Soft Colour Interactions and Parton Rescattering in QCD

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

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People involved:

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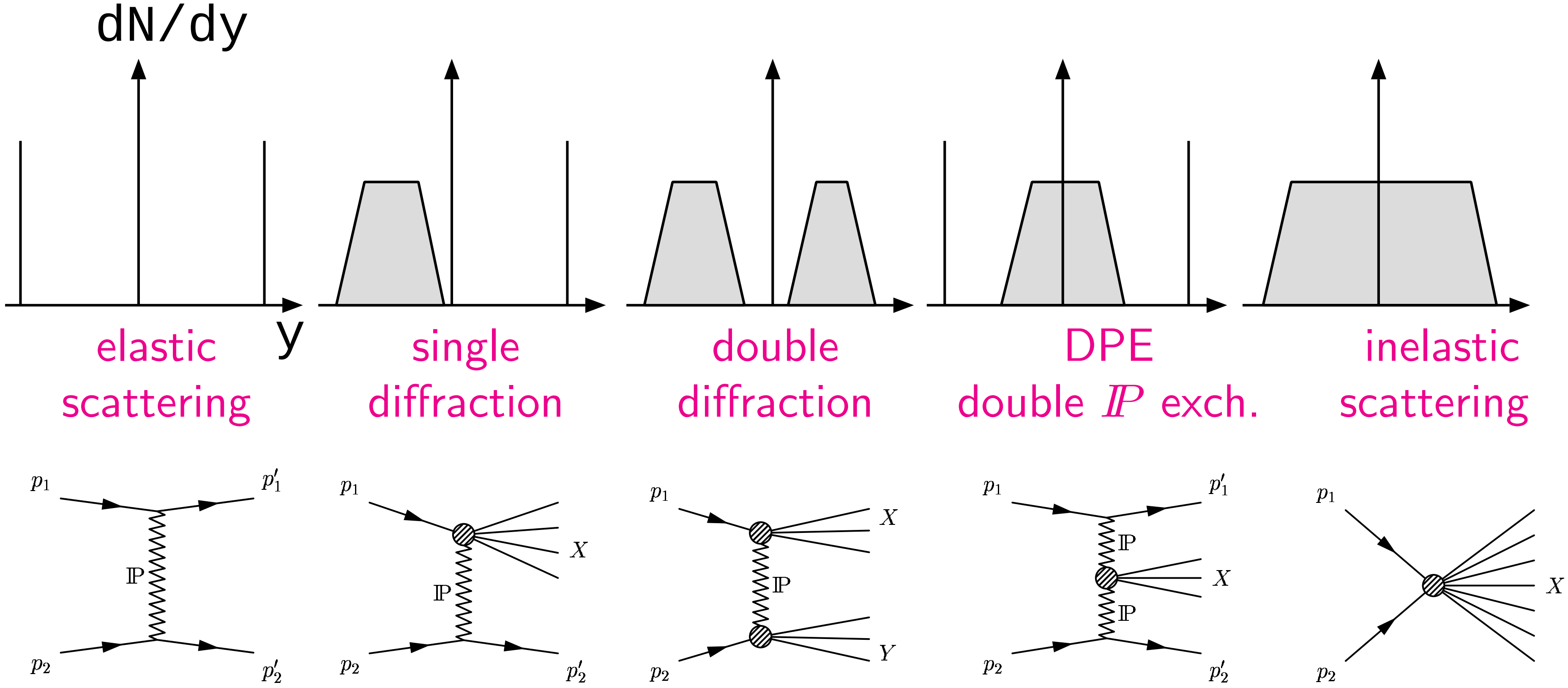
- Stan Brodsky
- Paul Hoyer

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

Rapidity gap events given by final state topology

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



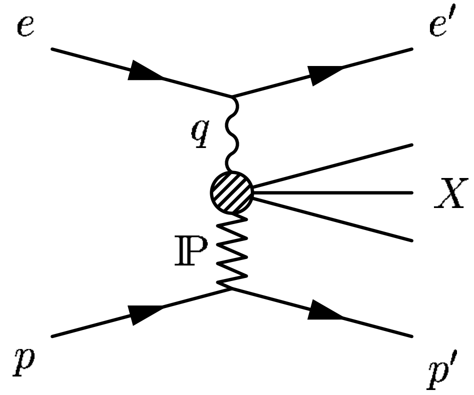
Pomeron exchange in Regge theory/phenomenology

Diffractive hard scattering

Idea:
Ingelman-Schlein, Physics Letters 1985
– hard scale probes parton level
– $I\!P$ flux
– $I\!P$ structure function
Predicted:
– jets etc. in single diffraction
– diffractive deep inelastic scatering

Discovery: UA8 at S$p\bar{p}$S 1988
– jets in single diffraction $\simeq$ model
– hard gluons $xg(x) \sim x(1-x)$ in $I\!P$
– 'superhard' $\delta(1-x)$ component
More exp's: HERA ep, Tevatron $p\bar{p}$

Diffractive DIS – HERA discovery



GI+Prytz 1993:

$$\frac{d\sigma}{dx\,dQ^2\,dx_{I\!P}\,dt} =$$

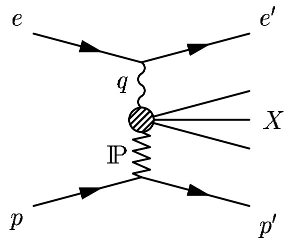
$$\frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right)F_2^{D(4)}$$

$$F_2^{D(4)}(x,Q^2,x_{I\!P},t) =$$

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

Fits HERA rapidity gap data

Pomeron problems:



- $I\!P$ model fitted to HERA data
  $\longrightarrow$ fails for Tevatron data
  σ(hard diffr) factor 6–100 too large
  $\longrightarrow$ need 'damping' at high energies,
  e.g. $I\!P$ flux 'renormalisation'

- $I\!P$ flux & structure not universal
  ill-defined for virtual $I\!P$

- Factorisation broken in diffractive $p\bar{p}$
  – coherent interactions

- Improper with $I\!P$ 'emitted' from p
  soft, long space-time-scale interaction
  $\longrightarrow$ $I\!P$–p cross-talk

Soft Colour Interactions:

- hard pQCD left unchanged
  – not affect by soft interactions

- non-pQCD below $Q_0^2 \sim 1$ GeV^2

- α_s large $\Rightarrow$ large interaction probability
  e.g. unity for hadronisation!

- no proper theory $\longrightarrow$ models

- colour exchange modifies colour/string
  topology $\longrightarrow$ different final state

- single model describing all final states
  – diffractive $\leftrightarrow$ nondiffractive

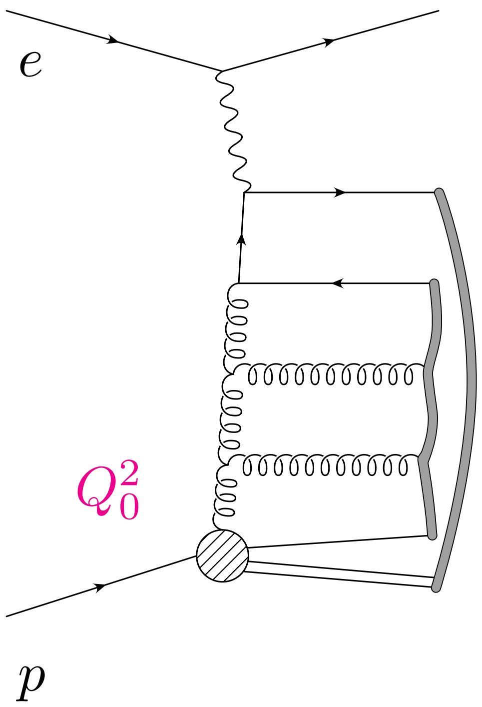
Soft Colour Interaction model (SCI)

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

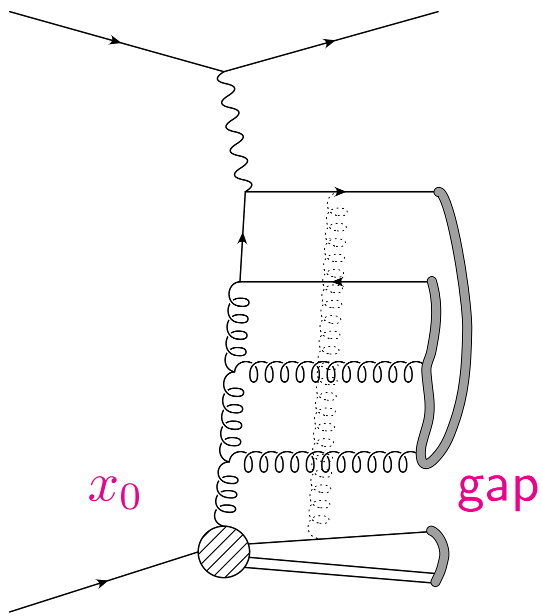
Add-on to Lund Monte Carlo's LEPTO (ep) and PYTHIA ($p\bar{p}$)

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

Single model describing all final states: diffractive $\leftrightarrow$ nondiffractive

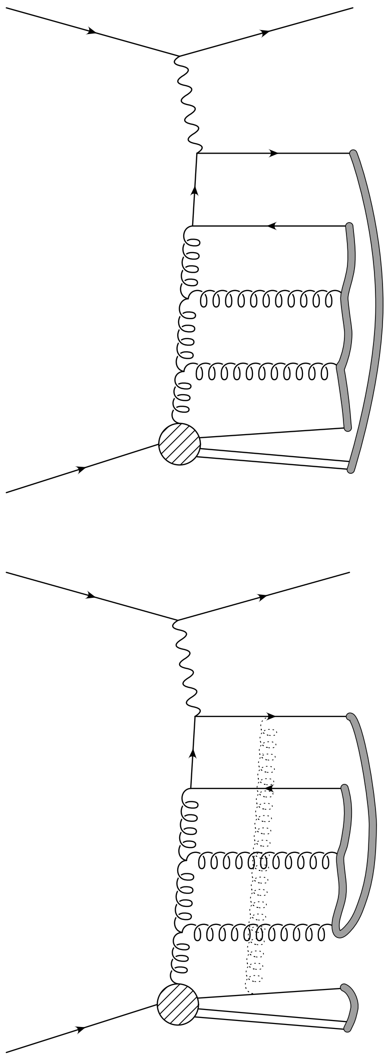


Single parameter $P = const \approx 0.5$
gives probability for soft ($p \simeq 0$)
colour-anticolour (gluon) exchange
between parton pairs,
determined from HERA rap-gap data

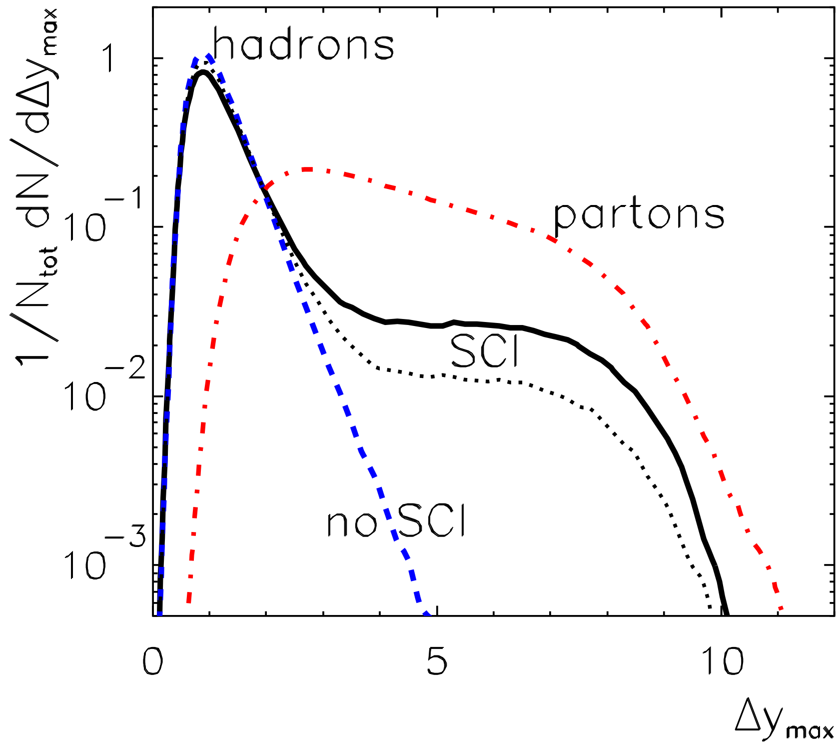


Proton remnant with $(1 - x_0)$ important for large gaps

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
— $P = 0.5$
$\cdots$ $P = 0.1$

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

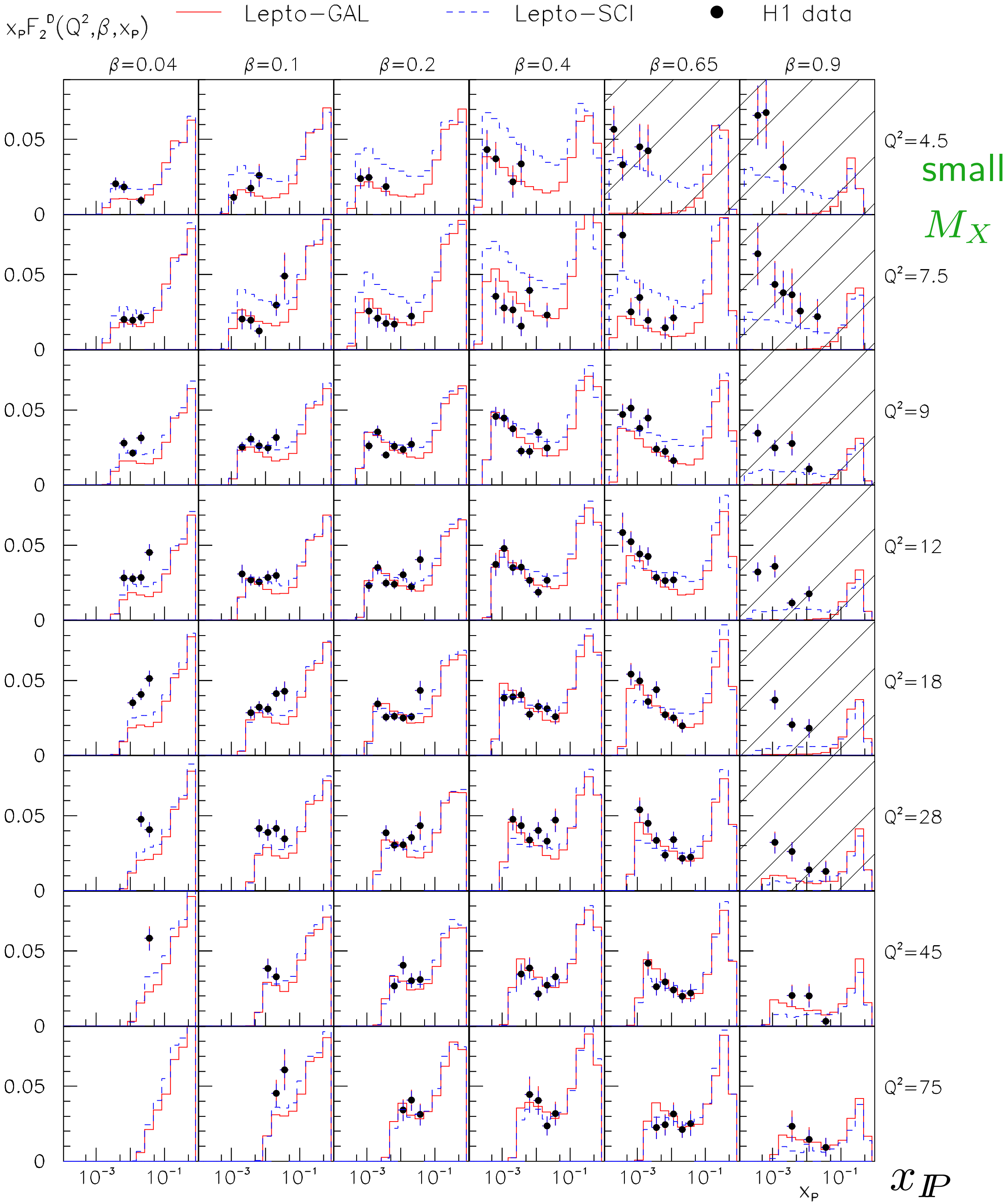
Diffractive structure function in DIS

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

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



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

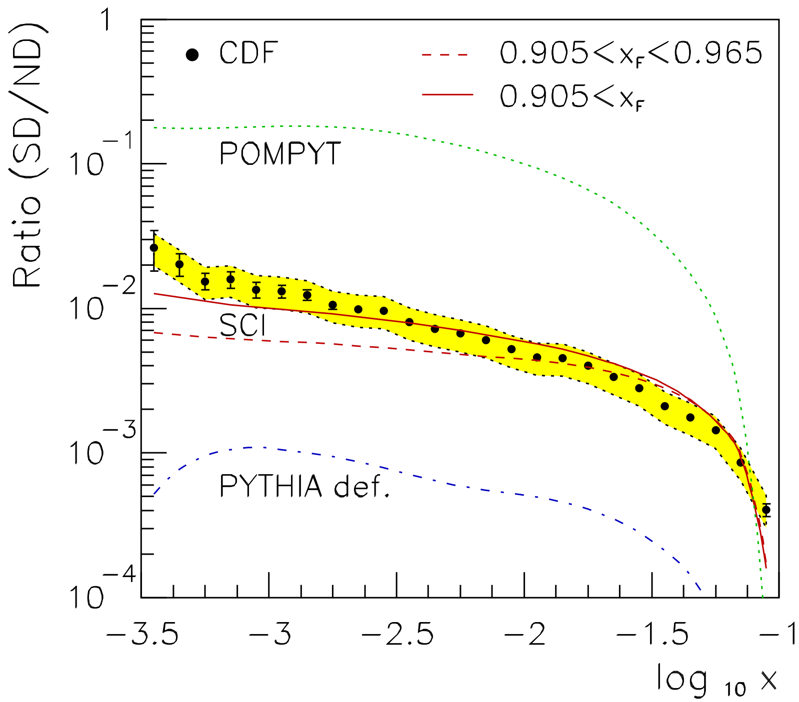
$$R_{\text{hard}} = \frac{1}{\sigma_{\text{hard}}^{\text{tot}}} \int_{x_{F\min}}^{1} dx_F \, \frac{d\sigma_{\text{hard}}}{dx_F}$$

$R_{\text{hard}}[\%]$	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

SCI → gap & $c\bar{c}$ colour octet → singlet → J/ψ

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



SCI model OK, Pomeron model too high, default PYTHIA too low

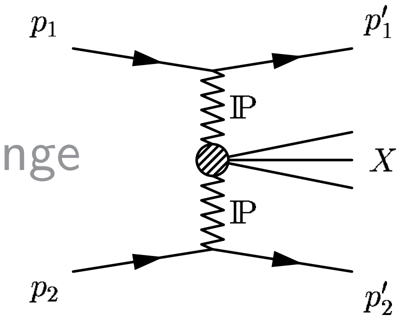
SCI also correctly describes two-gap events (Double Pomeron Exchange)

⇒ 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"

Double Pomeron Exchange



Tevatron $p\bar{p} \longrightarrow$ dijets in DPE

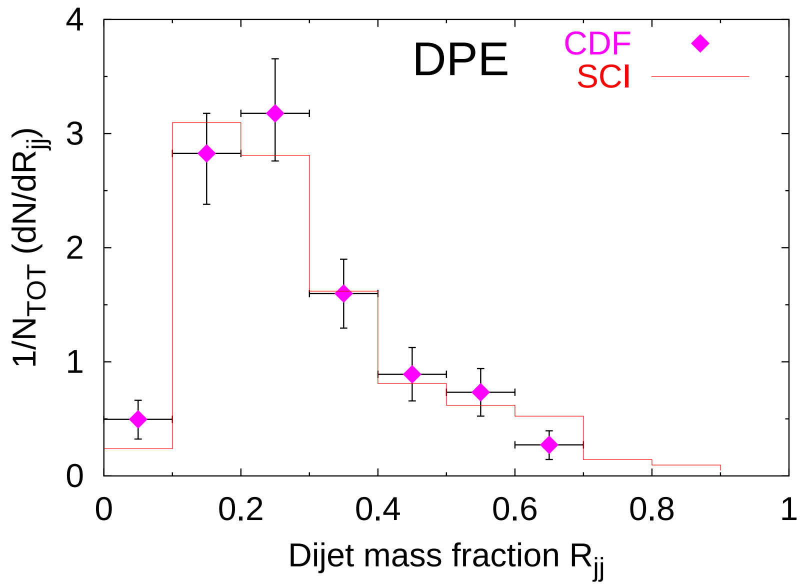
defined by leading $\bar{p}$ and gap on p side

	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

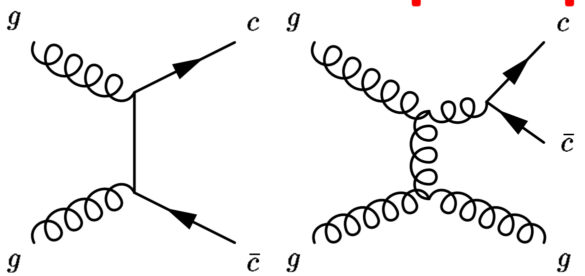
Good ratios and cross sections



Measured dijet mass fraction

$M_{jj}/\sqrt{\hat{s}}$ well reproduced

SCI → prompt charmonium and bottomonium

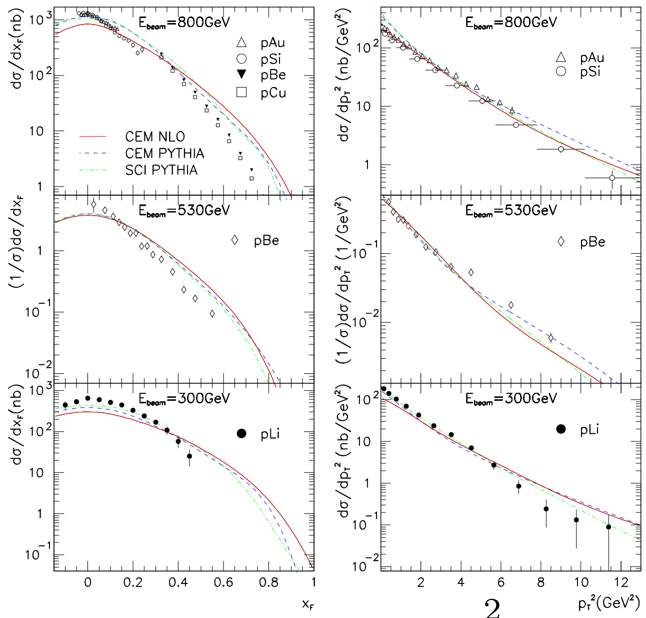


(a) (b)

pert. QCD
↓
$c\bar{c}$ pair

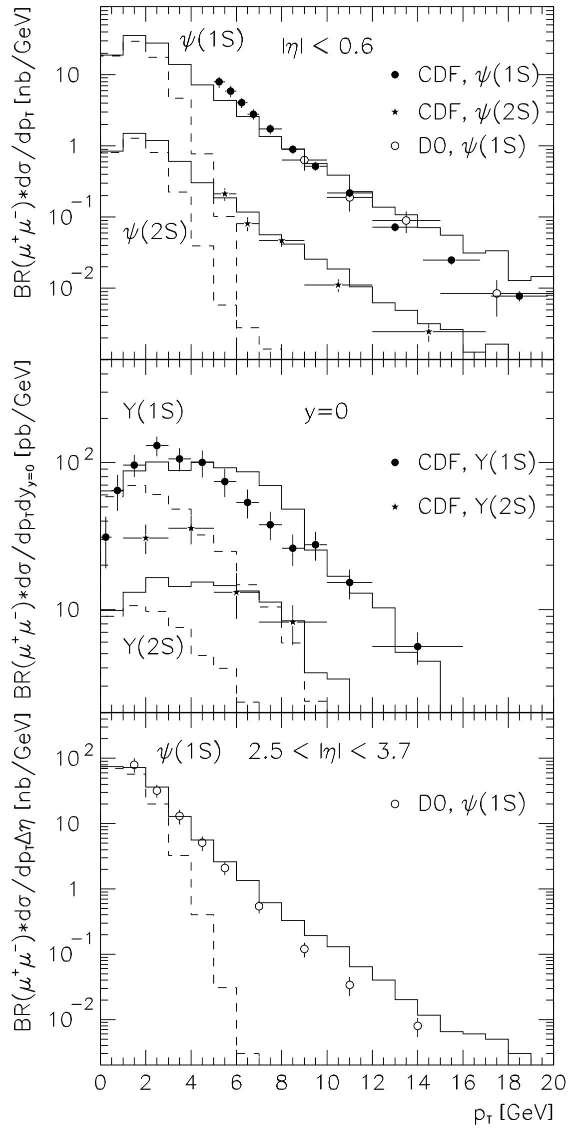
Colour octet $c\bar{c}$ turned into singlet $c\bar{c}$

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



x_F $p_\perp^2$

pA @
800 GeV
530 GeV
300 GeV

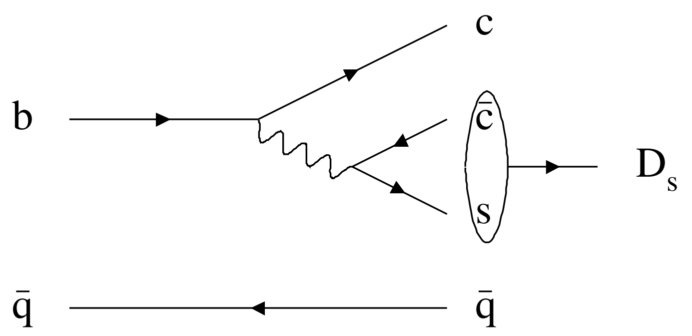


$p_\perp$

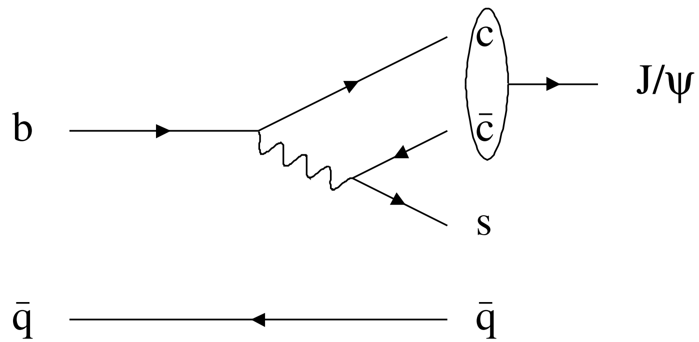
$J/\psi,\ \psi'$ in fixed target πA, pA is OK High-$p_\perp$ $J/\psi,\ \psi', \Upsilon$ at Tevatron is OK

Soft colour interactions in B-decays

Normal decay mode $\longrightarrow$ D meson

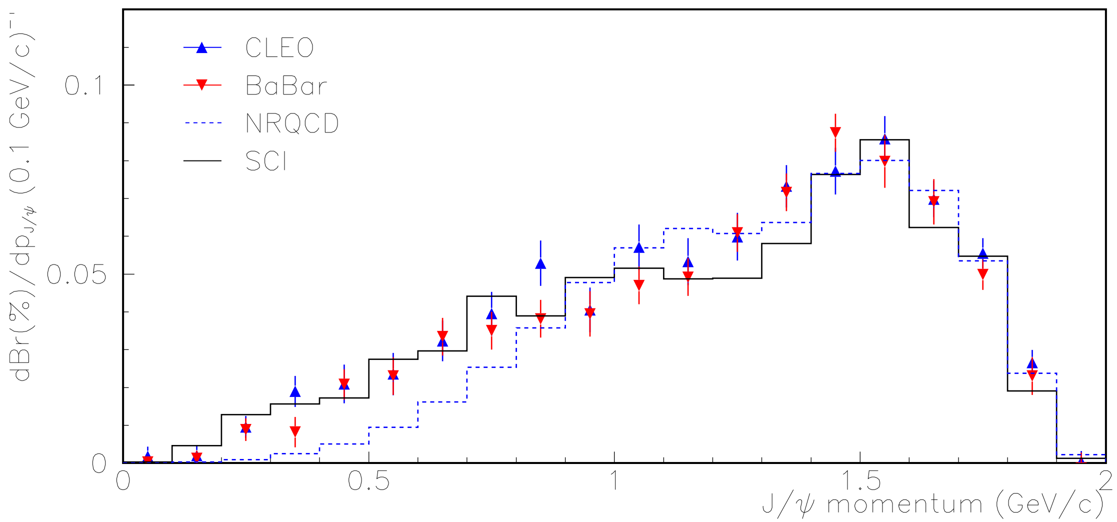


Colour-suppress decay mode, enhanced by SCI colour rearrangement



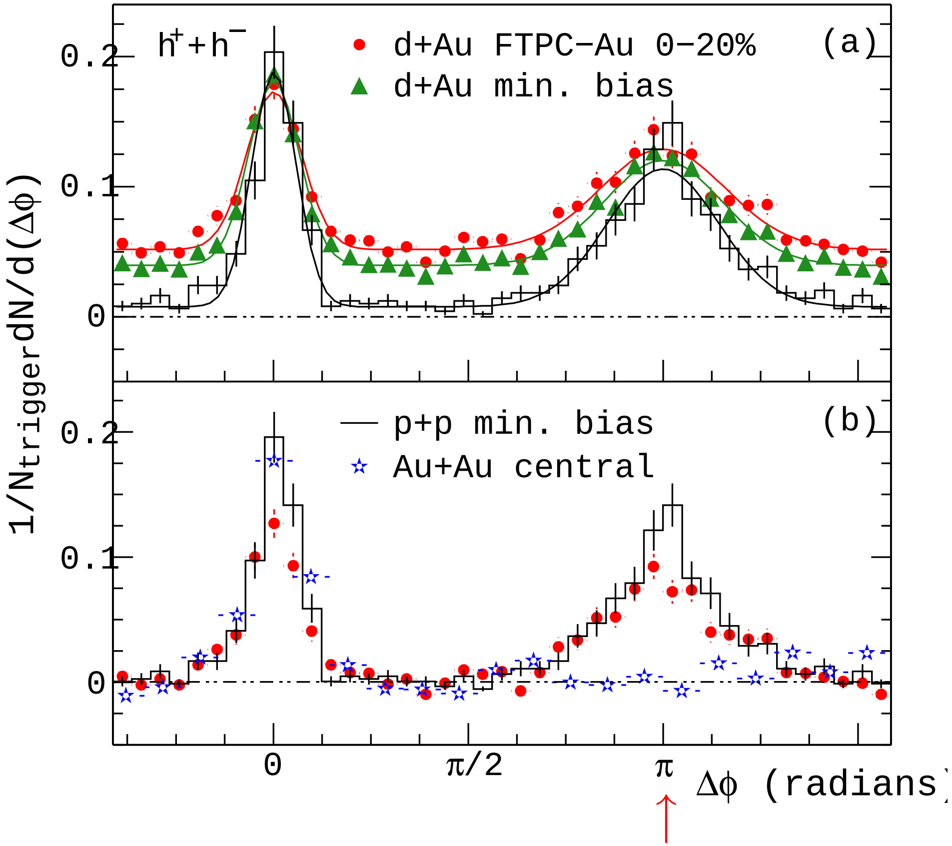
Make fit to branching ratios
$B \to D_s D$, $B \to J/\psi K_S$ (CP̸),
$B \to D_s X$, $B \to J/\psi X$
to fix parameters

Gives good overall description:
incl. J/ψ momentum distribution



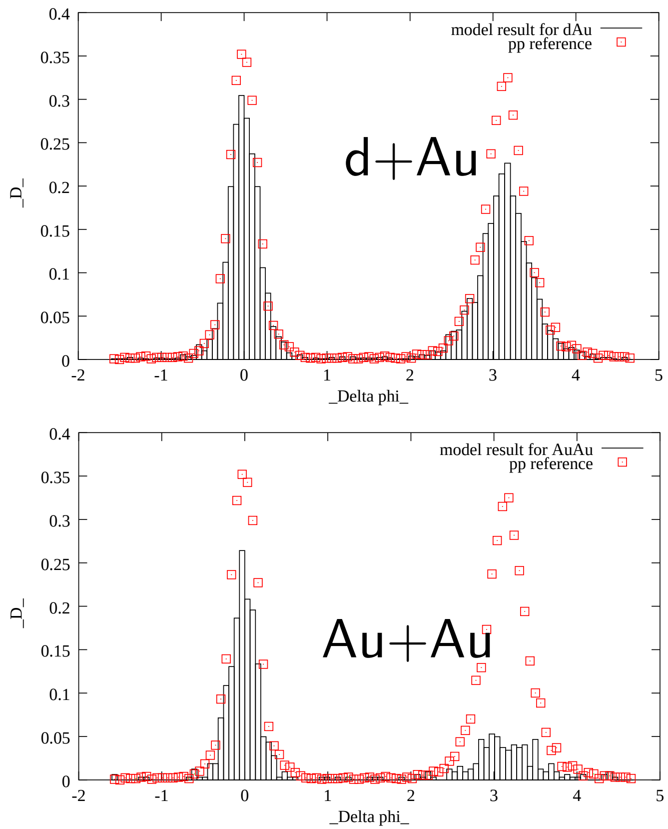
Jet quenching in quark-gluon plasma

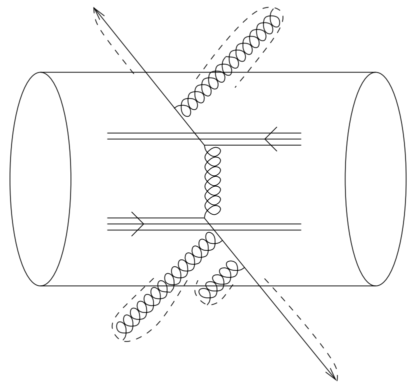
Hadron flow in azimuth $\Delta\phi$
relative to trigger particle/jet



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

Soft colour interactions of parton
with background quark-gluon plasma





K. Zapp

Uppsala–
Heidelberg
collaboration

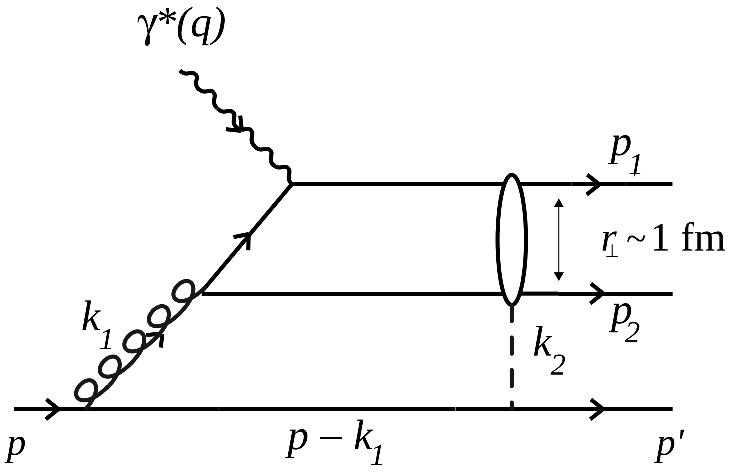
Reproduces effects qualitatively

New theoretical basis for SCI model

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

Parton rescattering in QCD:

Leading twist gluon exchange between
fast outgoing partons and target 'spectators'
Instantaneous 'Coulomb' gluons (light-front/Breit frame)
$\to$ soft rescattering on 'frozen' target



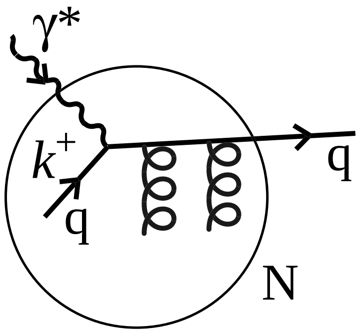
Gluon attached *after* photon vertex $\Rightarrow$ no pre-existing pomeron in proton
Shadowing and diffraction are rescattering effects

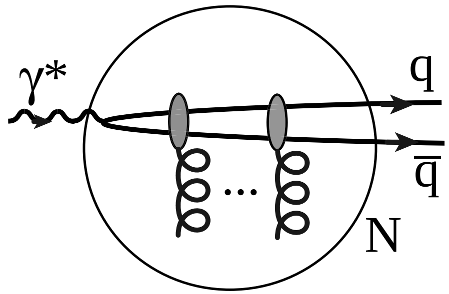
Colour exchange $\to$ modified colour (string) field topology
$\to$ modified hadronic final state $\to$ gaps may arise

- gluon k_2 quickly after k_1 $\Rightarrow$ can screen colour giving singlet exchange
- even/odd # gluons $\to$ pomeron/odderon exchange
- path-ordered exponential of gluon field (Wilson line)
- on-shell intermediate state $\Rightarrow$ imaginary amplitude $\leftrightarrow$ diffraction
  k_2 is 'soft' $\to$ small kinematic effect
- $F_2^D \sim g_p(x_{I\!P})\, q_g(\beta)$, *i.e.* gluon distr. $\leftrightarrow$ $I\!P$ and $g \to q\bar{q}$ gives $\left(\beta^2 + (1-\beta)^2\right)$

DIS on the 'Light Front'

Light Front (LF, or Light Cone LC) formalism – invariant under boosts along z
$\longrightarrow$ 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 (Ioffe) length $x^- \sim 1/m_p x_B$

QCD factorisation and rescattering

QCD factorization theorem $\Rightarrow$ separation of hard and soft

Quark parton density function (PDF) is given by

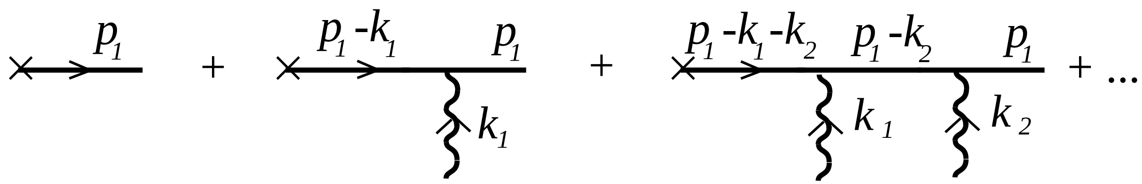
$$f_{q/N} \sim \int dx^- e^{-ix_B p^+ x^-/2} \langle\, N(p)\,|\, \bar\psi(x^-)\gamma^+ W[x^-;0]\,\psi(0)\,|\,N(p)\,\rangle_{x^+=0}$$

where $W[x^-;0] = \mathrm{P}\exp\left[ig\int_0^{x^-} dw^- A_a^+(0,w^-,0_\perp)t_a\right]$ is the Wilson line

Expanding the exponential we have

$$W[x^-;0] \sim 1 + g\int \frac{dk_1^+}{2\pi}\frac{\tilde A^+(k_1^+)}{k_1^+ - i\varepsilon} + g^2\int\frac{dk_1^+ dk_2^+}{(2\pi)^2}\frac{\tilde A^+(k_1^+)\tilde A^+(k_2^+)}{(k_1^+ + k_2^+ - i\varepsilon)(k_2^+ - i\varepsilon)} + \dots$$

corresponding to the diagrams

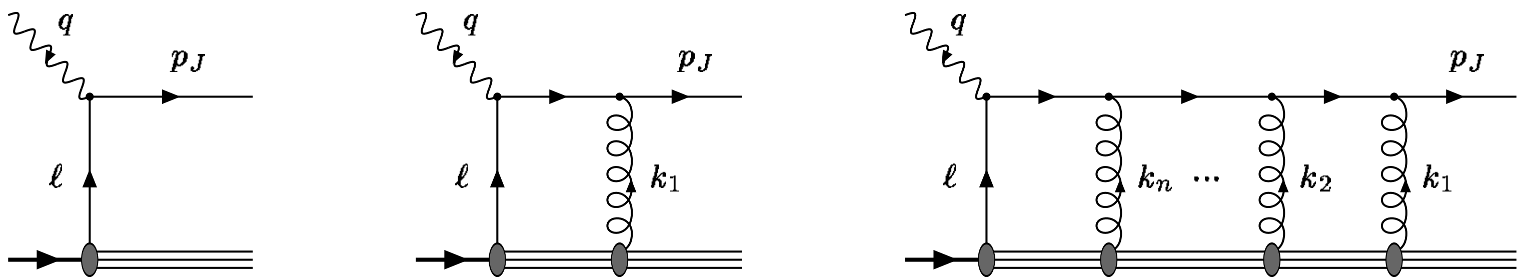


for rescattering of the struck quark via longitudinal (A^+) *instantaneous* (in x^+) gluon exchange. No $A^\perp$ within Ioffe coherence length $x^- \sim 1/m_p x_B$

Brodsky, Hoyer, Marchal, Peigné, Sannino, Phys. Rev. D65 (2002) 114025

QCD rescattering and factorisation in DIS

The Wilson line means that DIS looks something like this:



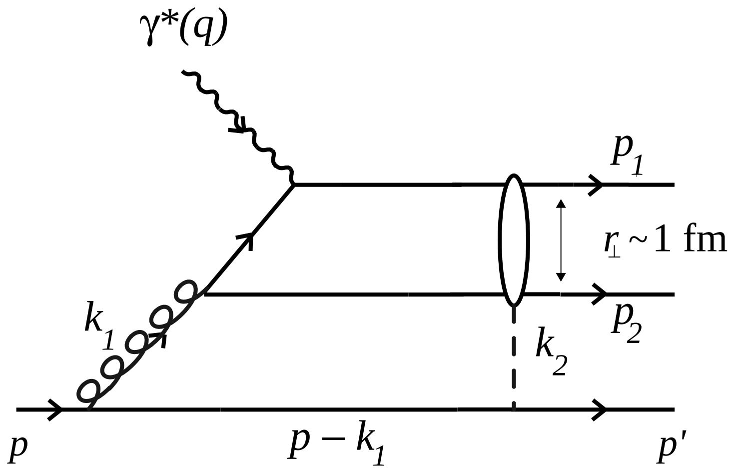
- Rescattering compatible with factorization theorems *by construction*
  Wilson line part of definition of PDF ⇒ rescattering part of PDF

- Experimentally measured PDF's *include* rescattering

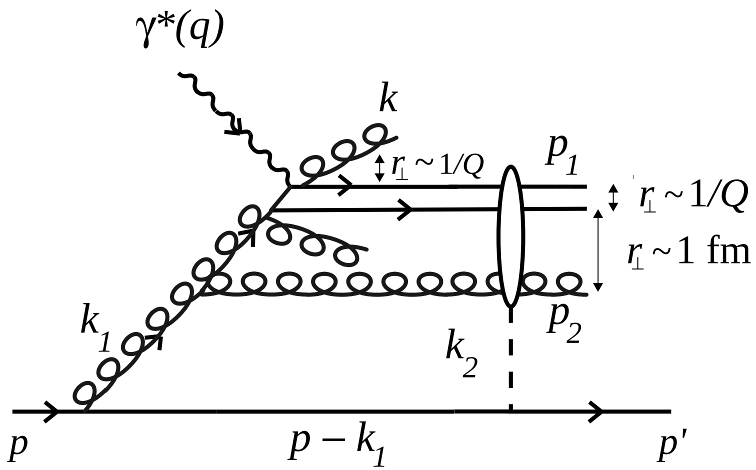
- Diffractive PDF's included in inclusive PDF's

- Rescattering can give on-shell intermediate states and
  imaginary amplitudes ⇒ diffraction

Mechanism for diffraction in DIS



(a)



(b)

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

1. A soft gluon with $k_1^+/p^+ \sim x_{I\!P}$ splits into large $q\bar{q}$ pair
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
  – 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

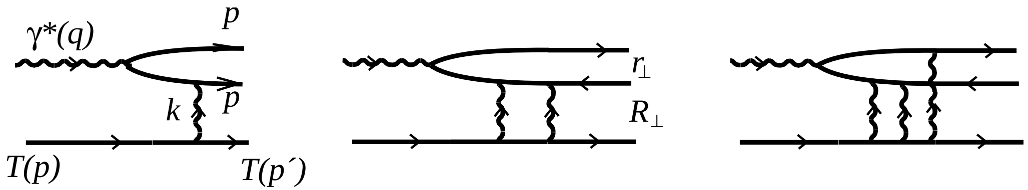
$\Rightarrow$ $\sigma_{\mathrm{diff}}/\sigma_{\mathrm{tot}}$ independent of x_B and Q^2, as observed in data

- Amplitudes from rescattering dominantly imaginary,
  as expected for diffraction
- Rescattering gluons have small momenta $\Rightarrow$ β dependence of diffractive PDF's from underlying (non-perturbative) $g \to q\bar{q}$ and $g \to gg$ processes
- Effective $I\!\!P$ flux: $\quad f_{I\!\!P/p}(x_{I\!\!P}) \sim g(x_{I\!\!P}, Q_0^2)$

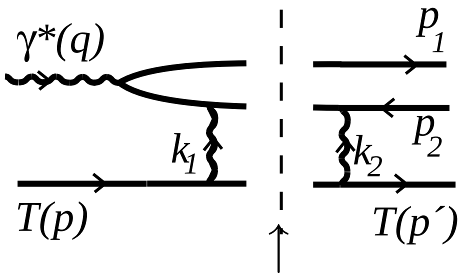
  Effective $I\!\!P$ structure function: $\quad f_{q/I\!\!P}(\beta, Q_0^2) \sim \beta^2 + (1-\beta)^2$

Colour coherence and SCI

Resolve partons $\Leftrightarrow$ short gluon wave length



Amplitudes for $1, 2, \ldots n$–gluon exchange

$A_2 =$ 

imaginary for $x_B \to 0$

$\Rightarrow$ on-shell intermediate state

$\Rightarrow$ factorized amplitudes:

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

$$A_2 = \frac{-ieg^4}{2} \mathcal{C}\, V(m, x_B, \boldsymbol{r}_\perp)\, W^2(\boldsymbol{r}_\perp, \boldsymbol{R}_\perp) = \frac{-ig^2}{2!} W A_1$$

$\vdots$

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

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

Fourier transform to coordinate space

$\boldsymbol{r}_\perp$ $q\bar{q}$ colour dipole size
$\boldsymbol{R}_\perp$ conjugate coord. to $\boldsymbol{k}_\perp$
frozen during scattering process

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

$\Rightarrow$ gluon coupling to dipole decreases

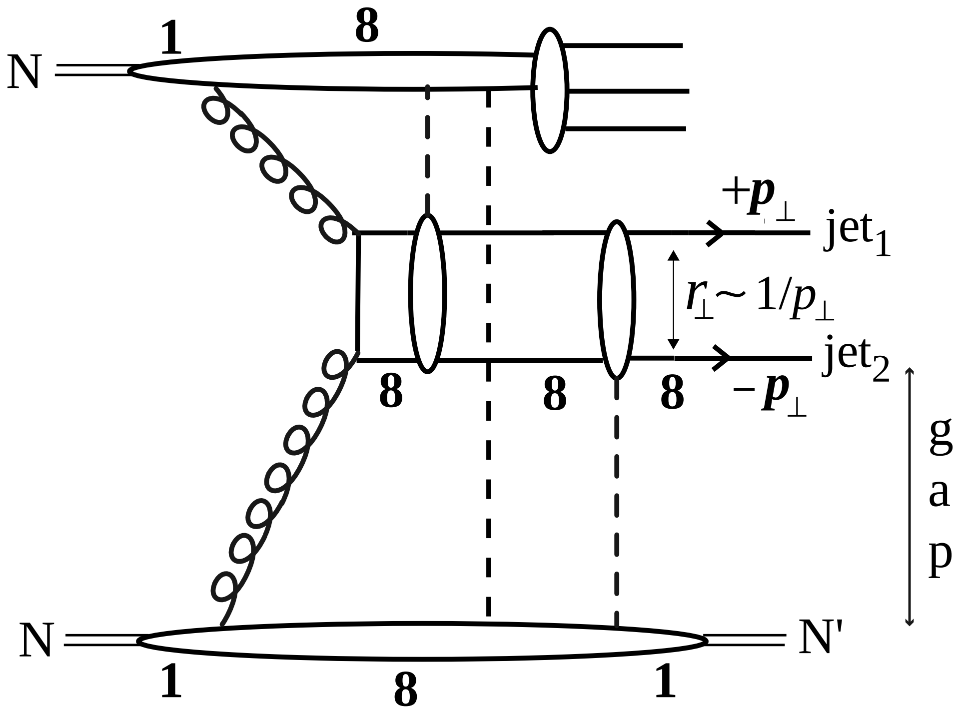
for $|\boldsymbol{r}_\perp|/|\boldsymbol{R}_\perp| \lesssim 1$, *i.e.* $|\boldsymbol{k}_\perp| \lesssim 1/|\boldsymbol{r}_\perp|$

$\Rightarrow$ SCI colour exchange probability should vary dynamically with W^2
Softer ($k_\perp$) gluon $\to$ less interaction with small colour dipole (not resolved)

$\updownarrow$

colour coherence

Hard diffraction in hadron–hadron collisions



- Diffractive factorization theorem does not hold
- Data shows $\sim$ 1% diffraction instead of $\sim$ 10 % in DIS
- Both target and projectile coloured
  $\rightarrow$ different rescattering
  $\rightarrow$ lower probability for colour neutralization
- DPE possible
- SCI model reproduces data

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

Outlook

- Non-perturbative QCD major unsolved problem
- QCD rescattering theory
  - theory for diffraction/gaps
  - basis for successful SCI model
  - implies developments of SCI model
    $e.g.$ colour coherence from dynamical gluon exchange probability
- Parton interaction with colour background field
  - 'old' idea with new aspects
  - parton traversing quark-gluon plasma $\rightarrow$ jet quenching
- New ideas, new collaborations . . . lots of fun . . .

$\Rightarrow$ Better understanding of non-perturbative QCD

Additional material . . .

Related models

- Colour evaporation model (Halzen *et al.*)
  many exchanges → random colour

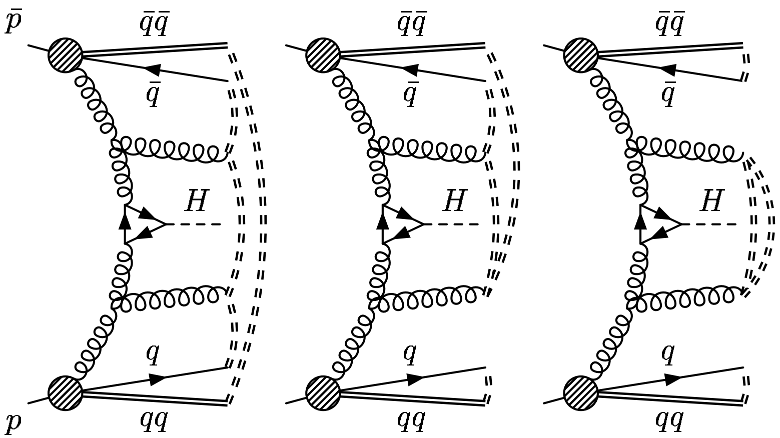
  Diffractive DIS (Buchmüller *et al.*)
  $\gamma g \to q\bar{q}$ octet → singlet $q\bar{q}$ (prob=1/9)
  which decouples from remnant → gap event

- 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: $\gamma \to q\bar{q}$ which traverses proton colour field
  interaction ∼ Wilson loop averaging over colour field

- String reconnection models (Lund group)
  e.g. applied to $e^+e^- \to WW \to q\bar{q}\,q\bar{q}$
  gives shift in W mass determination

SCI → diffractive Higgs at Tevatron/LHC



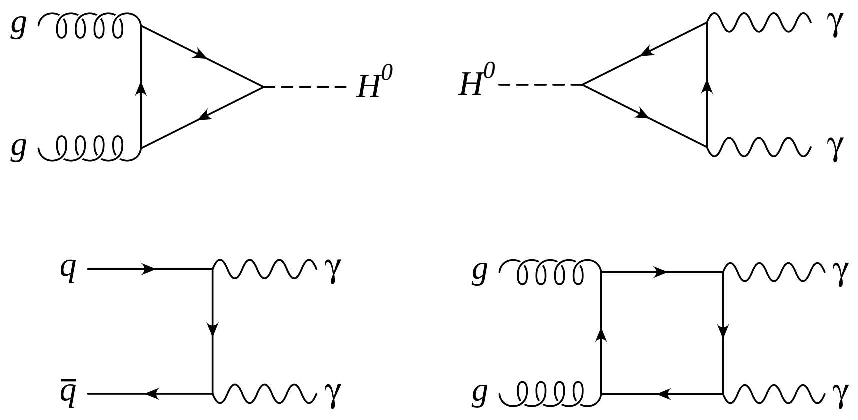
Idea: diffractive events cleaner
→ easier Higgs reconstruction
→ Higgs discovery channel ?

$m_H = 115$ GeV		Tevatron $\mathcal{L} = 20$ fb^{-1}	LHC $\mathcal{L} = 30$ fb^{-1}
	σ[fb] Higgs-total	600	27000
SD	σ [fb] leading-p	1.2	190
	σ [fb] gap	2.4	27
	# H + leading-p	24	5700
	↪ # H → $\gamma\gamma$	0.05	13
DPE	σ [fb] leading-p's	$1.2 \cdot 10^{-4}$	0.19
	σ [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 → kinematical conflict → reduced cross-section

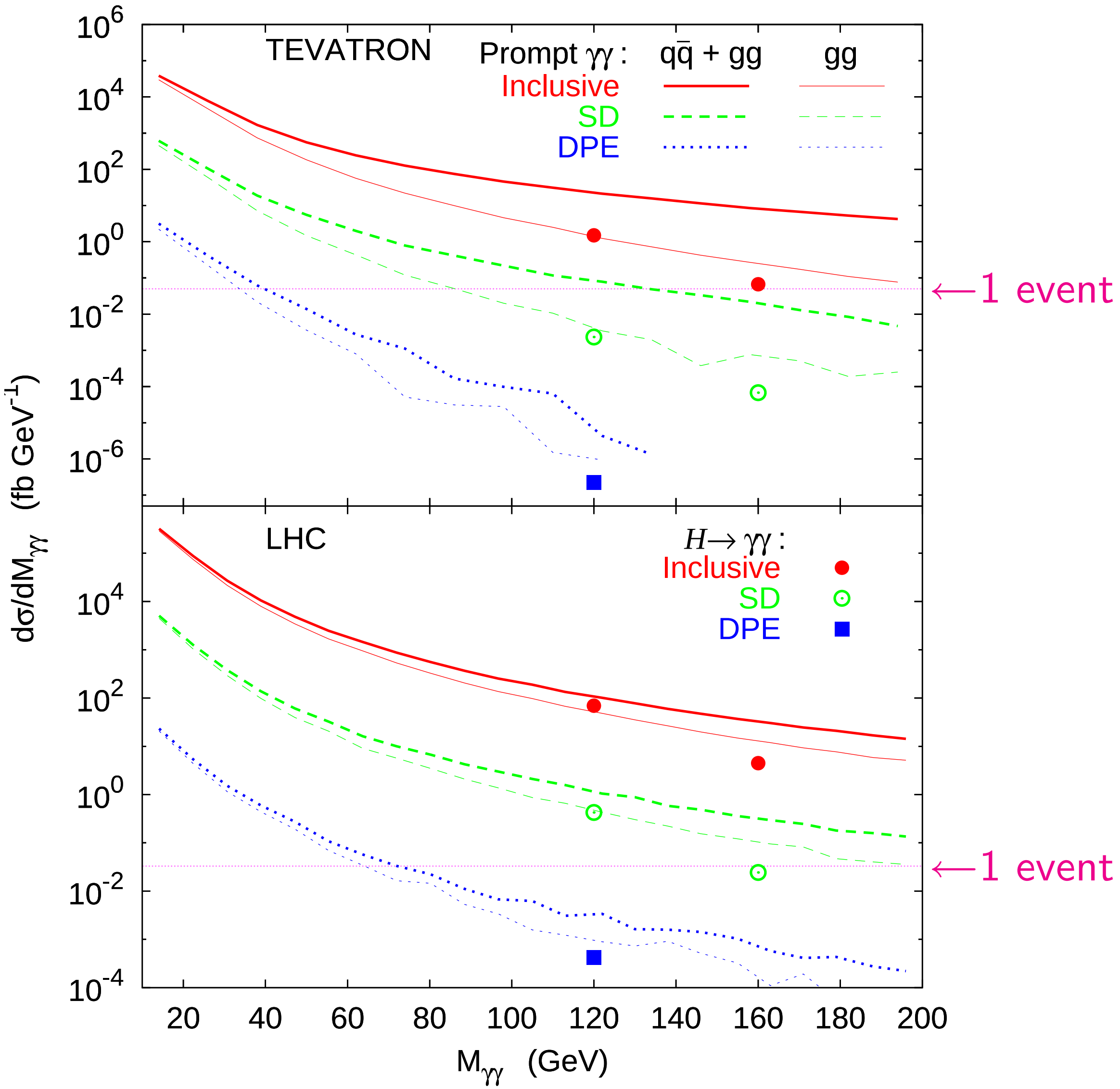
Tevatron: only few SD Higgs ⇒ $H \to b\bar{b}$ background/reconstruction problems
LHC: Higgs observable in SD (also $H \to \gamma\gamma$) and DPE
but not so clean since particles in 'gap' region → 'pots' better

Diffractive $H \to \gamma\gamma$ and prompt $\gamma\gamma$



Prompt $\gamma\gamma$ irreducible background
$> \sigma(H) \cdot \mathrm{BR}(\mathrm{H} \to \gamma\gamma)$

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

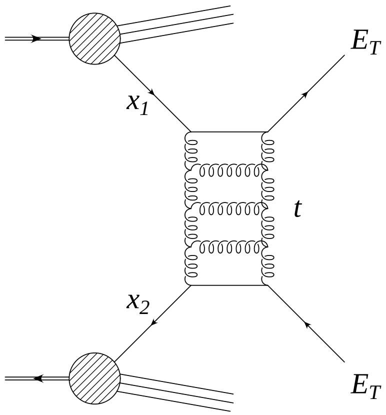


Soft and hard rapidity gaps

Soft/hard gap $\Leftrightarrow$ small/large momentum transfer across gap
non-perturbative/perturbative QCD description

Hard gap between jets:

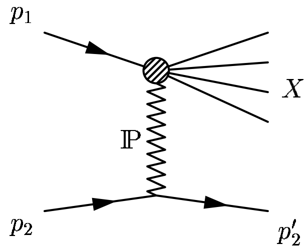
- observed at Tevatron
- understood/described by exchange of colour singlet BFKL gluon ladder with non-leading corrections



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

Soft gap $\leftrightarrow$ leading proton:

- 'soft-soft' $\Rightarrow$ hadron basis $\rightarrow$ Regge



- 'hard-soft' $\leftrightarrow$ hard int'n – gap – proton
  DIS/jets/W + gap
  $\rightarrow$ pQCD partons + hadronisation

$\Rightarrow$ mixed basis: parton & hadron

Models:

- Regge $\rightarrow$ pomeron structure works, but problematic
- Soft Colour Interactions . . .

Gap between jets $\rightarrow$ hard QCD exchange

Rapidity gap between a pair of jets

$\rightarrow$ $|t|$ across gap is large

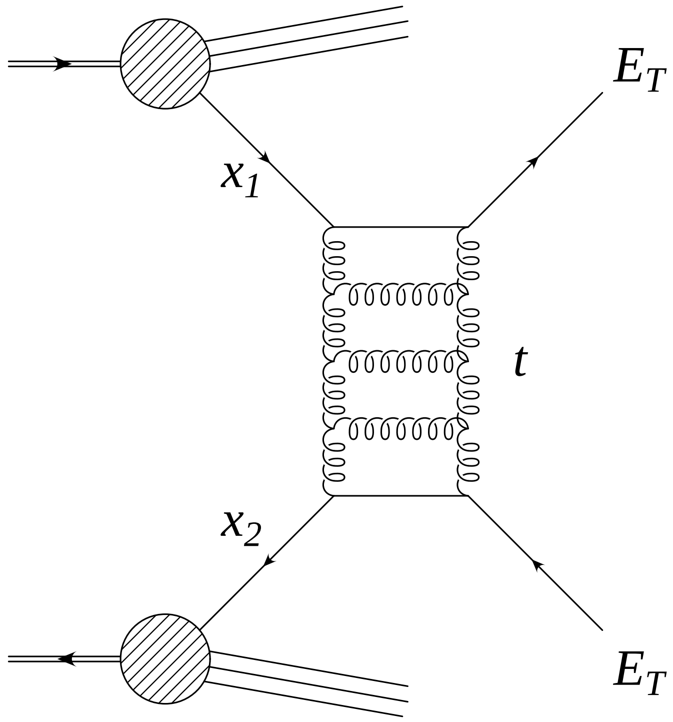
$\rightarrow$ different from "normal" diffraction

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, including

- virtual corrections
- reggeization of the exchanged gluons



Numerical solution of BFKL eqn. with non-leading corrections

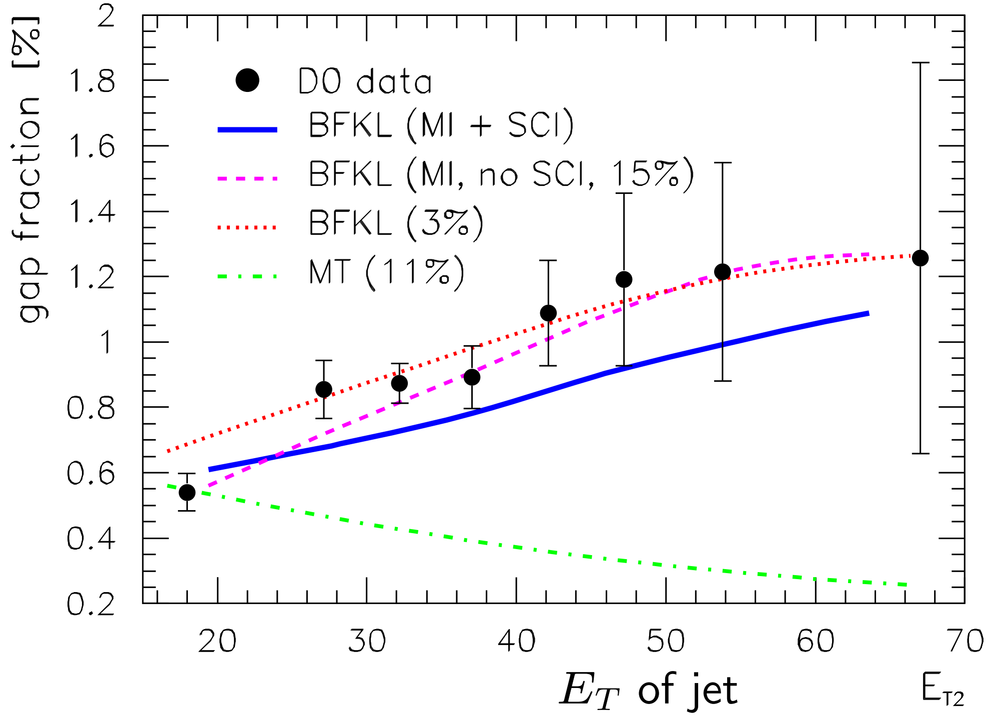
consistency constraint & running coupling $\longleftrightarrow$

Comparison to data – gap survival

This subprocess implemented in PYTHIA → account for gap survival depending on HO parton emissions, multiple scatterings, hadronization

SCI destroys gaps by re-arranging strings across gaps

- Good agreement with DØ data
  - E_T and $\Delta\eta$ dependences OK
  - absolute normalisation OK
    $i.e.$ correct gap survival probability
    too large gap survival prob. without SCI
- Previous asymptotic result (Mueller-Tang) ⇒ wrong E_T-dependence



First clear evidence of BFKL dynamics ⇒ better understanding of data and QCD