

# Leading neutron production in DIS: from HERA to EIC

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Based on F.A.Ceccopieri EPJ C74 (2014)

## Outline

### A case study at HERA:

- leading neutron production in DIS
- factorisation and  $Q^2$  dependence of the cross section
- determination of neutron fracture functions
- factorisation tests in dijet production in PHP and DIS associated with a leading neutron

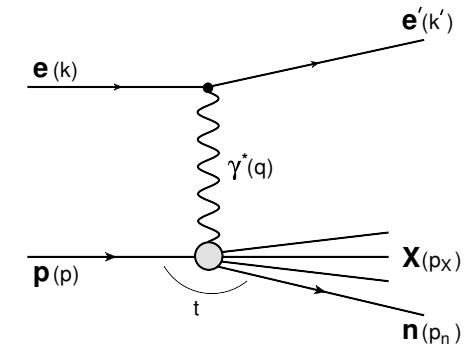
### Leading neutron production at the EIC:

- predictions
- opportunities

# Leading neutron production at HERA

Process:

- $e^+(k) + p(P) \rightarrow e^+(k') + n(P_n) + X(p_X)$
- $E_e = 27.6 \text{ GeV}, E_p = 920 \text{ GeV}, \sqrt{s} = 319 \text{ GeV}, \int \mathcal{L} dt = 122 \text{ pb}^{-1}$ .

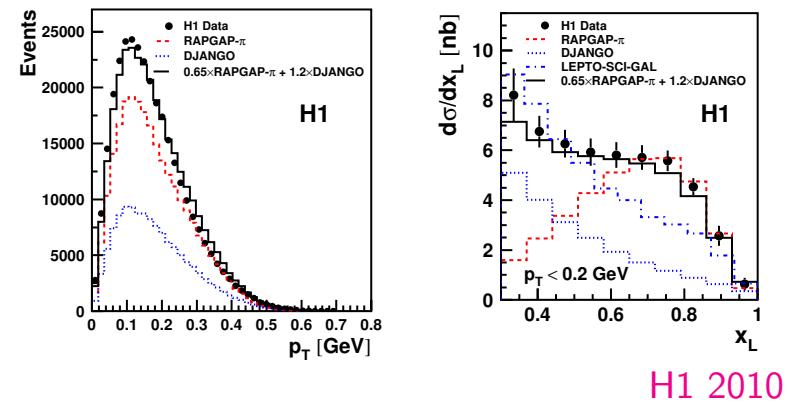


DIS selection:

- $6 < Q^2 < 100 \text{ GeV}^2, 0.02 < y < 0.6$
- $1.5 \cdot 10^{-4} < x_B < 3 \cdot 10^{-2}$ .

Neutron selection:

- $x_L = 1 - \frac{q \cdot (P - P_n)}{P \cdot q} \simeq E_n/E_p$
- $0.365 < x_L < 0.905$
- neutron  $p_T < 0.2 \text{ GeV}$
- $\beta = \frac{x_B}{1-x_L}$



H1 2010

Observable:

- $\sigma_r^{LN(3)}(\beta, Q^2, x_L) = F_2^{LN(3)}(\beta, Q^2, x_L) - \frac{y^2}{1+(1-y)^2} F_L^{LN(3)}(\beta, Q^2, x_L).$

## Theory setup

Hard-scattering factorisation:

$$F_k^{LN(4)}(\beta, Q^2, x_L, p_T) = \sum_i \int_\beta^1 \frac{d\xi}{\xi} M_{i/P}^N(\beta, \mu_F^2; x_L, p_T) C_{ki} \left( \frac{\beta}{\xi}, \frac{Q^2}{\mu_F^2}, \alpha_s(\mu_R^2) \right) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

Grazzini, Trentadue, Veneziano'98, Collins '98

- $C_{ki}$  ( $k = 2, L$ ) calculable as a power expansion  $\alpha_s$ , same as in iDIS
- New non-perturbative distribution: proton-to-neutron fracture functions  $M_{i/P}^N(\beta, \mu_F^2, x_L, p_T^2)$

In our case nFFs are integrated up to  $p_{T,max}$ :

$$M_{i/P}^N(\beta, Q^2, x_L) = \int^{p_{T,max}} dp_T M_{i/P}^N(\beta, Q^2, x_L, p_T)$$

and obey DGLAP evolution equations

$$Q^2 \frac{\partial M_{i/P}^N(\beta, Q^2, x_L)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u} P_i^j(u) M_{j/P}^N\left(\frac{\beta}{u}, Q^2, x_L\right)$$

F.C., Trentadue '07

## Fitting strategy

Important remark:

- hard-scattering factorisation holds at fixed values of  $x_L$  and  $p_T$
- dependence on  $x_L$  and  $p_T$  fully contained in nFFs
- these conditional parton distributions are uniquely fixed by the kinematics of the outgoing neutron and they are, at least in principle, different for different values of  $x_L$  and  $p_T$ .

In practice:

- perform a series of QCD fits at fixed values of  $x_L$  with a common initial condition controlled by a set of parameters  $\{p_i\}$ .
- infer the approximate dependence of parameters  $\{p_i\}$  on  $x_L$
- construct a generalised initial condition in the  $(\beta, x_L)$ -space to be used in a  $x_L$ -combined QCD fit.
- if four-differential cross sections were available same procedure at fixed  $x_L$  and  $p_T$ .

## $\chi^2$ definition

Definition:

$$\chi^2 = \sum_i \left( \frac{m_i - f_i(\mathbf{p}, \mathbf{s})}{\sigma_i} \right)^2 + \sum_k s_k^2 \quad \text{Pascaud and Zomer '95}$$

Systematics effects are incorporated in theory model predictions

$$f_i(\mathbf{p}, \mathbf{s}) = t_i(\mathbf{p}) + \sum_k s_k \Delta_{ik}$$

- $m_i$  is the measurement  $i$ ,
- $t_i$  is the model prediction depending on a set of parameters  $\mathbf{p}$
- $\sigma_i$  are the unc. and stat. errors added in quadrature
- $\Delta_{ik}$  is the correlated systematic error from source  $k$  on the data  $i$ .
- $s_k$  is a Gaussian random variables with zero mean and unit variance.
- minimisation performed with MINUIT, stat  $\oplus$  uncorr
- systematic errors treated with offset method,  $s_k$  minimized as free pars.

## Fixed $x_L$ fits

QCD settings

- Evolution and convolution with QCDNUM17 [Botje '11](#)
- ZM VFNS scheme to NLO
- $m_c = 1.4 \text{ GeV}$ ,  $m_b = 4.5 \text{ GeV}$ ,  $\alpha_s(M_Z^2) = 0.118$ ,  $Q_0^2 = 1 \text{ GeV}^2$
- $\mu_F^2 = \mu_R^2 = Q^2$

Momentum distributions at  $Q_0^2$ :

$$\beta M_{\Sigma/P}^N(\beta, Q_0^2) = A_q \beta^{Bq} (1 - \beta)^{Cq},$$

$$\beta M_{g/P}^N(\beta, Q_0^2) = A_g \beta^{Bg} (1 - \beta)^{Cg}$$

- **Caveat** : nFFs may show valence structure at large  $\beta$
  - However highest accessible  $\beta$  in data is 0.1 at the highest  $x_L = 0.95$
- Assume a quark-symmetric singlet distribution  $\Sigma$  at  $Q_0^2$

## Fixed $x_L$ fits : Result

- large- $\beta$  coefficient  $C_q$  is loosely constrained by data:  
set  $C_q = 0.5$
- gluon constrained only by scaling violations
- $B_g$  strongly correlates with  $A_g$ ,  
set  $C_g = 1$  and  $B_g = 0$
- initial condition contains 3 free parameters in each  $x_L$ -bin:

$$\beta M_{\Sigma/P}^N(\beta, Q_0^2) = A_q \beta^{Bq} (1 - \beta)^{0.5}$$

$$\beta M_{g/P}^N(\beta, Q_0^2) = A_g \beta^0 (1 - \beta)^1$$

- Mild dependence of  $\chi^2$  on  $Q_0^2$
- good quality fits obtained in each  $x_L$ -bin with the common initial condition
- → necessary condition for the  $x_L$ -combination procedure to work

$x_L$	$\chi^2$	Fitted points
0.365	12.0	29
0.455	25.5	29
0.545	19.9	29
0.635	21.0	29
0.725	23.6	29
0.815	17.1	29
0.905	15.7	29
Sum	134.8	203

## $x_L$ -combination (1)

- Generalised initial conditions.

→  $A_q$ ,  $B_q$  and  $A_g$  are  $x_L$ -dependent:

$$\beta M_{\Sigma/P}^N(\beta, Q_0^2, x_L) = A_q(x_L) \beta^{B_q(x_L)} (1 - \beta)^{0.5}$$

$$\beta M_{g/P}^N(\beta, Q_0^2, x_L) = A_g(x_L) (1 - \beta)^1$$

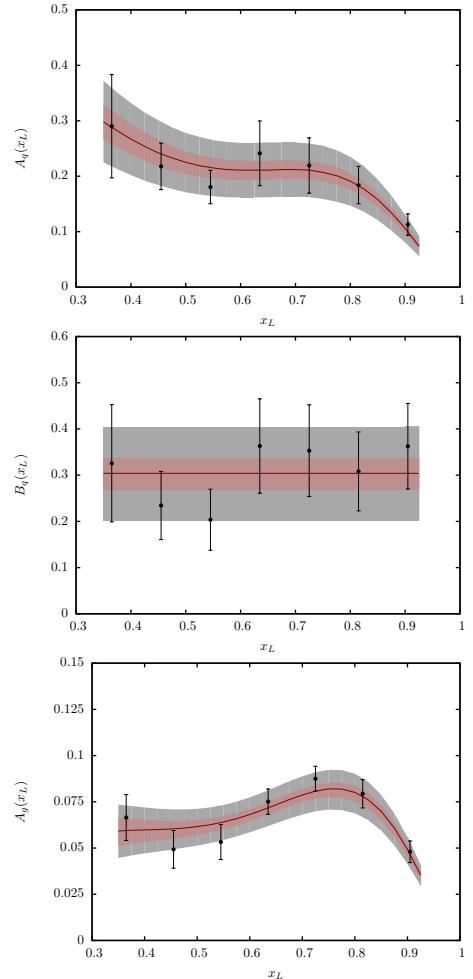
- inspecting the plots we assume the  $x_L$  dependence:

$$A_q(x_L) = a_1 x_L^{b_1} (1 + c_1 x_L^{d_1})(1 - x_L)^{e_1}$$

$$B_q(x_L) = a_2 + b_2 x_L + c_2 x_L^2$$

$$A_g(x_L) = a_3 x_L^{b_3} (1 + c_3 x_L^{d_3})(1 - x_L)^{e_3}$$

- Redundant parametrization.



## $x_L$ -combination (2)

- QCD settings as in fixed- $x_L$  fits
- For each fit study eigenvalues of Hessian matrix → parameter reduction
- At large  $x_L$ ,  $A_q$  and  $A_g$  can be described by a common  $g(x_L)$  :  

$$g(x_L) = (1 + c_1 x_L^{d_1})(1 - x_L)^{e_1}$$
- Therefore set  $b_1 = 0$  and  $b_2 = c_2 = 0$

Final choice (7 free parameters)

$$A_q(x_L) = a_1 x_L^0 g(x_L)$$

$$B_q(x_L) = a_2 + 0 \cdot x_L + 0 \cdot x_L^2$$

$$A_g(x_L) = a_3 x_L^{b_3} g(x_L)$$

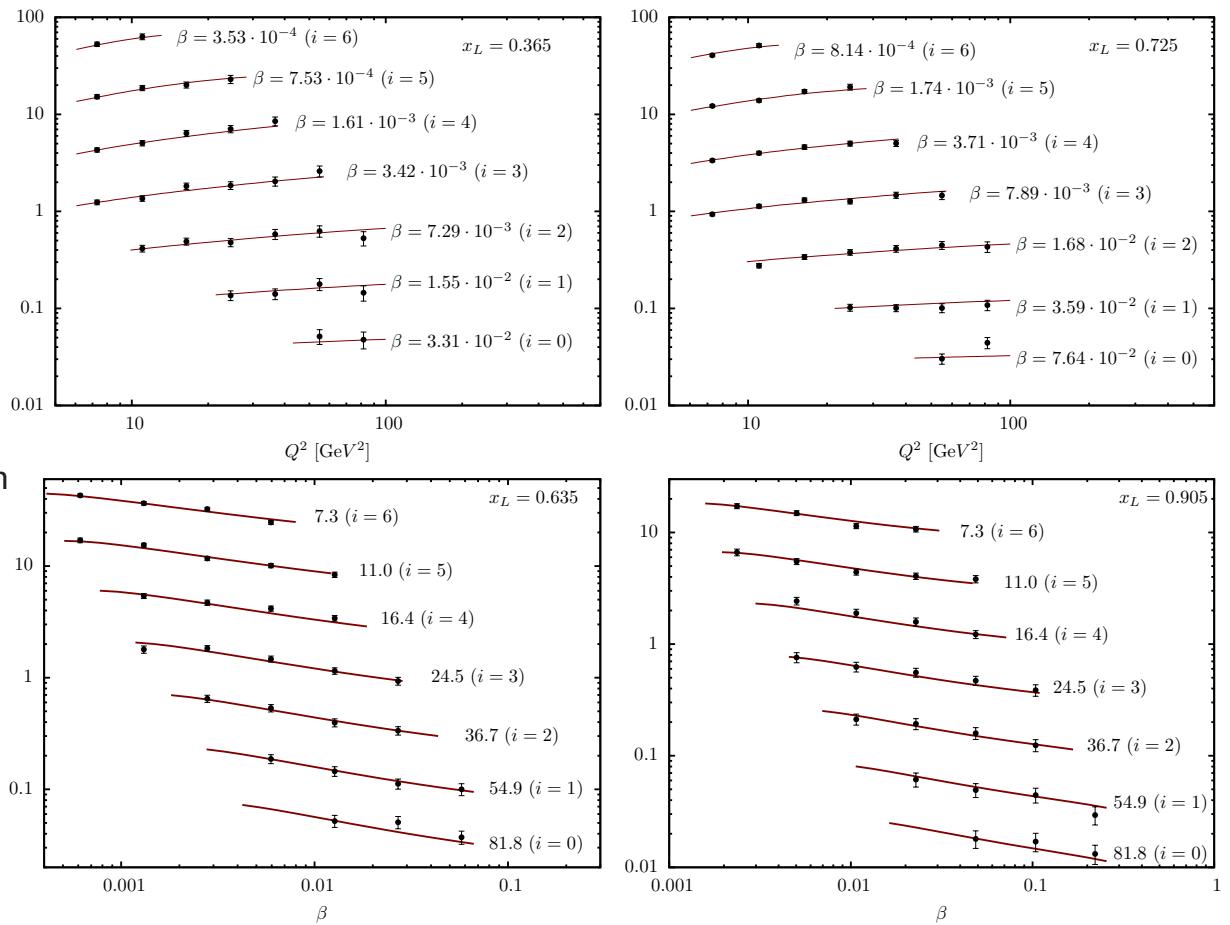
$x_L$	$\chi^2$	$\Delta\chi^2$
0.365	12.7	+0.7
0.455	27.5	+2.0
0.545	22.0	+2.1
0.635	22.3	+1.3
0.725	25.5	+1.9
0.815	17.3	+0.2
0.905	16.3	+0.6
Tot	143.6	+8.8

- Best fit :  $\chi^2 = 143.6$  for 196 degrees of freedom
- Exp error propagation with eigenvector method:  
 $\Delta\chi^2 = 1$  and  $\Delta\chi^2 = 9$
- Combination price w.r.t. to fixed  $x_L$  fits ( $\chi^2 = 134.8$ ): +8.8

## Best fit vs H1 data

First results:

- Overall good description of data
- positive scaling violations in the explored kinematics: gluon dominated evolution.
- $\sigma_r^{LN(3)}$  rises at small  $\beta$  like  $F_2$
- hard-scattering factorisation  $\oplus$  nFFs describe data down to the lowest  $Q^2 = 7.3 \text{ GeV}^2$ .



## On proton-vertex factorisation

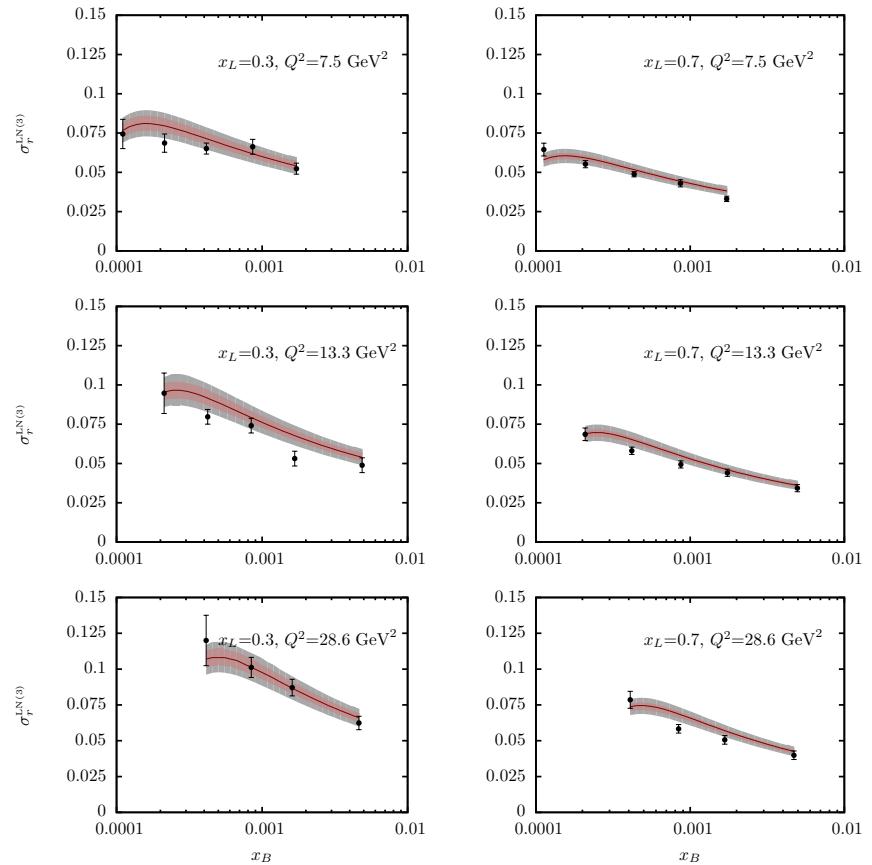
Additional proton-vertex factorisation hypothesis:

$$M_{i/P}^N(\beta, Q_2, x_L) = \widetilde{M}_{i/P}^N(\beta, Q^2) \cdot f(x_L)$$

- $A_q$  and  $A_g$  have a different behaviour at small  $x_L$
- parton content identical for different  $x_L$  ( $B_q$  is just a constant)
- all this implies a violation of the so-called proton vertex factorisation.
- If this hypothesis is enforced, that is if we set  $b_1 = b_3$  and let this parameter free to vary in the fit, we obtain a  $\chi^2 = 150$  vs 143.
- in the explored kinematical range and given the accuracy of the present data, proton vertex factorisation holds to a good approximation.

## Best fit vs ZEUS data

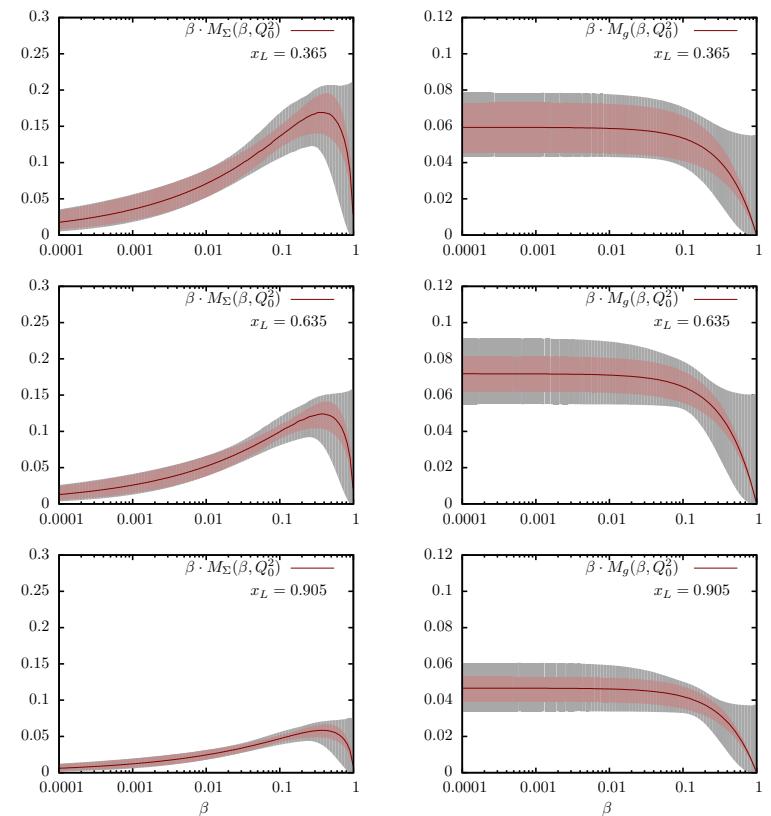
- Error bars on data points : stat  $\oplus$  uncor  $\oplus$  syst
- Light red band : propagation exp errors eigenvector method with  $\Delta\chi^2 = 9$
- Grey band : propagation of systematic errors with offset method added in quadrature to previous



ZEUS 2002

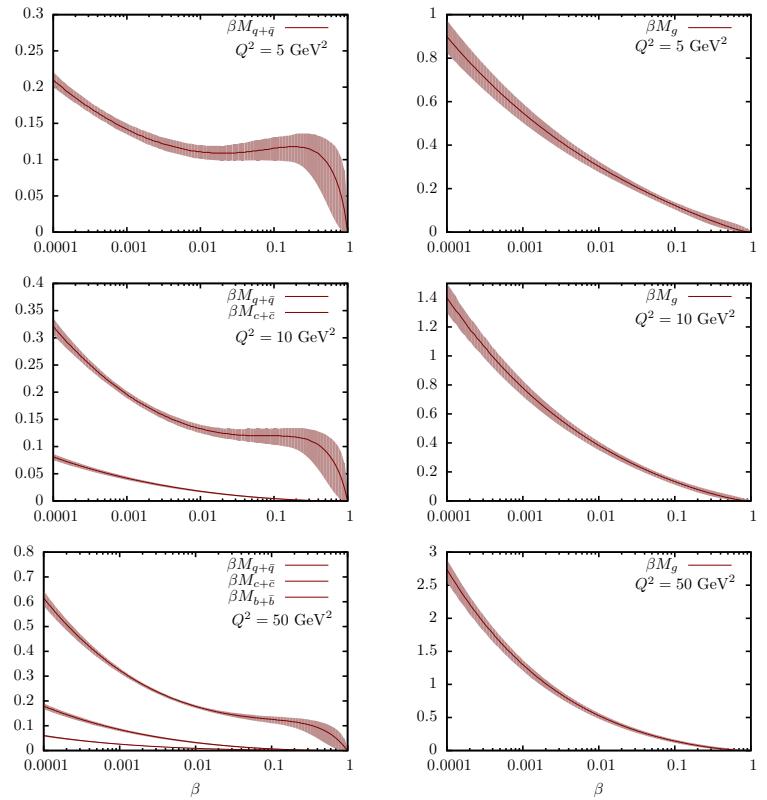
## nFFs at $Q_0^2$

- initial condition at  $Q_0^2 = 1 \text{ GeV}^2$
- Light red band :  $\Delta\chi^2 = 9$
- grey band : 4 additional large- $\beta$  eigenvectors



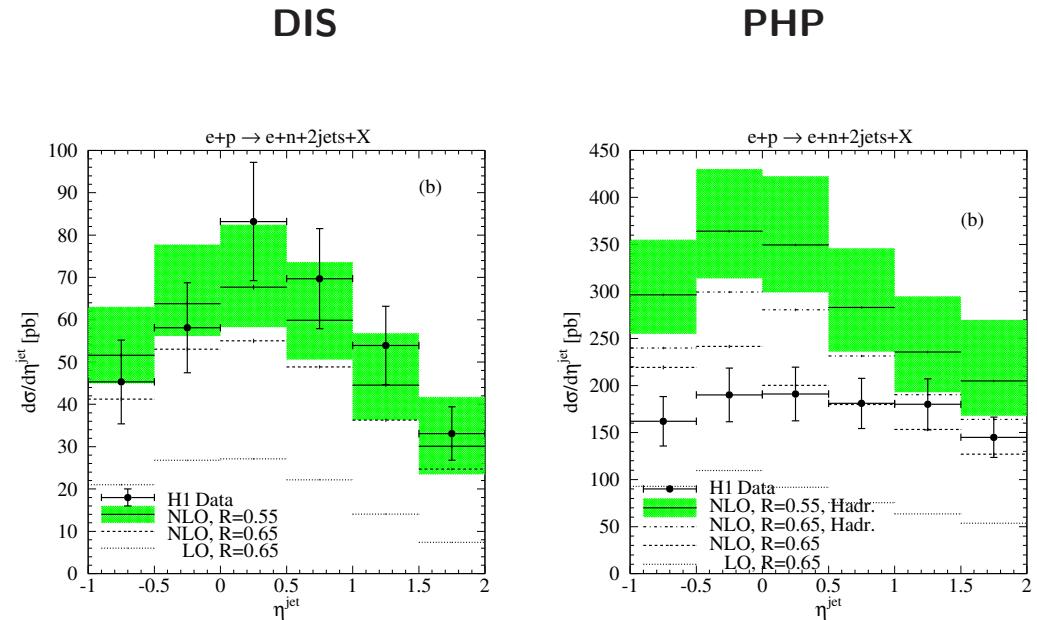
## Evolved nFFs

- Singlet and gluon momentum distributions at  $x_L = 0.635$
- Light red band :  $\Delta\chi^2 = 9 \oplus 4$  additional large- $\beta$  eigenvectors



## Factorisation tests

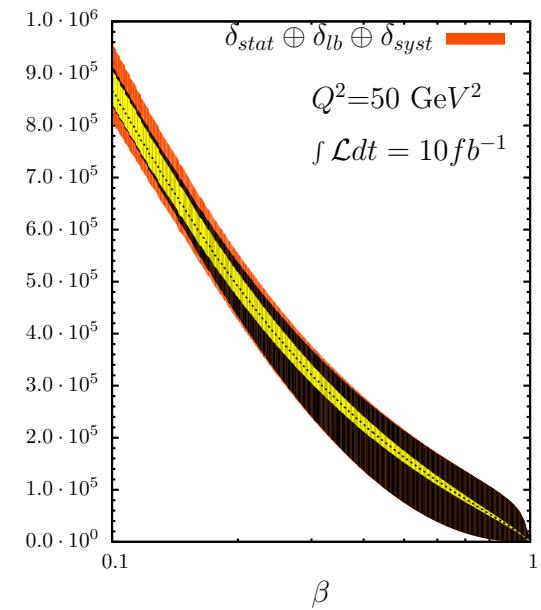
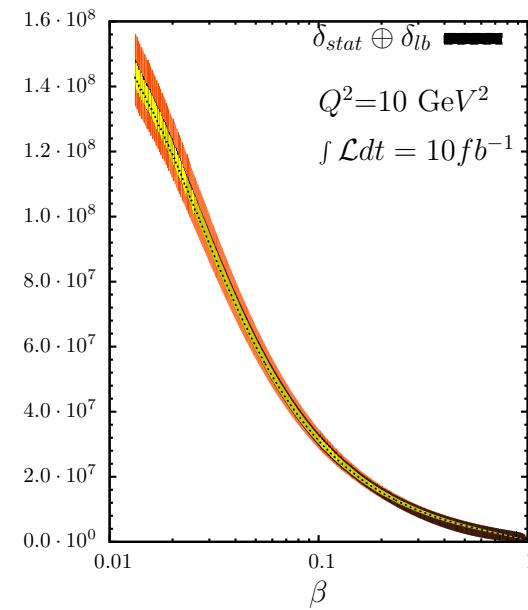
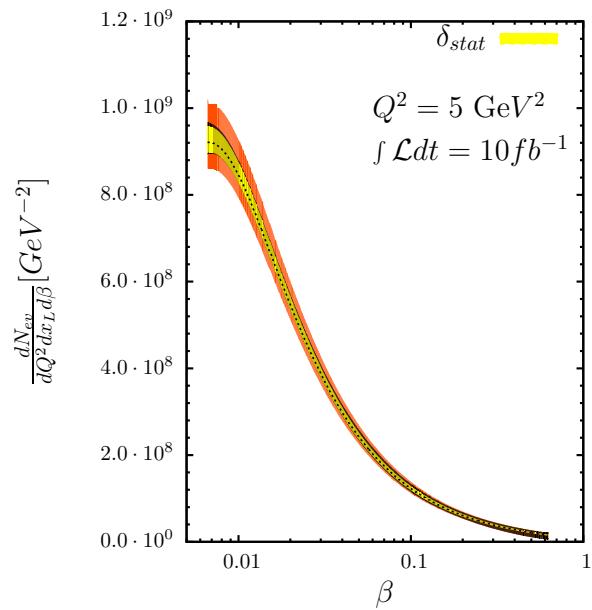
- factorisation test:  
dijet production in DIS and PHP  
associated with a leading neutron
- nFFs = pion PDF's  $\otimes$   $\pi$ -flux  
 $\pi$ -flux from hadron scattering data
- DIS :  
factorisation OK with NLO theory
- PHP :  
deficit in normalisation  $\simeq 0.5$
- Large hadronic corrections at low  $E_T$
- Large NLO corrections (minimum  $E_T \simeq 6$  GeV)



Klasen and Kramer '07

## EIC preliminar results: $N_{ev}$ vs $\beta$

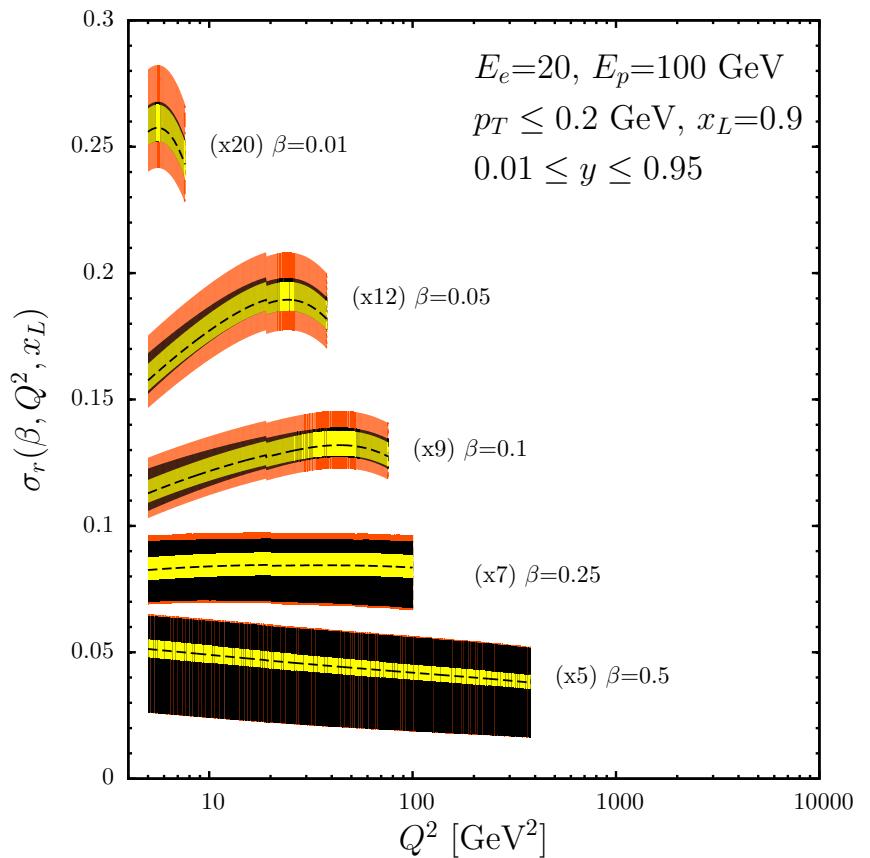
- $E_e=20 \text{ GeV}, E_p=100 \text{ GeV}, \int \mathcal{L} dt = 10 \text{ fb}^{-1}$ ,
- $0.01 < y < 0.95, p_T < 0.2 \text{ GeV}, x_L=0.9$



- at small  $\beta$  and  $Q^2$  nFFs affected by systematic errors (orange band)
- at large  $\beta$  and  $Q^2$  nFFs not constrained by H1 data (black band)

## EIC preliminar results: $\sigma_r$ vs $Q^2$

- Reduced cross section  $\sigma_r$  as a function of  $Q^2$  at fixed  $\beta$  and  $x_L$
- Popular "Scaling violation" plot
- $E_e=20$  GeV,  $E_p=100$  GeV
- $0.01 < y < 0.95$ ,  $p_T < 0.2$  GeV,  $x_L=0.9$
- negative scaling at large  $\beta$  : valence structure of t-channel exchange
- positive scaling at small  $\beta$ : gluon dominated evolution



## Summary

- We have presented a set of proton-to-neutron fracture functions obtained from a fit of 2010 H1 data based on an integrated luminosity of  $122\text{pb}^{-1}$
- The adopted fitting strategy and nFFs initial condition are inspired by the factorisation theorem for this class of semi-inclusive processes
- Extracted nFFs from H1 data give a good description of ZEUS leading neutron data in DIS
- This new set will allow tests of factorisation in dijet production PHP and DIS associated with a leading neutron
- The large integrated luminosity expected from EIC operation will improve the knowledge of nFFs, especially at large  $\beta$  where now, due to lack of data, nFFs are unconstrained
- At the same time, proton-to-neutron fracture functions extracted in  $ep$  DIS at the EIC, will help to understand leading neutron production data in  $eA$  DIS.