

SOFT COLOUR INTERACTIONS AND PARTON RESCATTERING IN QCD

(or: Gaps — in my understanding after 20 years)

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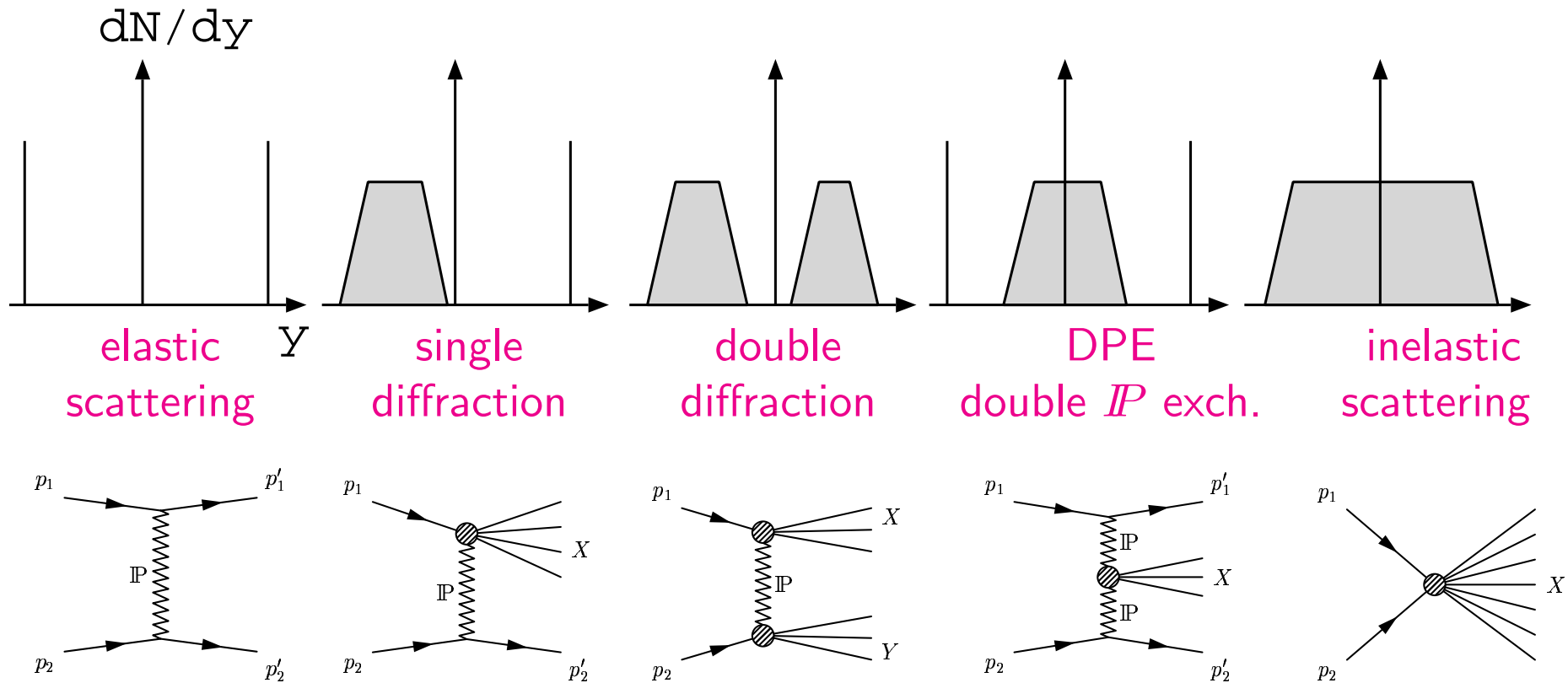
People involved:

- Johan Rathsman
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- Rikard Enberg
- Cristiano Brenner Mariotto
- David Eriksson
- Korinna Zapp
- Stan Brodsky
- Paul Hoyer

- Introduction
- Soft Colour Interaction model
 - ↪ soft gaps in ep and $p\bar{p}$
 - ↪ charmonium production
 - ↪ B decays
 - ↪ jet quenching in QGP
- Parton rescattering in QCD
 - ↪ theoretical basis
 - ↪ model developments
- Conclusions & Outlook

Rapidity gap events given by final state topology

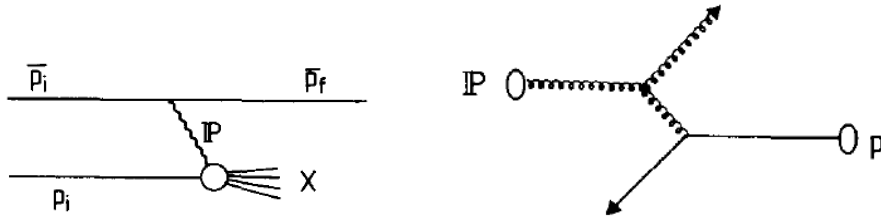
$$\text{Rapidity} = y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} \approx -\ln \tan \frac{\theta}{2} = \eta = \text{pseudorapidity}$$



Pomeron exchange in Regge theory/phenomenology

Diffractive hard scattering

Idea: Ingelman-Schlein, Phys. Lett. 1985



- hard scale probes parton level
- IP flux
- IP structure function

Predicted:

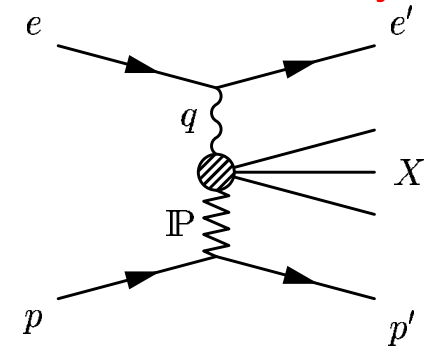
- jets etc. in single diffraction
- diffractive deep inelastic scattering

Discovery: UA8 at $Spp\bar{S}$ 1988

- jets in single diffraction \simeq model
- hard gluons $xg(x) \sim x(1-x)$ in IP
- 'superhard' $\delta(1-x)$ component

More exp's: HERA ep , Tevatron $p\bar{p}$

Diffractive DIS – HERA discovery



GI+Prytz 1993:

$$\frac{d\sigma}{dx dQ^2 dx_{IP} dt} =$$

$$\frac{2\pi\alpha^2}{xQ^4} (1 + (1-y)^2) F_2^{D(4)}$$

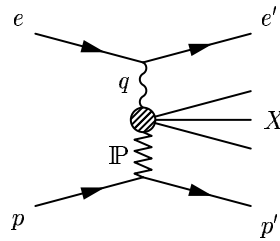
$$F_2^{D(4)}(x, Q^2, x_{IP}, t) =$$

$$\underbrace{f(x_{IP}, t)}_{IP \text{ flux}} \underbrace{F_2^{IP}(\beta, Q^2)}_{IP \text{ structure}}$$

Fits HERA rapidity gap data
using both IP and IP Reggeon

$\Rightarrow IP$ parton densities

Pomeron problems:



- IP model fitted to HERA data
→ fails for Tevatron data
 $\sigma(\text{hard diff})$ factor 6–100 too large
→ need ‘damping’ at high energies,
e.g. IP flux ‘renormalisation’
- IP flux & structure not universal
ill-defined for virtual IP
- Factorisation broken in diffractive $p\bar{p}$
– coherent interactions
- Improper with IP ‘emitted’ from p
soft, long space-time-scale interaction
→ IP – p cross-talk

Alternative approach:

- no ‘initial’ IP , not in proton wave fcn
- hard pQCD left unchanged
– not affect by soft interactions
- non-pQCD below $Q_0^2 \sim 1 \text{ GeV}^2$
- α_s large \Rightarrow large interaction probability
e.g. unity for hadronisation!
- colour exchange modifies colour/string
topology \rightarrow different final state
- single model describing all final states
– diffractive \leftrightarrow nondiffractive

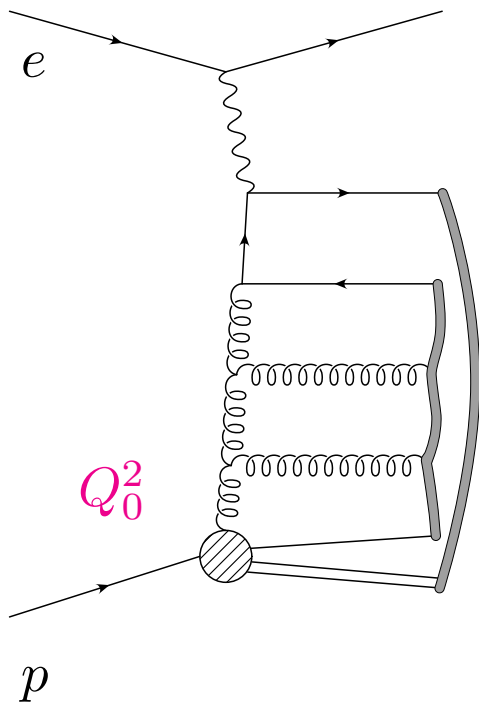
Soft Colour Interaction model (SCI)

Soft interactions among partons & remnants (\leftrightarrow proton colour field) below $Q_0^2 \sim 1 \text{ GeV}^2$

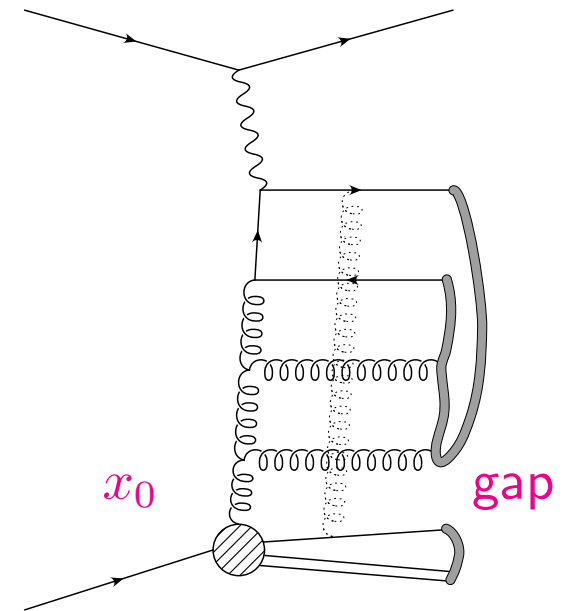
Add-on to Lund Monte Carlo's LEPTO (ep) and PYTHIA ($p\bar{p}$)

ME + DGLAP PS $> Q_0^2$ \rightarrow SCI model \rightarrow String hadronisation $\sim \Lambda$
 colour ordered parton state \rightarrow rearranged colour order \rightarrow modified final state

Single model describing all final states: diffractive \leftrightarrow nondiffractive



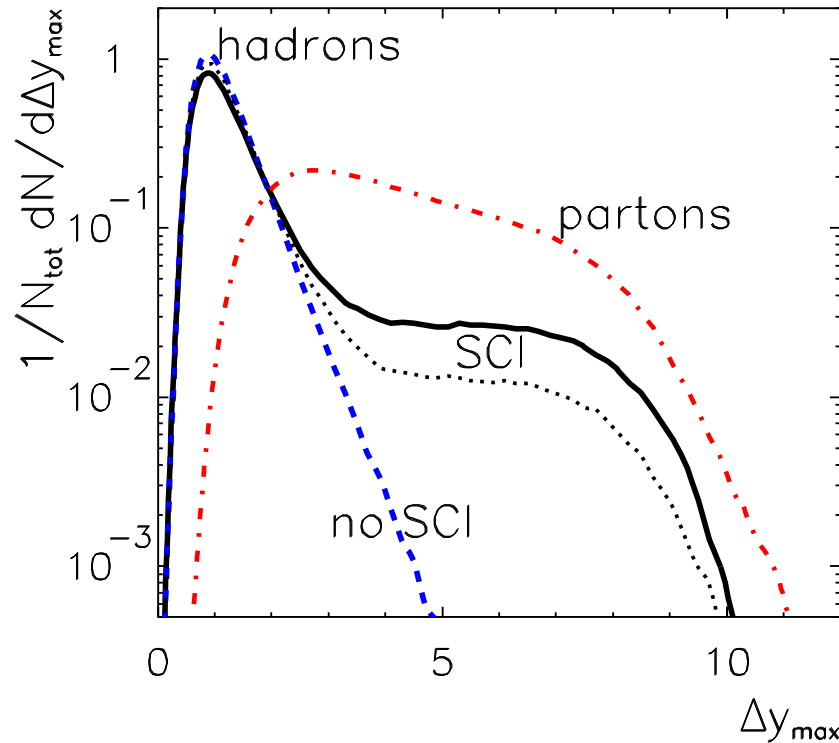
Single parameter $P = const \approx 0.5$
 gives probability for soft ($p \simeq 0$)
 colour-anticolour (gluon) exchange
 between parton pairs,
 determined from HERA rap-gap data



Proton remnant with $(1 - x_0)$ important for large gaps

Gap-size is infrared sensitive observable !

Size Δy_{max} of largest gap in DIS events



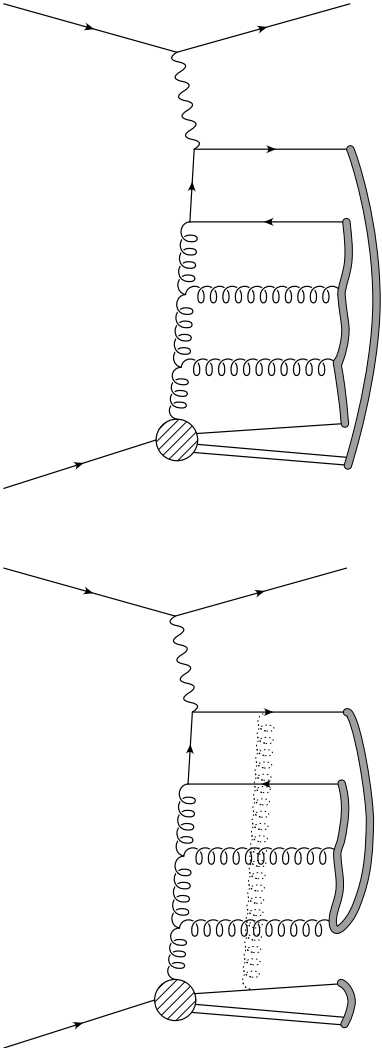
SCI \Rightarrow plateau in Δy_{max}
characteristic for diffraction

Small parameter sensitivity

— $P = 0.5$

... $P = 0.1$

Large gaps at parton level
normally string across \rightarrow hadrons fill up
SCI \rightarrow new string topologies, some with gaps



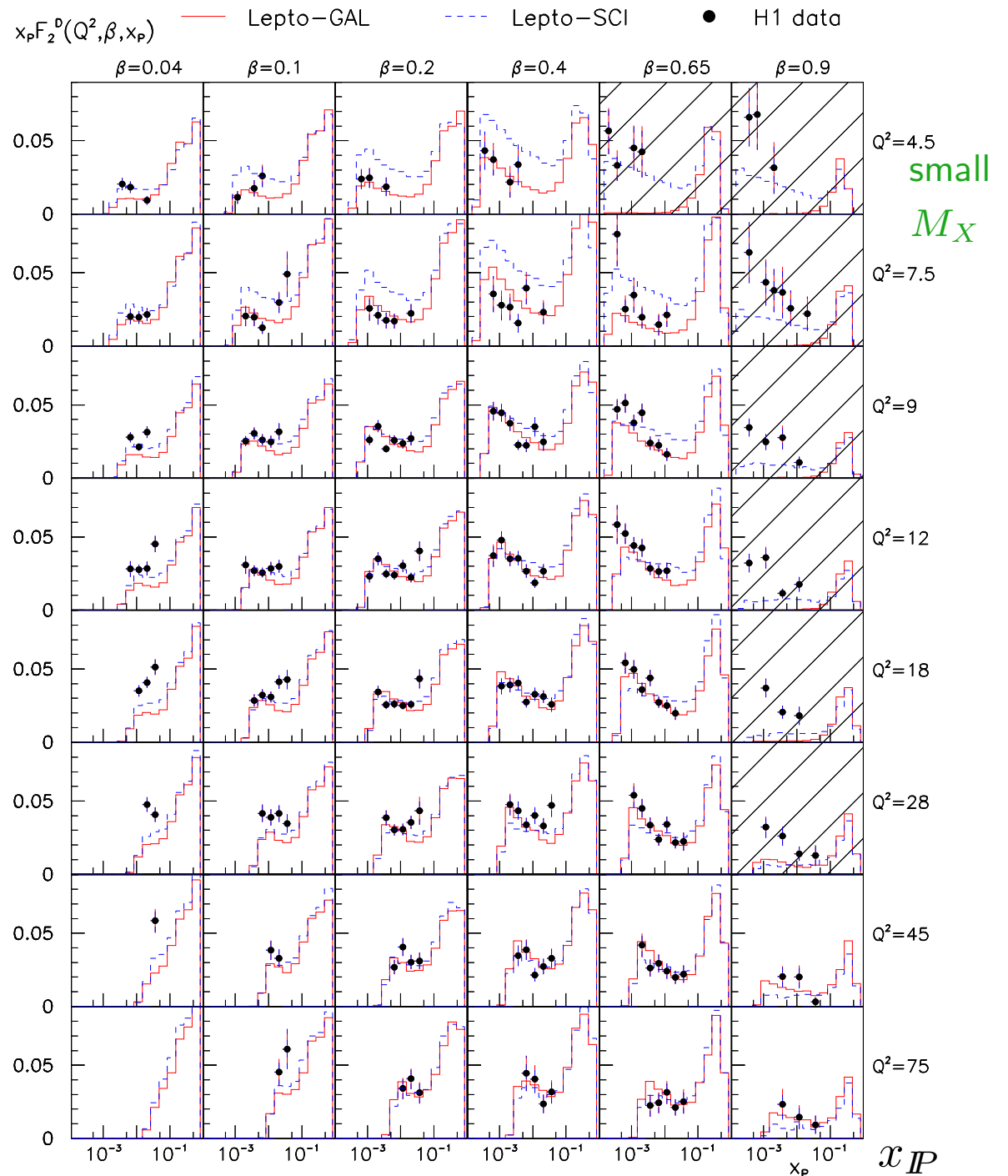
Diffractive structure function in DIS

$$x_{\mathcal{I}P} F_2^{D(3)}(Q^2, \beta, x_{\mathcal{I}P})$$

SCI model describes
main features of HERA
rapidity gap data

Not bad for a
one-parameter model !

GAL is an alternative
formulation of the model,
based on string interactions



Leading neutron spectrum

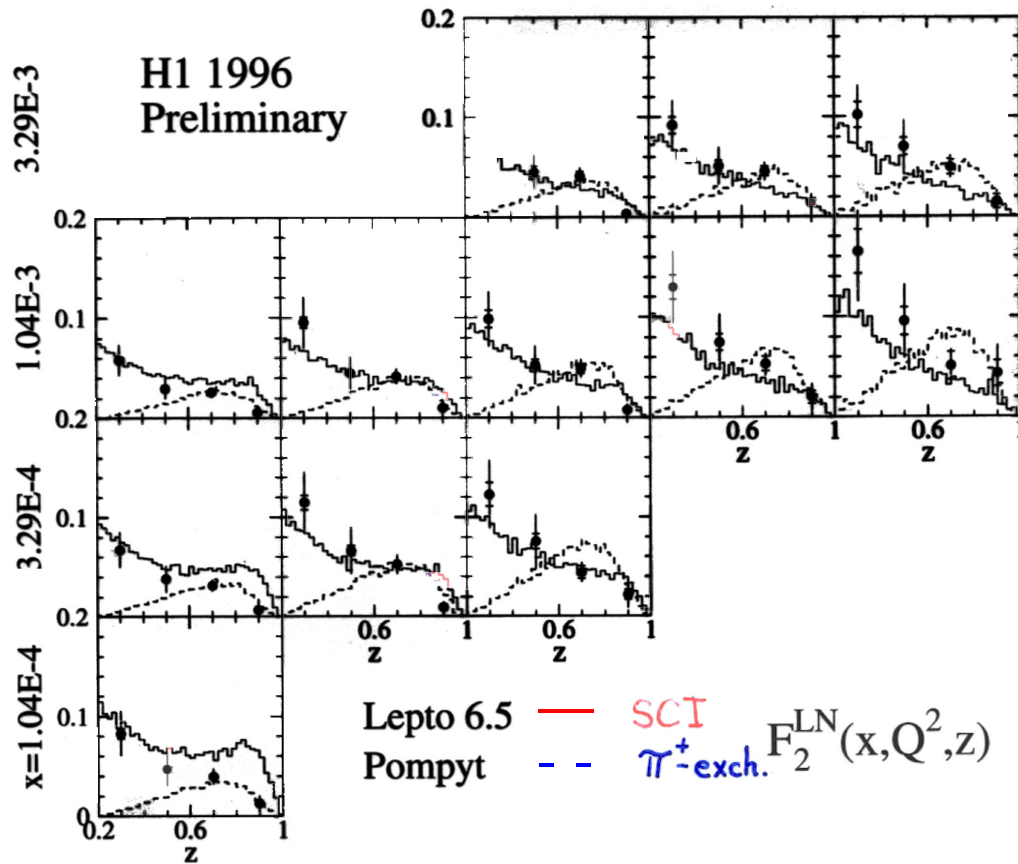
Leading Neutron Structure Function

$F_2^{LN(3)}$ defined for $p_T^n < 200$ MeV

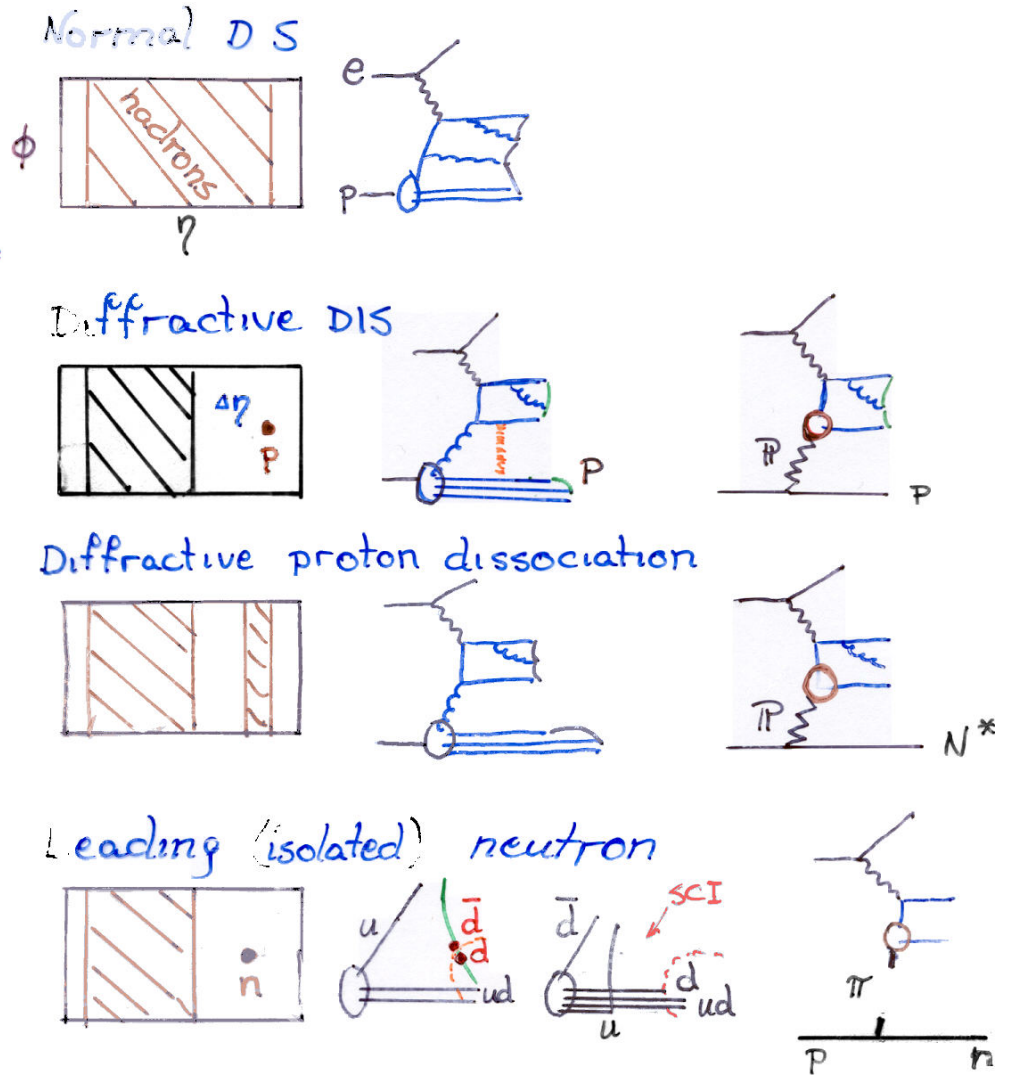
Measured for $0.2 < x_L < 1$

Compared with POMPYT implementation of π^+ exchange and with LEPTO.

$Q^2 = 2.5 \quad 4.4 \quad 7.5 \quad 13.3 \quad 28.6 \text{ GeV}^2$



SCI \Rightarrow different final states



Final state \Rightarrow event classification
- as in experiments

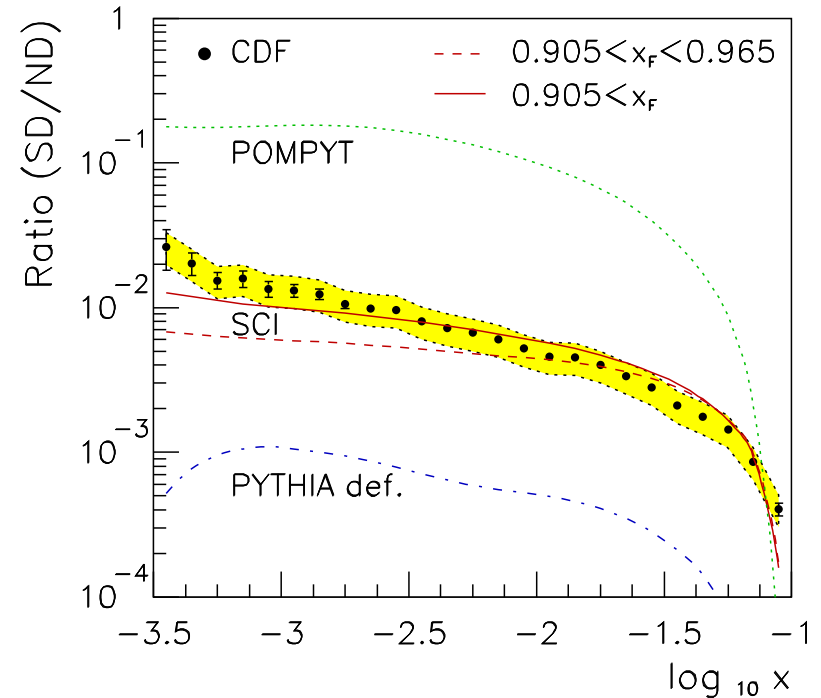
Single diffractive jets, W , Z , $b\bar{b}$, J/ψ at the Tevatron

$$R_{\text{hard}} = \frac{1}{\sigma_{\text{hard}}^{\text{tot}}} \int_{x_{F\text{min}}}^1 dx_F \frac{d\sigma_{\text{hard}}}{dx_F}$$

$R_{\text{hard}}[\%]$	Exp.	observed	SCI
dijets	CDF	0.75 ± 0.10	0.7
W	CDF	1.15 ± 0.55	1.2
W	DØ	$1.08^{+0.21}_{-0.19}$	1.2
$b\bar{b}$	CDF	0.62 ± 0.25	0.7
Z	DØ	$1.44^{+0.62}_{-0.54}$	1.0
J/ψ	CDF	1.45 ± 0.25	1.4

↑
predictions

R_{dijets} vs x of parton in \bar{p}

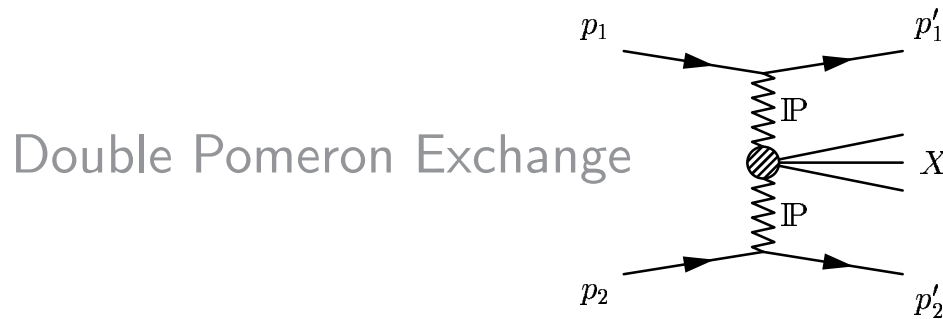


SCI \rightarrow gap & $c\bar{c}$ colour octet \rightarrow singlet $\rightarrow J/\psi$

SCI model OK, Pomeron model too high, default PYTHIA too low
 SCI also correctly describes two-gap events (Double Pomeron Exchange)

\Rightarrow Basis for predictions of diffractive Higgs production at Tevatron & LHC
 Idea: easier to reconstruct Higgs in gap-event with less hadronic activity

DPE: “Double leading Proton Events”

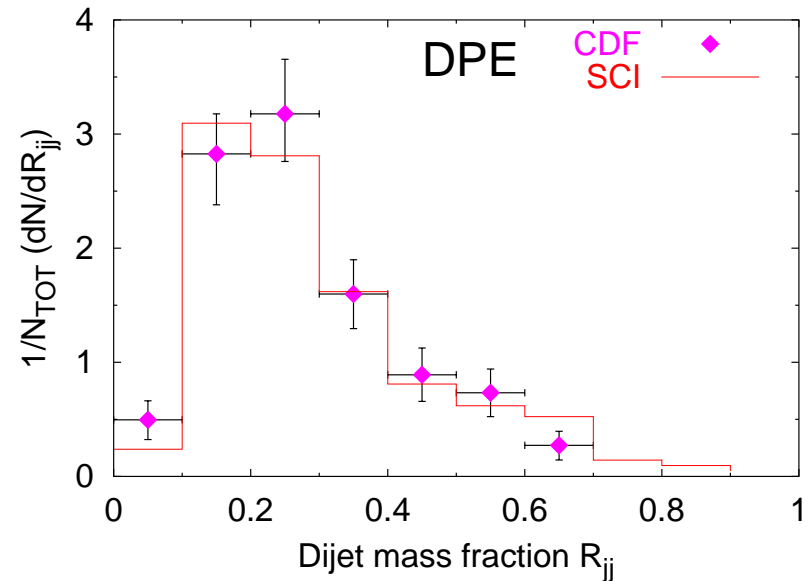


Tevatron $p\bar{p} \rightarrow$ dijets in DPE
 defined by leading \bar{p} and gap on p side

	CDF	SCI
\tilde{R}_{SD}^{DPE} [%]	0.80 ± 0.26	0.54
σ^{DPE} [nb]	43.6 ± 22.0	5–25

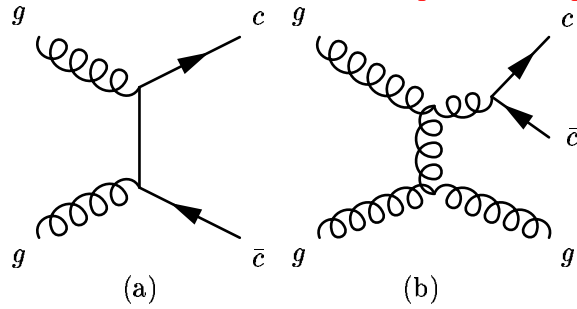
↑ ↑
proton gap

Strong dependence on remnant treatment
 Good ratios and cross sections



Measured dijet mass fraction
 $M_{jj}/\sqrt{\hat{s}}$ well reproduced

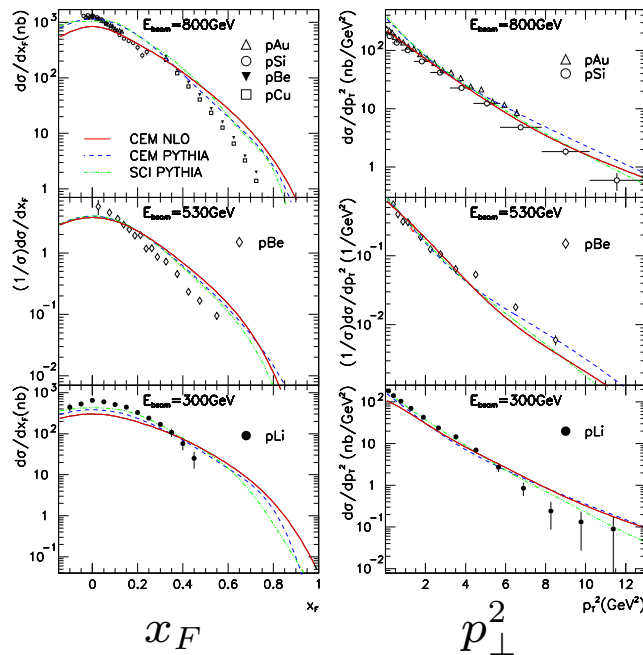
SCI → prompt charmonium and bottomonium



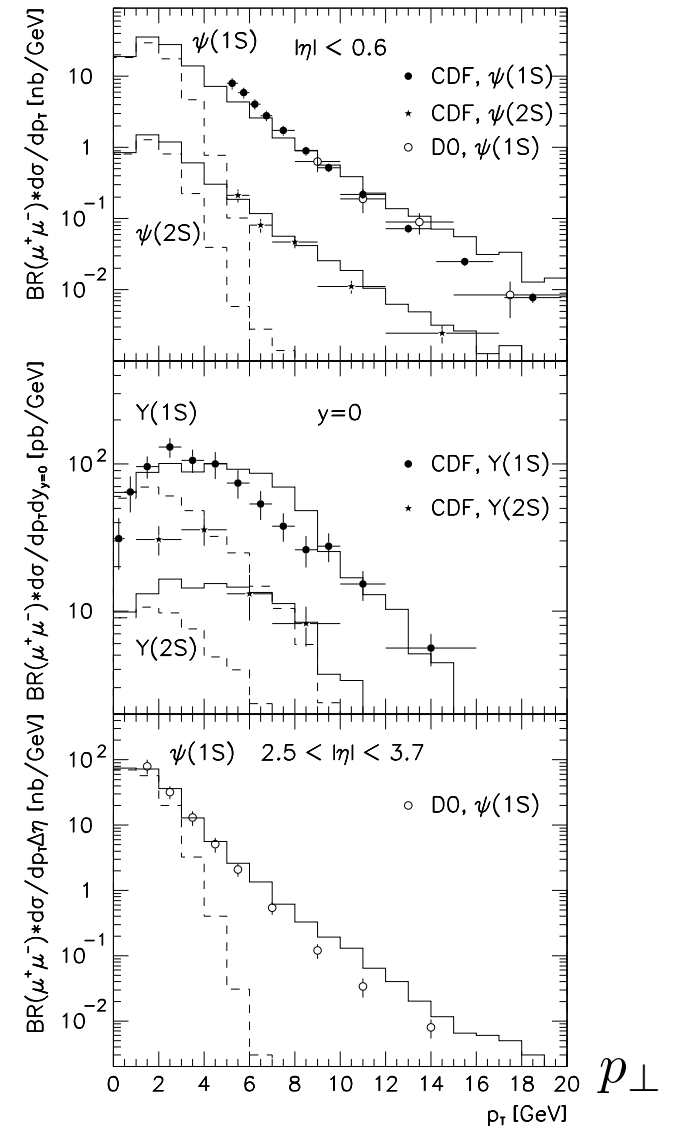
pert. QCD

↓
 $c\bar{c}$ pair

Colour octet $c\bar{c}$ turned into singlet $c\bar{c}$
 $m_{c\bar{c}} < 2m_D$ mapped on charmonium states
 with spin statistics (+ soft smearing)



pA @
 800 GeV
 530 GeV
 300 GeV

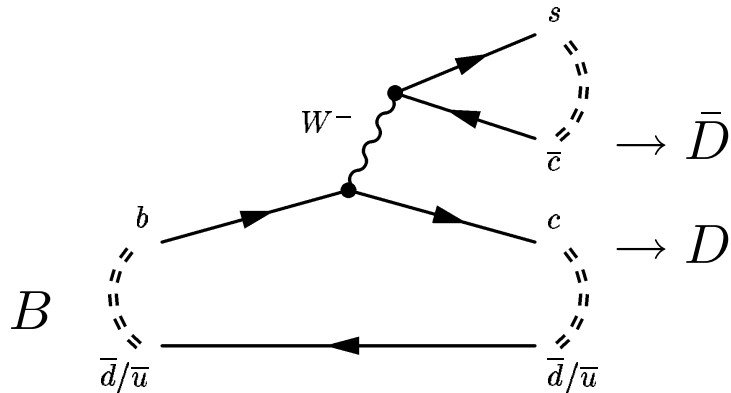


$J/\psi, \psi'$ in fixed target $\pi A, pA$ is OK

High- $p_{\perp} J/\psi, \psi', \Upsilon$ at Tevatron is OK

Soft colour interactions in B -decays

Normal decay mode $\rightarrow D$ meson



Make fit to branching ratios

$B \rightarrow D_s D, B \rightarrow J/\psi K_S$ (\mathcal{CP}),

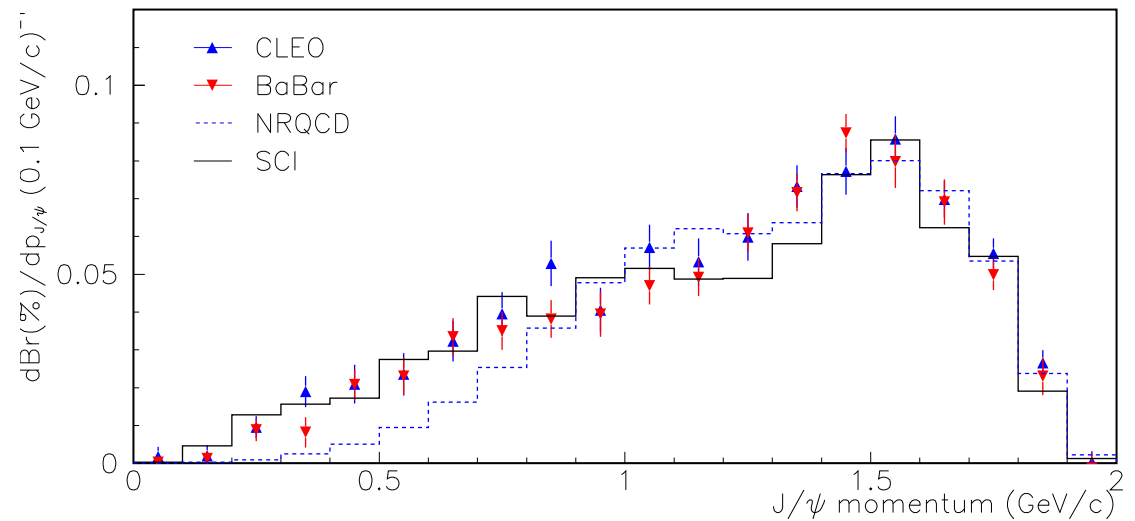
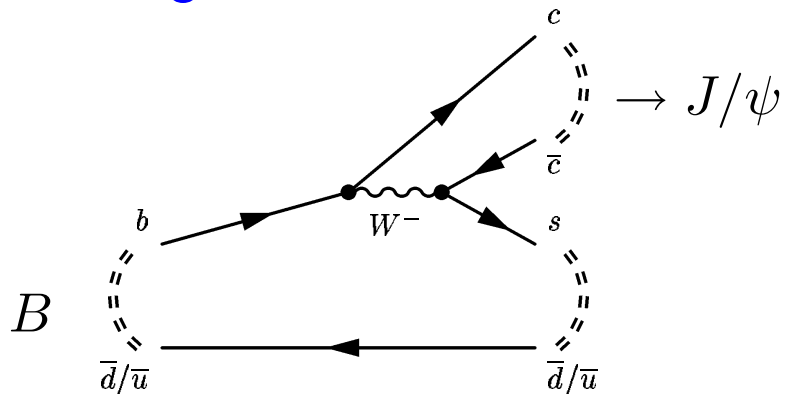
$B \rightarrow D_s X, B \rightarrow J/\psi X$

to fix a few parameters

Gives good overall description:

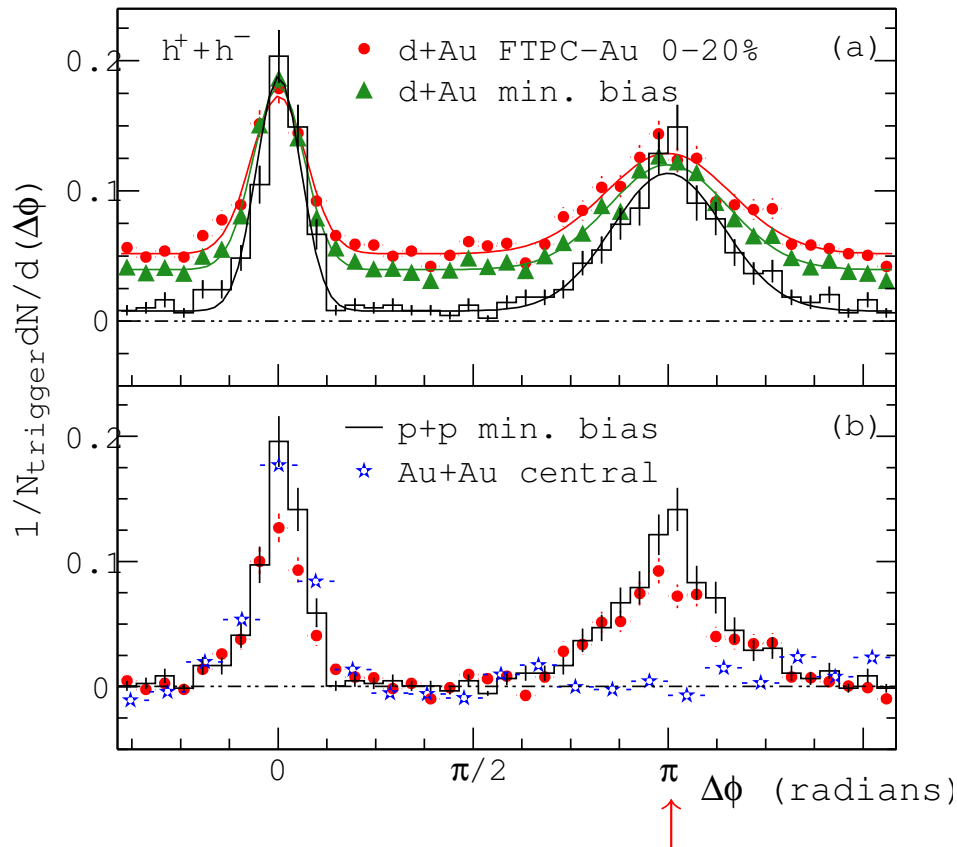
incl. J/ψ momentum distribution

Colour-suppress decay mode, enhanced by SCI colour rearrangement



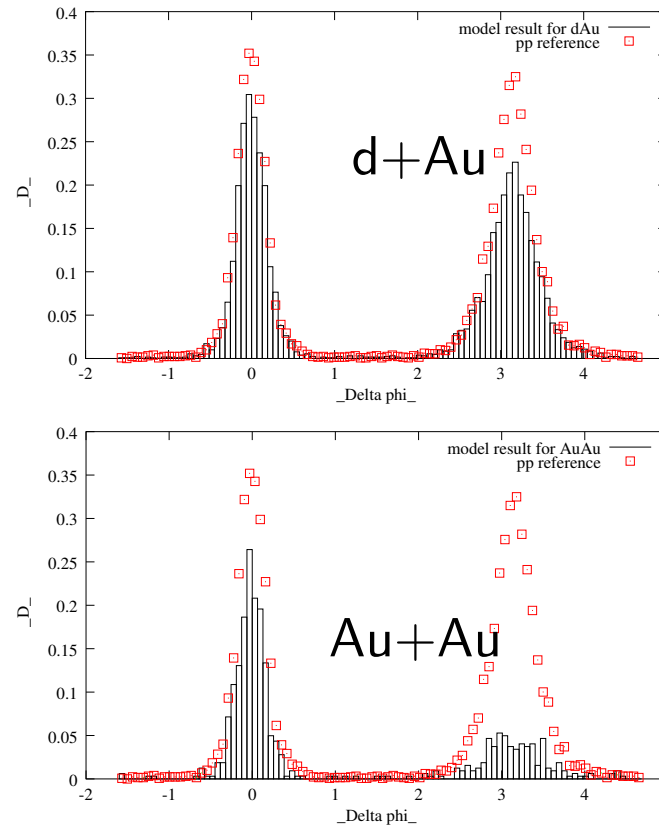
Jet quenching in quark-gluon plasma

Hadron flow in azimuth $\Delta\phi$
relative to trigger particle/jet



Disappearance of back-to-back jet
in central gold-gold collisions

Soft colour interactions of parton
with background quark-gluon plasma



Reproduces effects qualitatively,
but depends on model details ...

K. Zapp
Uppsala-
Heidelberg
collaboration

New theoretical basis for SCI model

Brodsky, Enberg, Hoyer, GI, hep-ph/0409119, PR D

Parton rescattering in QCD:

Leading twist gluon exchange between fast outgoing partons and target 'spectators'

Instantaneous 'Coulomb' gluons (light-front/Breit frame)

→ soft rescattering on 'frozen' target

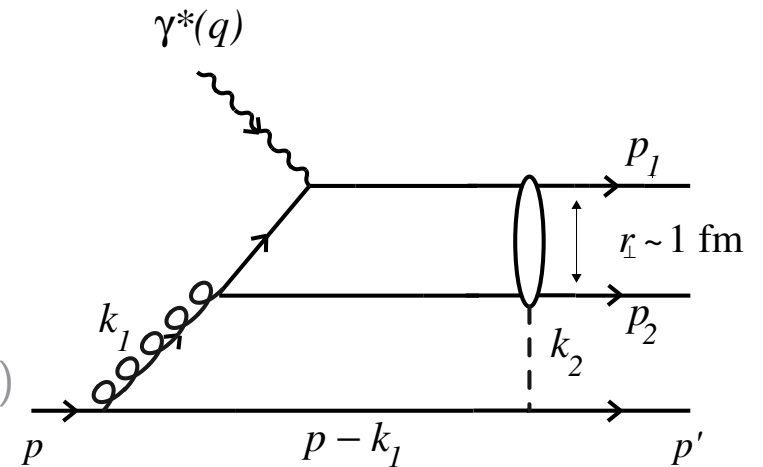
Gluon attached *after* photon vertex ⇒ no pre-existing pomeron in proton

Shadowing and diffraction are rescattering effects

Colour exchange → modified colour (string) field topology

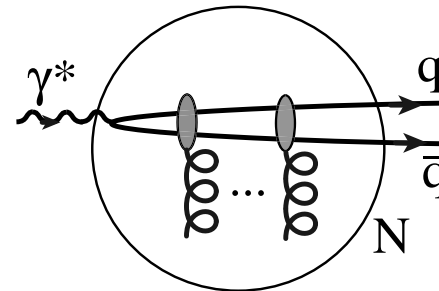
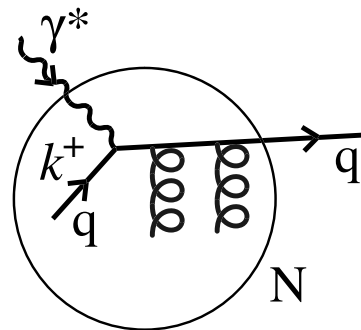
→ modified hadronic final state → gaps may arise

- gluon k_2 quickly after k_1 ⇒ can screen colour giving singlet exchange
- even/odd # gluons → pomeron/odderon exchange
- path-ordered exponential of gluon field (Wilson line)
- on-shell intermediate state ⇒ imaginary amplitude ↔ diffraction
 k_2 is 'soft' → small kinematic effect
- $F_2^D \sim g_p(x_{\mathbb{P}}) q_g(\beta)$: gluon distr. ↔ \mathbb{P} and $g \rightarrow q\bar{q}$ (or gg) gives β -dependence



DIS on the 'Light Front'

Light Front (LF, or Light Cone LC) formalism – invariant under boosts along z
 → proton rest frame: interpretation depends on q_z (LF time $x^+ = t + z$)



'parton model' frame:

$$q = (\nu, 0, 0, -\sqrt{\nu^2 + Q^2})$$

$$q^+ \simeq -m_p x_B, \quad q^- \simeq 2\nu$$

Photon probes target at an
 instant in LF time x^+

'dipole model' frame:

$$q = (\nu, 0, 0, +\sqrt{\nu^2 + Q^2})$$

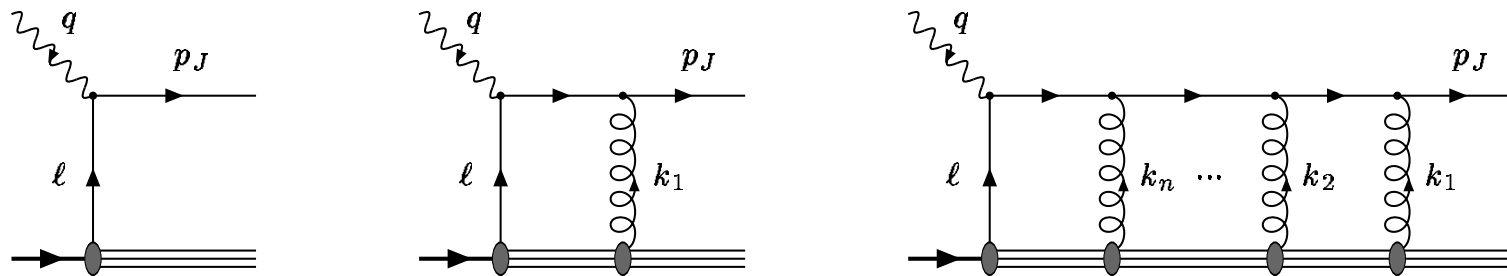
$$q^+ \simeq 2\nu, \quad q^- \simeq -m_p x_B$$

Dipole scatters on target
 within finite LF time x^+

The gluons are rescatterings within coherence (loffe) length $x^- \sim 1/m_p x_B$

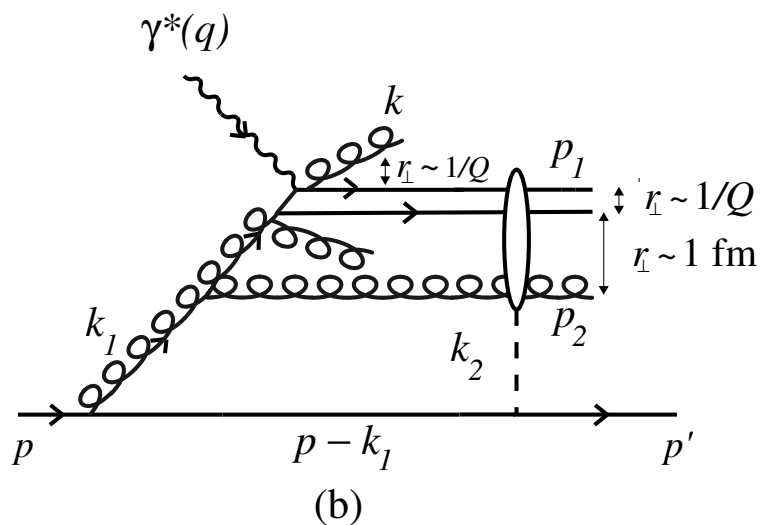
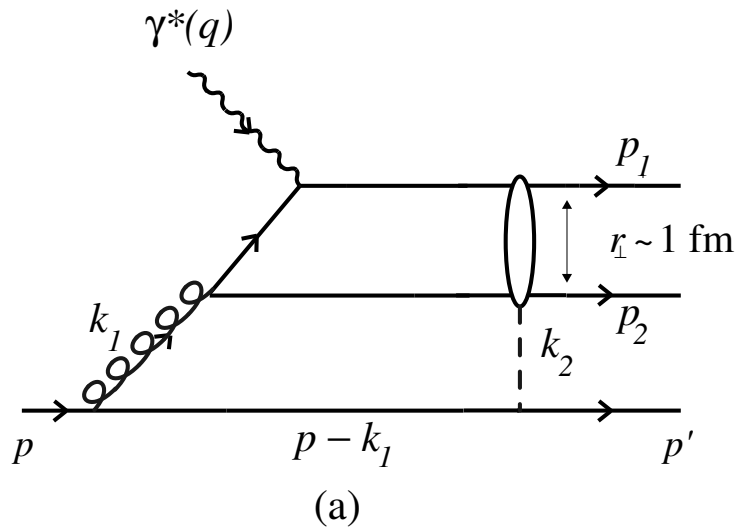
QCD rescattering and factorisation in DIS

The Wilson line means that DIS looks something like this:



- Rescattering compatible with factorization theorems *by construction*
Wilson line part of definition of PDF \Rightarrow rescattering part of PDF
- Experimentally measured PDF's *include* rescattering
- Diffractive PDF's included in inclusive PDF's
- Rescattering can give on-shell intermediate states and *imaginary amplitudes* \Rightarrow diffraction

Mechanism for diffraction in DIS



The 'pomeron remnant' is soft
— first splitting is in the sea

1. A soft gluon with $k_1^+ / p^+ \sim x_{\mathbb{P}}$ splits into large $q\bar{q}$ pair
 $g \rightarrow q\bar{q} \Rightarrow f(\beta) \sim \beta^2 + (1 - \beta)^2$
2. The γ^* scatters and a large size $q - \bar{q}$ 'dipole' is formed
3. **Instantaneous gluon exchanges** may make dipole color singlet

- At large M_X , $q\bar{q} - g$ dipole dominates
 - soft gluon splits into gg pair
 $g \rightarrow gg \Rightarrow f(\beta) \sim 1/\beta$
 - compact $q\bar{q}$ pair not resolved

- Higher order emissions do not destroy the rapidity gap!

$k_\perp \gg p_{2\perp}$ and $k^+ \lesssim p_2^+$
 \Rightarrow rapidity of k larger than that of p_2

Radiation is close to γ^* vertex and is not resolved by the rescattering

Consequences for diffractive DIS

- Same hard sub-process in diffractive and non-diffractive events
- Same Q^2 dependence in diffractive and inclusive DIS
- Same energy (W or x_B) dependence in diffractive and inclusive DIS

$\Rightarrow \sigma_{\text{diff}}/\sigma_{\text{tot}}$ independent of x_B and Q^2 , as observed in data

- Amplitudes from rescattering dominantly imaginary, as expected for diffraction
- Rescattering gluons have small momenta $\Rightarrow \beta$ dependence of diffractive PDF's from underlying (non-perturbative) $g \rightarrow q\bar{q}$ and $g \rightarrow gg$ processes

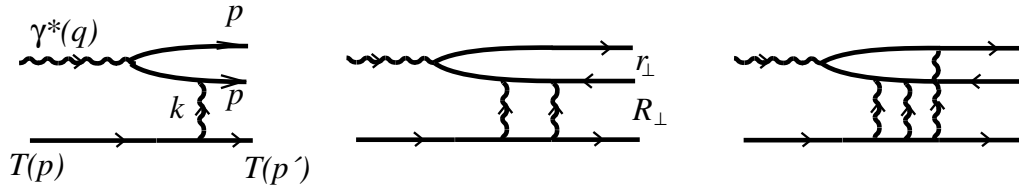
- Effective \mathbb{P} flux:
$$f_{\mathbb{P}/p}(x_{\mathbb{P}}) \sim g(x_{\mathbb{P}}, Q_0^2)$$

Effective \mathbb{P} structure function:
$$f_{q/\mathbb{P}}(\beta, Q_0^2) \sim \beta^2 + (1 - \beta)^2$$

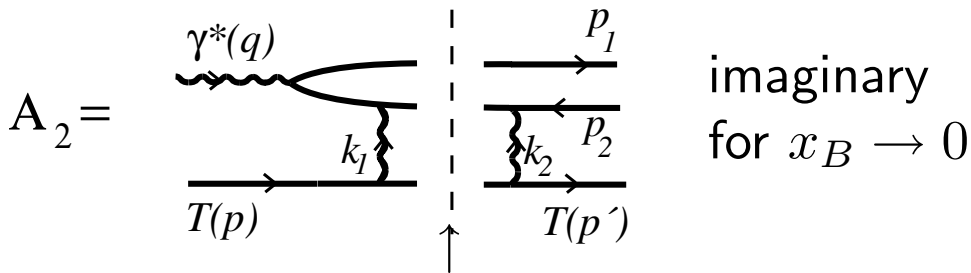
$$f_{g/\mathbb{P}}(\beta, Q_0^2) \sim 1/\beta$$

Colour coherence and SCI

Resolve partons \Leftrightarrow short gluon wave length



Amplitudes for 1, 2, ... n-gluon exchange



\Rightarrow on-shell intermediate state

\Rightarrow factorized amplitudes:

$$A_1 = eg^2 \mathcal{C} V(m, x_B, \mathbf{r}_\perp) W(\mathbf{r}_\perp, \mathbf{R}_\perp)$$

$$A_2 = \frac{-ieg^4}{2} \mathcal{C} V(m, x_B, \mathbf{r}_\perp) W^2(\mathbf{r}_\perp, \mathbf{R}_\perp)$$

$$= \frac{-ig^2}{2!} W A_1$$

\vdots

$$A_n = \frac{(-ig^2)^{n-1}}{n!} W^{n-1} A_1$$

\mathcal{C} = kinematics, V = photon wave function

Fourier transform to coordinate space

\mathbf{r}_\perp $q\bar{q}$ colour dipole size

\mathbf{R}_\perp conjugate coord. to \mathbf{k}_\perp

frozen during scattering process

$$W(\mathbf{r}_\perp, \mathbf{R}_\perp) = \frac{1}{2\pi} \log \frac{|\mathbf{R}_\perp + \mathbf{r}_\perp|}{|\mathbf{R}_\perp|}$$

\Rightarrow gluon coupling to dipole decreases

for $|\mathbf{r}_\perp|/|\mathbf{R}_\perp| \lesssim 1$, i.e. $|\mathbf{k}_\perp| \lesssim 1/|\mathbf{r}_\perp|$

\Rightarrow SCI colour exchange probability

should vary dynamically with W^2

Softer (k_\perp) gluon \rightarrow less interaction with small colour dipole (not resolved)

\updownarrow

colour coherence

Summary

SCI model OK with data:

- gap events in DIS
- leading protons/neutrons in DIS
- diffractive jets, W , Z , $b\bar{b}$, J/ψ at Tevatron
- high- p_{\perp} J/ψ , ψ' , Υ at Tevatron
- J/ψ , ψ' in fixed target πA and pA

Not bad for simple (one-parameter) model !

\exists alternative/related models

Parton rescattering theory in QCD:

- Hard sub-process universal
not affected by soft interaction
- PDF \sim LF wave fcn \otimes soft rescattering
- Rescattering via soft gluons,
instantaneous in LF time
May shield colour \rightarrow rapidity gap
- Soft rescattering does not resolve
hard emissions
- Different colour environments
(particles/collisions)
 \Rightarrow diffraction/gaps process dependent

Conclusions

- Non-perturbative QCD is major unsolved problem
 - QCD rescattering theory
 - theory for diffraction/gaps
 - IP not in proton wave function, but effect of scattering
 - ↪ avoids IP problems (conceptual, flux)
 - ↪ one model for gap and no-gap final states
 - basis for successful SCI model, implies developments
 - e.g.* colour coherence from dynamical gluon exchange probability
 - Parton interaction with colour field, 'old' idea with new aspects
 - parton traversing quark-gluon plasma → jet quenching
 - Wilson loop over colour field → semiclassical approach
 - But, still gaps in my (our) understanding
 - Future with interesting problems
 - New ideas/approaches, new collaborations ⇔ Lots of fun
- ⇒ Better understanding of non-perturbative QCD

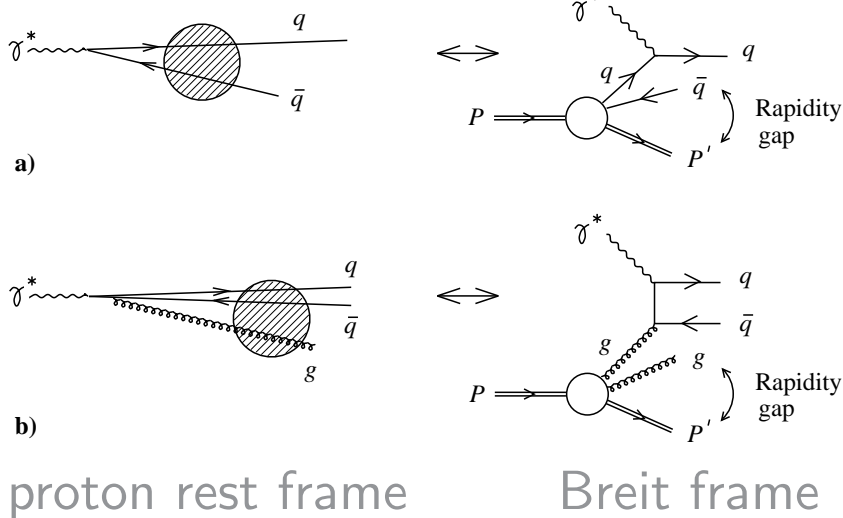
Additional material . . .

Related models

- **Colour evaporation model** (Halzen *et al.*)
many exchanges \rightarrow random colour
Diffractive DIS (Buchmüller *et al.*)
 $\gamma g \rightarrow q\bar{q}$ octet \rightarrow singlet $q\bar{q}$ (prob=1/9)
which decouples from remnant \rightarrow gap event
- **Interactions with background colour field** (Nachtmann *et al.*)
e.g. quark traversing colour field gives 'synchrotron' radiation
of soft γ 's
- **Semiclassical model** (Buchmüller, Hebecker *et al.*)
Diffractive DIS: $\gamma \rightarrow q\bar{q}$ which traverses proton colour field
interaction \sim Wilson loop averaging over colour field
- **String reconnection models** (Lund group)
e.g. applied to $e^+e^- \rightarrow WW \rightarrow q\bar{q} q\bar{q}$
gives shift in W mass determination

Semiclassical approach

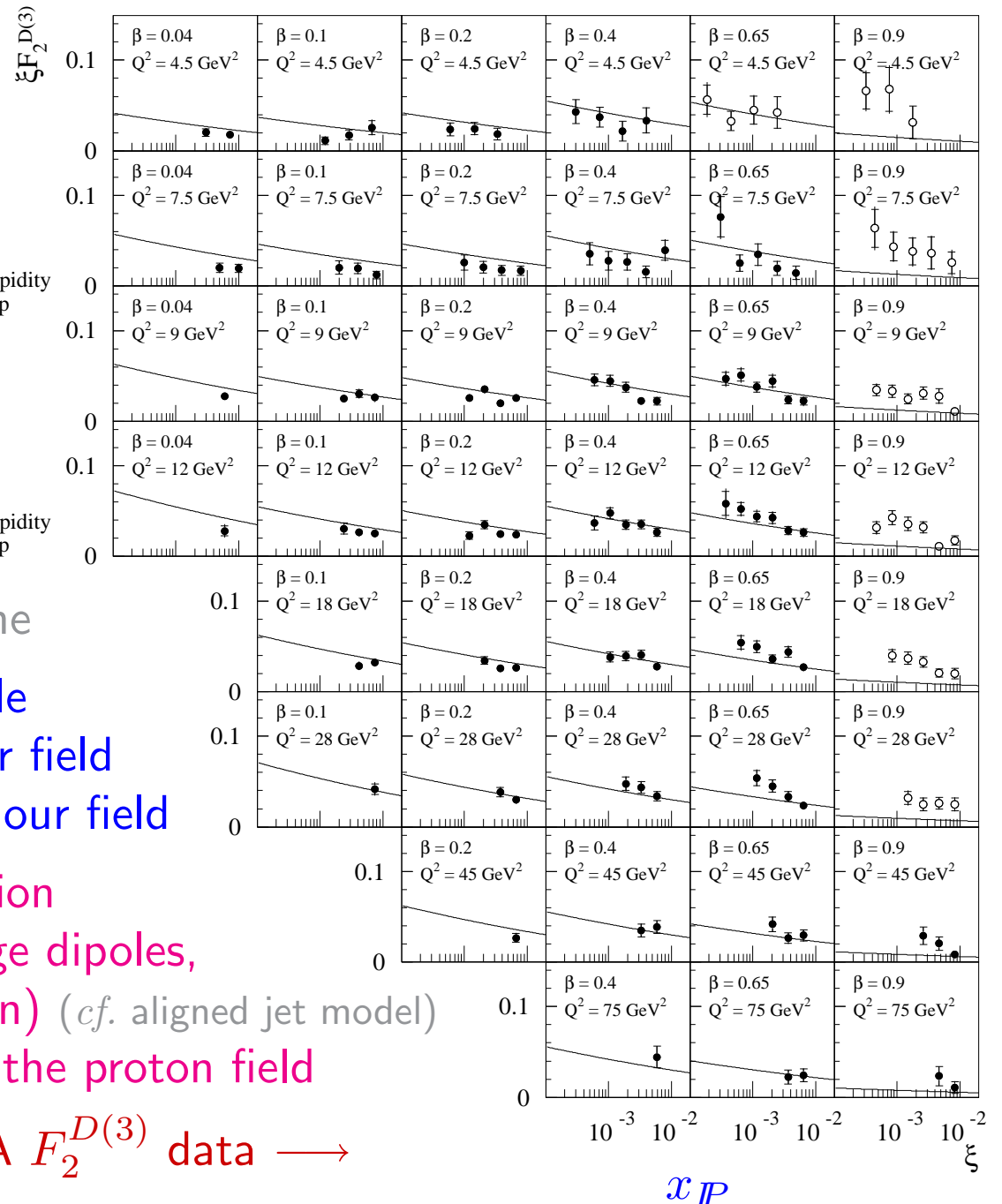
Buchmüller, Hebecker *et al.*



p rest frame: $\gamma \rightarrow q\bar{q}$ or $q\bar{q}g$ dipole
 soft interaction with proton colour field
 estimated by Wilson loop over colour field

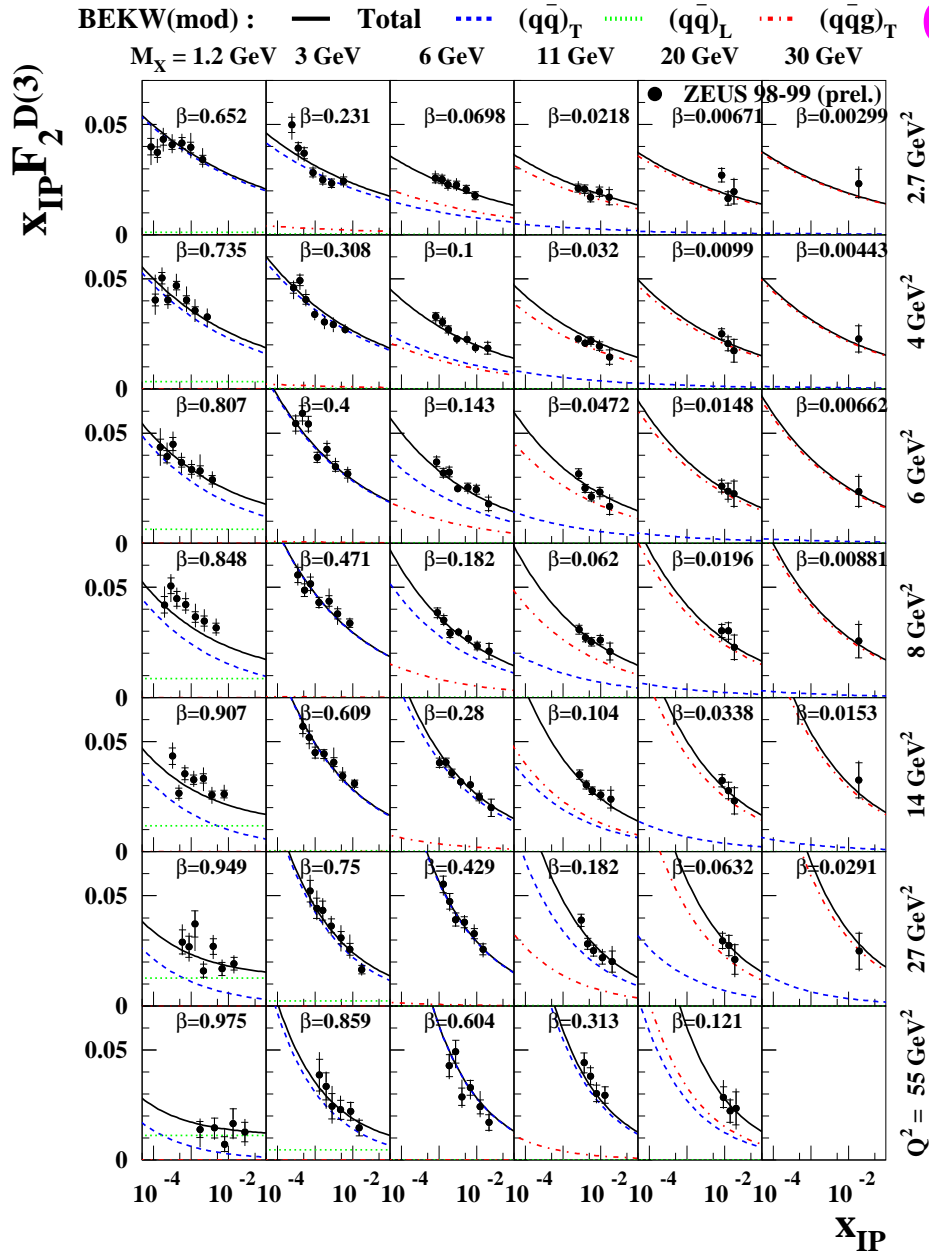
Color singlet exchange \Rightarrow diffraction
 Leading twist diffraction from large dipoles,
 with one soft parton (mostly gluon) (*cf.* aligned jet model)
 which tests the large distances in the proton field

Model fits HERA $F_2^{D(3)}$ data \longrightarrow

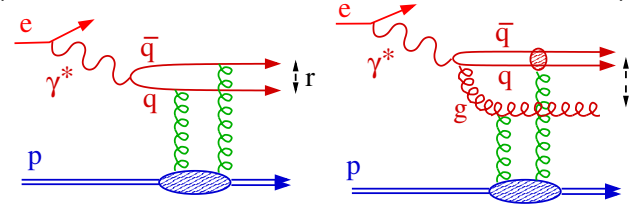


Perturbative QCD approach for two-gluon exchange

Comparison with the BEKW model



(Bartels, Ellis, Kowalski and Wüsthoff, 1998)



- $x_{IP} F_2^{D(3)} = c_T \cdot F_{q\bar{q}}^T + c_L \cdot F_{q\bar{q}}^L + c_g \cdot F_{q\bar{q}g}^T$

$$F_{q\bar{q}}^T = \left(\frac{x_0}{x_{IP}}\right)^{n_T(Q^2)} \cdot \beta(1 - \beta),$$

β from theory

$$F_{q\bar{q}}^L = \left(\frac{x_0}{x_{IP}}\right)^{n_L(Q^2)} \cdot \frac{Q_0^2}{Q^2 + Q_0^2} \cdot x_{IP} \text{ fitted}$$

$$\left[\ln\left(\frac{7}{4} + \frac{Q^2}{4\beta Q_0^2}\right)\right]^2 \cdot \beta^3(1 - 2\beta)^2,$$

$$F_{q\bar{q}g}^T = \left(\frac{x_0}{x_{IP}}\right)^{n_g(Q^2)} \cdot \ln\left(1 + \frac{Q^2}{Q_0^2}\right) \cdot (1 - \beta)^\gamma$$

From data, $n_L(Q^2) \approx 0$ and

$$n_T(Q^2) \approx n_g(Q^2) \approx n_1 \ln\left(1 + \frac{Q^2}{Q_0^2}\right)$$

$$\therefore c_T = 0.117 \pm 0.003, c_L = 0.171 \pm 0.012$$

$$c_g = 0.0093 \pm 0.0003, n_1 = 0.066 \pm 0.003$$

$$\gamma = 8.32 \pm 0.51, \chi^2/\text{ndf} = 132/198$$

- $(q\bar{q})_L$ only substantial at very large β
- $(q\bar{q})_T$ dominates at $\beta > 0.15$
- $(q\bar{q}g)_T$ dominates at small β

Gap between jets \Rightarrow hard QCD exchange

Rapidity gap between a pair of jets

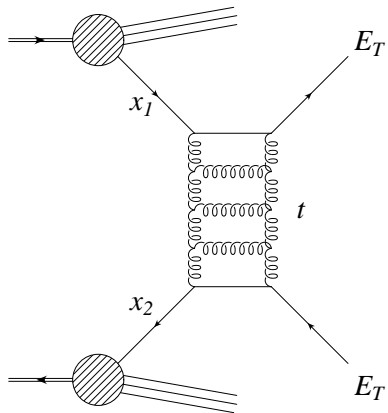
- $\rightarrow |t|$ across gap is large
- \rightarrow different from “normal” diffraction

Elastic parton-parton scattering by hard colour singlet exchange (hard pomeron)

High energy limit $s/|t| \gg 1 \Rightarrow$ amplitude dominated by terms $\sim [\alpha_s \ln(s/|t|)]^n$

BFKL equation resums these terms, with

- virtual corrections
- reggeization of exchanged gluons

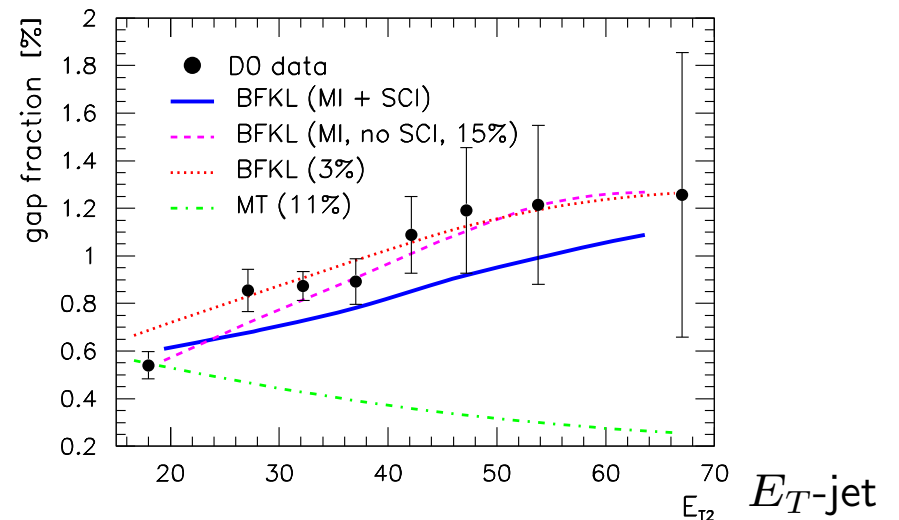


Evidence for BFKL dynamics \Leftrightarrow

Enberg, GI, Motyka, PL B524 (2002) 273

Numerical solution of BFKL eqn. with non-leading corrections

consistency constraint & running coupling in PYTHIA reproduces Tevatron data



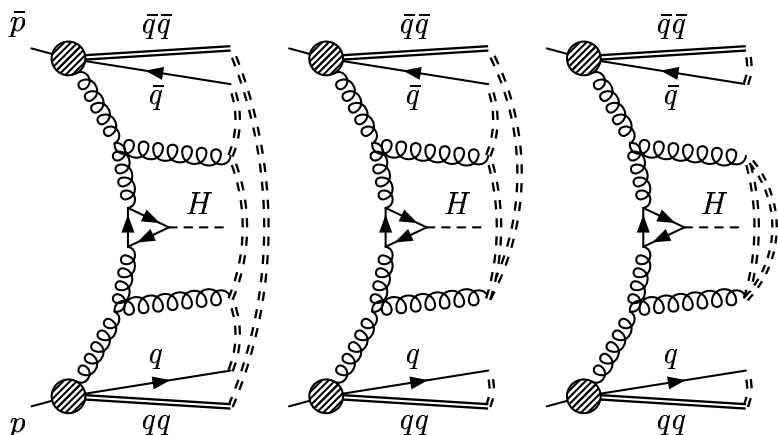
E_T and $\Delta\eta$ dependences OK

asymptotic Mueller-Tang \Rightarrow wrong E_T -dep.

Absolute normalisation OK

correct gap survival probability with SCI that destroy gaps

SCI \rightarrow diffractive Higgs at Tevatron/LHC



Idea: diffractive events cleaner
 \rightarrow easier Higgs reconstruction
 \rightarrow Higgs discovery channel ?

$m_H = 115 \text{ GeV}$		Tevatron $\mathcal{L} = 20 \text{ fb}^{-1}$	LHC $\mathcal{L} = 30 \text{ fb}^{-1}$
	$\sigma [\text{fb}]$ Higgs-total	600	27000
SD	$\sigma [\text{fb}]$ leading-p	1.2	190
	$\sigma [\text{fb}]$ gap	2.4	27
	$\#$ H + leading-p	24	5700
	$\hookrightarrow \#$ H $\rightarrow \gamma\gamma$	0.05	13
DPE	$\sigma [\text{fb}]$ leading-p's	$1.2 \cdot 10^{-4}$	0.19
	$\sigma [\text{fb}]$ gaps	$2.4 \cdot 10^{-3}$	$2.7 \cdot 10^{-4}$
	$\#$ H + leading-p's	0.0024	6

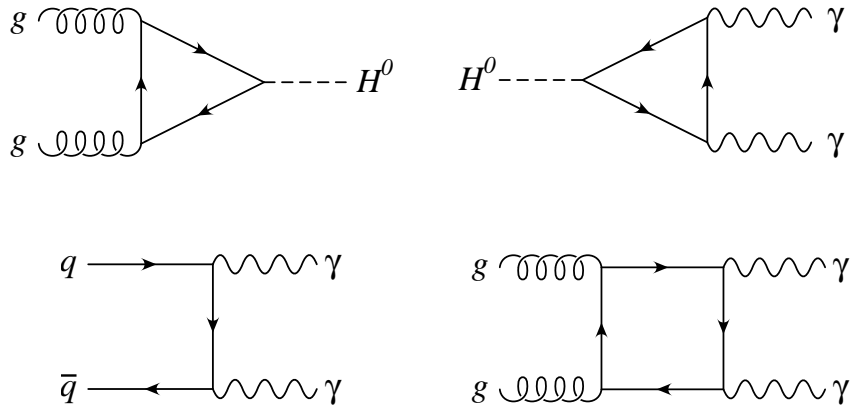
large m_H + large x_F proton \rightarrow kinematical conflict \rightarrow reduced cross-section

Tevatron: only few SD Higgs $\Rightarrow H \rightarrow b\bar{b}$ background/reconstruction problems

LHC: Higgs observable in SD (also $H \rightarrow \gamma\gamma$) and DPE

but not so clean since particles in 'gap' region \rightarrow 'pots' better

Diffractive $H \rightarrow \gamma\gamma$ and prompt $\gamma\gamma$



Prompt $\gamma\gamma$ irreducible background
 $> \sigma(H) \cdot \text{BR}(H \rightarrow \gamma\gamma)$

$\gamma\gamma$ tests gg fusion via quark loop
 \Rightarrow safer Higgs prediction

