Theoretical description of deeply virtual Compton scattering off ^{3}He

Matteo Rinaldi & Sergio Scopetta

Dipartimento di Fisica dell'Università di Perugia

and INFN, Sezione di Perugia, Italy.

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Outline

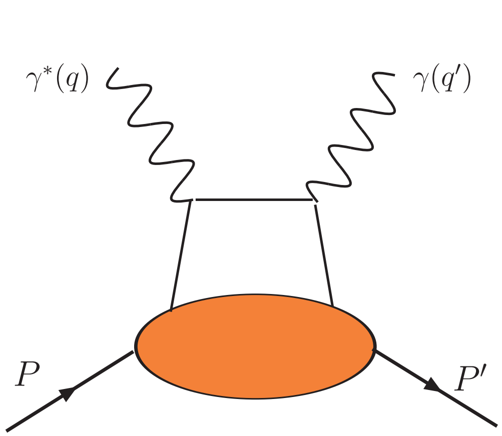
- Deeply virtual Compton scattering (DVCS) and nuclear Generalized Parton Distributions (GPDs)
- GPDs of ^{3}He:
  - * GPDs H, E, $\tilde{H}$ in Impulse Approximation (IA)

    (**S.S., PRC 70 (2004) 015205; PRC 79 (2009) 025207**)
  - * Extracting the neutron information from ^{3}He data

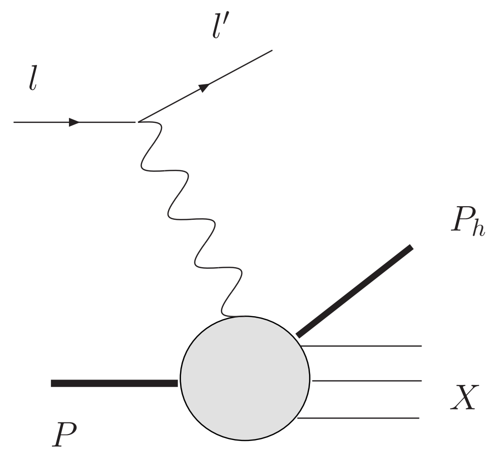
    (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**)
- Preliminary results for the GPD $\tilde{H}$ of ^{3}He
- Conclusions

GPDs - why?

- Initially, the interest in GPDs was a consequence of the "Spin crisis"(EMC, '88): most of the proton spin NOT carried by the quark helicities Σ
- Spin Sum Rule: $$\boxed{\Sigma + L_q + J_g = \frac{1}{2}}$$
- OAM (L_q) accessed through non forward processes:



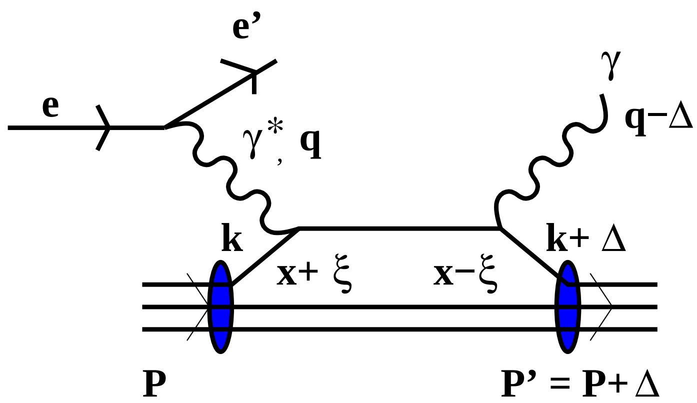
DVCS –> GPDs



SiDIS –> TMDs

GPDs: Definition (X. Ji PRL 78 (97) 610)

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
($Q^2, \nu \to \infty$)
such as (coherent) DVCS:



- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu/2$, $n \cdot \bar{P} = 1$, $n \cdot n = 0$
- $x = \bar{k} \cdot n / \bar{P} \cdot n \to \bar{k}^+ / \bar{P}^+$; ξ = "skewness" = $-n \cdot \Delta/2 \to -\Delta^+/(2\bar{P}^+)$
- $x \leq -\xi \longrightarrow$ GPDs describe $antiquarks$;
  $-\xi \leq x \leq \xi \longrightarrow$ GPDs describe $q\bar{q}\ pairs$; $x \geq \xi \longrightarrow$ GPDs describe $quarks$

the GPDs $H_q(x, \xi, \Delta^2)$ and $E_q(x, \xi, \Delta^2)$ are introduced:

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \quad \psi_q(\lambda n/2) | P \rangle = H_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P)$$

$$+ \quad E_q(x, \xi, \Delta^2) \bar{U}(P') \frac{i\sigma^{\mu\nu}\Delta_\nu}{2M} U(P) + ...$$

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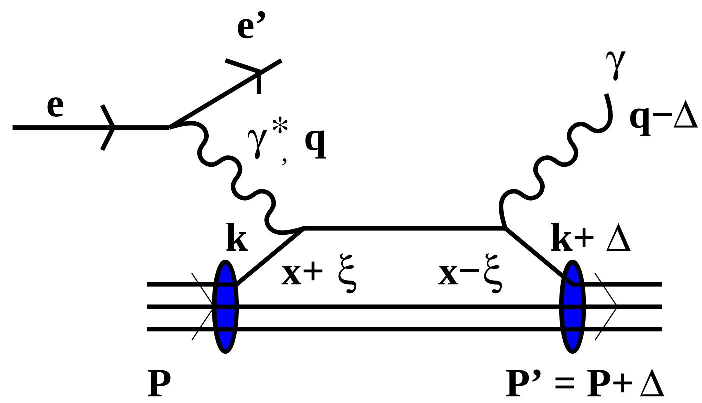

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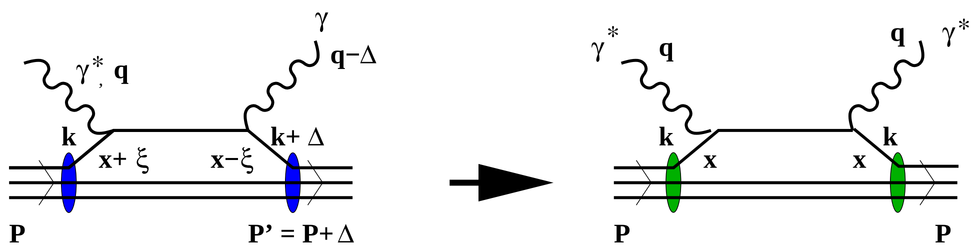
and the helicity dependent ones, $\tilde{H}_q(x, \xi, \Delta^2)$ and $\tilde{E}_q(x, \xi, \Delta^2)$, obtained as follows:

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \quad \gamma^\mu \gamma_5 \quad \psi_q(\lambda n/2) | P \rangle = \tilde{H}_q(x, \xi, \Delta^2) \bar{U}(P') \gamma^\mu U(P)$$

$$+ \quad \tilde{E}_q(x, \xi, \Delta^2) \bar{U}(P') \frac{\gamma_5 \Delta^\mu}{2M} U(P) + ...$$

GPDs: limits

- when $P' = P$, i.e., $\Delta^2 = \xi = 0$, one recovers the usual PDFs:



$$H_q(x,0,0) = q(x); \quad \tilde{H}_q(x,0,0) = \Delta q(x); \quad E_q(x,0,0), \tilde{E}_q(x,0,0) \ unknown$$

- the x–integration yields the q-contribution to the Form Factors (ffs)

$$\int dx \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}_q(-\lambda n/2) \gamma^\mu \psi_q(\lambda n/2) | P \rangle =$$

$$\int dx\, H_q(x,\xi,\Delta^2) \bar{U}(P') \gamma^\mu U(P) + \int dx\, E_q(x,\xi,\Delta^2) \bar{U}(P') \frac{\sigma^{\mu\nu}\Delta_\nu}{2M} U(P) + ...$$

$$\Longrightarrow \int dx\, H_q(x,\xi,\Delta^2) = F_1^q(\Delta^2) \qquad \int dx\, E_q(x,\xi,\Delta^2) = F_2^q(\Delta^2)$$

$\Longrightarrow$ Defining $\boxed{\tilde{G}_M^q = H_q + E_q}$ one has $\int dx\, \tilde{G}_M^q(x,\xi,\Delta^2) = G_M^q(\Delta^2)$

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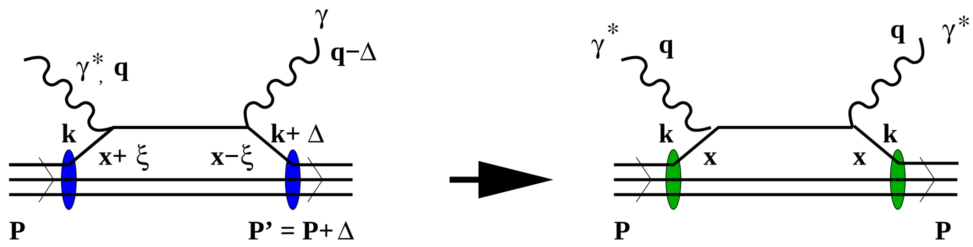

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$$\int dx\, \tilde{H}_q(x,\xi,\Delta^2) \bar{U}(P')\gamma^\mu U(P) + \int dx\, \tilde{E}_q(x,\xi,\Delta^2) \bar{U}(P') \frac{\gamma_5 \Delta^\mu}{2M} U(P) + \ldots$$

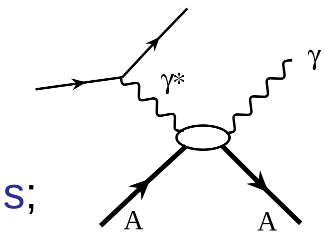
$$\Longrightarrow \int dx\, \tilde{H}_q(x,\xi,\Delta^2) = g_A^q(\Delta^2) \qquad \int dx\, \tilde{E}_q(x,\xi,\Delta^2) = g_P^q(\Delta^2)$$

GPDs: A unique tool...

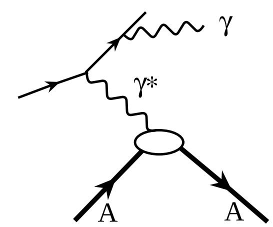
- to explore the 3-dimensional structure of hadrons at parton level and for many other aspects...
- ...the most important here: access to the parton orbital angular momentum (OAM), solution (?) of the "Spin Crisis": **Ji Sum Rule**:

$$\boxed{\langle J_q \rangle = \langle \Sigma_q \rangle + \langle L_q \rangle = \int_{-1}^{1} dx\, x\, \tilde{G}_M^q(x,0,0)}$$

... but also an experimental challenge:



DVCS



BH

- Hard exclusive processes $\longrightarrow$ small X-sections;
- Difficult extraction:

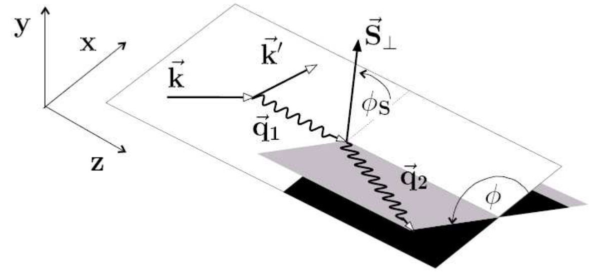
$$T_{\mathbf{DVCS}} \propto \int_{-1}^{1} dx \frac{H_q(x,\xi,\Delta^2)}{x-\xi+i\epsilon} + \ldots \quad ,$$

- Competing **BH** process! Interference (σ-differences) measured.

$$d\sigma \propto |T_{\mathbf{DVCS}}|^2 + |T_{\mathbf{BH}}|^2 + 2\,\Re\{T_{\mathbf{DVCS}} T^*_{\mathbf{BH}}\}$$

Extracting GPDs

One measures asymmetries: $A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$



- Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \simeq \sin\phi \left[F_1 \mathbf{H} + \xi(F_1 + F_2)\tilde{\mathbf{H}} + (\Delta^2 F_2/M^2)\mathbf{E}/4 \right] d\phi \quad \Longrightarrow \quad \mathbf{H}$$

- Unpolarized beam, longitudinally polarized target:

$$\Delta\sigma_{UL} \simeq \sin\phi \left\{ F_1 \tilde{\mathbf{H}} + \xi(F_1 + F_2) \left[\mathbf{H} + \xi/(1+\xi)\mathbf{E} \right] \right\} d\phi \quad \Longrightarrow \quad \tilde{\mathbf{H}}$$

- Unpolarized beam, transversely polarized target:

$$\Delta\sigma_{UT} \simeq \cos\phi \sin(\phi_S - \phi) \left[\Delta^2 (F_2 \mathbf{H} - F_1 \mathbf{E})/M^2 \right] d\phi \quad \Longrightarrow \quad \mathbf{E}$$

To evaluate cross sections, e.g. for experiments planning, one needs **H**, $\tilde{\mathbf{H}}$, **E**

This is what we have calculated for **^{3}He. Why nuclei? Why ^{3}He?**

Why nuclei?

Several relevant issues can be investigated...:

- the nuclear short range structure, at quark level, can be accessed and the reaction mechanism of DIS off nuclei, e.g. the validity of I.A. and the relevance of effects beyond it (non nucleonic degrees of freedom, nucleon modifications...) can be investigated... origin of the EMC effect...
- very important here: **the neutron**, always from nuclear targets

... with some effort: measurements are difficult:

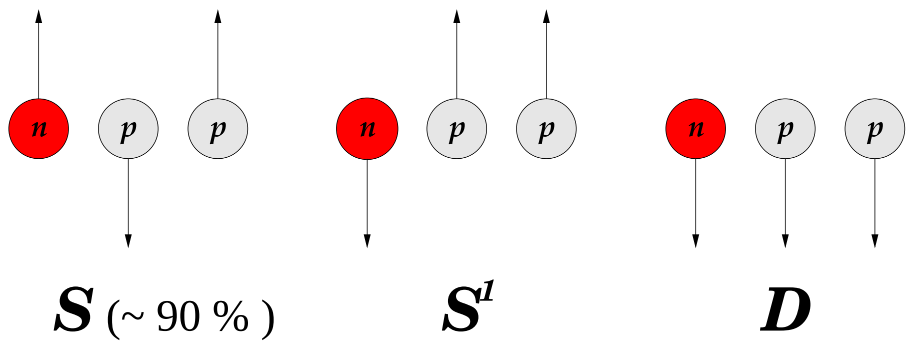
- In principle, need for a recoil detector to be sure that the nucleus did not break (despite of this, some data are already available!);
- Few data already available:

  Airapetian et al. (Hermes) NPB 829, 1 (2010); PRC 81, 035202 (2010)
  $D(\vec{e}, e'\gamma)X$, $\vec{D}(\vec{e}, e'\gamma)X$, $Ne(\vec{e}, e'\gamma)X$; and then He, N, Ne, Kr, Xe...
  Little A-dependence found

  Mazouz et al. (JLab Hall A) PRL 99.242501 (2007); experiment E08-025 (2010)
  $D(\vec{e}, e'\gamma)X = d(\vec{e}, e'\gamma)d + n(\vec{e}, e'\gamma)X + p(\vec{e}, e'\gamma)X$; **^{3}He target?**

GPDs for ^{3}He: why?

- ^{3}He is theoretically well known. Even a relativistic treatment may be implemented.
- ^{3}He has been used extensively as an effective neutron target, especially to unveil the spin content of the free neutron, due to its peculiar spin structure:

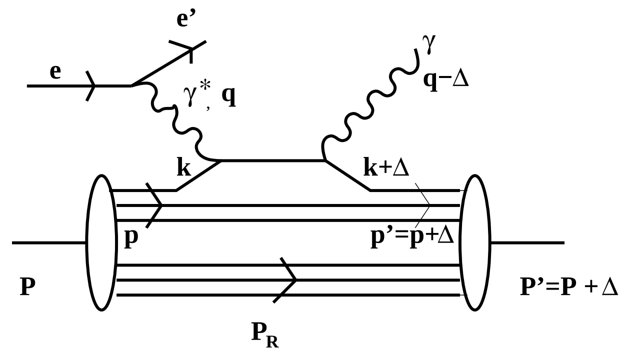


In $S-$wave
$^3\vec{He} = \vec{n}$!

^{3}He always promising when the neutron angular momentum properties have to be studied. To what extent for OAM and $\tilde{G}^q_M$? The answer here.

- To this aim, ^{3}He is a unique target:
  - * **in isoscalar systems, such as ^{2}H and ^{4}He, the contribution of the neutron E_q is basically cancelled by that of the proton one ($\kappa_p \simeq -\kappa_n$); vey difficult to extract the neutron E_q, crucial to access OAM, in coherent experiments;**
  - * **heavier targets do not allow refined theoretical treatments.**

GPDs of ^{3}He in IA



coherent DVCS in I.A.
(^{3}He does not break-up, $\Delta^2 \ll M^2, \xi^2 \ll 1$,):

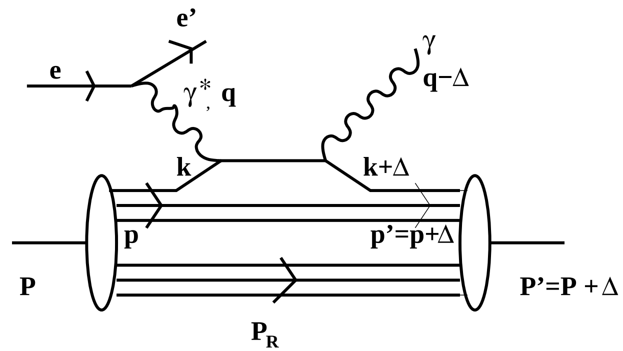
In a symmetric frame ($\bar{p} = (p + p')/2$) :

$$
\begin{aligned}
k^+ &= (x+\xi)\bar{P}^+ = (x'+\xi')\bar{p}^+ \; , \\
(k+\Delta)^+ &= (x-\xi)\bar{P}^+ = (x'-\xi')\bar{p}^+ \; ,
\end{aligned}
$$

one has, for a given GPD, H_q, $\tilde{H}_q$ or $\tilde{G}^q_M$,

$$
GPD_q(x,\xi,\Delta^2) \simeq \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} {}_A\langle P'S'|\hat{O}^\mu_q|PS\rangle_A|_{z^+=0, z_\perp=0} \, .
$$

GPDs of ^{3}He in IA



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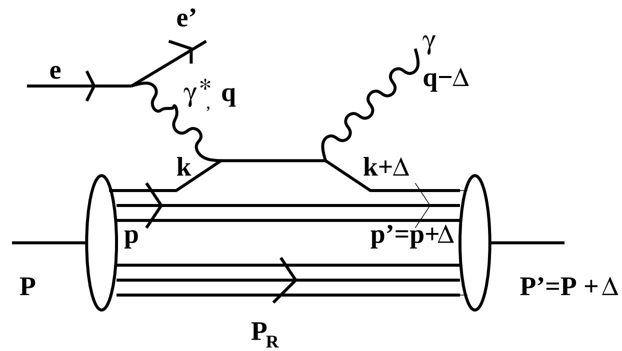
By properly inserting complete sets of states for the interacting nucleon and the recoiling system :

GPDs of ^{3}He in IA



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one has, for a given GPD, H_q, $\tilde{H}_q$ or $\tilde{G}^q_M$,

$$GPD_q(x,\xi,\Delta^2) = \int \frac{dz^-}{4\pi} e^{ix'\bar{p}^+z^-} \langle P'S'| \sum_{\vec{P}'_R, S'_R, \vec{p}', s'} \{|P'_R S'_R\rangle |p's'\rangle\} \langle P'_R S'_R| \langle p's'|\, \hat{O}^\mu_q \sum_{\vec{P}_R, S_R, \vec{p}, s} \{|P_R S_R\rangle |ps\rangle\} \{\langle P_R S_R| \langle ps|\} \;\; |PS\rangle \,,$$

and, since $\{\langle P_R S_R|\langle ps|\}|PS\rangle = \langle P_R S_R, ps|PS\rangle (2\pi)^3 \delta^3(\vec{P} - \vec{P}_R - \vec{p}) \delta_{S, S_R\, s}$,

GPDs of ^{3}He in IA

H_q^A can be obtained in terms of H_q^N (**S.S. PRC 70, 015205 (2004), PRC 79, 025207 (2009)**):

$$H_q^A(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p} \overline{\sum_S} \sum_s P^N_{SS,ss}(\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} H_q^N(x',\Delta^2,\xi') \; ,$$

$\tilde{G}_M^{3,q}$ in terms of $\tilde{G}_M^{N,q}$ (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**):

$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) = \sum_N \int dE \int d\vec{p} \left[P^N_{+-,+-} - P^N_{+-,-+} \right] (\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x',\Delta^2,\xi') \; ,$$

and $\tilde{H}_q^A$ can be obtained in terms of $\tilde{H}_q^N$ (*preliminary*):

$$\tilde{H}_q^A(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p} \left[P^N_{++,++} - P^N_{++,--} \right] (\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} \tilde{H}_q^N(x',\Delta^2,\xi') \; ,$$

GPDs of ^{3}He in IA

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$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) = \sum_N \int dE \int d\vec{p} \left[P^N_{+-,+-} - P^N_{+-,-+} \right](\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x',\Delta^2,\xi') \ ,$$

where $P^N_{SS,ss}(\vec{p},\vec{p}\,',E)$ is the one-body, spin-dependent, off-diagonal spectral function for the nucleon N in the nucleus,

$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{1}{(2\pi)^6} \frac{M\sqrt{ME}}{2} \int d\Omega_t \sum_{s_t} \langle \vec{P}' S' | \vec{p}\,' s', \vec{t} s_t \rangle_N \langle \vec{p} s, \vec{t} s_t | \vec{P} S \rangle_N \ ,$$

evaluated by means of a realistic treatment based on Av18 wave functions

(**w.f. from A. Kievsky** *et al* **NPA 577, 511 (1994), overlaps from A. Kievsky** *et. al*, **PRC 56, 64 (1997)**).

Nucleon GPDs: initially, a simple model by Radyushkin&Musatov (**PRD 61, 074027 (2000)**)

The $\tilde{G}_M^{3,q}$ calculation has the correct limits:

For H_q^3, correct forward limit and $x-$integral (**S.S. PRC 70, (2004), PRC 79, (2009)**);

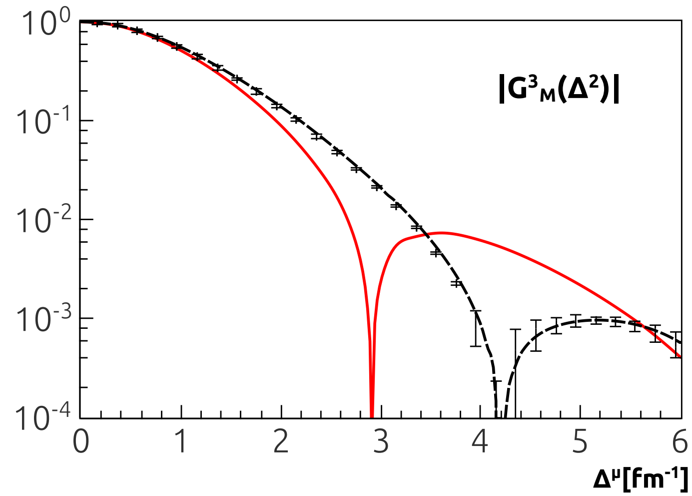
For $\tilde{G}_M^3$ (**M. Rinaldi, S.S. PRC 85, 062201(R) (2012); PRC 87, 035208 (2013)**):

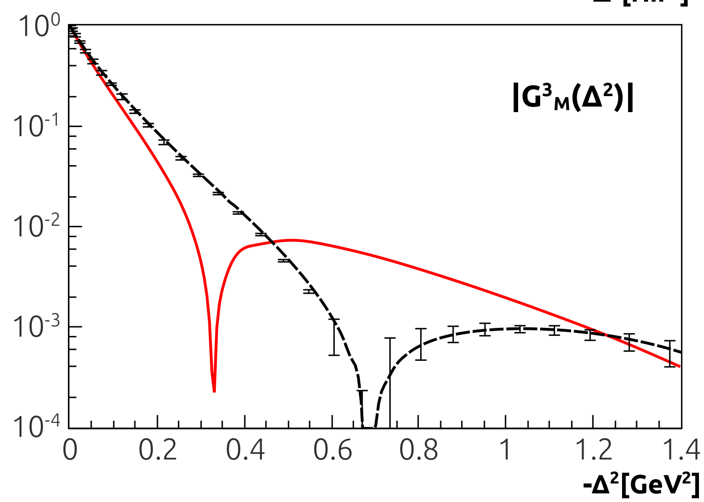
1 - Forward limit: no control on $E_q^3(x,0,0)$
no possible check;

2 - Magnetic F.F.:

$$\sum_q \int dx\, \tilde{G}_M^{3,q}(x,\xi,\Delta^2) = G_M^3(\Delta^2)$$

- in perfect agreement with previous IA, Av18 calculations (**L.E. Marcucci et al. PRC 58 (1998)**)
- in good agreement with data in the region relevant to the coherent process, $-\Delta^2 \ll 0.15$ GeV^2
- To have agreement at higher Δ^2, effects beyond IA are necessary: not important for the coherent channel!

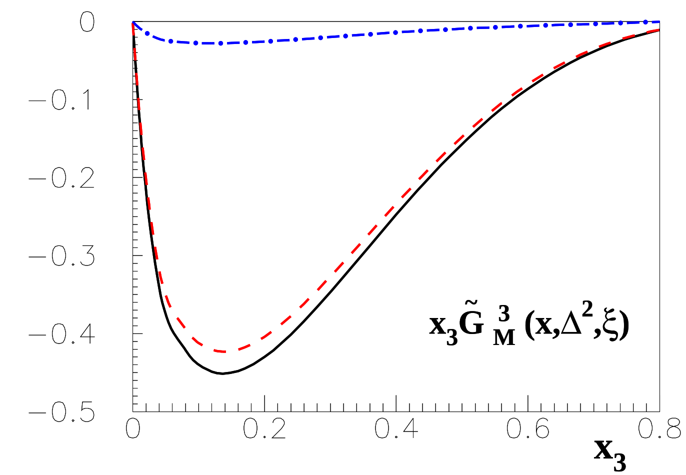




$\tilde{G}_M^{3,q}$: proton and neutron contributions

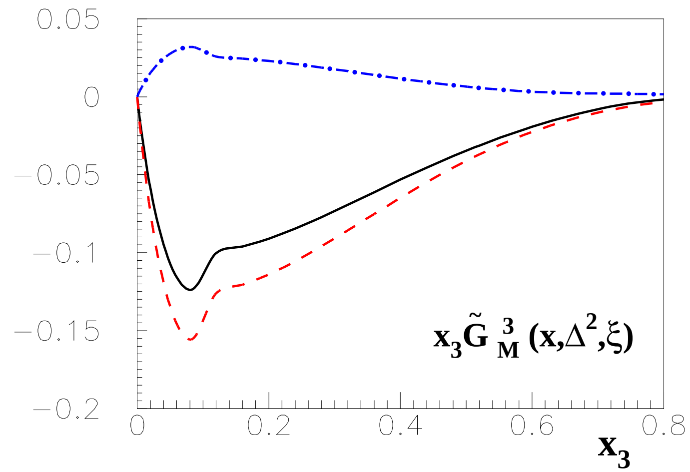
1 - Forward limit, $\Delta^2 = 0,\ \xi = 0$:

As we hoped, the neutron contribution to ^{3}He largely dominates! ($x_3 = (M_A/M)x \simeq 3x$):
The proton contribution to ^{3}He is almost negligible!



2 - Non-forward, $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$:

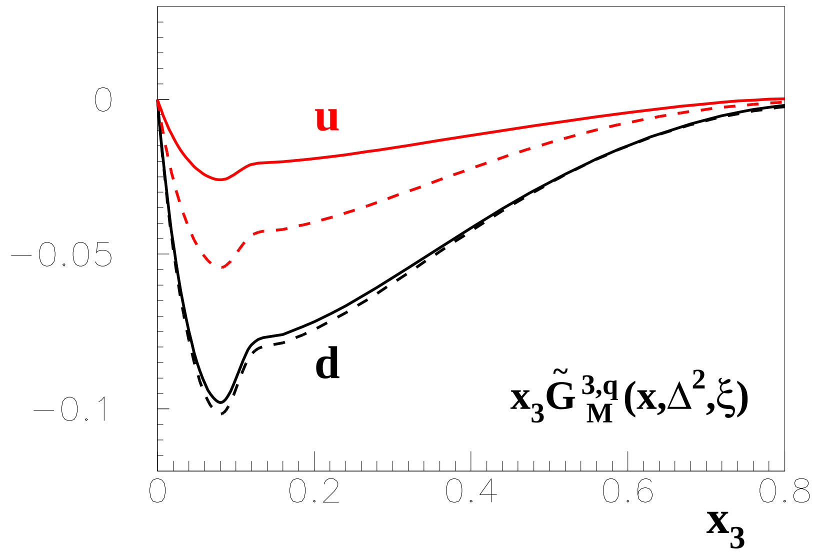
The neutron contribution to ^{3}He still dominates
The proton contribution to ^{3}He gets sizable



How to get the neutron information?

$\tilde{G}_M^{3,q}$: Flavor separation

For the u flavor, the neutron contribution (dashed) to ^{3}He (full) is less important than for the d flavor:



Understandable, sketching the formula:

$$\tilde{G}_M^{3,q} \approx P_p^3 \otimes \tilde{G}_M^{p,q} + P_n^3 \otimes \tilde{G}_M^{n,q} \, ,$$

where $P_{p(n)}^3$ describes the proton (neutron) dynamics in ^{3}He.

As already explained, due to the spin structure of ^{3}He,
$P_n^3 >> P_p^3 \longrightarrow$ neutron dominates in the forward limit.

With increasing Δ^2, for the u flavor, $\tilde{G}_M^{p,u} >> \tilde{G}_M^{n,u} \longrightarrow$ the proton contribution grows. Not for d!

Besides, 1/2 of the d content of ^{3}He comes from the neutron, only 1/5 of the u one comes from it.

Extracting the neutron - I:

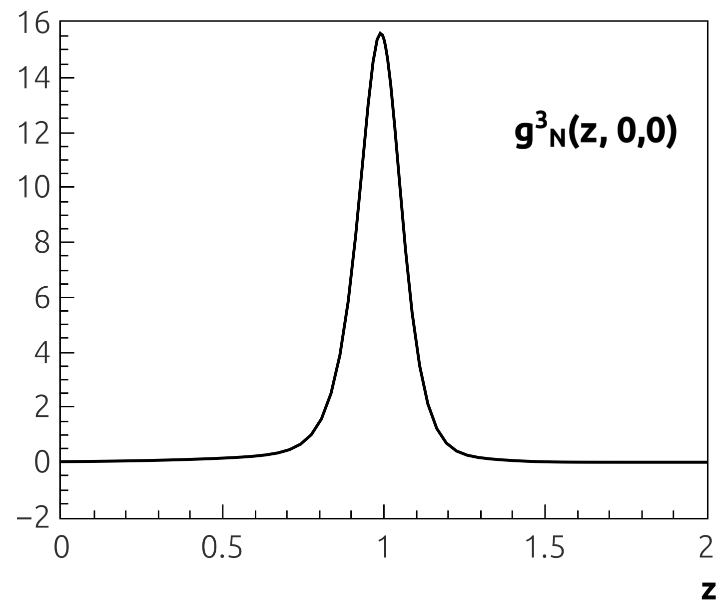
The convolution formula can be written as

$$\tilde{G}_M^{3,q}(x_3, \Delta^2, \xi) = \sum_N \int_{x_3}^{\frac{M_A}{M}} \frac{dz}{z} g_N^3(z, \Delta^2, \xi) \tilde{G}_M^{N,q}\left(\frac{x_3}{z}, \Delta^2, \frac{\xi}{z},\right) \,,$$

where $g_N^3(z, \Delta^2, \xi)$ is a “light cone off-forward momentum distribution” and, since close to the forward limit it is strongly peaked around $z = 1$

$$g_N^3(z, \Delta^2, \xi) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$$

$$\delta\left(z + \xi - \frac{M_A}{M}\frac{p^+}{\bar{P}^+}\right)$$



Extracting the neutron - I:

The convolution formula can be written as

$$\tilde{G}_M^{3,q}(x_3,\Delta^2,\xi) = \sum_N \int_{x_3}^{\frac{M_A}{M}} \frac{dz}{z} g_N^3(z,\Delta^2,\xi) \tilde{G}_M^{N,q}\left(\frac{x_3}{z},\Delta^2,\frac{\xi}{z},\right) ,$$

where $g_N^3(z,\Delta^2,\xi)$ is a “light cone off-forward momentum distribution” and, since close to the forward limit it is strongly peaked around $z=1$

$$\begin{aligned} \tilde{G}_M^{3,q}(x_3,\Delta^2,\xi) &\simeq low\,\Delta^2 \simeq \sum_N \tilde{G}_M^{N,q}\left(x_3,\Delta^2,\xi\right) \int_0^{\frac{M_A}{M}} dz g_N^3(z,\Delta^2,\xi) \\ &= G_M^{3,p,point}(\Delta^2)\tilde{G}_M^p(x_3,\Delta^2,\xi) + G_M^{3,n,point}(\Delta^2)\tilde{G}_M^n(x_3,\Delta^2,\xi) \,. \end{aligned}$$

where, at $x_3 < 0.7$, the magnetic point like ff has been introduced

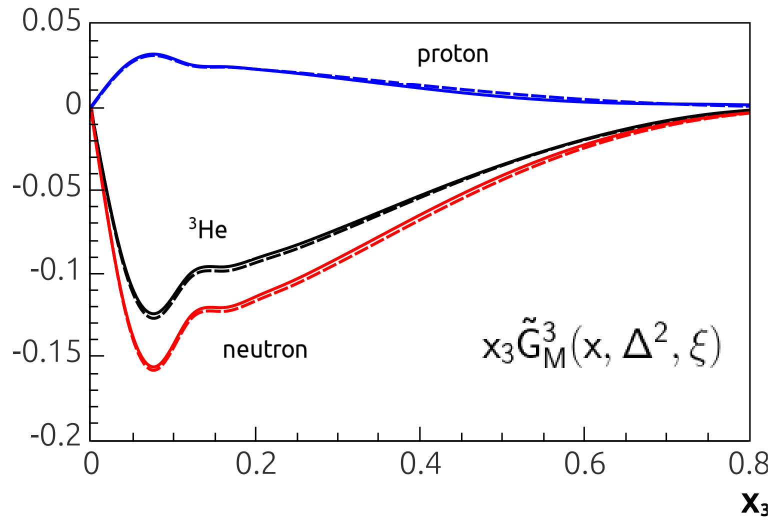
$$G_M^{3,N,point}(\Delta^2) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p},\vec{p}+\vec{\Delta},E) = \int_0^{\frac{M_A}{M}} dz\, g_N^3(z,\Delta^2,\xi) \,.$$

Extracting the neutron - II:

Validity of the approximated formula:

full: IA calculation, $\tilde{G}^3_M(x, \Delta^2, \xi)$ and proton and neutron contributions to it, at $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;

dashed: same quantities, with the approximated formula:



$$\tilde{G}^{3,q}_M(x, \Delta^2, \xi) \simeq G^{3,p,point}_M(\Delta^2)\tilde{G}^p_M(x, \Delta^2, \xi) + G^{3,n,point}_M(\Delta^2)\tilde{G}^n_M(x, \Delta^2, \xi)$$

Impressive agreement! The only Nuclear Physics ingredient in the approximated formula is the magnetic point like ff, which is under good theoretical control:

Δ^2 [GeV^2]	$G^{3,p,point}_M$ Av18	$G^{3,p,point}_M$ Av14	$G^{3,n,point}_M$ Av18	$G^{3,n,point}_M$ Av14
0	-0.044	-0.049	0.879	0.874
-0.1	0.040	0.038	0.305	0.297
-0.2	0.036	0.035	0.125	0.119

Extracting the neutron - III:

The approximated relation can now be solved to extract the neutron contribution:

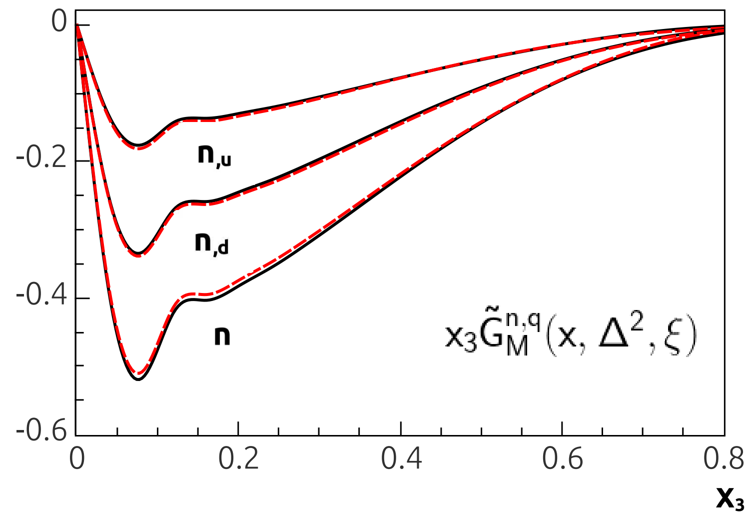
$$\tilde{G}_M^{n,extr}(x,\Delta^2,\xi) \simeq \frac{1}{G_M^{3,n,point}(\Delta^2)} \left\{ \tilde{G}_M^3(x,\Delta^2,\xi) - G_M^{3,p,point}(\Delta^2)\tilde{G}_M^p(x,\Delta^2,\xi) \right\} ,$$

from data for $\tilde{G}_M^3(x,\Delta^2,\xi)$ and $\tilde{G}_M^p(x,\Delta^2,\xi)$, using as theoretical ingredients the magnetic point like ffs only.

The procedure works nicely!

full : the neutron model for $\tilde{G}_M^n(x,\Delta^2,\xi)$ and the different flavor contributions to it used in the IA calculation, at $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;

dashed: the neutron extracted using the IA calculation for $\tilde{G}_M^3(x,\Delta^2,\xi)$ and the model used in it for $\tilde{G}_M^p(x,\Delta^2,\xi)$ together with the magnetic point like ffs.



Extracting the neutron - IV:

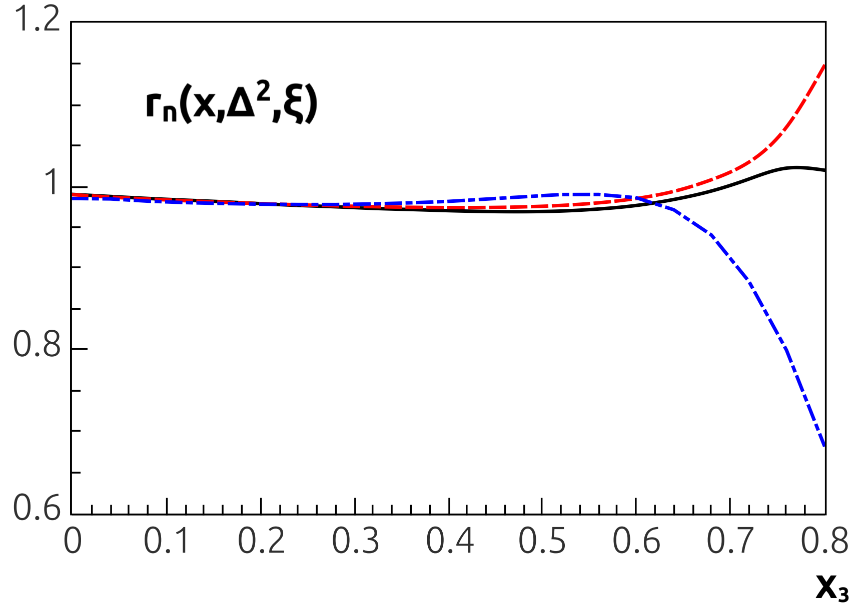
The validity of the extraction procedure is emphasized showing the following ratio, which would be one if the procedure were perfect:

$$r_n(x, \Delta^2, \xi) = \frac{\tilde{G}_M^{n,extr}(x,\Delta^2,\xi)}{\tilde{G}_M^{n}(x,\Delta^2,\xi)}$$

full: forward limit

dashed: $\Delta^2 = -0.1$ GeV^2, $\xi = 0$;

dot-dashed: $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;



at $x < 0.7$, in all the kinematical range relevant for coherent DVCS at JLab, the error in the extraction is a few percents.

Extracting the neutron - V:

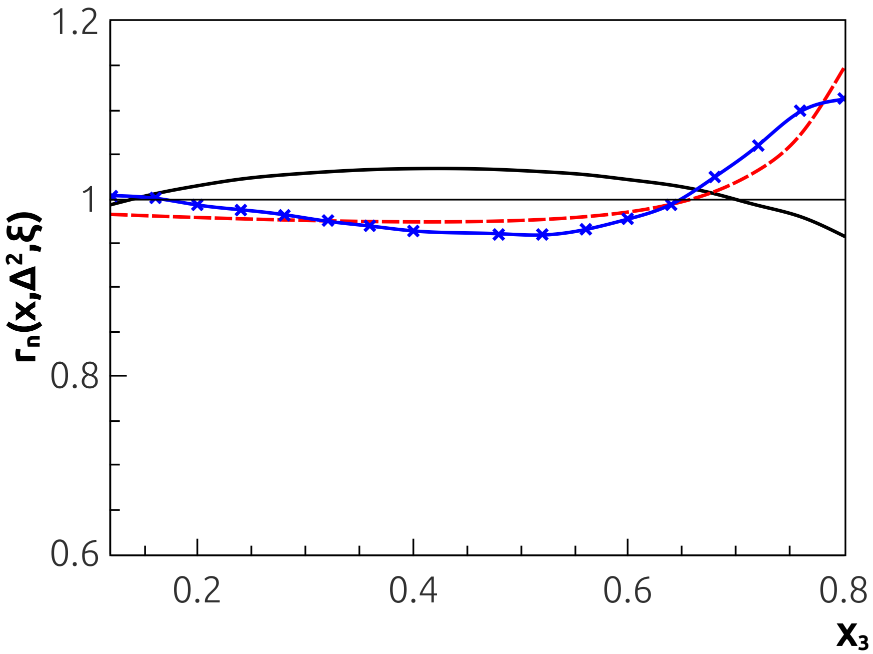
The validity of the extraction procedure is emphasized showing the same ratio, evaluated using different models for the GPDs as input in the IA calculation:

$$r_n(x,\Delta^2,\xi) = \frac{\tilde{G}_M^{n,extr}(x,\Delta^2,\xi)}{\tilde{G}_M^{n}(x,\Delta^2,\xi)}$$

dashed: the model of Radyushkin, at $\Delta^2 = -0.1$ GeV^2, $\xi = 0$;

full: a very different model based on a constituent quark scenario (**S.S, V. Vento EPJA 16, 527 (2003)**) at $\Delta^2 = -0.1$ GeV^2, $\xi = 0$;

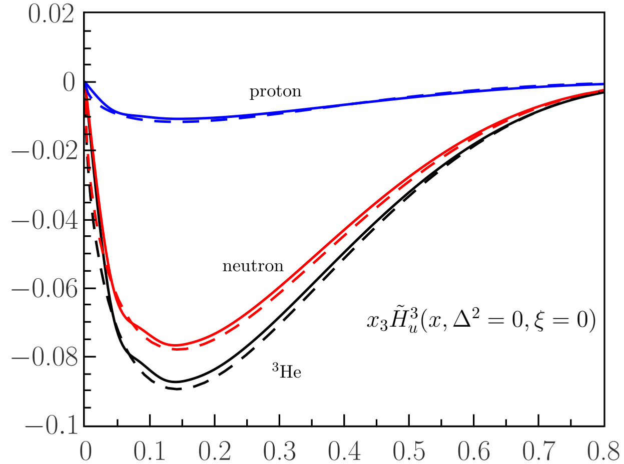
crosses: another very different model, the MIT bag model (**X.-D. Ji et al., PRD 56 (1997) 5511**) at $\Delta^2 = -0.1$ GeV^2, $\xi = 0$.



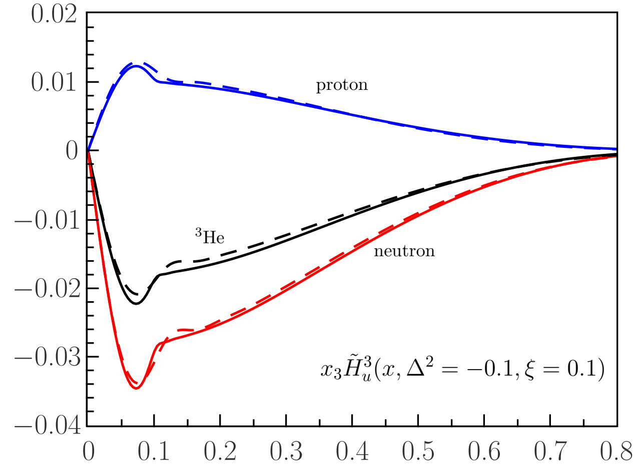
at $x < 0.7$, in all the kinematical range relevant for coherent DVCS at JLab, the error in the extraction due to the use of a different nucleonic model is a few percents at most.

The GPD $\tilde{H}$: *preliminary*

$\tilde{H}^{3,u}(x,\Delta^2,\xi)$ and proton and (dominant!) neutron contributions to it:



Forward



Non-forward

full: IA calculation; dashed: approximated formula:

$$\tilde{H}^{3,u}(x,\Delta^2,\xi) \simeq g_A^{3,p,point}(\Delta^2)\tilde{H}^{p,u}(x,\Delta^2,\xi) + g_A^{3,n,point}(\Delta^2)\tilde{H}^{n,u}(x,\Delta^2,\xi)$$

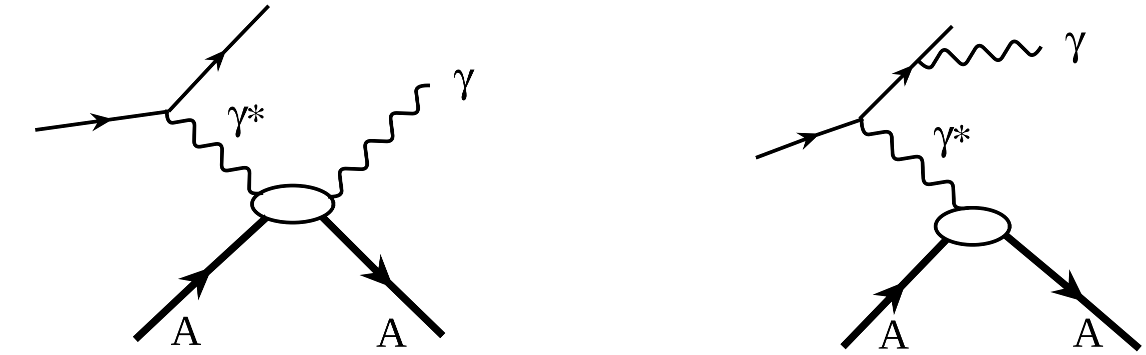
Good agreement! The only Nuclear Physics ingredient in the approximated formula is the axial point like ff, which is under good theoretical control.
One has $g_A^{3,N,point}(\Delta^2=0)=p_N$, nucleon effective polarizations (within AV18, $p_n=0.878,\ p_p=-0.024$), used in DIS for extracting the neutron information from ^{3}He (**C. Ciofi, S.S, E. Pace and G. Salmè, PRC 48 R968 (1993)**). Forward limit correctly recovered!

Conclusions

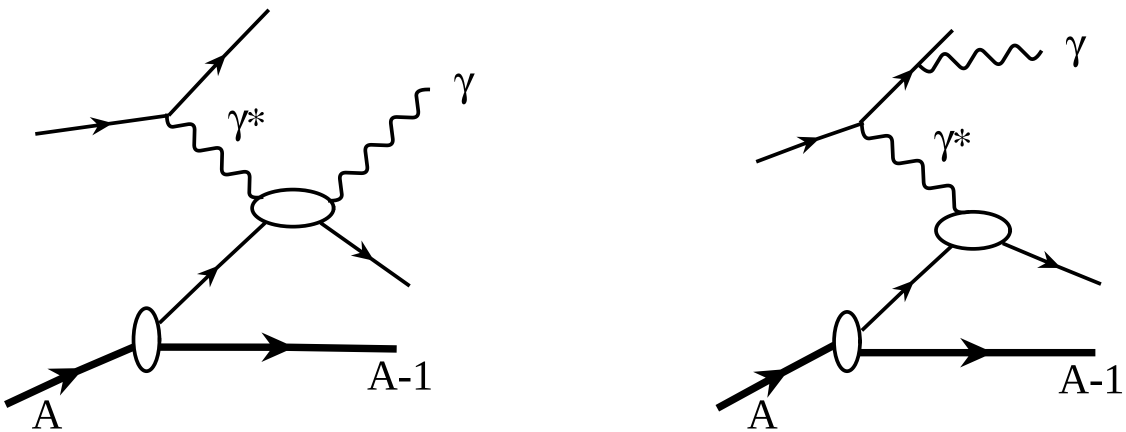
- What we have:
  - * An instant form, I.A. calculation of $H^3, \tilde{G}^3_M, \tilde{H}^3$, within AV18;
  - * the neutron contribution dominates $\tilde{G}^3_M$ and $\tilde{H}^3$ at low Δ^2;
  - * an extraction procedure of the neutron information, able to take into account all the nuclear effects encoded in an IA analysis, weakly dependent on both the nuclear potential and the nucleonic model used in the calculation;
- What we can do now: to estimate X-sections (DVCS, BH, Interference) $\longrightarrow$ a proposal of coherent DVCS off ^{3}He at JLab@12 GeV?
- What has to be done, in case experiments are performed at higher Δ^2:
  - * To implement a RELATIVISTIC TREATMENT (ready!) (**A. Del Dotto's talk, later in this session**)
  - * and/or to go beyond IA, including many body currents into the scheme.
- What is expected:
  - * The OAM parton structure of the neutron;
  - * A deeper understanding of the nuclear parton structure;

Importance of nuclear FB systems for QCD studies

coherent vs. incoherent DVCS:



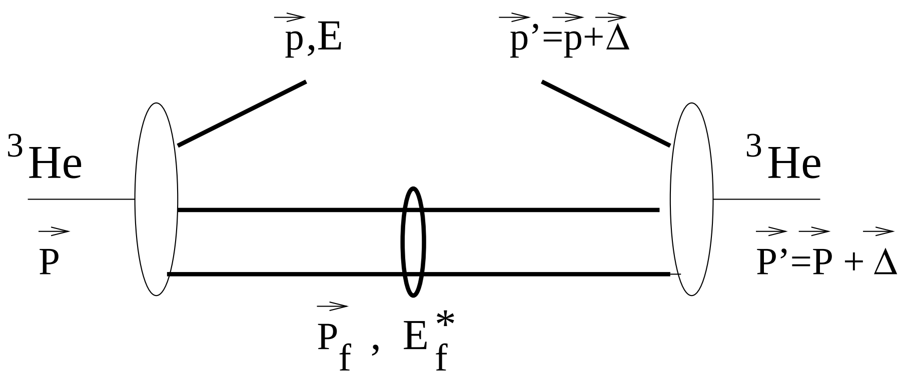
Coherent



Incoherent

A few words about $P^3_N(\vec{p}, \vec{p} + \vec{\Delta}, E)$:

$$P^3_N(\vec{p}, \vec{p} + \vec{\Delta}, E) = \frac{1}{(2\pi)^3} \frac{1}{2} \sum_M \sum_{f,s} \langle \vec{P}' M | (\vec{P} - \vec{p}) S_f, (\vec{p} + \vec{\Delta}) s \rangle$$
$$\times \langle (\vec{P} - \vec{p}) S_f, \vec{p} s | \vec{P} M \rangle \, \delta(E - E_{min} - E^*_f) \, .$$



- the two-body recoiling system can be either the deuteron or a scattering state;
- when a deeply bound nucleon, with high removal energy $E = E_{min} + E^*_f$, leaves the nucleus, the recoling system is left with high excitation energy E^*_f ;
- the three-body bound state and the two-body bound or scattering state are evaluated within the same (Av18) interaction: the extension of the treatment to heavier nuclei would be extremely difficult

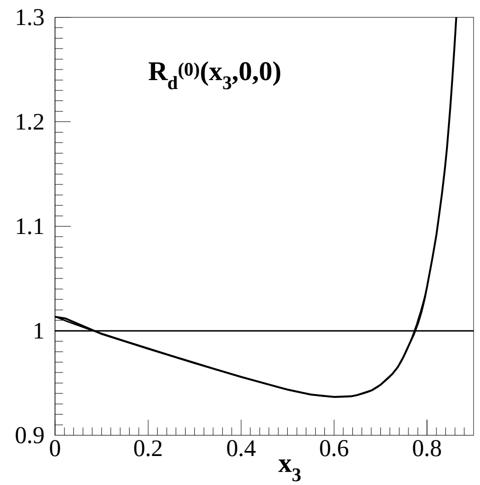
The calculation has the correct limits:

1 - Forward limit: the ratio:

$$R_q(x,0,0) = \frac{H_q^3(x,0,0)}{2H_q^p(x,0,0)+H_q^n(x,0,0)}$$

$$= \frac{q^3(x)}{2q^p(x)+q^n(x)}$$

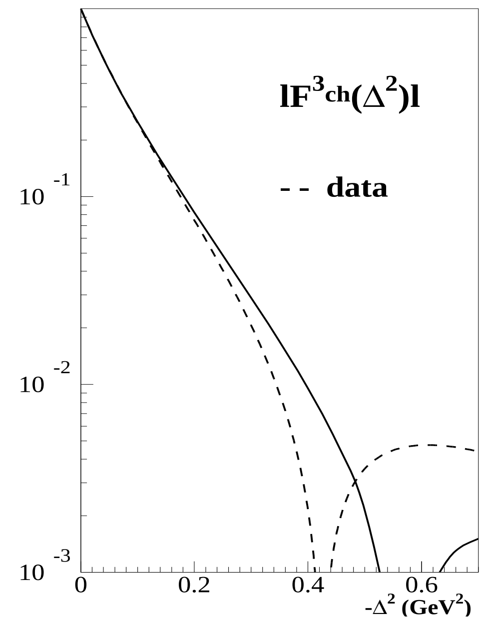
shows an EMC-like behavior;



2 - Charge F.F.:

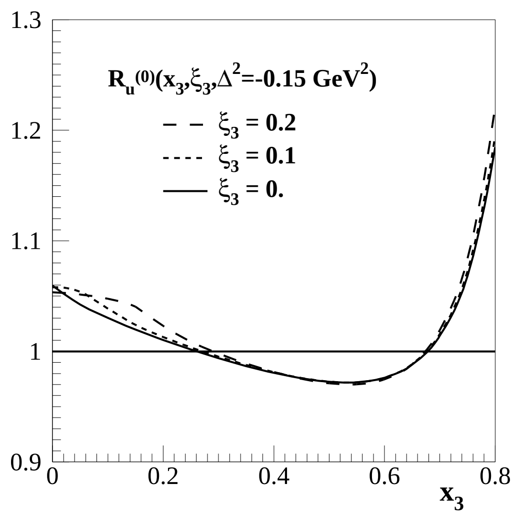
$$\int dx H_q^3(x,\xi,\Delta^2) = F_q^3(\Delta^2)$$

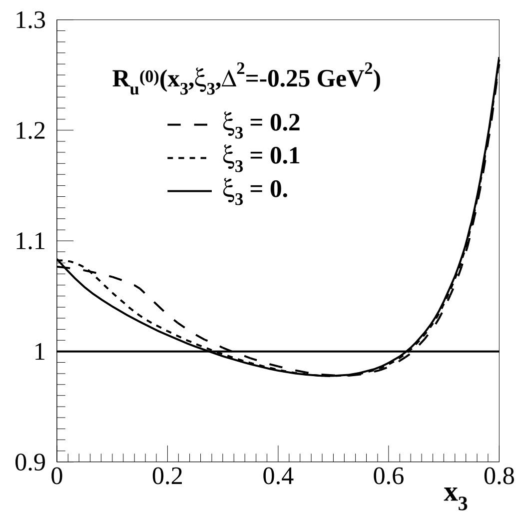
in good agreement with data in the region relevant to the coherent process, $\Delta^2 \ll 0.25$ GeV^2.



Nuclear effects - general features

- Nuclear effects grow with ξ at fixed Δ^2, and with Δ^2 at fixed ξ:





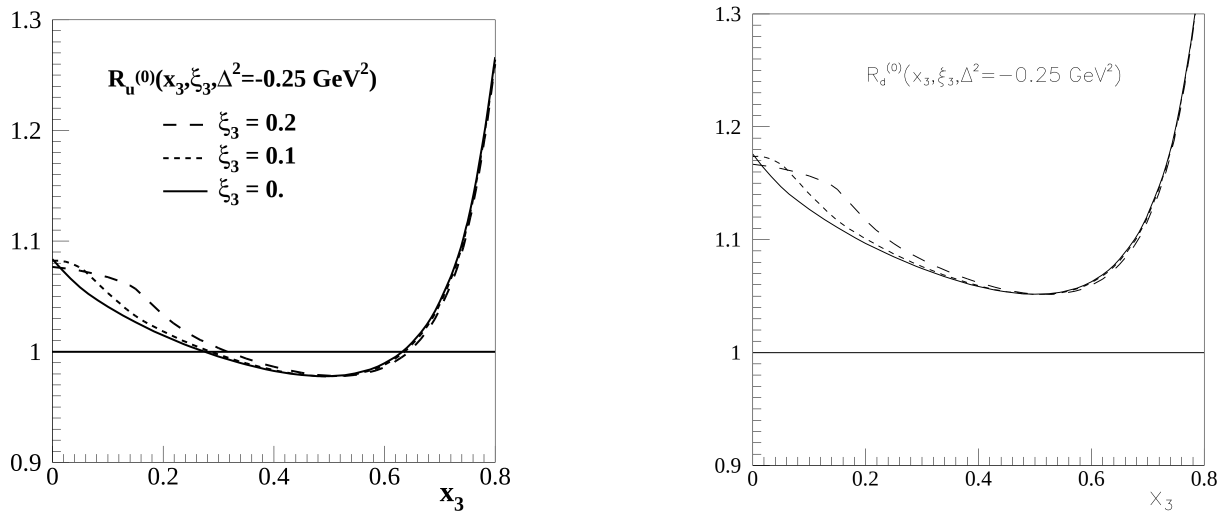
$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi) F_q^3(\Delta^2)$$

$R_q^{(0)}(x,\xi,\Delta^2)$ would be one if there were no nuclear effects;
as it is found also for the deuteron, there is no factorization into terms dependent separately on Δ^2 and x, ξ (the factorization hypotheses has been used to estimate nuclear GPDs).

Nuclear effects - flavor dependence

- Nuclear effects are bigger for the d flavor rather than for the u flavor:



$$R_q^{(0)}(x,\xi,\Delta^2) = \frac{H_q^3(x,\xi,\Delta^2)}{2H_q^{3,p}(x,\xi,\Delta^2) + H_q^{3,n}(x,\xi,\Delta^2)}$$

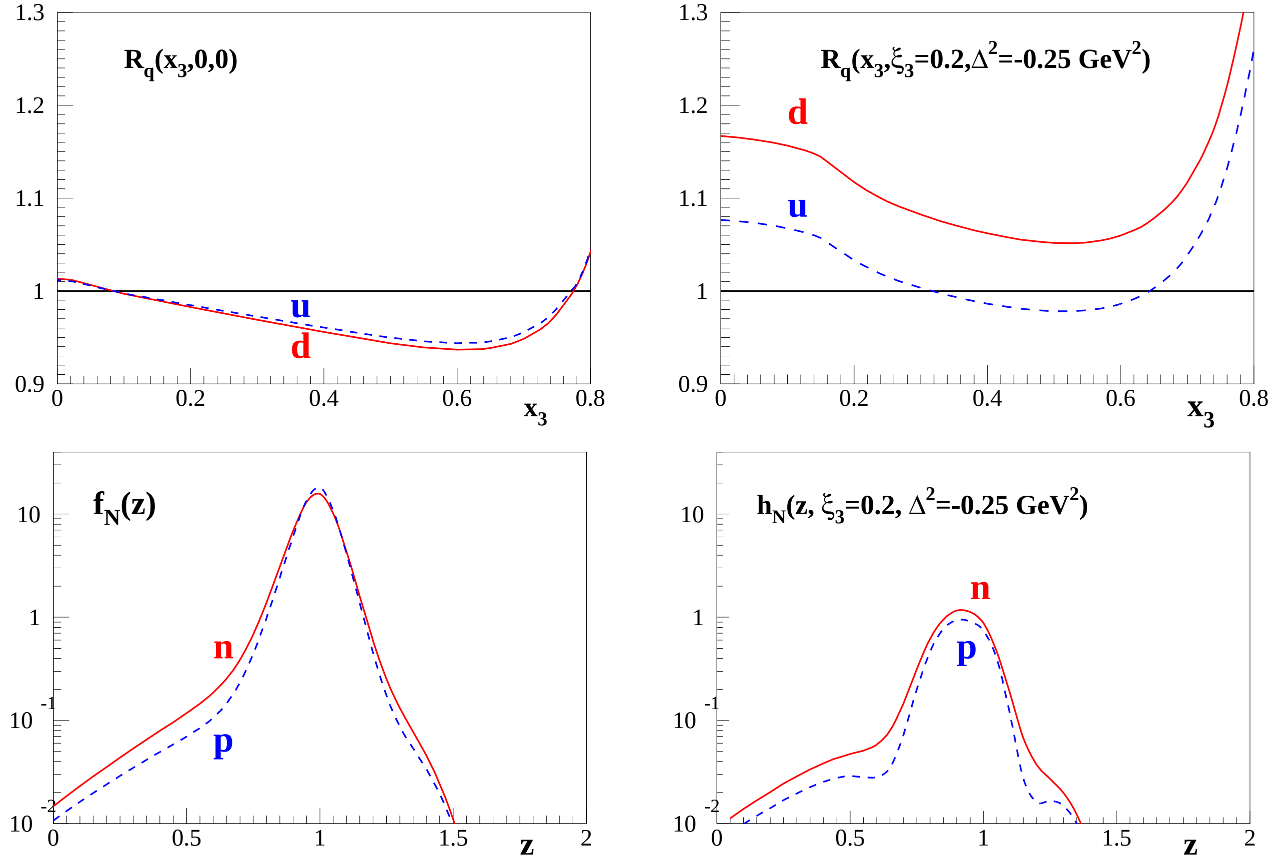
$$H_q^{3,N}(x,\xi,\Delta^2) = \tilde{H}_q^N(x,\xi)F_q^3(\Delta^2)$$

$R_q^{(0)}(x,\xi,\Delta^2)$ would be one if there were no nuclear effects;

- This is a typical conventional, IA effect (spectral functions are different for p and n in ^{3}He, not isoscalar!); if (not) found, clear indication on the reaction mechanism of DIS off nuclei.

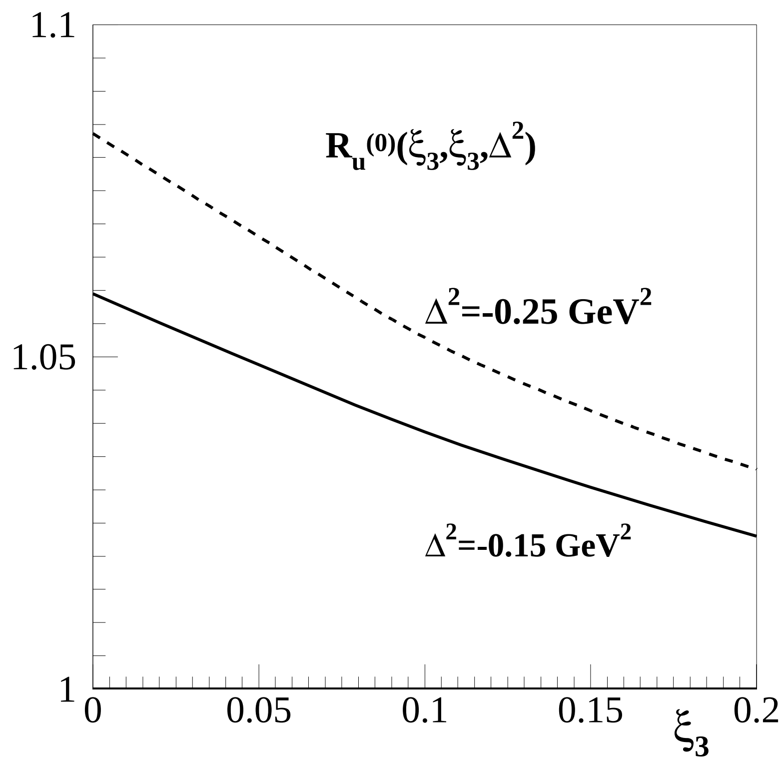
Nuclear effects - flavor dependence

- The d and u distributions follow the pattern of the neutron and proton light-cone momentum distributions, respectively:



Nuclear effects @ $x = \xi$

- Nuclear effects are large even in the important region $x = \xi$:



Nuclear effects - the binding

General IA formula: $H_q^A(x,\xi,\Delta^2) \simeq \sum_N \int_x^1 \frac{dz}{z} h_N^A(z,\xi,\Delta^2) H_q^N\left(\frac{x}{z},\frac{\xi}{z},\Delta^2\right)$

where

$$h_N^A(z,\xi,\Delta^2) = \int dE d\vec{p}\, P_N^A(\vec{p},\vec{p}+\vec{\Delta},E)\delta\left(z+\xi-\frac{p^+}{\bar{P}^+}\right)$$

$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) = \bar{\sum}_M \sum_{s,f} \langle \vec{P}' M | \vec{P}_f, (\vec{p}+\vec{\Delta})s\rangle$$

$$\times \langle \vec{P}_f, \vec{p}s|\vec{P}M\rangle\, \delta(E - E_{min} - E_f^*)$$

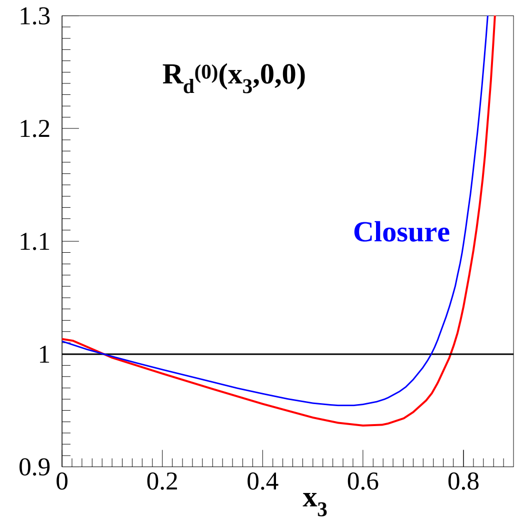
using the Closure Approximation, $E_f^* = \bar{E}$:

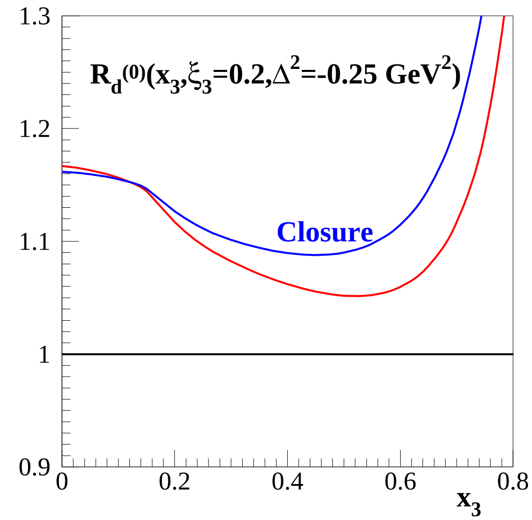
$$P_N^3(\vec{p},\vec{p}+\vec{\Delta},E) \simeq \bar{\sum}_M \sum_s \langle \vec{P}' M | a_{\vec{p}+\vec{\Delta},s} a^\dagger_{\vec{p},s} | \vec{P} M\rangle$$

$$\delta(E - E_{min} - \bar{E}) =$$

$$= n(\vec{p},\vec{p}+\vec{\Delta})\, \delta(E - E_{min} - \bar{E})\ ,$$

Spectral function substituted by a Momentum distribution

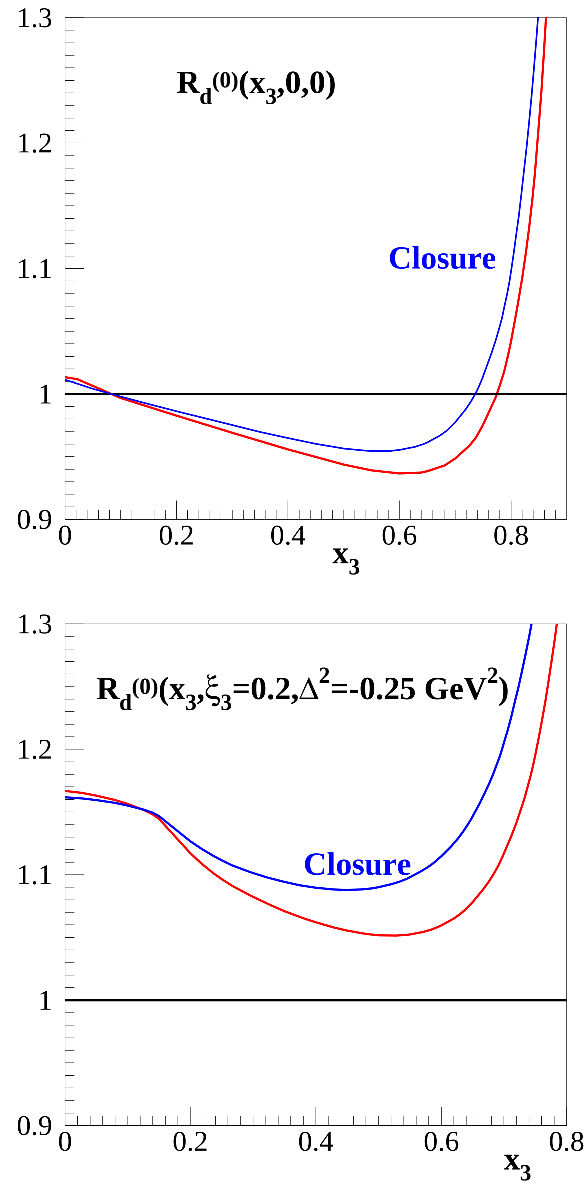




Nuclear effects - the binding

Nuclear effects are bigger than in the forward case: dependence on the binding

- In calculations using $n(\vec{p}, \vec{p} + \vec{\Delta})$ instead of $P_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$, in addition to the IA, also the Closure approximation has been assumed;
- 5 % to 10 % binding effect between $x = 0.4$ and 0.7 - much bigger than in the forward case;
- for $A > 3$, the evaluation of $P_N^3(\vec{p}, \vec{p} + \vec{\Delta}, E)$ is difficult - such an effect is not under control: Conventional nuclear effects can be mistaken for exotic ones;
- for ^{3}He it is possible : this makes it a unique target, even among the Few-Body systems.

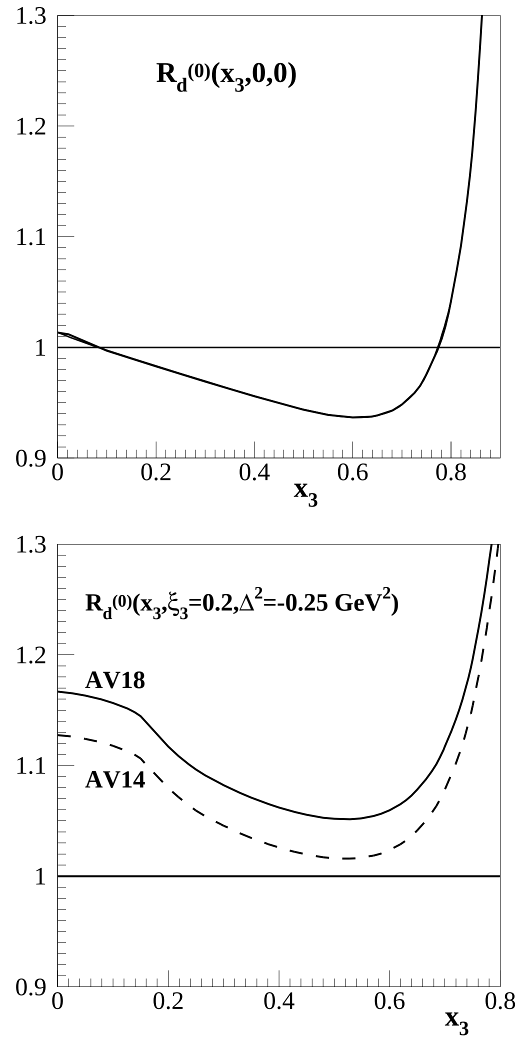


Dependence on the NN interaction

Nuclear effects are bigger than in the forward case: dependence on the potential

- Forward case: Calculations using the AV14 or AV18 interactions are indistinguishable

- Non-forward case: Calculations using the AV14 and AV18 interactions do differ:



Why nuclei? - (many reasons...)

I will show results for ^{3}He, in IA, for the coherent channel... But there is much more:

- for the deuteron:
  Berger, Cano, Diehl, Pire, PRL 87 (2001) 142302); Cano & Pire, EPJA 19 (2004) 423; Kirchner & Müller, EPJC 32 (2003) 347.
- beyond the coherent channel:
  Liuti & Taneja PRC 72 032201 (R) 2005: spin-0 nuclei, applied to ^{4}He;
  Guzey, PRC 78 (2008) 025211: constraining the neutron information from incoherent DVCS off nuclei at large t (spin-0 nuclei);
- beyond IA (Shadowing: low x_{Bj}, large distances):
  Freund & Strikman, PRC 69 (2004) 015203; Goeke et al., EPJ. A36 (2008) 49-60;
- for finite-heavy nuclei:
  Guzey & Strikman, PRC 68 (2003) 015204; Kirchner & Müller, EPJC 32, 347 (2003)
- discussing other issues: Color Transparency phenomena, Liuti & Taneja, PRD 70, 074019 (2004); Energy-momentum tensor in nuclei: Polyakov PLB 555 (2003) 57; Guzey & Siddikov J. Phys. G 32, 251 (2006); Guzey, Thomas, Tsushima PRC 79 (2009) 055205 ...