F)$$

$$\hat{\sigma}[ij \to c\bar{c}X](x_1 P_A, x_2 P_B, \mu_F, \mu_R) \delta(\hat{s} - x_1 x_2 s)$$



$$\left.\frac{d\sigma}{dx_F}\right|_{J/\psi} = F \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{s\sqrt{x_F^2 + 4M_{c\bar{c}}{}^2/s}} \times f_i^{\pi}(x_1, \mu_F) f_j^N(x_2, \mu_F) \times \hat{\sigma}[ij \to c\bar{c}X](x_1 p_\pi, x_2 p_N, \mu_F, \mu_R),$$

$$x_F = 2p_L/\sqrt{s}, \qquad x_{1,2} = \frac{\sqrt{x_F^2 + 4M_{c\bar{c}}{}^2/s} \pm x_F}{2},$$

LO/NLO calculations of $\hat{\sigma}[ij \to c\bar{c}X]$:

- P.Nason, S. Dawson and R.K. Ellis, Nucl. Phys. B303 (1988) 607
- M.L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B405 (1993) 507

Color evaporation model (CEM)

Phys. Rev. D 102, 054024 (2020); arXiv: 2006.06947

PHYSICAL REVIEW D **102,** 054024 (2020)

Constraining gluon density of pions at large x by pion-induced J/ψ production

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Department of Physics, Osaka City University, Osaka 558-8585, Japan

(Received 12 June 2020; accepted 8 September 2020; published 24 September 2020)

The gluon distributions of the pion obtained from various global fits exhibit large variations among them. Within the framework of the color evaporation model, we show that the existing pion-induced J/ψ

https://agenda.infn.it/event/20446/contributions/124767/attachments/76906/99037/PietroFaccioli_Trieste2020.pdf

NRQCD

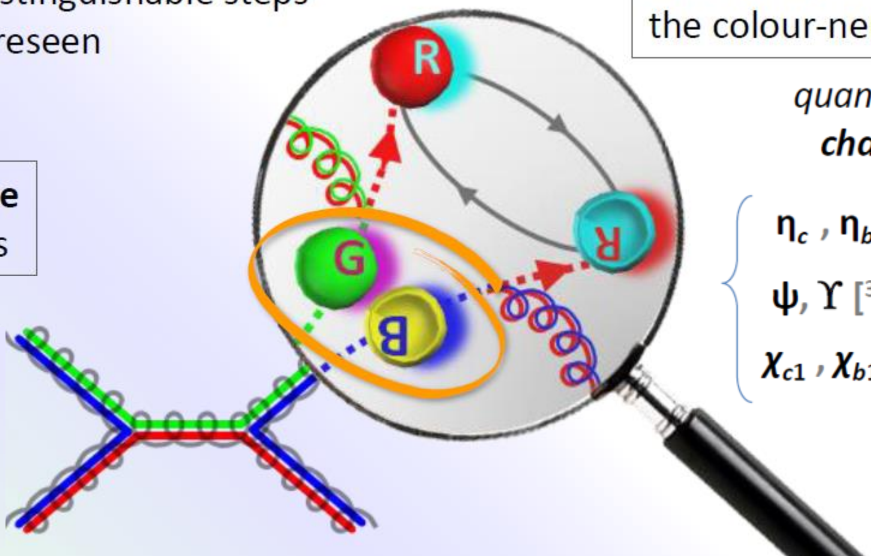
The "cascade" (*factorization*) approach of NRQCD

For **heavy** quarkonia two distinguishable steps are foreseen

1) **short-distance** partonic process

produces ***in general a coloured*** $Q\bar{Q}$ pair *of any* $^{2S+1}L_J$ *quantum numbers*

$^1S_0$ $^1S_0$ $^3S_1$ $^3P_0$ $^3P_2$ $^1D_2$ $^1P_1$ $^3S_1$ $^3P_1$ $^3P_2$ $^3D_3$ $^1P_1$ $^3D_2$ $^3D_1$ $^3P_1$



2) **long-distance** evolution to the colour-neutral bound state

quantum numbers ***change*** to final

η_c , η_b $[^1S_0]$

ψ, Υ $[^3S_1]$ χ_{c0} , χ_{b0} $[^3P_0]$

χ_{c1} , χ_{b1} $[^3P_1]$ χ_{c2} , χ_{b2} $[^3P_2]$

1) *short-distance coefficients* (**SDCs**): p_T-dependent partonic cross sections

2) *long-distance matrix elements* (**LDMEs**): constant, **fitted from data**

$$\sigma(A + B \to \mathcal{Q} + X) = \sum_{S,\,L,\,C} \underbrace{\mathcal{S}\{A + B \to (Q\bar{Q})_C[^{2S+1}L_J] + X\}}_{\text{SDCs}} \cdot \underbrace{\mathcal{L}\{(Q\bar{Q})_C[^{2S+1}L_J] \to \mathcal{Q}\}}_{\text{LDMEs}}$$

$Q\bar{Q}$ **angular momentum** and **colour** configurations

Non-relativistic QCD model (NRQCD)

Chin.J.Phys. 73 (2021) 13; arXiv: 2103.11660

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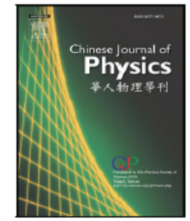

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NRQCD analysis of charmonium production with pion and proton beams at fixed-target energies

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[a] *Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[b] *Department of Physics, National Central University, 300 Jhongda Road, Jhongli 32001, Taiwan*
[c] *Department of Physics, National Kaohsiung Normal University, Kaohsiung County 824, Taiwan*
[d] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[e] *IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[f] *Department of Physics, Osaka City University, Osaka 558-8585, Japan*

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Color-octet matrix elements
Gluon

ABSTRACT

We present an analysis of hadroproduction of J/ψ and $\psi(2S)$ at fixed-target energies in the framework of non-relativistic QCD (NRQCD). Using both pion- and proton-induced data, a new determination of the color-octet long-distance matrix elements (LDMEs) is obtained. Compared with previous results, the contributions from the $q\bar{q}$ and color-octet processes are significantly enhanced, especially at lower energies. A good agreement between the pion-induced J/ψ production data and NRQCD calculations using the newly obtained LDMEs is achieved. We find that the pion-induced charmonium production data are sensitive to the gluon density of pions, and favor pion PDFs with relatively large gluon contents at large x.

Non-relativistic QCD model (NRQCD)

Phys. Rev. D 107, 056008 (2023); arXiv: 2209.04072

PHYSICAL REVIEW D **107,** 056008 (2023)

Fixed-target charmonium production and pion parton distributions

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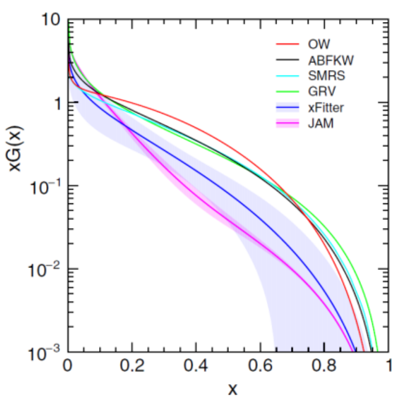
[1]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[2]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[3]*IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[4]*Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka Metropolitan University, Osaka 558-8585, Japan*

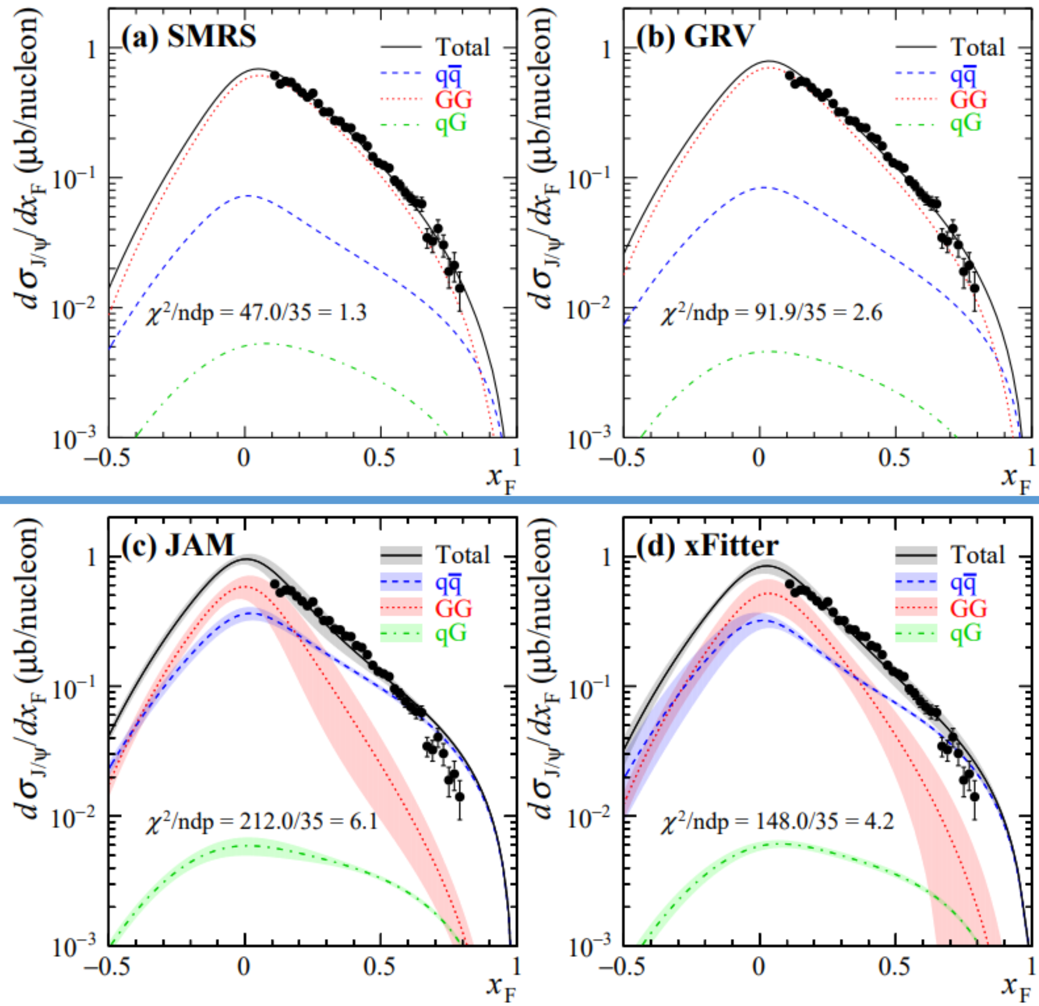
(Received 8 September 2022; accepted 31 January 2023; published 7 March 2023)

We investigate how charmonium hadroproduction at fixed-target energies can be used to constrain the gluon distribution in pions. Using nonrelativistic QCD (NRQCD) formulation, the J/ψ and $\psi(2S)$ cross sections as a function of longitudinal momentum fraction x_F from pions and protons colliding with light targets, as well as the $\psi(2S)$ to J/ψ cross section ratios, are included in the analysis. The color-octet long-distance matrix elements are found to have a pronounced dependence on the pion parton distribution functions (PDFs). This study shows that the x_F differential cross sections of pion-induced charmonium production impose strong constraints on the pion's quark and gluon PDFs. In particular, the pion PDFs with larger gluon densities provide a significantly better description of the data. It is also found that the production of the $\psi(2S)$ state is associated with a larger quark-antiquark contribution, compared with J/ψ.

Data vs. NRQCD

[$\pi^- + Be \rightarrow Jpsi + X$ at 515 GeV, PRD 53, 4723 (1996)]





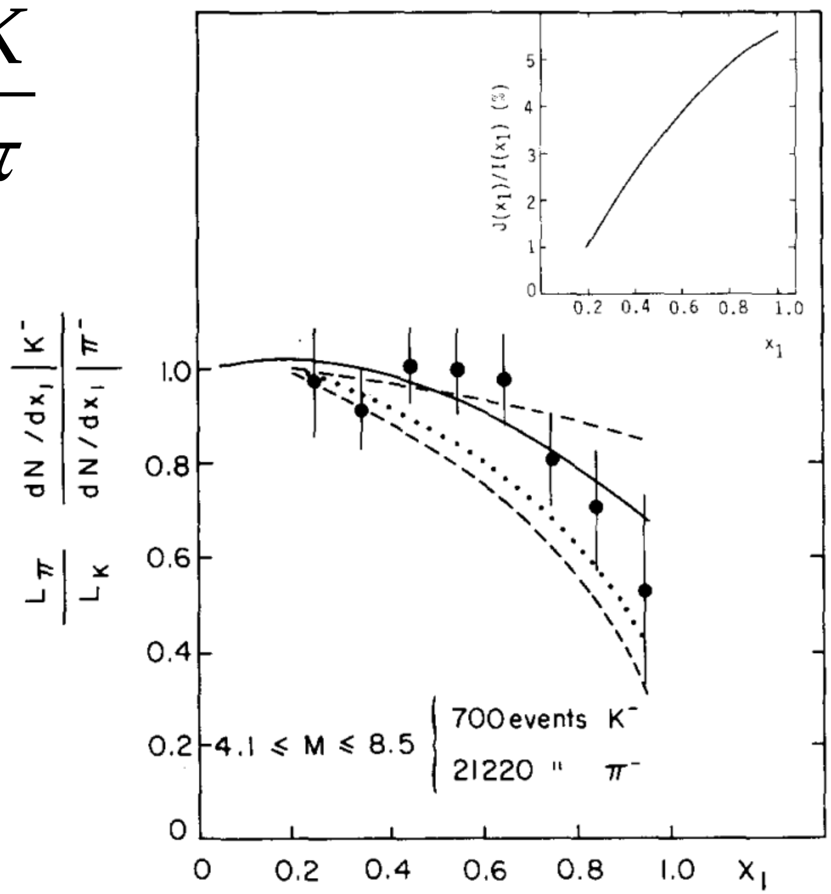
Data favor SMRS and GRV PDFs with larger gluon densities at x > 0.1.

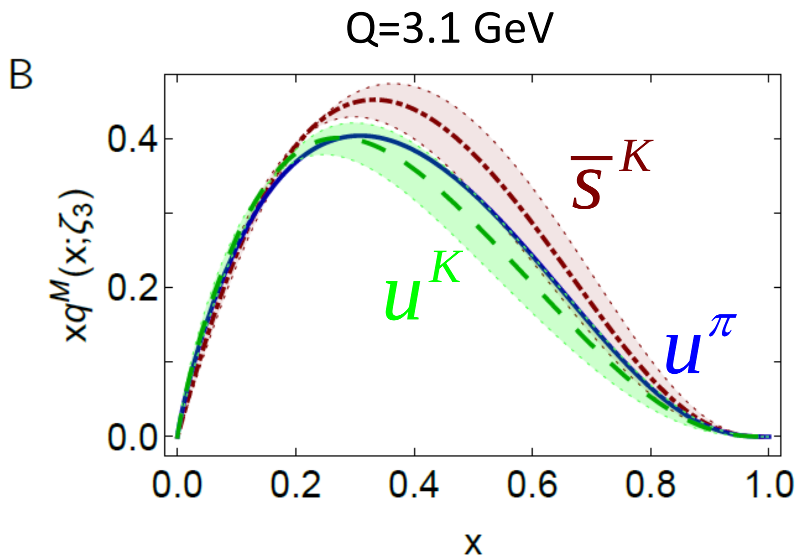
Kaon/Pion Drell-Yan Ratios

NA10: J. Badier et al., Phys. Lett. B 93, 354 (1980)

$$\frac{\sigma^{DY}(K^-)}{\sigma^{DY}(\pi^-)}(x_F) = \frac{\bar{u}^K(x_1)u^N(x_2)}{\bar{u}^\pi(x_1)u^N(x_2)} = \frac{\bar{u}^K}{\bar{u}^\pi}(x_1)$$

$$\frac{K}{\pi}$$

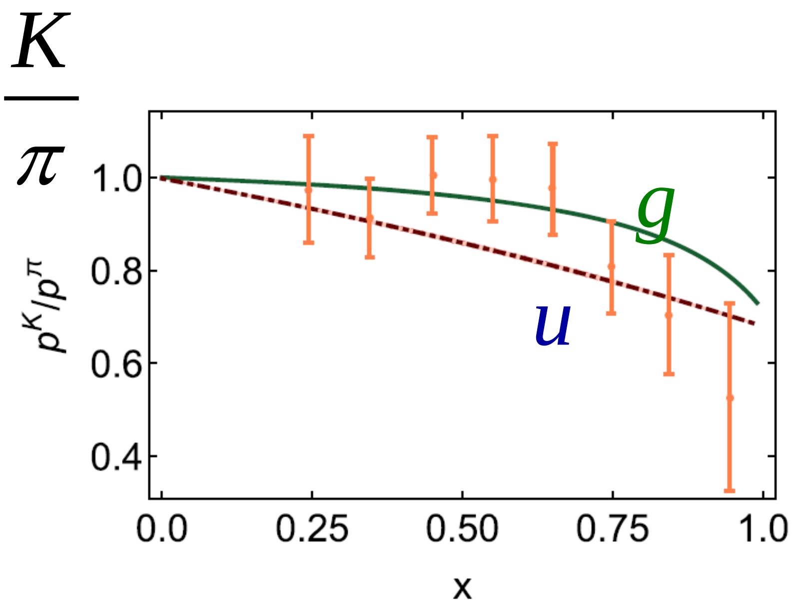




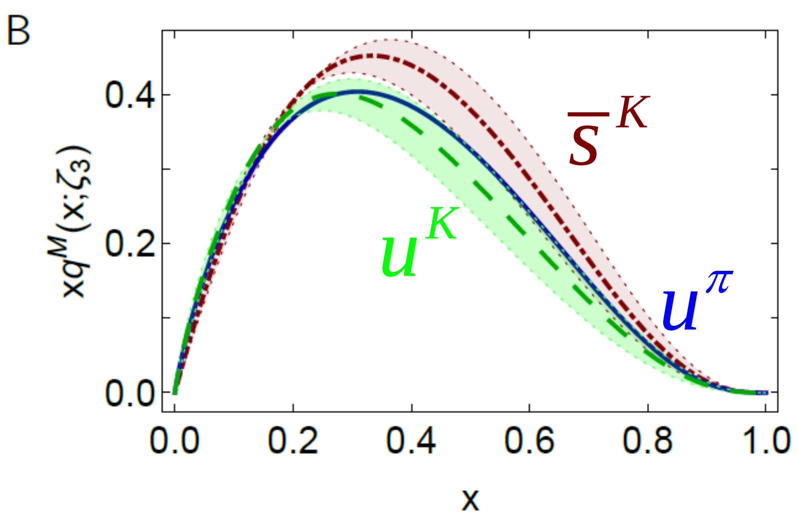
The $\bar{u}$ distribution of kaon is softer than pion's.

Kaon PDFs:
Dyson-Schwinger Equation (DSE)

Z.-F. Cui, M. Ding, F. Gao, K. Raya, D. Binosi, L. Chang, C. D. Roberts, J. Rodríguez-Quintero & S. M. Schmidt, Eur. Phys. J. C (2020) 80:1064



Q=3.1 GeV

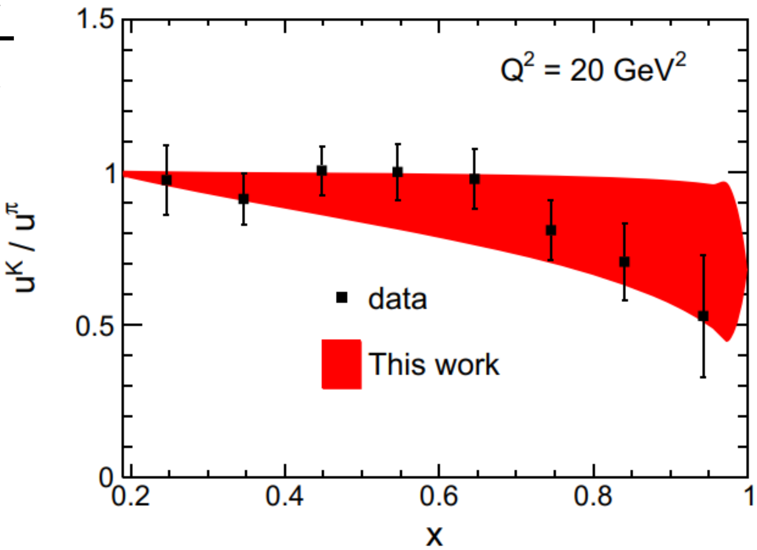


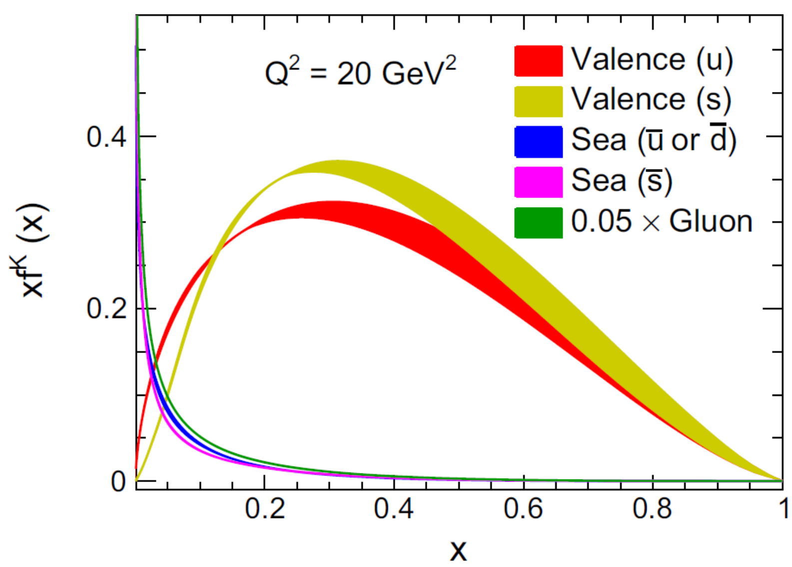
$$\langle x[2u^\pi(x;\zeta_3) + g^\pi(x;\zeta_3) + S^\pi(x;\zeta_3)]\rangle = 1$$

Kaon PDFs:
Maximum Entropy Input

C. Han, G. Xie, R. Wang, X. Chen, Eur. Phys. J. C 81:302 (2021)

$$\frac{K}{\pi}$$





Kaon PDFs
PLB 855,138820, (2024); arXiv: 2402.02860

Phys. Lett. B 855 (2024) 138820

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PHYSICS LETTERS B

Letter

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Constraining kaon PDFs from Drell-Yan and J/ψ production

Wen-Chen Chang [a,*], Jen-Chieh Peng [b,c], Stephane Platchkov [d], Takahiro Sawada [e]

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[b] Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[c] Department of Physics, National Central University, Chung-Li, 32001, Taiwan
[d] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
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A R T I C L E   I N F O

Editor: H. Gao

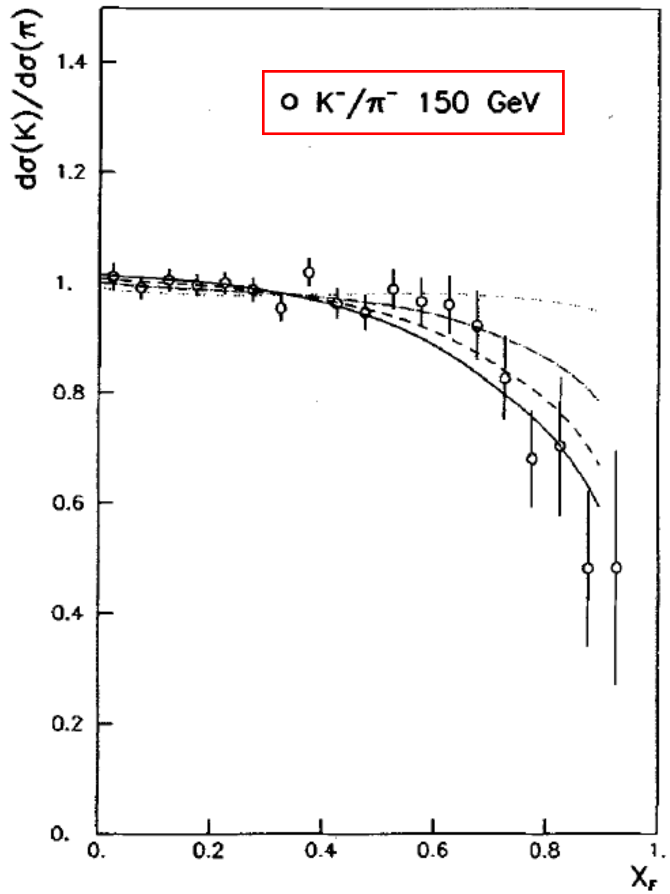
A B S T R A C T

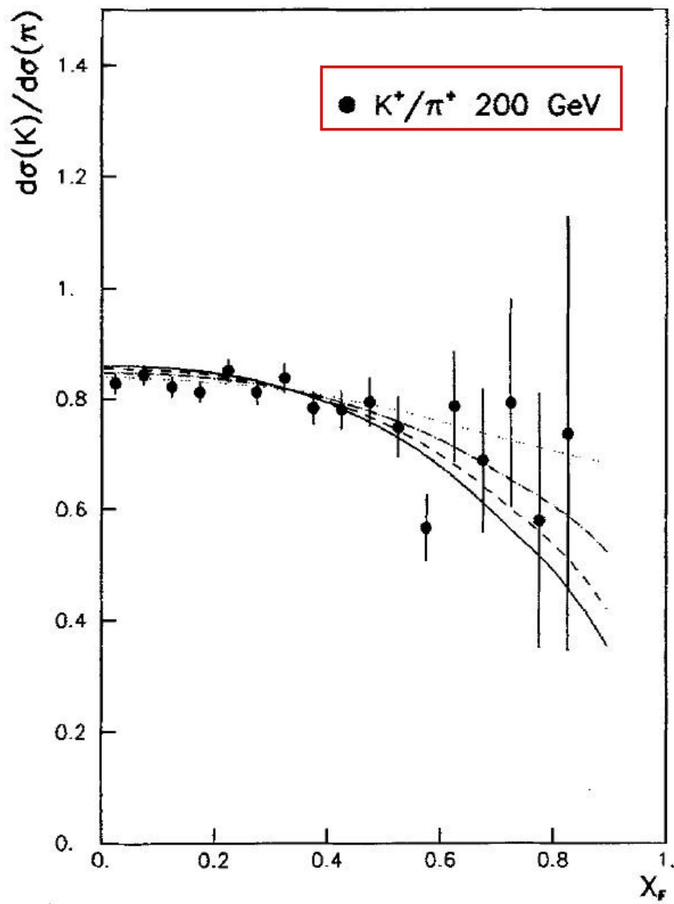
The kaon parton distribution functions (PDFs) are poorly known due to paucity of kaon-induced Drell-Yan data. Nevertheless, these Drell-Yan data suggest a softer valence u quark distribution of the kaon compared to that of the pion. We discuss the opportunity to constrain the kaon PDFs utilizing the existing kaon-induced J/ψ production data. We compare the K^-/π^- and K^+/π^+ cross-section ratio data with calculations based on two global-fit parametrizations and two recent theoretical predictions for the kaon and pion PDFs, and test the results with two quarkonium production models. The K^-/π^- cross-section ratio for J/ψ production provides independent evidence of different valence quark distributions in pion and kaon. The K^+/π^+ J/ψ data are found to be sensitive to the gluon distribution in kaon. We show that these J/ψ production data provide valuable constraints for evaluating the adequacy of currently available sets of kaon PDFs.

Kaon/Pion Jpsi Ratios

NA3: Z. Phys. C 20, 101 (1983)

$$\frac{\sigma^{Jpsi}(K^-)}{\sigma^{Jpsi}(\pi^-)}(x_F) = \frac{\sigma(\bar{u}^K(x_1)u^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(\bar{u}^\pi(x_1)u^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))} \quad \frac{\sigma^{Jpsi}(K^+)}{\sigma^{Jpsi}(\pi^+)}(x_F) = \frac{\sigma(u^K(x_1)\bar{u}^N(x_2)) + \sigma(\bar{s}^K(x_1)s^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(u^\pi(x_1)\bar{u}^N(x_2)) + \sigma(\bar{d}^\pi(x_1)d^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))}$$

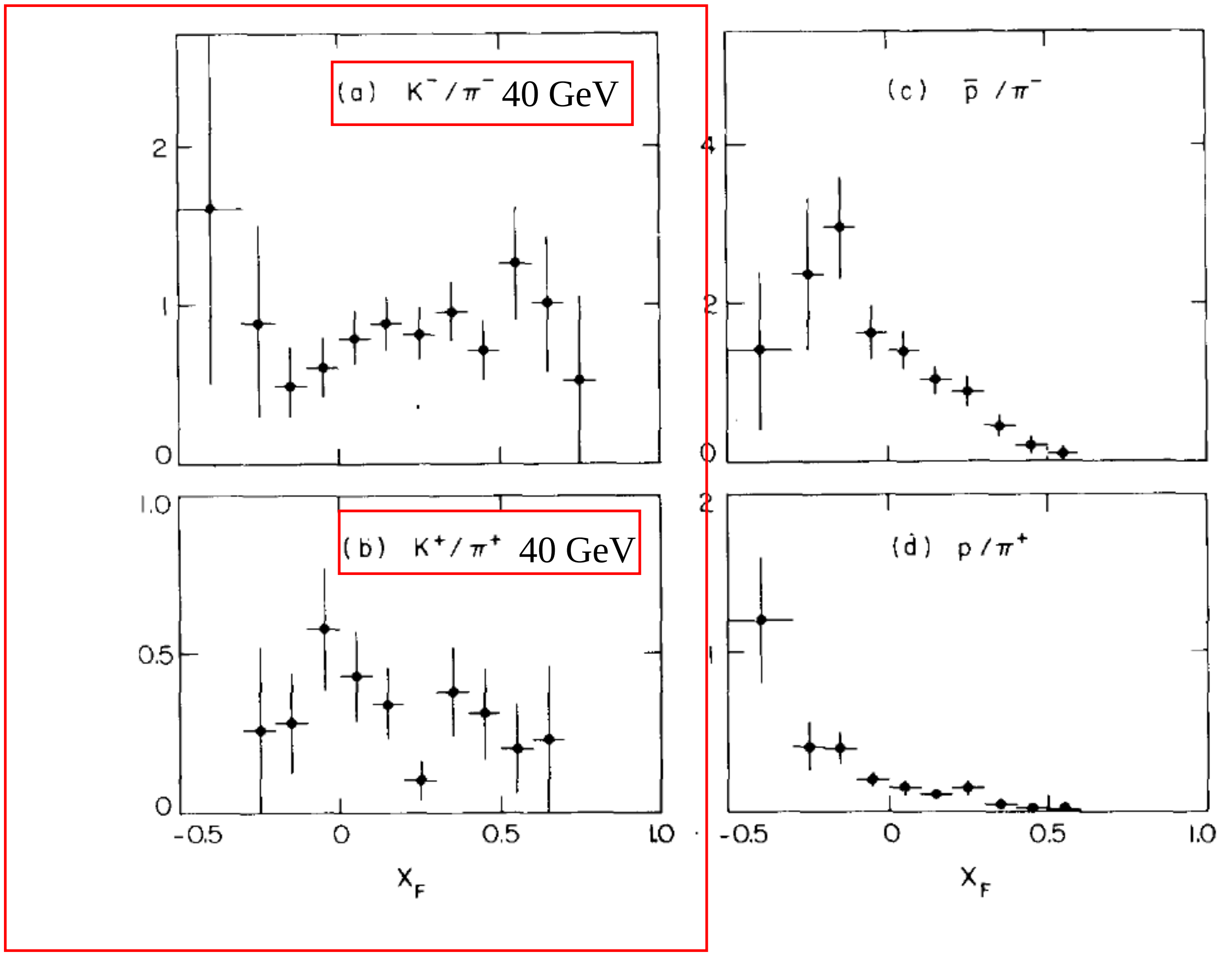




Kaon/Pion Jpsi Ratios

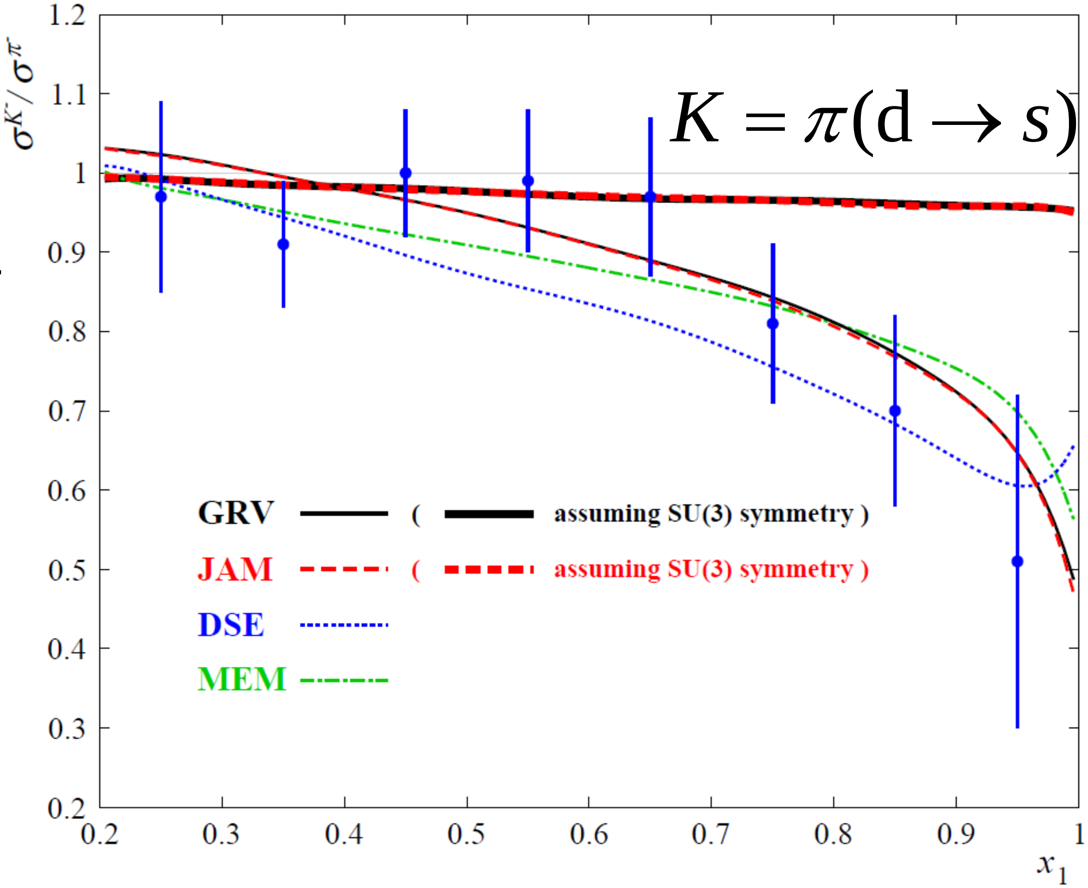
WA39: Phys. Lett. B 96, 411 (1980)

$$\frac{\sigma^{Jpsi}(K^-)}{\sigma^{Jpsi}(\pi^-)}(x_F) = \frac{\sigma(\bar{u}^K(x_1)u^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(\bar{u}^\pi(x_1)u^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))} \quad \frac{\sigma^{Jpsi}(K^+)}{\sigma^{Jpsi}(\pi^+)}(x_F) = \frac{\sigma(u^K(x_1)\bar{u}^N(x_2)) + \sigma(\bar{s}^K(x_1)s^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(u^\pi(x_1)\bar{u}^N(x_2)) + \sigma(\bar{d}^\pi(x_1)d^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))}$$



K/pion Drell-Yan Ratios

$$\frac{K}{\pi}$$

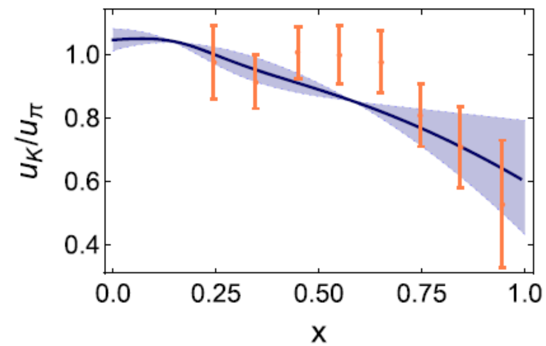


GRV, JAM: GRS ansatz

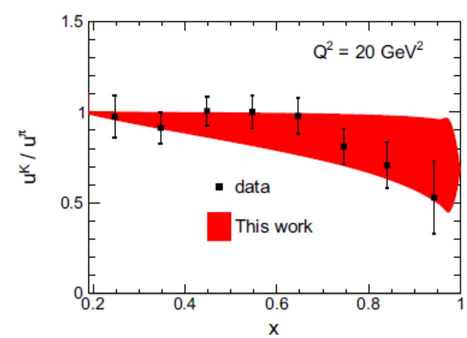
$$\bar{u}_v^K(x) = N_u \bar{u}_v^\pi(x)(1-x)^{0.17}$$

$$s_v^K(x) = 2\bar{u}_v^\pi(x) - \bar{u}_v^K(x)$$

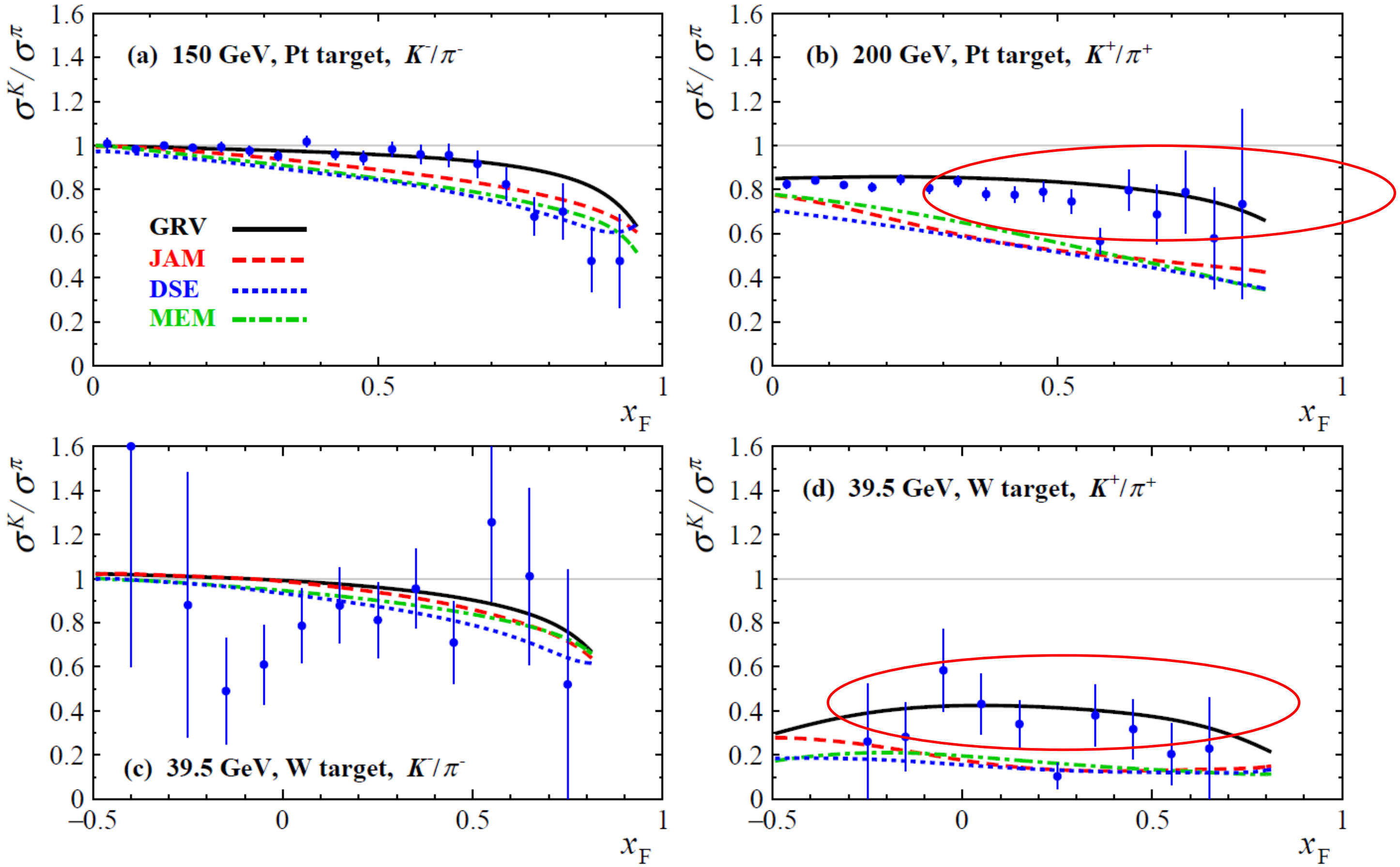
DSE: Eur. Phys. J. C (2020) 80:1064



MEM: Eur. Phys. J. C (2021) 81:302

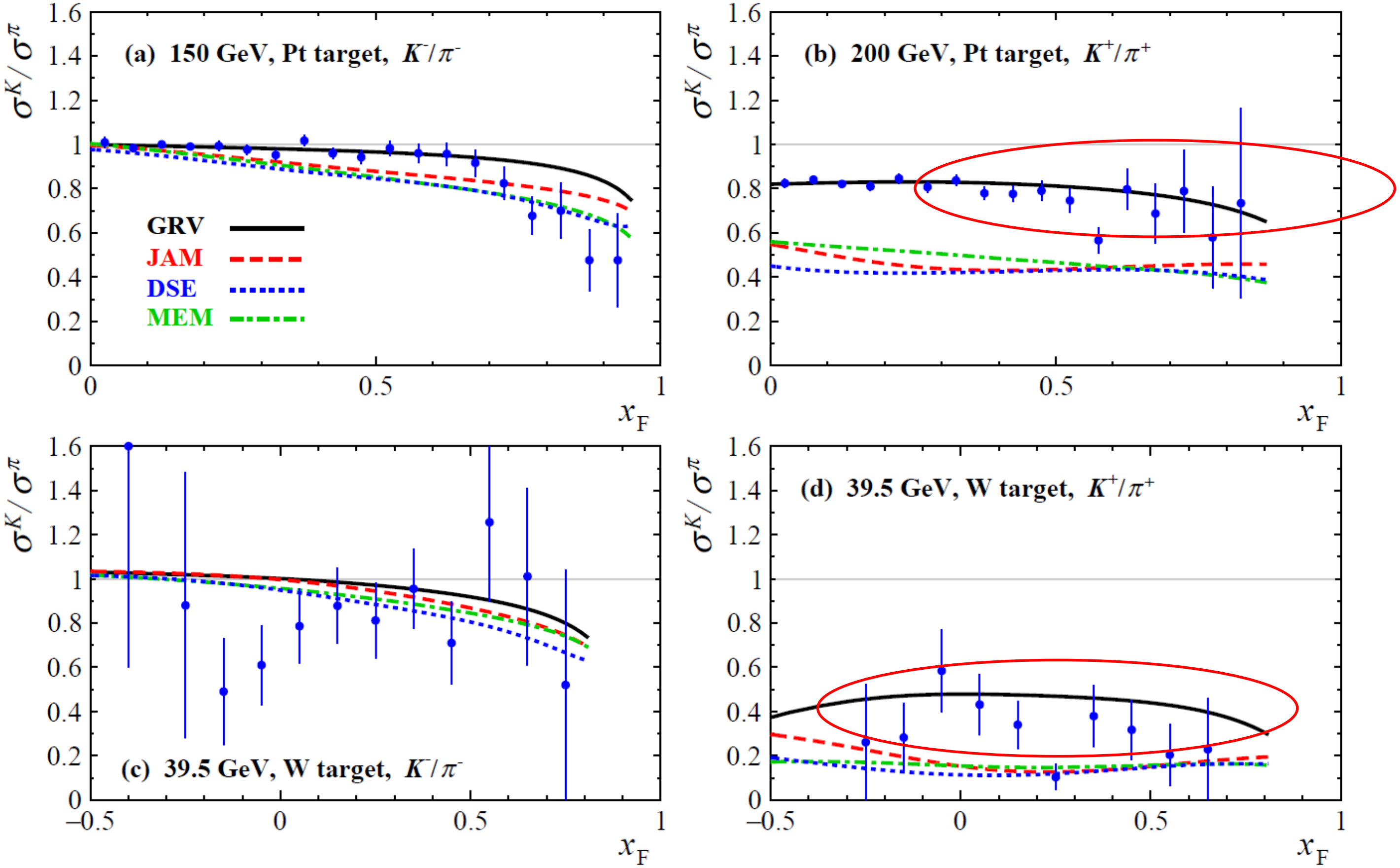


K/pion Jpsi Ratios: CEM



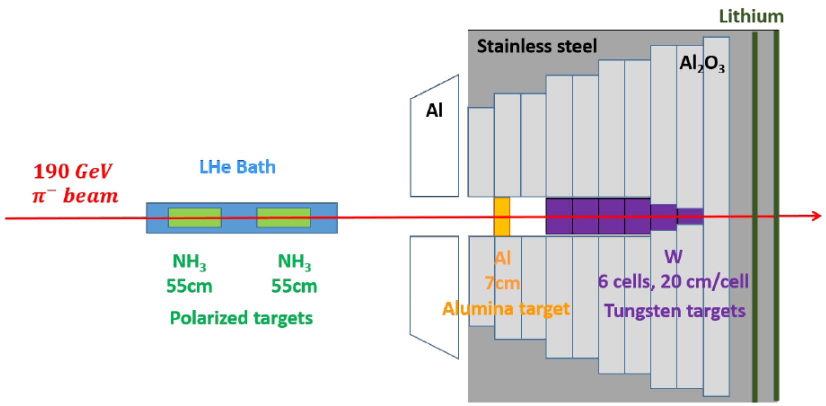
Data favor GRV PDFs with larger gluon densities at x > 0.1.

K/pion Jpsi Ratios: NRQCD



Data favor GRV PDFs with larger gluon densities at x > 0.1.

COMPASS
: π^--induced DY/Jpsi

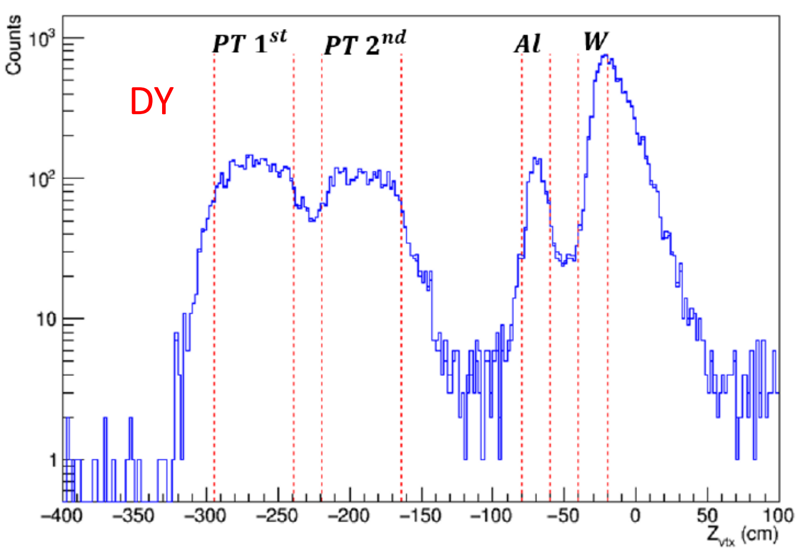


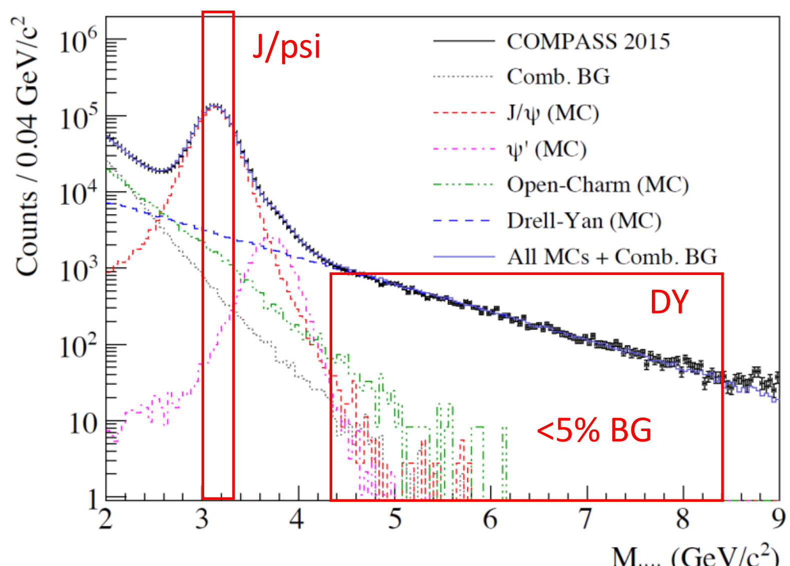
$$\pi^- + p \to \mu + \mu^- + X$$

π^- beam | NH_3, Al, W targets | *Dimuon events* | *Hadron absorber*

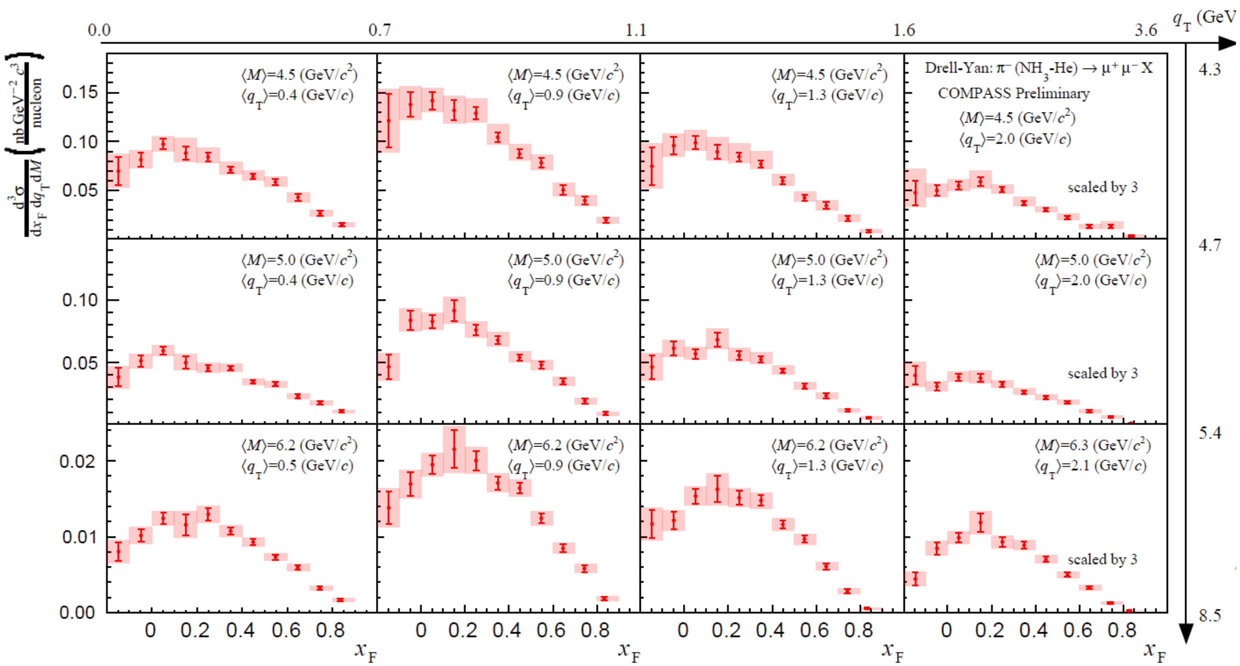
- **Beam : ** 190 GeV π^-
- **Target :**

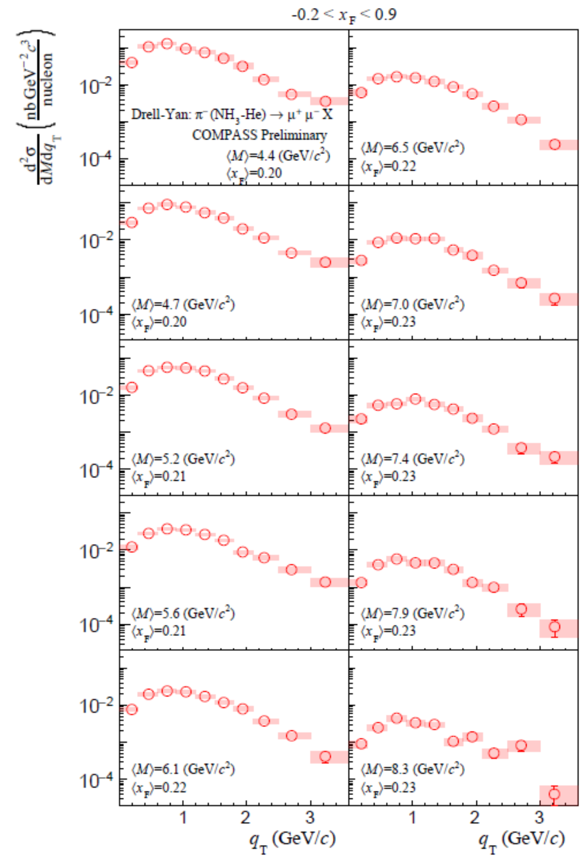
Polarized ammonia targets(PT), Al, W





COMPASS at CERN :
Drell-Yan Cross Sections by 190-GeV pions



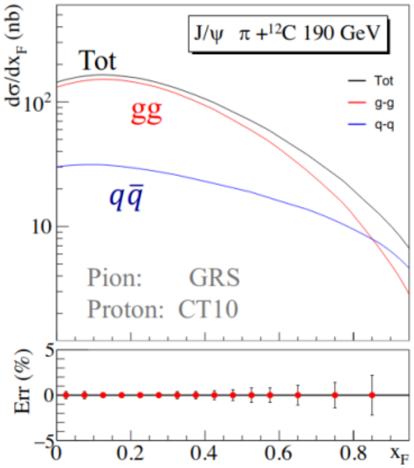


Important information to construct the PDFs and transverse-momentum distributions of pions

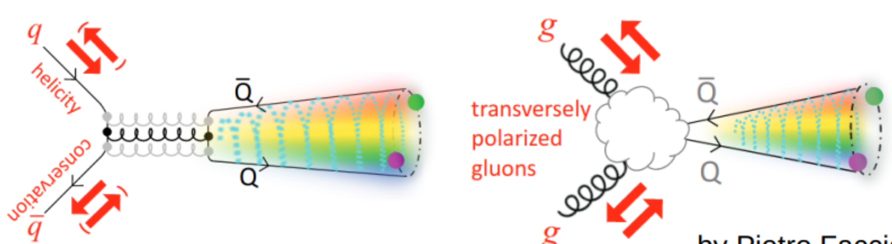
SPIN2023 https://indico.jlab.org/event/663/contributions/13272/

AMBER
:$\pi^{\pm}$/ $K^{\pm}$ -induced DY/Jpsi

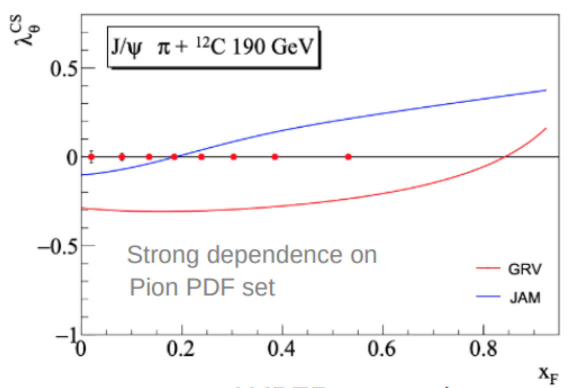
Phase-I: J/Ψ & Gluon content in the pion



- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-pT regime
- Expected to have dominant contribution from $2 \rightarrow 1$ processes
- Use J/ψ polarization to distinguish production mechanism:



by Pietro Faccioli



AMBER proposal

https://indico.lip.pt/event/1183/contributions/4269/attachments/3462/5360/CQuintans_Jornadas2022.pdf

AMBER
: $\pi^{\pm}$/ $K^{\pm}$ -induced DY/Jpsi

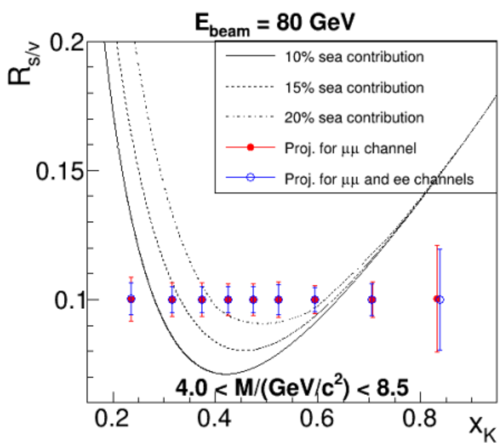
AMBER
Apparatus for Meson and Baryon Experimental Research

Phase-II: Kaon structure

Kaon structure: a window to the region of interference between the Higgs mechanism and the EHM mechanism

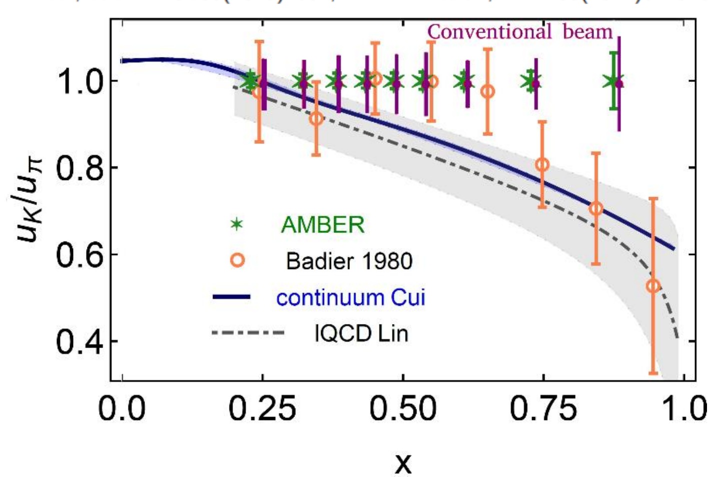
Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516

The only available experimental data:
NA3 → 200 GeV K⁻ beam on 6 cm Pt target
→ 700 kaon-induced Drell-Yan events



Kaon sea-valence separation using both charges kaon beams:

$$R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}} \propto u_v^K u_v^p$$



Assumed an RF-separated beam of 2 x 10⁷ kaons/second.

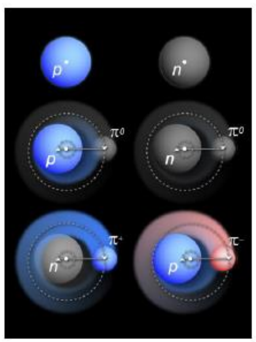
16

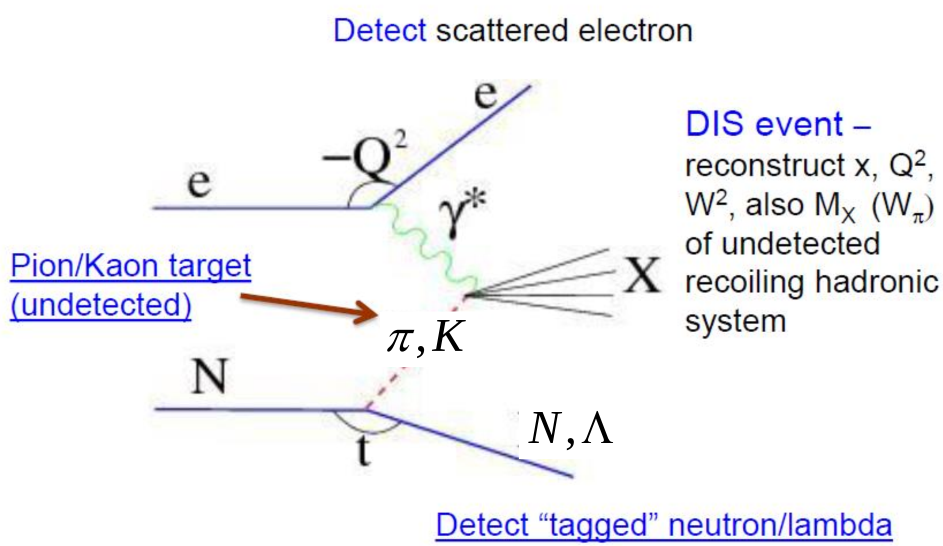
https://indico.lip.pt/event/1183/contributions/4269/attachments/3462/5360/CQuintans_Jornadas2022.pdf

EIC: Tagged processes of DIS

Physics Objects for Pion/Kaon Structure Studies

- Sullivan process – scattering from nucleon-meson fluctuations





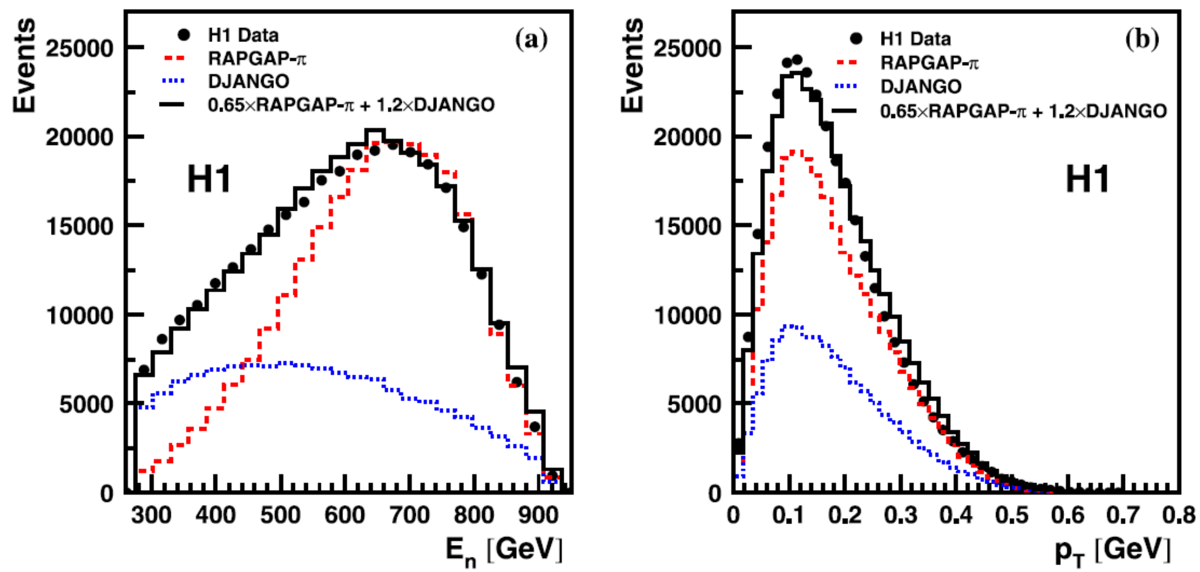
https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf

https://arxiv.org/abs/1907.08218

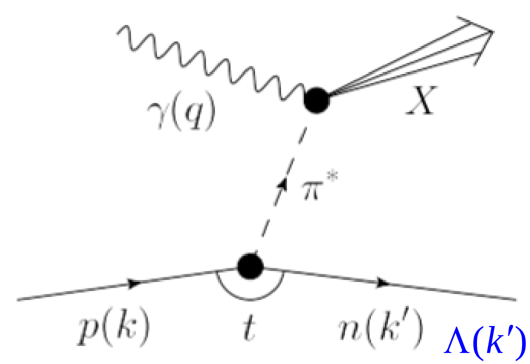
Sullivan Process: H1 (DESY)

Eur. Phys. J. C (2010) 68: 381–399 387

Fig. 3 The observed neutron energy (**a**) and transverse momentum (**b**) distributions in the kinematic range $6 < Q^2 < 100$ GeV^2 and $1.5 \cdot 10^{-4} < x < 3 \cdot 10^{-2}$. The data are compared to the predictions of RAPGAP-π (*dashed line*) and DJANGO (*dotted line*) Monte Carlo simulations. Also shown is a weighted combination of those two simulations (*full line*), as described in Sect. 3.4



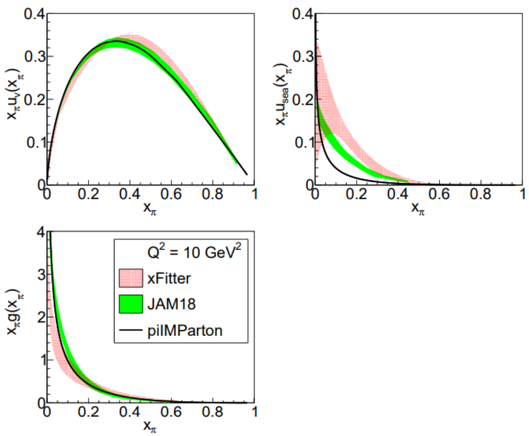
tion in this region. The best description of the data is achieved if the predictions of the RAPGAP-π and DJANGO Monte Carlo programs are added, using weighting factors of 0.65 and 1.2 for RAPGAP-π and DJANGO, respectively. This Monte Carlo combination is labelled as "0.65$\times$ RAPGAP-π + 1.2$\times$DJANGO" in the figures and is used to correct the data.

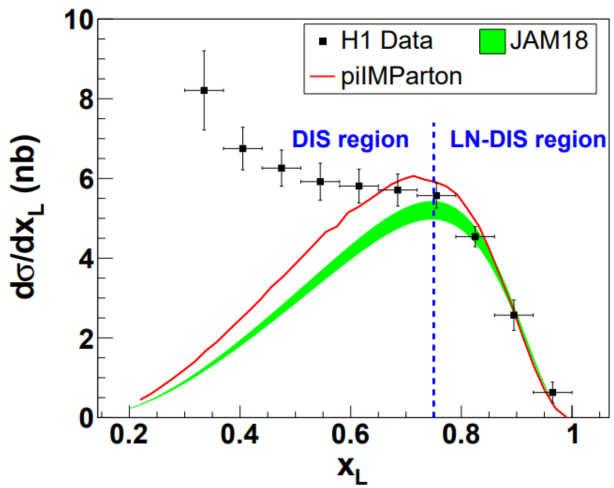


Sullivan Process at EicC

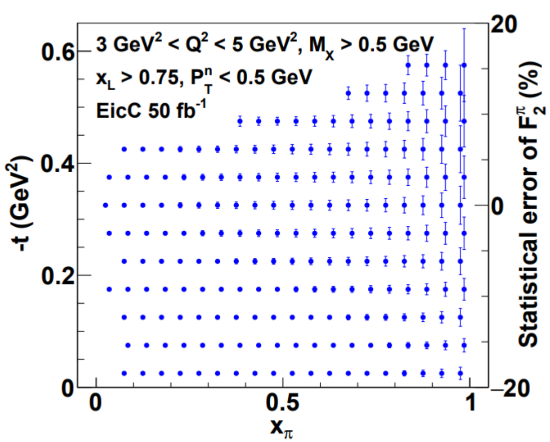
G. Xie, M. Li, C. Han, R. Wang, X. Chen, Chin. Phys. C 45 5, 053002 (2021)

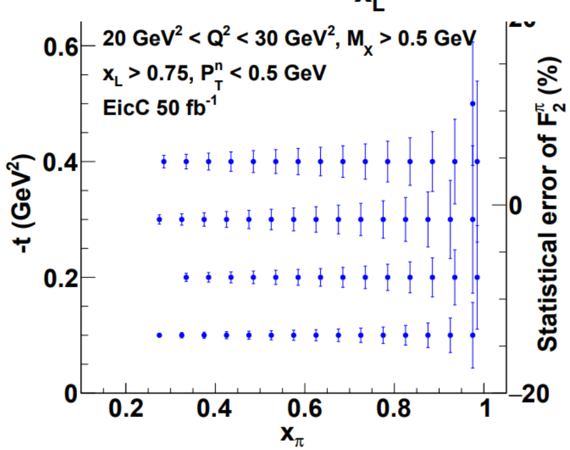
G. Xie, C. Han, R. Wang, X. Chen, Chin. Phys. C 46 064107 (2022)

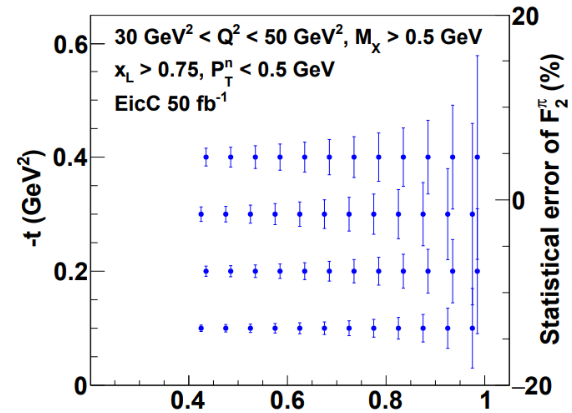




$$\sqrt{s} = 20 \text{ GeV},\ 0.01 \le x_\pi \le 1$$







Summary

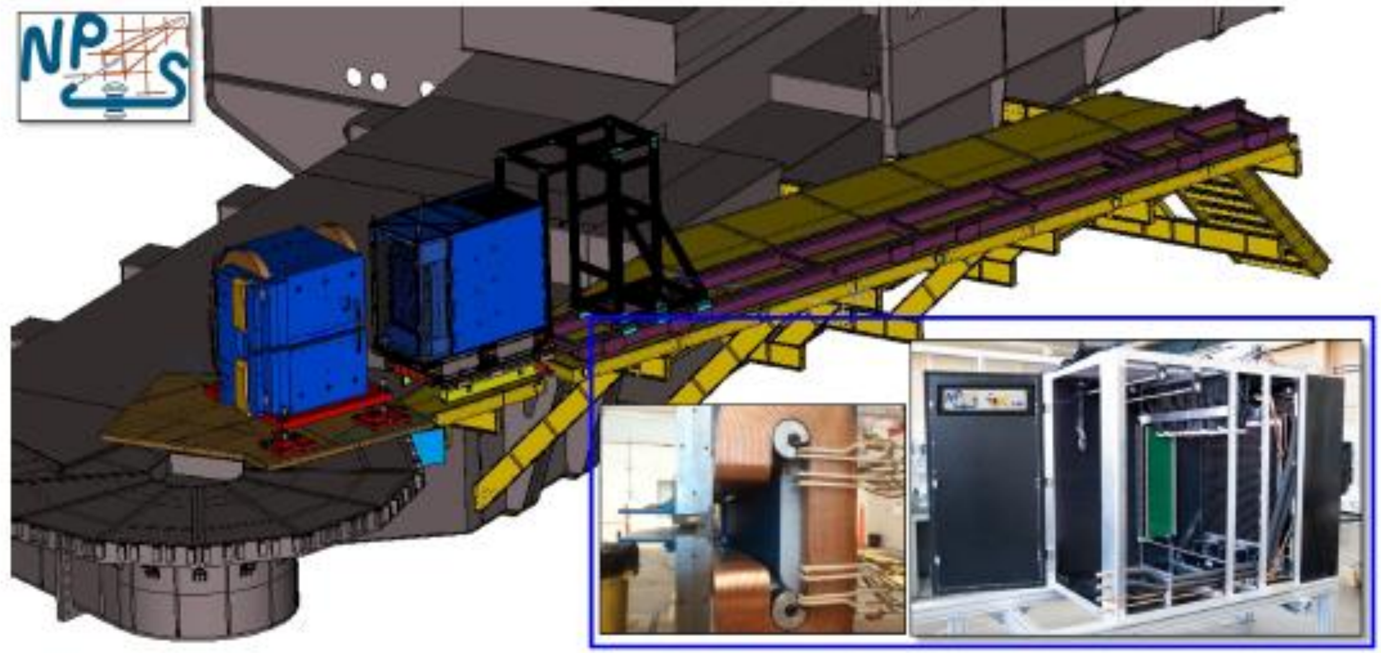
- Pion/kaon PDFs are poorly known. Existing fixed-target Jpsi data could provide valuable constraints on the gluon distributions.
- More theoretical efforts are required to extract pion/kaon PDFs from charmonium production and Sullivan process in a reliable way.
- Outlook
  - New COMPASS results of pion-induced DY/Jpsi
  - Future AMBER results of $\pi\pm/K\pm$-induced DY/Jpsi
  - Future measurements of Sullivan process in EicC and U.S. EIC.

Brief update of activities of Taiwan nuclear physics community

Experimental Programs

- **Hadron Physics**: LEPS,LEPS2@SPring8, SeaQuest@FNAL, COMPASS@CERN, E16, E50@J-PARC, NPS@Jlab [*W.C. Chang , AS; P.J. Lin, NCU*]
- **Neutrino Physics**: TEXONO@KSNL & Dark Matter Search: CDEX@CJPL [*H.T. Wong, AS*]
- **Heavy Ion Physics**: STAR@BNL [*Y. Yang, AS*], CMS@CERN [*C.M. Kuo, NCU*], sPHENIX@BNL [*R.S. Lu, NTU; C.M. Kuo, P.J. Lin, NCU*]
- **EIC**: AS, NTU, NCU, NTHU

NPS Experiment @ JLab Hall C

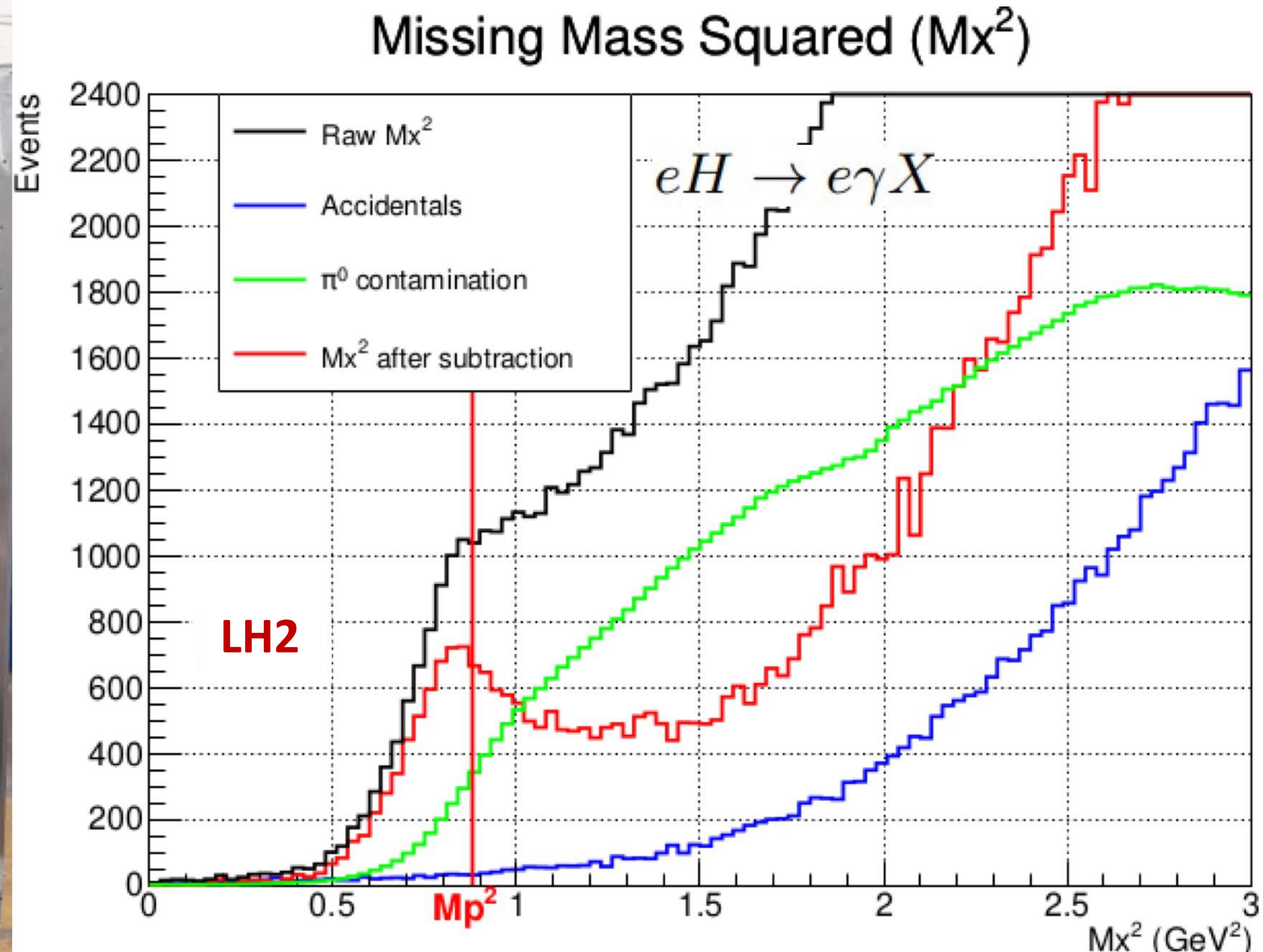


Neutral
Particle
Spectrometer
→ $PbWO_4$

- Beam energies 6.6-11 GeV, luminosity ~$10^{38}\,\frac{Hz}{cm2}$
- The first round of data taking has finised
  - **DVCS**, Exclusive π^0 → extend to higher Q^2 and smaller x_B than previous Hall A coverage with high precision.
- **On-going data analysis**

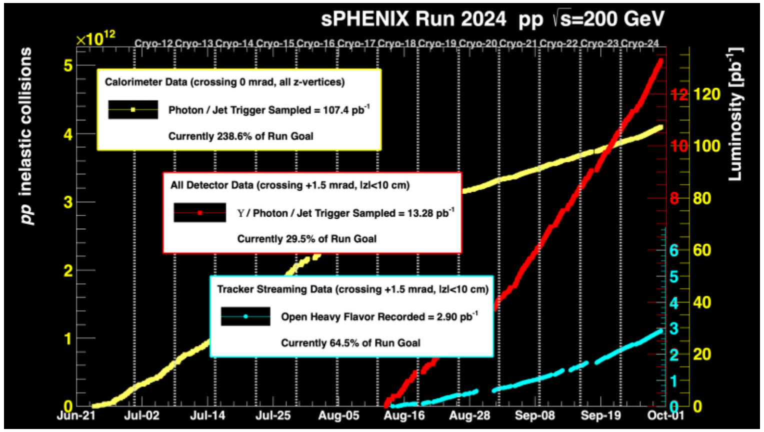
NPS Experiment @ JLab Hall C

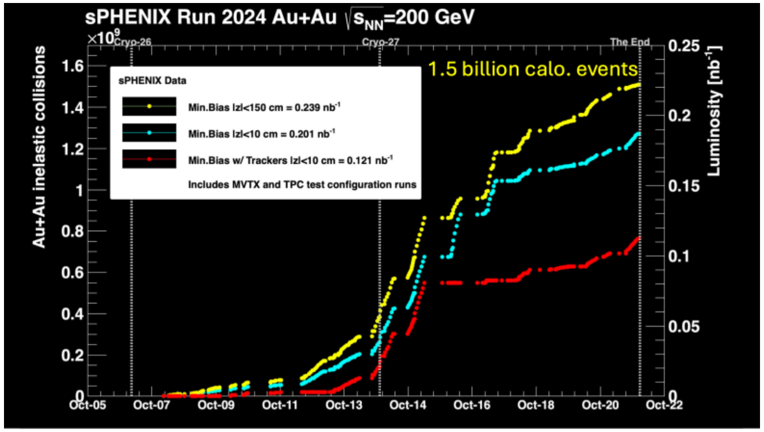
NPS Calorimeter



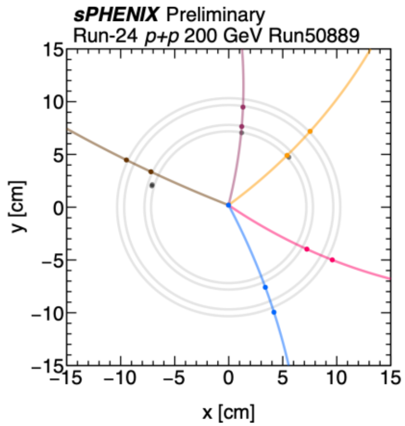
- The mass peak of the missing proton can be identified in the very preliminary study.

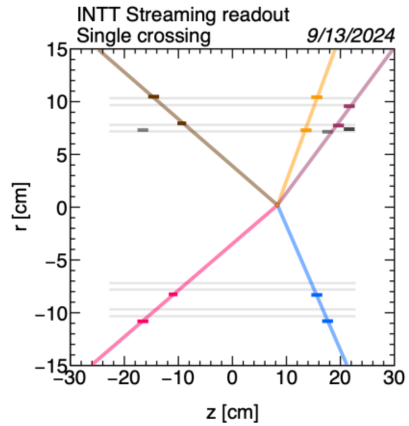
sPHENIX Run-24





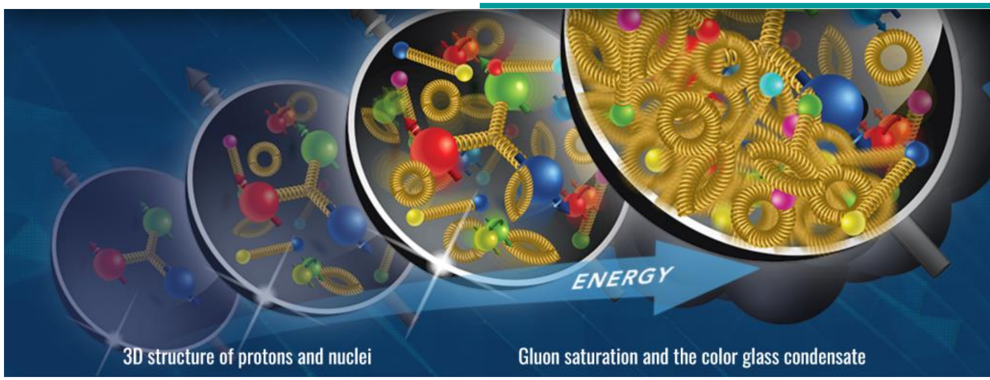
A long and challenging and fun sPHENIX Run-24

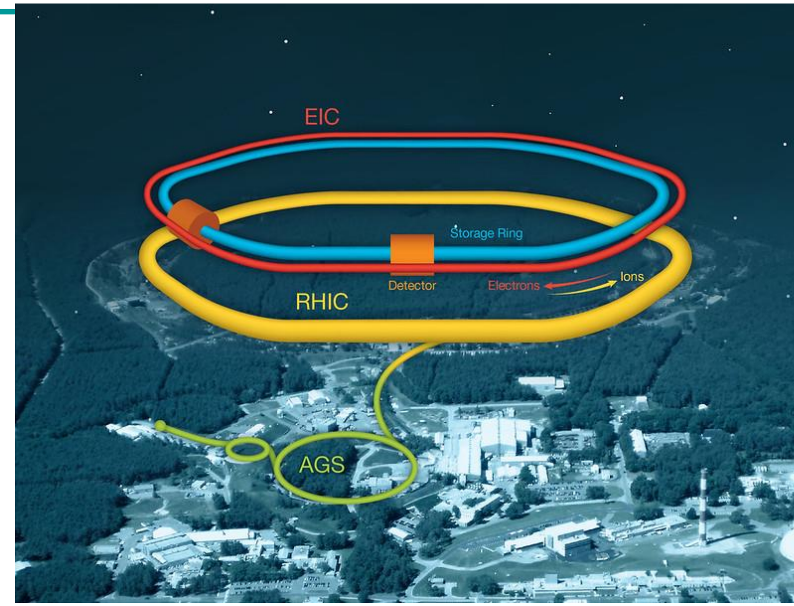


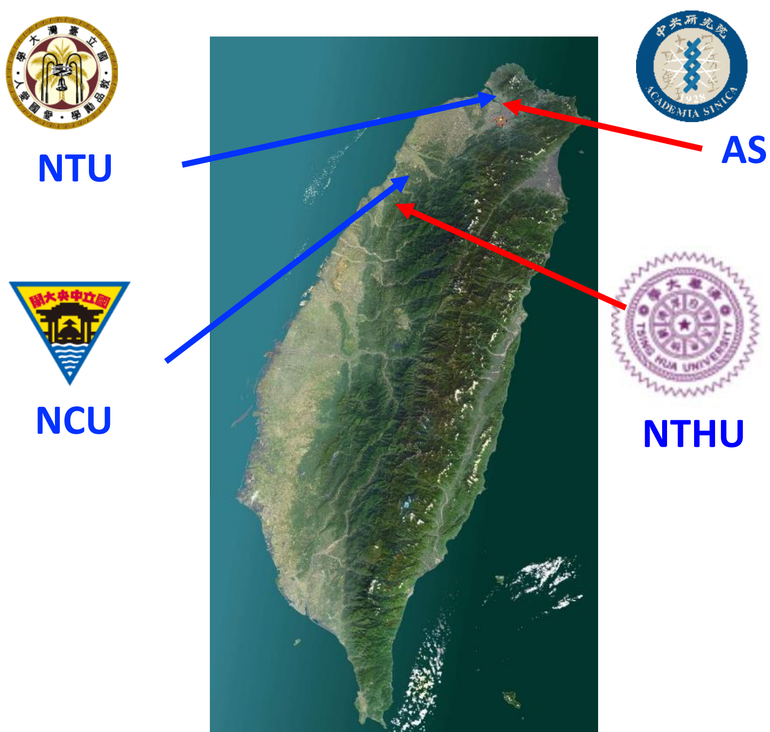


take part in the INTT operation, detector performance study, Vernier scan, and physics analysis

U.S. Electron-Ion Collider and ePIC Collaboration



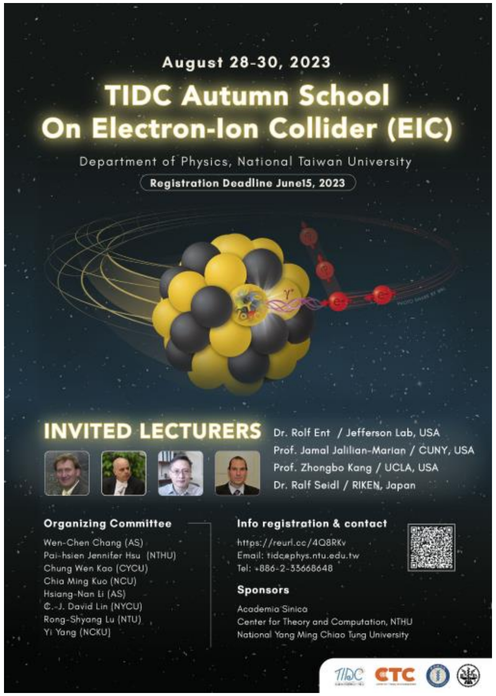


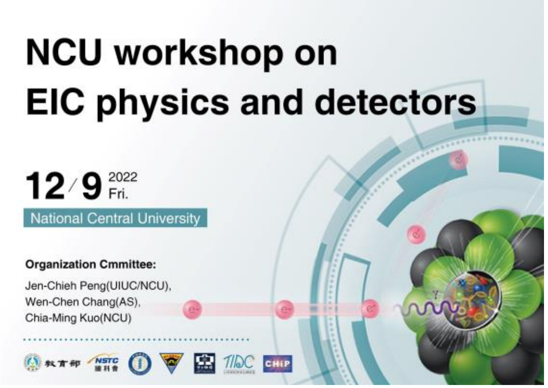


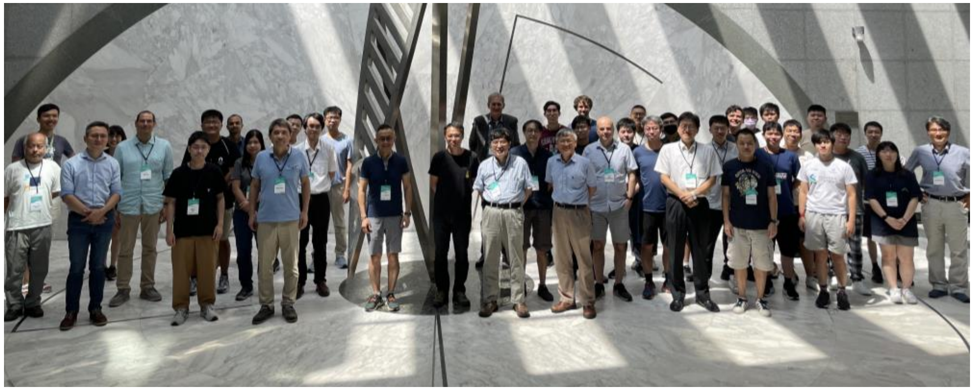
Physics Goals

- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for saturation
- Quark and gluon confinement
- Quarks and gluons in nuclei

EIC Meetings in Taiwan

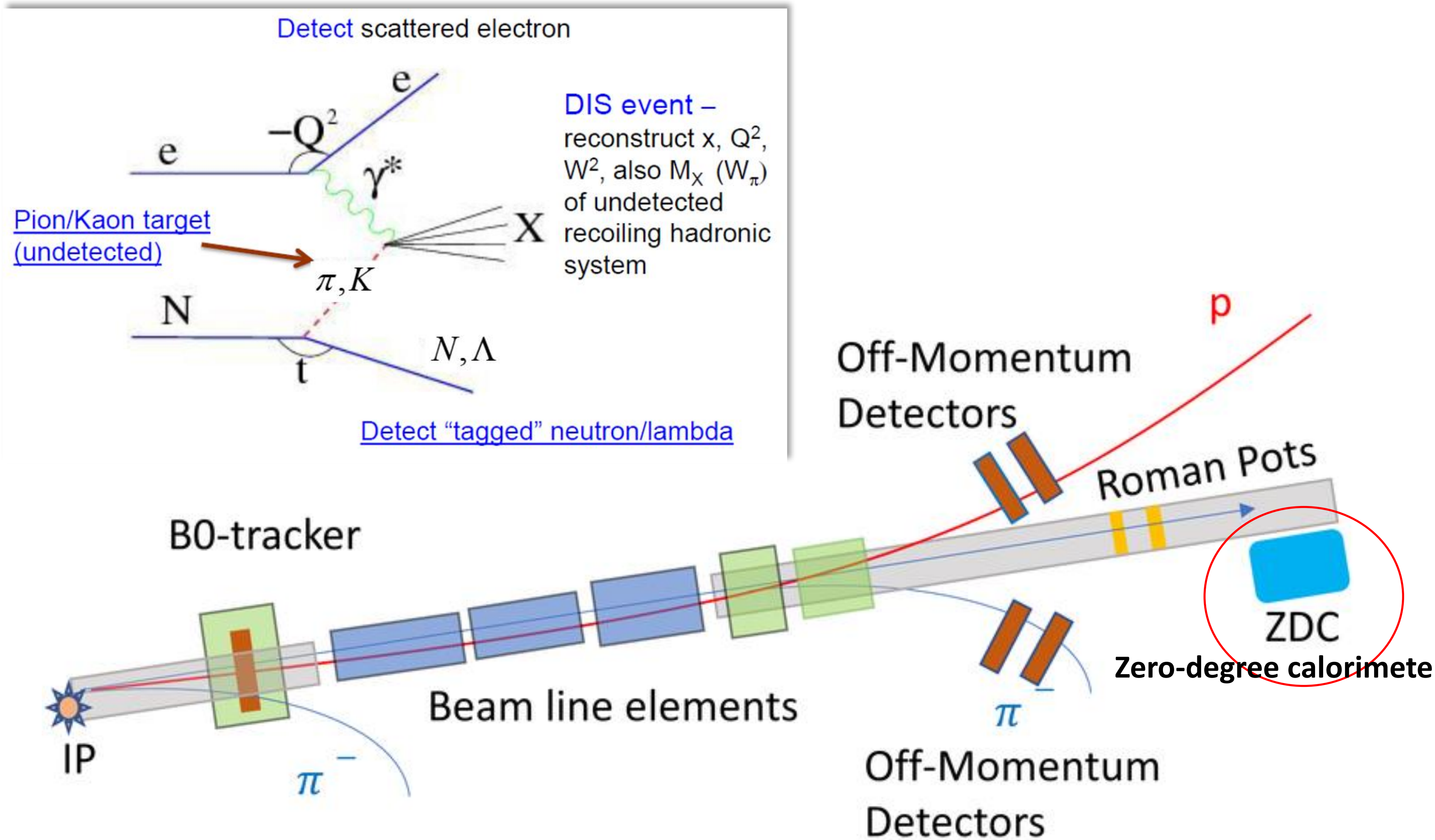




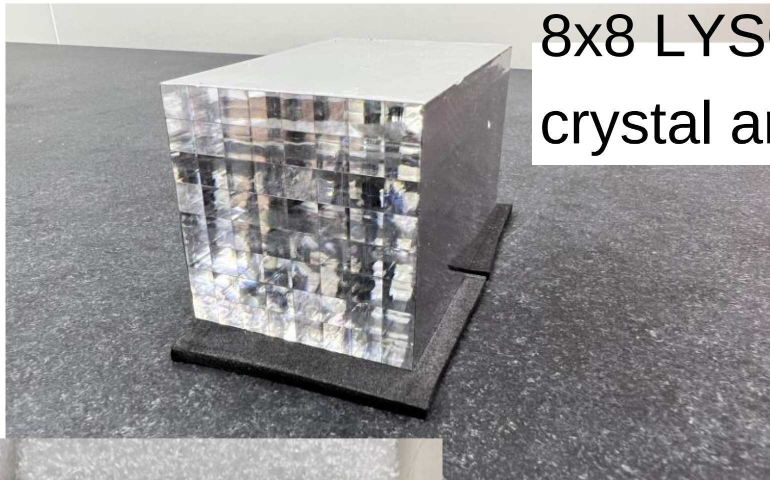


The 3rd EIC-ASIA Workshop
(NCKU, Jan. 29-31, 2024)

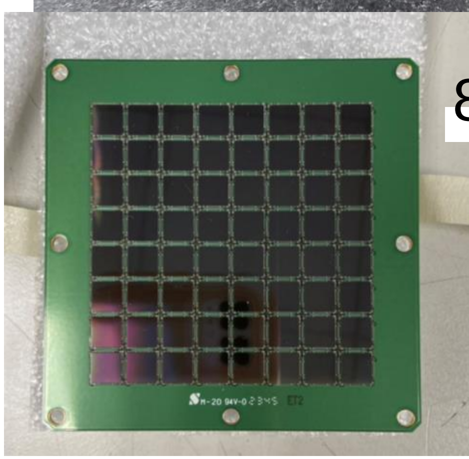
Far-Forward detectors



ZDC Prototype: LYSO Crystals

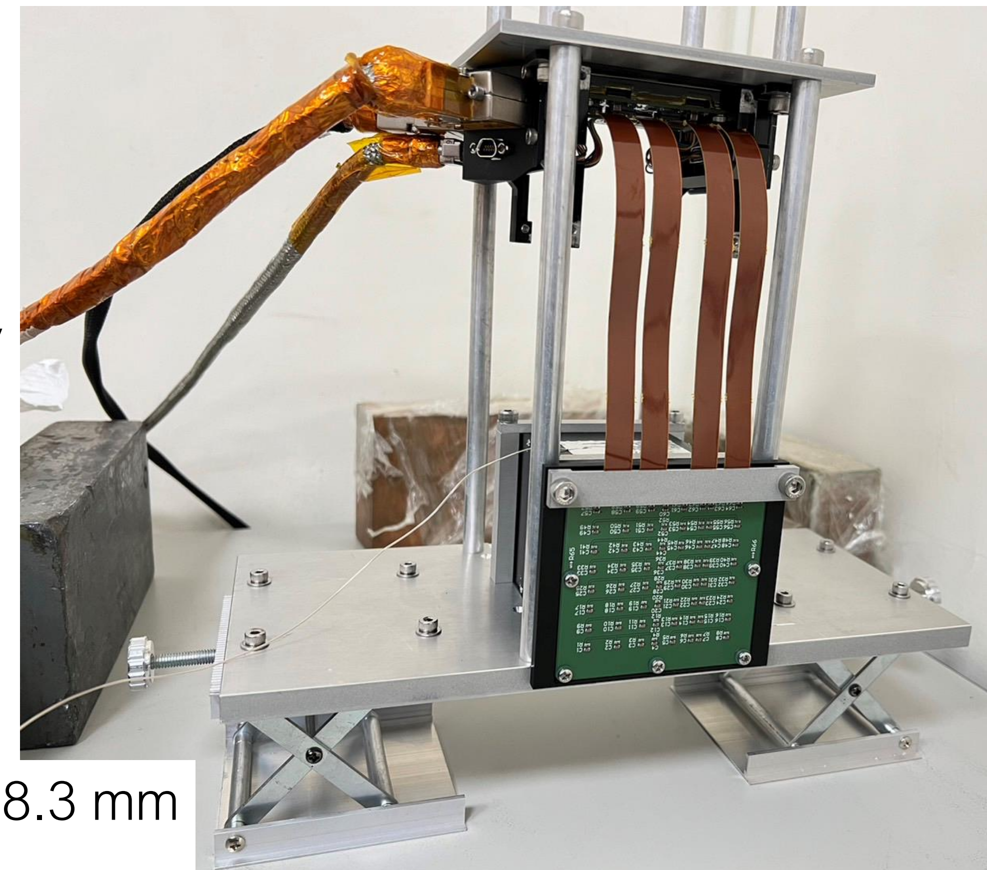


8x8 LYSO crystal array



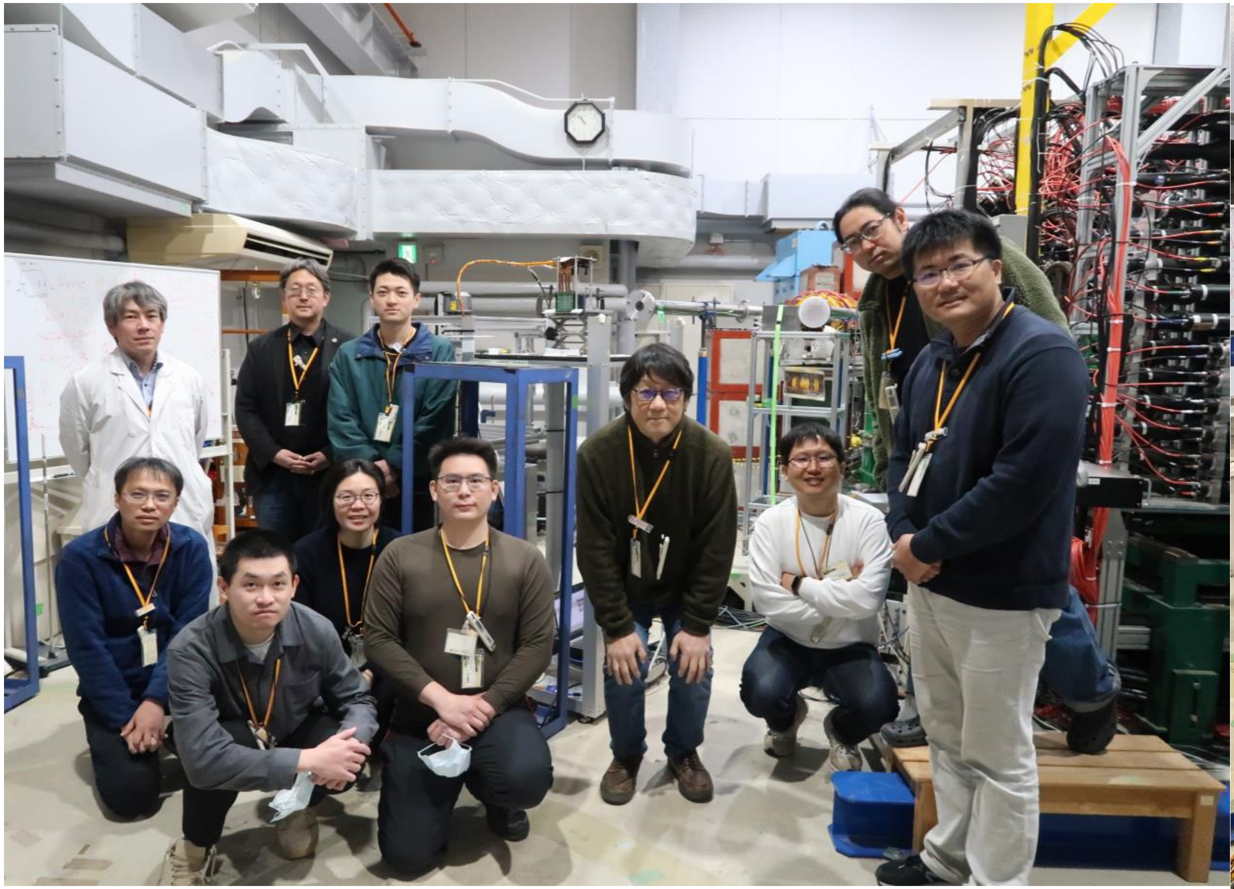
8x8 SiPM array

LYSO calorimeter prototype



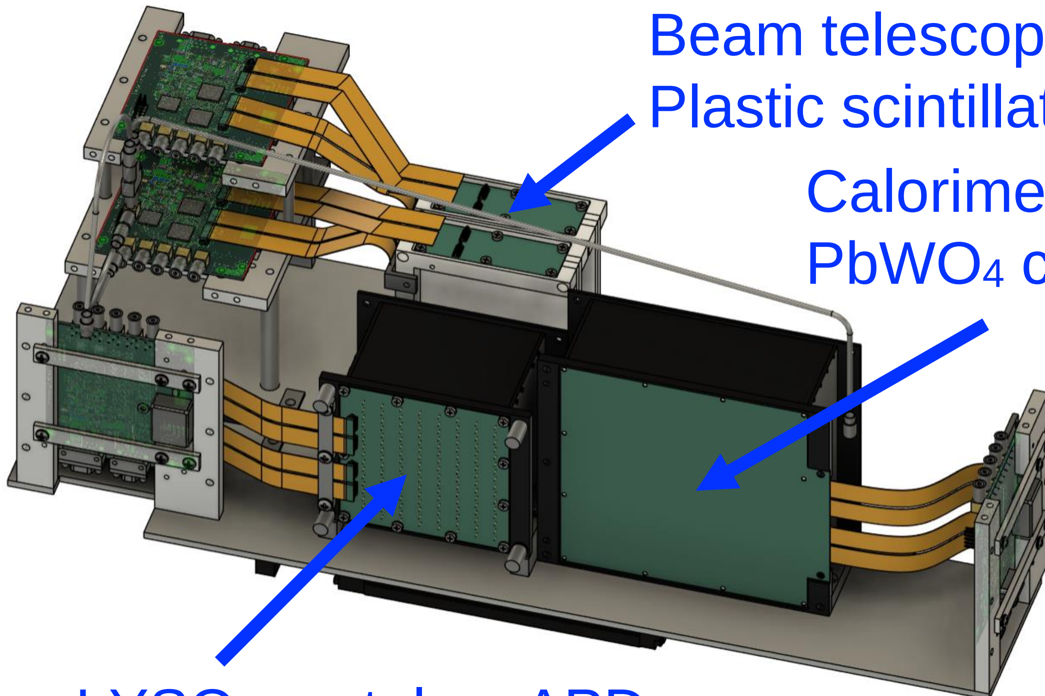
One crystal: 7.12 mm x 7.12 mm x 88.3 mm
8x8 array: 56.96 mm x 56.96 mm

Beam test @ RARIS, Japan 2024/2
[Teams of Japan, Korea and Taiwan]



Data analysis is on-going

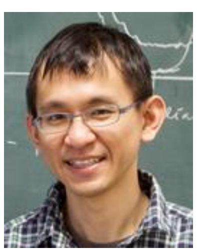
2nd beam test @ RARIS



- Scheduled for February 2025
- Test two proptypes: LYSO+APD and $PbWO_4$+SiPM

Theoretical Programs

- Integrated well with theory program on particle physics, astrophysics & cosmology
- Esp. aspects of nucleon/hadron physics with
  - QCD effective theories & Lattice QCD
  - parton distribution functions & transverse momentum distributions
  - aspects of atomic/nuclear physics in particle-matter interactions
  - heavy element nucleosynthesis; collective neutrino oscillations
- Practitioners: H.N. Li, M.R. Wu, D.L. Yang (AS) ; J.W. Chen (NTU) ; A. Francis, D. Lin (NYCU) ; C.W. Kao (CYCU) ; C.P. Liu (NDHU)





Excited Glueball States

Chinese Physics Letters **41**, 101101 (2024)

Dispersive Analysis of Excited Glueball States

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(Received 15 August 2024; accepted manuscript online 23 September 2024)

Motivated by the determination for the spin-parity quantum numbers of the $X(2370)$ meson at BESIII, we extend our dispersive analysis on hadronic ground states to excited states. The idea is to start with the dispersion relation which a correlation function obeys, and subtract the known ground-state contribution from the involved spectral density. Solving the resultant dispersion relation as an inverse problem with available operator-product-expansion inputs, we extract excited-state masses from the subtracted spectral density. This formalism is verified by means of the application to the series of ρ resonances, which establishes the $\rho(770)$, $\rho(1450)$ and $\rho(1700)$ mesons one by one under the sequential subtraction procedure. Our previous study has suggested the admixture of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ mesons (the $\eta(1760)$ meson) to be the lightest scalar (pseudoscalar) glueball. The present work predicts that the $f_0(2200)$ ($X(2370)$) meson is the first excited scalar (pseudoscalar) glueball.

DOI: 10.1088/0256-307X/41/10/101101

NYCU Lattice QCD Efforts

Gauge fields, hot photons and exotic hadrons

OPEN LATtice initiative (Founder)

- **Hunt for doubly heavy tetraquarks continues:**

Milestones, challenged and opportunities reviewed, improved results published

Improved analysis of strong-interaction-stable doubly bottom tetraquarks on the lattice

B. Colquhoun[1], A. Francis[2], R. J. Hudspith[3], R. Lewis[4], K. Maltman[5,6] and W. G. Parrott[4]

[1]*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
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Review

Lattice perspectives on doubly heavy tetraquarks

Anthony Francis

Institute of Physics, National Yang Ming Chiao Tung University, 1001 Daxue Road, 30010 Hsinchu City, Taiwan

- **OpenLat continues to push the envelope for gauge ensembles:**

30.000 configurations available in 16 ensembles, 3 at 200MeV pion mass, 1 at the physical point with 2 more in preparation.

Progress in generating gauge ensembles in OpenLat

Anthony Francis [1] Patrick Fritzsch [2] Jangho Kim [3] Andrea Shindler [4] Antonio Rago [5] Giovanni Pederiva [3] Andre Walker-Loud [6] Savvas Zafeiropoulos [7]

[1]National Yang Ming Chiao Tung University, Taiwan [2]Trinity College Dublin, Ireland [3]Forschungszentrum Jülich GmbH [4]RWTH Aachen, Germany [5]University of Southern Denmark, Denmark [6]Lawrence Berkeley National Lab, USA [7]CNRS & Aix Marseille Université, France

- **Tackling the inverse problem:**

Calculation of thermal photon production rate in QGP from first principles.

PHYSICAL REVIEW D **110**, 054518 (2024)

Lattice QCD estimates of thermal photon production from the QGP

Sajid Ali,[1,6] Dibyendu Bala,[1] Anthony Francis,[2] Greg Jackson,[3,4] Olaf Kaczmarek,[1] Jonas Turnwald,[5] Tristan Ueding,[1] and Nicolas Wink[5]

(HotQCD Collaboration)

Neutrino interaction, oscillations, and nucleosynthesis of elements

PHYSICAL REVIEW C **110**, 015504 (2024)

Neutrino-neutron scattering opacities in supernova matter

Gang Guo,[1,*] Gabriel Martínez-Pinedo,[2,3] and Meng-Ru Wu[4,5,6]

PHYSICAL REVIEW D **109**, 123008 (2024)

Fast neutrino flavor conversions in a supernova: Emergence, evolution, and effects

Zewei Xiong,[1,*] Meng-Ru Wu,[2,3,4] Manu George,[2] Chun-Yu Lin,[5] Noshad Khosravi Largani,[6] Tobias Fischer,[6] and Gabriel Martínez-Pinedo[1,7]

Progress in Particle and Nuclear Physics 137 (2024) 104107

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ELSEVIER

Review

Neutrinos and nucleosynthesis of elements

Tobias Fischer[a], Gang Guo[b], Karlheinz Langanke[c,d], Gabriel Martínez-Pinedo[c,d], Yong-Zhong Qian[e], Meng-Ru Wu[f,g,h,*]

PHYSICAL REVIEW D **109**, 083020 (2024)

Effects of annihilation with low-energy neutrinos on high-energy neutrinos from binary neutron star mergers and rare core-collapse supernovae

Gang Guo,[1] Yong-Zhong Qian,[2] and Meng-Ru Wu[3,4,5]

PHYSICAL REVIEW D **109**, 043024 (2024)

Physics-informed neural networks for predicting the asymptotic outcome of fast neutrino flavor conversions

Sajad Abbar,[1] Meng-Ru Wu,[2,3,4] and Zewei Xiong[5]

Initial Stages 2025

ANPhA 2025

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