Studying the gluon and charm content of the deuteron

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Introduction

Why the deuteron?

The simplest nucleus

- Well-known in nuclear physics ⇒ Quantify nuclear effect

  E.g. : used in the EMC ratio

- Minimal nuclear effect ⇒ Extract neutron PDF

- Build a base to extend to heavier nuclei

  Required from astrophysics:

  Gluon PDF of ^{4}He for cosmic ray reaction with interstellar matter

  Charm PDF of atmospheric nuclei (^{14}N, ^{16}O) for the study of high energy (prompt) neutrino

- PDF near the endpoint is predicted in perturbative QCD :

  e.g. gluon PDF in deuteron $G^d(x) \propto (2-x)^{11}$

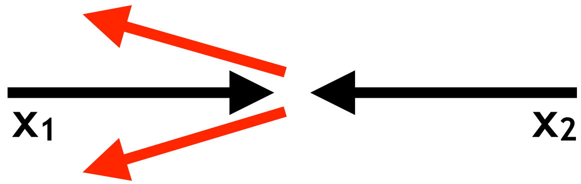
- The gluon and charm content of the deuteron may be studied with future fixed-target experiments at the LHC

  In particular, the high-x region (c.f AFTER@LHC)

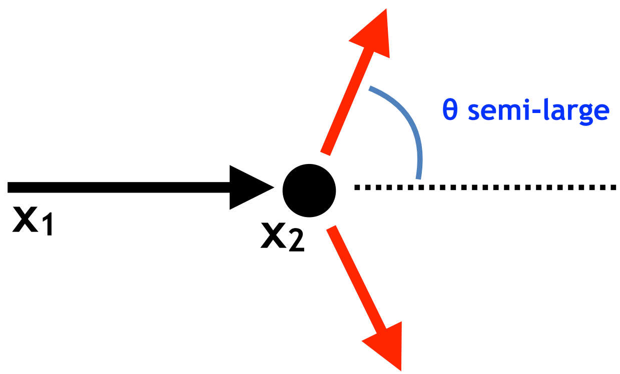
Kinematic coverage of bottomonium prod. at AFTER@LHC

Let us estimate up to which x LHCb can cover with Upsilon production off pp
(Fixed target mode of LHCb)

$x_1 << x_2$



Hadron center-of-mass



Target rest frame

Kinematics of Upsilon production: $x_{1,2} = \frac{m_{b\bar{b}}}{\sqrt{s}} e^{\pm y_{\rm c.m.s.}}$ ($\sqrt{s}$ = 115GeV for fixed-target)

Production threshold at CM: $x_1 x_2 s = m_{b\bar{b}}^2$

LHCb rapidity coverage: $[2,5]_{\rm Lab\ frame} = [-2.8,0.2]_{\rm c.m.s.}$

➡ **Can access up to "x" = 1.4 with LHCb in the fixed-target mode**

Prospects for astrophysics (2 important cases)

Interstellar reactions

Cosmic ray sources
of high energy protons
(acceleration, dark matter,…)

Primary CR

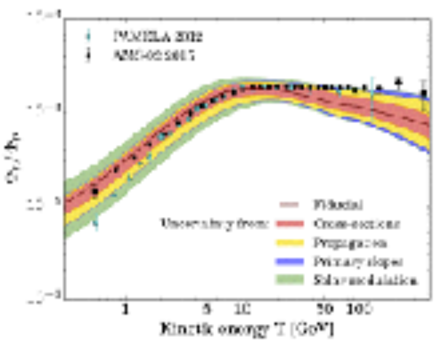
Hard reactions with
interstellar matter
(mostly p and ^{4}He)

^{4}He

p

Secondary CR

NASA, AMS-02



PAMELA, AMS-02, DAMPE, …

In high energy reactions, low-x is important

⇒ Gluons !

Atmospheric neutrinos productions

High energy cosmic protons from space

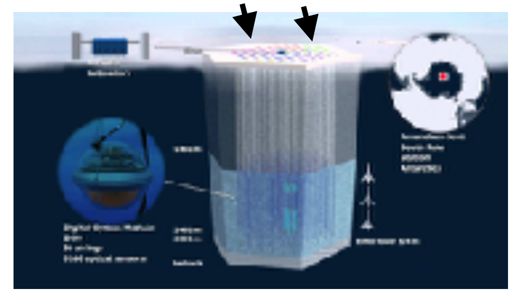
^{14}N

Atmospheric nuclei

Charmed hadrons

D Λ_c

Prompt neutrinos



IceCube

High energy hadrons are produced from high-x charm quarks

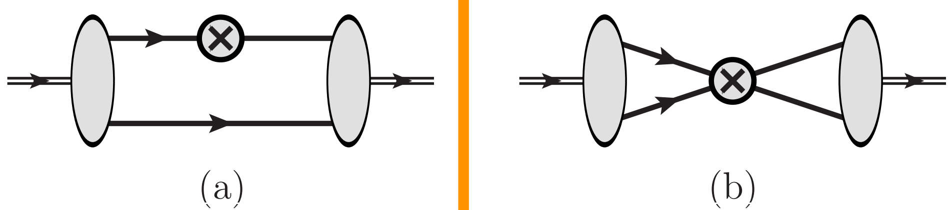
Chiral effective field theory description of nuclear PDF

Moments of the PDF can be expanded in terms of the nucleon velocity:

$$\langle x^n \rangle_{g|A} = v_{A,\mu_0} \cdots v_{A,\mu_n} \langle A | \mathcal{O}_g^{\mu_0 \cdots \mu_n} | A \rangle$$

Leading contribution to nuclear PDF in chiral EFT :

$$\langle x^n \rangle_{g|A} = \langle x^n \rangle_g [A + \langle A | \alpha_n (N^\dagger N)^2 | A \rangle]$$



Impulse approximation

J.-W. Chen and W. Detmold, PLB625 (2005) 165

(a) : Impulse approximation ⇒ Leading effect in chiral EFT
(≒ velocity expansion)

(b) : Nucleon-nucleon correlation effect : subleading in chiral EFT

- **Short-range correlation : connected to quark EMC effect, but unknown for gluons**
  L. B. Weinstein et al., PRL 106, 052301 (2011)
  J.-W. Chen et al., PRL 119, 262502 (2017)
- **Long-range correlation (pion-exchange current) : O(v^3) effect ⇒ Small**
  J.-W. Chen and W. Detmold, PLB625 (2005) 165

S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Nonrelativistic deuteron wavefunction

Calculate deuteron wave function in nonrelativistic nuclear physics .
We use the phenomenological nuclear force Av18.

R. B. Wiring et al., Phys. Rev. D 51, 38 (1995).

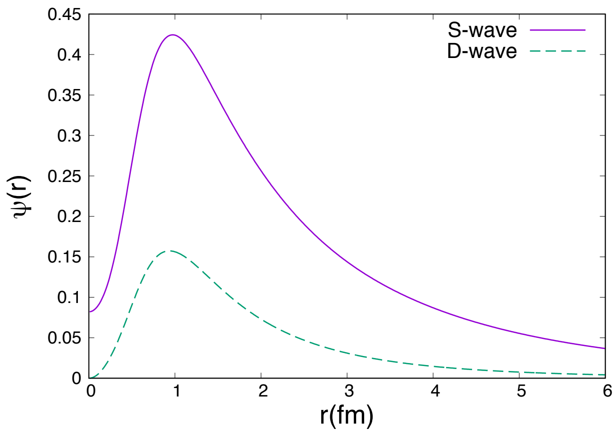
We solve the Schroedinger equation with the Gaussian expansion method

E. Hiyama et al., Prog. Part. Nucl. Phys. 51, 223 (2003).

Basis of wavefunction is a superposition of Gaussians:

$$\Phi_{nlm}(\mathbf{r}) = N_{nl} r^l e^{-\nu_n r^2} Y_{lm}(\hat{r})$$ **(truncate with finite n)**

Solve Schroedinger eq. by variational principle,
numerical diagonalization of Hamiltonian



Radial wavefunction of deuteron

With sufficient number of basis functions (*n*), the Schroedinger eq. can be solved with high precision (10^{-10})

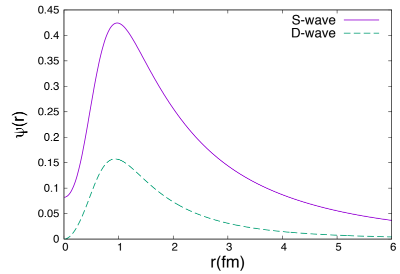
S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Conversion from rest-frame to light-front-frame

Conversion from rest- to light-front-frame is ambiguous (not a Lorentz boost)

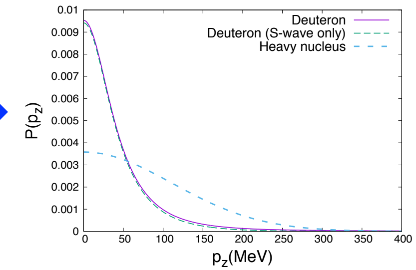
⇒ Here we use the Recipe of Terentev

Project the wavefunction to the z-axis and Fourier transform



Radial WF

FT

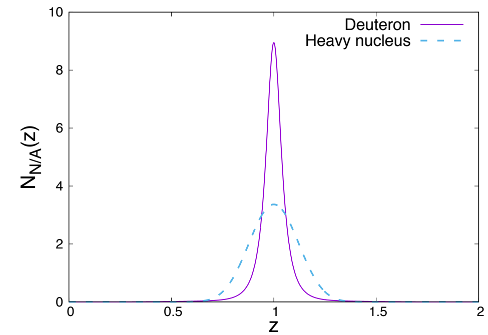


Cylindrical WF (momentum-space)

Convert p_z to momentum fraction

$$\psi(\mathbf{p}_\perp, z) = \sqrt{\frac{\partial p_z(\mathbf{p}_\perp, z)}{\partial z}}\psi(\mathbf{p}_\perp, p_z) \qquad p_z = (z-1)\sqrt{\frac{m_N^2 + \mathbf{p}_\perp^2}{z(2-z)}}$$

M. V. Terentev, Sov. J. Nucl. Phys. 24 (1976) 106. [Yad. Fiz.24,207(1976)]
H. Merabet et al, Phys. Lett. B 307, 177 (1993)
P. Hoyer and S. Peigne, Phys. Rev. D 61, 031501 (2000)
J. Hufner, Yu. P. Ivanov, B. Z. Kopeliovich, Phys. Rev. D 62, 094022 (2000)
B. Kopeliovich, A. Tarasov, J. Hufner, Nucl. Phys. A 696, 669 (2001)



LF distribution of nucleon

Fold with nucleon PDF (GRV98, CJ15)

M. Glueck, E. Reya, and A.Vogt, Eur. Phys. J. C 5, 461 (1998)
A. Accardi et al., Phys. Rev. D 93, 114017 (2016)

PDF of deuteron

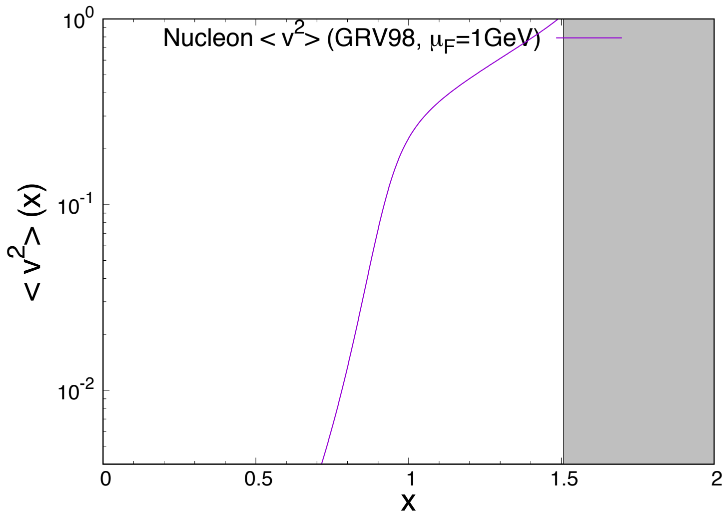
S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Region of applicability

Our framework is based on velocity expansion : nucleon should be nonrelativistic

To examine the validity, we inspect the average velocity in function of x (gluon)

We solve $\langle v^2 \rangle$ in the function of x



Velocity distribution of nucleon in terms of gluon x

Strict limit of applicability ($v < 1$) :

➡ $x < 1.5$

0-th moment of PDF cancels,
1st moment is small

A. S. Rinat and M. F. Taragin, PRC **72**, 065209 (2005)

The important corrections start from $O(v^2)$

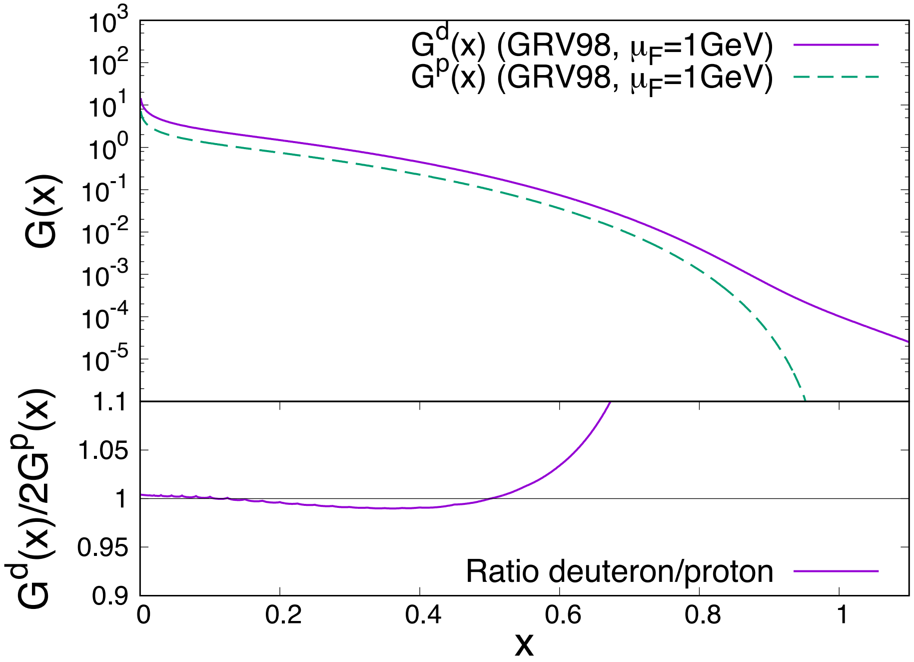
Let us take $\langle v^2 \rangle < 0.3$ to be conservative

➡ We expect our framework to be applicable for $0 < x < 1.1$ and to break down for $x > 1.5$ since $\langle v^2 \rangle > 1$

S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Result (gluon PDF)

Gluon PDF:



We use GRV98 for proton PDF (behaves well near x=1)

M. Glueck et al., Eur. Phys. J. C 5, 461 (1998).

S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

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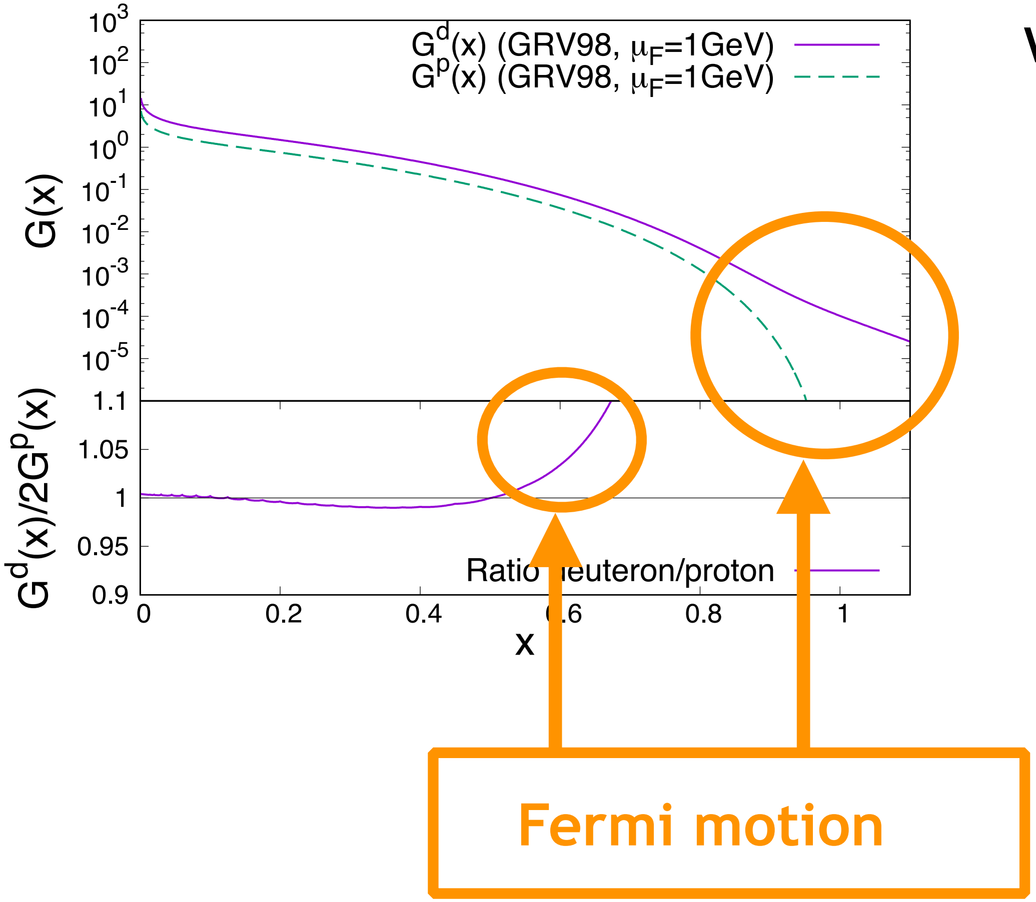

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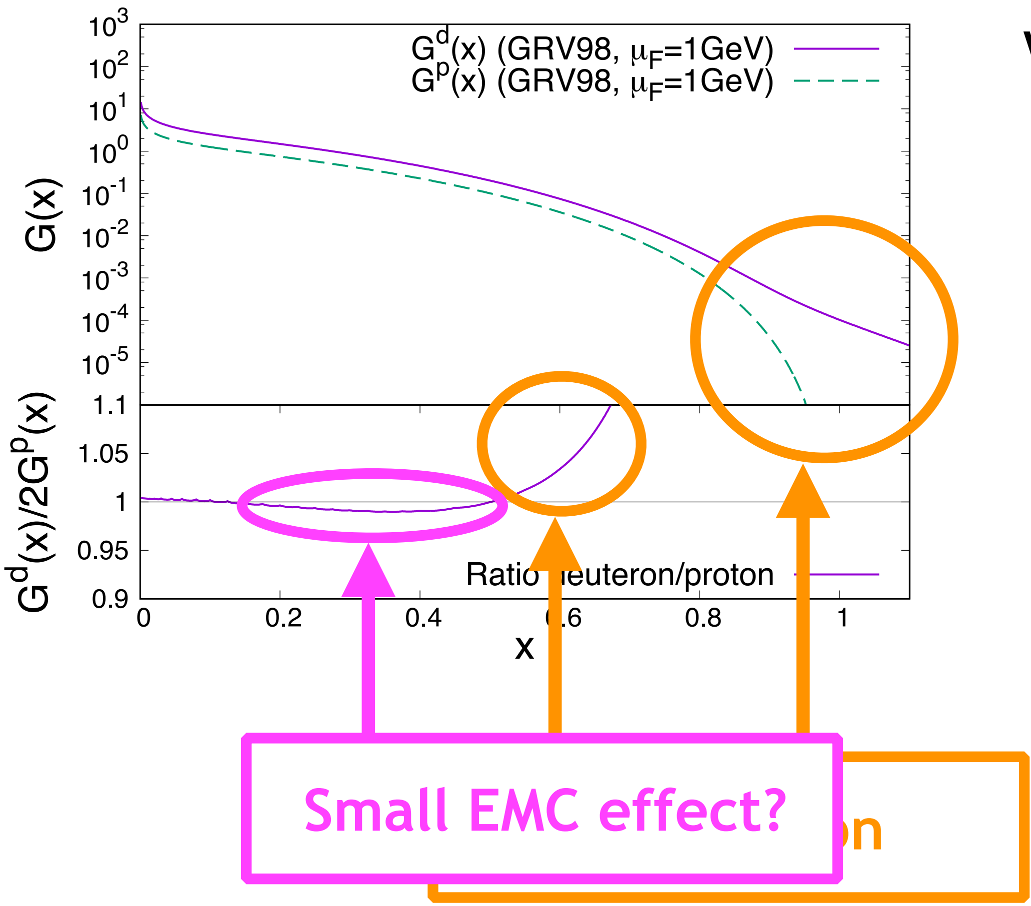

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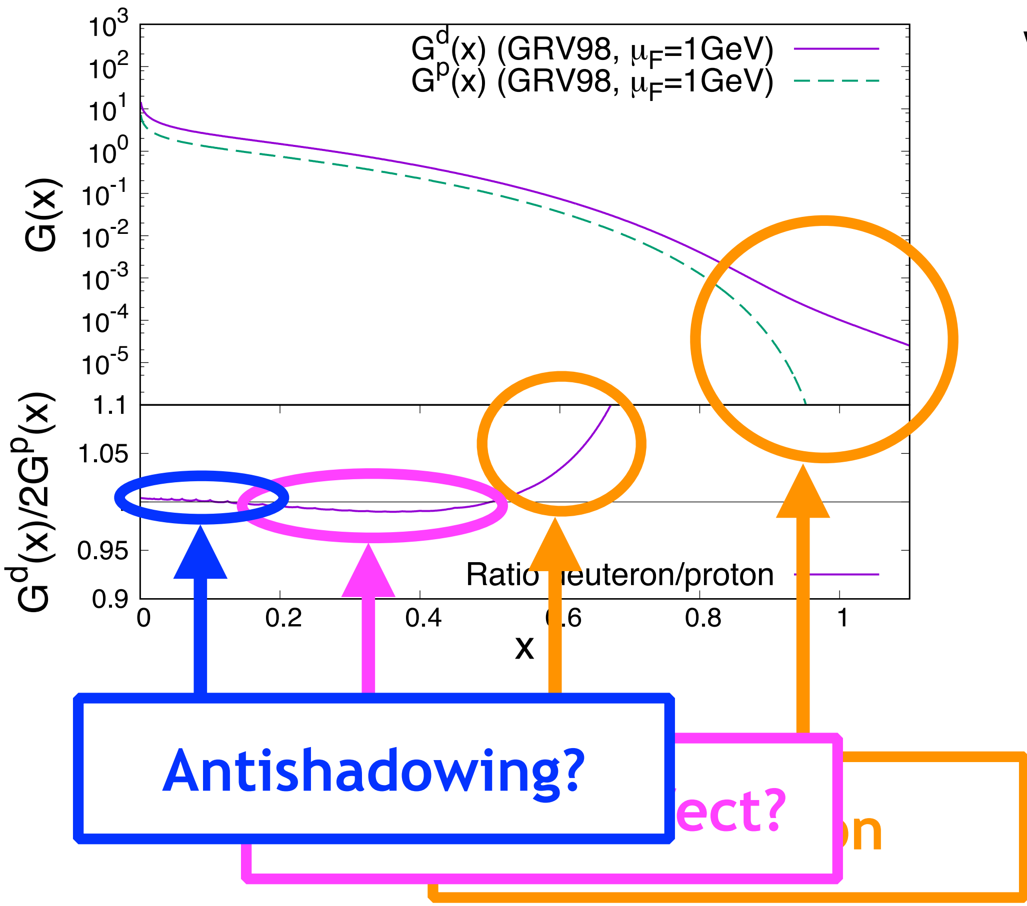

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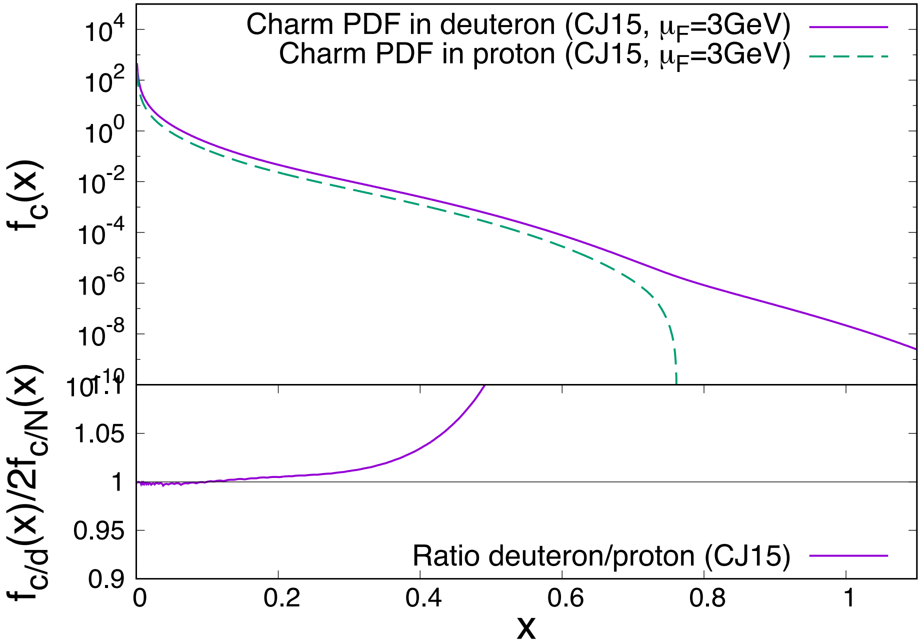
S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Result (charm PDF)

Charm:



We use CJ15 for proton PDF (charm PDF available)

A. Accardi et al., Phys. Rev. D 93, 114017 (2016).

S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

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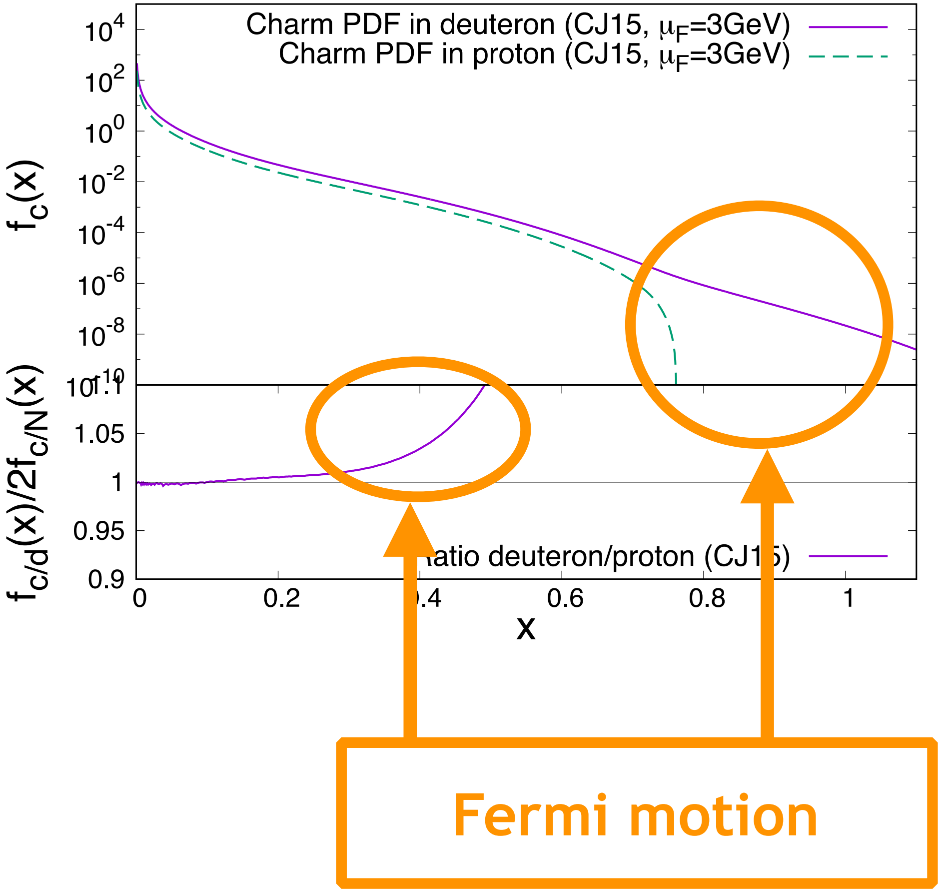

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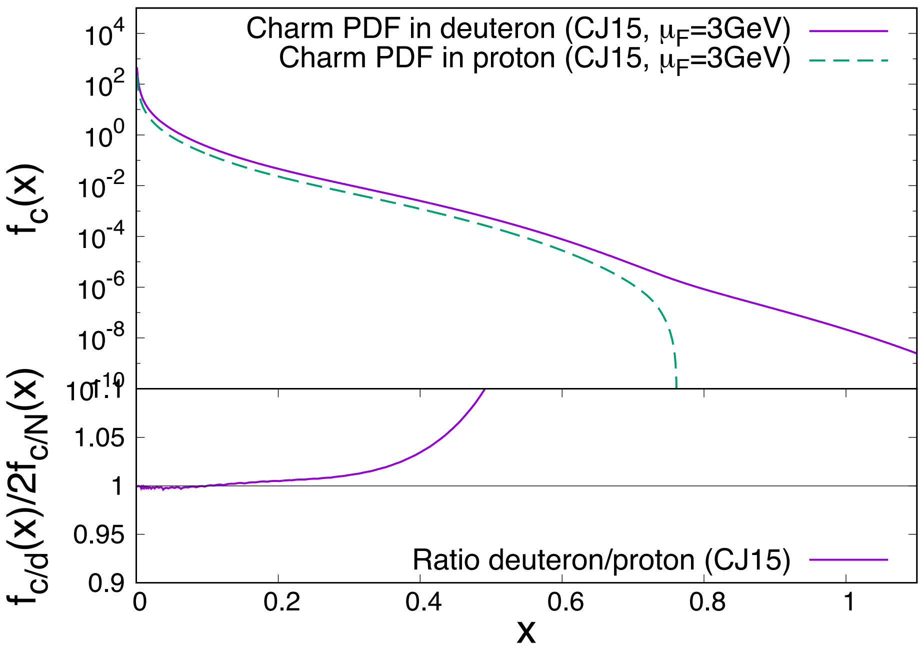
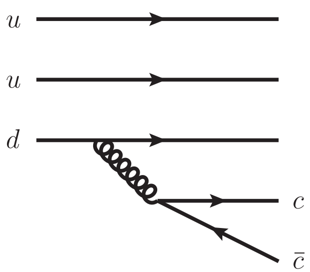
Intrinsic charm

Charm:



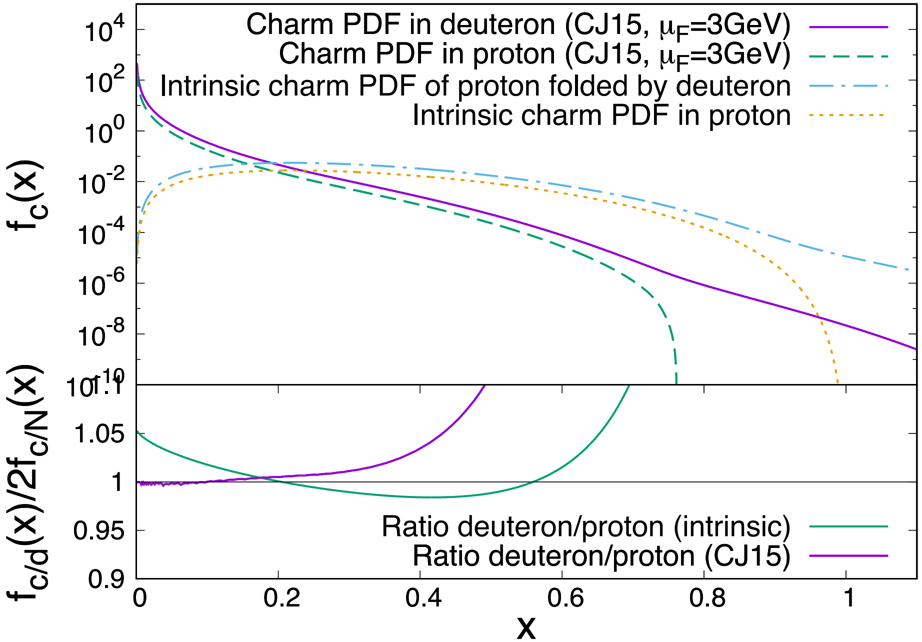
Gluon splitting:



Distribution similar to gluon PDF (3 diagrams)

Intrinsic charm

Charm:



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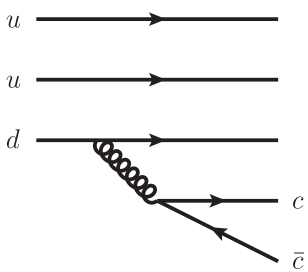

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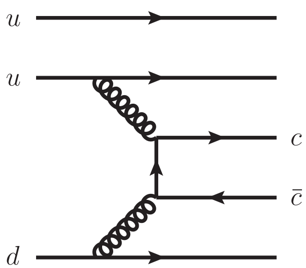
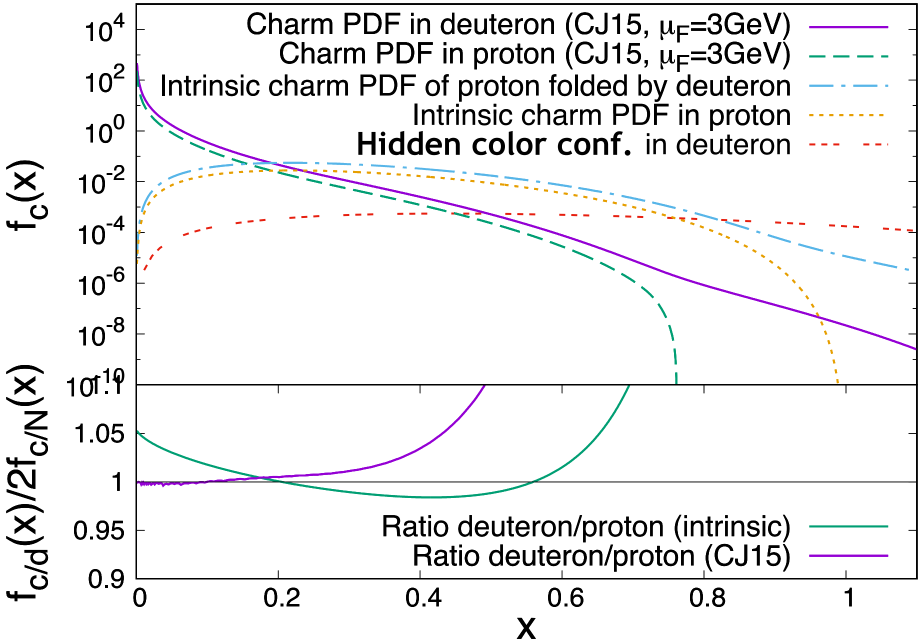


More important than gluon splitting at large x (3 diagrams)

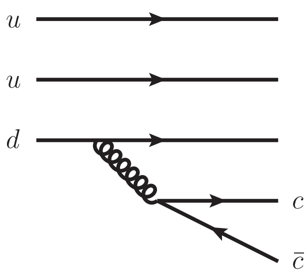
S. J. Brodsky, P. Hoyer, C. Peterson, N. Sakai, PLB93 (1980) 451.

Intrinsic charm

Charm:



Gluon splitting:



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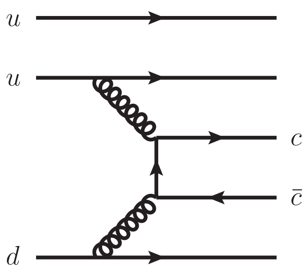

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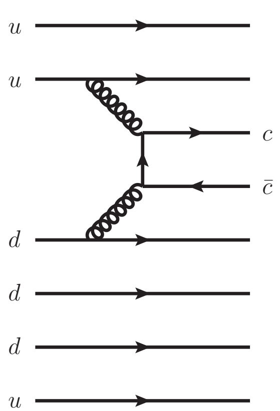
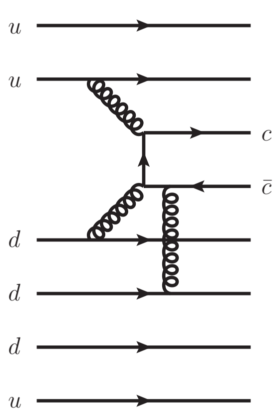
Hidden color configuration of deuteron:



(15 diagrams)



(20 diagrams)

Further enhanced at large x compared to the intrinsic charm nucleon PDF

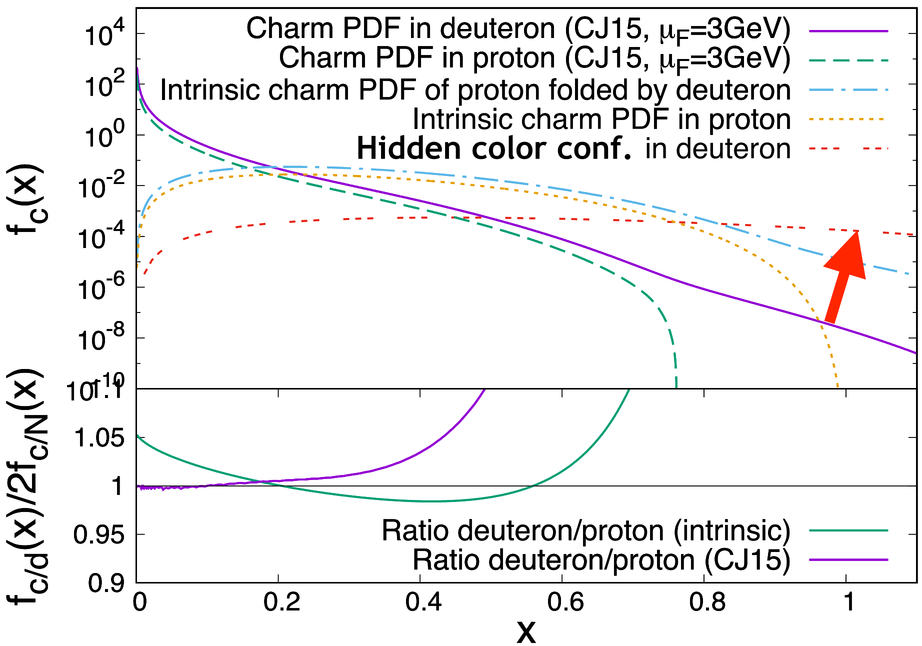
Normalization not known, but may be enhanced by combinatoric factors (compare the number of diagrams)

This enhancement is potentially important in astrophysics!

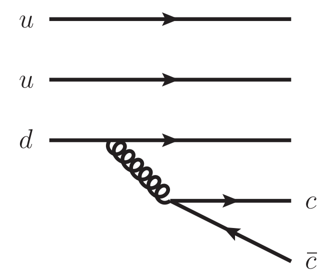
S. J. Brodsky, K.Y.J. Chiu, J.P. Lansberg, NY, arXiv:1805.03173 [hep-ph]

Intrinsic charm

Charm:

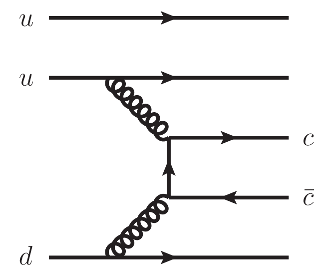


Gluon splitting:



Distribution similar to gluon PDF (3 diagrams)

Intrinsic charm:



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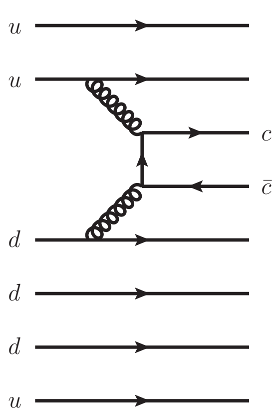

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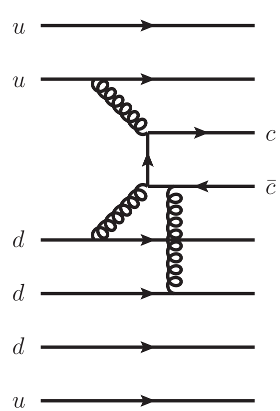

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Summary

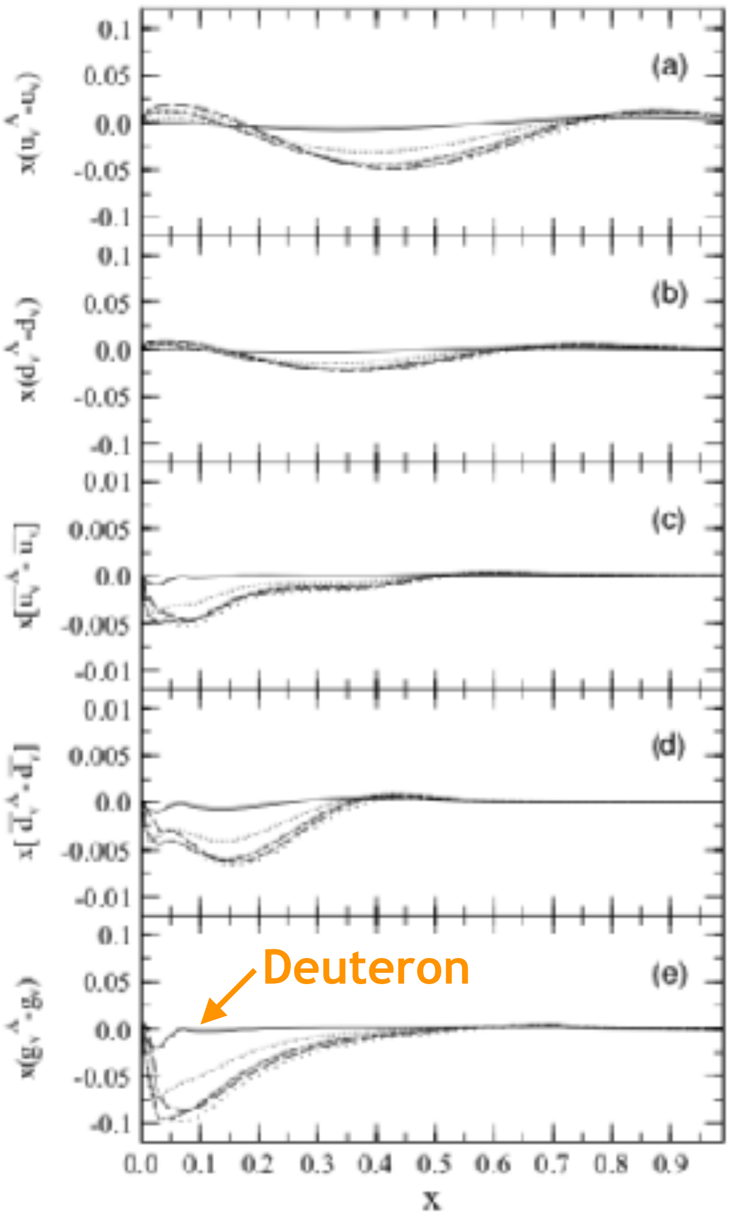
- We have studied the gluon and charm PDF of the deuteron with nonrelativisitic inputs.
- Chiral EFT suggests the validity of our nonrelativistic framework in the region $0 < x < 1.1$.
- The gluon PDF of the deuteron shows Fermi motion at $x > 0.6$, and a small EMC effect at $x \sim 0.4$.
- Hidden color may enhance the charm PDF of deuteron in the high-x region : may be important in astrophysics.

Future subjects:

- Studies of NN correlation required for quantitative analysis.
- Normalization of hidden color states to be fixed.
- Extension to heavier nuclei is on-going : stay tuned.

Backup

1st moments of nuclear PDF



Difference between PDF of single nucleon and nuclear PDF (per nucleon)

The 1st moments are much smaller than 1

A. S. Rinat and M. F. Taragin, Phys. Rev. C **72**, 065209 (2005).