Factorization breaking in diffractive jet production

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21 September 2012

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HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

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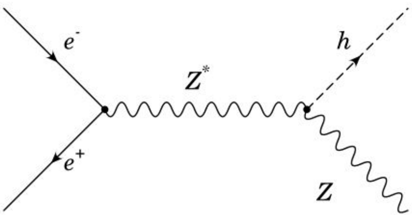
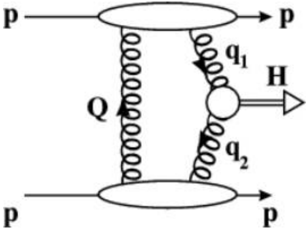
Gefördert vom Bundesministerium für Bildung und Forschung

Properties of the "new particle with a mass of 125 GeV"?



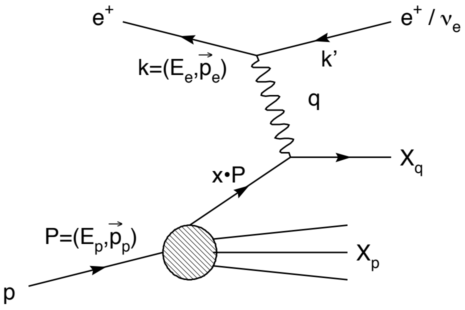


Huge uncertainty from rescattering probability

Reference	Process	Survival factor T^2	Survival factor S^2	Norm.	σ_{Higgs} (fb) Teva.	σ_{Higgs} (fb) LHC	Notes
Cudell, Hernandez [21]	excl incl	no	no	σ_{tot}	30 200	300 1200	Overshoots CDF dijets by 1000.
Levin [20]	excl incl	yes (no DL)	yes	σ_{tot}	20 70	–	Overshoots CDF dijets by 300.
Khoze, Martin, Ryskin [16]	excl incl C.inel	yes	yes	pdf pdf	0.2 1 ~ 0.03	3 40 50	Uses skewed gluons. CDF dijets OK.
Cox, Forshaw, Heinemann [5]	C.inel	$T \simeq 1$	norm	CDF dijet	0.02	6	No LO, only NLO, QCD i.e., no Fig.2a, only 2c.
Boonekamp, De Roeck, Peschanski, Royon [7]	C.inel	$T \simeq 1$	norm	CDF dijet	2.7	320	No LO, only NLO, QCD. Assume $S^2_{\text{CDF}} = S^2_{\text{LHC}}$.
Enberg, Ingelman, Kissavos, Timneanu [19]	incl C.inel	yes	yes	$F_2^{\text{Diff.}}$	< 0.01	0.2	No coherence.

Khoze, Martin, Ryskin, EPJC 26 (2002) 229

QCD factorization for inclusive DIS



Kinematic variables:

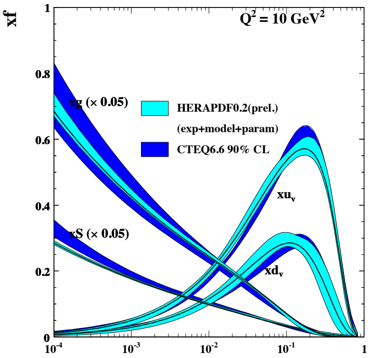
$$Q^2 = -q^2 = -(k-k')^2$$
$$x = \frac{Q^2}{2m_p(E_e - E'_e)}$$
$$y = \frac{q.p}{k.p} = \frac{\sum_h (E_h - p_{z,h})}{2E_e}$$

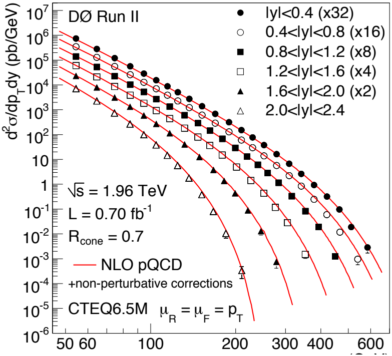
Inclusive structure function:

$$F_2(x,Q^2) = \sum_{a=q,g} C_{2a} \otimes f_{a/p} + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

Collins, Soper, Sterman, in: *Perturbative QCD*, A. Mueller (ed.), World Scientific, 1989

Experimental test of factorization



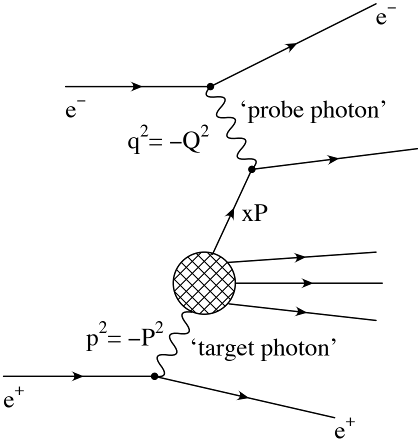


De Roeck, Thorne, PPNP 66 (2011) 727

$\rightarrow$ PDFs determined in *ep* at HERA also describe $p\bar{p}$ Tevatron data

$\rightarrow$ Hard scale Q set by jet p_T; PDFs needed for p and $\bar{p}$

QCD factorization for inclusive DIS on photons



Kinematic variables:

$$\begin{aligned} P^2 &= -p^2 \simeq 0 \\ x_\gamma &= \frac{Q^2}{(q+p)^2 + Q^2 + P^2} \end{aligned}$$

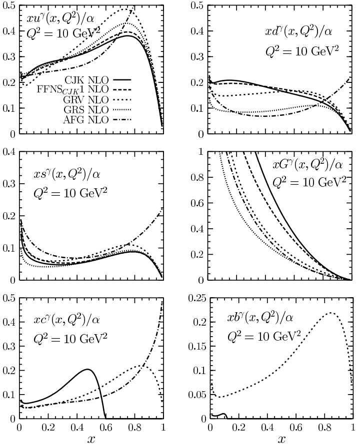
Inclusive structure function:

$$F_2^\gamma(x_\gamma, Q^2, P^2) = \sum_{a=\gamma,q,g} C_{2a} \otimes f_{a/\gamma} + \dots$$

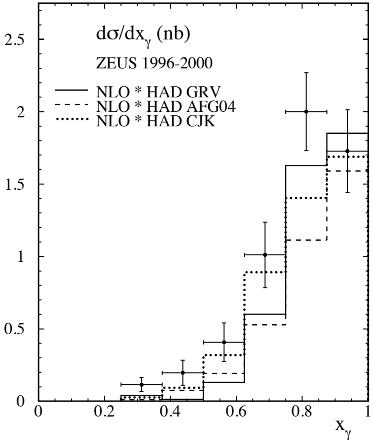
Direct + resolved components (VMD)

Nisius, Phys. Rep. 322 (2000) 165

Experimental test of factorization for photons



Cornet, Jankowski, Krawczyk, PRD 70 (2004) 093004

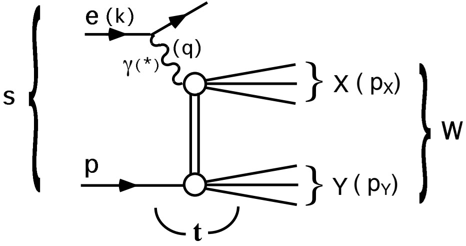


Klasen, Kramer, EPJC 71 (2011) 1774

→ PDFs determined in $e\gamma$ at LEP also describe γp HERA data

→ Hard scale Q set by jet p_T; PDFs needed for γ and p

QCD factorization for diffractive DIS



Final state separated by rapidity gap:

- X = contains hard jets
- Y = proton or low-mass excitation

Additional variables:

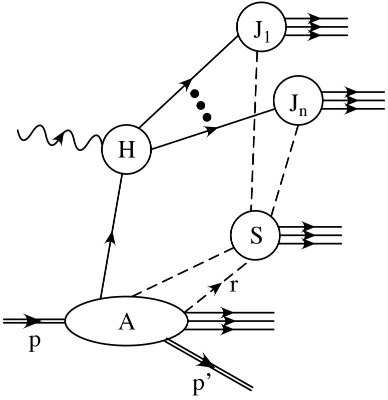
$$t = (p - p_Y)^2$$

$$x_{IP} = \frac{q(p - p_Y)}{qp} \quad (= \xi)$$

Diffractive structure function:

$$F_2^D(x, Q^2; x_{IP}, t) = \sum_a C_{2a} \otimes f^D_{a/p}$$

Proof of QCD factorization for diffractive DIS (1)



Leading regions:

- A = remnant jets $\parallel$ p and p'
- H = hard with momenta $\sim Q$
- S = soft with momenta $\ll Q$
- J_i = hard jets

Light-cone coordinates:

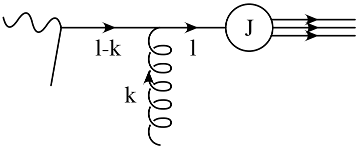
$$q^\mu = (q^+, q^-, \mathbf{q}_T)\ ,\ \ q^\pm = \frac{q^0 \pm q^3}{\sqrt{2}}$$

Breit frame:

$$q^\mu = \left(-\frac{Q}{\sqrt{2}}, \frac{Q}{\sqrt{2}}, \mathbf{0}\right)\ ,\ \ q^0 = 0$$

Collins, PRD 57 (1998) 3051

Proof of QCD factorization for diffractive DIS (2)



Soft gluon attachments (only FS):

$$\begin{aligned} J^\mu &= \frac{1}{(l-k)^2 - m^2}\,\Gamma^\mu \\ &= \frac{1}{-2l^- k^+}\,\Gamma^- \hat{l}^\mu + \mathcal{O}(Q^0) \\ &= k^+ J^- \frac{\hat{l}^\mu}{k^+} + \mathcal{O}(Q^0) \end{aligned}$$

Jet momentum:

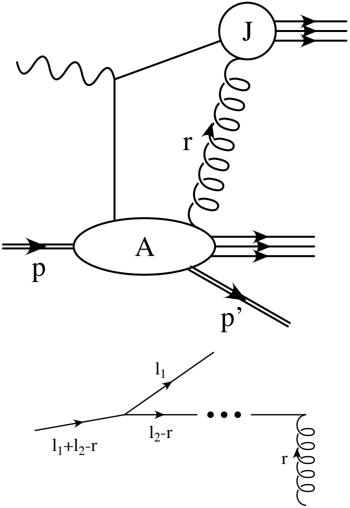
$$l^\mu = \left(0, \frac{Q}{\sqrt{2}}, \mathbf{0}\right) + \mathcal{O}(Q^0)$$

Ward identity, proof as in e^+e^-.

For small k^+, can deform to $k^+ - i\varepsilon$

Collins, PRD 57 (1998) 3051

Proof of QCD factorization for diffractive DIS (3)



Proton momenta:

$$p^{(\prime)\mu} = \left(\frac{(1-x_{IP})}{x}\frac{Q}{\sqrt{2}}, 0, \mathbf{0}\right) + \mathcal{O}(Q^0)$$

Soft gluon attachments (IS and FS):

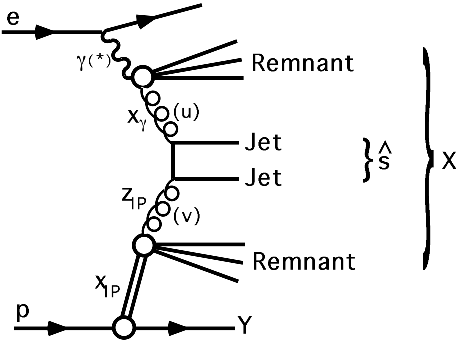
$$A^\mu \quad = \quad r^- A^+ \frac{\hat{p}^\mu}{r^-} + \mathcal{O}(Q^0)$$

Can not deform contour for small r^-.

Route r back from jet with small r^+ component, until one hits large A^+. So the poles at $r^- = 0$ must cancel.

Collins, PRD 57 (1998) 3051

Regge factorization



Additional variable:

$$z_{IP} \;=\; \frac{x}{x_{IP}} \;(\;=\;\beta)$$

Regge factorization (cf. WWA):

$$f^D_{a/p}(x, Q^2; x_{IP}, t) = f_{IP/p}(x_{IP}, t)\, f_{a/IP}(z_{IP}, Q^2) + n_{IR}\, f_{IR/p}(x_{IP}, t)\, f_{a/IR}(z_{IP}, Q^2)$$

Pomeron/Reggeon fluxes ($\sim \sigma^{el.}_{pp}$):

$$f_{IP/p}(x_{IP}, t) \;=\; C_{IP}\,\frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

Leading/subleading trajectories:

$$\alpha_{IP}(t) \;=\; \alpha_{IP}(0) + \alpha'_{IP}\, t$$

Ingelman, Schlein, PLB 152 (1985) 256

Regge factorization at HERA

No theoretical proof, but well supported by experimental data.

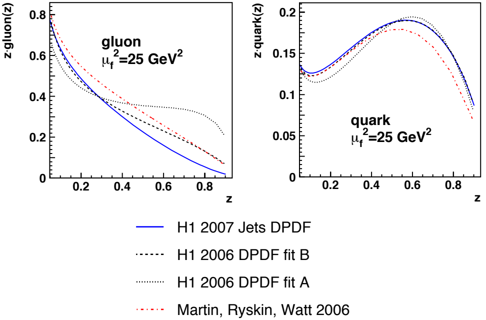
Parameter	H1 2006 fit A	H1 2006 fit B	H1 2007 jets
B_{IP}	5.5 GeV^{-2}	idem	idem
$\alpha_{IP}(0)$	1.118	1.111	1.104
α'_{IP}	0.06	idem	idem
n_{IR}	1.7×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
B_{IR}	1.6 GeV^{-2}	idem	idem
$\alpha_{IR}(0)$	0.50	idem	idem
α'_{IR}	0.3	idem	idem

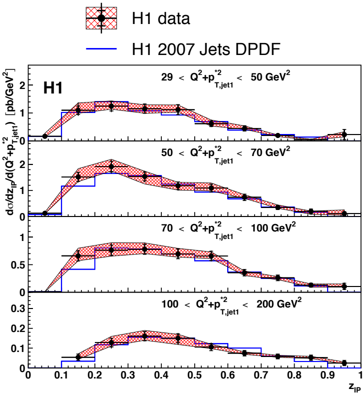
At small $x_{IP} < 0.03$ (0.025 for $\gamma p \to$ jets) and $|t| < 1$ GeV^2:

- Reggeon n_{IR} small, but needed for a good fit
- Contributes 30 % at large $x_{IP} \simeq 0.03$
- Pion PDFs (not very sensitive)

H1 Coll., EPJC 48 (2006) 715
H1 Coll., JHEP 0710 (2007) 042

Experimental test of factorization for pomerons

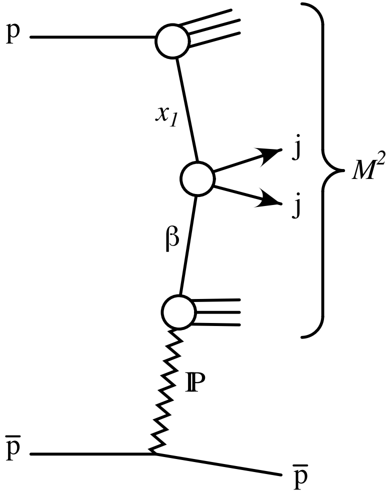




H1 Coll., JHEP 0710 (2007) 042

→ Pomeron dominated by gluon; quarks ($u = d = s$) much smaller
→ Inclusive DIS data not enough; must also include DIS dijet data

Diffractive dijet production at the Tevatron (1)



Tevatron Run IC (1995-96):

- $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV

32.629 non-diffractive (ND) events:

- 2 jets with cone size $R = 0.7$
- $E_T^{1,2} > 7$ GeV, $|\eta^{1,2}| < 4.2$
- $x_{\bar{p}} = \frac{1}{\sqrt{s}} \sum_i E_T^i e^{-\eta^i}$

30.410 single-diffractive (SD) events:

- $\bar{p}'$ triggered in Roman pot (57 m)
- $\xi\,(= x_{IP}) \in [0.035; 0.095]$
- $|t| < 1$ GeV^2

CDF Coll., PRL 84 (2000) 5043

Diffractive dijet production at the Tevatron (2)

Cross section ratio:

$$R(x, Q^2, \xi, t) = \frac{N_{JJ}^{\mathrm{SD}}(x, Q^2, \xi, t)}{N_{JJ}^{\mathrm{ND}}(x, Q^2)} \simeq \frac{F_{JJ}^{\mathrm{SD}}(x, Q^2, \xi, t)}{F_{JJ}^{\mathrm{ND}}(x, Q^2)}$$

(Single-) diffractive structure function:

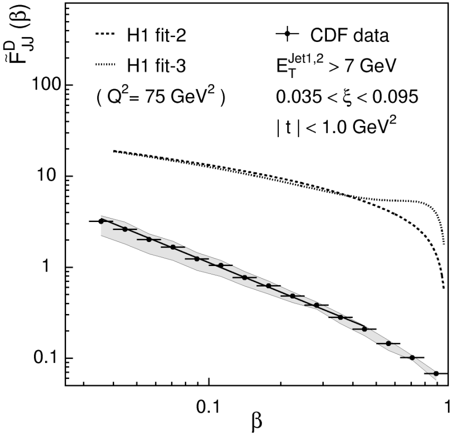
$$\tilde{F}_{JJ}^{\mathrm{D}}\left(\beta = \frac{x}{\xi}\right) = R(x, Q^2, \xi, t) \times F_{JJ}^{\mathrm{ND}}(x, Q^2)$$

Non-diffractive structure function:

$$F_{JJ}^{\mathrm{ND}}(x, Q^2) = x\left[f_{g/p}(x, Q^2) + \frac{4}{9}\sum_q f_{q/p}(x, Q^2)\right]$$

with GRV 98 LO PDFs.

Diffractive dijet production at the Tevatron (3)



Comparison with F_2^D from H1:

- Smaller by 0.06 (0.05) for fit 2 (3)
- QCD factorization is broken!

Shape disagrees as well:

- For $\beta < 0.5$, $\tilde{F}^D_{JJ} \sim 1/\beta$ (solid line)

Corrections and uncertainties:

- UE of 1.16 (0.54) GeV for ND (SD)
- 3- and 4-jet contributions (band)
- Systematic error on norm.: $\pm 25\,\%$

CDF Coll., PRL 84 (2000) 5043

Diffractive dijet production at the Tevatron (4)

Experimental analysis:

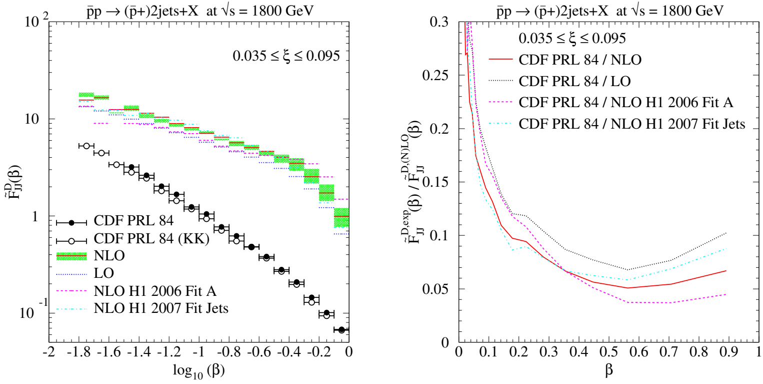
- Cone algorithm, ambiguous $\rightarrow$ Need $R_{\rm sep} = 1.3 \times R$
- Equal cuts on $E_T^{1,2} > 7$ GeV $\rightarrow$ Need $E_T^2 \geq 6.5$ GeV
- Remedied in PRL 88 (2002) 151802 with $\overline{E_T} > 10$ GeV

Theoretical interpretation:

- No unfolding of Wilson coefficients (simple division)
- Only color factors taken into account in F_{JJ}^{ND}
- No evolution effects, assume $Q^2 = 75$ GeV$^2 \simeq \langle E_T^2 \rangle$
- Outdated LO parameterization for proton PDFs
- H1 DPDFs obtained at smaller $x_{IP} < 0.03$, but Reggeon is small
- H1 DPDFs include dissociation, must be divided by 1.23
- Must also take into account $F_2^{D,c}(x, Q^2, x_{IP}, t) = 2\,x\,e_c^2\,f_{c/p}^D$

Klasen, Kramer, PRD 80 (2009) 074006

Diffractive dijet production in NLO QCD



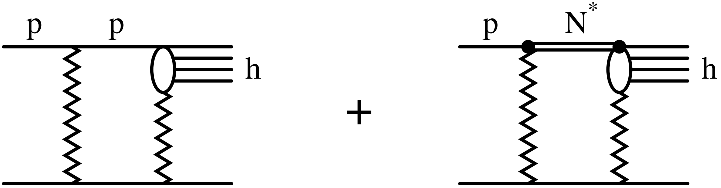
→ Qualitatively similar results with correlations and new DPDFs

→ Impact of NLO corrections visible, strong β-dependence at NLO

Klasen, Kramer, PRD 80 (2009) 074006

Non-factorizable multipomeron exchanges

Two-channel eikonal model:



Diffractive eigenstates:

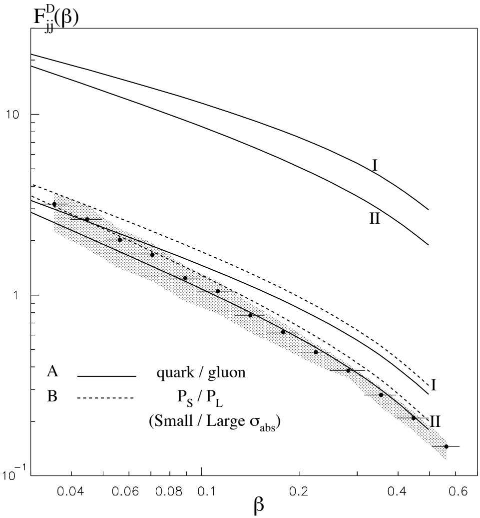
$$|\phi_s\rangle = \frac{1}{\sqrt{2}}(|p\rangle + |N^*\rangle) \quad , \quad |\phi_v\rangle = \frac{1}{\sqrt{2}}(|p\rangle - |N^*\rangle)$$

Absorptive cross sections $\sim$ size of components:

- Gluons and sea quarks (s) = large
- Valence quarks (v) = small

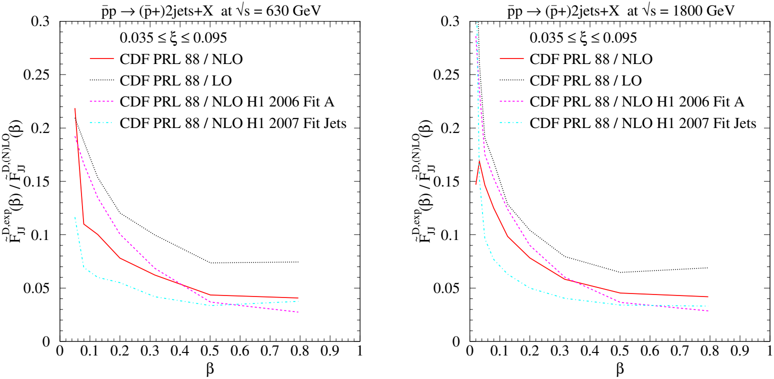
Kaidalov, Khoze, Martin, Ryskin, EPJC 21 (2001) 521

Survival probabilities in LO QCD



Kaidalov, Khoze, Martin, Ryskin, EPJC 21 (2001) 521

Survival probabilities in NLO QCD

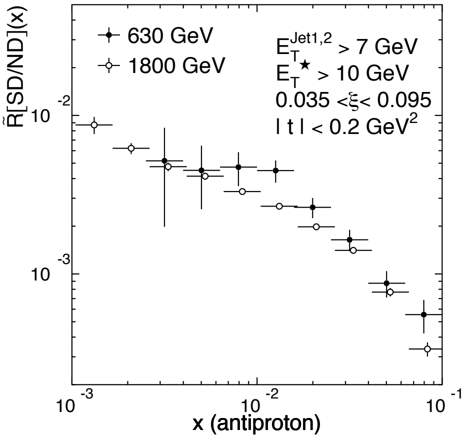


→ Valence quarks in proton dominate at small β, less suppression

→ No significant $\sqrt{s}$ dependence

Klasen, Kramer, PRD 80 (2009) 074006

Center-of-mass energy dependence (1)



Low-x partons important at large $\sqrt{s}$, but little dependence on $\sqrt{s}$ observed

Opacity / optical density:

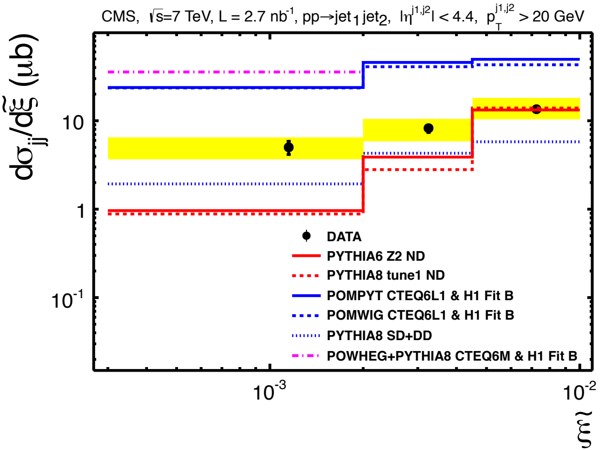
$$\Omega_i \sim \frac{(g_{pp}^{IP})^2 (s/s_0)^{\alpha_{IP}(0)-1}}{4\pi B}$$

H1 2006 fits A,B and H1 2007 jets:

- $\alpha_{IP}(0) = 1.104 \ldots 1.118$

CDF Coll., PRL 88 (2002) 151802

Center-of-mass energy dependence (2)

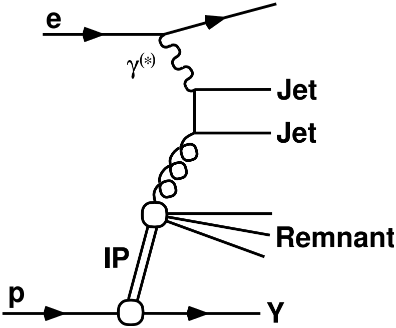


→ Similar rapidity gap: $\Delta\eta = 3 \ldots 4.9$; smaller $\xi \in [0.0003; 0.002]$

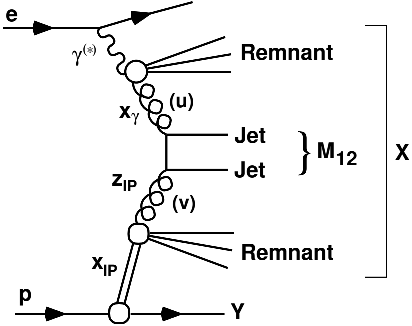
→ Survival probability: 0.12±0.05 at LO, 0.08±0.8 at NLO

CMS Coll., arXiv:1209.1805

Diffractive dijet photoproduction (1)



Direct photons



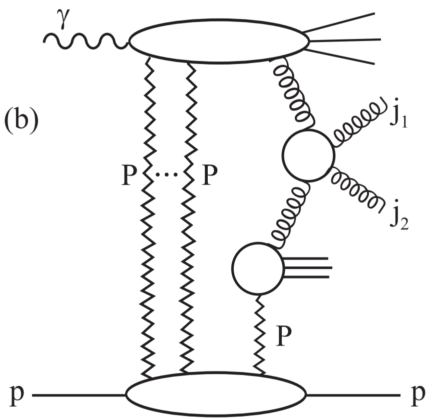
Resolved photons

Diffractive dijet photoproduction (2)

The proof of factorization would appear to apply also to direct photo-production of jets, etc., because the initiating particle of the hard scattering is a lepton. However the proof does not apply to resolved photoproduction processes, since these are in effect hadron-hadron processes. The lack of an absolutely unambiguous separation between direct and resolved photoproduction will presumably limit the accuracy of the application of the factorization formula to direct diffractive photoproduction.

Collins, PRD 57 (1998) 3051

Non-factorizable multipomeron exchanges



Generalized vector meson dominance:

- $J^{PC} = 1^{--}$: $\gamma \to \rho, \omega, \ldots$

Fitted parameters at $W = 200$ GeV:

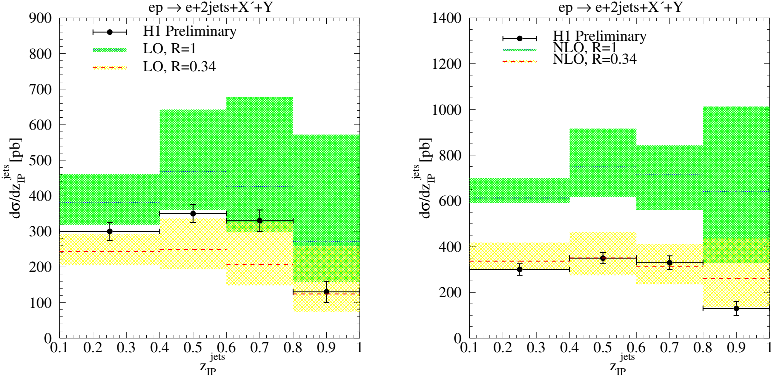
- $\sigma_{tot}(\rho p) = 34$ mb
- Pomeron slope: $B = 11.3$ GeV^{-2}
- $\gamma = 0.6$ for large ρ excitation prob.

Survival probability:

- Direct photons: $|S|^2 = 1$
- Resolved photons: $|S|^2 = 0.34$

Kaidalov, Khoze, Martin, Ryskin, PLB 567 (2003) 61

Diffractive dijet photoproduction in NLO QCD (1)

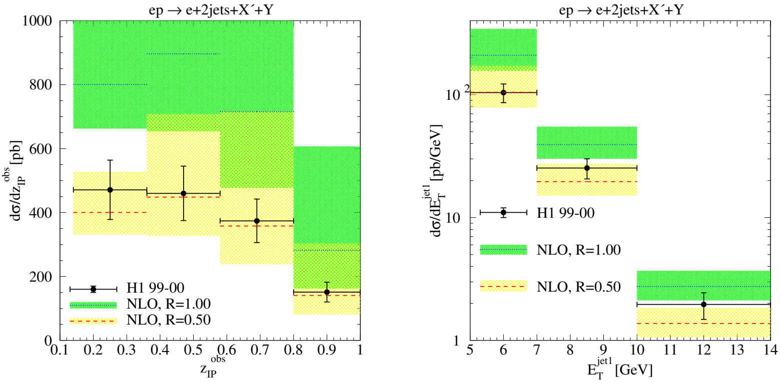


→ No factorization breaking at LO, but clearly at NLO

→ Constant suppression factor $R = 0.34$ for resolved component

Klasen, Kramer, EPJC 38 (2004) 39

Diffractive dijet photoproduction in NLO QCD (2)



→ Data also described by global suppression of $R = 0.50$

→ Suppression depends on E_T. Note: Direct component is harder

Klasen, Kramer, EPJC 70 (2010) 91

Diffractive dijet photoproduction in NLO QCD (3)

Comparison of H1 low-E_T, high-E_T and ZEUS analyses:

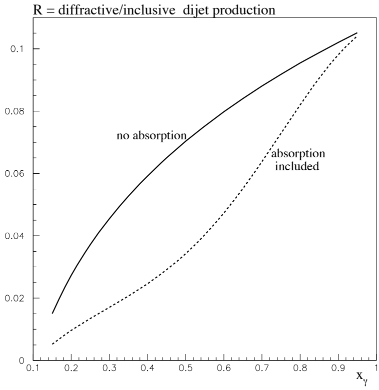
Suppression	H1 low-E_T^{jet} EPJC 70 (2010) 15	H1 high-E_T^{jet} H1-prelim-08-012	ZEUS EPJC 55 (2008) 177	ZEUS ren. id.
global	0.50	0.62	0.71	0.56 ± 0.05
res	0.40	0.38	0.53	0.42 ± 0.04
res+dir-IS	0.37	0.30	0.45	0.36 ± 0.03
res, fit A	0.32	0.16	0.27	0.21 ± 0.01

→ ZEUS data renormalized for proton dissociation
→ Good agreement with H1 high-E_T analysis
→ Direct initial-state influences only scale dependence
→ Suppression factor depends (slightly) on DPDFs

Klasen, Kramer, EPJC 70 (2010) 91

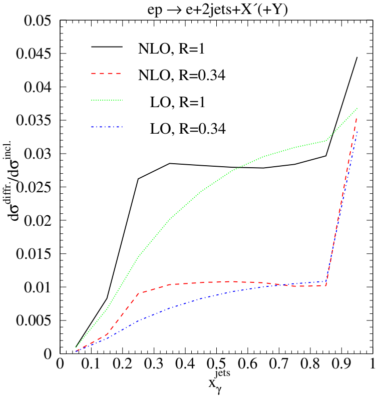
Diffractive vs. inclusive dijet photoproduction

$R = f_{g/IP} \otimes f_{IP/p} / f_{g/p}$:



Kaidalov, Khoze, Martin, Ryskin, PLB 567 (2003) 61

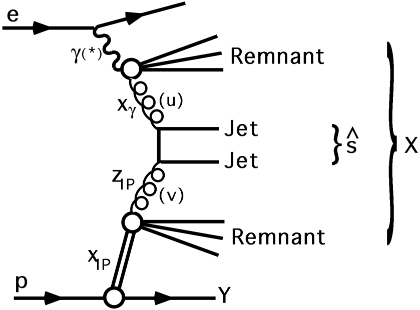
$R = \sigma_{diff} / \sigma_{incl}$:

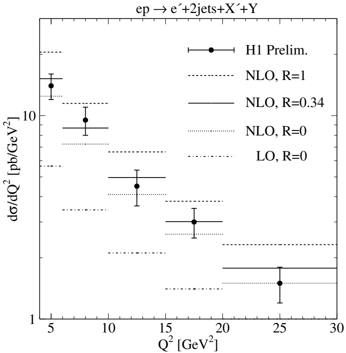


Klasen, Kramer, EPJC 38 (2004) 39

→ Full kinematics important, but similar *K*-factors

Diffractive dijet production at low Q^2 in NLO QCD





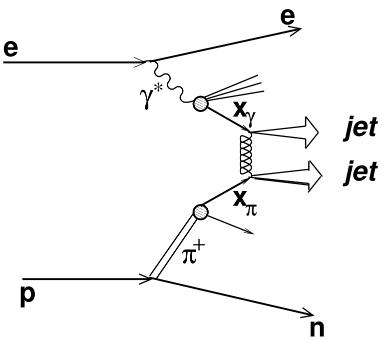
→ Important transition region from photoproduction to DIS

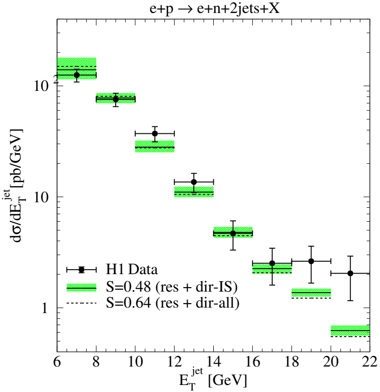
→ Resummation of higher orders into PDFs needed at low Q^2

→ Similar suppression factor applies to this resolved contribution

Klasen, Kramer, PRL 93 (2004) 232002

Dijet photoproduction with leading neutron in NLO QCD





→ Dominated by π exchange → can be used to determine π PDFs

→ Flux: Light-cone form factor with $R = 0.55$ GeV^{-1} from DIS

→ Pion PDFs dominated by q, not g → different supression factor

Klasen, Kramer, EPJC 49 (2007) 957

Conclusion

Diffractive events:

- Large fraction of DIS events at HERA (10-15%)
- Clean events at Tevatron/LHC, perhaps even for Higgs studies

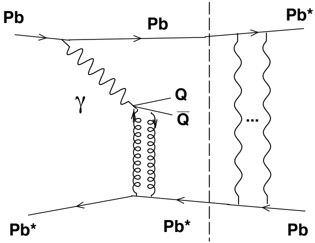
Theoretical description:

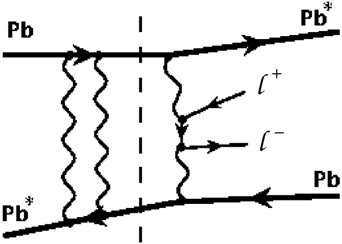
- QCD factorization proven in DIS
- Regge factorization well supported by experimental data
- DPDFs best constrained by also including jets in DIS

Factorization breaking:

- Initial and final state rescatterings $\rightarrow$ no contour deformation
- Multipomeron exchanges $\rightarrow$ two-channel eikonal model
- *pp*: NLO qualitatively similar to LO, β-dependent
- γp: Direct/resolved related at NLO, resolved supp. $\sim$ constant

Ultraperipheral heavy-ion collisions at the LHC





→ Heavy ions produce strong el.magn. fields → photoproduction
→ Central events with diffractive (J/Ψ) + photon (DY) cont.s

Baltz, MK et al., PR 458 (2008) 1

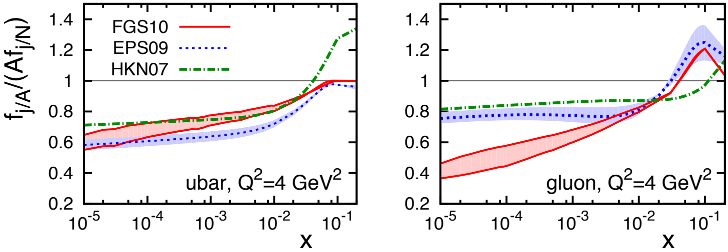
Leading twist theory of nuclear shadowing

Geometric interpretation (Glauber, 1955):

- Nucleon in front absorbs part of incoming flux
- Casts shadow on the nucleon behind
- Include anti-shadowing to conserve momentum sum rule

Relation to diffraction (Gribov, 1969):

- At large $\sqrt{s}$, intermediate state of double scattering is diffractive
- Therefore leading twist, needs only HERA data



Frankfurt, Guzey, Strikman, PR 512 (2012) 255