sPHENIX INTT mini-Workshop
National Central University
2023/11/17

Fixed-target charmonium production and pion PDFs

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Predictions for the sPHENIX physics program [arXiv:2305.15491]

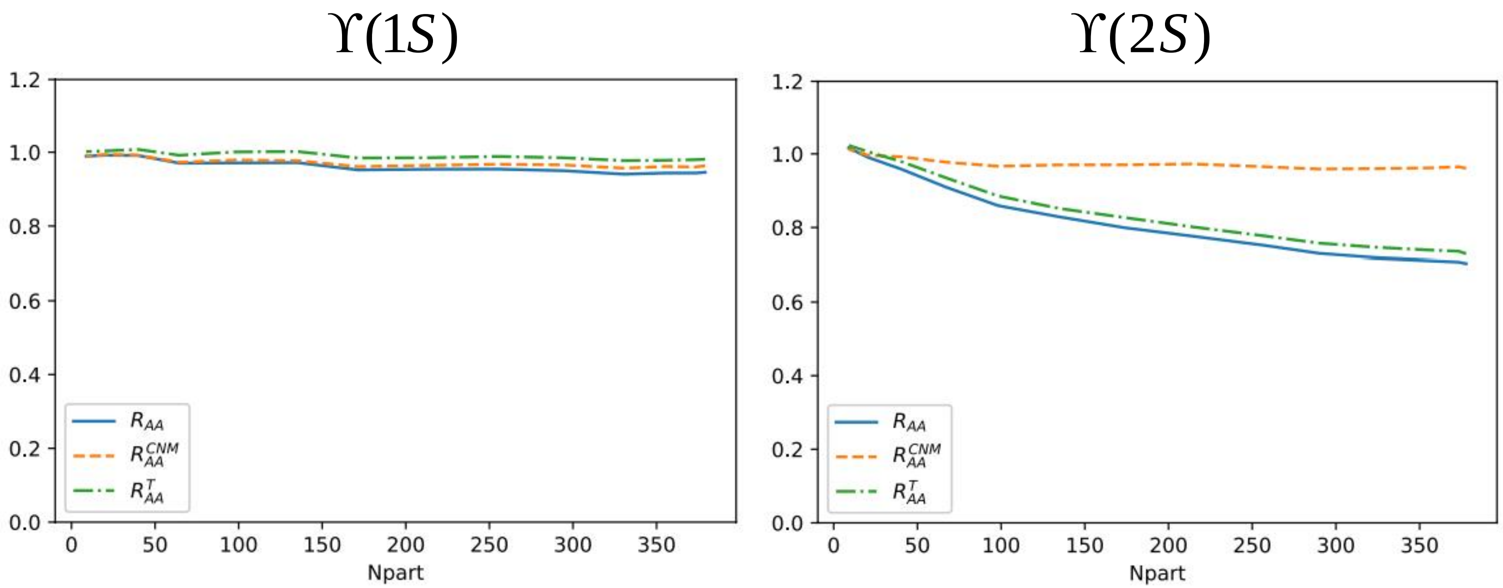


Figure 22: Predictions for the R_{AA} vs N_{part} of $\Upsilon(1S)$ (left) and $\Upsilon(2S)$ (right) in sPHENIX at RHIC, showing the cold nuclear matter (orange) and thermal (green) contributions to the total R_{AA} (blue).

- Transversely polarized p+p and p+Au running in 2024
- High-statistics Au+Au running in 2025

Cold Nuclear Matter Effects of Quarkonium Production

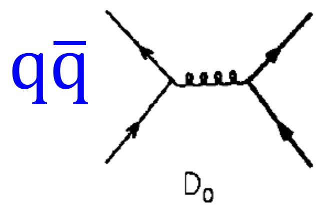
- Initial-state effect: shadowing, parton densities (esp. gluon) of nuclear PDFs (nPDFs)
- **Production mechanism: CEM, CSM and NRQCD**
- Initial-state interaction: parton energy loss
- Final-sate interaction: absorption and regeneration

https://journals.aps.org/prc/abstract/10.1103/PhysRevC.61.035203
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.81.044903

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

LO

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



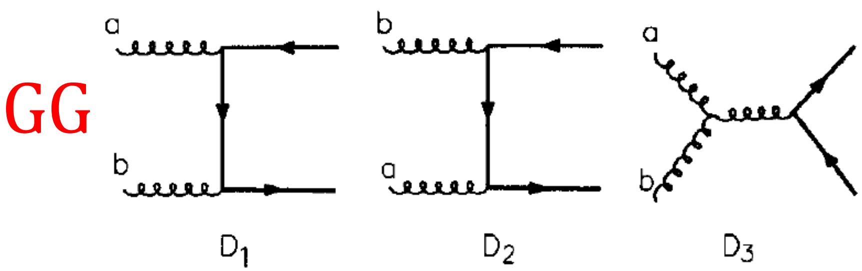
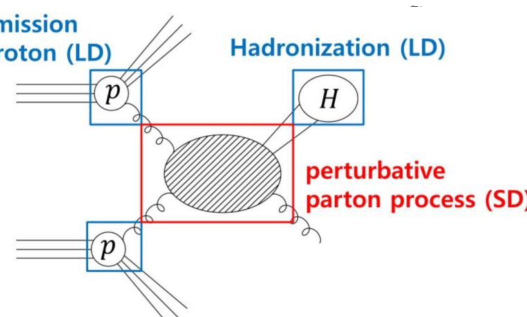


Fig. 2. Diagrams for the $q\bar{q}$ and g



NLO

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

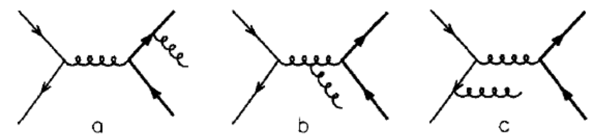
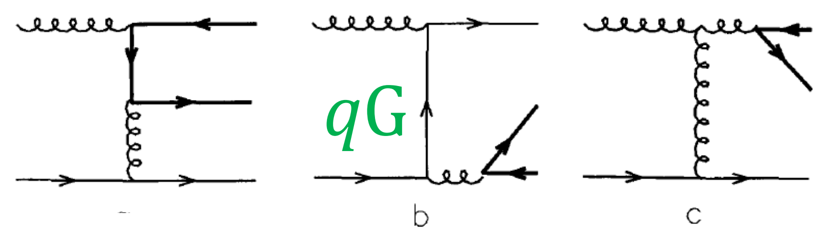


Fig. 8. Diagrams for the real corrections to the $q\bar{q}$ channels. Permutations of outgoing gluons and/or reversal of fermion lines are always implied.

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



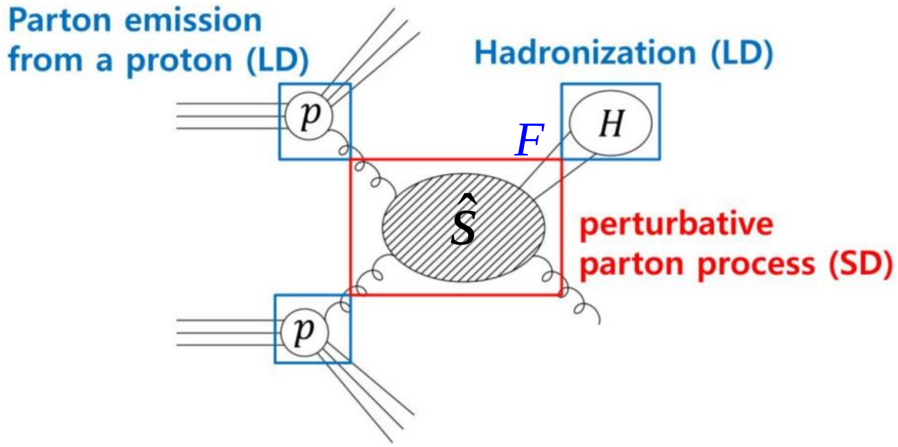
the gq channels. Reversal of fermion lines is always implied.

Color Evaporation Model

$$\sigma[AB \to J/\psi X]$$
$$= F \sum_{i,j} \int_{2m_c}^{2m_D} d\hat{s} \int dx_1 dx_2 \, f_{i/A}(x_1, \mu_F) f_{j/B}(x_2, \mu_F)$$
$$\hat{\sigma}[ij \to c\bar{c}X](x_1 P_A, x_2 P_B, \mu_F, \mu_R)\delta(\hat{s} - x_1 x_2 s)$$

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

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

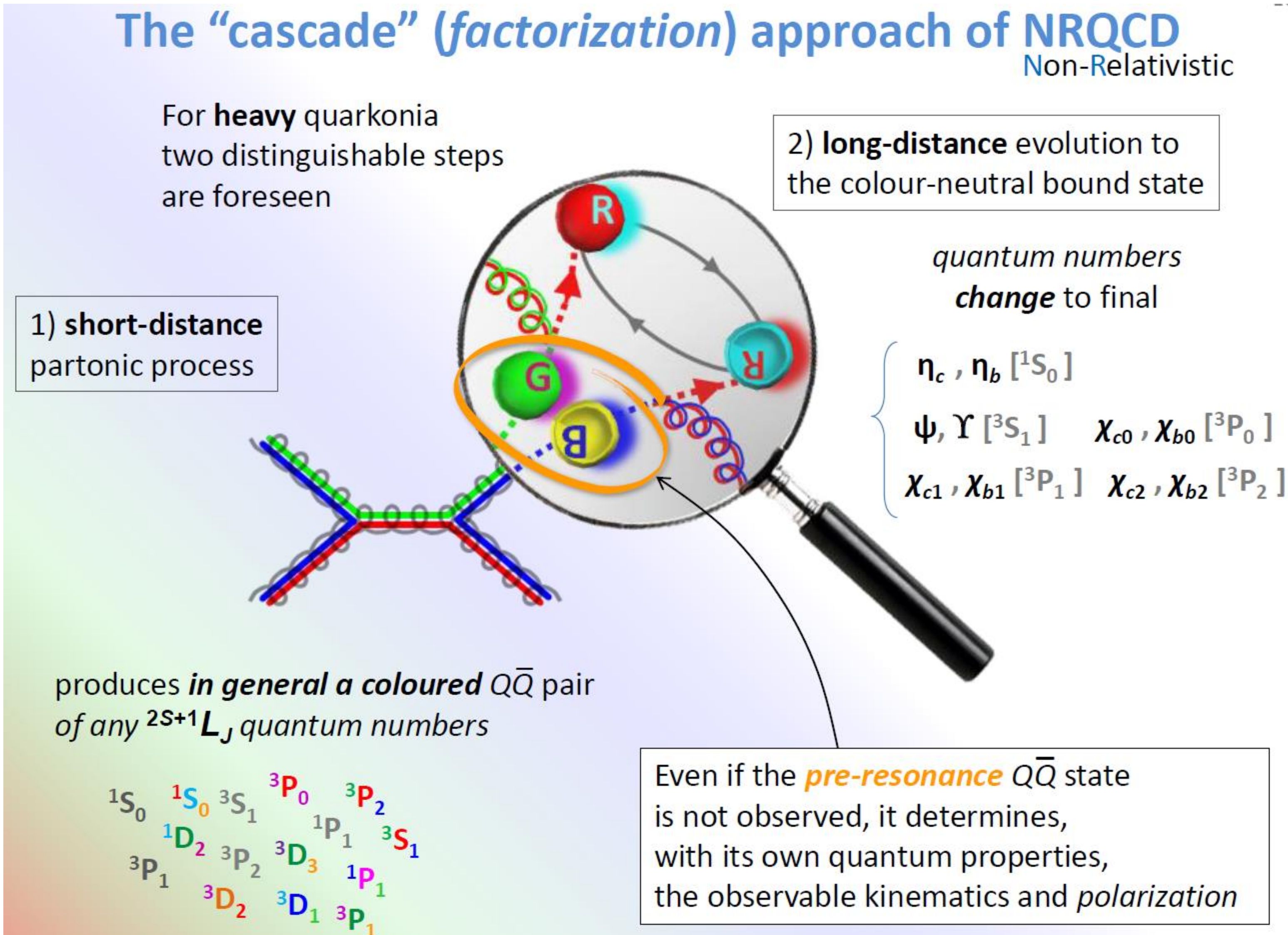


LO/NLO calculations of $\hat{\sigma}[ij \to c\bar{c}X]$:

- 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

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

NRQCD



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

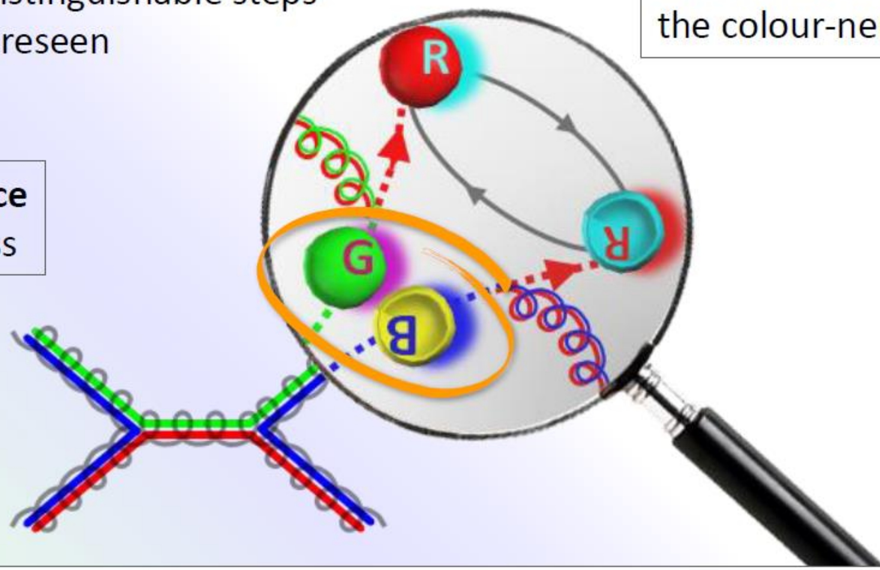
NRQCD

The “cascade” (*factorization*) approach of NRQCD

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

1) **short-distance** partonic process

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



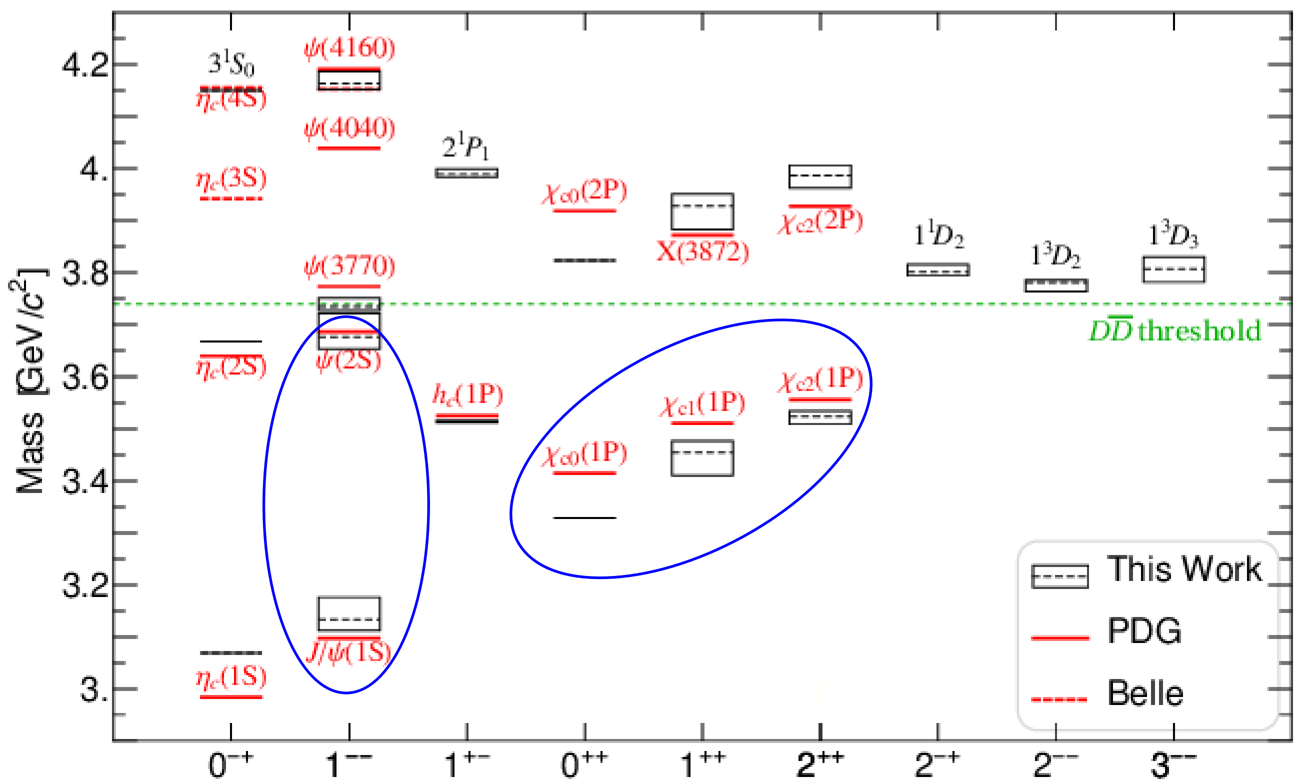
1) *short-distance coefficients* (**SDCs**): p_T-dependent partonic cross sections

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

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

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

Charmonium Spectroscopy



https://arxiv.org/abs/1509.07212

Long-Distance Matrix Elements (LDMEs) PRD 54, 2005 (1996)

$$\left\langle O_{1,8}^{H}\left[{}^{2S+1}L_J\right]\right\rangle$$

H	$q\bar{q}$	GG	qG
$J/\psi,\ \psi(2S)$	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\Delta_8^{H}*\ (\mathcal{O}(\alpha_s^2))$ $\langle \mathcal{O}_1^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^3))$	
χ_{c0}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_0]\rangle\ (\mathcal{O}(\alpha_s^2))$	
χ_{c1}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_1]\rangle\ (\mathcal{O}(\alpha_s^3))$	$\langle \mathcal{O}_1^H[{}^3P_1]\rangle\ (\mathcal{O}(\alpha_s^3))$
χ_{c2}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_2]\rangle\ (\mathcal{O}(\alpha_s^2))$	

$$\Delta_8^H = \langle \mathcal{O}_8^H[{}^1S_0]\rangle + \frac{3}{m_c^2}\langle \mathcal{O}_8^H[{}^3P_0]\rangle + \frac{4}{5m_c^2}\langle \mathcal{O}_8^H[{}^3P_2]\rangle$$

H	$\langle \mathcal{O}_1^H[{}^3S_1]\rangle$	$\langle \mathcal{O}_1^H[{}^3P_0]\rangle/m_c{}^2$	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle$	Δ_8^H
J/ψ	1.16		6.6×10^{-3}	3×10^{-2}
$\psi(2S)$	0.76		4.6×10^{-3}	5.2×10^{-3}
χ_{c0}		0.044	3.2×10^{-3}	

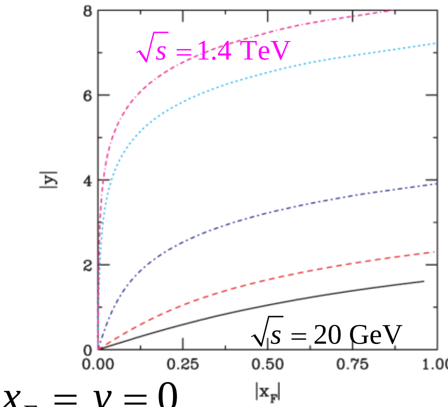
color-singlet (CS) LDMEs color-octet (CO) LDMEs

Determined by fit of proton- and pion-induced data

$$\sigma_{J/\psi} = \sigma_{J/\psi}^{direct} + Br(\psi(2S)\to J/\psi X)\sigma_{\psi(2S)} + \sum_{J=0}^{2} Br(\chi_{cJ}\to J/\psi\gamma)\sigma_{\chi_{cJ}}$$

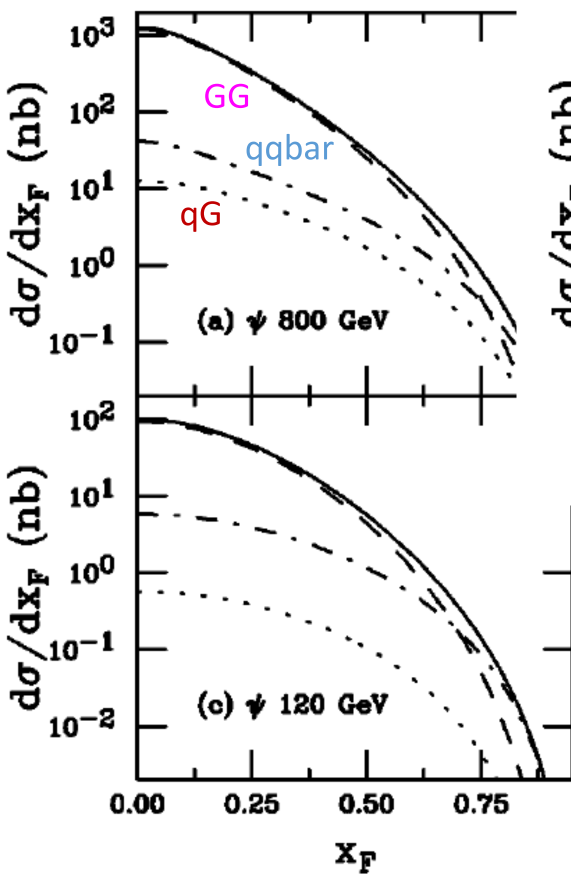
Rapidity Distributions

PRC 61, 035203 (2000)

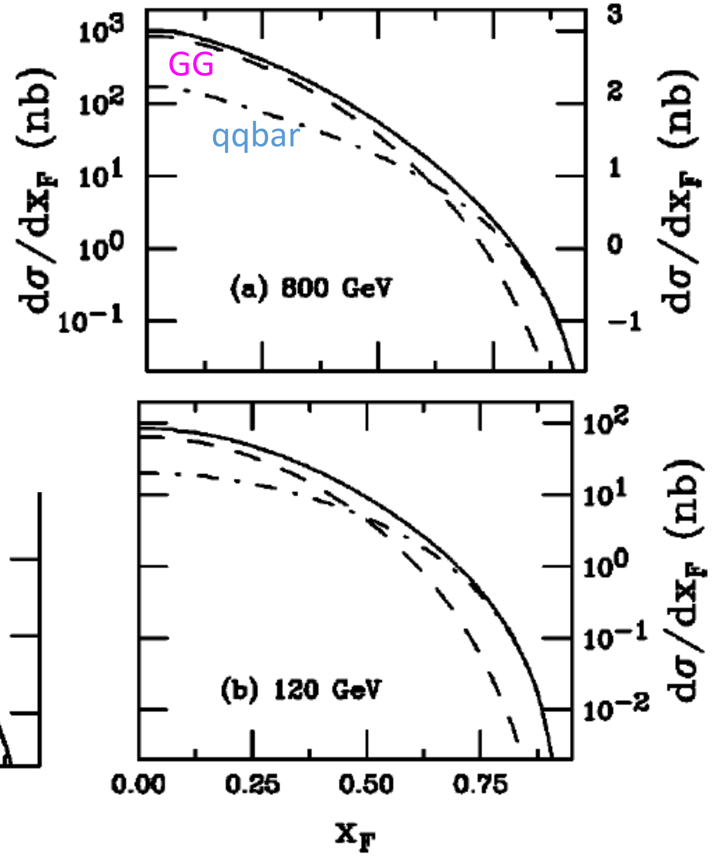


$x_F = y = 0$

NRQCD



CEM



$$x_F = x_{\mathrm{beam}} - x_{\mathrm{target}}$$

One Possible measurement RpA (Jpsi/psi')

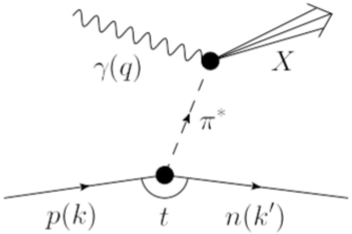
- The GG fusion process is the dominant channel for charmonium production at high energies.
- If both pA and pp data are taken at the same CMS energy, the comparison of them could be used to probe the nuclear gluon density.

$$\frac{\sigma_{pA}(\sqrt{s_{NN}})}{\sigma_{pp}(\sqrt{s_{NN}})}(y) \propto \frac{1}{A}\frac{f_G^A(x,\mu^2)}{f_G^p(x,\mu^2)}$$

The RpA (Upsilon) is more sensitive to the valence/sea parts of nPDFs.

Pion PDFs

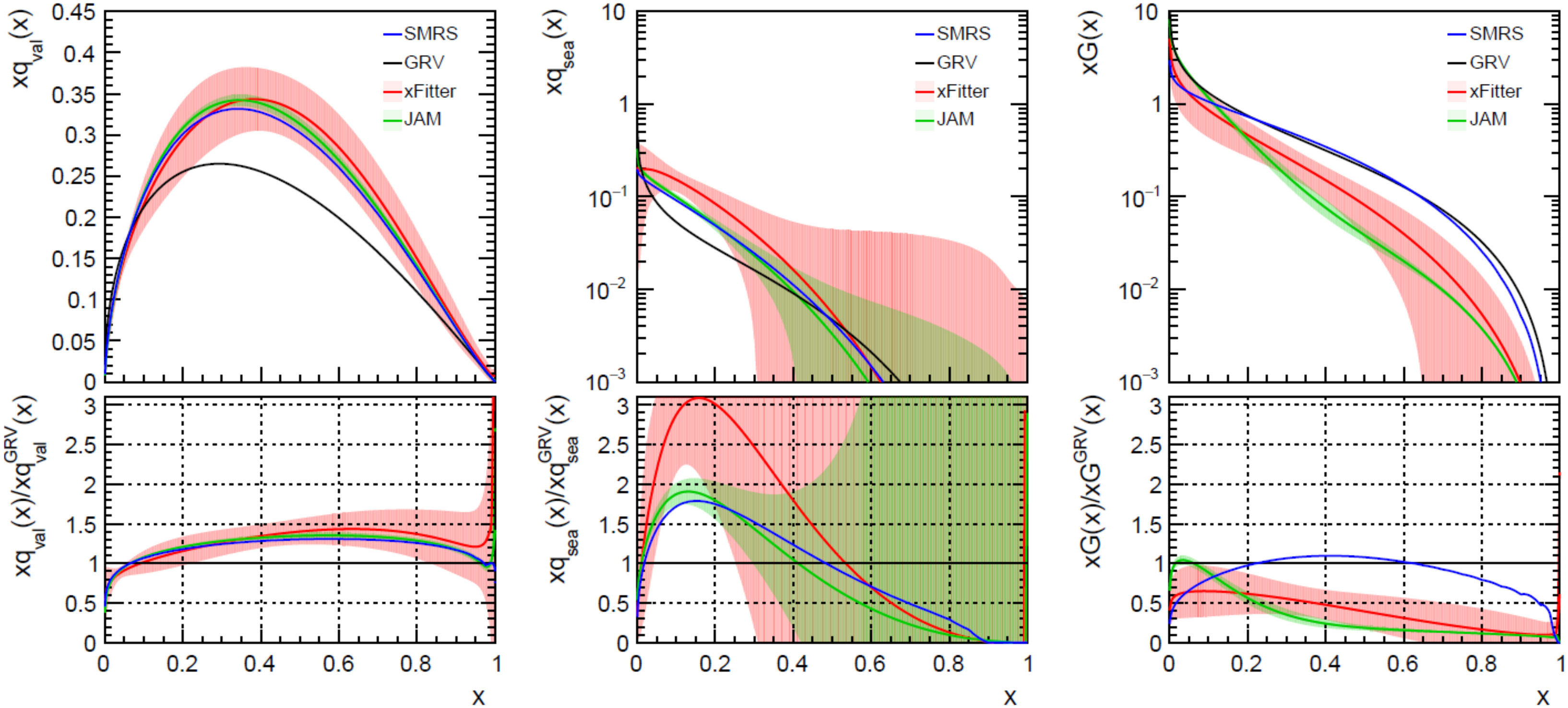
- Drell-Yan: $\pi^{\pm}p \rightarrow \mu^{+}\mu^{-}X$ (LO: sensitive to valence quarks)
  - **LO: $\boldsymbol{q\bar{q} \rightarrow \mu^{+}\mu^{-}}$**
  - NLO: $q\bar{q} \rightarrow \mu^{+}\mu^{-}G, qG \rightarrow \mu^{+}\mu^{-}q$ (large p_T)
  - NNLO: $q\bar{q}G \rightarrow \mu^{+}\mu^{-}G, qG \rightarrow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



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

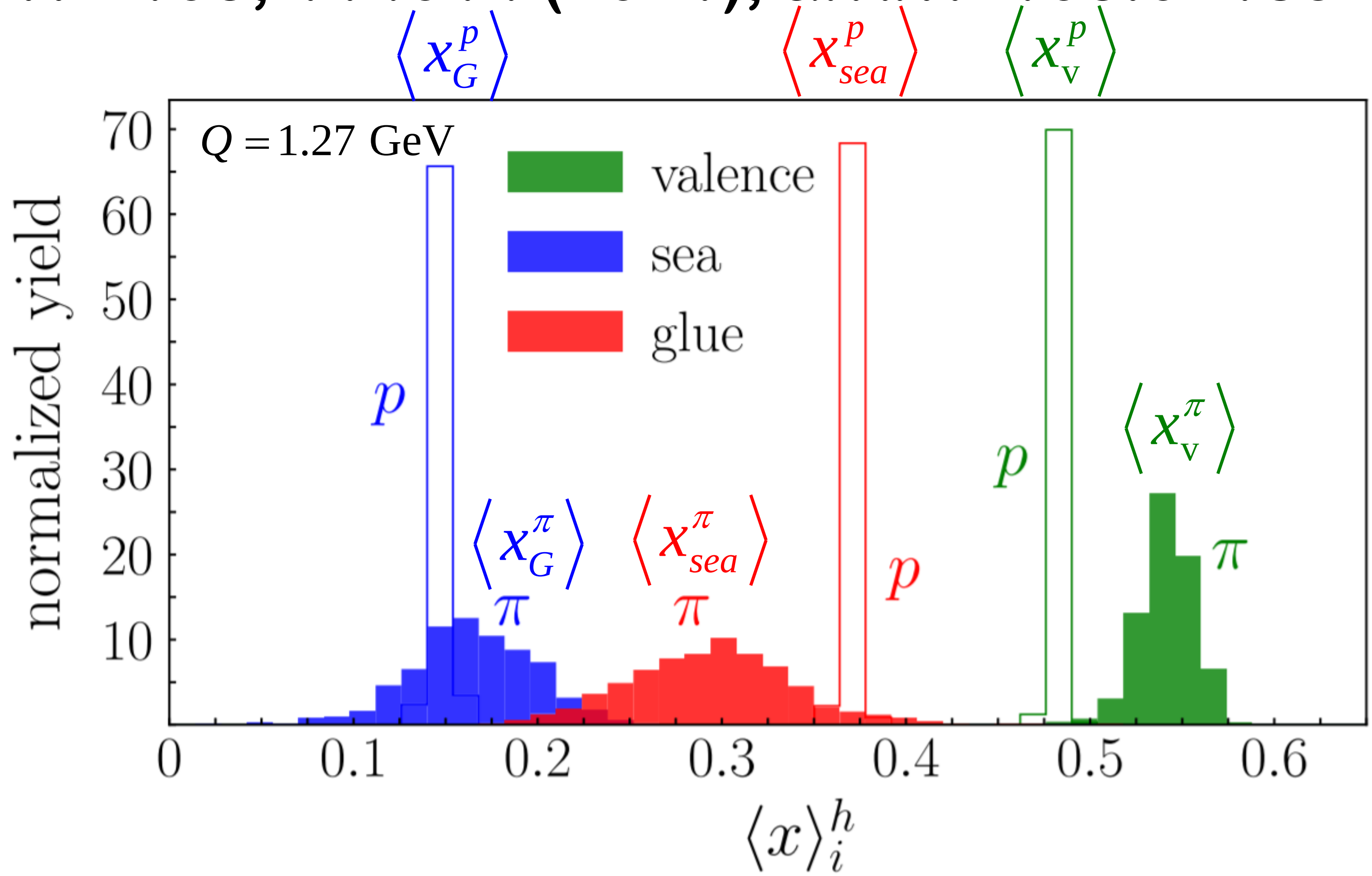
$Q^2 = 9.6\ \mathrm{GeV}^2$



The gluon distributions of SMRS and GRV are significantly larger than JAM and xFitter for x>0.1.

JAM21

PRD 103, 114014 (2021); arXiv:2103.02159



Pion's PDFs are much less determined than proton's.

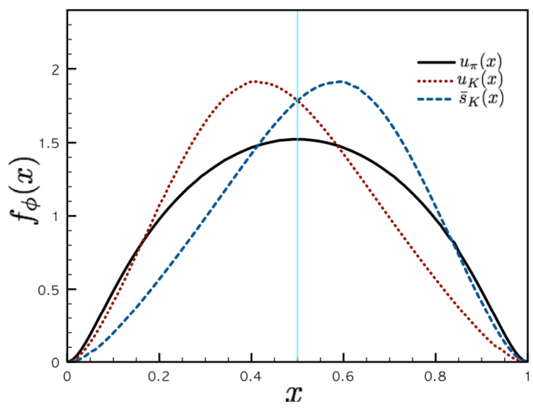
Theoretical Models of Pion/Kaon PDFs

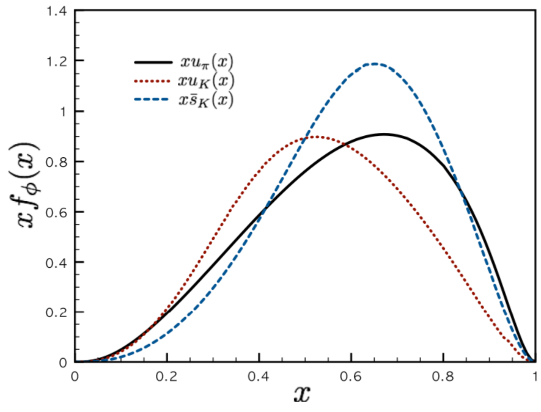
- **Nambu–Jona-Lasinio (NJL) model:** PRC 94, 035201 (2016); PRD 105, 034021, (2022)
- **Chiral constituent quark model:** PRD 86, 074005 (2012); PRD 97, 074015 (2018); 2302.05566
- **Dyson-Schwinger Equations (DSE):** PRD 93, 074021 (2016); PRD 93, 054029 (2018); PRL 124, 042002 (2020); EPJC (2020) 80:1064
- **Light-front & Holographic QCD:** PRD 101, 034024 (2020); PRD 106, 034003 (2022); PRD 107, 114023 (2023)
- **Maximum Entropy Input:** EPJC (2021) 81:302

Parton-distribution functions for the pion and kaon in the gauge-invariant nonlocal chiral-quark model

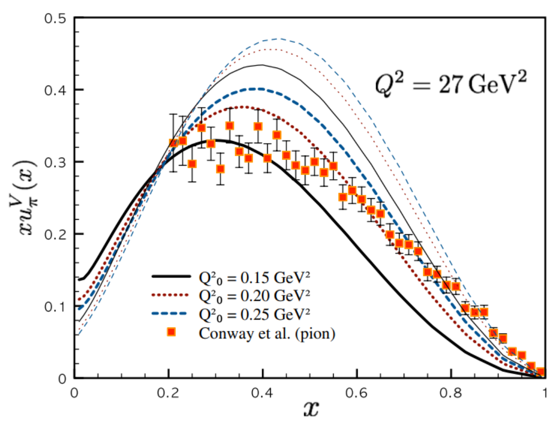
[Seung-il Nam, PRD 86, 074005 (2012)]

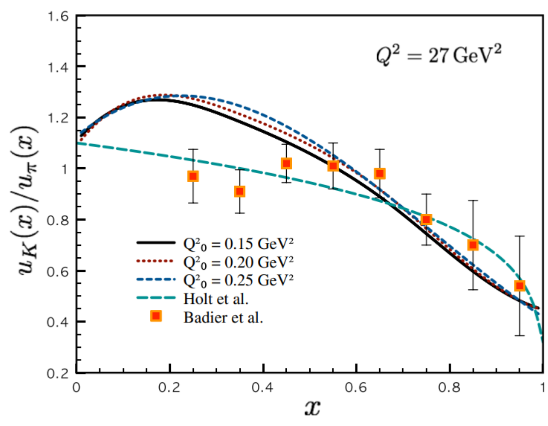
Model constructed at an intial scale Q_0





DGLAP QCD evolution





LQCD: Pion Momentum Fractions
[Alexandrou et al., PRL 127, 252001 (2021)]

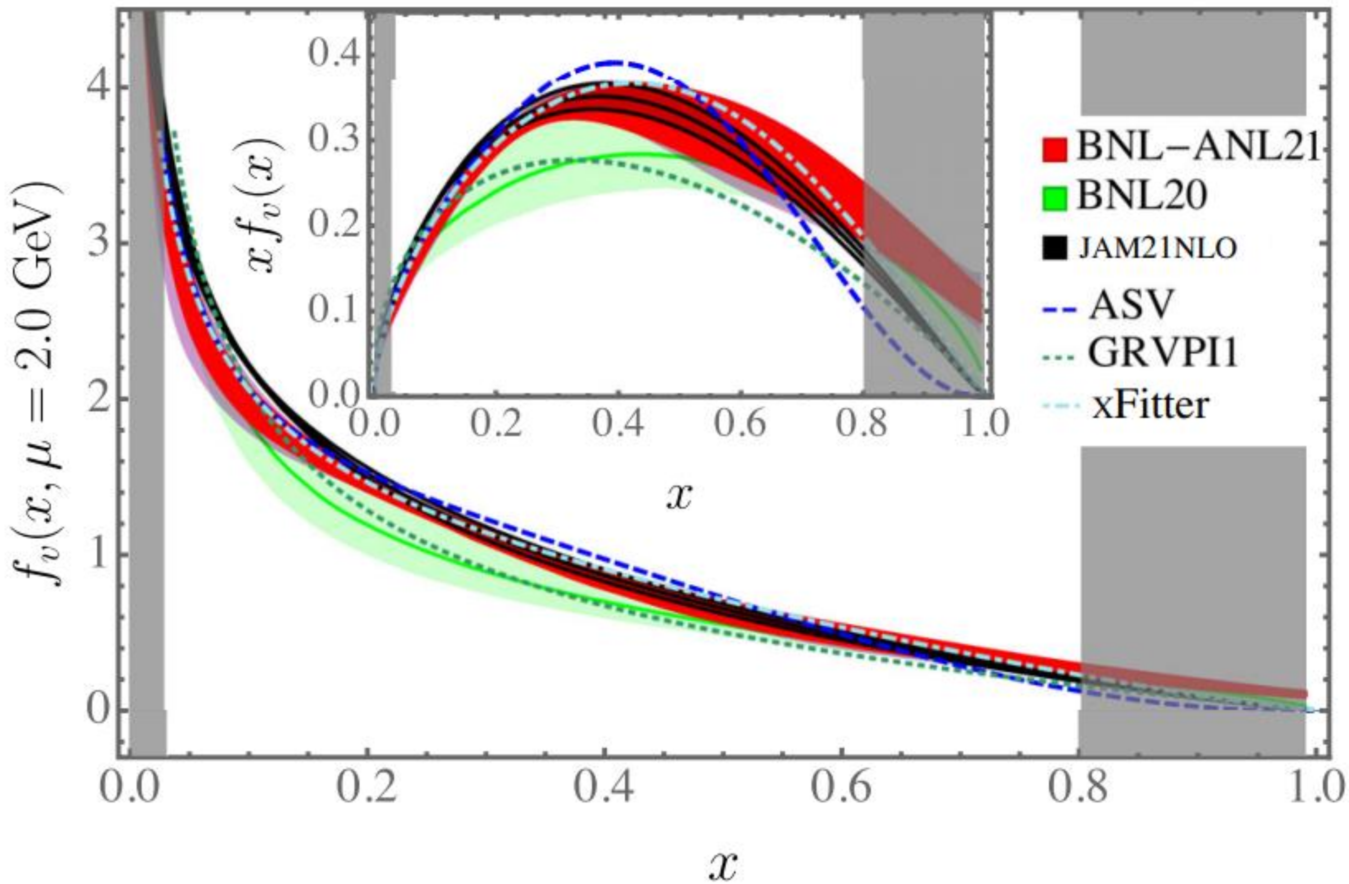
TABLE I. Compilation of results and comparison to literature. All values are at 2 GeV in the $\overline{\text{MS}}$ scheme.

	This work	RQCD [20]	JAM [45]	xFitter [46]
$\langle x\rangle^R_l)$	$0.601(28)(_{-21})$	...	...	...
$\langle x\rangle^R_s$	$0.059(13)(_{-10})$	...	...	...
$\langle x\rangle^R_c$	$0.019(05)(_{-10})$	...	...	...
$\langle x\rangle^R_g$	$0.52(11)(^{+02})$	...	0.42(4)	0.25(13)
$\Sigma_f\langle x\rangle^R_f$	$0.68(05)(_{-03})$	0.220(207)	0.58(9)	0.75(18)
$\langle x\rangle^R_{u+d-2s}$	0.48(01)	0.344(28)	...	...
$\langle x\rangle^R_{u+d+s-3c}$	0.60(03)	...	...	...

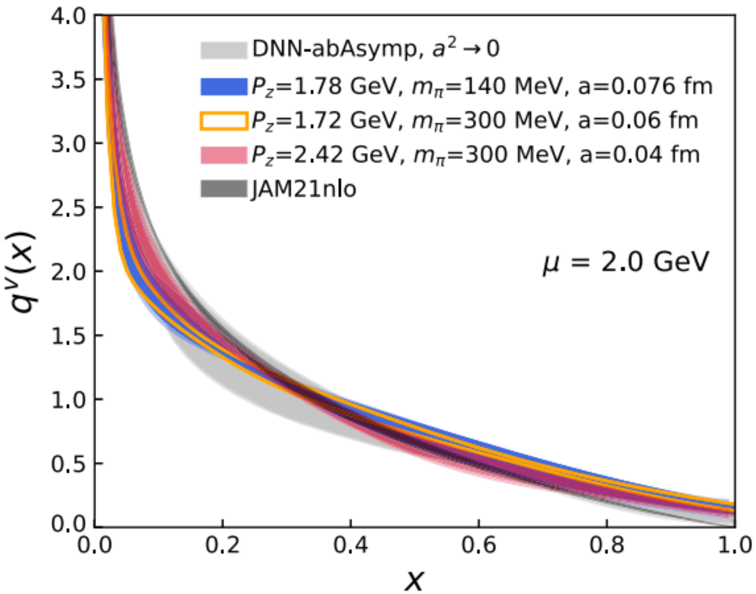
The gluon momentum fraction from LQCD is larger than those of JAM and xFitter.

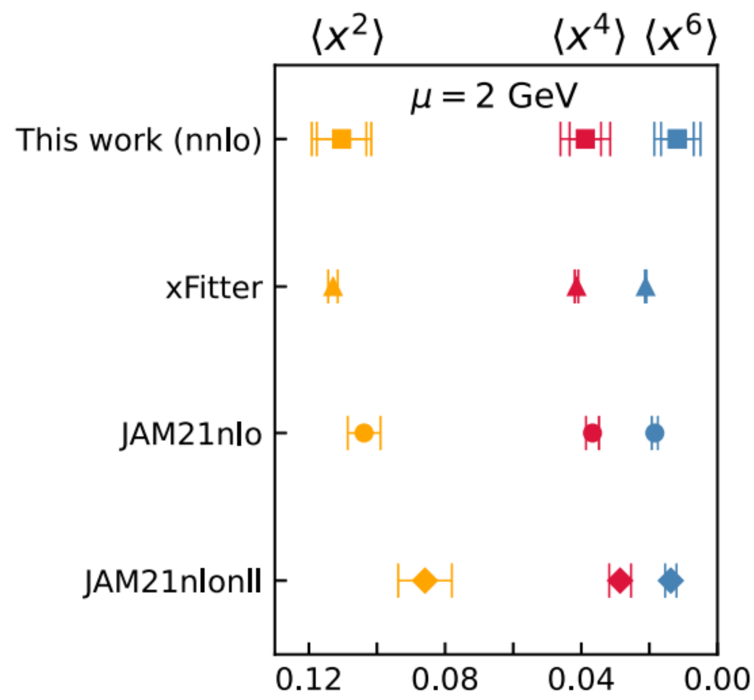
LQCD: Pion Valence PDFs

[Gao et al., PRL 128, 142003 (2022)]



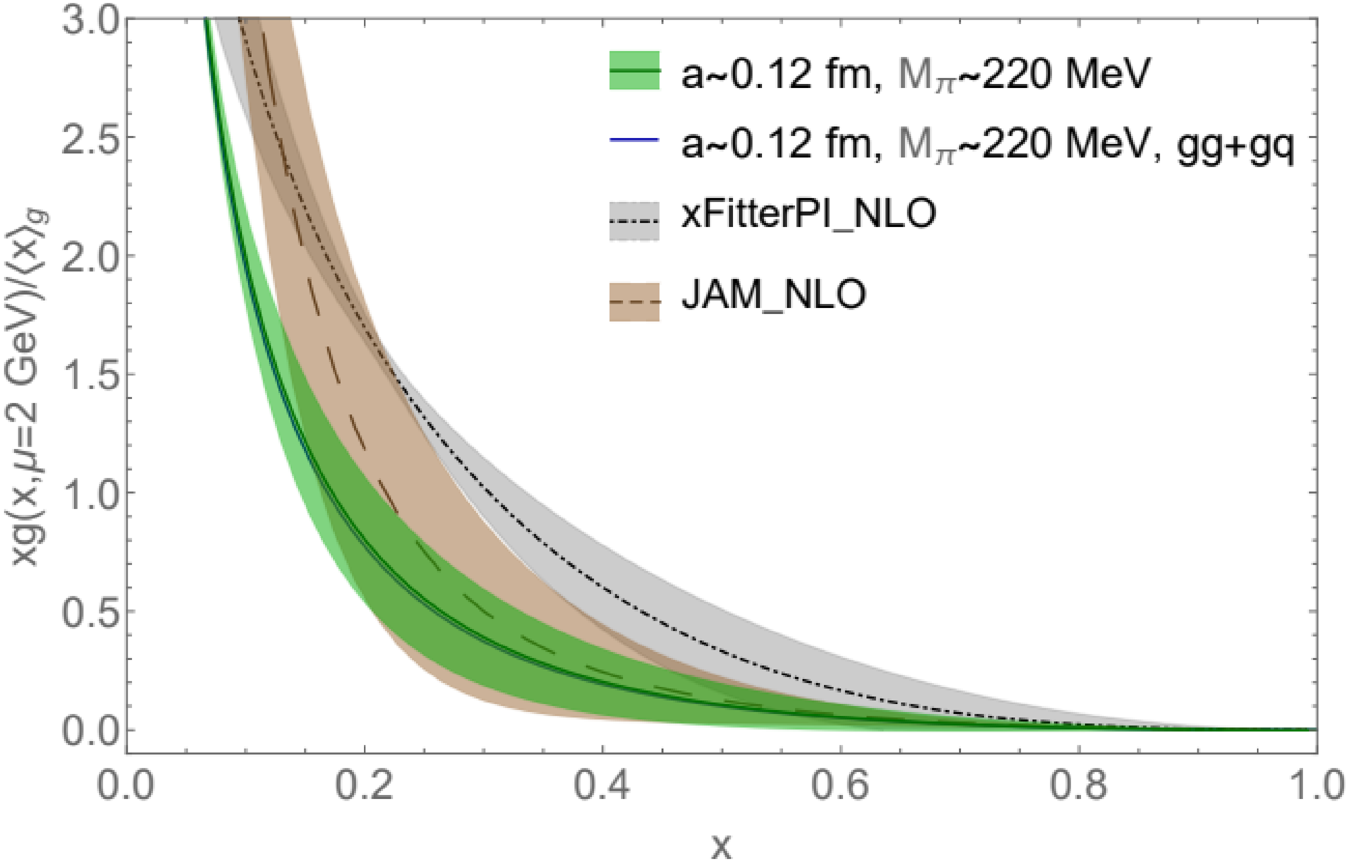
LQCD: Pion Momentum Fractions
[Gao et al., PRD 106, 114510 (2022)]





LQCD: Pion Gluon PDFs

[Z. Fan, H-W Lin, PLB 823, 136778 (2021)]



NYCU Lattice QCD Efforts

Pion DAs from a heavy-quark OPE

PHYSICAL REVIEW D **104**, 074511 (2021)

Parton physics from a heavy-quark operator product expansion: Formalism and Wilson coefficients

William Detmold,[1,2,*] Anthony V. Grebe,[1,†] Issaku Kanamori,[3,‡] C.-J. David Lin,[4,5,§] Robert J. Perry,[4,∥] and Yong Zhao[6,7,¶]

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[3]*RIKEN Center for Computational Science, Kobe 650-0047, Japan*
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PHYSICAL REVIEW D **105**, 034506 (2022)

Parton physics from a heavy-quark operator product expansion: Lattice QCD calculation of the second moment of the pion distribution amplitude

William Detmold,[1,2,*] Anthony V. Grebe,[1,†] Issaku Kanamori,[3,‡] C.-J. David Lin,[4,5,6,§] Santanu Mondal,[7,∥] Robert J. Perry,[4,5,¶] and Yong Zhao[8,**]

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PROCEEDINGS OF SCIENCE

2311.01322

Lattice QCD Constraints on the Fourth Mellin Moment of the Pion Light Cone Distribution Amplitude using the HOPE method

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[h]*Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA*

see also:
2111.14563

The lattice extraction of the TMD soft function using the auxiliary field representation of the Wilson line

Wayne Morris
with
Anthony Francis (NYCU), Issaku Kanamori (R-CCS, RIKEN), C.-J. David Lin (NYCU), Yong Zhao (Argonne)

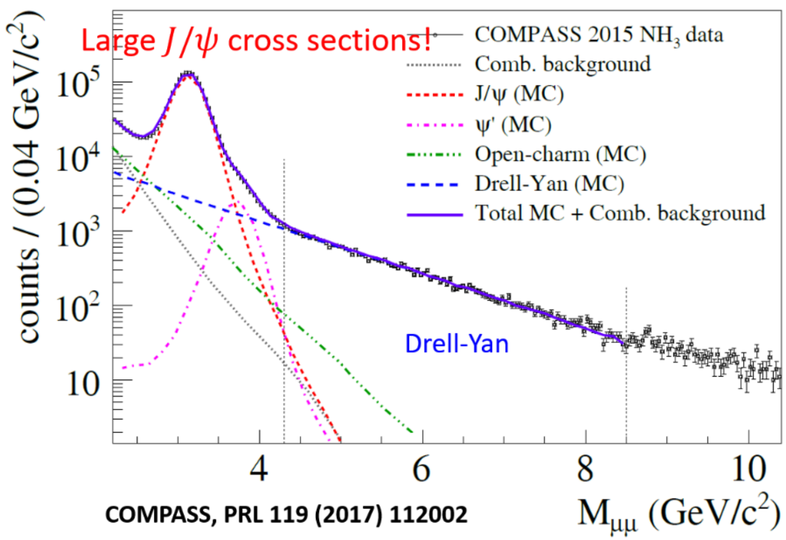
National Yang Ming Chiao Tung University (國立陽明交通大學)

August 4, 2023

2023 LATTICE

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

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

Wen-Chen Chang

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Jen-Chieh Peng

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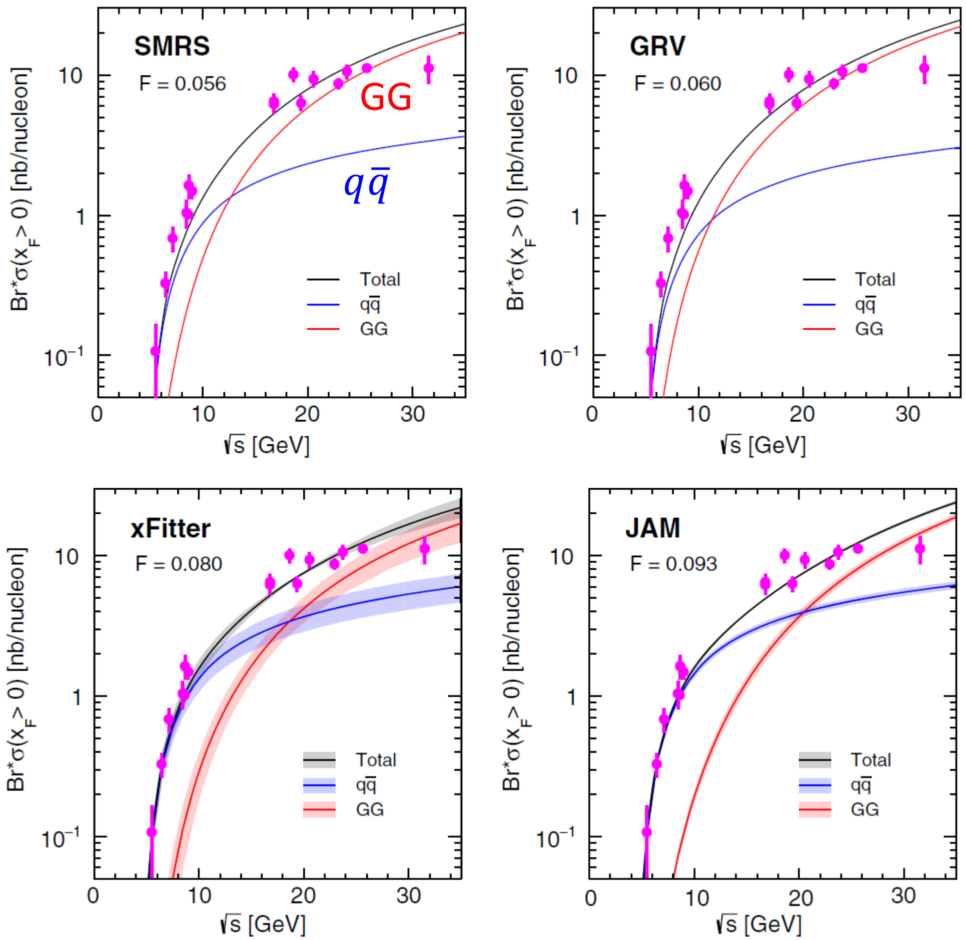
(Received 12 June 2020; accepted 8 September 2020; published 24 September 2020)

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

Data vs. CEM NLO: $\sigma(\sqrt{s})$

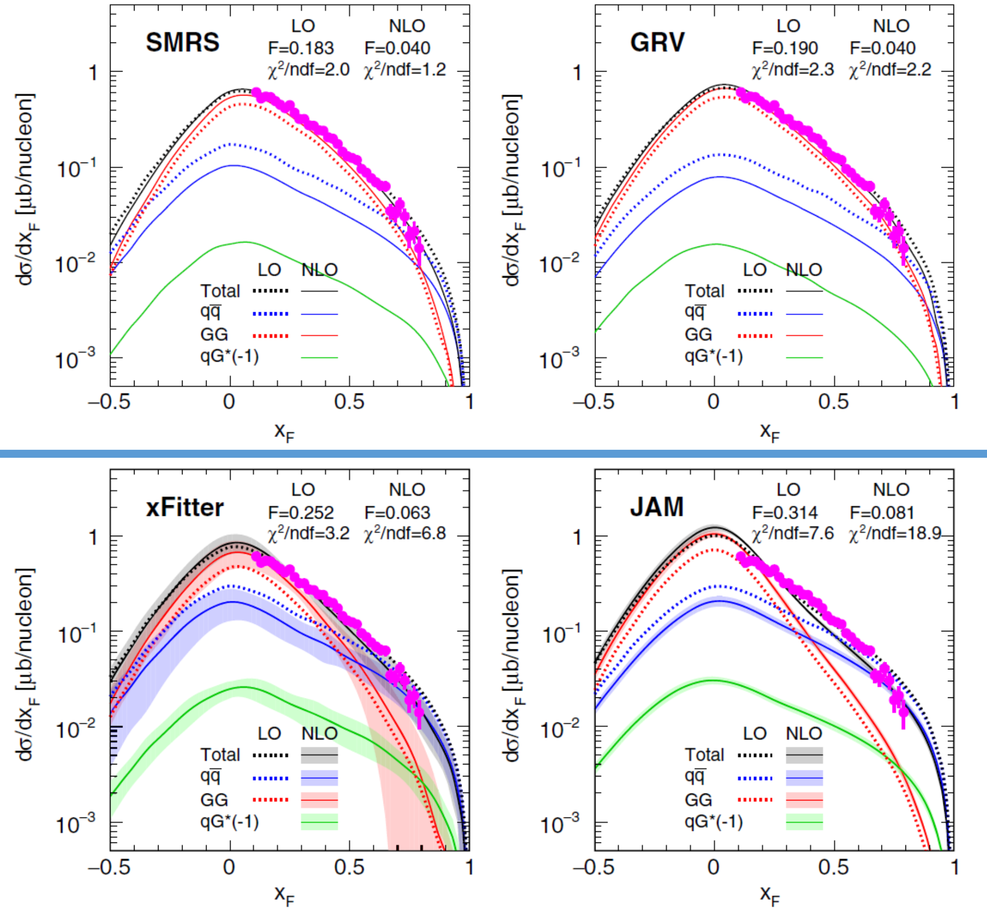
$$\pi^{-} + N \rightarrow Jpsi + X$$



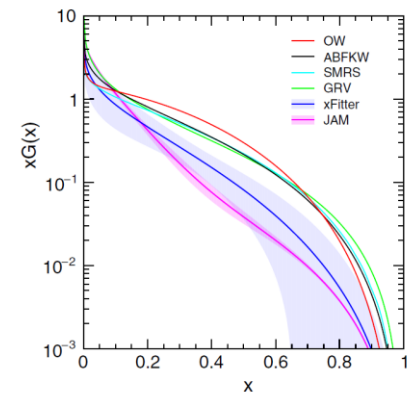
Dominant process:
Threshold- qqbar
High energies- GG

Data vs. CEM NLO

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



Dominant process:
xF=0- GG
Large xF- qqbar



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

Data vs. CEM Calculations

TABLE III. Results of F factor and χ^2/ndf value of the best fit of the NLO CEM calculations for SMRS, GRV, xFitter, and JAM pion PDFs to the data listed in Table II. The F^* factor and χ^2/ndf* are the ones corresponding to the fit with inclusion of PDF uncertainties for xFitter and JAM.

Data	SMRS		GRV		xFitter				JAM			
Experiment (P_{beam})	F	χ^2/ndf	F	χ^2/ndf	F	F^*	χ^2/ndf	χ^2/ndf*	F	F^*	χ^2/ndf	χ^2/ndf*
E672, E706 (515)	0.040	1.2	0.040	2.2	0.063	0.063	6.8	4.7	0.081	0.081	18.9	18.5
E705 (300)	0.052	2.3	0.053	1.9	0.073	0.076	3.2	1.3	0.086	0.086	16.1	15.9
NA3 (280)	0.046	1.5	0.049	2.0	0.067	0.069	5.0	3.2	0.081	0.081	10.4	10.3
NA3 (200)	0.046	2.1	0.050	2.2	0.065	0.066	5.0	1.3	0.081	0.081	7.7	7.6
WA11 (190)	0.054	5.0	0.058	7.2	0.078	0.076	19.4	6.2	0.091	0.091	73.7	72.9
NA3 (150)	0.065	1.1	0.071	1.0	0.089	0.091	2.6	1.6	0.108	0.108	3.9	3.8
E537 (125)	0.044	1.5	0.049	1.5	0.065	0.065	3.1	1.4	0.083	0.083	3.5	3.5
WA39 (39.5)	0.068	1.3	0.079	1.4	0.073	0.072	1.1	0.8	0.080	0.080	1.2	1.2

- The hadronization F factor is stable across energy.
- High-energy J/ψ data have a large sensitivity to the large-x gluon density of pions.
- The valence-quark distributions plays a minor role if away from the threshold.
- **CEM NLO calculations favor SMRS and GRV PDFs whose gluon densities at x > 0.1 are higher, compared with xFitter and JAM PDFs.**

Are these observations model dependent?

NRQCD for Jpsi

- **PYTHIA 6 or 8**:
  NLO; results hard to understand…
- **PRD 54, 2005 (1996)**:
  LO; theoretical expressions available
- **NPB 514 (1998) 245**; **PLB 638 (2006) 202**:
  NLO; (complicated) theoretical expressions available, but open source codes are not available

Non-relativistic QCD model (NRQCD)

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

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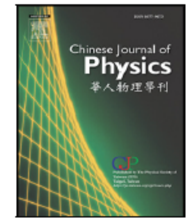

Check for updates

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

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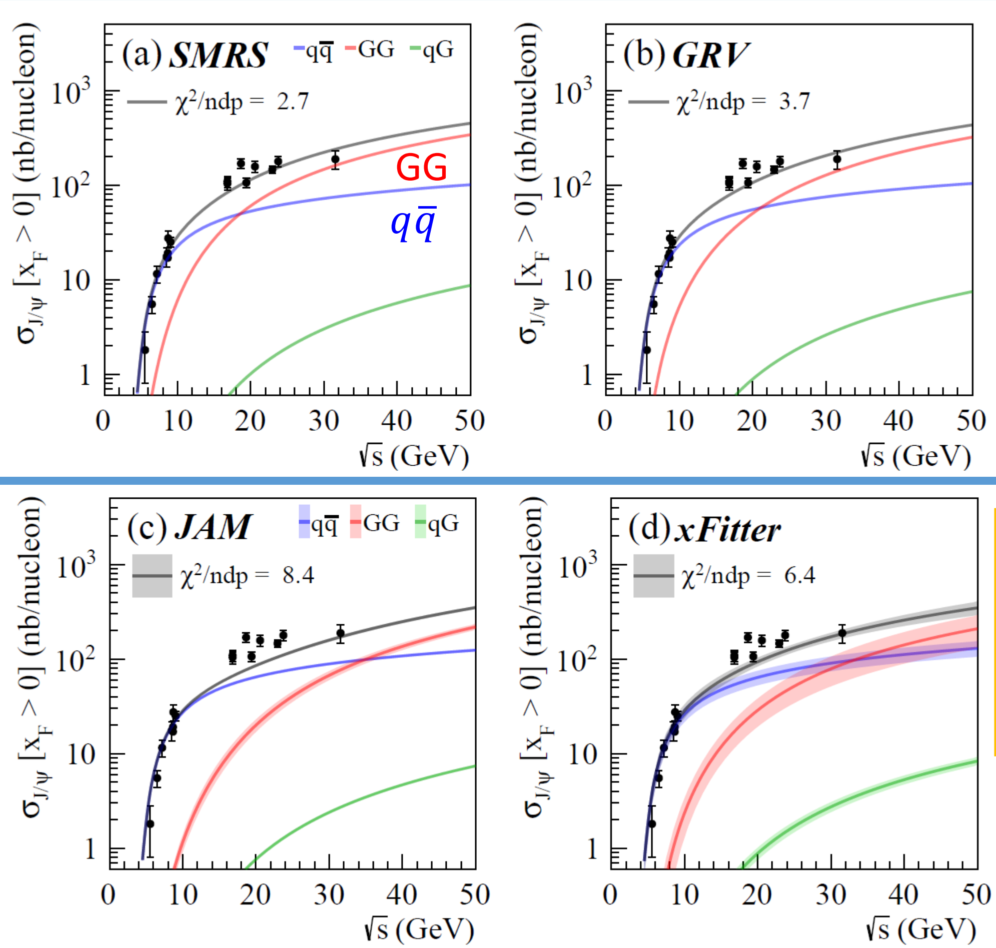
ARTICLE INFO

Keywords:
Charmonium production
Pion PDFs
NRQCD
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.

π^-+N→Jpsi+X: pion PDFs



Dominant process:
Threshold- qqbar
High energies- GG

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

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

Wen-Chen Chang,[1] Jen-Chieh Peng,[2] Stephane Platchkov,[3] and Takahiro Sawada[4]

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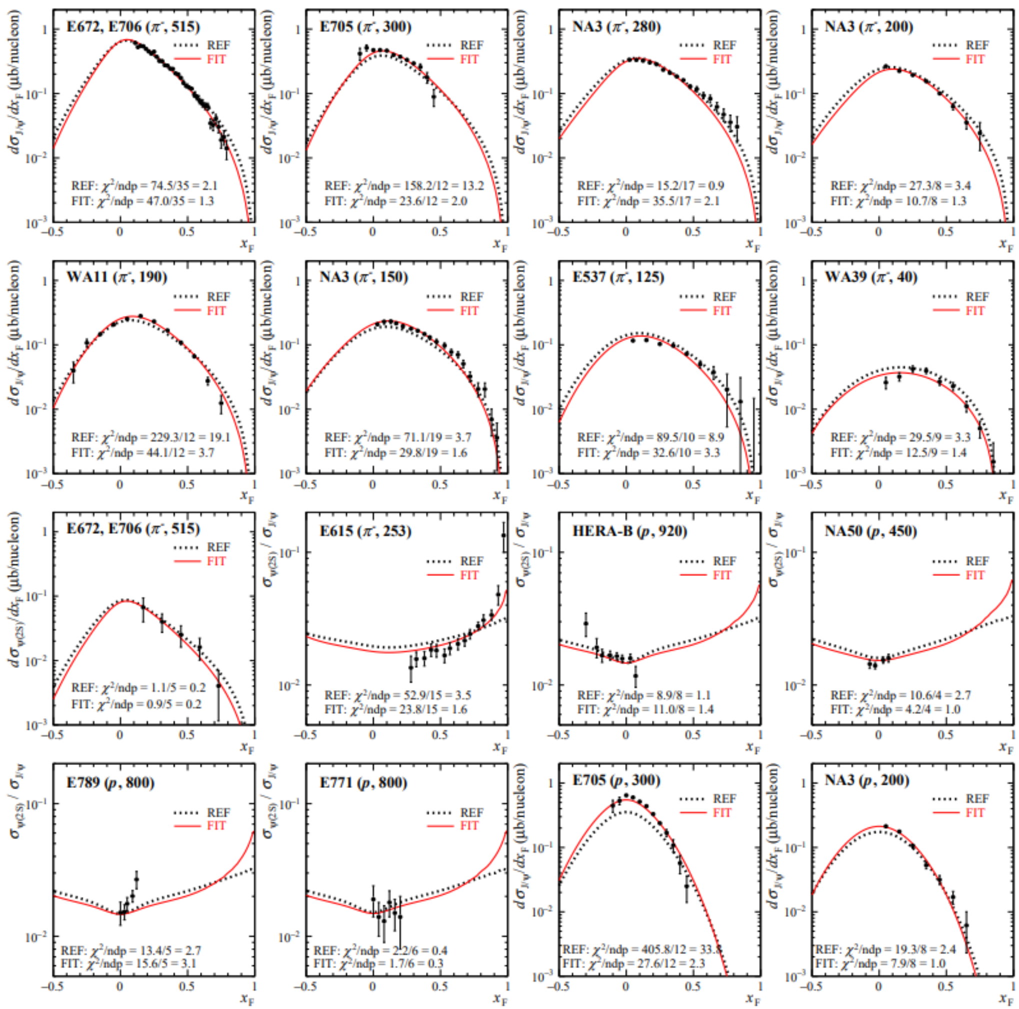
(Received 8 September 2022; accepted 31 January 2023; published 7 March 2023)

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 (Jpsi, psi') vs. NRQCD

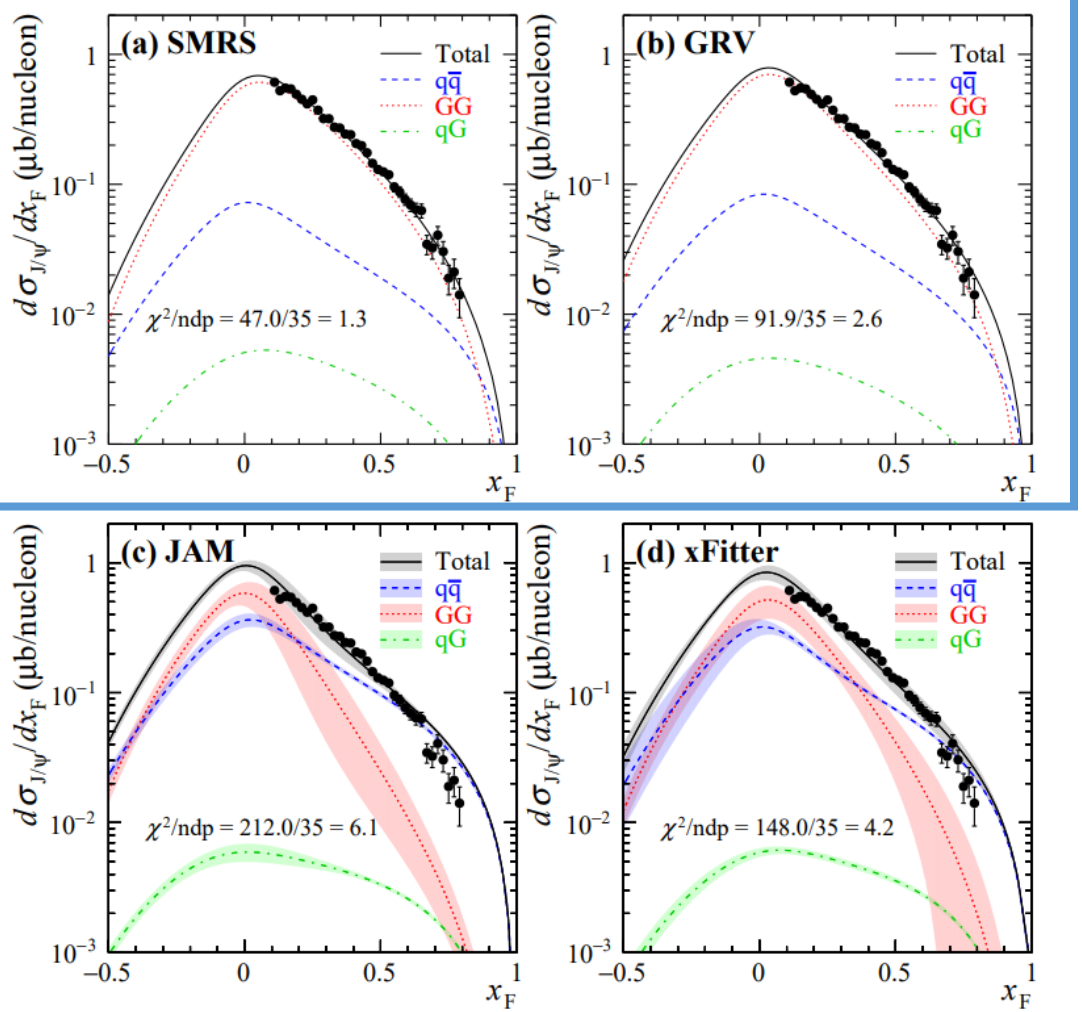


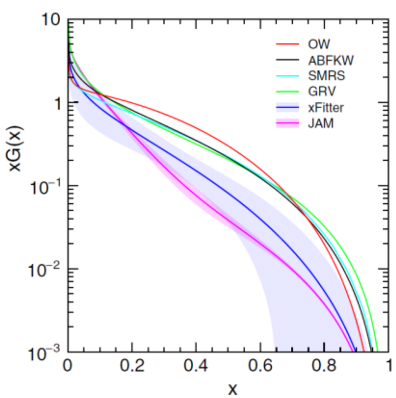
We can achieve a reasonable description of the charmonium data with the proton and pion beams by NRQCD calculations with similar LDMEs obtained in Chin. J. Phys. 73 (2021) 13.

Data vs. NRQCD

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

Dominant process:
xF=0- GG
Large xF- qqbar

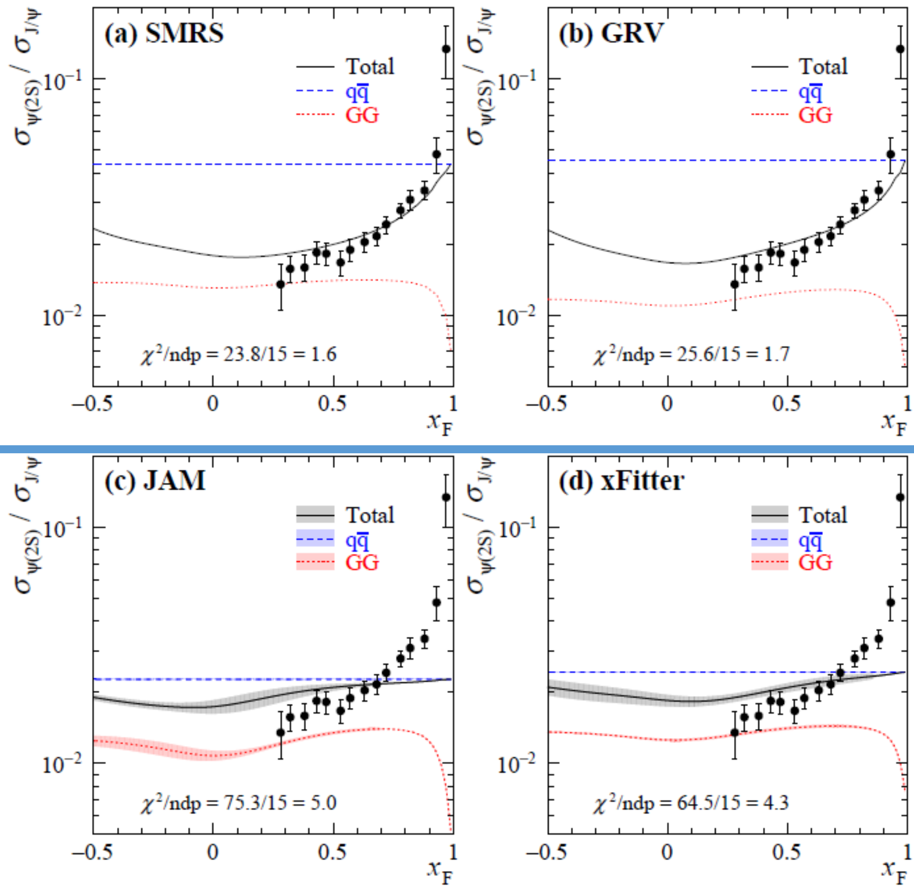




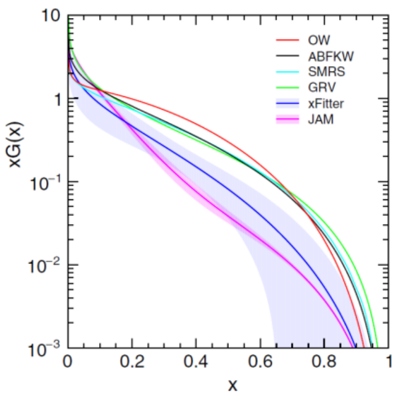
Data favor SMRS and GRV PDFs with larger gluon densities at x > 0.1.

Data vs. NRQCD

[$\pi^- + W \rightarrow Jpsi/psi' + X$ at 252 GeV, PRD 44, 1909 (1991)]



Psi' receives stronger contributions from qqbar, compared to Jpsi.



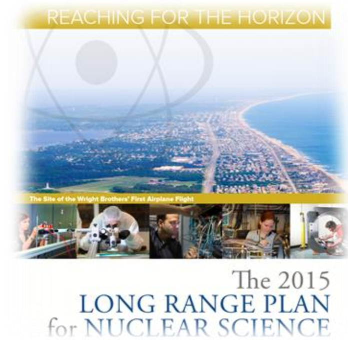
Data favor SMRS and GRV PDFs with larger gluon densities at x > 0.1.

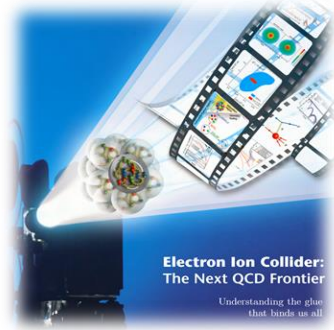
Data vs. NRQCD Calculations

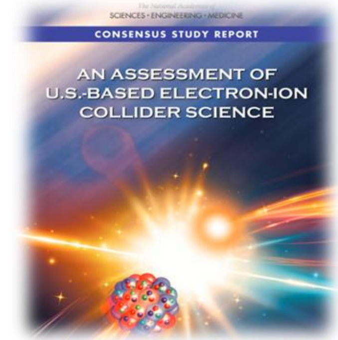
Data	SMRS		GRV		JAM		xFitter	
Exp	χ^2/ndp	F	χ^2/ndp	F	χ^2/ndp	F	χ^2/ndp	F
E672, E706 ($\sigma^{J/\psi}$)	1.3	0.80 ± 0.01	2.6	0.79 ± 0.01	6.1	1.14 ± 0.01	4.2	1.08 ± 0.02
E705 ($\sigma^{J/\psi}$)	2.0	0.98 ± 0.02	1.7	0.96 ± 0.02	4.1	1.19 ± 0.01	2.6	1.18 ± 0.01
NA3 ($\sigma^{J/\psi}$)	2.1	0.86 ± 0.02	2.3	0.87 ± 0.02	2.7	1.00 ± 0.02	2.9	1.01 ± 0.02
NA3 ($\sigma^{J/\psi}$)	1.3	0.87 ± 0.02	0.9	0.89 ± 0.02	1.8	0.92 ± 0.02	1.5	0.95 ± 0.02
WA11 ($\sigma^{J/\psi}$)	3.7	1.02 ± 0.02	8.5	1.02 ± 0.02	29.9	1.09 ± 0.01	22.0	1.12 ± 0.02
NA3 ($\sigma^{J/\psi}$)	1.6	1.24 ± 0.03	1.3	1.23 ± 0.03	1.5	1.10 ± 0.02	1.6	1.18 ± 0.03
E537 ($\sigma^{J/\psi}$)	3.3	0.88 ± 0.00	1.6	0.88 ± 0.01	2.6	0.88 ± 0.00	2.1	0.88 ± 0.01
WA39 ($\sigma^{J/\psi}$)	1.4	1.30 ± 0.04	1.4	1.18 ± 0.07	2.9	0.70 ± 0.00	1.3	0.70 ± 0.05
E672, E706 ($\sigma^{\psi(2S)}$)	0.2	0.80 ± 0.01	0.2	0.79 ± 0.01	0.3	1.14 ± 0.01	0.2	1.08 ± 0.02
E615 ($\sigma^{\psi(2S)}/\sigma^{J/\psi}$)	1.6	1 ± 0	1.7	1 ± 0	5.0	1 ± 0	4.3	1 ± 0
HERA-B ($\sigma^{\psi(2S)}/\sigma^{J/\psi}$)	1.4	1 ± 0	1.5	1 ± 0	1.2	1 ± 0	1.2	1 ± 0
NA50 ($\sigma^{\psi(2S)}/\sigma^{J/\psi}$)	1.0	1 ± 0	1.6	1 ± 0	1.3	1 ± 0	1.1	1 ± 0
E789 ($\sigma^{\psi(2S)}/\sigma^{J/\psi}$)	3.1	1 ± 0	3.3	1 ± 0	2.8	1 ± 0	2.9	1 ± 0
E771 ($\sigma^{\psi(2S)}/\sigma^{J/\psi}$)	0.3	1 ± 0	0.3	1 ± 0	0.3	1 ± 0	0.3	1 ± 0
E705 ($\sigma^{J/\psi}$)	2.3	1.20 ± 0.00	2.2	1.20 ± 0.00	5.7	1.20 ± 0.00	3.1	1.20 ± 0.00
NA3 ($\sigma^{J/\psi}$)	1.0	1.00 ± 0.01	1.2	1.00 ± 0.01	1.9	1.00 ± 0.01	1.6	1.00 ± 0.01

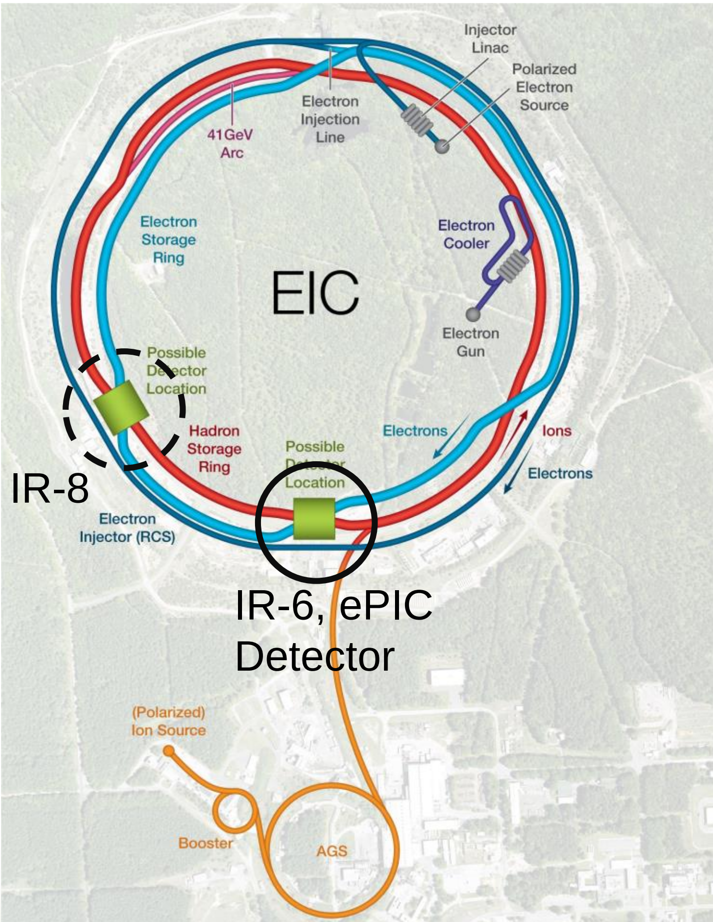
NRQCD calculations favor SMRS and GRV PDFs whose gluon densities at x > 0.1 are higher, compared with xFitter and JAM PDFs.

EIC Scope









Project Design Goals

- High Luminosity: L= $10^{33} - 10^{34}$ $cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

IR-8

p/A beam → ← e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

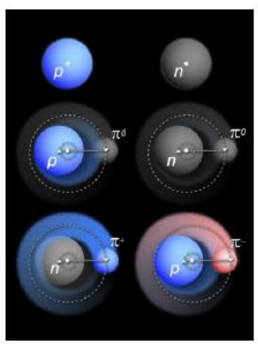
https://indico2.riken.jp/event/4389/contributions/20377/attachments/11865/17180/EIC_Science_and_Project_Status_EIC_Asia.pptx

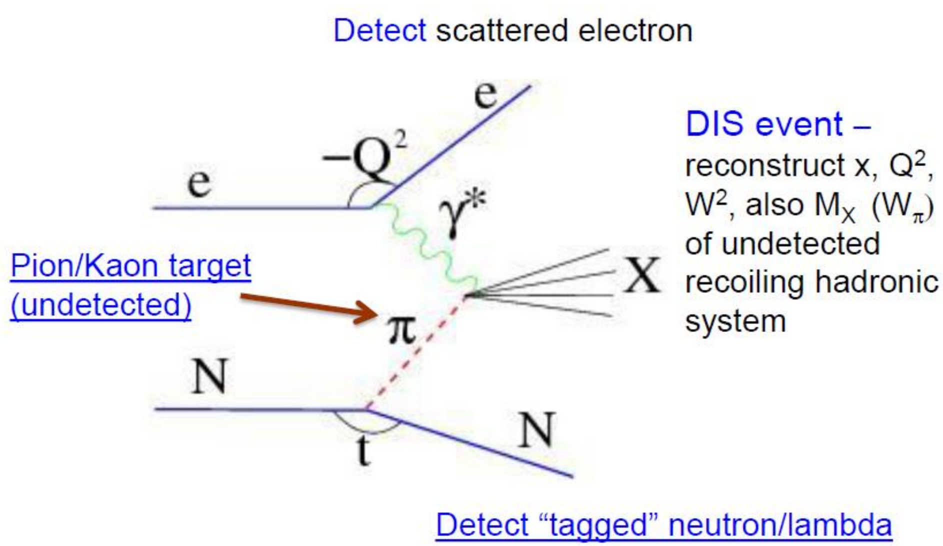
EIC: Tagged processes of DIS/Jpsi

Year >2030

Physics Objects for Pion/Kaon Structure Studies

- Sullivan process – scattering from nucleon-meson fluctuations





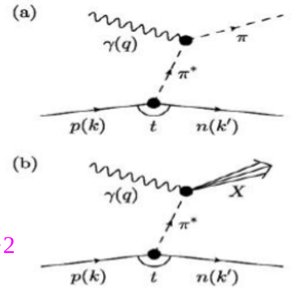
https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf

https://arxiv.org/abs/1907.08218

EIC: Sullivan Process

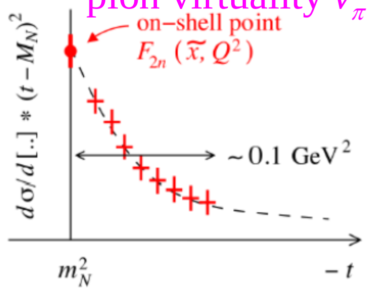
Year >2030

Pion and Kaon Sullivan Process



- The **Sullivan process can provide reliable access to a meson target** as t becomes space-like if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality.

pion virtuality $v_\pi = \frac{m_\pi^2 - t}{m_\pi^2} \leq 30 \rightarrow -t \leq 0.6\ \mathrm{GeV}^2$



- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations found that for $-t \leq 0.6$ GeV^2, all changes in pion structure are modest** so that a well-constrained experimental analysis should be reliable Similar analysis for the kaon indicates that Sullivan processes can provide a valid kaon target for $-t \leq 0.9$ GeV^2

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

12

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

https://arxiv.org/abs/1907.08218

EIC: Sullivan Process

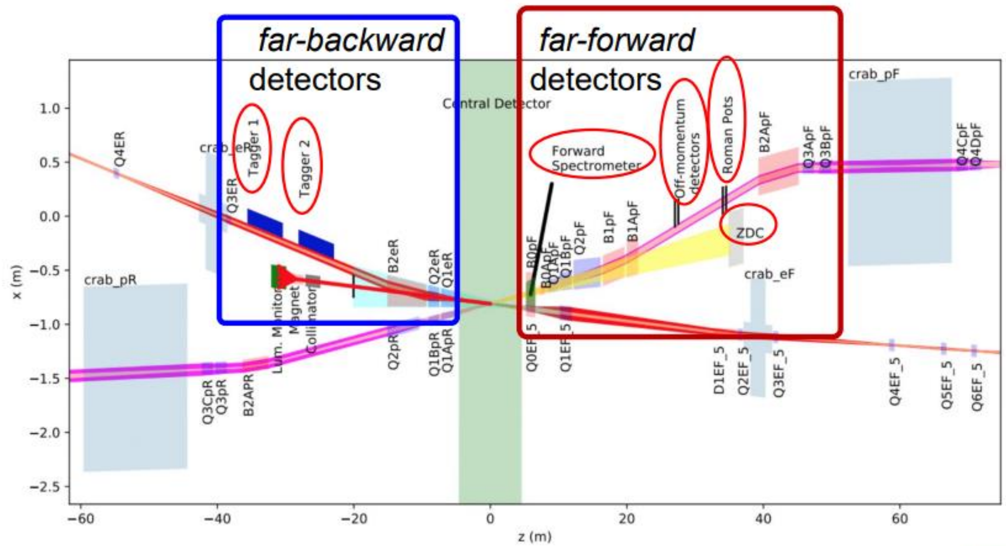
Year >2030

EIC Far-Forward Detector

Highly Integrated detector system: ~75m
1. Central detector: ~10m
2. Backward electron detection: ~35m
3. Forward hadron spectrometer: ~40m

Lesson learned from HERA – ensure low-Q^2 coverage

Various stage detector to capture forward-going protons and neutrons, and also decay products (Δ, Λ).



https://indico.cern.ch/event/971469/contributions/4107843/attachments/2152646/3630025/EIC_PIK_EHM_AMBER_CERN_113020.pdf

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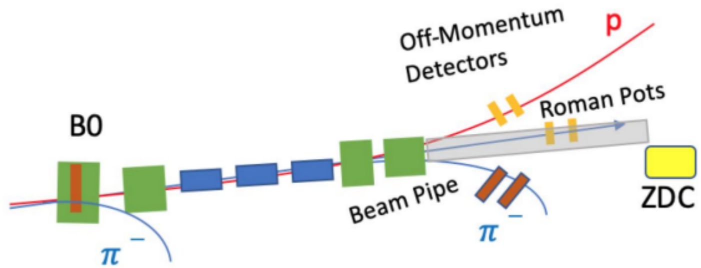
EIC: Sullivan Process

Year >2030

Meson Structure: Summary of EIC Detector Requirements



- **For π-n:**
  - Lower energies (5 on 41, 5 on 100) require at least 60 x 60 cm^2
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
- **For π-n and K^+/Λ:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better
- **K^+/Λ benefits from low energies (5 on 41, 5 on 100) and also need:**
  - $\Lambda \to n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - $\Lambda \to p + \pi^-$: additional trackers in opposite direction on path to ZDC – more challenging
- Standard electron detection requirements
- Good hadron calorimetry for good x resolution at large x

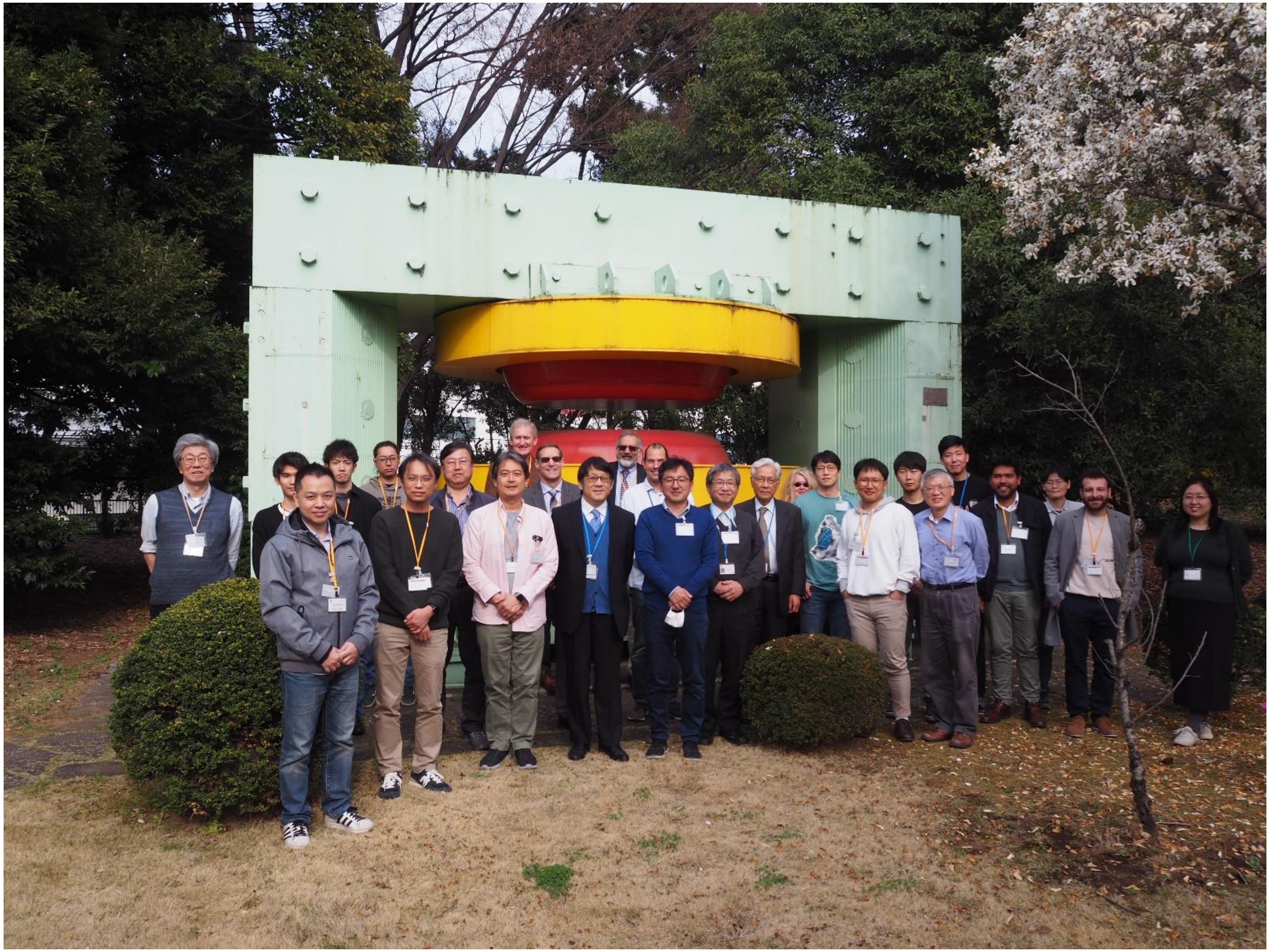
https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf
https://arxiv.org/abs/1907.08218 , https://arxiv.org/abs/2102.11788

EIC Asia Workshop

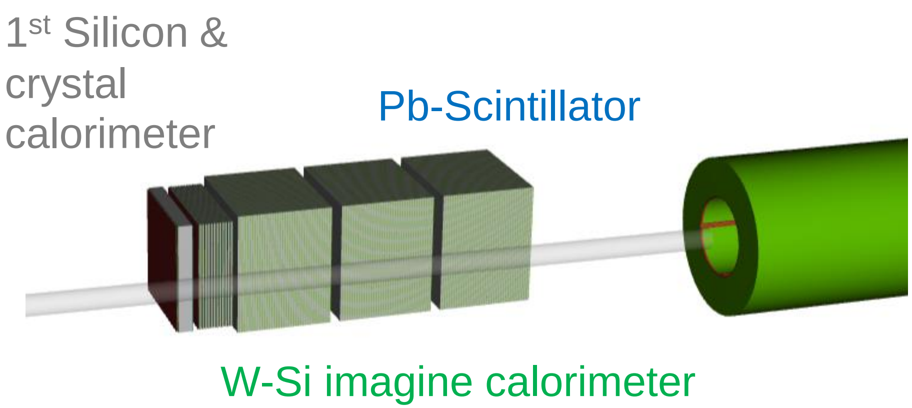
16 Mar 2023, 07:00 → 18 Mar 2023, 13:30 Asia/Tokyo

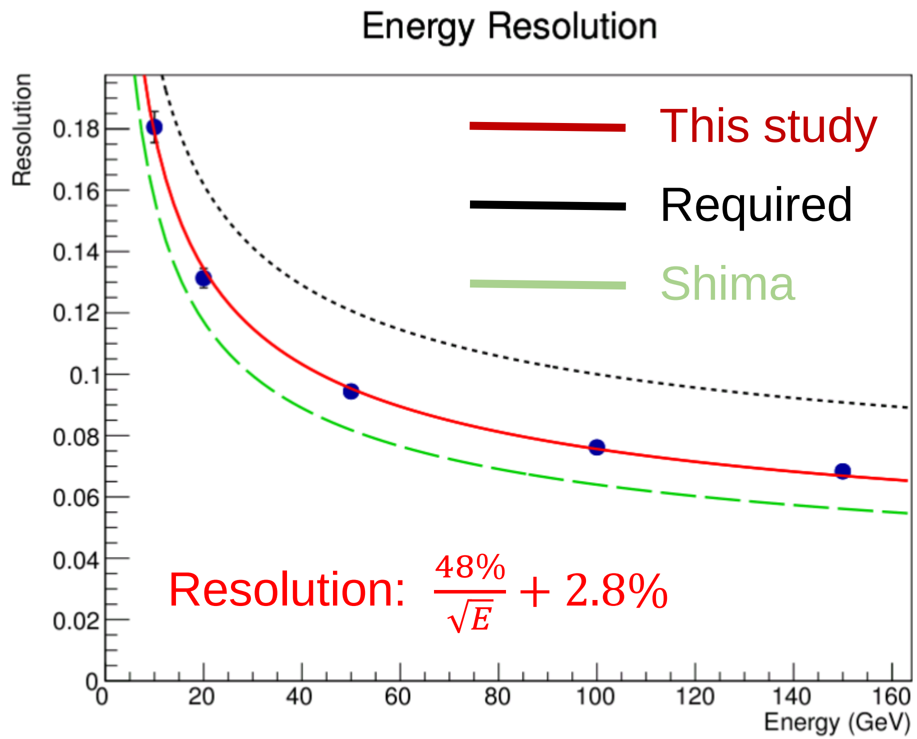
Okochi-hall (Bldg C32) (RIKEN)

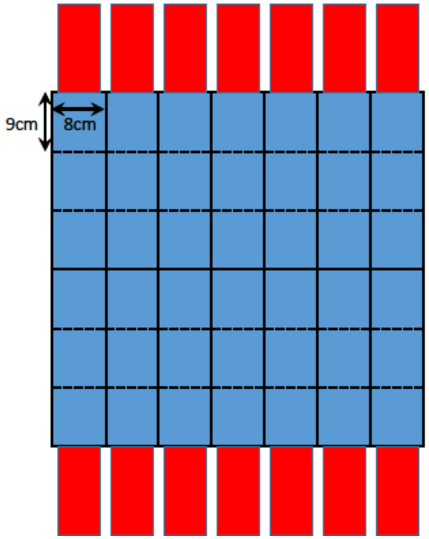
Ralf Seidl (RIKEN) , Taku Gunji (Center for Nuclear Study, the University of Tokyo) , Yuji Goto (RIKEN)



ePIC ZDC – Simulation



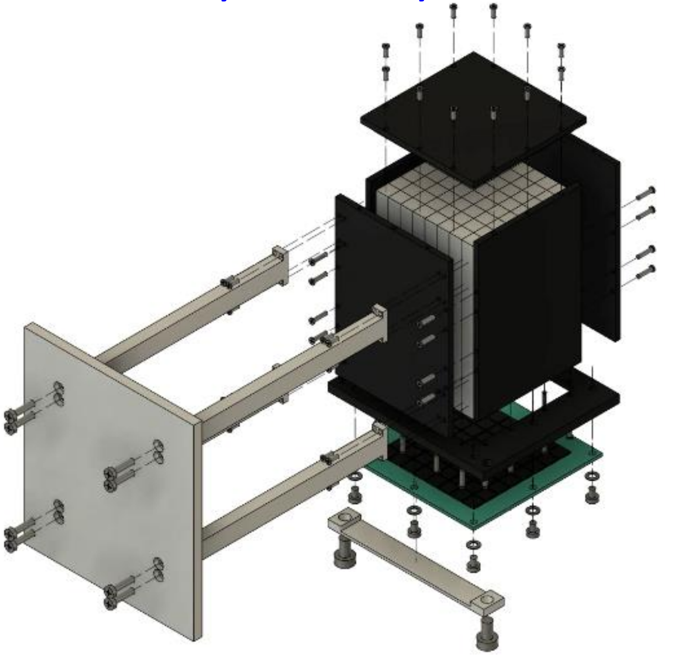




- ZDC simulation updated
  - Upstream modules with smaller lateral size to fit between beam pipes
  - Overall length about 183 cm, within 2m limit
  - More cost effective, Pb-Silicon module removed
  - HCAL resolution improved
- Base design, meets the resolution requirement

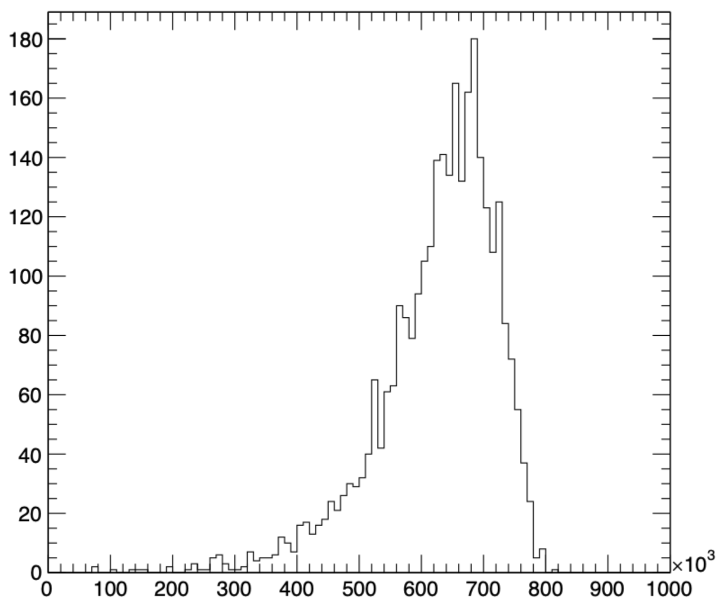
ePIC ZDC Prototype with LYSO Crystals

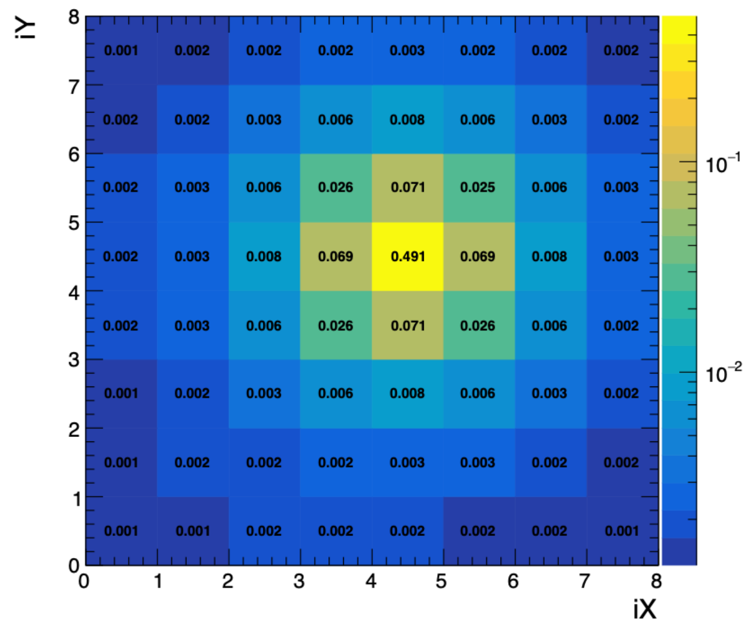
8x8 LYSO crystal array



- Aim to have a beam test at Tohoku University in February 2024 to compare the performance between the LYSO and $PbWO_4$ crystals

Standalone ZDC ECAL Simulation with LYSO Crystals

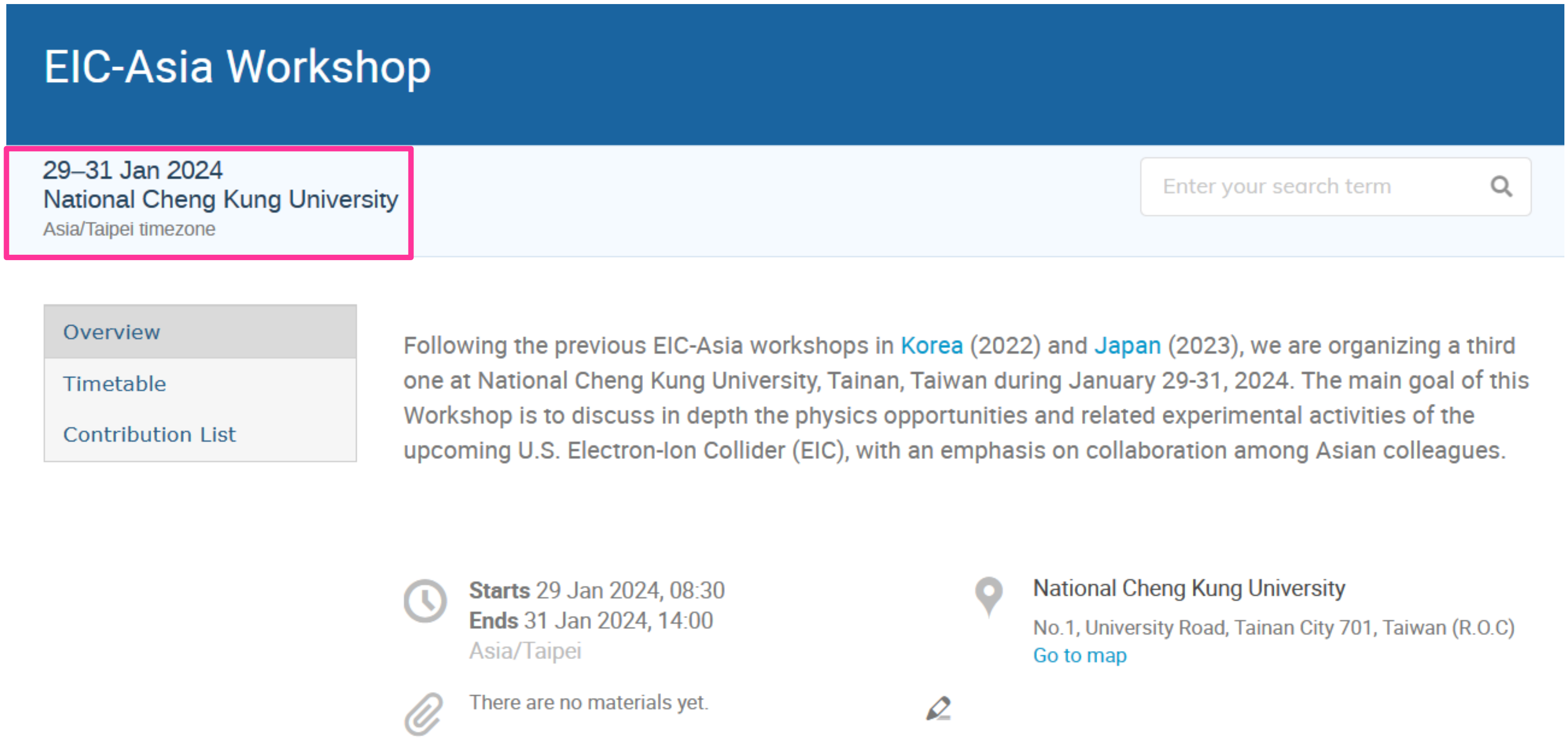




- For the beam test in February 2024
- 900 MeV positron beam
- Various optical properties in the G4 simulation are being studied

EIC-Asia workshop in Taiwan

https://indico.phys.sinica.edu.tw/event/88/



Summary

- Light meson partonic structures are mostly determined by Drell-Yan process, supplemented by the other data of prompt-photon, charmonium production and the DIS Sullivan process.
- Lattice QCD makes significant progress in predicting the pion/kaon PDFs. Recent studies show that the large-x gluon strengths of modern xFitter and JAM pion PDFs seem too weak to describe both data sets of pion- and kaon-induced Jpsi production.
- Via the tagged-DIS, the future EIC shall significantly improve our knowledge of pion/kaon PDFs. The far-forward detectors are essential for this measurement. Asia EIC team are working on this project.
- The measurement of R_{pa} of Jpsi/psi' by sPHENIX could be used to explore the gluon density of nuclear PDFs.