QCD analysis of Lambda hyperon production in DIS target-fragmentation region

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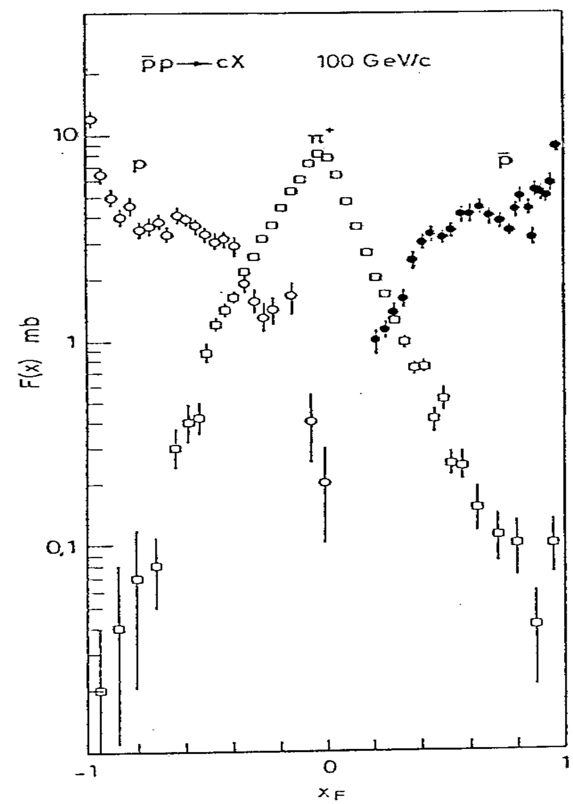
Motivations

- In the standard QCD framework, the cross section for one-particle production in semi-inclusive DIS involves parton distribution functions (PDFs) and fragmentation functions (FFs).
- This approach applies to the so called current fragmentation region, where the struck quark hadronises into the observed hadron.
- So far, the target fragmentation region, where the fragments of the proton hadronise, was disregarded due to the lack of QCD-based formalism.
- Such formalism has been put forward in '94 by Trentadue and Veneziano and requires the introduction of new non-perturbative distributions, called Fracture Functions.
- Aim of this work: build a quantitative fracture functions model for backward Lambda leptoproduction in DIS out of available data.

The leading particle effect in hadronic collisions

- Consider the following reaction : $\bar{p}p \to c + X$
- $x_F = 2p_{||}/\sqrt{s}$ in hadronic centre of mass
- Leading particle effect : privileged quark-flavour quantum number flow from the initial state particle to the final state one
- 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 → pQCD can not be applied

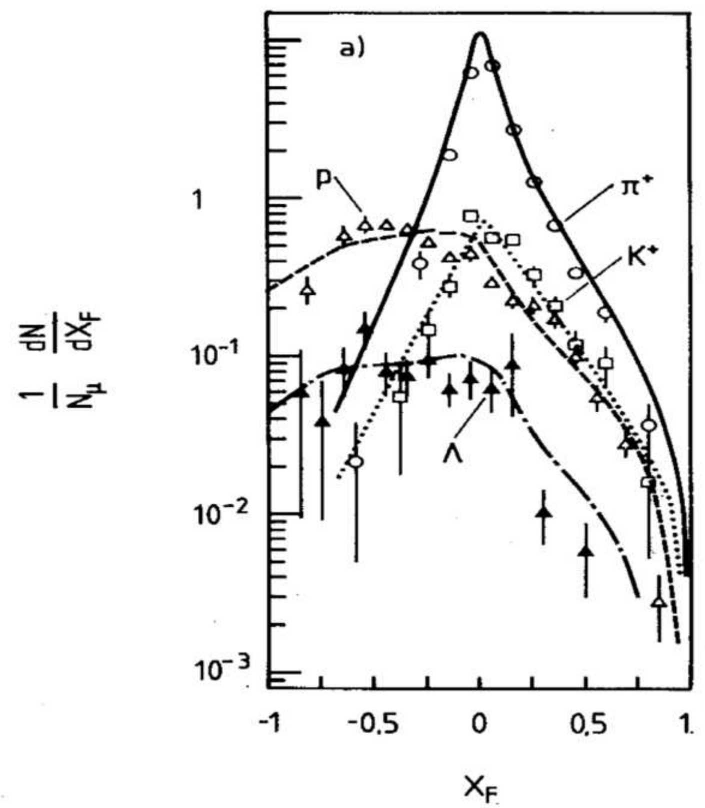
Basile & al. 1981



The leading particle effect in DIS

EMC Coll. 1981

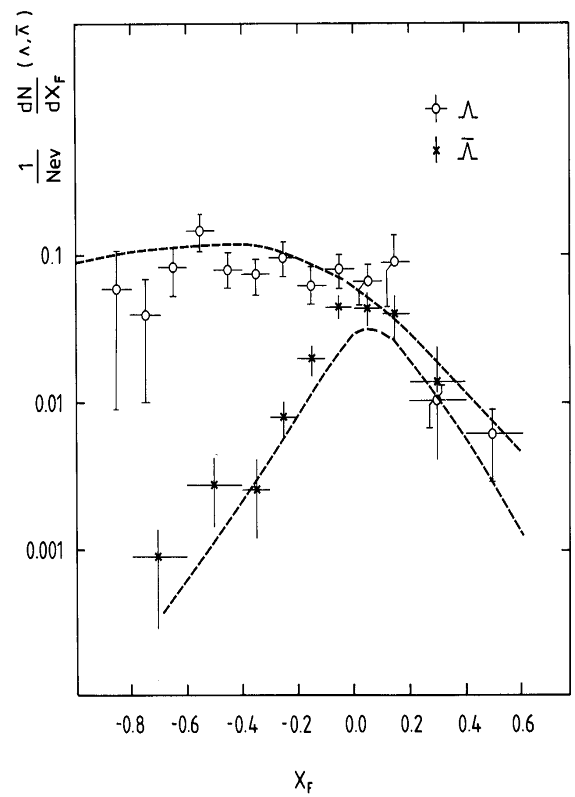
- Is there any similar effect in DIS as well?
- $\mu P \to \mu' h X$ @ 280 GeV, DIS regime
- Same pattern as in hadronic collisions
- LPE for backward proton (uud) and Λ (uds)
- No LPE for $\bar{\Lambda}$ ($\bar{\text{u}}\bar{\text{d}}\bar{\text{s}}$), $\bar{p}$ ($\bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$) and mesons
- But here we have hard scale, $Q^2 \gg \Lambda^2_{QCD}$



Λ and $\bar{\Lambda}$ leptoproduction in DIS

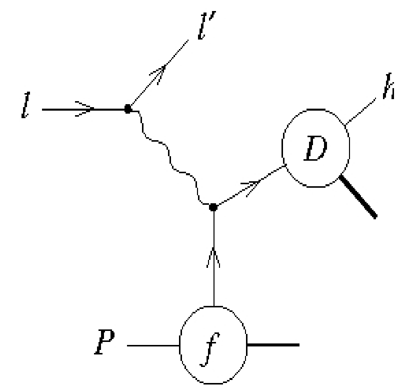
EMC Coll. 1981

- $\mu P \to \mu' \Lambda X$ @ 280 GeV, DIS regime
- Forward $(x_F > 0)\Lambda$ 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

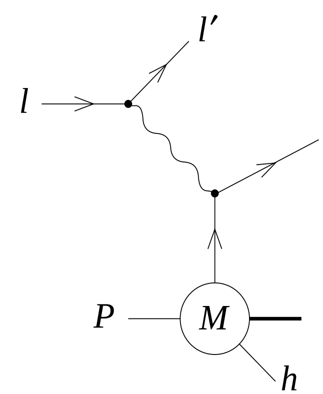


NB: Fracture Functions formalism is not restricted to the description of particles that show LPE

Theoretical status : factorisation and fragmentation in DIS



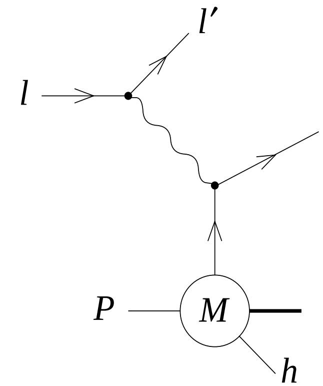
- Factorization theorem allows the decoupling of short distance (ME) from long distance (f, D, M) physics
- f, D, M are not calculable from first principles
- The evolution of f, D, M however is known (RGE)
- At lowest order, in the current region ($x_F > 0$) $d\sigma \propto f \otimes D$ and in the target region ($x_F < 0$) $d\sigma \propto M$



- Factorization 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 DIS

- Fracture functions parametrize backward hadron production in semi-inclusive DIS processes



- $M^i_{h/P}(\xi,\zeta)$ give the conditional probability that a parton i with a fractional momentum ξ of the incoming nucleon momentum P enters the hard vertex while an hadron h with fractional momentum ζ is detected in the TFR of P
- $M^i_{h/P}(\xi,\zeta)$ RGE equation read:

$$\frac{\partial M_{i,\Lambda/p}\left(\xi,\zeta,Q^2\right)}{\partial\log Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_{\xi/(1-\zeta)}^{1}\frac{du}{u}\,P^i_j(u)\,M_{j,\Lambda/N}\left(\frac{\xi}{u},\zeta,Q^2\right)$$
$$+\frac{\alpha_S(Q^2)}{2\pi}\int_{\xi}^{\xi/(\xi+\zeta)}\frac{du}{\xi(1-u)}\,\hat{P}^{i,l}_j(u)\,f_{j/p}\left(\frac{\xi}{u},Q^2\right)\,D_{\Lambda/l}\left(\frac{\zeta u}{\xi(1-u)},Q^2\right)$$

Trentadue, Veneziano '94

DIS kinematics and cross section

- The analysis is performed in the $\gamma^*/W^{\pm}N$ centre of mass frame : this allows a better kinematical separation of target and current emisphere

- lepton variables : $x_B = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot l} = 1 - \frac{E_l'}{E_l}, \quad W^2 = Q^2 \frac{1-x_B}{x_B}$

- hadron variables : $z = \frac{E_h}{E_p(1-x)}, \quad \zeta = \frac{E_h}{E_p}, \quad x_F = -\sqrt{z^2 - \frac{4m_\Lambda^2}{W^2}}$

- A generic (NC or CC DIS) LO cross section in term of these variables then reads

$$\frac{d\sigma^{\Lambda/N}}{dx_B\, dy\, dz} \propto \sum_i c_i \left[f_{i/N}(x_B)\, D_{\Lambda/i}(z) + (1-x_B)\, M_i^{\Lambda/N}(x_B, (1-x_B)z) \right]$$

NC and CC DIS cross sections

- Assuming $F_L = 0$ as appropriate lowest order calculation, ignoring Cabibbo suppressed contributions, considering light quarks only, the NC and CC semi-inclusive DIS cross-sections in the target region read

$$\frac{d^3\sigma^{\mu^+P}}{dx_B dQ^2 d\zeta} = J\,\frac{2\pi\alpha_{em}^2(1+(1-y)^2)}{Q^4}\sum_{q=u,d,s} e_q^2\Big[M_q^{\Lambda/P} + M_{\bar{q}}^{\Lambda/P}\Big]$$

$$\frac{d^3\sigma^{\nu P}}{dx_B dQ^2 d\zeta} = J\,\frac{2\pi\alpha_{em}^2}{Q^4} 8\eta_W\Big[2(M_d^{\Lambda/P} + M_s^{\Lambda/P}) + 2(1-y)^2 M_{\bar{u}}^{\Lambda/P}\Big]$$

$$\frac{d^3\sigma^{\bar{\nu} P}}{dx dQ^2 d\zeta} = J\,\frac{2\pi\alpha_{em}^2}{Q^4} 8\eta_W\Big[2(M_{\bar{d}}^{\Lambda/P} + M_{\bar{s}}^{\Lambda/P}) + 2(1-y)^2 M_{u}^{\Lambda/P}\Big]$$

$$M_q^{\Lambda/P} = M_q^{\Lambda/P}(x_B, Q^2, \zeta), \quad J = \frac{\zeta}{(1-x_B)|x_F|}, \quad \eta_W = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha_{em}}\frac{Q^2}{Q^2+M_W^2}\right)^2.$$

Observable choice and reconstruction

- Golden observable is the normalised x_F distribution, other distributions are contaminated by current contribution

- No data available to test the scale dependence of FF : it is assumed and it constitutes a full predictions of the FF model to be tested against forthcoming data

- Fracture functions are evolved in kinematics relevant to experiments

- The normalised x_F-differential cross section in the i-bin is reconstructed as

$$\frac{1}{\sigma_{DIS}} \frac{\Delta \sigma^{i,lP}}{\Delta x_F} = \frac{1}{\sigma_{DIS}} \frac{1}{\Delta x_F} \int_{\text{cuts}} dx dQ^2 d\zeta \Phi(E_l) dE_l \frac{d^3 \sigma^{lP}(E_l)}{dx dQ^2 d\zeta} \, \Gamma^i$$

$$\Gamma^i = \theta(x_F(x,Q^2,\zeta) - x_F^i) \cdot \theta(x_F^{i+1} - x_F(x,Q^2,\zeta)), \quad \Delta x_F = x_F^{i+1} - x_F^i$$

Heavy targets and definition of the Λ sample

- SKAT collaboration observed sizeable A-dependence of backward Λ production
- Temptative explanation : secondary interactions, $\pi N \to \Lambda X$, inside nuclear medium
- Include in the analysis only data from DIS experiments performed on light targets (proton and deuteron) which guarantees minimal quark flavour discrimination
- Inclusive Λ sample : Λ coming from higher mass resonance decays included in the sample

SKAT '07

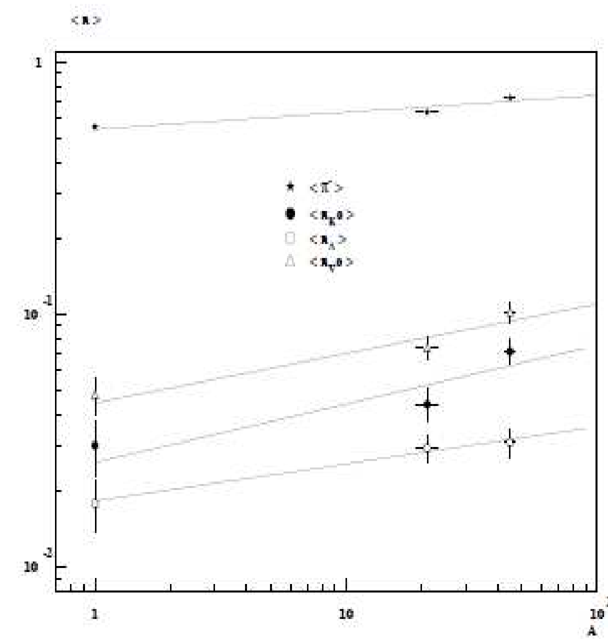


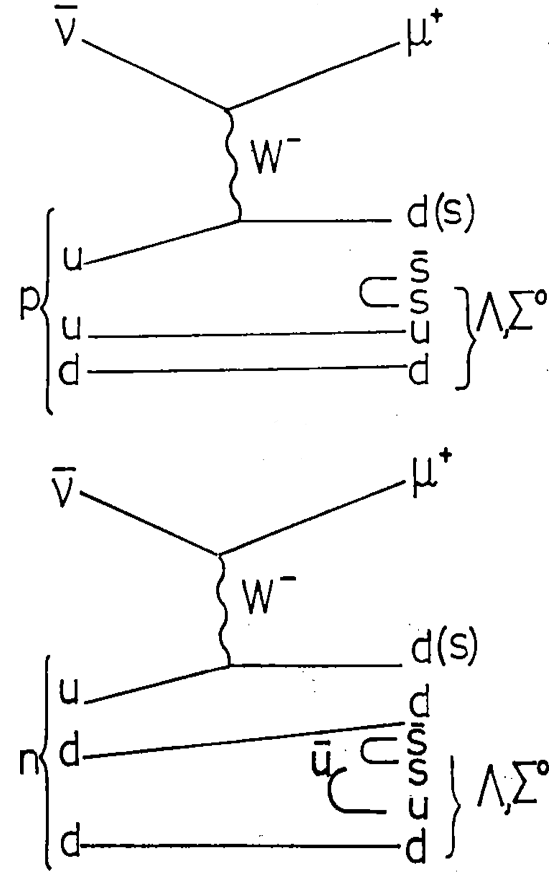
Figure 1: The A- dependence of the total yields of K^0, Λ, V^0 and π^-. The curves are the result of the exponential fit.

Data set used in the fit

Reaction type	Ref.	$\langle E_i \rangle$ (GeV)	$\langle W^2 \rangle$ (GeV^2)	$\langle Q^2 \rangle$ (GeV^2)	$\langle x_B \rangle$	Λ rates (%)
μp	EMC, ZP C34 (1987) 283	280	130	12	0.11	-
μD_2	"	280	130	12	0.11	-
μD_2	E665, ZP C61 (1994) 539	490	292	8.6	0.036	7.8 ± 1.6
νp	WA21, ZP C57 (1993) 197	42	34.7	8.7	0.2	5.2 ± 0.3
$\bar{\nu} p$	"	38.5	20.4	5.2	0.2	5.7 ± 0.4
νp	PR D27 (1983) 2776	50.0	-	-	-	7.0 ± 1.2
νn	"	50.0	-	-	-	7.0 ± 0.8

Initial conditions and model building (1)

- The electroweak current probes the "struck quark" on very short "time scale", $\sim 1/Q$
- A parton with flavour i and momentum x is then removed from the proton with probability $f_{i/P}(x_B, Q^2)$
- The leftover coloured system (diquark?) reassembles to give colourless Λ with fractional momentum z on much longer "time scale", $\sim 1/\Lambda_{QCD}$, with probability $\widetilde{D}_i^{\Lambda/P}(z)$



Initial conditions and model building (2)

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

$$M_i^{\Lambda/P}\left(x_B,\, \zeta, Q_0^2\right) = \frac{M_i^{\Lambda/P}\,(x_B,\; z, Q_0^2)}{1-x_B} = \frac{f_{i/P}(x_B, Q_0^2)\,\widetilde{D}_i^{\Lambda/P}(z, Q_0^2)}{1-x_B}$$

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

- $\widetilde{D}^i_{\Lambda/P}(z, Q_0^2)$ are unknown spectator fragmentation functions

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

Initial conditions and model building (3)

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

$$
\begin{aligned}
(1-x_B)M_{u,\Lambda/P}(x_B,z,Q_0^2) &= u_{val}(x_B,Q_0^2)N_u^{'}z^{\alpha u}(1-z)^{\beta u} + u_{sea}(x,Q_0^2)N_s^{'}z^{\alpha s}(1-z)^{\beta s} \\
(1-x_B)M_{d,\Lambda/P}(x_B,z,Q_0^2) &= d_{val}(x_B,Q_0^2)N_d^{'}z^{\alpha d}(1-z)^{\beta d} + d_{sea}(x,Q_0^2)N_s^{'}z^{\alpha s}(1-z)^{\beta s} \\
(1-x_B)M_{g,\Lambda/P}(x_B,z,Q_0^2) &= g(x,Q_0^2)N_s^{'}z^{\alpha s}(1-z)^{\beta s} \\
(1-x_B)M_{qsea,\Lambda/P}(x_B,z,Q_0^2) &= q_{sea}(x_B,Q_0^2)N_s^{'}z^{\alpha s}(1-z)^{\beta s}
\end{aligned}
$$

- In case of scattering on a sea quark, the spectator fragments independtly of the flavour of the latter: $N_s^{'}z^{\alpha s}(1-z)^{\beta s}$

- no extra energy (x_B) dependence

- Gluon spectator fragmentation function set equal to sea one (mostly unconstrained)

Initial conditions and model building (4)

- In order to reduce correlations among parameters, the $N_i^{'}$ are renormalized and actually fitted instead of N_i

$$N_i^{'} = \frac{N_i}{\int_0^1 dz z^{\alpha_i}(1-z)^{\beta_i}}, \quad i = u_{val}, d_{val}, sea$$

- In the case of Lambda leptoproduction off neutron invoke isospin symmetry

$$\begin{aligned} M_{d(ud)}^{\Lambda/N}(x_B, z, Q^2) &= M_{u(ud)}^{\Lambda/P}(x_B, z, Q^2) \\ M_{u(dd)}^{\Lambda/N}(x_B, z, Q^2) &= M_{d(uu)}^{\Lambda/P}(x_B, z, Q^2) \end{aligned}$$

- Valence quarks : $\widetilde{D}_{ud}$ same for u and d but $\widetilde{D}_{dd} = \widetilde{D}_{uu}$
- Sea quarks : given the model, apply $M_q \leftrightarrow M_{\bar{q}}$, but breakdown expected if $M_q \neq M_{\bar{q}}$ is allowed

Study of the eigenvalues of the Hessian matrix

- CTEQ approach (Pumplin & al. 2001)
- Consider a best fit parameter set $\{a_i^0\}$
- $\chi^2 = \chi_0^2 + \sum_{i,j} H_{ij} y_i y_j, \quad y_i = a_i - a_i^0$
- $H_{ij} = \frac{1}{2}\left(\frac{\partial^2\chi^2}{\partial y_i \partial y_j}\right)_0, \qquad \sum_j H_{ij} v_{jk} = \epsilon_k v_{ik}$
- Large $\epsilon_k \rightarrow$ well determined sub-set of $\{a_i^0\}$
- 3 Normalization N are OK
- β's can be determined with (large) errors but α's are mostly unconstrained

k	ϵ_k
1	0.40
2	0.71
3	0.85
4	13.8
5	21.9
6	60.0
7	19510
8	106603
9	191783

Best fit and parameters

	N	α	β
u_{val}	0.046 $\pm$ 0.006	2.82 $\pm$ 1.19	0.39 $\pm$ 0.33
d_{val}	0.027 $\pm$ 0.006	$\alpha_{u_{val}}$	1.28 $\pm$ 0.51
sea	0.078 $\pm$ 0.010	0	1.84 $\pm$ 0.63

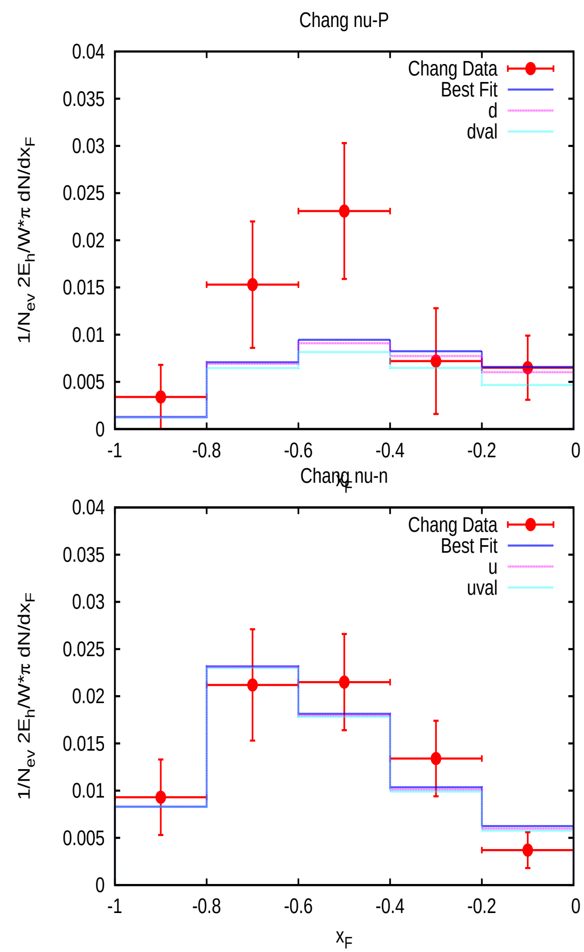
Reaction type	χ^2	# fitted points ($x_F < 0$)
μp	9.90	8
μD_2	10.58	9
μD_2	0.20	3
νp	6.36	8
$\bar{\nu} p$	9.08	8
νp	4.77	5
νn	3.25	5

$$\chi^2/d.o.f. = 44.14/(46-7) = 1.13$$

Best Fit discussion (1)

- $\nu P \to \mu^- \Lambda X$, $\langle E_\nu \rangle = 50$ GeV
- Cut : $x_B > 0.2$ and $W > 4$ GeV
- $d\sigma^{\nu-P} \propto 2(M_d + M_s) + 2(1-y)^2 M_{\bar{u}}$
- This set mainly determines M_{dval} parameters

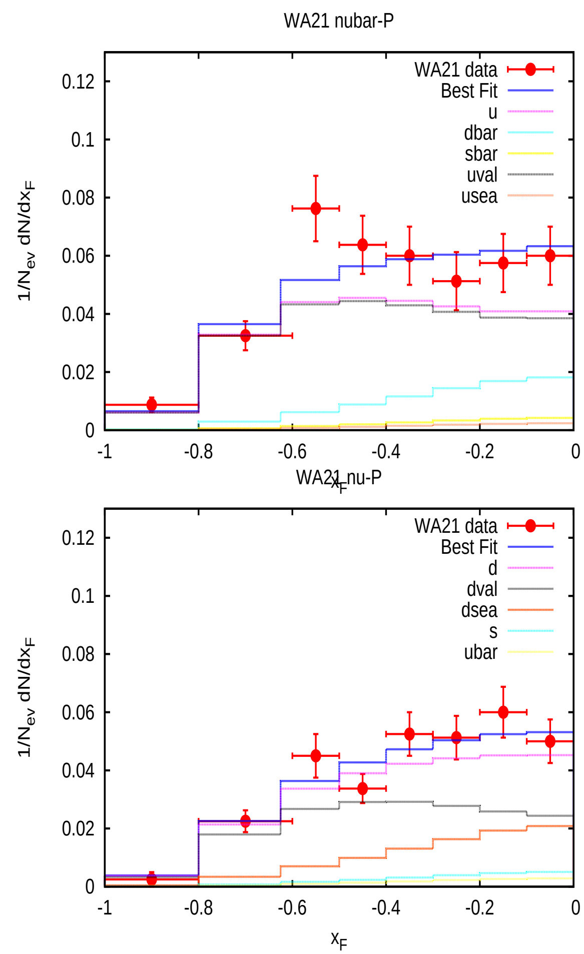
- $\nu N \to \mu^- \Lambda X$, $\langle E_\nu \rangle = 50$ GeV
- Cut : $x_B > 0.2$ and $W > 4$ GeV
- $d\sigma^{\nu-N} \propto 2(M_u + M_s) + 2(1-y)^2 M_{\bar{d}}$
- This set mainly determines M_{uval} parameters



Best Fit discussion (2)

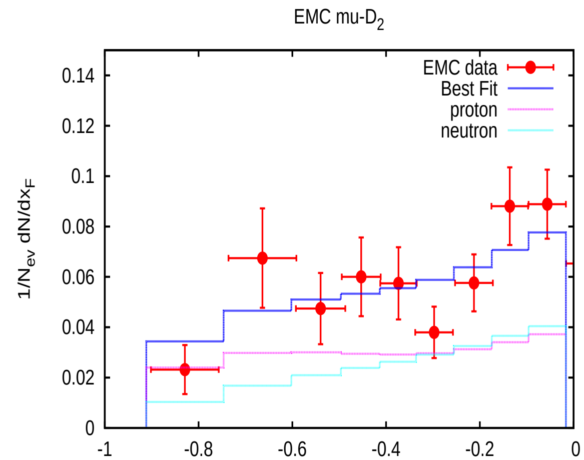
- $\bar{\nu} P \to \mu^+ \Lambda X$, $\langle E_\nu \rangle = 38.5$ GeV
- $d\sigma^{\bar{\nu}-P} \propto 2(M_{\bar{d}} + M_{\bar{s}}) + 2(1-y)^2 M_u$
- Sizeable effect of sea at intermediate $|x_F|$

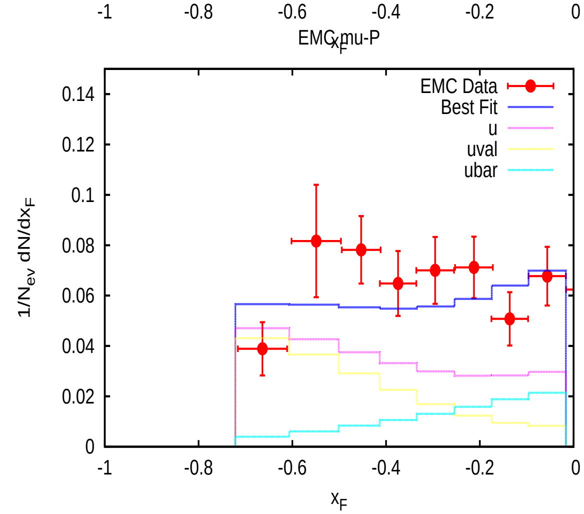
- $\nu P \to \mu^- \Lambda X$, $\langle E_\nu \rangle = 42$ GeV
- $d\sigma^{\nu-P} \propto 2(M_d + M_s) + 2(1-y)^2 M_{\bar{u}}$
- At large $|x_F|$ dominance of :
  M_{uval} in $\bar{\nu} P$ and of M_{dval} in νP



Best Fit discussion (3)

- $\mu D_2 \rightarrow \mu' \Lambda X$ @ 280 GeV
- Different asymptotics for different target
- $\mu P \rightarrow \mu' \Lambda X$ @ 280 GeV
- $d\sigma^{\mu-P} \propto \sum_{q=u,d,s} e_q^2 (M_q + M_{\bar{q}})$
- Energy dependence appears to be compatible with data

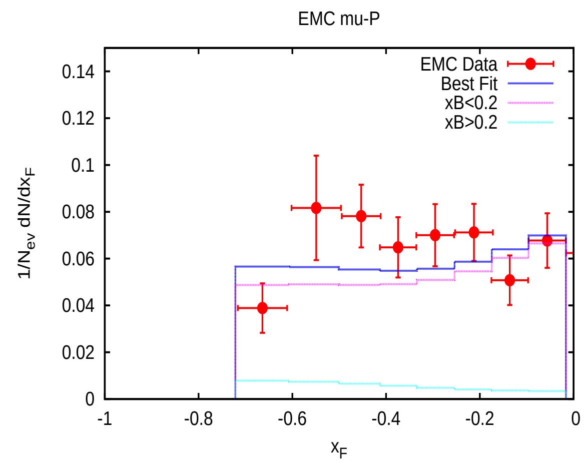




Best Fit discussion (4)

- $\mu P \to \mu' \Lambda X$ @ 280 GeV

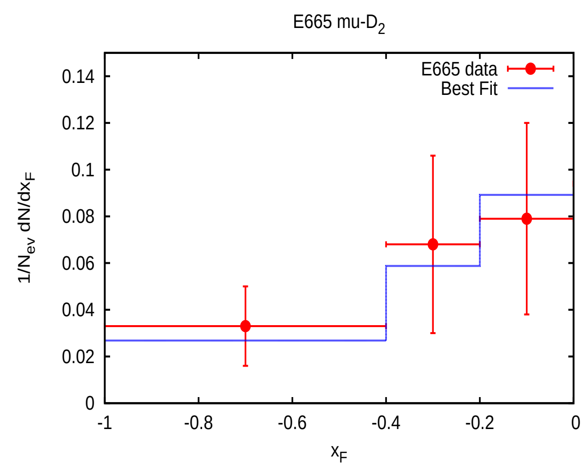
- spectrum dominated by $x_B < 0.2$



- $\mu D_2 \to \mu' \Lambda X$ @ 490 GeV

- At even higher beam energy the model appears to be compatible with data

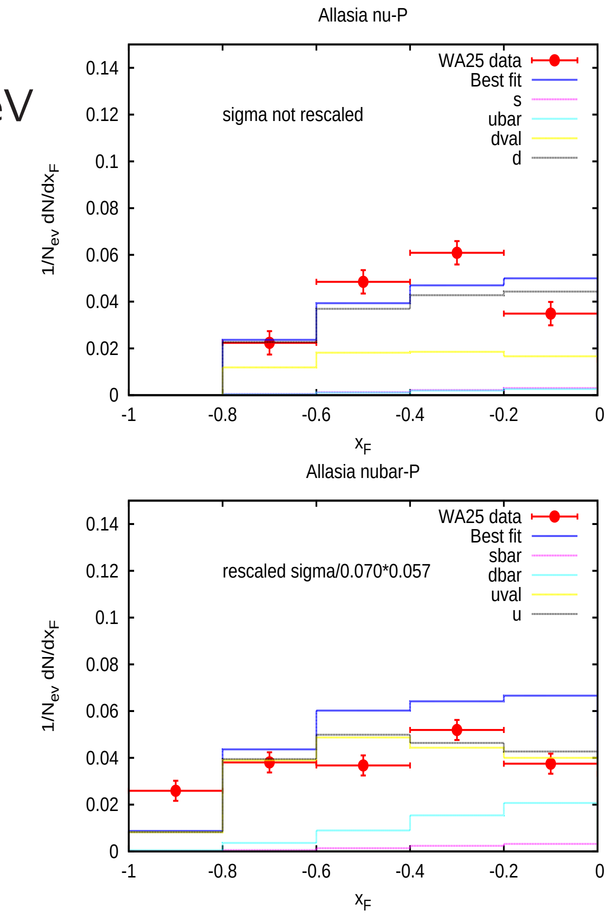
- Extra modulation in x requires more differential data



Predictions for other data sets (1)

- $\bar{\nu}$-P and ν-P cross-sections on proton $\langle E_\nu \rangle \sim 50$ GeV
- not included in the fit because lack of errors in exp paper : errors are (under)estimated from quoted errors on yields
- For the proton target there is rough agreement

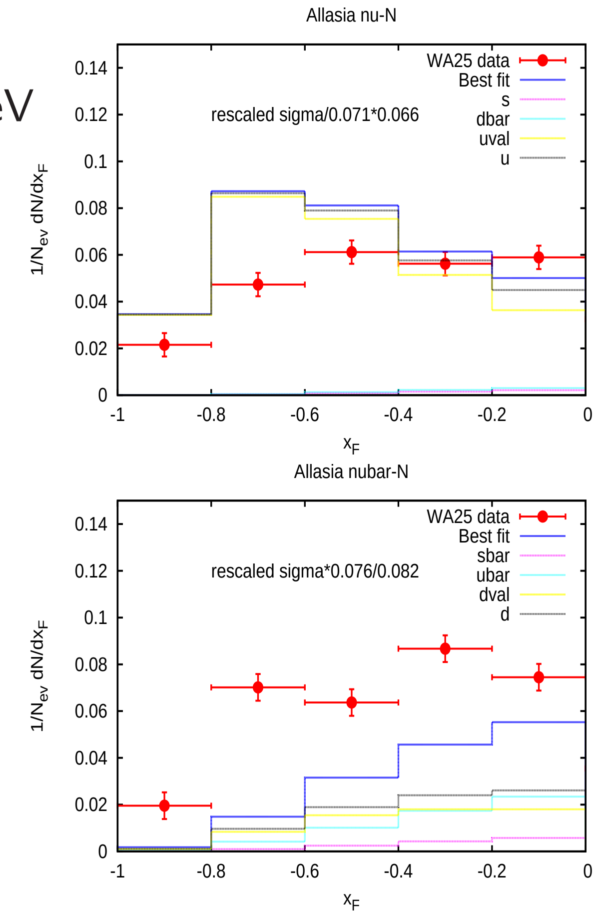
Allasia 1985



Predictions for other data sets (2)

- $\bar{\nu}$-n and ν-n cross-sections on neutron $\langle E_\nu \rangle \sim 50$ GeV
- not included in the fit because lack of errors in exp paper : errors are (under)estimated from quoted errors on yields
- ν-n CS overestimated : problem with M_{uval} normalization & shape!
- $\bar{\nu}$-n CS underestimated : sensitive to the flavour combination $d\sigma^{\bar{\nu}-N} \propto 2(M_{\bar{u}} + M_{\bar{s}}) + 2(1-y)^2 M_d$
- M_{dval} too small, need to improve the sea treatment?

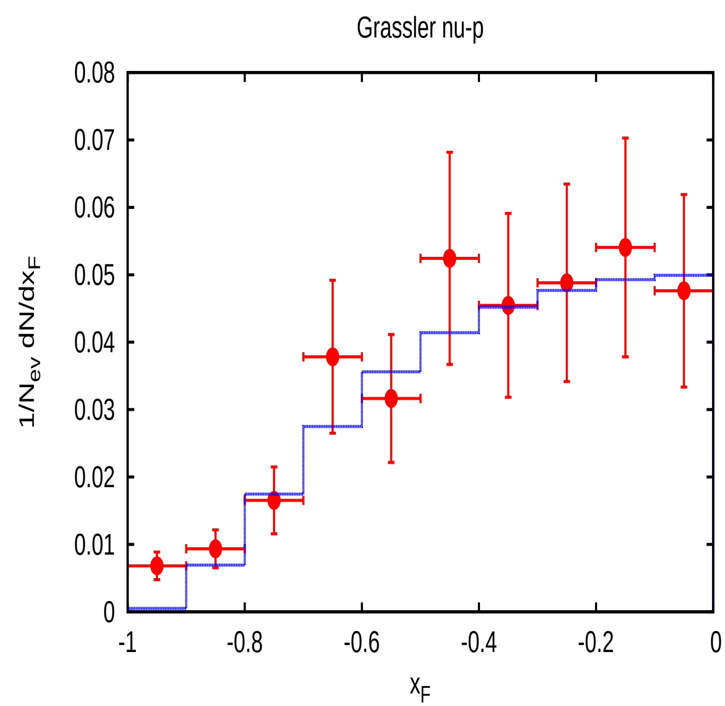
Allasia 1985



Predictions for other data sets (3)

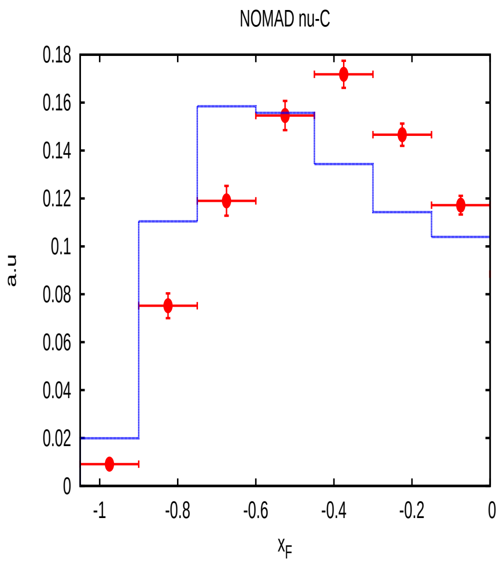
Grassler & al. 1981
(WA21 with lower statistics)

- $\nu P \to \mu^- \Lambda X$, $\langle E_\nu \rangle = 43$ GeV
- $d\sigma^{\nu - P} \propto 2(M_d + M_s) + 2(1-y)^2 M_{\bar{u}}$
- Not included in the fit because no Q^2-cut present on data
- Predictions for $Q^2 > 1$ GeV^2

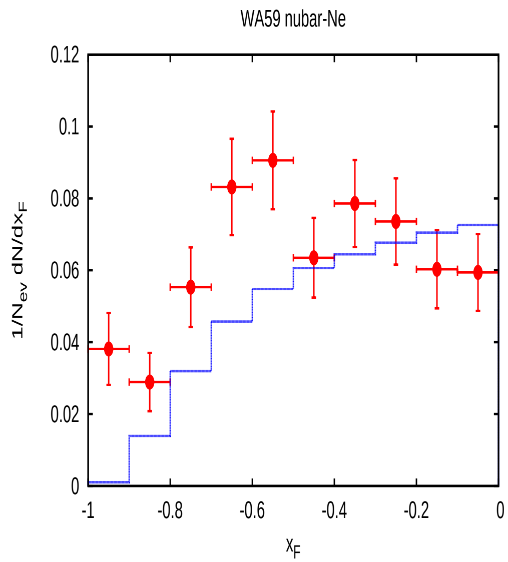


Predictions for other data sets (4)

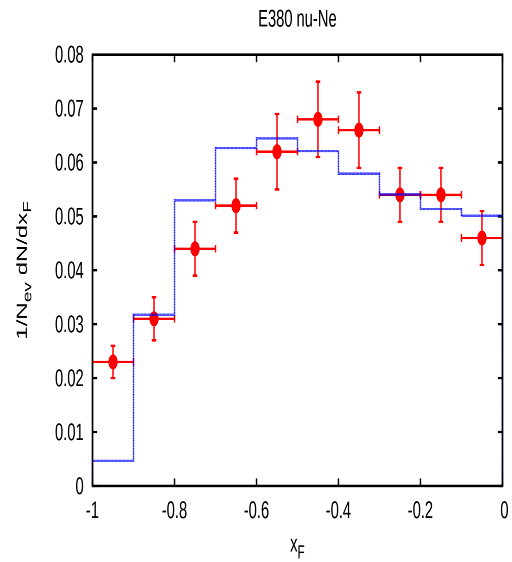
NOMAD νC



WA59 $\bar{\nu}$-Ne



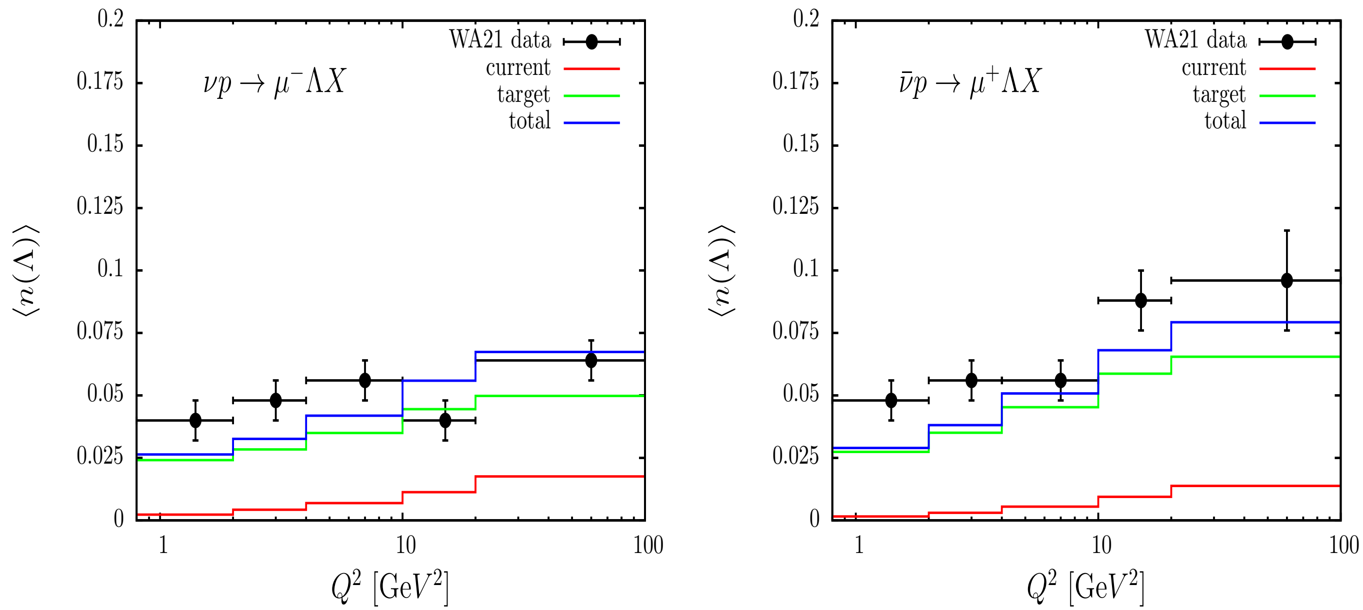
E380 ν-Ne



- Difficult to judge eventual distortion due to nuclear medium corrections
- $\bar{\nu}$ and ν scattering on heavy target sensitive to neutron component : bad description is anticipated.

Predictions for other observables (1)

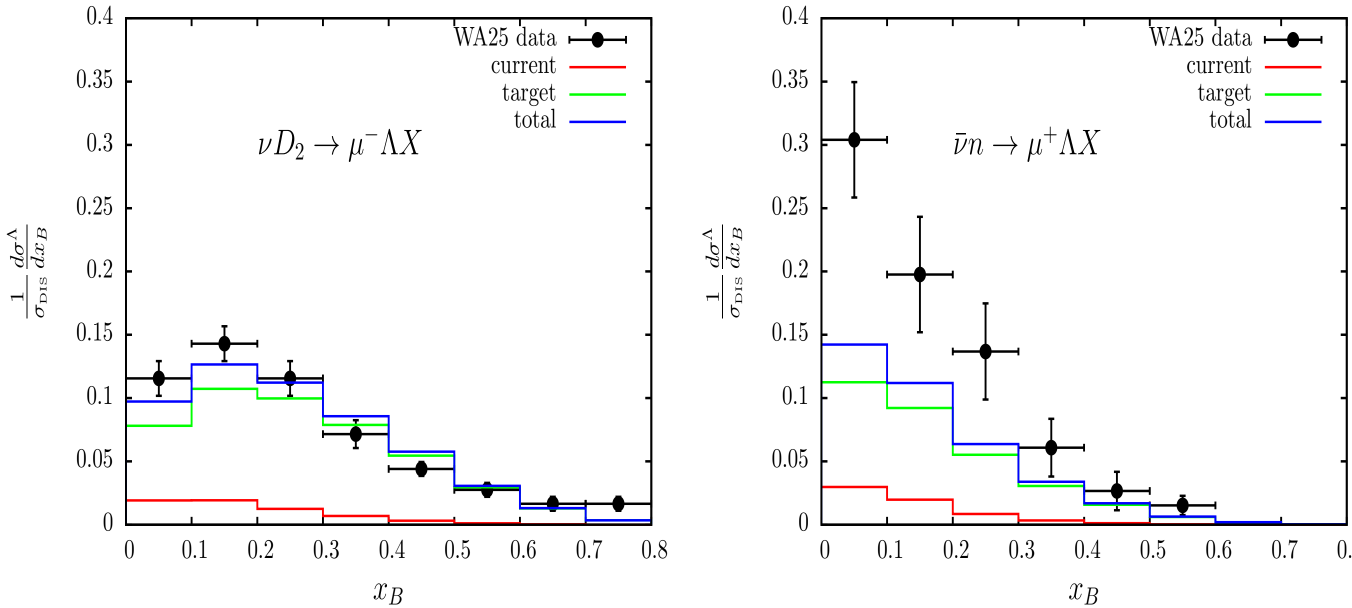
- WA21 data



- Multiplicity vs Q^2 reproduced in shape and almost in normalisation

Predictions for other observables (2)

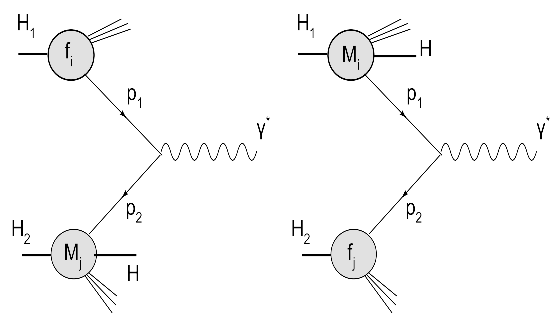
- WA25 data



- Multiplicity vs x_B reproduced in shape and normalisation for νD but differences are observed in $\bar{\nu} n$ at small x_B: $M_{\bar{s}} \gg M_s$?

Perspectives in hadronic collisions

- Parton model formula for the associated production of a particle and a Drell-Yan pair



$$\frac{d\sigma^{H,T,(0)}}{dQ^2 dz} \propto \sum_{i,j} \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} \left[M_i^{[1]}(x_1, z)\, f_j^{[2]}(x_2) + M_i^{[2]}(x_2, z)\, f_j^{[1]}(x_1) \right] \frac{d\hat{\sigma}^{ij\to\gamma^*}}{dQ^2}$$

- $\mathcal{O}(\alpha_s)$ for this process have been computed (FC, Trentadue '08, FC '11)

- The $M's$ in principle are not related to DIS ones without factorization theorem

Conclusions

- A model for the description of backward Λ production has been constructed in the fracture functions framework
- The non-perturbative spectator fragmention functions are obtained through a combined fit to a variety of DIS cross-section
- The model is able to predict other cross sections not included in the fit
- Notable the model can describe the Lambda multiplicity versus x_B and Q^2
- Discrepancies are however observed when the model is used to predict cross sections on neutron target
- Observing in data the predicted Q^2-dependence built-in the model can be decisive in its validation, so more precise data are needed