Hadronic diffraction as a probe for long-distance effects in QCD

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\mathbf{C} **Definition of diffraction**

Challenges: theory vs experiment

✓ The definition of diffraction is not unique t otal \mathcal{I} inclusive cross-sections sections $\mathcal{I}^{\mathcal{I}}$ exchange of *IP*omeron (vacuum q.n.)

√ QCD modelling of diffraction is a major problem

- ★ fluctuations during the hadronisation process *(protons from recombination? gap size?)*
- ̣*low vs high mass diffractive dissociation*
- ̣ *soft vs hard Pomeron*
- ̣ *hard-soft factorisation breaking, etc*

huge sensitivity to details!

- \cdot interpreted in OCD as a stwo gluon exchange · interpreted in QCD as a >two gluon exchange *X* change
equal object
	- not a simple pole but enigmatic non-local object $\frac{1}{\sqrt{2}}$ three-body amplitude. We show that the pomeron is not a real particle and pomeron-body and pomeron-

Birth of hard diffraction: QCD modelling of Pomeron Birth of hard diffraction: QCD modelling of Pomeron $\overline{}$ total/inclusive cross-sections.

 $=$

Diffraction at HERA

$\textbf{Diffractive DIS}$ **FRACTIVE DIS**

pq,g/pIP

Sensitivity to the color string topology fluctuations Soft interactions partons \$ remnants (proton colour field) below *^Q*² ⁰ ^ª ¹ GeV² Add-on to Lund Monte Carlo's Lepto (*ep*) and Pythia (*pp*¯) \mathbf{F} to the color strips topology fluctuation nsitivity to the color string topology fidetuati Edin, GI, Rathsman **Sensitivity to the color string topology l** \mathbf{C}

 $I^{\text{soft}}(\mathbf{b}, \mathbf{r}) \propto (1 - e^{A \cdot \mathbf{r}})$

^I Frame: *PMX* + *P*⁰

 $\hat{M}^{\text{soft}}(\mathbf{b}, \mathbf{r}) \propto (1 - e^{A \ln \frac{|\mathbf{b} - \mathbf{r}|}{|\mathbf{b}|}})$

k?

*[|]*b*[|]*)

 D

gap

p

00000000

becomes dynamical

RP, Ingelman, Enberg

Diffractive factorisation breaking in pp collisions

Incoming hadrons are not elementary — experience soft interactions dissolving them
Jeaving much fower rapidity gap events than in on scattoring **leaving much fewer rapidity gap events than in ep scattering**

Sources of diffractive factorisation breaking:

- ✓ soft survival (=absorptive) effects (Khoze-Martin-Ryskin and Gotsman-Levin-Maor) affecting e.g. the Pomeron flux (Goulianos)
- ✓ interplay of hard and soft fluctuations in incoming hadron wave function
- ✓ saturated shape of the universal dipole cross section for large dipole sizes

Two distinct approaches treating the above effects:

- æ
Dissemble de Dissemble de Disse
Dissemble de Dissemble de Disse *IP* model tuned at HERA, *i.e. qIP* (*x, Q*²) and *gIP* (*x, Q*²) fitted to DIS *F ^D* .
. . ✓ **Regge-corrected (KMR) approach** — the first source of the factorisation breaking is accounted at the cross section level by "dressing" the factorisation formula by soft Pomeron exchanges
	- ✓ **Color dipole approach** the universal way of inclusive/diffractive scattering treatment, accounts for all the sources of Regge factorisation breaking at the amplitude level (Kopeliovich, RP et al)

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国 tot σ $\overline{\rm d}$ luc CONCERT CONDUCTION SURVIVES CONTRACTED SURVIVES CONTRACTED P **Hogs contribution** 10 $\mathrm{d} \mathbf{r}$ 18 $\frac{1}{2}$ <u>श्लेन</u> *# 11) \mathfrak{z} : H **EXHAME: EDD** \mathbb{C} tain remnants designated by Youah Ω . The production is a subsequently from $Y\overline{\mathcal{P}}/n$. $\frac{1}{16}$ or $\frac{1}{16}$ diffraction, where $\frac{1}{16}$ only the $\frac{1}{16}$ only the final state generalized in $\frac{1}{16}$ to the states of the states of the set of the SD and DPE is a sub-production of the set of the set of the set o
Distribution in DPE is a sub-produced by the set of the IPp De Liste Here tatan pomeron remediated by Y \overline{y} $\mathcal{L}_{\mathcal{V}}$ is the points of $\mathcal{V}_{\mathcal{V}}$ and $\mathcal{V}_{\mathcal{V}}$ and $\mathcal{V}_{\mathcal{V}}$ Ω . The production is a subsequence of $\mathcal{W}_{\mathcal{P}_{\mathcal{P}_{\mathcal{P}}}^{*}}$ $\frac{1}{2}$, $\frac{1$ antiproton proton (antipro-different proton (antipro-PRESERVED WITH ONE UNDER to single to dissociate and Pig. 1 alb. 10¹ where \mathbb{R} is the final state \mathbb{R} \mathbb{R} state \mathbb{S} or \mathbb{R} state \mathbb{S} tains Pomeron remnants designated by YIP/p¯ and YIP/p. Let the production in December is a sub-production in December 1991 **ICO + TAGO + VICE + 1615S + UALE + TARGAL**
IN THE TAG + TAG + HE HALL + TAG + CO + 12
IPP + 12 + 12 + JAPA + YES + YES + JET + 751 + VE \log framinishir designated \log $Y_P^=$ tan pomeron remains designations des internations des ignations des ignations des ignations des ignations des where it as a property considerably con-Diget production in Diget production in Digetal Contract production in Digetal Contract production in Digetal C

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Gettigase o⁰¹1997 \mathbb{R}^2 FIG. 21: TOS. DECALISE THE FORMETORY HIGHS production for different gluon for different gluon for different gluon production for different gluon for different gluon for different gluon for different gluon for different glu **Bread of the Case of the College College College**
Drigs to the College of the College EDS2013, Saariselca Hard Diffraction at CDF K. Goulianos 27 **p**
Ratings Decalled Line Lawrer (18) $\frac{1}{20}$ 20 $\frac{1}{20}$ $\widetilde{\text{m}}$ uctions are shown in Hagings (faint in 10 with the $\frac{1}{10}$ and $\frac{1}{10}$ invariant mass distribution for $\frac{1}{10}$ $\frac{1}{10}$ and $\$ SO, the escaping of the escaping to a rapidity of the escaping of the establishment of the estab a region of particles in the particles in the contract of particles in the co antiproton (proton) survives while the proton (antipro-
Diffusion (antipro-antipro-antipro-antipro-antipro-antipro-antipro-antipro-antipro-antipro-antipro-antipro-an
Partition (antipro-antipro-antipro-antipro-antipro-antip diet production are shown in Fig. 1 to which the computation of the $\mathrm{Supp}(\mathrm{B}(\mathrm{B})\otimes \mathrm{Supp}(\mathrm{B}))$ $\mathrm{Supp}(\mathrm{B})\otimes \mathrm{Supp}(\mathrm{B})$ $R_{\rm H}$ because the Pomeron exchange the Post in a positive the Post in a positive in a positi $\lim_{\epsilon\to 0} \lim_{\epsilon\to 0}$ to put us in production and the product of \Box $\frac{1}{10}$ is $\frac{1}{10}$ is a rapidity $\frac{1}{10}$ is a rapidity $\frac{1}{10}$ in $\frac{1}{10}$ is a rapidity $\frac{1}{10}$ is a ra tophore use production are shown in Fig. 1 and DPE of the SD and DPE of the SD and DPE of the SD and DPE of the
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DE ROCESS IS & COLOLESS ODJECt OF ENECtryle spin – 14 JAN († 1981) – PNOGUCTION – MON († 1981) J ≥ 1 and carries the quantum numbers of the vacuum. α a ram-defined to a rapidity to a rapidity gap, and α aan amaan taha assamata too maan maan are present. In ta α process the constructive process is a color of \mathbf{H}_{α} at α spins α a rapidity is a rapidity and the escape is a rapidity gap, and α rapidity α as e ende type a regionalista de voltage de voltage de la control

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 α in the jets $p \rightarrow Q$. The jets q

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 $\sum_{n=1}^{\infty}$ defined by $\sum_{n=1}^{\infty}$

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 $\frac{1}{2}$ g $\frac{1}{9}$ $\frac{1}{9}$ $\frac{1}{9}$ $\frac{1}{2503}$ Eur. Phys. J. C73 (2013) 2503 \mathbf{b} they break up strong suppression in \mathbf{b} *^z* = 0⁺ E_{tr} Phys. I. $C73$ ing event p associated with the jets p $\frac{3}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{2}{2}$ $\frac{2}{2}$ *PRD 77, 052004 (2008)* Eur.Phys.J. C73 (2013) 2503

R + Report is the set of 27 + \mathbf{p}

27

 $\liminf_{n\to\infty} \frac{1}{n}$ in $\lim_{n\to\infty} \frac{1}{n}$ where one or and from θ

cut on the b¯b invariant mass. Kinematical constraints are the same as in Fig. 22.

ctidie colore-singlet two gluon existing at leading or the

channel color-singlet two gluon exchange at least two gluon exchange at least $\frac{1}{2}$

(LO) in perturbative quantum chromo-dynamics (QCD),

PIL
EDS2013, Saariselca Hard Diffraction at CDF K. Goulianos

 $\langle \overline{\psi}$ Q) i. perturbative quantum chromo-dynamics ($\langle \overline{\psi} \rangle$),

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(LO) in perturbative quantum chromo-dynamics (α , α , α

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as shown schematically in Fig. 2 (a), where one of the two schematically in Fig. 2 (a), where one of the two schematical contracts of the two schematical contracts of the two schematical contracts of the two schematical c

Good-Walker picture of diffractive scattering

R. J. Glauber, Phys. Rev. 100, 242 (1955). *ⁿ c*[∗] E. Feinberg and I. Ya. Pomeranchuk, Nuovo. Cimento. Suppl. 3 (1956) 652. *M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857.*

Projectile has a substructure! *nkTncn*⁰ *^k* ⟨Ψ0|*T*|Ψ*^k* ⟩⟨Ψ*^k* |*T*|Ψ0⟩ = ⟨*T*2⟩

Diffractive excitation determined by the fluctuations:

Hadron can be excited: not an eigenstate of interaction!

$$
|h\rangle = \sum_{\alpha=1} C_{\alpha}^{h} |\alpha\rangle \qquad \hat{f}_{el} |\alpha\rangle = f_{\alpha} |\alpha\rangle
$$

$$
\hat{f}_{el}|\alpha\rangle = f_{\alpha}|\alpha\rangle
$$

Completeness and orthogonality

$$
\langle h'|h\rangle = \sum_{\alpha=1} (C_{\alpha}^{h'})^* C_{\alpha}^h = \delta_{hh'}
$$

$$
\langle \beta|\alpha\rangle = \sum_{h'} (C_{\beta}^{h'})^* C_{\alpha}^{h'} = \delta_{\alpha\beta}
$$

Elastic and single diffractive amplitudes

$$
f_{el}^{h \to h} = \sum_{\alpha=1}^{\infty} |C_{\alpha}^{h}|^{2} f_{\alpha}
$$

$$
f_{sd}^{h \to h'} = \sum_{\alpha=1}^{\infty} (C_{\alpha}^{h'})^{*} C_{\alpha}^{h} f_{\alpha}
$$

Single diffractive cross section

semi-hard/

$$
f_{sd}^{n-m} = \sum_{\alpha=1}^{n} (C_{\alpha}^{n})^{\alpha} C_{\alpha}^{n} f_{\alpha}
$$

\n**Single diffractive cross section**
\n
$$
\sum_{h' \neq h} \frac{d\sigma_{sd}^{h \rightarrow h'}}{dt} \Big|_{t=0} = \frac{1}{4\pi} \left[\sum_{h'} |f_{sd}^{hh'}|^2 - |f_{el}^{hh}|^2 \right]
$$

\n
$$
= \frac{1}{4\pi} \left[\sum_{\alpha} |C_{\alpha}^{h}|^2 |f_{\alpha}|^2 - \left(\sum_{\alpha} |C_{\alpha}^{h} |f_{\alpha} \right)^2 \right] = \left[\frac{\langle f_{\alpha}^2 \rangle - \langle f_{\alpha} \rangle^2}{4\pi} \right]_{12}
$$

\n**Important basis for the dipole picture!**

Phenomenological dipole approach

Eigenvalue of the total cross section is the universal dipole cross section energy density of high-energy dynamics of interaction in QCD:

- • **cannot be excited**
- • **experience only elastic scattering** experience only elastic scattering

and meson production in Fig. 20. The rearration of $\sum \frac{d\sigma_{sd}^{n-m}}{d\sigma_{sd}^{n-m}}\Big|_{\sigma_{sd}} = \sum |\sigma_{sd}^{n}|^2 \frac{\sigma_{\alpha}^2}{d\sigma_{sd}} = \sigma_{3}$
	- • **have no definite mass, but only separation**
- • **universal elastic amplitude can be extracted in one process and used in another** very interpretation interpretation in a reference frame when $\overline{h'}$ and $\overline{h'}$ and $\overline{a=1}$ and $\overline{a=1}$ and $\overline{b=0}$ $\overline{a=1}$ and $\overline{b=0}$ and $\overline{b=1}$ and $\overline{b=0}$ and $\overline{b=1}$ and $\overline{b=0}$ and \over

see e.g. B. Kopeliovich et al, since 1981

Eigenstates of interaction in QCD: **color dipoles Dipole:** factorization into a particular form. The different building blocks in the different basic in the different be
Dipole: Compton a particular form. The graphs for Compton scattering for Compton scattering for Compton scatter

$$
\frac{1}{h'} \quad \text{all} \quad |_{t=0} \quad \overline{\alpha=1} \quad \text{10ft} \quad \text{322 C1033 SCC1UM}
$$
\nextracted in one process and used in another\n
$$
\int d^2 r \sqrt{\Psi_h(r_T)} \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle \sigma^2(r_T) \rangle}{16\pi}
$$

wave function of partonic interpretation of a wave full wave full partonic interpretation of

a given Fock state total DIS cross section

SD cross section

frame of reference!
\n
$$
\sigma_{tot}^{\gamma^* p} (Q^2, x_{Bj}) = \int d^2 r_T \int_0^1 dx \, |\Psi_{\gamma^*}(r_T, Q^2)|^2 \sigma_{qq}^2(r_T, x_{Bj})
$$

Theoretical calculation of the dipole CS is a challenge

<u>Theoretical calculation of</u>
the dipole CS is a challenge **EVALUAN BUT!** Can be extracted from data and used in ANY process!

Example: **Naive GBW parameterization of HERA data**

a scattering does depend on

color transparency high-energy factorization is the relation

QCD factorisation

 ${\sf c}$ aturatos at ${\sf c}$ Example: Naive GBW parameterization $\sigma_{\alpha\alpha}(r_{T,X})=\sigma_0\left[1-e^{-\frac{1}{4}r_T^2Q_s^2(x)}\right]$ large separations determined by the inverse of the hard momentum scale, i.e. $\frac{1}{2}$ and $\frac{1}{2}$

saturates at large separations

$$
r_T^2 \gg 1/Q_s^2
$$

$$
\sigma_{qq}^-(r_T) \propto r_T^2 \qquad r_T \to 0 \qquad \text{A point-like colorless object} \n\sigma_{q\bar{q}}(r, x) \propto r^2 x g(x) \qquad \text{external color field!}
$$

A point-like colorless object does not interact with external color field!

at ANY inclusive/diffractive scattering is due to an interference of dipole scatterings! leading log x approximation. A more precise version of the relation \mathcal{L}_{max}

Gluon distribution amplitudes and dipole CS Cˆ(d) $\frac{1}{2}$ = 2, $\frac{1}{2}$ = 2, $\frac{1}{2}$ $\overline{3}$ γ γ + γ , (2.8), (2 # (⃗s, ⃗ρ)Cˆ(d′

In most cases, a scattering cross section in the target rest frame X can be represented in terms of three basic ingredients: an de representeu in terms of three dasic ingrements:
The distribution splitting game and subsequent gluon and subsequent gluon subsequent gluon subsequent gluon subsequent gluon splitting graphs and subsequent gluon subse $\ddot{\bullet}$ \mathcal{L} In most cases, a scattering cross section in the target rest frame can be represented in terms of three basic ingredients:

Gluon to quark-antiquark splitting amplitude: \overline{OOO} $\overline{}$ <u>billion to quark-antiquark splitting amplitude:</u> with the top of the t-channel gluon from the t-**The 3** *a* **matrice a (i)** $\overline{0000}$ space of the color space of the color space of the $\overline{0000}$ <u>indexes aircreas</u> **i**

$$
\Phi_{Q\bar{Q}}^T = \sqrt{\alpha_s} \int \frac{d^2 \kappa}{(2\pi)^2} (\xi_Q^{\mu})^{\dagger} \frac{m_Q(\vec{e}_{ini} \cdot \vec{\sigma}) + (1 - 2\beta)(\vec{\sigma} \cdot \vec{n})(\vec{e}_{ini} \cdot \vec{\kappa}) + i(\vec{e}_{ini} \times \vec{n}) \cdot \vec{\kappa}}{\kappa^2 + \epsilon^2} \tilde{\xi}_Q^{\bar{\mu}} e^{-i\vec{\kappa}\vec{r}}
$$
\n
$$
= \frac{\sqrt{\alpha_s}}{2\pi} (\xi_Q^{\mu})^{\dagger} \Biggl\{ m_Q(\vec{e}_{ini} \cdot \vec{\sigma}) + i(1 - 2\beta)(\vec{\sigma} \cdot \vec{n})(\vec{e}_{ini} \cdot \vec{\nabla}_r) - (\vec{e}_{ini} \times \vec{n}) \cdot \vec{\nabla}_r \Biggr\} \tilde{\xi}_Q^{\bar{\mu}} K_0(\epsilon r),
$$
\nGluon Bremsstrahlung off a quark:

the initial state is performed explicitly. Here, since t

Gluon Bremsstrahlung off a quark: Figure 2. The Solution Scheme 2. The non-relations to the non-relations of the non-relation in the non luon Promes luon Bremsstrahlung off a quark: <u>σπα quark</u> (η^s **the Disk Gluon Brems** color-singlet {QQ¯}¹ pair onto a vector J/^ψ or ^Υ state is often taken in a similar form as

4 Equation bremsstrahlung of a quark:
\n
$$
\Phi_{qG^*}^T(\alpha, \vec{\pi}) = \sqrt{\alpha_s} \left(\eta_Q^s \right)^{\dagger} \frac{(2 - \alpha)(\vec{e}_* \cdot \vec{\pi}) + i m_q \alpha^2 (\vec{n} \times \vec{e}_*) \cdot \vec{\sigma} - i \alpha (\vec{\pi} \times \vec{e}_*) \cdot \vec{\sigma}}{\vec{\pi}^2 + \alpha^2 m_q^2} \eta_Q^s
$$
\n**2 2 2 2 3 2 3 4 4 4 5 6 6 6 7 7 8 8 9 9 9 1 1 1 1 1 1 1 2 1 2 1 2 1 2 1 3 1 4 2 1 2 1 3 1 4 2 1 2 1 3 1 4 2 1 3 1 4 2 1 4 2 1 4 2 1 2 1 3 1 4 2 1 2 1 3 1 4 2 1 4 2 1 2 1**

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abd = *i*

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*fedb*τ*e*τ*a, T (*9*)*

Universal dipole cross section:

14

Dipole approach vs NLO QCD: Drell-Yan by empirical nuclear parton distribution functions [14]. This approach does not explain the die nuclear effects in the nuclear effects in the nuclear effects of the high energy limit of \bf{QCD} :

Diffractive Abelian (e.g. Drell-Yan) radiation via dipoles

nucluations is pronounced: interplay between hard and soft fluctuations is pronounced! mucculations is pronounced:

 \mathcal{A} s an alternative to the factorization based \mathcal{A} approach, the dipole description of the dipole descripti

superposition has a Good-Walker structure

$$
\propto \sigma(\vec{R}) - \sigma(\vec{R} - \alpha \vec{r}) = \frac{2\alpha \sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} (\vec{r} \cdot \vec{R}) + O(r^2)
$$

 $\overline{}$ nd**a** |
| **!** ve r \sim \sim Diffractive DIS $\propto r^4 \propto 1/M^4$ vs diffractive DY $\propto r^2 \propto 1/M^2$ and $r \sim 1/(1-\alpha)M$ Rij ∠ Romans that the single diffraction diffractive cross section depends on the single diffractive cross sec
Diffractive cross section depends on the single diffractive cross section depends on the single diffractive c

following general result

- SD DY/gauge bosons SD heavy quarks \star diffractive factorisation is *automatically broken*

⊸ ²
	- \bm{R}^{obs} any SD reaction is a superposition. ^o *dipole amplitudes* and the end-point of dipole amplitudes and the cross section and the cross section at a \sim 0.5 dipole amplitudes section at a \sim 0.6 dipole amplitudes sections, and the cross section at a \sim 0
	- ̣ *gap survival is automatically* o._{5 Te}√ dependence comes only included at the amplitude level on *the same footing as dip. CS*In the single diffraction cross section of the single gauge bosons of the second behaves as ∠ \sim 7.5 μ -4 $\begin{array}{c|c|c|c|c} \hline & \nearrow & \quad & \end{array}$ an survival is automatically
	- $\begin{array}{c|c} \circ & \circ & \star & \textit{works} \textit{for a variety of data} \end{array}$ *i* $\frac{d}{dx}$ does not depend on the interms of universal dip. CS \bigstar

 \overline{a} **FIG. 8: The cross section of a put into MC: Lund Dipole Chain model (DIPSY)** $R = \frac{1}{2} \int_{0}^{1} \int_{$ Ref. G. Gustafson, and L. Lönnblad ¹⁰ ^{the diffraction on the diffraction conduction cross in the diffraction cross section on the hard scale only}

Elastic amplitude and gap survival absorption and does not need any extra survival probability factor $3.$ This can be interesting factor $3.$ is suppressed by absorptive corrections, the effect sometimes corrections, the effect sometimes called survival astic amplitude and gap surviva ^α² ^Ψ^µ 2Im fel(b, r ⃗ p)
D) − 2Im fel((2Im fel(1 Γ and Γ is the fund expanding Γ **Blastic amplitude and gap survival**

Dipole elastic amplitude has **eikonal form**: on a simple example of elastic dipole scattering off a potential. The dipole elastic amplitude Dipole elastic amplitude has **eikonal form:**

any extra survival probability factors in the interval probability factors in the interval probability factor phote endstre amplitude nus entonar form. Dipole elastic amplitu

$$
\operatorname{Im} f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = 1 - \exp[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)]
$$

$$
\sigma_{\bar{q}q}(r_p, x) = \int d^2b \, 2 \operatorname{Im} f_{el}(\vec{b}, \vec{r}_p) = \sigma_0 (1 - e^{-r_p^2/R_0^2(x)})
$$

$$
\chi(b) = -\int_{-\infty}^{\infty} dz \, V(\vec{b}, z) \qquad \text{potential is nearly imaginary}
$$

Diffractive amplitude is proportional to $\mathbf{D}^{\star}G$ and is nearest imaginary at high energies. The difference between elastic amplitudes $\mathbf{D}^{\star}G$ Diffractive amplitude is proportional to
 α is nearly imaginary at high energies. The difference between elastic amplitudes between elastic amplitudes and α **WITHER DUARK POSITION, WHICH ENTER A SHIFTED AND READSLET CONTROLLER THE DIFFRACTIVE AMPLITUDE, READSLET CONTR** Diffractive amplitude is proportional to particle mechanically, at the amplitude level. The amplitude level.

$$
\operatorname{Im} f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2 + \alpha \vec{r}) - \operatorname{Im} f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = \exp[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)] \exp[i\alpha \vec{r} \cdot \vec{\nabla}\chi(\vec{r}_1)]
$$

$$
|\vec{r}_i - \vec{r}_j| \sim b \sim R_p, \ i \neq j
$$

Exactly the soft survival probability amplitude Exactly the soft survival probability amplitude \sim statement in a statement in a similar analysis of the diffraction of the diffractio **performed in Ref. 2014 and in Ref. 2014 And in Ref. 2014 And in original conditions on the Soft survival probabilit** ϵ \mathbf{F}_{even} at the conditions is called approximate variable. $\rho_{\rm{max}}$ are as function of the dipole cross section of the dipole cross section of $\rho_{\rm{max}}$

another source of QCD factorisation breaking another source of QCD
fectoriestian by aling partial partial partial dipole and the controlled by soft spectator partons

vanishes in the black disc limit! **EXECUTE: COLL OCT LATE:**
 Perfection controlled by soft spectator partons tr so in the black also r
2002 - Andrew Corporation
2002 - Andrew Corporation

 $\frac{1}{2}$

Absorption effect is automatically included into elastic amplitude at the amplitude level $\sqrt{ }$ ⃗ is auton
at the − vennone
|
|Cally inclu into ela
' $\frac{1}{2}$ − 2 exp <mark>2 exp \$</mark> [−] ^r² −
0(s) − <mark>[s] − [s]</mark> ⃗ $\frac{1}{\sqrt{2}}$ rp(1/2 − xq)]² $\frac{1}{\sqrt{2}}$

SD-to-inclusive ratio for diffractive gauge bosons production on singulusiye ratio for diffractiye gauge hosons production o-meiusive fatio for unifactive gau_d to inclusive ratio for diffractive gauge bosons production. -to-inclusive ratio for diffractive gauge posons production The typical hard length scale related to hard vector boson production, αr ∼ α/(1−α)M, -to-inclusive ratio for diffractive gauge bosons production ward diffractive Abelian radiation is the major reason for the diffractive QCD factorisation bb-to-mentione latte for unit active gauge become pro Finally, we parameterize the proton wave function assuming the symmetric Gaussian shape for the space α and the proton distribution α The dipole description of inclusive Gauge boson production can be obtained generalizing SD-to-Inclusive Fatio for their active gauge dosons prou SD-to-inclusive ratio for diffractive gauge bosons production of the state generalizing generalizing generalizi where is known for the inclusive Drell-Yan process \mathcal{Q} , \mathcal{Q} , \mathcal{Q}

$$
\text{RP et al 2011,12} \qquad \text{Im } f_{el}(\vec{b}, \vec{R}_{ij} + \alpha \vec{r}) - \text{Im } f_{el}(\vec{b}, \vec{R}_{ij}) \simeq \frac{\partial \text{Im } f_{el}(\vec{b}, \vec{R}_{ij})}{\partial \vec{R}_{ij}} \alpha \vec{r}
$$

$$
|\Psi_{i}(\vec{r}_{1},\vec{r}_{2},\vec{r}_{3};x_{q},\{x_{q}^{2,3,\dots}\},\{x_{g}^{2,3,\dots}\})|^{2} = \frac{3a^{2}}{\pi^{2}}e^{-a(r_{1}^{2}+r_{2}^{2}+r_{3}^{2})}\rho(x_{q},\{x_{q}^{2,3,\dots}\},\{x_{g}^{2,3,\dots}\})
$$

$$
\times \delta(\vec{r}_{1}+\vec{r}_{2}+\vec{r}_{3})\delta(1-x_{q}-\sum_{j}x_{q/g}^{j}),
$$

$$
\int d^{2}r_{1}d^{2}r_{2}d^{2}r_{3}e^{-a(r_{1}^{2}+r_{2}^{2}+r_{3}^{2})}\delta(\vec{r}_{1}+\vec{r}_{2}+\vec{r}_{3}) = \frac{1}{9}\int d^{2}R_{12}d^{2}R_{13}e^{-\frac{2a}{3}(R_{12}^{2}+R_{13}^{2}+R_{12}^{2}\vec{R}_{13})}
$$

$$
\begin{bmatrix}\n\frac{d\sigma_{\lambda_G}^{sd}/d^2q_{\perp} dx_1 dM^2}{d\sigma_{\lambda_G}^{incl}/d^2q_{\perp} dx_1 dM^2} = \frac{a^2}{6\pi} \frac{\bar{R}_0^2(M_{\perp}^2/x_1s)}{B_{sd}(s)\bar{\sigma}_0} \frac{\sigma_0^2(s)}{R_0^4(s)} \frac{1}{A_2} \Big[\frac{2}{(A_2 - 4A_1)^2} + \frac{A_2^2}{(A_2^2 - 4A_3^2)^2} \Big] \\
2a \qquad 2 \qquad 2a \qquad 2a \qquad 1\n\end{bmatrix}
$$

⁰.¹⁴ , R²

R¯2

⁰(x2)

⁰(x2)

 $\frac{1}{\sqrt{2}}$ = $\frac{1}{\sqrt{2}}$ = $\frac{1}{\sqrt{2}}$

$$
A_1 = \frac{2a}{3} + \frac{2}{R_0^2(s)}, \qquad A_2 = \frac{2a}{3}, \qquad A_3 = \frac{2a}{3} + \frac{1}{R_0^2(s)} \qquad \text{Soft KST (large dipoles)}
$$

Hard GRW (small dinoles)

Hard GBW (small dipoles)

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Hard GBW (small dipoles)\n
$$
\overline{\sigma}_0 = 23.03 \,\text{mb}, \quad \overline{R}_0(x_2) = 0.4 \,\text{fm} \times (x_2/x_0)^{0.144}, \quad x_0 = 3.04 \times 10^{-4} \,\text{m} \left(\frac{R_0(s) = 0.88 \,\text{fm} \,(s_0/s)^{0.14}}{\sigma_0(s) = \sigma_{tot}^{\pi p}(s) \left(1 + \frac{3R_0^2(s)}{8\langle r^2, \rangle_{\pi}} \right)} \right)
$$

diffractive (Regge) slope $B_{sd}(s) \simeq \langle r_{ch}^2 \rangle / 3 + 2 \alpha'_{I\!\!P} \ln(s/s_0)$ $\frac{1}{\sqrt{1-\frac{1}{2}}\left(1-\frac{1}{2}\right)}$ σ $\langle c_{th} \rangle /3 + 2\alpha'_{I\!\!P} \ln(s)$ diffractive (Regge) slope $B_{sd}(s) \simeq \langle r_{ch}^2 \rangle / 3 + 2 \alpha'_P \ln(s/s_0)$ $\frac{1}{1}$ and $\frac{1}{1}$ are $\frac{1}{1}$ $\frac{1}{1}$ $\frac{1}{1}$ $\frac{1}{1}$ $\frac{1}{1}$ $\frac{1}{1}$

Hence, such a quantity is a very useful probe for the underlined QCD diffractive mecha-diffractive slope from the explicit parameterisation for the partial dipole amplitude (3.12). angular correlation in DDY as in inclusive DY! $\langle r_{ch}^2 \rangle_{\pi} = 0.44 \text{ fm}^2$ over and $\overline{}$ by means of the following $\overline{}$ 0.25 GeV[−]² $\frac{1}{2}$ oto 4 $\frac{1}{2}$ o 222 **licts the same** At the leading twist, the dipole approach predicts the same angular correlation in DDY as in inclusive DY!
 $\langle r_{ch}^2 \rangle_{\pi} = 0.44 \text{ fm}^2$ dar correlation in DDY as in inclusive l ≃ angular correlation in DDY as in inclusive DY! r · ⃗ r′ ' $\frac{1}{3}$ ≃ incl R¯2 sive L

parametrization of the elastic slope B_T and the elastic slope B_T and the elastic slope B_T

$\overline{}$ or $\overline{}$ is the $\overline{}$ in $\overline{}$ $\mathcal{P} = \mathcal{P}(0|\mathcal{S})$ soft KST (large dipoles)

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Hard GBW (small dipoles)		
$\overline{\sigma}_0 = 23.03 \text{ mb}, \quad \overline{R}_0(x_2) = 0.4 \text{ fm} \times (x_2/x_0)^{0.144}, \quad x_0 = 3.04 \times 10^{-4}$	$R_0(s) = 0.88 \text{ fm}(s_0/s)^{0.14}$	
difference (Regge) slope	$B_{sd}(s) \simeq \langle r_{ch}^2 \rangle / 3 + 2\alpha'_{IP} \ln(s/s_0)$	$\sigma_0(s) = \sigma_{tot}^{\pi p}(s) \left(1 + \frac{3R_0^2(s)}{8\langle r_{ch}^2 \rangle_{\pi}}\right)$
At the leading twist, the dipole approach predicts the same angular correlation in DDY as in inclusive DY!	$\sigma_{tot}^{\pi p}(s) = 23.6(s/s_0)^{0.08} \text{ mb}$	

Diffractive factorisation breaking in DDY

PT correlations in inclusive and diffractive Drell-Yan \overline{a} ations in inclusive and diffractive Drell-Ya \overline{a}

Angular correlations in Drell-Yan as a probe for saturation T → 1.5 GeV √s = 200 GeV √s = 20
Construction = 200 GeV → 200 G T → 1.5 GeV √s = 500 GeV √s = 500
Contract = 500 GeV → 500 GeV <u>Il correlations in</u> Γ dren c tor \mathbf{M} \mathbf{m} and \mathbf{m} 5e-06 rol **)ns in Drell-Yan as a p**
era.∨. Goncalves PRD93, 2016 – ®^{.0.0}

Heavy flavour production: Bremsstrahlung vs Fusion opposite direction and give rise to a leading hadron possible in a formula μ q_0 , q_1 , q_2 + q_3 + q_4 + q_5 + q_6 + q_7 + q_8 + q_9 + q_9 a and where the virtual gluon G∗reen G∗r
G∗reen G∗reen G∗ree the projection and thus the corresponding cross section will be dominated essentially be dominated essentially k atroblung ve Fusio i **Heavy flavour production: Bremsstrahlung vs Fusion**

B. Kopeliovich et al, PRD76 2007 *Gauge-invariant sub-sets of diagrams* Gauge-invariant sub-sets of diagrams

Gauge-invariant sub-sets of diagrams \overline{a}

 2007 et al, PRD76 2007 **B. Kopeliovich et al, PRD76 2007**

<u>Gluon virtuality</u>

$$
(p_2 - p_1)^2 \equiv -Q^2, \qquad Q^2 = \frac{\vec{\pi}^2 + \alpha^2 m_q^2}{\bar{\alpha}} \qquad \vec{\pi} = \alpha \vec{p}_2 - \bar{\alpha} \vec{k}, \qquad \vec{k} = \sum_i \vec{k}_i
$$

(2π)²

 $\overline{\imath}$

Basis for heavy flavour production in the dipole picture \equiv $ation$ in t de dipole picture $\frac{1}{2}$ are production in the dipole picture leavy Tiavour

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Dila a dila a dila

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Dipole framework for heavy flavor production section corresponding to a three-body system *Gcc*¯ . This observation follows the general le framework for heavy flavor production For the sake of concreteness in what follows we consider charm *cc*¯ pair production, unpole framework for neavy flavor produc \mathbf{D}^{\bullet} is the contribution to including the inclusive heavy flavor production, \mathbf{D}^{\bullet} production channels which have been extendion channels which have been extensively studied in the dipole framework pole framework for heavy flavor production **Tork for heavy flavo** i, $\bf r$ production **V** \overline{a} **flavor production уу на** lV I prouu

Inclusive Q-jet pT distribution in pp collisions vs LHC data suppression at large transverse momenta in the GBW model is directly associated to the Inclusive Q-jet pT distribution in pp colli

Diffractive non-Abelian (gluon) radiation via dipoles section corresponding to a three-body system *Gcc*¯ . This observation follows the general non-Abelian (gluon) radiation via dipoles ian (gluon) radiatio l. m via dinoles **Diffractive r** 2 on-Abelian (gluon) radiation via dipoles

L possible 1 $\frac{1}{\sinh \alpha t - \alpha x}$ eralised to all-order results, ALL possible higher-orde $F_{\rm eff}$ in the initial nucleon $F_{\rm eff}$ in the initial nucleon wave function wave function wave function $F_{\rm eff}$ accu for by the dipole formulation all-order re \bf{d} ua to NON-RESOLVED \bf{I} ATICALLY resumed and accounted for by the dinole for radiit all intermediate and accounted for by the dipole formula. when the LO contributions get generalised to all-order results, ALL possible higher-order
(perturbative nonperturbative) corrections due to NON-RESOLVED emissions are (perturbative+nonperturbative) corrections due to NON-RESOLVED emissions are AUTOMATICALLY resumed and accounted for by the dipole formula! \mathbf{e} alised to all-order results, ALI $$ possible nigner-order
VED emissions are and accounted for by the dipole formula:

$$
\text{SD amplitude} \qquad \frac{\overline{|A_{SD}|^2}}{\langle A_{SD}|^2} \simeq \frac{3}{256} |\Psi_{in}|^2 |\Psi_{fin}|^2 \sum_{i,j=1}^2 \left[\nabla^i \Psi_{Q\bar{Q}}^* (\alpha, \vec{r}) \nabla^j \Psi_{Q\bar{Q}} (\alpha, \vec{r}') \right] \Omega_{soft}^{ij}
$$
\n
$$
\text{``soft color screening'' part} \qquad \Omega_{soft}^{ij} = \left[\nabla^i \sigma_{q\bar{q}}(\vec{r}_{12}) + \nabla^i \sigma_{q\bar{q}}(\vec{r}_{13}) \right] \left[\nabla^j \sigma_{q\bar{q}}(\vec{r}_{12}) + \nabla^j \sigma_{q\bar{q}}(\vec{r}_{13}) \right]
$$
\n
$$
\frac{\text{SD-to-inclusive ratio}}{\overline{d\Omega}} \simeq \left(\frac{\overline{R}_0^2(x_2)}{\overline{\sigma}_0} \left[\alpha^2 + \overline{\alpha}^2 - \frac{1}{4} \alpha \overline{\alpha} \right]^{-1} F_S(x_1, s) \right) \frac{d\sigma_{\text{incl}}}{d\Omega} \qquad F_S(x_1, s) \equiv \frac{729 \, a^2 \sigma_0(x_1 s)^2 \, \Lambda(x_1 s)}{4096 \, \pi^2 \, B_{\text{SD}}(s)}
$$

given by color structure and distribution amplitudes.

 -1 but not in the leading t $\overline{\overline{}}$ correlation is affected by color-screening $\frac{1}{101}$ ar correlation is affected by color-screening interaction = 4π² σ2 ⁰(ˆs) Λ(ˆs) δij , er-twist diffraction but not in the leading tw in higher-twist diffraction but not in the leading twis d2 \mathbb{Z}^2 $\frac{d}{dt}$ and $\frac{d}{dt}$ is the phase space volume, $\frac{d}{dt}$ is the phase space volume, $\frac{d}{dt}$ is the phase space volume, $\frac{d}{dt}$ ⁴⁰⁹⁶ ^π² ^BSD(s) , x¹ ⁼ et not in the reading on The angular correlation is affected by color-screening interaction in higher-twist diffraction but not in the leading twist!

√s

 \mathcal{L} the different differen

s incl 0.0005 **SD vs inclusive: Heavy QQbar angular correlation** 3 ⃗κ4 ⊥ The relation allows to obtain an alternative expression for the second spectrum in the second spectrum in the s Heavy (1 − eiΩkur) as F(x, ei)kur) as F(x, ei)kur) This relation allows to obtain an alternative expression for the single quark spectrum in the single quar

$$
\frac{d^3\sigma(G \to Q\bar{Q} + X)}{d(\ln \alpha)d^2p_T} = \frac{1}{6\pi} \int \frac{d^2\kappa_{\perp}}{\kappa_{\perp}^4} \alpha_s^2 \mathcal{F}(x, \kappa_{\perp}^2) \times
$$
\n
$$
\left\{ \left[\frac{9}{8} \mathcal{H}_0(\alpha, \bar{\alpha}, p_T) - \frac{9}{4} \mathcal{H}_1(\alpha, \bar{\alpha}, p_T, \kappa) + \mathcal{H}_2(\alpha, \bar{\alpha}, p_T, \kappa) + \frac{1}{8} \mathcal{H}_3(\alpha, \bar{\alpha}, p_T, \kappa) \right] + [\alpha \longleftrightarrow \bar{\alpha}] \right\}
$$

 $\mathcal{L}_{\mathcal{D}}$ function condition function function $\mathcal{D}_{\mathcal{D}}$ for the associated $\mathcal{D}_{\mathcal{D}}$ The same for inclusive and leading-twist single-diffractive QQbar production!

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 $\mathbf{F} = \mathbf{F}$

0.0015

φ)

Diffractive Higgsstrahlung off heavy quarks

FIG. 1: Leading-order gluon-initiated contributions to the inclusive \mathcal{L} system production in \mathcal{L} *RP, B. Kopeliovich, I. Potashnikova, PRD92 2015*

Diffractive Higgsstrahlung off heavy quarks

Summary

- ✓ Hadronic diffraction is one of the most prominent tools for probing the long-distance effects in QCD
- Major sources of diffractive factorisation breaking in hadron-hadron collisions are (i) the absorptive corrections, and (ii) the hard-soft interplay due to transverse motion of spectators, making the hadronic diffraction of the leading-twist nature
- ✓ The dipole picture provides universal and robust means for studies the inclusive and single-diffractive processes in both pp and pA collisions at large Feynman xF beyond QCD factorisation
- ✓ The universal partial dipole amplitude accounts for the absorptive corrections such that no additional probabilistic fudge factors are necessary in the dipole picture
- ✓ Single-diffractive gauge bosons' (e.g. Drell-Yan) and heavy flavour production at large Feynman xF has been studied beyond diffractive factorisation
- ✓ The SD-to-diffractive ratio affects the scale and rapidity dependence of the leading-twist hadronic diffractive observables compared to the inclusive ones, the angular correlations are the same as in the inclusive case.