Target fragmentation and fracture functions

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Outline

Motivations for target fragmentation studies:

- complete the description of particle production in SIDIS
  - baryon : abundantly produced in the target, $h = p, n, \Lambda, \ldots$
  - mesons : study the fragmentation of initial state radiation

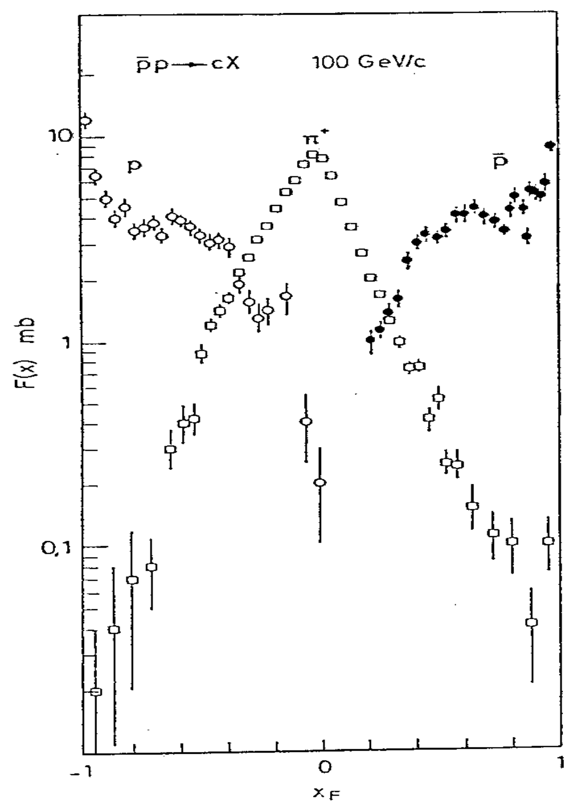
Brief review on the following topics:

- Lambda and neutron production in DIS target fragmentation region
- Hard diffraction in DIS and ep dijet PhotoProduction (PHP) at HERA
- factorisation tests in pp collisions: the Semi-Inclusive Drell-Yan process
- hard diffraction : single-diffractive Drell-Yan and factorisation breaking

The leading particle effect in hadronic collisions

- Consider the following reaction : $\bar{p}p \to h + X$
- $x_F = 2p^h_{||}/\sqrt{s}$ 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

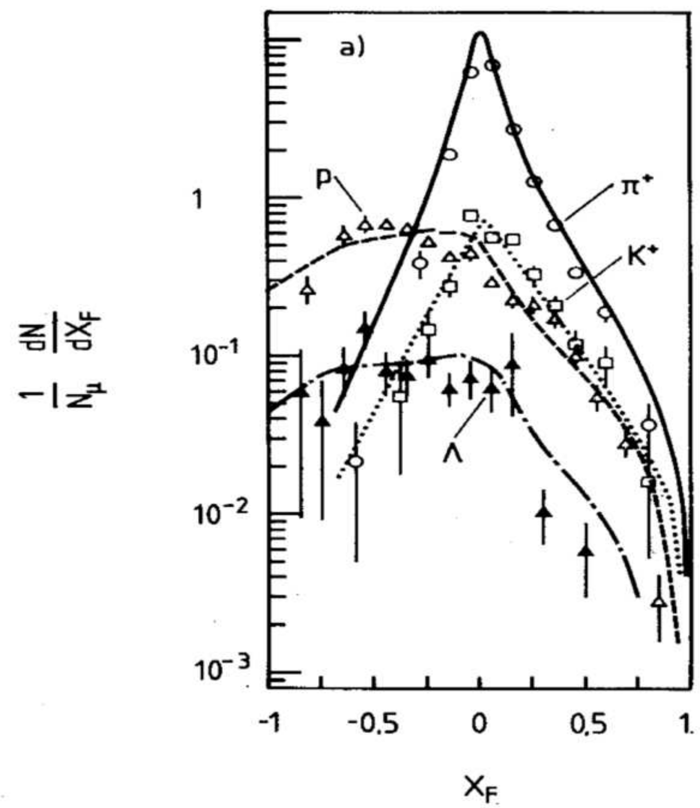
Basile & al. 1981



The leading particle effect in DIS

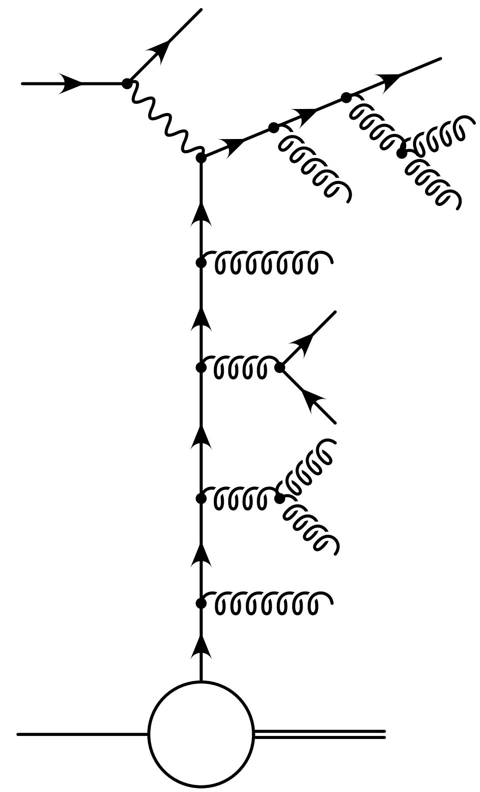
EMC Coll. 1981

- DIS : $\mu P \to \mu + h + X$, $\sqrt{s}$ =280 GeV
- 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, $Q^2 \gg \Lambda^2_{QCD}$
  $\to$ in principle pQCD techniques applicable.



Fragmentation in SIDIS

- Consider a Deep Inelastic Scattering event in which a virtual photon of mass Q^2 interacts with a parton fluctuation in the nucleon
- define $t = (P - p_h)^2$ the invariant momentum transfer between the proton and a produced hadron h
- $t \sim Q^2$ current fragmentation
- $t \sim 0$ target fragmentation
- $0 < t < Q^2$ central fragmentation region

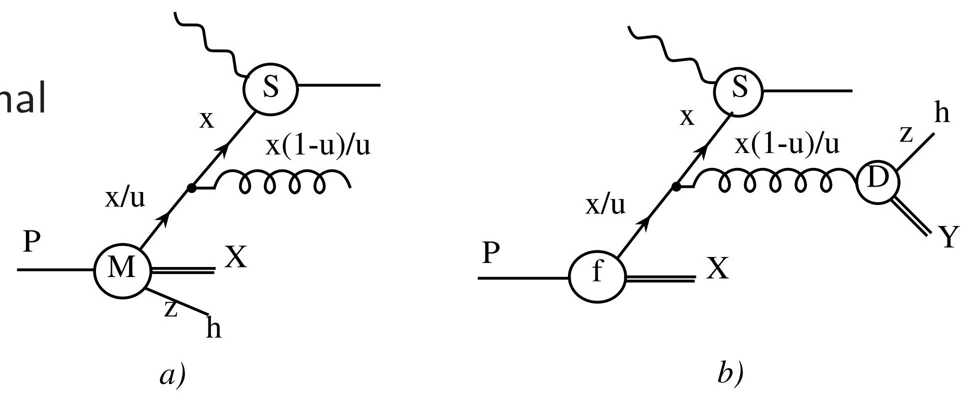


Fracture functions in SIDIS

- t-integrated Fracture functions M complete the description of SIDIS final state: Trentadue, Veneziano, '94

- 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.

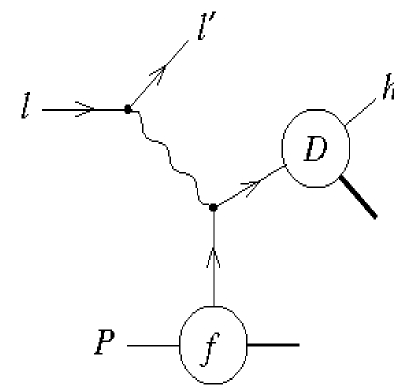


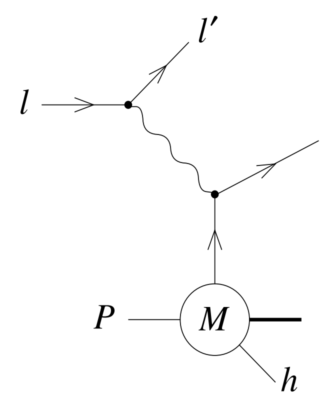
- They obey a DGLAP-type inhomogeneous evolution equations:

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

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)





Extended fracture functions

- Extended FFs : $M^h_{i/p}(\beta, Q^2, z, t)$

- they obey DGLAP evolution equations

$$Q^2 \frac{\partial M^h_{i/P}(\beta, Q^2, z, t)}{\partial Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u} P_i^j(u) \, M^h_{j/p}\Big(\frac{\beta}{u}, Q^2, z, t\Big)$$

Camici, Grazzini, Trentadue '98

- Very forward particle production in DIS at HERA: measurements of proton and neutrons at low t

- When extended FFs are integrated up to $t_{max} \ll Q^2$:

$$M^h_{i/p}(\beta, Q^2, z, t_{max}) = \int^{t_{max}} dt \, M^h_{i/p}(\beta, Q^2, z, t)$$

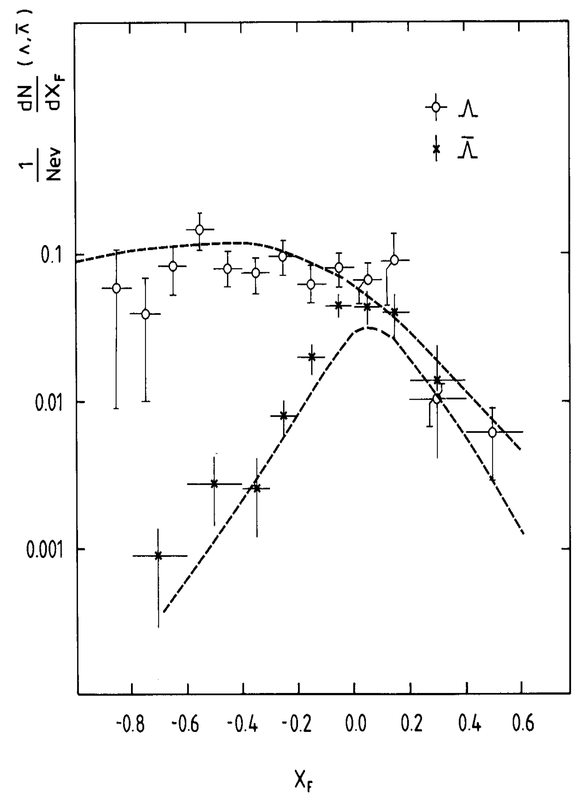
they, again, obey ordinary DGLAP evolution equations

Ceccopieri and Trentadue '07

Λ 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 backward Lambdas with $x_F \ll 0$



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:

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

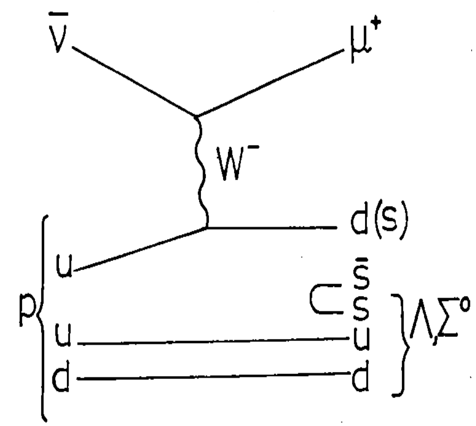
- The Lambda leptoproduction cross section in term of these variables reads

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

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

Initial conditions for Λ fracture functions

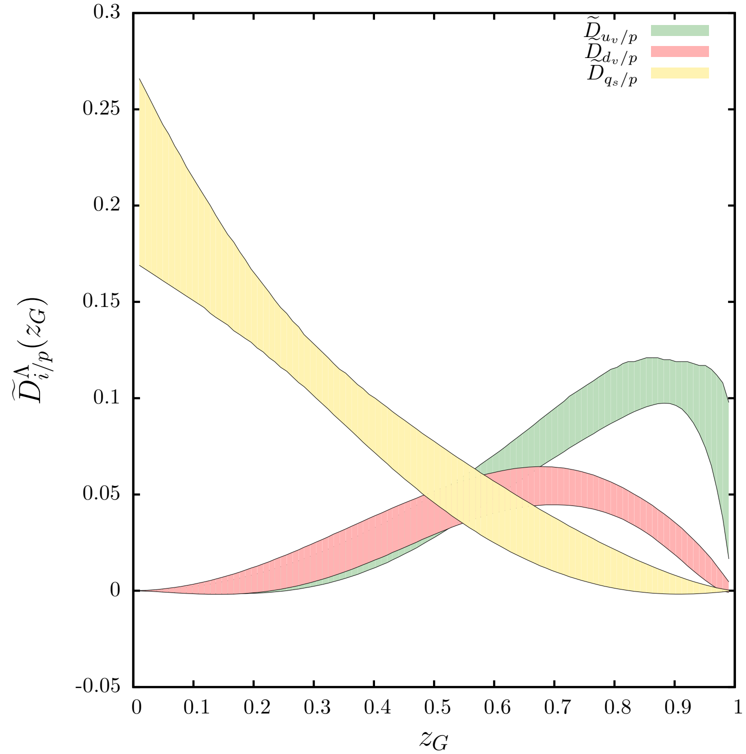
- The electroweak current probes the "struck quark" on very short "time scale", $\sim 1/Q_0$
- A parton with flavour i and momentum x is then removed from the proton with probability $f_{i/P}(x_B, Q_0^2)$
- The leftover coloured system reassembles to give colourless Λ with fractional momentum z on much longer "time scale", $\sim 1/\Lambda_{QCD}$, with probability $\widetilde{D}_i^{\Lambda}(z)$



- HP: factorization at $Q_0^2 \sim 1$ GeV^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 evolved to arbitrary scales via FF evolution equations.

Fit results and error propagation

- Study of the eigenvalues of the Hessian matrix parameter reduction : 7 free pars
- $\widetilde{D}_i^{\Lambda} = N_i z^{\alpha_i}(1-z)^{\beta_i}$
- 3 normalization N_i are OK
- 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 $\Delta\chi^2 = 1$



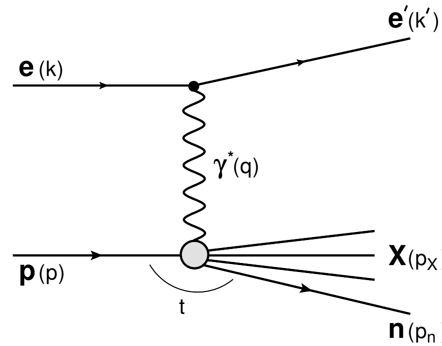
Ceccopieri Mancusi 2012

- Predictions for CLAS@12 GeV available, Ceccopieri 2015

Leading neutron production at HERA

Process:

- $e^+(k) + p(P) \to e^+(k') + n(P_n) + X(p_X)$
- $E_e = 27.6$ GeV, $E_p = 920$ GeV, $\sqrt{s} = 319$ GeV.

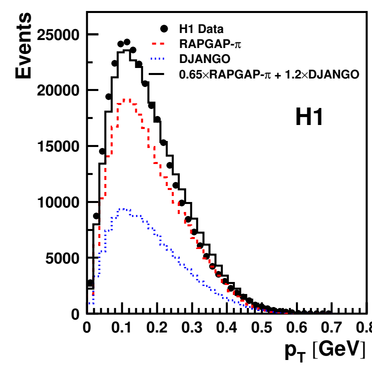


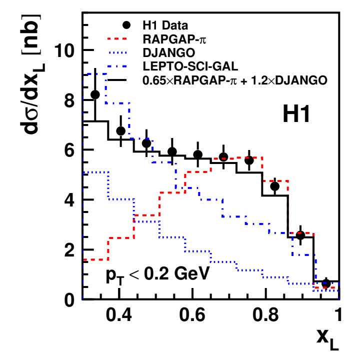
DIS selection:

- $6 < Q^2 < 100$ 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 $p_T < 0.2$ GeV
- $\beta = \frac{x_B}{1 - x_L}$

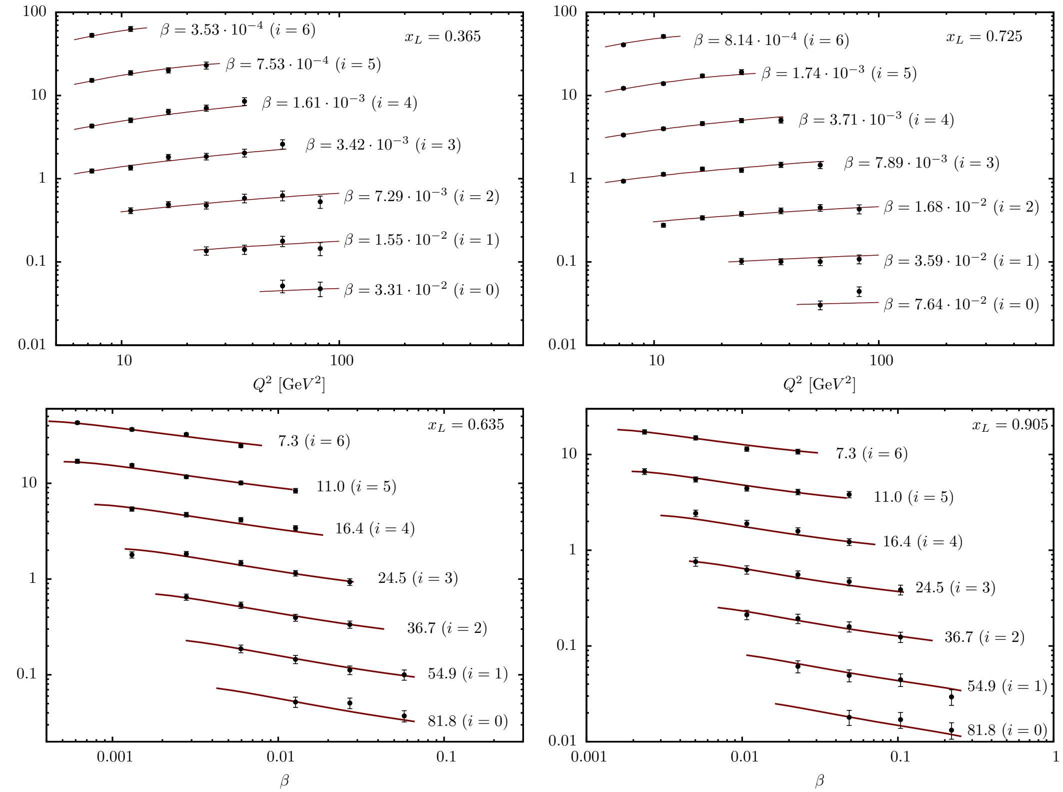




H1 2010

Best fit vs H1 data

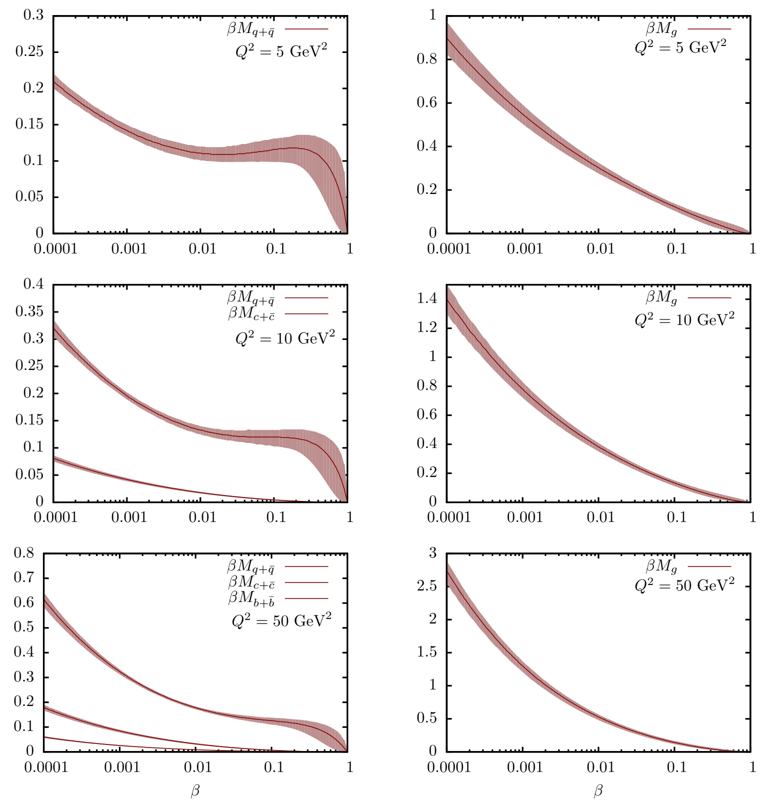
- Fit proton-to-neutron FFs
- always positive scaling violations
- hard-scattering factorisation $\oplus$ nFFs describe data down to the lowest Q^2.
- $\sigma_r^{LN(3)}$ rises at small β like F_2



Ceccopieri 2014

A glance to proton-to-neutron FFs

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

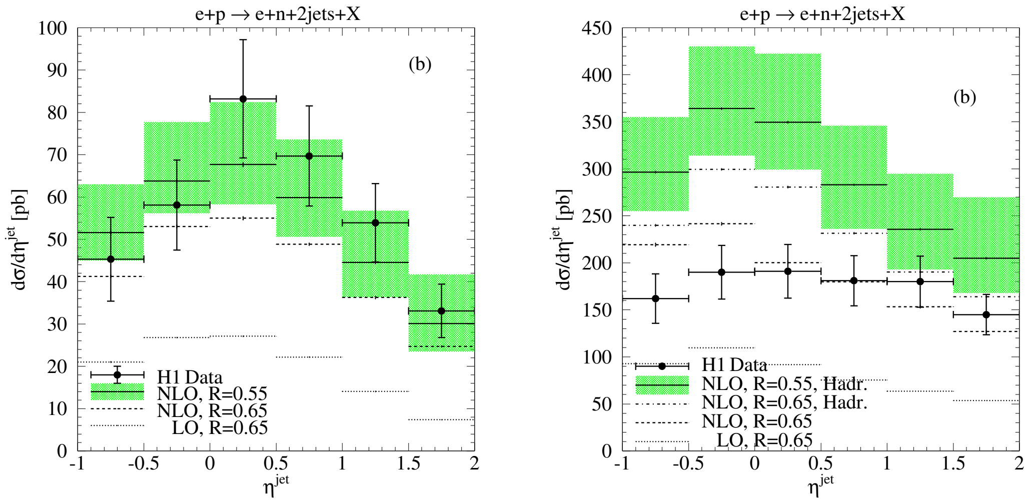


Ceccopieri 2014

Factorisation tests: $ep \to e + dijet + n + X$

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

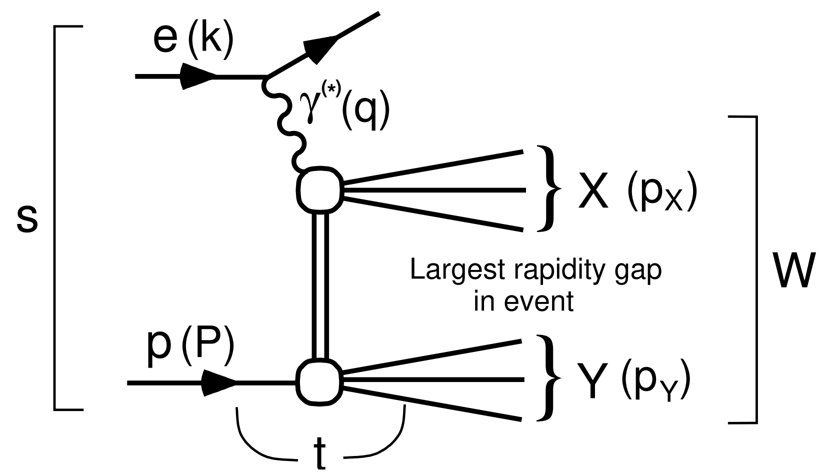
DIS **PHP**



Klasen and Kramer '07

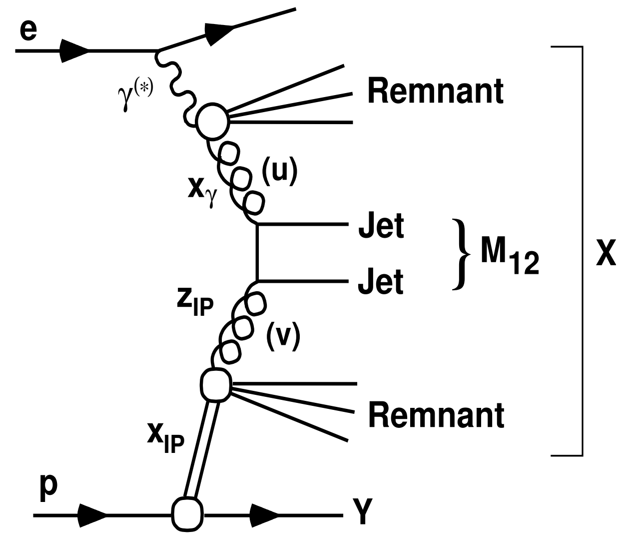
Hard diffraction in DIS at HERA

- Experiment
  - (hard) diffraction rebirth at HERA
  - $e(k) + p(P) \to e(k') + p(P') + X$
- kinematics
  - Target fragmentation region
  - $|t| \leq 1$ GeV^2
  - $x_{I\!P} \simeq 1 - E_{P'}/E_P < 0.1$
- diffractive selection:
  - large rapidity gap
  - M_X-method
  - proton tagging
- Key features
  - Leading twist: $\mathcal{O}(Q^{-4})$ (as iDIS)
  - scaling violations $\to$ parton dynamics



Factorisation in hard diffraction: overview

- Diffractive PDFs have extracted been from DDIS
  and used to test hard-scattering factorisation in
  - dijet in DIS
  - dijet in PHP ($Q^2 \simeq 0$, $E_T \sim 5, 6$ GeV)
  - dijet or $W^{\pm}$ in $p\bar{p}$ collisions



- Results:
  - dijet in DIS: data/NLO $\simeq 1$
  - dijet in PHP: debated
    H1 reports violation: data/NLO $\simeq 0.5$
    ZEUS consistent with no violation: data/NLO $\simeq 1$
  - pp : Striking breakdown observed at Tevatron: data/NLO $\simeq 0.1$

- NB: Factorisation predicted to fail in Resolved PHP and hadronic collisions

Factorisation tests at HERA

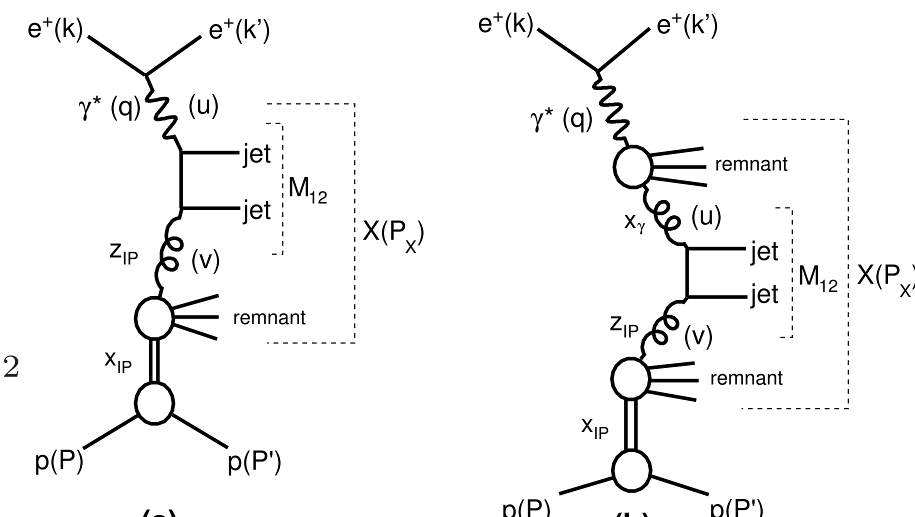
- Focus on the latest H1 results : DESY-14-242

   1. Event phase space:
      PHP : $Q^2 < 2$ GeV^2
      DIS : 4 GeV$^2 < Q^2 < 80$ GeV^2
   2. diffractive phase space:
      $0.010 < x_{I\!P} < 0.024$
   3. jet phase space:
      $E_T^{*\mathrm{jet}1(2)} > 5.5(4.0)$ GeV

- Theory

   1. NLO accuracy
   2. scale set to $\mu_R^2 = \mu_F^2 = \langle E_T^{*\mathrm{jet}} \rangle^2 + Q^2$
   3. Theo uncertainty: $\mu \rightarrow 0.5\mu, 2.0\mu$
   4. DPDFs from previous H1 '06 analysis

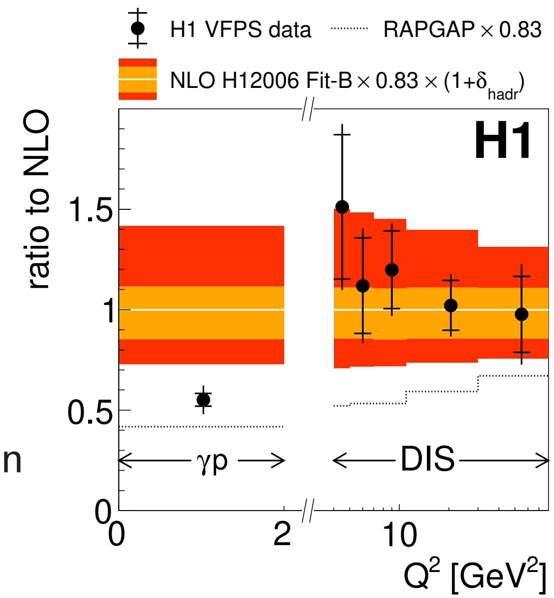
DIS PHP

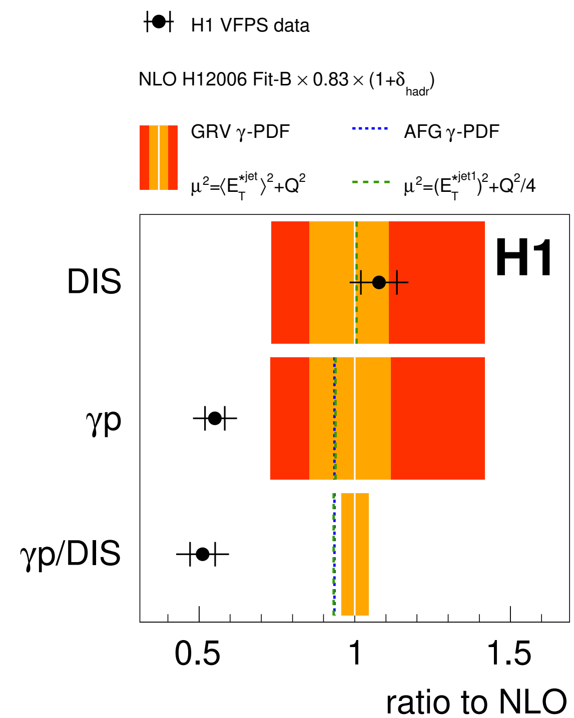


(a) (b)

Results: ratios

- Ratio: get rid of large NLO corrections
- H1 confirms an overall suppression factor ~ 0.5
- Critical variable: Q^2 not E_T
- factorisation broken for on-shell hadrons or nearly on-shell photon
- factorisation OK for pointlike probes, *i.e. virtual photon*





Drell-Yan : motivations

- Drell-Yan process : $p\, p \to \gamma^* + X$ Drell, Yan 1970
- Factorization of the process at "soft" level

Lindsay, Ross, Sachrajda, 1983, Collins, Soper, Sterman 1984, Bodwin, 1985

1. Perturbative trigger: the invariant mass Q^2 of the lepton pair can be accurately reconstructed;
2. The process is free of final state QCD corrections;
3. Higher order corrections known for $d\sigma/dQ^2$, $d\sigma/dy\, dQ^2$ and $d\sigma/dq_\perp^2 dQ^2$

$\oplus$ soft gluon resummations.

$\Downarrow$

Prototype process for factorisation studies in hadronic collisions.

Factorisation in Semi-Inclusive DY

- Consider the Semi-inclusive Drell-Yan process:

$$p\,p \to \gamma^* + h + X$$

  in which an additional hadron h is detected in the final state.

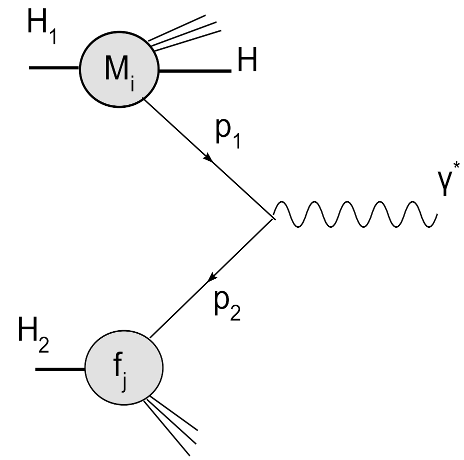
- The factorization property of the corresponding cross-section should depend on the region of phase space in which h is detected:

  DeTar, Ellis, Landshoff, 1975

  1. at high $p_{h\perp}^2$ (central fragmentation region) factorization should apply;
  2. at low $p_{h\perp}^2$ (target fragmentation region) arguments against factorization have been given

  Collins, Frankfurt, Strikman, 1993
  Berera, Soper, 1994, Collins 1998

A parton model formula



- Factorisation of collinear singularities in semi-inclusive DY works with the same subtraction used in SIDIS for M

  Trentadue Ceccopieri '08, Ceccopieri '11

- The "conjectured" parton model formula is thus:

$$\frac{d\sigma^H(\tau)}{dQ^2 dz} = \sigma_0 \int_\tau^{1-z} \frac{dx_1}{x_1} \int_{\frac{\tau}{x_1}}^1 \frac{dx_2}{x_2} \sum_q e_q^2 \Big[M_q^{[1]}(x_1,z) f_{\bar{q}}^{[2]}(x_2) + M_{\bar{q}}^{[1]}(x_1,z) f_q^{[2]}(x_2) \Big] \, \delta\Big(1 - \frac{\tau}{x_1 x_2}\Big) + \dots$$

  - the formula works at the collinear at $\mathcal{O}(\alpha_S)$ but not at the soft level

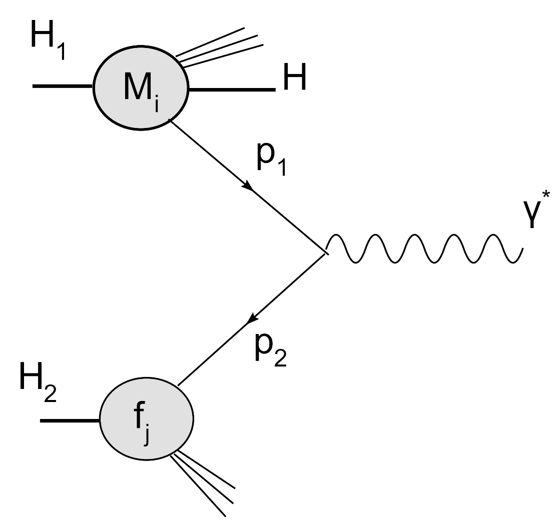
  - Without factorization theorem for such a process in hadronic collisions, the $M's$ are not related to DIS ones. Still they can be used for a quantitative estimation of factorization breaking effects.

AFTER: A Fixed Target ExpeRiment @ LHC

- extraction LHC beam with the use of a bent crystal
- deflect part of the beam halo without affecting LHC collider experiments
  - 7 TeV proton beam on fixed targets : $\sqrt{s_{NN}}$=115 GeV for pp, pd and pA.
  - 2.76 TeV lead beam on fixed tasrgets : $\sqrt{s_{NN}}$=72 GeV for $P_b\,p$, $P_b\,d$ and $P_b\,A$
- Acceptance $0 \leq \eta_{lab} \leq 5$ combined with high luminosity allows to measure down to the very end of the backward space space region:
  - center-of-mass rapidity boost $\Delta y = 4.8$, measurements to be carried out in the region $-4.8 \leq y_{cms} \leq 1$.
- "Physics opportunities of a fixed-target experiment using LHC beams" S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys.Rept. 522 (2013) 239

Single Hard diffraction @AFTER

- we consider the single hard diffractive production of a DY pair :
  $p(P_1) + p(P_2) \to p(P) + \gamma^*(q) + X$
- The diffractively produced proton p has almost the incoming projctile proton energy and very small p_t w.r.t. the collision axis:
  - The detection of such fast proton will require the installation of forward proton taggers.
  - The lepton pair instead will be measured by the main AFTER@LHC detector.



Single Diffractive DY production

- dPDFs f_i^D are proton-to-proton fracture functions M_i
- Dependences:
  - final state proton energy loss, $x_{IP} = 1 - z$, $z = \frac{2h\cdot(P_1+P_2)}{s} \equiv \frac{2E_H^*}{\sqrt{s}}$
  - fractional momentum of the interacting parton with respect to the pomeron momentum, $\beta = x/x_{IP}$ and the virtuality Q^2.
  - invariant momentum transfer $t = (P - P_1)^2$ at the proton vertex.
  - HERA dPDFs are defined by $|t| < 1$ GeV^2
- $M_i(x_1, z, Q^2) = x_{IP}^{-1} f_i^D(\beta, x_{IP}, Q^2)$

Single Diffractive DY production

- Let us assume factorization, *i.e.* rapidity gap survival (RGS) $S = 1$.
  Then, the SD DY differential cross section reads in leading order:

$$\frac{d\sigma^D}{dQ^2 dx_{IP} dy^{CM}} = \frac{\sigma_0}{N_c s} \sum_{q,\bar{q}} e_q^2 x_{IP}^{-1} f_q^D(\beta, x_{IP}, \mu_F^2)\, f_{\bar{q}}(x_2, \mu_F^2)$$

  – the fractional momenta of parton in the pomeron and proton is given by

  $\beta = \frac{\sqrt{\tau}}{x_{IP}} e^{y^{CM}}, \quad x_2 = \sqrt{\tau}\, e^{-y^{CM}}$

  – the rapidity range of the pair is given by

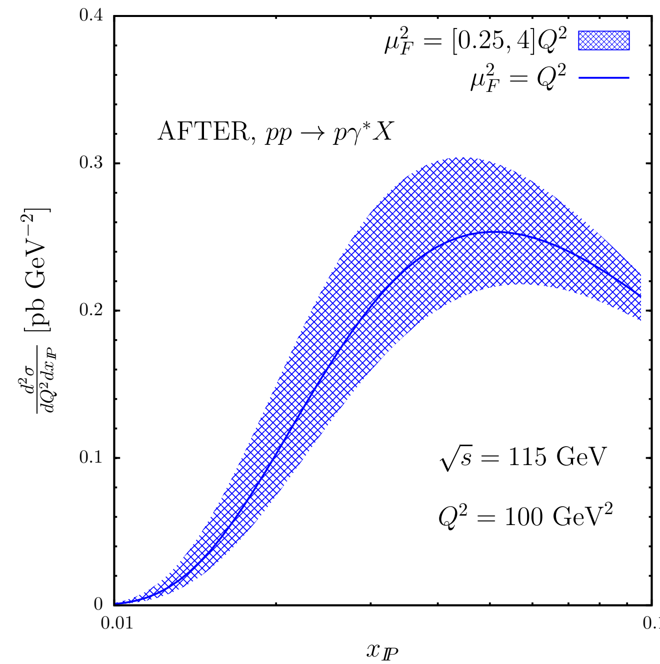
  $\ln\sqrt{\tau} < y^{CM} < \ln\frac{\sqrt{\tau}}{x_{IP}}$ with $\tau = Q^2/s$

  – as expected, it turns out to be asymmetric due the kinematic constraint $x_1 < x_{IP}$.

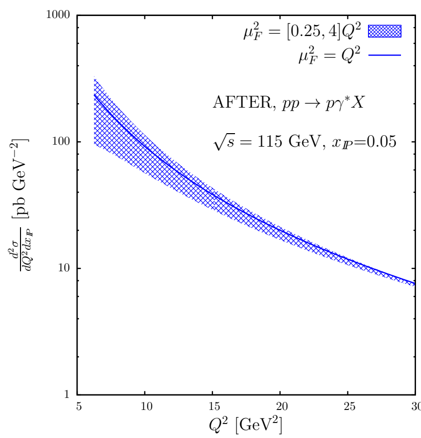
Single Diffractive DY production

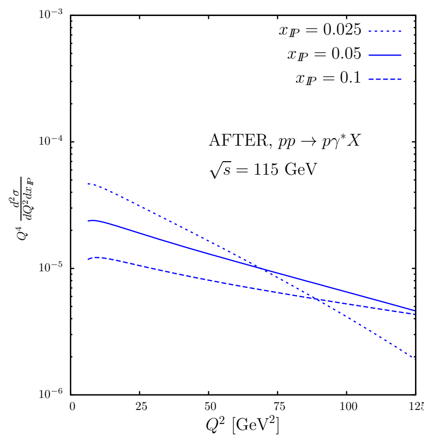
- The distribution shrinks as lower $x_{IP} \to 0$
- From hard diffraction at HERA, diffractive cross section rises as x_{IP}^{-1} as $x_{IP} \to 0$
- Such effect therefore is then attributed to phase space threshold effects.
- DY invarinat mass is given by: $Q^2 = \beta x_{IP} x_2 s$

  for $\beta \to 1$ and $x_2 \to 1$ gives an upper bound on $Q^2 < x_{IP} s$, at fixed x_{IP} and s.
- The lowest values of x_{IP} are then accessed only by lowering the invariant mass of the pair.



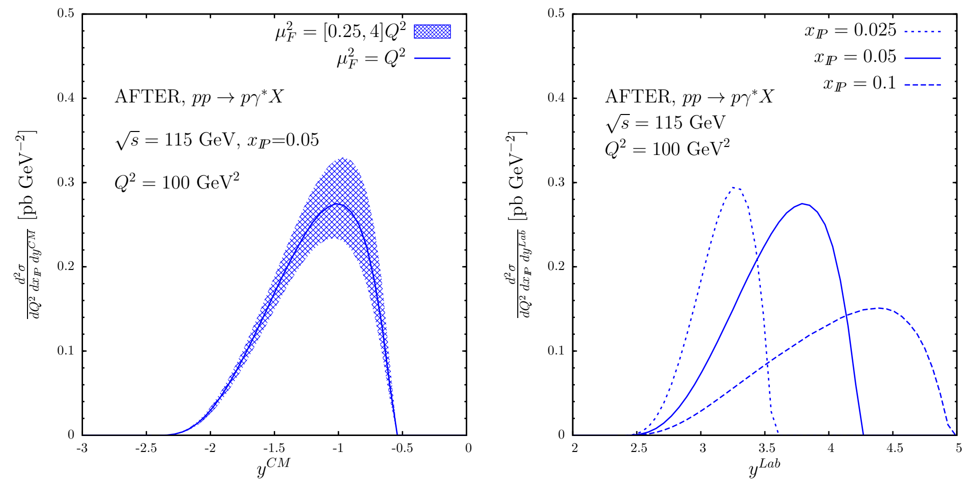
Single Diffractive DY production





- Q^2 distribution allows to investigate the possible dependence of the RGS factor on Q^2 and spot the underlying dynamics.
- the Q^2 dependence (when distribution is multiplied by Q^4) is accounted for by that of fracture and parton distributions evolution (important check)
- These curves and the corresponding slopes can be interpreted as genuine results of QCD evolution modulo threshold effect appearing at such moderate values of $\sqrt{s}$.

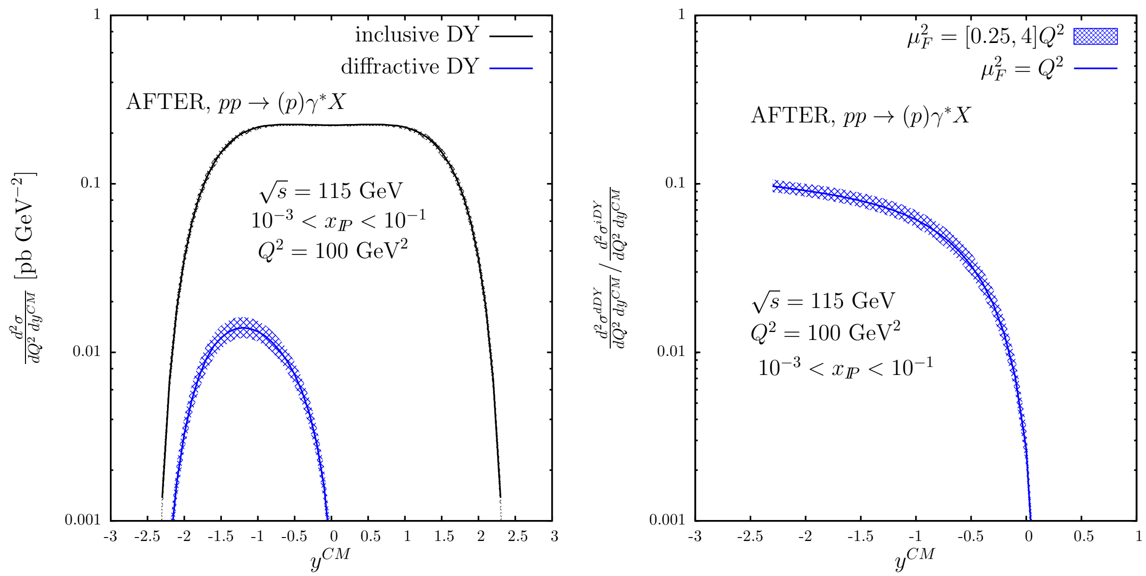
Single Diffractive DY production



- DY rapidity distributions are sensitive to the shape the dPDFs and allow to investigate any possible kinematic dependence of the RGS factor.
- On average, the parton originating from the target proton carries more momentum than the one originating from the pomeron.
- For increasing x_{IP}, the Drell-Yan pair spans a wider rapidity range and the corresponding spectrum is increasingly more forward.

Single Diffractive DY production

- Compare SD DY vs iDY (no RGS applied)
- $Q^2 = 100$ GeV^2
- SD DY : integrated in $10^{-3} < x_{IP} < 10^{-1}$.



- The rapidity distributions in the SD case is strongly asymmetric whereas in the inclusive case it is symmetric around $y^{CM} = 0$:
- This effect is primarily due to the different kinematics + fractional momentum distributions of partons in proton and pomeron.
- The ratio gives direct information on the suppression factor SD vs inclusive DY

Summary

- A comprehensive description of the hadronic final state in DIS requires the introduction of new distributions, fracture functions.
- The QCD analysis, in this case, is supported by a dedicated factorization theorem
- Forward Lambda and neutron production in DIS are succesfully described within this formalism
- Forward proton, and in general, diffractive process are also well described in DDIS.
- With such a knowledge, factorisation tests can performed in hadronic collisions:
  - Especially in hard diffraction where factorization is not expected to hold.
  - Factorization breaking effects, however, can be estimated using diffractive PDFs extracted from DDIS data, possibly pointing to the dynamical origin of the suppression