Particle production in the DIS target fragmentation region

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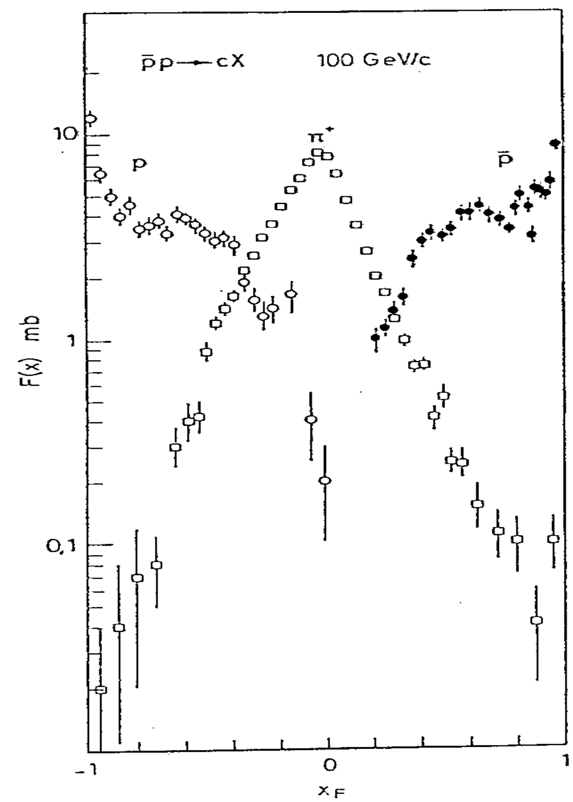
Outline of the talk

- Hadronic final state in DIS
- Factorisation and evolution in the target region
- Target fragmentation in SIDIS : the Λ case
- Predictions for CLAS@12 GeV
- K-Λ correlation in DIS final state

The leading particle effect in hadronic collisions

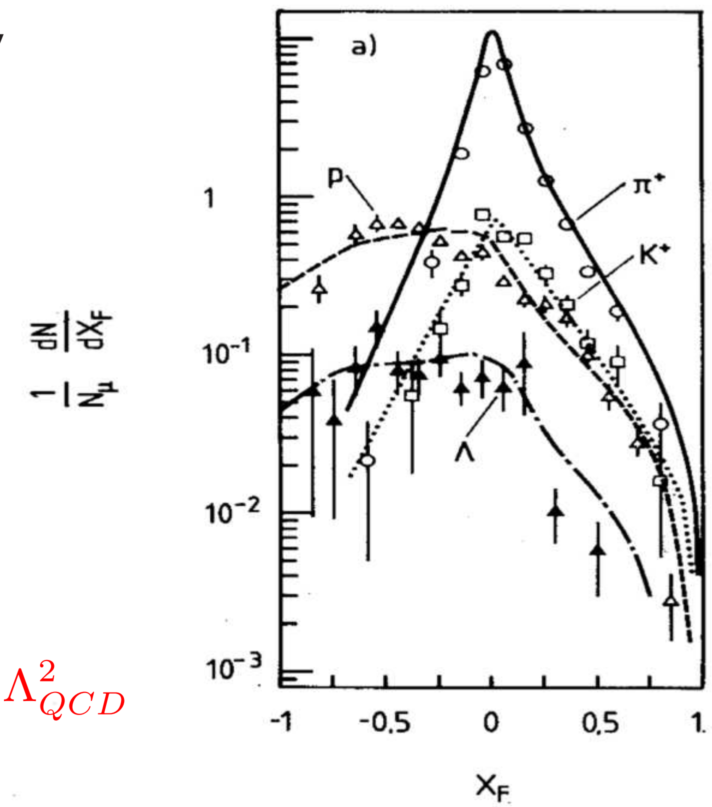
- Consider : $\bar{p}p \to c + X$
- $x_F = 2p_{||}/\sqrt{s}$ in hadronic centre of mass
- Leading particle effect : privileged quark-flavour quantum number flow from the initial state particle (either $\bar{p}$ or p)to the final state one (c)
- the more the quark-flavour content is conserved from initial to final state hadron, the more the latter carries a substantial fraction of the energy available in the reaction.
- Pions (Gribov QCD light) don't show LPE
- However no hard momentum transfer is present in this reaction $\to$ pQCD can not be applied



Basile & al. '81

The leading particle effect in DIS

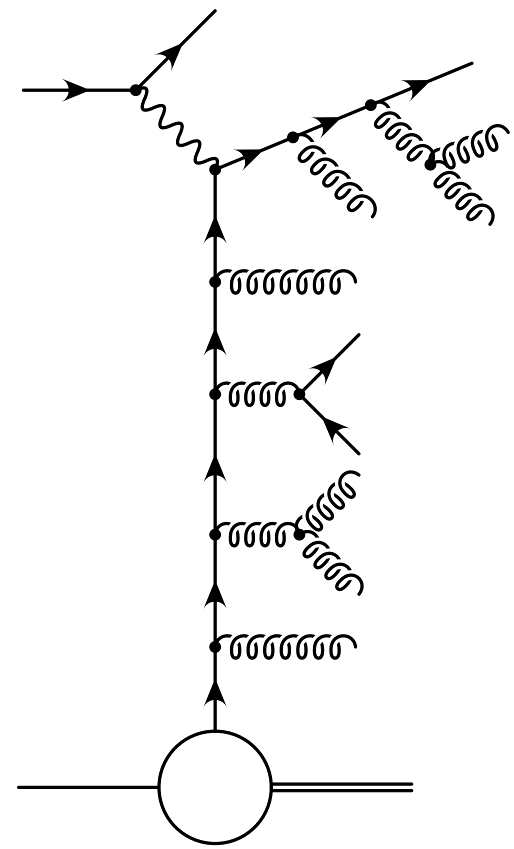
- Consider : $\mu p \to \mu + h + X$, DIS@280 GeV
- The same effect is observed in the DIS target fragmentation region, $x_F < 0$
- LPE for backward proton (uud) and Λ (uds)
- No LPE for $\bar{\Lambda}$ ($\bar{\text{u}}\bar{\text{d}}\bar{\text{s}}$), $\bar{p}$ ($\bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$) and mesons in $x_F < 0$
- But here we DO have hard scale now, $Q^2 \gg \Lambda^2_{QCD}$



EMC Coll. '81

Fragmentation in SIDIS

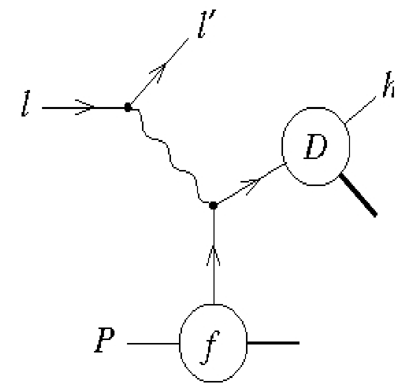
• Consider a Deep Inelastic Scattering event in which a highly virtual photon probes a parton fluctuation on timescale $1/Q$ in a nucleon with momentum P



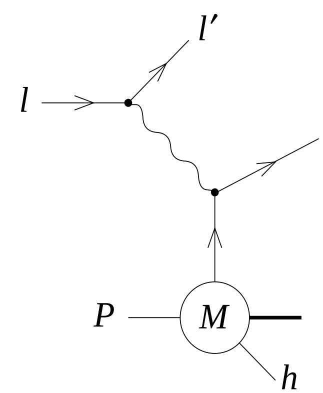
Define $t = (P - p_h)^2$:

- for $t \sim Q^2 \to$ current fragments
- for $t \sim 0$ target fragments
- for $0 < t < Q^2$ central fragmentation region: higher order corrections

Factorisation in SIDIS

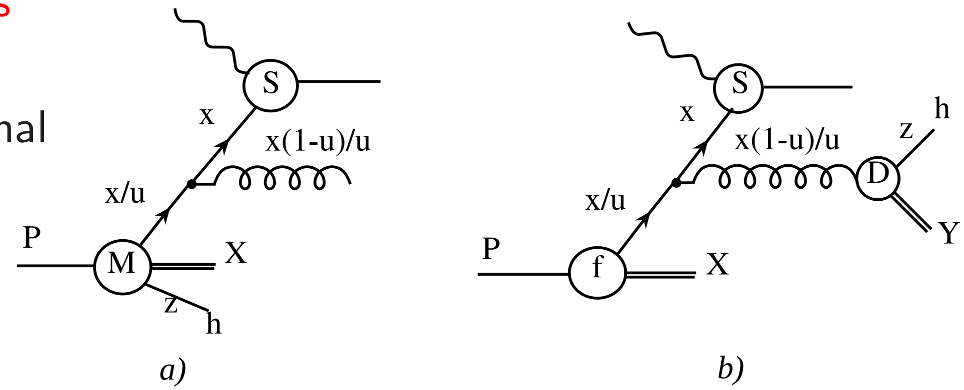


- Factorization theorem allows the decoupling of short distance (ME) from long distance (f, D, M) physics
- f, D, M are not calculable from first principles
- The evolution of f, D, M however is known (RGE)
- At lowest order, in the current region ($x_F > 0$) $d\sigma \propto f \otimes D$ and in the target region ($x_F < 0$) $d\sigma \propto M$
- Factorisation for M in SIDIS has been proven at collinear and soft level (Grazzini, Trentadue, Veneziano 1998; Collins 1998)
- Collinear factorization confirmed in fixed order pQCD calculation at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ (Graudenz, 1994; Daleo & al 2003)



Fracture functions in SIDIS

- Fracture functions M complete the description of SIDIS final state:
- M parametrize soft QCD dynamics in forward semi-inclusive processes.
- $M^h_{i/p}(x, z, Q^2)$ gives the conditional probability that a parton i with a fractional momentum x of the incoming proton enters the hard scattering while an hadron h with fractional momentum z is detected in the TFR of p.



- They obey a DGLAP-type inhomogeneous evolution equations:

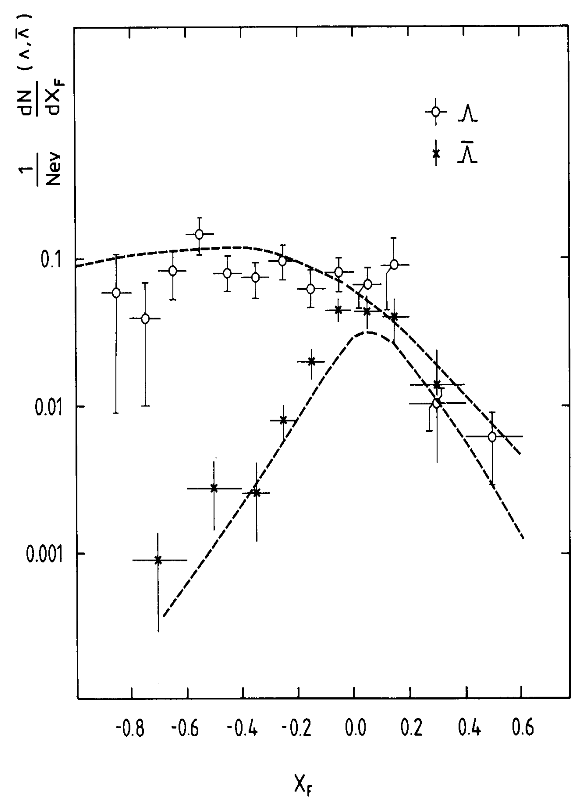
$$Q^2 \frac{dM^h_{i/p}}{dQ^2} = \frac{\alpha_s}{2\pi} P_{ji} \otimes M^h_{j/p} + \frac{\alpha_s}{2\pi} \widehat{P}^l_{ji} \otimes f_{j/p} D^h_l \, .$$

Trentadue, Veneziano '94

Λ leptoproduction in DIS

EMC Coll. 1981

- $\mu p \to \mu \Lambda X$ @ 280 GeV, DIS regime
- Forward ($x_F > 0$) Λ and $\bar{\Lambda}$ production comparable
- No LPE for $\bar{\Lambda}$s, symmetric around $|x_F| \sim 0$
- LPE for Λs (uud $\to$ uds)
- Focus on Lambdas in the following



SIDIS variables and cross section

- z_h not good for target: mixes soft and target hadrons for $z_h \to 0$

$$z_h = \frac{P \cdot h}{P \cdot q} = \frac{E_h^*}{E_p^*(1 - x_B)} \frac{1 - cos\theta}{2}$$

- hadron variables in $\gamma^* N$ c.o.m. frame:

$$z_G = \frac{E_h^*}{E_p^*(1 - x_B)}, \quad E_p^*(1 - x_B) = W/2, \quad \zeta = \frac{E_h^*}{E_p^*}, \quad x_F = \pm\sqrt{z_G^2 - \frac{4m_T^2}{W^2}}$$

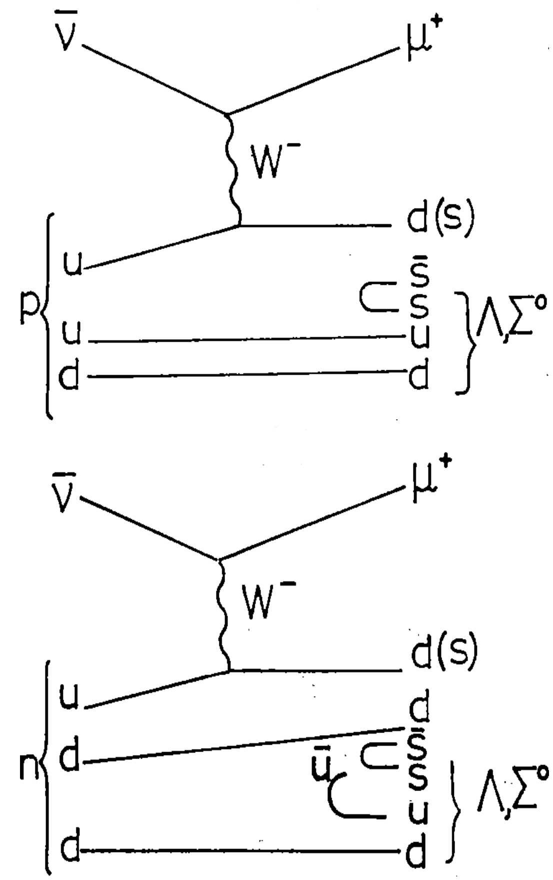
- The Lambda leptoproduction cross section in term of these variables reads

$$\frac{d\sigma^{\Lambda/N}}{dx_B\, dQ^2\, dz_G} \propto \frac{z_G}{|x_F|} \sum_i c_i \left[f_{i/N}(x_B, Q^2)\, D_i^{\Lambda}(z_G, Q^2) + (1 - x_B)\, M_{i/N}^{\Lambda}(x_B, (1 - x_B) z_G, Q^2) \right]$$

- Best strategy to extract M: subtract the current from z_G spectra
- But: Large uncertainties on FFs at low Q, no z_G spectra available in the literature..
- Resort to kinemtical separation in x_F : associate target fragments to $x_F < 0$

Initial conditions for Λ fracture functions (1)

- The hard scattering process occurs on times scales of the order $1/Q$ much shorter than the typical ones of spectator fragmentation, $\sim 1/Q_0$
- At such low scale, a parton with flavour i and momentum x is then removed from the proton with probability $f_{i/P}(x_B, Q_0^2)$
- The leftover coloured system reassembles to give colourless Λ with fractional momentum z on much longer "time scale", $\sim 1/\Lambda_{QCD}$, with probability $\widetilde{D}_i^{\Lambda}(z)$
- Phenomenological factorisation: $M \propto f \times \widetilde{D}$



Initial conditions for Λ fracture functions (2)

- Assumption : fracture functions can be factorized, at some low and arbitrary $Q_0^2 \sim 1$ GeV^2 scale, in the form

$$(1-x_B)M_{i/p}^{\Lambda}(x_B,\,\zeta,Q_0^2) = M_{i/p}^{\Lambda}(x_B,\,z,Q_0^2) = f_{i/p}(x_B,Q_0^2)\widetilde{D}_i^{\Lambda}(z)$$

- $f_{i/p}(x,Q_0^2)$ are standard parton distribution functions (GRV'94)

- $\widetilde{D}_i^{\Lambda}(z)$ are unknown spectator fragmentation functions

- The input distributions are then evolved to arbitrary scales via FF evolution equations.

Initial conditions for Λ fracture functions (3)

- Exploit GRV'94 valence/sea decomposition $\oplus$ simplied flavour and energy dependence

$$
\begin{aligned}
(1-x_B)M^{\Lambda}_{u/p}(x_B,z,Q_0^2) &= u_v(x_B,Q_0^2)N_u z^{\alpha_u}(1-z)^{\beta_u} + u_s(x,Q_0^2)N_s z^{\alpha_s}(1-z)^{\beta_s} \\
(1-x_B)M^{\Lambda}_{d/p}(x_B,z,Q_0^2) &= d_v(x_B,Q_0^2)N_d z^{\alpha_d}(1-z)^{\beta_d} + d_s(x,Q_0^2)N_s z^{\alpha_s}(1-z)^{\beta_s} \\
(1-x_B)M^{\Lambda}_{g/p}(x_B,z,Q_0^2) &= g(x,Q_0^2)N_s z^{\alpha_s}(1-z)^{\beta_s} \\
(1-x_B)^{\Lambda}_{qs/p}(x_B,z,Q_0^2) &= q_s(x_B,Q_0^2)N_s z^{\alpha_s}(1-z)^{\beta_s}
\end{aligned}
$$

- In case of scattering on a sea quark, the spectator fragments independently of the flavour of the latter: $N_s z^{\alpha_s}(1-z)^{\beta_s}$
- x_B dependence driven by pdfs. 12 free pars
- Gluon spectator fragmentation unconstraind, set $\widetilde{D}^{\Lambda}_{g} = \widetilde{D}^{\Lambda}_{qs}$, $\rightarrow$ 9 free pars

Data set used in the fit

- fit data only on light targets : $N = p, D, n \rightarrow$ flavour sep., avoid nuclear effects
- observable : $d\sigma^{\Lambda}/dx_F$
- Inclusive Λ sample : Λ from higher mass resonance decays included in the sample

Reaction type	$\langle E_i \rangle$ (GeV)	$\langle W^2 \rangle$ (GeV^2)	$\langle Q^2 \rangle$ (GeV^2)	$\langle x_B \rangle$	Λ rates (%)
νp [1]	50.0	-	-	-	7.0 ± 1.2
νn [1]	50.0	-	-	-	7.0 ± 0.8
νp [2]	42	34.7	8.7	0.2	5.2 ± 0.3
$\bar{\nu} p$ [2]	38.5	20.4	5.2	0.2	5.7 ± 0.4
μp [3]	280	130	12	0.11	-
μD_2 [3]	280	130	12	0.11	-
μD_2 [4]	490	292	8.6	0.036	7.8 ± 1.6

[1] C. C. Chang *et al.*, *Phys. Rev.* **D27** (1983) 2776.

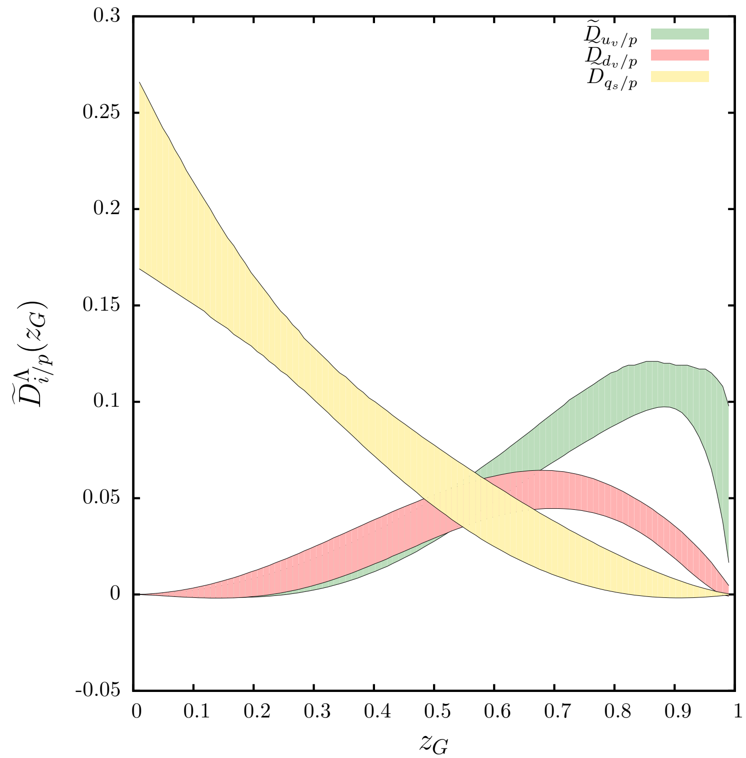
[2] G. T. Jones *et al.* (WA21 Collaboration), *Z. Phys.* **C57** (1993) 197.

[3] M. Arneodo *et al.* (EMC Collaboration), *Z. Phys.* **C34** (1987) 283.

[4] M. R. Adams *et al.* (E665 Collaboration), *Z. Phys.* **C61** (1994) 539.

Fit results and error propagation

- Study of the eigenvalues of the Hessian matrix $\rightarrow$ parameter reduction : 7 free pars
- $\widetilde{D}_i^{\Lambda} = N_i z^{\alpha_i} (1-z)^{\beta_i}$
- 3 normalizations N_i well determined
- β_i determined with acceptable errors
- α_i mostly unconstrained:
  $\alpha_u = \alpha_d$ and $\alpha_{qs} = 0$
- $\chi^2/d.o.f. = 44.14/(46-7) = 1.13$
- propagation experimental uncertanties :
  14 additional ΛFF set corresponding
  to $\Delta\chi^2 = 1$



Ceccopieri, Mancusi EPJC 2013

Predictions for CLAS@12GeV

SIDIS selection:

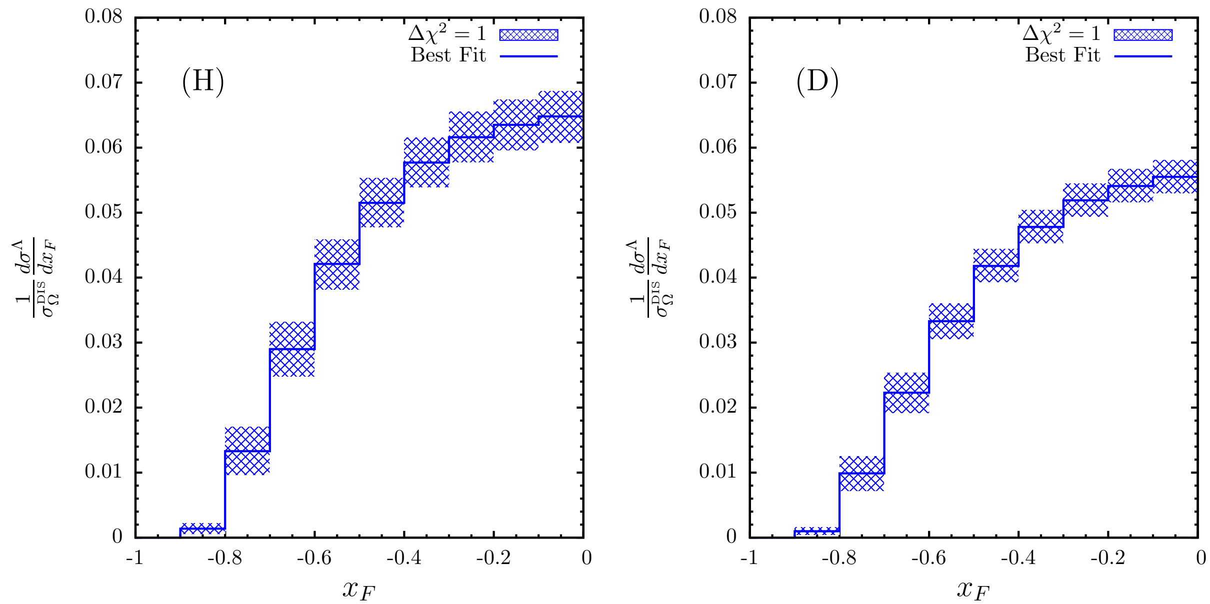
- $0.2 < y < 0.8, \quad Q^2 > 1$ GeV^2, $\quad W^2 > 5$ GeV^2
- target Λ : $x_F < 0$

Target/Observable	$\langle n(\Lambda) \rangle$
proton	$0.038 \pm 0.003(exp)^{+0.004}_{-0.004}(mass)^{+0.002}_{-0.001}(scale)$
deuteron	$0.032 \pm 0.002(exp)^{+0.003}_{-0.004}(mass)^{+0.001}_{-0.001}(scale)$

Target/Observable	σ^{Λ} [pb]
proton	$2382 \pm 170(exp)^{+247}_{-269}(mass)^{+159}_{-125}(scale)$
deuteron	$1758 \pm 102(exp)^{+196}_{-206}(mass)^{+119}_{-92}(scale)$

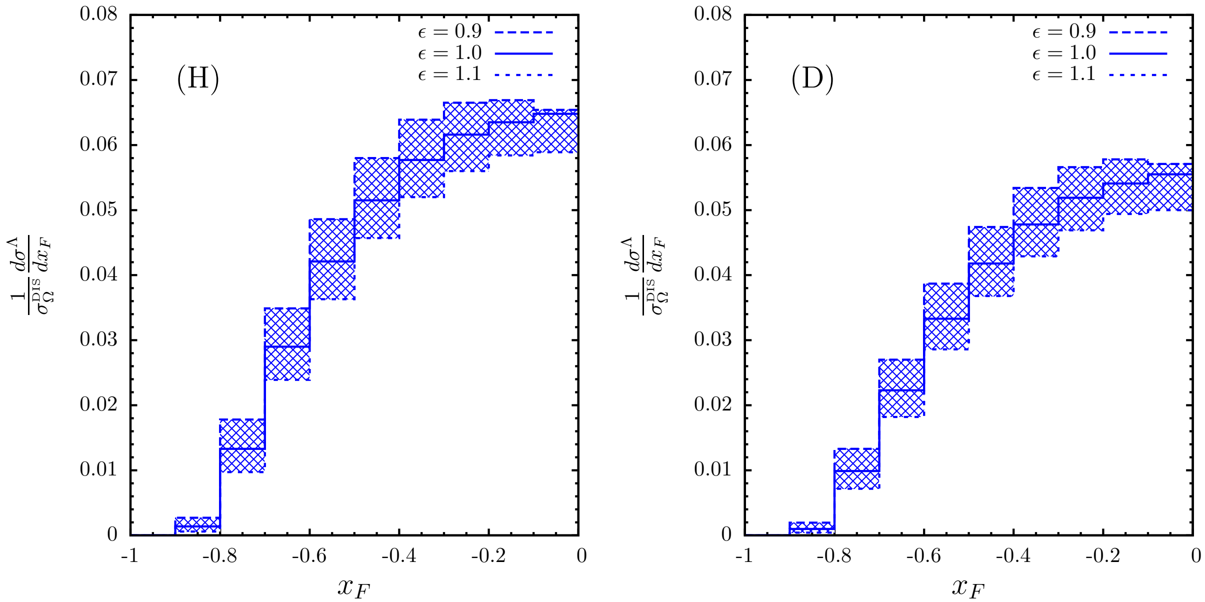
Ceccopieri EPJC 2016

Propagation of exp uncertainties from the ΛFF fit



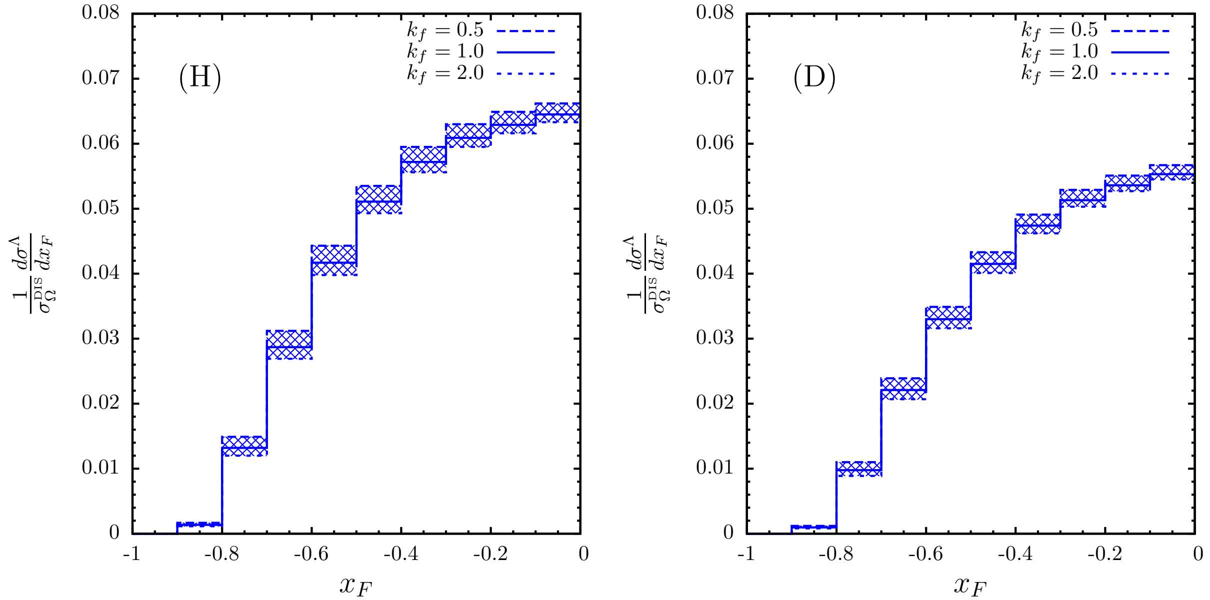
- Best fit + 14 additional ΛFF set corresponding to $\Delta\chi^2 = 1$ built from eigenvectors of the Hessian matrix
- $\delta\langle n(\Lambda)\rangle = \pm 0.003$

Sensitivity to mass corrections



- mass corrections : $x_F = \pm\sqrt{z_G^2 - \frac{4\epsilon m_T^2}{W^2}}$, $m_T \simeq m_\Lambda$ since $p_t^\Lambda \ll m_\Lambda$ (exp)
- Arbitrary variations: $\epsilon = \{0.9, 1, 1.1\}$
- $\delta\langle n(\Lambda)\rangle = \pm 0.004$, slight shape change

Sensitivity to higher orders

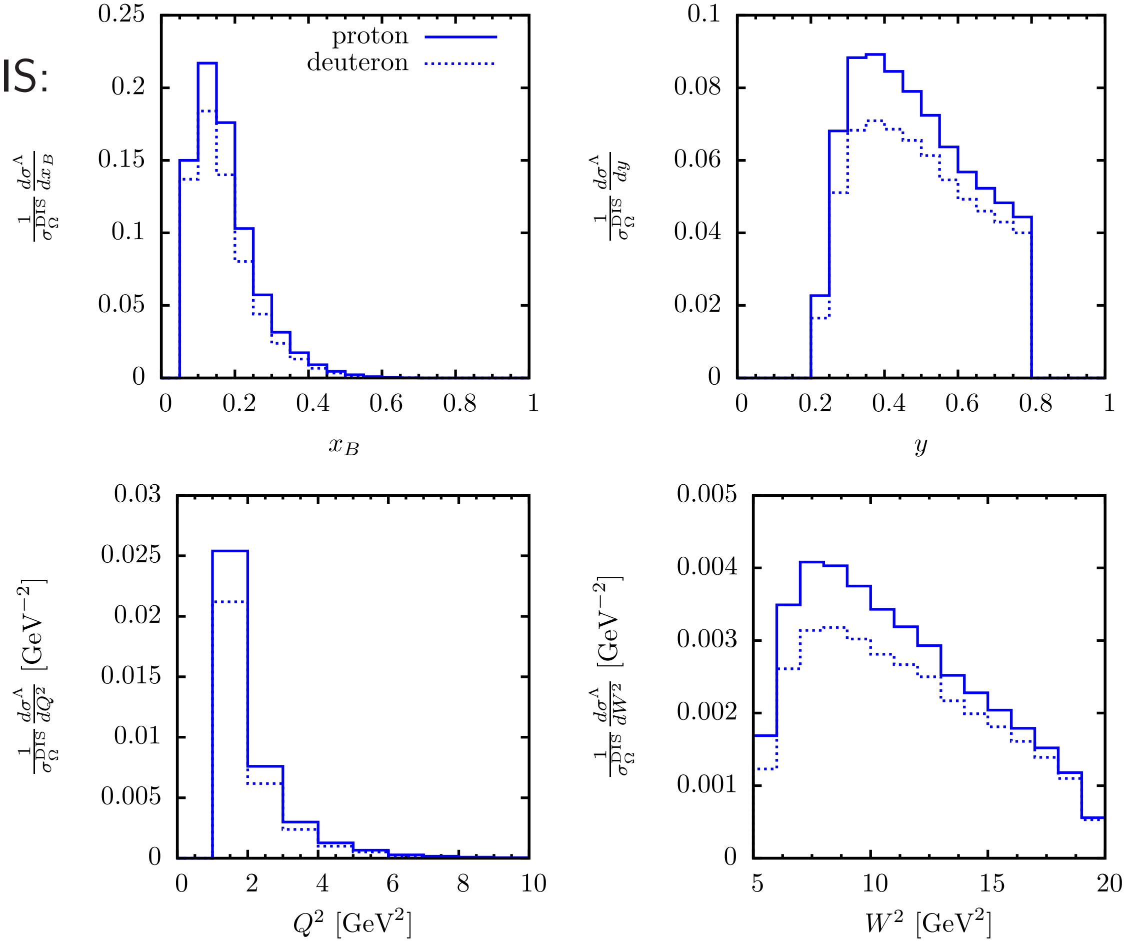


- factorisation scale: $\mu_F^2 = \{1/2Q^2, Q^2, 2Q^2\}$
- moderate scale dependence for differential yield $\rightarrow$ compensation with scale dependence iDIS
- $\delta\langle n(\Lambda)\rangle = \pm 0.001$

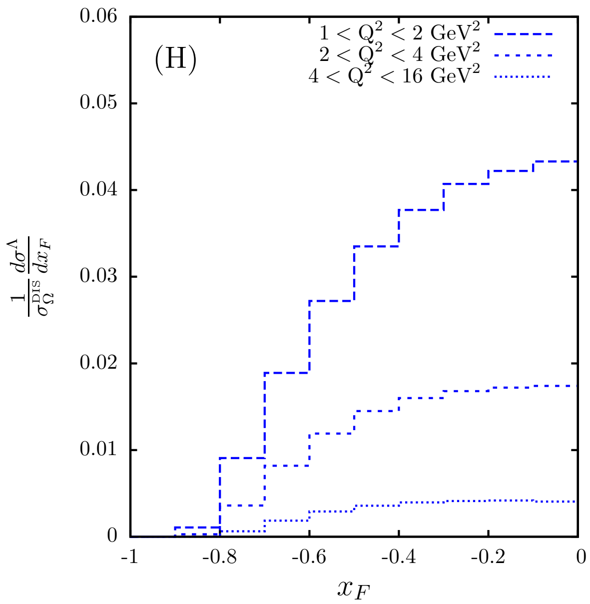
Predictions for CLAS@12GeV

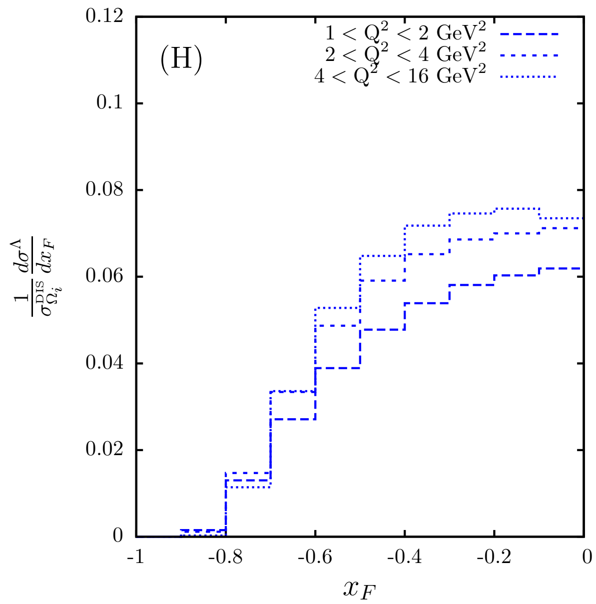
- comparison with inclusive DIS: correlation between hard scattering and target Λ production

Variable	iDIS	ΛDIS
$\langle x_B \rangle$	0.18	0.17
$\langle y \rangle$	0.45	0.48
$\langle Q^2 \rangle$ [GeV^2]	1.9	2.0
$\langle W^2 \rangle$ [GeV^2]	10.3	11.1



Predictions for CLAS@12GeV



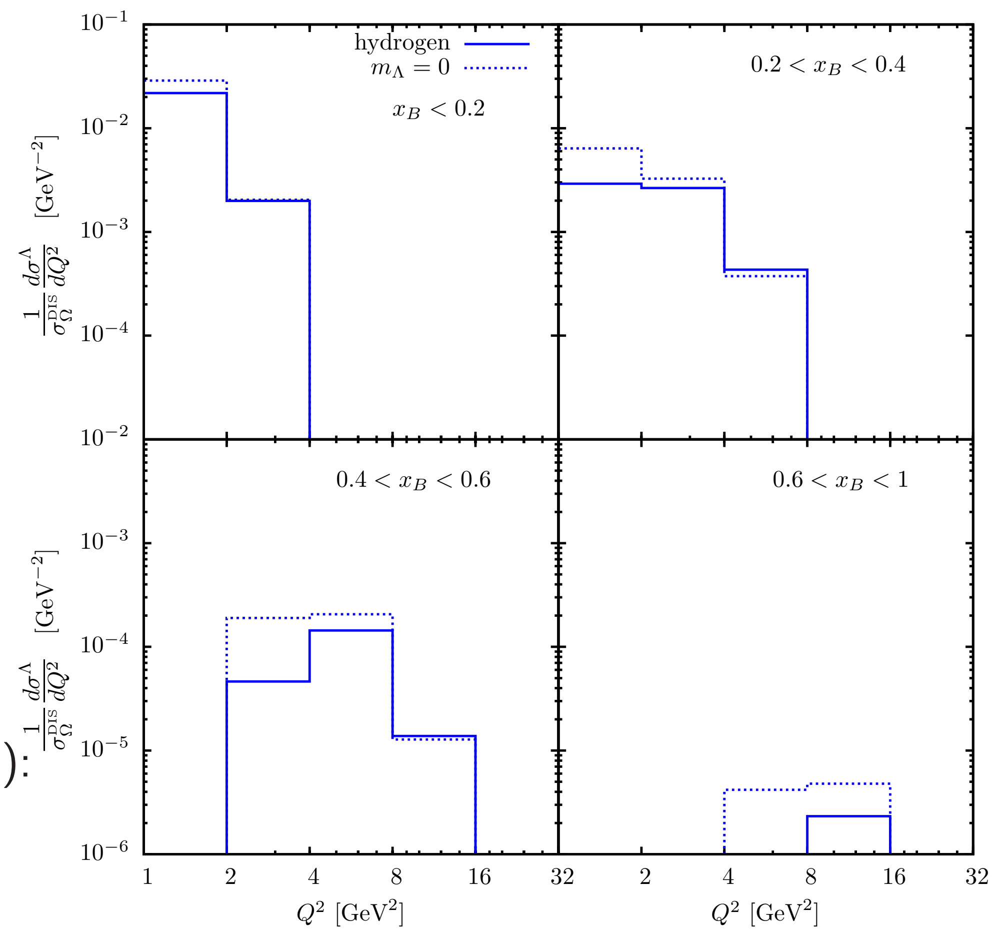


- Left: test leading twist hypothesis, assumed by fracture functions formalism
- Right : mild rise of Λ multiplicity with Q^2: test pQCD evolution of fracture functions
- compare spectra in DIS and PHP regime: how the transition to the non-perturbative regime in Q^2 affects the Lambda spectrum in the target region.

Predictions for CLAS@12GeV

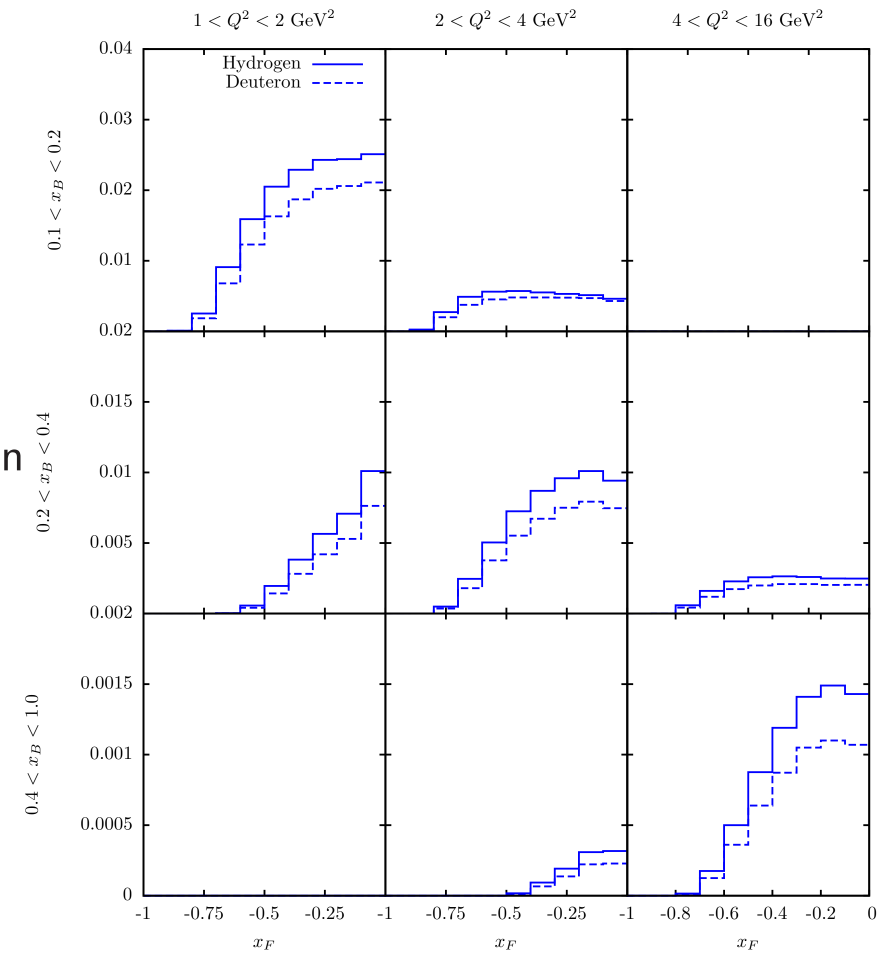
- The Q^2-differential cross section deserve special attention
- it may provide crucial test for the predicted evolution of FFs
- BUT : low values of W^2 accessed by the experiment
- the Q^2 spectrum receives significant hadron mass corrections
- They suppress the cross section as x_B increases.
- to spot Q^2 scaling violations from FF evolution use reduced cross section (all Q^2-dep. from M):

$$\frac{1}{\sigma_0}\frac{d\sigma^{\Lambda/N}}{dx_B\,dy\,dz} = \frac{z}{|x_F|}\sum_i e_i^2\, M_{i/N}^{\Lambda}$$

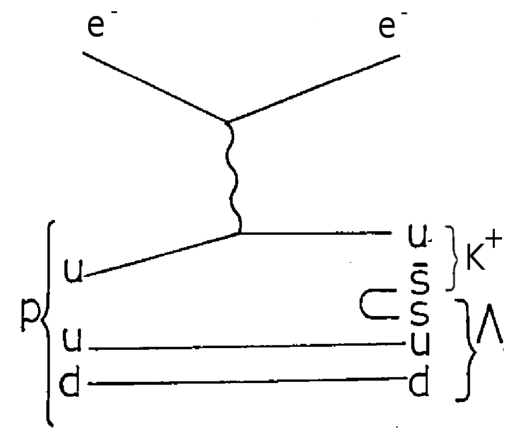


Predictions for CLAS@12GeV

- $\frac{1}{\sigma^{\text{DIS}}}\frac{d\sigma^{\Lambda}}{dx_F}$ in (x_B, Q^2) ranges for both proton and deuteron targets
- This way of presenting the data is probably the more exhaustive and it might be valuable for the determination of Lambda fracture functions in forthcoming global fit analyses:
- maximal sensitivity to $\widetilde{D}$'s parameters



Strange correlation in SIDIS final state



- Consider double inclusive cross section: $lN \to \Lambda K^+ X$, in DIS regime
- Trigger on very backward Lambdas (uds), $-1 < x_F < -0.5$ and K^+ $(u\bar{s})$ for all x_F
- Measure cross section as a function of the rapidity difference $\Delta y = y_{K^+} - y_\Lambda$
- for forward K^+ (say $x_F > 0.5$), the cross section can predicted: $d\sigma/d\Delta y \propto M_{i/N}^{\Lambda} \otimes D_i^{K^+}$
- for backward K^+ (say $x_F < -0.5$), the cross section depends on unknown two particles fracture functions: $d\sigma/d\Delta y \propto M_{i/N}^{K^+,\Lambda}$
- Such an observable is sensitive to strangeness propagation accross the DIS final state

Conclusions

- For a complete description of SIDIS one has to deal with target fragmentation: its description in terms fracture functions is slowly improving (Relevant for EIC)
- Phenomenology at all energy and for different particles (p, n, Λ, π, $\bar{p}$) is required
- A model for the description of backward Λ production has been constructed in the fracture functions framework (CM12)
- Predictions for a number of observables for CLAS@12GeV have been presented: potential to test underlying theory and to sharpen the model to investigate
- ... strange correlations in DIS final state
- ... to give baseline for Lambdas production off nuclei
- ... to give baseline for target/current spin correlation studies