Dipole picture of diffractive production: from Drell-Yan to di-jets

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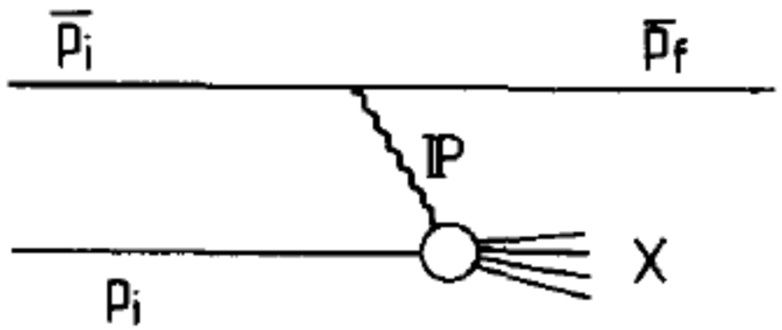
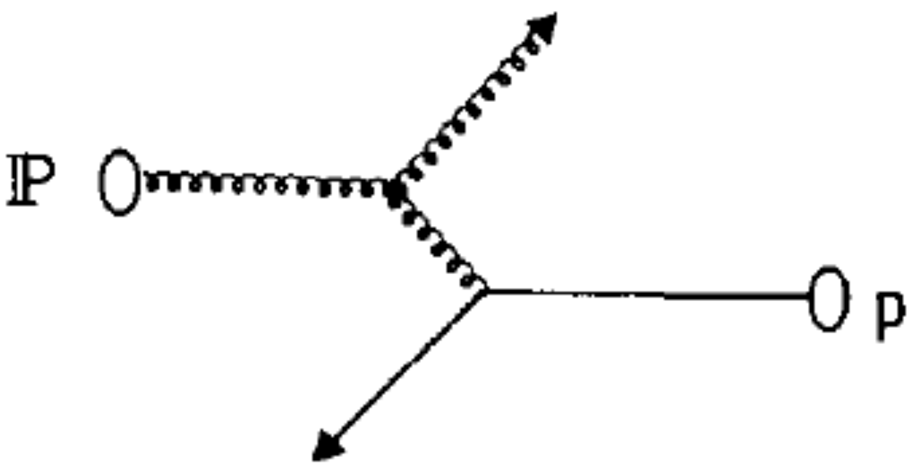
Birth of hard diffraction: QCD modelling of Pomeron

Ingelman-Schlein, Phys. Lett. 1985

Introduce a hard scale to probe "parton skeleton" of the Pomeron!





Monte-Carlo model with effective

$I\!P$ flux $f_{I\!P/p}(x_{I\!P}, t)$

$I\!P$ parton densities $f_{q,g/I\!P}(z, Q^2)$

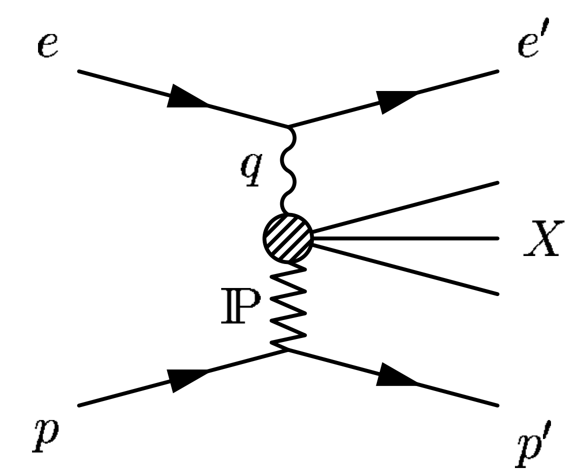
$\Rightarrow \boxed{d\sigma \sim f_{I\!P/p}\, f_{q,g/I\!P}\, f_{q,g/p}\, d\hat{\sigma}_{\text{pert. QCD}}}$

Diffractive factorisation concept

Implemented in POMPYT, CASCADE, and PYTHIA8 MC

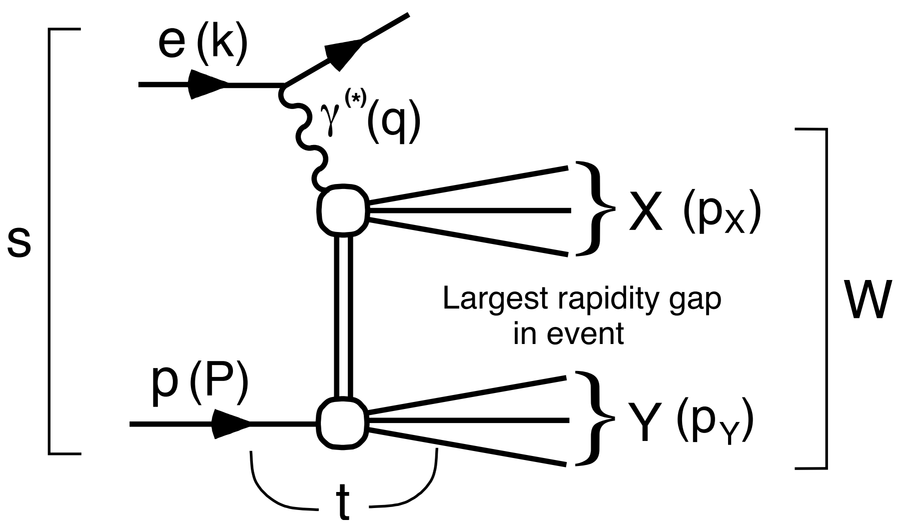
Predictions for

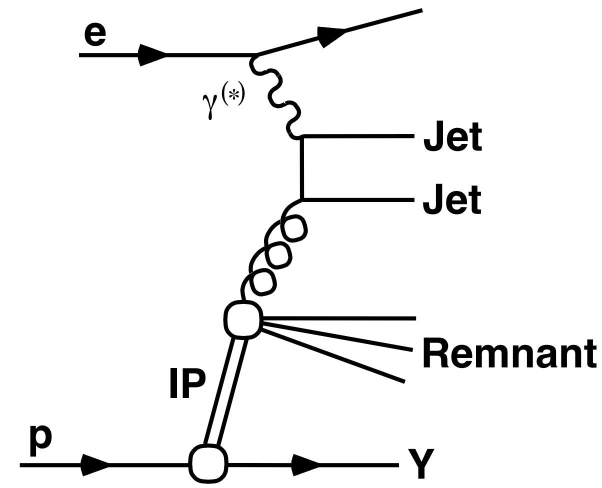
- ★ jets in diffractive $p\bar{p}$ scattering
  - $\Rightarrow$ basis for UA8 experiment
- ★ diffractive DIS at HERA

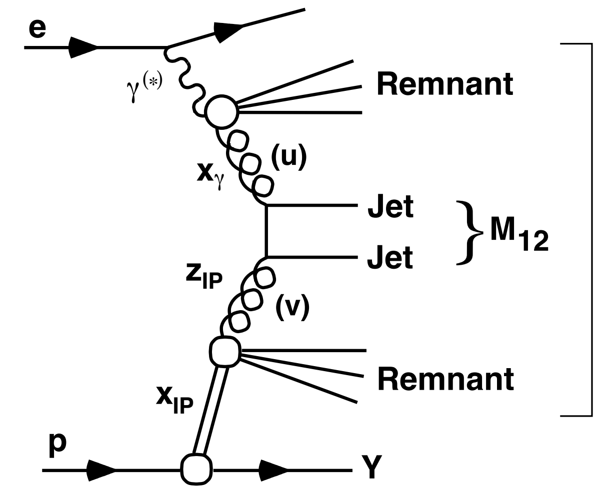


Diffractive factorisation scheme: diffractive di-jet

generic diffractive scattering at HERA | **LO di-jet (photon-gluon)** | **LO di-jet (gluon-gluon)**







Introduce a hard scale to probe "parton skeleton" of the Pomeron!

Access to gluon content of the Pomeron!

DIS kinematics $Q^2 \equiv -q^2\,, \quad y \equiv \frac{q\cdot P}{k\cdot P}\,, \quad x \equiv \frac{Q^2}{2P\cdot q} \quad Q^2 \approx sxy \quad s \equiv (k+P)^2$

$$W = \sqrt{(q+P)^2} \approx \sqrt{y\,s - Q^2} \qquad M_X^2 \equiv p_X^2\,, \quad M_Y^2 \equiv p_Y^2\,, \quad t \equiv (P-p_Y)^2\,, \quad x_{I\!P} \equiv \frac{q\cdot(P-p_Y)}{q\cdot P}$$

factorisation formula

$$\boxed{\begin{aligned} d\sigma(ep \to e + 2\,\text{jets} + X' + Y) &= \sum_{i,j} \int \mathrm{d}y\, f_{\gamma/e}(y) \int \mathrm{d}x_\gamma\, f_{j/\gamma}(x_\gamma, \mu_F^2)\ \times \\ &\times \int \mathrm{d}t \int \mathrm{d}x_{I\!P} \int \mathrm{d}z_{I\!P}\, d\hat{\sigma}(ij \to 2\,\text{jets})\, f_i^D(z_{I\!P}, \mu_F^2, x_{I\!P}, t) \end{aligned}}$$

- ✓ Diffractive PDFs are non-universal
- ✓ They can not be exported to describe other hard diffractive processes (e.g. in pp)
- ✓ We need to calculate the survival probability of the LRG's which is process-dependent

QCD factorisation in diffraction

We have two different factorisations:

- diffractive fact.n: proven by Collins for a hard diffractive scattering (hep-ph/9709499)
- Regge fact.n: relates the power of $x_{\mathbb{P}}$ in diffractive DIS to the power of s in hadron-hadron elastic scattering and can be broken

Pomeron PDFs

DPDF $$f_i^D(z_{I\!P}, \mu_F^2, x_{I\!P}, t) = f_{I\!P}(x_{I\!P}, t)\ f_{i,I\!P}(z_{I\!P}, \mu_F^2)$$

soft and hard scales are separated!

Berera, Soper PRD'96

universal (soft) Pomeron flux in the proton (Regge theory)

DGLAP-evolved parton density in the Pomeron

At larger x subleading "Reggeon" is to be included

fit to inclusive diffraction data by H1 (2006) and ZEUS (2009)

$x_{I\!P} > 0.01$

$$\ldots + f_{IR}(x_{IP}, t) f_i^{IR}(z, Q^2)$$

Reggeon PDFs taken from pion (GRV)

Fit z and Q^2 dependence at fixed x_{IP} and t

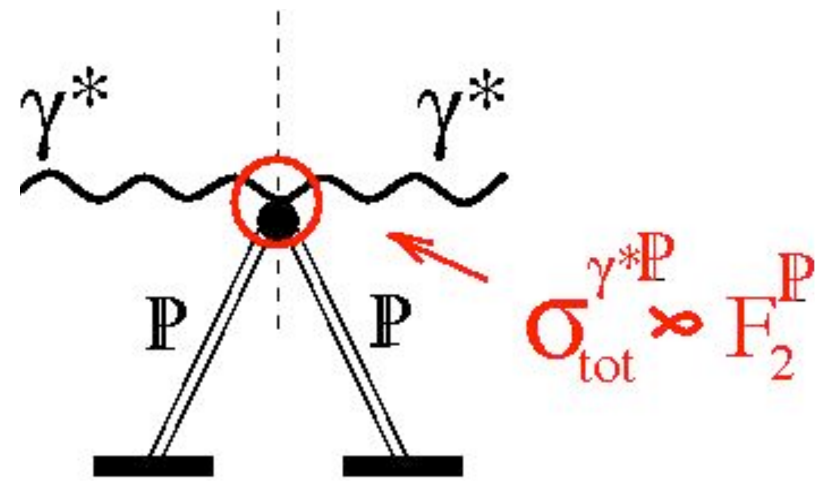
Flux parametrisation

$$f(x_{IP}, t) = \frac{Ae^{Bt}}{x_{IP}^{2\alpha(t)-1}}$$

with $\alpha(t) = \alpha(0) + \alpha' t$

- ✓ DPDFs are extracted from global NLO fits of inclusive diffraction data at HERA
- ✓ Predictions based upon extracted DPDFs are fairly consistent with theoretical models
- ✓ Important tool for diffractive factorisation breaking studies (especially in had-had coll.)

QCD factorisation in diffraction



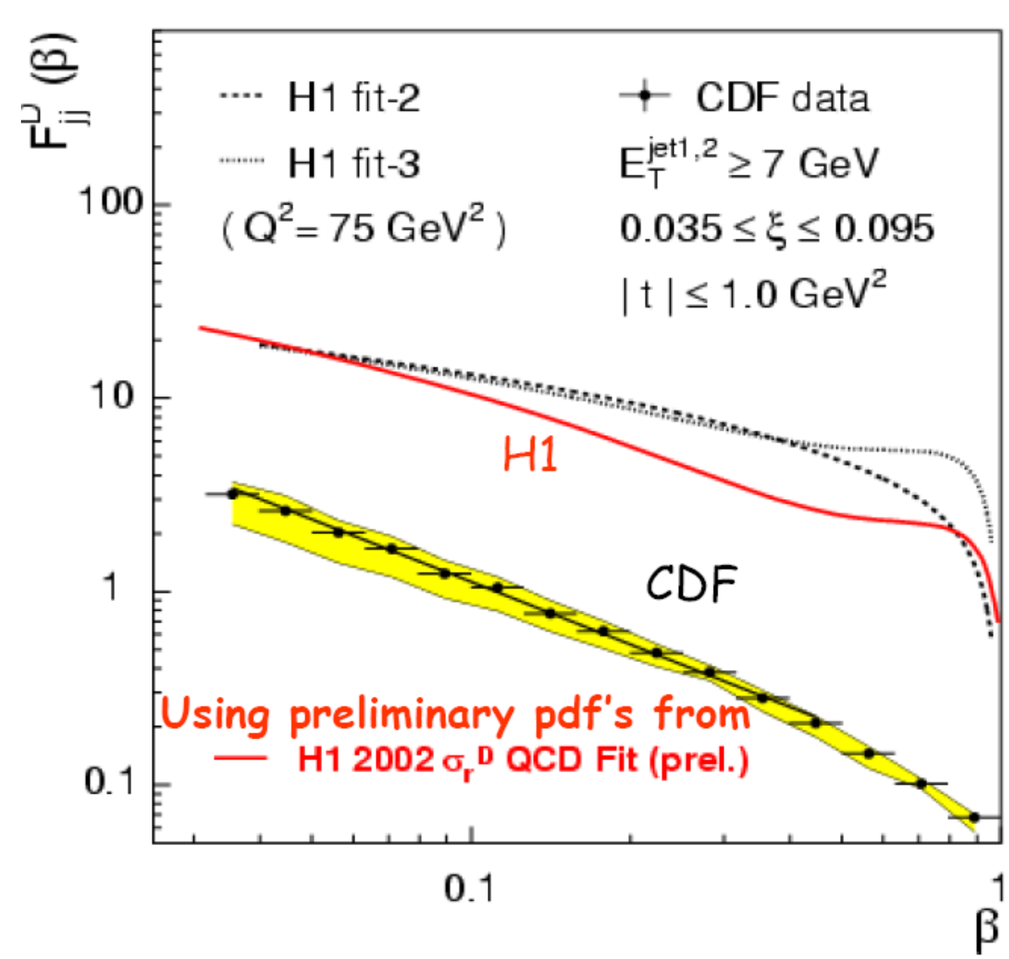
- Triple-Regge graphs for diffractive DIS offer a way to probe the structure function of the Pomeron

- Provided that the parton densities in the Pomeron are known, and factorisation holds, one can predict the cross section of any hard diffractive process

- Diffractive di-jets production in hadron-hadron collisions is an important probe of QCD factorisation in hadronic diffraction, historically has been used to test QCD factorisation at Tevatron

- Attempts to use the diffractive PDFs of the Pomeron for diffractive jets production have failed: Tevatron data contradict the predictions by an order of magnitude

- The reason: QCD factorisation is broken for hard hadronic diffraction!



QCD factorisation breaking in had-had collisions

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

Sources of QCD factorisation breaking, usually discussed:

- ✓ soft survival (=absorptive) effects (Khoze-Martin-Ryskin and Gotsman-Levin-Maor)
- ✓ 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:

- ✓ **Regge-corrected (KMR) approach** — the first source of Regge factorisation breaking is accounted at the cross section level by "dressing" QCD 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)

Good-Walker formulation

Kopeliovich & Povh, Z.Phys. A354 (1997)

R. J. Glauber, Phys. Rev. 100, 242 (1955).
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!

Diffractive excitation determined by the fluctuations

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

Hadron can be excited: not an eigenstate of interaction!

Mean dipole separation:

$$\langle r^2 \rangle = \frac{1}{Q^2 z(1-z) + m_q^2}$$

Completeness and orthogonality

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

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

semi-hard/ semi-soft   soft

		$\|C_\alpha\|^2$	σ_α	$\sigma_{tot} = \sum_{\alpha=soft}^{hard} \|C_\alpha\|^2 \sigma_\alpha$	$\sigma_{sd} = \sum_{\alpha=soft}^{hard} \|C_\alpha\|^2 \sigma_\alpha^2$
$\langle r^2 \rangle \sim 1/Q^2$	Hard	~ 1	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^4}$
$\langle r^2 \rangle \sim 1/m_q^2$	Soft	$\sim \frac{m_q^2}{Q^2}$	$\sim \frac{1}{m_q^2}$	$\sim \frac{1}{Q^2}$	Aligned jets! $\sim \frac{1}{m_q^2 Q^2}$

Elastic and single diffractive amplitudes

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

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

Single diffractive cross section

$$\sum_{h'\neq h} \frac{d\sigma_{sd}^{h\to h'}}{dt}\bigg|_{t=0} = \frac{1}{4\pi}\left[\sum_{h'} |f_{sd}^{hh'}|^2 - |f_{el}^{hh}|^2\right]$$

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

Dispersion of the eigenvalues distribution

Important basis for the dipole picture!

Phenomenological dipole approach

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

Eigenvalue of the total cross section is the universal dipole cross section

Eigenstates of interaction in QCD: color dipoles

SD cross section

$$\sum_{h'} \frac{d\sigma_{sd}^{h\to h'}}{dt}\bigg|_{t=0} = \sum_{\alpha=1} |C_\alpha^h|^2 \frac{\sigma_\alpha^2}{16\pi} =$$

$$\int d^2 r_T |\Psi_h(r_T)|^2 \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle\sigma^2(r_T)\rangle}{16\pi}$$

wave function of a given Fock state

total DIS cross section

$$\sigma_{tot}^{\gamma^* p}(Q^2, x_{Bj}) = \int d^2 r_T \int_0^1 dx \left|\Psi_{\gamma^*}(r_T, Q^2)\right|^2 \sigma_{\bar{q}q}(r_T, x_{Bj})$$

Theoretical calculation of the dipole CS is a challenge

BUT! *Can be extracted from data and used in ANY process!*

Example: Naive GBW parameterization of HERA data

$$\sigma_{\bar{q}q}(r_T, x) = \sigma_0 \left[1 - e^{-\frac{1}{4} r_T^2 Q_s^2(x)}\right]$$

saturates at large separations

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

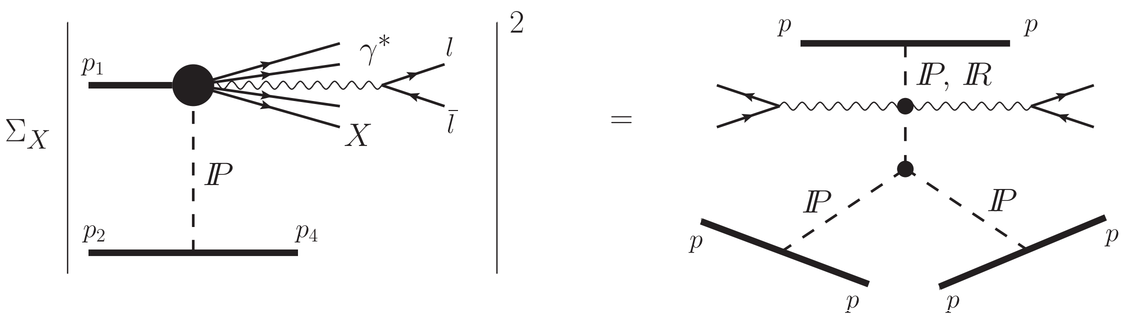
color transparency $\sigma_{\bar{q}q}(r_T) \propto r_T^2 \qquad r_T \to 0$

QCD factorisation $\sigma_{q\bar{q}}(r, x) \propto r^2 x g(x)$

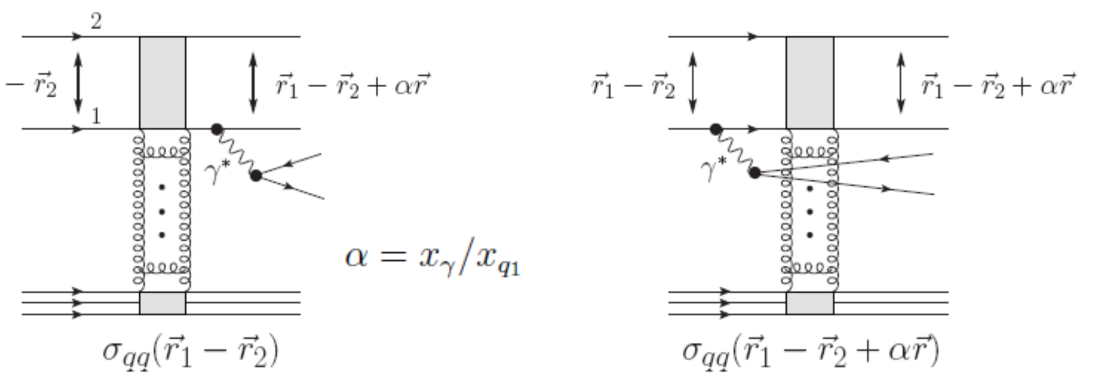
A point-like colorless object does not interact with external color field!

ANY diffractive scattering is due to a destructive interference of dipole scatterings!

Hadronic diffraction via dipoles: diffractive Drell-Yan



Diffractive Drell Yan (semi-hard)



interplay between hard and soft fluctuations is pronounced!

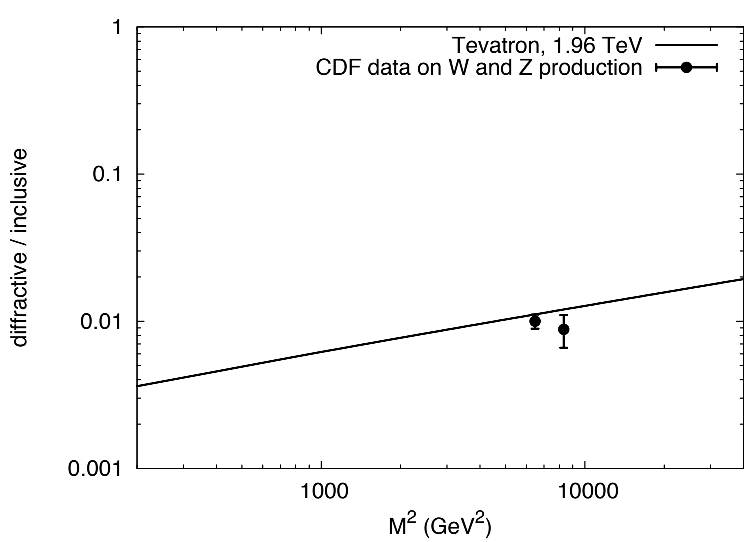
superposition has a Good-Walker structure

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

Diffractive DIS $\propto r^4 \propto 1/M^4$ vs diffractive DY $\propto r^2 \propto 1/M^2$

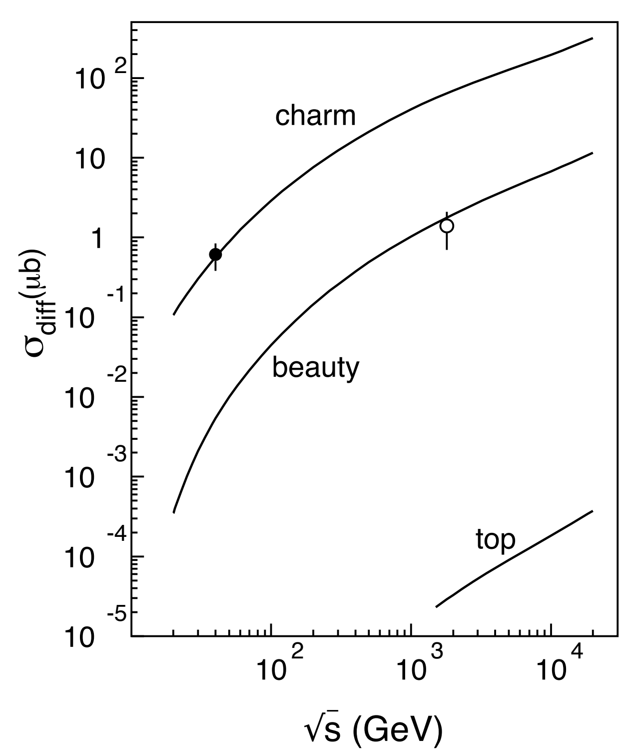
$$\frac{\sigma_{\rm sd}^{\rm DY}}{\sigma_{\rm incl}^{\rm DY}} \propto \frac{\exp(-2R^2/R_0^2)}{R_0^2}$$

SD DY/gauge bosons



RP et al 2011,12

SD heavy quarks



Kopeliovich et al 2006

★ *diffractive factorisation is automatically broken*

★ *any SD reaction is a superposition of dipole amplitudes*

★ *gap survival is automatically included at the amplitude level on the same footing as dip. CS*

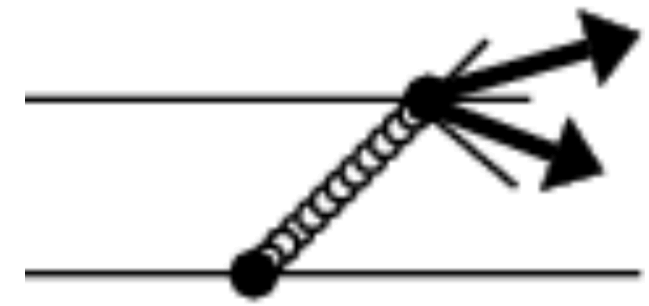
★ *works for a variety of data in terms of universal dip. CS*

Sophisticated dipole cascades are being put into MC: Lund Dipole Chain model (DIPSY)
Ref. G. Gustafson, and L. Lönnblad

Diffractive vs inclusive di-jets

RP, B. Kopeliovich, I. Potashnikova, arXiv:1897.05548

$$\mathcal{R}_{\rm SD/incl} = \frac{\Delta\sigma_{\rm SD}/\Delta\xi}{\Delta\sigma_{\rm incl}}\,, \qquad \Delta\xi = 0.06\,, \qquad \xi \equiv 1 - x_F = \frac{M_X^2}{s}$$



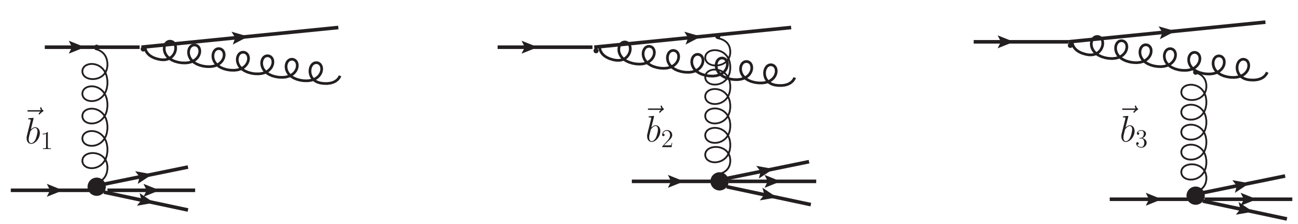
fractional longitudinal momentum of the recoil p

Scale

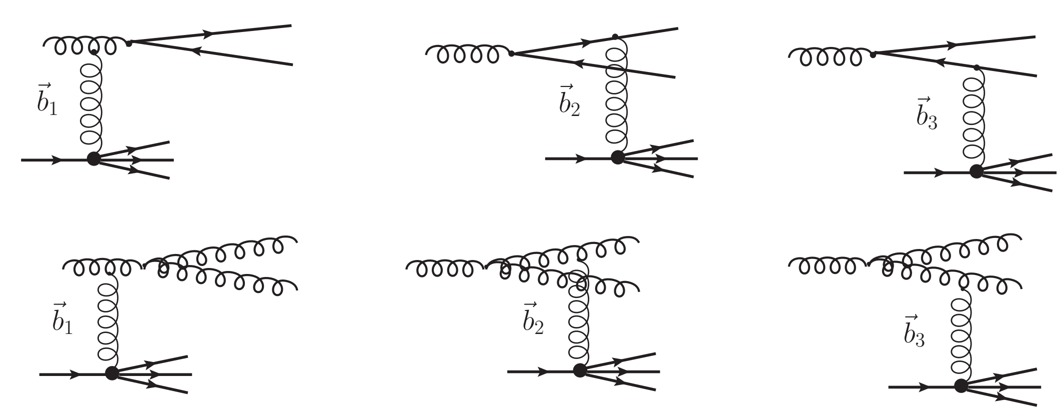
$$Q^2 = \frac{(E_T^1 + E_T^2)^2}{4}\,, \qquad x_{\rm Bj} = \frac{1}{\sqrt{s}} \sum_{i=1}^{3\,\rm jets} E_T^i e^{-\eta_i}$$

fractional LC momentum of the target parton (analog x2 in Drell-Yan)

Quark-gluon dijets



Quark-antiquark & gluon-gluon dijets



Inclusive quark-nucleon cross section

$$\frac{d\sigma_{\rm incl}(qN \to qGX)}{d(\ln\alpha)} = \int d^2r\, |\Psi_{q\to qG}(\vec{r},\alpha)|^2\, \Sigma_{\rm eff}^{q\to qG}(\vec{r},\vec{r},\alpha)$$

$$\Sigma_{\rm eff}^{q\to qG}(\vec{r},\vec{r},\alpha) \simeq \mathcal{K}_{\rm incl}^{q\to qG}(x_2,\alpha)\, r^2\,, \quad \mathcal{K}_{\rm incl}^{q\to qG}(x_2,\alpha) = \frac{\sigma_0}{R_0^2(x_2)} \cdot \left[\frac{9}{4}\bar{\alpha} + \alpha^2\right], \quad x_2 = \frac{M^2}{x_q\, s}$$

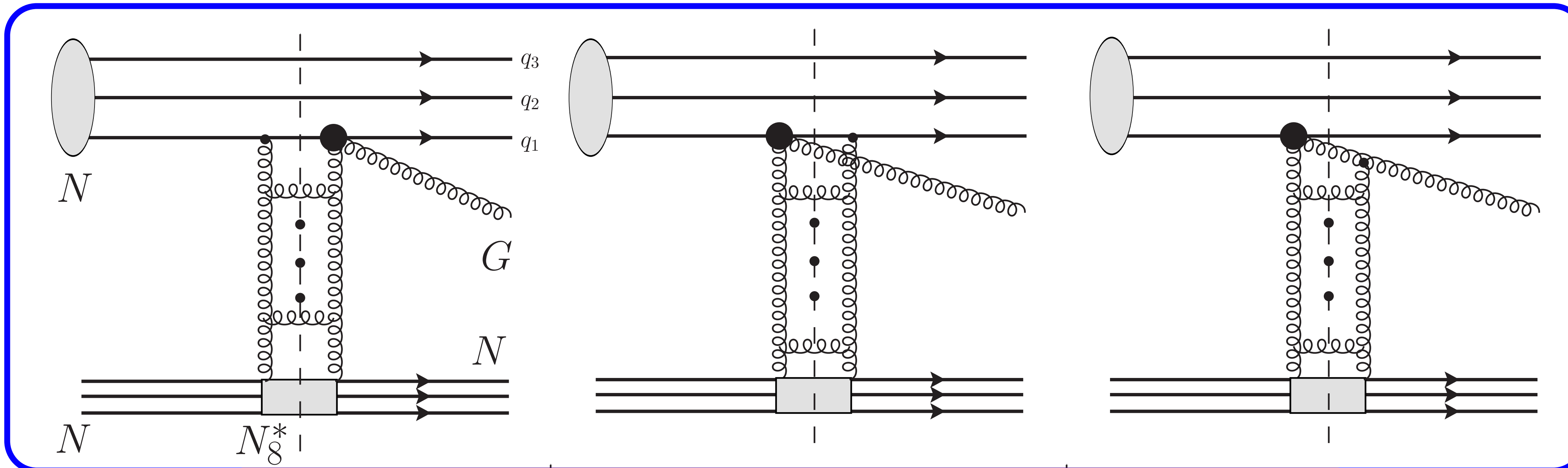
$$\mathcal{K}_{\rm incl}^{G\to q\bar{q}}(x_2,\alpha) = \frac{\sigma_0}{R_0^2(x_2)} \cdot \left[1 - \frac{9}{4}\alpha\bar{\alpha}\right]$$

$$\mathcal{K}_{\rm incl}^{G\to G_1G_2}(x_2,\alpha) = \frac{9\sigma_0}{4R_0^2(x_2)} \cdot \left[1 - \alpha\bar{\alpha}\right]$$

Diffractive di-jets: qN vs NN collisions

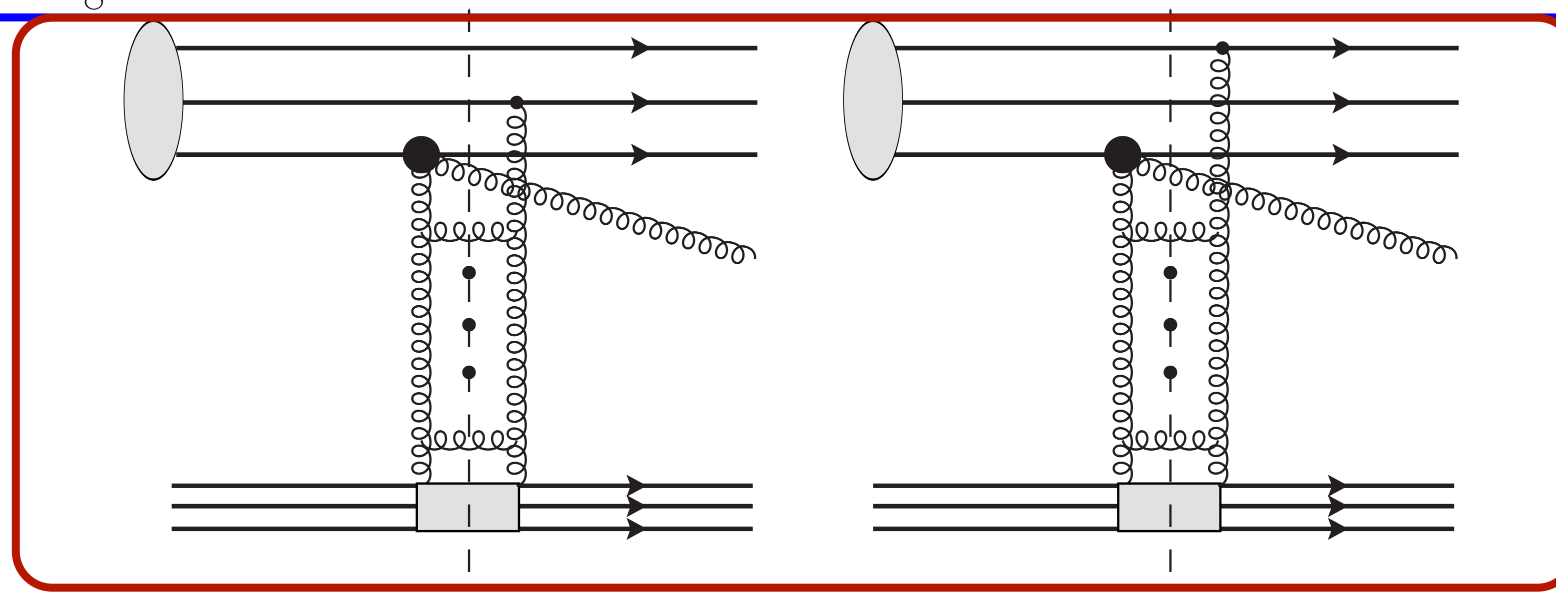
Higher-twist

(diffractive quark-nucleon scattering)



Leading-twist

(diffractive pp scattering)



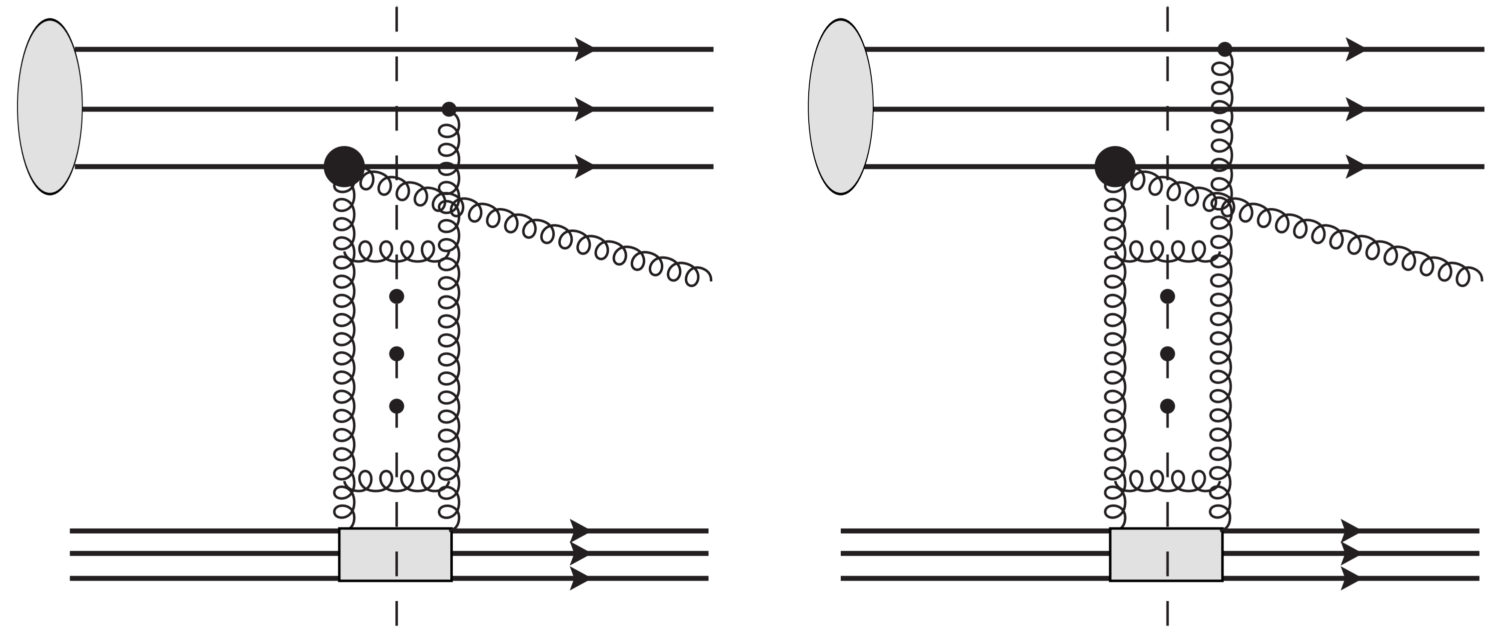
SD quark-nucleon cross section

$$\frac{d^3\sigma_{\rm SD}(qN\to qGN)}{d(\ln\alpha)d^2q_\perp}\Big|_{q_\perp\to 0} = \frac{1}{16\pi^2}\int d^2r\left|\Psi_{q\to qG}(\vec{r},\alpha)\tilde{\sigma}_{q\bar{q}}(\vec{r})\right|^2, \quad \tilde{\sigma}_{q\bar{q}}(\vec{r})\equiv\frac{9}{8}\sigma_{q\bar{q}}(\vec{r})$$

$$\frac{d^3\sigma_{\rm SD}(qN\to qGN)}{d(\ln\alpha)d^2\kappa\, d^2q_\perp}\Big|_{q_\perp\to 0} = \frac{1}{16\pi^2}\,\frac{81}{64}\,\frac{\sigma_0^2}{R_0^4(x)}\,\frac{1}{(2\pi)^2}\boxed{\frac{1}{2}\sum_{i,f,\lambda_G}\left|(\vec{\nabla}_\kappa\cdot\vec{\nabla}_\kappa)\,\hat{\tilde{\Psi}}_{q\to qG}(\vec{\kappa},\alpha)\right|^2}$$

$$\frac{128\alpha_s}{3}\,\frac{2-\alpha(2-\alpha)}{\kappa^6}$$

Diffractive di-jets in NN collisions



Interplay of hard and soft scales!

Integrating out all soft-scale phenomena over the incoming projectile wave function:

$$\frac{d\sigma_{\rm SD}^{q\to qG}}{d\Omega} \simeq \frac{\mathcal{K}_{\rm SD}^{q\to qG}(s,\hat{s},\alpha)}{(2\pi)^2}\, q(x_q,\mu^2) \int d^2\rho d^2\rho'\, e^{i\vec{\kappa}(\vec{\rho}-\vec{\rho}\,')}\, (\vec{\rho}\cdot\vec{\rho}\,') \times \overline{\sum} \hat{\Psi}_{q\to qG}(\vec{\rho},\alpha) \hat{\Psi}^{\dagger}_{q\to qG}(\vec{\rho}\,',\alpha)\,,$$

$$\mathcal{K}_{\rm SD}^{q\to qG} = \frac{1}{B_{\rm SD}} \frac{9a\overline{\sigma}_0(\hat{s})^2}{256\pi} \Big\{ \mathcal{W}_1(\hat{s}) \Big[1 - \frac{2\alpha}{3} + \frac{7\alpha^2}{27}\Big] + \mathcal{W}_2(\hat{s}) \Big[1 + \frac{2\alpha}{3} - \frac{13\alpha^2}{27}\Big] \Big\}\,,$$

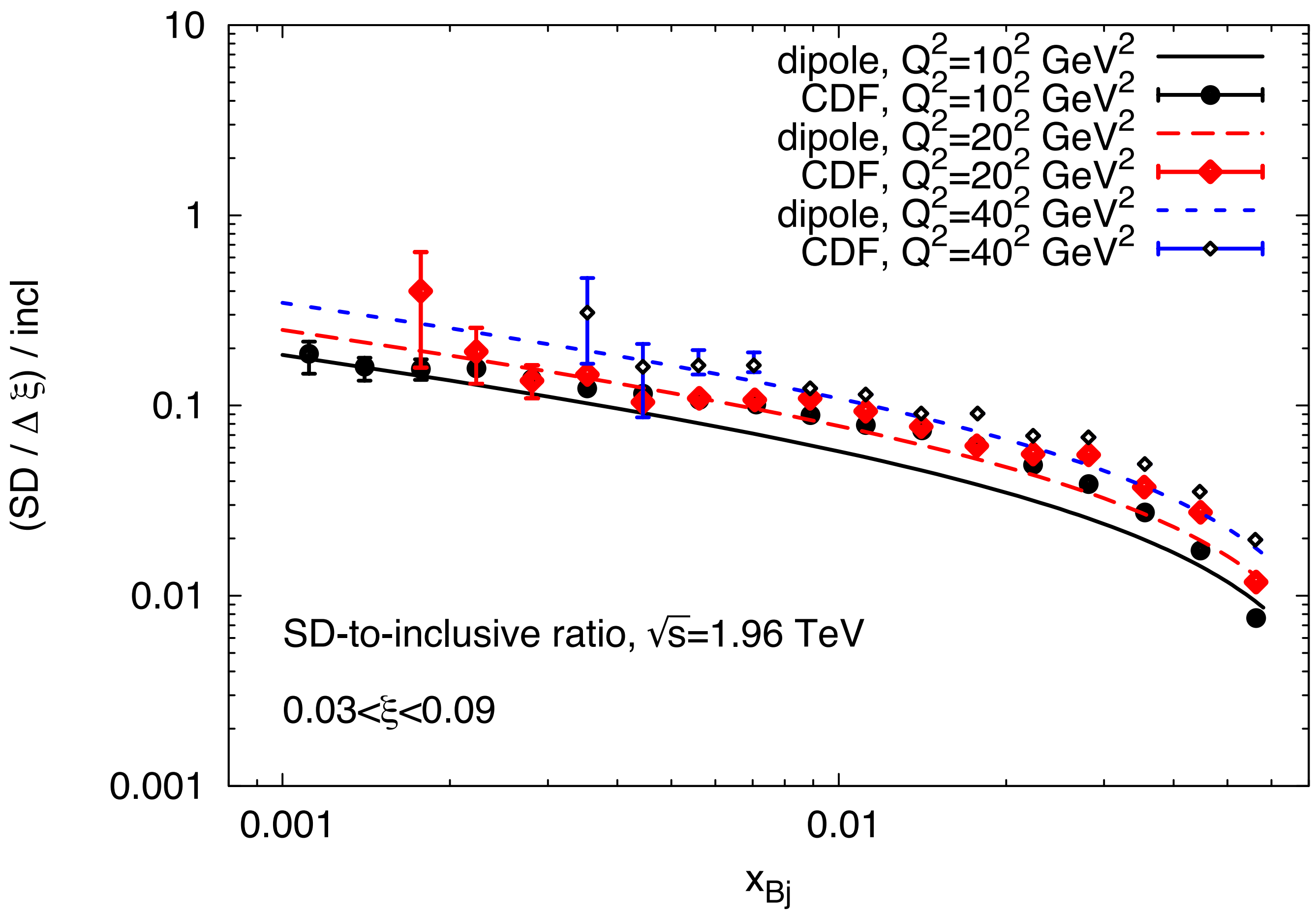
$$\mathcal{W}_1(\hat{s}) = \frac{8}{(4+a\overline{R}_0^2)^2} + \frac{12}{(12+a\overline{R}_0^2)^2}\,, \qquad \hat{s} = x_q\, s\,, \qquad \overline{R}_0 = \overline{R}_0(\hat{s})\,,$$

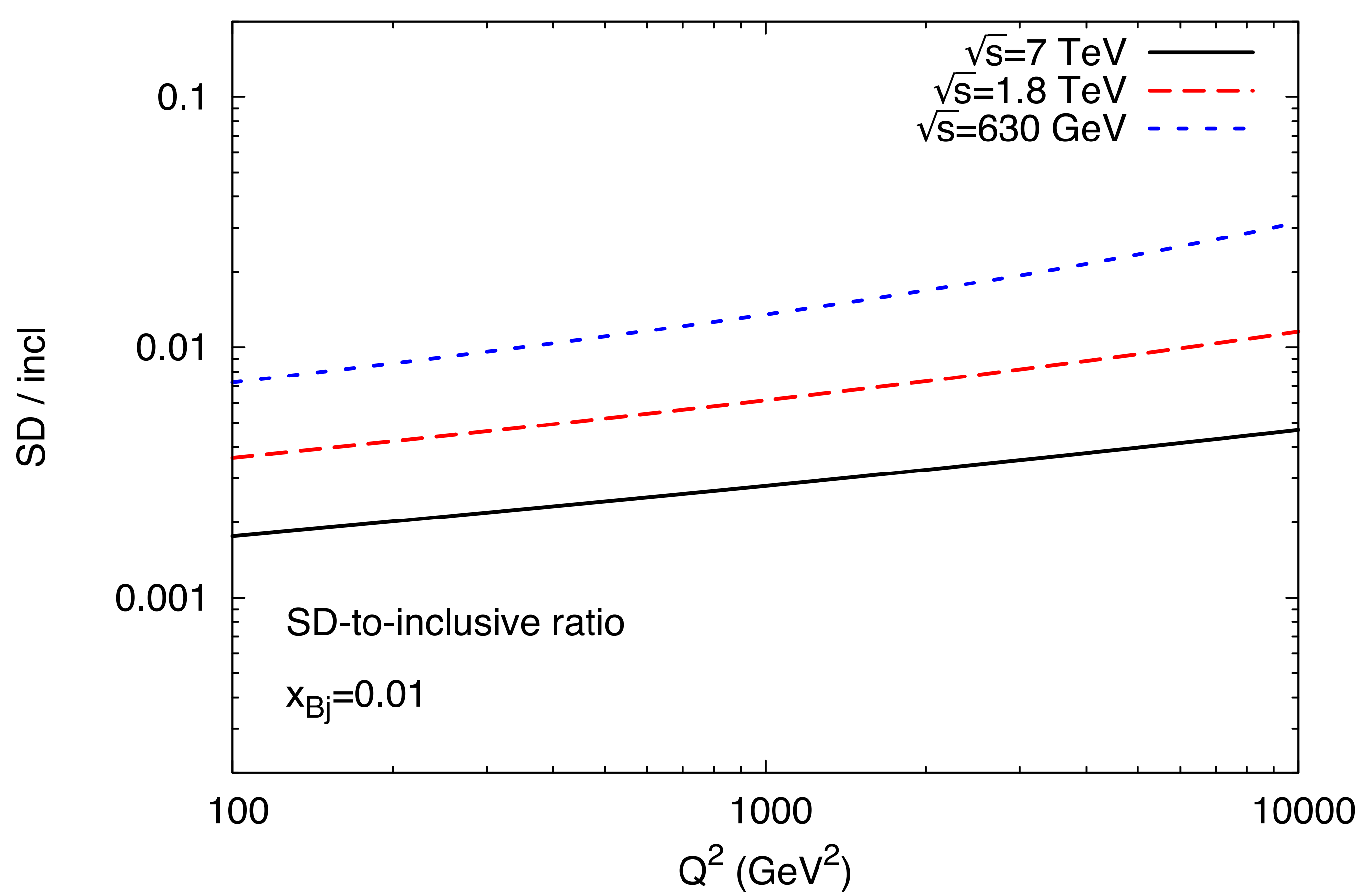
$$\mathcal{W}_2(\hat{s}) = \frac{6a^2\overline{R}_0^4}{(3+8a\overline{R}_0^2+a^2\overline{R}_0^4)^2} - \frac{a^2\overline{R}_0^4}{(3+4a\overline{R}_0^2+a^2\overline{R}_0^4)^2}\,.$$

...and analogically for qqbar & GG dijets!

Diffractive di-jets in NN collisions: results

$$\mathcal{R}_{\rm SD/incl} = \frac{1}{\Delta\xi}\,\frac{d\sigma_{\rm SD}^{q\to qG}/dx_G + d\sigma_{\rm SD}^{G\to q\bar{q}}/dx_G + d\sigma_{\rm SD}^{G\to G_1G_2}/dx_G}{d\sigma_{\rm incl}^{q\to qG}/dx_G + d\sigma_{\rm incl}^{G\to q\bar{q}}/dx_G + d\sigma_{\rm incl}^{G\to G_1G_2}/dx_G}$$





Scale and energy dependence driven by linear (in r) dependence of the diffractive amplitude is similar to that of Drell-Yan!

Conclusions

✓ The dipole picture enables to visualise the dominant configurations in diffractive reactions such as diffractive DIS in ep collisions, as well as diffractive Drell-Yan and di-jets production

✓ In DDIS, the dominant fluctuations are soft, arising from the aligned-jets configurations, yielding the same scale dependence as for the inclusive DIS.

✓ In diffractive NN collisions, the hadron-induced diffraction is driven by a different mechanism: such processes receive mixed (semi-hard/semi-soft) dominant contributions due to an interplay of hard and soft fluctuations from the hadron-scale destructively interfering projectile dipoles in the incoming hadron.