Science at the Luminosity Frontier:
Jefferson Lab at 22 GeV
9–13 Dec 2024, INFN, Laboratori Nazionali di Frascati

Charmed pentaquark production at the EicC and JLab 12 to 22 GeV

and other related topics

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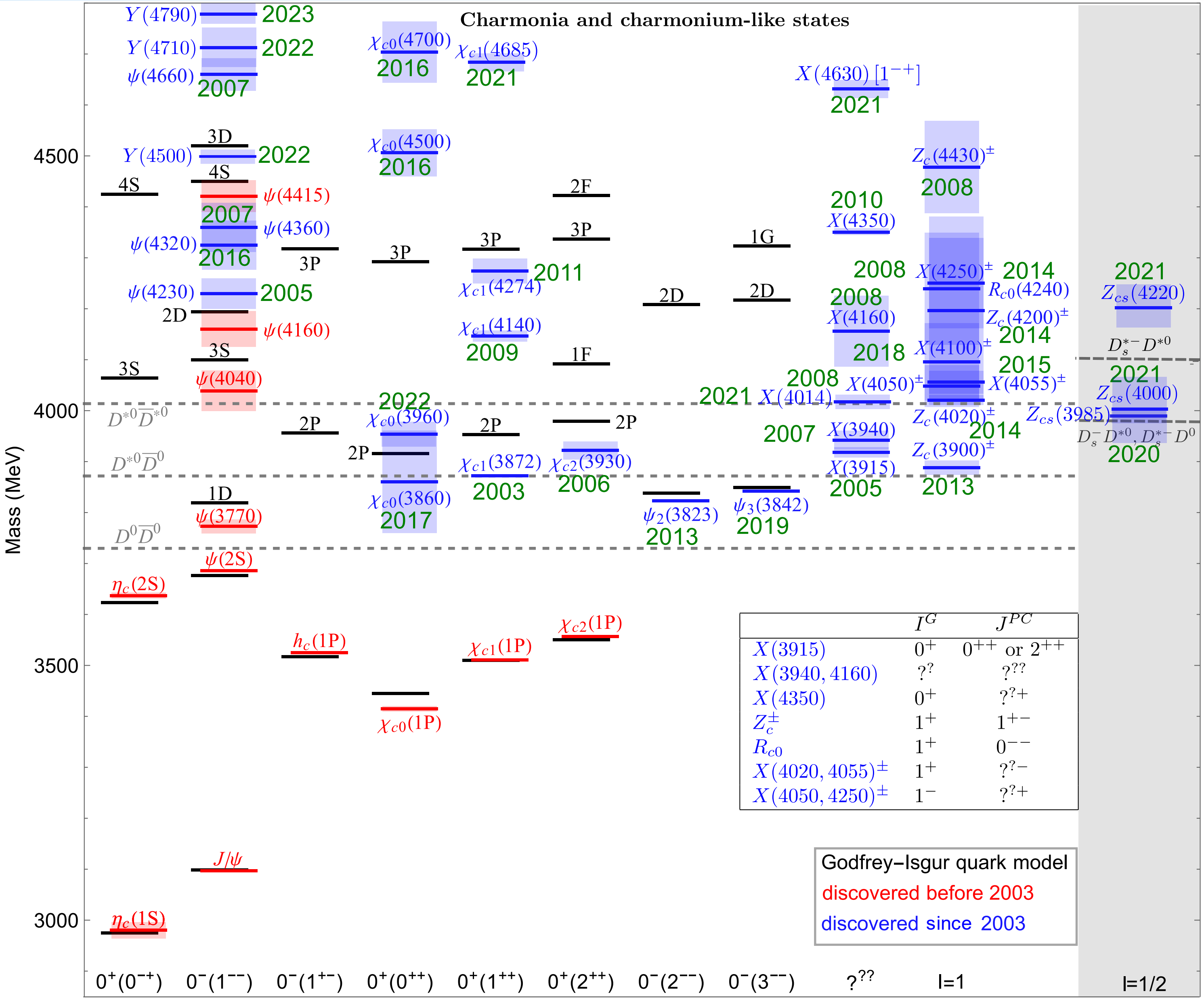
Z. Yang, FKG, Semi-inclusive lepto-production of hidden-charm exotic hadrons, arXiv:2107.12247;
P.-P. Shi, FKG, Z. Yang, Semi-inclusive electroproduction of hidden-charm and double-charm hadronic molecules, arXiv:2208.02639;
X.-H. Cao, M.-L. Du, FKG, Photoproduction of the X(3872) beyond vector meson dominance: the open-charm coupled-channel mechanism, arXiv:2401.16112;
B. Wu, X.-K. Dong, M.-L. Du, FKG, B.-S. Zou, Deciphering the mechanism of J/ψ-nucleon scattering, arXiv:2410.19526;
X.-H. Cao, FKG, Q.-Z. Li, D.-L. Yao, Precise determination of nucleon gravitational form factors, arXiv:2411.13398

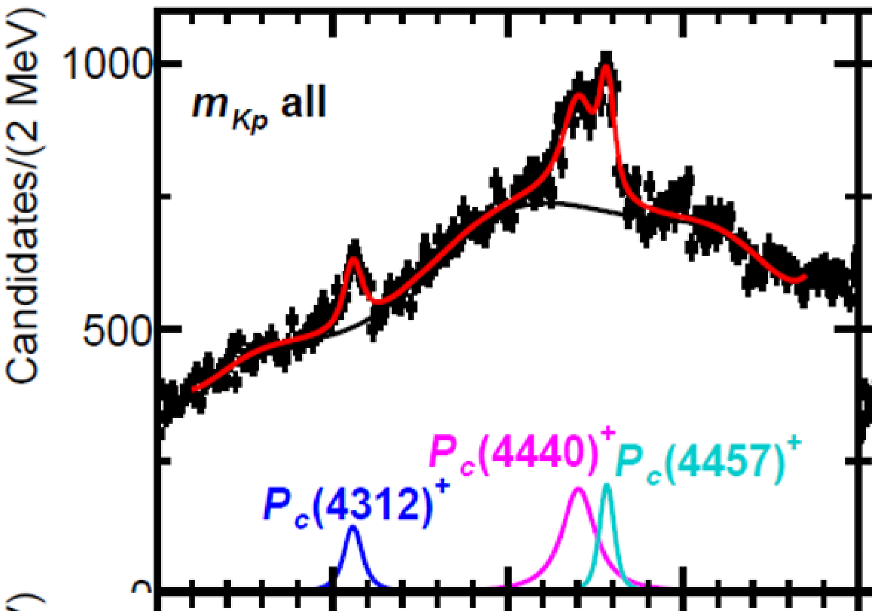
Hidden-charm states



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^\pm$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^\pm$	1^+	$?^{?-}$
$X(4050, 4250)^\pm$	1^-	$?^{?+}$

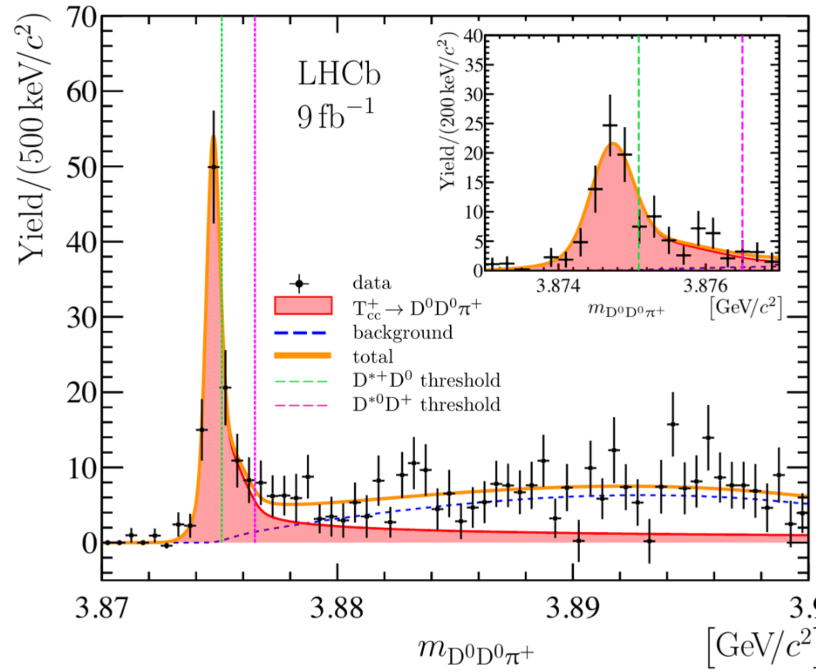
Hidden-charm and double-charm states

Hidden-charm P_c LHCb (2015, 2019)



$\Lambda_b^0 \to J/\psi\, p\, K^-$

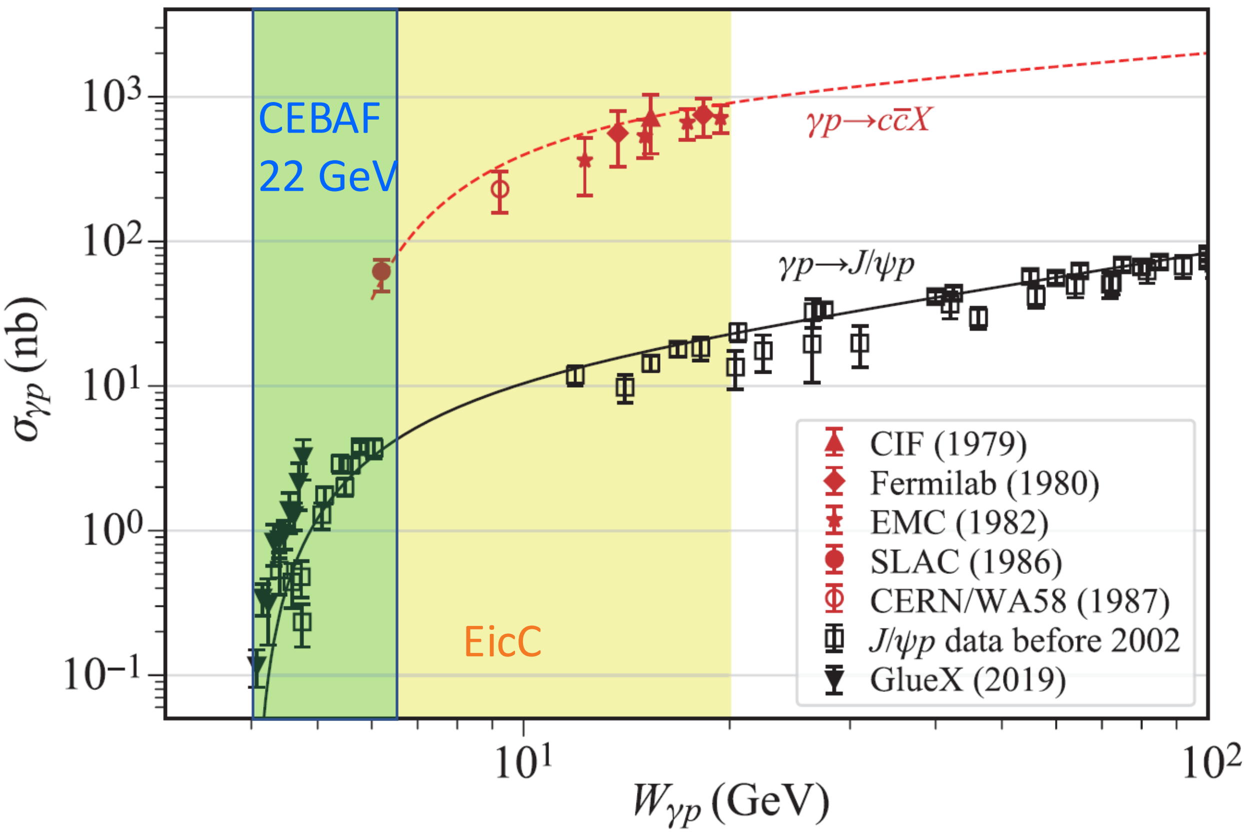
Double-charm T_{cc} LHCb (2021)



- Many structures are near threshold; candidates of hadronic molecules

Photoproduction: charm

Figure from D. P. Anderle et al., Front.Phys. 16 (2021) 64701



- Leptoproduction: cross sections are roughly two orders of magnitude (α) smaller
- Many more open-charm hadrons D and Λ_c

Exclusive production of charmonium(-like) states

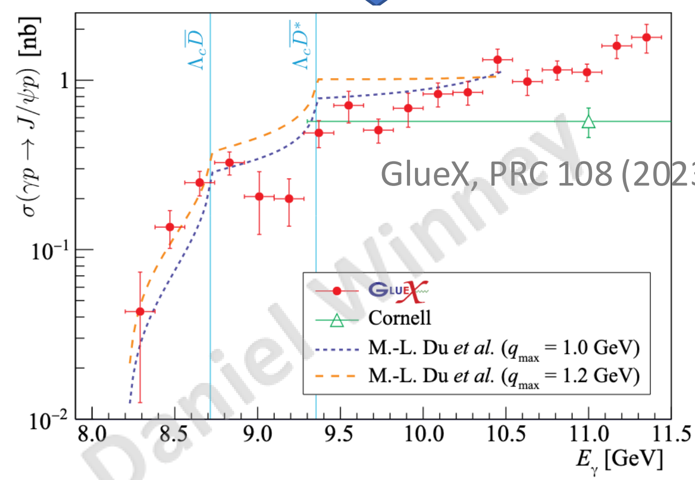
- Open-charm channels easier to be produced than $J/\psi p$; thresholds nearby

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, A. Nefediev, I. Strakovsky, EPJC 80 (2020) 1053

Unitarity: $J/\psi p \to J/\psi p$ enters w/o VMD, but cannot be singled out

$\Lambda_c^+ + D^-$: 2286 + 1865 = 4151 MeV
$J/\psi + p$: 3097 + 938 = 4035 MeV

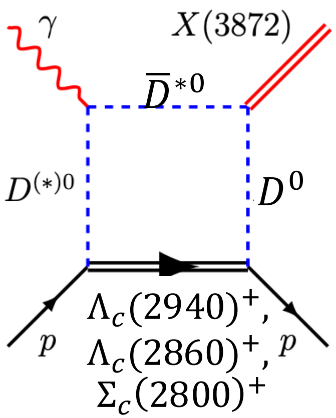
- Feature: cusps at $\Lambda_c \bar{D}^{(*)}$ thresholds



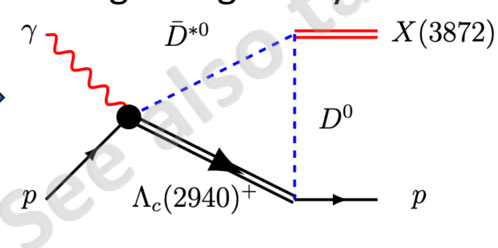
GlueX, PRC 108 (2023) 025201

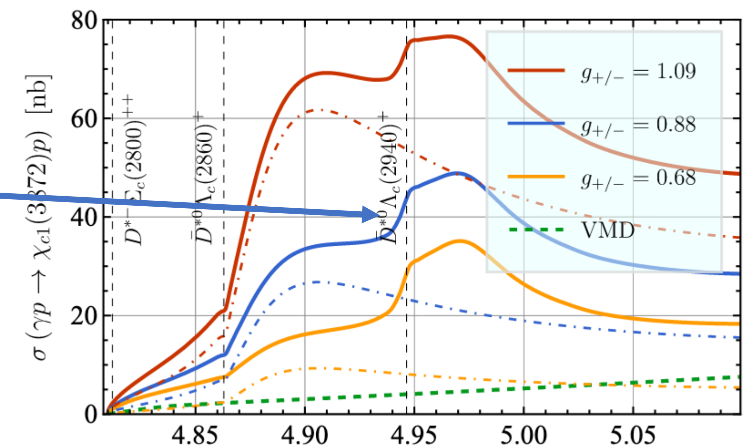
- Nontrivial prediction for $\gamma p \to X(3872)p$

X.-H. Cao, M.-L. Du, FKG, JPG 51 (2024) 105002



Triangle singularity effects



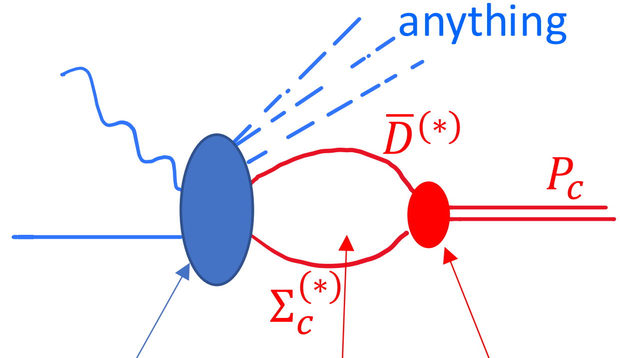


VMD: JPAC, PRD 102 (2020) 114010 $W_{\gamma p}$ [GeV]

Cross section estimates for inclusive productions

- Order-of-magnitude estimates of inclusive lepto-production of near-threshold hadronic molecules
- The cross section can be estimated as

  e.g., for P_c states

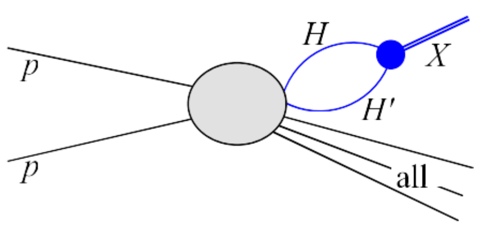


$$\propto \sigma\left(\Sigma_c^{(*)}\bar{D}^{(*)}\right) \times |G^\Lambda|^2 \times |g_{\text{eff}}|^2$$

Event generators

- The method has been used to estimate the X(3872) production at hadron colliders; despite the debates regarding the X(3872) structure, correct order of magnitude was reproduced

Artoisenet, Braaten, PRD83(2011)014019; FKG, Meißner, W. Wang, Z. Yang, EPJC 74 (2014) 3063



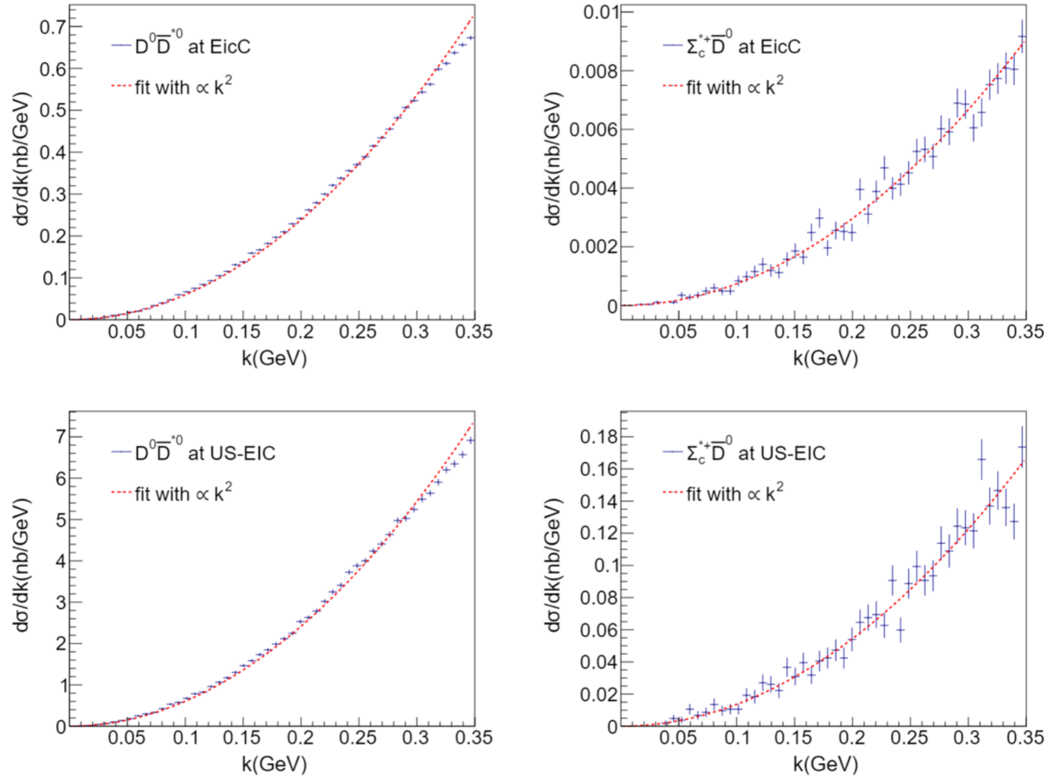
$\sigma(pp/\bar{p}\to X)$ [nb]	Exp.	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

Albaladejo, FKG, Hanhart et al., CPC 41 (2017) 121001

Cross section estimates

Z. Yang, FKG, CPC 45 (2021) 123101

- Charm hadron pairs generated using Pythia6.4



- Considered machine configurations

	EicC	EIC	CEBAF (24 GeV)
e^- energy (GeV)	3.5	20	24
proton energy (GeV)	20	250	0
luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	2×10^{33}	10^{34}	10^{36}

Cross section estimates

Z. Yang, FKG, CPC 45 (2021) 123101; P.-P. Shi, FKG, Z. Yang, PRD 106 (2022) 114026

- Order-of-magnitude estimates of the semi-inclusive electro-production of hidden/double-charm hadronic molecules (in units of pb)

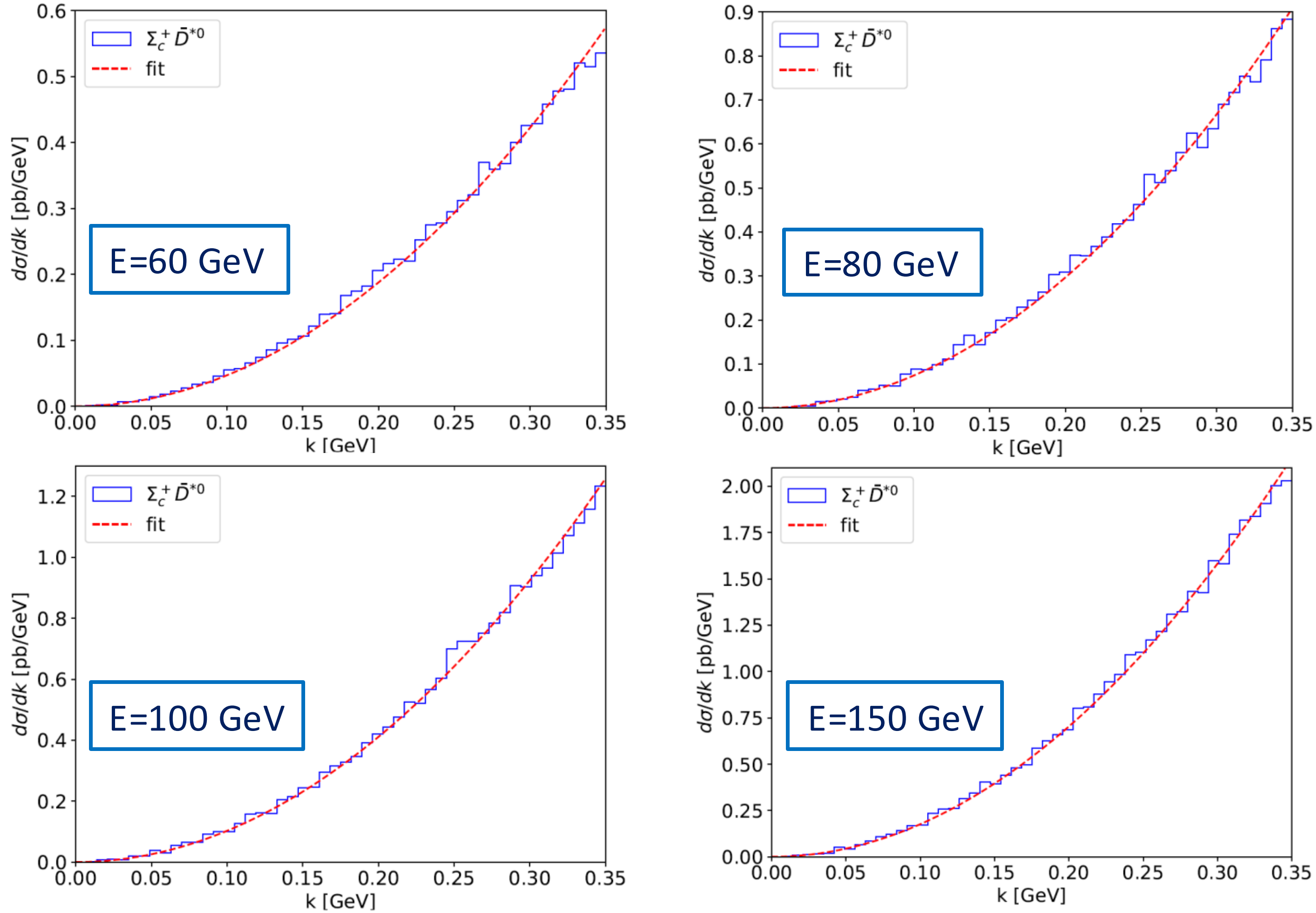
	Constituents	$I, J^{P(C)}$	EicC	EIC
$X(3872)$	$D\bar{D}^*$	$0, 1^{++}$	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	$1, 1^{+-}$	$0.4\times 10^3(1.3\times 10^3)$	$3.8\times 10^3(14\times 10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$1/2, 1^+$	19(69)	250(900)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2, 1/2^-$	0.8(4.1)	15(73)
$P_{cs}(4338)$	$\Xi_c\bar{D}$	$0, 1/2^-$	0.1(1.6)	1.8 (30)
Predicted	$\Lambda_c\bar{\Lambda}_c$	$0, 0^{-+}$	0.3 (3.0)	10 (110)
Predicted	$\Lambda_c\bar{\Sigma}_c$	$1, 0^-$	0.01 (0.12)	0.5 (5.5)
T_{cc}^+	DD^*	$0, 1^+$	0.3×10^{-3} (1.2 $\times 10^{-3}$)	0.1 (0.5)

Results for more systems can be found in the above refs.

Semi-inclusive production at CEBAF 22 GeV

P.-P. Shi, FKG, Z. Yang, PRD 106 (2022) 114026

- For beam energy of 22 GeV, the ep c.m. energy: 6.49 GeV; too low for Pythia
- Choose a few higher energy points, and extrapolate the results done to 22 GeV
- Rough order-of-magnitude estimates (may be underestimated)



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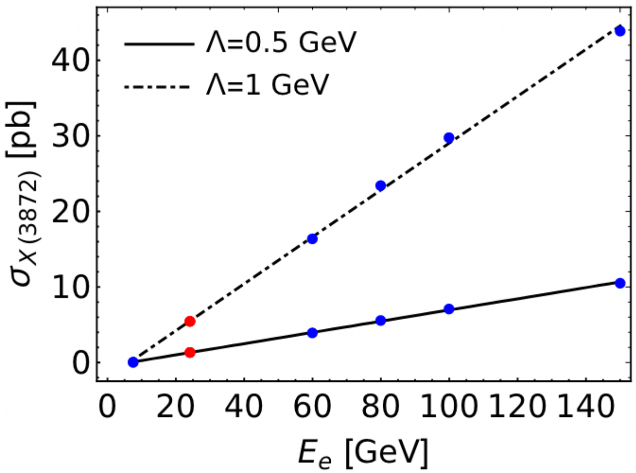
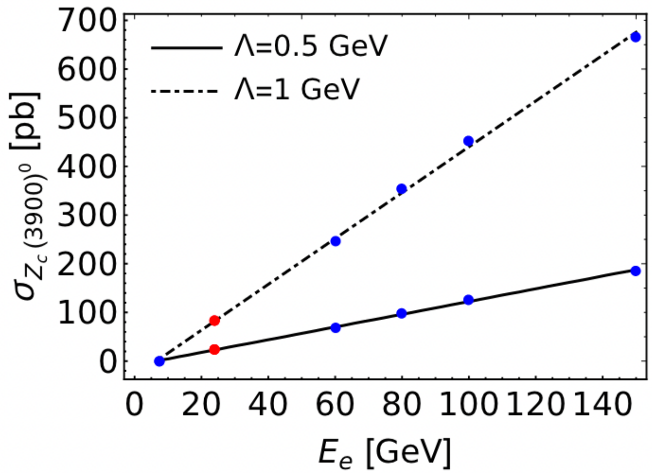
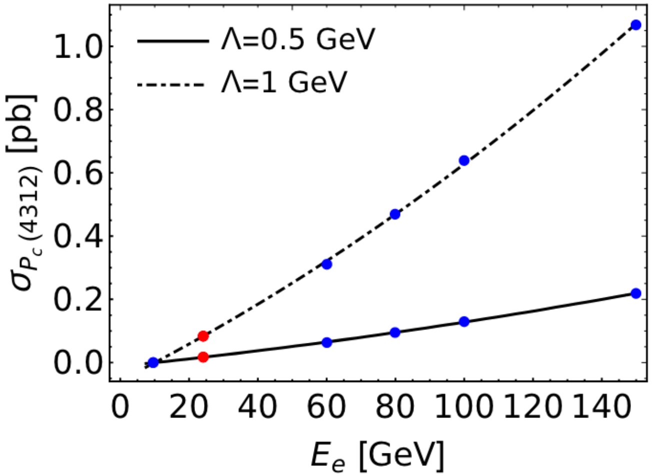






Semi-inclusive production at CEBAF 22 GeV

P.-P. Shi, FKG, Z. Yang, PRD 106 (2022) 114026

- Order-of-magnitude estimates of the electro-production cross sections with 22 GeV electron beam

	Constituents	$J^{P(C)}$	σ_X/pb
$X(3872)$	$D\bar{D}^*$	1^{++}	1 (5)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	20 (80)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2^-$	0.02 (0.08)
$P_{cs}(4459)$	$\Xi_c\bar{D}^*$	$3/2^-$	0.005 (0.03)

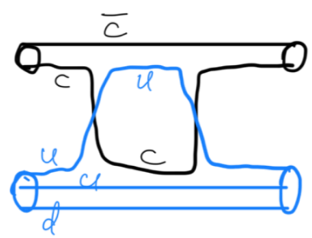
- With a luminosity of $10^{36}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, for an integrated luminosity of $10^7\ \mathrm{pb}^{-1}$, a large number of hidden-charm exotics can be produced after accounting for branching fractions, e.g., $\mathcal{B}(P_c \to J/\psi p) = \mathcal{O}(1\%)$, $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 12\%$

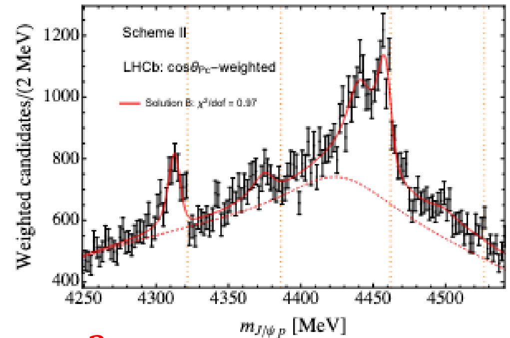
Mechanism of low-energy $J/\psi N$ scattering

- $J/\psi N$ scattering length

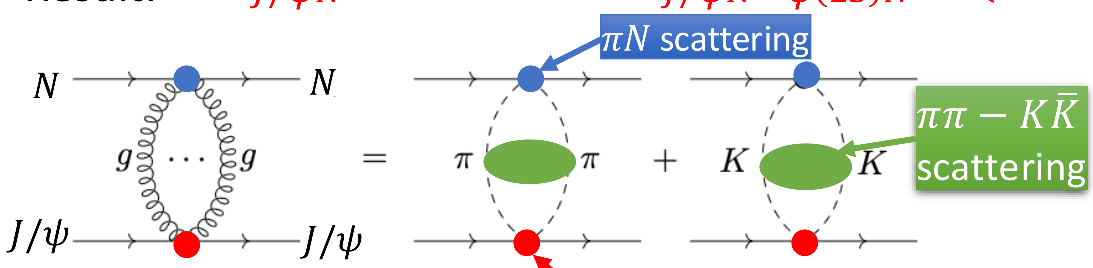
B. Wu, X.-K. Dong, M.-L. Du, FKG, B.-S. Zou, arXiv:2410.19526

- Open-charm coupled channels $(J/\psi N - \Lambda_c \bar{D}^{(*)}/\Sigma_c^{(*)}\bar{D}^{(*)} - J/\psi N)$
  - Based on solution of coupled-channel Lippmann-Schwinger equation fitted to P_c data
    M.-L. Du et al., PRL 124, 072001 (2020); JHEP 08, 157 (2021)
  - Result:
    $\mathcal{O}(-(0.1 \ldots 10) \times 10^{-3}\ \mathrm{fm})$

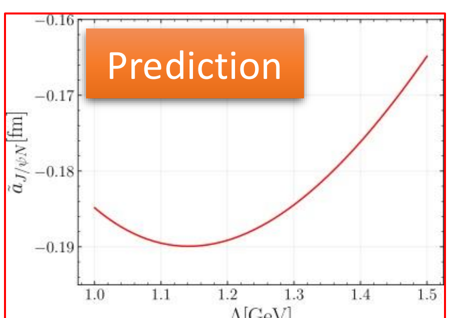


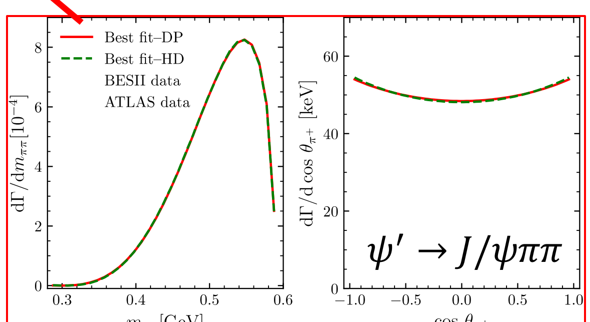


- Soft-gluon exchange
  - Based on dispersion relation
  - Result: $a_{J/\psi N} \lesssim -0.16$ fm, $a_{J/\psi N}\, a_{\psi(2S)N} \geq (-0.15\ \mathrm{fm})^2$



> - Confirmed by recent lattice QCD calculation
>   Y. Lyu et al. [HALQCD], arXiv:2410.22755
> $a_{J/\psi N\,(S=3/2)} = -0.30^{+0.02+0.00}_{-0.02-0.02}$ fm





Nucleon gravitational FFs

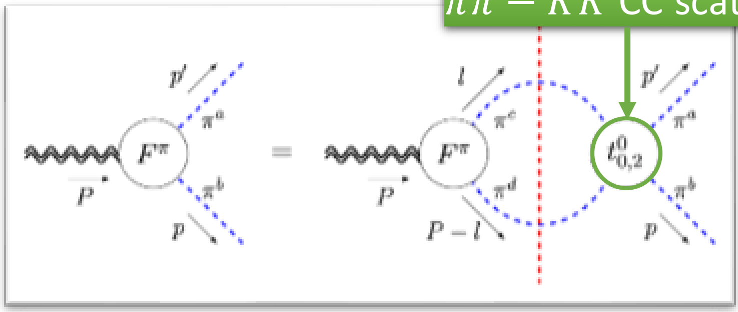
Reviews: Polyakov, Schweitzer, IJMPA (2018); Burkert et al., RMP (2023)

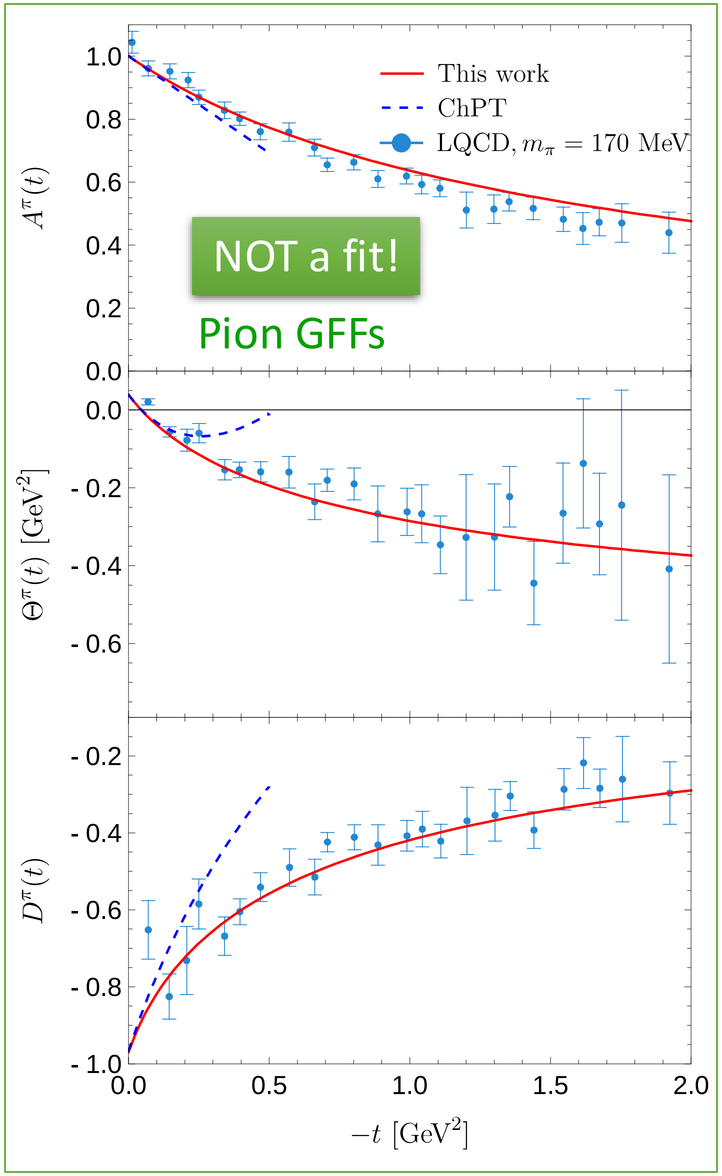
X.-H. Cao, FKG, Q.-Z. Li, D.-L. Yao, arXiv:2411.13398

- Gravitational FFs (GFFs) be model-independently predicted using data-driven dispersion relations + ChPT

Hoferichter et al. (2012)

$\pi\pi - K\bar{K}$ CC scattering





ChPT: Donoghue, Leutwyler, ZPC 52, 343 (1991)

LQCD: Hackett et al., PRD 108, 114504 (2023)

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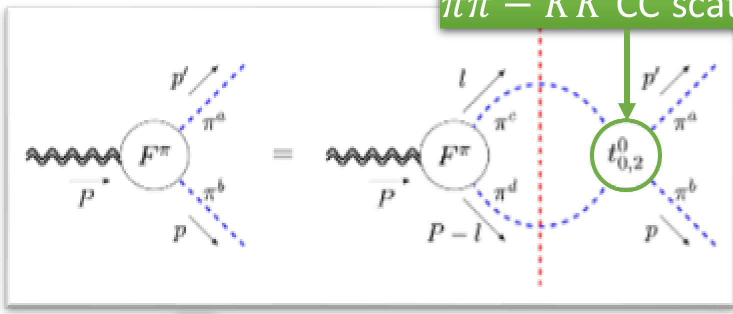
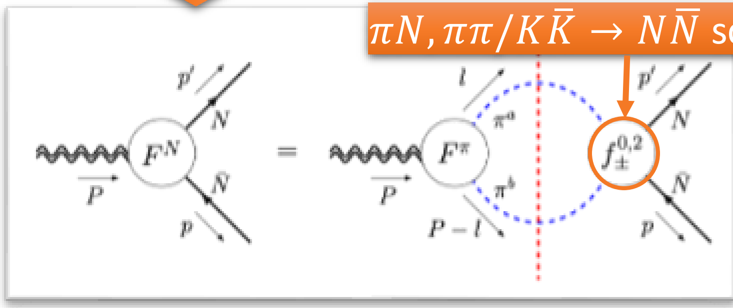


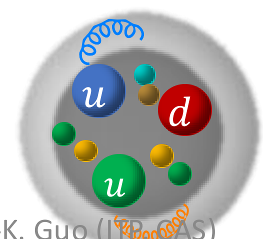
Hoferichter et al. (2016); Cao et al. (2022); …

$\pi N, \pi\pi/K\bar{K} \to N\bar{N}$ scattering



LQCD (170 MeV): Hackett et al., PRL 132, 251904 (2024);
LQCD (253 MeV): B. Wang et al., PRD 109, 094504 (2024)

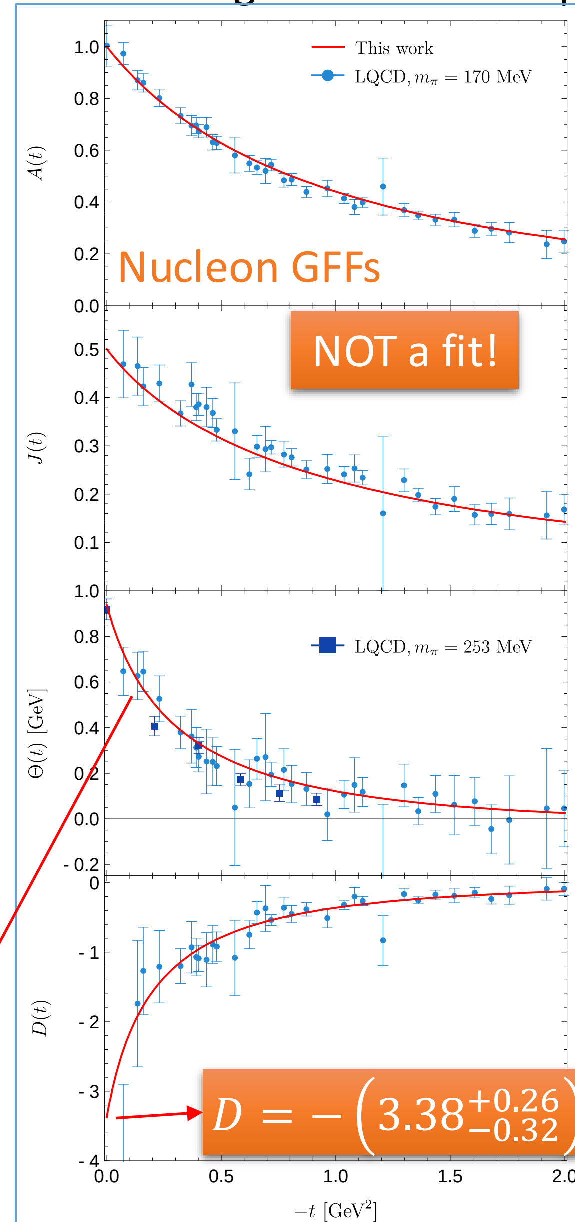
Mass radius as defined in Kharzeev, PRD 105, 054015 (2021)



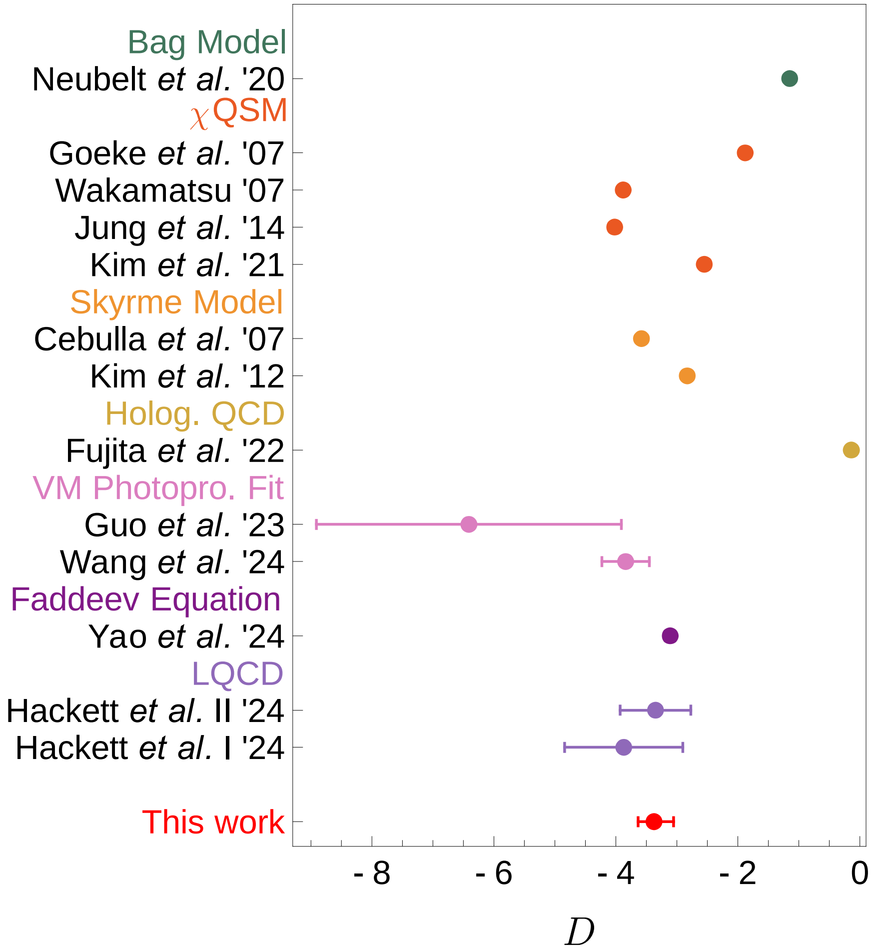
$$\langle r^2_{\rm mass}\rangle = \frac{6\Theta'(0)}{m_N} = \left(0.97^{+0.02}_{-0.03}\ {\rm fm}\right)^2$$

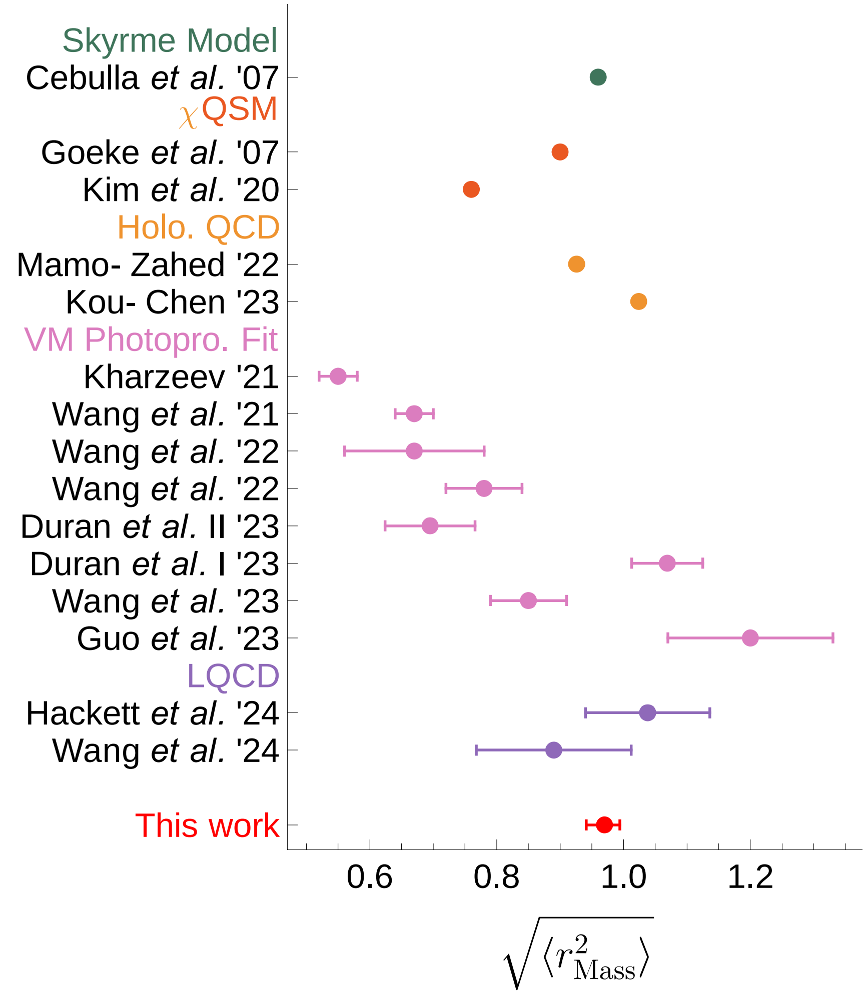
$\vee$

$$\langle r^2_{E,p}\rangle = (0.84075(64){\rm fm})^2$$



Nucleon gravitational FFs





Summary

- Future electron-proton machines will be able to contribute a lot to hadron spectroscopy
  - ✓ A large amount of hidden-charm exotic hadrons can be observed at CEBAF 22 GeV for a luminosity of $10^{36}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Low-energy $J/\psi N$ scattering dominated by soft-gluon exchange
- Nucleon gravitational form factors predicted in a model-independent way: $\langle r_{\mathrm{mass}}^2 \rangle = (0.97^{+0.02}_{-0.03}\ \mathrm{fm})^2$, $D = -\left(3.38^{+0.26}_{-0.32}\right)$

Thank you for your attention!