3-D parton structure of light nuclei

Sergio Scopetta

Dipartimento di Fisica e Geologia, Università di Perugia
& INFN, Sezione di Perugia

and

Alessio Del Dotto – Università di Roma Tre and INFN, Roma 3, Italy

Leonid Kaptari – JINR, Dubna, Russia & Perugia & JLab

Emanuele Pace – Università di Roma "Tor Vergata" and INFN, Roma 2, Italy

Matteo Rinaldi – Università di Perugia and INFN, Sezione di Perugia, Italy

Giovanni Salmè – INFN, Roma, Italy

Pisa, 22 Aprile 2016

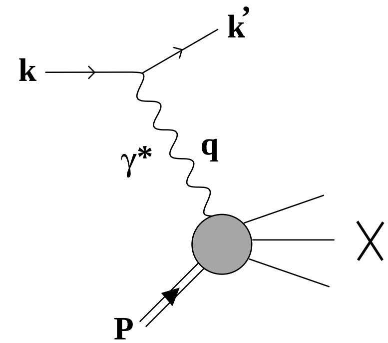
Indice

- **Effetto del mezzo nucleare sulla struttura partonica del nucleone.**
  A 30 anni dalla scoperta dell' effetto EMC, a che punto siamo?

- **Verso una visione 3-D (recent report, R. Dupré and S.S., EPJA (2016), in stampa): nuovi esperimenti oltre le "classiche" misure DIS:**
  - **"vedere" dove sono i partoni nel nucleone legato: processi esclusivi duri e distribuzioni partoniche generalizzate (GPDs) (e, anche, interazioni partoniche multiple (MPI) ai collisionatori adronici (LHC) (vedi talk di M. Rinaldi)**
  - **processi semi-inclusivi (SiDIS): distribuzioni dipendenti dal momento trasverso (TMDs) nei nucleoni, liberi e legati**

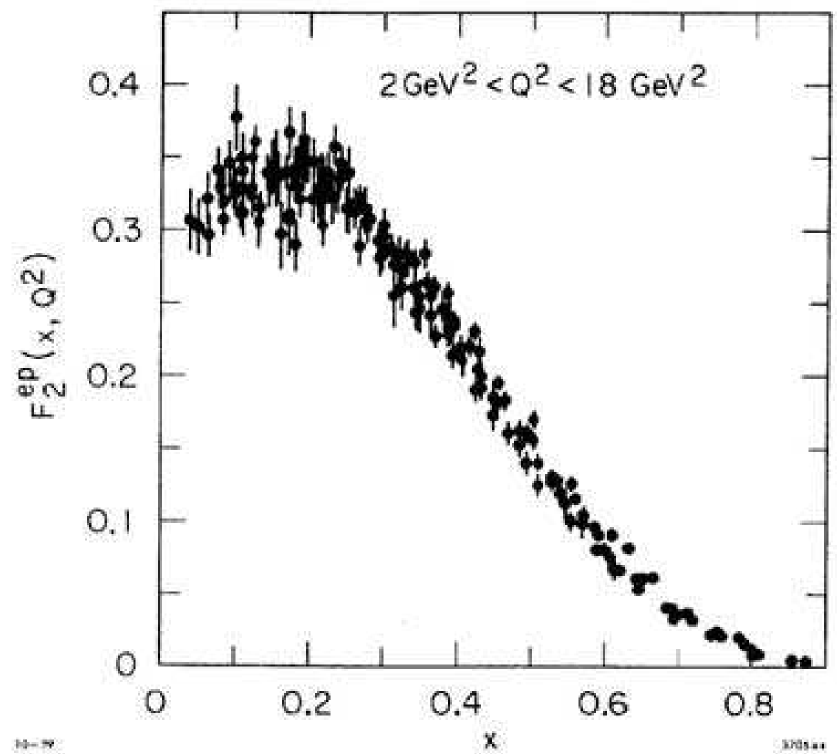
- **Conclusioni**

Il contesto: DIS



Parliamo di diffusione profondamente anelastica (DIS); $A(e,e')X$,
Se il bersaglio A ha $J_A = 1/2$, nel sistema del laboratorio (LAB) dove $q = (\nu, 0, 0, -q)$
nel limite di Bjorken, $Q^2 = -q^2, \nu \to \infty, Q^2/\nu$ finito,

$$\frac{d^2\sigma}{d\Omega dE'} \propto F_2(x) \simeq \sum_q e_q^2 x f_q(x)$$



$F_2(x)$ = funzione di struttura

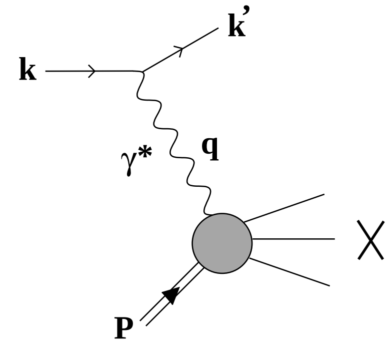
$f_q(x)$ = distribuzione partonica (PDF)

$x = \frac{Q^2}{2P_A \cdot q}$ è un invariante:

- $x = \frac{Q^2}{2M_A\nu}$ (LAB);
- x = frazione di momento del bersaglio portata dal quark. nell' *Infinite Momentum Frame* (IMF) ($p_z \to \infty$)

In generale, F_2 dipende da Q^2. Nel limite di Bjorken, F_2 scala in x: diffusione incoerente su costituenti puntiformi, i partoni (Al LO in QCD, solo i quark contribuiscono ad F_2).

L'effetto EMC: l'inizio

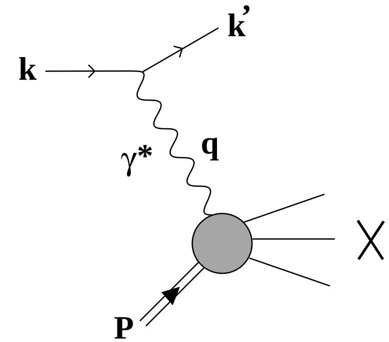


30 anni fa, la European Muon Collaboration (EMC) misurò

$$R(x) = F_2^{56}{}^{Fe}(x)/F_2^{2}{}^{H}(x)$$

Risultato atteso: $R(x) = 1$ a meno di piccole correzioni dovute al moto di Fermi dei nucleoni.

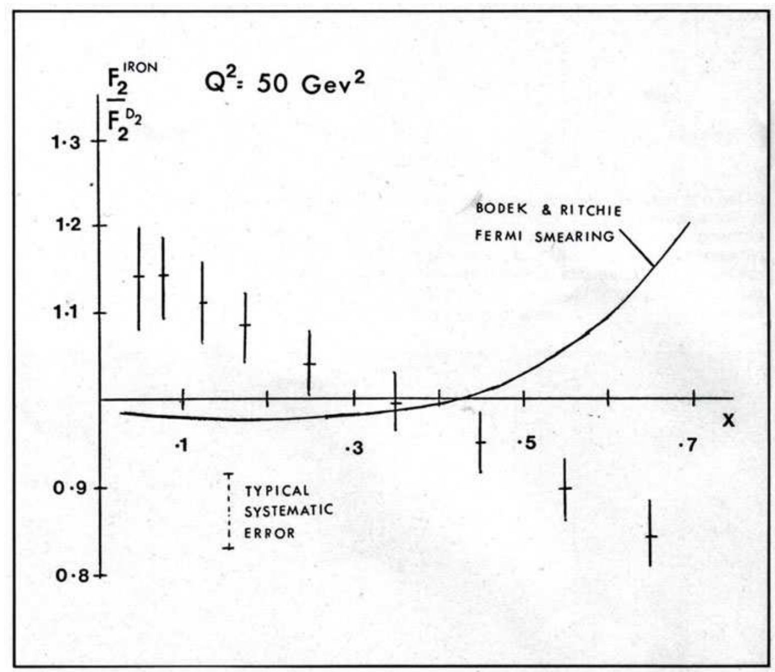
L'effetto EMC: l'inizio



30 anni fa, la European Muon Collaboration (EMC) misurò

$$R(x) = F_2^{56Fe}(x)/F_2^{2H}(x)$$

Risultato atteso: $R(x) = 1$ a meno di piccole correzioni dovute al moto di Fermi dei nucleoni.



Risultato:

Aubert et al. Phys.Lett. B123 (1983) 275

1180 citazioni (inSPIRE)

Interpretazione nel modello a partoni:

"I quark di valenza, nel nucleone legato,
sono mediamente più lenti
che nel nucleone libero"

E nello spazio delle coordinate?

Forse il nucleone legato è più grande di quello libero???

effetto EMC: più in dettaglio

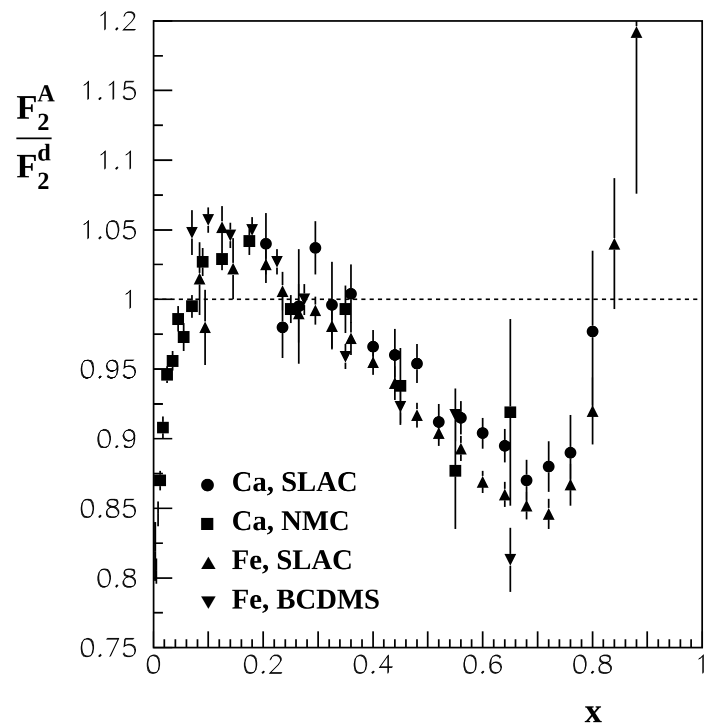
Per DIS su nucleo, $0 \leq x = \frac{Q^2}{2M\nu} \leq \frac{M_A}{M} \simeq A$

- $x \leq 0.3$ “Shadowing region”
  effetti di coerenza, γ^* interagisce
  con partoni di diversi nucleoni

- $0.2 \leq x \leq 0.8$ “EMC (binding) region”:
  quello di cu parlerò

- $0.8 \leq x \leq 1$ “Fermi motion region”

- $x \geq 1$ “TERRA INCOGNITA”
  Quark superveloci in nucleoni superveloci:
  sono pochi! Piccole σ, grandi errori



Caratteristiche salienti andamento universale indipendente da Q^2; dipende debolmente da A; scala con la densità $\rho \to$ proprietà globale

Spiegazioni (esotiche) invocate: raggio di confinamento maggiore per nucleoni legati, quark nucleari in *bag* contenenti 6, 9, $3A$ quark, effetti di nuvola pionica...
Da sole o combinate con spiegazioni più convenzionali...

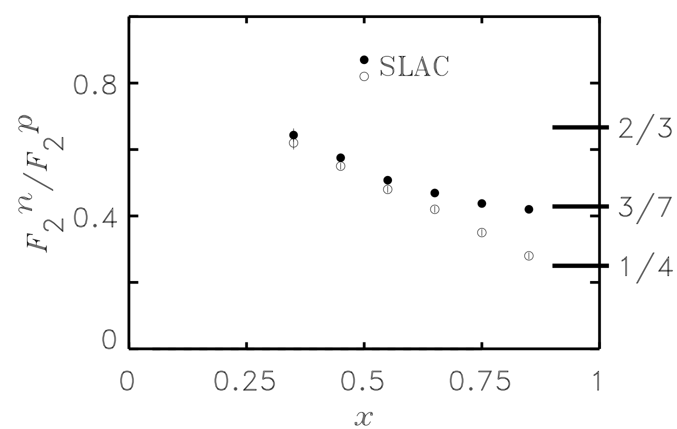
Effetto EMC: a che punto siamo ?

In genere, con qualche parametro, ogni modello spiega i dati:
EMC effect = "Everyone's Model is Cool" (G. Miller)

In realtà: molte spiegazioni $\equiv$ nessuna spiegazione

Ma una spiegazione è necessaria: il problema è rilevante *per se* (siamo fatti di nucleoni legati) e, inoltre, è fondamentale conoscere il meccanismo di reazione dei processi duri su nuclei e quali gradi di libertà sono coinvolti:

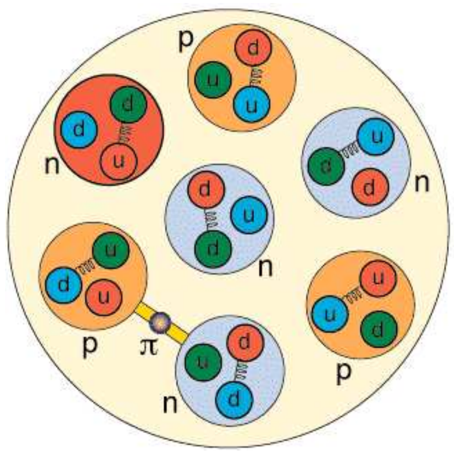
- PDFs nucleari cruciali per l'analisi dei dati di LHC (ALICE...);
- Per ogni separazione in sapore (u vs. d) di proprietà partoniche, il solo protone non è sufficiente; **il neutrone**, partner ovvio, non può essere usato come bersaglio libero. Non dimenticare mai: per il neutrone, i "dati" sono sempre **pseudodati**, estratti da esperimenti su nuclei. (figura: **Melnitchouk et al., 1996**)



Esempio di come la Fisica Nucleare sia rilevante per studi di QCD

effetto EMC: come se ne esce?

Quali di questi spaccati somiglia di più alla sezione di un nucleo?

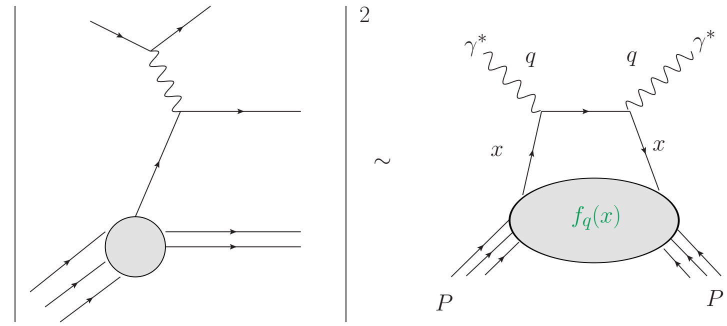


Per saperlo, dovremmo fargli una *tomografia...*

Si può fare!

Deeply Virtual Compton Scattering
& Generalized Parton Distributions (GPDs)

Aiuto dalle GPDs



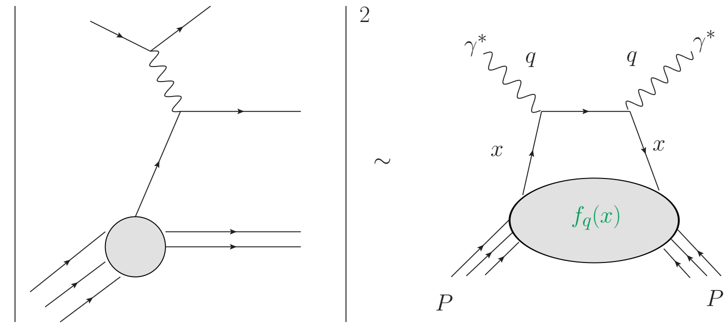
La distribuzione partonica, PDF, è una densità:

$$f_q(x) = \int dr^- e^{ixP^+r^-} < P|\hat{O}_q|P >$$

$$\hat{O}_q = \bar{q}(-r^-/2, 0, 0_\perp)\gamma^+ q(r^-/2, 0, 0_\perp) \qquad x = \frac{Q^2}{(2P\cdot q)} \stackrel{IMF}{\rightarrow} k^+/P^+ \quad a^\pm = a_0 \pm a_3$$

Nel limite di Bjorken (IMF), tutto è *collineare*

Aiuto dalle GPDs



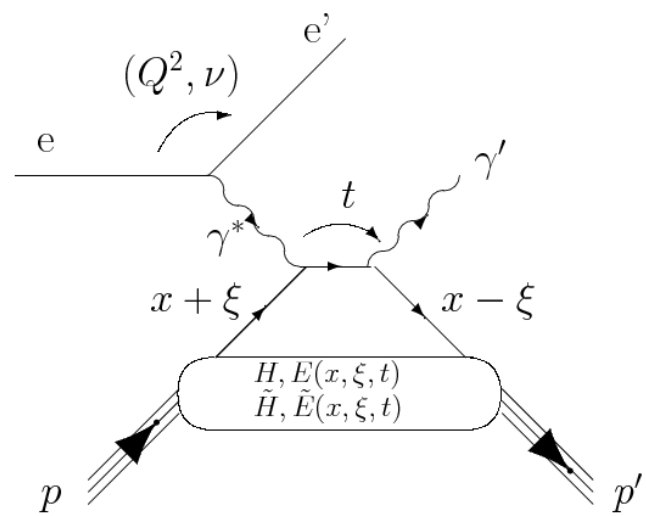
La distribuzione partonica, PDF, è una densità:

$$f_q(x) = \int dr^- e^{ixP^+r^-} < P|\hat{O}_q|P >$$

$$\hat{O}_q = \bar{q}(-r^-/2, 0, 0_\perp)\gamma^+ q(r^-/2, 0, 0_\perp) \qquad x = \frac{Q^2}{(2P\cdot q)} \overset{IMF}{\rightarrow} k^+/P^+ \quad a^\pm = a_0 \pm a_3$$

Nel limite di Bjorken (IMF), tutto è *collineare*

Per avere informazioni "non collineari"
(Es., L_z), sia $P - P' = \Delta \neq 0 \Longrightarrow$ **GPD**!



La GPD NON è una densità e dipende da 3 invarianti:

$$t = \Delta^2, x \overset{IMF}{\rightarrow} \frac{(k+k')^+}{(P+P')^+}, \xi \overset{IMF}{\rightarrow} \frac{\Delta^+}{2(P+P')^+}$$

Se $\xi = 0$, $\Delta^+ = 0\,(P^+ = P'^+)$, si ha una sola GPD:

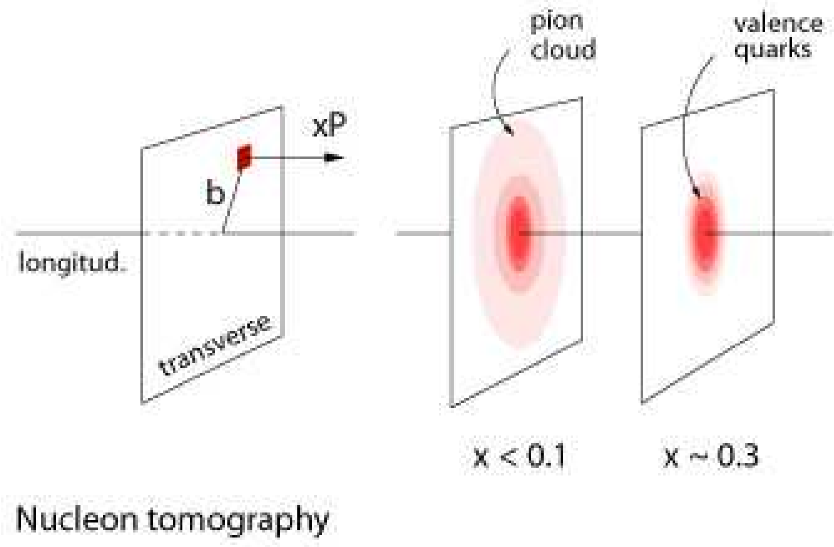
$$H_q(x, 0, \Delta_\perp^2) = \int dr^- e^{ixP^+r^-} < P^+, P_\perp|\hat{O}_q|P^+, P'_\perp >$$

e, nell' IMF ($P^+ >> P_\perp$), si può dimostrare che (**Burkart 2001**)

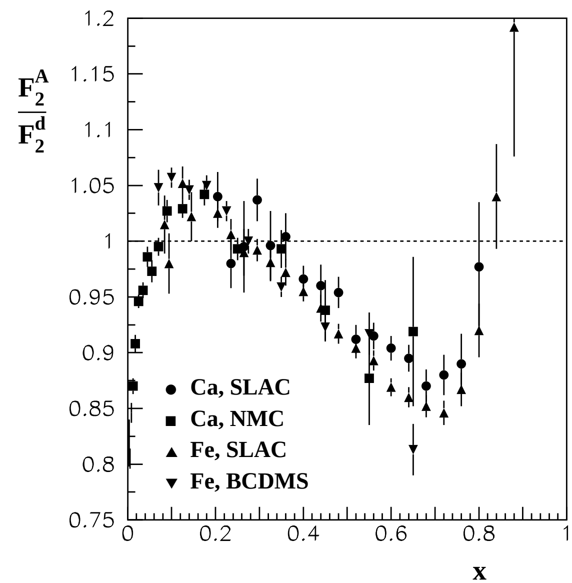
$$\rho(x, \vec{b}_\perp) = \int d\vec{\Delta}_\perp e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} H_q(x, 0, \Delta_\perp^2) \qquad \text{è una densità}$$

GPDs e struttura 3D degli adroni

$\rho(x, \vec{b}_\perp)$, nell'IMF,
conta il numero di partoni
con momento longitudinale x
e parametro d'impatto $\vec{b}_\perp$:
$\Longrightarrow$: "tomografia"
dell'adrone bersaglio



Disponendo di dati per il protone e per
il nucleo, le sezioni potrebbero essere
confrontate per diversi valori di x
per stabilire, ad esempio, se i quark
di valenza (regione EMC) nel nucleone legato
sono meno localizzati che nel protone



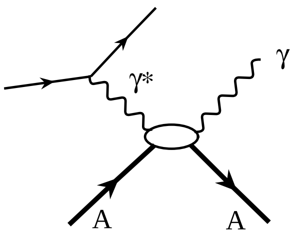
Possibile spiegazione dell'effetto EMC...

Ma non è facile...

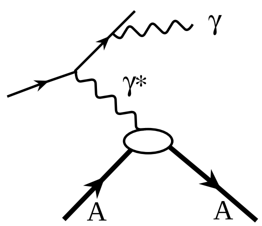
GPDs: uno strumento unico...

- non solo per esplorare la struttura 3-dimensionale, a livello partonico, degli adroni, ma per molti altri aspetti: inizialmente introdotte, nell'onda della "Spin Crisis" (**J.Ashman et al., EMC collaboration, PLB 206, 364 (1988), 1890 citazioni INSPIRE**), per avere accesso al momento angolare totale dei partoni...

... ma anche una sfida sperimentale:



DVCS



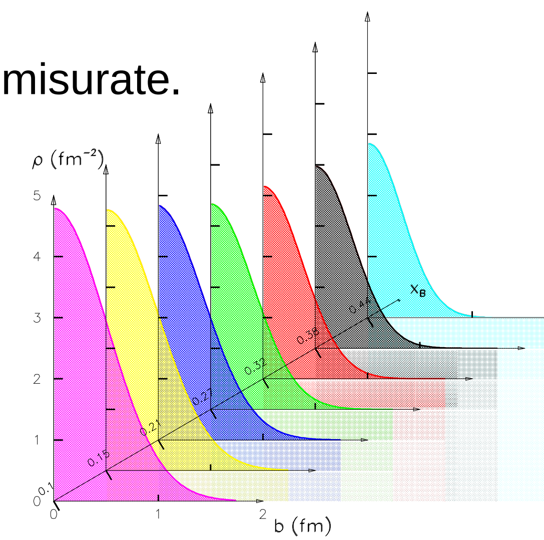
BH

- Process esclusivo duro $\longrightarrow$ piccole σ;
- Difficile estrazione:

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

- Competizione con il processo **BH**! Interferenza (differenze in σ) misurate.

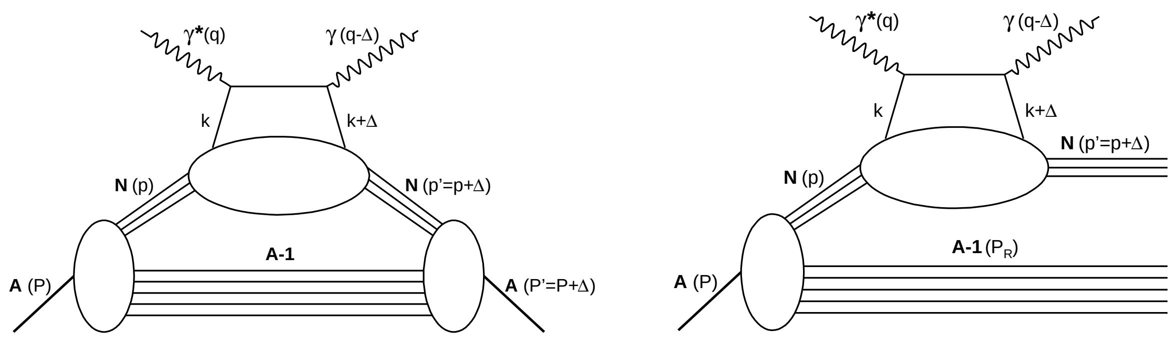
$$d\sigma \propto |T_{\mathbf{DVCS}}|^2 + |T_{\mathbf{BH}}|^2 + 2\,\Re\{T_{\mathbf{DVCS}} T^*_{\mathbf{BH}}\}$$



Eppure, per il protone, i primi dati sono stati analizzati.
(M. Guidal et al., Rep. Prog. Phys. 2013)

GPD nucleari... Difficile ma...

- L'informazione descritta si ottiene nel "canale coerente" $\equiv$ il nucleo non si rompe $\longrightarrow$ difficile misura (serve un *recoil detector*), piccole σ.



- dati: DVCS coerente o incoerente?

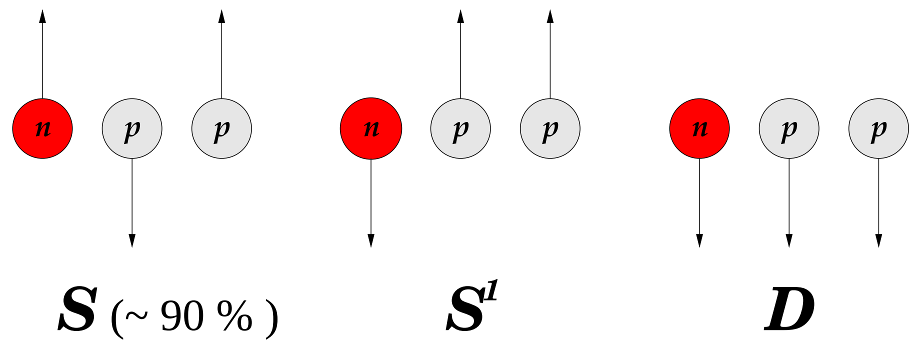
  Airapetian et al. (Hermes) NPB 829, 1 (2010); PRC 81, 035202 (2010)
  $D(\vec{e},e'\gamma)X$, $\vec{D}(\vec{e},e'\gamma)X$, $Ne(\vec{e},e'\gamma)X$**; and then** $He, N, Ne, Kr, Xe \longrightarrow$ **No** A**-dep.**

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

- Teoria: ^{3}He (**S.S., PRC 70 (2004) 01520, PRC 79 (2009) 025207, M. Rinaldi and S.S., PRC 85 (2012) 062201; PRC 87 (2013) 3, 035208**) ma anche ^{2}H (**Berger, Cano, Diehl and Pire, PRL 87 (2001) 142302**), ^{4}He (**Liuti & Taneja PRC 72 032201 (R) 2005**), nuclei finiti (**Kirchner & Müller, EPJC 32, 347 (2003)**)

Importance of ^{3}He for DIS structure studies

- ^{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:



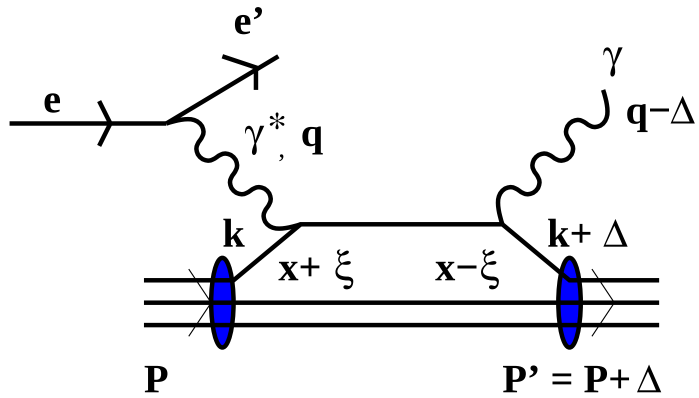
In $S-$wave
$^3\vec{He} = \vec{n}$!

^{3}He always promising when the neutron polarization properties have to be studied.

- To this aim, ^{3}He is a unique target:
  - ★ **in DIS, together with ^{3}H, for the extraction of F_2^n (Marathon experiment, JLab);**
  - ★ **in polarized DIS, for the extration of the SSF g_1^n;**
  - ★ **in polarized SiDIS, for the extraction of neutron transversity and related observables;**
  - ★ **in DVCS, for the extraction of neutron GPDs**

GPDs of ^{3}He

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
($Q^2, \nu \to \infty$)
such as (coherent) DVCS
(Definition of GPDs from X. Ji PRL 78 (97) 610):



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

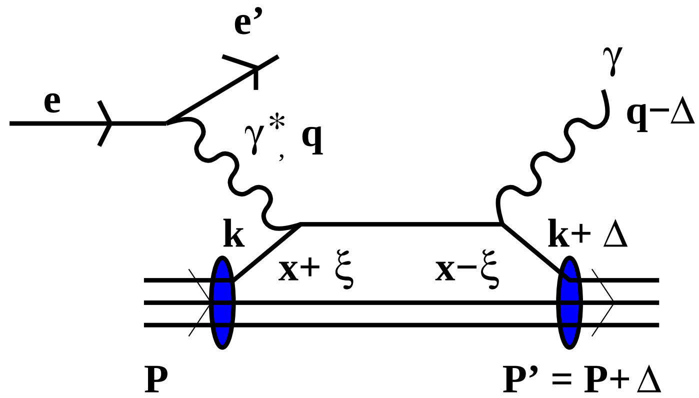
the GPDs $H_q(x, \xi, \Delta^2)$ and $E_q(x, \xi, \Delta^2)$ are introduced:

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

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

GPDs of ^{3}He

For a $J = \frac{1}{2}$ target,
in a hard-exclusive process,
$(Q^2, \nu \to \infty)$
such as (coherent) DVCS
(Definition of GPDs from X. Ji PRL 78 (97) 610):



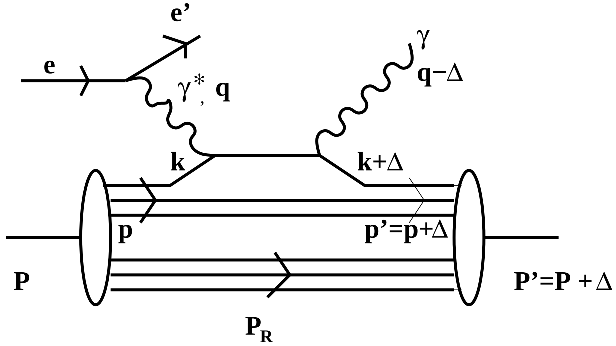
- $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu / 2$
- $x = k^+/P^+$; ξ = "skewness" = $-\Delta^+/(2\bar{P}^+)$
- $x \leq -\xi \longrightarrow$ GPDs describe $antiquarks$;
  $-\xi \leq x \leq \xi \longrightarrow$ GPDs describe $q\bar{q}$ $pairs$; $x \geq \xi \longrightarrow$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

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

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

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

GPDs of ^{3}He: the Impulse Approximation



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

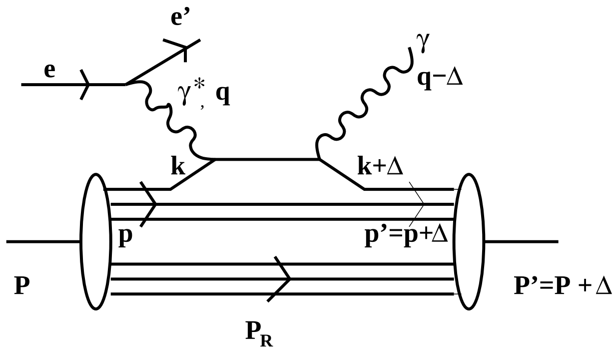
In a symmetric frame ($\bar{p} = (p + p')/2$) :

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

one has, for a given GPD, H_q, $\tilde{G}_M^q = H_q + E_q$, or $\tilde{H}_q$

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

GPDs of ^{3}He: the Impulse Approximation



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

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

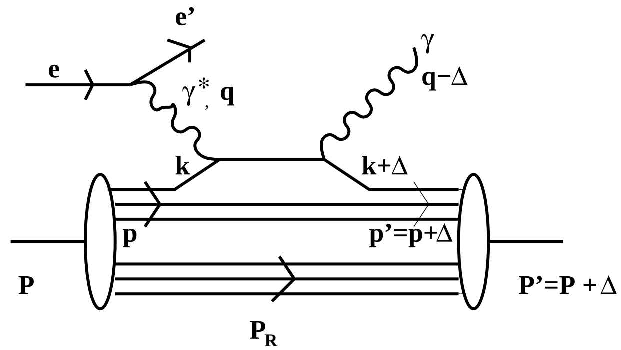
$$
\begin{aligned}
k^+ &= (x+\xi)\bar{P}^+ = (x'+\xi')\bar{p}^+ \;, \\
(k+\Delta)^+ &= (x-\xi)\bar{P}^+ = (x'-\xi')\bar{p}^+ \;,
\end{aligned}
$$

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

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

By properly inserting a tensor product complete basis for the nucleon (PW) and the fully interacting recoiling system :

GPDs of ^{3}He: the Impulse Approximation



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

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

$$k^+ = (x+\xi)\bar{P}^+ = (x'+\xi')\bar{p}^+ \, ,$$
$$(k+\Delta)^+ = (x-\xi)\bar{P}^+ = (x'-\xi')\bar{p}^+ \, ,$$

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

$$GPD_q(x,\xi,\Delta^2) \simeq \sum_N \int \frac{dz^-}{4\pi} e^{ix'\bar{p}^+ z^-} \langle P'S'| \sum_{\vec{P}'_R, f'_{A-1}, \vec{p}\,', s'} \{|P'_R, \Phi^{f'}_{A-1}\rangle \otimes |p's'\rangle\}$$

$$\langle P'_R, \Phi^{f'}_{A-1}| \otimes \langle p's'| \, \hat{O}^{\mu,N}_q \sum_{\vec{P}_R, f_{A-1}, \vec{p}, s} \{|P_R, \Phi^f_{A-1}\rangle \otimes |ps\rangle\} \{\langle P_R, \Phi^f_{A-1}| \otimes \langle ps|\} \, |PS\rangle \, ,$$

and, since $\{\langle P_R, \Phi^f_{A-1}| \otimes \langle ps|\}|PS\rangle = (2\pi)^3 \delta^3(\vec{P} - \vec{P}_R - \vec{p}) \langle \Phi^f_{A-1}, ps|PS\rangle$,

(NR! Separation of the global motion from the intrinsic one!)

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)**):

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

$\tilde{G}_M^{3,q}$ 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 $\tilde{H}_q^N$:

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

GPDs of ^{3}He in IA

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

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

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

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

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

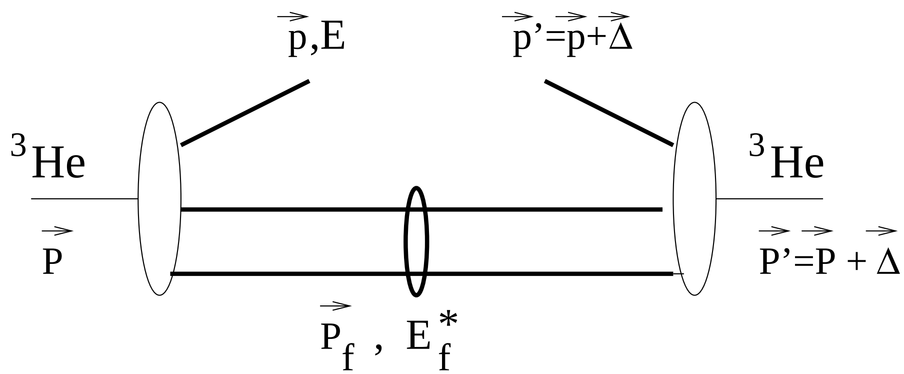
$$\mathbf{P}^N_{\mathcal{M}'\mathcal{M}\sigma'\sigma}(\vec{p},\vec{p}\,',E) = \sum_{f_{A-1}} \delta(E - E_{A-1} + E_A)$$

$$\underbrace{{}_{S_A}\langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p},\sigma; \phi_{f_{A-1}} \rangle}\ \underbrace{\langle \phi_{f_{A-1}}; \sigma' \vec{p}\,' | \pi_A J_A \mathcal{M}'; \Psi_A \rangle_{S_A}}$$

$\nwarrow$ intrinsic overlaps $\nearrow$

The spectral function: a few words more

$$\mathbf{P}^{N}_{\mathcal{M}'\mathcal{M}\sigma'\sigma}(\vec{p},\vec{p}\,',E) = \sum_f \delta(E - E_{min} - E^*_f)$$
$$_{S_A}\langle \Psi_A; J_A \mathcal{M} \pi_A | \vec{p}, \sigma; \phi_f(E^*_f)\rangle \, \langle \phi_f(E^*_f); \sigma' \vec{p}\,' | \pi_A J_A \mathcal{M}'; \Psi_A \rangle_{S_A}$$



- 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 interaction (in our case, Av18, from the Pisa group): the extension of the treatment to heavier nuclei would be very difficult

Nuclear GPDs: from ^{3}He to ^{4}He

- What we have, for ^{3}**He:**
  - * 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;
- One can imagine a relativistic (LF) extension...
- 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?

BUT

- Actually, data for ^{4}**He** are becoming available from the CLAS collaboration at JLab **(M. Hattawy, Ph.D. Thesis, Orsay, September 2015)**;

  New proposals will be presented at the JLab PAC, next month

  Experimentally, for DVCS, ^{4}He is the simplest target one can imagine (only one GPD, H)

DVCS off ^{4}He: *preliminary* analysis

(M. Hattawy, Ph.D. Thesis, Orsay, September 2015)

It is too early to comment on these results... But it is enough to stress that:

- Measurements are possible, in the coherent and incoherent channels;
- $A-$dependence is found;
- Serious calculations are needed
  (^{4}He realistic spectral function, or a good model one).

Back to ^{3}He... Why? 12 GeV Program @JLab:

- DIS regime, e.g.

  Hall A, $http://hallaweb.jlab.org/12GeV/$

  MARATHON Coll. E12-10-103 (Rating A): MeAsurement of the F_{2n}/F_{2p}, d/u Ratios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

  Hall C, $https://www.jlab.org/Hall-C/$

  J. Arrington, et al PR12-10-008 (Rating A$^-$): Detailed studies of the nuclear dependence of F_2 in light nuclei

- SIDIS regime, e.g.

  Hall A, $http://hallaweb.jlab.org/12GeV/$

  H. Gao et al, PR12-09-014 (Rating A): Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reaction on a Transversely Polarized ^{3}He Target

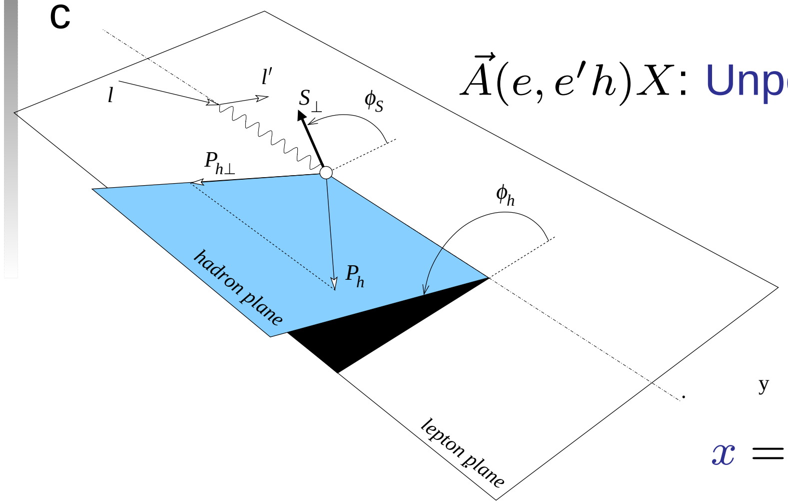
  J.P. Chen et al, PR12-11-007 (Rating A): Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target

- Others? DVCS, spectator tagging...

  In ^{3}He conventional nuclear effects are under control...

TMDS: Single Spin Asymmetries - 1

c



$\vec{A}(e,e'h)X$: Unpolarized beam and T-polarized target $\to \sigma_{UT}$

$$d^6\sigma \equiv \frac{d^6\sigma}{dx dy dz d\phi_S d^2 P_{h\perp}}$$

$$x = \frac{Q^2}{2P\cdot q} \quad y = \frac{P\cdot q}{P\cdot l} \quad z = \frac{P\cdot h}{P\cdot q} \quad \boxed{\hat{q} = -\hat{e}_z}$$

The number of emitted hadrons at a given ϕ_h depends on the orientation of $\vec{S}_\perp$!

In SSAs 2 different mechanisms can be experimentally distinguished

$$A_{UT}^{Sivers(Collins)} = \frac{\int d\phi_S d^2 P_{h\perp} \sin(\phi_h - (+)\phi_S) d^6\sigma_{UT}}{\int d\phi_S d^2 P_{h\perp} d^6\sigma_{UU}}$$

with $d^6\sigma_{UT} = \frac{1}{2}(d^6\sigma_{U\uparrow} - d^6\sigma_{U\downarrow})$ $\qquad d^6\sigma_{UU} = \frac{1}{2}(d^6\sigma_{U\uparrow} + d^6\sigma_{U\downarrow})$

SSAs - 2

SSAs in terms of parton distributions and fragmentation functions:

- $A_{UT}^{Sivers} = N^{Sivers}/D \qquad A_{UT}^{Collins} = N^{Collins}/D$

$$N^{Sivers} \propto \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k_T} \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{P}_{\mathbf{h}\perp}} \cdot \mathbf{k_T}}{\mathbf{M}} f_{1T}^{\perp q}(x, \mathbf{k_T}^2) D_1^{q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

$$N^{Collins} \propto \sum_q e_q^2 \int d^2\kappa_{\mathbf{T}} d^2\mathbf{k_T} \delta^2(\mathbf{k_T} + \mathbf{q_T} - \kappa_{\mathbf{T}}) \frac{\hat{\mathbf{P}_{\mathbf{h}\perp}} \cdot \kappa_{\mathbf{T}}}{\mathbf{M_h}} h_1^q(x, \mathbf{k_T}^2) H_1^{\perp q,h}(z, (z\kappa_{\mathbf{T}})^2)$$

$$D \propto \sum_q e_q^2 f_1^q(x) D_1^{q,h}(z)$$

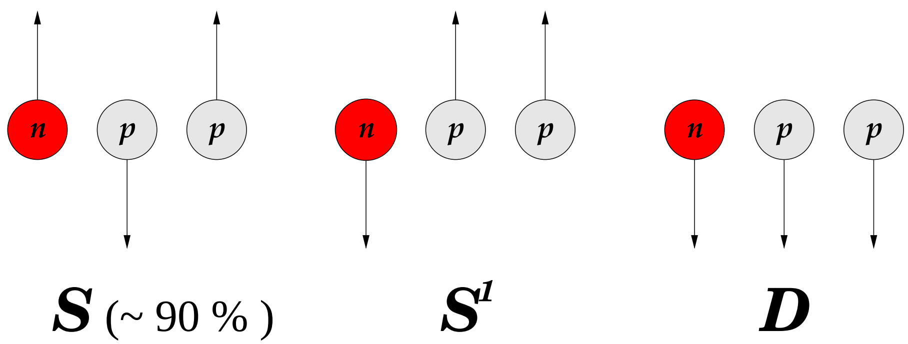
- LARGE A_{UT}^{Sivers} measured in $\vec{p}(e, e'\pi)x$ HERMES PRL 94, 012002 (2005)
- SMALL A_{UT}^{Sivers} measured in $\vec{D}(e, e'\pi)x$; COMPASS PRL 94, 202002 (2005)

A strong flavor dependence

Importance of the neutron for flavor decomposition!

The neutron information from ^{3}He

^{3}He is the ideal target to study the polarized neutron:



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

... But the bound nucleons in ^{3}He are moving!

Dynamical nuclear effects in inclusive DIS ($^3\vec{He}(e,e')X$) were evaluated with a realistic spin-dependent spectral function for $^3\vec{He}$, $P_{\sigma,\sigma'}(\vec{p},E)$. It was found that the formula

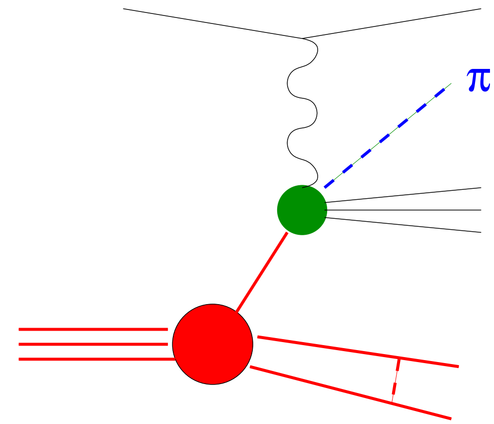
$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{exp} - 2p_p f_p A_p^{exp}\right), \quad (Ciofi\ degli\ Atti\ et\ al., PRC48(1993)R968)$$

$$(f_p, f_n \quad dilution factors)$$

can be safely used $\longrightarrow$ widely used by experimental collaborations.
The nuclear effects are hidden in the "effective polarizations"

$$p_p = -0.023 \quad (Av18) \qquad p_n = 0.878 \quad (Av18)$$

$\vec{n}$ from ${}^3\vec{H}e$: SIDIS case, IA



Can one use the same formula to extract the SSAs ?
in SiDIS also the fragmentation functions can be modified
by the nuclear environment !

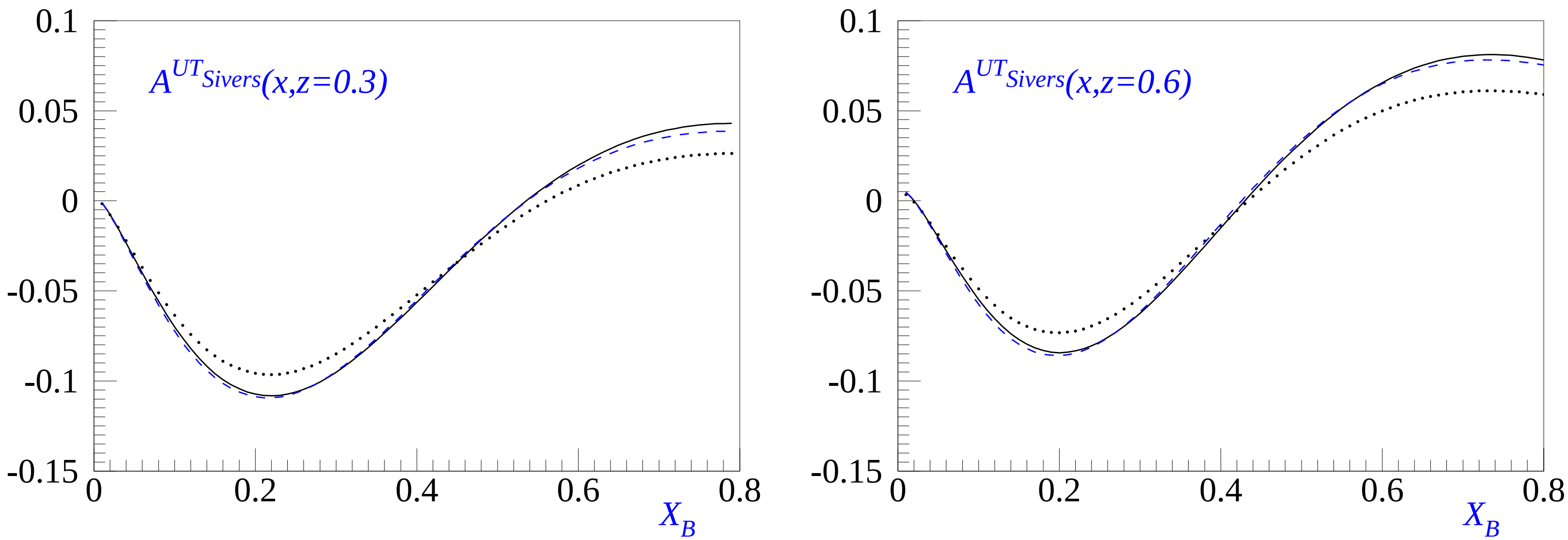
The process ${}^3\vec{H}e(e, e'\pi)X$ has been evaluated :
in the Bjorken limit
in IA $\longrightarrow$ no FSI between the measured fast, ultrarelativistic π
the remnant and the two nucleon recoiling system
$E_\pi \simeq 2.4\ GeV$ in JLAB exp at $6\ GeV$ - Qian et al., PRL 107 (2011) 072003

SSAs involve convolutions of the spin-dependent nuclear spectral function, $\vec{P}(\vec{p}, E)$, with
parton distributions AND fragmentation functions [S.Scopetta, PRD 75 (2007) 054005] :

$$A \simeq \int d\vec{p}\, dE .... \vec{P}(\vec{p}, E)\ f_{1T}^{\perp q}\left(\frac{Q^2}{2p \cdot q}, \mathbf{k_T^2}\right)\ D_1^{q,h}\left(\frac{p \cdot h}{p \cdot q}, \left(\frac{p \cdot h}{p \cdot q}\kappa_\mathbf{T}\right)^2\right)$$

The nuclear effects on fragmentation functions are new with respect to the DIS case
and have to be studied carefully

Results: $\vec{n}$ from $^3\vec{H}e$: A_{UT}^{Sivers}, @ JLab, in IA



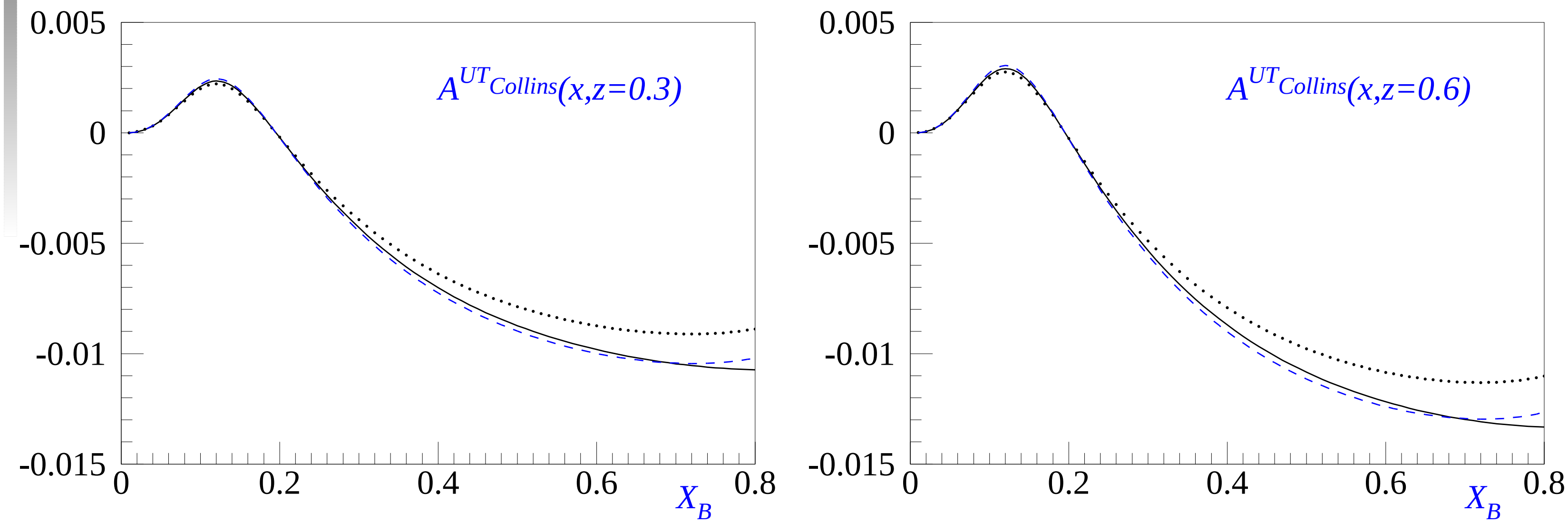
FULL: Neutron asymmetry (model: from parameterizations or models of TMDs and FFs)

DOTS: Neutron asymmetry extracted from ^3He (calculation) neglecting the contribution of the proton polarization $\bar{A}_n \simeq \frac{1}{f_n} A_3^{calc}$

DASHED : Neutron asymmetry extracted from ^3He (calculation) taking into account nuclear structure effects through the formula:

$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{calc} - 2 p_p f_p A_p^{model}\right)$$

Results: $\vec{n}$ from $^3\vec{He}$: $A_{UT}^{Collins}$, @ JLab



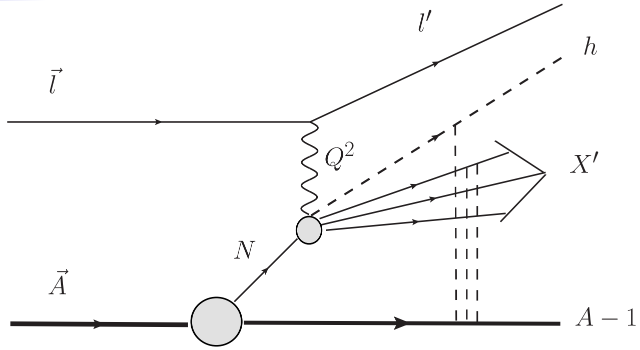
In the Bjorken limit the extraction procedure successful in DIS works also in SiDIS, for both the Collins and the Sivers SSAs !

What about FSI effects ?

(thinking to E12-09-018, A.G. Cates et al., approved with rate A @JLab 12)

FSI: Generalized Eikonal Approximation (GEA)

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206



Relative energy between $A-1$ and the remnants: a few GeV
$\longrightarrow$ eikonal approximation.

$$d\sigma \simeq l^{\mu\nu} W^A_{\mu\nu}(S_A)$$

$$W^A_{\mu\nu}(S_A) \approx \sum_{S_{A-1},S_X} J^A_\mu J^A_\nu \qquad J^A_\mu \simeq \langle S_A \mathbf{P} | \hat{\mathbf{J}}^{\mathbf{A}}_\mu(\mathbf{0}) | \mathbf{S_X}, \mathbf{S_{A-1}}, \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle$$

$$\langle S_A \mathbf{P} | \mathbf{r_1 r_2 r_3} \rangle = \mathbf{\Phi_{^3He}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathcal{A}\, \mathbf{e^{iPR}} \mathbf{\Psi^{S_A}_3}(\rho, \mathbf{r})$$

$$\langle \mathbf{r_1 r_2 r_3} | S_X, S_{A-1} \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle = \Phi^*_f(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \mathbf{\Psi}^{*\mathbf{f}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

$$\approx \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \sum_{\mathbf{j>k}} \chi^+_{\mathbf{S_X}} \phi^*(\xi_{\mathbf{x}}) \mathbf{e}^{-\mathbf{ip_X r_i}} \mathbf{\Psi}^{*\mathbf{f}}_{\mathbf{jk}}(\mathbf{r_j}, \mathbf{r_k}) \,,$$

$\hat{S}_{Gl} = Glauber\ operator$

$$J^A_\mu \approx \int d\mathbf{r_1} d\mathbf{r_2} d\mathbf{r_3} \Psi^{*f}_{23}(\mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}_X \mathbf{r_i}} \chi^+_{S_X} \phi^*(\xi_x) \cdot \hat{S}_{Gl}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) \hat{j}_\mu(\mathbf{r_1}, X) \vec{\Psi}^{\mathbf{S}_A}_3(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3})$$

IF ($FACTORIZED$ FSI !) $\left[\hat{S}_{Gl}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3), \hat{j}_\mu(\mathbf{r_1})\right] = 0$ THEN:

$$W^A_{\mu\nu} = \sum_{N,\lambda,\lambda'} \int dE\, d\mathbf{p}\, w^{N,\lambda\lambda'}_{\mu\nu}(\mathbf{p})\, P^{FSI,A,N}_{\lambda\lambda'}(E, \mathbf{p}, ...) \qquad CONVOLUTION!$$

FSI: *distorted* spin-dependent spectral function of ^{3}He

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206

Relevant part of the (GEA-distorted) spin dependent spectral function:

$$\mathcal{P}_{||}^{IA(FSI)} = \mathcal{O}_{\frac{1}{2}\frac{1}{2}}^{IA(FSI)} - \mathcal{O}_{-\frac{1}{2}-\frac{1}{2}}^{IA(FSI)}; \qquad \text{with:}$$

$$\mathcal{O}_{\lambda\lambda'}^{IA(FSI)}(p_N, E) = \sum\!\!\!\!\!\!\!\int_{\epsilon^*_{A-1}} \rho\left(\epsilon^*_{A-1}\right) \ \langle S_A, \mathbf{P_A}|(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}}, \lambda', \mathbf{p}_N\}\rangle \ \times$$

$$\langle(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}}, \lambda, \mathbf{p}_N\}|S_A, \mathbf{P_A}\rangle \delta\left(E - B_A - \epsilon^*_{A-1}\right).$$

Glauber operator: $\hat{S}_{Gl}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) = \prod_{i=2,3}\left[1 - \theta(z_i - z_1)\Gamma(\mathbf{b}_1 - \mathbf{b}_i, z_1 - z_i)\right]$

(generalized) profile function: $\Gamma(\mathbf{b}_{1i}, z_{1i}) = \frac{(1-i\,\alpha)\ \sigma_{eff}(z_{1i})}{4\,\pi\,b_0^2} \exp\left[-\frac{\mathbf{b}_{1i}^2}{2\,b_0^2}\right]$,

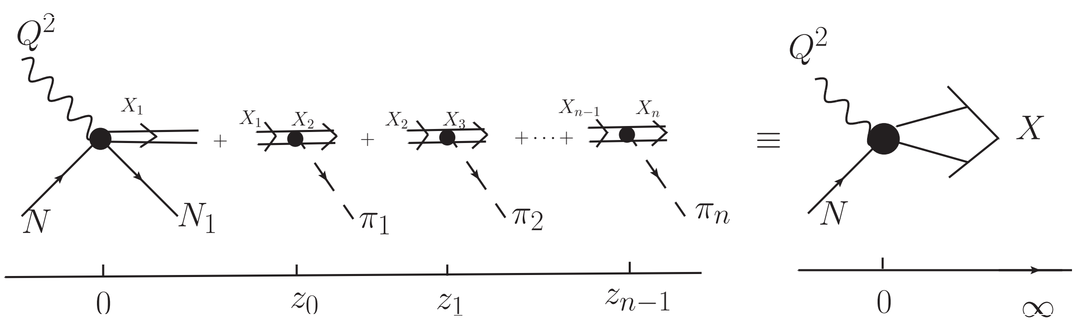
GEA (Γ depends also on the traveled longitudinal distance z_{1i}!) very succesfull in q.e. semi-inclusive and exclusive processes off ^{3}He

see, e.g., Alvioli, Ciofi & Kaptari PRC 81 (2010) 02100

A hadronization model is necessary to define $\sigma_{eff}(z_{1i})$...

FSI: *the hadronization model*

Hadronization model **(Kopeliovich et al., NPA 2004)**
+ σ_{eff} model for SIDIS **(Ciofi & Kopeliovich, EPJA 2003)**
GEA + hadronization model succesfully applied to unpolarized SIDIS $^2H(e,e'p)X$
(Ciofi & Kaptari PRC 2011).



$$\sigma_{eff}(z) = \sigma_{tot}^{NN} + \sigma_{tot}^{\pi N}\left[n_M(z) + n_g(z)\right]$$

- The hadronization model is phenomenological: parameters are chosen to describe the scenario of JLab experiments (e.g., $\sigma_{NN}^{tot} = 40$ mb, $\sigma_{\pi N}^{tot} = 25$ mb, $\alpha = -0.5$ for both NN and πN...).

FSI: *distorted* spin-dependent spectral function of ^{3}He

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., PRC 89 (2014) 035206

- While P^{IA} is "static", i.e. depends on ground state properties, P^{FSI} is dynamical ($\propto \sigma_{eff}$) and process dependent;
- For each experimental point (given x, Q^2...), a different spectral function has to be evaluated!
- Quantization axis (w.r.t. which polarizations are fixed) and eikonal direction (fixing the "longitudinal" propagation) are different)... States have to be rotated...
- P^{FSI}: a really cumbersome quantity, a very demanding evaluation ($\approx$ 1 Mega CPU*hours @ "Zefiro" PC-farm, PISA, INFN "gruppo 4").

The convolution formulae for a generic structure function can be cast in the form

$$\mathcal{F}^A(x_{Bj}, Q^2, ...) = \sum_N \int_{x_{Bj}}^A f_N^A(\alpha, Q^2, ...)\, \mathcal{F}^N(x_{Bj}/\alpha, Q^2, ...)\, d\alpha$$

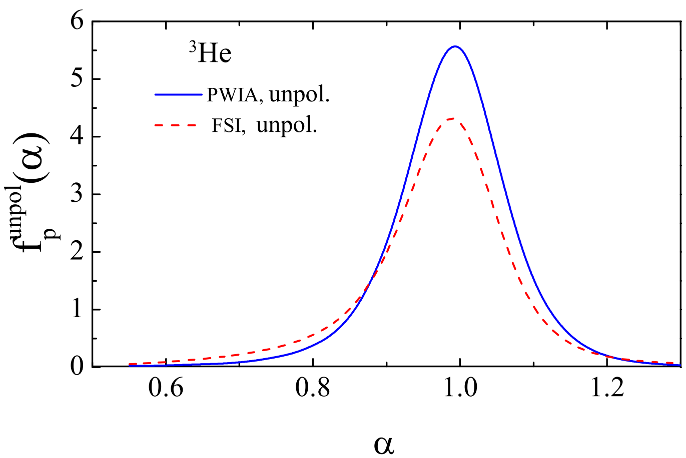
with the distorted light-cone momentum distribution:

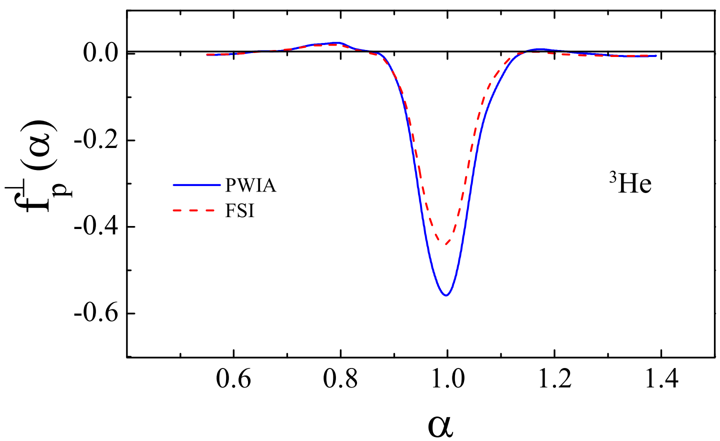
$$f_N^A(\alpha, Q^2, ..) = \int dE \int_{p_m(\alpha,Q^2,..)}^{p_M(\alpha,Q^2,..)} P_N^{A,FSI}(\mathbf{p}, E, \sigma..)\, \delta\left(\alpha - \frac{pq}{m\nu}\right)\, \theta\left(W_x^2 - (M_N + M_\pi)^2\right) d^3\mathbf{p}$$

light-cone momentum distributions with FSI:

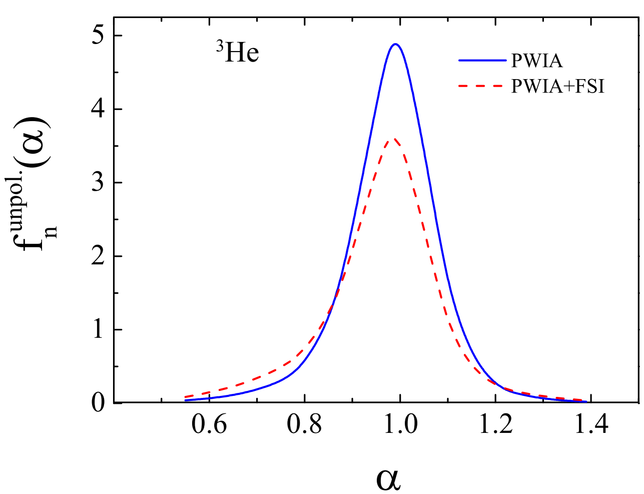
A. Del Dotto, L.P. Kaptari, E. Pace, G. Salmè, S.S., “ready” for submission

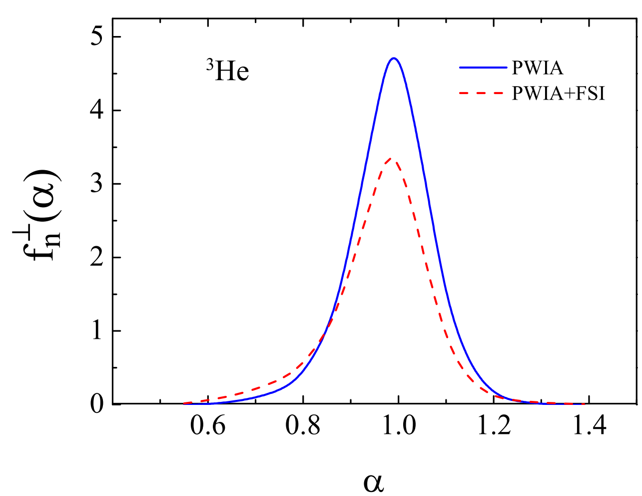
PROTON @ E_i = 8.8 GeV





NEUTRON @ E_i = 8.8 GeV





Actually, one should also consider the effect on dilution factors...

DILUTION FACTORS

$$A_3^{exp} \simeq \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Longrightarrow \frac{\langle\vec{\mathbf{s}}_{\mathbf{n}}\rangle\boldsymbol{\Delta}\vec{\sigma}(\mathbf{n}) + \mathbf{2}\langle\vec{\mathbf{s}}_{\mathbf{p}}\rangle\boldsymbol{\Delta}\vec{\sigma}(\mathbf{p})}{\langle\mathbf{N}_{\mathbf{n}}\rangle\sigma_{\mathbf{unpol.}}(\mathbf{n}) + \mathbf{2}\langle\mathbf{N}_{\mathbf{p}}\rangle\sigma_{\mathbf{unpol.}}(\mathbf{p})} = \langle\vec{\mathbf{s}}_{\mathbf{n}}\rangle\mathbf{f}_{\mathbf{n}}\mathbf{A}_{\mathbf{n}} + \mathbf{2}\langle\vec{\mathbf{s}}_{\mathbf{p}}\rangle\mathbf{f}_{\mathbf{p}}\mathbf{A}_{\mathbf{p}}$$

PWIA:

$$\langle\vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}(E,\mathbf{p}) = \mathbf{p_{n(p)}};$$
$$\langle N\rangle = \int dE \int d^3p P_{unpol.}(E,\mathbf{p}) = 1.$$

$$\mathbf{f}_{\mathbf{n},(\mathbf{p})}(\mathbf{x},\mathbf{z}) = \frac{\sum_{\mathbf{q}} \mathbf{e}_{\mathbf{q}}^{\mathbf{2}} \mathbf{f}_{\mathbf{1}}^{\mathbf{q},\mathbf{n}(\mathbf{p})}(\mathbf{x}) \mathbf{D}_{\mathbf{1}}^{\mathbf{q},\mathbf{h}}(\mathbf{z})}{\sum_{\mathbf{N}}\sum_{\mathbf{q}} \mathbf{e}_{\mathbf{q}}^{\mathbf{2}} \mathbf{f}_{\mathbf{1}}^{\mathbf{q},\mathbf{N}}(\mathbf{x}) \mathbf{D}_{\mathbf{1}}^{\mathbf{q},\mathbf{h}}(\mathbf{z})}$$

FSI:

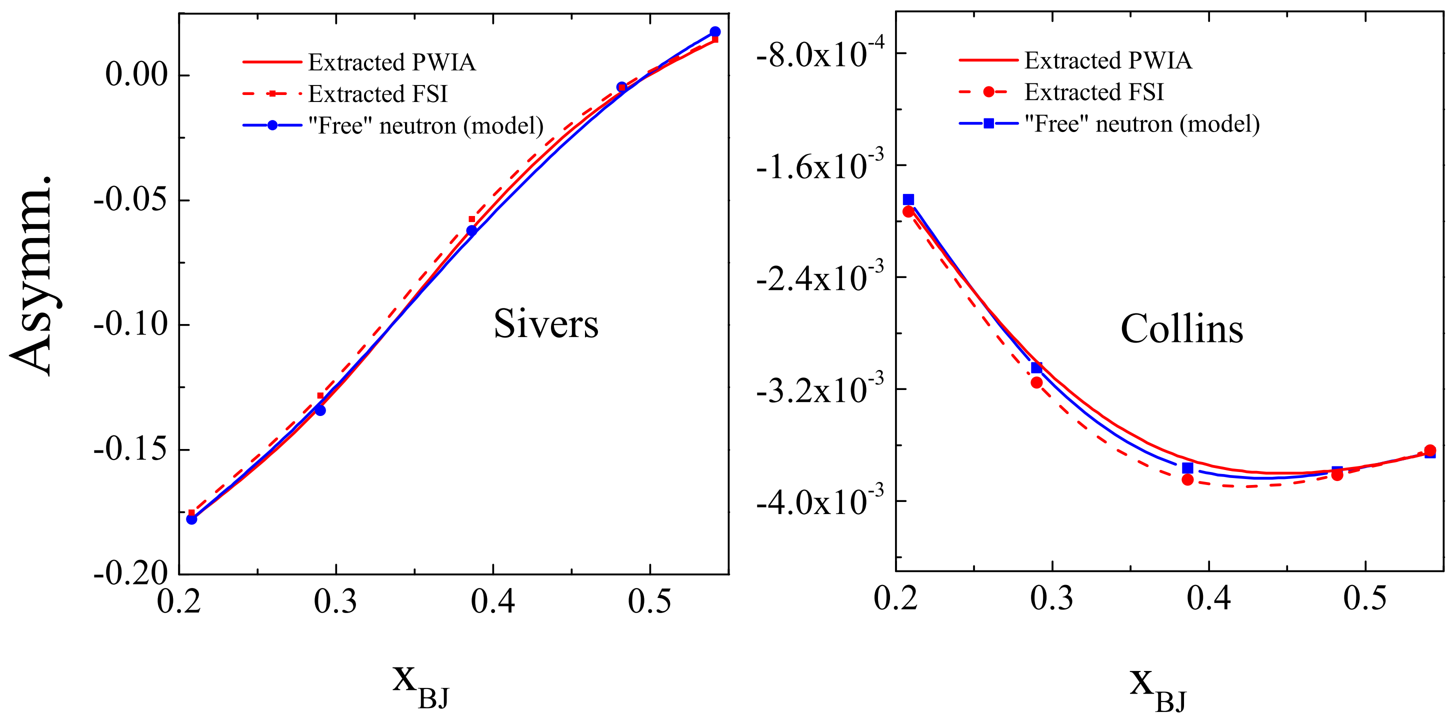
$$\langle\vec{s}_{n(p)}\rangle = \int dE \int d^3p P_{||}^{FSI}(E,\mathbf{p}) = \mathbf{p}_{\mathbf{n(p)}}^{\mathbf{FSI}};$$
$$\langle N\rangle = \int dE \int d^3p P_{unpol.}^{FSI}(E,\mathbf{p}) < 1.$$

$$\mathbf{f}_{\mathbf{n},(\mathbf{p})}^{\mathbf{FSI}}(\mathbf{x},\mathbf{z}) = \frac{\sum_{\mathbf{q}} \mathbf{e}_{\mathbf{q}}^{\mathbf{2}} \mathbf{f}_{\mathbf{1}}^{\mathbf{q},\mathbf{n}(\mathbf{p})}(\mathbf{x}) \mathbf{D}_{\mathbf{1}}^{\mathbf{q},\mathbf{h}}(\mathbf{z})}{\sum_{\mathbf{N}}\langle\mathbf{N}\rangle\sum_{\mathbf{q}} \mathbf{e}_{\mathbf{q}}^{\mathbf{2}} \mathbf{f}_{\mathbf{1}}^{\mathbf{q},\mathbf{N}}(\mathbf{x}) \mathbf{D}_{\mathbf{1}}^{\mathbf{q},\mathbf{h}}(\mathbf{z})}$$

$$A_n \approx \frac{1}{p_n^{FSI} f_n^{FSI}}\left(A_3^{exp} - 2{p_p}^{FSI} f_p^{FSI} A_p^{exp}\right) \approx \frac{1}{p_n f_n}\left(A_3^{exp} - 2p_p f_p A_p^{exp}\right)$$

2

Good news from GEA studies of FSI!



Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

$$A_n \approx \frac{1}{p_n^{FSI} f_n^{FSI}} \left(A_3^{exp} - 2 p_p{}^{FSI} f_p^{FSI} A_p^{exp} \right) \approx \frac{1}{p_n f_n} \left(A_3^{exp} - 2 p_p f_p A_p^{exp} \right)$$

L. Kaptari, A. Del Dotto, E. Pace, G. Salmè, S.S., “ready” for submission

Conclusions

Status of ^{3}He spectral function calculations:

	Impulse Approximation		including FSI	
	unpolarized	spin dep.	unpolarized	spin dep.
Non Relativistic	✓	✓	✓	✓
Light-Front	Def: ✓ Calc: 	Def: ✓ Calc: 		

Retrospective: selected contributions from Rome-Perugia:

- Ciofi, Pace, Salmè PRC 21 (1980) 505 ...
- Ciofi, Pace, Salmè PRC 46 (1991) 1591: spin dependence
- Pace, Salmè, S.S., Kievsky PRC 64 (2001) 055203, first Av18 calculation
- Ciofi, Kaptari, PRC 66 (2002) 044004, unpolarized with FSI (q.e.)
- Kaptari, Del Dotto, Pace, Salmè, S.S., PRC 89 (2014), 035206, spin dep. with FSI
- LF, preliminary, see, e.g., S.S., Del Dotto, Kaptari, Pace, Rinaldi, Salmè, Few Body Syst. 56 (2015) 6, 425 and references there in

... Ready for ^{4}He (?)...